High-energy events in the Frasnian–Famennian boundary interval of the Płucki section in the Holy Cross Mountains, Poland

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Abstract

Of all the Devonian stratigraphic boundaries, the Frasnian–Famennian transition (372.2 ± 1.6 Ma) preserves the record of one of the most significant crises in the history of life, the final stages of which lie buried in the distinctive Kellwasser limestone. The Kellwasser facies occur in Western and Central Europe and the commonly cited Płucki area of Poland's geologically rich Holy Cross Mountains is the only site in that region where the Frasnian–Famennian boundary is considered to occur within Kellwasser facies. At this locality, the limestone contains slump structures, comprising contorted beds and folds. Actually the Kellwasser-like limestone from Płucki is composed of a mixture of three distinct types of sediment, occurring as clasts, commonly deformed and sheared, and matrix, rather than being one homogenous bed, as previously considered. Thus, earlier studies and interpretations of this limestone may need revising. This paper documents the evidence for sediment erosion and reworking, debris flows, sliding and soft-sediment deformation on a submarine slope, and suggests that seismic events were the likely triggering mechanism for slumping and resedimentation.

Keywords Kellwasser limestone · Slumps · Frasnian–Famennian boundary · Holy Cross Mountains · Tectonic activity

Introduction

The Devonian stratigraphic interval close to the Frasnian–Famennian boundary preserves the effects of one of the largest mass extinction events in the history of life: namely, the collapse of the stromatoporoid–coral reef biota, an overall breakdown of carbonate production as well as the disappearance of many nektonic species (e.g., House 2002; Bond et al. 2004; Racki 2005; McGhee 2013). It is also widely accepted that the causes of this mass extinction were Earth-related rather than a global cosmic catastrophe (Racki 1998, 2005; Ma et al. 2016; Racki et al. 2018).

In most stratigraphic sections, the Frasnian/Famennian boundary is characterized by the presence of Upper

Kellwasser facies (Bratton et al. 1999; Gereke and Schindler 2012; Rakociński et al. 2016), which have become the focus of attention. The bituminous limestone and black shale units of the Kellwasser facies are characterized by the occurrence of pelagic fossils. One of the best-known sections with a Kellwasser horizon occurs at Płucki in the Holy Cross Mountains, Poland, where many detailed analyses have been undertaken (Racki et al. 2002; Bond et al. 2004; Woroncowa-Marcinowska 2006).

The first account of the disturbed nature of the Upper Devonian deposits from the Płucki area was presented by Radwański and Roniewicz (1962), who described submarine slumps in the lower Famennian at Łagów (1 km from Płucki) and subsequently reported similar features from other locations in the Holy Cross Mountains (e.g., Szulczewski 1968, 1971, 1989; Kaźmierczak and Goldring 1978; Vierek 2007, 2013). These authors interpreted the mechanism for the initiation of slumps as a result of either tectonic activity or to the effect of storms.

Descriptions of the site in Płucki were provided by Sobolev (1912) and Czarnocki in the 1920s (general geology field notes, unpublished until 1989), and then by Makowski (1963, 1971). Dzik (1985) is credited with describing the

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rich fauna of goniatites that occur within the black bituminous limestone.

Details of the section exposed in Płucki were published by Szulczewski (1989), who was the first to employ the term “Upper Kellwasser Limestone” in reference to the black bituminous limestone which is found there. In the past 20 years, a number of different papers on the stratigraphy, geochemistry and paleontology of the site have been published (e.g., Ginter 1995, 2002; Ivanov and Ginter 1997; Dzik 2002, 2007; Filipiak 2002; Racki et al. 2002; Bond et al. 2004; Woroncowa-Marcinowska 2006; Janiszewska et al. 2007; Szrek 2007a, 2008; Dworczak and Szrek 2016). In particular, the Płucki locality is one of the richest for placoderm remains with about 500 specimens collected. This locality has also been the source of material for several scientific projects and MSc and PhD theses (e.g., K. Janiszewska unpub. M.Sc. thesis, Univ. of Warsaw, 2008; P. Szrek unpub. Ph.D. thesis, Univ. of Warsaw, 2009; P. Dworczak unpub. M.Sc. thesis, Adam Mickiewicz Univ., Poznań, 2016). All of the authors mentioned above have published numerous generalized and specific interpretations of this particular section but there are differences in their descriptions of the composition of the various lithological units (Fig. 1). In 2015, our field work revealed that the succession at Płucki is much more complicated than previously described, mainly because of the large lateral variability in the section as reflected by varying thicknesses of certain layers over distances of several meters (Figs. 3, 10). The aim of this article is to report new insights of the strata exposed.

Geological setting

The outcrop in Płucki near Łagów is located in the central part of the Holy Cross Mountains, about 36 km E of Kielce and 190 km S of Warsaw, (Fig. 2a) at GPS coordinates: 50°47'11.2"N, 21°04'39.1"E. The dip of the strata is about 32–36° toward the SSE.

The Płucki section is one of the key places to study the Upper Devonian of the Holy Cross Mountains. There are two outcrops located to the northeast of Łagów town on the southern slope of the Łagowica River Valley, which is geologically situated in the eastern part of the Kielce–Łagów Synclinorium. The Upper Devonian sequence, the so-called Łagów Beds (Sobolev 1912; Czarnocki 1950, 1989; Wolska 1967; Dzik 1985, 2006) in the Łagowica Valley, consists of a deep-water succession of more than 150 m of rhythmically bedded marly limestone and shale, deposited in the Łysogóry Basin (Racki 1993a, b; Fig. 2b). The Łagów Beds range stratigraphically from the Frasnian late *rhenana* Zone to the Famennian *triangularis* Zone (Racki et al. 2002).

The Lower and Upper Kellwasser horizons are both characterized by the occurrence of black bituminous

Fig. 1 Comparison of stratigraphic settings of the F/F transition in the Płucki locality (Holy Cross Mountains, Poland) performed (in order from the left to the right) by Racki et al. (2002, Fig. 6), Bond et al. (2004, Fig. 8), Woroncowa-Marcinowska (2006, Fig. 2) and Stachacz et al. (2016, Fig. 3). 1—marlstone interbedded with silty shale; 2—dolomitic limestone; 3—micritic limestone; 4—mudstone; 5—shale. Dotted line points to the most probable position of the Frasnian–Famennian boundary

limestones, which have been well dated based on conodonts. The origin of these two horizons is connected to anoxic episodes in the Late Devonian (Racki et al. 2002; Bond et al. 2004; Janiszewska et al. 2007; Szrek 2007a; Rakociński et al. 2016; Stachacz 2016).

The Upper Kellwasser horizon (Fig. 2c) is about 0.5-m thick and records several events that document a hiatus in the geological record (Janiszewska et al. 2007; Szrek 2007a; Szrek and Ginter 2008). The entire horizon is heterogeneous, with the Frasnian–Famennian boundary situated within the middle part, according to the precise analysis presented by Racki et al. (2002) and Janiszewska et al. (2007). Płucki was once referred to as a Lagerstätte (Szrek 2011), in view of the large number of well-preserved fossils found in this section, but the use of this term is widely considered to be a misinterpretation considering the fragmentary state of preservation (particularly the fish) and the lack of mineralized soft tissues. However, this horizon may still be called at least a Konzentrat-Lagerstätte.

Fig. 2 Location of the investigated outcrop in the Holy Cross Mountains. **a** Location map of the Holy Cross Mountains (HCM), central Poland (modified from Kowalczewski 1971). **b** Diagrammatic cross section through the Holy Cross Mountains from the Givetian to the top of the Upper Devonian (after Szulcowski 1995, modified) with the probable position of the localities investigated (1—marly limestone and shale; 2—condensed cephalopod and crinoidal limestone; 3—marly limestone; 4—bedded limestone; 5—calcirudite; 6—cephalopod limestone; 7—massive and bedded limestone; 8—clayey and marly shale; 9—dolomite). **c** General view of the outcrop; picture taken from the WNW. Arrow points to the Kellwasser-like horizon

Material and methods

With the aid of a heavy excavator, a new section was uncovered to a depth of 6 m and a width of more than 6 m (Fig. 2c). The section was washed with water and brushed thoroughly to reveal a particularly interesting surface, which has been further analyzed starting from the bottom of the marl that lies beneath the Upper Kellwasser horizon which was the deepest level in the outcrop due to the technical limitations of the excavator. For sedimentological analysis, 15 thin sections and 46 polished hand samples were prepared and studied under a transmitted-light microscope and

Fig. 3 Sketch of the approximately 6-m-high and 6-m-long cut with genetic units marked with arrows. Person in the picture is 176-cm tall

a cathodoluminescence microscope. The material used for analyses is housed in the Geological Museum of the Polish Geological Institute-National Research Institute, Warsaw.

Description

The succession at Plucki village consists of rhythmically bedded marly limestone and shale; it probably ranges from the Upper *rhenana* Zone to the undivided *triangularis* Zone (Racki et al. 2002). Five units have been distinguished in the section studied: (1) an undisturbed unit of marlstone interbedded with silty shale, (2) the Upper Kellwasser-like horizon, (3) a pinch-and-swell horizon, (4) a slump roll and sheet unit, and (5) an upper undisturbed unit of marlstone interbedded with silty shale (Fig. 3).

Unit 1: Marlstone interbedded with silty shale

The lowest unit exposed consists of marlstone, beds around 10-cm thick, interbedded with silty shale, up to 5-cm thick. Horizontal lamination occurs in both lithological types; however, some marlstone is slightly bioturbated (Stachacz et al. 2016). The thickness of this unit visible in the outcrop is about 1 m but exposures nearby suggest a total thickness of about 20 m (Racki et al. 2002).

Unit 2: Upper Kellwasser-like horizon

The Kellwasser-like horizon is in total about 0.5-m thick (Fig. 4) and is characterized by the occurrence of erosional surfaces, current-oriented and fragmented nautiloids (Szrek and Ginter 2007, Figs. 4b, 8) and goniatite shells

Fig. 4 Details of Unit 2, the Upper Kellwasser-like part of the section. **a** Kellwasser-like horizon (the hammer lying on the floor of the Kellwasser package). **b1–3** Cross section through the Kellwasser-like limestone showing its internal structure (all three pictures show true

thickness of the horizon but have been taken in different places within it). **c** Specimen showing a clast of the black fossiliferous limestone in a dolomitic non-fossiliferous limestone

(Janiszewska et al. 2007). The oriented nautiloids demonstrate a NEE direction of palaeocurrents. The lower, entirely Frasnian part (up to 30 cm) is characterized from bottom to top by a marl which rapidly and abruptly changes upwards into micritic limestone (Fig. 1). The middle segment of almost 10-cm thickness shows the highest concentration of fossils, particularly of cephalopods and minute arthrodire placoderms. According to the precise analysis of Janiszewska et al. (2007), the Frasnian–Famennian boundary is situated within this part of the horizon (Fig. 1). The uppermost 10 cm belong entirely to the basal Famennian and is characterized by numerous invertebrate and fish fossils. Locally, the upper part of the Kellwasser-like horizon is subdivided

by thin, irregular ferrous crusts. The internal structure of the Kellwasser-like horizon is characterized by the occurrence of a breccia-like structure (Fig. 4b1–3, c), composed of three lithological varieties (Figs. 5a–c, 6a, b): (1) compact black, fossiliferous limestone, (2) black limestone with few or no fossils, both occurring as clasts, and (3) weakly cemented, dark-brown dolomitic limestone. These microfacies types occur in varying proportions depending on their positions within the unit. Sizes of clasts vary from a few mm to several cm. Their shredded–sheared character is well recognizable and occurs exclusively within the upper part of the Unit 2. Compact black, fossiliferous limestone usually occurs in a form of pebbles. Within these, most of the small fossils

Fig. 5 Selected thin sections of Unit 2, the Upper Kellwasser-like horizon. **A** (transmitted light), **A1** (cathodoluminescence)—nautiloid shell fill with dolomitic limestone (1) and black, fossiliferous lime-

stone (2) in fossiliferous limestone (3); **b**—placoderm bone fragment (1) filled partially with dolomitic limestone (2) and fossiliferous limestone (3)

have been found, unlike the weakly cemented, dark-brown dolomitic limestone, where large bones (up to 30 cm long) and cephalopod fragments are very common. Apart from fossils within the weakly cemented, dark-brown dolomitic

limestone, nodules composed of compact black, fossiliferous limestone are present and they are usually cracked.

The fossils found in the Upper Kellwasser-like horizon are generally well preserved, especially the small

Fig. 6 Geopetal structure within the cross section of a nautiloid shell. **a** General picture of the specimen. **b** Thin section of the part with nautiloid shell, rotated and filled with sediment at different stages (1–5)

invertebrates. The horizon contains, apart from the described pelagic cephalopods (Makowski 1971; Dzik 1985; Woroncowa-Marcinowska 2006), many benthic elements such as bivalves and brachiopods (Szrek and Ginter 2007) and likewise several bottom-dwelling fish (Dworczak and Szrek 2016). Within the brachiopods and nautiloids, geopetal structures in rotated positions have been frequently observed (Fig. 6).

Numerous vertebrate remains are represented mainly by arthrodire placoderms and show various states of preservation, reflecting their history before subsequent burial (Szrek and Wilk 2018). Most of the fragments are disarticulated and show marks of abrasion (Fig. 7a). The only articulated specimens are represented by skull-roofs and belong to small individuals (comp. Ivanov and Ginter 1997, Fig. 4a). Several samples contain rare disarticulated elements. The remains of large placoderms, whose heads reached more than 0.5 m in length, are always disarticulated and show signs of mechanical damage prior to fossilization (Szrek and Wilk 2018, Figs. 1, 2, 3, 4 and 5), manifested by the

occurrence of numerous fractured and broken bones surrounded by sediment (Fig. 7a).

Within the assembled vertebrate remains, there are two distinct types of preservation (Szrek *in press*). The first is characterized by a relatively good state of almost fully articulated skeletons (Ivanov and Ginter 1997, Fig. 4a) and/or associations of disarticulated remains of smaller placoderms. The second type of preservation consists of fragments of larger disarticulated placoderms, characterized by broken and abraded plates (Fig. 7a; Szrek and Wilk 2018, Figs. 1, 2, 3, 4, 5). Notably, almost all of these armored nektonic fish remains are found in the dark-brown limestone rather than in the black limestone, which in contrast contains diverse invertebrates. Another common bioclast within the brown limestone of the Upper Kellwasser-like horizon is represented by styliolinids and tentaculites within the brown limestone (Fig. 7c).

Above the Upper Kellwasser-like horizon (units 3–5), fossils are much less numerous or are totally absent, and comprise only pelagic invertebrates.

Fig. 7 Placoderm remains fragmented during slumping and/or reworking. **a** A part of a median dorsal plate of a large representative of the placoderm *Dunkleosteus*, with the side covered with abraded fossiliferous dolomitic limestone full of orthocone nautiloids; the

clast is prepared from the dark-brown sediment from the Upper Kellwasser-like horizon. **b** Surface of placoderm plate corroded and covered with sediment; **c** Magnified area marked on A with numerous, oriented tentaculitids

Unit 3: pinch-and-swell-like structures

The beds directly above contrast sharply with the Kellwasser-like horizon since they are composed mostly of micritic limestone, marly limestone and silty shale (see also Woroncowa-Marcinowska 2006). Unit 3 is about 30-cm thick (4A) and consists of three beds of micritic limestone nodules with surrounding silty shale (Figs. 4a, 8). The lower and middle layers of the unit consist of thin (less than 10 cm) horizons composed of nodules embedded in dark shale. The nodules are arranged horizontally at a distance of about 5 cm from each other (Fig. 8). Nodules are asymmetric, with dimensions varying from 5 to 20 cm in length and 4–12 cm in thickness. In cross section, they usually have a pillow-like

Fig. 8 Pinch-and-swell structures within shale and limestone above the Upper Kellwasser-like horizon

oval shape, which is locally deformed into a more irregular shape. The nodules have sharp boundaries with the surrounding dark shale. Traced laterally over half a meter, the nodules are disconnected with a few cm between each. The internal structure of the nodules is characterized by a homogenous lower part with a lamination that is folded laterally upwards. In a few samples, the nodules contain no lamination but are fractured with dark shale in the cracks.

The upper part of unit 3 is less than 10-cm thick and is characterized by the presence of reworked pebbles of fossiliferous black limestone in a dark-gray limestone.

Unit 4: slump rolls and sheets

Unit 3 with the limestone nodules is followed by Unit 4 consisting of highly disturbed beds of about 4 m in thickness of micritic limestone alternating with shale 10–20-cm thick (Figs. 3, 9). The disturbances include folds, as well as dismembered layers and nodules with geopetal structures in various positions preserved within brachiopod and nautiloid shells (Figs. 6, 9a). The folds incorporate

individual limestone beds which thicken in the region of the overfolds (Fig. 9a) which usually end the bed's continuity (Fig. 10a, b). Where beds are disrupted, the original horizontal lamination disappears and internal laminae become disordered (Fig. 9c). Fold axes are commonly oriented at about 26° to NNE and suggest a southeasterly movement. Thickness variability is apparent in this part of the section and in some places, the beds decrease in thickness from 70 to 0 cm over a distance of 2 m (Fig. 10). Some features (e.g., fold-axis orientation, southern convergence of their axial surfaces and slices and, additionally directions based on nautiloid shells) have a SSE orientation which fits the reconstructed current direction based on the study of adjacent nautiloid shells (Szrek and Ginter 2007, Fig. 8) which is longitudinal to down-slope. The shale intercalated within the limestone beds has also been strongly folded, with the continuity of the limestone beds not interrupted or broken. The thickness of shale varies from several tens of cm to zero. The original lamination in the shale is poorly visible or absent. In places where shale reaches more than 10 cm in thickness, rounded and structureless clasts of limestone as large as 10 cm are present.

Fig. 9 a Details of the slump deformations in the section. a Slump-folded part of a limestone bed with a thinner flank towards the WNW (left) and a thicker limb towards the ESE (right); the original horizontal lamination has disappeared

Unit 5: undisturbed marly limestone beds and shale

Up to 1-m thickness, Unit 5 is observed at the top of the excavation. In this part of the section, there are no folds or disturbances, apart from subtle variations in bed thickness from tectonic shearing.

Discussion

The Frasnian–Famennian biodiversity crisis is especially well recorded in reef development and its eventual collapse. Before the crisis, reefs (in general terms) covered 5000,000 km² globally (McGhee 2013); whereas after, reefs survived to cover only around 5000 km² (Copper 1994; McGhee 2013). This reduction is also visible in the fossil record of the Holy Cross Mountains, where all bioherms disappeared by the end of the Frasnian and tectonic activity caused unconformities, stratigraphic gaps and synsedimentary block-faulting in the Famennian deposits (e.g., Szulczewski 1971; Racki 1993a, 1998; Racki and Baliński 1998; Skompski and Szulczewski 2000; Racki et al. 2002; Fig. 2b). Thus, the final disappearance of reef organisms in the Holy Cross Mountains most probably resulted from depth changes caused by tectonic movements, along with anoxia in restricted basins.

The recent excavations of the Płucki section have allowed the further study of the site's lateral variability of lithology, which has been given little attention in the past. Now, the Upper Kellwasser-like horizon can be more thoroughly analyzed in several cross sections at 6–7-m distance. The deformations described above resulted from synsedimentary submarine movements and are manifested by the disintegration and redeposition of sediments and plastic deformation (Figs. 3, 4b, c, 6, 10, 11), as discussed below.

The succession at Płucki is interpreted to be the result of three major synsedimentary resedimentation events (see Figs. 3, 10, 11), affecting the Upper Kellwasser-like horizon (Unit 2), the pinch-and-swell horizon (Unit 3), and the limestone with slump rolls and sheets (Unit 4).

The Upper Kellwasser-like horizon occurs within the slope of the deep-shelf part of the Łysogóry Basin of the Holy Cross Mountains and is regarded as a shallower sedimentary environment than the rest of the profile which is represented by deep-shelf Łagów Beds (Rakociński et al. 2016). Redeposition of the material may be a reason for the occurrence of shallow-water sediments. This is supported by conodont biofacies which change from a deeper-water environment in the *linguiformis* Zone to a shallower one in the Early *triangularis* Zone (Matyja and Narkiewicz 1992, 1995). At Płucki this change was noted by previous authors (e.g., Racki et al. 2002; Janiszewska et al. 2007). For the equivalent-age Janczyce I section (about 20 km from Płucki),

Matyja and Narkiewicz (1992) postulated that shallow-water faunal elements represented autochthonous constituents during eustatic shallowing. For the Płucki section, the shallowing resulted in in situ reworking of the sediments and the origin of the internal structure of the Kellwasser-like horizon. Such a scenario is plausible for homogenous sediment without any trace of redeposition. Such conditions are not observed for the discussed horizon in Płucki. In our opinion, instead of sea-level change (not excluded totally), more influential is redeposition of shallower-water sediment to the deeper part of the basin on the slope. The composition and internal structure of this horizon suggest that the dark-brown limestone as well as the black fossiliferous and non-fossiliferous dolomitic limestone were transported en masse from the shallower part of the basin, because they usually contain abraded clasts in a form of conglomerate (Figs. 4b, c, 6). The already identified source area for redeposited deposits was located in the western part of the region (around Kielce city; 36 km from Płucki), where shallow-water fossiliferous facies (including subaerial exposure features) have been documented (e.g., Szulczewski 1971; Skompski and Szulczewski 2000). However, it has not been fully resolved that this area was the source for the Płucki area. Within the debris flows, dolomitic limestone fragments were combined as they traveled with dark-brown partially lithified limestone and were finally deposited as a sheet of black sediment with clasts of black dolomitic limestone embedded in dark-brown limestone. Black dolomitic limestone must have been partially lithified when the slump process was triggered; whereas, the brown limestone still exhibited its loose nature, confirmed by the numerous broken margins and jagged shapes of clasts (Fig. 4b, c). Geopetal structures also point to transport with shells of brachiopods or nautiloids being filled with dolomitic sediment (Figs. 5, 6). This suggests that such shells must have been lying buried below the seafloor for some time, while calcite was precipitated in cavities inside the shell. Afterwards, they were transported (possibly within the slump) and rotated to different orientations (Fig. 6). The presence of dolomitic limestone pebbles and clasts in the Kellwasser-like horizon suggests erosion and reworking in the source area. The Kellwasser-like horizon (Unit 2), the pinch-and-swell horizon (Unit 3) and the slumped Unit 4 above, could have been formed during separate seismic events. Thus, the slump character of the most of the sections studied (Racki et al. 2002, Fig. 9; Bond et al. 2004, Fig. 8; Woroncowa-Marcinowska 2006, Fig. 2; Stachacz et al. 2016, Fig. 3) resulted in great lateral variability. Logs presented by previous authors are difficult to correlate since different section lines were accessible over the years of study. Wider exposure shows that one horizon may end over a very short distance of a few cm as described above.

The interpretation of three slump horizons in the Płucki section complements similar phenomena described by

Fig. 10 **a** Detailed picture of the Plucki cut with a sketch showing the interpretation **(b)** of the structures discussed (see also Fig. 3)

Szulczewski (1968, Figs. 3, 4) and Kazmierczak and Goldering (1978). They described large blocks of limestone and slump sheets in a Frasnian section at Kowala (about 40 km from Płucki), along with reef-derived clasts. The occurrence of the breccia horizon at the Frasnian–Famennian boundary in Płucki fits with other reports of a “pseudo-brecciated” lower part to the first bed of the Famennian situated at the top of the Upper Kellwasser Horizon (Szulczewski 1971; Schindler 1990, 1993; Racki et al. 2002; Gereke and Schindler 2012). The difference is that in Płucki, the “pseudo-brecciation” encompasses the entire Upper Kellwasser-like horizon, including the Frasnian part.

In view of the features of the fossils, particularly the vertebrates, it is probable that their remains were transported over a geographically significant distance. The Kellwasser-like horizon is the only place in the profile where a large diversity of this fauna is identified.

The Kellwasser limestone generally consists of several dark-gray and black bioclastic wacke-/packstone beds (e.g., Buggisch 1991; Joachimski et al. 2001). The thickness of these horizons globally ranges between a few cm and more than 2 m. The Lower Kellwasser Limestone occurs in the Frasnian *rhenana* Zone and the Upper Kellwasser Limestone at the Frasnian–Famennian boundary (*linguiformis*–*trangularis* transition). In view of this, we conclude that the horizon exposed at Płucki does not meet all the requirements and so should be named as a Upper Kellwasser-like horizon. Despite being at the same stratigraphic position, the horizon in Płucki represents a redeposited assemblage of different carbonate facies and cannot be precisely determined as Upper Kellwasser limestone (Joachimski and Buggisch 1993).

Also interesting and geologically significant is how the pinch-and-swell horizon (Unit 3) shows syndimentary deformation which is similar to ball-and-pillow structure but differs from these by the lack of loading into the underlying bed (Knaust 2002). Deformation structures attributed to seismic activity include ball-and-pillow structures (Porter and Pettijohn 1963), pseudonodules and cycloids (Hempton and Dewey 1983), pinch-and-swell structures, and lenticular boudins, pocket-and-pillar structures (Postma 1983), flame-like structures (Visser and Cunningham 1981) and sedimentary dykes. Pinch-and-swell structures result from necking when a stiff layer and its weaker matrix are subject to layer-parallel extension or layer-normal shortening (Schmalholz et al. 2008; Knaust 2002). The deformation mechanism affecting Unit 3 limestones is characterized by a lack of significant vertical loading into underlying beds and only minor horizontal disruptions of parts of the otherwise intact bed. This is atypical for the mechanism that leads to the development of ball-and-pillow structures and pseudonodules and cannot be explained by slumping on a slope. The structures at Płucki identified as pinch-and-swell structures

are different from those described by Knaust (2002) from the Middle Triassic of Thuringia, Germany, mostly in their much smaller sizes when compared to the threshold of 10 cm of the longer axis at Płucki. Our interpretation of the origin of this horizon is that the poorly lithified limestones were disturbed by an earthquake, which initiated extension and separation of the horizon into smaller loaf-shaped fragments, which reshuffled the sedimentary strata together. In view of the well-preserved interior lamination of the nodules, which has not been rotated or erased, transportation and subsequent rotation might be excluded, such that an in situ origin of this deformation is likely for the Płucki example. Similar-sized structures have been described by Scott and Price (1988), Dugué (1995) and Calvo et al. (1998). Radwanski and Roniewicz (1962, pl. 15, Figs. 1, 2), reported similar pebble-like pseudonodules, and interpreted their origin as a result of a disruption and then a dip of the layer fragments. Such seismic structures have been described from siliciclastic successions, but deformational structures attributed to seismic liquefaction and/or fluidization have also been reported from shallow-marine carbonate successions (Cisne 1986; Pratt 1994; Pope et al. 1997; Spalluto et al. 2007; Mastrogiacomo et al. 2012).

The strongly deformed beds occurring in Unit 4 above the pinch-and-swell horizon are typical slump features with folds, rolls, multiplications (slices) and the discontinuity of beds. Imbrication of the limestone layers is common for slump deposits. Similar structures have been reported from many sites around the world in many formations including: Waterhouse and Bradley (1957, Paleogene of New Zealand), Radwanski and Roniewicz (1962, Upper Devonian of the Holy Cross Mountains, Poland), Tucker (1973, Upper Devonian of Germany), Spreng (1967, Carboniferous of Arkansas, USA), Szulczewski (1968, Upper Devonian of the Holy Cross Mountains, Poland), Gill (1979, Carboniferous of Ireland), in part, by Knaust (2002, Triassic of Germany) and by Alberti et al. (2017, Jurassic of north India).

Since the plastic deformation in Unit 4 involved the whole 4-m-thick limestone-shale package above the pinch-and-swell horizon (Unit 3), we maintain that this resulted from a single slump event.

Taking into consideration all the aforementioned described geological features, a timeline for the section's deposition can be outlined as follows (Fig. 11a–e): First, the Upper Kellwasser-like horizon (Unit 2) was deposited as a series of slumps of semi-consolidated black, bituminous limestone and dolomitic limestone aggregated with dark-brown grainy limestone (Fig. 11b). The succeeding Unit 3 limestone intercalated with shale (Fig. 11c) was disturbed during an earthquake to develop pinch-and-swell-like structures (Fig. 11d). This was followed by a major slump depositing the deformed limestone shale of Unit 4 (Fig. 11e). The previously reported fragmentation of invertebrate shells

Fig. 11 Schematic diagrams showing successive stages in the evolution of the Plucki section. **a** Initial stage with an undisturbed Łagów beds on a deep-marine shelf on the right and sedimentation of fossiliferous and non-fossiliferous dolomitic limestone in shallower-water area—Unit 1. **b** First slump event leads to the deposition of the Upper Kellwasser-like horizon—Unit 2. **c** Calm sedimentation above the Upper Kellwasser-like horizon. **d** A seismic event leads to the destabilization of the 20-cm-thick unit and to the origin of the pinch-and-swell structures—Unit 3. **e** Second slump event leads to deposition of the deformed unit with slump rolls and sheets—Unit 4

(Rakociński et al. 2016), the occurrence of discontinuity levels (Janiszewska et al. 2007), and the above-described breccia structure of the Upper Kellwasser-like horizon with numerous abraded bones and fragments, all suggest transportation and reworking, before final deposition. The state of bone preservation differs from fragmentary fish remains affected by posthumous decomposition, which are typically disarticulated with no trace of transport. Such examples are known from contemporary deposits of the area discussed by Szrek (2004, 2007b). The abundance of fossils also supports redeposition; however, it may also have been the result of a faunal bloom. The high diversity of invertebrates (brachiopods, trilobites, bivalves, gastropods, tentaculites, cephalopods), conodonts and vertebrates represented by placoderms, chondrichthyans and actinopterygians (see, Szrek and Ginter 2008: Table 1) suggests a range of environments where these animals lived and from where their remains came.

While the ultimate causes of the occurrences of the numerous submarine slumps within the Upper Devonian of the Holy Cross Mountains (Radwański and Roniewicz 1962; Szulczewski 1968, 1971) have not been finally determined, Szulczewski (1971, 1989), Kaźmierczak and Goldring (1978), Szulczewski et al. (1996) and Skompski and Szulczewski (2000) attributed these features to tectonic activity and associated earthquakes. Near the end of the Frasnian, the carbonate complex disintegrated, with local, uplifted and eroded blocks. Since the cause of triggering mechanisms is not preserved in the sedimentary record (Shanmugam 2016), the arguments for a tectonic cause come from an analysis of the regional development of the Frasnian strata in the southern part of the Holy Cross Mountains. However, this concerns exclusively the pinch-and-swell horizon which especially shows characters indicating an origin directly related to earthquake activity. The Kellwasser horizon and the slump-and-rolls part of the section do not present any feature that could exclude storms or more generally stronger wave activity, as the triggering mechanism which led to the initiation of the slump.

The stratigraphic position of tectonic events at the Plucki section documented by slumps correlates with evidence from radiometric dating of tectonically deformed strata from other sites world-wide (e.g., Averbuch et al. 2005; McGhee 2013), demonstrating that the Late Devonian was

a period of intense tectonic activity (Racki 1998; McGhee 2013). This resulted from the collision of major continental crustal blocks: Laurussia, Gondwana, Kazakhstan and Siberia during the so-called Acadian-EoVariscan mountain building event (Averbuch et al. 2005; Racki et al. 2018) over the course of about 50 million years. In the Holy Cross Mountains, this tectonic activity resulted in the fragmentation of an extensive carbonate platform into blocks, as documented by three generations of neptunian dykes and deeper hydrothermal mineralization (Szulczewski 1973; Szulczewski et al. 1996), and most demonstrably as facies differentiation (Sobolev 1912; Szulczewski 1971, 1989). This tectonic activation is also linked with intraformational erosional pulses, manifested by coarse breccias and conglomerates (Radwański and Roniewicz 1962; Szulczewski 1968, 1971; Racki 1993a, b, 1999). Extensional block-tilting led to rapidly uplifted areas (reefs, shelf carbonates) on one side, and steepened slopes and deepening basins on the other. As uplifted areas were eroded, associated earthquakes in combination with steep slopes provided the seismic and gravitational energy for rapid, chaotic transport and redeposition. Intensive erosion and redeposition of breccia layers in the lowermost Famennian has also been described from Moravia (Czech Republic; Hladil and Kalvoda 1993) and attributed to a tsunami. The influence of storms on the origin of such deposits has been discussed mainly by Kaźmierczak and Goldring (1978), Racki (1993a), Racki and Narkiewicz (2000) and Vierek (2007, 2013). The Late Devonian of the Holy Cross Mountains was characterized by a tropical climate (Matyja 1993; Vierek 2013). The palaeoclimatic conditions with tropical temperatures, together with the palaeogeographical position of the Holy Cross Mountains, would have favored the influence of tropical high-energy events (hurricanes, storms) on the fossil record.

The influence of the slump within the Upper Kellwasser-like horizon on fossil preservation has resulted in positive conditions for study despite their fragmentation (for details see Szrek *in press*). The transport of the sediment, which contained fossils from shallower and well-oxidized parts of the basin, to deeper, anoxic conditions, probably allowed the preservation of most of the minuscule remaining fragments.

Conclusions

Recent observations suggest that the assumed continuity of strata of the Plucki section must be reconsidered and, moreover, previous conclusions based on this locality need to be revisited as the diverse nature of these sections has never been adequately explained. The new data from the debris flow and slump structures described from Plucki provide the first evidence for syndimentary disturbances within the profile and demonstrate episodic re-sedimentation.

Numerous imbrications of beds as the result of a major slump and changes in thickness may have had an influence on results of previous studies dealing with detailed stratigraphic, geochemical and geophysical investigations. Sampling within the slumped unit in different locations may have led to spurious and confusing results depending on the sample site (Fig. 1).

The overall stratigraphic framework for the Plucki section reveals a generally continuity of beds. The age of sediments involved in slump events is confined to within one conodont Zone, including resedimentation over a relatively short period of time. The mixed character of the Kellwasser horizon and the section generally prohibits the use of the term “Upper Kellwasser Limestone” (*sensu e.g.*, Klapper et al. 1993). This horizon at Plucki can be regarded, at least, as a “Time-Specific Facies” (Gereke and Schindler 2012).

Thus, the Upper Kellwasser-like horizon from Plucki cannot be considered suitable for studying the causes of the supposed anoxia in the context of the mass extinction that occurred at the Frasnian–Famennian boundary.

In the light of the available data, it is difficult to decide explicitly whether seismic or storm/tsunami wave activity was the triggering mechanism of the slumps and resedimentation.

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