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ORIGINAL PAPER

Early Cambrian wave-formed shoreline deposits: the Hardeberga Formation, Bornholm, Denmark

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Abstract During the early Cambrian, the Danish island Bornholm was situated on the northern edge of the continent Baltica with palaeolatitudes of about 35°S. An early Cambrian (Terreneuvian) transgression inundated large areas of Baltica including Bornholm creating shallow marine and coastline environments. During this period, wave-formed shoreline sediments (the Vik Member, Hardeberga Formation) were deposited on Bornholm and are presently exposed at Strøby quarry. The sediments consist of fine- and medium-grained quartz-cemented arenites in association with a few silt-rich mudstones. The presence of well-preserved subaqueous dunes and wave ripples indicates deposition in a wave-dominated upper shoreface (littoral zone) environment, and the presence of interference ripples indicates that the littoral zone environment experienced water level fluctuations due to tides and/or changing meteorological conditions. Discoidal structures (medusoids) are present in the quarry, but due to the relative poor preservation of their fine-scale structures it is difficult to determine if the discoids represent true medusae imprints or inorganic structures. The preservation of the shallow-water bedforms as well as the possible medusae imprints is related to either the formation of thin mud layers, formed during a period of calm water when winds blew offshore for a longer period, or to the growth of bacterial mats. The orientation of the wave-formed bedforms indicates a local palaeoshoreline trending NE–SW and facing a large ocean to the north.

Keywords Early Cambrian · Hardeberga Formation · Shoreline deposits · Wave-formed sediments · Medusoids · Bornholm

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Introduction

The gradual sea-level rise through the Cambrian was characterized by a number of shorter term sea-level fluctuations many of which can be correlated globally (Haq and Schutter 2008). The early Cambrian transgressions resulted in deposition of shallow marine and shoreline sediments across most of the continents (Banks 1973; Hiscott et al. 1984; Matthews and Cowie 1979; Dott et al. 1986; McKie 1990; Hamberg 1991; Desjardins et al. 2010). The continent Baltica, present-day Scandinavia and eastern Europe, was located on the southern hemisphere between 35° and 60°S during the early Cambrian (Fig. 1; Torsvik and Rehnström 2001; Cocks and Torsvik 2002, 2005). Parts of Baltica were also inundated during transgressive events in the early Cambrian (Terreneuvian), and clastic sediments were deposited in wide shallow seas across the continent (e.g. Jensen 1997; Nielsen and Schovsbo 2011). Today these shallow marine and shoreline sandstones are known from southern Norway, southern Sweden, the Danish Basin, Bornholm, the Baltic Sea, NE Poland, Lithuania, Latvia, Estonia and further east (Nielsen and Schovsbo 2011).

In southern Sweden (Scania), these early Cambrian sandstones (Hardeberga Formation; Nielsen and Schovsbo 2011) were deposited in inner shelf, shoreface and tidal shoreline (barrier island) environments (Hamberg 1991).

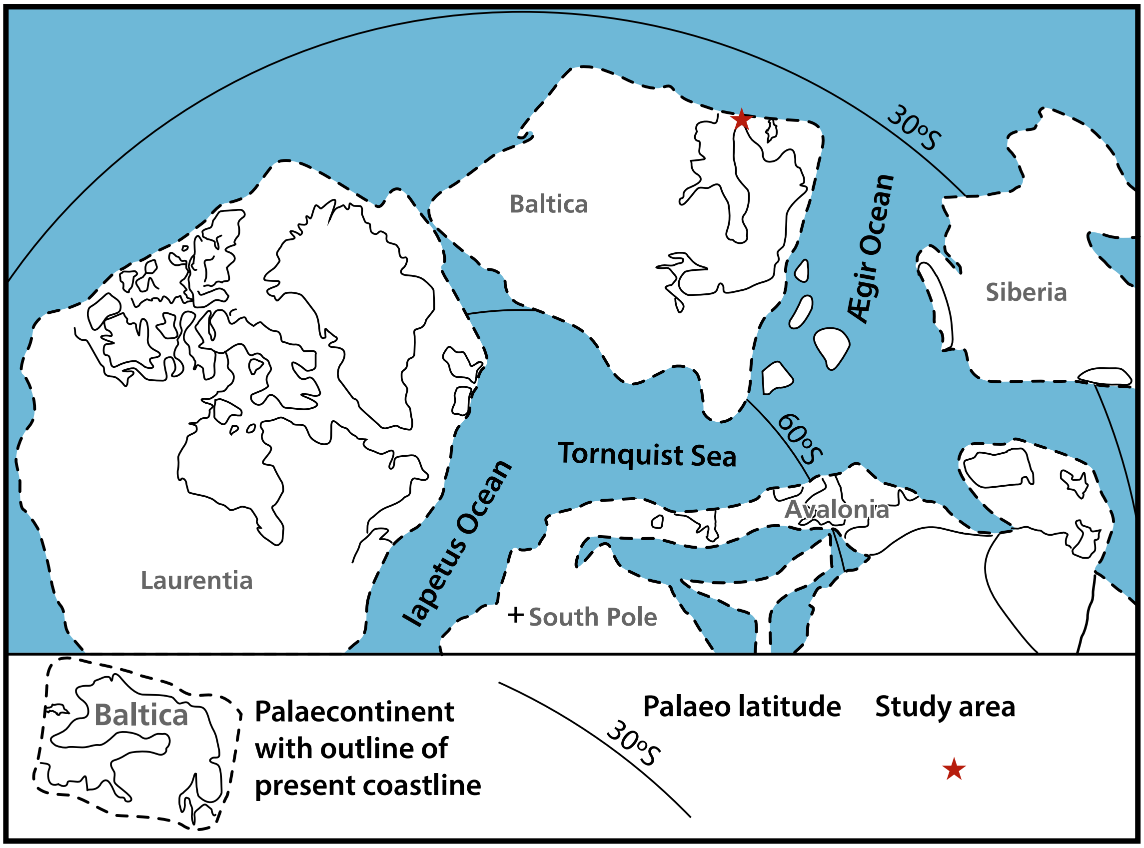

Fig. 1 Position of Baltica at the Ediacaran/Cambrian transition (550 Ma). Baltica was inverted and situated at the southern hemisphere. Map after Cocks and Torsvik (2005) and Nielsen and Schovsbo (2011)

Coastal zone sandstones were deposited on the nearby Danish island Bornholm simultaneously (Surlyk 1980; Hamberg 1989; Poulsen et al. 2000; Bromley 2002; Nielsen and Schovsbo 2011).

The Hardeberga Formation is presently exposed at a few outcrops on Bornholm. One locality is at the Strøby quarry (Fig. 2; GPS 'WGS84': 55°3′42.5″N 14°54′33.8″E) on southern Bornholm, which is a 6000 m^2 open quarry that stopped being active during the 1960 s and is open for the public. Not only the quarry possesses well-preserved shallow-water bedforms formed in an early Cambrian shoreline environment, but bedding surfaces also contain discoidal structures (medusoids) that might represent true organic structures and therefore be one of the very few examples of fossilized medusae imprints in the geological record (Hagadorn et al. 2002; Young and Hagadorn 2010; Hagadorn and Miller 2011). The purpose of this study is to describe the shoreline deposits of the Vik Member in the Hardeberga Formation at Strøby quarry in some detail in order to interpret the processes that controlled the formation of the bedforms and to discuss the origin of the medusoids.

Geological setting

The Danish island Bornholm (55°N/15°E) is located in the south-westerly part of the Baltic Sea, southeast of Sweden (Fig. 2). The pre-Quaternary map of Bornholm shows a mosaique of fault blocks with Precambrian crystalline rocks, Lower Palaeozoic and Mesozoic sedimentary deposits.

In the early Cambrian Bornholm was a part of the continent Baltica, which included the Precambrian terranes of the Baltic Shield. Palaeomagnetic studies indicate that Baltica was positioned on the southern hemisphere in the latest Precambrian and early Cambrian, at latitudes between 35° and 60°S with modern northern Scandinavia closest to the South Pole (Torsvik and Rehnstrøm 2001; Cocks and Torsvik 2002, 2005). These reconstructions suggest that southern Sweden and Bornholm constituted the northernmost part of Baltica at around 35°S (Fig. 1) and that this part of the continent had a generally east–west trending coastline against an enormous ocean, which lay north of the continent and covered large parts of the southern hemisphere. Bornholm was most likely situated in a warm temperate

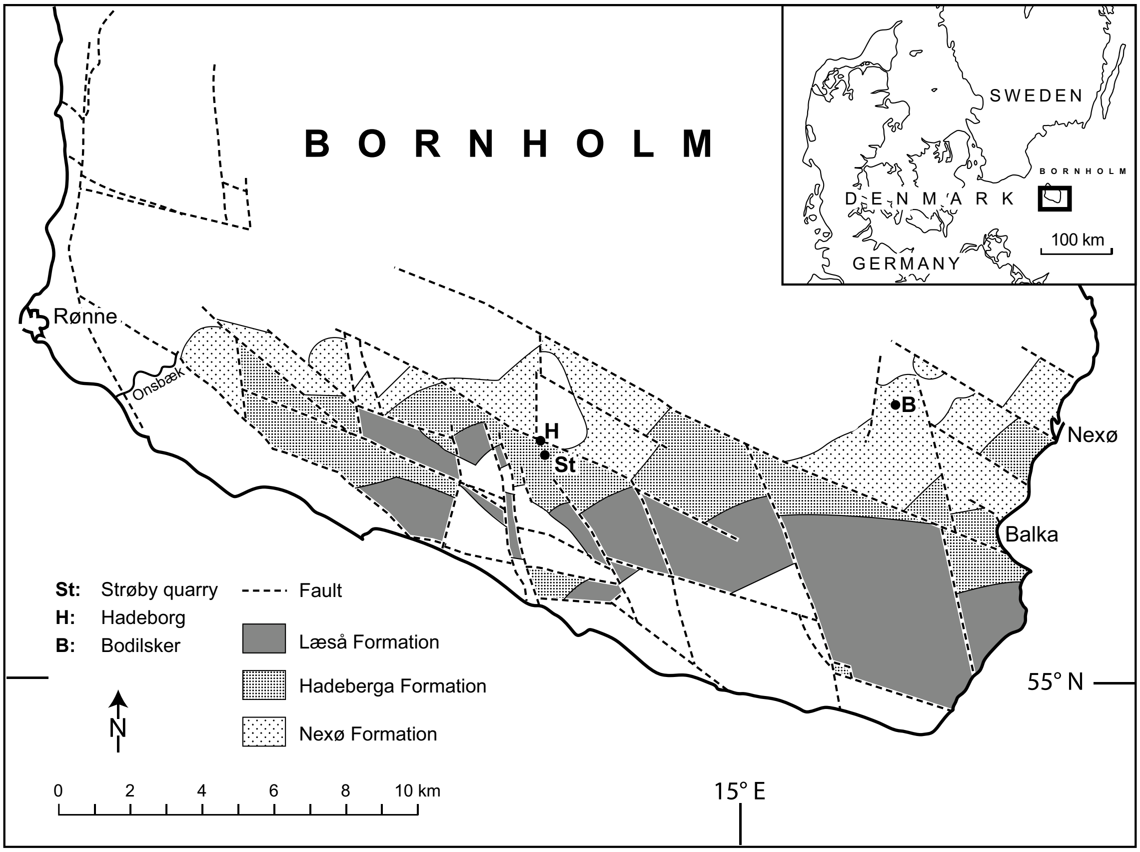

Fig. 2 Geological location map showing the distribution of the Nexø Formation, the Hardeberga Formation and the Læså Formation within fault blocks in southern Bornholm. The Strøby quarry (St), the Hadeborg section (H) and the Bodilsker quarry (B) are indicated. Map modified from Gravesen (1996)

climate belt with prevailing winds supposedly from the west (Hamberg 1991; Nielsen and Schovsbo 2011).

Stratigraphical framework

The lithostratigraphy, overall depositional environment and sequence stratigraphy of the lowermost Cambrian sandstones and siltstones of Bornholm have been established by Nielsen and Schovsbo (2007, 2011), who divided the succession on Bornholm into three formations (Fig. 3): the lower Nexø Formation (fluvio-aeolian and nearshore marine deposits), the middle Hardeberga Formation (nearshore marine deposits) and the upper Læså Formation (offshore deposits). The Hardeberga Formation, previously known as the Balka Sandstone on Bornholm, is subdivided into four members: the Hadeborg Member, the Vik Member, the Brantevik Member and the Tobisvik Member (Fig. 3). The non-continuous and incomplete nature of the exposures of the Hardeberga Formation on Bornholm makes it difficult to establish a precise thickness of the succession. In the Borggård core 5 km southwest of the studied quarry, the Hardeberga Formation reaches a thickness of 109 m (Nielsen and Schovsbo 2007).

The studied sandstones of the Hardeberga Formation in the Strøby quarry correspond to the Vik Member (Nielsen and Schovsbo 2011). In a trench north of the quarry, the Nexø Formation is overlain by quartz arenites and by greenish, silty sandstones of the Hadeborg Member. These are succeeded by the Vik Member sandstones of the Strøby quarry, which comprise fine- to medium-grained, pale grey, quartz arenites, strongly cemented by quartz (Hansen 1936; Møller and Friis 1999). In Scania, the Vik Member is 40–50 m thick, whereas it is only 12 m thick on Bornholm (Nielsen and Schovsbo 2011).

The Hardeberga Formation does not contain macrofossils; however, it is referred to the Terreneuvian Series, Stage 2, of Cohen et al. (2013), which may be correlated to the Lontovan and Dominopolian Baltoscandian stages (Nielsen and Schovsbo 2011; Fig. 3). There are no trace fossils apart from medusoids in the studied quarry, but at nearby localities the formation comprises weakly or intensely burrowed beds, characterized by the trace fossils

Cohen et al. (2013)			Nielsen & Schovsbo (2011)			
Series/Epoch	Global stages	Baltoscandian stages	Biozonation	Sequence	Lithostratigraphy of Bornholm	
Series 2	*Stage 4*	Vergalian – Rausvian	*H. kjerulfi – 'O'. linnar.* Zone (T)			
	Stage 3	'Ljubomlian'	*Heliosph. dissimilare – Skiagia ciliosa* Zone (A)	LC1-7	Læså Fm	Rispebjerg Mb
		Dominopolian	*Skiagia ornate – F. membrane* Zone (A)	LC1-6		Norretorp Mb
				LC1-5		
Terreneuvian	*Stage 2*			LC1-4	Hardeberga Fm	Tobisvik Mb
						Brantevik Mb
		Lontovan	*Asteridium tornatum – C. velvetum* Zone (A)	LC1-3		Vik Mb
				LC1-2		Hadeborg Mb
					Nexø Fm	Langeskanse Mb
				LC1-1		Gadeby Mb
	Fortunian	Rovnian				

Fig. 3 Stratigraphical scheme. The Vik Member is part of the Hardeberga Formation and the shoreline sandstones in this member formed in *Stage 2* of the Terreneuvian. According to Nielsen and Schovsbo (2011) the Vik Member formed during a progradational event during a long-term stepwise transgression of Baltica during the Terreneuvian. Under biozonation *(T)* refers to trilobite zones and *(A)* to acritarch zones

Diplocraterion parallelum and *Skolithos linearis* (Bromley and Uchman 1999), while the presence of *Planolites* was recorded by Clausen and Vilhjálmsson (1986). Bruun-Petersen (1973) described unusual 'conical structures' from the formation and interpreted these as sand-filled funnels belonging to either *Monocraterion* or *Diplocraterion* tubes. On Bornholm, the Hardeberga Formation is overlain by the Læså Formation, a thick succession of greenish, strongly bioturbated marine siltstones (the Norretorp Member) to sandstones (the Rispebjerg Member). The Læså Formation on Bornholm straddles the *Skiagia ornata–F. membrana* and *Heliosphaeridium dissimilare–Skiagia ciliosa* acritarch zones (Moszydlowska and Vidal 1992). The overlying Gislöv Formation (not preserved on Bornholm) is referred to the *Holmia kjerulfi–'Ornamentaspis' linnarssoni* Zone (trilobite zone) according to Nielsen and Schovsbo (2011).

The sequence stratigraphical analysis of the early Cambrian sandstones and siltstones on Bornholm by Nielsen and Schovsbo (2011) indicates that the Vik Member formed during a period of falling sea level that occurred in between longer periods of rising sea level and related deposition in transgressive and highstand systems tracts.

The shoreline deposits in the Strøby quarry

Within the Strøby quarry, about 5 m of sandstone is exposed in association with a few 0.5–5-cm-thick layers of silt-rich mudstone. In the quarry walls, sedimentary structures are hard to detect, but at two bedding-parallel surfaces, approximately 1 m apart, well-preserved subaqueous bedforms are seen. Symmetrical wave ripples and subaqueous dunes characterize the lower level, whereas symmetrical wave ripples as well as relative large asymmetrical wave ripples characterize the upper level, in association with one relative small dune. During the description of wave ripple and dune orientation, present day coordinates are used. Several imprints of disc-like structures (medusoids) are also seen on the lower level in association with numerous small, loosely cemented spheroidal sand bodies with a diameter of 1–3 cm.

Wave-formed bedforms

Description

Symmetrical ripples with rounded profiles and occasional bifurcation are seen in the troughs and on the stoss sides

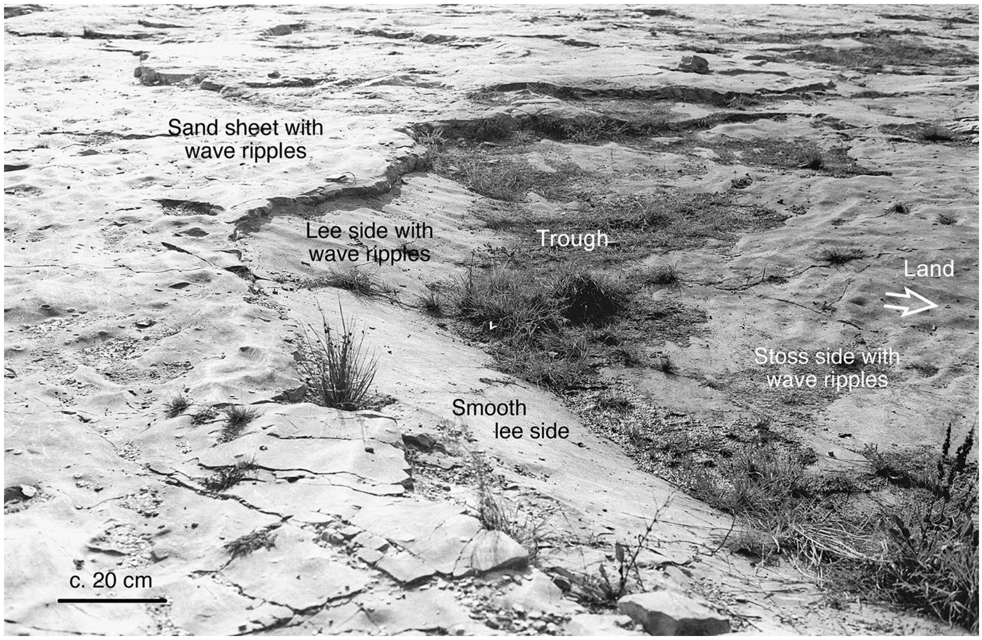

Fig. 4 Shallow-water bedforms, lower level of quarry at Strøby. In this example, the dune is truncated by a thin sand sheet. The lee side of the dune is curved. Symmetrical wave ripples are present both in front of the dune lee side and on top of the truncating sand sheet. Outcrop is viewed from the north (see also Fig. 5)

of lunate to straight-crested dunes in the lower level of the Strøby quarry (Figs. 4, 5, 6; Table 1). Like most other ripples in the quarry, these wave ripples are relatively flat with a ripple index between 10 and 15 (Table 1). They have crestlines running NE–SW (Fig. 7a), and their trends are parallel to, or more commonly, slightly oblique to the dune lee sides. Close to the dune fronts, the crestlines of the wave ripples vary to some degree (Fig. 5). Symmetrical wave ripples are also seen on top of the dunes (Fig. 6; Table 1). Their crestlines also trend NE–SW (Fig. 7b), but crestline orientation varies somewhat across the dune top. Finally, symmetrical wave ripples are present on top of 5–10-cm-thick sand sheets, which truncate the dunes (Figs. 4, 5; Table 1). These ripples also have crestlines trending NE–SW (Fig. 7b). Locally, a second set of symmetrical wave ripples overprint the primary one (Fig. 6; Table 1). These secondary wave ripples are seen on both dune tops and in dune troughs; they have crestlines running in variable directions, but many are almost perpendicular to the primary ones and form interference ripples.

In the upper level of the Strøby quarry, relatively small, symmetrical wave ripples are also present (Table 1); their crestlines are oriented around WNW–ESE (Fig. 7d). These small, symmetrical ripples are seen on the top of a subaqueous dune and overprint relatively large asymmetrical wave ripples on top of the dune and at the margins of the dune trough (Fig. 8a, c). Large asymmetrical wave ripples are present at many areas on the upper level (Table 1), but they are particularly well preserved in front of a straight-crested dune (Fig. 8a, b). The large asymmetrical ripples have crestlines oriented NNE–SSW (Fig. 7d); most of the asymmetrical ripples have lee faces pointing towards WNW (Fig. 8a, b).

The subaqueous dunes are best exposed in the lower level in the Strøby quarry. At this level, the dunes are lunate or, more rarely, straight-crested and their crestlines may be traced for up to 5 m (Figs. 4, 5, 6). The stoss sides of the bedforms are gently inclined (less than 6°–8°). The lee sides are relatively steep (up to 20°), but only the lowest 20 cm are preserved in most cases, as many of the bedforms are truncated by an erosion surface (Figs. 4, 5). The distance between adjacent dunes is around 5 m, they are arranged out-of-phase and well-developed troughs occur between the bedforms. The marginal parts of the dune lee sides are typically overlain by wave ripples, whereas the central (and highest and steepest) part of the lee sides is typically smooth. Measurements of the orientation of 16 dune lee sides indicate a mean migration direction towards WNW (Fig. 7c).

At the upper level, only one, straight-crested dune is present; the dune is fronted by relatively large asymmetrical wave ripples (Fig. 8a). The lee side of the dune is 10–15 cm high and has dip angles around 16°; the lee side faces towards the WNW and trends NNE–SSW (20°–200°).

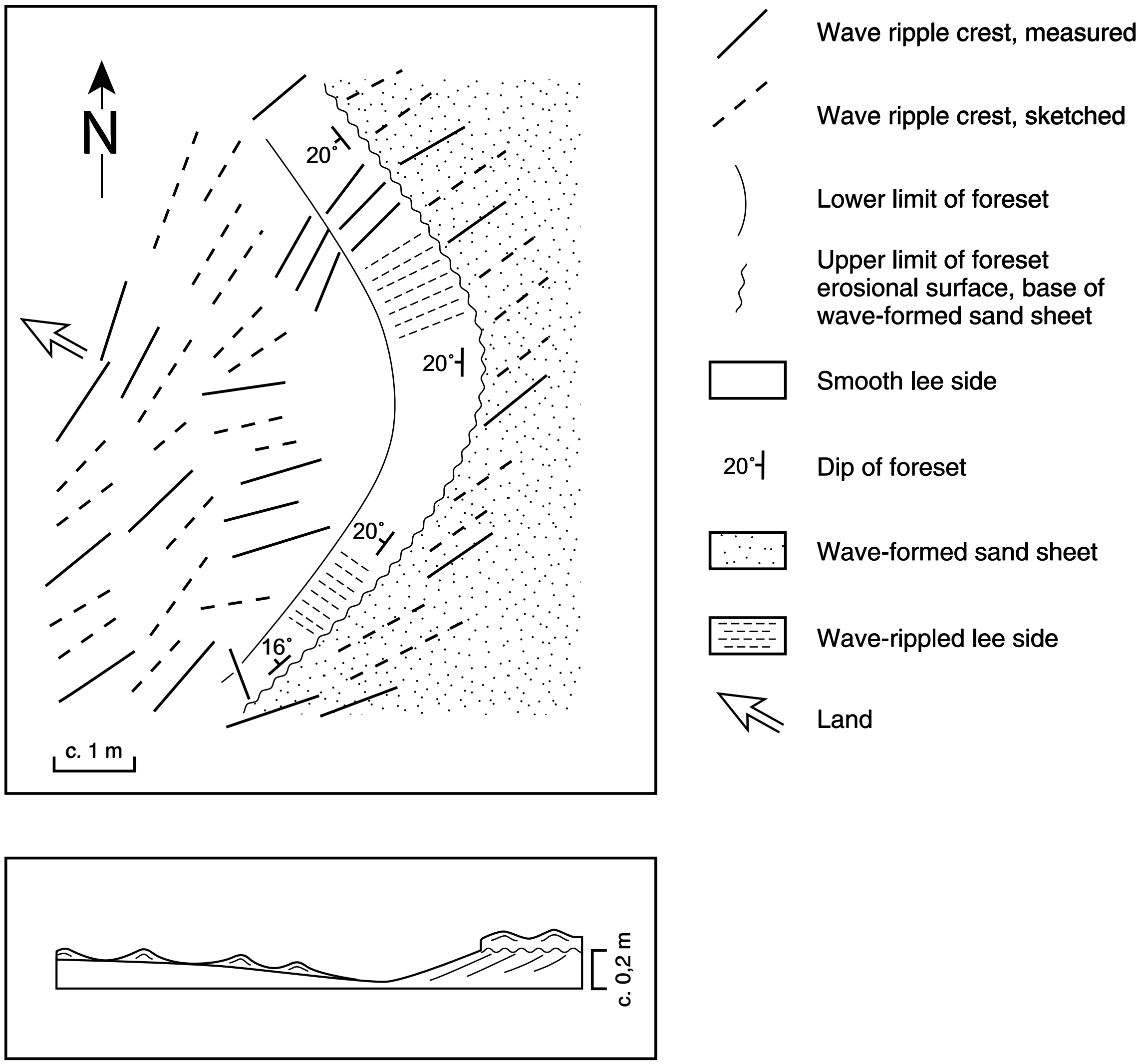

Fig. 5 Map view and section of lunate dune and associated wave ripples at the lower level at the Strøby quarry showing the bedforms in map view and section (compare with Fig. 4). The dune is truncated by a sand sheet also with wave ripples

Interpretation

The close association of wave ripples and dunes at both levels suggests that these bedforms were deposited almost simultaneously in a wave-affected, littoral zone environment. The wave ripples at the lower level are considered to have formed during low- to medium-energy oscillatory water motion in a nearshore, shallow-water environment (Allen 1997). The wave ripples are somewhat flatter and less steep than modern vortex ripples that have ripple index values (steepness) below 7.5 (Allen 1997). This could reflect compaction of the sand after deposition. Alternatively, the ripples could be classified as post-vortex ripples indicating that they formed during periods of very high sediment transport rates (Allen 1997). The wave ripples formed shortly after the dunes, and the changing crestline orientation of wave ripples adjacent to the dunes indicates that the waves were affected by the bottom topography. The superimposed ripples that locally are preserved probably indicate the influence of a wind blowing along the shore during falling water.

The relatively large asymmetrical ripples at the upper level of the quarry formed during combined flow and could also be named wave–current ripples (Allen 1982). Ripple asymmetry developed due to a net shoreward motion of water towards land (Allen 1982); ripple migration was towards WNW (~290°). Subsequently a weak wind (which presumably blew from either NNE or from SSW) generated small symmetrical wave ripples in shallower water on top of the dunes and the sides of the troughs, but had little effect in the deeper troughs. The difference between dune crest and trough is only in the

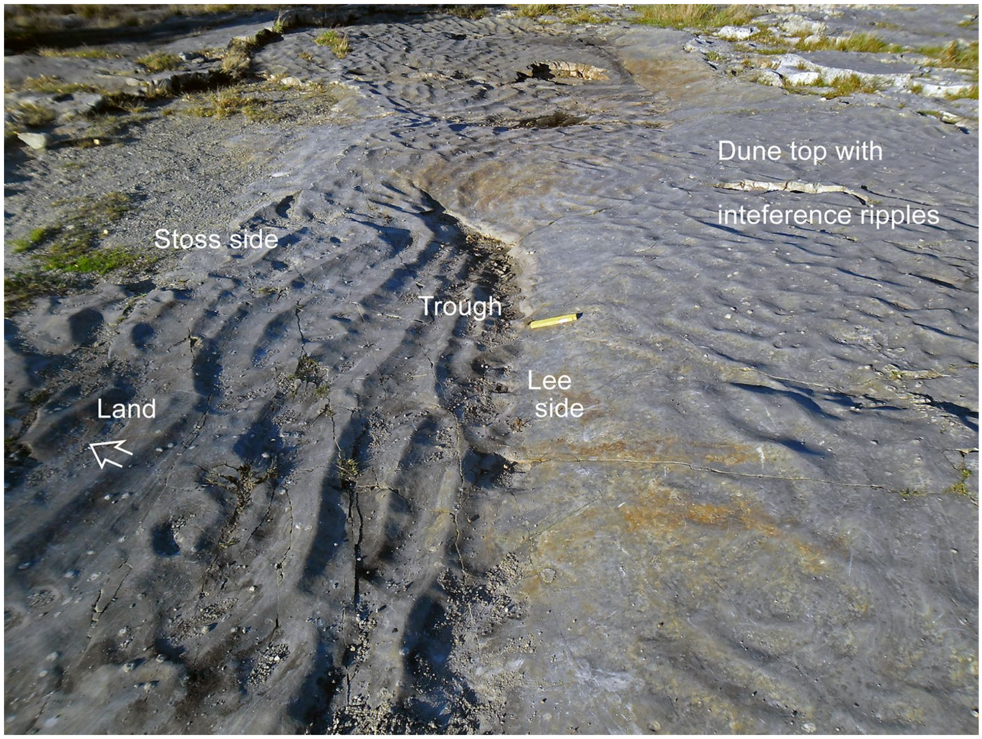

Fig. 6 Shallow-water bedforms, lower level of quarry at Strøby. In this example, the complete dune has been preserved. Primary, symmetrical wave ripples are seen in the dune trough and in a landward direction on the stoss side of the next dune (only partly preserved). These wave ripples in front of the dune have relatively straight crests and are almost parallel to the dune lee side which runs NNE–SSW. The relatively large wave ripples are locally overprinted by small-scale wave ripples with crestlines trending almost perpendicular to the primary ripples. Symmetrical wave ripples are also seen on the dune top. These ripples have somewhat undulatory crestlines and are oblique to the dune lee side; they are overprinted by a second set of wave ripples creating interference ripples. Outcrop is viewed from the south. Ruler is 20 cm

Table 1 Data on wave-formed ripples, Hardeberga Formation, Strøby quarry, Bornholm

Level	Ripple type	Ripple height (*H*) (mm)	Ripple wave length (*L*) (mm)	Ripple index (*L*/*H*)	Ripple crest orientation
Upper level	Symmetrical superimposed	8–27 (15)	100–250 (190)	~13	WNW–ESE
Upper level	Asymmetrical primary	25–45 (33)	275–415 (320)	~10	NNE–SSW
Lower level	Symmetrical superimposed	7–12 (10)	95–175 (130)	~13	NNW–SSE
Lower level	Symmetrical primary, dune tops	19–26 (20)	230–405 (300)	~15	NE–SW
Lower level	Symmetrical primary, dune troughs	20–34 (23)	180–385 (243)	~10	NE–SW

order of 20 cm, meaning that orbital wave action during this second phase of deposition must have been gentle and water depth very shallow.

The dunes are interpreted to have formed by medium- to high-energy wave-induced currents in the build-up or surf zone (cf. Clifton et al. 1971). At the high-energy, non-barred coast studied by Clifton et al. (1971), the dunes formed by onshore directed currents in water depths between 2 and 3 m, but in the studied example water depths were probably shallower.

The wave ripples at the lower level of the quarry have crestlines that trend NE–SW, and in agreement with other ancient (e.g. Hamberg 1991) and modern examples (e.g. Becker et al. 2007), they most likely formed parallel to a shoreline trending NE–SW. The crests of the asymmetrical wave ripples at the upper level are also assumed to be parallel or subparallel to the coastline, indicating that this was trending NNE–SSW. The slight variations in coastline orientation indicated by the two levels of the quarry may reflect that the alignment of the shoreline shifted with time.

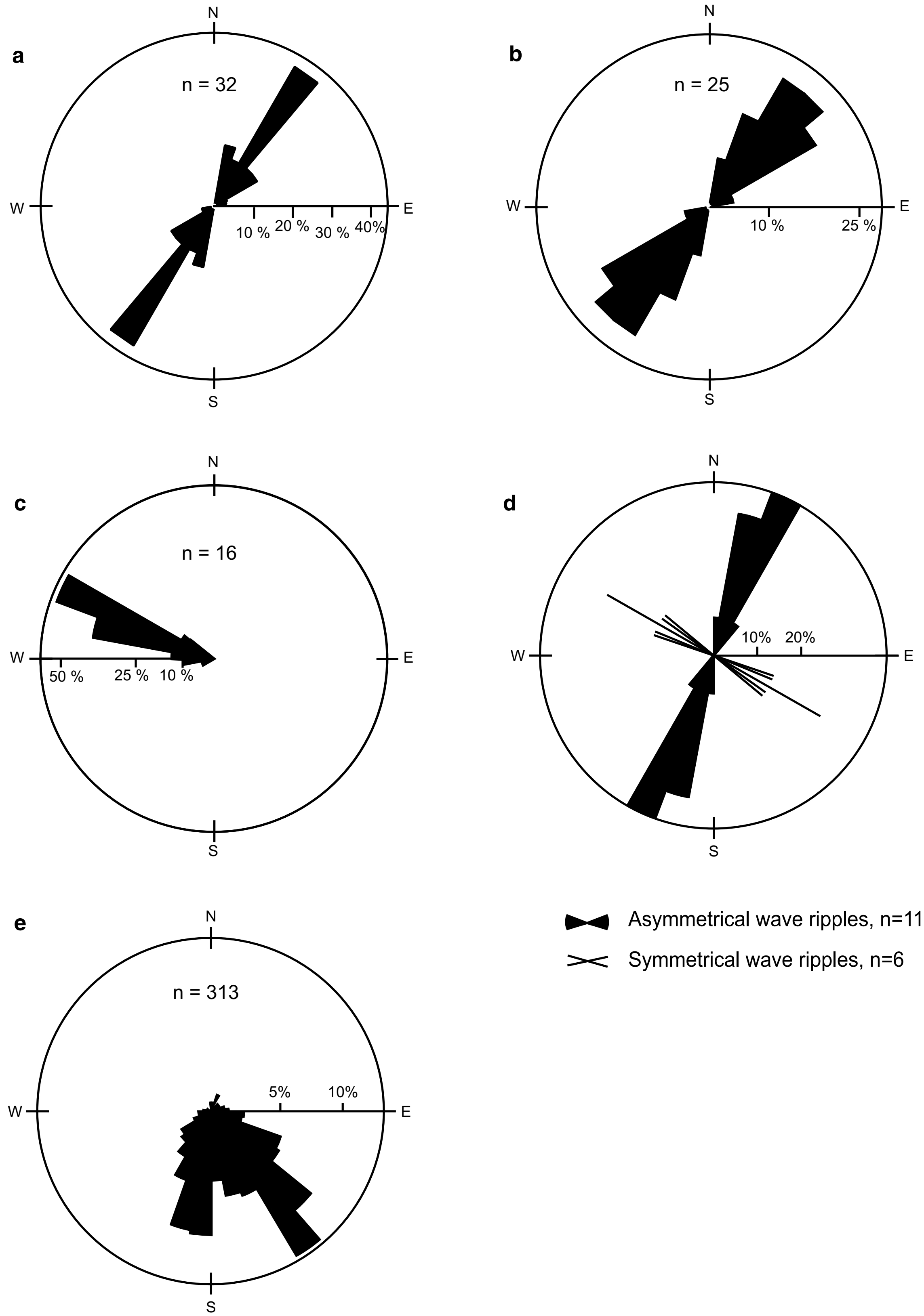

Fig. 7 Directional data. **a** Crests of wave ripples in front of dunes; lower level of quarry. **b** Crests of wave ripples on dune *tops* and in truncating sand sheets; lower level of quarry. **c** Lee sides of dunes; lower level of quarry. **d** Wave ripple crests; upper level of quarry. *Solid black* crests of larger asymmetrical wave ripples. *Thin lines* crests of smaller symmetrical wave ripples. **e** Fluvial transport direction in the Nexø Formation, Bodilsker Quarry (see Fig. 2). All data given in present day coordinates

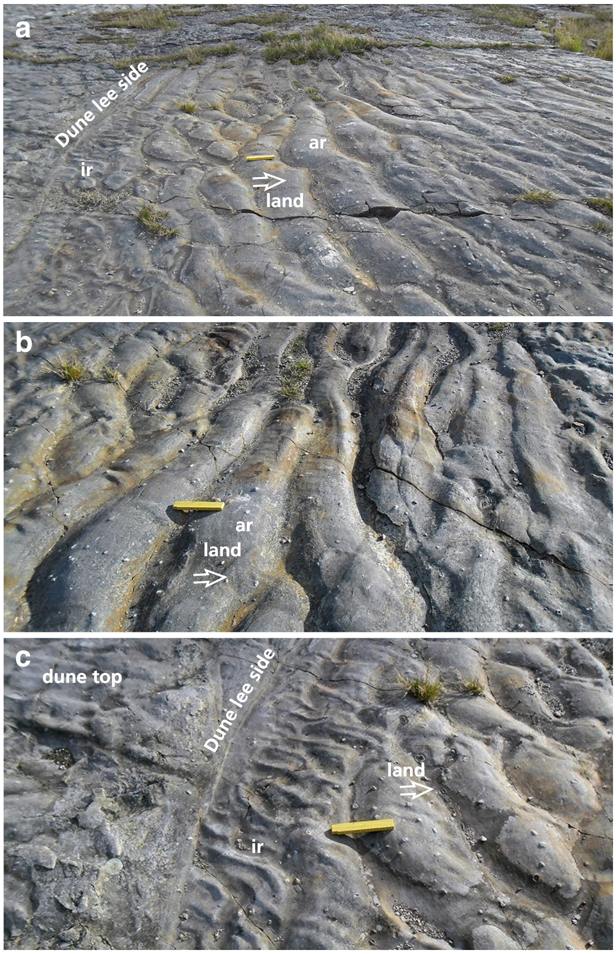

Fig. 8 Shallow-water bedforms, upper level of quarry at Strøby. **a** Relatively low, straight-crested dune (lee side indicated) is overlain and fronted by wave ripples; the dune lee sides is aligned NNE–SSW (20°–200°). Note relatively large asymmetrical ripples (ar) and interference ripples (ir). Outcrop is viewed from the north. Ruler is 20 cm. **b** Close-up of the relatively large asymmetrical wave ripples (ar) in front of the dune. Ripples are aligned NNE–SSW (compare with Fig. 7d). Note that ripple morphology changes in a westward (presumed landward) direction. Asymmetrical wave ripples with lee sides facing landward are followed by one or two almost symmetrical ripples and then by asymmetrical wave ripples with lee side facing seaward. Note also the local existence of small overprinting ripples. **c** Close-up of ripples formed close to the dune lee side. Small symmetrical ripples overprint the asymmetrical ripples creating interference ripples (ir)

Fig. 9 Ripple-like erosional structures, lower level of quarry at Strøby. The symmetrical ridges are seen to truncate subaqueous dune deposits and the foresets of these can be traced almost perpendicular to the ridge crests. Compass for scale

The dunes at the lower level of the quarry have crestlines that trend slightly obliquely to the crestlines of the symmetrical ripples, and we therefore infer that dune migration towards WNW was slightly oblique towards the shoreline (cf. Gallagher et al. 1998).

Ripples at both levels, as well as the subaqueous dunes, are typically found beneath a layer of greenish silt-rich mudstone. These mudstones are discontinuous layers, have a maximum thickness between 1 and 5 cm, and can be traced laterally for up to 7 m. The mud layers contributed to the preservation of the bedforms.

Ripple-like erosional structures

Description

Unusual, rarely preserved, erosional ridges are seen on bedding surfaces in the lower level of the quarry (Fig. 9). The external shape resembles that of symmetrical wave ripples, whereas the internal structures comprise the foresets of the underlying dune facies. The ridges are straight to weakly undulatory, can be traced for 20–40 cm and occur at regular intervals over areas of 1–2 m^2. The spacing between the ridges is around 15–18 cm, their height is around 2 cm and their outer morphology and orientation are similar to that of the closely associated wave ripples. The internal structures are discordant to the external shape of the ridges/bedforms, which indicate that they formed by erosion of the underlying dune deposits. The eroded surface has little overall relief indicating the original dunes were eroded to a subhorizontal level.

Interpretation

Symmetrical, erosional ridges may form by longitudinal scour (Collinson et al. 2006), but surfaces with longitudinal ridges and furrows are clearly different from those observed in the quarry. Rubin (1987) stated that purely erosional structures are rare, but that they may form where the rate of erosion approaches the rate of ripple migration and the ripples therefore scour downward into the underlying substrate without accumulating sediment. Rubin (1987) shows an example of erosional ripples covered by a silt-rich deposit, and it is suggested that the erosional structures in the quarry were produced in a similar way by wave ripple migration and erosion of underlying dune deposits.

Bedding surfaces with small, rounded pits or spheroidal bodies

Description

The bedding surfaces in the quarry show an abundance of rounded pits with a diameter of 1–3 cm (Fig. 10), previously mentioned by Poulsen (1966), Gravesen (1996) and Bromley (2002). Their density varies from a few to some 10 s pr. 1 m^2. A study by Edlich (2009) links these pits to equidimensional to slightly ellipsoidal spheres of porous sandstone, 1–3 cm in diameter. The spheres occur on upper and lower surfaces of the sandstone beds as well as within the beds. Thin sections show that the spheres consist of loosely cemented, friable sandstone, where the grains locally have a thin rim of phyllosilicates.

Interpretation

The rounded pits have been interpreted as traces of gas bubbles from underlying bituminous layers (Poulsen 1966; Gravesen 1996), although it has not yet been explained how gas bubbles may have been trapped in the clean, well-sorted, permeable sandstone. Traces of pyrobitumen locally stain the sandstone at Strøby dark grey (Møller and Friis 1999). Hydrocarbons are known to inhibit cementation and might be an explanation for the loosely cemented spheres, if these had been dark in colour, which is not the case. Bromley (2002) suggested that the pits are weathered-out concretions, perhaps originally pyrite; however, no staining by Fe-oxides is observed in the spheres. A final possibility is that the pits and weakly cemented spheroidal bodies were originally filled with mat chips or microbially bound sand (cf. Pflüger and Gresse 1996; Schieber et al. 2007).

The porosity in the spheres is interpreted as due to localized protection against the pervasive quartz cementation. No traces of this have been detected in thin sections or through backscattered electron analysis (Edlich 2009). The rounded pits (Fig. 10) are interpreted as removal of loosely cemented sandstone, but the cause of the weak cementation remains elusive.

Fig. 10 Medusoid exposed at the lower level of the Strøby quarry. The imprint is preserved on top of a surface with symmetrical wave ripples. The surface also displays a number of small rounded pits or loosely cemented speroidal sand bodies

Medusoids

Description

The sandstones of the Strøby quarry contain several discoidal structures (Fig. 10) that remained unidentified until 2006 when the German ichnologist Adolf Seilacher interpreted four of these structures as fossilized impressions of a Scyphozoan medusae (Seilacher 2008). Due to the relative poor preservation of these discoids and a rarity of fine-scale structures, it is difficult to describe these structures with certainty as imprints of medusae and hence they are here termed medusoids (Young and Hagadorn 2010).

During this study, additional medusoids to those recognized by Adolf Seilacher were discovered, one of which is a possible double structure. Here, however, only the four best preserved discoids are described. The structures are preserved on a surface in the lower level with wave ripples and subaqueous dunes (Fig. 10). They are overlain by a silt-rich

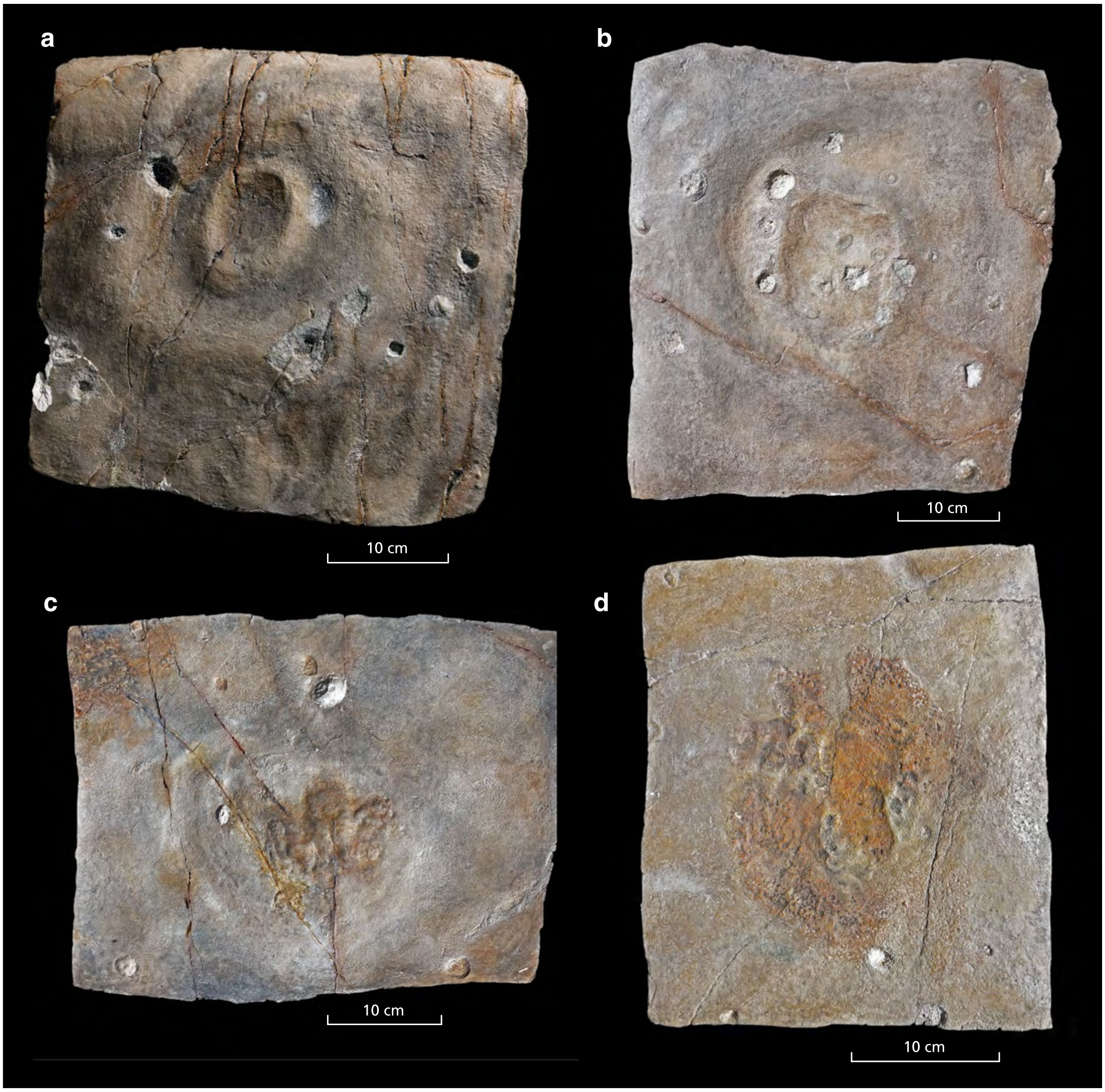

Fig. 11 Medusoids, lower level of quarry at Strøby. All casts were prepared by Hans Luginsland, and three of these (**b**, **c**, **d**) are now exhibited in the museum of NaturBornholm; the casts are replica of actual surface structures and painted to match the original surface. **a** Shallow discoidal depression with an inner ellipsoidal ring and an outer near-perfect circular ring; the ellipsoidal ring has as an outer diameter of 9–12 cm, while the circular ring has an outer diameter of 26–27 cm (compare with Fig. 31f in Seilacher 2008). Areas of loosely cemented sand frequently forming small pits are present on this as well as on the other casts (compare with Fig. 10). **b** Shallow discoidal depression with two circular rings; the inner ring has as an outer diameter of 13 cm, while the outer ring has diameter of 29 cm. **c** Shallow discoidal depression with a loosely defined marginal ring with a diameter of 22 cm; fine-scale structures in the central part of the medusoid might represent imprints of gonads. **d** Loosely defined medusoid with a diameter of about 16 cm; a number of fine-scale structures are present in the central part

mudstone although this layer is missing at most places due to modern erosion. Two of the structures are round to ellipsoid depressions in the sandstones; they have an outer ring with a diameter of 26 and 29 cm and inner ring with diameters of 9 and 13 cm (Fig. 11a, b). These two discoids, however, lack other fine-scale structures. The two other medusoids have a less clear margin to the host sediments; they have a roughly circular appearance with a diameter of 16 and 22 cm (Fig. 11c, d). These two examples do contain fine-scale internal structures in the form of central, irregular to globular moulds (Fig. 11c, d).

Interpretation

The size of the medusoids, their circular to near-circular shape, the presence of an outer ring as well as an inner mound or smaller ring-formed structure suggest that they could be imprints of medusae (cf. Hagadorn et al. 2002).

Two medusoids contain fine-scale, central structures that might represent imprints of gonads, decomposing mesoglea, and/or tangled mass of oral arms (Fig. 11c, d), but the remaining medusoids are devoid of distinct structures that could represent impressions of the stomach, gonads, tentacles and oral arms, and no structures can be linked to drag marks (cf. Young and Hagadorn 2010).

Alternatively, the medusoids could represent sand-volcano-like structures formed by subsurface blistering of a near-surface bed (Dornbos et al. 2007; Hagadorn and Miller 2011). Such structures should be characterized by a central sediment plug, radial lineations that extend outward from the central plug, concentric rings and a broad trough surrounding ring margins; these structures may have up to five concentric rings surrounding the central plug (Hagadorn and Miller 2011). If the structures represent persistent sand volcanos, they should contain a vertical (fluid) shaft beneath the central plug; however, if the structures record short-lived blisters and fluidization processes, such a shaft could be lacking (Hagadorn and Miller 2011). Unfortunately, the vertical structure of the medusoids is not revealed in the quarry, and due to protected nature of the quarry it was not possible to make sections of the discussed structures.

The present medusoids have a complete lack of radial cracks, and they never contain more than one ring surrounding the central structures. This could tentatively indicate that the structures indeed are true imprints of medusae as original suggested by Seilacher (2008). The discoidal structures overprint wave ripples, and if they represent imprints of medusae, it can be inferred that jellyfish were stranded in connection with emergence of the sandy sediment. The lack of fine-scale structures in most examples could be related to the relatively well-sorted sandy substrate. The discoidal structures are only found on the lower level, and their preservation here is probably related to the following deposition of a thin silty mud layer or to the formation of biofilms.

Discussion and conclusions

The sedimentary features observed in the Strøby quarry suggest deposition in a littoral zone (upper shoreface) environment along a wave-dominated shoreline. The quartz sand was transported shoreward primarily by wave action and deposited as subaqueous dunes or large asymmetrical wave ripples in the build-up or surf zone (cf. Clifton et al. 1971; Gallagher et al. 1998; Miles et al. 2014). During somewhat reduced wave energy, symmetrical wave ripple formed in front of and on top of the inactive dunes. Water depths were shallow, and the close association of dunes and wave ripples, the presence of interference ripples as well as the imprints of possible medusae (subaerial exposure) suggest water level fluctuations in the order of 0.5 m or more. It is unknown whether these water level variations were due to tidal influence or changing meteorological conditions. The silt-rich mud that drapes the bedforms could have been deposited in a shallow subtidal environment during periods of slack water (cf. Becker et al. 2013); the relative thick mudstone layers seen here, however, must have formed during a prolonged period of calm water. Such conditions could have occurred during periods when tidal influence was minimal (neap tide) and winds were blowing offshore and changed the upper shoreface environment to one of inactive dunes separated by quiet pools. The silt and clay that were deposited in these pools could have been blown in from the barren land surfaces (cf. Dalrymple et al. 1985; Hamberg 1991; Nielsen and Schovsbo 2011).

If the discoidal structures indeed represent imprints of jellyfish, the medusae were either blown or swam into the littoral zone during elevated water (spring tide or onshore winds) and stranded when the water receded. Similar stranding events are frequently seen along modern sandy coasts in Denmark (Fig. 12). Some of the medusae seem to have been alive after stranding forming either a central mound by pumping their stomach full of sand or a marginal ring by repeated contraction of the bell margin (cf. Hagadorn et al. 2002). Preservation of the imprints indicates that little or no reworking of the substrate took place after the carcasses had decayed. Silt and clay deposited in the quiet pools after stranding could have protected the imprints from erosion during following episodes of wave activity. Microbial mats that commonly develop on sandy tidal flats and on sandy beaches could also have protected the discoidal structures from erosion (Noffke 1998, 2008).

From the data in the Strøby quarry, it is difficult to interpret the shoreline type that prevailed during deposition of the sand. Comparison with data from southern Scania (Hamberg 1991) suggests that the sand was deposited in front of a barrier island system. In such a setting, back-barrier deposits are also expected to occur; however, they are not present in the quarry, but they do occur elsewhere in the Hardeberga Formation (Hamberg 1991). We tentatively suggest that the sand in the Strøby quarry was deposited in front of a mainland beach (Fig. 13). This system apparently changed alongshore (or with time) to a barrier island coast. The symmetrical wave ripples in the lower level suggest that the shoreline was trending NE–SW (similar trend in Cambrian times). Subaqueous dunes were migrating towards the WNW (ESE in Cambrian times) slightly obliquely towards the shoreline. The shoreline trend, however, may have been local, and in a more regional perspective the shoreline may have been running E–W (Fig. 13; Hamberg 1991).

Fig. 12 Stranding of jelly fish, Danish beach facing the microtidal Belt Sea. The crests of the wave ripples are parallel to the shoreline

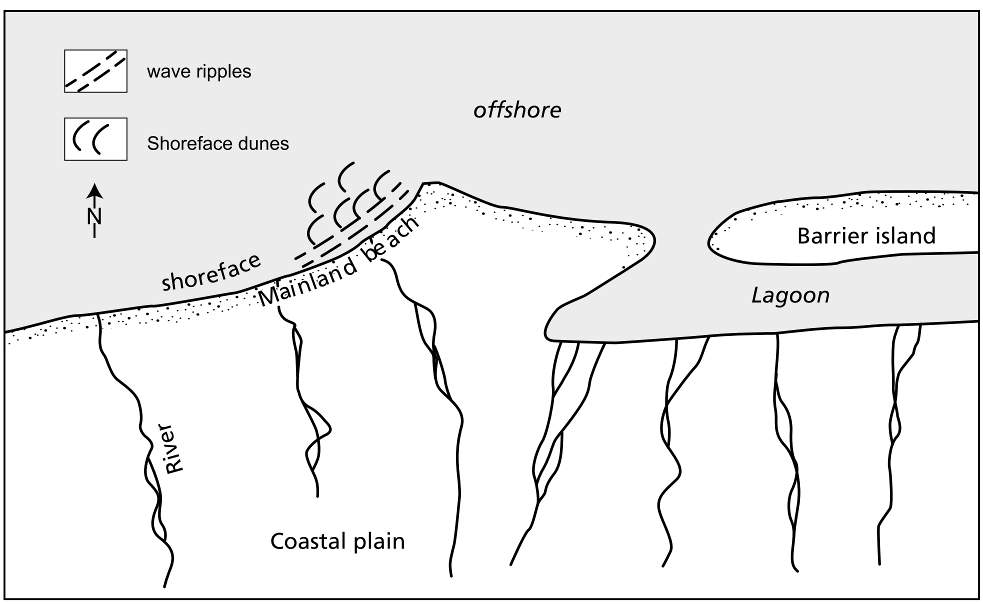

Fig. 13 Early Cambrian palaeogeography and tentative depositional models for the Hardeberga Formation on Bornholm (bedforms not to scale). Model based on observations done in the lower level of the Strøby quarry supplemented by data from Hamberg (1991). North refers to Cambrian palaeogeography

Rivers in the Nexø Formation flowed towards the south (north in the early Cambrian) towards the Cambrian sea (Clemmensen and Dam 1993), and this drainage pattern probably still existed during deposition of the Vik Member in the Hardeberga Formation (Fig. 7e). The northward-directed fluvial drainage supports the suggested palaeogeographical reconstruction with an overall E–W trending shoreline facing a sea to the north (Fig. 13).

In early Cambrian, Baltica was located in the southern hemisphere, at the southern margin of a large ocean in the early Cambrian (Torsvik and Rehnström 2001; Cocks and Torsvik 2005), and the position of Bornholm on latitudes around 35°S adjacent to the ocean suggests a high-energy coastline affected by strong wave activity. In agreement with this setting, Hamberg (1991) suggested that the barrier island system in southern Scania was deposited during the influence of winter storms. There is less evidence of storm activity in the study area although the formation of the subaqueous dunes probably took place under high-energy wave action. The erosive base of the sand sheet that truncates some of the dunes in the lower level may have formed during peak storm activity followed by the formation of ripple-like ridges during the waning storm.

The unusually good preservation of various subaqueous bedforms as well as the medusoids in the Strøby quarry is exceptional and should lead to continued studies of the scenario that allowed preservation. A detailed study of the lithology and grain size composition of the silty mud layers that apparently protected the structures from reworking is needed in order to test that the grains were wind transported. Biofilms may also have contributed to the preservation of the structures, but no features have yet been identified to support the former presence of microbial mats. Features associated with the development of biofilms include erosional remnants (small elevated surfaces with flat tops) and pockets or small depressions as well as chips of microbial mats (Noffke 2008). While the erosional remnants and the pockets may be very hard to identify on the bedding surfaces in the quarry, the small chips may stand a better chance of preservation and could possibly be identified as intraformational clasts in polished slabs of the sandstones. The interpretation of the sandstones as littoral deposits that experienced occasional emergence would be supported if continued studies led to the discovery of features such as adhesion ripples, swash and backwash structures as well as small-scale drainage channels.

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