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Small-scale cyclic deposition in the Frasnian (Upper Devonian) of the Holy Cross Mountains, Poland

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Abstract

In sections exposing Frasnian limestones at five outcrops in the Holy Cross Mountains, five lithofacies (L1 to L5) that represent upper slope to basinal environments are identified. These lithofacies are characterised by dark-coloured micritic limestones–marly shale couplets with many light-coloured intercalations of fine- to coarse-grained limestones (= event beds). This lithofacies pattern characterises mostly low-energy domains punctuated by storm episodes. In addition, these upper-slope to basinal lithofacies are arranged into small-scale, coarsening-upward beds and cycles. The cycles are locally composed of fining/thinning-upward beds. The small-scale cycles have a calculated duration of 19 to 42 kyr. The differential thickness of beds and cycles within and between sections was probably caused by differential subsidence and local tectonics. Possible evidence of tectonic activity is also related to a difference in number of cycles recorded in the time-equivalent sections. The recognised cyclicity shows sea-level fluctuations and a few deepening episodes. Some of them are correlated with the Timan global eustatic events. However, local tectonics and episodic subsidence may have played a significant role in recording brief deepening pulses. Thus, low-amplitude sea-level changes were major factors in platform generation and evolution in the Frasnian of the Holy Cross Mountains modified by local, block-related subsidence.

Keywords: sedimentology; carbonate platform; limestones; shallowing-upward cycles; event beds

1. Introduction

An important feature of carbonate successions is the repetition of similar beds or groups of beds. In shallow environments, these form the cyclic successions of carbonate deposits, in which each cycle is deposited in progressively shallower conditions (= shallowing-upward sequences). The tops of these sequences show signs of intertidal to supratidal exposure, or are eroded (e.g., James, 1984). In deeper water, subtidal depositional cycles are characterised by a coarsening-upward trend in high-energy structures such as grain size, bed thickness and cross-bedding, and the lack of intertidal sediments or subaerial exposure (Flügel, 2004, p. 806; references therein). In addition, limestones may have upward-fining/thinning beds formed primarily during eustatic sea level rises related to Milankovitch cycles (e.g., Larsen *et al*., 1989; Johnson *et al*., 2005). In the present paper rhythmically interbedded micritic limestones and marly shales (or limestones) and the depositional cycles in the deep-water, Upper Devonian (Frasnian) carbonate succession in the western part of the Holy Cross Mountains (HCM; Fig.1) are described. A few studies have documented such rhythmically interbedded limestones and marly shales in deeper water, Palaeozoic carbonate deposits (e.g., Elrick, 1995; Whalen *et al*., 2000; Elrick & Snider, 2002; Chen & Tucker, 2003; Elrick & Hinnov, 2007).

Shallowing- and deepening-upward cycles have been described from the Devonian in different parts of the HCM (e.g., Préat & Racki, 1993; Skompski & Szulczewski, 1994; Szulczewski *et al.*, 1996) and neighbouring areas (e.g., Hofmann & Keller, 2006; da Silva & Boulvain, 2008), but all of these sections represent a stage of carbonate platform development older or younger than the ones described in the present paper. Racki (1993) was among the first ones to document Givetian–Frasnian deposits from the southern part of the HCM, but the cycles were developed in a lagoonal and intershoal environment, definitely different from the ones described here. Skompski & Szulczewski (2000) described other Lofer-type cyclothems in the quasi-time equivalent upper part of the Frasnian carbonate succession in the southern part of the HCM. These successions represent a restricted inner, back-reef, lagoonal setting, and according to authors the origin of the cyclothems is connected with tectonic control of the carbonate platform margin linked to a rapidly subsiding basin. In turn, Whalen *et al.* (2000) described the Upper Devonian (uppermost Givetian to Frasnian) succession deposited during the second-order transgressive-regressive cycles on two isolated carbonate platforms in western Alberta (Canada). The slope and basin sequences surrounding these platforms consist of basin-restricted, onlapping wedges of fine-grained background sediment deposited from suspension and coarse-grained, platform-derived sediment redeposited by a variety of gravity-flow mechanisms. Successive stages of platform development were controlled by accommodation changes driven by relative sea-level fluctuations.

1.1. Objectives

Recognition of cycles and their capping facies enables a better definition of palaeoenvironmental conditions of the HCM during the Late Devonian. The present contribution has four main objectives: (1) describe and interpret lithofacies and depositional environments on the isolated platform margin; (2) identify Frasnian shallowing- and deepening-upward carbonate cycles; (3) interpret the origin of these cycles; (4) determine influences of local tectonics, episodic subsidence and sea-level change on cycle development.

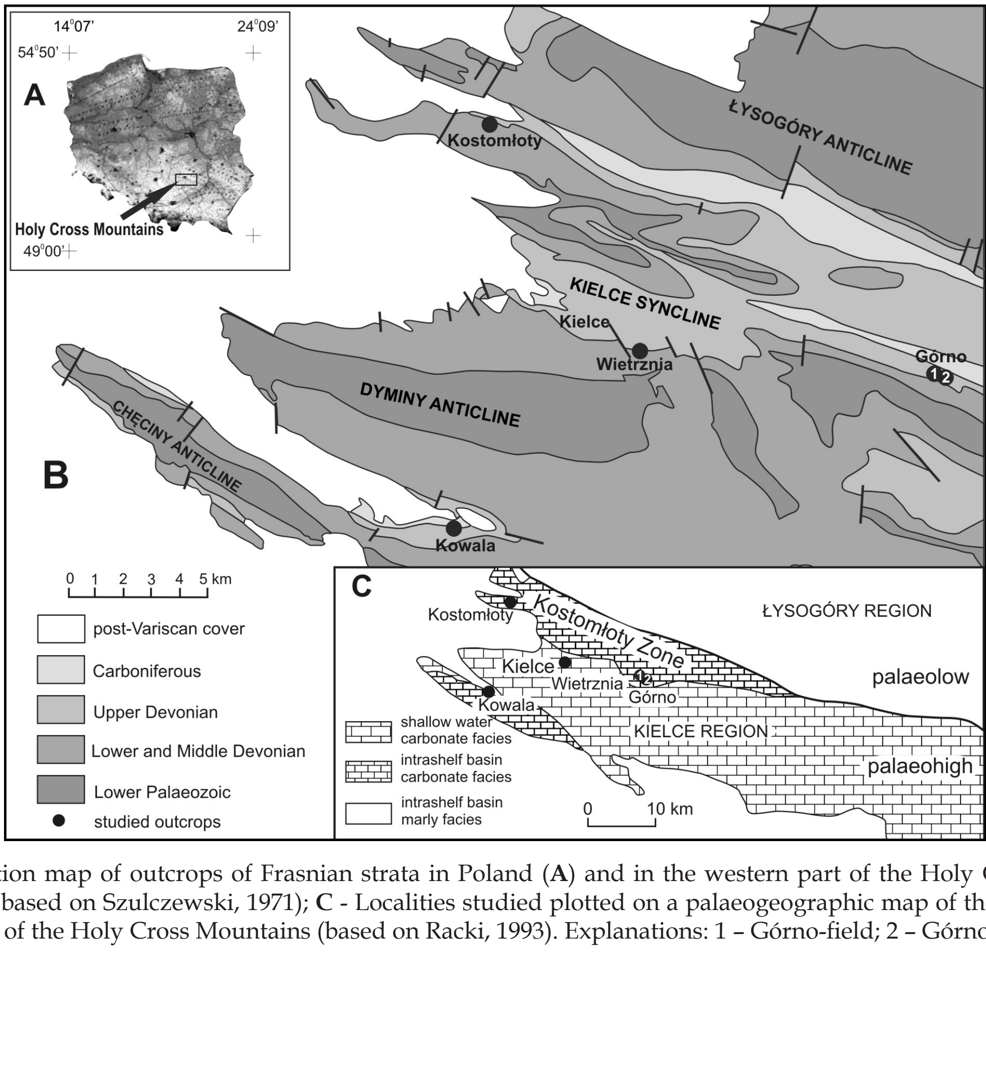

Fig. 1. Location map of outcrops of Frasnian strata in Poland (**A**) and in the western part of the Holy Cross Mountains (**B**; based on Szulczewski, 1971); **C** - Localities studied plotted on a palaeogeographic map of the Givetian to Frasnian of the Holy Cross Mountains (based on Racki, 1993). Explanations: 1 – Górno-field; 2 – Górno-Józefka

2. Geological setting

2.1. Sedimentary processes and tectonics

Devonian strata in Poland were deposited on a pericratonic shelf ranging from 150 to 600 km across (Narkiewicz, 1985). The shelf formed the Polish fragment of a pericratonic basin stretching from western Europe into the Ukraine along the outer periphery of the Laurussian continent. Sedimentation on the outer shelf of Laurussia was primarily controlled by: (1) pre-existing topography, (2) the supply of clastics sourced from the eroded landmass, (3) Emsian rifting and (4) eustatic events which controlled important depositional episodes, particularly during the Late Devonian (Narkiewicz, 2007; Bełka & Narkiewicz, 2008).

Two distinct palaeogeographic-tectonic regions were distinguished (Szulczewski, 1971, 1977): the northern palaeolow in the Łysogóry region and the southern palaeohigh in the Kielce region (Figs. 1C and 2). Later research (Racki, 1993; Racki & Bultynck, 1993) identified a separate Kostomłoty transitional zone between the shallow-water Kielce stromatoporoid-coral platform and the broadly-defined Łysogóry basin deposits.

Lower Devonian strata in the HCM are represented by a siliciclastic sequence of continental and shallow-marine facies (Szulczewski, 1977, 1995). At the transition from the Early to Middle Devonian, a marine transgression led to reduction in siliciclastic deposition and resulted in a variety of marine environments in the HCM area. In the Kielce region (Fig. 2), a biostromal-colonised platform typical of the Givetian evolved into a stromatoporoid-coral reef-rimmed platform complex – the Dyminy reef of Narkiewicz (1988) or the Dyminy reef complex of Racki (1993). The Dyminy reef developed over the northern marginal zone of the extensive Kielce carbonate platform. According to Szulczewski (1971, 1977, 1995) syndepositional block-faulting occurred, which resulted in a relative uplift of the

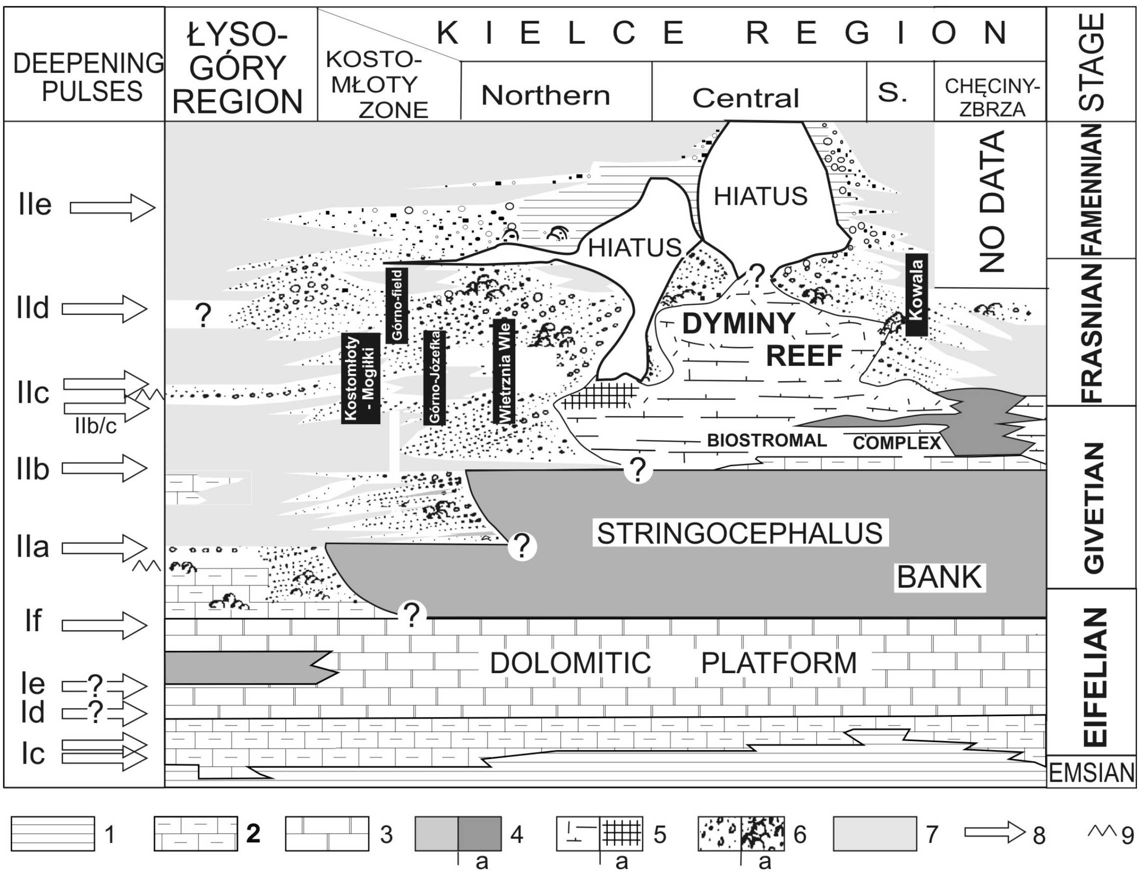

Fig. 2. Sedimentary stages of the Devonian carbonate platform in the Holy Cross Mountains area, against eustatic events (Ic to IIe – global cycles of Johnson et al., 1985) (based on Racki & Narkiewicz, 2000) and location of Frasnian sections studied. Explanations:
1 – siliciclastic facies; 2 – calcareous-marly, open-shelf facies; 3 – dolomitic facies; 4 – carbonate bank facies (a–intershoal facies); 5 – reef facies (a–Kadzielnia-type bioherms); 6 – foreslope facies (a–organic buildups); 7 – marly to clayey (basinal) facies; 8 – transgressions; 9 – tectonic events

northern portion of the Kielce block along which a stromatoporoid-coral Dyminy reef developed and bounded to the northern Łysogóry-Kostomłoty basin. A simultaneous greater subsidence of the southern portion of the block shaped the Chęciny-Zbrza Basin.

The northern Łysogóry-Kostomłoty Basin in the Givetian and Lower Frasnian consists of marly shales and marly limestones defined as the Szydłówek Beds. The Szydłówek Beds reflect quiet hemipelagic deposition in the oxygen-depleted basin below the storm wave base (SWB), and contain sporadically bioclastic debris derived mainly from the evolving Kielce carbonate platform (e.g., Racki & Bultynck, 1993; Racki *et al*., 2004; Vierek, 2008, 2010). They underlie Middle to Upper Frasnian coarse-grained limestones and build a succession of slope deposits (= the Kostomłoty Beds), which reflect high-energy deposition (e.g., Szulczewski, 1995; Vierek, 2010).

The Upper Devonian strata in the southern part of the Kielce region are composed mainly of marly deposits intercalated with micritic and grainy limestones as well as flat-pebble conglomerate (FPC). Szulczewski (1968, 1971) recognised the fine- and coarse-grained limestones, typical of the northern and southern Kielce region, as sediment reflecting subaqueous mass movements and turbidity currents. According to Szulczewski (1995), syndepositional block-faulting and associated seismicity induced gravity debris flows. On the other hand, Vierek (2007b, 2010, 2013) interpreted the coarse-grained limestones, including FPC, as sediment representing storm-wave erosion of the reef flank deposited in a deeper fore-reef facies.

The Late Devonian epicontinental succession reflects the continuous but punctuated drowning of an increasingly differentiated carbonate platform (Szulczewski, 1971; Narkiewicz, 1988; Racki, 1993; Szulczewski, 1995; Racki & Narkiewicz, 2000). Synsedimentary block faulting, resulting in a stepwise disintegration of the carbonate platform, is mainly responsible for considerable differences of the stratigraphic and sedimentary record (Szulczewski, 1989; Racki & Narkiewicz, 2000). Evidence of these factors has been documented in most sections of the Upper Devonian of the HCM (Szulczewski, 1989; Pisarzowska *et al*., 2006; Sobstel *et al*., 2006; Vierek, 2007b).

2.2. Eustatic cycles

The Early-Middle Frasnian transition on the Kielce platform coincides with extensive facies changes related to an intermittent sea-level rise (IIc – global cycles of Johnson *et al*., 1985 and IIb/c of Racki, 1993, 1997; Pisarzowska *et al*., 2006), probably separated by a stillstand phase. During the later part of the *Palmatolepis transitans* conodont Zone, the transgressive Timan Event (House, 2002; Sobstel *et al*., 2004) was marked by episodic blooms of unique goniatite- and styliolinid-rich associations, and on the other hand, by a gradual decline of early Frasnian reef-related biota (Racki *et al*., 2004; Pisarzowska *et al*., 2006). At the beginning of the middle Frasnian, the marine IIc transgression (sensu Johnson *et al*., 1985; = Middlesex Event) transformed the sedimentation into a marly-bituminous type (Pisarzowska *et al*., 2006). Two extensive deepening phases were established in styliolinid-rich, benthos-poor marly lithofacies in the upper *Pa. punctata* Zone and correspond with the initiation of the multiphase Rhinestreet Event (Pisarzowska *et al*., 2006; Sobstel *et al*., 2006).

During the late Frasnian, sea level reached a maximum, termed the Kellwasser anoxic event (Johnson *et al*., 1985; Racki, 1993). As the Dyminy reef drowned, facies differences gradually disappeared and pelagic limestone facies developed (Szulczewski, 1971).

3. The study area

Five outcrops were examined in different parts of the Holy Cross Mountains (Figs. 1 and 2).

Wietrznia Hill is located in the south-eastern part of the town of Kielce in the western part of the HCM. The sediments visible in outcrop belong to the southern flank of the Kielce Syncline, which forms part of the Kielce-Łagów Synclinorium. The Wietrznia quarry is situated between the shallow-water Devonian carbonate platform in the Kielce region and the deeper Łysogóry Basin (= transitional facies of Szulczewski, 1971). The present study concerned only the middle part of the Wietrznia Beds (set *C* of Szulczewski, 1971) and included the eastern, distal and deeper succession (= Wie, designated after Szulczewski, 1971; Racki *et al*., 1993 and Pisarzowska *et al*., 2006; see also Vierek, 2007b, section WgI therein), comprising sediment deposited above or below the SWB. The examined set *C* belongs to the lower to middle Frasnian *Palmatolepis transitans* and *Palmatolepis punctata* conodont Zones (Pisarzowska *et al*., 2006) and the boundary between these two zones lies in the highest part of the succession.

The village of Kostomłoty lies a few kilometres NNW of Kielce in the north-western part of the HCM. The abandoned Kostomłoty-Mogiłki quarry is situated on the east side of the Kostomłoty Hills. The Kostomłoty Hills trace the Upper Devonian outcrops of the axial part of the Miedziana Góra Syncline. The Kostomłoty-Mogiłki quarry is situated in the Kostomłoty transitional zone between the shallow-water Kielce stromatoporoid-coral platform and the deeper Łysogóry Basin (Racki, 1993; Racki & Bultynck, 1993). The present study concerned the upper part of the Szydłówek Beds comprising the lower Frasnian (*transitans* Zone with *Ancyrodella africana–A. pramosica*) and the lower part of the Kostomłoty Beds, belongs to the middle Frasnian *punctata* Zone with *A. gigas* (Pisarzowska *et al*., 2006). The Szydłówek Beds represent the deeper-water basin environment (= basin facies of Szulczewski, 1971) with mostly oxygen-depleted bottom conditions (Racki & Bultynck, 1993; Pisarzowska *et al*., 2006).

An abandoned outcrop (the so-called Górno-field) along the Kielce-Lublin road and a large, active quarry (Górno-Józefka) on Józefka Hill are located 1.4 km south of the village of Górno in the central part of the HCM. Both the Górno-Józefka quarry and the outcrop Górno-field are situated in the Kostomłoty transitional zone. The upper part of the Szydłówek Beds, *c*. 14 m thick, is visible in the eastern part of the Górno-Józefka quarry (Vierek, 2008). They represent a deeper-water basin environment (= basin facies of Szulczewski, 1971) and probably belong chiefly to the lower Frasnian *transitans* Zone with *Ancyrodella africana–A. pramosica.* In the Frasnian limestones exposed at the Górno-field, using conodont data from Małkowski (1981), his five sets (A–E) ranged from the *transitans* to the *Palmatolepis rhomboidea* Zone. The present study concerns only set ?*C*, which probably is equivalent to the Late *hassi* s.l. to the Early *rhenana* zones (Ziegler & Sandberg, 1990).

The outcrop at Kowala is located in the south-western part of the HCM, at the eastern part of the Gałęzice Syncline. Upper Devonian deposits are exposed along the railroad cutting (Kielce–Busko), *c*. 0.8 km S of the village of Kowala. The Kowala railroad cutting is situated in the southern Kielce subregion. The present study referred to the upper part of the succession (set *G* and part of set *H* of Szulczewski, 1971), belonging mostly to the upper Frasnian (*Pa. hassi* to ?*Pa. linguiformis* Zone; Sartenaer *et al*., 1998). Set *H* represents a deeper-water basin setting (= basin facies of Szulczewski, 1971).

4. Methods

Five sections were studied bed-by-bed, with particular attention to textures and sedimentary structures. Individual layers in sections were counted, and thicknesses and maximum grain diameters were measured. Five lithofacies were distinguished on the basis of field observations. Additionally, 42 thin sections of approximately 2.5x5.5 cm each and 74 thin sections of approximately 5.5x8.0 cm each were examined under a microscope. Individual event layers were described by Energy Index (EI; from I to V according to Plumley *et al*., 1962) and Clasticity Index (CI). According to Carozzi (1958), CI is defined as the mean diameter of 10 largest grains present in the thin sections. In the present study, CI were studied in thin sections and in polished slabs. This index is used for grains, such as bioclasts, fossils, intraclasts, peloids, which have undergone transport, and corresponded to maximum apparent grain size.

In the sections small-scale cycles were identified on the basis of field and microscopic observations. The hierarchy of sedimentary cycles recognised herein, in descending order, is *bed* and *cycle*. The *bed* is cm-scale depositional unit, differentiated by lithology, commonly 1–20 cm thick. Their lateral extent ranges from a few metres to a maximum of several hundred metres. Several beds (commonly three to nine) bundle into a *cycle*. A cycle (= *parasequence* according to Van Wagoner *et al*., 1988; Flügel, 2004, p. 817 and Coe & Church, 2005, p. 61) is a succession of beds showing an upward-coarsening and/or bed-thickening (= shallowing-upward), or locally upward-fining and/or bed-thinning (= deepening-upward). These *parasequences* form the smallest fundamental composite blocks of carbonate successions; in the study area they measure 30–75 cm in thickness.

5. Results

5.1. Lithofacies and depositional environment

Five lithofacies (L1 to L5) are differentiated by grain size, composition, sorting, texture and sedimentary structures. These are: marly shales and marly limestones (L1; Fig. 3A, B); nodular to wavy-bedded limestones (L2; Fig. 3D); micritic limestones (calcisiltites; L3; Fig. 3A, C); fine-grained limestones (calcarenites; L4; Fig. 4) and coarse-grained limestones (calcirudites; L5; Fig. 5) includ-

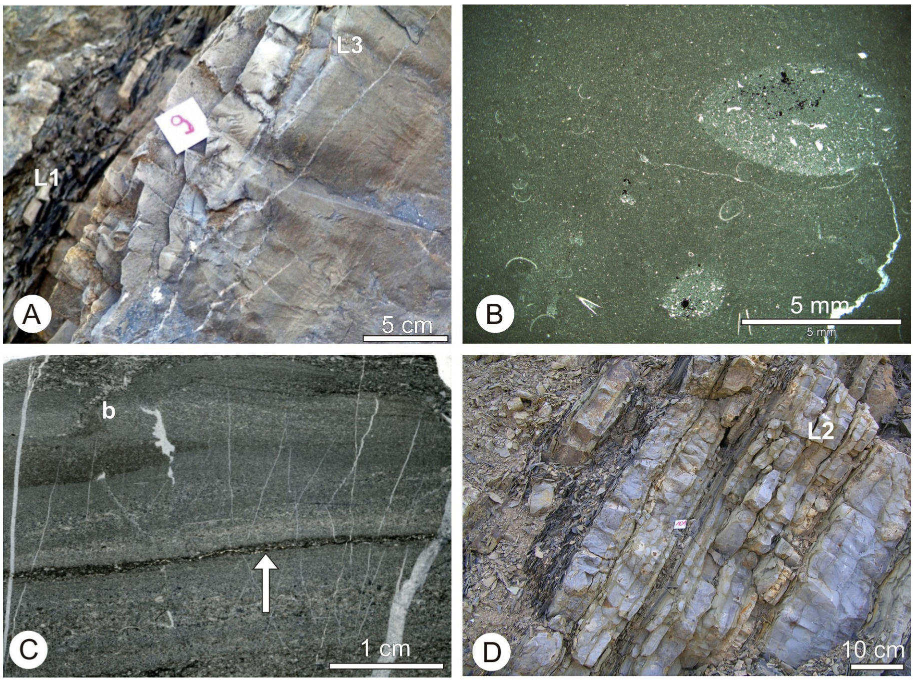

Fig. 3. A – Micritic limestones – marly shaly interval: dark grey, thin-bedded marly shales (L1) and laminated micritic limestones (L3); Szydłówek Beds in the Kostomłoty-Mogiłki section; **B** – Styliolinid biomicrite background microfacies disturbed by bioturbations; thin section GII 22a at Górno-field section; **C** – Laminated micritic limestones (L3): lamination defined by pelsparite and biopelsparite laminae; note horizontal lamination of lower part grading upwards into wavy lamination; arrow indicate stylolites, b- bioturbation; thin section 20 at Kostomłoty-Mogiłki section; **D** – Nodular to wavy-bedded limestones (L2): densely packed nodules within a marly matrix; lower part of Kostomłoty Beds in the Kostomłoty-Mogiłki section

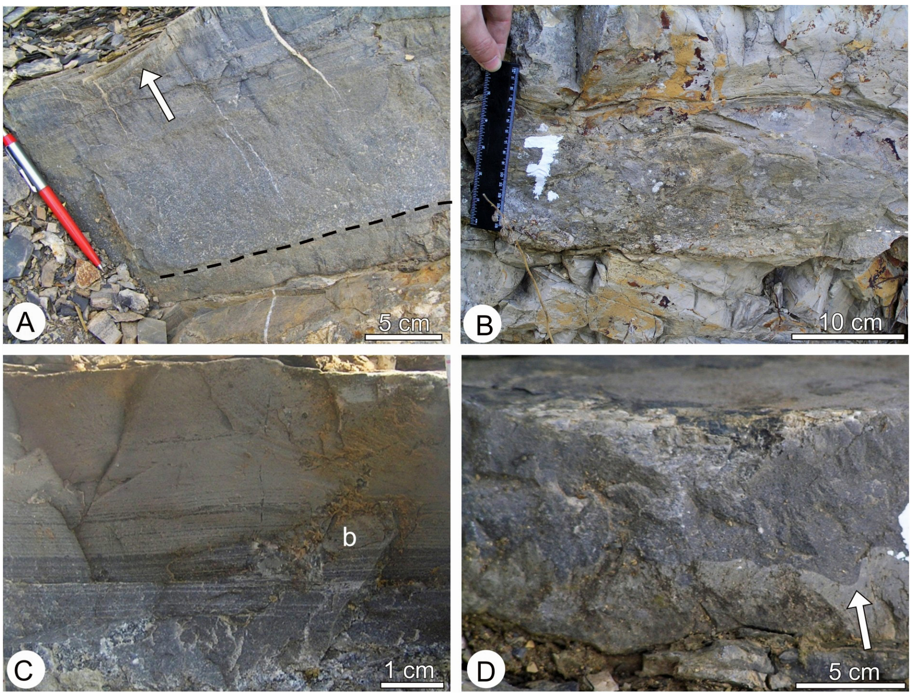

Fig. 4. Fine-grained limestones (L4):
A – Flat, erosional base, normal grading and horizontal lamination passing into small-scale ?HCS (arrow); layer 21 at Kostomłoty-Mogiłki section; **B** – Tempestite beds: erosional base, graded and hummocky-like lamination at the top; layer 7 at Górno-field section; **C** – Distal tempestites: horizontal lamination disturbed by bioturbation (b); layer 31 at Wietrznia WIe section; **D** – Sharp base showing erosional relief with distinct V-shaped depressions (arrow); layer 61 at Kostomłoty-Mogiłki section

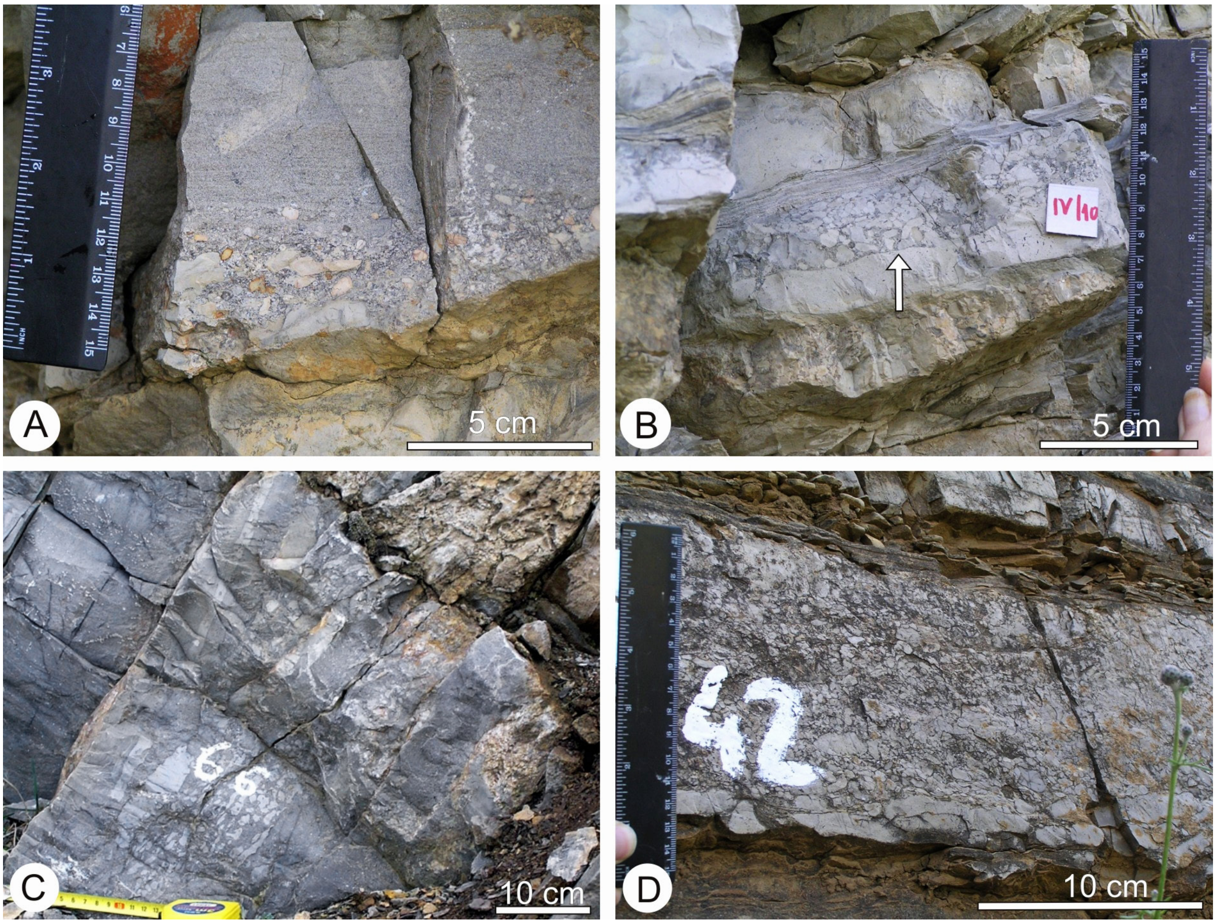

Fig. 5. Coarse-grained limestones (L5):
A – Graded tempestite showing a gradual transition from coarse-grained breccia to laminated micritic limestones; layer 7 at Górno-field section; **B** – Breccia (lithofacies L5a) with erosive base (arrows) and horizontal lamination at top; note irregular micritic intraclasts and grain-support fabric; sample IV/10 at Górno-field section; **C** – Flat-pebble conglomerate (L5b) in the basal Kostomłoty Beds, showing a diversity of intraclast types, matrix-supported fabric and inverse grading; layer 66 at Kostomłoty-Mogiłki section; **D** – Grain-supported breccia (L5a): note irregular arrangement of micritic intraclasts, which are of irregular shape and variable size, and flat-pebble conglomerate at the base; layer 42 at Górno-field section

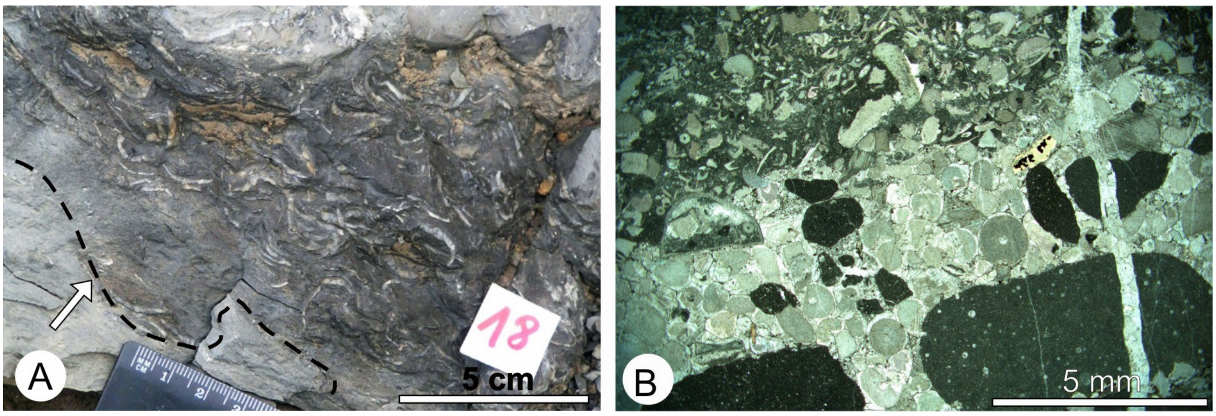

Fig. 6. Coquina bed (L5c):
A – Brachiopod shells arranged in stable and unstable positions, arrow indicating erosional base with U-shaped depressions; layer 18 at Górno-Józefka section; **B** – Crinoidal limestones with small micritic clasts; thin section 34, Wietrznia WIe sections

Table 1. Lithofacies distinguished in Frasnian sequences, their characteristics and depositional environment. SWB – storm wave base; HCS – hummocky cross-stratification

Lithofacies	Localities	Description	Components	Depositional environment
marly shales, marly limestones (L1)	Kostomłoty-Mogiłki, Wietrznia WIe, Kowala, locally Górno-field, lower and upper parts of Górno-Józefka	dark grey, thin-bedded (locally medium- to thick-bedded), finely laminated, flat boundaries; locally organic matter; micrites/biomicrites	styliolinids, autochthonous rhynchonellid brachiopods, rare cephalopods	quiet, weakly-oxygenated waters below SWB
nodular to wavy-bedded limestones (L2)	Wietrznia WIe, middle and upper parts of Kostomłoty-Mogiłki, lower part of Górno-field	grey, marly or limy micrites/biomicrites, wavy and/or knobby in shape; regular or irregular, elongated and lenticular nodules (approximately 12 cm long); marly matrix; stylolites	small amounts of detritus: crinoids and brachiopods, single calcispheres and tubular algae (Jansaella ridingi)	pelagic carbonate platform, slope, foreslope
micritic limestones (calcisiltites; L3)	all sections studied	grey, thin- to medium-bedded (locally thick-bedded); horizontal and wavy (or HCS) lamination: millimetre-scale micrite and pel(bio)sparite laminae or pelsparite and biopelsparite; bioturbations; distinct and smooth boundaries (or rare erosional base and undulose top); stylolites	rare styliolinids, crinoids and brachiopods; gastropods (at Kowala); autochthonous rhynchonellids, single algae (Jansaella ridingi)	hemipelagic/pelagic below SWB; event-like drop-downs of wave base
fine-grained limestones (calcarenites; L4)	all sections studied	grey, thin- to medium-bedded; moderately to well-sorted (calci)pel(bio)sparites; normally graded; horizontal or wavy lamination; locally HCS and undulose top; sharp base with gently wavy to distinctly V-shaped depressions (in some cases boundaries smooth and planar); geopetal fillings; rare bioturbations	abundant skeletal fragments of crinoids, brachiopods, rare calcispheres and styliolinids; mud peloids, aggregate grains	slope above SWB, influenced by storm event (normal or distal tempestites)
coarse-grained limestones (calcirudites; L5):				
– breccia (L5a)	Wietrznia WIe, Kostomłoty-Mogiłki, Górno-field, rare at Górno-Józefka	light grey, thin- to medium-bedded; poor- to moderately sorted intramicrudites and intrabiopelspar(rud)ites; sharp and non-erosive or erosive bases; sharp and flat upper boundaries; matrix- or grain-supported; (micro)stylolites	crinoids, brachiopods, rugose and tabulate corals, stromatoporoids, bryozoans, trilobite fragments, calcispheres, single *Jansaella ridingi*; styliolinids; irregular, subangular or subrounded intraclasts (approximately 5 cm long), mud peloids, aggregate grains	fore-reef, strongly turbulent water, high-energy, proximal tempestite (and/or gravity-flow)
– flat-pebble conglomerate (L5b)	Kostomłoty-Mogiłki	light grey, medium-bedded; poorly sorted intrabiopelspar(rud)ites; often erosional base; geopetal structures; rare (micro)stylolites	numerous flat, discoidal and rounded intraclasts (up to 15 cm in size); bioclasts as above	high-energy storm conditions, tempestites
– coquina (L5c)	Górno-Józefka; Wietrznia WIe; locally in other sections	grey, thin- or medium-bedded; moderately sorted biopel(micro)spar(rud)ites; sharp and erosional base with U- and V-shaped depressions (or rare indistinct base); locally graded; horizontal or wavy lamination at top; rare bioturbations; geopetal structures	abundant crinoids (= crinoidal limestones) and brachiopods (= crinoidal/brachiopod limestones); mud peloids, aggregate grains; sparse micritic clasts (approximately 2 cm long)	slope above SWB, activity of waves or currents

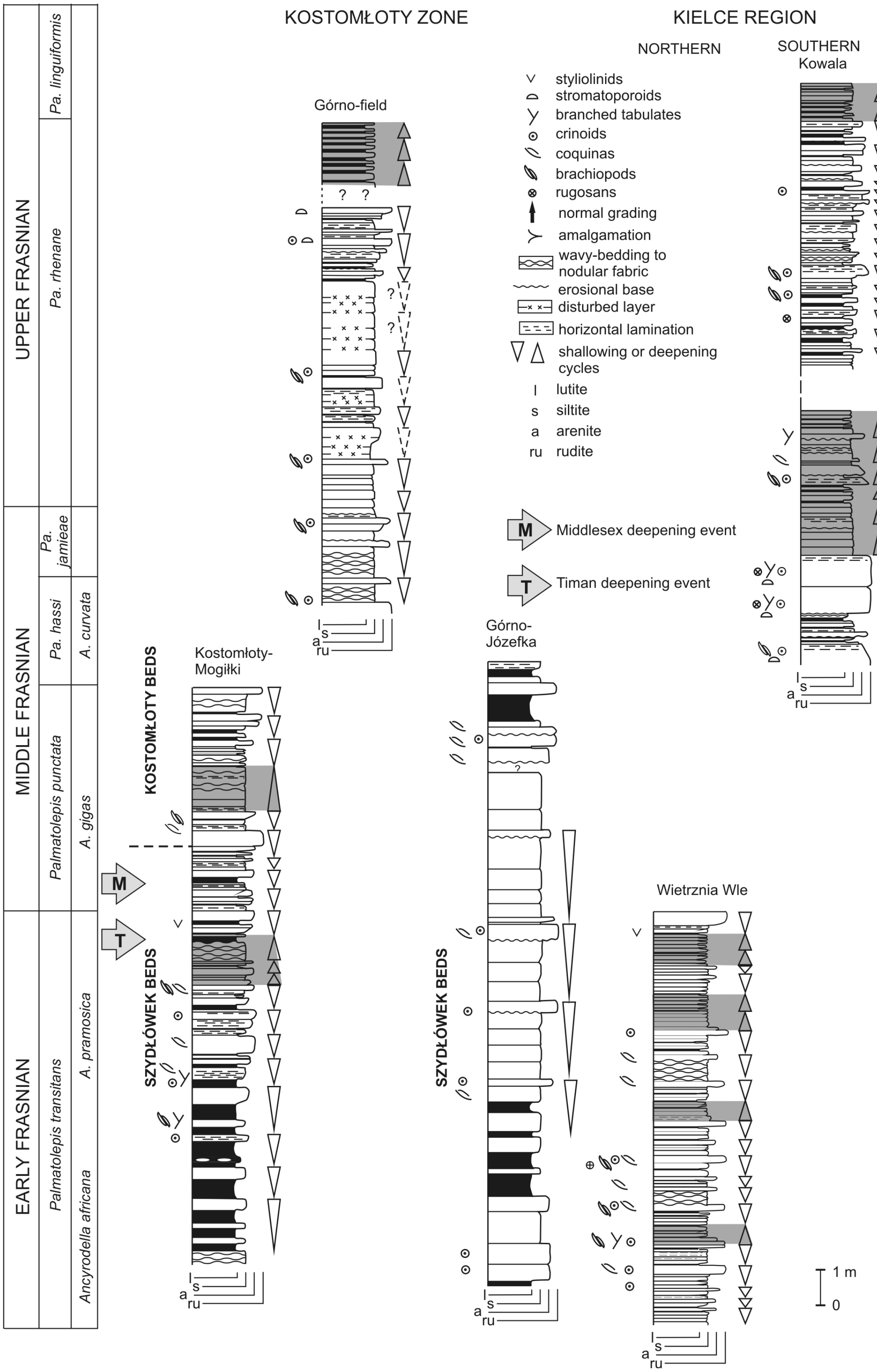

Fig. 7. Lithology of depositional cycles in the Frasnian sections studied. Conodont biostratigraphy based in part on Sartenaer *et al*. (1998) and Pisarzowska *et al*. (2006), and Timan and Middlesex deepening pulses based on Pisarzowska *et al*. (2006, fig. 18 therein)

ing: breccia (L5a; Fig. 5A, B, D), flat-pebble conglomerate (FPC; L5b; Fig. 5C, D) and coquina beds (L5c; Fig. 6). Detailed descriptions and depositional environments of these are presented in Table 1.

5.2. Types of depositional cycles

Sedimentary structures, compositional data and size, sorting, roundness and sphericity of grains indicate changes in energy levels (EI) during deposition. On this basis, Plumley *et al*. (1962) distinguished five major limestone categories I to V, representing a gradational spectrum from quiet-water to strongly agitated-water deposits (= Energy Index Classification, see Flügel, 2004, p. 591). Type I represents minimum water energy and lack of recognisable transported particles. Type V indicates deposition in strongly agitated water and are characterised by calcirudites with both rounded and angular bioclasts and rock fragments (intraclasts). Generally, an increase in the intensity of wave action and currents leads to changes from unsorted to sorted sediments as well as increase in rounding of clasts. But, both sorting and rounding of grains will decrease when extreme water energy (e.g., storms) affects the sediments (Flügel, 2004, p. 589). The Clasticity Index (= CI) is interpreted similarly (e.g., limestone turbidite study by Eder *et al*., 1983).

The upper-slope to basinal lithofacies are arranged into small-scale, mostly shallowing-upward depositional *cycles* (Fig. 7). The cycles are typified by an upward increase in grain size, bed thickness (i.e., coarsening/thickening-upward) and some high-energy structures. In addition, the cycles are locally composed by fining/thinning upward beds (= deepening-upward cycles). Shallowing- or deepening-upward patterns are indicated by significant lithofacies change.

The composite Wietrznia WIe section (Figs. 7 and 8) comprises rhythmically stratified, thin-bedded (2–11 cm thick, average 5.7 cm) micritic limestones (L3) and marly shales (L1; 1–5 cm thick), which in places are wavy- to nodular-bedded (L2) and rarely horizontally laminated. Thin or medium (6–28 cm, average 14.3 cm thick) layers of fine- to coarse-grained limestones (L4, L5a, L5c; Figs. 4C, 6B and 8B, C) occur sporadically. In section 23 *cycles* were distinguished:

1. Seventeen shallowing-upward cycles: typically, four to nine beds are bundled into a *cycle* (17–47 cm thick) exhibiting upward-coarsening/thickening bed patterns (Fig. 8A). In general, a complete cycle has basal marly shales/micritic limestones (L1/L3) overlain by grained limestones. In the lower and middle part of the section the amount of grained layers increases upwards, whereas in the uppermost part of the section grained layers are infrequent.
2. Six deepening-upward cycles: five to nine beds are bundled into a *cycle* (25–38 cm thick) exhibiting upward-fining/thinning bed patterns.

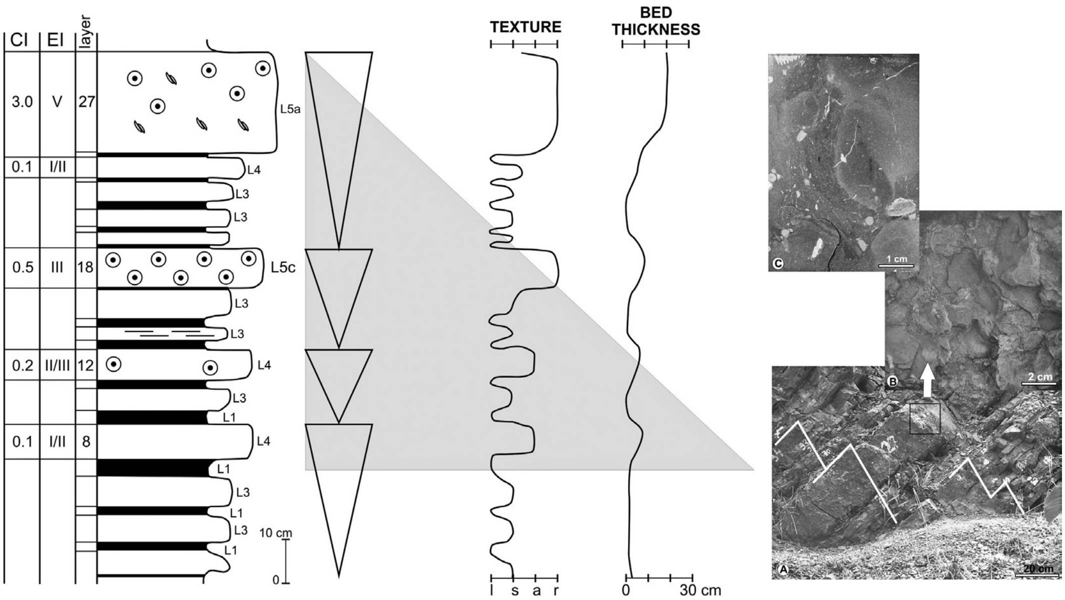

Fig. 8. Four superimposed coarsening/thickening-upward cycles in the lower part of Wietrznia WIe section
A – Outcrop view showing bed-bundling cycles; **B** – Coarse-grained limestones with grain-supported fabric, and **C** – thin section of layer 27, to show large subrounded micritic intraclast and skeletal matrix with rare crinoid and brachiopod debris. L1 to L5 – lithofacies (see text). Abbreviation: EI – energy level; CI – clasticity index (cm); for other explanations see Fig. 7

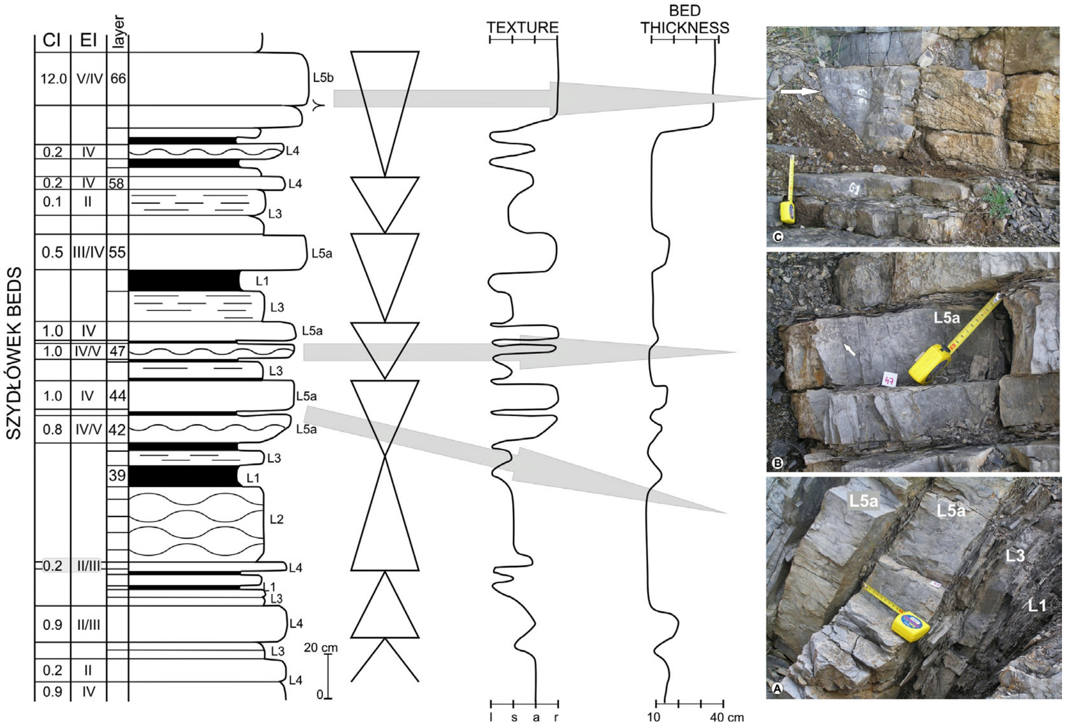

Fig. 9. Shallowing-upward cycles followed by a deepening-upward cycle; Kostomłoty-Mogiłki section
A – Outcrop view of upper part of the Szydłówek Beds with marly shale/micritic limestones (L1/L3) and coarse-grained lithofacies (L5a); **B** – Limestone breccia (L5a) and differential relief of erosive base (arrow); **C** – Top of the Szydłówek Beds and flat-pebble conglomerate (layer 66, arrow) in the basal Kostomłoty Beds. L1 to L5 – lithofacies (see text). Abbreviation: EI – energy level; CI – clasticity index (cm); for other explanations see Fig. 7

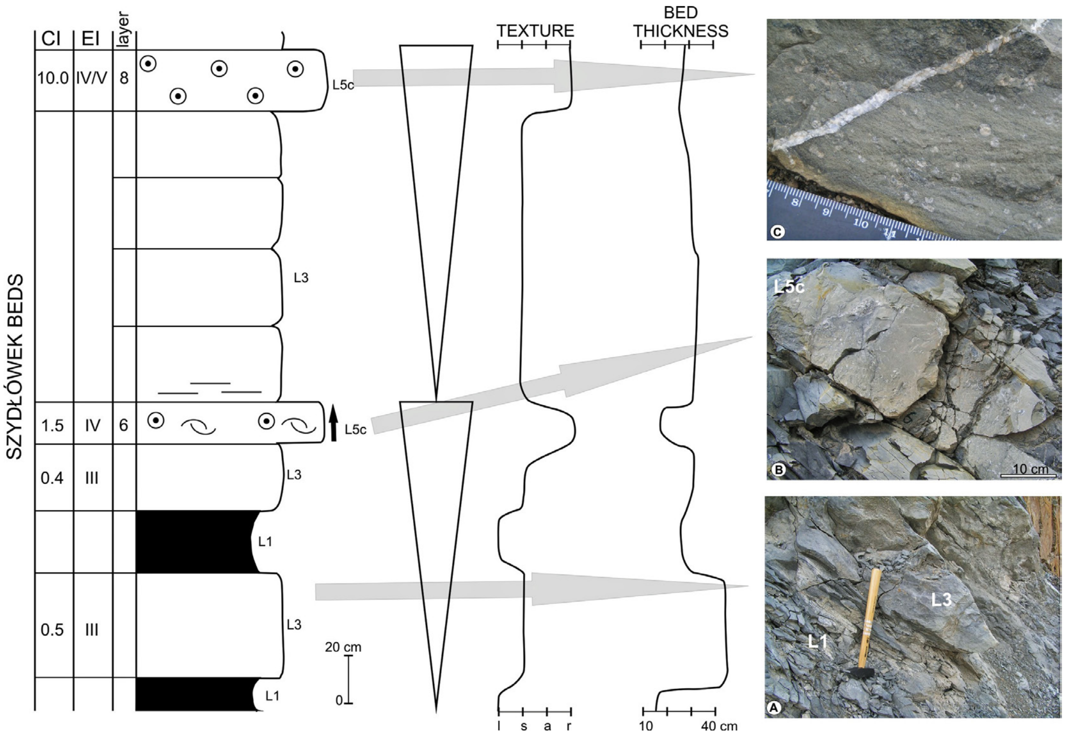

Fig. 10. Two shallowing-upward cycles in the middle part of the Górno-Józefka section
A – Disturbed exposure in July 2007, showing marly shale/micritic limestones lithofacies (L1/L3); **B** – Graded coquina bed (L5c) with crinoid and brachiopod debris. **C –** Crinoidal limestones (L5a) at the top of cycle. L1 to L5 – lithofacies (see text). Abbreviation: EI – energy level; CI – clasticity index (cm); for other explanations see Fig. 7

The Szydłówek Beds at the Kostomłoty-Mogiłki section (Figs. 7 and 9) are characterised by intercalations of dark-coloured marly shales and marly limestones (L1; 2–34 cm thick, average 12.4 cm) with nodule horizons. Numerous laminated micritic limestones (L3; up to 30 cm; Fig. 3A, C) and fine-grained limestone (L4; *c.* 3–17 cm thick; Fig. 4A, D), or locally coarse-grained limestones with erosional bases, represent the uppermost part of the Szydłówek Beds (Fig. 9A, B). The first thicker (*c.* 35 cm thick) coarse-grained conglomerate bed (L5b; FPC; Figs. 5C and 9C) define the base of the Kostomłoty Beds. The lower part of the Kostomłoty Beds comprise fossil–poor, horizontally laminated micritic limestones (L3), rare marly limestones and marly shales (L1), which in places are wavy bedded (L2; Fig. 3D), with a few fine- or coarse-grained layers (L4/L5). In the Kostomłoty-Mogiłki section, 21 *cycles* were distinguished:

1. Seventeen shallowing-upward cycles: typically, three to eight beds are bundled into a *cycle* (28–108 cm thick) exhibiting upward-coarsening/thickening bed patterns.
2. Four deepening-upward cycles: three to seven beds are bundled into a *cycle* (18–86 cm thick) with upward-fining/thinning bed patterns.

The lithologies and thicknesses of the Szydłówek Beds in the Górno-Józefka quarry (Figs. 7 and 10) are different from those in the Kostomłoty-Mogiłki quarry, as described above. These are usually medium- and thick-bedded (15–70 cm thick, average 35.3 cm) dark-grey, fossil-poor marly shales and micritic limestones (L1/L3). A few intercalated thin- to thick-bedded (10–38 cm, average 23.5 cm thick) fine-grained layers (L4) and coquinas (L5c; Figs. 6A and 10B, C) contain abundant detritus of brachiopods and crinoids. At the quarry, detailed observations are difficult to carry out because of intensive exploitation, thus vertical cycle-stacking patterns are generally not very clear due to outcrop quality (Fig. 10A). Nevertheless, 4 *cycles* were recognised in the middle part of the succession. The average cycle thickness is greater than in other examined sections: four to seven beds are bundled into a *cycle* (120–180 cm thick). In general, a complete cycle has basal marly shale/micritic limestones (L1/L3) overlain by coquina or graded fine-grained beds (L5c or L4)

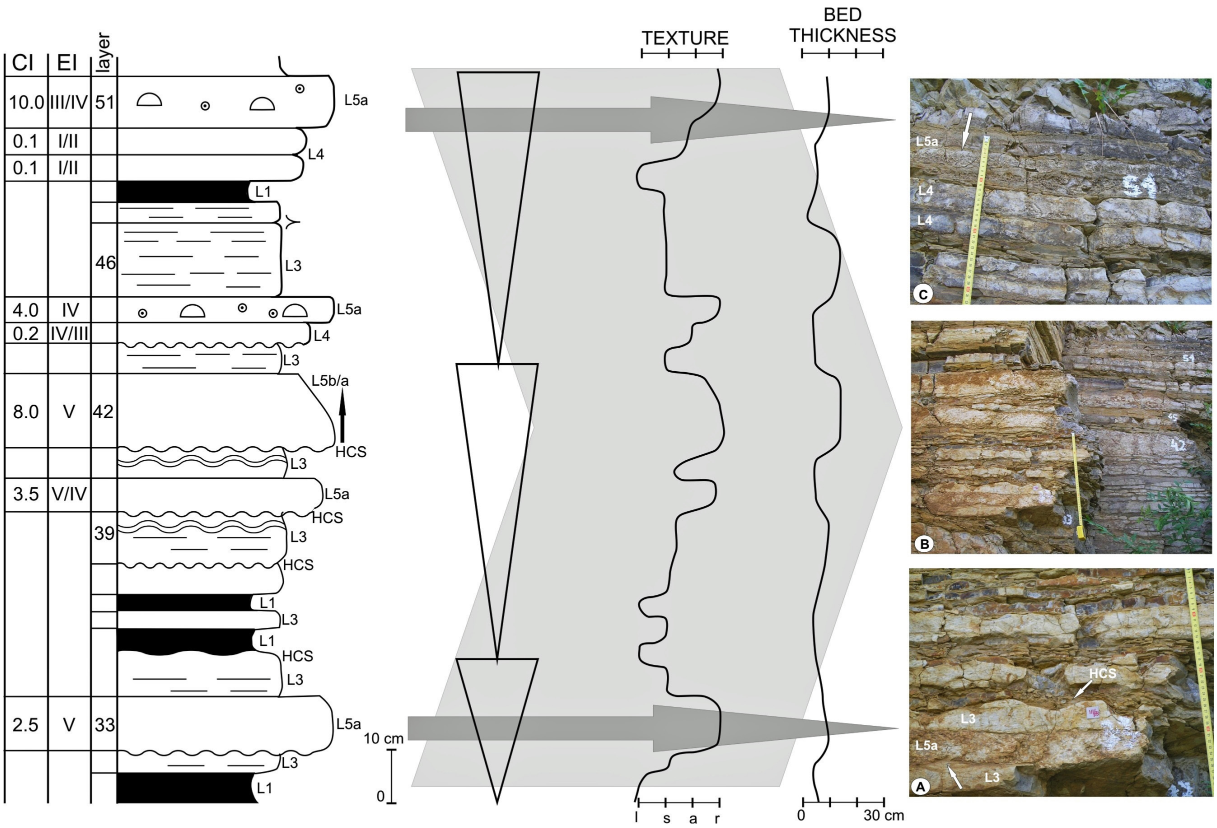

Fig. 11. Three shallowing-upward cycles in the upper part of the Górno-field section
A – Tempestite bed (lower part of photograph) with erosional base (arrow), gradation and HCS at top; layer 33; **B** – Outcrop view in July 2008; **C** – Uppermost shallowing-upward cycle: fine-grained limestone (L4) and limestone breccia (L5a) with stromatoporoids (arrow) at top. L1 to L5 – lithofacies (see text). Abbreviation: EI – energy level; CI – clasticity index (cm); for other explanations see Fig. 7

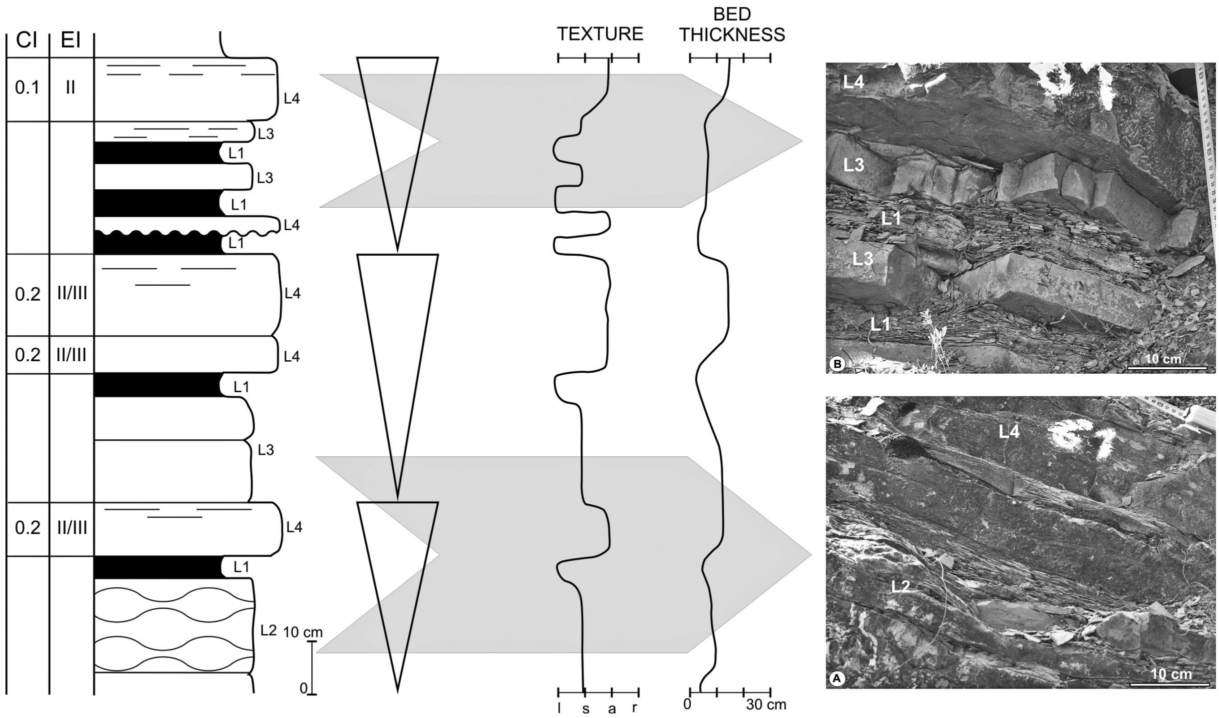

Fig. 12. Shallowing-upward cycles in the Kowala section
A – Wavy-bedded to nodular lithofacies (L2) in the lower part and fine-grained limestones (L4) at top of cycle; **B** – Outcrop photograph showing decimetre-scale, coarsening/thickening-upward cycles composed of marly shale/micritic limestones (L1/L3) and fine-grained lithofacies (L4) at top. L1 to L5 – lithofacies (see text). Abbreviation: EI – energy level; CI – clasticity index (cm); for other explanations see Fig. 7

with occasional erosional surfaces (see also Vierek, 2008).

The deposits of the Górno-field outcrop (Figs. 7 and 11B) are characterised by alternating thin-bedded (8–16 cm) micritic limestones (L3; or rare marly shales L1; Fig. 3B), which in places are wavy-bedded (L2; see lower part section) and/or disturbed by synsedimentary tectonics (i.e. thick, ca. 1.5–2.0 m, homogeneous micritic beds originated from a ?fluidised sediment flow), and many thin- to medium-bedded (4–37 cm; average 12.6 cm thick) fine- to coarse-grained limestones (L4 to L5a; Fig. 5A, B, D). These limestones are characterised by horizontal, wavy and hummocky-like laminations (Figs. 4B, 5A, B and 11). In comparison with other sections laminated limestones can be found most frequently. Abundant intercalations of thin (*c*. 6 cm thick) marly shales (L1) appear in the upper, thin-bedded interval. In the Górno-field section, 17 *cycles* were distinguished:

1. Fourteen shallowing-upward cycles: three to nine beds are bundled into a *cycle* (40–75 cm thick) exhibiting upward-coarsening/thickening bed patterns.
2. Three deepening-upward cycles in the uppermost part of the section, *c*. 1.6 m thick: five to eight beds are bundled into a *cycle* (30–50 cm thick), exhibiting distinctly upward-fining/thinning bed patterns. This part of the section is marked by a lack of grained beds.

In the lower part of the Kowala section (Fig. 7), the deposits are characterised by alternating, thin- to medium-bedded micritic limestones (L3; 2–21 cm thick, average 8 cm) and marly shales (L1; *c*. 2.7 cm) with a few grained limestones (L5a; up to 60 cm thick). The composite upper part of the section (Figs. 7 and 12) comprises rhythmically stratified, thin-bedded micritic limestones (L3) and marly shales (L1, *c*. 6 cm) pairs and numerous intercalations of fine- or more rarely, coarse-grained limestones (L4, L5a; 10 cm thick on average). Locally, the limestones are wavy-bedded and horizontally laminated (Fig. 12A, B). The wavy- or hummocky-like laminations, as in the Górno-field section, are absent. In the Kowala section, 24 *cycles* were distinguished:

1. Sixteen shallowing-upward cycles: typically, three to eight beds are bundled into a *cycle* (26–50 cm thick) exhibiting upward-coarsening/thickening bed patterns and rare horizontal laminae.
2. Eight deepening-upward cycles: four to ten beds are bundled into a *cycle* (30–50 cm thick) exhibiting upward-fining/thinning bedding.

The amount, thickness and clast diameters of grained limestones decrease upwards. In the uppermost part of the section, shallowing-upward units are capped by upward-deepening cycles.

6. Discussion

6.1. Sedimentary processes

The Frasnian carbonate platform from the HCM is a reef-rimmed isolated platform akin to the rimmed platform base-of-slope aprons (*sensu* Mullins & Cook, 1986 and Coniglio & Dix, 1992; see Vierek, 2007b). Base-of-slope carbonate aprons develop along relatively steep (>4^0) platform margins and occasionally exhibit thickening-upward cycles. The topography of the isolated platforms (e.g., modern-day northern Bahamas) is variable and shows significant changes in geometry and facies as oceanographic conditions vary around the margins (see Chen *et al*., 2001). The Frasnian platform from the HCM commonly exhibited an asymmetrical profile indicated by significant lithofacies change as well as various types of redeposited carbonates, and a tendency to increase the slope angle in the upper Frasnian (Szulczewski, 1971, 1995; Racki, 1993; Vierek, 2007b, 2010).

In the Frasnian strata of the HCM, depositional facies are recognised from the upper slope to basinal environments that include coarse-grained gravity-flow carbonate breccias (L5a), FPC (L5b) and coquina beds (L5c), as well as other fine-grained (L4), micritic (L3) and nodular to wavy-bedded (L2) limestones and marly shales (L1; see also Vierek, 2007a, b, 2008, 2010, 2013). The lithology of these beds and their proportion in the particular sections examined are varied and depend of the depositional bathymetry and of different positions across the platform. Also, the differences between the different sections reflect the variability of depositional conditions in time as well as an asymmetrical profile of the Frasnian platform. In all of the sections measured, depositional facies are characterised by dark-coloured or grey micritic limestone–marly shale (L3–L1) alternations with many light-coloured intercalations of fine- to coarse-grained limestones (calcarenite to calcirudite: L4–L5; = event beds). This implies that the major type of background facies were deposited in a low-energy regime punctuated by high-frequency subordinate storm events (Vierek, 2007b, 2013) and/or tectonic activity (Vierek, 2010).

As interpreted by Vierek (2007b, 2010), frequent storm events and storm-generated flows were the main cause of erosion and redeposition of differentiated fine- and coarse-grained lithofacies. For example, the storm-controlled proximal reef-slope is laterally traced in the Wietrznia Beds set *C* (Wietrznia quarry; see Vierek 2007b, figs. 3 and 10 therein) in gradual changes from coarse-grained tempestites, marked by amalgamation and cannibalism paired with FPC fabric, by fine-grained graded limestones with hummocky cross-stratification, to diluted muddy tempestites characterised by finer graded, locally laminated micritic limestones (see Fig. 7, Wietrznia WIe section). The particular sedimentological analysis of tempestite successions in the Wietrznia quarry shows at least 21 different-scale storm events (see the review in Vierek & Racki, 2011, p. 6). The storm events were also noted in the fine-grained lithofacies as well as FPC described by Vierek (2010) in the uppermost part of the Szydłówek Beds and lower part of the Kostomłoty Beds at the Kostomłoty-Mogiłki quarry. Diagnostic features of tempestites and microfacies data were described in the Górno-field outcrop; the sedimentological analysis of the successions shows at least 12 storm events (see review in Vierek, 2013, p. 267).

Moreover, relatively steep slopes, such as on the isolated platform, favour offshore transport. The instability of the steep slope induced sudden remobilisation, intensive erosion as well as the development of gravity flows and offshore transport, often to depths of over 50 metres, which is too deep to be reworked and transported by storm waves (Nott, 2006, p. 86). Hüneke & Krienke (2004) described a Givetian reef-rimmed platform (Morocco) and calcareous debris as redeposits mostly transported by surge-like concentrated density flows and turbidity flows. The intense storm wave may disturb stability of even relatively more gentle slope, and then after storm events on the slope and/or on the basinal floor adjacent to the slope, gravity-flow deposits are formed as coarse-grained carbonate breccias. Bábek *et al*. (2007) interpreted coarse-grained, normally graded and poorly sorted event beds (Frasnian carbonate platform, Morawo-Silesian Basin) as storm sedimentation above the SWB or gravity-flow sedimentation in moderately deep-water, reef-flank settings. Whereas, the intraclast breccias with identical composition of clasts and matrix, according to those authors, indicates short, gravity-driven transport on depositional slopes in the depth below the SWB. Likewise, Vierek (2007a, b: Wietrznia Beds – western, proximal succession therein, and Vierek, 2010: higher part of Kostomłoty Beds in the Kostomłoty-Mogiłki quarry) suggested that part of the coarse-grained limestones with clast-supported fabric, biodetrital matrix and irregular chaotic orientation of intraclasts as gravity flows initiated by storm and/or tectonic activity. However, it should be noted that the deep-water sections examined consist predominantly of micritic and fine-grained lithofacies (from L1 to L4), and coarse-grained limestones (L5a) are relatively rare. Comparing features of lithofacies in the sections analysed to the ones mentioned above, it can be stated that the limestones of the Górno-field sections were deposited in shallower water because fine-grained graded limestones with hummocky-like tops (L4) are present. HCS and graded units are features of proximal tempestites that commonly form between fair-weather and storm wave base (e.g., Aigner, 1985). A deeper-water environment of the Wietrznia WIe and Kowala limestones is proposed because only diluted muddy sediments (= distal tempestites) characterised by finer grains and horizontal lamination are present. The Szydłówek Beds (in the Kostomłoty-Mogiłki section) with pelagic biota represent an environment of relatively deep, quiet and poorly oxygenated water in the aphotic zone. As described by Racki *et al.* (2004), the Kostomłoty Basin was susceptible to transient oxygenation episodes from the early to middle Frasnian. This is revealed by rare bioturbations and benthic biota in the fine-grained limestones (see Vierek, 2010). The disappearance of marly shales and gradual introduction of laminated micritic limestones paired with fine- and coarser-grained limestones in the lower part of the Kostomłoty Beds recorded shallowing-upward evolution from deep environments, below the SWB, to environments influenced by current activity close to the SWB. Instead, the coquina limestones (L5c; Szydłówek Beds in the Górno-Józefka section) may be an example of deposition which was occasionally affected by bioclastic-debris supplied from adjacent areas nutrient- and oxygen-enriched with a bloom of benthic biota (Vierek, 2008). These data suggest shallower water and a tendency to increased bottom oxygenation, e.g. during sea-level drop.

6.2. Autocyclicity

The basic problem with respect to the origin of cyclicity is whether it was formed by auto- or allocyclic depositional processes. In the present study, deep-water depositional cycles point to an autocyclic model of sedimentation in which the control is within the basin. The autocyclic processes include vertical accretion, variations in sediment production and redistribution as controlled by the source area (Jones & Desrochers, 1992). The nature of the cycles may be influenced by energy regimes. Prominent examples are storm-generated tempestites and/or turbidite beds caused by gravity-flows (Einsele, 1992, p. 272). In the present study, most of the cyclicity is developed in the event-dominated depositional realm, so every single coarse-grained bed is primarily a storm event. However, autocyclic processes may be disturbed by tectonics which initiate the influx or redeposition of coarse-grained sediments. As discussed by Racki & Narkiewicz (2000), synsedimentary tectonics probably caused large-scale resedimentation phenomena and coarse-detrital deposition during the basal middle Frasnian sea-level rise. Additionally, the autocyclic gravity-flows may be commonly controlled by allocyclic eustatic sea-level changes.

In the present study, vertical accretion of sediments is limited by storm reworking and erosion of the sea floor above the SWB. On the other hand, episodic gravity-flows from the platform margin locally supplied a quantity of coarse-grained sediments. These processes together may disturb vertical accretion and determine the nature of the cycles. Consequently, to differentiate local storm-deposited layers from cycles which were driven by changes of sea level is very difficult.

One of the arguments favouring an autocyclic nature is the thickness of cycles and limited stratigraphic continuity of beds. Typical autocyclic sequences are characterised by thinner, *c.* 1.5 m, cycles (e.g., Skompski & Szulczewski, 1994). But at first, the autocyclic model of Ginsburg (1971) envisaged deposition taking place on a gently inclined shelf. The Ginsburg model assumes approximately static sea level and constant subsidence to create sediment accommodation space. A similar model was proposed by Wong & Oldershaw (1980 – Middle Devonian cyclicity in Canada) and developed by Préat & Mamet (1989 – Devonian carbonate platform in Belgium). In this autogenic model, the environment was subtidal, carbonate sedimentation outpacing subsidence and subtidal areas gradually being replaced by intertidal to supratidal marshes. The deeper water, from the upper slope to basinal environments of the sections studied on the isolated platform margins, as well as local, block-related subsidence and synsedimentary tectonic pulses (see section 6.5) complicate the processes described above.

6.3. Cycle-stacking patterns

The small-scale (= parasequence) carbonate cyclicity, according to Van Wagoner *et al.* (1988) and

Church & Coe (2005, p. 99), is recognised in the sections examined. In general, three to nine beds are bundled into a cycle. The thicknesses of the cycles are highly variable, ranging from 17 to 50 cm, locally up to *c*. 75 cm, in the sections studied. Compared with the deep-water cyclostratigraphy as described by Chen & Tucker (2003), only the Górno-Józefka section shows a different scenario: the beds and cycles are thick, locally up to 170 cm, less numerous and less regular. On the one hand, the smaller number of obvious cycle boundaries and lack of cycles in uppermost part of Górno-Józefka section may have been caused by poorer exposure quality because of active exploitation. On the other hand, significantly thicker beds and cycles may reflect the variability of depositional conditions in space and time. In the carbonates studied, first of all, their deeper-water depositional setting should be taken into consideration. Accommodation space of this environment of deposition probably played little or no role in controlling the character of the cycles. Changes in accommodation space on the platform top might influence the cycles by determining when sediments are exported off the platform top. On the other hand, as described by Coe & Church (2005, p. 61), the small-scale units result from a small-amplitude, short-term oscillation in the balance between sediment supply and accommodation space. It seems that this controlling factor is important because the facies studied were laid down, at most, a few kilometres away from their shallow-water, reef source area. The varying rate of increase of accommodation space is thus lower than the rate of sediment supply, although this depends of the bathymetric position of the different localities.

Elrick (1995) suggested that cycles could also be formed through glacio-eustatic sea-level changes. For carbonates, climate is even more significant for sediment supply. Therefore, the thickness of cycles may be reflected by a change of temperature. The sea level rises about 1–2 m for each 1°C of change in temperature (Church & Coe, 2005, p. 102), therefore, amplitude of greenhouse eustatic cycles is lower than that of icehouse conditions. The Late Devonian (Frasnian and Frasnian-Famennian transition; 383–375 Ma) was characterised by warm tropical temperatures of around 30°C (Joachimski *et al*., 2009) and the magnitudes of climatically induced sea-level fluctuations were small, resulting in the development of thin, *c*. 5 m, cycles that generally lack any evidence of extensive subaerial exposure and meteoric diagenesis (e.g., Hardie & Shinn, 1986; Elrick, 1995). According to Préat & Racki (1993), in the Middle Devonian of the HCM, the amplitude of climatically induced sea-level oscillations was very low (about 2 m), but may also have contributed to the sedimentary record. On the other hand, Pisarzowska (2009) provided geochemical data showing that temperature, starting from the early-middle Frasnian of the HCM decreased from 28°C to 23°C. Therefore, the beds and cycles deposited in the early Frasnian should be thinner compared to the middle Frasnian cycles. The Kostomłoty-Mogiłki and Górno-Józefka sections (see Fig. 7) show a completely inversed trend; thus, this cooling trend is not recorded in the cycles examined. It seems that a slight difference of temperature within greenhouse conditions and small-scale fluctuations of sea level can produce changes on shallow-carbonate production and as a consequence on resedimentation to deeper areas, but the lithofacies studied were deposited at depths where small-scale sea level fluctuations have little effect. To sum up, from sea-level cycle amplitude to thickness of cycles is a long way, especially in the subtidal environment.

6.4. Duration of beds and cycles

The time required to deposit a single bed and cycle is difficult to determine. A variety of assumptions is inherent in estimates of cycle duration: (1) a known Devonian time scale, (2) a well-constrained chronometric dating and conodont zonation for the Frasnian Stage, (3) a mean cycle thickness, (4) rate of subsidences, and (5) sediment compaction. The duration of cycles was checked for the Wietrznia section and was calculated on the basis of cycle number recognised in set C, and for the Kostomłoty-Mogiłki section on the basis of cycle number recognised in the Szydłówek and Kostomłoty Beds (see Fig. 7). At the Wietrznia quarry, during the approximately 400 – 450–kyr long *transitans* Zone (according to Kaufmann, 2006, fig. 9 therein and new data from De Vleeschouwer *et al*., 2012) 23 cycles are observed. At the Kostomłoty-Mogiłki quarry, during the approximately 900–kyr–long *transitans* and *punctata* zones, 21 cycles are observed. Using these data, the small-scale cycles have a calculated duration of 19 to 42 kyr. The ~42 kyr value is a maximum, because some cycles in the Szydłówek Beds have a greater thickness than others, due to amalgamation processes. The calculated values are the same (Scaturo *et al*., 1989: 20–40 kyr), or little lower (e.g., McLean & Mountjoy, 1994; Elrick, 1995) than other calculated values for Devonian small-scale cycles. According to Chen *et al*. (2001), cycles in the Frasnian ranged between 50–110 kyr, but average values for the Givetian and Frasnian stages range between 30–72 kyr. The cycle durations would be shorter if deep-subtidal missed beats (see Goldhammer *et al*., 1993) are taken into account.

The calculated sedimentation rates of the deposits studied are in the range of 0.02-0.06 m/kyr. This is consistent with the average depositional rates commonly used for modelling carbonate platform stratigraphy (see Bosence & Wilson, 2005, p. 251, table 12.1 therein), which take into consideration compaction and erosion of sediments.

6.5. Syndepositional tectonics and deepening pulses

The small-scale, shallowing-upward cycles examined are non-rhythmic. Such cycles may form if the mechanism producing the accommodation space is differentiated by non-uniform subsidence (e.g., Goldhammer *et al*., 1990). According to Hofmann & Keller (2006), thick sediment packages are controlled by rapid subsidence in areas close to the shore, while lesser sediment thickness could have been caused by slower subsidence in the open-marine sections. On the other hand, Szulczewski (1971) showed uniform subsidence causing an incessant sedimentation of rhythmically bedded marly limestones and shales. The rate of subsidence in the Upper Devonian of the HCM was inconsiderable (*c.* 25 m/myr) but speeded up in the Frasnian (Racki & Narkiewicz, 2000). Additionally, the tectonic subsidence analysis confirms differences in the development of the Łysogóry and Kielce regions and reflects locally block-related subsidence (Szulczewski, 1971; Racki & Narkiewicz, 2000). Préat & Racki (1993) and Skompski & Szulczewski (2000) implied that sedimentation in the Givetian and Frasnian of the HCM was primarily controlled by local subsidence. It may seem that this factor surely had an impact on the varied and irregular thickness of the beds and cycles in the sections examined.

The accommodation space changes are most probably related to the tectonic activity at that time (e.g., Elrick, 1995; Keller, 1997; Chen *et al*., 2001; Hofmann & Keller, 2006). Multiple episodes of fault-induced subsidence have been invoked to explain the development of the decimetre-scale carbonates cycles. The possible evidence of tectonic activity is reflected by the different number of cycles recorded in the time-equivalent sections (i.e., in the *Pa. transitans* Zone there are 12 in Kostomłoty-Mogiłki and 23 in Wietrznia WIe). The next argument for a local tectonic event generating the Frasnian cycles is that abrupt deepening would be expected from a fault-induced movement. If rates of fault movement outstrip rates of carbonate production, then deeper-water? subbasins form (compare the fault-block platform of Bosence & Wilson, 2005, p. 244). In the sections studied, a few deepening episodes were observed. The Frasnian deepening pulses occurred irregularly in the development of the Łysogóry and Kielce regions (see Fig. 7). The cyclostratigraphic data show that in the Kielce region (Wietrznia section) in the early Frasnian there were two short deepening episodes (early and middle *Pa. transitans* Zone), each of which lasted between 12–18 kyr. These cycles indicate that the upper *Pa. transitans* Zone was marked by significant, repeated sea-level fluctuations visible in the Kielce (Wietrznia WIe sections) and Łysogóry (Kostomłoty-Mogiłki section) regions. In the Kielce region deepening pulses were longer, in the range of 62–93 kyr, and punctuated by shallowing-upward cycles. In the Kostomłoty area the deepening pulse was shorter (*c.* 30 kyr). The major drowning trend corresponds to the Timan global hypoxic-transgressive events (see Pisarzowska *et al*., 2006). The next short, 16–24 kyr, sea-level rise was signalled at the base of the Kostomłoty Beds (see Fig. 7) in the middle of the *Pa. punctata* Zone. Earlier, the early–middle Frasnian passage interval was marked by the Middlesex global transgressive event (IIc according to Johnson *et al*., 1985; see Racki, 1993; Pisarzowska *et al*., 2006, fig. 18 therein), but not recorded as distinct in the sections studied. Probably local tectonic activity was responsible for masking the eustatic pulse (see Racki & Narkiewicz, 2000).

In the southern Kielce region (Kowala section), the ?*Pa. hassi-jamieae* interval was recorded as the long transgressive episode (range 78–117 kyr). The last deepening episodes in the sections studied are connected with the late Frasnian (?*rhenana* zone) and were marked in the Kostomłoty area (Górnofield section; duration *c.* 36–54 kyr).

The correlation of major sea-level fluctuations in the successions studied with global Timan transgressive events perhaps confirms eustatic trends. However, local tectonics and episodic subsidence played a significant role in the record of the cycles studied. On the other hand, the deepening pulses provide evidence of synsedimentary tectonics in the Frasnian of the HCM. As stressed by Skompski & Szulczewski (2000), the most probable explanation of the Frasnian deepening-upward cyclicity (southern part of the HCM) is linked to tectonic control of the carbonate platform margin by a rapidly subsiding basin.

In conclusion, episodic subsidence and local synsedimentary tectonic contributed to the origin and variation in the small-scale cycles within and between the sections. However, low-amplitude sea-level changes are also factors in platform cycle generation and in its evolution in the Frasnian of the HCM. These are consistent with the general hypothesis of an essential effect of eustasy on Devonian sedimentation in Poland (Narkiewicz, 1988; Racki, 1993; Racki & Narkiewicz, 2000) and around the world (Larsen *et al*., 1989; Elrick, 1995; Chen & Tucker, 2003; Hofmann & Keller, 2006) as modified by local tectonics.

7. Conclusions

1. Five depositional lithofacies (L1 to L5), from upper slope to basinal environments, include coarse-grained limestones (calcirudites: breccia L5a, FPC L5b and coquina beds L5c), fine-grained (calcarenites: L4) and micritic (calcisiltites: L3) limestones as well as nodular to wavy-bedded limestones (L2) and marly shales (L1), are recognised from five measured sections located on the isolated platform slope in Frasnian of the HCM. The lithofacies represent mostly low-energy sedimentary regimes punctuated by storm events;
2. These deposits are arranged into small-scale, mostly coarsening-upward *beds* and *cycles* (= shallowing-upward cycles). Locally, the cycles are composed by fining/thinning-upward beds (= deepening-upward cycles). Shallowing- or deepening-upward patterns are indicated by significant lithofacies changes. The small-scale cycles have a calculated duration of 19 to 42 kyr.
3. The thickness of the cycles is highly variable, ranging from 17 to 50 cm, locally up to *c*. 75 cm. The differential thickness of beds and cycles within and between sections are caused by mostly episodic subsidence and local tectonics. Possible evidence of tectonic activity is also the different number of cycles recorded in the time-equivalent sections;
4. The cyclicity shows sea-level fluctuations and a few deepening episodes. Some of them are correlated with the Timan global eustatic events. However, local tectonics and episodic subsidence may have played a significant role in recording brief deepening pulses.

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