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Correlation of Tethyan and Peri-Tethyan long-term and high-frequency eustatic signals (Anisian, Middle Triassic)

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Abstract: During Anisian times, broad ramp systems developed on the northwestern Tethys shelf and in the adjacent Peri-Tethyan realm. In both paleogeographical settings carbonate series display characteristic cyclic patterns, reflecting long-term and high-frequency eustatic sea-level changes. Facies successions recognized within the small-scale sedimentary cycles document a rapid transgressive phase followed by a prolonged highstand phase. The erosional base of these deposits is interpreted as a sequence boundary. Transgressive deposits are characterized by bioclastic limestones with reworked lithoclasts. Bioturbated mudstones represent the highstand deposits. Sedimentation of laminated mudstones is documented during the late highstand phase. Maximum flooding is recognized by thin condensed marly layers at the top of bioclastic beds. Such meter-scale sedimentary cycles are the basic stratigraphic building blocks of the Anisian series of Hungary and Germany, representing ramp deposits of the proximal Tethys shelf and the northern Peri-Tethys Basin, respectively. Comparison of both depositional environments leads to a better understanding of cyclic sedimentation of shallow-water carbonates and controlling factors. Eustatic signals of different scales are analysed and used for correlation of sedimentary series between different paleogeographical settings.

Key words: Anisian, Germany, Hungary, Peri-Tethys Basin, NW Tethys shelf, sedimentary cycles, carbonate ramps.

Introduction

Accumulation and preservation of sediment on shallow ramps are controlled by eustatic sea level, subsidence, the hydrodynamic regime of the system, and the ramp morphology. Consequently, lateral and stratigraphic facies changes are a common feature, and sediment accumulation rate is highly variable through time. Sea-level fluctuations of different amplitudes and frequencies play an important role for shallow ramp systems and are recorded in a hierarchical stacking of depositional sequences.

Depositional sequences are defined as stratigraphic units comprising a succession of genetically related strata (Mitchum et al. 1977) and based on seismic stratigraphy, Vail et al. (1977) introduced the term first-, second-, and third-order sequences with durations of 200–300 Myr, 10–80 Myr, and 1–10 Myr, respectively. Later, when sequence analysis was first applied to outcrops, the detection of small-scale sequences enabled a higher time resolution. Thus, Vail et al. (1991) distinguished six orders of depositional sequences, lasting from tens of millions of years to a few ten-thousand years, with third-order sequences spanning a time interval of 0.5–3 Myr (Haq et al. 1987). Such third-order sequences are usually called sequences or depositional sequences. However, there is still a controversial discussion on the origin and duration of third-order sequences. While first- and second-order sequences are seen to be related to tectonic and tectono-eustatic changes and fourth-, fifth- and sixth-order sequences are explained by climatically driven sea-level fluctuations in the Milankovitch frequency band, third-order sequences are discussed as resulting from a combination of tectonic and glacio-eustatic changes (Vail et al. 1991). Additionally, changes in intraplate stress (Cloetingh 1988) as well as a combination of plate rifting and convergence superimposed on second-order volume changes of mid-ocean ridges (Miall 1990) are under discussion causing third-order cyclicity. Finally, Strasser et al. (2000) suggested the formation of third-order depositional sequences, at least within a passive-margin setting such as the northern margin of the Tethys Ocean, being related to the 400,000 year eccentricity cycle of the Earth's orbit.

Hierarchical stacked cyclic patterns are well documented in the Anisian (Middle Triassic) carbonate series studied in Germany and Hungary (Fig. 1) and enable a detailed analysis of eustatic signals used for long-distance correlation.

Sedimentary cycles were first described from the Anisian Muschelkalk series of NW Germany by Fiege (1938). Later, Schüller (1967) and Schulz (1972) published sections from Lower Saxony and N Hesse and interpreted small-scale facies successions as shallowing-upward cycles. A first sequence-stratigraphic interpretation of meter-scale cycles recognized in Lower Muschelkalk sections from Central Germany was published by Götz (1996). Middle Triassic third-order depositional sequences (sensu Vail et al. 1991) of the eastern part of the Germanic Basin, and corresponding sedimentary deposits of the Alpine realm, were addressed in the works of Szulc (1999, 2000).

In S Hungary, Middle Triassic ramp deposits of the Mecsek Mountains show characteristic facies successions, related to large-scale sea-level changes at the scale of third-order cy-

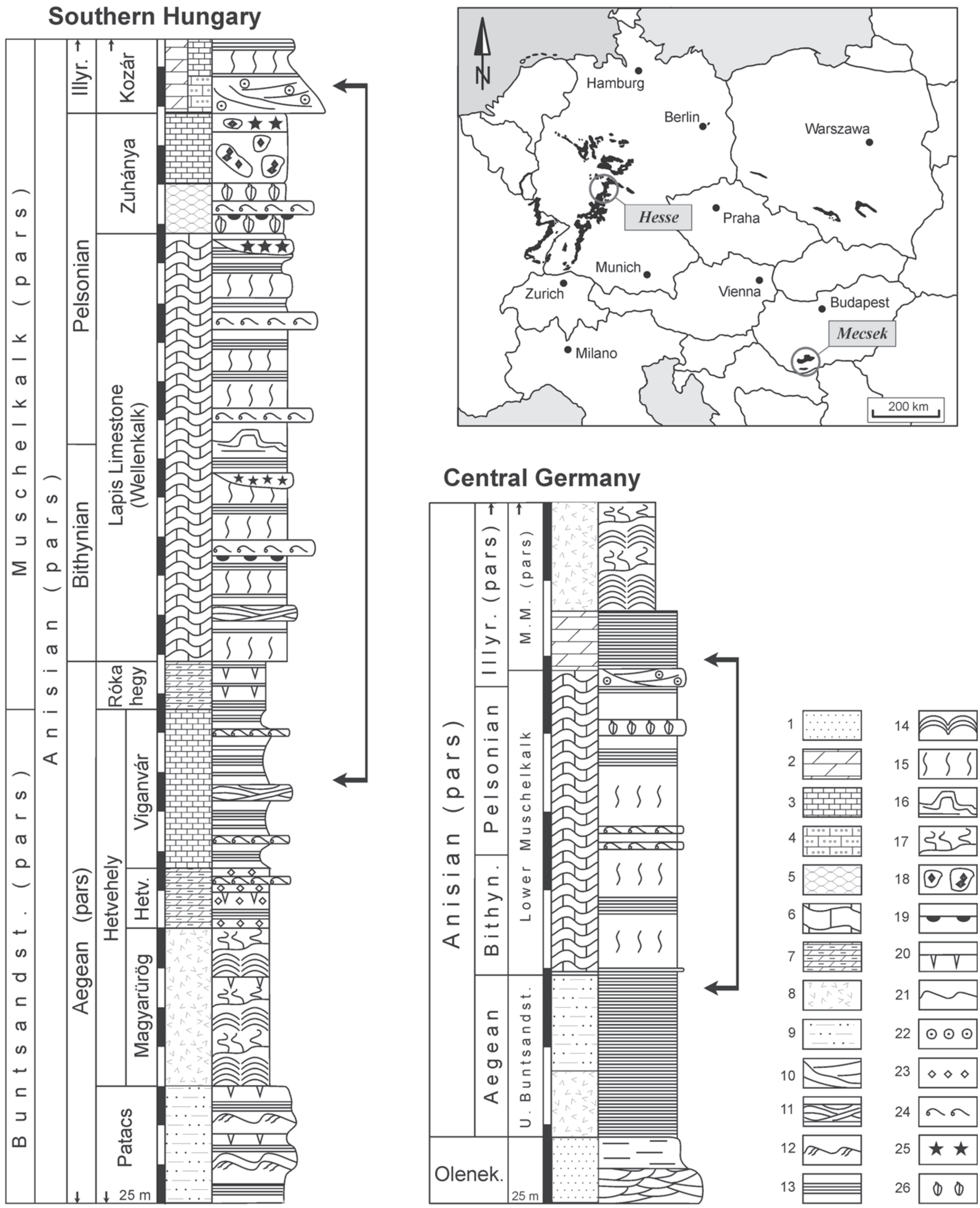

Fig. 1. Stratigraphy, lithology and sedimentary features of the Upper Buntsandstein and Muschelkalk in Germany (Hesse) and Hungary (Mecsek Mountains). M.M. — Middle Muschelkalk. Arrows mark the Anisian interval studied. Legend: **1** — sandstones, **2** — dolomites, **3** — limestones, **4** — oolitic limestones, **5** — nodular limestones, **6** — flaser-bedded limestones, **7** — marly dolomites, **8** — evaporites, **9** — siltstones, **10** — cross-bedding, **11** — hummocky cross-stratification, **12** — current ripple cross-lamination, **13** — parallel lamination, **14** — undulating lamination in evaporites, **15** — bioturbation, **16** — slumps, **17** — chicken wire structures, **18** — dolomitic mottling, **19** — gutter casts, **20** — dessication cracks, **21** — current ripples, **22** — ooids, **23** — evaporite pseudomorphs, **24** — bioclasts, **25** — crinoids, **26** — brachiopods.

clicity (Török 1998, 2000). A correlation of these Tethyan sequences with those described from the Peri-Tethys Basin was first published by Török (2000). New biostratigraphic data (Götz et al. 2003; Ruckwied et al., in prep.) enable a more precise correlation of Anisian sequences of these two different paleogeographical settings. The composition and preservation of small-scale sequences within this ramp system is addressed by the present study for the first time.

A detailed description of the sedimentary facies and palynofacies of the sections in Central Germany and S Hungary is found in Török (1993, 1998), Götz (1996), Götz & Feist-Burkhardt (1999) and Götz et al. (2003).

Geological setting

During Anisian times, Central Europe was subdivided into two major depositional areas: The northwestern Tethys shelf and the semi-enclosed Peri-Tethys Basin (Germanic Basin) that was connected with the Tethys Ocean via gate ways in the South (Fig. 2). Broad ramp systems developed along the Tethys shelf and in the adjacent Peri-Tethys Basin. Today outcrops in the Northern Calcareous Alps (Rüffer 1995), the Western Carpathians (Michalík et al. 1992), the Dolomites (Zühlke 2000) and southern Hungary (Török 1998) document the evolution of such ramps in the northwestern Tethyan shelf area (Dercourt et al. 2000). Muschelkalk sections described from the Netherlands (Pöppelreiter 2002), Central Germany (Götz & Feist-Burkhardt 1999; Rameil et al. 2000) and Poland (Szulc 2000; Kedzierski 2002) display the Anisian ramp morphology along a NW-SE cross-section in the Germanic realm.

In Central Germany and S Hungary (Mecsek Mts), the Anisian ramp deposits are mud-dominated (Götz 1996; Török 1998). The major lithofacies type is bioturbated mudstone, the so-called "Wellenkalk". Bioclastic marker beds and fossil-rich units are used for lithostratigraphic subdivision (Fig. 1). Biostratigraphy is based on conodonts (Kozur 1974; Götz 1995; Kovács & Rálisch-Felgenhauer 2005; Ruckwied et al., in prep.), palynomorphs (Mädler 1964; Barabás-Stuhl 1993; Götz et al. 2003; Ruckwied et al., in prep.) and crinoids (Hagdorn & Głuchowski 1993; Hagdorn et al. 1997).

Cyclic stacking patterns and eustatic evolution

The Anisian deposits of the Peri-Tethys Basin document the evolution of a NW-SE striking homoclinal ramp system

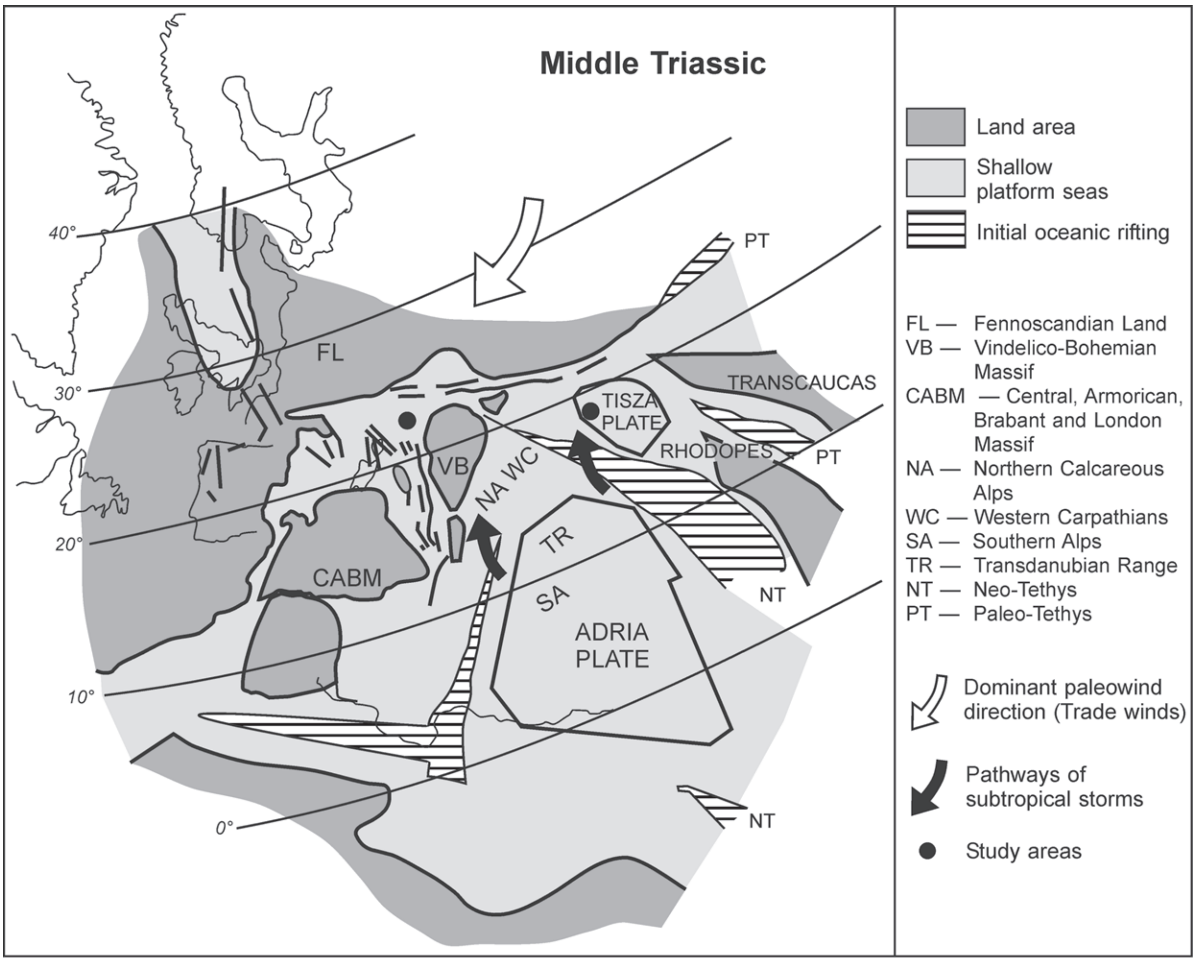

Fig. 2. Paleogeography of the Middle Triassic, modified after Szulc (2000) and Haas (2001), based on data by Ziegler (1982) and Mostler (1993).

with a characteristic lateral facies distribution of lagoonal marls and inner ramp peritidal dolomites, bioclastic mid-ramp grain-/packstones and outer ramp mudstones (Lukas 1991; Götz 1996; Pöppelreiter 2002). The stratigraphic series is build up of bioturbated mudstones and bioclastic beds, showing characteristic deepening-shallowing trends. The basal mudstones of the Anisian (Lower Wellenkalk, Wellenkalk 1 Member) overlay the Upper Buntsandstein (Röt) siltstones and become marlstones up section. A some meters thick marly interval in the middle part of the Lower Wellenkalk is overlain by bioturbated mudstones and platy mudstones with bioclastic grainstones (Oolithbank Member) on top. The succeeding bioturbated mudstone package (Middle Wellenkalk, Wellenkalk 2 Member) is overlain by brachiopod grain-/packstones (Terebratelbank Member). A third platy mudstone series (Upper Wellenkalk, Wellenkalk 3 Member) with bioclastic peloid-grainstones (Schaumkalkbank Member) terminates the Lower Muschelkalk carbonate series. The biostratigraphic framework of the carbonate series studied is based on conodonts (Götz 1995; Narkiewicz 1999), indicating a Bithynian to early Illyrian age. Thus, the correlation of the Anisian Tethyan and Peri-Tethyan series is very precise and enables a high time resolution. The stratigraphic stacking of these sediments displays the long-term eustatic history of the Peri-Tethyan realm with two major flooding phases (Fig. 3). The first transgressive phase during the Bithynian is recognized in the Lower Wellenkalk (Wellenkalk 1 Member) mudstones with maximum flooding in the uppermost part of this member, documented by a marly interval with numerous hardgrounds. Bioclastic grainstones of the Oolithbank Member represent the highstand deposits. The next transgressive pulse occurred within the Pelsonian (Wellenkalk 2 Member) and culminated with the deposition of thick brachiopod shell beds (Terebratelbank Member) representing the most pronounced Anisian flooding phase recognized over the whole Peri-Tethys Basin (Szulc 1999). Mudstones of the Upper Wellenkalk (Wellenkalk 3 Member) are interpreted as early highstand deposits. Prograding shoal deposits of the uppermost Lower Muschelkalk (Schaumkalkbank Member) are a characteristic sedimentary feature of the late highstand phase.

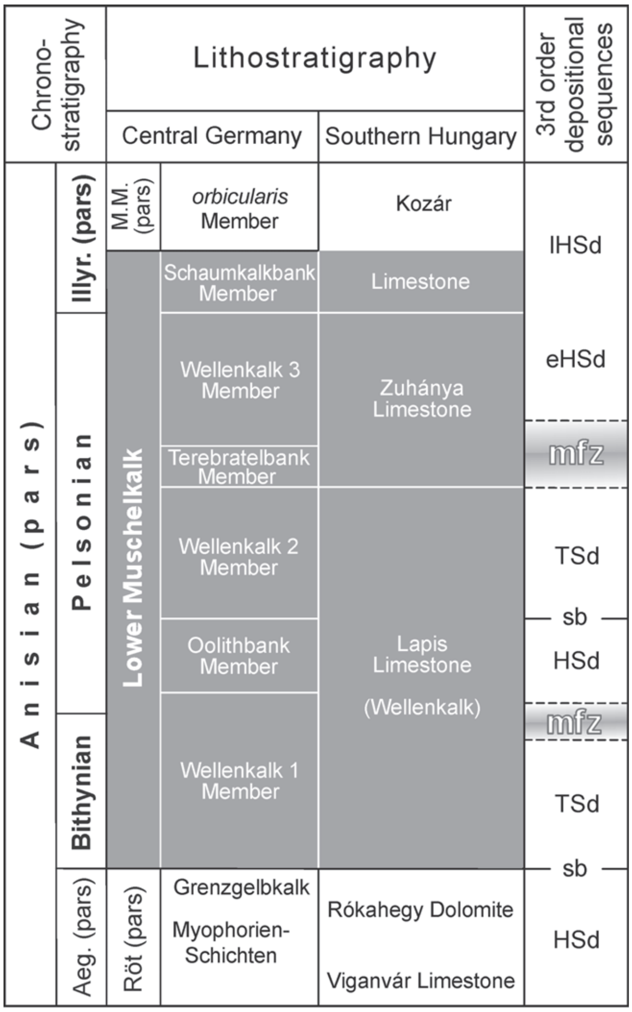

Fig. 3. Third-order depositional sequences of the Anisian in Central Germany and Southern Hungary. Abbreviations: **sb** — sequence boundary, **TSd** — transgressive deposits, **mfz** — maximum flooding zone, **eHSd** — early highstand deposits, **lHSd** — late highstand deposits. **M.M.** — Middle Muschelkalk.

Characteristic meter-scale facies successions build small-scale sequences. These are the basic stratigraphic blocks of the third-order depositional sequences (Götz & Feist-Burkhardt 1999), and represent simple sequences sensu Vail et al. (1991) and small-scale sequences after Strasser et al. (1999), respectively. Götz (1996) interpreted these cycles as high-frequency cycles that display orbital induced high-frequency sea-level changes during Anisian times (Götz 2002, 2004). Stacked small-scale sequences form characteristic sets of 3 to 4 sequences (Rameil et al. 2000; Kedzierski 2002) that are characteristic features of the third-order depositional sequences described by Aigner & Bachmann (1992) and Szulc (1999).

Depending on the position within the ramp system, sedimentary cycles show a spatially different development of facies successions. Deposits of the proximal ramp in the western part of the Peri-Tethys Basin show asymmetrical sequences (Götz 1994, 1996; Rameil et al. 2000; Götz & Wertel 2002). Bioclastic beds with reworked hardground pebbles represent the transgressive phase. Since pebbles were reworked during transgression, the hardground may correspond to the sequence boundary. Bioturbated and laminated mudstones are interpreted as highstand deposits (Fig. 4). Maximum flooding is recognized by thin condensed marly layers at the top of bioclastic beds. Lowstand deposits are not recorded so that the transgressive surfaces at the base of bioclastic beds directly overlie the sequence boundaries or even erode it away (Götz 1996; Rameil et al. 2000). Reworked lithoclasts at the base of bioclastic beds derive from mudstones or hardgrounds below these beds; they may be completely reworked or are partially eroded. These erosional (ravinement) surfaces are developed within the entire basin and are used for basin-wide high-resolution correlation (Pöppelreiter 2002; Götz 2004; Fig. 5).

Deposits of the distal ramp are represented by nodular and platy mudstones and crinoidal wackestones/packstones, showing symmetrical cycle patterns (Kedzierski 2002;

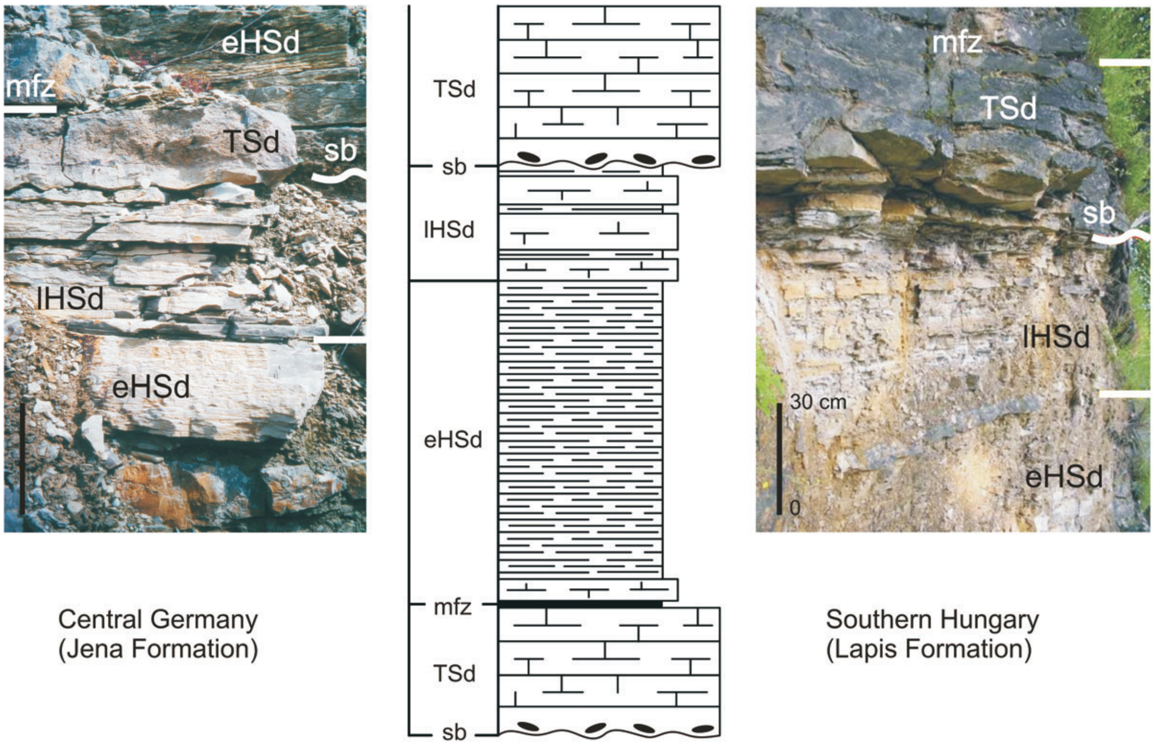

Fig. 4. Small-scale sequences within the Lower Muschelkalk series (lower Jena Formation) of Central Germany and within the lower Lapis Formation of Southern Hungary (Mecsek Mountains). Both cycles represent characteristic small-scale facies successions of proximal ramp deposits. Abbreviations: **sb** — sequence boundary, **TSd** — transgressive deposits, **mfz** — maximum flooding zone, **eHSd** — early highstand deposits, **lHSd** — late highstand deposits. Scale 30 cm.

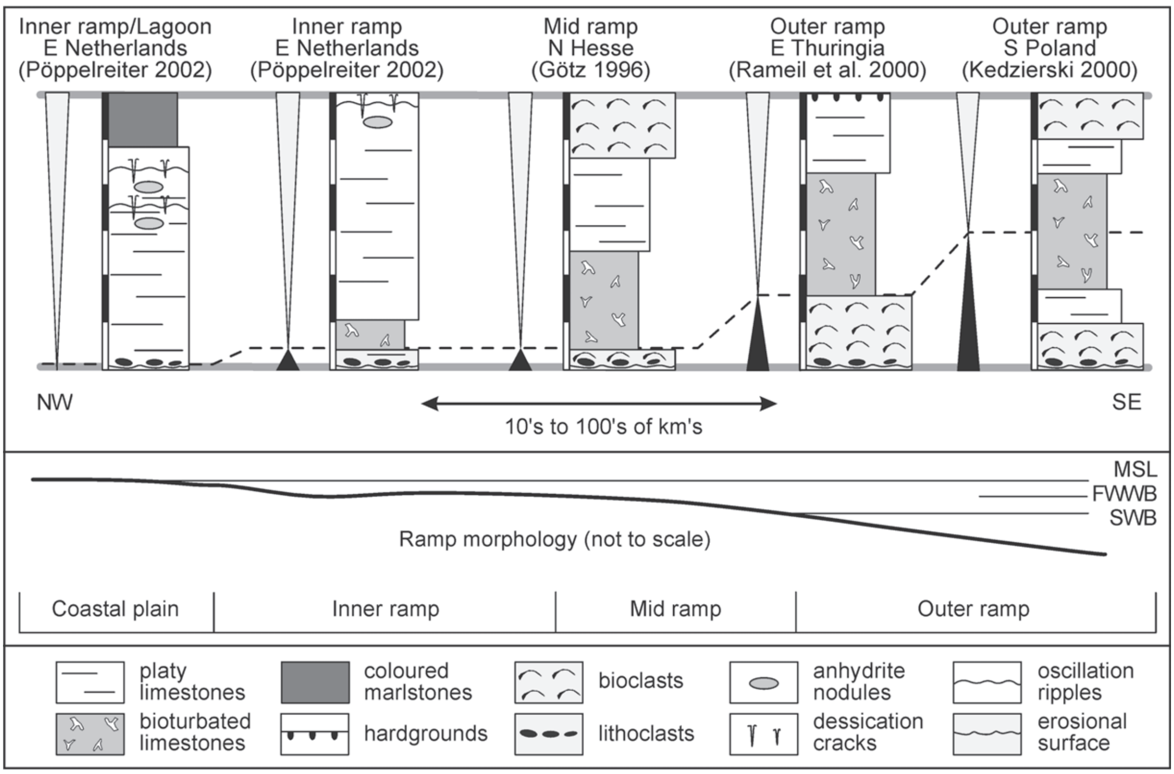

Fig. 5. Correlation of small-scale sequences of the Lower Muschelkalk ramp system (Peri-Tethys Basin), modified after Pöppelreiter (2002). Grey line — sequence boundary, dashed line — maximum flooding.

Fig. 5). Highly proximal sedimentary series are characterized by small-scale sequences built of dolomitic mudstones and red marlstones of the lagoonal and inner ramp setting. These sediments represent highstand deposits. Due to permanent reworking, transgressive deposits are recorded by a pebble lag (Pöppelreiter 2002; Fig. 5).

Cyclic patterns change in space and time. The superimposition of high-frequency and long-term sea-level changes is stratigraphically documented by different thicknesses and changing shallowing-up patterns. Within the long-term transgression aggradational sedimentary successions and increasing thickness of cycles are observed. Phases of maximum flooding are characterized by starvation, documented in basin-wide deposition of condensed, organic-rich marls and amalgamated brachiopod and crinoid shell beds with numerous firmgrounds and hardgrounds. In the Peri-Tethys Basin the upper part of the Lower Wellenkalk and the Terebratel Beds represent these phases (Fig. 3). Long-term highstand deposits show shallowing-up facies successions and increasing thickness of cycles. In addition, dolomitic mudstones are characteristic features of the highstand phase (Götz 2002). In the Peri-Tethys Basin the Oolith Beds and Schaumkalk Beds represent these periods. Both units are shallowing-up sediment bodies, reflecting phases of regression during the late highstand. In these stratigraphical units emersion surfaces were described from the southeastern part of the basin, representing sequence boundaries (Szulc 1999, 2000).

The number of small-scale sequences described from the Lower Muschelkalk (Bithynian-early Illyrian) series of the Peri-Tethys Basin is relatively constant (E Netherlands: 16 (Pöppelreiter 2002); Hesse, W Thuringia and Lower Francony: 20 (Kramm 1994; Götz 1994; Götz & Feist-Burkhardt 1999; Götz & Wertel 2002); E Thuringia and Brandenburg: 21 (Rameil et al. 2000; Kedzierski 2002); and S Poland: 23 (Kedzierski 2002)). Small-scale sequences described from carbonate series of the proximal ramp (E Netherlands) are commonly incomplete successions or not recorded at all. Distal sections (Poland) show the most complete sedimentary series with the highest number of cycles. Considering that the Lower Muschelkalk was deposited within 2 to 3 million years (Harland et al. 1990; Gradstein et al. 1995; Menning 1995; Hardenbol et al. 1998; Ogg 2004; Menning et al. 2005), the small-scale cycles may represent the short orbital eccentricity cycle of 100,000 years. Stacked small-scale sequences forming sets of 3 to 4 sequences (Rameil et al. 2000) may be interpreted as reflecting the eustatic signal related to the 400,000 year eccentricity cycle.

The Mid-Triassic ramp system of S Hungary displays a characteristic lateral facies distribution of coastal sabkhas, inner ramp peritidal dolomites, shoal deposits and lagoonal marls, storm to fair-weather influenced mid-ramp carbonates, proximal to distal shell beds and low-energy outer ramp deposits (Török 1998). The stratigraphic stacking of these facies units records long-term sea-level changes at a third-order scale (Török 2000).

The earliest sediments of the ramp system are greenish-red siltstones (Patacs Siltstone, Fig. 1) with pseudomorphs of anhydrite after gypsum, desiccation cracks, bird's eye structures and ripple marks indicating a peritidal setting. Phyllopods reflect a hypersaline environment, while lingulid brachiopods are indicators of restricted marine influence. Sporomorphs indicate an early Anisian age for the Patacs Siltstone (Barabás-Stuhl 1993; Barabás & Barabás-Stuhl 2005). The succeeding anhydrite and gypsum layers (Magyarürög Anhydrite) are arid tidal flat, that is sabkha deposits (Török 1998) that are overlain by dolomitized peritidal carbonates (Hetvehely Dolomite). The next unit of the deepening-upward succession consists of bituminous limestones (Viganvár Limestone) with bivalve coquinas (Szente 1997) interpreted as storm influenced, temporarily anaerobic to dysaerobic mid-ramp deposits (Török 1998). The overlying dolomitized calcarenites (ooid packstones) of the Rókahegy Dolomite represent small carbonate sand bars of an inner ramp setting.

Anisian mid- and outer ramp deposits are characterized by flaser-bedded limestones and marlstones (Lapis Limestone) with numerous coquinas (tempestites) and hummocky cross-laminated calcisiltite beds, indicating permanent storm activity. In the Mecsek Mountains the deepest facies are represented by brachiopod beds (Zuhánya Limestone), displaying outer ramp deposits (Török 1993). Open marine conditions are indicated by the presence of ammonites and conodonts (Kovács & Rálisch-Felgenhauer 2005) as well as maximum abundance of marine acritarchs (Götz et al. 2003). A Bithynian-Pelsonian age for these beds is based on crinoids (Hagdorn et al. 1997) and palynomorphs (Götz et al. 2003). The Lapis Limestone corresponds to the lower and middle part of the German Lower Muschelkalk (lower Jena Formation; Török 2000); the lower Zuhánya Limestone represents a stratigraphical equivalent of the German Terebratelbank Member (Götz et al. 2003; Fig. 3).

In the upper Anisian (Illyrian) significant spatial differences occur in the grade of dolomitization and facies development. In the western Mecsek Mountains, carbonates are extensively dolomitized (Csukma Dolomite). These beds formed in the supratidal to peritidal zone of the inner ramp. In the central part of the Mecsek Mountains limestones with intercalated beds of ooid-crinoid packstones/grainstones prevail (Kozár Limestone). These sediments are considered to be reworked crinoidal bioherms and ooid shoals and may mark a lowering of the wave base due to relative sea-level fall (Török 1998).

Small-scale sequences are well documented within inner and shallow mid-ramp deposits. During transgression, bioclastic limestones were deposited. A thin clay horizon on top of these bioclastic beds marks the phase of maximum flooding. Sequence boundaries are recognized by the erosional base of transgressive deposits, showing reworked lithoclasts. As in siliciclastic systems, these surfaces may display ravinement surfaces. Calcareous marls characterize the early highstand phase, whereas late highstand deposits are represented by calcareous marls with intercalating platy limestones (Fig. 4).

The characteristic feature of high-frequency cycles within outer ramp deposits (Zuhánya Limestone) is a succession of limestone beds and calcareous marls. A thick limestone unit at the base of the cycle represents the transgressive phase, whereas the following nodular limestone-marl alternation is interpreted as highstand deposits (Fig. 6). Bioturbated mudstones occur during the early highstand phase, whereas late

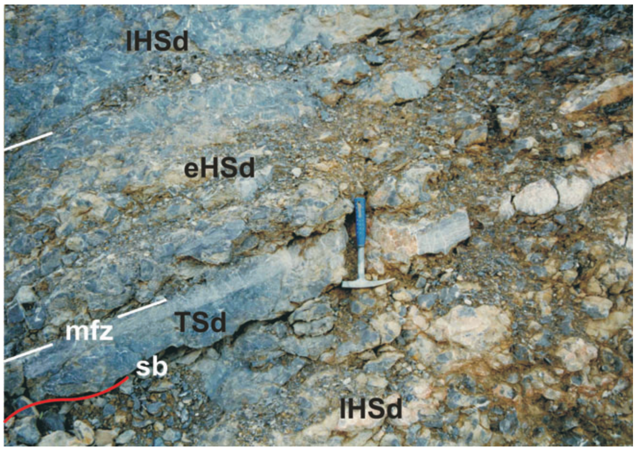

Fig. 6. High-frequency cycle within the Zuhánya Limestone Formation of Southern Hungary (Mecsek Mountains), representing the small-scale facies succession of outer ramp deposits. Abbreviations: **sb** — sequence boundary, **TSd** — transgressive deposits, **mfz** — maximum flooding zone, **eHSd** — early highstand deposits, **lHSd** — late highstand deposits.

highstand deposits are characterized by massive limestone beds with thin marly layers.

The described sedimentary features clearly express a cyclic sedimentation related to relative sea-level changes. The long-term eustatic signals are also recognized by characteristic palynofacies patterns and stable isotope signatures. In both settings, the semi-closed Peri-Tethys Basin and the open Tethys shelf, two striking plankton peaks occur in the Bithynian and Pelsonian, respectively. Within these stratigraphic intervals the $\delta^{13}C$ values reach two local maxima (Fig. 7) and are interpreted as displaying the most open marine conditions during major transgression phases, which, in terms of sequence stratigraphy, represent maximum flooding. The coinciding trends in $\delta^{13}C$ values and relative abundance and diversity of acritarchs support this interpretation (cf. discussion in Feist-Burkhardt et al. 2008). Furthermore, similar trends are recognized in Anisian series of Poland and Switzerland (Szulc 2000; Götz et al. 2005; Feist-Burkhardt et al. 2008). Therefore, organic facies proves to be a powerful correlation tool in sequence stratigraphic interpretation and correlation of different paleogeographical settings.

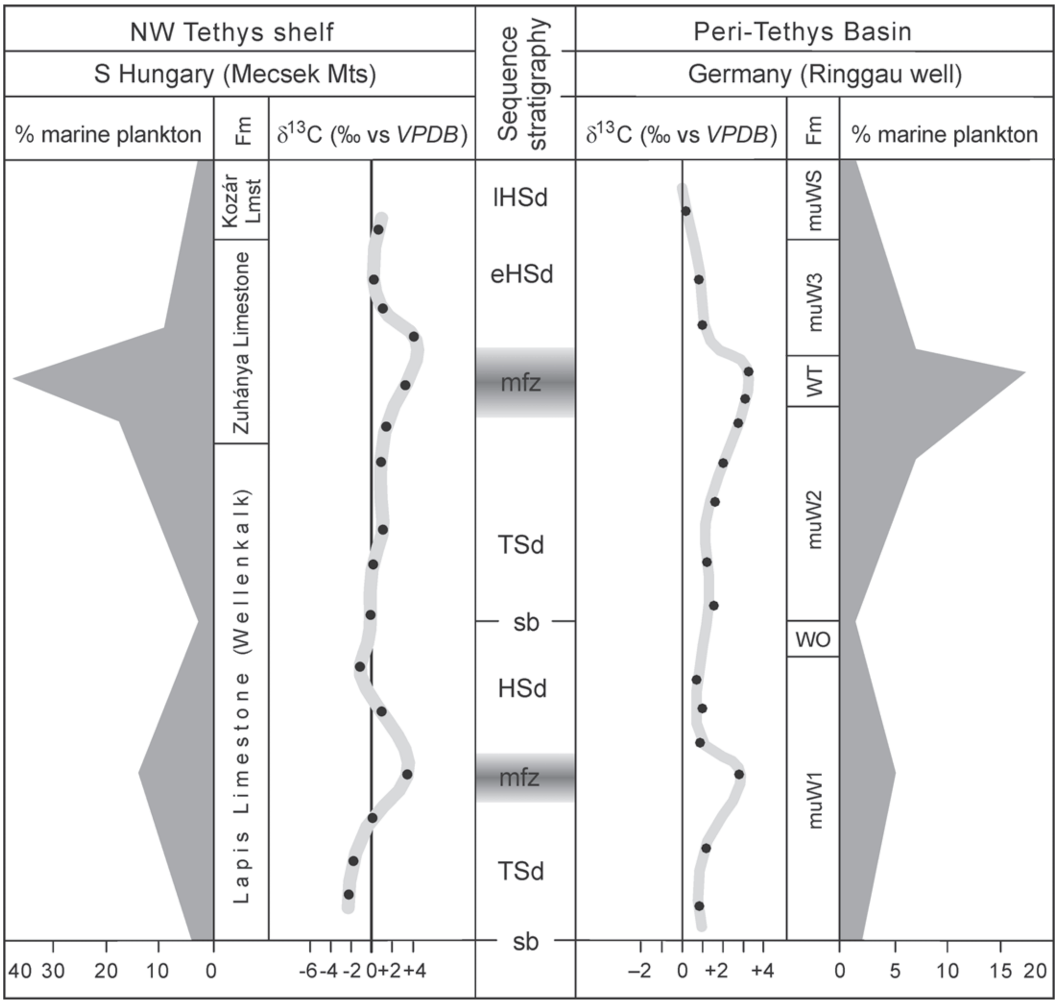

Fig. 7. Relative abundance of marine plankton and $\delta^{13}C$-signatures within the Anisian of Southern Hungary (reference sections Bükkösd, Orfü, Kozár) and Central Germany (reference section Ringgau) and sequence stratigraphic interpretation. Abbreviations: **sb** — sequence boundary, **TSd** — transgressive deposits, **mfz** — maximum flooding zone, **eHSd** — early highstand deposits, **lHSd** — late highstand deposits, **Fm** — formation.

Short-term fluctuations in sea level are well documented in small-scale sequences. The cyclic pattern is depending on the particular ramp position, namely inner, mid or outer ramp setting. High-frequency cycles are traceable along the ramp systems studied using distinct erosional and flooding surfaces (Fig. 5). Similar small-scale successions recorded in carbonate series of both an open proximal shelf and an epeiric setting enable a high-resolution correlation.

The Anisian carbonate series of the Northern Calcareous Alps (Fig. 8) represent the Tethyan shelf area composed mainly of pure calcareous homoclinal ramp deposits of the Steinalm Formation and strongly bioturbated shelf deposits of the Virgloria Formation, the latter consisting of carbonates with a low clastic content. In late Anisian (Pelsonian/Illyrian) times, the clastic input gradually diminished and finally disappeared, resulting in the predominance of the Steinalm Formation with respect to the Virgloria Formation (Rüffer 1995; Rüffer & Bechstädt 1998). The Steinalm Formation comprises mud-dominated inner to outer ramp deposits. In this environment, characterized by unstable muddy substrate, reef-building organisms were completely absent. Neither reef-builders nor high-energy shoals were present during Anisian times. Tempestites were intercalated with typically mud-supported carbonates, especially during the final (Illyrian) stage of the homoclinal ramp.

During Pelsonian times, a major transgression gave rise to open marine pelagic conditions.

The resulting deposits (Hallstatt Formation) occur throughout the Alpine shelf, mainly in the southern and easternmost parts of the depositional area of the Northern Calcareous Alps (Mandl 1984, 1996; Rüffer 1995).

Within the Anisian series, transgressive surfaces characterized by crinoidal wackestones are the most prominent signatures. After a decrease in particles, the late transgressive and early highstand deposits comprise crinoids, fecal pellets, and brachiopods. Mid-ramp microbial packstones and inner ramp stromatolites are characteristic of the late highstand phase. Due to the low depositional relief, third-order sea-level fluctuations caused extensive lateral shifts in facies, but did not change the mechanism of sediment production, reworking and transportation. The lack of erosional surfaces and supratidal facies in most areas of the Northern Calcareous Alps hinders the detection of sequence boundaries and lowstand deposits, respectively. However, based on conodont data the depositional sequences A3 and A4 detected in the western Northern Calcareous Alps (Rüffer & Zühlke 1995) are corre-

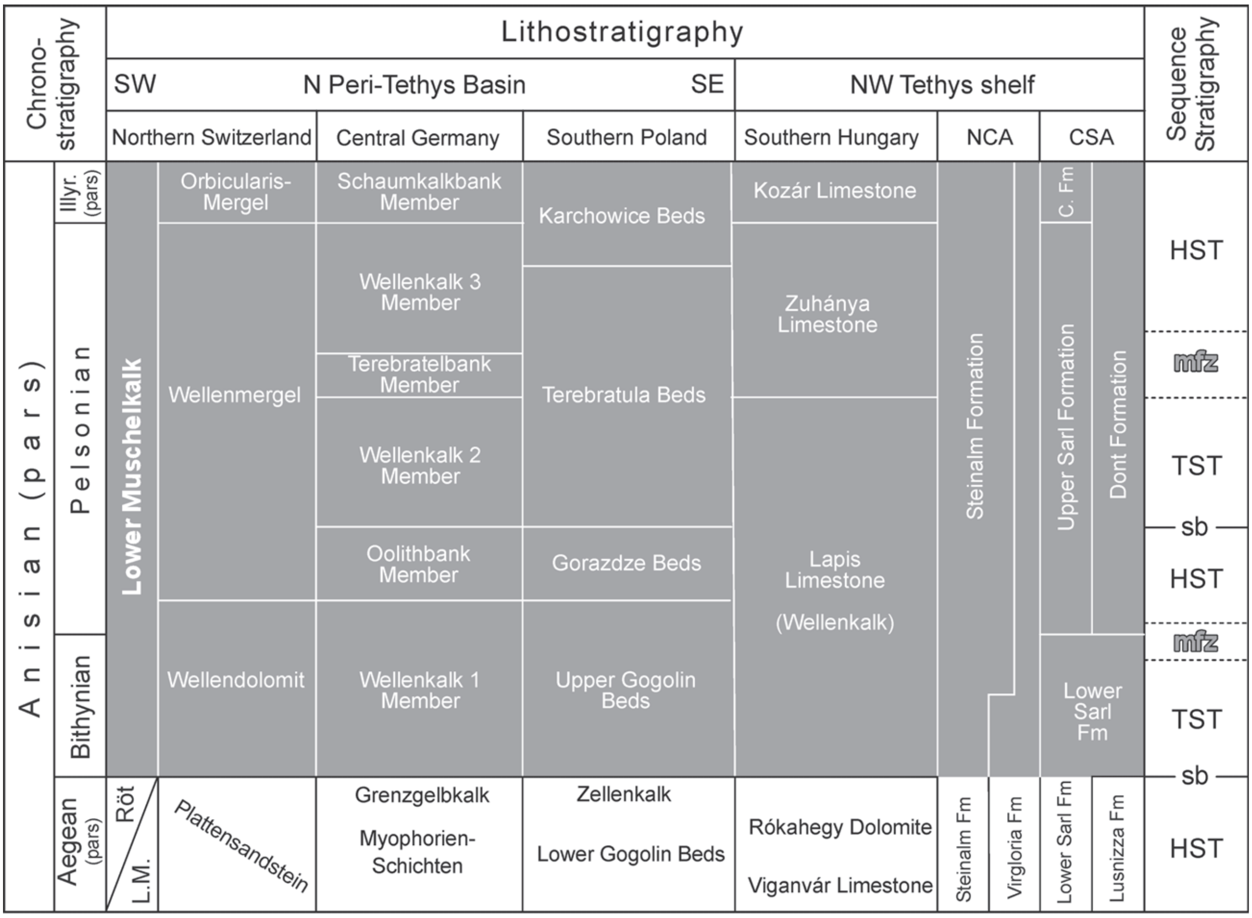

Fig. 8. Correlation of Anisian third-order depositional sequences of the Peri-Tethys Basin and Tethys shelf. Abbreviations: **NCA** — Northern Calcareous Alps, **CSA** — Central Southern Alps (Dolomites), **L.M.** — Lower Muschelkalk, **Fm** — Formation, **C. Fm** — Contrin Formation, **sb** — sequence boundary, **TSd** — transgressive deposits, **mfz** — maximum flooding zone, **HSd** — highstand deposits. Compiled after Rüffer (1995), Zühlke (2000), Götz et al. (2003, 2005), Feist-Burkhardt et al. (2008) and this study.

latable with the two third-order depositional sequences of the Lower Muschelkalk of the Peri-Tethyan realm.

In the Western Carpathians, the Anisian Geldek Member of the Vysoká Formation documents the evolution of a mud-dominated homoclinal ramp system with most open marine conditions during the Pelsonian (Michalík 1992). Conodonts serve as age-diagnostic index fossils and will enable a precise correlation for sequence stratigraphic interpretation, not available for this depositional series yet.

In the Southern Alps, marked facies variations in time and space, as well as differential subsidence/uplift characterize the Anisian basin development in this part of the NW Tethyan shelf area (Zühlke 2000). As a result of these variations, the basin fill includes a large number of lithostratigraphic units. In the eastern Southern Alps and parts of the central Southern Alps, carbonate-evaporite ramps of the Lower Sarl and Lusnizza Formations (Fig. 8) conformably overlie the Early Triassic Werfen Formation. Further to the W, the Lower Sarl Formation was erosionally truncated or did not develop at all. The western and southern Dolomites (central Southern Alps, CSA) were the site of several large structural highs with a long-term depositional gap, which lasted until the early Pelsonian or the early Illyrian. In the eastern and central Southern Alps, carbonate ramps of the Lower Sarl and Olang Formations persisted until the late Bithynian and earliest Pelsonian, respectively. Around the Bithynian/Pelsonian boundary, the basin architecture in the central Southern Alps changed completely. Partitioning of the basin into structural highs/lows became distinct and the depocentres moved to the W. In the late Pelsonian, homoclinal and distally steepened carbonate ramps of the Upper Sarl Formation developed. Coeval structural lows feature dysaerobic to oxic basinal deposition with interbedded turbidites (Dont Formation) shed from adjacent structural highs.

In the central Southern Alps, late Pelsonian carbonate ramps of the Upper Sarl Formation are bounded by an erosional unconformity or a disconformity. In the Illyrian characteristic facies transitions between distally steepened carbonate ramps (Contrin Formation) and narrow marine inlets (Moena Formation) or regional basins (Ambata Formation) are recognized. The two third-order depositional sequences An3 and An4 of Bithynian-early Illyrian age described from the central Southern Alps (Rüffer & Zühlke 1995) correspond to the Lower Muschelkalk sequences of the Peri-Tethys Basin.

Conclusions

The Anisian depositional series from Southern Hungary and Central Germany represent shallow marine carbonates of two different paleogeographical settings: the proximal shelf of the Tethys Ocean and its northern Peri-Tethyan realm. Both settings are mud-dominated with reworked material due to periodical storm activity. Storms were more severe in the open shelf position than in the semi-closed setting, which is documented in the different development and quantity of tempestites.

Sea-level changes are clearly recorded. Characteristic facies successions as well as palynofacies and stable isotope signatures document third-order cyclicity, and small-scale sequences can be interpreted as having formed through high-frequency sea-level changes in tune with orbital cycles. The detected cyclic patterns are very similar in both settings and therefore enable a high-resolution long-distance correlation of large-scale sequences.

The sedimentary organic matter and isotopic signals of the Anisian successions of the gate ways connecting the semi-closed Germanic Basin and the open Tethys shelf were studied (Götz et al. 2005; Feist-Burkhardt et al. 2007) and they match the signals from the S Hungarian depositional series. The most open marine facies occurs in the Pelsonian, reflecting a major flooding phase in the NW Tethyan shelf domain (major flooding surface 237.05 Ma of Haq et al. 1987) and its northern peripheral basin. Two third-order depositional sequences are detected in the two different paleogeographical settings studied (Fig. 8) and are traceable along the entire NW Tethyan realm (Rüffer & Zühlke 1995; Hardenbol et al. 1998; Szulc 2000; Götz et al. 2003). The detected eustatic signals were also described from the Northern Calcareous Alps (Rüffer 1995) and the Southern Alps (Zühlke 2000) and are therefore interpreted as over-regional signatures of the northern Tethys margins and adjacent basins. However, regional tectonically events cannot be excluded for the Middle Triassic and the interpretation of solely climatically driven fluctuation of sea level resulting in characteristic cyclic patterns within the sedimentary record during the Anisian still has to be done carefully. In many cases there are also tectonic changes controlling accommodation, and/or sea-floor spreading influencing long-term sea-level changes. Therefore, further studies on sedimentary cycle patterns of different scales and in different settings are needed.

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