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The palaeogeographical background of Late Devonian storm events in the western part of the Holy Cross Mountains (Poland)

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Abstract

Late Devonian coarse-grained carbonate deposits in the Holy Cross Mountains were studied for possible storm depositional systems and catastrophic tsunami events, as it must be assumed that the investigated area was strongly affected by tropical hurricanes generated in the open ocean North of Gondwana. This assumption appears consistent with diagnostic features of carbonate tempestites at several places in the Holy Cross Mountains. Sedimentary structures and textures that indicate so are, among other evidence, erosional bases with sole marks, graded units, intra- and bioclasts, different laminations and burrowing at the tops of tempestite layers.

It has been suggested before that a tsunami occurred during the Late Devonian, but the Laurussian shelf had an extensional regime at the time, which excludes intensive seismic activity. The shelf environment also excluded the generation of tsunami waves because the depth was too shallow. Additionally, the Holy Cross Mountains region was surrounded in the Devonian by shallow-marine and stable elevated areas: the Nida Platform, the Opatkowice Platform and the Cracow Platform to the South, and the elevated Lublin-Lviv area to the NE. Thus, tsunami energy should have been absorbed by these regions if tsunamites would have occurred.

Key words: carbonate tempestites, tropical hurricanes, tsunami, palaeogeography, Late Devonian, Holy Cross Mountains, Poland

1. Introduction

The Upper Devonian in the western part of the Holy Cross Mountains (HCM, Fig. 1A) is characterised by carbonate deposits. These are rhythmically stratified, thin-bedded micritic limestones, marly shales and marly limestones, locally with a wavy to nodular-fabric. The diverse, mainly reef–derived coarse-grained deposits (from calcarenites to calcirudites, including both flat-pebble conglomerates and carbonate breccias) with many sedimentary structures contain intercalations of limestone/marl deposits (Table 1).

Szulczewski (1968, 1971) described fine-grained marly limestones as autochthonous deposits in deeper-water settings. In contrast, he considered (Szulczewski, 1968) the coarse-grained limestones to represent subaqueous mass-flow deposits and turbidites. Later, Szulczewski *et al.* (1996), Racki & Narkiewicz (2000) and Vierek (2007a, b) suggested that storm surges affected the sedimentation in the HCM region. Earlier, Kaźmierczak & Goldring (1978) had interpreted the flat-pebble conglomerates as high-energy deposits of tsunamis.

Flat-pebbles are particular deposits that have been described from various sedimenta-

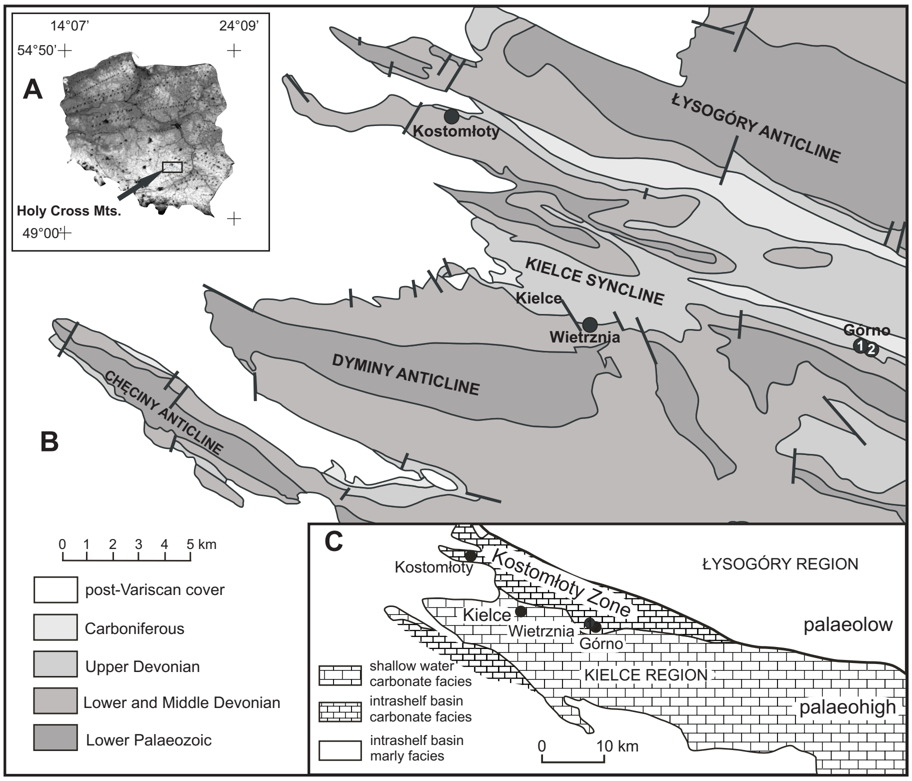


Fig. 1. Geographical, geological and palaeogeographical setting.
A: Location of the Holy Cross Mountains in Poland.
B: Simplified geological map of the western part of the Holy Cross Mountains (after Szulczewski, 1971).
C: Palaeogeography of the Givetian to Frasnian in the Holy Cross Mountains (after Racki, 1993) with the location of the Wietrznia, Kostomłoty and Górno outcrops (1 = Górno-field; 2 = Górno-Józefka).

ry environments (e.g., Mount & Kidder, 1993; Van Loon *et al.*, 2012, 2013), and they are ascribed to various processes in diverse high-energy events. For example, deformation by cracks, a rare occurrence of such conglomerates, a high degree of scouring, and an angular character of the intraclasts may point at generation by occasional tsunamis (e.g., Pratt, 2002). In contrast, conglomerates composed of flat and (sub)rounded intraclasts with imbrication of pebbles and edgewise breccia fabrics may indicate storm-influenced sedimentation (e.g., Myrow *et al.*, 2004) or submarine mass movements (e.g., Kullberg *et al.*, 2001).

The different opinions and interpretations of the origin of the coarse-grained limestones in the study area require a closer examination. The interpretation and sedimentary record of storm/event deposits should be considered on the basis of palaeoclimate and palaeogeographical reconstructions. The present-day distribution of storm systems provides a basis for a palaeostorm model. It can be assumed that the environmental and meteorological conditions for generation of ancient tropical hurricanes or intense winter storms (see table 1 in Marsaglia & Klein, 1983) were identical in the Late Devonian as nowadays. The meteorological phenomena did not change fundamentally, and the palaeogeographical positioning of the continents is a key to the reconstruction of atmospheric circulation patterns and hurricane generation patterns in the geological past (e.g., Lloyd, 1982).

1.1. Objectives

The present contribution has three main objectives.

The first objective is to consider the occurrence of storm activity in the context of the palaeogeographical position and palaeoclimate conditions of the HCM during the Late Devonian. One should realise, however, that palaeogeographical data do not provide evidence, but only premises regarding possible storm activity. Only sedimentological analyses of the criteria that might indicate tempestites can confirm or reject an interpretation of storm deposits.

The second objective is to describe the features in the study area that might be diagnostic of carbonate tempestites.

Table 1. Lithofacies of the sediments under study and their characteristics.

lithofacies	location	description
marly shales, marly limestones	Wietrznia, Kostomłoty–Mogiłki, Górno–Józefka; locally Górno-field	dark grey; thin-bedded (locally medium- to thick-bedded); finely laminated; flat boundaries; locally organic matter; fossil-poor
nodular to wavy-bedded limestones	Wietrznia, Kostomłoty–Mogiłki, Górno-field	grey; medium-to thick-bedded; marly or lime mudstones; wavy and/or knobby in shape; in situ regular or irregular, elongated and lenticular nodules (approx. 12 cm long); marly matrix; stylolites
micritic limestones (calcisiltites)	all studied sections	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; normally graded; distinct and smooth boundaries (or rare erosional base and undulating top); locally amalgamated with coarse-grained limestones; stylolites; locally bioturbated
fine-grained limestones (calcarenites)	all studied sections	grey; thin- to medium-bedded; moderate to well-sorted packstone to grainstone; normally graded; horizontal or wavy lamination; locally HCS and undulating top; sharp erosional base with gently wavy to distinctly v- or u-shaped depressions (in some cases boundaries are smooth and planar); geopetal infillings; rare bioturbation; (micro)stylolites
coarse-grained limestones (calcirudites):		
– breccia	Wietrznia, Kostomłoty–Mogiłki, Górno-field, rare in Górno–Józefka	light grey; thin- to thick-bedded; poor- to moderately sorted grainstone/rudstone; irregular, subangular or subrounded intraclasts (approx. 6 cm long); sharp and non-erosional or erosional bases; sharp and flat upper boundaries; matrix- (or grain-) supported; (micro)stylolites; amalgamation
– flat-pebble conglomerate	Wietrznia, Kostomłoty–Mogiłki, Górno-field	light grey; medium-bedded; poorly sorted; flat and tabular pebbles (up to 25 cm in size); horizontally oriented (in thin layers) or edgewise fabric (in thicker layers); normally (or sporadically inversely) graded; often erosional base; geopetal structures; matrix-supported; rare (micro)stylolites
– coquina	Górno–Józefka	grey; thin- or medium-bedded; moderate- (or well-) sorted grainstone/rudstone; sharp and erosional base with sole marks (or rarely no distinct base); locally graded; horizontal or wavy lamination at the top; grain- (or rarely matrix-) supported; rare bioturbation; geopetal structures; stylolites

Finally, the third objective is to provide evidence for the existence or non-existence of the tsunami that was hypothesised by Kaźmierczak & Goldring (1978).

1.2. Geological setting

The present contribution is based on compilation, review and analysis of published and unpublished sedimentological data. Four outcrops of the Upper Devonian were studied for the purpose in the western part of the HCM (Fig. 1B). Three of them (the Wietrznia succession, the Kostomłoty-Mogiłki and Górno-Józefka quarries) have been described earlier (Vierek, 2007a, b, 2008, 2010). This new study focuses on the Górno outcrop.

The Wietrznia Hill is located in the south-eastern part of the town of Kielce (Fig. 1B). The exposed rocks form part of the southern flank of the Kielce Syncline. The carbonates of the middle Wietrznia Beds (= set *C*, Lower Frasnian *Palmatolepis transitans* Zone: Pisarzowska *et al.*, 2006) developed in a transitional facies (according to Szulczewski, 1971) and are built mainly of micritic-marly (basin) and coarse-grained (reef-derived) deposits (Table 1). Some centimetre-thick, rhythmically stratified, locally laminated, platy bituminous micritic limestones, which in places are wavy bedded to nodular, are intercalated with marly shale partings (= basin deposits). Thicker (up to 0.75 m) coarse-grained limestones (calcarenites and calcirudites) with intra- and bioclasts and commonly erosional bases as well as normal grading (= reef deposits), are second in frequency. Set *C* shows normal lateral variations in lithology and bed thickness within a downslope fore-reef facies from west to east, toward a more distal facies, traced over a distance of approx. 160–180 m (Vierek, 2007b; Vierek & Racki, 2011). The mainly storm-controlled proximal gradient is laterally characterised by gradual changes from coarse-grained tempestites, represented by a flat-pebble conglomerate fabric, to diluted muddy tempestites. The clast diameters and the number of coarse-grained layers increase westwards. Towards the east, more intercalations of micritic limestones and marly shales occur. This variation is accompanied by a gradual decrease in the thickness of the coarse-grained layers towards the E, and locally these beds may disappear completely. These carbonates were deposited mainly at a depth of 50–90 m in oxygen-depleted middle to distal slope settings (see fig. 5 in Vierek & Racki, 2011).

The abandoned Kostomłoty-Mogiłki quarry is situated on the east side of the Kostomłoty Hill, a few kilometres NNW of Kielce in the NW part of the HCM (Fig. 1B). In the quarry, the upper part of the Szydłówek Beds (Lower Frasnian *Palmatolepis transitans* Zone: Racki *et al.*, 2004) and the Kostomłoty Beds (Middle Frasnian *punctata* Zone with *A. gigas* to the *hassi* s.l. Zone with *A. curvata*: Pisarzowska *et al.*, 2006) are exposed (Racki, 1985; Racki & Bultynck, 1993). The lowermost part of the Kostomłoty-Mogiłki succession (= the upper part of the Szydłówek Beds) is characterised by intercalations of marly limestones and shales, in part strongly tectonically disturbed, with laminated and fine-grained limestones (calcisiltites to calcarenites). The first thicker coarse-grained conglomerate beds define the base of the Kostomłoty Beds. The lower part of the Kostomłoty Beds comprise fossil-poor, horizontally laminated limestones (calcisiltites) and marly shales, which in places show wavy bedding, with a few calcarenite and calcirudite layers (Table 1). According to Racki & Bultynck (1993) and Pisarzowska *et al.* (2006), both the Szydłówek Beds and the Kostomłoty Beds represent a deeper basin environment (= basin facies of Szulczewski, 1971) with mostly oxygen-depleted bottom conditions. As interpreted by Vierek (2010), the laminated calcisiltites, calcarenites and part of the calcirudites (including both flat-pebble conglomerates and breccias) were formed by storm activity and combined flows, and deposited on the upper or middle part of the slope of the carbonate platform.

The abandoned Górno outcrop (the so-called Górno-field), which is located along the road from Kielce to Lublin and the big, active Józefka quarry on the Józefka Hill are located 1.4 km S of Górno village (Fig. 1B). In the eastern part of the Górno-Józefka quarry, the upper part of the Szydłówek Beds (Lower Frasnian *Palmatolepis transitans* Zone to Middle Frasnian *Palmatolepis punctata* Zone with *A. gigas*: Racki *et al.*, 2004) is visible (Vierek, 2008). Just like in the Kostomłoty–Mogiłki succession, the Szydłówek Beds represent a deeper environment (= basin facies of Szulczewski, 1971). They are usually medium- and thick-bedded dark-grey, fossil-poor marly limestones and shales. A few intercalated thin- to medium-bedded calcarenites and coquinas contain abundant detritus of brachiopods and crinoids, and are characterised by erosional surfaces and graded bedding (Table 1). According to Vierek (2008), calcarenites and coquina beds, characterised by erosional bases with sole marks, horizontal lamination at the top and skeletal concentrations of crinoids and brachiopods, were deposited around the storm-wave base (SWB) and should be interpreted as tempestites.

In the exposed Frasnian limestones of the Górno-field, conodont data led Małkowski (1981) to distinguish five sets (*A-E*) ranging 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* Zone (Ziegler & Sandberg, 1990). The deposits of Górno-field are characterised by alternating thin-bedded micritic limestones and/or marly shales, which in some places are wavy- to nodular-bedded or disturbed by synsedimentary tectonics, and by frequent thin- to medium-bedded calcarenites and calcirudites with intra- and bioclasts (brachiopods and crinoids). An erosional bottom surface, graded bedding and undulating tops are common (Table 1).

2. Regional palaeogeographical setting

During the Early Devonian, a new large supercontinent, Euramerica (also called Laurussia) was formed. This continent with extremely wide shelf areas was positioned at equatorial latitudes (e.g., Lewandowski, 2003). The outer part of the Laurussia shelf constitutes a complex system of carbonate platforms, intracratonic basins and intrabasinal highs, and extends from southern England through Belgium and the central part of Germany to southern Poland and Moravia (Bełka & Narkiewicz, 2008). In Poland, epicontinental Devonian facies developed in a shelf area trending roughly NW-SE, with a variable width ranging from 150 to 600 km (Narkiewicz, 1988). This shelf formed part of an elongated pericratonic basin stretching from western Europe to the Ukraine.

According to the Late Devonian palaeoclimate reconstruction of Witzke (1990), SW to central Europe was situated south of the equator at 10–30° L. New palaeogeographical reconstructions by Golonka (2000) show, however, that the Polish part of the Devonian shelf of Laurussia was situated around the equator at 5–10° S in the (sub)tropical zone (Fig. 2). The present area of the HCM region was located in the central part of the carbonate shelf, which was far away from the land and adjacent to the Holy Cross Fault (Pożaryski, 1986; Narkiewicz, 2007).

The palaeogeography of the Givetian to Frasnian in the HCM region shows two distinct palaeogeographical/tectonic regions (Fig. 1C): the northern Łysogóry region (a palaeolow) and the southern Kielce region (a palaeohigh; Szulczewski, 1971, 1977). 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. The Givetian in the Kielce region was characterised by an extensive biostrome-colonized platform. As the result of a global sea-level rise during the Early Frasnian, the widespread carbonate platform shrank to isolated reef complexes (the Dyminy reef of Narkiewicz, 1988; and the Dyminy reef complex of Racki, 1993). There were two main types of Frasnian reefs: stromatoporoid/coral reefs and microbial mud mounds. The Dyminy reef developed close to Kielce (over the northern marginal zone of the Kielce carbonate platform), where it attained a thickness of 200–300 m. The core of reef, approx. 10 km in diameter (Narkiewicz, 1988), is composed of stromatoporoid/coral limestones indicating a shallow-marine environment. On the other hand, drowned, poorly oxygenated deeper-shelf areas (= intrashelf basins) surrounded the Frasnian Dyminy reef: the Chęciny-Zbrza Basin to the South and the Łysogóry–Kostomłoty Basin to the North (Racki, 1993; Szulczewski, 1995). The mud mounds developed in quiet water below SWB (Szulczewski, 1971; Racki, 1993). At the beginning of the Famennian, the platform was smaller than it had been before, and the Late Devonian epicontinental succession indicates continuous but punctuated drowning of an increasingly differentiated carbonate platform, which was completed in the Visean (Szulczewski, 1995).

3. The Devonian climate

The Devonian position of Euramerica has been reconstructed on the basis of numerous palaeomagnetic data (see, for instance, fig. 16 in Scotese & McKerrow, 1990; fig. 6 in Kent & Van der Voo, 1990; figs 12–13 in Torsvik *et al.*, 1990; fig. 12 in Golonka, 2000; figs 11–12 in Golonka, 2007); the thus obtained reconstruction is in good agreement with Devonian palaeoclimate indicators. Likewise, the history of the Devonian reefs is generally considered as reflecting the palaeoclimate, which is interpreted to have been a warm greenhouse time-span (e.g., Golonka, 2000; Joachimski *et al.*, 2009).

According to palaeoclimate reconstructions and palaeotemperatures calculated by Joa-

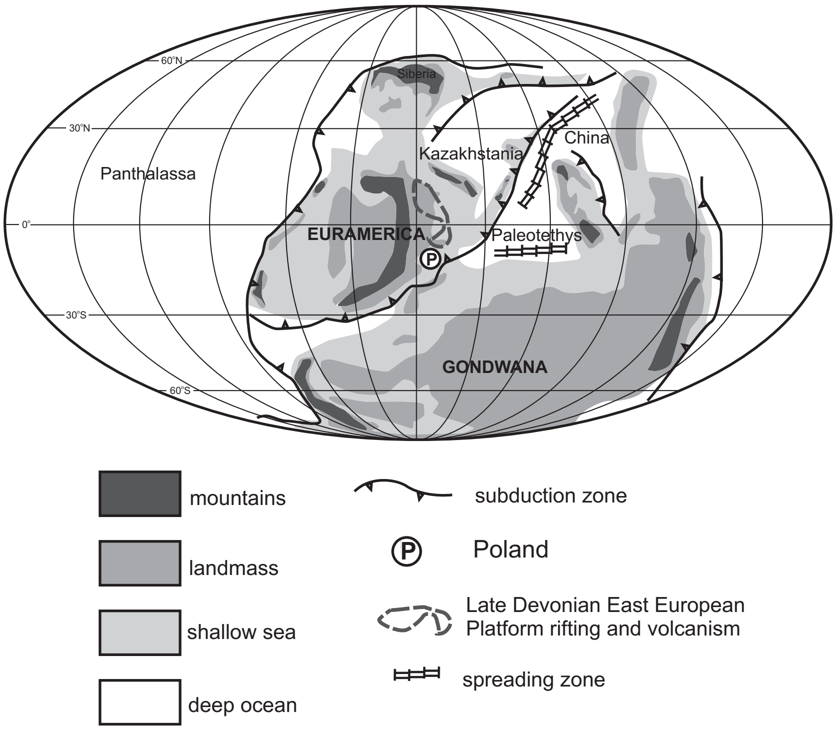


Fig. 2. Palaeogeographical reconstruction of the Late Devonian with the location of the southern part of the Polish Laurussian shelf (P), of subduction zones, and of Late Devonian rifting and volcanism affecting the East European Platform (after Pujol *et al.*, 2006).

chimski *et al.* (2009) from oxygen isotopes in apatite, the Early Devonian was characterised by warm temperatures of about 30°C. A cooling trend started in the Pragian, with intermediate temperatures of 23–25°C for the Middle Devonian. During the Frasnian (Frasnian and Frasnian/Famennian transition; 383–375 Ma), temperatures increased again, with average warm tropical temperatures of about 30°C. On the other hand, according to geochemical calculations of Pisarzowska (2009) for the Frasnian succession of the Wietrznia outcrop, the average temperature was 28°C, and temperatures decreased between the Early and Middle Frasnian from 28°C to 23°C.

In the marine environments, stromatoporoid/coral reefs flourished in the early Late Devonian (= Frasnian), building reefs in the HCM region (see above) and other areas (see Krebs, 1974; Kiessling, 2001; Kiessling *et al.*, 2003; George *et al.*, 2009). The reef ecosystem supports the reconstruction of warm tropical temperatures. In the present-day marine realm, the optimum temperature for the development of reefs ranges between 23°C and 29°C; similar temperatures seem reasonable for the Devonian HCM environment. In addition, microbial reefs and mud mounds started to flourish during the Frasnian and were present in many areas (see, for example, Tsien, 1988; Whalen *et al.*, 2002) as well as in the Holy Cross region (Szulczewski, 1971). As stressed by Joachimski *et al.* (2009), microbial reefs predominated during time-spans characterised by warm and very warm tropical sea surface temperatures – definitely with higher temperatures than the flourishing reef ecosystems characterised by rugose corals and stromatoporoids.

To sum up, the Late Devonian was characterised by greenhouse conditions and the study area was located in the southern tropics (Matyja, 1993; Kiessling *et al.*, 2003).

A large ocean was present in the Early Devonian around the equator, covering half of the globe. The ocean was situated east of China and Gondwana. The eastern tropical winds generated warm surface currents. Tropical hurricanes therefore must have traversed around the eastern part of Gondwana and in a smaller sea between Laurussia and Kazakhstania, and between Laurussia and Gondwana (Marsaglia & Klein, 1983). Major mixed hurricane/winter-storm zones were situated in both north-central and north-eastern Gondwana, southern Siberia and north-eastern China.

Table 2. Examples of Devonian storm deposits (modified after Marsaglia & Klein, 1983). R = probably of different origin; H = hurricane; W = winter storm; M = mixed winter storm and hurricane; T = tsunami. Grey-shaded =deposits from study area and nearest adjacent areas.

authors	storm type	palaeolatitude	location/formation	sediment type	sedimentary structures and/or textures
Carss & Carozzi (1965)	R	8°	Arrow Canyon Formation, Nevada, USA	carbonate	poorly to well sorted calcarenites; breccias and conglomerates
Folk (1973)	R	16°	Caballos Novaculite, Teksas, USA	carbonate/ siliciclastic	ripples; breccias, conglomerates; geopetal structures
Goldring & Bridges (1973)	R	15°	Mahatango Formation, Pennsylvania, U.S.A.;	siliciclastic	all:
	R	13°	Soneya Group, New York, U.S.A.;	siliciclastic	interbedded coarse (storm) and fine (fair-weather) beds;
	H	9°	Baggy Formation, U.K.;	siliciclastic	sharp base, gradational/burrowed tops; sublittoral sheet sandstone; escape burrows; wave-generated undulating lamination
	H	9°	Pilton Formation, U.K.;	siliciclastic	
	H	15°	Eifelian, Germany	siliciclastic	
Stel (1975)	M	26°	Upper La Vid Shale, Spain	carbonate	nodular limestones; differences in composition between tempestite beds and under- and overlying beds
Narkiewicz (1978)	no data	no data	southern Poland	carbonate	intraformational conglomerates; erosional base; grading; lamination
Kaźmierczak & Goldring (1978)	H/T	4°	Holy Cross Mountains, Poland	carbonate	considerable size of the flat pebbles and bioclasts derived from different offshore environments
Cant (1980)	H	22°	Arisaig Group, Canada	siliciclastic	sharp base; horizontal to low-angle lamination and HCS; coquinas; coarse and fine interbeds
Della-Favera (1982)	W	56°	Pimenteiras Formation, Brazil	siliciclastic	HCS
Harms *et al*. (1982)	H	15°	Esopus Formation, New York, U.S.A.	siliciclastic	HCS
Duke (1985)	H	14°	Oriskany–OnondagaTransition, Pennsylvania, U.S.A.	siliciclastic	HCS; amalgamation; sharp base; grading; medium to coarse sandstone
Dreesen *et al*. (1988)	H/T	~20°	Ardennes, NW Europe	carbonate/ siliciclastic	HCS; oolitic ironstones; coquinas
Schieber (1994)	no data	no data	Chattanoga Shale, Tennessee, U.S.A.	siliciclastic	erosion base; HCS; bioturbation of shales
Devleeschouwer *et al*. (2001)	no data	no data	Steinbruch Schmidt, Germany	carbonate	wavy lamination; erosional base; grading; distinct increase in thickness of layers and bioclast size
Hofmann & Keller (2006)	no data	no data	Santa Lucia Formation, Cantabrian Mountains, NW Spain	carbonate	poorly sorted crinoidal grainstone; rare amalgamation
Bábek *et al*. (2007)	no data	10-20°	Moravo – Silesian Basin, Czech Republic	carbonate	sharp bases, grading, wavy lamination; fine- to coarse-grained skeletal wackestone to packstone passing upwards into lime mudstone
Vierek (2007b)	no data	5–10°	Wietrznia, Holy Cross Mountains, Poland	carbonate	amalgamation; grading; wavy lamination, HCS; intraformational conglomerates and breccias, crinoidal limestones

For the Middle and Late Devonian (Fig. 2), the palaeogeography of the oceanic realm between Laurussia and Gondwana is not entirely clear; it is presented as being either a narrow oceanic domain (~400 km: Lewandowski, 2003) or a wide ocean (to 3000 km: Tait *et al.*, 2000). Apart from a wide oceanic domain between both margins, Laurussia and Gondwana, the areas were hurricane-influenced. This is confirmed by the Devonian sedimentary record (Table 2).

4. Diagnostic features of tempestites

Proximal tempestites represent storm deposits, formed by large waves and strong currents; they show evidence of disturbance of pre-existing sediments and rapid redeposition in shallow-water environments, and in deeper water below storm-wave base as diluted muddy tempestites (=distal tempestites; e.g., Walker, 1984; Einsele, 2000; Flügel, 2004; Karim, 2007). As summarized by Aigner (1985) and Myrow & Southard (1996), tempestites show much variation in thickness, grain size and internal structures, depending mainly on a proximal or distal position (Monaco, 1992; Molina *et al.*, 1997). In storm-affected basin fills, proximity criteria can be recognised at both lateral and/or vertical facies zones. In ascending order, ideal tempestites include: (1) sharp, often erosional bases with sole marks; (2) basal lags of coarse-grained reworked sediments, pebbles and skeletal grains; (3) graded basal parts overlain by parts with parallel laminae, hummocky structures, and/or cross-lamination; (4) mudstone units and post-event colonisation as well as reworking by organisms during following fair-weather intervals (Table 3).

Diagnostic features of tempestites and microfacies data in the Late Devonian deposits of the HCM have been described by the present author earlier (Vierek 2007a, b; 2010; Vierek & Racki, 2011). As stressed by Vierek (2007a, b), frequent storm events and storm-generated flows were the main cause of erosion and redeposition of coarse-grained lithofacies in the Wietrznia succession. The particular sedimentological analysis of tempestites shows between 13 and 21 different–scale storm events (see the review in Vierek & Racki, 2011, p. 6).

Table 3. Features of carbonate tempestites (after Aigner, 1985 and Myrow & Southard, 1996) and their presence in the Wietrznia succession, Kostomłoty-Mogiłki quarry and Górno outcrops.

tempestite features	Wietrznia	Kostomłoty–Mogiłki	Górno–Józefka	Górno field
proximal:				
– intra- and bioclasts	+	+	–	+
– flat-pebble conglomerate	+	+	–	+
– edgewise conglomerate fabric	+	+	–	–
– amalgamation	+	–	–	–
– lack of grading	+	–	–	+
– channel fills	+	+	–	–
normal/transitional:				
– sharp, erosional base with sole marks	+	+	+	+
– erosional contact between breccias and underlying micritic limestones	+	+	–	+
– basal lag of coarse-grained reworked sediments, pebbles and skeletal grains	+	–	–	+
– coquinas	–	–	+	+
– graded unit	+	+	+	+
– horizontal lamination	+	+	+	+
– wavy lamination and HCS	+	+	–	+
distal:				
– increasing number of tempestite beds	+	–	–	–
– thinner, finer and mud-dominated tempestite beds	+	–	–	+
– sharp and planar base	+	+	+	+
– lack basal lags	+	+	–	+
– bioturbation and/or burrowing	+	+	+	+

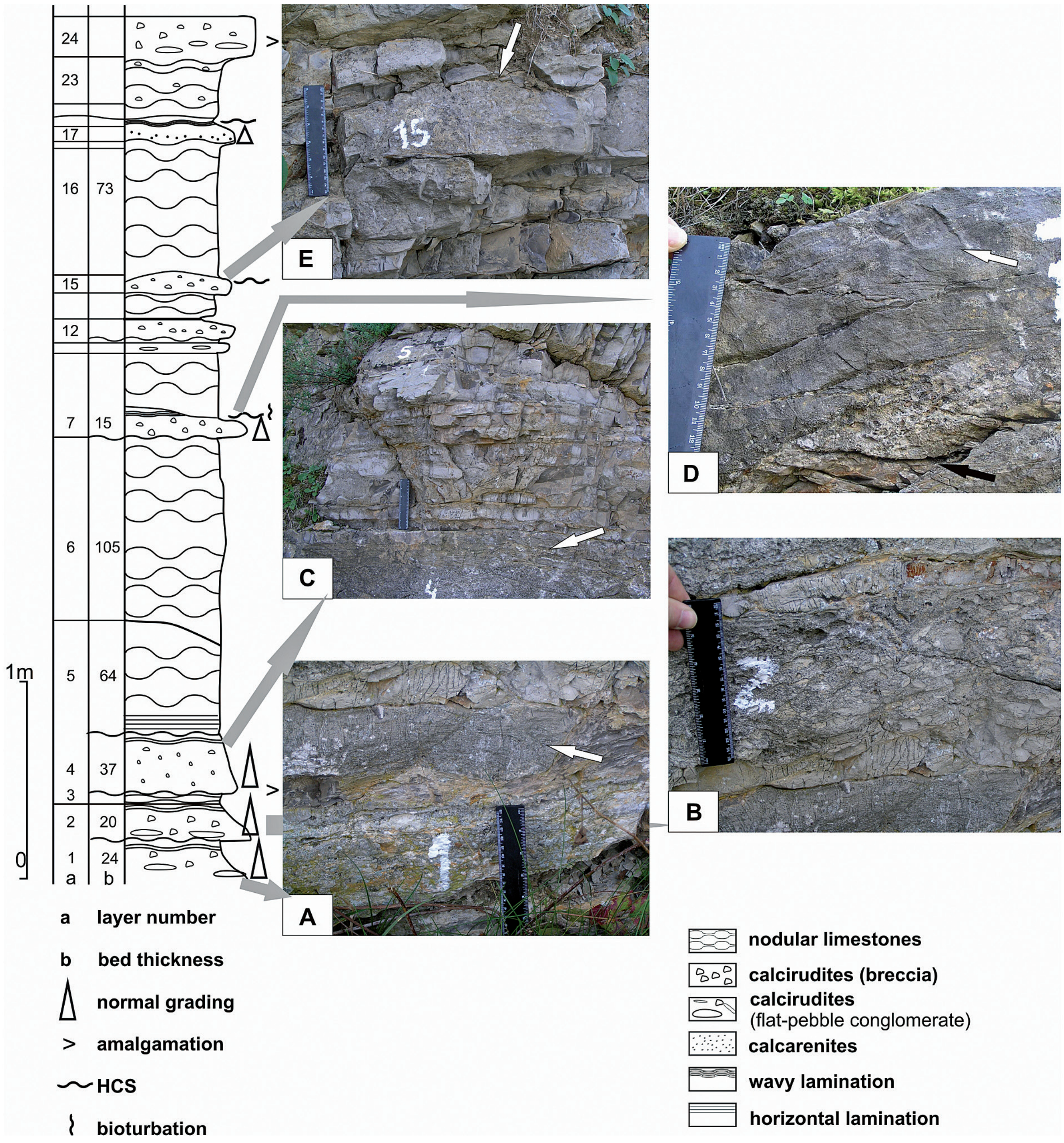
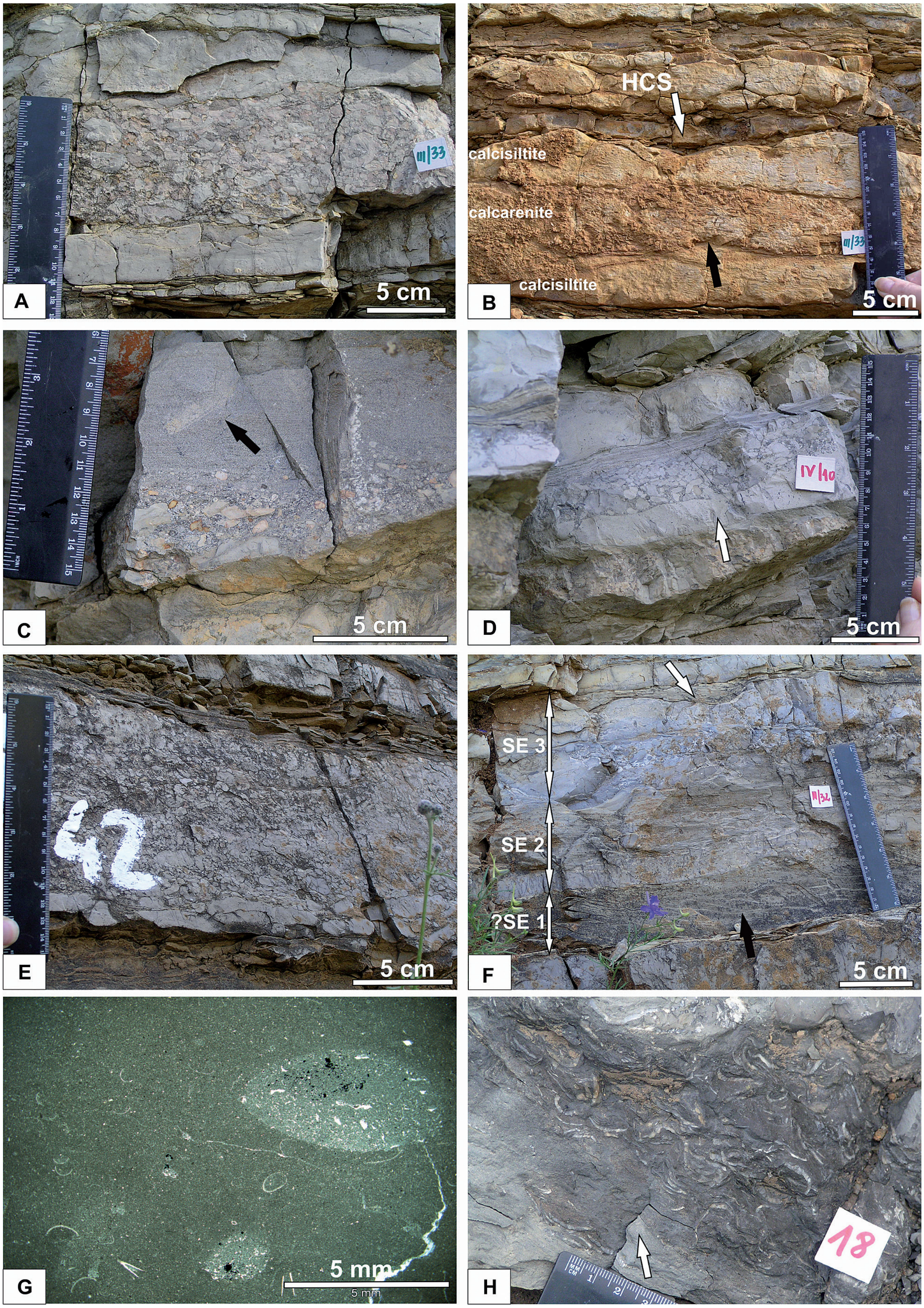


Fig. 3. The Górno-field exposure, with part of the succession (left).
A, B: Graded, conglomeratic and partly bioclastic layers (1 and 2); wavy lamination at the tops (arrow).
C: Thin-bedded micritic and partly nodular limestones; in the lower part graded calcarenites (layer 4) with cross-lamination at the top (arrow).
D: Tempestite layer 7 (compare Fig. 4 C) characterised by basal lags of coarse-grained reworked sediment and normal grading; black arrow shows erosional base with sole marks; the low-angle cross-lamination (white arrow) possibly represents part of hummocky cross-stratification.
E: Coarse-grained breccia with undulating top (arrow; layer 15).

Sedimentary structures and textures in the Kostomłoty Beds (Vierek, 2010) also shows that storms were likely the main causes of erosion of the Kielce carbonate-platform margin and slope (Table 3).

Newly studied sedimentary structures and sequences of tempestites in the Górno- field outcrop are described below. The textures and sedimentary structures in this quarry have been deformed by tectonics. Two layers show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C
5 cm
IV/40
D
5 cm
42
E
5 cm
SE 3
SE 2
?SE 1
II/32
F
5 cm
5 mm
G
18
H

a proximal-to-distal trend of tempestites over a distance of only some 20 m (Fig. 4 A, B). Their lithologies change from NE to S in the outcrop. Clast diameters, as well as thickness of coarse-grained layers decrease southwards. This is paired with appears hummocky structures and lamination. The sedimentological analysis of the succession shows at least 12 storm events (Figs. 3 and 4 F).

The thickness and grain size of the tempestite layers often differs considerably from that of the under- and overlying layers (Fig. 4 A, B). The grain size of tempestite varies greatly and their distribution tends to be bimodal with a coarser-grained succession at the base and, separated by a kind of small hiatus, a finer-grained top part (Einsele & Seilacher, 1991). The limestones are normally graded (Table 3; Figs 3 A-D and 4 C). However, the graded unit is often thin or lacking at all in relatively shallow water with high-energy conditions (Figs 3 E and 4 A); proximal tempestite facies have no muddy interbeds. Instead, amalgamation is characteristic. Examples of amalgamation are present, indeed, in the Górno-field (Fig. 4 D). These are thin calcirudite beds that have an erosional contact with the underlying micritic limestones. Locally, the tops of the calcirudites show horizontal or wavy lamination. As stressed by Duke (1985) (see also Dott & Bourgeois, 1982; Walker *et al.*, 1983; Einsele, 2000; Vierek, 2007b), these deposits reflect a decreasing wavy energy in comparison with the most proximal slope and characterised transitional (= normal) tempestites. In this site muddy intercalation increased.

Another feature of proximal tempestites is an erosional and sharp bottom contact with numerous sole marks (Fig. 3 D). Erosional surfaces vary in character – from flat, gently wavy to a distinctly U- or V-shaped depressions (Fig. 4 A, B, D, F, H). Basal lags include millimetre- to centimetre-sized micritic spherical clasts and coarse flat-shaped intraclasts (Figs 3 A, B and 4 C, E) as well as crinoid and brachiopod skeletal grains. The material is poorly or moderately sorted and shows several matrix- or grain-supported fabrics. Skeletal concentrations are common features in the upper part of the Szydłówek Beds in the Górno-Józefka quarry (Fig. 4 H; see also the coquina beds in Vierek, 2008). The graded coquinas composed of brachiopod shells and crinoid debris, characterised by erosional bases with sole marks, unstable position (convex-down) of shell and laminated tops, were deposited at approximately storm-wave base and are interpreted as tempestites.

On the tops of several layers, low-angle cross-lamination and hummocky cross-stratification (HCS) are characteristic features (Figs 3 A, C, D and 4 B, F); they indicate a high-energy current regime during deposition (e.g., Harms *et al.*, 1975; Kreisa, 1981; Dott & Bourgeois, 1982; Duke, 1985; Molina *et al.*, 1997). The upper boundaries are also undulating (Fig. 3 E). At larger water depths, where the water is more quiet, HCS becomes less distinct and is replaced by parallel and horizontal lamination that may indicate unidirectional currents (cf. Flügel, 2004, p. 596). The horizontal lamination is often disturbed by bioturbation (Fig.

Fig. 4. The Górno-field.

A, B: Layer III/33 exhibiting a proximal-to-distal trend; the most proximal part (**A**) has a coarse-grained character and a grain-supported fabric; the tempestite in intermediate position (**B**) shows an erosional base (black arrow) and hummocky structure at the top (white arrow); the grain size of the tempestite differs clearly from that of the under- and overlying layers.

C: Graded tempestite layer 7 (compare Fig. 3 D) showing a transition from bioclastic/conglomeratic to laminated micritic limestones; the arrow indicates bioturbation.

D: Breccia layer IV/10 with an erosional base (arrow) and horizontal lamination at the top; note irregular micritic intraclasts and grain-supported fabric.

E: Coarse-grained layer III/42 showing features of a most proximal, high-energy tempestite: grading, flat pebbles at the base and a grain-supported fabric.

F: Sedimentary structures supposed to be formed by ?three storm events of different intensity: the layers are amalgamated, but erosional bases between SE 1, SE 2 and SE 3 are visible; the black arrow indicates cross-lamination whereas the white arrow shows hummocky structure; note the abundance of intraclasts at the base of SE 3.

G: Bioturbated biomicrite background microfacies at Górno-field. Thin section II/22a.

H: Brachiopod shells arranged in random positions. The arrow indicates the erosional base; layer 18 in the Górno-Józefka outcrop.

4 C). Distal layers are thin, fine-grained and mud-dominated. Their bases are sharp, planar, and lacking basal lag deposits. The tops are burrowed and bioturbated (Fig. 4 G).

5. Discussion

5.1. Formation of tropical cyclones

As summarized by Bourrouilh–Lejan *et al.* (2007), the areas and depth affected by strong hurricanes and waves are the first 30 m of the upper shelf as well as shallow-water platforms. Storm systems have E-W directed zones that can climatically be called hurricane, winter storm, and mixed hurricane-and-winter storm zones (see table 1 in Marsaglia & Klein, 1983; see also Duke, 1985). At present, tropical hurricanes typically form in warm tropical seas (oceans) between 5° and 10° N (and with a lesser extent S). Sporadically they occur in both hemispheres between 10° and maximally 30°. Intense winter storms occur in turn, at middle and high latitudes (above 25°), forming along fronts between cold and warm air masses (see also Table 2).

Tropical hurricanes do not form over the equator (at least to 500 km S and N) due to the lack of influence of the Coriolis effect, which is required to develop wind rotation around the system (Nott, 2006, p. 78).

Several factors are necessary to generate hurricanes. The sea-surface temperature is the most important of them. It should be at least 27°C (Marsaglia & Klein, 1983) and reach a depth of 50 m (Nyoumura & Yamashita, 1984); only then hurricanes obtain sufficient energy. Nowadays, the strongest hurricanes are frequently formed at the western side of tropical seas and oceans, where warm water accumulates because of the movement of the ocean currents and eastern equatorial winds.

According to Bourrouilh-Lejan *et al.* (2007), the locations of hurricanes in tropical zones depend also on specific tropical biocenoses, such as coral reefs and green and red calcareous algae. Dynamic carbonate production (by the so-called carbonate factory) influences the precipitation of $CaCO_3$ and, on the other hand, intensifies transfer of CO_2 to the atmosphere (resulting in high atmospheric CO_2 levels). A specific barrier, which maintains a high temperature over reef ecosystems, is thus formed. However, study of the atmospheric CO_2 concentrations proves that these are not consistent with climate warming during the Frasnian. The GEOCARB III model (Berner & Kothavala, 2001) and data from Simon *et al.* (2007) indicate a decrease in pCO_2 during the Devonian, from 2000 ppm(v) in the Early Devonian to 900 ppm(v) in the Middle Devonian, and do not show an increase during the Frasnian.

To sum up, the palaeoclimate conditions with average temperatures reaching about 30 ^{0}C, and the palaeogeographical position of the HCM region in the Late Devonian between 5° and 10° S favoured influence of tropical hurricanes on the sedimentary record of carbonates. The carbonate platform of the HCM is a reef- and shoal-rimmed isolated platform with a relatively steep margin (Szulczewski, 1995; Vierek, 2007b). On such platforms, as on the modern Bahama Banks, intensive storm waves are particularly important in controlling depositional facies along the platform margins. The platform-margin reefs are partly isolated from full-marine conditions and form diverse environments. This results in a variety of carbonate deposits and in the presence of layers characterised by diverse sedimentary structures, as described above.

5.2. Tsunamis in the Late Devonian of the HCM region

Were tsunamis possible in the Late Devonian of the HCM region? Such an event must be considered fairly hypothetical; it has been suggested only by Kaźmierczak & Goldring (1978), but the sedimentological record does not support this hypothesis.

The shelf of Laurussia was characterised in the Late Devonian by an extensional regime. Subsidence successively increased and the Late Devonian epicontinental succession indicates continuous but punctuated drowning of the carbonate platform, which process became completed during the Visean (Szulczewski, 1995; Szulczewski *et al.*, 1996). Carbonate sedimentation of the study area then became controlled primarily by eustatic sea-level fluctuations, local tectonics and episodic subsidence (e.g., Narkiewicz, 1988) that might have caused tsunamis under favourable conditions. It should be realised, however, that tsunamis generated by earthquakes are extremely rare during extensional tectonics (cf. Kulberg *et al.*, 2001). Even if tectonic activity was low, slope failure of the Late Devonian isolated carbonated platform of the HCM region (see Vierek, 2007b) was, however, a possible trigger for tsunamis.

According to Racki & Narkiewicz (2000), tectonic activity occurred the Early and Late Frasnian, the Frasnian/Famennian transition and the Middle Famennian. Synsedimentary tectonics was, however, of only limited magnitude and deformed the sediments only locally.

The rate of subsidence of the HCM region during the Late Devonian was relatively low (approx. 25 m/Ma) but increased during the Frasnian (Racki & Narkiewicz, 2000). Additionally, the tectonic subsidence developed differently in the Łysogóry and Kielce regions and reflects locally block-related subsidence (Szulczewski, 1971; Racki & Narkiewicz, 2000). Previous works by Preat & Racki (1993) and Skompski & Szulczewski (2000) imply that sedimentation in the HCM region during the Givetian and Frasnian was primarily controlled by local subsidence. The subsidence rate was low during the Late Devonian, however, thus diminishing the possibility of locally generated tsunamis. The then position of the study area on a shelf probably excludes the occurrence of a tsunami because the water was too shallow.

On the other hand, however, one can hypothesize that activity in a subduction zone generated occasional tsunamis (Fig. 2; see also fig. 11 in Golonka, 2007). Such a wave would, however, not reach the present-day area of the HCM. As the shelf sea was characterised during the Late Devonian by different types of morphology. Inshore/offshore carbonate platforms were present over most of its extent (e.g., Narkiewicz & Racki, 1985; fig. 11 in Bełka *et al.*, 1996; Narkiewicz, 1996); the HCM region was surrounded by shallow water and by stable elevated areas: the Nida Platform, the Opatkowice Platform and the Cracow Platform to the South, and the elevated Lublin-Lviv area to the NE. Thus, tsunami energy should have been absorbed by these regions if tsunamites would have occurred.

Finally, tsunamis travel over long distances and affect large areas, so that their effects should be visible also in adjacent areas of the HCM region. The outer part of Laurussia shelf included an area from southern England through Belgium (Ardennes area), central Germany (Rhenish Massif and Harz Mountains) to southern Poland and Moravia (Bełka & Narkiewicz, 2008).

Yet, Dreesen *et al.* (1988) do not exclude the possibility of the a local Late Devonian tsunami generated in the unstable area of the Ardennes-Rhenish Massif, where seismic and volcanic activity often accompanied tectonic movements along fault blocks. Hladil & Kalvoda (1993) described episodes of intensive erosion and redeposition of breccia layers (Lowest Famennian, Moravia) and they connect this with a tsunami. The tectonic instability and volcanic activity in adjacent areas of the present-day HCM (the analysed part of the Laurussia shelf) thus seems related to the Frasnian/Famennian boundary, rather than to a possible tsunami.

6. Conclusions

The palaeoclimate conditions, with average temperatures of about 28 ^{0}C, and the palaeogeographical location of the Holy Cross Mountains region during the Late Devonian between 5° and 10° S favoured the influence of tropical hurricanes on the sedimentary environment and deposition of carbonate rocks.

The sedimentological observations as well as sedimentary structures and context of tempestites in the Wietrznia succession, the Kostomłoty-Mogiłki quarry and the Górno outcrops are evidence of storm events in the Late Devonian of the HCM region (Table 3).

The palaeogeographical position of the HCM area in the middle part of a carbonate shelf (= shallow-water environment) and between other platforms and elevated areas exclude the activity of tsunami waves, and thus of a tsunami-related sedimentary history of the limestones under study.

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