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Storm-dominated deposition on a Frasnian carbonate platform margin (Wietrznia, Holy Cross Mts., Poland)

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The Wietrznia quarry in Kielce is situated between the shallow-water Devonian carbonate platform in the Kielce region and the deeper Łysogóry basin. This palaeogeographic setting affected carbonate sedimentation in Late Devonian times. The transitional facies of the Wietrznia Frasnian comprises two overlapping types of deposits: (1) micritic and marly limestone of shelf basin facies and (2) coarse-grained limestone of fore-reef facies. The first type includes laminated- and graded micritic limestone and nodular limestone. The second includes intraformational conglomerates and breccias, and crinoidal limestone. The limestones in the middle Wietrznia Beds formed within storm wave base in a shallow (possibly only a few tens of metres) sea that deepened eastwards. Storms are likely to have been the main cause of erosion and transport. In the western part of the quarry, proximal tempestites show evidence of amalgamation and cannibalism as do some high-energy flat-pebble conglomerates. With abating storm winds, finer-grained graded and laminated limestones accumulated. Toward the eastern part of the quarry, the high-energy effects of near-shore storm waves are less evident; the deposits there are transitional or more distal tempestites.

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INTRODUCTION

Storm beds (=tempestites) are most common on shelves, ramps and platform margins in windward settings. The sediment-laden storm surges transport sediment from onshore to deeper offshore outer ramp settings via unidirectional return flows (Flügel, 2004, p. 594).

Three types of carbonate systems are recognized:

— carbonate ramps,

— attached platforms,

— isolated carbonate platforms (Seilacher and Aigner, 1991).

In each of these types storm processes have different effects. On carbonate ramps (e.g. the modern Arabian Gulf), storm deposits show distinct proximality-distality trends (see: Wilson, 1975; Wright, 1986; Seilacher and Aigner, 1991; Lee and Kim, 1992; Flügel, 2004, p. 594). Storm deposits of attached platforms (the modern environment of South Florida) display strong variations in internal composition because storm beds tend to be different from place to place (Seilacher and Aigner, 1991). On isolated carbonate platforms, storm processes are particularly important in controlling the depositional facies along platform margins. Storms can quickly and radically alter sediment distribution on any part of the platform that is above storm wave base (Jones and Desrochers, 1992). On isolated platforms there are distinct differences between windward and leeward platform margins, as established in the modern Bahama Banks (Hine *et al*., 1981 in Seilacher and Aigner, 1991) or in the Middle Triassic Latemar Massif (Egenhoff *et al*., 1999). According to Szulczewski (1995) the Frasnian carbonate platform in the Holy Cross Mts. is a reef- and shoal rimmed isolated carbonate platform. On such an isolated carbonate platform the effects of storms are concentrated at the platform margins.

The carbonates described herein of the Wietrznia Beds were episodically deposited on the northern flank of the Late Devonian carbonate platform.

Wietrznia Hill is located in the southeastern part of the town of Kielce in the western part of the Holy Cross Mountains (Fig. 1). The deposits visible at exposure belong to the southern flank of the Kielce Syncline composed of Devonian strata overlying Silurian, Ordovician and Cambrian deposits. Gürich (1896) noted that the Devonian limestones at Wietrznia are dis-

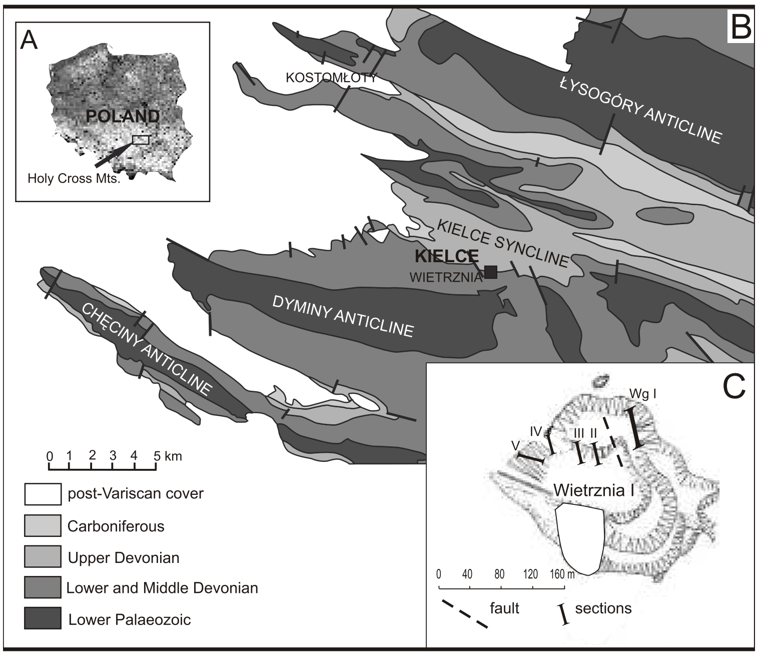

Fig. 1. A — location in Poland of the area examined; B — geological sketch map of the western part of the Holy Cross Mts. (after Szulczewski, 1971) with quadrangle showing quarry location; C — Wietrznia I quarry showing the position of five measured sections

tinctly bedded and rich in fossils. On the basis of these fossils, he considered the limestones to be transitional between the Middle and Upper Devonian ("Uebergangschichten von Wietrznia"). Szulczewski (1971) emphasized their intermediate position between fore-reef and shelf basin facies.

This transitional character is evident in the middle part of the Wietrznia Beds (set C) in the Wietrznia quarry (Wietrznia I — according to Szulczewski, 1971) which shows a considerable degree of lithological diversity and varying proportions of grained carbonate components (Fig. 2). Interbedded dark marly micritic limestones and marly shales dominate. Several pale coloured thick beds of coarse-grained limestone (also called "event beds") are intercalated in the micritic limestone.

Szulczewski (1968, 1971) recognized the grained limestones as sediments reflecting subaqueous mass movements and turbidity currents. In subsequent years, Kaźmierczak and Goldring (1978), Szulczewski *et al.* (1996) and Racki and Narkiewicz (2000) suggested the possible influence of storm events on the sedimentation of Upper Devonian limestones in the Holy Cross Mts. Kaźmierczak and Goldring (1978) had written earlier about the possible occurrence of tsunami. According to Racki and Narkiewicz (2000), high-energy conditions and tectonic-seismic activity accompanied Late Devonian deposition from the Early *rhenana*- to the Late *triangularis* Zone.

Alternative possibilities for the interpretation of the origin of the coarse-grained limestones merit review. The aims of this paper are as following:

— to describe the transitional facies of the middle part of the Wietrznia Beds (set C),

— to describe the lateral changeability of fore-reef to shelf-basin facies,

— to provide evidence for the deposition of limestones caused by storm processes,

— to propose a model for the origin of the storm-generated Wietrznia Beds. In the previous paper the present author provided describes and interprets the transitional facies of the Wietrznia Frasnian as determined by microfacies analysis (see: Vierek, 2007).

REGIONAL PALAEOGEOGRAPHIC SETTING

Epicontinental Devonian deposits in Poland may be ascribed to an extracratonic shelf of variable width ranging from 150 to 600 km across (Narkiewicz, 1985). According to Racki *et al.* (2002) the shelf formed the Polish fragment of a pericratonic basin stretching from western Europe to Ukraine along the periphery of the "Old Red Sandstone Continent" (Laurasia). Two distinct palaeogeographic-tectonic regions of the HCM area were distinguished: the northern Łysogóry region (palaeolow) and southern Kielce region (palaeohigh) (see: Szulczewski, 1977, 1995; Racki, 1993; Racki and Bultynck, 1993; Racki *et al.*, 2002).

The Lower Devonian in the HCM is a distinct terrigenous sequence of continental and shallow-marine deposits (Szulczewski, 1995). At the transition from Early to Middle Devonian times, a marine transgression resulted in decreasing siliciclastic sedimentation and a diversification of marine environmental conditions. The biostromal platform characterizing the Givetian was transformed into a reef construction (Dyminy Reef of Narkiewicz, 1988 or Dyminy Reef Complex of Racki, 1993) as a result of the early and middle Frasnian transgression (IIb/c and IIc — global cycles of Johnson *et al.*, 1985; Racki, 1993). Drowned, poorly oxygenated deeper-shelf areas (=intrashelf basins) surrounded the Frasnian Dyminy Reef: the Chęciny–Zbrza to the south and the Łysogóry–Kostomłoty to the north (Racki, 1993; Szulczewski, 1995).

There are two main types of Frasnian reefs in the Kielce Syncline: mud-mounds and stromatoporoid-coral reefs. The core of the Dyminy Reef in the central Kielce region is composed of stromatoporoid-coral limestone indicating a shallow-water environment. Coarse-grained limestones, typical of the northern (Wietrznia) and southern Kielce regions, represent erosion of the reef flank deposited in a deeper fore-reef facies. The Kadzielnia-type mud-mounds (Szulczewski, 1971) developed in quiet water below storm wave base.

According to Szulczewski (1971), the Dyminy Reef existed up to the early Famennian. Narkiewicz (1988) noted there a stromatoporoid-coral community, that was seriously influenced by a transgressive pulse in the Early *gigas* Zone. At the beginning of the middle Frasnian, the marine IIc transgression (Johnson *et al.*, 1985) transformed the sedimentation into a marly-bituminous type. During the late Frasnian, sea level reached a maximum, termed the Kellwasser anoxic event (Johnson *et al.*, 1985; Racki, 1993). The Dyminy reef

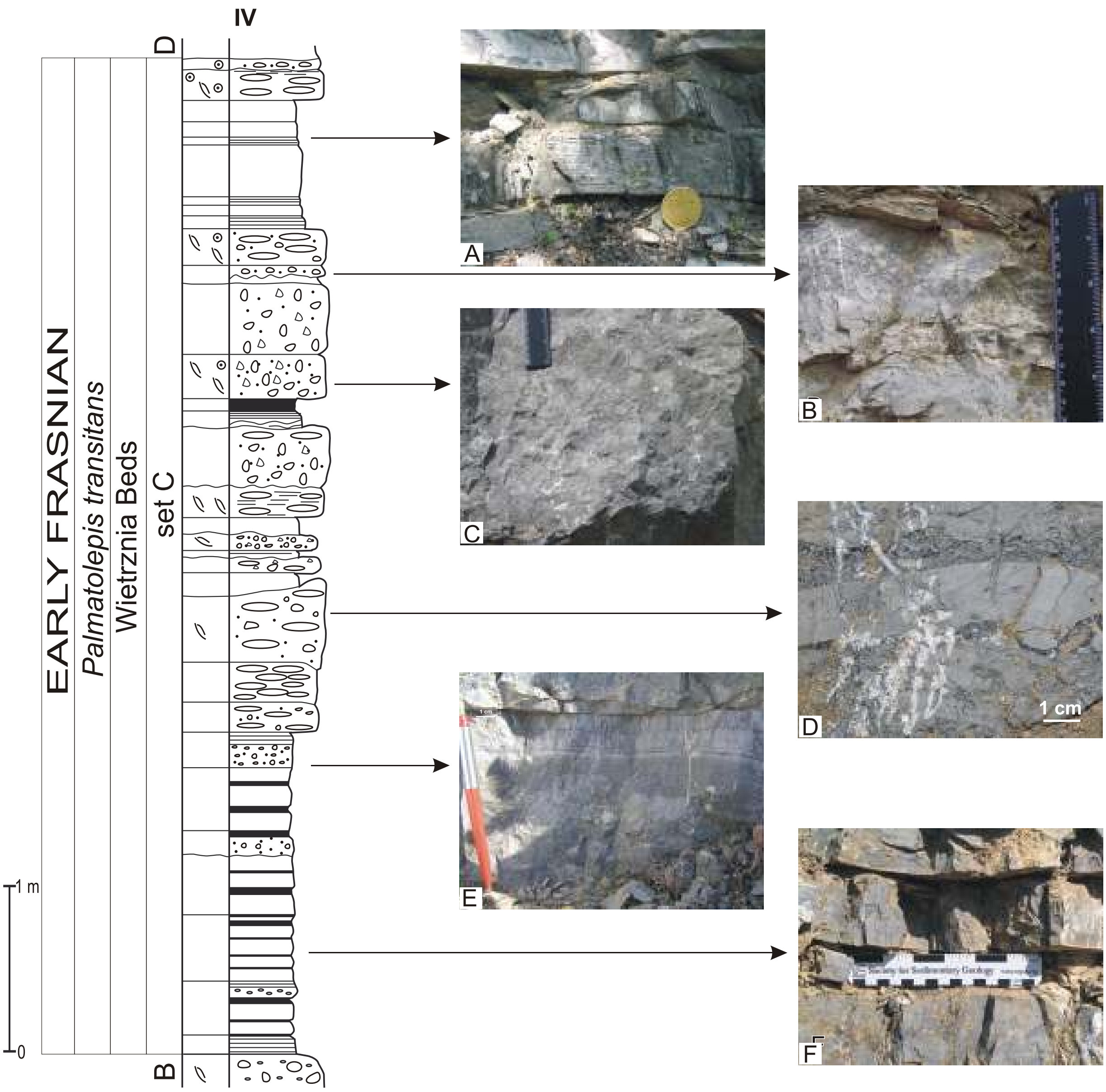

Fig. 2. Types of limestone in the Wietrznia Beds (set C, section IV)

A — horizontal-laminated micritic limestone, B — amalgamated beds of grained/micritic limestone, C — limestone breccia, D — flat-pebble conglomerate, E — graded breccia with horizontal lamination at the top, F — interbedded marly limestone and marly shale

was drowned and a pelagic limestone facies replaced the reef facies (Szulczewski, 1971).

METHODS

About 160 metres of the middle part (set C) of the Wietrznia Beds are exposed in the Wietrznia quarry. Five sections were macroscopically studied bed-by-bed (Fig. 3). 66 rock samples were collected for microscopic analysis. The petrographic study allowed six major microfacies to be recognized (Table 1): further details are given in Vierek (2007).

RESULTS

In this study the following limestone types were distinguished:

— micritic, typically laminated or graded, and nodular limestones corresponding to the shelf basin facies;

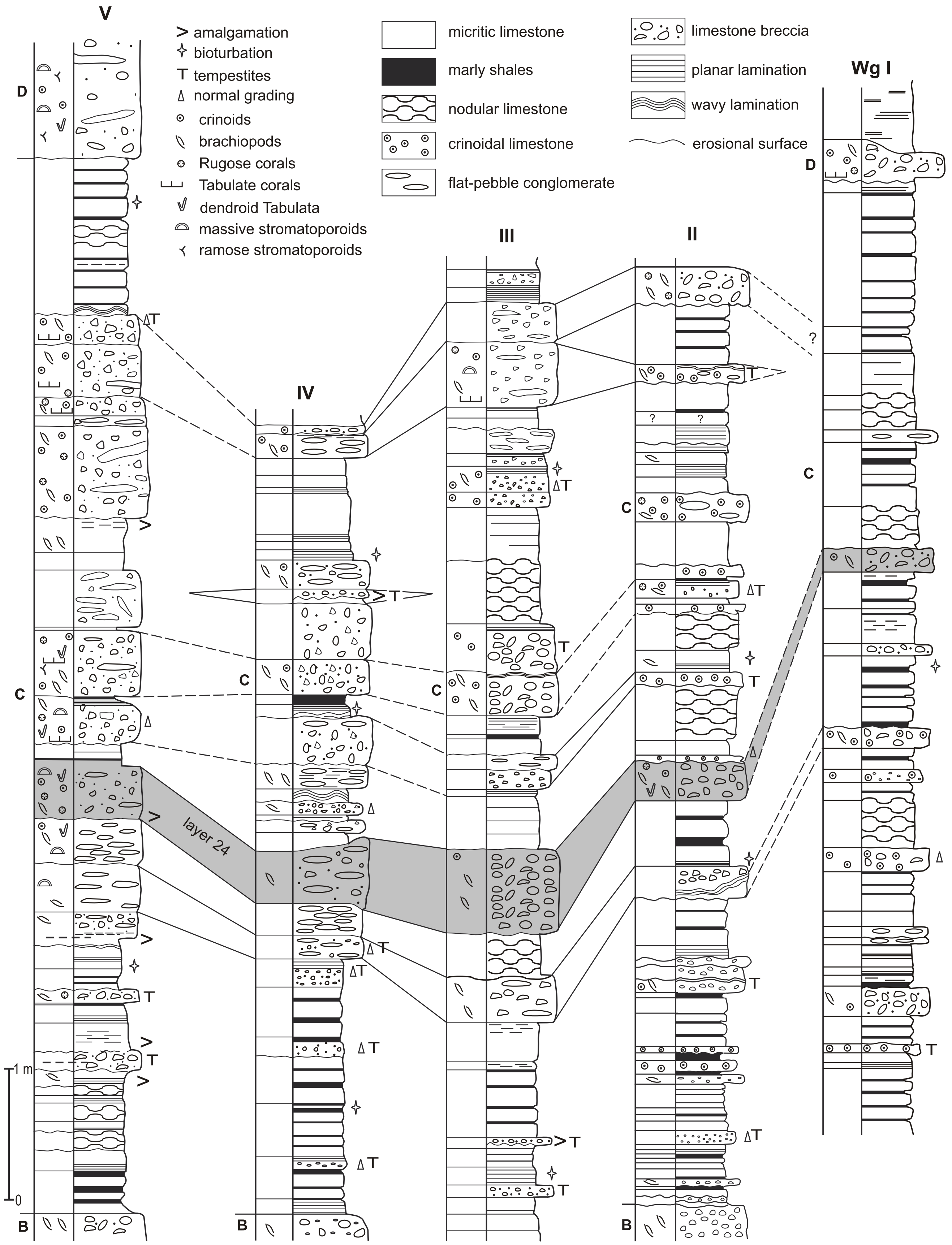

Fig. 3. Lithological sections from the Wietrznia I quarry

Table 1

Microfacies and depositional environments

Limestone types		Microfacies	Description	Grain types/fossils	Depositional environment
Micritic limestones	horizontal and wavy lamination	MF1a pelsparites/micrites pelbiosparites/micrites	mudstone-wackestone; horizontal to wavy lamination, occasionally cross-lamination, bioturbation	peloids and aggregate grains (12.5–40%), rare oncoids, brachiopods and crinoids (2.5–10%), tubiform *Jansaella ridingi*, *Renalcis* (?), calcispheres (2.5%)	FZ 2–3: open shelf, low- moderate energy
		MF1b calcipelsparites and calcipelbiosparites	wackestone; horizontal and wavy lamination, bioturbation	calcispheres (15–40%), peloids (25–30%), small amounts of bioclast fragments: brachiopods, crinoids, trilobites, foraminifera, tubiform *Jansaella ridingi,* few *Renalcis*(?), oncoids	
	normal grading	MF2 pelbiomicrosparites pelbiosparites	wackestone; normally graded, horizontal and wavy laminae, stylolites	peloids and aggregate grains (25–30%), rare crinoids, brachiopods, few calcispheres and *Renalcis,* recrystallized skeletal fragments, oncoids	
nodular limestones		MF3 micrites/biomicrites	mudstone; lenticular to irregular nodules of micritic limestones, stylolites, well-developed fabric, flaser lamination	lime mud, small amounts of bioclast fragments (<10%)	aerobic conditions, pelagic carbonate platform, slope, foreslope; 20–35 m depth
Coarse-grained limestones	crinoidal limestones	MF4 biopelmicrosparites/sparites	densely packed rudstone, moderately sorted, base usually erosional	large fragments (<9 mm) of crinoids (up to 60%), few brachiopods, calcispheres and trilobites, peloids (<10%)	FZ 6: platform margin, shallow-water, high energy
	flat-pebble conglomerate	MF5 intrabiopelspar(rud)ites	poorly sorted rudstone; stylolites, geopetal structures, numerous flat, highly discoidal and rounded (mm–cm) intraclasts, base often erosional	crinoids, brachiopods, trilobites, bryozoans, calcispheres, few rugose and tabulate corals, tubiform *Jansaella ridingi,* single *Moravamminide*(?) and *Renalcis,* peloids (30%), oncoids, recrystallized skeletal fragments	FZ 4–5: fore-reef, strongly turbulent water, high energy
	limestone breccia	MF6a intramicrudites	moderate - well sorted rudstone, geopetal structures, numerous irregular intraclasts (mm–cm) subangular or subrounded, base often erosional	bioclasts (10%): detritus of crinoids, brachiopods, trilobites, tabulata corals, green algae, rare calcispheres	
		MF6b intrabiopelspar(rud)ites		bioclasts (60%): crinoid fragments, brachiopod shells, stromatoporoids, corals, numerous calcispheres, single tubiform *Jansaella ridingi*, bryozoans, trilobites; peloids and aggregate grains (5–20%)	
		MF6c laminated biopelintraspar(rud)ites	poorly sorted grainstone-rudstone, stylolites, few intraclasts (up to 10 mm), horizontal, rarely wavy laminae		

FZ — facies zones after Wilson (1975)

— intraformational conglomerates and breccias and crinoidal limestones corresponding to the fore-reef talus facies. Intercalations of thin-bedded (1–3 cm), dark-coloured marly shales occur among them.

MICRITIC LIMESTONES

Description: these are thin-bedded (3–25 cm) micritic limestones with horizontal lamination (Fig. 2A). The lamination is the result of alternate thin layers of micrite (2–6 mm) and pelsparite (1–2 mm). The lamination is locally barely visible or is disturbed by bioturbation (Fig. 4A). Horizontal lamination often grades into wavy lamination or low-angle cross-lamination, and into hummocky cross-stratification (HCS) at the tops of some beds.

Micritic limestones are occasionally graded. The matrix in the top part of the micro-section is micrite which has undergone change first into microspar (downwards) and then into pseudosparite. Except for rare erosional bases and undulose tops (Fig. 4B), bottom and top surfaces are typically distinct, smooth and planar. There was no fauna visible during field sampling.

Interpretation: according to Seguret *et al*. (2001), the laminated intervals reflect the deposition of carbonate silts by low-energy tractional processes. The lamination and the grain-size distribution characterize material deposited at the base of a slope, from fine-grained suspensions carried by currents initiated by, for example, hurricane or storm winds (Reineck and Singh, 1972). Hummocky cross-stratification is one of the diagnostic sedimentary structures of storm-dominated shallow-marine environments (Harms *et al*., 1975; Dott and Bourgeois, 1982; Duke, 1985; Ito *et al*., 2001; Yang *et al*., 2006). When hurricane or storm winds have ceased, horizontal lamination forms (Narkiewicz, 1978*a*) perturbed sometimes by intensive burrowing (Einsele, 2000, p. 102). According to Flügel (2004, p. 596)

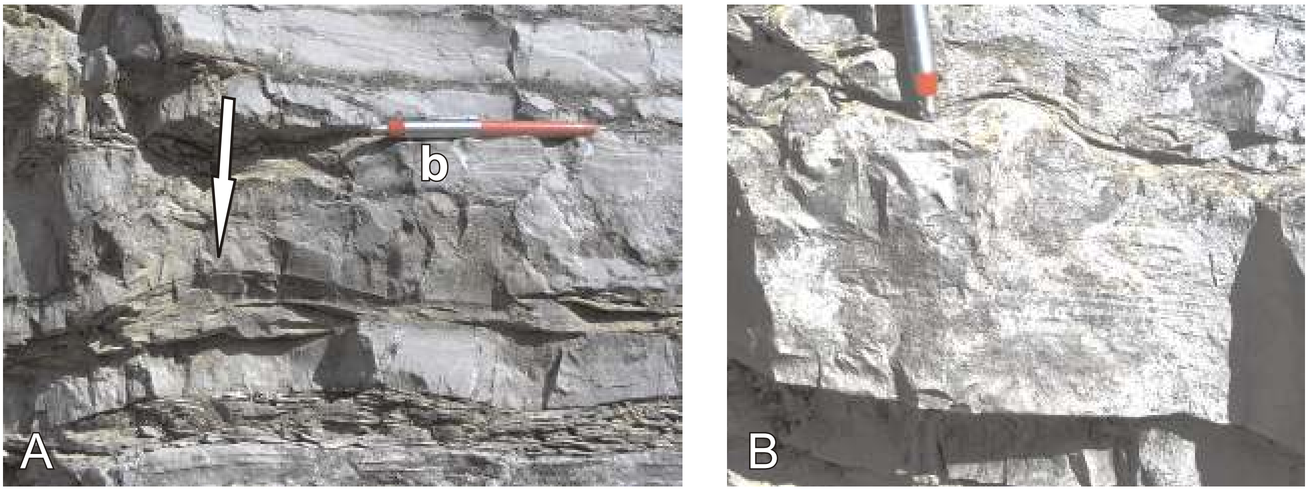

Fig. 4. Laminated micritic limestones

A — bioturbated lamination (b) and hummocky cros-stratification (arrow), section II; B — undulose top of micritic layer, section V

and Perez-Lopez (2001), strong bioturbation is indicative of breaks in storm activity and of slow and continuous sedimentation under low-energy conditions.

NODULAR LIMESTONES

Description: these are relatively thick-bedded (14–48 cm) micritic limestones composed of *in situ* regular, elongated and/or lenticular nodules. The nodules, measuring from a few to *ca*. 10 cm thick, are locally aggregated into discontinuous layers. They are typically embedded in a poorly-compacted marly-clay material. Bottom and top bedding surfaces are smooth and distinct and, as in the micritic limestones, there are no visible macroscopic faunal remains.

Interpretation: there are strong similarities between the nodular limestones described in this paper and those interpreted as eogenetic concretions by Narkiewicz (1978*b*). This supports the view that the formation of the nodules was associated with selective cementation around nucleation centres.

Palaeozoic nodular limestones were deposited on pelagic carbonate platforms, on slopes and in sediment-starved basins with low terrestrial influx and where bottom waters were well-oxygenated (Ricken and Eder, 1991). According to the Wendte and Uyeno (2005, p. 276, fig. 17), such nodular limestones were deposited on fore-slopes at depths between 20 and 35 metres.

COARSE-GRAINED LIMESTONES

Description: these are thick-bedded (<70 cm) limestones characterized by a high proportion of accompanying calcirudites and thick calcarenites. They contain intraformational limestone breccias and flat-pebble conglomerates associated with detrital crinoidal limestones.

The intraclasts of the breccias are irregular, chiefly subangular in shape and range up to 50 mm in size. According to the Krumbein and Sloss (1963) chart, their sphericity is 0.7–0.9 and their roundness is 0.3–0.5. The clasts are usually haphazardly and irregularly arranged and locally strongly compacted. Some of the breccia beds are distinctly graded (Figs. 2E and 5). Clast–clast contacts may be pointed, sutured (microstylolites) or, rarely, concave-convex. Matrix-clast junctions

Fig. 5. Graded limestone breccia with wavy lamination at the top, section IV

Fig. 6. Amalgamated bed (a) of grained/micritic limestone

Erosional surface separates breccia from underlying micrite; hummocky cross-stratification (arrow), section II, sample II/70 are usually sharp though some may be indistinct. The matrix of these limestones is calcarenite.

Set C is also characterized by layers 7–12 cm thick with their lower parts comprising micrite and their upper parts limestone breccia (clast-size <10 mm). Erosional surfaces separate breccia and underlying micrite (Figs. 2B and 6). The top surfaces of these beds, observed over several metres, are undulose.

The intraclasts of the flat-pebble conglomerate are tabular and highly discoidal (Fig. 2D). The typical discoidal pebble is 5–10 cm in longest dimension though occasional examples range up to 25 cm. According to the Krumbein and Sloss (1963) chart, clast sphericity is 0.3–0.5 and roundness is 0.5–0.7. The strongly elongated and flattened intraclasts, some showing a fine horizontal lamination, are embedded in a fine-grained matrix. Locally, small (<10 mm) and more spherical clasts lie between the larger clasts.

In thin layers the pebbles are distributed horizontally. Thicker layers contain randomly oriented, steeply inclined and vertically stacked edgewise intraclasts (Fig. 7). Some intraclasts are broken, cracked or bent. In the most westerly section (V), large, sharply angular fragments (length <100 mm and width <30 mm) of horizontally laminated micritic limestones occur within the coarse-grained limestones.

The bottom surfaces of the grained beds are usually sharp and erosional. The upper surfaces are flat, distinct or, in some cases, undulose. The tops of these layers may display wavy lamination (Fig. 5) or low-angle cross-lamination passing, in a few cases, into HCS (Fig. 8).

Broken or complete brachiopod shells, crinoid debris in abundance, as well as corals and stromatoporoids, are randomly distributed in the matrix.

Toward the eastern side of the quarry, a 4.5–25 cm thick horizon of crinoidal limestones composed of crinoid trochites and single, small (<10 mm) micritic clasts is exposed. The base of these crinoidal limestones is sharp and erosional. The top displays horizontal or wavy lamination (Fig. 9A, B).

Interpretation: the coarse-grained nature of the deposits indicates strongly turbulent water within the fair-weather wave zone (Whalen *et al*., 2002). The presence of many intraclasts ripped from the substrate clearly reflects high wave energies. Their morphology suggests varying conditions of redeposition. Sharp contacts between the matrix and the intraclasts indicate consolidation of the substrate (Radwański, 1960). Nevertheless, the sporadic presence of indistinct intraclasts suggests the existence of less consolidated sediment. The larger, flattened, elongated and slightly rounded intraclasts of the flat-pebble conglomerates were produced by sudden reworking of limestone layers characterized by varying degrees of consolidation and subsequent minor rounding during transport. Many authors have considered that intraformational flat-pebble conglomerates have resulted from storms (Jones and Dixon, 1976; Kaźmierczak and Goldring, 1978; Seilacher, 1991; Sepkoski *et al*., 1991).

In comparison with those of the flat-pebble conglomerates, the breccia intraclasts are smaller, more sharply edged and usually display only slightly-elongated shapes. According to Szulczewski (1968; 1971), these intraclasts may have been be produced by strong erosion of the superficial parts of semi-consolidated sediments caused by suspension-type currents or by mudflows. Their origin may also reflect a lowering of the wave

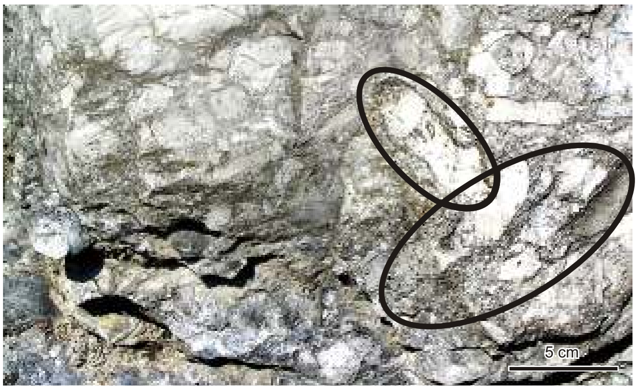

Fig. 7. Edgewise texture in flat-pebble conglomerate, section V, sample V/37

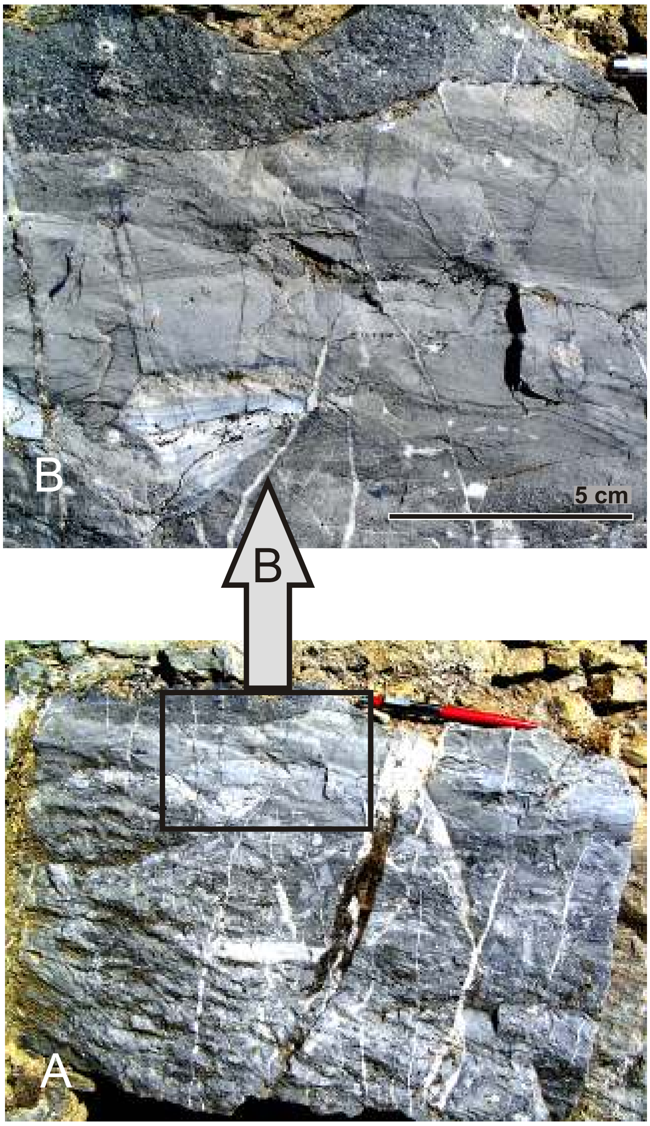

Fig. 8. Coarse-grained limestones

A — wavy lamination passing into hummocky cross-stratification; B — enlarged portion of the left upper corner of the photograph, section II

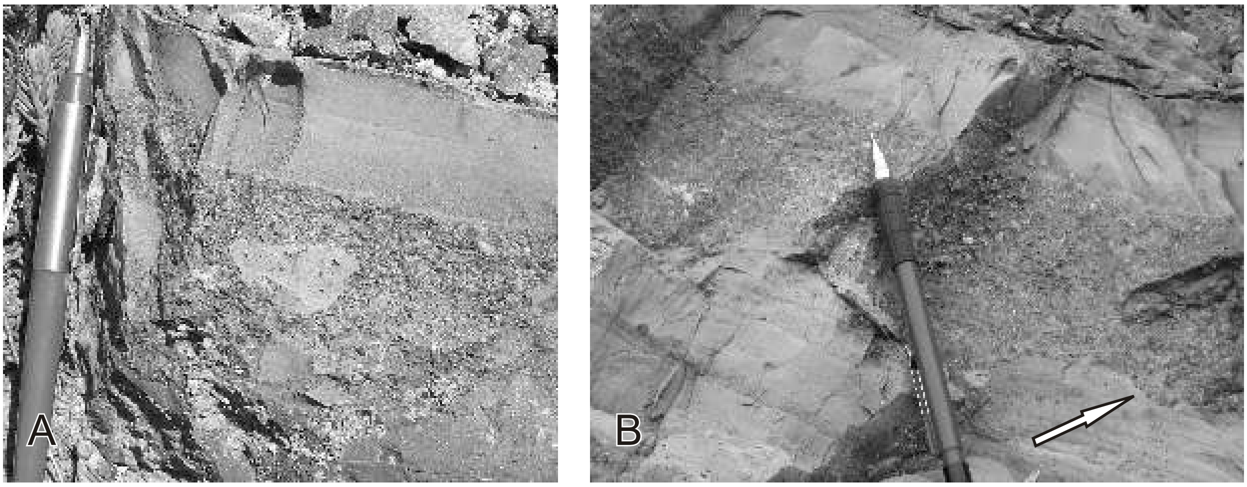

Fig. 9. A — crinoidal limestones with small individual micritic clasts; horizontal lamination is visible at the top, section III, sample III/A; B — crinoidal limestones with wavy lamination and (arrow) erosional base, section IV

base due to storms and strong winds that, in turn, provoked erosion, reworking and sediment redeposition (Sepkoski *et al*., 1991; Seguret *et al*., 2001; Flügel, 2004, p. 596). According to Pratt (2002), the sporadic distribution and angularity of the intraclasts argues that the conglomerates were generated by occasional tsunami rather than by storms. The lack of sorting and the grain-supported fabric indicate rapid deposition in dynamic, high-energy environments (Bełka *et al*., 1996). The presence of an erosive base may indicate occasional high-energy conditions, e.g., tempestites (Aigner, 1985) or turbidites. Furthermore, the increased sizes of both the bioclasts and intraclasts places deposition of this limestone type closer to the storm wave base, associating them with turbidite or storm processes.

Crinoidal limestones formed in shallow-water, high-energy environments, usually on platform slopes (Wilson, 1975). Allochthonous accumulations which are observed in slope and basinal settings correspond to downward transport leading to the formation of crinoidal turbidites (Tucker, 1969 in Flügel, 2004, p. 552).

LATERAL CHANGES

From west to east in the quarry, there is a gradual decrease in the thickness of the coarse-grained layers; here and there the layers can disappear entirely (Fig. 3). Nevertheless, in the central part of the quarry (sections IV and III), a clear increase in thickness is seen in several layers, e.g., layer 24 is 38 cm thick in section V, 65 cm in section III and barely 16 cm in section WgI. In the western section V, a distinct amalgamation of thick coarse-grained layers is evident. In sections IV–II thin (7–12 cm) amalgamated beds of grained/micritic limestone occur. These beds can extend for up to a maximum of tens of metres.

Lithologies progressively change from west to east in the quarry. Clast diameters increase westwards. Towards the east, the number of coarse-grained layers grows less and more intercalations of micritic and marly shales appear. In the western side of the quarry, the micritic and marly shale intercalations mostly appear in the bottom of set C whereas to the east they occur almost everywhere throughout the section. Together with these changes, the laminated micritic limestone disappears gradually eastwards and unlaminated limestone appears.

DISCUSSION

The considerable variety of microfacies (see Vierek, 2007) and the interbedding of different limestones, support the transitional nature (Szulczewski, 1971) of the Upper Devonian carbonates in the middle Wietrznia Beds (set C).

Textural characteristics and microfauna distribution indicate varying conditions of deposition. A low-energy environment is indicated by the relatively low biotic diversity and the fine-grained nature of the deposits. Where reflating higher-energy conditions, the quantity of bioclasts increases and the sediments coarsen in grain size and include many intraclasts. In the section examined, multiple intercalations of thick (up to 70 cm) event beds occur. Here, the nature of redeposited fauna can be instructive. Large crinoid stems and brachiopod shells, stromatoporoids, and corals typical of coarse-grained limestone derive from shallower areas in the sedimentary basin, e.g. reefs. The conodont biofacies, identified in the micritic and grained limestone (Pisarzowska *et al*., 2006), reflect a variety of depths: a shallower (polygnatid–icriodid) biofacies and a deeper (polygnatid–mesotaxid) biofacies. Furthermore, the occurrence of reef-builders (corals) and an *Ancyrodella*-rich conodont fauna in the grained beds (Pisarzowska *et al*., 2006) indicate an environment peripheral to reefs and mud-mounds (Ziegler and Sandberg, 1990).

The intraclasts in the coarse-grained limestones are unequivocal indicators of strong turbulence and high energy. The large sizes of the intra- and bioclasts, the degree of clast rounding (subrounded-rounded — flat-pebble conglomerate), the clast-supported fabric, the abrupt vertical grain-size changes and the sorting of grain components (poor to moderate), suggest that high energy and strong erosion above storm wave base was responsible for the disintegration of the carbonate material. The intimate interbedding of higher-energy facies with shales is a recognized indicator of deposition below fair-weather wave base but above storm wave base (Aigner, 1985; Myrow and Southard, 1996).

MECHANISM OF TRANSPORT

The composition, texture and microfacies features of the Wietrznia limestones, and comparison with Polish (Narkiewicz, 1978*a*) and German (Devleeschouwer *et al*., 2002) grained carbonate deposits of similar age, suggests storms as the main factor in erosion and transport.

Szulczewski (1968, 1971), in discussing the origin of carbonate detrital deposits, outlined the characteristics of subaqueous mass flows and turbidity currents. Tempestites and turbidites are produced by intermittent high-energy events, show similar characters and are difficult to distinguish apart. In Table 2, the characteristics that distinguish carbonate tempestites and turbidites in the Wietrznia quarry are given.

Lateral changes in layer thickness and grain size (Seilacher and Aigner, 1991), rapid and multiple facies changes within the lithological section (Einsele, 2000, p. 102), large intra- and bioclast sizes, and erosive bases to coarse-grained layers, are all indicative of high-energy environments typical of tempestites (Aigner, 1985). All characterize the Wietrznia limestones.

In the westernmost section V, coarse-grained layers show the greatest thicknesses and tendency to amalgamate. In this section, micritic/marly shale intercalations are intermittent. This is interpreted as reflecting advanced tempestite-bed cannibalism. According to Einsele (2000, p. 102), these are features typical of proximal tempestites deposited not far below the fair-weather wave base. Cannibalism and amalgamation may occur repeatedly until a major storm event ultimately produces a bed with a base that can be preserved.

Towards the centre of the quarry, there is a further example of layer amalgamation. A thin calcirudite bed displays an erosional contact with the underlying micritic limestones. Similar layers described by Duke (1985) serve to make a link with amalgamation and with hummocky cross-stratification. According to Dott and Bourgeois (1982) and Walker *et al*. (1983), occurrences of these beds are indicative of more energetic and frequent storm events, shallow depths and close proximity to source. Comparison with the amalgamation and cannibalism of preceding layers indicates decreasing wave energy.

Flat-pebble conglomerates are a feature of calcareous tempestites (see: Sepkoski, 1982; Sepkoski *et al*., 1991; Flügel, 2004, p. 596). Kaźmierczak and Goldring (1978) recognized intraformational conglomerates of similar age as tempestites deposited in a subtidal environment. As detailed by Sepkoski (1982), the origin of the flat-pebble conglomerates requires the episodic deposition of thin carbonate layers separated by muddy partings, and erosion and reworking by intense storms to produce the tabular intraclasts. The common edgewise orientation of clasts in the thicker conglomerates of the Wietrznia Beds reflects deposition from powerful oscillatory currents (Futterer, 1982).

The section of the Wietrznia Beds also reveals the presence of more spherical and angular intraclasts within breccia. These micrite intraclasts may also reflect redeposition of storm-derived material (Flügel, 2004, p. 596).

The Wietrznia coarse-grained limestones show no evidence of the bioturbation that is seen in the micritic layers. In the context of storms, this observation may be explained as follows. The destructive phase of an intense storm erodes bottom material. Subsequent waning allows constructive deposition of new sediment. Initially, coarser calcareous material falls to the bottom. The remaining, finer sediment held in temporary suspension gradually drops to form graded- and laminated beds — as in the Wietrznia Beds. These late sediments provide a habitat for organisms that cause the bioturbation common in the upper, fine-grained part of storm beds and links active bioturbation

Table 2

Criteria distinguishing tempestites from turbidites (modified from Einsele and Seilacher, 1991) and their presence in the Wietrznia Beds

Features	Tempestites	Turbidites	Wietrznia Beds
Wave ripples and wave ripple cross laminations	common	absent	present
Current ripples and current ripple bedding	less common	common	absent
Convolute lamination	rare	common	absent
HCS	common	absent	present in the micritic limestones and few in the coarse-grained limestones
Amalgamation and/or cannibalism	very common	less common	present
Continuity of single beds	mostly limited	often over wide distances	mostly limited
Thickness of sequence	limited, associated with shallow-water facies	in general great, can reach many hundreds and even thousands of metres, associated with deep-water facies	limited (up to 10m)
Bioturbation	in thin mud tempestites and/or distal tempestites	rare/absent	present in the thin micritic limestones and distal areas
Fauna	shallow-water	mixed shallow/deep assemblage	shallow-water

with breaks in storm activity (Duke, 1985; Sepkoski *et al*., 1991; Perez-Lopez, 2001).

The post-storm phase of deposition is associated with the origin of wavy lamination, low-angle cross-lamination, and of hummocky cross-stratification — a sedimentary structure diagnostic of storm-dominated shallow-marine environments (Harms *et al*., 1975; Hamblin and Walker, 1979; Dott and Bourgeois, 1982; Duke, 1985; Walker, 1992; Ito *et al*., 2001). HCS occurs in fine-grained deposits and is characterized by gently-curved, low-angle cross-lamination (Duke, 1985). The characteristic features of HCS are, at best, weakly and indistinctly visible in the Wietrznia Beds. However, variants of HCS are described in the literature. For instance, Duke (1980, 1985) distinguished a variant in which swales are preferentially preserved and hummocks rare or absent. Jach (2004) interpreted structures with curved upper surfaces and sharply truncated bottoms as HCS; the geometries of some layers in Wietrznia are comparable with these. Though HCS is not fully understood, Myrow and Southard (1996) see the structure as an indicator of storm-generated oscillatory currents. Skeletal concentrations of brachiopods and crinoids observed in the Wietrznia Beds are also storm-related (see: Flügel, 2004, p. 596).

The composition and sedimentary structures of the Wietrznia limestones support the proposed interpretation that intense storm waves were the main erosion and transport agent. In addition, a component of the coarse-grained beds (limestone breccia) may reflect gravity-flow initiated by storm conditions (Myrow and Southard, 1996). Walker (1992) described recent examples of comparable sediments generated by storm or hurricane events. Storms were intermittent during the deposition of the monotonous marly limestones and shales in the Wietrznia quarry. After storm events, rare grain-flows resulted in grain-supported carbonate breccias.

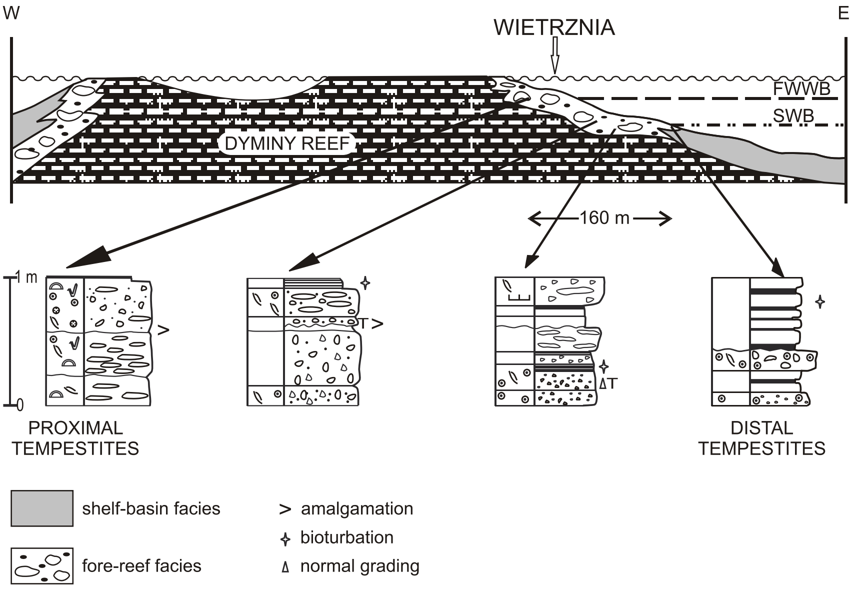

Fig. 10. A generalized model for the storm-generated Wietrznia Beds

FWWB — fair-weather wave base, SWB — storm wave base; for other explanations see Figure 3

CONCLUDING REMARKS

The limestones in the middle Wietrznia Beds (set C) were generated, in the main, by redeposition in a dynamic environment. The stromatoporoid-coral reef (Dyminy Reef — Narkiewicz, 1988) located in the central part of the Kielce region was the source. Storms were the main agent of erosion and transport.

Proximal tempestites, occurring in the western part of the quarry, display features indicative of amalgamation and cannibalism (Fig. 10). With storm abatement, finer graded and laminated micritic limestones accumulated. In the eastern part of the quarry, decreasing wave energies led to the deposition of transitional or more distal tempestites.

Changes in lithology and bed thickness over an interval of about 160 m in the Wietrznia quarry are marked. Seilacher and Aigner (1991) have shown that storm beds deposited on a shelf tend to vary from place to place and, in contrast, sediments deposited on gently inclined carbonate ramps trend to be more uniformly continuous. The varied topographic relief of the Devonian reef (Narkiewicz, 1988) was probably an important influence — as was synsedimentary tectonism (Szulczewski, 1989; Racki and Bultynck, 1993) on the differentiation of facies in the Wietrznia sub-region. An early Frasnian deepening pulse interrupted shallow-water deposition in the Wietrznia slope area (Racki and Bultynck, 1993).

According to Pomar (2001) basin-floor morphology and sea level changes influence the size and efficiency of the carbonate factory. Playford *et al*. (1989 in Pomar, 2001) considers that the evolution and morphology of the Canning Basin reefal platforms (Middle/Late Devonian) were controlled by variation in rates of relative sea level change due to combined eustasy and tectonism.

Some of the coarse-grained beds might have been generated as a result of grain-flow initiated by earlier storm conditions. The minimum inclination angle of the slope that is necessary for initiation of grain flow is 18° (Bagnold, 1954). Kenter (1990) noted that gradients are still steeper (30–40°) for these sediments with cohesionless and grain-supported fabrics. According to Coniglio and Dix (1992), the steepening of a carbonate slope, particularly the upper slope, can result from organic binding and framework building by reef-forming organisms. In addition, carbonates with frame-building skeletal structural elements (i.e. reefs) may construct slopes up to 90° (James and Ginsburg, 1979 in Spence and Tucker, 1997). For example, the Devonian carbonate platforms from the Canning Basin (Western Australia) are mostly rimmed platforms flanked by high-relief margins and very steep (2–85°) marginal slopes (Ward, 1999 in Pomar, 2001, fig. 10). To summarize, the Upper Devonian carbonate platform from Holy

Cross Mts. is a reef-rimmed isolated platform with a relatively steep margin akin to the rimmed platform base-of-slope aprons described by Coniglio and Dix (1992).

The depth to storm wave-base can vary, but commonly fluctuates between 50 and 200 m (Cheel and Leckie, 1993). Hummocky cross-stratification is indicative of storm sedimentation in a shallow marine environment below fair weather wave base, probably with a water depth of less than 20 m (Dott and Bourgeois, 1982; Duke, 1985; Schieber, 1994). According to Schieber (1994) the epicontinental sea setting and the presence of HCS together with amalgamation may reflect a relatively shallow water depth of up to a few tens of metres.

Variations in water depths are reflected in storm layers by their thicknesses, which should decrease distally (see: Kreisa, 1981). This general relationship is modified by basin morphology and by the character of the substrate. Deposition on an uneven, undulose surface may be excluded as redeposited material would have filled in any sea-floor depressions. The increase in bed thickness in the central section III of Wietrznia quarry might also reflect the formation of calcareous channel-fills (Seguret *et al*., 2001; Albani *et al*., 2005). According to Albani *et al*. (2005) channelized limestone beds may have occurred during sea level lowstand under conditions of increased hydrodynamic energy. In the Wietrznia succession, this might correspond to stepwise drowning of the Kielce platform and short and rapid relative sea level fluctuations (see: Sobstel *et al*., 2006).

Thus, it is concluded that the Wietrznia quarry limestones formed above storm wave base in a shallow (possibly only a few tens of metres) sea that deepened eastwards.

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