Integrated stratigraphy of the Sarmatian (Upper Middle Miocene) in the western Central Paratethys

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ABSTRACT: The Vienna Basin and the Styrian Basin have been cornerstones for the definition and description of the Central European Sarmatian Stage. New inter- and intrabasin correlations of well-logs and surface outcrops reveal a rather uniform development of depositional systems in all considered basins, which excludes local autocyclic processes as the sole trigger. The lithostratigraphy of these basins is critically summarized and the Wolfsthal Member is introduced as a new lithostratigraphic unit.

The more than 1000-m-thick Sarmatian basin-fill is recorded in geophysical logs by a characteristic succession of serrated funnel- to bell-shaped curves separated by shale-line intervals. The correlative floodings are well preserved in marginal settings and accessible in surface outcrops. Slight falls of the relative sea-level are also reflected in the littoral zone by erosive surfaces, caliche formation and progradation of fluvial facies. The stratigraphic position and duration of the Sarmatian suggests a relation to the 3rd order cycle TB. 2.6. Internally, two 4th order cycles are depicted.

An exact correlation with Mediterranean standard stages and the "Haq-cycles" is difficult due to the endemic marine fauna that flourished in the nearly land-locked Paratethys Sea during the Sarmatian. This obstacle may be overcome by a first cautious calibration of the sedimentary sequence with astronomical target curves. Hence, the 400-Ka eccentricity component might have triggered the 4th order cycles, with the maximum flooding surfaces coinciding with the maxima of that band. An overall trend from a pelitic-siliciclastic Lower Sarmatian 4th order cycle towards an oolitic Upper Sarmatian 4th order cycle could be forced by the inflection of the 2.35-Ma component. The tentative calibration requires a new positioning of the Badenian/Sarmatian boundary close to 12.7 Ma, which would fit excellently to the glacio-eustatic isotope event MSI-3.

The coincidence of the final retreat of the sea from the Molasse Basin with a major phase of progradation of alluvial fans into the Styrian and the Vienna Basins suggests a pulse of uplift in the eastern Alpine region at 12.1-12.3 Ma.

INTRODUCTION

The rise of the Alpine mountain belt led to a partition of the Tethyan Ocean around the Eocene/Oligocene boundary. This geodynamic process caused the Tethys to disappear as a paleogeographic and paleobiogeographic entity, and two different paleogeographic areas evolved - the (Neogene) Mediterranean and the Paratethys Seas. This geographic separation also resulted in a biogeographic differentiation and necessitated the establishment of different chronostratigraphic/geochronologic scales (text-fig. 1). Within the Paratethys the distinction between Western, Central and Eastern Paratethys reflects internal differentiation and a complex pattern of changing seaways and landbridges between the Paratethys and the Mediterranean as well as the western Indo-Pacific (e.g., Rögl 1998; 1999).

Within that system, the upper Middle Miocene Sarmatian Stage is outstanding due to its highly endemic marine fauna. At that time, the Paratethys Sea formed a huge inland sea which was nearly completely disconnected from the Mediterranean Sea. This Sarmatian stage was defined in the Vienna Basin as a regional stage by Suess (1866). That stratigraphic entity in its original content corresponds to the Upper Serravallian of the Mediterranean scale (text-fig. 1) and covers a time span of approximately 1.1 Ma between ~11.6 and ~12.7 Ma before present. The deposits of the Sarmatian s.s. are represented only in the Central Paratethys (e.g. Austria, Hungary, Slovakia, Czech Republic). In the Eastern Paratethys (e.g. Rumania, Bulgaria, Ukraine) this stage is opposed by the regional stages Volhynian and the Lower Bessarabian (Papp et al. 1974; Popov 2001). Biogeographically, however, both areas - the Central Paratethys and its eastern counterpart - were united during the Sarmatian (or Volhynian) and offer a strikingly similar faunistic inventory (Kolesnikov 1935; Papp 1974a).

BIOSTRATIGRAPHY

Aside from foraminifera, only molluscs allow a reliable biostratigraphic zonation of the Sarmatian and its temporal equivalents in the Eastern Paratethys. Even Suess (1866) defined the Sarmatian largely by its mollusc fauna. Later, Fuchs (1875), Winkler (1913), Papp (1956), and Veit (1943) among several others established a rather elaborated ecostratigraphic mollusc zonation for the Vienna and Styrian Basins. Herein, we define the Sarmatian as a twofold stage, consisting of a Lower and an Upper Sarmatian part. The Lower Sarmatian spans the *Mohrensternia* Zone and the lower part of the *Ervilia* Zone of the mollusc zonation along with the *Anomalinoides dividens* Zone, *Elphidium reginum* Zone, and *Elphidium hauerinum* Zone of the foraminifera zonation (Grill 1941). The Upper Sarmatian comprises the upper part of the *Ervilia* Zone and the *Sarmatimactra vitaliana* Zone of the mollusc zonation along with the entire *Porosononion granosum* Zone of the foram zonation (see Papp et al. 1974 and Cicha et al. 1998 for discussion and references concerning this ecostratigraphic concept).

GEOLOGICAL SETTING AND LITHOSTRATIGRAPHIC FRAME

Sarmatian deposits crop out along the western margin of the former Central Paratethys Sea in 4 main areas. These are the Austrian/Slovakian/Czech Vienna Basin with its Austrian/Hungarian Eisenstadt-Sopron subbasin, the Styrian Basin, and the Molasse Basin. Most comments on Sarmatian stratigraphy focused mainly on nearshore deposits which are accessible in surface outcrops (e.g. Papp et al. 1974; Friebe 1994). An interbasin synthesis of such outcrop data and a correlation with well-log data from basinal settings is still completely missing.

The Vienna Basin

This basin (text-fig. 2) is surrounded by the Eastern Alps, the West Carpathians, and the western part of the Pannonian Basin, and represents one of the best-studied pull-apart basins of the world (Royden 1985; Wessely 1988). It is rhombic, strikes roughly southwest-northeast, is 200km long and nearly 60km wide, and extends from Gloggnitz (Lower Austria) in the SSW to Napajedl (Czech Republic) in the NNE. The south-western border is formed topographically by the Eastern Alps and to the north-west by the Waschberg Unit. In the east it is bordered in the south by the hills of the Rosalia, Leitha, and the Hainburg Mountains, and in the north-east by the Male Karpaty Mountains; all four hill ranges are part of the Alpine-Carpathian Central Zone. The Vienna Basin is connected with the Danube Basin via the Hainburg gateway and with the Eisenstadt-Sopron Basin via the Wiener Neustadt gateway. The maximum thickness of the Neogene basin fill is 5500 m; the Sarmatian portion attains more than 1000 m in the central Vienna Basin (OMV data; Wessely 2000).

Lithostratigraphy: According to the formalized scheme of Vass (2002), the Sarmatian of the Vienna Basin can be subdivided into two formations: the Holíè Formation and the Skalica Formation.

The Lower Sarmatian Holíè Formation is represented by mainly grey calcareous clay, silt, and rare acidic tuff layers. The lowermost Sarmatian deposits within that formation are recorded from the Kúty and Kopcany grabens in the northern Vienna Basin in the form of variegated and spotted pelites with scattered lenses of sand, defined as Kopèany Member by Eleèko and Vass (2001) and Vass (2002). Due to the characteristic limnic/terrestric mollusc assemblage with numerous specimens of the gastropod *Carychium*, this member has been also treated as the *Carychium* beds in the older literature (Jiricek and Senes 1974). At the same time, fluvial gravel was shed via a drainage system from the Molasse Basin into the north-western Vienna Basin, where it is exposed at the Siebenhirten section on the Mistelbach Block (see also Grill 1968). Its equivalent in the northern tip of the basin is the gravel of the Radimov Member (Vass 2002). In the central and southern Vienna Basin, Brix (1988) introduced the informal lithostratigraphic term Beds of Hölles for Lower Sarmatian deposits composed mainly of marls with intercalations of clay, sand, and fine gravel. Sand and gravel predominate in marginal positions, whereas basinal settings display a predominance of marls with coarse intercalations.

In marginal settings, a characteristic Lower Sarmatian lithology is represented by bryozoan-serpulid-algae bioconstructions. These were erroneously intermingled by Nagy et al. (1993) within the Karlova Ves Member, but in fact a valid lithostratigraphic term is not available (see discussion below). Along the Leitha Mountains in the southern Vienna Basin, these bioconstructions are accompanied by several-meters-thick pale limestones (Harzhauser and Piller 2004). Another marginal facies is represented by the conglomerate of the Brunn Member (Brix 1988) along the western margin of the basin.

The Upper Sarmatian Skalica Formation displays an extraordinary variety of lithologies, ranging from marl and silt to sandstone and gravel but includes also various mixed siliciclastic-carbonatic deposits such as oolites, rock-forming coquinas, and foraminiferal bioconstructions (Eleèko and Vass 2001; Vass 2002).

Within the Skalica Formation we propose the Wolfsthal Member as a new lithostratigraphic unit. Deposits of that newly described member represent most of the Sarmatian surface outcrops in the Vienna Basin. Its oolites were exploited in numerous pits and it turned out to be an excellent lithostratigraphic marker throughout the basin.

The designated type section is the wall in the entrance of the abandoned quarry at the Wolfsthal section, which is now a deer park (N 48°07.79, E 16° 59.47). The base of the member is not exposed, but according to Wessely (1961) the oolite rests directly on granite of Lower Austro-Alpine units. The overlying unit is missing in surface outcrops due to erosion. The type section exposes a 20-m-thick succession of oolites, sandy oolites, and coquinas (see also text-fig. 10). The basal 7 m display intercalations of calcareous sand with scattered ooids. Upsection, these are followed by thick-bedded oolites with mollusc coquinas. In the middle of the section, stromatolitic layers and a tilted bioconstruction formed by the sessile foraminifer *Sinzowella* occur. A layer of caliche separates the uppermost 7 m of the section, which is characterised by a coquina of mactrid bivalves in its basal part.

At its type section the member comprises sediments of the Upper *Ervilia* Zone and lower parts of the *Sarmatimactra vitaliana* Zone (topmost 7m).

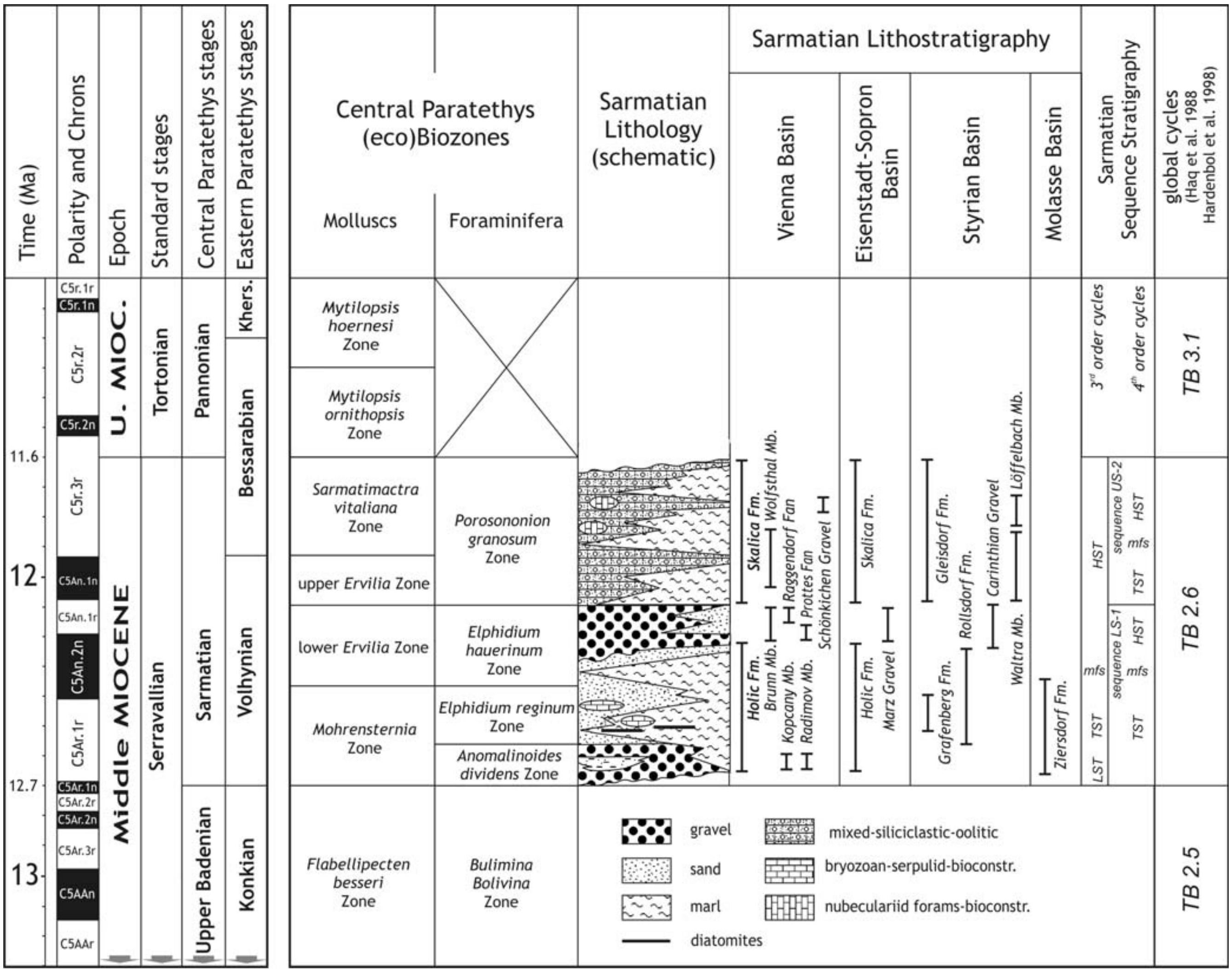
The Wolfsthal Member is widespread along the margins of the Vienna Basin, including the rock-forming oolitic coquinas of Atzgersdorf (Vienna), Hauskirchen (Lower Austria), and Nexing (Lower Austria). In basinal settings, this carbonatic facies is replaced by fossiliferous sandy to clayey marls, which have been named in the central and southern Vienna Basin Beds of Kottingbrunn by Brix (1988).

Equivalents of the Wolfsthal Member have been described as Karlova Ves Member by Nagy et al. (1993) and Vass (2002). Unfortunately, these authors mixed Lower Sarmatian carbonates deriving from bryozoan-serpulid-algae bioconstructions with the Upper Sarmatian oolites and coquinas. The former should be treated as a member of the Holíè Formation, the latter, however, must be retained as a member of the Skalica Formation. As this mistake is incorporated within the definition of the type section by Nagy et al. (1993), the term Karlova Ves Member should be abandoned.

In the Styrian Basin, the temporal and facial equivalent of the Wolfsthal Member is the Waltra Member defined by Friebe (1994).

The Eisenstadt-Sopron (Sub)Basin

This small basin is a subbasin of the Vienna Basin (text-fig. 3). It is more or less trigonal and measures about 20 x 20km in size (Piller and Vavra 1991). In the north it is limited by the NE-SW



TEXT-FIGURE 1
Chronstratigraphy, biostratigraphy, lithostratigraphy, and sequence stratigraphy of the Sarmatian in the Vienna Basin and the Styrian Basin. Mollusc biozones according to Papp et al. (1974); foram-zonation modified after Grill (1941) and Cicha et al. (1998). The chronostratigraphic calibration of the schematic lithology and the correlation of the biozones follows the herein-proposed relation to isotopic events. The Serravallian/Tortonian boundary is drawn according to the suggestions of Lirer et al. (2002) and Hilgen et al. (2000; 2003). The global 3rd order cycles are taken from Haq et al. (1988) and are refined according to new stratigraphic data compiled by Hardenbol et al. (1998).

trending Leitha Mountains and the associated SE dipping Eisenstadt fault (Fodor 1992). In the east, the basin is limited by the N-S trending Köhida fault system (Schmid et al. 2001). The Rust-Fertörakos Mountains separate the basin from the Danube Basin in the east. A crystalline ridge, covered by Lower Miocene gravel extending from the Rosalia Mountains to the Brennberg, defines the southern margin. This topographical barrier separates the Eisenstadt-Sopron Basin from the Styrian Basin-complex. The development of the Eisenstadt-Sopron Basin is closely linked with that of the Vienna Basin, although the thickness of the basin fill is much less (about 200 m in the marginal Mattersburg embayment according to Pascher 1991).

Lithostratigraphy: Lower Sarmatian deposits of the Eisenstadt-Sopron Basin have been described by Rögl and Müller (1976) and Pascher (1991). These pelitic and sandy sediments with scattered intercalations of gravel or serpulid-limestones agree fully with those of the adjacent Vienna Basin and should be included within the Holíè Formation. Near the top of that formation, a unit of gravel was observed by Papp (1974c) and by Pascher (1991). Due to the very poor outcrop situation, this lithological unit is only informally termed Marz Gravel in the literature.

Correspondingly, the Upper Sarmatian Skalica Formation of the Vienna Basin extends into the Eisenstadt-Sopron Basin. A mixed siliciclastic-carbonatic succession of gravel, sand, oolitic sand, and marls is typical for the Upper Sarmatian deposits (Papp 1974c; Pascher 1991; Rosta 1993; Harzhauser and Kowalke 2002).

According to Trunkó (1996), however, this succession is united in the Tinnye Formation, which was originally defined in the Transdanubian Mid-Mountains and the Budapest area. We propose to restrict the Tinnye Formation to its Hungarian type area until future investigations prove both lithological units to be synonymous.

The Styrian Basin

As a subbasin of the Pannonian Basin System, the Styrian Basin established during the Neogene at the eastern margin of the Eastern Alps (text-fig. 4). It is about 100km long and about 60km wide and contains about 4km of Neogene sediments. It is divided into several small subbasins such as the Western Styrian Basin, the Mureck Basin, the Gnas Basin, and the Fürstenfeld Basin. It is separated from the Pannonian Basin by the South Burgenland Swell and is internally structured by the Middle Styrian Swell and the Auersbach Swell. An overview of the tectonic evolution of the Styrian Basin is given by Sachsenhofer (1996), and a detailed introduction into the surface distribution of the Sarmatian deposits is presented by Kollmann (1965). A composite section of the Sarmatian basin fill in the Styrian Basin suggests a thickness of up to 1050 m (Brix and Schultz 1993).

Lithostratigraphy: The pelitic and sandy basinal deposits of the Lower Sarmatian have not been integrated in any lithostratigraphic scheme and remain formally unnamed. These are followed above by a widespread and thick unit of gravel and coarse sand of up to 100 m thickness. This package is termed Carinthian Gravel in the literature (Winkler-Hermaden 1927; Kollmann 1965; Kosi et al. 2003) and is ubiquitous in well-logs; surface outcrops, however, are rare and do not offer an insight into the stratigraphic position as do the well results.

A lithostratigraphic framework for the Upper Sarmatian of the Styrian Basin was proposed by Friebe (1994), based on scattered surface outcrops along the margins of the basin. He united all mixed-siliciclastic-carbonatic deposits in a single lithostratigraphic unit called Gleisdorf Formation, being composed of the Waltra Member, the Löffelbach Mb., the Grafenberg Mb., and the Rollsdorf Mb. This concept, however, needs major refinement. We enlarge the original definition of the Gleisdorf Formation and apply this name to the entire Upper Sarmatian mixed-siliciclastic-oolitic deposits in the Styrian Basin, as variously drilled in wells of the RAG and OMV oil companies. Hence, the Gleisdorf Formation is a temporal and genetic equivalent of the Skalica Formation in the Vienna Basin.

Within the Gleisdorf Formation, only the Waltra Member can be accepted as a valid subunit in the original definition of Friebe (1994). This member is characterised by a cyclic succession of several silty-sandy beds, each grading into oolites. This lithofacies is highly characteristic for the upper *Ervilia* Zone and corresponds to the optimum of ooid production within the Styrian Basin. The Löffelbach Member comprises marly limestones with scattered ooids, but lacks pure oolites. Stratigraphically, it is restricted to the *Sarmatimactra vitaliana* Zone and is represented by temporal and lithological equivalents in the Eisenstadt-Sopron Basin (e.g. sections St. Margarethen, Wiesen). Although unrecorded by Friebe (1994), it is also well developed at St. Anna am Aigen at the type section of the Waltra Member, where it overlays the Waltra Mb. Unfortunately, Friebe (1994) also included fluvial gravel within the definition of the Löffelbach Member, which now – due to a better outcrop situation – turned out to be an Upper Miocene fluvial channel which erosively cuts into the Sarmatian deposits. Fluvial gravel does, however, separate the Waltra Member from the overlying Löffelbach Member in well-logs and at St. Anna am Aigen. Yet, this gravel is not exposed at the type section of the Löffelbach Member and must not be intermingled with the Pannonian fluvial gravel erroneously included by Friebe (1994).

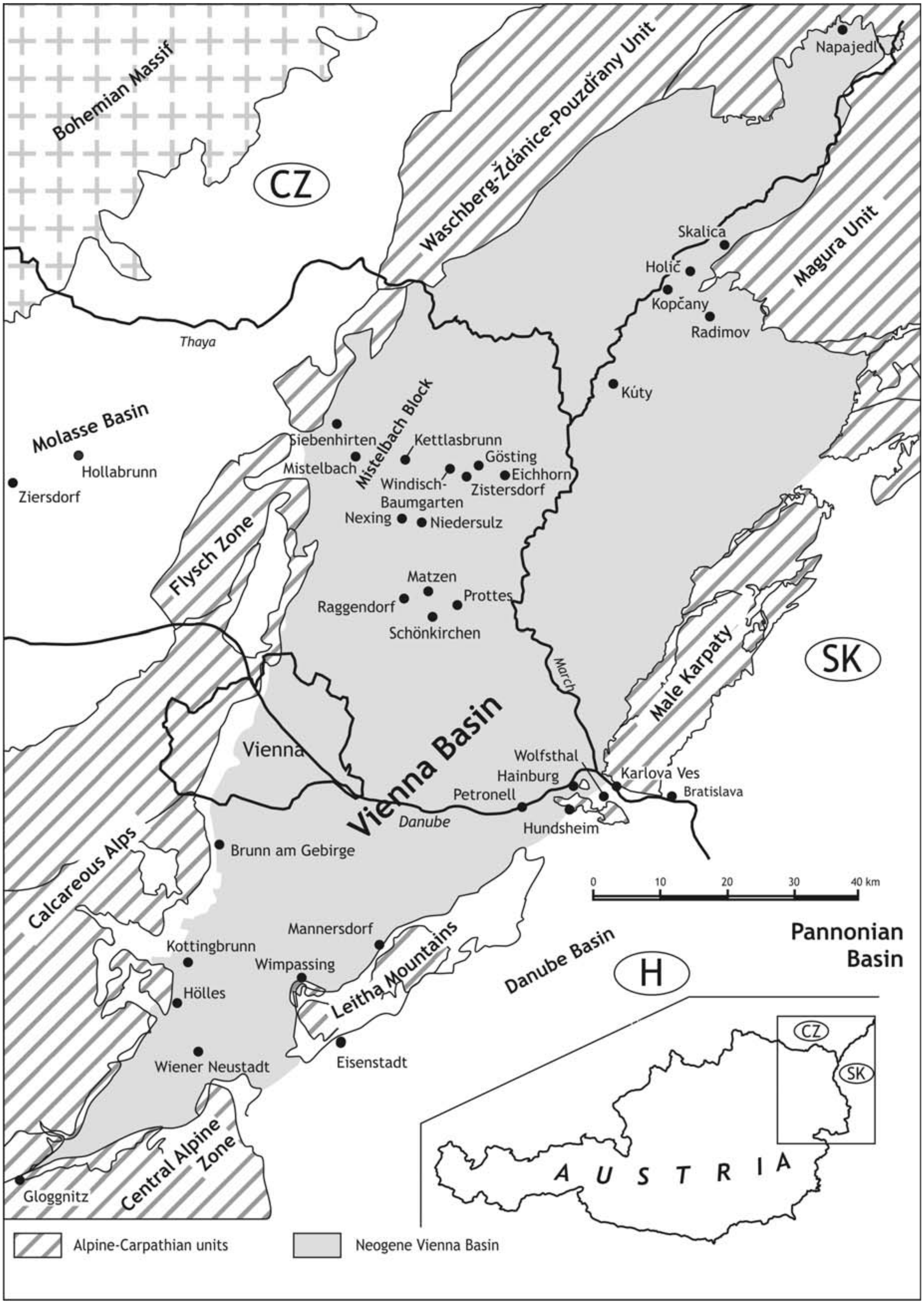
Similar to Nagy et al. (1993), Friebe (1994) mixed up the characteristic Lower Sarmatian bryozoan-serpulid bioconstructions with the oolitic deposits of the Upper Sarmatian when introducing the Grafenberg Member. As these bioconstructions are genetically and lithologically independent from the Upper Sarmatian oolites of the Gleisdorf Formation, we propose a strict separation. The Grafenberg Member has to be restricted to the bioconstructions and associated sediments and should be considered as the Grafenberg Formation, which is overlain by oolitic sand of the Gleisdorf Formation. Correspondingly, the Rollsdorf Member is considered herein to be independent from the Gleisdorf Formation and is introduced as the Rollsdorf Formation. Again, the proximity of Lower Sarmatian siliciclastics as described in detail by Krainer (1984) to Upper Sarmatian oolites and limestones of the Gleisdorf Formation induced Friebe (1994) to subsume the entire deposits within a single member.

In conclusion, the following lithostratigraphic units are differentiated within the Sarmatian of the Styrian Basin: Rollsdorf Formation for siliciclastics of the Lower Sarmatian, being characterised by the occurrence of the gastropod *Mohrensternia* and the bivalve *Crassostrea*. Grafenberg Formation, uniting the Lower Sarmatian bryozoan-serpulid bioconstructions and associated sediments. Breccias derived from reworking of the basement during the Sarmatian transgression or pelites separating single phases of the bioconstructions' growth are typical (e.g. Klapping section in Harzhauser and Piller 2004). Carinthian Gravel, an informal but useful term for the significant gravelly unit underlying the Gleisdorf Formation. Gleisdorf Formation, comprising mixed siliciclastic-oolitic deposits of the Upper Sarmatian characterised by the frequent to rock-forming occurrence of the gastropod *Cerithium rubiginosum* and the bivalves *Ervilia* and/or *Sarmatimactra*. The term Waltra Member is restricted to the oolite/pelite succession typically developed in the Upper *Ervilia* Zone. It is separated by gravel and sand from the carbonatic Löffelbach Member, which lacks the pure oolites and seems to be rather isochronously restricted to the *Sarmatimactra vitaliana* Zone of the Upper Sarmatian.

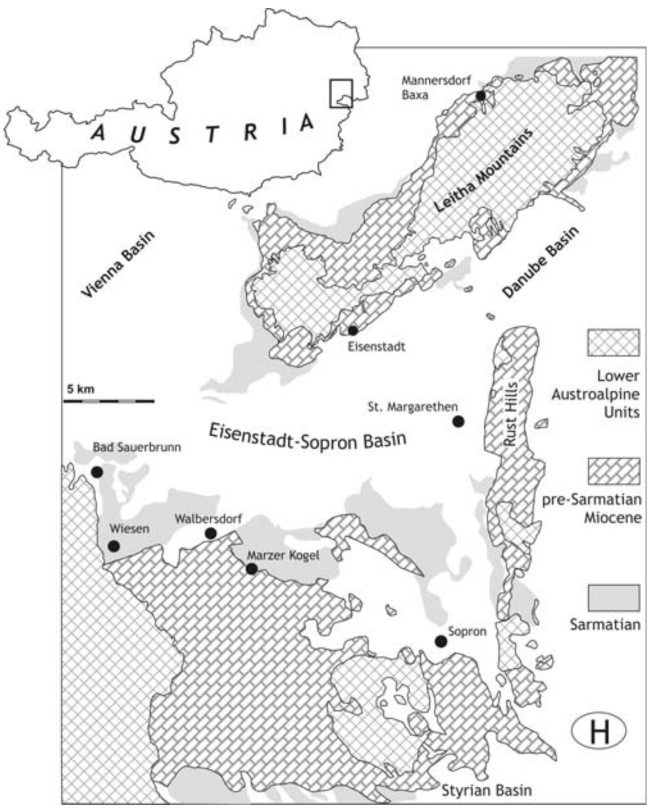
The Molasse Basin

The eastern Molasse Basin, being part of the Alpine-Carpathian Foredeep, is a W-E trending trough in front of the prograding nappes of the Alpine orogen. In its herein-discussed easternmost part, it covers the area between the Alpine mountain chain in the south and the Bohemian Massif in the north and is separated from the Vienna Basin in the east by external thrust sheets of the Alpine-Carpathian system (text-fig. 1). The foreland basin stage was initiated during the Oligocene (Rögl 1998). Marine deposition lasted throughout the Early and Middle Miocene up to approximately 15 Ma, when uplift caused the sea to retreat. The very last marine ingression into the already dry Molasse Basin took place during the Early Sarmatian.

Lithostratigraphy: The Sarmatian of the Molasse Basin is confined to a rather narrow, about 40-km-long trough following a roughly W-E trending belt from the Bohemian Massif in the west to the Vienna Basin in the east (Weinhandl 1959; Milles and Papp 1957; Papp 1962; Grill 1968). This distribution follows an older incised valley which became flooded during the Early Sarmatian. The same valley was used before by the paleo-Zaya river which is documented by the above-mentioned lowermost Sarmatian fluvial gravel on the Mistelbach block in



TEXT-FIGURE 2
The Vienna Basin (grey area) within Alpine-Carpathian units. Important localities with surface outcrops or wells mentioned in the text are indicated. Gateways from the Vienna Basin into the Danube Basin are known from the south of the Leitha Mountains and between the Male Karpaty and the Leitha Mountains. A marine lough reached via the Mistelbach block from the Vienna Basin into the Molasse Basin (Alpine Carpathian Foredeep), where Lower Sarmatian sediments are exposed at Ziersdorf and Hollabrunn.



TEXT-FIGURE 3
Location map of the investigated outcrops in the Eisenstadt-Sopron Basin. The small basin displays a wide connection with the Vienna Basin via the Wiener Neustadt gateway. During the Sarmatian, its southern part was shut off from the adjacent Styrian and Danube Basins and formed a shallow embayment.

the northern Vienna Basin. These relics are united in the Ziersdorf Formation (Roetzel et al. 1999), consisting mainly of sand and gravel with pelitic intercalations; carbonates are unknown.

The dating of the Ziersdorf Formation proves an Early Sarmatian age based on the occurrence of several species of the gastropod *Mohrensternia* (Kowalke and Harzhauser 2004) and rare *Elphidium reginum* (Papp et al. 1974). Upper Sarmatian deposits are missing in the Molasse Basin, clearly due to the final retreat of the Paratethys Sea from that area.

Basinal settings and correlation with studied surface outcrops

Due to extensive hydrocarbon exploration, thousands of wells penetrated Sarmatian sediments in the Vienna and the Styrian Basins (text-figs. 5-8). Various oil fields have been discovered in those basins by the oil companies OMV AG and RAG. As these companies were mainly interested in within-field-correlations, each field was originally characterised by an individual scheme of numberings referring to "sand horizons" (e.g. Friedl 1936; Papp 1974b; Kreutzer 1974). To avoid misinterpretations due to the inconsistent use of numbers referring to Sarmatian marker horizons, a new and independent scheme is adopted as indicated in text-fig. 5. The herein-used code numbers and letters represent synchronous phases of deposition but do not imply a laterally continuous lithological unit. An integration of the biozone-concepts is based on the wells Gösting 4/Rag 2 and on Niedersulz 5 and 9, which have been proposed as the Sarmatian/Pannonian boundary stratotype by Papp (1974b). Based on these wells Friedl (1936) and Papp (1974b) calibrated the surface-based mollusc-biozones; further data derive from unpublished OMV-reports by Wessely (1967) and Harzhauser (2003).

Geophysical and lithological logs of two main target areas in the Vienna Basin are involved in this study, namely logs from the northern Vienna Basin along the Steinberg fault (Niedersulz, Eichhorn, Gösting, Zistersdorf, text-fig. 5) and from the field Matzen in the central part of the basin (Matzen, Schönkirchen, Prottes, text-fig. 6). Further logs and 2-D seismic data from the eastern Styrian Basin have been integrated (text-fig. 7). Log-data derive from the papers of Friedl (1936), Janoschek (1942; 1943), Kreutzer (1974), Wessely (2000), and Kosi et al. (2003). Further information was kindly provided by the OMV AG and RAG companies.

INTER- AND INTRABASIN CORRELATION

For a reasonable inter- and intrabasin correlation, the general trends in geophysical logs have been compared. Despite the different sedimentation rates and the different tectonic settings, all considered areas display several parallel trends. The correlation of various wells in the northern Vienna Basin as proposed in text-fig. 5 allows a comparison of marginal logs such as Niedersulz 5-9 with basinal settings as represented by the Eichhorn 1 section. The correlative intervals in that area display rather similar thicknesses. In contrast, the Sarmatian in the Matzen oil field in the central Vienna Basin differs by its minor thicknesses due to its position on a major intrabasinal high. A comparison of synchronized logs of Matzen with those from the northern Vienna Basin as illustrated in text-fig. 6 shows that the general trends are reflected in both areas. Hence, a long shale-line interval (#f) is confined by two characteristic serrations (#33 base, #31 top). In both areas, major parts of the lower *Ervilia* Zone are represented by an interval of strongly serrated, irregular curves (#31-20) overlain by another typical shale-line interval (#c). Local tectonics and different basin subsidence is expressed in slightly different sedimentation rates. The major trends, however, are similar.

The same hypothesis is applied to the interbasin correlation between the Vienna and the Styrian Basins. One of the most characteristic and convincing intervals for an interbasin correlation is represented between #17-a. In text-fig. 8, gamma-logs of Niedersulz 5 and 7 from the Vienna Basin are opposed to the logs Ilz 1 and Fürstenfeld FFTH1 from the Styrian Basin. In theses logs, the biostratigraphic framework allowed a clear correlation. Balancing the higher sedimentation rate of the Vienna Basin against that of the Styrian Basin resulted in an extremely good fit of the curves. Hence, the characteristic long-term coarsening upward trend, comprising #c-15 and the overlying, strongly serrated, cylinder-shaped part, culminating in a significant, short, funnel-shaped peak (#7), is visible in the Styrian Gleisdorf Formation as well as in the Skalica Formation of the Vienna Basin. In the same way, the log-shape of the Carinthian Gravel is highly reminiscent of that of the time-equivalent deposits in the Vienna Basin (cf. text-fig. 8). Based on the similarities of the log shapes, the new code-number scheme of the Vienna Basin can partly be transferred into the Styrian Basin (text-fig. 7).

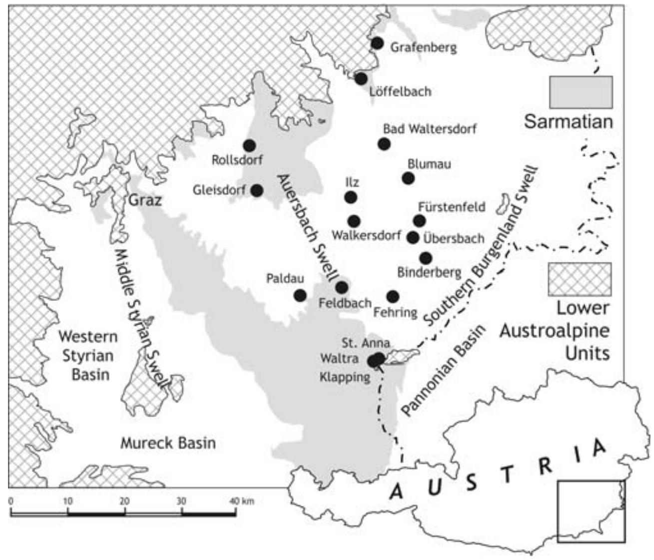
In all wells in the area of Niedersulz as well as in Zistersdorf Uet 2A and Uet 1a, the basal part of the Sarmatian is missing. This apparent hiatus results from the position of the wells close to the huge Steinberg fault. Only the well Niedersulz 9 yields deposits of the lowermost Sarmatian due to its greater distance to the fault. The strong mixing and transport of the microfauna in most wells makes it very difficult to detect the Badenian/ Sarmatian boundary in the logs. Thus, in none of the herein-discussed wells can a reliable position of that boundary be given. Especially in Niedersulz 9 the interval #55-48 might be part of the Badenian and is excluded herein from most interpretations. Similarly, the definition of the very basal Sarmatian in the Styrian Basin is difficult in the wells. On the one hand, the deposits are poor in fossils. On the other hand, this zone, which is now treated as the basal Sarmatian *Anomalinoides* Zone (Kollmann and Rögl 1978), was frequently integrated into the Badenian as the so-called *Cibicides-Rotalia* Zone in the literature and by the oil companies.

#45-33: In the Vienna Basin this interval corresponds to a basal fining upward and an overlying coarsening upward unit separated by a flooding surface which is termed herein #g (text-fig. 7). The basal part, mainly #40-42, represents a prominent peak in the curves and is also reflected in the Styrian Basin by the occurrence of sand and gravel (e.g. Binderberg 1, Walkersdorf 1). At #33, the succession ends with another prominent peak; it can be used as a marker in the Matzen area as well as in the Styrian Basin and serves as a further key horizon for correlation. Most of that interval represents the *Elphidium reginum* Zone. As mentioned above, only the lower boundary towards the *Anomalinoides dividens* Zone is hard to define because significant fossils are missing. In terms of mollusc zones, the corresponding *Mohrensternia* Zone can be traced up to #33 (cf. Wessely 1967).

The flooding of the Molasse Basin during the *Mohrensternia* Zone and the abrupt transgression of marine clay over fluvial gravel at the Siebenhirten section in the Vienna Basin are tentatively correlated with the interval #g. At Petronell in the southern Vienna Basin, the same phase is expressed by the formation of off-shore pelites overlying cross-bedded littoral sand and clay of the *Anomalinoides dividens* Zone (Harzhauser and Piller 2004). In the Styrian Basin, this phase is documented by the transgression of the Rollsdorf Formation, e.g. at the Steingrub/Ilzberg section described by Krainer (1984).

The bryozoan-serpulid-algae bioconstructions and associated limestones that formed during the *Mohrensternia* Zone along the coasts give evidence for swift fluctuations of the relative sea-level. Harzhauser and Piller (2004) describe caliche formation and minor floodings separating single phases of carbonate production from the Styrian Klapping section and from Mannersdorf in Lower Austria. An exact correlation of these phases with the well information, however, is impossible.

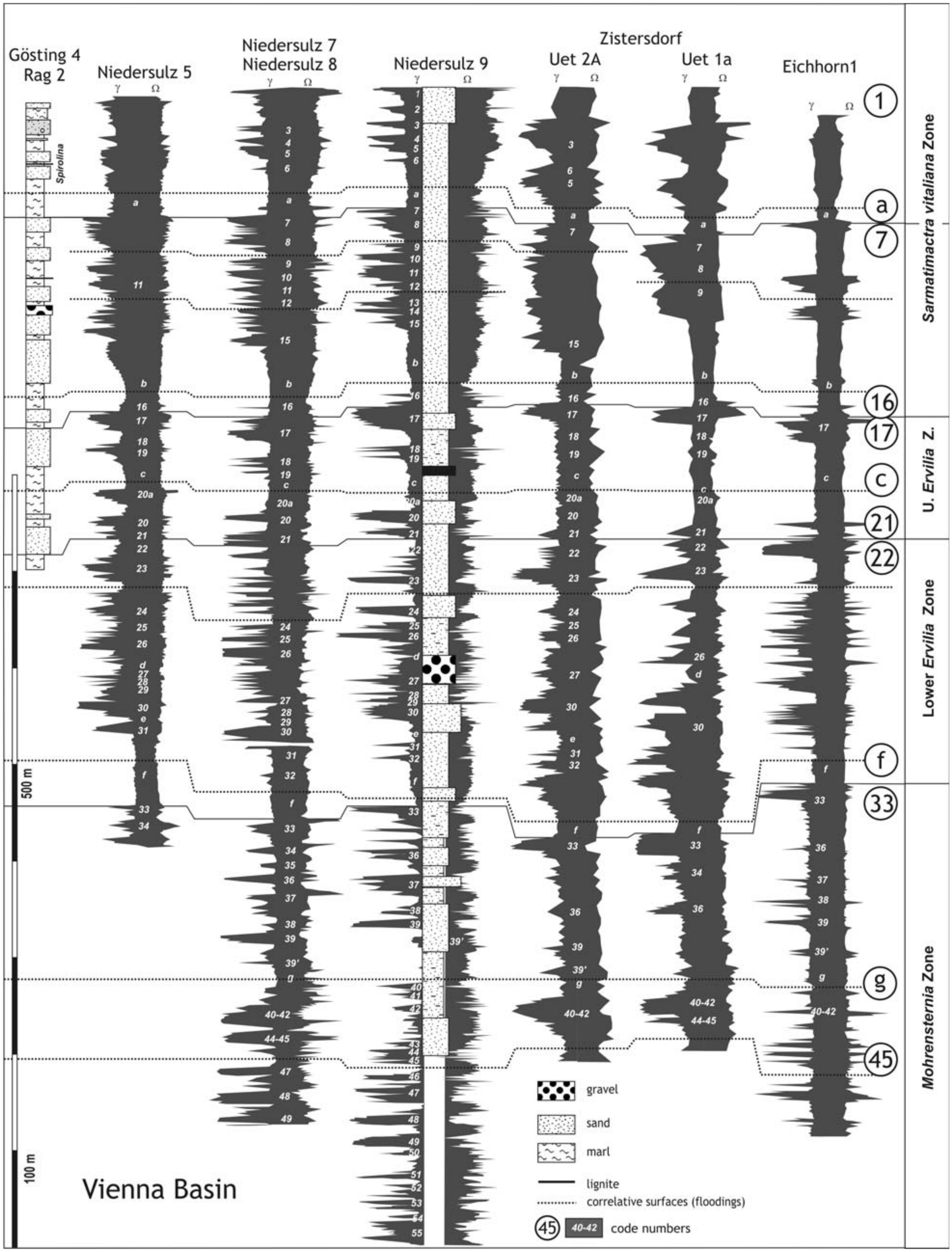
#f-22: This part is interpreted to represent the lower part of the *Ervilia* Zone of the mollusc zonation and corresponds to the *Elphidium hauerinum* Zone. The absence of the gastropod *Mohrensternia* and the occurrence of the forams *Articulina sarmatica* and *Elphidium hauerinum* in the marly fine-sand indicated as #f document the onset of that zone. A shallow marine setting can be assumed based on the occurrence of *Elphidium, Articulina,* and *Nonion*. Freshwater influx is evident based on the occurrence of characeans mentioned by Wessely (1967). The Styrian Basin mirrors the lithological development but differs in the scarceness of indicative fossils (Kollmann 1965). The interval #f is represented in all basins by grey marls. They are overlain abruptly by a thick sequence (#32-22) of a succession of coarse sand and/or gravel with irregular intercalations of thin pelitic layers, causing an irregular, strongly serrated shape of the geophysical logs. These deposits attain a thickness of up to 270 m in the Vienna Basin and up to 130 m in the Styrian Basin, where they are summarized as Carinthian Gravel. In the Vienna Basin, although neglected in most studies, these gravels were already detected and used as a marker by Bittner (1892) and Schaffer (1906). A uniting term is missing, but single layers have been depicted as Raggendorf Fan and Prottes Fan in the Matzen area by Kreutzer (1974), and Brix (1988) described parts of this phase as Brunn Conglomerate. Channels and erosive contact of individual channels have been described by Kreutzer (1974); consequently, abandoned fluvial meanders became visible during a 3-D seismic survey in the Matzen field.



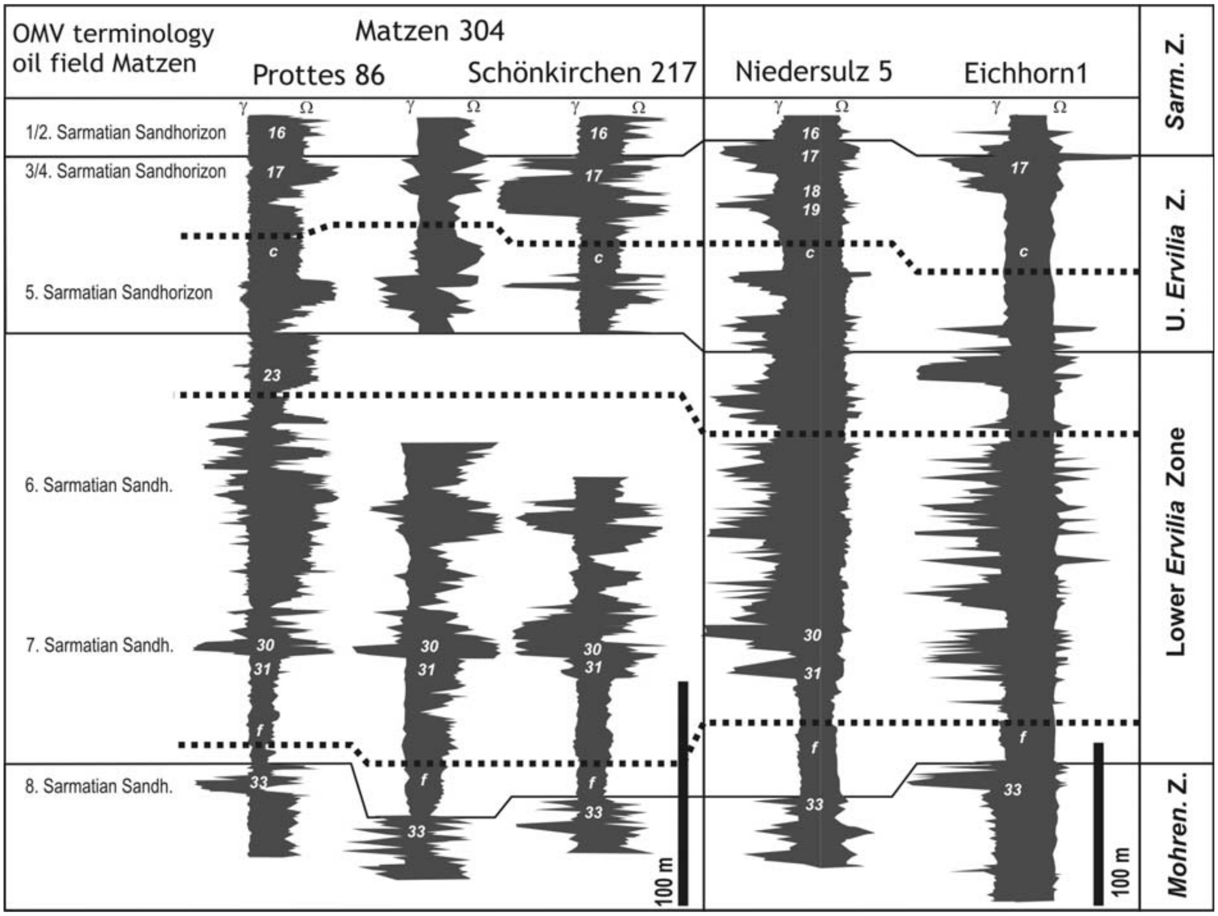
TEXT-FIGURE 4
Location map of the investigated outcrops and well-logs in the Styrian Basin. The South Burgenland swell formed an island chain that separated the Styrian Basin somewhat from the open sea.

Surface outcrops are rare within the lower *Ervilia* Zone. Sandy marls corresponding to interval #f are preserved at the outcrop Walbersdorf/Marzer Kogel in the Eisenstadt-Sopron Basin (Rögl and Müller 1976) and at Rollsdorf and Wohngraben in the Styrian Basin (Krainer 1984). Erosion during the subsequent deposition of the Carinthian Gravel and its equivalents in the Vienna Basin might have destroyed most of those sediments in marginal settings.

21-17: This part corresponds to the upper part of the *Ervilia* Zone and the lower part of the *Porosononion granosum* Zone. The coquinas occurring at #21 (1560-1580 m) in the Niedersulz 9 well are reminiscent of the coquina sand-waves that crop out at the nearby Nexing, Windischbaumgarten, and Kettlasbrunn sections and are indicative for the upper *Ervilia* Zone. A characteristic interval of marl sedimentation (#c) is developed throughout the Vienna Basin and in many logs in the Styrian Basin (Ilz 1, Binderberg 1, Walkersdorf 1). It successively grades into a serrated curve which culminates in a very promi-



TEXT-FIGURE 5
Geophysical logs (SP- and restivity) of Sarmatian deposits from the Vienna Basin (data from Janoschek 1942; 1943; Friedl 1936; Wessely 1967; 2000; Papp 1974b; unpublished data on logs Niedersulz 5, 7, 8 and 9 provided by OMV). White letters and numbers indicate synchronous phases of deposition but do not imply a continuous sedimentary body. Dotted lines correspond to flooding surfaces, bold lines represent boundaries between biostratigraphic zones. Important code numbers for correlation are encircled.



TEXT-FIGURE 6
Correlation of geophysical logs of the central Vienna Basin (logs after Kreutzer 1974) with those from the northern Vienna Basin. Note the well-developed 3rd order maximum flooding surface f.

nent layer (#17) with funnel-shaped and sometimes depressed cylinder-shaped gamma-log curve.

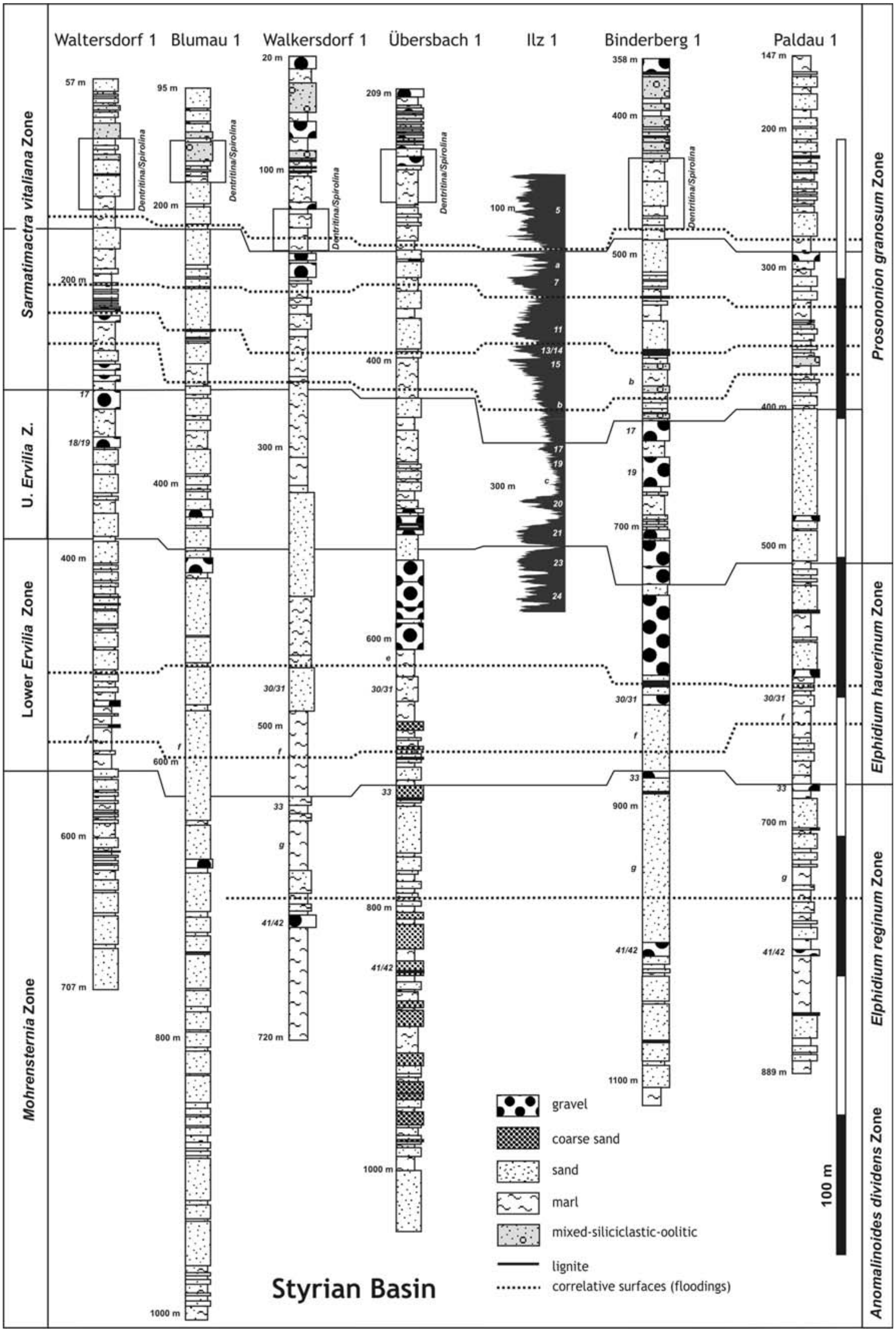
This interval is well presented by surface outcrops (text-figs. 9-10) such as the Nexing section, which is the holostratotype of the Sarmatian. At the Nexing section, huge, steeply inclined sand-waves of shell hash and ooids developed. Up to 20-m-thick oolites formed at Wolfsthal isolated from the coast, whereas characteristic successions of oolites and sandy/silty intercalations developed along the margin of the Vienna Basin (Gloriette section; Tauber 1939) and along the South Burgenland Swell in Styria (Waltra section). The marked coarsening observed in well-logs (#17) can also be correlated with surface outcrops. At that time, sedimentation of coquinas ceased at Nexing on the elevated Steinberg block and a short episode of erosion by fluvial gravel started. Close to this level, within the 20-m-thick oolitic succession of Wolfsthal, a several-metre-thick layer of caliche formed due to emersion (text-fig. 10). In the Styrian Basin and the Eisenstadt-Sopron Basin this interval coincides with the intercalation of gravel and sand at the Waltra, Hartberg, St. Margarethen, and Sauerbrunn sections (Steininger and Thenius 1965; Nebert 1951).

 # 16-7: The sedimentary sequence is correlated with the *Sarmatimactra vitaliana* Zone and the middle part of the *Porosononion granosum* Zone. It is rather homogeneously developed in all logs and basins, starting with a marly-sandy interval (#b) with distinct coarsening upward trend (e.g. Ilz 1, Niedersulz 5). In basinal settings it is recognised easily by its shaleline appearance (Eichhorn 1). This is followed upsection by a significant, strongly serrated succession which is subdivided into 2-3 units. The lower 1-2 are represented by serrated bell- to serrated funnel-bell-shaped curves, whilst the upper one (#7) displays a very typical serrated, funnel-shaped outline. A similar subdivision of the *Sarmatimactra vitaliana* Zone into 2-3 units is also reflected in surface outcrops in the Styrian Basin (Waltra section) and the Eisenstadt-Sopron Basin (St. Margarethen section).

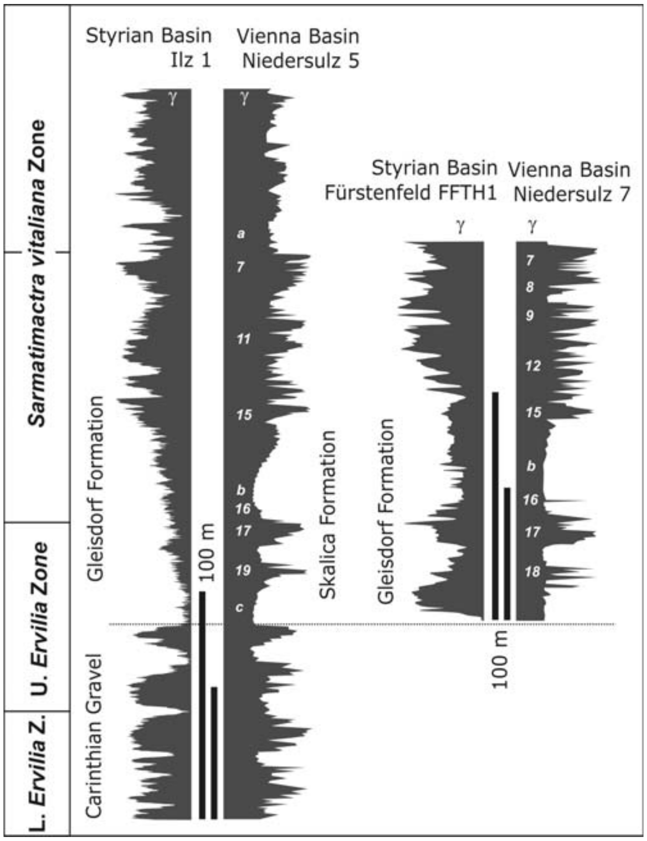
 # a-1: The uppermost part of the Sarmatian, represented in the wells, corresponds to the "pauperization Zone" of Papp (1974a) and the upper part of the *Porosononion granosum* Zone. Oolitic sediments are highly characteristic; furthermore, this interval is unique in bearing extraordinary quantities of the larger foraminifers *Dentritina* and *Spirolina* (e.g. Gösting 4, Waltersdorf 1, Binderberg 1). Due to the progradation of the coastline into the basin and due to widespread erosion at the Sarmatian/Pannonian boundary, deposits of that zone are restricted to basinal settings, whereas uppermost Sarmatian sediments are only patchy relics on topographic highs.

SEQUENCE STRATIGRAPHY

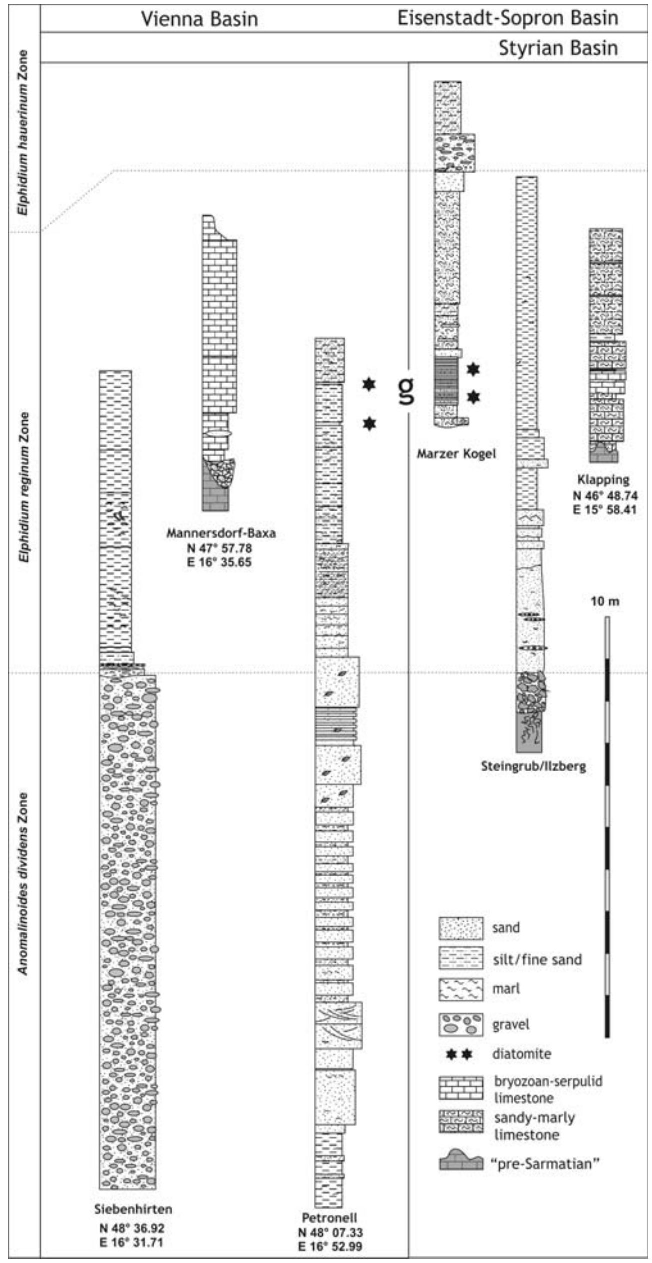
The sequence stratigraphic frame of the lower Middle Miocene Badenian Stage of the Central Paratethys was improved lasting



TEXT-FIGURE 7
Well-logs from the Sarmatian of the Styrian Basin (data from Kosi et al. 2003 and RAG) with a correlation of the internal numbering-system proposed for the Vienna Basin in text-fig. 5. Note the characteristic horizon with the foraminifera *Spirolina* and *Dendritina*.



TEXT-FIGURE 8
Geophysical logs (SP- and restivity) of Sarmatian deposits from the Vienna Basin (OMV data) and the Styrian Basin (after Kosi et al. 2003). Both basins mirror a very similar development, which is most eye-catching during the *Sarmatimactra vitaliana* Zone. Despite the different tectonic regimes in both basins and differing thicknesses of the basin-fills, due to different subsidence, the overall signature is not obscured by tectonics.



TEXT-FIGURE 9
Outcrops representing marginal settings of the Early Sarmatian. The LST is reflected by the fluvial gravel exposed at Siebenhirten, whereas shallow marine to littoral settings of the *Anomalinoides dividens* Zone develop in the southern basin. The flooding during the *Elphidium reginum* Zone marked as "g" in text-fig. 5 might correspond to the formation of diatomites. Bryozoan-serpulid-algae limestones develop along the shores. (Steingrub/Ilzberg log modified from Krainer 1984).

recent years by Pogácsás and Seifert (1991), Weissenbäck (1996), Vakarcs et al. (1998), Hudáckova et al. (2000), and Baráth and Kováè (2000). In contrast, the resolution of the upper Middle Miocene Sarmatian stage is still poor. Generally, a single 3rd order cycle spanning the Sarmatian is accepted by most workers (Vakarcs et al. 1998; Baráth and Kováè 2000; Harzhauser and Piller 2004). Based on wells in the oil field Matzen in the Vienna Basin, Kreutzer (1990) suggested a two-fold Sarmatian sequence with a transgressive Lower Sarmatian part and a second, sand-rich cycle with channelised sands and alpine gravels.

Even the chronostratigraphic concepts which sometimes strongly influence the sequence stratigraphic interpretation of the Sarmatian in the literature are quite confusing. Vakarcs et al. (1998) interpreted the Sarmatian sedimentary sequences as being bound by the Ser-2 and Ser-3 sequence boundaries of Hardenbol et al. (1998). However, Vakarcs et al. (1998) calibrated their Ser-2 sequence boundary in the base of the Sarmatian with the base of the nannoplankton zone NN6. The latter corresponds to the Langhian/Serravallian boundary, indicated by the last occurrence of *Sphenolithus heteromorphus* (Deflandre), which was recently re-calibrated by Foresi et al. (2002) to occur at 13.59 Ma. We cannot follow this surprising correlation of Vakarcs et al. (1998), since the NN6 zone comprises Upper Badenian deposits throughout the former Central Paratethys area (e.g. Hudáckova et al. 2000; Chira 2000). The Sarmatian/Pannonian boundary is roughly dated at 11.5 Ma, based on magnetostratigraphic data from the Pannonian Basin by Vass et al. (1987), and to 11.6 Ma by Harzhauser et al. (in press). These ages correspond to the astronomically based Serravallian/Tortonian boundary, which was recently dated to occur at either 11.539 Ma (Lirer et al. 2002) or 11.608 Ma

(Hilgen et al. 2000), coinciding with the glacio-eustatic sea-level lowstand of TB3.1. The first occurrence of the three-toed horse *Hippotherium* at 11.3-11.4 Ma in the Pannonian Zone C of Lake Pannon and the Upper Bessarabian of the Eastern Paratethys allows a further constraint for the stratigraphic extension of the Sarmatian (see Bernor et al. 1988, Daxner-Höck 1996, and Steininger 1999 for discussion).

The Sarmatian 3rd order Cycle *Sa-1* – an expression of the TB 2.6 Cycle

A correlation of the unconformities bounding the Sarmatian sequences 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) matches well with the biostratigraphic frame of the Sarmatian stage. According to Abreu and Haddad (1998), the sequence boundary TB 2.6 of Haq et al. (1988) corresponds to the major isotope event MSI-3 at 12.7 Ma, which is associated with chron C5A.3n. An even younger date at 12.5 Ma is proposed by Sen et al. (1999) as the begin for that cycle. Both dates contrast to the traditional but tentative placement of the Badenian/Sarmatian boundary at approximately 13 Ma by Rögl (1998), Harzhauser and Piller (2004), and most other "Paratethys workers".

Consequently, we propose a single 3rd order cycle spanning the entire Sarmatian, beginning at 12.7 Ma and ending at 11.6 ma (text-figs. 1 and 12). Its lowstand systems tract is reflected by an incised valley in the Molasse Basin. A riverine system entered the Vienna Basin via that valley and shed coarse gravel which is currently exposed at the Siebenhirten section. Badenian corallinacean limestone which then formed the shoreline of the basins suffered strong erosion (Harzhauser and Piller 2004). The multi-coloured limnic Kopèany Member represents this phase in the Czech part of the Vienna Basin. In the southern Vienna Basin and in basinal settings, this phase is represented by marine sediments. A coarsening upward sequence in the *Anomalinoides dividens* Zone at the Petronell section (Harzhauser and Piller 2004) and in the Styrian Stiefingtal well (Kollmann and Rögl 1978) indicates a first parasequence, which might correspond to the interval below #45 in the Niedersulz 9 well.

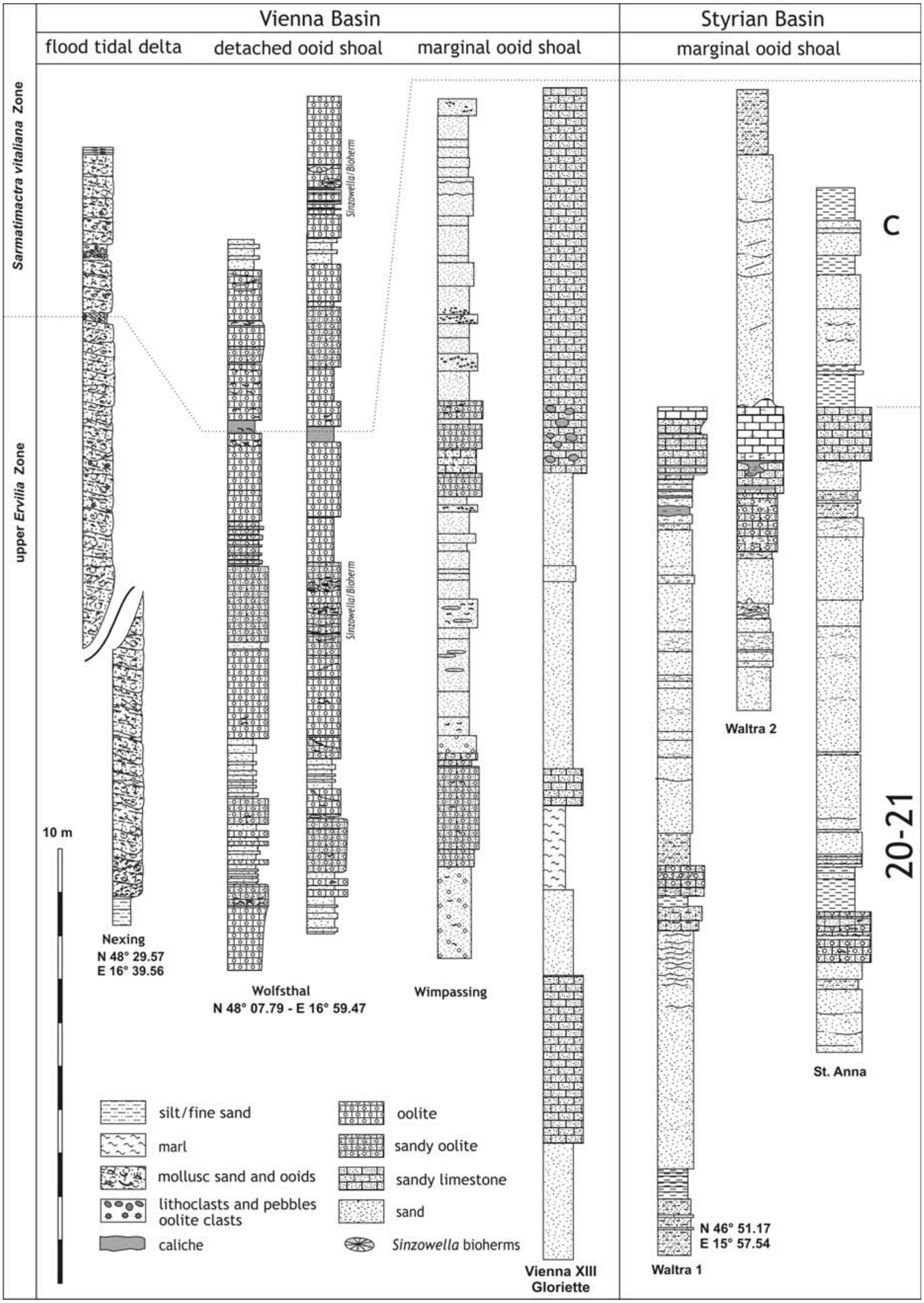
The 3rd order transgressive systems tract is indicated by a fining upward sequence in well-logs and a predominance of marls. The development culminates in the formation of the maximum flooding surface (mfs) within marls of the lower part of the lower *Ervilia* Zone and the *Elphidium hauerinum* Zone (interval #f). This mfs was already recognised by Baráth and Kováè (2000) based on geophysical logs in the Slovakian part of the northern Vienna Basin. Deposits encompassing this 3rd order maximum flooding phase are virtually missing in all nearshore settings. This might best be explained by the strong erosion during the following 4th order LST in the upper *Elphidium hauerinum* Zone. Only at Mannersdorf/Baxa in the southern Vienna Basin do marls with plant debris and rock-forming quantities of elphidiids seem to represent at least the late TST corresponding approximately to the interval #33-39 of basinal settings (Harzhauser and Piller 2004).

The 3rd order highstand systems tract is indicated by the onset of coarse sedimentation, starting with gravel and sand in its basal part termed Carinthian Gravel in the Styrian Basin – and grading into a mixed siliciclastic-oolitic top which may attain a thickness of more than 400 m. As already discussed by Kosi et al. (2003), the very top of the Sarmatian succession, represented by an aggrading parasequences set, may be interpreted as a shelf-margin systems tract. At that level a characteristic horizon with masses of the foraminifer *Spirolina* developed in all basins.

Nevertheless, the complex and multifaceted facies pattern observed in the well-logs and in more than 25 outcrops allows a much finer tuning and separation of sedimentary cycles. Thus, this 3rd order cycle can be subdivided into a Lower Sarmatian 4th order cycle and a second 4th order cycle spanning the Upper Sarmatian. These cycles coincide with a drastic change in biocontent and lithofacies which is also reflected in an elaborate ecostratigraphic biozonation. In terms of ecostratigraphic zones the first cycle comprises the *Mohrensternia* Zone and basal parts of the *Ervilia* Zone according to the mollusc zonation of Papp (1956) and the *Elphidium reginum* Zone and *Elphidium hauerinum* Zone of the foram zonation of Grill (1941). The second cycle spans the upper parts of the *Ervilia* Zone and the *Sarmatimactra vitaliana* Zone (molluscs), and the *Prosononion granosum* Zone (forams).

The Lower Sarmatian 4th order cycle *LS-1*

This first 4th order cycle (text-fig. 12) is a mainly siliciclastic cycle. Its lowstand systems tract corresponds to that of the superimposed 3rd order cycle. Correspondingly, the mfs of both cycles is identical. However, the TST is modulated by several transgressive pulses as already emphasised by Harzhauser and Piller (2004). Two major flooding surfaces are traceable. The lower one corresponds to a minor transgression during the *Anomalinoides dividens* Zone. Its correlative pelitic sediments are currently exposed at the base of the Petronell section in the southern Vienna Basin. The second flooding surface is expressed in most logs (#g) and corresponds to the maximum transgression of the sea during the *Mohrensternia* Zone. At that time, the Molasse Basin became flooded and the former incised valley turned into a marine lough. Further, rather erratic occurrences of Lower Sarmatian deposits in the Lavanttal (Carinthia, Austria, Papp, 1952) and at Graz (Styria, Austria) document the wide extension of the Sarmatian Sea into Alpine embayments during the LS-1 cycle. The pelitic deposits of that phase are variously exposed, containing several species of the rissoid gastropod *Mohrensternia* and the potamidid gastropod *Granulolabium bicinctum*. At the Siebenhirten section in the northern Vienna Basin, these littoral pelites grade quickly into sublittoral clay with thin-shelled *Abra reflexa* and the agglutinated tubes of the polychaete *Pectinaria*. This development can also be detected along the eastern border of the Vienna Basin by a deepening upward sequence at Petronell. There, littoral sands pass into shallow sublittoral pelites with extensive bioconstructions of the polychaete *Hydroides pectinata*, overlain by 1-2 m of diatomite-bearing pelite topped by dark silty clay with small-sized *Abra reflexa*. This diatomite can also be traced in the Eisenstadt-Sopron Basin at the Walbersdorf section (Rögl and Müller 1976). It thus had a wide distribution in the westernmost part of the Central Paratethys and is interpreted here as an expression of the major flooding surface in #g. The formation of carbonates by the serpulid *Hydroides,* by bryozoans such as *Cryptosula* and *Schizoporella,* and by several corallinaceans during the *Mohrensternia* Zone might be largely bound to the late 4th order TST overlying the flooding surface in #g. These carbonates are well developed within the Styrian Basin, the Vienna Basin, the Eisenstadt-Sopron Basin, and the western margin of the Danube Basin.



TEXT-FIGURE 10
Typical logs from marginal oolite shoals of the upper *Ervilia* Zone. Note the characteristic alternation of oolites with sandy-marly intervals. This pattern is only suppressed in autocyclic settings such as the flood-tidal-delta in Nexing or in isolated settings such as the detached shoal of Wolfsthal, which lacked major siliciclastic input. (Logs Wimpassing and Vienna XIII modified from Piller et al. 1996 and Tauber 1939)

Various short regressive pulses during the late TST are documented by repeated progradation of coarse facies (e.g. #33, #36, #39). During these phases, littoral carbonates became repeatedly exposed and vadose leaching and caliche formation as described by Harzhauser and Piller (2004) from Klapping and Mannersdorf/Baxa took place.

The corresponding 4th order HST comprises the interval #32-24 in the well-logs. It is characterised by progradation of coarse clastic facies and gravel into the basins. In the central Vienna Basin, several rivers entered the basin and shed delta fans such as the Raggendorf Fan and the Prottes Fan (Kreutzer 1974). The synchronous Carinthian Gravel covered large areas of the Styrian Basin with a preferential WSW-ENE direction (Skala 1967), and the Marz Gravel prograded into the Eisenstadt-Sopron Basin. This indicates a backstepping of the basinal facies and suggests an erosional phase in the nearshore areas. Oolitic sediments and rock-forming coquinas are apparently missing in deposits of that 4th order HST.

The Upper Sarmatian 4th order cycle *US-2*

Above LS-1, a sequence boundary is developed, as indicated by the extensive erosion of Lower Sarmatian sediments within the Hainburg Mountains (Hundsheim), the Leitha Mountains (Mannersdorf), the Rust Mountains (St. Margarethen), the South Burgenland Swell (Klapping), and the northern margin of the Styrian Basin (Grafenberg). The erosion is reflected by reworked Lower Sarmatian carbonates and the formation of paleokarst fissures in the relictic carbonates. In all marginal settings, the erosional gap covers most of the *Elphidium hauerinum* Zone. Overlying sediments usually represent oolitic sediments which are already part of the *Prosononion granosum* Zone. Hence, bryozoan-serpulid limestones of the Lower Sarmatian cycle which escaped erosion are frequently overlain directly by oolites of the Upper Sarmatian cycle. This situation induced several workers such as Nagy et al. (1993) and Friebe (1994) to include both lithologies within a single lithostratigraphic entity.

This second Sarmatian 4th order cycle might be best termed a Sarmatian mixed siliciclastic-oolitic cycle (text-figs 1 and 12). It starts in the upper *Ervilia* Zone of the mollusc zonation and comprises the entire *Prosononion granosum* Zone. In contrast to the "aggressive" Lower Sarmatian cycle, the second cycle reflects rather stable conditions.

Its 4th order TST comprises the interval #23-16 and is characterised by a marked flooding surface within #c. Marginal areas, such as the elevated Mistelbach block in the northern Vienna Basin, are flooded. Along the Leitha Mountains (St. Margarethen, Hummel), Badenian and Lower Sarmatian carbonates, which were exposed during the *Elphidium hauerinum* Zone, are again covered by the sea (Harzhauser and Piller 2004). Above this major flooding surface, a minor parasequence is developed, being reflected by the coarsening upward cycles #19-18 and #17. This is the best recorded phase of the Sarmatian, being documented by numerous outcrops.

Rock-forming coquinas, such as those typically outcropped at the holostratotype Nexing, and up to 20-m-thick successions of oolites developed. Ooid shoals extended along the margins of the basins.

This parasequence is indicated at Nexing by gravel and sand intercalations above steeply inclined shell-hash sand waves. Parts of the Mistelbach block even became subaerially exposed, and vegetation covered the emerged ooid shoals (own observations). In the Styrian Basin and the Eisenstadt-Sopron Basin this interval coincides with the intercalation of gravel and sand at the Waltra, Hartberg, St. Margarethen, and Sauerbrunn sections (Steininger and Thenius 1965; Nebert 1951). In positions detached from the mainland such as at the Wolfsthal section, these siliciclastics are missing, but a several-metre-thick layer of caliche formed instead.

This phase coincides with the boundary between the upper *Ervilia* Zone and the *Sarmatimactra vitaliana* Zone. Some tectonic activity is documented by tilting of the Mistelbach block.

The strange erosive episode in the late 4th order TST is followed by another major flooding that culminates in the maximum flooding surface of that cycle. Shale-line features occur in all geophysical logs within that interval (#b). As this position is supposed to correspond to the onset of the Bessarabian in the Eastern Paratethys, this major transgression is probably linked to a "pan-Paratethyan" process and should be traceable throughout the sedimentation area of the former sea.

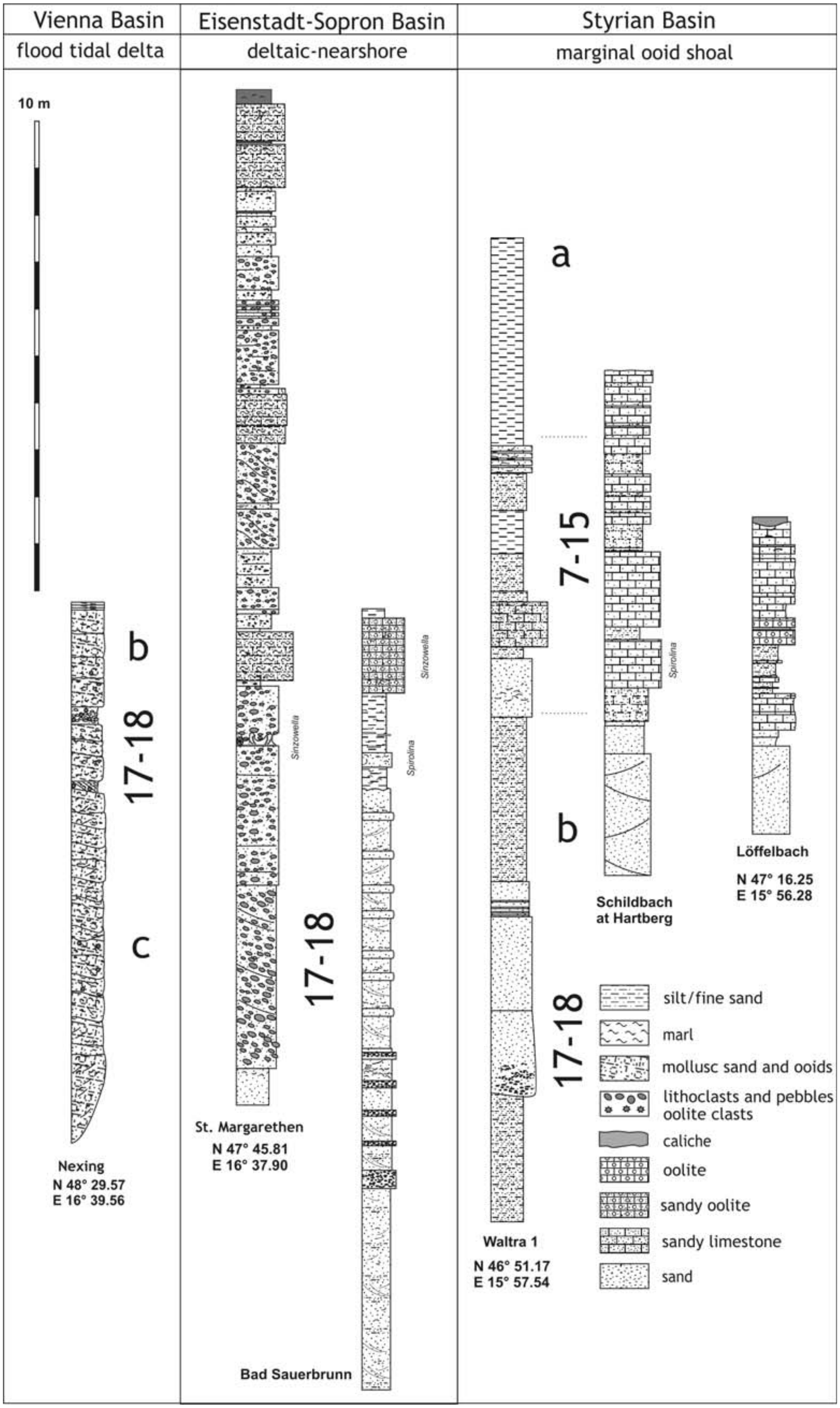
The 4th order HST is correlated with the *Sarmatimactra vitaliana* Zone (Mollusca) and the upper *Prosononion granosum* Zone. Deposits of the latest Sarmatian are completely eroded along the margins of the Vienna Basin. In the Styrian Basin (Waltra and Löffelbach sections) and in the Eisenstadt-Sopron Basin (St. Margarethen section), however, the well-preserved sedimentary successions indicate at least two or three parasequences which coincide with the formation of marly and oolitic limestones separated by siliciclastics. The fauna of these layers is characterised by thick-shelled mactrid bivalves and an acme of the gastropod *Gibbula podolica,* which seems to serve as a marker horizon in all basins. These low order cycles or parasequences are also obvious in geophysical logs, which suggest a separation of the bundles #15-13, #12-9, and #8-7 by minor flooding surfaces.

The very top of the Sarmatian succession is only recorded in wells. It starts with the last major flooding in interval #a and grades into oolitic sediments with characteristic mass-occurrences of the foraminifer *Spirolina*. In addition, Fuchs (1979) described a typical level of statoliths of mysid crustaceans in the uppermost Sarmatian; it can be traced throughout the Paratethys area. The occurrence of littoral potamidid-bearing sand with scattered lignites indicates a shift of the littoral zone far into the basin. Kosi et al. (2003) interpreted this part of the Sarmatian 3rd order cycle as a shelf-margin systems tract, which consequently might also be applied to the 4th order Upper Sarmatian cycle.

The Sarmatian/Pannonian boundary is characterised by deep valley incisions and erosion in the Styrian Basin and the Vienna Basin, indicating a type 1 sequence boundary (Kosi et al. 2002; Kováè et al. 1998).

CONSIDERATIONS ON ASTRONOMICAL FORCING

During recent years, the calibration of sedimentary sequences with astronomical target curves has turned out to be an excellent tool for basin research. An accurate magnetostratigraphic backbone allowed this method to be tested especially in continental basins such as the Calatayud and Teruel Basins in Spain (Abdul Aziz 2001), the Ptolemais and Megalopolis Basins in Greece (van Vugt et al. 1998; van Vugt 2000), and the Oltenia Basin in Rumania (van Vugt et al. 2001). In the former Paratethys Sea



TEXT-FIGURE 11
Outcrops representing marginal facies of the *Sarmatimactra vitaliana* Zone. The progradation of fluvial facies indicated by the interval 17-18 in basinal settings (see text-fig. 5) is reflected by gravel, sand, and erosion. Intervals b and 7-15 are characterised by a succession of oolitic marls and limestones alternating with sand and gravel. (Log Bad Sauerbrunn modified from Steininger and Thenius 1965)

area, however, only the Upper Miocene deposits have been discussed up to now in the light of astronomical forcing (e.g. Juhász et al. 1999; Harzhauser and Mandic 2004; Harzhauser et al. 2004).

The highly correlative patterns of geophysical logs of the Sarmatian of the Vienna Basin and the Styrian Basin as shown in text-fig. 8 demonstrate that the depositional cycles are not overridden by local tectonic movement. Thus, overall parallel developments in these basins might rather be linked to allocyclic triggers such as represented by the Milankovitch frequency band. However, a second scenario would be that the sea-level patterns are driven by large-scale movements of the entire Alpine-Carpathian region.

The 2.35-Ma component of the eccentricity band as proposed by Laskar (1990) was recently suspected by Harzhauser et al. (2004) to be reflected in the paleo-hydrology of the Late Miocene Lake Pannon. Hence, the glacio-eustatic sea-level low-stand TB3.1 and the Sarmatian/Pannonian boundary coincide fairly with a minimum of the 2.35-Ma cycle. The subsequent transgressive systems tract and the maximum flooding in Lake Pannon correspond to the maximum of that curve. Finally, during the fading of the 2.35-Ma maximum, the Vienna Basin dried up in the Late Miocene. Some parallels may be deduced for the land-locked Paratethys Sea during the Sarmatian. The pelitic TST and mfs of the Sarmatian 3rd order cycle clearly coincide with the late maximum of the 2.35-Ma component. The switch towards mixed-siliciclastic-carbonatic HST conditions follows the turning point of the 2.35-Ma curve towards the minimum.

Due to its duration of approximately 1.1 Ma, however, the entire 3rd order Sarmatian cycle might better be explained by the influence of the 1.2-Ma component of the obliquity band. Lourens and Hilgen (1997) determined that this long-periodic shift in obliquity is well expressed in the 3rd order eustatic cycles and correlates conspicuously with the isotope events as identified by Miller et al. (1991).

On a finer scale, the gamma-log curves of the geophysical logs seem to record cyclicities of higher frequency. In text-fig. 12 a tentative correlation of the logs Niedersulz 5/8 and 9 with the 400-Ka and 100-Ka eccentricity components is proposed. Due to the lack of any chronostratigraphic datings, these correlations cannot be more than a first attempt, which will have to pass future tests. Nevertheless, the patterns of several parts of the logs, such as # 40-50, # 20-30 or #7-15, reveal a very clear cyclicity and indicate an overall progradation of marginal facies. These intervals are separated by two highly similar intervals #f-g and #b-c, which are related to major floodings and comprise the maximum flooding surfaces of the two 4th order cycles. This partition suggests a relation to the 400-Ka eccentricity component, which displays 2 maxima and 3 minima during the considered time-interval. Hence, the 4th order maximum flooding surfaces are correlated with the maxima of the 400-Ka band.

A further higher-frequency modulation is obvious by the nearly identical interruption of these flooding intervals by short but pronounced intercalations (# 33-39 and # 17-19). Hence, the single flooding events (e.g. #f, g, c, b, a) could be influenced by the 100-Ka eccentricity component as indicated in text-fig. 12. Finally, the periodicity in the intervals #20-30 or #7-15 – caused by minor flooding surfaces which separate serrate funnel- to bell-shaped bundles of the geophysical logs – might best be correlated with obliquity or insolation. The poor fit of the insolation curve with the interval #7-15 suggests obliquity to be the driving force. Correspondingly, the interval #20-30 fits best to the obliquity curve. However, the characteristic two-fold serration of each bundle indicates a modulation by the insolation curve. This interval fits excellently to the astronomical target curves between 12.05 and 12.25 Ma and might serve as the most reliable benchmark for the performed correlation.

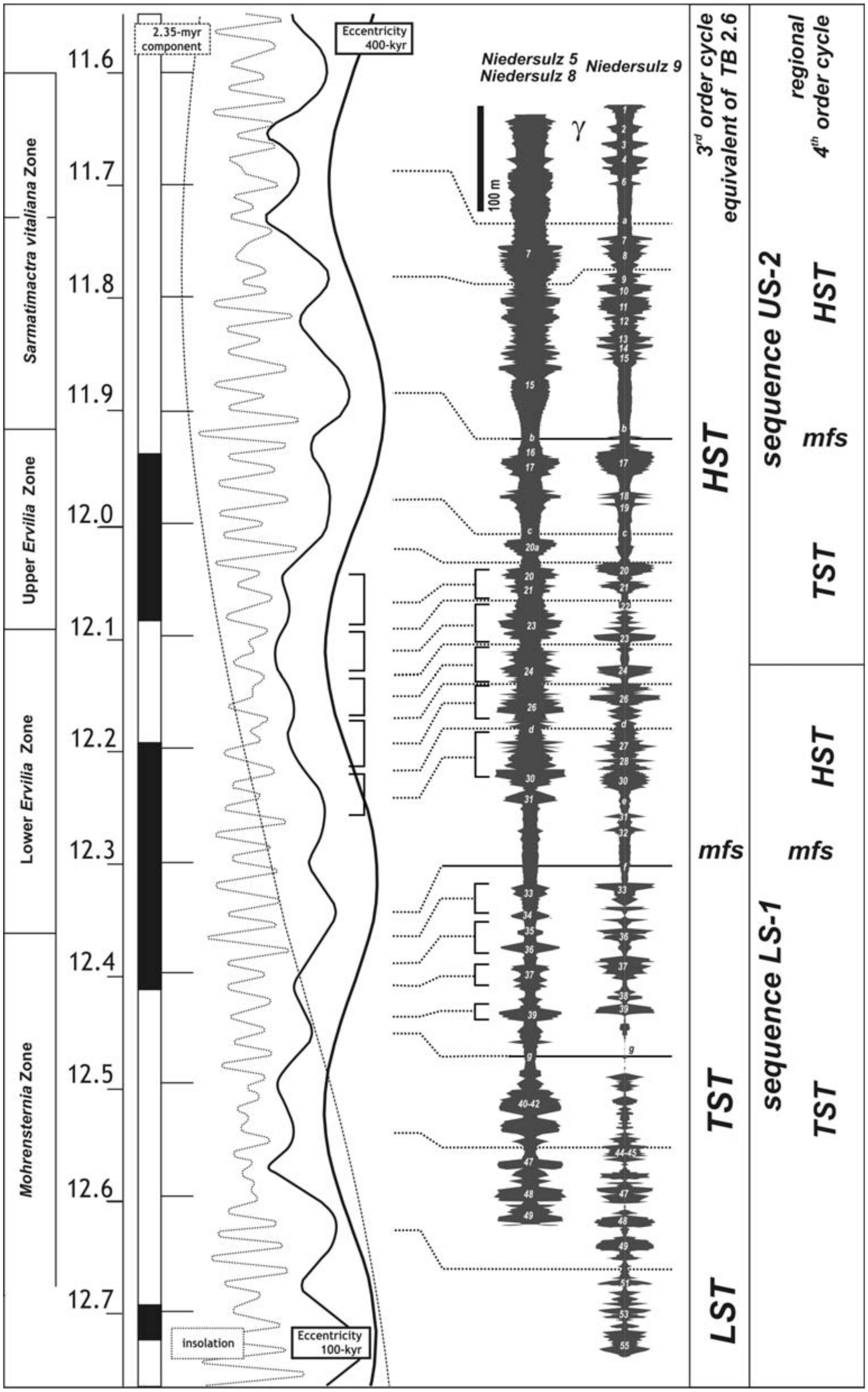
Note that these considerations lack any verification by paleomagnetic data. Datings from the cores are also still missing. Therefore, the discussed relation of astronomical cycles with Sarmatian sedimentation remains a working hypothesis. Based on this hypothetic correlation, however, the Badenian/Sarmatian boundary is suggested to be somewhere between 12.6 and 12.8 Ma. This date fits excellently to the glacio-eustatic isotope event MSI-3 at 12.7 Ma (Abreu and Haddad 1998). Hence, this co-incidence might support our proposed correlation.

Regional versus local: aspects of a pan-Paratethyan story

The presented concept of astronomically forced sedimentary sequences should be of more than mere local character. In fact, a comparison with several sites in the Central Paratethys, as well as with those at the gate into the Eastern Paratethys, reveals analogous sedimentary successions. A twofold succession of a pelitic Lower Sarmatian (Lower Volhynian) versus a carbonatic Upper Sarmatian (Upper Volhynian, Lower Bessarabian) can be observed throughout the Central Paratethys and even in the Eastern Paratethys.

The geographically and biogeographically closest area for comparison is Hungary. There, a threefold Hungarian Sarmatian s.s. was proposed by Görög (1992) based on foraminifera data from borehole analyses in the Zsámbék Basin. The zonation into an *Elphidium reginum* Zone, *Elphidium hauerinum* Zone, and a *Spirolina austriaca* Zone equals that from the western part of the Central Paratethys. The *Elphidium reginum* Zone is characterised by pelitic, marly, and sandy deposits and bears bentonites and diatomites (e.g. Sajóvölgy Formation in Hámor 1985; well Karád in Strausz 1955). A full Hungarian equivalent to formations of the Vienna and Styrian Basins is also represented by the Upper Sarmatian Tinnye Formation (Trunkó 1996). The occurrence of the *Spirolina austriaca* horizon is well developed at the faciostratotype Söreg at Tinnye about 30km W of Budapest (Boda 1974) and supports the correlation of the Tinnye Formation with the Skalica Fm. and the Gleisdorf Fm.

Sarmatian deposits in Serbia serve as a counterpart in the southern territory of the Paratethys Sea. A rather complete, though condensed, nearshore section is described by Gagic (1981) from the Mišljevac River near Beograd. The section comprises a clayey-silty basal part of a few metres thickness assigned to the *Elphidium reginum* Zone. This is followed by silty marly deposits with intercalations of oolites yielding a foraminifera assemblage typical for the *Elphidium hauerinum* Zone. The top of this middle part is formed by about 3 metres of pelite. The very top of the section consists of about 12 metres of limestones with scattered oolites characterised by abundant molluscs and caliche formation. In the uppermost part, Gagic (1981) detected a rich foraminifera fauna, predominated by *Peneroplis, Spirolina, Dendritina*, and *Sinzowella* and suggested this short unit of about 2 m to represent the lowermost Bessarabian. The general lithological trends and bioevents agree fully with those of the Vienna and Styrian Basins. The only difference between that succession and the western margin of the Central Paratethys



TEXT-FIGURE 12

A solely tentative correlation of Sarmatian deposits as shown in text-fig. 5 with astronomical cycles (Laskar 1990). For an easier recognition of cyclic sedimentary successions, the gamma-logs of the Niedersulz 5-8 and 9 wells are mirrored. The leap from the pelitic Lower Sarmatian 4th order cycle towards the oolitic Upper Sarmatian 4th order cycle might be linked to the 2.35-ma component of eccentricity, which switches from its maximum (during the latest Badenian) towards a minimum. A further correlation between maxima of the 400-ka band and high-amplitude 100-ka maxima with the major flooding surfaces is reasonable but unproved. Finally, the poorly developed 100-ka cycles within the 400-ka minimum between 12.05 and 12.25 fully agree with the onset of the 4th order HST and the progradation of fluvial facies into the basins. The magnitude of that event, however, seems to be pushed by tectonic uplift in the eastern Alpine area. The proposed sequence stratigraphy is indicated to the right (see text for details).

is the intercalation of oolites in the *Elphidium hauerinum* Zone, whereas this phase is represented by the Carinthian Gravel and its equivalents in the Austrian basins. Hence, the HST of the Lower Sarmatian 4th order cycle coincides with basinward progradation of fluvial facies along the margin of the Alpine chain but is marked by first oolite deposition in Serbia.

Farther to the southeast, the Rumanian basins allow further correlations. Crihan (1999) presented a detailed analysis of the faunistic composition of the Sarmatian in the Subcarpathians of Muntenia in SE-central Rumania, which at that time was part of the Eastern Paratethys. The Sarmatian deposits have been united by her in the Macesu Formation, which comprises a lower, clayey-marly complex, followed by a sandy-oolitic subunit, which is overlain again by a predominately clayey-silty subunit in the top. The basal clays are rich in microfossils such as *Cycloforina ovata* and *Anomalinoides dividens*, which appear together with the characteristic mollusc assemblage contributed by *Mohrensternia, Granulolabium, Acteocina,* and *Ervilia*. All together, the fauna corresponds fully to that of the *Elphidium reginum* Zone and the *Mohrensternia* Zone of the western Central Paratethys. A widespread tuffitic layer – distributed throughout the subcarpathian area and the Moldavian Platform – separates this lower part of the Macesu Formation from the sandy middle part, which has intercalations of oolitic limestones that are dated as Volhynian by Crihan (1999). The third, clayey-marly part of the formation bears oolitic limestones rich in peneroplids such as *Dendritina* and *Spirolina* aside from the nubeculariid *Sinzowella*. These are already considered as Bessarabian by Crihan (1999), representing the Lower Bessarabian *Porosononion sarmaticum* Zone and the Late Bessarabian *Porosononion aragviensis* Zone. It is worth mentioning that the level with the abundant peneroplids appears in the basal part of the Lower Bessarabian Zone and seems to be a very well-developed bioevent that allows a pan-Paratethyan correlation.

According to Filipescu (1996), Volhynian and Lower Bessarabian deposits occur in the western part of the Transylvanian Basin. These are united in the Feleac and Dobarca Formations in the northern distribution area and in the Mahaceni Formation in the more western part. In both areas the basal part of the formations is characterised by the occurrence of abundant *Anomalinoides dividens.* The Aiton section is part of the Feleac Formation; the recorded mollusc faunas represent assemblages of the *Mohrensternia* and the *Ervilia* Zones in the western Central Paratethys (Chira 1999). In the Bessarabian parts of both formations, Filipescu (1996) reports occurrences of mysid statoliths, which strongly support a direct correlation with the mysid-level introduced by Fuchs (1979). A quite similar development for the Volhynian-Lower Bessarabian is reported by Munteanu and Munteanu (1997) for the Subcarpathians of Muntenia, starting with so-called "*Lobatula*-clays" which are overlain by Sipotelu Formation. The latter is correlated with the synchronous Coto Vaii Formation in the southern Dobrogea area. There, the Volhynian starts with clay and diatomites which are overlain by various limestones, dated as Upper Volhynian and Lower Bessarabian. Again, a relation to the development along the western shore of the Paratethys is obvious.

CONCLUSIONS

For the first time, an integration of well-log data with surface data allows the depositional history of the Sarmatian to be evaluated in the western part of the Central Paratethys. The interbasin correlation, combining data from 4 different basins and subbasins, suggests the Sarmatian stage to be a product of a single 3rd order eustatic cycle. This cycle corresponds to the TB 2.6 cycle of Haq et al. (1988) and is composed of two lithologically quite different 4th order cycles. A peltic-siliciclastic, strongly transgressive Lower Sarmatian cycle contrasts with a mixed siliciclastic-oolitic Upper Sarmatian cycle. This change in lithology is paralleled by changes within the mollusc faunas: thin-shelled Early Sarmatian faunas dominated by *Mohrensternia* and *Abra* are replaced by thick-shelled taxa such as *Venerupis* and *Sarmatimactra* at the dawn of the Late Sarmatian.

The shift in lithology correlates conspicuously with the run of the 2.35-Ma component of eccentricity and might reflect the turning point from its maximum towards the minimum phase. A further influence of the 400-Ka eccentricity band might explain the position of the maximum flooding surfaces of each 4th order cycle. Associated major flooding surfaces are probably triggered by the superimposed 100-Ka eccentricity component.

Within that hypothetic scheme, some regional processes influenced the general trends. Thus, the progradation of fluvial facies during the initial 3rd order HST correlates not only with a minimum of the 400-Ka component. The deposition of the Carinthian Gravel and its equivalents in the Vienna Basin and the Eisenstadt-Sopron basins also coincided with the final retreat of the Paratethys Sea from the Molasse Basin. Hence, it seems reasonable that tectonic uplift might have amplified the HST conditions. This is further supported by the fact that the increasing amounts of gravel deriving from Alpine units could be linked with an increased relief in the hinterland. Another hint at a tectonic modulation of the relative sea-level is the tilting of the Mistelbach block at the boundary between the upper *Ervilia* Zone and the *Sarmatimactra vitaliana* Zone, described by Harzhauser and Piller (2003). The late Middle Miocene uplift phase might thus be a regional "eastern Alpine" phenomenon.

This new but still tentative calibration of the depositional sequences with astronomical target curves would require a refinement of the position of the Sarmatian stage within "traditional" chronostratigraphic tables. Based on the performed correlation, the Badenian/Sarmatian boundary should not be placed at 13.0 Ma as done in many published tables because this would cause a misfit between log-response and target curves. Based on the correlation, the boundary is suggested to be somewhere between 12.6 and 12.8 Ma. This date, moreover, fits excellently to the glacio-eustatic isotope event MSI-3 at 12.7 Ma (Abreu and Haddad 1998). Similarly, the Sarmatian/Pannonian boundary was calibrated by Harzhauser et al. (2004) to the glacio-eustatic sea-level lowstand of cycle TB3.1 at 11.6 Ma based on new data of Hilgen et al. (2000).

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