Aphanitic buildup from the onset of the Mulde Event (Homerian, middle Silurian) at Whitman's Hill, Herefordshire, UK: ultrastructural insights into proposed microbial fabrics

Jan-Filip Päßler[a], Emilia Jarochowska[a], David C. Ray[b], Axel Munnecke[a] and Graham Worton[c]

[a] GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen-Nürnberg, Loewenichstr. 28, 91054 Erlangen, Germany; jan_p92@yahoo.de, Emilia.Jarochowska@fau.de, Axel.Munnecke@fau.de
[b] Neftex, 97 Jubilee Avenue, Milton Park, Abingdon, Oxfordshire, OX14 4RW, UK; daveray01@yahoo.com
[c] Dudley Museum and Art Gallery, St. James' Road, Dudley, West Midlands DY1 1HZ, UK; graham.worton@dudley.gov.uk

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Abstract. A microbial origin has been proposed for matrix-supported, low-diversity buildups reported from different palaeocontinents during the onset of the Mulde positive carbon isotope excursion. We have investigated a small aphanitic buildup from the Lower Quarried Limestone Member of the Much Wenlock Limestone Formation, exposed at Whitman's Hill (Herefordshire), corresponding to the central part of the Midland Platform (UK). Up to 50% of the rock volume in this buildup consists of mottled micrite. The SEM studies revealed that the micrite is largely detrital and does not show features characteristic of calcareous cyanobacteria or leiolites. The aphanitic character of the buildup is suggested to be controlled by the depositional rate, and the widespread occurrence of matrix-supported reefs in this interval to be driven by a mid-Homerian rapid eustatic transgression.

Key words: Midland Platform, Much Wenlock Limestone Formation, Lower Quarried Limestone Member, oncoids, automicrite, Wenlock Series.

INTRODUCTION

The Mulde Event (Homerian, middle Silurian) has been introduced as an extinction event affecting conodonts (Jeppsson 1993) and corresponds to the 'Big Crisis' in graptolites, known as the *lundgreni* event (Jaeger 1991; for a summary see Cramer et al. 2012). It is associated with the first peak of a double-peaked positive stable carbon isotope excursion (CIE) recognized in low- to mid-latitudes across different palaeocontinents (summarized in Munnecke et al. 2010). The event is associated with faunal turnover, the proliferation of microbial carbonates (e.g., Kõrts 1991; Calner 2005; Jarochowska et al. 2014a) and the occurrence of low-diversity, aphanitic reefs (e.g., Kaljo et al. 1995; Ratcliffe & Thomas 1999; Calner et al. 2000; Kershaw & Da Silva 2013). Among the explanations for the observed changes in reef composition are reduced grazing, increased nutrient input or elevated seawater alkalinity, each of which is interpreted to favour microbially-mediated carbonate precipitation (e.g., Munnecke et al. 2010; Jarochowska et al. 2014a). In the present study, we have investigated a matrix-supported buildup from near the onset of the Mulde CIE in the central part of the Midland Platform (UK), and using micro- and ultrafacies (SEM) analysis, we have performed a preliminary test of the microbial origin of the aphanitic matrix of this buildup.

GEOLOGICAL SETTING

Whitman's Hill Quarry (SO 7490 4830, Fig. 1), Storridge, Herefordshire, is a Regionally Important Geological Site (RIGS) exposing a thick continuous succession of Homerian Stage strata, representing a mid-platform setting upon the Midland Platform (Ray et al. 2013). The exposed interval comprises the uppermost Coalbrookdale Formation (CF) and the Lower Quarried Limestone (LQLM) and Nodular Beds (NBM) members of the Much Wenlock Limestone Formation (Fig. 2A). Ray et al. (2013) have developed a sequence stratigraphic interpretation allowing correlation of the section at Whitman's Hill with sections across the northern Midland Platform at the parasequence level. This interpretation, supported by bentonite correlations, identifies a pronounced regression associated with the boundary between the CF and the LQLM. The LQLM is associated with grainstones, oncoid-rich limestones and buildups and is considered to represent the onset

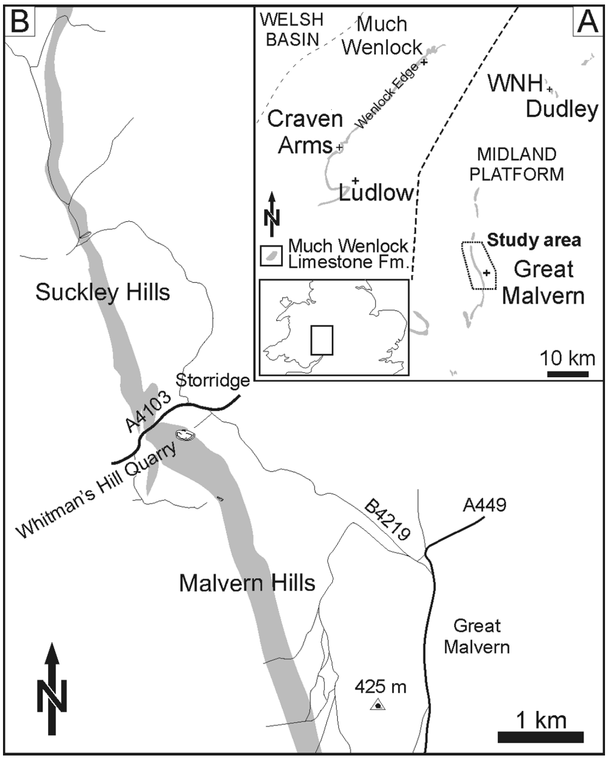


Fig. 1. Geographical position of Whitman's Hill Quarry. Grey areas mark outcrops of the Wenlock Series. **A**, position of the main outcrop belts of the Much Wenlock Limestone Formation in the western part of West Midlands. The dashed line marks the westernmost range of the Lower Quarried Limestone Member. The stippled line marks the area shown in **B**.

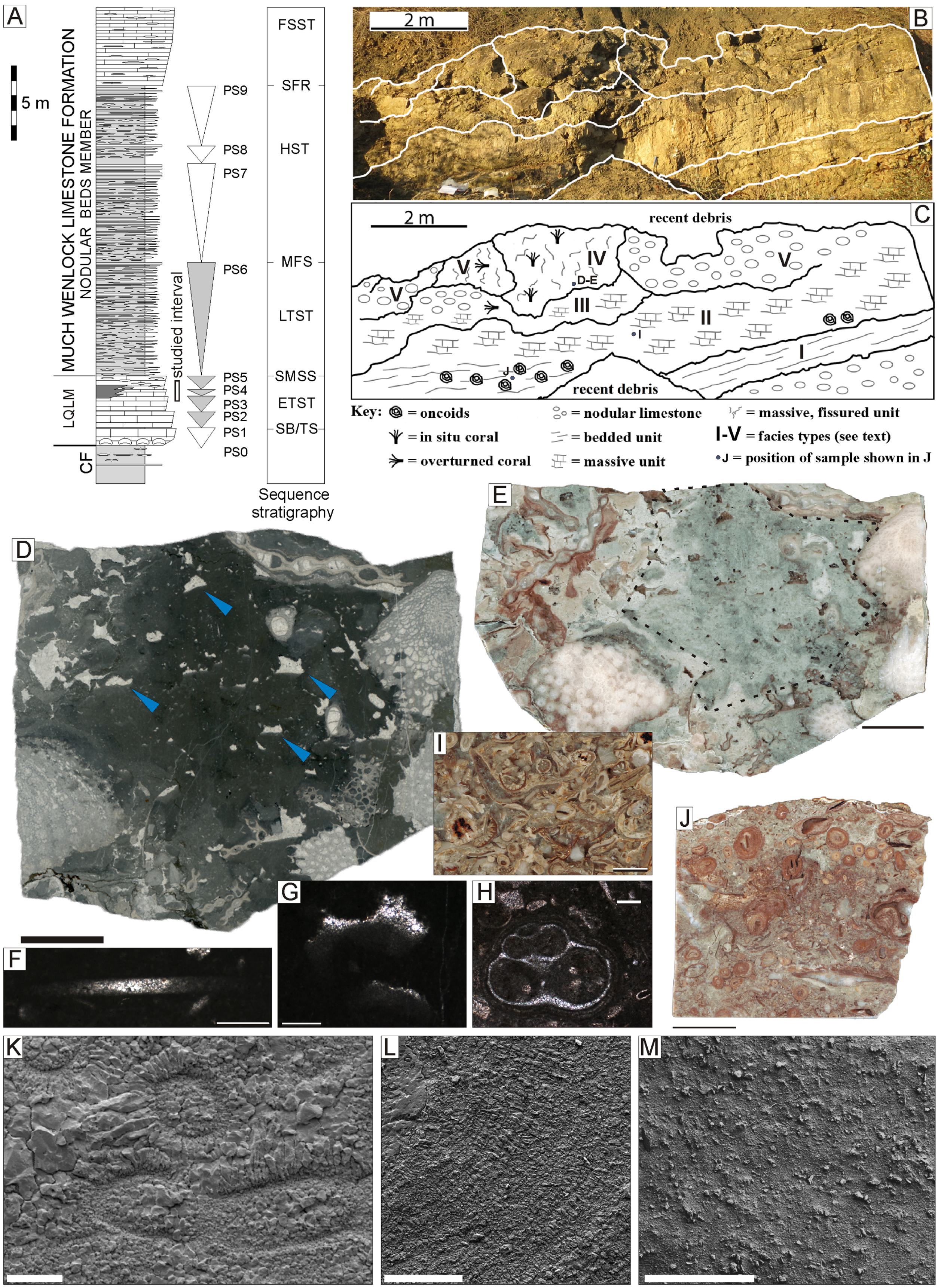
of transgression (early transgressive systems tract). Above, the lower NBM is associated with nodular limestones and silty mudstones and is considered to represent more rapid transgression (late transgressive systems tract) and the overlying maximum flooding surface. The onset of the Mulde positive CIE has been identified in the northern Midland Platform (Dudley, West Midlands) at the boundary between the CF and LQLM (Corfield et al. 1992; Marshall et al. 2012). Such studies indicated that the peak $\delta^{13}C_{carb}$ values of the Mulde CIE correspond to the upper part of the LQLM and amount to values up to +5.5‰ (V-PDB). At Whitman's Hill, the Mulde CIE has been identified by Jarochowska et al. (2014b), who recorded peak $\delta^{13}C_{carb}$ values up to +4.8‰ (V-PDB) within the LQLM, corresponding to an interval immediately below the buildup described herein. The buildup occurs in the upper LQLM and is exposed in the northern wall of the quarry (oriented in E–W direction). The exposed interval is 12 m long and 3.5 m high (Fig. 2B, C).

RESULTS

Microfacies of the buildup and adjacent strata

The entire exposure is contained within the LQLM (Fig. 2A). Its base falls within nodular limestone facies, overlain by a prominent unit of bedded crinoidal grainstone (facies I, Fig. 2C). The grainstone is moderately sorted. Elongated components (predominantly crinoid ossicles – 60%) are aligned parallel to the bedding plane. The grainstone has an admixture of up to 3.5 mm large well-rounded lithoclasts encrusted by *Rothpletzella* and *Allonema*. The top of the grainstone unit is sharp and overlain by porostromate oncoidal rudstone-floatstone (facies II, Fig. 2I, J). The oncoidal unit has a massive appearance in the central part of the outcrop (Fig. 2B, C). Towards the eastern part of the section, it grades into 10 to 20 cm thick beds characterized by better sorting and a decreasing proportion of oncoids and micritic matrix (Fig. 2I). Within the massive unit, oncoid diameters range from 0.4 to 7 mm, amounting to ca 65% of rock surface (Fig. 2J). Benthic fauna, dominated by gastropods, crinoids and brachiopods, makes up ca 30% of the skeletal components, many of which are encrusted with *Rothpletzella*, *Girvanella*, *Hedstroemia* and *Allonema*. The bedded unit is poorly sorted and characterized by high abundance of tabulate and rugose corals and bryozoans, showing evidence of

Fig. 2. Stratigraphic position and microfacies types of the buildup at Whitman's Hill. **A**, position of the studied interval within the section, modified from Ray et al. (2013); PS, parasequence; SB/TS, sequence boundary/transgressive surface; SMSS, surface of maximum sediment starvation; MFS, maximum flooding surface; SFR, surface of forced regression; ETST, early transgressive systems tract; LTST, late transgressive systems tract; HST, highstand systems tract; FSST, falling stage systems tract. **B**, main lithological units marked on the buildup photograph. **C**, distribution of facies types and of samples presented in D–M. **D–H**, coral bafflestone (facies IV): D, thin section, arrows indicate *stromatactis*-like structures; E, polished slab; D, E, scale bar 1 cm; F, sponge spicule; G, close-up of a *stromatactis*-like structure; G, H, scale bar 500 µm; H, recrystallized gastropod with *Rothpletzella* coating, scale bar 200 µm. **I**, **J**, oncoidal rudstone (facies II), polished slabs, scale bars I – 500 µm, J – 1 cm. **K–M**, SEM photographs of polished slabs, etched with 1N HCl for 30 s and sputter-coated with gold: K, L, sample shown in J; K, ?*Girvanella* floating in micritic matrix, scale bar 20 µm; L, porostromate oncoid, scale bar 100 µm; M, allochthonous micrite in the area marked with a dashed line in E, scale bar 500 µm.


A
5 m
MUCH WENLOCK LIMESTONE FORMATION
NODULAR BEDS MEMBER
LQLM
CF
studied interval
PS9
PS8
PS7
PS6
PS5
PS4
PS3
PS2
PS1
PS0
FSST
SFR
HST
MFS
LTST
SMSS
ETST
SB/TS
Sequence stratigraphy
B
2 m
C
2 m
recent debris
IV
V
V
V
D-E
III
II
I
I
J
recent debris
Key:
= oncoids
= in situ coral
= overturned coral
= nodular limestone
= bedded unit
= massive unit
= massive, fissured unit
I-V = facies types (see text)
J = position of sample shown in J
D
E
F
G
H
I
J
K
L
M

short-term transport and redeposition in the form of large, only slightly disarticulated fragments which are overturned and sheltering geopetal structures. Recrystallized sheaths of the udoteacean alga ?*Dimorphosiphon* sp. are also common.

The massive unit of facies II is overlain by massive to nodular poorly sorted float- to rudstone (facies III, Fig. 2C). The largest proportion (25%) of the rock surface is occupied by brachiopods, rugose and tabulate corals (10%) and branching bryozoans (10%). Up to 15% of the surface is formed by encrusting organisms: bryozoans represented mainly by *Asperopora aspera* and the calcareous microproblematicum *Rothpletzella*.

The central part of the buildup is formed by coral bafflestone (facies IV, Fig. 2B, C, D–H) partly overlain by brachiopod-rich facies III. The buildup is formed by several pillow-shaped units (Fig. 2B). The transition to surrounding bedded facies V is gradual. The buildup framework is formed by complete, in situ colonies of rugose and tabulate corals, stromatoporoids and branching bryozoans. The sediment baffled between the framework builders consists of very poorly sorted echinoderm ossicles, brachiopods and rare ?*Dimorphosiphon* fragments, but the buildup fabric is distinguished by a high (ca 50%) micritic matrix. *Allonema* and *Rothpletzella* are present as crusts and *Rothpletzella* also as loose accumulations within the matrix. These are associated with mottled, peloidal-like structures (Fig. 2D, E) containing structures tentatively identified as sponge spicules (Fig. 2F). The mottled fabrics contain multiple small (up to 0.4 cm wide) *stromatactis*-like cavities filled with spar, characterized by sharp basal parts and irregular undulating upper parts (Fig. 2D, G).

In SEM images, oncoids and *Rothpletzella* accumulations floating in the matrix are built by tubes filled with sparitic cement (Fig. 2K, L). The tube walls are 5–6 µm thick, formed by regularly arranged needle-shaped calcite crystals oriented perpendicular to the porostromate tube in longitudinal sections and radially in cross sections (Fig. 2K). In contrast, the mottled, peloidal matrix of facies IV is composed of chaotically arranged microcrystalline calcareous mud containing a high proportion of clay particles and scattered fragments of skeletal grains (Fig. 2M).

The buildup is overlain by nodular wacke- to packstones composed of well-sorted echinoderm, brachiopod, gastropod, trilobite and coral fragments (facies V) and onlapping the units represented by facies II, III and IV.

Reconstruction of buildup development

The onset of buildup growth is associated with the sharp upper surface of the crinoidal grainstone unit (facies I in Fig. 2C). It is formed by fully marine faunal components and characterized by current sorting and alignment of skeletal grains indicative of a shallow environment well above the upper storm-weather wave base. Oncoids in the overlying facies II correspond to *type A* of Ratcliffe (1988), indicating their formation in a moderately agitated environment. Winnowing was limited within the massive unit of the oncoidal rudstone-floatstone, suggesting protected, back-buildup setting. The unit intercalates with the bedded oncoidal rudstone, representing thallus composed of material shed from the buildup core facies III and IV. The high proportion of micritic matrix, lack of photosynthetic organisms and diverse, fully marine fauna present in facies V indicate deposition in a fore-buildup setting, below the fair-weather wave base and below the euphotic zone, as indicated by the disappearance of green algae.

DISCUSSION

The deepening trend, visible in the onset and demise of the carbonate buildup at Whitman's Hill, reflects the overall retrogradational character of the LQLM above the basal sequence boundary (Ray et al. 2013). The buildup growth interval approximates to the upper part of the LQLM in the main quarry wall (Fig. 2A) and the bioclastic wacke- to packstones of facies V – to an interval of an increased rate of relative sea level rise. This transgression, associated with the highest values of the Mulde CIE, is recognized on the Midland Platform, as well as in multiple basins across different palaeo-continents (e.g., Calner et al. 2006). In all these settings, the transgressive deposits are characterized by an abrupt appearance of microbially-mediated carbonates, either as oolites – e.g. the Bara Oolite Member of the Halla Formation in Gotland (Calner & Säll 1999) or the Limberlost oolite of the Cincinnati Arch (Brett et al. 2012) – or as oncoids, e.g. in Estonia (Kõrts 1991), Podolia (Jarochowska et al. 2014a) and Gotland (Calner 2005). The reef composition also appears to become altered at the onset of the Mulde CIE (Calner 2005). This is expressed as decreased species richness and colony sizes of skeletal reef-building organisms (Klaamann & Einasto 1977; Kaljo et al. 1995; Calner et al. 2000; Kershaw & Da Silva 2013) and an aphanitic structure dominated by micrite, e.g. in the Muksha thrombolitic buildups in Podolia (Jarochowska et al. 2014a) and the LQLM reefs (Penn 1971; Ratcliffe & Thomas 1999). The combination of an aphanitic, mottled, matrix-supported structure with scattered peloidal fabrics and with the overall increase in the proportion of microbial carbonates in the form of oncolites and floating porostromate problematica in the carbonate buildup at Whitman's Hill may suggest that the bulk of the buildup framework was leiolitic (Schmid 1996). This, in turn, would imply that the micritic component of the studied buildup originally was a cohesive, structureless micrite precipitated by means of microbial mediation ('automicrite', Kershaw et al. 2007). In the present study, we have investigated the ultrastructure of this aphanitic buildup, using the proportion of the micrite surface in thin sections as a proxy for its volume and obtaining values up to ca 50%. Ultrastructural study of this mottled micrite revealed a chaotic structure rich in detrital skeletal fragments and clay fragments, differing from the microcrystalline wall structure of the putative cyanobacterium *Rothpletzella* and from micrite derived from well-documented microbial constructions (e.g., Buczynski & Chafetz 1993; Westphal et al. 2010; Guido et al. 2011). This indicates that either the buildup was supported by cohesive microbial mucus, which did not mediate carbonate precipitation, but only bound detrital sediment, or that a different mechanism was responsible for the formation of the matrix-supported buildup. Matrix-supported buildups ('microbioherms') have been noted in this interval from various localities worldwide (Penn 1971; Archer & Feldman 1986; Kershaw et al. 2007; Jarochowska et al. 2014a), supporting the global control for their development. Brunton & Dixon (1994) have proposed that reef mounds, i.e. largely micritic reefs formed by microbes and siliceous sponges, proliferated specifically during prominent eustatic transgressions during the Palaeozoic. As matrix-supported or cluster reefs are broadly characteristic of deeper subtidal settings with low depositional rates (e.g., Riding 2002), the rapid mid-Homerian transgression (Calner & Jeppsson 2003; Ray et al. 2010, 2013) might be the primary force driving the expansion of this type of buildups. Consequently, the depositional rate, not specific composition would be the factor determining their aphanitic appearance and lower diversity compared to shallow subtidal skeletal reefs. Contemporary sponges commonly form symbioses with bacteria and this association has a relatively larger contribution to the framework of deep subtidal or low-energy reefs and particularly mud mounds. Thomka & Brett (2014) argued that matrix-supported reefs are not observed at every major middle Silurian transgressive surface and inferred that additional control was necessary to explain time-specific reef facies appearing specifically during Silurian carbon isotope excursions. Our observations suggest that microbial contribution may not be the distinguishing element of the Mulde Event reefs and that ultrastructural studies may help in clarifying erroneous assumptions on the microbial origin of matrix-supported reefs.

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