Late Triassic to Early Jurassic palaeogeography and eustatic history in the NW Tethyan realm: New insights from sedimentary and organic facies of the Csővár Basin (Hungary)

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Abstract
Sedimentary and organic facies of a continuous Late Triassic–Early Jurassic toe-of-slope to basin succession of the NE Transdanubian Range (N Hungary) was studied in order to reconstruct the palaeogeographical and eustatic evolution of the Csővár Basin, an intraplatform basin of the NW Neotethys margin. Characteristic facies successions point to sea-level changes of different hierarchies. Cyclic patterns, inferred to result from orbital eccentricity forcing, are also reflected in the stratigraphical distribution of sedimentary organic matter. Furthermore, both palaeontological and isotope data document drastic climatic changes around the Triassic–Jurassic boundary. Detecting sea-level changes leads to a more accurate interpretation of the Late Triassic palaeogeographic setting and evolution of the Transdanubian Range’s carbonate platform. Our integrated sedimentological and palynological data suggest a complex topography and dynamic sea-level history, which contradicts a previous model of broad, uniform platform setting and lack of any major drowning and emersion events during the Late Triassic.

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1. Introduction

Subsequent to initial rifting during Middle Triassic times, ocean floor spreading and development of large, continent-encroaching carbonate platforms characterized the evolution of the NW Neotethys in the Late Triassic. The opening of the ocean led to the thinning of the continental crust in the marginal zone and gave rise to tectonic backstepping of the shelf margin and development of narrow extensional basins on the shelf, near to the margin. One of them, the Csővár Basin in north-central Hungary, developed as an intraplatform basin during the Carnian and persisted till the Early Jurassic. During this long time interval, cherty carbonates of slope, toe-of-slope and hemipelagic basin facies were deposited in the neighborhood of the NE Transdanubian Range (N Hungary) was studied in order to reconstruct the palaeogeographical and eustatic evolution of the Csővár Basin, an intraplatform basin of the NW Neotethys margin. Characteristic facies successions point to sea-level changes of different hierarchies. Cyclic patterns, inferred to result from orbital eccentricity forcing, are also reflected in the stratigraphical distribution of sedimentary organic matter. Furthermore, both palaeontological and isotope data document drastic climatic changes around the Triassic–Jurassic boundary. Detecting sea-level changes leads to a more accurate interpretation of the Late Triassic palaeogeographic setting and evolution of the Transdanubian Range’s carbonate platform. Our integrated sedimentological and palynological data suggest a complex topography and dynamic sea-level history, which contradicts a previous model of broad, uniform platform setting and lack of any major drowning and emersion events during the Late Triassic.

2. Geologic setting

In north-central Hungary, east of the river Danube, small outcrops of Mesozoic rocks occur in fault-bounded, uplifted blocks, representing the north-easternmost part of the Transdanubian Range Unit. This tectono-stratigraphic unit forms part of the Alcapa terrane, and preserves an early Mesozoic stratigraphic succession deposited in the passive margin of the Neotethys and displaced during the Alpine orogeny (e.g. Kovács et al., 2000). The fault blocks are generally made up of Upper Triassic Dachstein-type platform carbonates. However, the Csővár block also contains coeval slope and basin facies along with platform facies (Fig. 1). Therefore, this part of the Transdanubian Range Unit is a particularly well-suited area to investigate a platform-to-basin transect with respect to the palaeogeographic and eustatic evolution of the NW Tethyan realm.

The north-western part of the Csővár block is characterized by shallow–water oncoidal facies of the Upper Carnian–Norian Dachstein Limestone (Fig. 1). South-eastwards, an about 1 km wide zone of
patch-reef and proximal foreslope facies of the Dachstein Formation, most likely of Late Carnian age (Kovács, 2004), documents the lateral development of the platform-to-basin setting. Progradation of foreslope facies onto cherty limestones of the Csővár Formation was also recognized (Benkő and Fodor, 2002; Kovács, 2004).

In the south-eastern part of the block, thin-bedded, cherty dolomites and limestones (Csővár Limestone Formation) are exposed in the abandoned Pokol-völgy quarry and in adjacent outcrops. The Csv-1 borehole drilled in the yard of the quarry penetrated the lower part of the Csővár Formation, representing the Upper Carnian–Lower Rhaetian interval (Haas et al., 1997). The upper part of the Csővár Formation is exposed in the Pokol-völgy quarry (Haas et al., 1997; Haas and Tardy-Filácz, 2004) and in outcrops and trenches on the south-western slope of the Vár-hegy (Castle Hill; Fig. 1). The lower part of the Pokol-völgy quarry yielded Vandautes stuerzenbaumi, whereas Choristoceras marshi is reported from the uppermost part (Haas et al., 1997). These age-diagnostic ammonite species indicate the Middle and the Late Rhaetian, respectively (Krystyn, 2008). Based on foraminifera, the Norian–Rhaetian boundary is located at about 20 m depth in the Csv-1 core (Oravecz-Scheffer in Haas et al., 1997). The conodonts Misikella hernsteini and Misikella posthernsteini from the basal part of the Vár-hegy section and Misikella ultima from stratigraphically higher beds (Fig. 2) are reported by Pálfy et al. (2007). Based on ammonites, conodonts, foraminifera, radiolarians and isotope chemostratigraphic constraints, the Triassic–Jurassic boundary is drawn within the Csővár Formation (Pálfy and Dosztály, 2000; Pálfy et al., 2001, 2007). Palynological data confirm this stratigraphic level for the Triassic–Jurassic boundary (Götz et al., 2008). Significantly, there is no striking lithological change between the Upper Triassic and Hettangian parts of the formation (Fig. 2). Sinemurian cherty limestones of radiolarian basinal facies (Kozur, 1993) occur at the top of the Vár-hegy section and represent the uppermost preserved part of the Csővár Formation.

3. Palaeogeographic setting

According to current palaeogeographic reconstructions (Haas et al., 1995; Gawlick et al., 1999; Haas, 2002), during the late Palaeozoic to early Mesozoic the Transdanubian Range Unit was located at the western termination of the Neotethys between the South Alpine and Drauzug–Upper Austroalpine units (Fig. 3). Its present-day position is a result of multi-phase dislocations during the Tertiary (Kázmér and Kovács, 1985; Balla, 1988; Csontos et al., 1992; Haas et al., 1995). For the entire Late Permian to Late Triassic interval, the present-day Transdanubian Range Unit represented a segment of the Tethys margin, showing a striking facies polarity. Its south-western part was the landward side of the shelf, whereas its north-eastern part represented the outer shelf.

Opening of the Neotethys Ocean led to segmentation of the previously undifferentiated ramp system and formation of extensional basins and carbonate platforms in the Middle Triassic (Budai and Vörös, 1992, 1993; Haas and Budai, 1995). The basins formed in the inner shelf filled up with fine siliciclastics during the Carnian, on top of which large carbonate platforms started to develop in the latest Carnian. However, in the north-eastern part of the Transdanubian Range Unit (Gerecse and Buda mountains, Danube east-side blocks) new extensional basins developed in the Carnian and some of them persisted for a long time. Upper Carnian to Rhaetian laminated dolomites and limestones of the Buda Mts. were formed in a restricted basin (Haas et al., 2000) which was more restricted than the Csővár Basin and records a continuous sedimentation during the Late Triassic and earliest Jurassic. Isolated platforms may have separated the two basins. Abundant fragments of land plants and a high amount of
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**Legend:**
- Limestone
- Argillaceous limestone
- Siliceous limestone
- Marl
- Clay
- Chert nodules
- Lamination
- Obscured lamination
- Bioturbation
- Slump ball
- Packstone/grainstone
- Coated grains
- Lithoclasts
- Plasticlasts
- Bioclasts

**Notations:**
- LO of Triassic foraminifera
- LO of Rhaetian palynomorphs
- Canoptum merum Zone
- Globoturcata tozen Zone
- Marsh Zone
- Palcocerat indet.
- Nevadophyllum cf. psalmophorum (ex. unst)
- Miserkella ultima
- Miserkella posthermanni
- Miserkella hermanni

**Stratigraphy:**
- Hettangian
- Early Jurassic
- Rhaetian
- Late Triassic
sporomorphs in the Rhaetian part of the Csővár Formation suggest the existence of islands on the platforms, implying a complex topography. Rising relative sea level resulted in drowning of the carbonate platforms in the NE part of the Transdanubian Range Unit. However, we have no data for this drowning event in the area of the Buda Mts. and Danube east-side blocks where the uppermost part of the Dachstein-type carbonate platform sequence has been eroded. Thus, the integrated study of sedimentary and organic facies of the Csővár Formation is important in providing new insights into the earliest Jurassic palaeogeographic and eustatic evolution of this region.

4. Sedimentary facies

Based on field observations and detailed microfacies investigations different lithofacies types were defined (Haas and Tardy-Filácz, 2004). The most important characteristics of these facies types, together with the interpreted depositional settings, are summarized below.

4.1. Lithoclastic–bioclastic grainstone/packstone (Lb) (Fig. 4a–b)

Fine-grained calcirudite to coarse-grained calcarenite. Fragments of echinoderms (mainly crinoids and echinoid spines) are predominant, whereas brachiopod and bivalve shell fragments, detritus of microproblematica and microbial crusts, benthic foraminifera, and thick-shelled ostracods are common (Fig. 4a–b).

These beds are grain-flow deposits or basal traction layers of high-density turbidites. Some of the bioclasts (microproblematica, foraminifera, and thick-shelled ostracods) are most likely of platform origin. The crinoids may have inhabited the foreslope, most likely the foreslope terraces. The lithoclasts are identified as reworked lithified basinal sediments.

4.2. Oncoid grapestone grainstone/packstone/wackestone (On) (Fig. 4c)

Coarse-grained calcarenite that is made up predominantly of coated grains (oncoids and grain aggregates). 1–2 cm-sized lithoclasts of radiolarian wackestone (Fig. 4d) and mm-sized fragments of cemented sediments are also common. Bioclasts are generally scarce but abraded shell fragments of mollusks, brachiopods, and ostracods are found sporadically. However, bivalve and brachiopod coquinas occur in distinct horizons.

The oncoids and the grapestones may have formed on the top of a carbonate platform or a shallow ramp in moderately agitated environments. However, the intercalation of the oncoid–grapestone facies within the deeper-water succession, and the common occurrence of lithoclasts of pelagite and coquina horizons indicate redeposition of the coated grains from a shallow environment to the basin.

4.3. Medium-grained calciturbidite (Mt) (Fig. 4e)

Graded packstone, coarse- to fine-grained calcarenite. Skeletal debris of crinoids is the predominant component. Fragments of mollusks, debris of microbial crusts and benthic foraminifera are common. Sand-sized lithoclasts may also occur in the basal part of the layers. Top-absent, amalgamated Bouma sequences that were formed by high-density turbidity currents and were deposited relatively far from the source area on the distal part of the lower slope or on the toe-of-slope. The platform margin and the foreslope may have been the source
of the redeposited bioclasts. In the foraminiferal assemblage, along with basinal elements, forms of carbonate platform origin are recognized.

4.4. Fine-grained calciturbidite (Ft) (Fig. 4f)

Laminated beds that are made up of an alternation of graded, fine-grained calcarenite packstones and wackestones. The calcarenite laminae are peloidal and contain fragments of echinoderms (mainly crinoids), mollusks, and ostracods. In the wackestone laminae sponge spiculae and radiolarians are common.

Incomplete, base-absent calciturbidites that were formed by low-density turbidity currents and were deposited far from the source area on the toe-of-slope or in the basin.

4.5. Calcisiltite–calcilutite laminite (La) (Fig. 5a–b)

Thin-bedded, platy or laminated fine-grained limestone. Fine calcarenite–calcisiltite laminae (peloidal biomicrite) alternate with calcilutite (peloidal microsparite and micrite) laminae. This facies is poor in recognizable bioclasts (radiolarians, sponge spiculae and thin-shelled ostracods) (Fig. 5a–b).
These laminites are interpreted as very distal, low-density turbidites that were deposited on the basin floor. The calcisiltite laminae settled out from diluted low-density turbidity currents. The peloids are most likely of platform origin. The finest material of the turbidity currents settled out together with the background pelagites forming the calcilutite laminae.

4.6. Sponge spicule wackestone (S) (Fig. 5c)

Thin-bedded limestone, locally with chert nodules. Sponge spiculae are the predominant bioclasts. Radiolarians (calcite moulds), fragments of echinoderms and thin-shelled bivalves are common in calcisiltite–calcilutite matrix. These sediments represent deep-water basin facies.

4.7. Thin-shelled bivalve wackestone (B) (Fig. 5d)

Thin-bedded limestone with a high amount of fragments of thin-shelled bivalves (“filaments”). In some layers, ostracods are quite common and occur along with radiolarians, echinoderm fragments, and foraminifera. These deposits represent deep-water basin facies.
4.8. Radiolarian wackestone (Rw) (Fig. 5e)

Thin-bedded limestone, locally with chert nodules. Radiolarians are predominant; sponge spiculae, thin-shelled bivalves, echinoderm fragments are common. These limestones represent deep-water basin facies.

4.9. Radiolarian packstone (Rp) (Fig. 5f)

Siliceous, cherty limestone. The radiolarians are present in rock-forming quantity. Sponge spiculae and fragments of echinoderms also occur. This condensed radiolarian facies most likely formed in the deep basin near to the carbonate compensation depth.

5. Distribution of sedimentary organic matter

An interval of 30 m spanning Beds 21 to 86 of the Csővár Formation (Fig. 6) exposed on the south slope of the Vár-hegy was sampled for palynofacies analysis of the Upper Rhaetian and Lower Hettangian sediment series. All samples were prepared using standard palynological processing techniques, including HCl (33%) and HF (73%) treatment for dissolution of carbonates and silicates, and saturated ZnCl₂ solution (D ≈ 2.2 g/ml) for density separation. Residues were sieved at 15 µm mesh size. Slides have been mounted in Eukitt, a commercial, resin-based mounting medium. The relative percentages of sedimentary organic constituents are based on counting at least 400 particles per slide.

For palynofacies analysis, the sedimentary organic matter of the studied Csővár Formation is grouped into a continental fraction including phytoflagellates, pollen grains and spores, and a marine fraction composed of acritarchs, prasinophytes and foraminiferal test linings. Three palynofacies parameters were calculated to detect stratigraphic changes in the composition of sedimentary organic matter reflecting eustatic signals (Fig. 6): (1) The proportion of marine plankton. This parameter quantifies the percentage rate of acritarchs and prasinophytes in the sedimentary organic matter. It is linked to the marine conditions of the water column, depending on distance to coastline, water depth, temperature, salinity, and nutrient availability; (2) The ratio of opaque to translucent phytoflagellates (OP/TR ratio). Opaque phytoflagellates (OP) partly consist of charcoal originating from forest fires, but mainly develop by oxidation of translucent phytoflagellates (TR). Another source for opaque phytoflagellates might be resedimentation of refractory particles. Generally, the ratio of opaque to translucent phytoflagellates increases basin-ward due to fractionation processes and the higher preservation potential of opaque particles (Summerhayes, 1987; Tyson, 1993; Pittet and Gorin, 1997; Bombardière and Gorin, 1998). Most of the oxidation is of subaerial, continental origin (Tyson, 1995). However, in proximal high-energy shelf areas this trend may be reversed by in-situ (bio)oxidation at the seafloor (Batten, 1982; Boulter and Riddick, 1986; Bustin, 1988; Tyson, 1993), enhanced by the high porosity and permeability of coarse-grained sediments (Tyson, 1993); and (3) The size and shape of plant debris (ED/BS ratio) are additionally used to decipher proximal-distal and transgressive-regressive trends. Small, equidimensional (ED) woody fragments are characteristic of distal deposits, whereas in proximal settings, large blade-shaped (BS) particles are quite abundant (Steffen and Gorin, 1993). In addition, proximal assemblages reveal a greater variety of particle sizes (Tyson, 1993; Tyson and Follows, 2000).

Generally, the preservation of sedimentary organic matter of the carbonates studied is very poor. However, distinct horizons show well preserved organic particles. The most striking feature is the very high content of terrestrial particles, mainly phytoflagellates (Fig. 7), throughout the studied section. The size and shape of plant debris shows a high variety with a high amount of large, needle-shaped fragments (Beds 30, 52, and 74). Translucent particles are abundant, whereas most phytoflagellates are opaque. Three intervals are characterized by maximum abundance of equidimensional, opaque phytoflagellates (Beds 26, 44, and 67) corresponding to peak abundance of marine plankton (Fig. 6). Upsection, palynofacies of the carbonates studied is dominated by degraded organic matter and small, equidimensional phytoflagellates. Spores reach maximum abundance in Bed 47.

Another striking feature is the high amount of prasinophytes within the marine fraction. Acritarchs are very rare (Beds 26, 44, and 67), dinoflagellate cysts are absent. A sudden increase in the abundance of prasinophytes is recognized in Bed 47 (Götz et al., 2009). Foraminiferal test linings become more common in the upper part of the interval studied (Beds 61 to 86) and are a dominant constituent in Beds 67 and 69.

6. Stable isotope stratigraphy

Carbon and oxygen stable isotope ratios were measured throughout the lower 55 m of the Csővár Vár-hegy section, across the Triassic–Jurassic boundary (Fig. 2). A prominent end-Triassic negative carbon isotope anomaly (CIE) was first documented in both bulk organic matter and bulk carbonate (Pálfy et al., 2001). Additional, high-resolution δ¹³C_carbon data from the same section was reported by Pálfy et al. (2007). Oxygen isotopic ratios in bulk carbonate are more prone to diagenetic overprint. Thus, inferences for palaeotemperature changes are somewhat tenuous but δ¹⁸O values are useful to detect and exclude samples with significant diagenetic alteration (Pálfy et al., 2007).

In the past few years, the negative CIE at the Triassic–Jurassic boundary was observed at numerous localities world-wide (see Hesselbo et al., 2007, for a review). It is important as both a stratigraphic correlation tool and as a proxy record for palaeoenvironmental and biotic changes, reflected in the global carbon cycle. The detailed anatomy of the Triassic–Jurassic boundary CIE appears to differ between individual sections. Some sections show a pattern of an initial negative CIE followed by a main negative CIE (e.g. Hesselbo et al., 2002; Ward et al., 2004; Ruhl et al., 2009), the initial negative CIE may be followed by a positive CIE (Willford et al., 2007), yet others are similar to the Csővár section in showing only one pronounced anomaly (Galli et al., 2007). The simultaneous negative CIE and prasinophyte spike at Csővár suggests correlation with the main CIE and broadly coeval algal bloom in the Northern Calcareous Alps (Kuerschner et al., 2007; Bonis et al., 2009). The CIE is thought to reflect a major perturbation in the global carbon cycle at the close of the Triassic, which is probably causally related to the biotic extinction.

7. Depositional cycles

The Csővár Formation represents foreslope and basin deposits of a broad carbonate platform and a related intraplatform basin. In this setting, the morphology of the platform and sea-level changes may have controlled the amount and composition of sediment exported to the slope and the adjacent basin. Consequently, changes in the quantity and composition of bioclasts and lithoclasts in the gravity flow deposits can be used as a proxy of relative sea-level changes. However, the palaeogeographic setting and assumed morphology of the adjacent platform must be taken into consideration as well.

High abundance of terrestrial phytoflagellates and palynomorphs in the basal light grey marl layer of the Pokol-völgy quarry suggests a significant sea-level drop in the late Early to Middle Rhaetian (basal part of the Vundaites steuerenzaum Zone), when large parts of the former platforms became subaerially exposed (Haas et al., 1997). The sea-level drop led to increasing restriction of the intraplatform basin and establishment of oxygen depleted conditions near the bottom. A high amount of prasinophytes (Góczán, 1997) points to a stratified water column (cf. Tyson, 1995).
Above this horizon the facies characteristics of the succession exposed in the Pokol-völgy quarry and the Vár-hegy section suggest a long-term deepening-upward trend in the Middle Rhaetian to Early Hettangian interval. It corresponds to the transgressive phase of the Rhaetian to Early Sinemurian cycle described by De Graciansky et al. (1998) and Hallam (2001), both in the Tethyan and the Boreal provinces of Western Europe.

Fig. 6. Stratigraphy, microfacies types, palynofacies patterns, and sequence stratigraphic interpretation of the Csővár (Vár-hegy) section. Three phases of maximum flooding are documented by maximum abundance of marine plankton, and equidimensional, opaque phytoclasts (Beds 26, 44, and 67). Transgressive intervals are marked by increasing marine components and equidimensional, opaque phytoclasts. The opposite trend is recognized within highstand deposits. Abbreviations of microfacies types: Lb — lithoclastic–bioclastic grainstone/packstone, On — oncoidal grapestone, Mt — medium-grained calciturbidite, Ft — fine-grained calciturbidite, La — calcisiltite–calcilutite laminite, S — sponge spicule wackestone, B — thin-shelled bivalve wackestone, Rw — radiolarian wackestone, Rp — radiolarian packstone. Abbreviations in depositional cycles: HST — Highstand Systems Tract, TST — Transgressive Systems Tract, LST — Lowstand Systems Tract. For key to lithologic symbols, see Fig. 2.
Superimposed upon the long-term deepening-upward trend, a 5 to 10 m cyclicity was encountered in the alternation of turbiditic (hemipelagic) and basinal (eupelagic) facies. The cyclic pattern of the succession is most clearly documented in the lower part of the Vár-hegy section where medium-grained turbidites are present. In this part of the section dm-scale deepening-upward cycles documented in a turbidite–pelagite alternation were also deciphered. The cyclicity is less pronounced in the upper part where turbidites are generally missing and calcisiltite–calcilutite laminites (most likely very distal turbidites) and typical fine-grained basinal deposits prevail.

The palynofacies patterns recognized within the sedimentary series studied clearly reflect the cyclicity described from sedimentological data. Maximum abundance of equidimensional, opaque phytoclasts and marine particles document three phases of maximum flooding. Furthermore, the general increase in marine components displays the superimposed transgressive trend from Late Rhaetian into Early Hettangian times.

The first cycle in the Vár-hegy section (Beds 1–15; Fig. 6) starts with proximal and distal turbidites grading upward into radiolarian basin facies. This trend may be interpreted to reflect retrogradation of...
the platform margin due to rising sea level. Within the turbiditic member, an alternation of crinoidal turbidites and radiolarian wackestone pelagites points to a higher frequency cyclicity, which either reflects sea-level fluctuations, or autogenic sedimentary processes such as lobe- and channel switching. This pattern is best observed in the upper part of this interval (Beds 5b–12) where coarser-grained turbidite layers occur.

Bed 16 contains large, redoubled bioclasts along with a high amount of crinoid ossicles of platform margin to upper slope origin (foraminifera, and microproblematica) and may be considered as the basal layer of the next cycle (Beds 16–29) that is made up mainly of medium to fine-grained turbidite facies. Decimetre-scale turbidite-pelagite cycles were also detected within this interval (Fig. 8). Maximum flooding is detected around Bed 26 with maximum abundance of small, equidimensional phytoclasts and marine particles, occurrence of acritarchs and last occurrence of Triassic ammonoids, indicating normal marine conditions. Conodonts are relatively abundant and diverse up to Bed 29 (Pálfy et al., 2007).

This interval is overlain by Bed 30 containing small lithoclasts (cemented fragments of crinoids) and a high amount of shallow-marine skeletal elements in a pelagic wackestone matrix. Coarse-grained detritus of corals and mollusks occur in the topmost part of the bed. Consequently, it may be interpreted as a lowstand deposit. Numerous large, needle-shaped opaque phytoclasts also point to a lowering of sea level, which forced the progradation of river deltas. Elevated amount of silt-sized terrigenous siliciclasts is found in cm-sized intraclasts in the topmost part of this bed and also in the overlying clay-rich Bed 31.

Above Bed 31, laminitic deposits and an increase of small, equidimensional phytoclasts as well as marine particles indicate a clear transgressive trend. An almost total lack of any recognizable bioclasts in the laminitic layers might be attributed to this facies change. Maximum flooding occurred around Bed 44 characterized by maximum abundance of small, equidimensional phytoclasts and acritarchs. Highstand deposits of radiolarian basin facies are marked by maximum abundance of prasinophytes (Beds 47 and 49). Additionally, a significant negative shift in the δ13Ccarb and a marked decrease in the TOC were encountered (Pálfy et al., 2001) within this interval. A drastic decline of the foraminiferan and conodont assemblages is observed in Bed 30, indicating a significant biotic change that may be related to the end-Triassic mass extinction event (Pálfy et al., 2007).

The next sedimentary cycle starts with a thin lithoclastic and bioclastic proximal turbidite layer (Bed 52), characterized by a high variety in size and shape of phytoclasts, both opaque and translucent and may also reflect an extraordinary event (“boundary-event horizon”). Upsection, various basal facies prevail and an increase of foraminiferal test linings is recognized, indicating continuation of the large-scale transgressive trend superimposed by a medium-scale transgressive trend with maximum flooding around Bed 67. This bed is characterized by maximum abundance of small, equidimensional phytoclasts and acritarchs, accompanied by the first occurrence of psiloceratid ammonoids. The lack of platform-derived bioclasts is most likely the consequence of the drowning of the adjacent platforms during maximum flooding and the early highstand phase. However, fragments of crinoids commonly occur both in the laminitic, distal turbidites and in the deposits of the typical basin facies. The top and the slope of the drowned platforms may have been the habitat of crinoid colonies.

The most striking lithological change in the Hettangian part of the section is the appearance of redeposited oncoids and grapestones in a 2 m thick, thickening-upward bundle (Bed 75–80), which may indicate the end of the Rhaetian to earliest Hettangian third-order sequence (Hardenbol et al., 1998). The coated grains may have formed on the top of the drowned platforms during the late highstand to lowstand period and redeposited at the toe of the slopes during the lowstand (Fig. 6). Sedimentary organic particles are not preserved in these sediments.

The oncoidal beds are overlain by distal turbidites. In the upper part of the studied section (Beds 75–80), various basal facies types prevail including biogenic components such as radiolarians, thin-shelled bivalves and sponge spicules which document a large-scale, deepening-upward trend.

8. Orbital signal

Estimation of the time represented by the above described depositional cycles remains ambiguous as any calculation must depend on the controversial duration of the Rhaetian Stage. The latest Geological Time Scale (Ogg et al., 2008) estimates the duration of the Rhaetian as 4 m.y. (between 199.6 and 203.6 Ma). However, this scale was compiled prior to agreement on the definition of the boundaries of the stage and before the latest radiometric ages (Schaltegger et al., 2008; Friedman et al., 2008) and new magnetostratigraphic constraints (Gallet et al., 2007 and references therein) became available for the latest Triassic and the Triassic–Jurassic boundary. A preliminary decision of the Subcommission on Triassic
Stratigraphy puts the base of the Rhaetian at the base of the Misikella posthersteinii Zone, whereas the International Commission on Stratigraphy agreed on defining the base of the Jurassic by the base of the Psiloceras speleae Zone. The new developments suggest a significantly shorter duration of the Rhaetian, probably not exceeding 2 my. Thickness ratios within the Upper Triassic platform carbonates may also suggest a relatively short duration of the Rhaetian, although a simple conversion of stratigraphic thickness to time of sedimentation must be treated with caution. In the NE part of the Transdanubian Range, the Norian Dachstein-type platform carbonates (Dachstein Limestone and Main Dolomite) are about 2000 m thick whereas the thickness of the Rhaetian Dachstein Limestone reaches only up to 200 m (Haas, 1995). Cyclostratigraphic analysis of the Dachstein-type platform carbonates in the Transdanubian Range led to the same conclusion, suggesting 2 my duration (Balog et al., 1997).

In the study area, the total thickness of the Rhaetian succession is about 55 m (Haas and Tardy-Filacz, 2004). Assuming that it was deposited in 2 my, the uppermost 20 m of the Rhaetian, exposed in the Vár-hegy section, may represent about 0.8 my. Two and a half depositional cycles are recognized within this interval, placing the duration of these cycles within the Milankovitch frequency band (20–400 ky), matching either the short (100 ky) or the long (400 ky) orbital eccentricity signal. Taking into account that the entire Rhaetian is built up by five fourth-order depositional cycles (Haas and Tardy-Filacz, 2004), the long eccentricity signal seems to be plausible. However, in coeval cyclic platform carbonates of the Transdanubian Range the 100 ky bundling is much more pronounced (Balog et al., 1997). The dm-scale turbidite successions (Fig. 8), recognized in the first and second depositional cycles, may reflect precessional cycles, comparable to those found in the Upper Norian to Lower Rhaetian calciturbiditic Pedata Beds of the Gosan Lake section, Northern Calcareous Alps (Reijmer and Everaars, 1991; Reijmer, 1991; Reijmer et al., 1994).

High-resolution sequence stratigraphic and cyclostratigraphic analyses of Upper Jurassic and Lower Cretaceous sections suggest that the 400 ky eccentricity cycle contributed to the genesis of major depositional sequences (i.e. third-order sequences in the charts of Hardenbol et al., 1998), whereas beds and bedsets formed in tune with the 20 ky precession and 100 ky eccentricity cycles (Strasser et al., 2000). Our observations permit a similar interpretation of stratigraphic intervals in the Csővár section. It is important to note that the duration of the long eccentricity cycle has remained relatively stable over geological time. For the latest Triassic–earliest Jurassic period, the precession cycles are presumed to be somewhat shorter but nevertheless close to 20 ky in duration, whereas the obliquity cycles were significantly shorter in the Mesozoic than at present (Strasser et al., 2006).

Calculations using sedimentation rate estimates from analogous deposits provide independent constraints on duration. Middle Triassic intraplatform basinal calciturbidites with precise radiometric age control yielded an average sedimentation rate of 13.5 m/ky (Maurer, 2003). At Csővár, the thickness of cycles (excluding the slumps) varies from 6 to 8 m. Assuming that the cycles represent 400 ky long eccentricity forcing, 15 to 20 m/ky average sedimentation range is estimated. This compares favorably with the estimates of Maurer (2003).

Furthermore, this tentative temporal framework is useful for the interpretation of the observed local sequence of events at the Triassic–Jurassic boundary. The following events took place within a single, presumably 400 ky cycle: 1) disappearance of ephemerally abundant platform-derived biota, possibly related to a drowning event; 2) decline of both planktonic and benthic biota (reduction in biogenic sedimentary components, and conodont and foraminiferal diversity); 3) significant perturbation of the biosphere as documented by marine and terrestrial palynomorph assemblages; 4) geochemical anomalies in C and O isotopes; and 5) concurrent reduction of TOC (Pálfi et al., 2001, 2007).

The first appearance of a new, Jurassic radiolarian fauna, the final extinction of decimated conodont populations, and the recovery of primary production occurred in the following cycle.

9. Discussion

In the Csővár Basin, the entire Rhaetian succession is characterized by a high amount of land-derived plant debris. Since the Pangaea continent did not serve as a proximal coastline to the Csővár Basin, it is supposed that several islands must have been situated between the restricted Buda Basin and the Csővár Basin (Haas, 2002). The redeposited shallow marine bioclasts and lithoclasts of platform margin and upper slope origin, occurring in some beds of the Rhaetian part of the Csővár Limestone Formation imply the establishment of small fringing platforms on the upper slope next to an island (Haas et al., 1997). Crinoid ossicles are the predominant components in the observed turbidites, i.e. crinoid meadows of the slope terraces produced a predominant part of the redeposited bioclasts; the platform-derived clasts are subordinate. For the evaluation of the sedimentary cycles this palaeogeographic setting must be taken into account. Since the source of the redeposited carbonates was mostly a slope (and moreover a slope of an island) and not a large carbonate platform, the concept of the highstand shedding (Droxler et al., 1983; Droxler and Schlager, 1985; Reijmer et al., 1992; Schlager, 2005) cannot be applied to this case. In contrast, it is very probable that instability of the slope increased during the lowstand and early transgressive stages, due to a decrease of hydrostatic pressure and forced progradation of deltas at low sea level. Reversing slope failures induced the gravity-driven redeposition.

Sedimentological features suggest a sea-level drop during the latest Rhaetian and another one coeval with the main isoce excursion near to the Triassic–Jurassic boundary (Haas and Tardy-Filacz, 2004; Pálfi et al., 2007). During these periods of low sea level the subaerially exposed areas may have extended over large parts of the inner platform in the NE part of the Transdanubian Range Unit, resulting in the erosion of the uppermost part of the Dachstein Limestone. This area may have been flooded again during the earliest Hettangian sea-level rise. However, sedimentation began somewhat later, probably as a consequence of the end-Triassic ecological crisis, and the tropical platform conditions did not resume.

The here presented palynofacies data suggest the existence of islands probably located between the Buda and Csővár basins also during the earliest Hettangian, although the fining-upward trend of redeposited carbonates implies transgression and accordingly a reduction of the subaerially exposed areas. A topographic high may have been the source of shallow marine coated and composite grains which were accumulated in the Csővár Basin during the next sea-level drop. It was followed by continuous deepening which terminated the high input of land-derived phytoclasts.

The detailed analysis of the high-frequency Lofer cycles in the central and NE part of the Transdanubian Range Unit (Bakony and Gerecse mountains) suggests a sequence boundary near to the Norian–Rhaetian boundary (Balog et al., 1997). In the Pokol-völgy quarry section, the horizon in the basal part of the Rhaetian succession, showing a high amount of land-derived plant remains, was correlated to this sequence boundary (Haas and Budai, 1999). This interval of major subaerial exposure was followed by continuance of the evolution of Dachstein-type platforms in the central and NE part of the Transdanubian Ranges that resulted in the formation of an about 200 m thick Lofer-cyclic succession. In the NE part of the Transdanubian Range Unit (Gerecse Mts., Tata) the uppermost part of the Dachstein Limestone is missing and the earliest overlying formation is the shallow-water Piszczne Limestone of Middle–Upper Hettangian age (Fülöp, 1976; Pálfi et al., 2007). The top of the Dachstein Limestone is truncated, and most probably a few metres of the formation were already eroded prior to the deposition of the
marine oncoidal lag deposits in the basal part of the Pisznice Limestone (Fülöp, 1976; Haas, 1995). A similar setting was reported from the Northern Calcareous Alps, where Upper Rhaetian reefal limestones are overlain by the Adnet Limestone with a hiatus of variable duration (Böhm et al., 1999). However, the history of this gap is not clear and is discussed controversially, both for the Transdanubian Range (Haas, 1995) and the Northern Calcareous Alps (Mazullo et al., 1990; Satterley et al., 1994; Flügel and Koch, 1995).

Due to subsequent erosion, the Upper Rhaetian is missing in the Buda Mts., both in the platform and basin facies (Haas, 2002), and in the Csővár block the Upper Norian and Rhaetian part of the platform carbonate succession was eroded prior to the Eocene (Haas, 2002).

The continuous latest Triassic to earliest Jurassic basin succession at Csővár provides valuable information on the palaeogeographic setting and evolution of the adjacent carbonate platform areas during the Triassic–Jurassic boundary interval. Two scenarios are proposed with respect to the evolution of the platform areas: a) subaerial exposure and erosion in the latest Triassic to earliest Jurassic followed by inundation from the Middle Hettangian onward, or b) solely submarine erosion and non-deposition during the period of the gap. The dominance of terrestrial plant debris with a large number of large blade-shaped particles and a significant variety of particle sizes as well as a high amount of pollen grains and spores in the latest Triassic to earliest Jurassic supports the hypothesis of the existence of small islands in the area of the outer platform, not only at the very end of the Triassic but also during Early Hettangian times. The new palynological data confirm the previous palaeogeographic model of a swell between the Hármashalat Árhegy Basin in the Buda Mts. and the Csővár Basin (Haas et al., 2000) that was subaerially exposed for a longer period. Furthermore, our data indicate subaerial exposure of a broader region during phases of low sea level.

10. Conclusions

The results of the integrated microfacies and palynofacies analysis of the Csővár section shed new light on the latest Triassic to earliest Jurassic evolution of the Transdanubian Range Unit which was part of the NW Tethys shelf region. Sedimentary organic matter content of the carbonates studied is crucial for the interpretation of similar platform-to-basin settings along the northern Tethys Ocean. Palynofacies patterns clearly reflect the cyclicity interpreted from sedimentological data. Generally, the high amount of prasinophytes points to a stratified water column of a deep basinal setting. On the other hand, the high amount of terrestrial plant debris and sporomorphs implies close terrestrial sources and thus a complex topography with small islands. The high input of terrestrial organic particles from these islands was continuous from the Late Triassic into the earliest Jurassic. The platform margin setting favored the development of toe-of-slope aprons characterized by turbidites, which contain distinct layers that allowed the preservation of sedimentary organic matter.

Both carbonate microfacies and palynofacies patterns clearly reflect a metre-scale cyclicity in the studied succession. The cycles show a deepening-upward trend with lithoclastic-coarse-grained bioclastic facies at their base overlain by distal or very distal turbidites and progressing into pelagic facies. Maximum abundance of equidi-mensional, opaque phototclasts and marine particles document three phases of maximum flooding. According to our approximate calculations, the 400 ky orbital eccentricity signal seems to be recorded. Using this temporal framework, the estimated average sedimentation rate of 15–20 m/my is in good agreement of published estimates of similar deposits. Local manifestation of Triassic–Jurassic boundary events is confined to a single 400 ky cycle.

Based on our studies of the Csővár succession, the Late Triassic palaeogeographic setting and evolution of the Transdanubian Range’s carbonate platform can be more precisely interpreted. Already during Carnian times, the beginning disruption of the marginal zone of the Dachstein-type platform is documented and a distinct topography, i.e. smaller platforms with islands and intraplatform basins among them, developed. The sea-level changes may have significantly modified the extension of the islands. There was a significant sea-level drop in the Early Rhaetian leading to restriction of the Csővár Basin and thus to development of a stratified water column and coeval extension of the subaerially exposed areas on the platform.

The palynofacies analysis implies a prolongation of the subaerial conditions also in the earliest part of the Jurassic. The new results support the former hypothesis that the Middle–Late Hettangian drowning affected a tens of km broad outer belt of the Dachstein platform and was preceded by a eustatically controlled emersion. However, the traces of subaerial exposure (karstification, and pedogenesis) are not recorded because they have been destroyed by the submarine erosion during the following inundation. High-energy conditions favored the formation of coated grains as lag deposits on the hard sea floor. In-situ embedded gravel-sized coated grains are characteristic of the basal strata of the Middle Hettangian in Tata. Fine gravel to sand-size redeposited coated grains appear in the higher part of the Hettangian sequence in the Csővár section.

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