Stratigraphic sequences in a storm-dominated, Late Triassic intra-shelf environment of the West Carpathians: implications for correlations with the Eastern Alps

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Abstract. Absence of stratigraphic correlations between Upper Triassic successions of the NW Tethyan shelf inhibits ecological and sedimentological analyses across the Triassic/Jurassic boundary on regional scales. Outcrop-based analyses of carbonate-dominated sequences of the Upper Triassic (Rhaetian) Fatra Formation reveal the presence of three, 6-14 m-thick large-scale depositional sequences delimited by three unconformities. The uppermost part of the Fatra Formation is formed by a 2 m-thick limestone interval that is sharply replaced by carbonate-poor deposits of the Kopienec Formation. Large-scale sequences record transgressive-regressive trends, and consist of small-scale, shallowing-upward parasequences bounded by flooding surfaces. The transgressive system tracts are formed by aggradational and retrogradational parasequence sets, and are interrupted by rapid backstepping events characterized by an onset of deeper water facies. During the highstand phase, a relatively rapid replacement of shallow subtidal deposits by progradation of restricted peritidal deposits indicates a decrease in rate of sea level rise. In contrast to traditional views that assume that bio-events recorded by the the Kössen and Fatra formations are substantially diachronous in time, it is suggested that the maximum flooding zone of the first large-scale sequence of the Fatra Formation correlates with the maximum flooding zone of the first third-order Rhaetian depositional sequence, and thus with the onset of the *Vandaites sturzenbaumi* Zone. Therefore, abundance peaks of the coral *Retiophyllia* in the Kössen and Fatra formations probably represent coeval events at the end of the *V. sturzenbaumi* Zone.

■ *Rhaetian, Tethys, carbonate sedimentology, sea level change, parasequence*

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Introduction

Stratigraphic correlations of Rhaetian sequences across geographic regions on the Tethyan shelf are poorly known owing to the lack or rarity of ammonites and conodonts in Tethyan basins (Gaetani et al. 1998, Gianolla & Jacquin 1998, Gianolla et al. 1998, Rüffer & Bechstadt 1998, Pálfy et al. 2007). The lack of regional correlations hampers any evolutionary and ecological analyses of extinction and origination rates across the Triassic/Jurassic (T/J) boundary below the stage level (Kiessling et al. 2007, Tomašových & Siblík 2007). It is generally assumed that Upper Norian-Rhaetian deposits in the western Tethyan consist of two third-order depositional sequences (Golebiowski 1990, 1991, Lakew 1990, Gaetani et al. 1998, Haas & Budai 1999, Cozzi & Hardie 2003). The maximum flooding zone interval in the first sequence marks an important environmental and biotic event and is recorded by the onlap of Kössen-type formations onto the carbonate platform (Golebiowski 1990, Gawlick 2000, Haas & Budai 1999). Following this transgressive peak (base of *Vandaites sturzenbaumi* Zone), intra-basinal or platform-marginal, extensive coral patch-reefs with the coral *Retiophyllia* started to form (Schäfer 1979, 1984, Schäfer & Senowbari-Daryan 1981, Piller 1981, Kuss 1983, Stanton & Flügel 1989, 1995, Bernecker et al. 1999, Flügel 2002). Fossil assemblages similar to the Kössen Formation are preserved in the Fatra Formation (Fatric

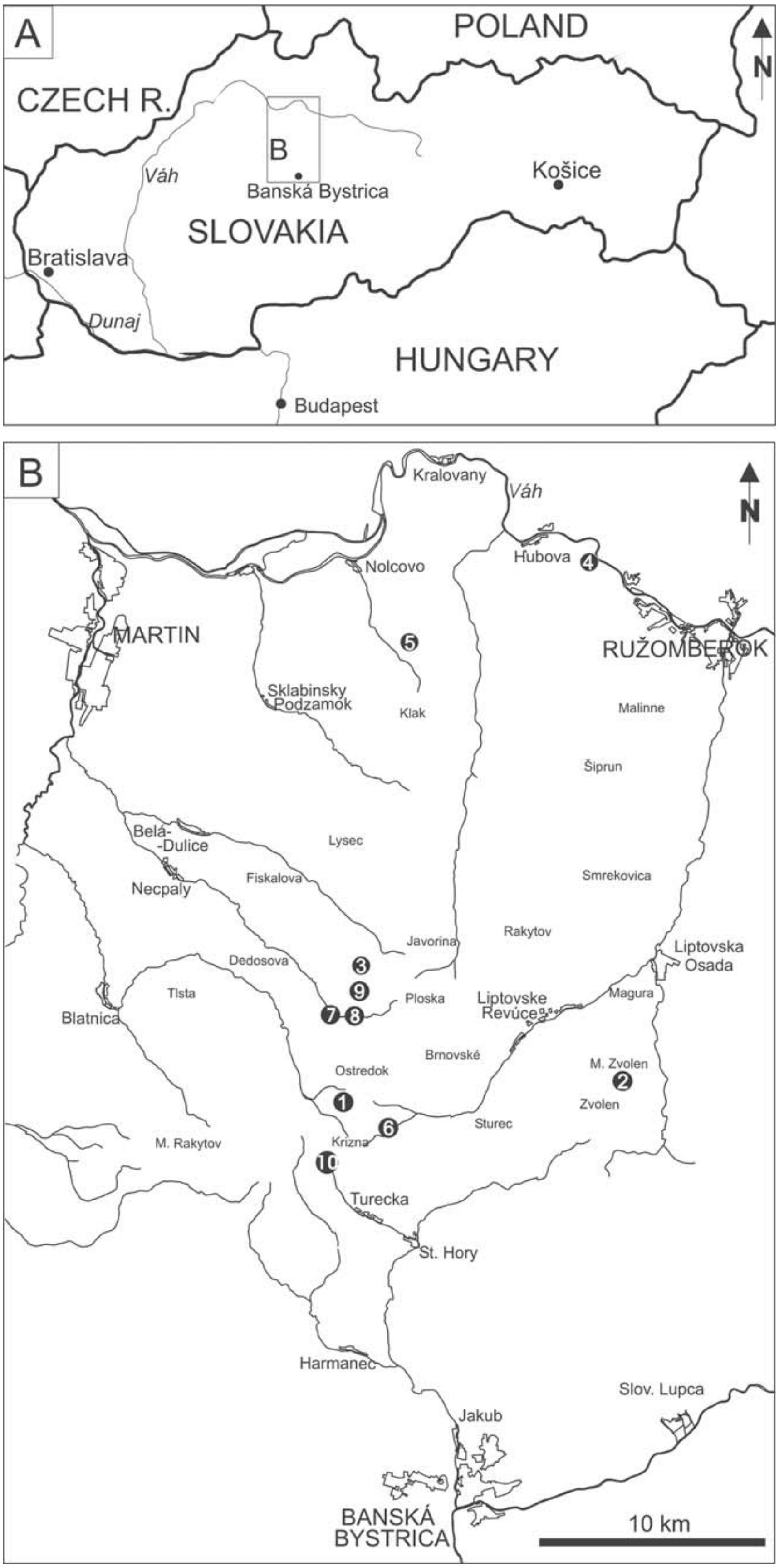
Unit) of the West Carpathians, and an about 2 m-thick interval with dense thickets of *Retiophyllia* in life position and a high spatial extent is present in the lower part of the Fatra Formation (TOMAŠOVÝCH 2004). However, there were few attempts to correlate depositional sequences and bio-events of the Norian-Rhaetian successions between the West Carpathians and the Eastern Alps. In accord with traditional views, GOLEBIOWSKI (1990) assumed that owing to the generally shallower depths and more proximal position of the Fatric Unit, bio-events recorded in the Fatra and Kössen formations are substantially diachronous in time. To resolve whether abundance peaks of *Retiophyllia* in the Kössen and Fatric basins correspond to the same time interval, the aim of this study is to document stratigraphic sequences of uppermost Triassic deposits in the Rhaetian Fatra Formation (West Carpathians), and to correlate them with the Kössen Formation in the Eastern Alps. In contrast to the Norian-Rhaetian carbonate deposits in the Eastern Alps, the thickness of the Fatra Formation is substantially reduced (30-80 m, MICHALÍK 1973, 1974, 1982, GAZDZICKI 1974, GAZDZICKI et al. 1979). However, in spite of the reduced stratigraphic completeness, its sequence stratigraphic interpretation allows tentative comparisons with other western Tethyan depositional sequences.

Geologic and stratigraphic setting

The West Carpathians were situated on the extensive epeiric shelf on the NW margin of the Tethys Ocean in the subtropical climatic belt in the Late Triassic (MICHALÍK 1994). This shelf was subdivided into several shore-parallel depositional settings. The most proximal near-shore zone was formed by continental or extremely shallow deposits, seaward followed by intra-shelf carbonate-siliciclastic basins, by the Dachstein carbonate platform, and the most distal zones were represented by rimming reefs (HAAS et al. 1995). The origin of intra-shelf basins is linked either to the tectono-eustatic sea level rise as a consequence of crustal extension of the Ligurian rifting phase (GRACIANSKY et al. 1998, COZZI 2002, COZZI & HARDIE 2003), or to a decrease in carbonate production as the consequence of strong input of terrigenous material in some areas (HAAS et al. 1995, GAWLICK 2000). The Rhaetian Fatra Formation was deposited in the shallow marine, intra-shelf, predominantly carbonate basin (Fatric Unit) of the West Carpathians. This basin was partly blocked from the open Tethys Ocean by the Dachstein platform (MICHALÍK 1982). Immediately below the Fatra Formation, the Carpathian Keuper Formation (Norian) is formed by light grey dolomites. Although ammonites and conodonts are absent in the Fatra Formation, the Rhaetian age is indicated by the first appearance of the Rhaetian foraminifers (MICHALÍK et al. 2007) and the appearance of the brachiopod *Austrirhynchia cornigera*. The upper part of the Fatra Formation is abruptly replaced by the Kopienec Formation that consists of siltstones and claystones with limestone and sandstone interbeds. In the beds overlying the basal, carbonate-poor member of the Kopienec Formation, the ammonites *Psiloceras psilonotum* (QUENSTEDT) and *Caloceras* cf. *torus* (D'ORBIGNY) indicate the Lower Hettangian *Psiloceras calliphyllum* Zone (RAKÚS 1993). Therefore, the age of the lowermost part of the Kopienec Formation, formed by about 5-20 m thick siltstones and claystones with signs of mm-scale, wavy and lenticular lamination and rare bioturbation, is not constrained. This interval is partly similar to the lowermost parts of the Kendlbach Formation of the Eastern Alps (GOLEBIOWSKI & BRAUNSTEIN 1988, MCROBERTS et al. 1997, KUERSCHNER et al. 2007) because it is carbonate-poor, contains rare macrofauna, and abruptly replaces coral-rich carbonates of the Fatra Formation (MICHALÍK et al. 2007).

Methods

Eleven sections with complete or partial succession of the Fatra Formation were measured in this study (Text-fig. 1). The spatial scale of this study includes only a portion of the intra-shelf Fatric Unit in central Slovakia, preserved now in a 40 km long transect in the Velká Fatra Mountains (ten sections), and in the southern part of the Malá Fatra Mountains (Trzinovo section). The Fatra Formation generally attains about 35 m in this transect. This uniformity in thickness allows to trace several widespread marker beds that occur at similar stratigraphic



Text-fig. 1. Geographic map of the study area. A. Regional map with location of the study area. B. Geographic location of sections of the Fatra Formation in the Velká Fatra Mountains. 1 – Dedošova, 2 – Sviniarka, 3 – Belianska-Borišov, 4 – Bystrý potok, 5 – Ráztoky, 6 – Krízna, 7 – Revúcky Mlyn, 8 – Balcierovo, 9 – Borišov-farm, 10 – Malá Ramziná. The Trzinovo section is present in the southern part of the Malá Fatra Mountains.

levels with respect to the base and the top of the Fatra Formation across the whole transect. These marker beds include (1) beds with densely packed and in situ preserved thickets of the coral *Retiophyllia* in the lower part of the Fatra Formation, (2) 1-3 m thick beds of microintraclastic-bioclastic packstones in the lower part of the Fatra Formation, and (3) three levels of stromatolitic limestones and dolomites that are associated with well sorted intraclastic/bioclastic deposits and unconformities.

Facies

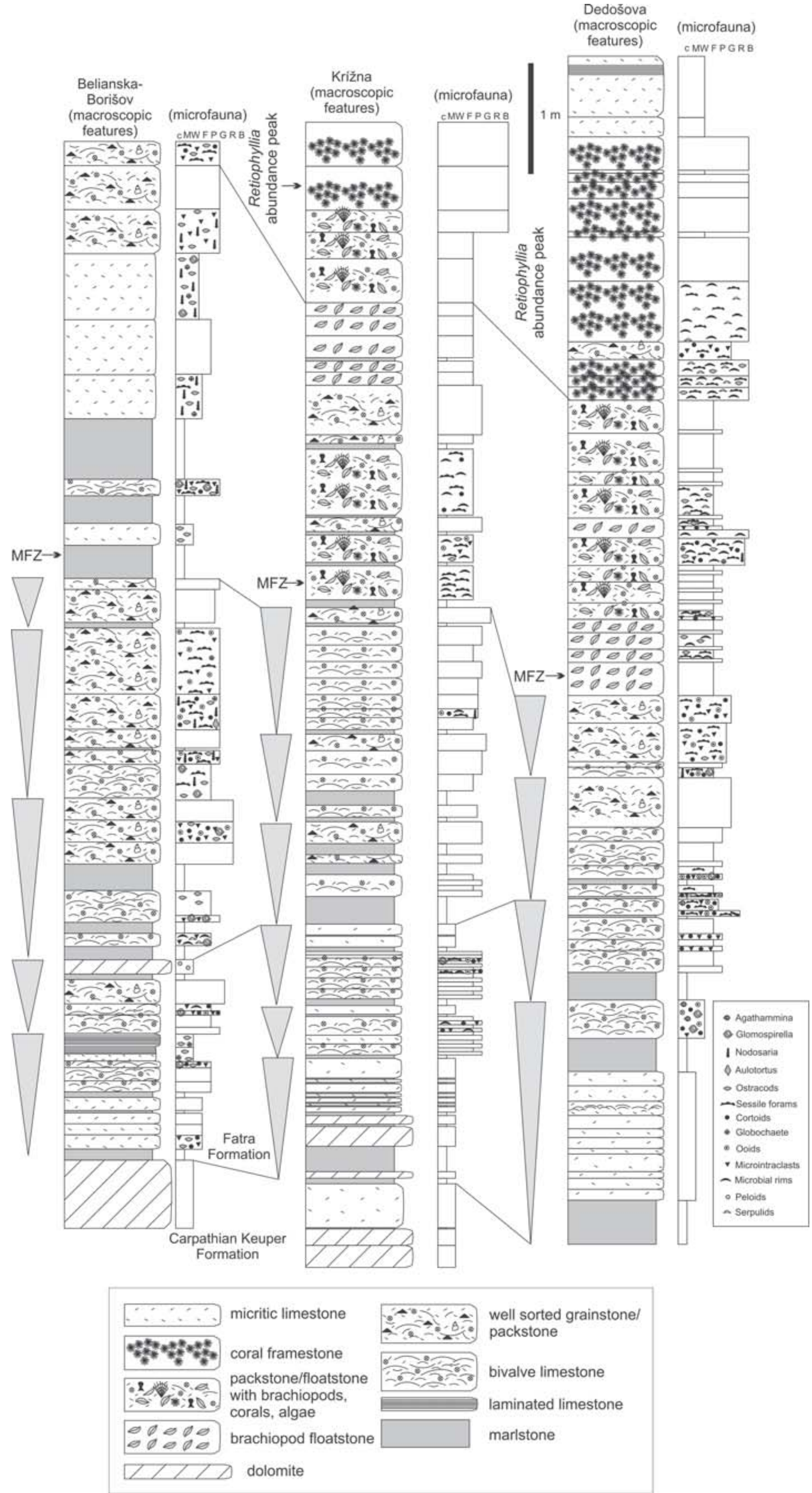
Four types of facies associations were recognized and interpreted with respect to a bathymetric gradient, including (1) restricted peritidal environments, (2) high-energy shoreface environments, above fair-weather wave base; (3) shallow subtidal environments, above normal storm wave base; and (4) environments above maximum storm wave base (TOMAŠOVÝCH 2004). The depositional environment can be characterized as a mosaic of low-relief peritidal flats and islands, shoreface banks and bars, and shallow subtidal depressions. Facies patterns are typical of ramp morphologies, where energy gradients are a consequence of gradual depth changes and carbonate production by coral patch-reefs is limited to low-energy settings below the fair-weather wave base (BURCHETTE & WRIGHT 1992).

Small-scale parasequences

Shallow subtidal and peritidal deposits form 1-4 m-thick sequences showing a gradual decrease in accommodation space. The term parasequence is used here (VAN WAGONER et al. 1987) because the boundaries between the sequences can be placed at the top of the shallowest beds that are abruptly replaced by deeper facies types. However, deposit types with in situ brachiopods and corals recording environments originating below normal storm wave base usually do not show any driven temporal variations in accommodation space. Vertical distribution of small-scale parasequences in the lower and upper parts of the Fatra Formation is shown in Text-figs. 2 and 3. Three types of shallowing-upward parasequences are recognized.

(1) The thickness of lagoonal-peritidal parasequences attains 1.5-2 m. Their lower part is formed by bio-wackestones and floatstones with rare benthic macrofauna, poorly diverse bivalve assemblages, or assemblages dominated by *Rhaetina gregaria*. Thickness and frequency of marlstones decrease upwards. Deposits show signs of complex structure with internal erosional boundaries and grading. Well sorted bio-packstones, pel-packstones and mudstones with common foraminifers (*Glomospirella*) and ostracods occur in the middle part. Limestones with planar laminations or dolomitic limestones and dolomites with wavy stromatolitic and fenestral fabric are present in uppermost parts. The preserved facies trend is thus directed towards restricted environments, with lowermost beds being deposited in low energy environments near the storm wave base. The uppermost parts correspond to peritidal flats and islands with occasional desiccation events.

(2) Lagoonal-skeletal bank parasequences are 1-4 m thick and are characterized by alternation of shell-rich floatstones with bivalves (*Placunopsis alpina, Rhaetavicula contorta, Bakevellia praecursor*), with dark marlstones in lower parts. Limestone beds consist of alternations of poorly sorted bivalve floatstones that alternate with well sorted oobio-packstones and bio-grainstones. Up-section, an increase in the thickness of limestone beds is associated with a decrease in the thickness and frequency of marlstone beds. Limestone beds are characterized by an increase in sorting and packing of components, and in the proportion of microintraclasts, ooids, and poorly preserved bioclasts. Well sorted bio-rudstones, bio- and oo-grainstones consisting of several amalgamated interbeds are present in the uppermost parts. The observed facies trend is directed towards high-energy, storm-dominated environments, thus recording an increase in the storm frequency and intensity. The basal alternation of biomicritic beds with marlstones represents low-energy conditions, with occasional distal storminduced flows. Middle parts were deposited above normal storm wave base, with increasing impact of storms represented by



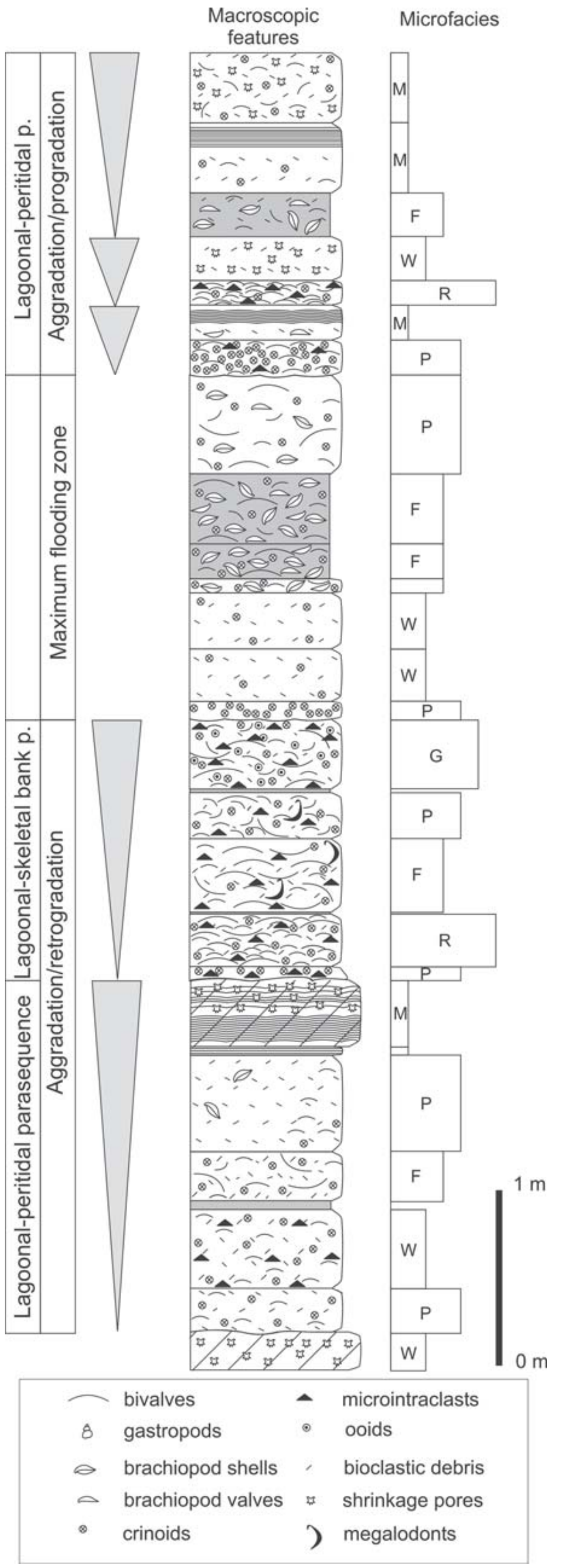
Text-fig. 2. Aggradational / retrogradational stacking of small-scale parasequences (triangles) in the lower part of the first large-scale sequence, showing the maximum flooding zone characterized by wackestones and floatstones with brachiopods and other euhaline benthic fauna, and abundance peaks of the coral *Retiophyllia*. Explanations: M – mudstone, W – wackestone, P – packstone, F – floatstone, G – grainstone, R – rudstone.

proximal tempestites. Uppermost parts correspond to a very shallow complex of skeletal banks.

(3) The thickness of lagoonal-skeletal bank-peritidal parasequences is about 1-1.5 m. The basal part comprises 0.1-0.2 m thick bivalve floatstones and wackestones that contain well-sorted storm-flow interbeds with internal erosional boundaries and normal grading. Storm-reworked, multiple-event bivalve shell beds are preserved in the middle parts. Bivalves are concordantly oriented, mostly with geopetal infillings and sparitic shelters. The upper parts are formed by dolomitic mudstones. The changes in the lower and middle parts of the parasequence show trends towards high-energy, storm-dominated environments. However, the storm-dominated part of the parasequence, representing incipient skeletal blankets or banks, is relatively thin. In contrast, uppermost parts are formed by restricted lagoonal or peritidal mudstones, or ostracod mudstones.

Shallowing-upward sequences often form a basic motive of carbonate accumulation (AIGNER 1985), and the Upper Triassic shallowing-upward sequences with peritidal capping facies were described from the Dachstein Formation of the Transdanubian Central Range (HAAS 1982, 1994, BALOG et al. 1997), West Carpathians (BORZA 1977), Eastern Alps (SCHWARZACHER 1948, FISCHER 1964, GOLDHAMMER et al. 1990, SATTERLEY 1996a, b, ENOS & SAMANKASSOU 1998), and the Middle and Upper Triassic of the Dolomites (HARDIE et al. 1986, GOLDHAMMER et al. 1987). One of the main reasons for their repetitive formation is that a rate of carbonate accumulation is much higher than average rates of subsidence. The absence of signs of subaerial erosion and of karstic surfaces at the top of described parasequences, and a continous subtidal-peritidal transitions in facies development indicate that the parasequences of the Fatra Formation are not primarily driven by eustatic sea level changes (STRASSER 1991). The genesis of small-scale parasequences of the Fatra Formation seems to be mainly related to combined effects of (1) autocyclic mechanisms driven by the subtidal carbonate factory, and (2) effects of extrinsic climate-driven variations that governed variations in terrigenous input and rate of sediment production by carbonate producers.

First, the presence of peritidal deposits or high-energy skeletal/ooidal banks in uppermost parts of the para-



Text-fig. 3. Aggradational / retrogradational stacking of small-scale parasequences in the third large-scale sequence (Bystrý potok section), replaced by the maximum flooding zone, and followed by progradation of skeletal banks. Explanations: M – mudstone, W – wackestone, P – packstone, F – floatstone, G – grainstone, R – rudstone.

sequences points to autocyclic models where shoaling is associated with tidal flat/tidal island progradation and migration (Ginsburg 1971, Pratt & James 1986), and with migration of carbonate sand bodies (Tucker & Wright 1990). Due to onshore storm transport and precipitation of carbonate on algal/microbial mats, peritidal areas prograde, acting as sediment traps until the production of carbonate rate in the adjoining subtidal setting decreases, leading to the formation of lagoonal-peritidal parasequences. In the tidal flat progradation model, relative sea level rise takes place with continuing subsidence. In the tidal island model, hydrographic forces can shift the focus of deposition to a different area. Progradation by shoaling of skeletal/ooidal banks that formed offshore can be responsible for origin of lagoonal-skeletal bank parasequences. These two types of shallowing-upward sequences can form end-members of an onshore-offshore environmental gradient because tidal flats/islands and restricted lagoons develop in the lee of the leading edge of the skeletal/ooidal banks. Lagoonal-skeletal bank-peritidal sequence can represent a change from the high-energy deposition to the low-energy deposition on prograding tidal flat (James, 1984). Second, the decrease in frequency and thickness of marlstones in parasequences points to the effects of climate-driven variations on sedimentation rates via higher rates of terrigenous input during humid conditions, and/or higher rates of carbonate production during arid conditions (e.g. Masetti et al. 1989, Burchell et al. 1990).

Unconformities and large-scale sequences

Michalík et al. (1979) and Gazdzicki et al. (1979) subdivided the Fatra Formation into five members: (1) *Basal beds* characterized by the presence of shell beds with bivalves; (2) *Lower biostromal member* with relatively diverse assemblages of corals, algae, brachiopods, and mollusks; (3) *Barren interval* formed by dolomites, dolomitic limestones and redeposited clastic limestones; (4) *Upper biostromal member* with coral, brachiopod, and mollusk assemblages; and (5) *Transition beds* characterized by higher amounts of siliciclastic admixture. After re-examination of sections in the Ve¾ká Fatra Mountains (central Slovakia), Tomašových (2004) subdivided the Fatra Formation into three, 6-14 m-thick large-scale sequences, and an about 2-2.5 m-thick limestone interval at the top of the Fatra Formation (Text-fig. 4). This subdivision partly overlaps with the five-fold subdivision of the Fatra Formation into five members, but it stresses the presence laterally extensive unconformities that segregate large-scale sequences, and their hierarchical subdivision and stacking patterns into parasequence sets and small-scale parasequences (Text-fig. 4). Later, Michalík et al. (2007) correlated several sections across the whole Fatric Unit that highly differ in thickness and amount of siliciclastic admixture, and subdivided the Fatra Formation into 14 meter-scale, shallowing-upward cycles. Their approach differs from that adopted in this study because their subdivision is primarily based on variations in component abundances and does not explicitly consider the hierarchical nature of the stratigraphic architecture. In the following, the unconformities and large-scale sequences are described in detail.

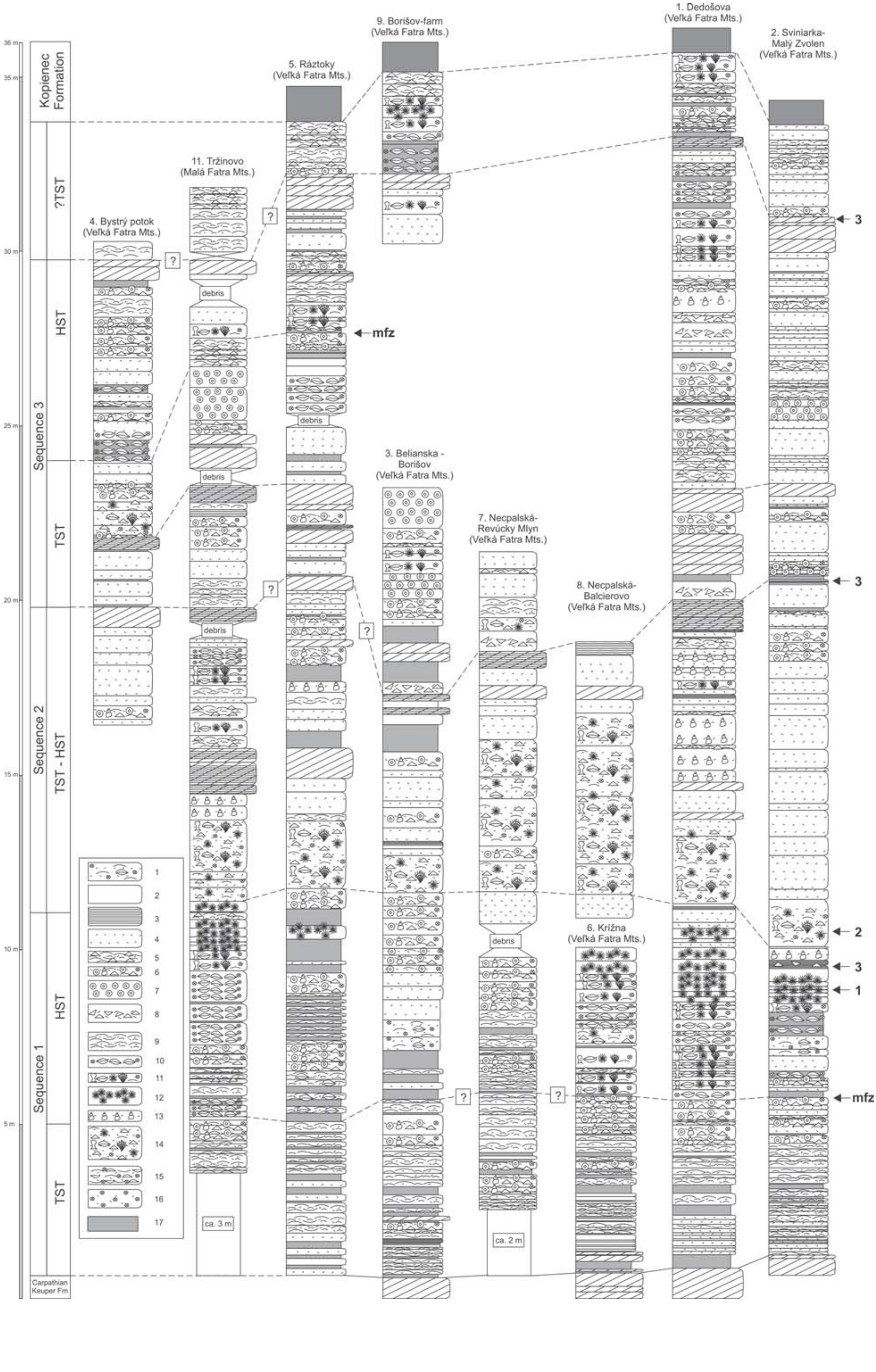
(1) The first large-scale sequence is 9-11 m thick. The lower part is represented by a aggradational/retrogradational parasequence set, which consists of two or three lagoonal-peritidal parasequences preserved in the lower parts, and three lagoonal-skeletal bank parasequences in the upper part (Text-fig. 2). This parasequence set represents a transition from restricted lagoonal deposits with bivalve assemblages (*Placunopsis alpina, Rhaetavicula contorta, Bakevellia praecursor*), to storm-dominated deposits, with increasing proportions of skeletal banks. The stacking pattern indicates that infilling of accommodation space due to aggradation/progradation of skeletal banks and incipient shoals was associated with slow sea level rise. The top of the third lagoonal-skeletal bank parasequence represents an abrupt change from bioclastic and intraclastic, cross-stratified or laminated biograinstones and oobio-packstones, to bio- wackestones and brachiopod floatstones and packstones, about 5-6 m above the base of the Fatra Formation. Bio-wackestones, floatstones, and multiple-event, storm-reworked packstones contain relatively diverse assemblages with bivalves (*Plagiostoma punctatum, Chlamys* sp., *Pteria* sp., *Antiquilima* sp., *Modiolus minutus*), brachiopods (*Rhaetina gregaria, Zugmayerella uncinata, Austri-*

rhynchia cornigera), corals, calcareous sponges, and red coralline algae, hinting at environments above and below the normal storm wave base. Low-energy deposits with diverse macrofauna compositionally differ from low-energy deposits with bivalves preserved at the base of small-scale parasequences in the lower part of the sequence. This abrupt replacement of skeletal bank packstones and grainstones by floatstones and wackestones deposited in low-energy environments thus indicates a very rapid retrogradation of skeletal banks. It probably reflects the maximum rate of relative sea level rise and can be interpreted as the maximum flooding zone of the first large-scale sequence. The uppermost parts of the first large-scale sequence are characterized by a 2 m-thick and spatially extensive development of coral patch-reefs with dense thickets of *Retiophyllia* preserved in life position. Local presence of skeletal banks implies renewed aggradation and progradation. The shallowing-upward trend from low-energy muddy environments to lagoons with coral thickets or high-energy shoals indicates a relatively rapid infilling of accommodation space, and probably represents the early highstand part of the sequence. The maximum shallowing corresponds to the widespread deposition of peritidal and skeletal bank deposits (late highstand phase), with the unconformity preserved at the top of mudstones and stromatolitic bindstones in protected areas (Sviniarka, Dedošova), or at the top of skeletal banks in exposed areas (Belianska).

(2) The thickness of the second large-scale sequence ranges from 6.5 m (Borišov), 10 m (Dedošova and Ráztoky) up to 12 m (Sviniarka). It starts with an unusually thick limestone bed (0.5-3 m) with amalgamated biointrapackstones and floatstones with bimodal sorting, large fragments of corals, and variable preservation of bioclasts. Poorly sorted ruditic bioclasts are dispersed in well sorted microintraclastic and peloidal debris. This indicates an exposed, shallow subtidal environment above the normal storm wave base, with reduced net rate of carbonate sedimentation, probably related to sediment winnowing and bypassing. Poorly sorted shells, high spatial variations in coral abundance, and presence of large coral colonies (*Retiophyllia*) is more indicative for in-situ reworking and local parautochthonous origin. Higher, lagoonal-peritidal parasequences consist of beds with brachiopods, corals, echinoderms and red algae, which pass upwards into gastropod or megalodontid limestones. The difference between transgressive and highstand phases is poorly marked and a distinct maximum flooding zone is missing in this sequence. A 0.3-1 m-thick interval of well bedded fenestral and cryptalgal bindstones or dolomudstones occurs in the uppermost parts of this sequence. They contain poorly sorted breccia interbeds with rip-up intraclasts and poorly sorted fragments of corals, brachiopods and bivalves.

(3) The third large-scale sequence attains 11 m (Sviniarka) to 14 m (Dedošova) in thickness. 0.3-0.6 m thick bio- and oo-grainstones and oobio-packstones occur above the basal unconformity. They contain well sorted (0.5-3 mm), rounded and micritized bioclasts, micritic intraclasts, and ooids. Uniformly poor preservation points to a long exposure on sediment/water interface. In the Bystrý potok section (Text-fig. 3), two lagoonal-peritidal parasequences, in both cases capped by dolomudstone with shrinkage pores, are replaced by a lagoonal-skeletal bank parasequence. Similarly, as in the first large-scale sequence, lagoonal-peritidal types replaced by the lagoonal-skeletal bank type form a retrogradational parasequence set. At the top of this parasequence set, there is an abrupt shift in deposition towards low-energy facies (Text-fig. 3). At the base, thin, well sorted crinoidal packstone passes into bio-wackestones and shell-rich floatstones with brachiopods and bivalves that were deposited below the storm wave base. This change probably corresponds to the maximum flooding zone of the third large-

Text-fig. 4. Sequence stratigraphic subdivision of the Fatra Formation into three, 6-14 m-thick large-scale sequences, and the uppermost, 2 m-thick carbonate interval. Three marker beds (see arrows) include (1) beds in situ preserved thickets of the coral *Retiophyllia*, (2) 1-3 m thick beds of microintraclastic-bioclastic packstones, and (3) three levels of stromatolitic limestones and dolomites that are associated with well sorted intraclastic/bioclastic deposits and unconformities. Two maximum flooding zones within the first and the third sequence are also shown. Explanations: 1 – wackestone with loose bioclasts, 2 – mudstone, 3 – bindstone, 4 – wackestone with dispersed bioclasts, 5 – rudstone, 6 – packstone/grainstone, 7 – ooidal grainstone, 8 – intraclastic packstone/grainstone, 9 – bivalve floatstone, 10 – brachiopod floatstone, 11 – coral floatstone, 12 – coral framestone, 13 – gastropod floatstone, 14 – microintraclastic/bioclastic packstone, 15 – bivalve rudstone, 16 – crinoidal floatstone, 17 – marlstone.



Kopienec Formation
?TST
HST
TST
Sequence 3
TST - HST
Sequence 2
HST
TST
Sequence 1
Carpathian Keuper Fm
5 m
10 m
15 m
20 m
25 m
30 m
35 m
36 m
4. Bystrý potok (Veľká Fatra Mts.)
11. Tržinovo (Malá Fatra Mts.)
5. Ráztoky (Veľká Fatra Mts.)
9. Borišov-farm (Veľká Fatra Mts.)
3. Belianska - Borišov (Veľká Fatra Mts.)
7. Necpalská-Revúcky Mlyn (Veľká Fatra Mts.)
8. Necpalská-Balcierovo (Veľká Fatra Mts.)
6. Krížna (Veľká Fatra Mts.)
1. Dedošova (Veľká Fatra Mts.)
2. Sviniarka-Malý Zvolen (Veľká Fatra Mts.)
debris
ca. 3 m
ca. 2 m
mfz
1
2
3
?
1
2
3
4
5
6
7
8
9
10
11
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17

scale sequence. This interval is associated with a moderately diverse level-bottom assemblages or small-scale patch-reefs in the Ráztoky and Dedošova sections. Uppermost parts of the third large-scale sequence are formed by a 0.25-1 m-thick interval with dolomudstones and limestones with fenestral and cryptalgal fabric, and probably represent an extensive shallowing.

(4) The top of the Fatra Formation is only 2-3 meters thick and consits of one or two lagoonal-skeletal bank sequences. The basal unconformity, lying 1.55-3.15 m below the boundary with the Jurassic Kopienec Formation, is preserved at the top of peritidal dolomites and mudstones. They are overlain by well sorted packstones and grainstones (Ráztoky, Sviniarka), bioclastic wackestones and floatstones (Bystrý potok, Borišov), or by dark marlstones (Dedošova). Uppermost beds of the Fatra Formation are represented by ooidal, bioclastic and intraclastic grainstones and packstones, and coral and bioclastic rudstones, and are generally characterized by the higher proportion of silt and quartz admixture. The upper boundary with siltstones and claystones of the Kopienec Fomation is relatively sharp, with no apparent evidence of erosion or non-deposition.

Sequence stratigraphic framework and correlation with the Eastern Alps

The architecture of the three large-scale sequences is interpreted as an alternation of aggradational/ retrogradational sets of small-scale parasequences deposited during transgressive periods (TST), with progradational sets of small-scale parasequences deposited during highstand periods (HST). The stacking pattern of TST parasequence sets (skeletal banks replacing peritidal caps in their uppermost parts) indicates that there was a temporal increase in the storm intensity and frequency, and that a rate of increase in accommodation space was higher than a rate of carbonate production. The rapid retrogradation of skeletal banks in the first large-scale sequence probably corresponds to rapid drowning. Abrupt facies shift from inner ramp facies to mid-outer ramp facies is typical of maximum flooding zone deposition when there is a little potential for continuous vertical accretion. Due to the stabilization of environmental conditions and reduced terrigenous input, this zone is characterized by the presence of moderately diverse, euhaline level-bottom assemblages. They occupied low-energy mid-ramp habitats below fair-weather wave base. In the third large-scale sequence, the interval between lagoonal-skeletal bank parasequence and overlying crinoidal and brachiopod floatstones is interpreted in a similar way as the maximum flooding zone.

In uppermost parts of the first three large-scale sequences, a decrease in the rate of relative sea level rise is marked by replacement of micrite-rich deposits by dense coral thickets, and prograding skeletal bank and peritidal deposits of the highstand system tract. This indicates that accommodation space became limited and was outpaced by carbonate production. The unconformities developed at the top of peritidal facies types in uppermost parts of large-scale sequences are probably not a simple result of autocyclic tidal flat/sand bar progradation, because (1) they are recognized in the whole Fatric Unit (MICHALÍK et al. 1979) and thus can span about 300 km in extent, and (2) shallow subtidal facies near storm wave base are rapidly replaced by peritidal deposits. The whole intra-shelf setting of the Fatric Unit was probably very shallow and restricted during such periods.

FRUTH & SCHERREIKS (1982), SATTERLEY (1996a, b) and COZZI & HARDIE (2003) interpreted rapid deepening events in the Upper Norian-Rhaetian deposits of the Alps as caused by abrupt subsidence events. One of these is the maximum deepening event in the Kössen Formation situated in the Unit 3 of the Hochalm Member, which represents a maximum flooding zone of the first Rhaetian third-order sequence. This maximum onlap of deep-water deposits onto the carbonate platform is also well preserved in the Transdanubian Central Range (HAAS 1993, HAAS & BUDAI 1999). It is marked by the immigration of open marine fauna (ULRICHS 1972, MOSTLER et al. 1978, GOLEBIOWSKI 1990) comparable to those that appear after the first maximum flooding zone in the Fatra Formation. These include the brachiopods *Zugmayerella uncinata* and *Austrirhynchia cornigera*. In the Kössen Formation, this event corresponds to the boundary between the *Sagenites reticulates* and *Vandaites sturzenbaumi* ammonite biozones (GOLEBIOWSKI 1990, KRYSTYN 1990, DAGYS & DAGYS 1994).

The conspicuous and widespread coral marker bed dominated by *Retiophyllia* („Hauptlithodendronkalk“) is preserved above this maximum flooding zone in the Kössen Formation, in the upper part of the *V. sturzenbaumi* Zone. Therefore, this abundance peak of *Retiophyllia* in the Kössen Formation is in a similar stratigraphic position as the extensive development of patch reefs with in situ *Retiophyllia* in the Fatra Formation, corresponding to the early highstand phase of the first large-scale sequence. Although COZZI & HARDIE (2003) assumed that this zone reflects a pulse of rapid subsidence rather than eustatic sea level rise, this event marks the important event of faunal immigration and colonization which is documented in most of the carbonate settings on the northwestern margin of the Tethys Ocean. Therefore, it is suggested that the maximum flooding zone of the first large-scale sequence of the Fatra Formation is coincident with the maximum flooding zone of the third-order, Rhaetian depositional sequence. The first unconformity should correspond to the sequence boundary between the first and the second third-order depositional sequences, represented by the boundary between the Hochalm and Eiberg members of the Kössen Formation (GOLEBIOWSKI 1990, HOLSTEIN 2004). This view contrasts with traditional interpretations that assume that these bio-events preserved in the West Carpathians and the Eastern Alps are substantially diachronous in time.

The interpretation of sea level changes across the T/J boundary is highly controversial (HESSELBO et al. 2004). The upper parts of the Kössen Formation and of the „Oberrhät“ Limestone show a general basinward progradation of carbonate deposits and thus a decrease in accommodation space (KUERSCHNER et al. 2007). KRYSTYN et al. (2005) assumed that a major drop in sea level took place at the end of the deposition of the Kössen Formation, leading to subaerial exposure of coral patch-reefs forming elevations (i.e. „Oberrhät“ Limestone). Note that the upper parts of the Fatra Formation were deposited in environments comparable to those of the „Oberrhät“ Limestone, but the boundary between the Fatra and Kopienec formations does not show any major changes in relative sea level. First, the shallowest, peritidal deposits in the upper part of the Kössen Formation are about 2 m below its top. Second, both topmost carbonates of the Fatra Formation and the lower siliciclastics of the Kopienec Formation were deposited in environments above normal storm wave base. Third, the uppermost limestone beds of the Fatra Formation do not show any signs of karstification or paleosols. Therefore, the general mismatch between the two large-scale sequences in the upper part of the Fatra Formation (plus the 2 m-thick limestone interval in its uppermost parts), and one third-order depositional sequence in the upper part of the Kössen Formation (i.e. Eiberg Member) might imply that regional variations in accommodation space were driven by differences in subsidence and sedimentation rates between the West Carpathians and the Eastern Alps, rather than by eustatic sea level changes.

Conclusions

6-14 m-thick, large-scale sequences with transgressive-regressive trends recognized within the Upper Triassic (Rhaetian) Fatra Formation of the western Carpathians consist of metre-scale shallowing-upward parasequences, most probably generated by combined effects of autocyclic aggradation/progradation of tidal flats/islands and carbonate skeletal banks, and effects of varying terrigenous input and carbonate production driven by climatic changes. The large-scale sequences are capped by three erosional unconformities preserved at the top of peritidal deposits. The architecture of the large-scale sequences is represented by aggradational/retrogradational parasequence sets in their lower parts, interrupted by zones characterized by deeper water facies in their middle parts, and replaced by progradational parasequence sets in their upper parts. Rapid replacements of skeletal banks by low-energy mid-ramp deposits in middle parts of the first and third large-scale sequences are indicative of maximum flooding zones. It is suggested that the maximum flooding zone of the first large-scale sequence of the Fatra Formation coincides with the maximum flooding zone of the third-order Rhaetian depositional sequence, and thus with the onset of the *Vandaites sturzenbaumi* Zone. Abundance peaks of the coral *Retiophyllia* in the Kössen and Fatra formations probably represent coeval bio-events at the end of the *V. sturzenbaumi* Zone.

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