

# Origin and resedimentation of rhodoliths in the Late Paleocene flysch of the Polish Outer Carpathians

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**Abstract** This study analyses the rhodolith-bearing deposits in the largest and most rhodolith-rich outcrop of the Polish Outer Carpathian flysch, located in the Silesian Nappe, at the village of Melsztyń. The rhodoliths and sparse associated biota occur as resedimented components in a deep-marine succession of siliciclastic conglomerates and coarse-grained sandstones, deposited by high-density turbidity currents and debris flows. The sediment was derived from a fan-delta system located at the southern margin of the Silesian flysch basin. Stratigraphic data indicate that the succession represents the Upper Isteńska Sandstone deposited during the Late Paleocene. The rhodoliths are composed mostly of coralline red algae with seven genera and eight species representing the family Sporolithaceae and the subfamilies Mastophoroideae and Melobesioideae. Rhodoliths show sub-spheroidal and sub-ellipsoidal shapes with encrusting, warty and lumpy growth forms. Lumpy growth forms show massive inner arrangements, whereas the encrusting growth forms are usually made of thin thalli and show more loosely packed inner

arrangements. The rhodoliths grew on a moderately mobile siliciclastic substrate in a shallow-marine environment with a low net sedimentation rate. It is inferred that the growth of rhodoliths was favored during a relative sea-level rise. During the subsequent sea-level fall, the rhodoliths and associated siliciclastic deposits were resedimented by gravity flows into the deep-sea setting. The analyzed deposits, like other Paleocene–Eocene deposits of the Polish Outer Carpathians, provide no evidence of coeval widespread shallow-marine carbonate sedimentation along the margins of the Outer Carpathian flysch basins.

**Keywords** Rhodoliths · Flysch · Depositional model · Paleocene · Silesian Nappe · Polish Carpathians

## Introduction

The Polish Outer Carpathians are the northernmost segment of Europe's Alpine orogenic belt. They comprise several tectono-stratigraphic units stacked upon one another as rootless nappes and thrust over the Neogene foredeep and the underlying European Platform (see Książkiewicz 1977). The nappes consist of latest Jurassic–Early Miocene deep-marine deposits, mainly siliciclastic, referred to as 'flysch' (Książkiewicz 1975; Geroch and Nowak 1984; Olszewska 1997). The flysch successions have been extensively studied, but much less known are the conditions in coastal and shallow-marine environments of the basin margins. Some authors have suggested periodic development of carbonate platforms along the margins (Rajchel and Myszkowska 1998b; Cieszkowski et al. 2003; Golonka et al. 2003, 2005), but no evidence of widespread carbonate sedimentation has thus far been found. A valuable insight in basin-margin conditions is provided by

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contemporaneous resedimented components, such as shallow-marine biota and carbonate clasts found in the flysch, particularly in its sandstones and paraconglomerates.

Poorly diversified, shallow-water carbonate debris, frequently coralline algae, occurs commonly in the Paleogene flysch of the Polish Carpathians. The debris occurs as a resedimented component in gravity-flow deposits (Golonka 1974; Leszczyński 1978; Rajchel and Myszkowska 1998a, b; Golonka et al. 2005), except for slivers of sedimentary cover within tectonic klippe near Andrychów (Książkiewicz 1951). Much less common are rhodoliths as well as pebbles and cobbles of coralline algal limestones (Leszczyński 1978; Bassi et al. 2000; Leszczyński et al. 2005). Only in the Inner Carpathians to the south do coralline algal limestones occur in situ in an Eocene transgressive succession (Malecki 1956). Detailed studies of Paleogene rhodoliths have generally been limited to occurrences in Upper Eocene to Oligocene strata, mainly in the Mediterranean region. Resedimented rhodoliths in flysch and the taxonomy of coralline algae from such deposits have seldom been investigated (Leszczyński 1978; Stockar 2000; Puga-Bernabéu et al. 2009).

The present study focuses on an abundant occurrence of rhodoliths in the Paleocene flysch of the central segment of the Silesian Nappe, cropping out at the village of Melsztyn (Fig. 1). The resedimented rhodoliths are the main carbonate component of the generally siliciclastic mass-flow deposits. The outcrop section is the largest exposure of a rhodolith-bearing flysch in the Polish Outer Carpathians, and also the richest in rhodoliths, providing a unique material for sedimentological and taxonomic analysis.

The aims of the study are: (a) to assess the depositional setting of the deep-marine sedimentary succession from its stratigraphic development; (b) interpret the depositional conditions of the mixed siliciclastic-carbonate sediment in its parental shallow-marine environment; (c) to improve the sparse existing knowledge on the range of basin-margin paleoenvironments in the Polish Outer Carpathians; and (d) to review the existing data on coralline algae in the Polish Carpathian flysch and discuss factors controlling their formation. Previous data (Leszczyński and Kołodziej 2004; Leszczyński et al. 2005) are supplemented with new field observations, biostratigraphic evidence and a detailed study of the rhodoliths.

## Geological setting

The Silesian Nappe is one of the main thrust-sheets of the Polish Outer Carpathians (Fig. 1a). It is bordered to the south by the thrust-folded Fore-Magura Group, the Dukla Nappe and locally by the Magura Nappe, whereas to the north it is thrust over the Sub-Silesian Nappe. The Late

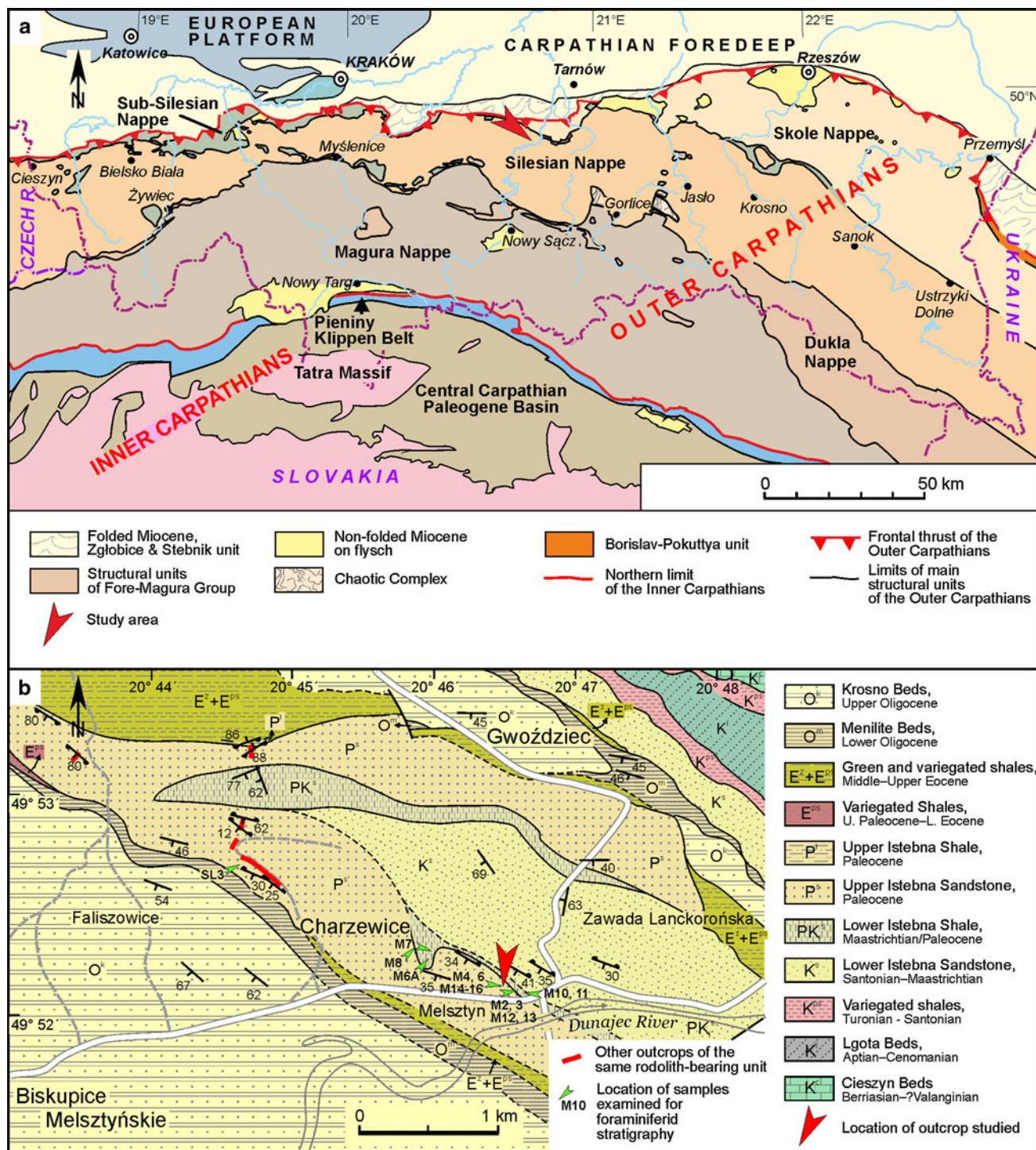
Cretaceous–Oligocene sedimentary succession of the Silesian Nappe, including the studied outcrop section (Fig. 2), was deposited in a deep-water sub-basin of the Carpathian Flysch Sea, referred to as the Silesian Basin (Książkiewicz 1975).

The Silesian Basin was bordered to the south by an intrabasinal ridge, originally called the Silesian Cordillera (Książkiewicz 1956) and more recently referred to as the Silesian Ridge. To the north, the basin was bordered by a ridge known as the Sub-Silesian Cordillera or Sub-Silesian Ridge (Koszarski and Żytko 1965; Fig. 3). The Silesian Ridge was uplifted in the Late Cretaceous to Paleocene time, during the Laramian phase of the Alpine orogeny. The uplift is reflected in the greater thickness and sediment coarseness of the Coniacian–Lower Eocene part of the flysch succession, particularly in the Silesian Nappe (Bieda et al. 1963; Unrug 1968). Paleocurrent directions in this part of the succession indicate sediment derivation mainly from the Silesian Ridge on the southern side of the basin (Książkiewicz 1962; Unrug 1963; Leszczyński 1981).

Sedimentary facies and their distribution suggest deposition in a system of coalescing basin-floor fans (Dziadzio et al. 2005). The increased supply of coarse-clastic sediment from the south indicates an elevated, tectonically active basin margin. In Campanian to Early Eocene time, the Istebsna Beds and the overlying Ciężkowice Sandstone were deposited in nearly the whole Silesian Basin. The studied outcrop section is in the north-central part of the Silesian Nappe, where the Istebsna Beds and the overlying Ciężkowice Sandstone show many lithofacies similarities and hence are often difficult to distinguish from each other in small, isolated outcrops. The deposits described here were included by Koszarski and Kuciński (1966) in the Lower Istebsna Sandstone (i.e., the lower part of the Istebsna Beds of the Silesian Nappe) and were ascribed a Senonian age (Bieda et al. 1963; Koszarski 1985), but without any supporting stratigraphic evidence. The data from the present study indicate that these deposits belong to the Upper Istebsna Sandstone and represent the Upper Paleocene.

## Materials and methods

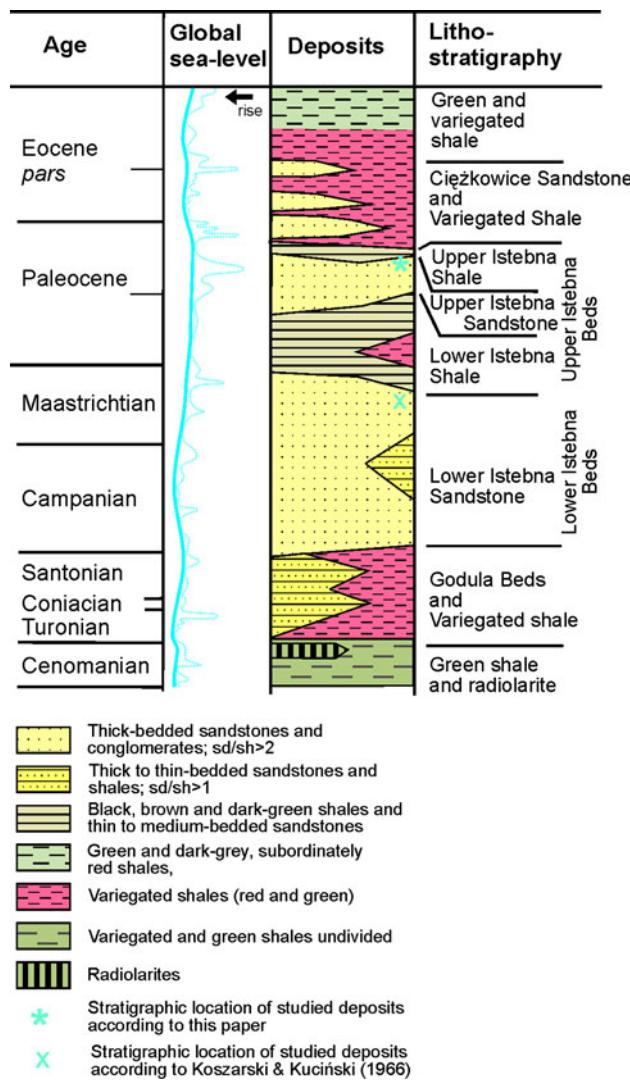
The field study was carried out in an outcrop section on the eastern slope of the castle hill in Melsztyn (Fig. 1b). The outcrop section is 170 m wide and up to 20 m high, showing a 16-m succession of sandstone and pebbly conglomerate beds (Fig. 4a). In order to understand better the sedimentary succession, it was mapped in strike-parallel direction in a 1.5-km zone over a distance of 4 km towards the northwest. The rhodolith-bearing deposits, up to 11 m thick, form an indistinctly bedded unit (composite



**Fig. 1** Location of the outcrop section studied (arrow). **a** Tectonic map of the Polish Carpathians (modified from Książkiewicz 1972). **b** Geological map of the study area (after Koszarski and Kuciński 1966, modified in the area near the Melsztyn village)

bed sensu Wood and Smith 1959) extending over the whole width of the outcrop. The most detailed investigation was done with the use of a climbing rope in the outcrop part directly below the southern margin of the castle ruins, where the deposits are richest in rhodoliths. The texture, mineral composition, and primary structure of deposits

were documented in the whole outcrop section. The size, shape, and internal structure of rhodoliths were studied in selected fresh rock samples and also in loose blocks fallen from the outcrop wall. Samples of the best preserved and most representative rhodolith varieties were taken for laboratory analysis.



**Fig. 2** Stratigraphy of the Late Cretaceous–Eocene sedimentary succession of the Silesian Nappe of the Polish Outer Carpathians (modified from Koszarski 1985). Global sea-level curve after Haq et al. (1988)

Foraminifera were analyzed in five samples of rip-up mudstone clasts from the rhodolith-bearing deposits, nine samples of mudshales from a stratigraphically adjacent part of the outcrop section (ca. 10–15 m below the rhodolith-bearing deposits), and seven thin sections of three limestone clasts from the rhodolith-bearing deposits (Fig. 1b). The foraminiferal analyses of fine-grained deposits were performed on samples disaggregated with Glaubert's salt and subsequently washed through a 63- $\mu\text{m}$  screen sieve. The laboratory study included analysis of the size, shape and internal structure of rhodoliths in six polished slabs and in 30 thin-sections of isolated rhodoliths. Thin-section analysis included also the content and distribution of fossils, microfacies, the mineral and textural composition of rhodolith-bearing sediment, and the characteristics of mudstone intraclasts.

The descriptive terminology for coralline algae growth-forms follows Woelkerling et al. (1993). The family and subfamily circumscriptions are according to Woelkerling (1988), Braga et al. (1993, 2010), Aguirre and Braga (1998), and Braga (2003). The study has taken into account all basic taxonomic uncertainties concerning fossil coralline algae, as discussed by Braga et al. (1993), Braga and Aguirre (1995), Rasser and Piller (1999), Bassi and Nebelsick (2000) and Iryu et al. (2009).

The field study with sampling was carried out by the first two authors (S.L. and B.K.), the analysis of coralline algae was done by the third author (D.B.), whereas the two other authors (E.M. and M.A.G.) analyzed the associated foraminifera assemblages.

## Results

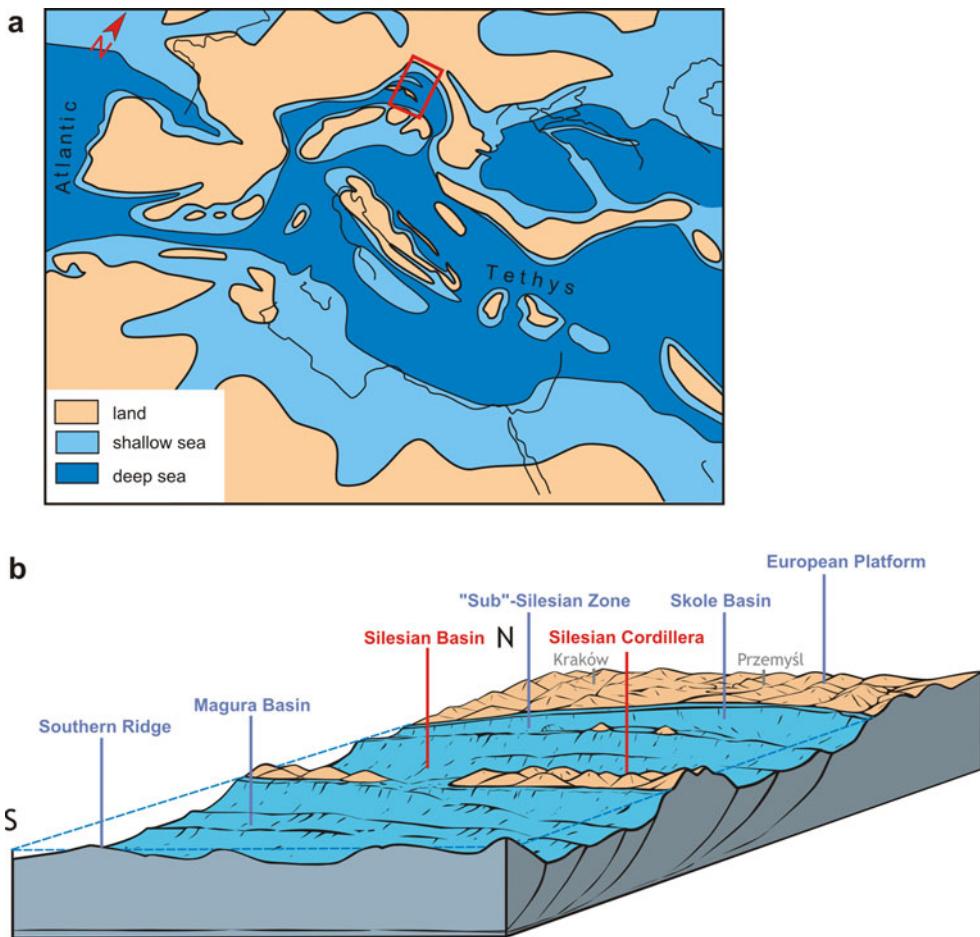
### The rhodolith-bearing flysch exposed in Melsztyn

The flysch succession in the outcrop section contains a composite bed (*sensu* Wood and Smith 1959) nearly 4 m thick composed of siliciclastic, granule-bearing to pebbly sandstone that grades upwards into a coarse-grained sandstone with calcitic cement patches (Fig. 4a). The patchy cementation makes sandstone pseudo-nodules stand out from the weathered rock surface. The nodules tend to be aligned parallel to bedding but locally show stock-like vertical grouping. Pebbles are up to 1 cm in size and, like the sand and silt fraction, consist mainly of quartz. Feldspar and mica are subordinate components of the sand and silt fraction, and the sandstone has a low mud content. The base of the bed is hidden by talus, whereas its top is uneven, erosional.

The overlying deposits are a package of indistinct and laterally discontinuous layers of pebble conglomerate and coarse-grained sandstone, rich in rhodoliths (Fig. 4). This rhodolith-bearing unit is 11 m thick and its component layers, up to 2 m thick, are massive (non-stratified) and seem to show normal or inverse grading or virtually lack grain-size grading. The normal-graded layers, are commonly underlain by non-graded ones and contain few rhodoliths, whereas the inversely graded layers, up to 40 cm thick, are rich in rhodoliths, whose abundance also increases upwards. The layer richest in rhodoliths occurs in the middle of the package, is non-graded, and nearly 2 m thick.

The abundance of rhodoliths thus varies from layer to layer and also laterally within the layers, and the rhodolith-rich deposits generally contain carbonate cement. The rhodolith-poor layers tend to be richer in mud and show little or no carbonate cement. The groundmass is dominated by light-grey quartz and the quartz pebbles are up to

**Fig. 3** Paleogeographic location of the study area. **a** Paleocene paleogeography of the European segment of the Tethys and adjoining areas (compiled from Ricou et al. 1986; Dercourt et al. 2000; Vlahović et al. 2005). The red rectangle indicates area shown in b. **b** Sedimentary basins of the Polish Outer Carpathians in the Paleocene



3.5 cm in size. Intraformational rip-up clasts of brown to blackish-brown or dark-grey mudstone are up to 1 m in length, some with sandy interlaminæ or thin laminated interbeds. The rip-up clasts tend to dip towards the southwest, which may suggest imbrications and transport direction towards the northeast. Pebble- to cobble-sized ?sideritic clasts occur mainly in the lower part of the rhodolith-bearing package.

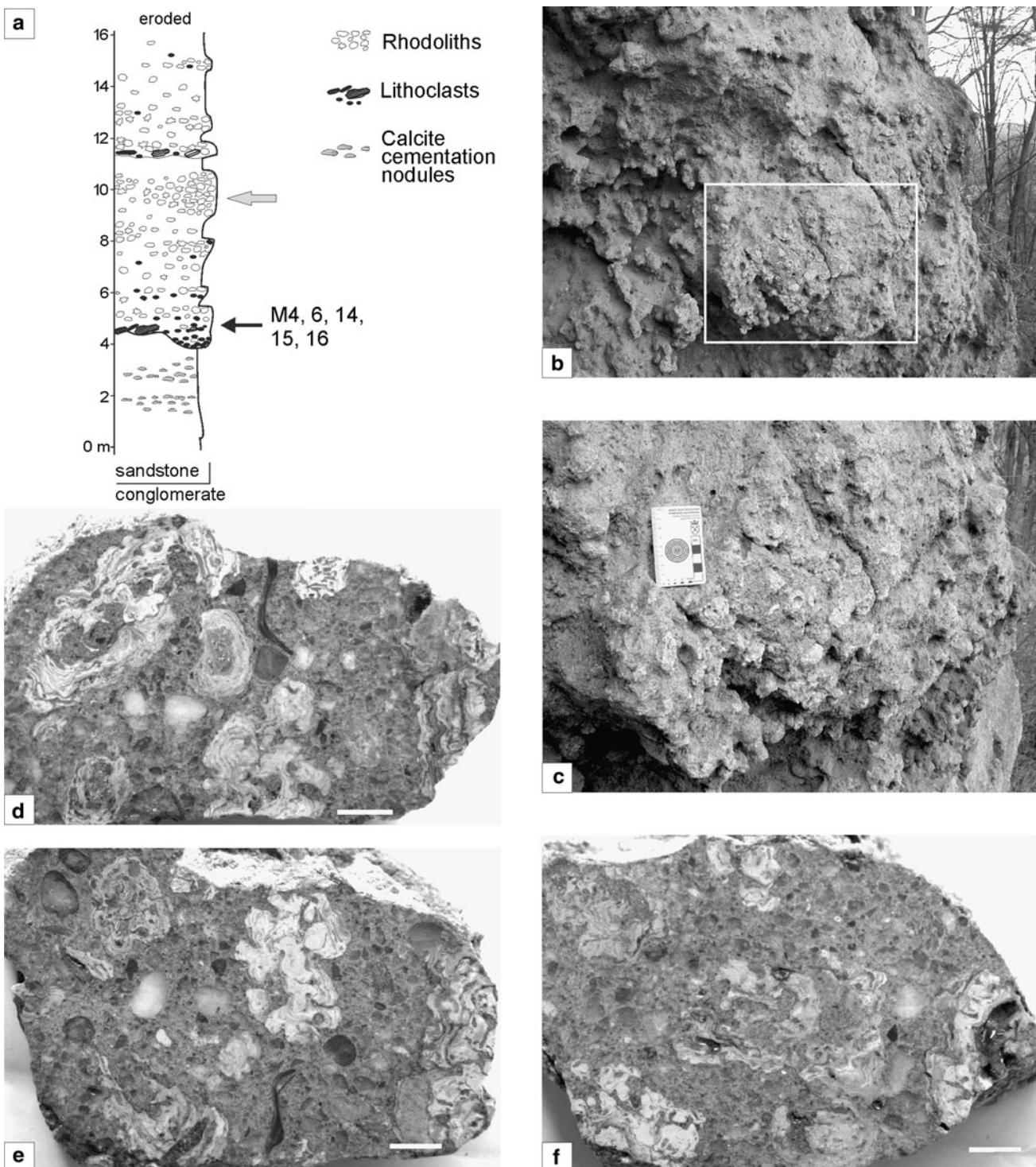
The local mapping has shown that the rhodolith-bearing deposits are cropping out at several other localities up to 3.5 km away from the outcrop in Melsztyn (Fig. 1b). These other outcrops are in a stream bed and banks, up to 2 m high and 50 m long, and show deposits similar to those exposed in Melsztyn.

#### Underlying and overlying deposits

Deposits underlying the rhodolith-bearing coarse-grained succession are poorly exposed in Melsztyn, covered with talus, and accessible nearby in only two small outcrops in the valley below. The closest outcrop is ~50 m away to the southeast and stratigraphically ~10 m below the outcrop section studied

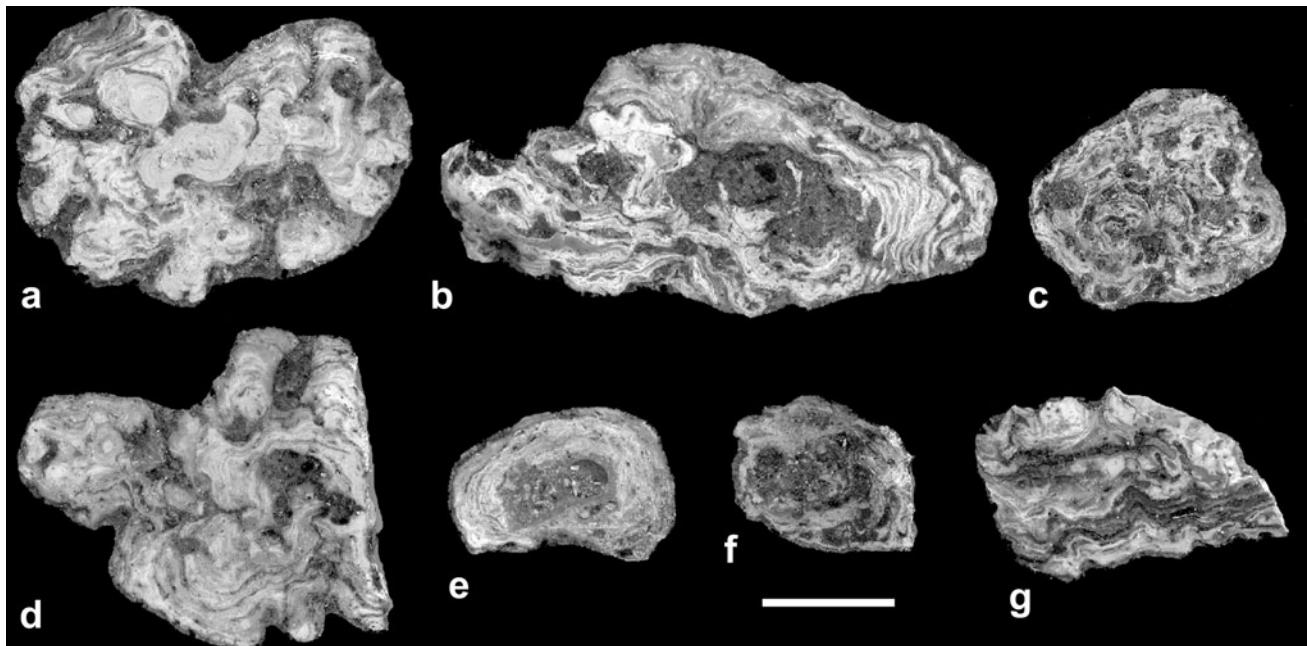
in Melsztyn. It shows greenish-grey mudshales interbedded with thin sandstone beds, but the exposed stratigraphic thickness is only ~1 m. The other outcrop, located ~50 m to the southeast from the former, shows faulted and variably tilted grey to dark-grey mud- and clayshales with rare thin sandstone interbeds, and a total exposed stratigraphic thickness of ~4 m. This outcrop section is estimated to be located ca. 5 m below that of the former outcrop.

Other outcrops of the deposits underlying the rhodolith-bearing succession are as far away as 0.7 km to the west and 2.3–2.5 km to the northwest (coordinates N: 49°52'54.66" to 49°53'3.6", E: 20°44'26.86" to 20°44'31.41"). Except for the outcrops at the passage to the coarse-grained, rhodolith-bearing deposits and one 6-m-thick package where thick-bedded sandstones interbedded with mudshales occur, they show dark greenish-grey clayey to silty shales with thin sandstone and siderite interbeds. The exposed stratigraphic thicknesses range from 50 cm to several tens of meters. Exact thickness in the widest outcrop (almost 360 m) is unclear as the deposits show tectonic tilting and brecciation indicative of thrust faulting. The deposits in the widest outcrop form the core of an anticline.



**Fig. 4** Lithofacies and stratigraphic position of the rhodolith-bearing flysch succession (the Late Paleocene Upper Istebsna Sandstone, Silesian Nappe, Polish Outer Carpathians). **a** Generalized lithofacies log and stratigraphic position of the flysch succession in Melsztyn. The grey arrow points to the bed segment shown in **b** and the black arrow indicates the location of samples collected from mudstone intraclasts for foraminiferid biostratigraphy. **b** Close-up view of the distribution of rhodoliths (marked as white spots and nodules) in a

siliciclastic matrix. The *white rectangle* indicates outcrop detail shown in **c**. **c** Indistinct cluster of rhodoliths. **d** Rhodoliths of different sizes and spheroidal to sub-ellipsoidal shapes occur embedded in a siliciclastic matrix. **e** Rhodoliths showing lumpy and warty growth forms. **f** Rhodoliths showing growth-form development from encrusting to lumpy; the inner void spaces in rhodoliths are filled with siliciclastic sediment. Scale bar 1 cm



**Fig. 5** Polished surfaces of the studied Upper Paleocene rhodoliths. **a–d** Laminar, sub-ellipsoidal rhodoliths with loosely packed inner structure and encrusting to lumpy growth-forms. **e–f** Massive sub-

spheroidal rhodoliths with encrusting growth forms. **g** Fragment of a rhodolith showing a thick laminar succession of superimposed encrusting thalli. Scale bar 1 cm

As to the deposits overlying the rhodolith-bearing succession in Melsztyn, their nearest outcrop is ~2.9 km to the northwest (coordinates N: 49°53'3.6", E: 20°44'31.41") and stratigraphically just above this succession. Their exposed thickness is several tens of meters. In the lower, 4-m-thick part of the section, these are dark-grey mudshales and clayshales. The higher part of the section is built of variegated (mainly red) mudshales and clayshales.

#### Rhodoliths and coralline algal debris

Rhodoliths and coralline algal debris are the most abundant carbonate components (up to 90 %) of the analyzed rhodolith-bearing sandstones and conglomerates exposed in Melsztyn.

Two types of rhodoliths were distinguished (Figs. 4d–f, 5): (1) abundant sub-ellipsoidal laminar rhodoliths with a looser internal packing, but few constructional voids; and (2) common sub-spheroidal rhodoliths with a massive, well-packed interior. They are mainly 2.5–3.5 cm in size, with a maximum diameter of 6 cm, and their growth-form ranges from encrusting to warty or lumpy.

The laminar rhodoliths show common encrusting, warty and lumpy growth-forms, with the outer surface commonly made of lumpy thalli. The massive rhodoliths are characterized by common encrusting and rare warty coralline growth forms; the last growth stage of these rhodoliths typically consists of encrusting thalli. However, in both

rhodolith shapes growth-form successions from encrusting to lumpy or vice versa are quite common.

Asymmetrical inner arrangements are dominant, but symmetrical ones are also present (Figs. 4d–f, 5). The asymmetry is usually greatest in the inner part of the rhodolith and decreases outwards. The rhodolith nuclei are relatively small and consist of an infilling of siliciclastic material or rarely of massive coralline thallus, coral, or mollusc shell. Siliciclastic matrix also fills the inner voids of rhodoliths.

The assemblage of coralline red algae consists of the family Sporolithaceae and the subfamilies Mastophoroidae and Melobesioideae (Table 1; Figs. 6, 7). The predominant coralline taxa are *Sporolithon* Heydrich (*S.* sp. A), *Lithothamnion* Heydrich (*L.* sp. A, *L.* sp. B) and *Mesophyllum* Lemoine (*M.* sp. A). Subordinate taxa are *Karpathia* Maslov (Bassi et al. 2005), *Spongites* Kützing (*S.* sp. A), *Neogoniolithon* Setchell and Mason (*N. cf. contii* (Mastrorilli) Quaranta, Vannucci & Basso), and *Lithoporella* Foslie (*L.* sp. A) and the peyssonneliaceous *Polystrata alba* (Pfender) Denizot, 1968. Rhodoliths can be multi-generic (no more than two genera) and multispecific (no more than two species). Monogeneric rhodoliths consist of *Sporolithon* sp. A and *Lithothamnion* sp. B. Accessory components of the rhodoliths include bryozoans, serpulids (relatively common and large in size), and encrusting foraminifera (acervulinids, planorbulinids).

The rhodoliths commonly show borings, with smooth rounded outlines in cross-sections, in four diameter ranges:

**Table 1** Identification key of the coralline algal genera and species recognized in the Late Paleocene rhodoliths in the Melsztyn flysch succession, Silesian Nappe, Polish Outer Carpathians

1. Calcified compartments, sori	<b>SPOROLITHALES</b>
1. Conceptacles	<b>CORALLINALES</b>
<b>SPOROLITHALES, SPOROLITHACEAE</b>	
1. Numerous sporangial compartments per sori	
2. Sporangial compartments elliptical in section, 40–45 µm in ID × 70–80 µm in IH	<i>Sporolithon</i> sp. A
<b>CORALLINALES</b>	
1. Sporangial conceptacles uniporate	<b>CORALLINACEAE</b>
1. Sporangial conceptacles multiporate	<b>HAPALIDIACEAE</b>
<b>CORALLINACEAE, Mastophoroideae</b> (cell fusions as predominant interfilamentous cell connections)	
1. Thallus dimerous	2
1. Thallus monomerous	3
2. Thallus with a conspicuous ventral layer of palisade-cell filaments	<i>Lithoporella</i> sp.
2. Thallus with a ventral layer of large, irregular cells	<i>Karpathia</i> sp.
3. Coaxial ventral core through most of the thallus	4
4. Thick coaxial ventral core, conceptacles 600–630 µm in ID × 170–190 µm in IH	<i>Neogoniolithon</i> cf. <i>contii</i> (Mastrorilli) Quaranta, Vannucci & Basso
3. Non-coaxial ventral core	5
5. Encrusting plants, thin plumose ventral core, sub-ellipsoidal conceptacles (~230 µm in ID × 100 µm in IH)	<i>Spongites</i> sp. A
<b>HAPALIDIACEAE, Melobesioideae</b>	
1. Ventral core coaxial through most of the thallus	<i>Mesophyllum</i> sp. A
1. Ventral core non-coaxial	2
2. Epithelial cells unknown	3
3. Lumpy plants, conceptacles >350 µm in ID	<i>Lithothamnion</i> sp. A
3. Encrusting plants, ventral core very thin, conceptacles <350 µm in ID	<i>Lithothamnion</i> sp. B

Note that the listed features are not themselves diagnostic of the taxa included in the key. *ID* internal diameter, *IH* internal height

0.07, 0.12–0.1, 0.4–0.6, 2.0 mm. Some borings show irregularly shaped, single or multiple, smooth-walled, oval chambers corresponding to the ichnogenus *Entobia* (Fig. 8a). Networks of branching micro-galleries with irregular changes in diameter between 0.10 and 0.20 mm can be ascribed to the activities of fungi, algae, bacteria, and/or sponges (Fig. 8b). Two galleries occasionally converge in a Y-shape pattern, and the borings in some cases seem to extend from the inner to the outer part of the rhodolith. Some borings enclose foraminifera, which may belong to the sedimentary infill or represent the boring forms or cavity dwellers (coelobites; see Schlagintweit 2005).

#### Bioclasts and algal limestone pebbles

Bioclasts consist mainly of coralline algal debris which is usually smaller than 1 cm, representing parts of fruticose and lumpy plants as well as superimposed encrusting thalli associated with other encrusting organisms. The coralline algal debris is invariably abraded, composed mainly of *Mesophyllum*, *Lithothamnion*, and *Sporolithon*.

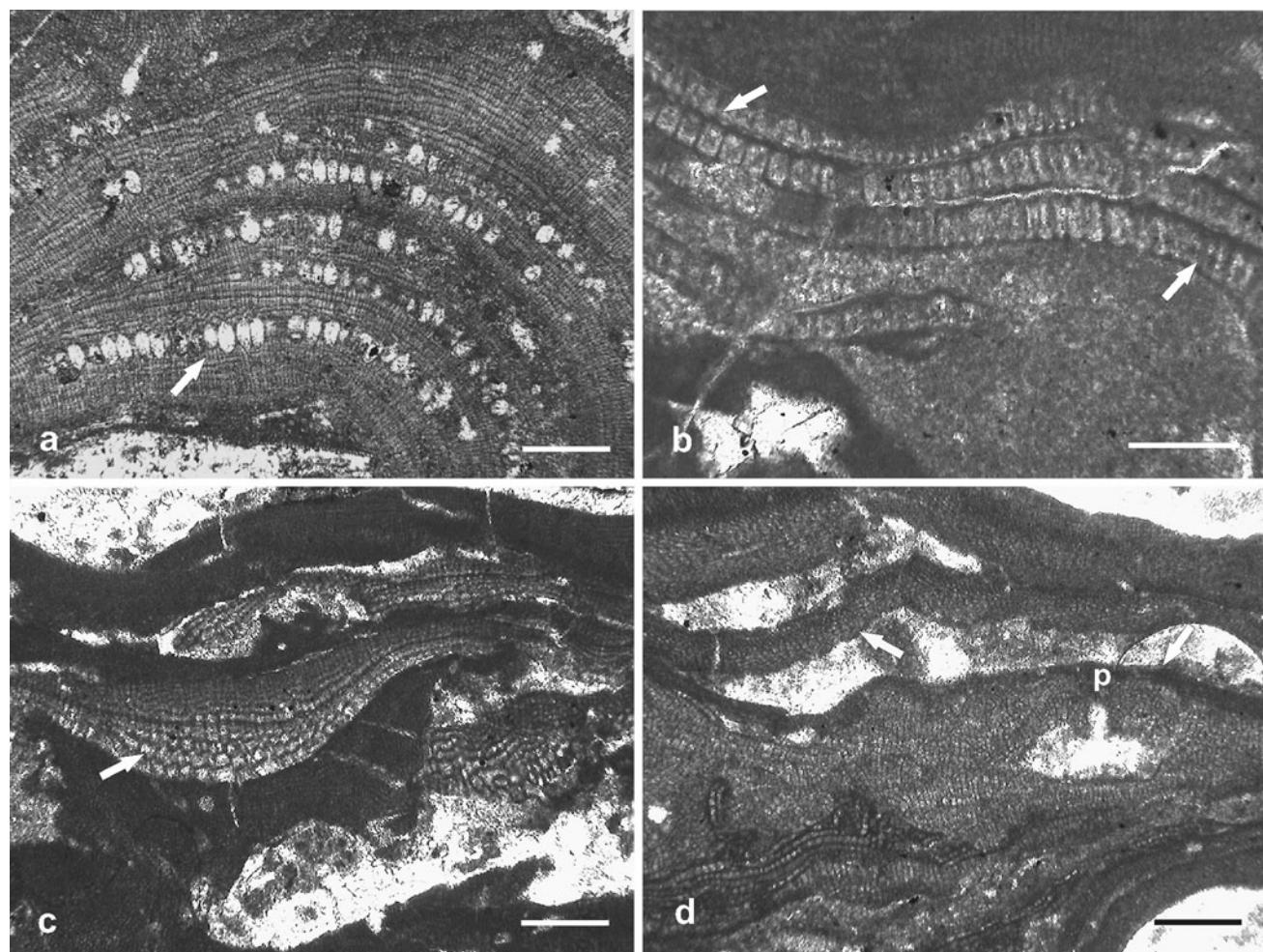
Molluscs are rare in the samples, represented mainly by ostreids scattered in siliciclastic sediment and present

inside some rhodoliths. Sporadic are poorly preserved fragments of originally aragonitic bivalve shells (“ghost structures”). Bryozoans, echinoderm plates, and small fragments of corals are very rare in the sediment. Foraminifera are represented by miliolids and rotaliids (Fig. 9).

Three pebble-sized clasts of algal limestones have been found, one composed of fruticose coralline algal fragments (*Mesophyllum*, *Lithothamnion*) in a micritic matrix, and the other two representing algal-bioclastic grainstone/packstone. The limestones contain also bivalves, echinoderms, foraminifera, serpulids, and bryozoans as bioclasts, but no larger foraminifera nor green calcareous algae have been found. Quartz and glauconite grains are minor, and also rhodoliths in these pebbles are rare and very small.

#### Foraminifera in the rhodolith-bearing and underlying deposits

Foraminiferal content has been examined in: (1) nine samples (M2, 3, 6A–8, 10–13) collected from the grey to greenish-grey mudstones stratigraphically located from ~10 to 20 m below the rhodolith-bearing succession; (2) five samples (M4, 6, 14–16) of mudstone rip-up clasts found



**Fig. 6** Thin-section photomicrographs of coralline algae from the studied rhodoliths. **a** *Sporolithon* sp. A, lumpy protuberance with sporangial compartments on a row of elongated cell layers (arrow), grouped in sori. **b** *Lithoporella* sp. A, single layers of palisade cells with cell fusion (arrows). **c** *Karpathia* sp., superimposed undulating

encrusting thalli showing cell fusion between adjacent cells (arrow). **d** *Spongites* sp. A, section through superimposed encrusting thalli showing a uniporate conceptacle with long cylindrical pore canal (*p*) and the non-coaxial core filaments (arrowhead). Scale bar 0.2 mm in **a**, **c-d**, and 0.1 mm in **b**

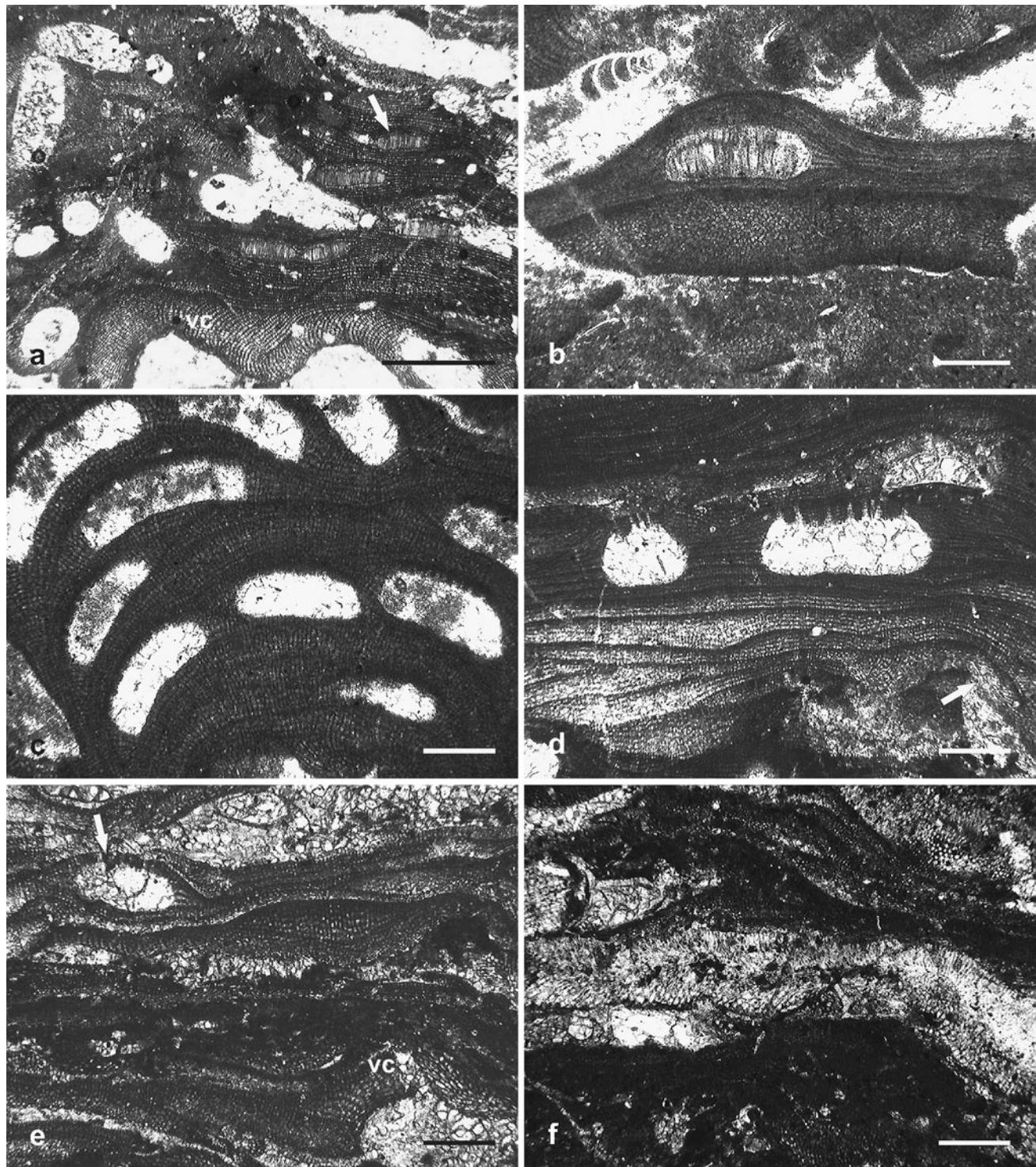
in the lower part of the rhodolith-bearing succession; and (3) thin-sections of rhodoliths and the three pebbles of algal limestone found in a stream-bank outcrop of the rhodolith-bearing succession ~1.5 km northwest of the outcrop in Melsztyn (coordinates N: 49°52'29.14", E: 20°44'44.15").

Foraminifera are rare in samples M2, 3, 8, and M10–13, which show the low-diversity, impoverished flysch-type assemblages of deep-water agglutinated forams (the DWAF association of Kuhnt and Kaminski 1989). Large tubular forms of *Nothia*, *Ammosphaeroidina pseudopauciloculata* (Mjatliuk) and *Gerochammina lenis* (Grzybowski), with solitary specimens of the planktonic genera *Heterohelix*, *?Rugoglobigerina*, and *Globigerinelloides*, have been found in sample M10.

Samples M6A and M7 yielded a typical DWAF assemblage with *Placentammina placenta* (Grzybowski), *Glomospira diffundens* Cushman and Renz, *Rzezhakina*

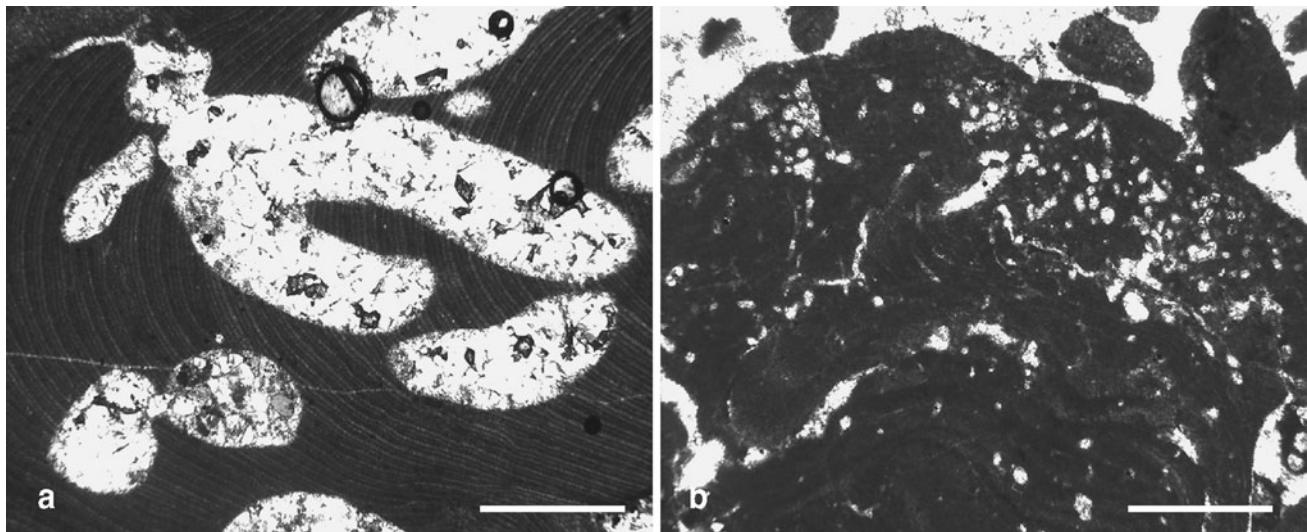
*epigona* (Rzezhak), *Rzezhakina fissistomata* (Grzybowski), *Caudammina excelsa* (Dylążanka), *Hormosina velascoensis* (Cushman), *Ammosphaeroidina pseudopauciloculata* (Mjatliuk), *Thalmannammina subturbinata* (Grzybowski), and *Trochamminopsis cf. altiformis* (Cushman and Renz), accompanied by tubular forms of *Nothia* and *Rhabdammina* as well as by *Trochamminoides* div. sp. and *Paratrocchamminoides* div. sp. Sample M6A contains also *Kalamopsis grzybowskii* (Dylążanka), *Ammobaculites cf. agglutinans* (Orbigny) emend. Bartenstein, 1952 and relatively abundant *C. excelsa*, whereas *Annectina grzybowskii* (Jurkiewicz) has been found in sample M7.

In sample M10, apart from large tubular forms of *Nothia*, *Ammosphaeroidina pseudopauciloculata* (Mjatliuk) and *Gerochammina lenis* (Grzybowski), single specimens of the planktonic genera *Heterohelix*, *?Rugoglobigerina* and *Globigerinelloides* have been found.



**Fig. 7** Thin-section photomicrographs of coralline algae from the studied rhodoliths. *Mesophyllum* sp. A; **a** superimposed encrusting thalli with several multiporate conceptacles (arrow) and the coaxial ventral core (vc); **b** longitudinal section of a multiporate conceptacle. *Lithothamnion* sp. A; longitudinal sections of a protuberance (**c**) and encrusting superimposed thalli (**d**) showing the multiporate

conceptacles and the non-coaxial ventral core (arrow). **e** *Lithothamnion* sp. B, superimposed encrusting thalli with non-coaxial ventral core (vc) and a longitudinal section of multiporate conceptacle (arrow). **f** *Polystrata alba* (Pfender) Denizot, longitudinal oblique section of an encrusting thallus. Scale bar 0.5 mm in **a**, and 0.2 mm in **b–f**



**Fig. 8** Thin-section photomicrographs of studied rhodoliths showing the morphologies of common bioerosion traces. **a** Rounded multi-chambers of sponge-related borings referable to the ichnogenus

*Entobia*. **b** Microgalleries with rounded transversal sections produced by fungi, algae, bacteria and/or sponges. Scale bar 0.5 mm

The mudstone-clast samples M4, M6 and M14–16 yielded mostly poor assemblages of agglutinated foraminifera. Sample M4 was barren. The relatively rich assemblage in sample M6 included a few pyritized specimens of *Praebulimina*, *Nonionella*, and fragments of *Chilostomella* and *Globigerina* s.l.

Foraminifera in one of the algal limestone clasts (SL3), examined in three thin-sections, consist of small benthic taxa, both agglutinated and relatively more numerous, calcareous. Agglutinated foraminifera include *Dorothia* sp. A, *Dorothia* sp. B, and *Clavulinoides* sp. Calcareous benthic taxa are represented by *Miliola ?andrusovi* Samuel, Köhler and Borza (Fig. 9a, b), *Mississippina binkhorsti* (Reuss) (Fig. 9c), *Coccarota orali* İnan (Fig. 9d) and encrusting *Planorbulina cretae* (Marsson) (Fig. 9e) as well as *Miniacina* sp. (Fig. 9f). Some other forms belonging to miliolids and rotaliids have also been found, but their exact taxonomic identification was hindered by sparse and non-diagnostic sections.

### Stratigraphic re-evaluation of the succession

#### Lithostratigraphic comparisons

In terms of their composition and sedimentary facies, the rhodolith-bearing deposits resemble the Ciężkowice Sandstone of latest Paleocene–Early Eocene age. The similarity includes especially the occurrence of rhodoliths, which are known from many outcrops of the Ciężkowice Sandstone (Leszczyński 1978), but not from the Senonian Lower Istebna Sandstone to which these deposits were

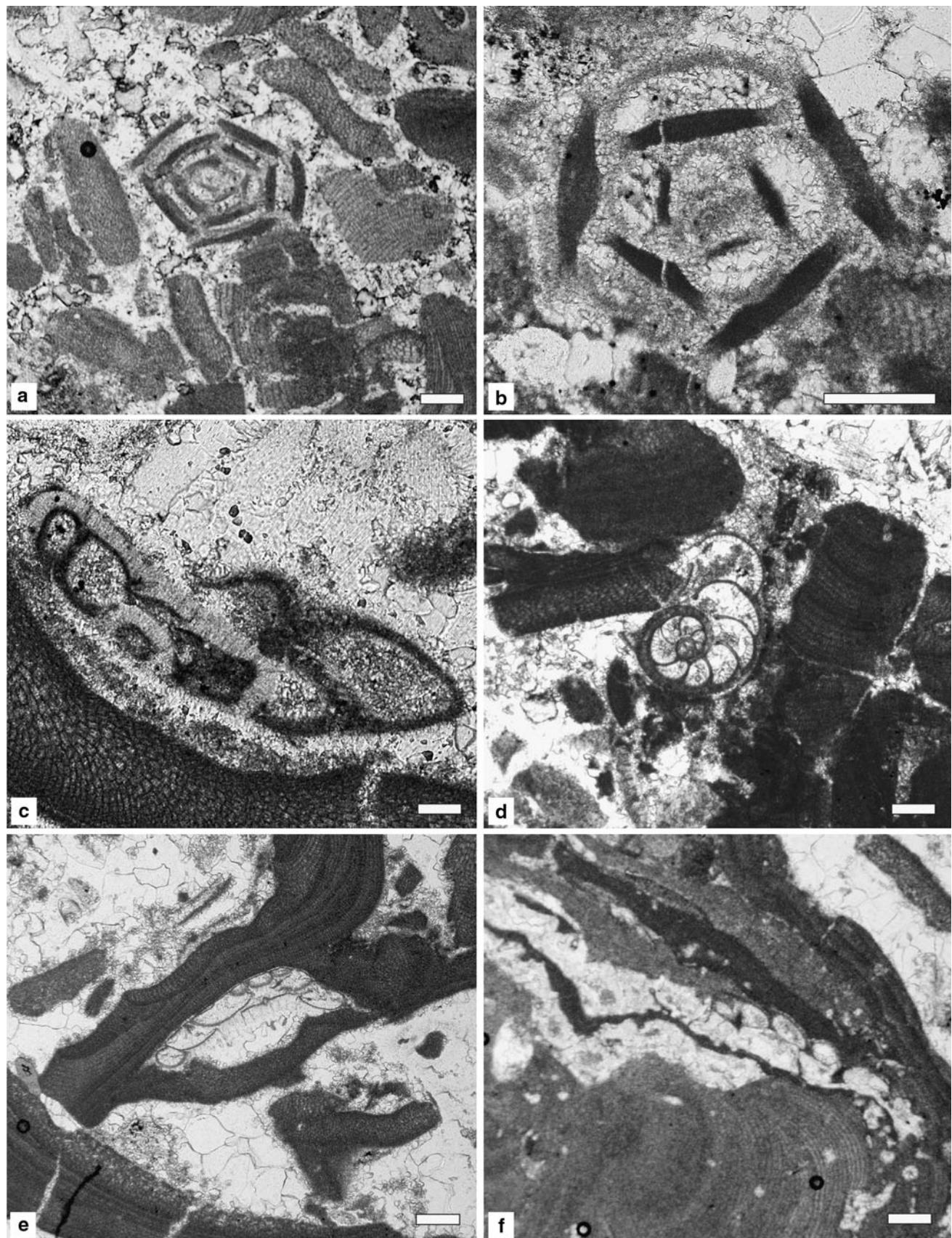
ascribed by Koszarski and Kuciński (1966). However, underlying and overlying dark-grey shales render the rhodolith-bearing deposits similar to the Upper Istebna Sandstone of the Late Paleocene (Unrug 1963; Bieda et al. 1963; Geroch and Nowak 1984; Koszarski 1985), rather than to the Ciężkowice Sandstone, as the latter formation is generally sandwiched between variegated, reddish-greenish shales. The Ciężkowice Sandstone seems to be absent in the study area, as noted earlier by Birkenmajer et al. (1962) and Koszarski and Kuciński (1966).

The underlying shale-rich succession with its facies and stratigraphic position correspond to the Lower Istebna Shale of latest Senonian–Early Paleocene (Bieda et al. 1963; Geroch and Nowak 1984; Koszarski 1985; Fig. 2), whereas the dark-grey shales overlying the rhodolith-bearing deposits appear to correspond to the Upper Istebna Shale of Late Paleocene age (Bieda et al. 1963; Geroch and Nowak 1984; Koszarski 1985). Although these overlying shales seem here to be considerably thinner than the regional unit of Upper Istebna Shale, the difference can be attributed a tectonic structural thinning.

#### Biostratigraphic inferences

In this section, the tentative lithostratigraphic correlations will be assessed on the basis of biostratigraphic data from the shales underlying the rhodolith-bearing flysch and from the mudshale and limestone clasts found in the coarse-grained siliciclastic flysch.

The underlying shale succession, correlated with the Lower Istebna Shale, contains relatively rare and long-ranging taxa of agglutinated foraminifera (samples M2, 3,



**Fig. 9** Benthic foraminiferids from a carbonate clast (sample SL 3) in the Late Paleocene Upper Istebsna Sandstone at Melsztyn. **a** *Miliola ?andrusovi* Samuel, Köhler and Borza. **b** *Miliola ?andrusovi* Samuel, Köhler and Borza. **c** *Mississippina binkhorsti* (Reuss). **d** *Cocoarota oralis* İnan. **e** *Planorbulina cretae* (Marsson). **f** *Miniacina* sp. Scale bar 1 mm

8, 10–13). Most of the taxa found in samples M6A and M7 are common in the Campanian–Paleocene assemblages of agglutinated forams in the Polish Outer Carpathians (Olszewska 1997; Kaminski and Gradstein 2005). However, some more exact inferences can be made. *Rzehakina fissistomata* has its first appearance in the Late Maastrichtian but if relatively abundant, it can serve as an index species of the Paleocene Rzehakina fissistomata zone of Geroch and Nowak (1984).

The total stratigraphic range of *Annectina grzybowskii* is Campanian–Paleocene (Kaminski and Gradstein (2005), but the taxon is thought to be characteristic of Paleocene foraminifera assemblages (Malata 2002). Accordingly, the shale represented by sample M7 is most likely of a Paleocene age. Sample M6A shows a considerable amount of *C. excelsa*, which is a characteristic component of Campanian–Maastrichtian assemblages in the Polish Outer Carpathians (Olszewska 1997; Malata 2002), but does not preclude a Paleocene age. The solitary specimens of the planktonic genera *Heterohelix*, *?Rugoglobigerina*, and *Globigerinelloides* found in sample M10 are generally indicative of a Late Cretaceous age. The foraminifera assemblages thus support regional correlation with the Late Senonian–Early Paleocene Lower Istebsna Shale.

The mudshale intraclasts in the flysch show mainly long-ranging foraminiferal taxa, but at least these found in sample M6 suggest an age not older than Paleocene. More indicative are foraminiferal taxa in the limestone clasts. The species *Miliola ?andrusovi*, found in one of the three clasts, is known from the Paleocene of the West Carpathians (Samuel et al. 1977), though it has recently been reported also from the Lower to Middle Illerian (Lower Eocene) of Sardinia (Dieni et al. 2008). *Cocoarota oralis* has not previously been reported from the Carpathian flysch, but was described from the Upper Maastrichtian–Lower Lutetian of Turkey (İnan 2003). *Mississippina binkhorsti* is common in Paleocene to Eocene shallow-water carbonate deposits (Samuel et al. 1972; İnan and İnan 2008; Olszewska 2009). *Planorbulina cretae* has been reported mainly from the Upper Cretaceous and Paleocene (Bignot and Larroue 1969; Samuel et al. 1972; Köhler and Buček 2005; Dieni et al. 2008), though found also in the Upper Paleocene–Lower Oligocene of Bulgaria (Dimitrova 2003). The co-occurrence of the above-mentioned species of small foraminifera suggests a Paleocene–Early Eocene (Illerian) age of the limestones from which the

clasts were derived. This evidence generally supports regional correlation of the coarse-grained flysch succession with the Upper Istebsna Sandstone.

## Discussion

### Origin of the rhodolith-bearing deposits

The coarse-grained sedimentary succession shows features indicative of deposition by submarine sediment-gravity flows, mainly high-density turbidity currents and debris flows (sensu Lowe 1982). The lowest composite bed in the outcrop section shows a repeated normal grading, which suggests two consecutive surges of a turbulent high-density flow. Multiple normal grading in the overlying rhodolith-bearing succession suggests deposition by several consecutive surges of one or more similar flows. The amalgamated mass-flow deposits and their facies resemble closely those of the Istebsna Beds and the Cięzkowice Sandstone (Unrug 1963; Leszczyński 1981), formed at bathyal depths (Koszarski and Żytko 1965; Książkiewicz 1975; Leszczyński 1981), and their origin can be attributed to a deep-sea channel-fill or channel-lobe transition zone (Palanques et al. 1995; Wynn et al. 2002). Either depositional setting might explain the occurrence of such deposits (Janbu et al. 2007; Wynn et al. 2002) and the emplacement of debris flows far away from the sediment source (Janbu et al. 2007; Ito 2008). Imbricated rip-up clasts indicate paleotransport towards the northeast. Paleogeographic reconstructions (e.g., Książkiewicz 1962), suggest that the probable shallow-marine environment for the growth of coralline algae and formation of rhodoliths was on the Silesian Ridge at the southern margin of the Silesian Flysch Basin. The narrow ridge is unlikely to have hosted extensive river systems and large deltas, and the coarse-grained siliciclastic deposits thus suggest resedimentation from a fan-delta (coastal alluvial fan) system.

### Paleoecology of rhodoliths

The examined rhodoliths and associated calcareous benthic biota represent shallow-marine biogenic components thriving mainly in the photic zone, above the storm wave base. Rhodoliths are free-living nodules composed predominantly of non-geniculate coralline red algae with an admixture of other encrusting organisms (peyssonneliacean algae, encrusting foraminifera, serpulids, bryozoans; e.g., Bosence 1983a; Marrack 1999; Bassi et al. 2009, 2011). Their development is controlled by an array of environmental factors, and hence rhodoliths are a valuable indicator of paleoenvironmental conditions (e.g., Bosence 1983b; Nebelsick and Bassi 2000; Nalin et al. 2008; Bassi et al. 2009, 2010).

The dominance of *Sporolithon* and melobesioids in the analyzed rhodoliths suggests a low light-intensity setting. Despite the cosmopolitan distribution of the group, *Sporolithon* is restricted mainly to tropical latitudes (Johnson 1963; Adey and Macintyre 1973; Johansen 1981), where it primarily occurs in relatively deep-water and cryptic sites (Adey 1979, 1986). However, the species, *S. ptychoides* Heydrich seems to be the only one confidently reported as currently inhabiting the Mediterranean Sea, where it is common on submarine cliffs and can occur down to infra- and circalittoral settings (e.g., Alongi et al. 1996; Bressan and Babbini 2003; Braga and Bassi 2007; Braga et al. 2009). Modern melobesioids, together with *Sporolithon*, increase in abundance with water depth in tropical and non-tropical seas (Adey 1979; Adey et al. 1982; Lund et al. 2000), but at higher latitudes where water turbidity is greater they are also common in shallower water rhodoliths and pebble coatings (Bosence 1983b; Foster 2001; Braga et al. 2009).

A shallow-marine origin of the studied rhodoliths is indicated also by the occurrence of subordinate mastophoroids (with three genera), which tend to predominate in shallow-water settings of modern tropical (e.g., Borowitzka and Larkum 1986; Braga and Aguirre 2004; Flamand et al. 2008) and temperate seas (e.g., Aguirre et al. 2000; Lund et al. 2000; Braga and Aguirre 2001). Fossil examples of shallow-water rhodolith deposits characterized by sporolithaceans, melobesioids, and mastophoroids have been described from the Upper Eocene and Oligocene of the western Tethys (e.g., Bassi 1998, 2005; Nebelsick et al. 2000, 2005; Rasser 2000; Rasser and Nebelsick 2003; Rasser and Piller 2004; Brandano et al. 2009; Bassi and Nebelsick 2010).

Rhodolith inner structure in several modern environments has been related to depth, sedimentation rate, and hydrodynamic regime (e.g., Minnery 1990; Bosence 1983a, b, 1991; Marrack 1999; Lund et al. 2000; Bassi et al. 2009). The rhodoliths of deeper water or low hydrodynamic-energy environments show large constructional void spaces, may lack an identifiable nucleus, and are composed of thin, irregular, encrusting thalli (e.g., Braga and Martín 1988; Barattolo et al. 2007; Bassi 1998, 2005; Nalin et al. 2008; Bassi et al. 2006, 2009, 2010). The predominantly asymmetrical and loosely packed inner structure of the studied rhodoliths in the present case indicates occasional overturning in an environment with moderate water turbulence.

The occurrence of siliciclastic material as an infill of voids in the rhodoliths indicates their growth on a substrate rich in such material. The abundance of borings in the rhodoliths supports the notion of an environment with a low net sedimentation rate, allowing a relatively long residence time on the substrate. The boring activity took place

during the active growth of the rhodoliths. The rounded shape of the borings, their size, curved course and scattered occurrence suggests the activity of sponges, fungi, algae, and polychaete worms (e.g., Rice and Macintyre 1982; Bromley 1992, 1994; Checconi et al. 2010). Microborings recognized in a coral in one of the rhodolith nuclei are similar to those produced or inhabited by foraminifera, as described from Paleocene peri-reefal deposits in Austria (Schlagintweit 2005).

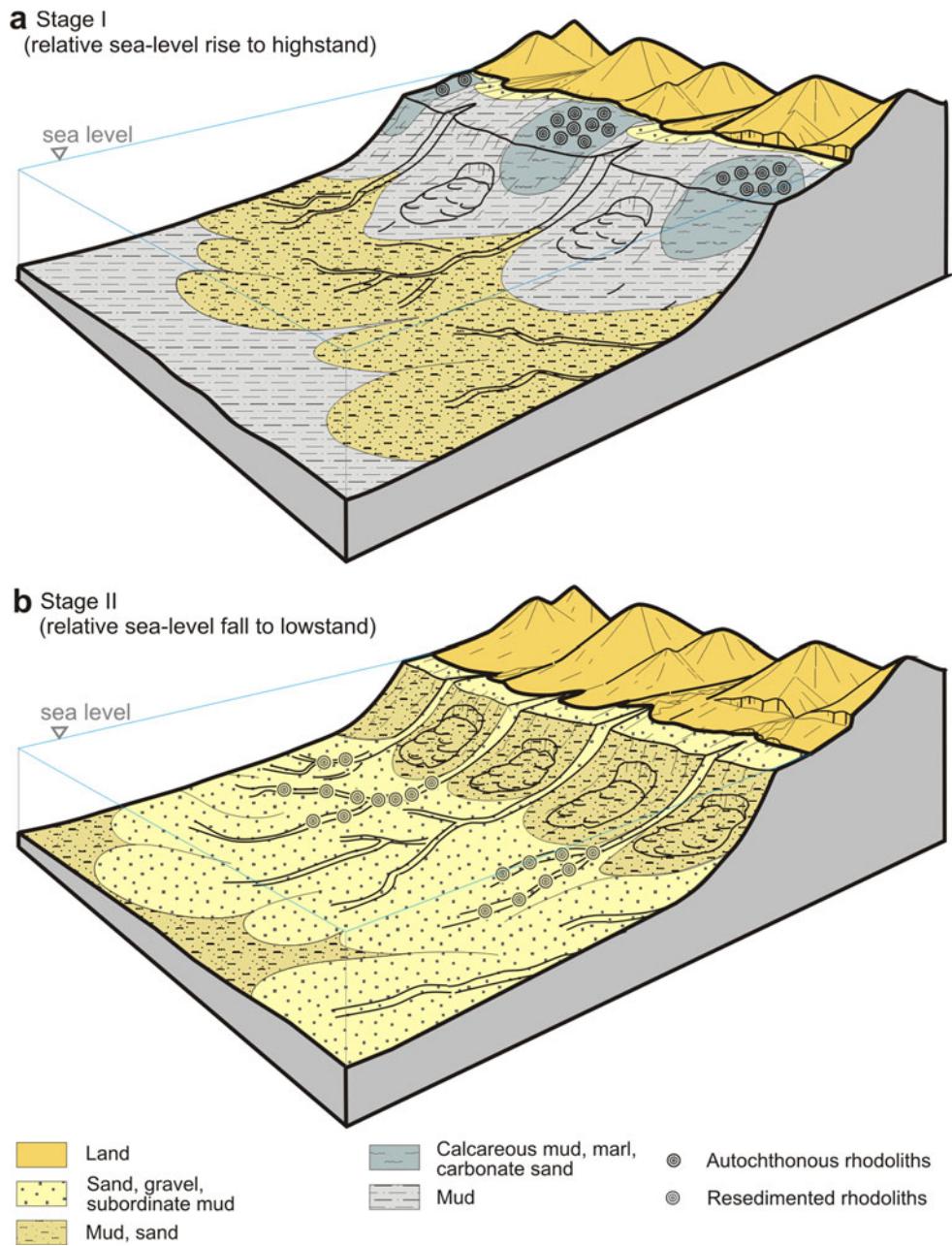
The low abundance of biota other than coralline algae and ostreids may suggest a non-hospitable environment, although this impression may partly be due to a taphonomic bias resulting from the low fossilization potential of aragonitic skeletons, mostly molluscs (Wright et al. 2003). The proportion of aragonitic shells may have originally been higher, as suggested by the patchy calcitic cementation of both the rhodolith-bearing deposits and the underlying ones. The same is suggested also to some extent by the “ghost structures” of molluscs.

#### Depositional model

The integrated analysis of regional stratigraphic correlation, flysch lithofacies, their biogenic components and rhodolith characteristics led us to the following depositional model of the rhodolith-bearing flysch succession in Melsztyn. Two main depositional stages are distinguished: (I) accumulation of mixed siliciclastic-carbonate sediment with rhodolith growth, in a shallow-marine environment of the southern margin of the basin (Fig. 10a) and (II) subsequent resedimentation into the deep-water settings (Fig. 10b). The two stages are thought to have been related to relative sea-level change. This interpretation is suggested by the spatially restricted and relatively short-lived, episodic supply of sediment enriched in contemporaneous neritic biota and carbonate rock debris. Regional evidence from the Outer Carpathian Flysch indicates that the shelf zone of the basin margin was dominated by siliciclastic sedimentation. The production of carbonate material was apparently restricted to one or more favorable areas of the shelf, with suitable bathymetry, hydraulic energy level, substrate composition, and sediment accumulation rate (Nalin et al. 2010). Shelf erosion is known to be greatly enhanced during a pronounced sea-level fall and lowstand (Catuneanu 2006), when also the local niches of carbonate production would likely become subject to resedimentation (e.g., Aybulatov and Drushchits 1986; Vecsei and Sanders 1997). In a tectonically active basin, the shedding of inner-shelf sediment may indicate a relative sea-level fall due to uplift of the basin margin.

In summary, we infer that the depositional stage I commenced with the onset of relative sea-level rise (Fig. 10a), when the accommodation space of the shelf

**Fig. 10** Depositional model for the shallow-water origin and ultimate deep-water emplacement of Late Paleocene mixed carbonate-siliciclastic deposits in the Outer Carpathian flysch basin. **a Stage I** A relative sea-level rise up to highstand creates local conditions for bioclastic carbonate production on a narrow, fan delta-hosting siliciclastic shelf at the basin margin. **b Stage II** A subsequent sea-level fall and lowstand cause erosion and resedimentation of the rhodolith-bearing deposits into deep water. Not to scale



zone increased, erosion declined, and sediment accumulation prevailed. Significant production of biogenic carbonates would occur in shallow-water areas with a suitable hydraulic energy and limited sediment supply (e.g., Monstad 2000; Philip 2003; Nalin et al. 2008). This stage would probably persist until at least the early highstand (Sarg 1988; Tucker and Wright 1990; Leinfelder 1993; Brachert et al. 2003), whereas erosion of the inner shelf might have commenced with the fall of relative sea level and persisted until the lowstand phase (Fig. 10b).

As discussed in the previous chapter, the rhodoliths were apparently formed on a moderately mobile sandy siliciclastic substrate, in restricted shoal-water, which suggests

coarse-grained coastal shoals provided commonly by fan deltas (e.g., Dutton 1982). Arguably, fan deltas are the only restricted shelf areas where considerable volumes of submature to mature gravel and sand can accumulate and where biogenic carbonate sedimentation may occur in abandoned or inactive shoal-water zones (e.g., Dabrio and Polo 1988). The subordinate admixture of carbonate components (mainly rhodoliths and ostreids) in the resedimented siliciclastic material suggests a volumetrically limited carbonate production and the limited thickness and spatial extent of the rhodolith-bearing flysch suggest further that the carbonate production was relatively short-lived and areally restricted. The common occurrence of

boring activity developed during the rhodolith growth testifies to periods with a very low sedimentation rate.

The occurrence of bioclast-free deposits below the rhodolith-bearing deposits in the outcrop section in Melsztyn implies that, in terms of an erosional shelf stripping, before resedimentation in deep water, the rhodolith production on the shelf had ceased at some point and the rhodolith-rich sediment was buried by bioclast-free sediment. The burial might most likely have occurred during normal regression (sea-level highstand), when sea-floor aggradation and shoreline progradation prevailed along the basin margin. The immediate burial of bioclast-rich sediment by barren sediment could first of all have happened in areas overwhelmed by sediment supply from river mouths and subject to delta progradation.

Stage II involved erosion of inner shelf and resedimentation of rhodoliths and associated siliciclastic sediments in deep-water. It might have commenced with a pronounced fall of relative sea level, and persisted until the lowstand phase (Fig. 10b). Such a sedimentary response to sea level change is characteristic of siliciclastic shelves (Catuneanu 2006) like mostly those of the Carpathian flysch basins.

#### Comparison with other rhodolith-bearing deposits and algal limestones in the Paleogene flysch of the Polish Outer Carpathians

Coralline algal detritus is a significant local component in some parts of the Paleogene flysch of the Polish Outer Carpathians. This carbonate material is scattered in sandstones and granule to pebble conglomerates in almost all of the lithostratigraphic units, particularly those spanning the Paleocene–Eocene and the Eocene–Oligocene boundary (e.g., Cieszkowski et al. 2003). In situ coralline algal limestones in the Polish Outer Carpathians have been reported only from the relics of Paleocene shallow-marine cover of tectonic klippe near Andrychów (Książkiewicz 1951). The existing regional literature and a cursory study of the outcrop in Targanice by one of us (SL), suggest that these limestones occur there in coralline algal debris facies. Some lithostratigraphic flysch units, such as the Paleocene Szydłowiec Sandstone, Czerwin Sandstone, and Bircza Limestone, or the Early Oligocene Łużna Limestone and Skalnik Limestone, are characterized by the common occurrence of coralline algal debris (Książkiewicz 1951; Rajchel and Myszkowska 1998a; Cieszkowski et al. 2005; Leśniak et al. 2005). Other units, such as the latest Paleocene–Early Eocene Ciężkowice Sandstone, contain coralline algal debris only in some beds (Bieda et al. 1963; Leszczyński 1978; Koszarski 1985; Rajchel and Myszkowska 1998a). It should be noted that the units traditionally referred to in the literature as limestones (e.g., the

Bircza Limestone, the Łużna Limestone, the Skalnik Limestone) are actually carbonate-rich sandstones to sandy limestones (see Bieda 1962, 1968).

In the above-mentioned Paleocene–Eocene lithostratigraphic units, the rhodoliths occur mainly in the Ciężkowice Sandstone (Leszczyński 1978). The best-known outcrop of this unit on the eastern side of Lake Roźnów (~20 km south of Melsztyn), is presently poorly exposed. It shows paraconglomerates of the lowermost part of the unit (latest Paleocene) containing pebbles and cobbles of rhodolith limestone, algal debris limestone, and *Discocyclina* limestone mixed with “exotic” pebbles and cobbles of crystalline and other sedimentary rocks. The algal limestones are packstones/grainstones and rhodolith floatstones. Coralline algae are represented by the genera *Mesophyllum*, *Lithothamnion*, *Lithoporella*, *Spongites*, *Karpathia sphaerocellulosa*, and *Sporolithon*, accompanied by large foraminifera such as *Discocyclina* spp. (Leszczyński 1978). The rhodoliths scattered in the sandstones and pebbly conglomerates are similar to those in the Melsztyn outcrop section.

In the village of Skawinki near Lanckorona, the Oligocene Krosno Beds of the Silesian Nappe contain an olistostrome, with pebbles and cobbles of limestones similar to those in the Ciężkowice Sandstone. The limestones represent rhodolith facies, coralline algal packstone/grainstone facies, and crustose coralline algal facies. Coralline algae are represented by the genera *Mesophyllum*, *Lithothamnion*, *Lithoporella*, *Spongites*, *Neogoniolithon*, and *Sporolithon*. Coral fragments are rare, representing four species. The associated large foraminifera suggest a Middle–Late Eocene age of the limestones, which are apparently free of siliciclastic material (Bassi et al. 2000).

Rajchel and Myszkowska (1998b), Cieszkowski et al. (2003) and Golonka et al. (2003) suggested a carbonate platform and algal reef provenance of the algal debris and the clasts of the bioclastic algal limestones found in the Polish Outer Carpathian flysch, but no convincing proof of such a provenance was provided. In reality, the rare occurrences of pebbles and cobbles of algal limestones, and particularly crustose coralline algal limestone suggest that there were probably no extensive carbonate platforms or shelves dominated by carbonate sedimentation along the margins of the Carpathian flysch basins. The benthic communities, particularly coralline algae, were only locally and occasionally able to thrive on the basin-margin shelf and contribute abundant carbonate components to the siliciclastic sediment.

Relatively diverse resedimented debris of colonial and solitary corals (some 15 species of 7 genera), albeit rare and small, occur in the Late Paleocene Babica Clays of the Skole Nappe. However, they represent level-bottom assemblages and not reefal ones, as indicated also by the

lack of a biogenic or abiogenic framework (Kołodziej and Stolarski 2000). The Paleocene reefal limestones known from the Inner Carpathians in Slovakia are irrelevant, as they represent a different geotectonic domain (Scheibner 1968; Köhler et al. 1993, Krobicki et al. 2004; Köhler and Buček 2005).

#### Remarks on Paleogene carbonate shelf sedimentation in the Polish Outer Carpathians

The Paleogene neritic carbonate debris found in the deep-water flysch of the Polish Carpathians has an irregular distribution limited to certain areas and relatively narrow stratigraphic intervals. The distribution may reflect derivation from isolated sources and over short periods. In this section, we discuss briefly the paleo-oceanographic and geodynamic factors that may have controlled carbonate sedimentation in the shelf zones of the flysch basin.

The occurrences of resedimented Paleocene–Eocene coralline algae, mainly as debris and rarely as rhodoliths or pebbles and cobbles of algal limestone, indicates some local shallow-marine environments suitable for algal growth at the basin margin. However, evidence of pure carbonate algal sedimentation is sparse, since algal limestone pebbles and cobbles are rare.

The Paleocene Carpathian flysch was deposited in a mid-latitude arm of the northern Tethys (see Scheibner and Speijer 2008), and the occurrence of coralline algal facies there may reflect the general increase in the diversification of coralline algae since the Late Paleocene (Aguirre et al. 2000, 2007). For comparison, well-developed algal facies, including crustose, are known from Eocene basins at similar paleolatitudes, such as the Eocene Alpine Foreland (Rasser and Piller 2004).

As suggested by the present study, the shelf niches for carbonate sedimentation may have been created episodically by a major sea-level rise and early highstand and have subsequently been removed by erosion and resedimentation during the relative sea-level fall and lowstand (major forced regression). The Carpathian flysch basins were tectonically active and their shelf zones were likely narrow, fringing a structural ridge, whereby the sea level might have occasionally fallen below the shelf edge.

According to Nalin et al. (2008), the deposition of Cenozoic rhodolith-bearing sediments occurred commonly during marine transgressions, particularly (though not uniquely) in non-tropical areas. At the advanced stage of transgression, these rhodolith-bearing deposits would be covered by fine-grained subneritic facies (Nalin et al. 2008) or buried by shoreline progradation during normal regression (Catuneanu 2006). For example, most of the Eocene shallow-water carbonates, including rhodolith facies, in the Alpine–Pannonian region were deposited with a major

basal unconformity over Mesozoic rocks and overlain by deeper-water siliciclastic sediments (Sahy et al. 2008).

Little is known about the Oligocene shallow-water carbonate sedimentation in the Polish Outer Carpathian flysch basins. Sparse resedimented carbonate debris occurs scattered chiefly in the Lower Oligocene. The lack of such contemporaneous debris in the higher part of the Oligocene may possibly reflect isolation of the northern part of Tethys, including the Outer Carpathian basins, from the main part of the ocean (Báldi 1984; Rögl 1999).

#### Conclusions

1. The studied section in Melsztyn, Polish Outer Carpathians, is the largest and most rhodolith-rich outcrop of the siliciclastic flysch of the Silesian Nappe.
2. The flysch lithofacies and regional stratigraphic correlations suggest that these rhodolith-bearing deposits represent the Upper Istebsna Sandstone deposited in the Late Paleocene, and not the Senonian Lower Istebsna Beds as earlier suggested in the literature.
3. The analyzed rhodoliths and sparse associated biota (small benthic foraminifera, ostracodes and fragments of echinoderms, bryozoans, and corals) occur as resedimented components in deep-marine siliciclastic conglomerates to coarse-grained sandstones deposited by high-density turbidity currents and debris flows. The sediment is inferred to have been derived from a fan-delta system developed on the shelf of the Silesian Ridge bordering the Silesian Basin from the south.
4. The rhodoliths are sub-spheroidal to sub-ellipsoidal in shape, with encrusting, warty, and lumpy growth forms. Lumpy forms have massive inner structure, whereas the encrusting forms are usually made of thin thalli and have a more loosely packed inner structure. The inner structure indicates rhodolith formation in an environment of moderate water turbulence. Common borings in the rhodoliths (ichnogenus *Entobia* and microborings) indicate a low net sedimentation rate.
5. The rhodoliths are composed mostly of coralline red algae with seven genera and eight species representing the family Sporolithaceae and the subfamilies Mastophoroideae and Melobesioideae. *Sporolithon*, *Lithothamnion*, and *Mesophyllum* are the dominant taxa. *Karpathia*, *Lithoporella*, *Neogoniolithon* and *Spongites* are subordinate.
6. The origin of the rhodoliths and associated biogenic carbonates and their emplacement in deep water as an admixture of siliciclastic flysch are inferred to have been related to major relative sea-level changes. Local niches for biogenic carbonate development on the shelf are thought to have formed during a major sea-level

- rise and early highstand, with rhodoliths growing on moderately mobile siliciclastic substrates under a low net sedimentation rates. The rhodoliths with the host siliciclastic sediment were then eroded and resedimented into deep water during a subsequent fall and lowstand of the relative sea level (major forced regression). The lack of, or poor early cementation allowed mobilization of skeletal particles and their resedimentation by mass flows.
7. There is no evidence of widespread carbonate sedimentation at the shallow-water margins of the Outer Carpathian flysch basins during the Paleogene. Significant algal sedimentation dominated by maerl facies was episodic and occurred only locally.

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