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The Mercia Mudstone Group of the Severn Basin

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The Mercia Mudstone Group of the Severn Basin

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The Branscombe Mudstone and Blue Anchor formations at Garden Cliff, Westbury-on-Severn, Gloucestershire.

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Executive Summary

This report is an output of the UK Stratigraphy thematic research area within BGS National Geoscience. The rationale for the work was to support the development of an improved stratigraphic framework for part of the Mercia Mudstone Group in the Severn Basin region (Newell, 2024) in light of recently published research on the topic (Milroy *et al*., 2019), and building on the framework established by Howard *et al*. (2008).

We find that, in the Severn Basin, the Formation-level identification scheme proposed by Milroy *et al*. (2019) holds true for newly studied drillcore from the Newport area. Furthermore, we suggest that the 'Dunscombe Mudstone', recently adopted by Newell (2024) in a national-scale correlation of borehole wireline data, may be a more appropriate term to encapsulate the markedly heterogeneous interval observed at outcrop in this study between what is currently (*sensu* Howard *et al*., 2008) the uppermost Sidmouth Mudstone and lowermost Branscombe Mudstone formations.

Herein we present new logs of several sections visited by Milroy *et al*. (2019) which were used to devise a stratigraphic framework for the region based on physical characteristics of the units such as fracture habit and sedimentology, as well as the logs of two previously unrecorded boreholes from the Newport area. Core from a borehole at Twyning was also studied.

1 Introduction

The Mercia Mudstone Group is predominantly composed of a series of claystones and siltstones and represents part of the Middle and most of the Upper Triassic in the UK. The group is present at the surface, or at depth, across a large area of the UK, notably beneath many cities and central regions of high infrastructure density. The unit is of particular interest in recent times due to its potential involvement in the subsurface storage of radioactive waste and carbon dioxide, as well as the harnessing of geothermal energy potential (Becker *et al*., 2021; Parkes *et al*., 2021; Jones *et al*., 2025). In the UK, the longstanding recognised lithostratigraphy of the Mercia Mudstone Group divides the Group into five Formations: the Tarporley Siltstone Formation, the Sidmouth Mudstone Formation, the Arden Sandstone Formation, the Branscombe Mudstone Formation, and the Blue Anchor Formation (Figure 1; Howard *et al.*, 2008). A lack of dateable body fossils present in the majority of the succession has prevented a detailed biostratigraphy and therefore age model of the Group from being established, though some information has been successfully gained through magnetostratigraphic techniques, and using geophysical log markers, clay mineral stratigraphy and palynology (Old *et al*., 1991; Radley, 2005; Baranyi *et al*., 2021; Hounslow & Gallois, 2023; Newell, 2024). Halite is present in the thicker basinal successions (such as in the Wessex and Cheshire Basins), and sulphate deposits (gypsum and anhydrite) are also common at certain stratigraphic horizons (Howard *et al.*, 2008; Newell, 2024).

This study focuses on the middle three formations of the Howard *et al*. (2008) Mercia Mudstone Group stratigraphy: the Sidmouth Mudstone Formation, the Arden Sandstone Formation and the Branscombe Mudstone Formation. The Sidmouth Mudstone Formation and Branscombe Mudstone Formation have similar characteristics, consisting of mostly structureless red-brown claystones and siltstones with grey-green reduction spots (Howard *et al*., 2008). Relatively thin decimetre scale beds of grey-green dolomitic siltstone and fine-grained sandstone are present at intervals throughout both formations. The Arden Sandstone Formation is composed of grey, green and purple interbedded claystone, siltstone and sandstone that can be planar- and ripple cross-laminated, in some cases cross-bedded, and are commonly extensively bioturbated (Barclay *et al*., 1997; Burley *et al*., 2023). The Arden Sandstone Formation is present in central and western England, such as in the Worcester Basin, Knowle Basin and on the East Midland Shelf (Figure 2), but is absent elsewhere, though there can be other sandstones present at a potentially similar stratigraphic level (Gallois & Porter, 2006; Dawson *et al*., 2022; Newell, 2024). In regions where the Arden Sandstone in its typical Worcester/Knowle Basin form is absent, such as the majority of the Severn Basin, it is challenging to divide the continuous succession of claystones and siltstones at Formation level.

Alternative Formation-level subdivisions of these strata have been proposed, most recently by Newell (2024). This scheme, developed primarily to aid in the correlation of strata using geophysically-logged boreholes, builds on the scheme developed by Howard *et al.* (2008) by reintroducing the Dunscombe Mudstone Formation proposed by Gallois (2001). This unit is suggested to lie between the Sidmouth Mudstone and Branscombe Mudstone formations, spanning the majority of the Carnian Stage (Figure 1) and encompassing the ‘Lincombe Hill’ and ‘Little Weston Mudstone’ members, the latter of which was formerly attributed to the topmost Sidmouth Mudstone Formation by Gallois (2001). Baranyi *et al*. (2021) propose a Julian (early- to mid-Carnian) age for the ‘Dunscombe Mudstone’ based on palynology. A result of Newell’s (2024) work is the proposed abandonment of the Arden Sandstone as a formal Formation. Instead, it becomes a discontinuous Member within the ‘Dunscombe Mudstone’. The work described herein seeks to evaluate how effectively the Howard *et al*. (2008) and Newell (2024) stratigraphic frameworks can be applied to exposures and core in the Severn Basin area, with the help of Milroy *et al*.’s (2019) formation identification scheme.

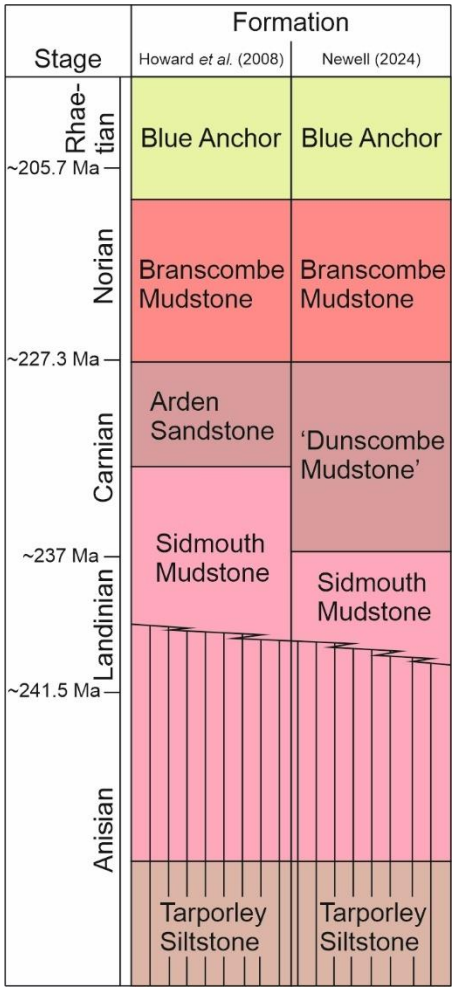

Figure 1. The Formation-level stratigraphy of the Mercia Mudstone Group as assigned by Howard *et al.* (2008) and Newell (2024). The framework of Howard *et al*. (2008) is the current formally recognised BGS stratigraphic framework of the Mercia Mudstone Group. The vertically hashed area indicates stratigraphy which is thought to be absent in the Severn Basin region, the units instead being unconformably underlain by older rocks predominantly of Carboniferous or Devonian age.

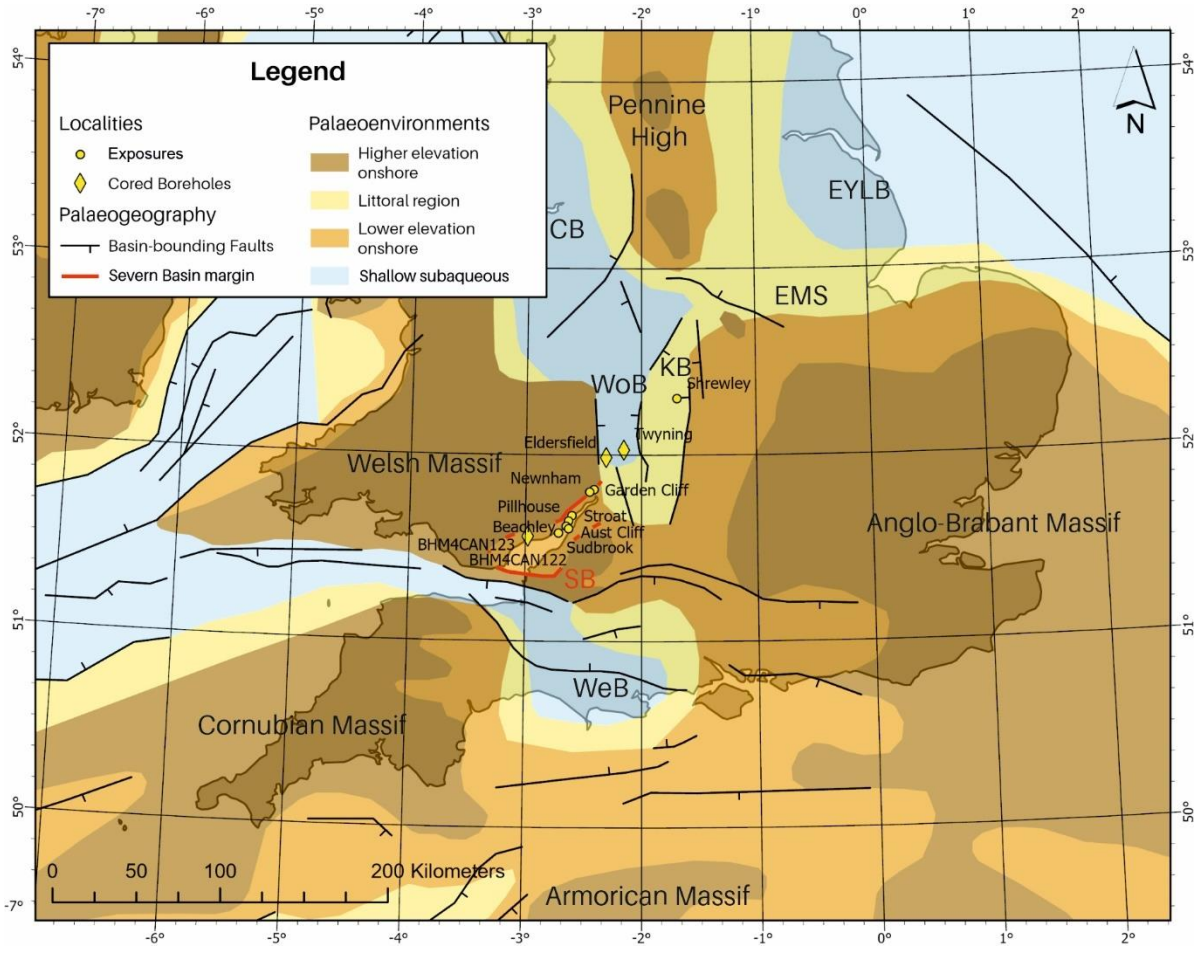

Figure 2. Map showing the palaeogeography of the UK during the Carnian Stage (c.230 Ma), the time period during which the Arden Sandstone Formation is thought to have been deposited (Burley *et al*., 2023), as well as the locations of major Triassic basin-bounding faults, and core and sections studied in this work. Abbreviations: EMS – East Midland Shelf; EYLB – East Yorkshire and Lincolnshire Basin; CB – Cheshire Basin; WoB – Worcester Basin; WeB – Wessex Basin; KB – Knowle Basin; SB – Severn Basin. Diagram based on Warrington & Ivimey-Cook (1992).

This report investigates the characteristics of the Mercia Mudstone Group in the Severn Basin, the south-western extension of the Worcester Basin or Graben (Figure 2). The Mercia Mudstone Group was logged at exposures along the River Severn, near Chepstow, and in nearby drillcore (Figure 2), to determine if variations in characteristics through the Group would allow division at Formation level where the Arden Sandstone Formation is absent. Additional drillcore from near Newport was also investigated to determine how characteristics vary westwards toward the margin of the Mercia Mudstone Group succession in modern-day onshore South Wales. A conspicuous, typically medium- to coarse-grained siliciclastic, cross-bedded and in places dewatered unit exposed on the northern shore of the Severn Estuary close to the village of Sudbrook, Monmouthshire, which has previously at this site been informally named the ‘Sudbrook Sandstone’ (Allen, 2005), is also described.

2 Prior research and rationale

Bedrock exposures along the River Severn and nearby drillcore were logged by Milroy *et al.* (2019). These borehole and section localities are shown in relation to Carnian palaeogeography in Figure 2, and in relation to mapped Mercia Mudstone Group deposits in Figure 3. Through the logging and correlation of cliff sections and drillcore material in the region, Milroy *et al*.

(2019) identified different characteristics in the claystones and siltstones present along the River Severn, dividing the rocks into different lithofacies. Of the facies associations identified, two are of critical importance to the authors' depositional model: the 'blocky claystone' and 'silty mudstone' facies associations. The 'blocky claystone' facies is characterised by a platy to subangular blocky structure, with features such as pseudoanticlines, curvilinear slickenside planes, and mud cracks present. The 'silty mudstone' facies association consists of massive to weakly stratified red-brown siltstones with units of grey-blue laminated siltstone that become more dominant upwards. Milroy *et al*. (2019) find that the 'blocky claystone' facies association dominates the Sidmouth Mudstone Formation and that the 'silty mudstone' facies association dominates the Branscombe Mudstone Formation, allowing the Mercia Mudstone Group to be divided at Formation level. They also identified more arenaceous units at the boundary between the Sidmouth and Branscombe Mudstone Formations at some exposures, which they interpret as the Arden Sandstone Formation.

This report describes how we tested the robustness of the Formation identification scheme described by Milroy *et al*. (2019) at exposures and in drillcore from within the same basin.

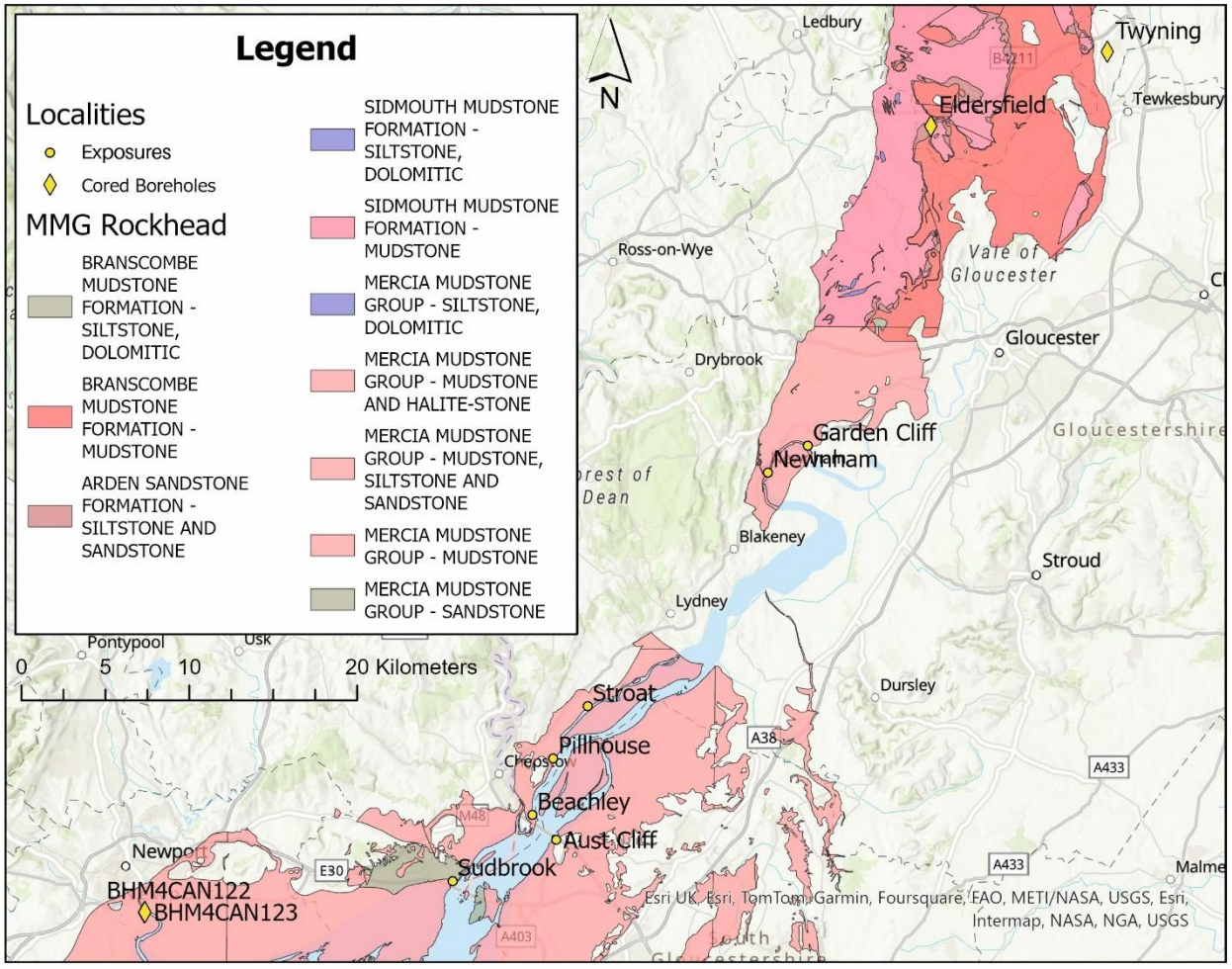

Figure 3. A map of the area of project interest, the Severn Basin region, showing where the Mercia Mudstone Group is mapped at geological rockhead on BGS 1:50 000 scale maps, and the locations of drillcore and exposures studied. *Contains British Geological Survey 1:50 000 scale geological map data © UKRI 2026*

3 Research methods

3.1 FIELD SECTIONS

The exposures visited during the study are listed in Table 1 and their locations are shown in Figure 3. In sections or boreholes where the Blue Anchor Formation or Arden Sandstone Formation are present, these units are distinguishable due to their sedimentological characteristics and colour which contrast with the Branscombe and Sidmouth Mudstone Formations, allowing a relative stratigraphy to be established. In sections or boreholes without the Blue Anchor or Arden Sandstone formations present, we take the stratigraphic interpretation already attributed by Milroy *et al.* (2019). With the exception of Aust Cliff, sedimentary logs were collected at all of the sections visited. A rising tide and challenging access prevented a high-quality log of the Aust Cliff section from being collected, though a measured section is presented in Milroy *et al*. (2019).

Table 1. Exposures visited as part of this work. Exposure locations are shown in Figure 3. The Formation(s) of the Mercia Mudstone Group present at each exposure were determined using relative stratigraphy where possible, whereby the position of the exposure within the succession was based on the identification of the Blue Anchor Formation or Arden Sandstone Formation. Where these diagnostic units were not present, we take the stratigraphic interpretation proposed by Milroy *et al*. (2019).

Exposure name	Exposure location (Easting and Northing)	Basis for establishment of stratigraphy at exposure
Garden Cliff	371507 213267	Relative stratigraphy
Newnham	369211 211572	Relative stratigraphy
Stroat	358541 197700	Interpretation proposed by Milroy *et al.* (2019)
Pillhouse	356401 194382	Relative stratigraphy
Beachley	355250 191104	Interpretation proposed by Milroy *et al.* (2019)
Aust Cliff	356559 189647	Relative stratigraphy
Sudbrook	350421 187232	Interpretation proposed by Milroy *et al.* (2019)
Shrewley	421166 267439	Howard *et al*. (2008)

Sections were logged at a decimetre-scale, though a finer centimetre-scale was used where strata were particularly thinly-bedded to allow sufficient resolution to be captured. Palaeocurrent direction data was collected from indicative bedforms such as cross-beds where appropriate. In addition, photographic mosaics and detailed images of the sections, sedimentary structures, and fracture habits were collected.

3.2 DRILLCORE

The material from two cored boreholes, BHM4CAN122 (BGS reference: ST38NW381) and BHM4CAN123 (BGS reference: ST38NW382), from near Newport, and one collection of discontinuous core samples from the Twyning borehole (BGS reference: SO83NE5) were studied. Borehole locations are shown in Figures 2 and 3. Boreholes BHM4CAN122 and BHM4CAN123 are from an area where the Arden Sandstone Formation is thought to be absent and these cores have not previously been logged to Formation level by any workers. The Twyning borehole is a reference section for the Arden Sandstone Formation. This core was examined by Milroy *et al.* (2019) who present a composite log of this and material from the nearby Eldersfield borehole (BGS reference: SO73SE6; for location, see Figure 3) in their work.

Table 2. Details of drillcore and samples studied as part of this work.

Borehole name	BGS reference	Borehole location (British National Grid reference)	Drilled depth (m)	Core interval studied (m)
BHM4CAN122	ST38NW381	332052 185373	90.3	26.0 – 61.2
BHM4CAN123	ST38NW382	332075 185382	90.7	27.8 – 50.3
Twyning	SO83NE5	389430 236640	323.09	222.5 – 323.09

The intervals of cores BHM4CAN122 and BHM4CAN123 studied were chosen by examining AGS logs for each borehole and calculating the expected depth of the Arden Sandstone Formation, if present, in this area. The interval of study for Twyning was selected to include the sections of the Sidmouth and Branscombe Mudstone Formations, separated by the Arden Sandstone Formation, as interpreted by Barclay *et al.* (1997) and Milroy *et al*. (2019).

4 Results

The characteristics of the formations of the Mercia Mudstone Group within the Severn Basin are described below, alongside sedimentary logs taken both at exposures and from drillcore (Figure 4). A key to the symbols used in sedimentary logs is shown in Figure 5.

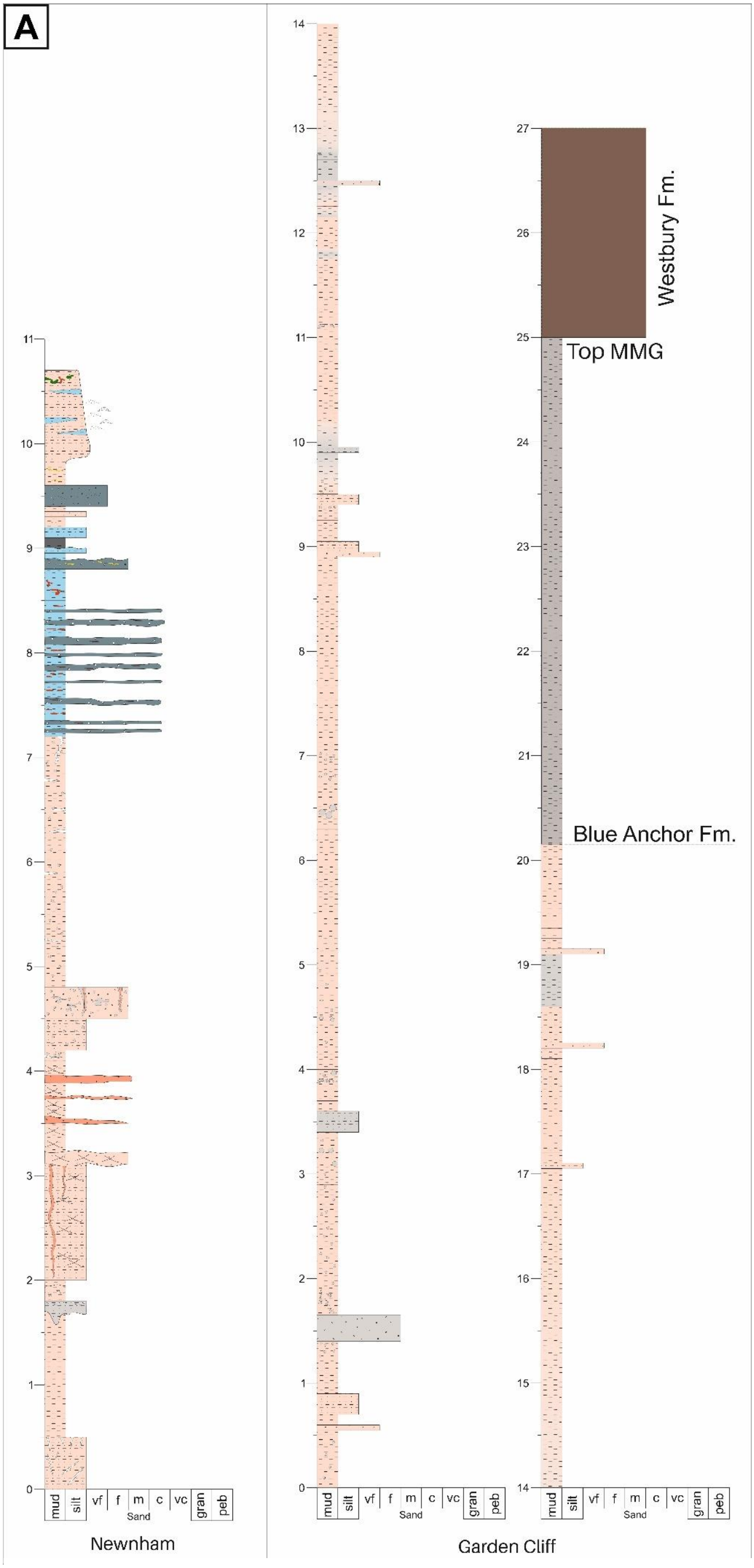

Figure 4. Sedimentary logs collected from A) Garden Cliff and Newnham; B) Sudbrook and Beachley; C) Pillhouse and Stroat.

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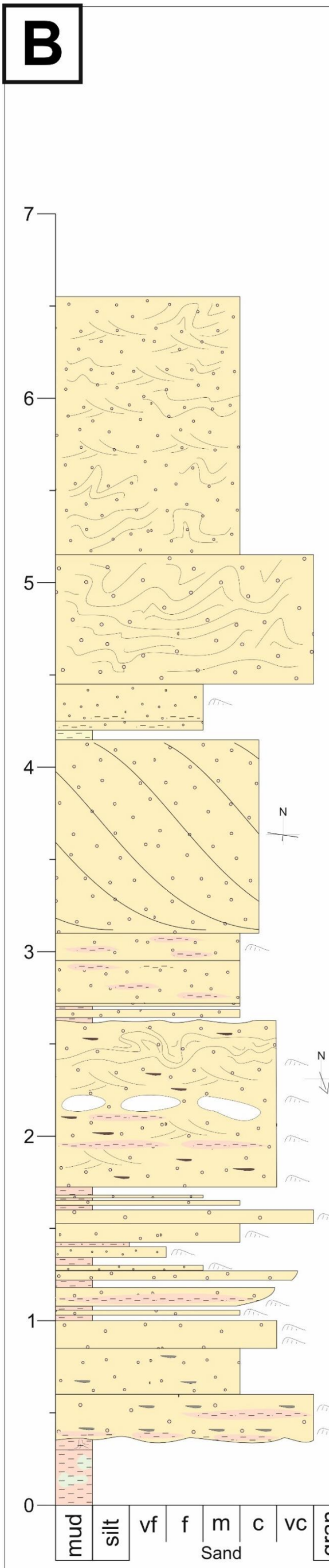

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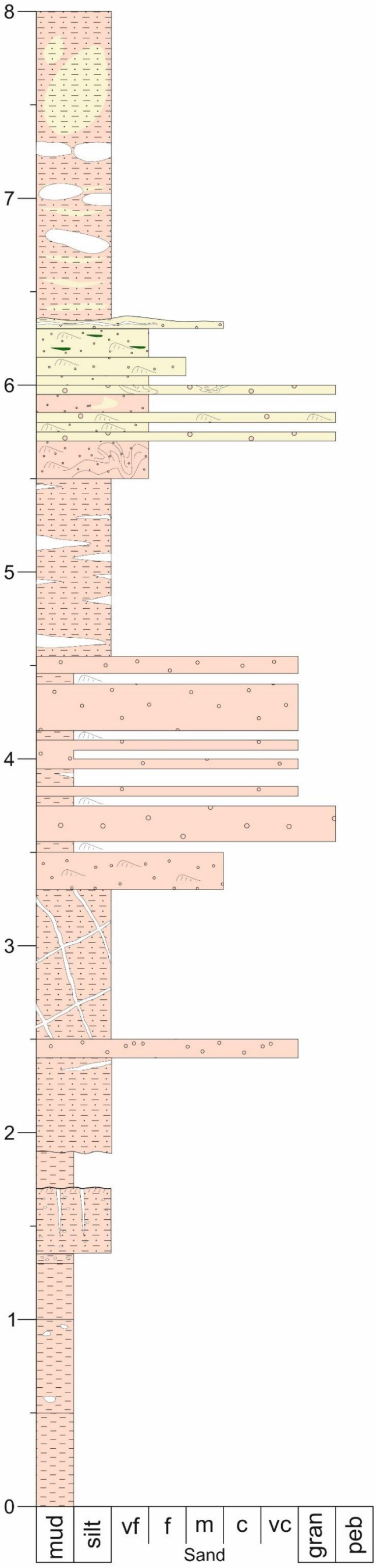

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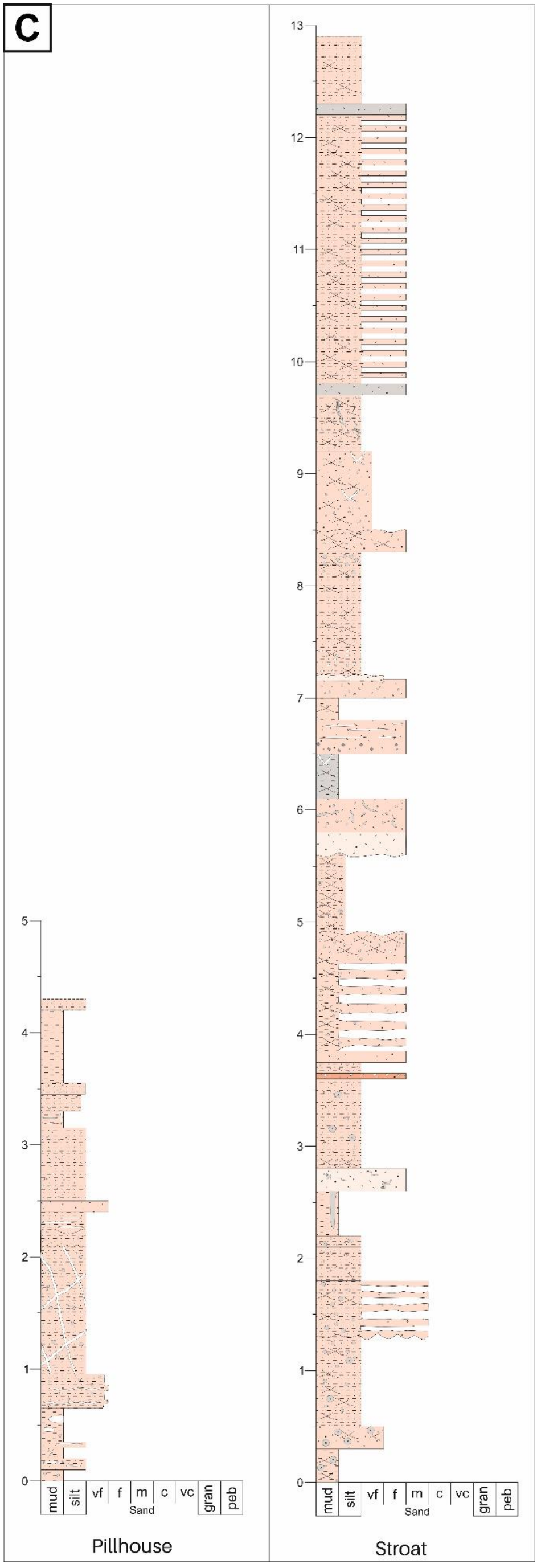
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Pillhouse
Stroat

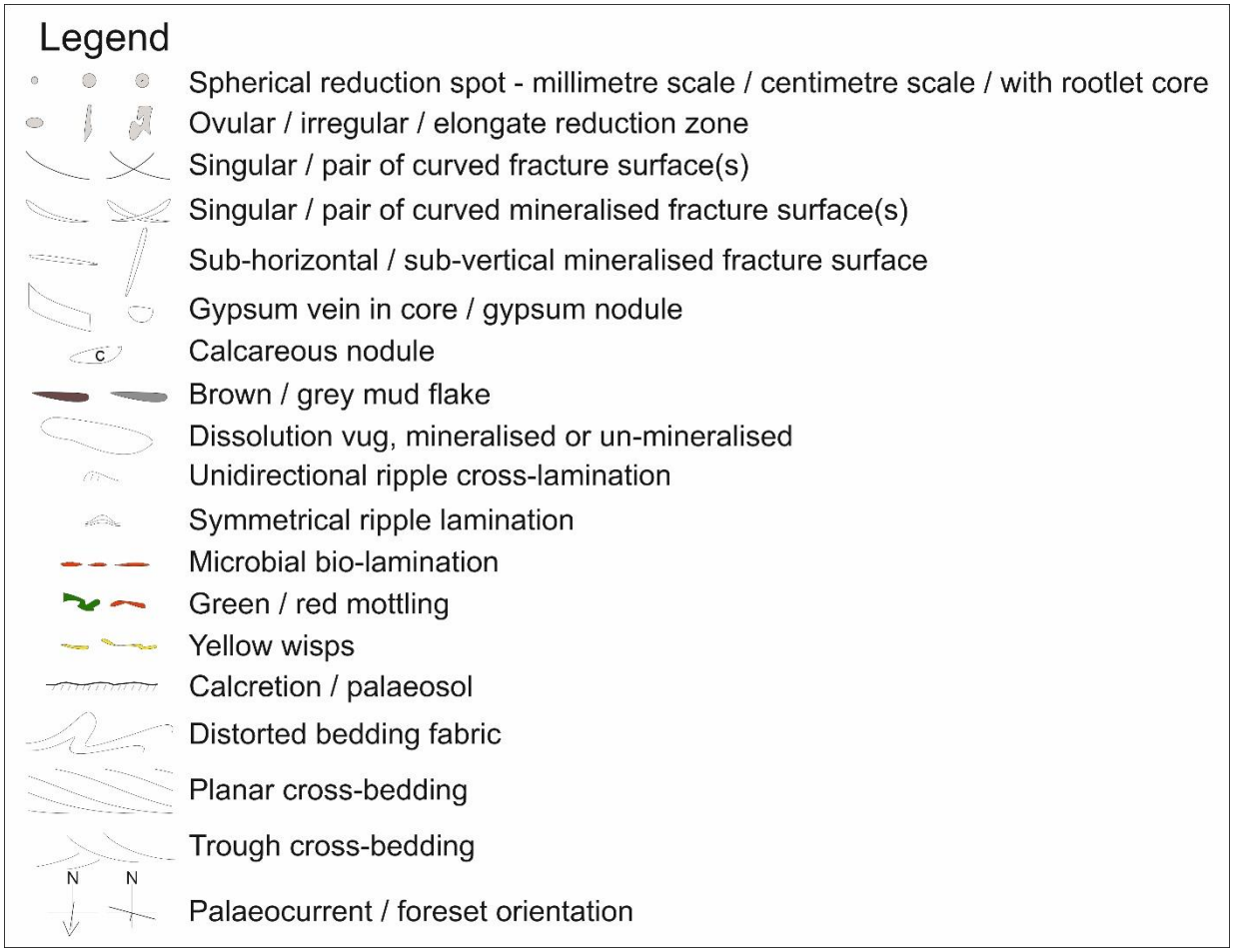

Figure 5. Legend of symbols used in sedimentary logs.

FIELD OBSERVATIONS OF MUDSTONE UNITS

The key characteristics of the mudstone units observed are described here and summarised in Table 4.

The Sidmouth Mudstone Formation, as seen most clearly at Newnham and Stroat (Figures 4A and C), is characterised by a generally deep red hue, a greasy lustre (Figure 6A) and is dominantly a claystone, though rare silty units become increasingly common upwards. Siltier beds are blue-grey in colour with silt to fine sand-sized grains, and are relatively hard compared to the surrounding beds; perhaps dolomitised (Figures 6B and 4C – Stroat log, 9.75 m). When fractured, the claystone forms millimetre- to centimetre-scale angular shards (Figure 6A). Sulphates, such as gypsum, are particularly common in this Formation in both nodule and vein form (Figure 4B – Beachley log, 0-1 m). Gypsum veins were observed to attain thicknesses of up to around 5-10 centimetres, though were typically centimetre-scale. Polygonal cracks were observed on numerous bedding planes at Stroat (Figure 6C). Spherical blue-grey zones of reduction are common and can be up to several centimetres across, in some cases with a dark centre up to 1 cm across (Figures 6D and 4C – Stroat log, 0-3.5 m). Dendritic blue-grey reduced zones approximately 50 cm long are seen to descend from relatively hard, slightly calcified white-coloured horizons, notably at Stroat (Figures 6E and 4C – Stroat log, 2.5 m). Curved pseudoanticlinal surfaces were observed at both Stroat and Newnham during both this work and that conducted by Milroy *et al*. (2019) (Figures 6F and 4C – Stroat log, full length; Milroy *et al*., 1998). These surfaces appeared to be related to a coarsening of the grainsize, perhaps owing to secondary granularity associated with brecciation of the mudstone. Surfaces which are cross-cut by these pseudo-anticlinal features are offset in some cases. Chaotic, disturbed bedding was also observed within the section at Newnham, and has been attributed to collapse brecciation (Fig. 6G) – whereby the sediment becomes fractured and amalgamated due to the post-depositional dissolution of gypsum.

On the whole the Branscombe Mudstone Formation appears to fracture in a conchoidal manner (Figures 7A and B), with curved planes, and forms almost spherical pseudo-nodules which can often be cleaved along conchoidal surfaces into smaller nodular clasts. This is particularly true of horizons containing a lower proportion of silt. The Formation typically has a duller appearance, typically coloured a dusty lighter red to pink (Figure 8). Grey-blue coloured beds (Figures 7B and C, and 9) which are typically of silt to fine sand grade are more common than in the Sidmouth Mudstone Formation (Figure 4A – Newnham log, 1.5 m). These bands commonly have sharp contacts at the top and base, though there are instances of rough-edged mottling (Figure 4A – Newnham log, 10 m), and can contain millimetre-scale pale silty to sandy partings (Figure 7A). Centimetre-scale polygonal cracks are common on bedding planes within blue-grey beds (Figure 7D).

Table 3. The key features of the Sidmouth and Branscombe Mudstone formations identified by Milroy *et al*. (2019) and observed during this study. The names given to some of the features in this table differ to those given by Milroy *et al*. (2019).

Branscombe Mudstone Formation		Sidmouth Mudstone Formation	
Feature name	**Description**	**Feature name**	**Description**
Dull silty appearance (Fig. 8)	Surfaces have dull appearance, often pink in colour.	Shiny deep red appearance (Fig. 6A)	Surfaces have shiny appearance and waxy lustre, deep red in colour.
Conchoidal fracture habit (Figs. 7A and B)	Conchoidal fracture pattern with spacing of 1-2 cm producing fragments with a bulbous, or pseudo-nodular appearance. Fracture surfaces appear dull with no sheen exhibited.	Vertic slickensides (Fig. 6F)	Curvilinear polished surfaces with slickensides at cm-dm scale spacing. May be iron oxide-stained, or cemented by gypsum or secondary carbonate.
Silt-rich laminae (Figs. 7A, 8 and 9)	Planar and ripple-cross laminated silt-rich beds up to 10 cm thick that can be dolomitic. Mostly blue-grey in colour with some red mottling. Sub-horizontal to hummocky, discontinuous white sand partings can be present. Mm-cm scale desiccation can be visible on surfaces of silt-rich beds. Beds are laterally persistent in character and thickness for >100 m in exposure, with about 1 m vertical spacing.	Pseudo-anticlines (Fig. 6F)	Larger, more continuous steeply-inclined slickensided surfaces >0.5 m length that intersect to create anticlinal appearance. May be cemented by gypsum or secondary carbonate.
Spherical reduction zones	Common pale blue-grey reduction spots generally 2 to 5 mm in diameter,	Sulphate nodules and veins (Fig. 8)	mm-scale crystals, cm-scale nodules, and dm-m chicken-wire or cross-hatched textures of gypsum and anhydrite. Can be

	and up to 5 cm in diameter.		concentrated in certain horizons >10 cm thick.
Blue-grey mottling	Irregular blue-grey mottled or blotchy zones up to 5 cm in length with gradational border with the surrounding red mudstone.	Desiccation mud cracks (Fig. 6C)	Downward-tapering subvertical cracks up to 2 m deep and 8 cm wide, commonly containing multi-generational fills of mud clasts, silt, and carbonate. Pale blue/grey/green in colour. Can be cross-cut and offset by slickensided planes.
Subvertical elongate reduction zones (Fig. 9)	Elongate blue-grey zones surrounding subvertical fractures or faults.	Discontinuous interbedded horizons	Interbedded sandstone and mudstone units 5-10 cm thick appear discontinuous where offset by listric fractures.
		Carbonate nodules	Angular nodules up to 3-4 cm across.
		Drab-haloed root traces (Fig. 6E)	Black circles a few mm in diameter at the core of numerous spherical reduction zones of up to around 5 cm diameter at exposure.
		Well-cemented sandstone horizons (Fig. 6B)	Well-cemented, pale horizons towards top of succession, some dolomitised. Hard beds that protrude cliff sections or form prominent benches.

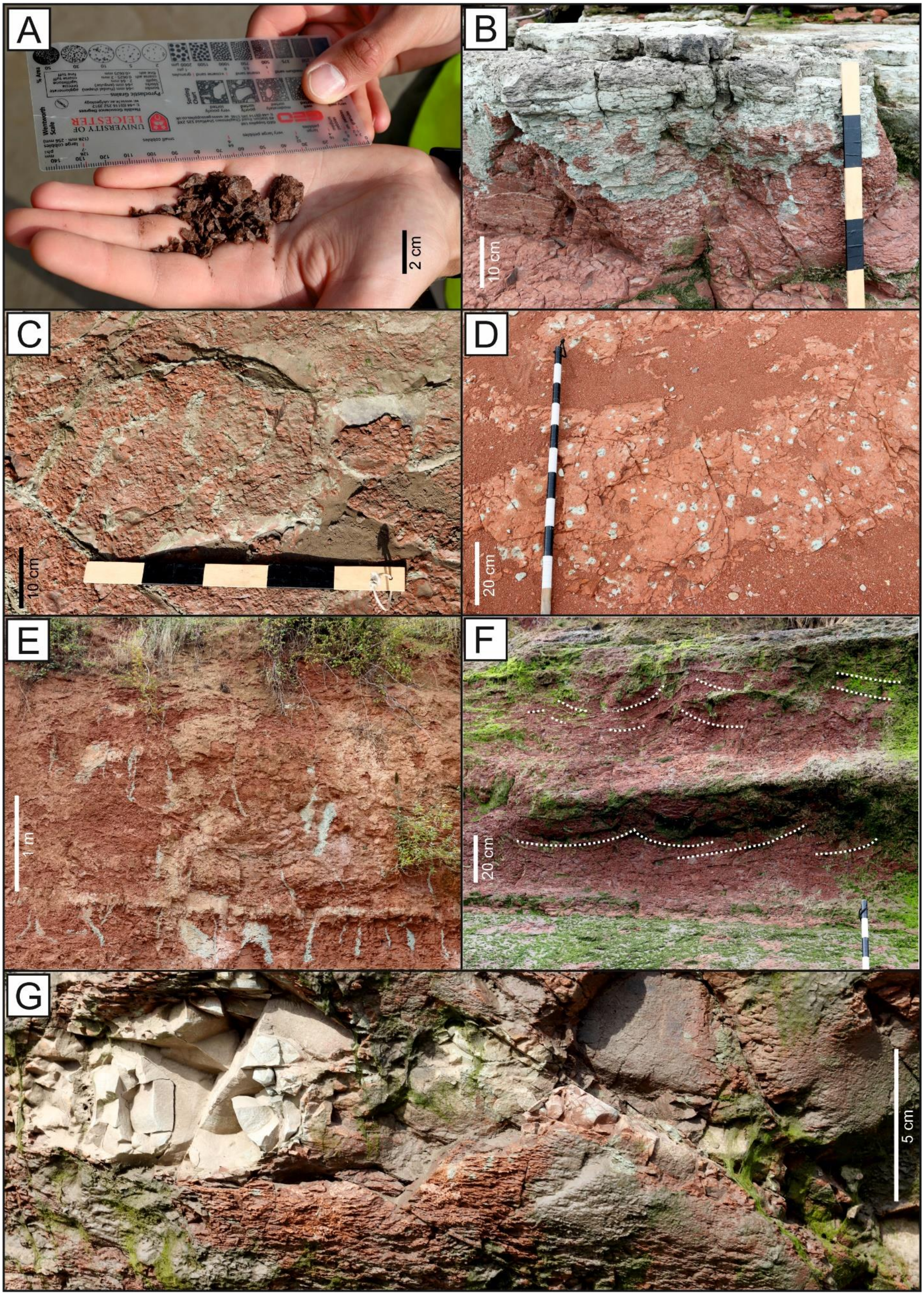

Figure 6. Characteristics of the Sidmouth Mudstone Formation observed at exposure. A) The typical angular fracture habit and greasy lustre observed at Newnham. B) A well-cemented pale blue horizon, perhaps a Pseudogley, at Stroat, which forms a bench-like platform within the section. C) Top-down view of a bedding plane with desiccation cracks, some mineralised, within a rock bench forming the river shoreline at Newnham. These cracks are surrounded by pale blue reduction zones up to 3 cm wide. D) A top-down view of centimetre-scalereduction spots

and desiccation cracks exposed in a bedding surface at Stroat. Note the dark mm-diameter circular core to some of the reduction spots, interpreted here as a rootlet. E) Sub-vertical reduction zones typically about 50 cm in length descending from mineralised horizon at Stroat. F) Pseudoanticline structures within the deep red, shattered-looking succession at Stroat. G) A collapse breccia as observed in exposure at Newnham, characterised by disturbed, fractured mudstone bedding.

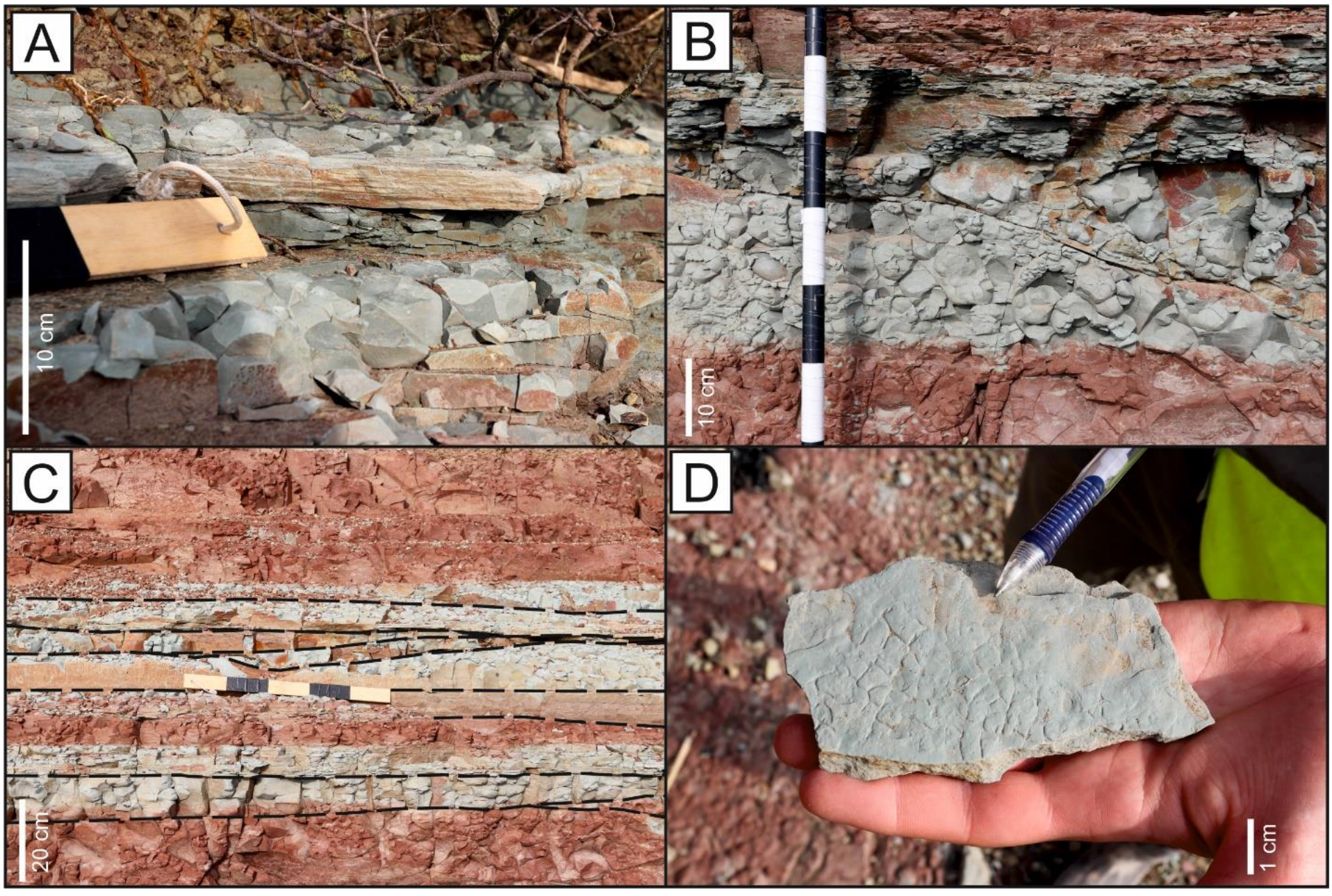

Figure 7. Characteristics of the Branscombe Mudstone Formation observed in exposure at Garden Cliff. A) Millimetre-scale pale-coloured silty partings within a silty horizon. B) Conchoidal fracture habit and mottled pale blue reduction spots. C) Sub-horizontal and discontinuous bedding within a siltier horizon, with some evidence for erosion on high-topography surfaces. D) Millimetre-scale desiccation cracks on the bedding surface of finely-laminated pale blue-coloured silty mudstone.

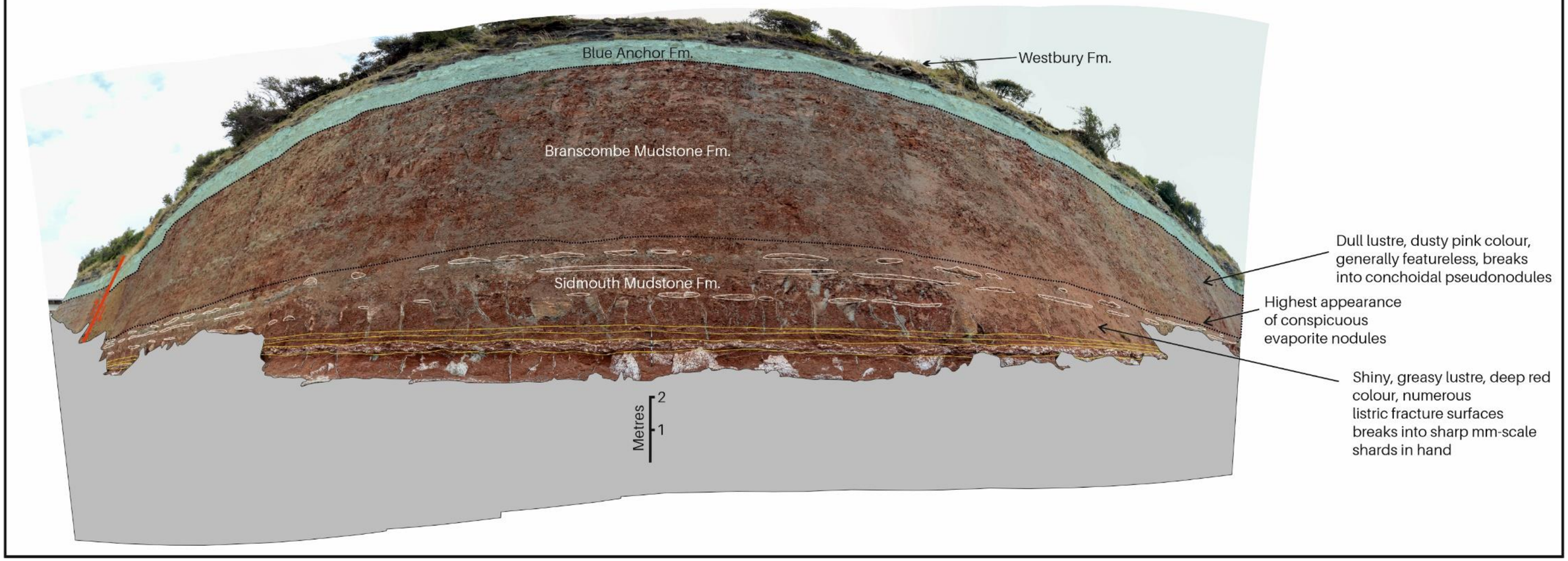

Figure 8. The succession at Aust Cliff, showing the proposed boundary between the Sidmouth and Branscombe Mudstone formations (as per the Howard *et al*. (2008) stratigraphic framework) and some textural features which support this hypothesis. The overlying Blue Anchor and Jurassic-aged Westbury formations are clearly visible at the top of the exposure.

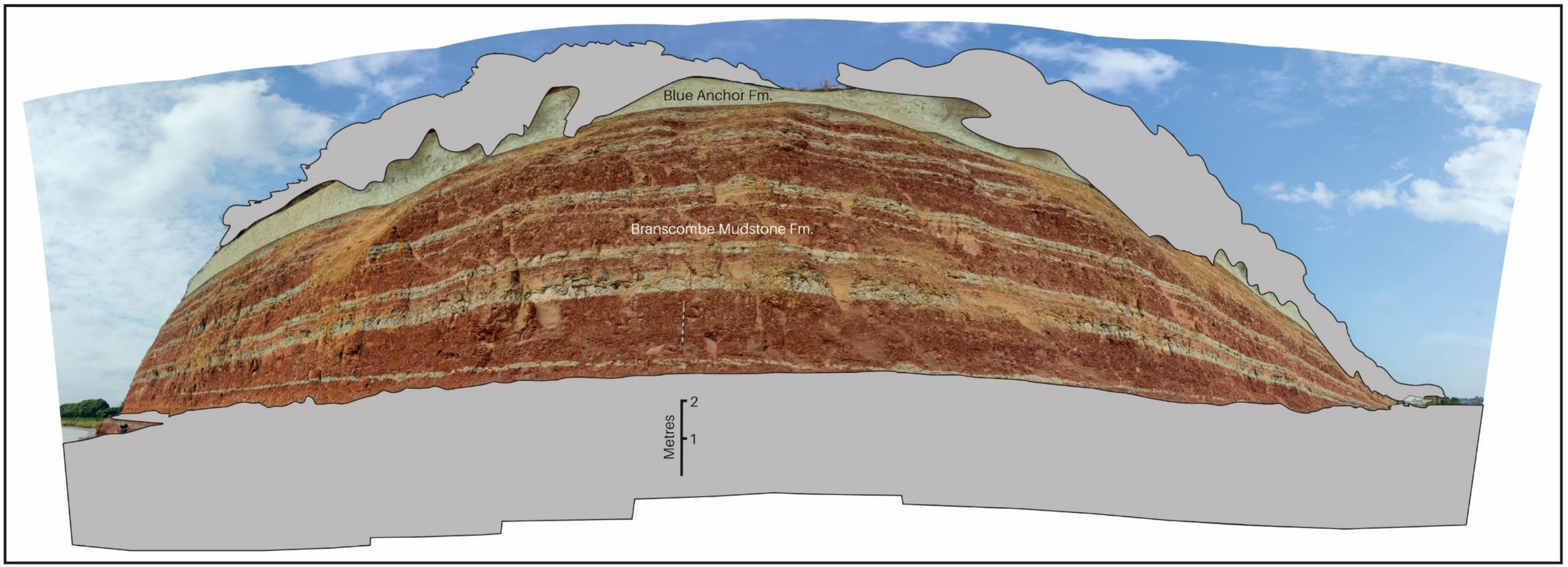

Figure 9. The succession at Garden Cliff, showing the laterally continuous and repetitive, pseudo-cyclic nature of often blue-coloured silty horizons within the Branscombe Mudstone Formation. The overlying Blue Anchor Formation is clearly visible at the top of the exposure.

4.1.1 Field observations of sandstone units

4.1.1.1 The Arden Sandstone Formation

We observed the Arden Sandstone Formation in its most 'traditional' arenaceous, blue-green coloured Worcester/Knowle Basin-type facies at the type section for the Formation at Shrewley (Figures 2, 10A and B), though this site lies within the Knowle and not the Severn Basin (Figure 2). The unit has been known for over a century (e.g. Brodie, 1887; 1896; Matly, 1912), and it is now generally suggested that it represents the deposition of largely siliciclastic material at the perhaps estuarine or deltaic (Old *et al*., 1991; Barclay *et al*., 1997; Burley *et al*., 2023) flank of a likely relatively shallow body of water which harboured fish, clams and coniferous flora among other species (Brodie, 1887; 1896; Radley, 2005; Burley *et al*., 2023).

At Newnham – a reference section for the Arden Sandstone Formation which lies within the Severn Basin region (Figure 2; Howard *et al*., 2008; Milroy *et al*., 2019; Burley *et al*., 2023), centimetre-scale interbeds of siltstone, sandstone, and claystone (Figures 10C) exhibiting ripple cross-laminae, rip-up mud clasts, and yellow and dark-coloured millimetre-scale wisps are present (Figure 4A – Newnham log). Interbedded siltstone and medium- to coarse-grained beds of centimetre-scale thickness indicate repeated variations in flow velocity. These repeated variations unlikely to be the result of tidal activity, since indicative bedforms such as mud-draped bi-directional ripple cross-laminae are not present. We propose instead that non- or weakly-channelised sheet flow-like input is more likely to be the cause, stimulated by rapidly increased overland flow as a result of significant precipitation in a hydrologically flashy catchment. These flash-flood episodes were the exception to ordinarily quiescent conditions during which suspension settling of fines dominated and produced siltstone interbeds (Burley *et al.,* 2023). Symmetrical ripple laminae toward the top of the Newnham section (Figure 4A – Newnham log) support the notion that water depths were sufficiently shallow for wind-driven oscillations in the water column to agitate lake-floor sediments.

The Arden Sandstone was not identified to be present in its traditional form at the other Severn Basin exposures visited in this study.

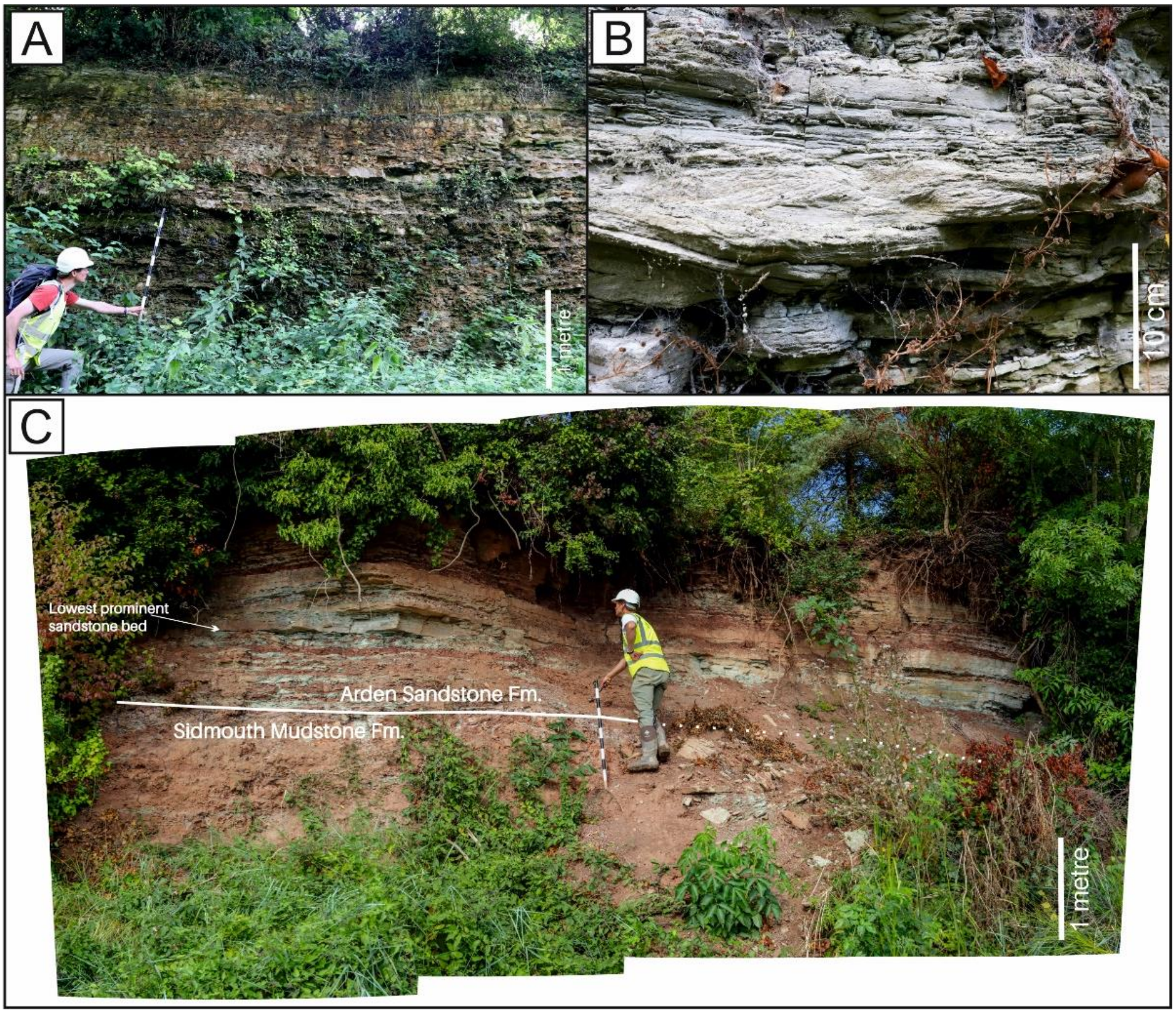

Figure 10. A) The Arden Sandstone Formation at its type locality – a canal cutting in the village of Shrewley, Warwickshire. Centimetre to decimetre-scale interbeds of sandstone, siltstone, and claystone are present, the coarser lithologies exhibit sedimentary structures such as ripple cross-laminae and hummocky cross-stratification. B) Trough cross-bedding on ~10 centimetre scale and upper-stage plane bedding in the typically blue-grey Arden Sandstone Formation at Shrewley. C) The Arden Sandstone Formation and underlying topmost Sidmouth Mudstone Formation (according to the Howard *et al*. (2008) stratigraphic framework) at Newnham, a reference section for the Arden Sandstone (Howard *et al*., 2008). There are around 1.5 m of thinly interbedded coarse sandstones and mudstones beneath the first prominent sandstone bed. If the stratigraphic framework proposed by Newell (2024) is adopted and applied to this section, all of the strata pictured would comprise the upper part of the 'Dunscombe Mudstone'.

4.1.1.2 THE 'SUDBROOK SANDSTONE'

At Sudbrook, on the banks of the River Severn (Figure 3), is a generally sand-dominated unit approximately 6 m thick (Figure 4B – Sudbrook log) that is markedly different from other sandstone facies described in this area (e.g. the Arden Sandstone Formation at Newnham). The unit is bounded at its base by an erosional contact with a red and grey mottled mudstone (Figure 4B – Sudbrook log, 0-0.3 m). The sandstone is predominantly buff-yellow in colour, and conspicuously exhibits decimetre to metre-scale tabular (Figure 11A) and trough cross-bedding (Figure 4B – Sudbrook log, 3.1-4.1 m) as well as smaller scale ripple cross-laminae and rip-up mud clasts (Figures 11B and 4B – Sudbrook log, 0.3-3.1 m; Milroy *et al*., 1998). The lower part of the succession consists of pink-coloured claystone and siltstone interbedded with medium to very coarse sandstone (Figures 11B and 4B – Sudbrook log, 0.3-3.1 m). There are mudstone interbeds that can exhibit desiccated bedding surfaces (Figures 11E and 4B – Sudbrook log, 1-1.75 m). The upper part of the succession consists of thick beds of typically medium to coarse sand (Figure 4B – Sudbrook log, 3.1-6.55 m). Chaotic, amalgamated fabrics are common in the upper 2 metres of the section (Figures 11C and 4B – Sudbrook log, 4.45-6.65 m), where cobbles and decimetre-scale iron-rich nodules are also present (Figure 11D).

The succession at Sudbrook contains a conspicuous, laterally persistent horizon of oval-shaped elongate 'vugs' ('ovoid cavities' of Milroy *et al*., 2019), some mineralised, up to around 25 cm in vertical thickness (Figures 11F and 4B – Sudbrook log, around 2 m), corresponding broadly with an upward cessation of significant clay and silt horizons. The mineral infill of these voids, where present, is white in colour, crystalline, and presumed to be calcitic, though Milroy *et al*. (2019) also report the presence of quartz. This horizon is similar to those observed at Beachley in this study (Figure 11G) and also observed by Milroy *et al*. (2019) at Stroat and Sedbury.

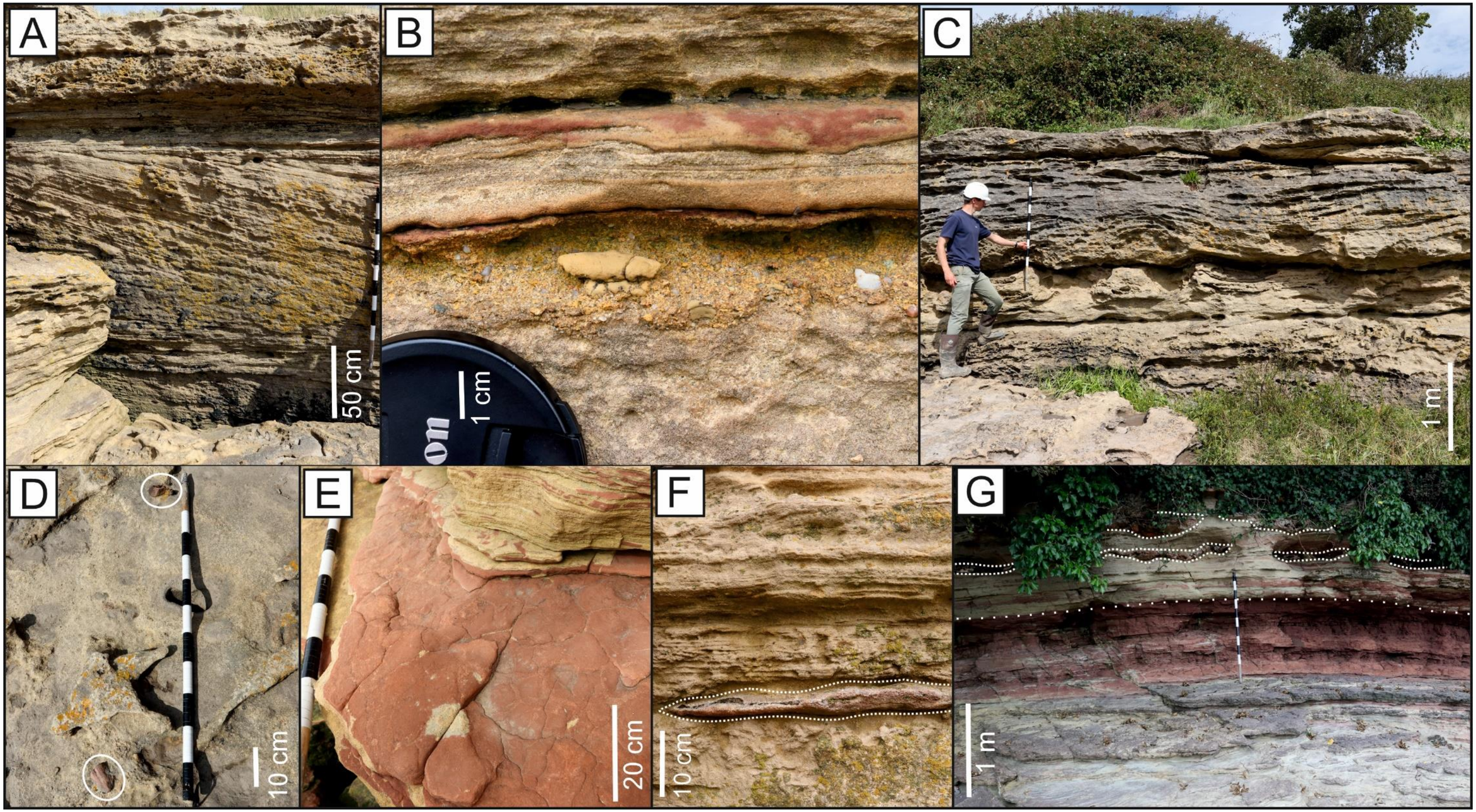

Figure 11. A) The metre-scale inclined beds of medium to coarse buff-yellow sandstone that typify the upper part of the 'Sudbrook Sandstone exposure. The surfaces dip toward 187.5 degrees on average. B) Interbedded buff-coloured fine sandstone and siltstone, yellow-orange coarse to very coarse sandstone, and red-buff mottled mudstone in the lowest 2 m of the succession logged at Sudbrook. There are abundant outsized quartz granules within the coarsest sandstone bed, as well as centimetre-scale buff coloured rip-up mud clasts, and ball and pillow structures. C) Disturbed beds within the upper 2 m of the 'Sudbrook Sandstone' exposure which exhibit soft sediment deformation structures likely resultant of dewatering. Centimetre to decimetre-scale ripple cross-laminae, and planar lamination are also visible within the section. D) Decimetre-scale cobbles, highlighted by white circles, within a deformed buff sandstone bed which also features potential theropod tracks. E) The desiccated surface of a centimetre-thick mudstone interbed within the Sudbrook succession. F) The discontinuous yet conspicuous partially mineralised dissolution horizon within the Sudbrook succession, highlighted by dashed white lines. G) Dissolution cavities exhibiting partial mineralisation within the Beachley section are horizontally extensive, highlighted by the closely-dashed white lines. In this instance, the largest cavities can persist laterally for around a metre. It is obvious from both sedimentary logging and the weathering character of this section that the muddiness of the strata decreases markedly in the region of the dissolution vugs, this transition is highlighted by the sparsely-dashed line.

4.1.1.3 SANDSTONE HORIZONS WITHIN THE SIDMOUTH MUDSTONE FORMATION

Numerous sandstone horizons within the Sidmouth Mudstone Formation were observed at exposures at Newnham, Beachley, Pillhouse and Stroat (Figure 4). Such sandstones were often well-cemented, in some cases perhaps dolomitised, and frequently featured blotchy grey colouration (Figure 6B). Sandstone beds contain typically fine to medium sand-sized grains and are up to 50 cm thick. The bed top surfaces are erosive in some cases (Figure 4C – Stroat log, 4.9 m). Sandstones are commonly interbedded at a centimetre-scale with siltstone and claystone, and are also commonly associated with gypsum veins (likely telogenetic; McEvoy *et al.*, 2025) and nodules (Figure 4C – Stroat log, 3.6 m). The character of the interbedded units at Beachley, particularly between 5.5-6.5 metres, is similar to that present within the lowest 2 metres of the section logged at Sudbrook (Figure 4B). Similar well-cemented sandstone features were also observed at Aust Cliff (Figure 8). Gypsum veins are notably common at the base of the section at Aust Cliff.

4.2 OBSERVATIONS OF DRILLCORE

The core from three boreholes logged as part of this work (BHM4CAN122, BHM4CAN123 and Twyning) is described below. Sedimentary logs of BHM4CAN122 and BHM4CAN123 are presented in Figure 12, and sample images of the Twyning drillcore are shown in Figure 13. All of the materials are currently held by the BGS National Geological Repository, Keyworth.

4.2.1 BHM4CAN122 and BHM4CAN123

BHM4CAN122 and BHM4CAN123 are situated around 25 m apart near Newport, South Wales (Figures 2 and 3). The material of BHM4CAN122 has been slabbed but sections of material are missing. The material of BHM4CAN123 is more complete but has not been slabbed, restricting the possible detail of observations made.

The base of the core studied (61.3-50 m in BHM4CAN122) consists of deep red claystone with a greasy lustre interrupted by decimetre-scale horizons of fine to medium sand (Figure 12). Gypsum veins up to 10 cm thick are present, as well as 1-2 cm-sized gypsum and/or calcite nodules. Between 50 m and 39 m (in BHM4CAN122 and BHM4CAN123), the core has a deep red colour with a greasy lustre. Curved listric fracture surfaces, in places mineralised with gypsum, are common in both cores at this depth. Millimetre and centimetre-scale reduction zones, in cases blotchy and irregular but often spherical, are also common, including those with dark rootlet traces at their core. The core is generally comprised of claystone and siltstone, though sandy and gypsum-fragmental intervals are present such as between 48.8 and 48.3 m depth in BHM4CAN123. The core starts to become slightly siltier moving upwards (above 47 m depth in BHM4CAN122) with evidence of bioturbation and large decimetre scale reduction zones in BHM4CAN122.

Above 39 m the character of both cores changes, becoming siltier with a paler appearance. Reduction spots typically mm to cm-scale below a depth of about 36 m become larger and more irregular in shape towards the top of the core. There are decimetre-thick intervals of medium to coarse sand sized grains of quartz and mudstone granules and angular, elongate detrital flakes, bound within a pair of V-shaped sub-vertically oriented fabrics which in some instances trend with reduction zones such as between 38 and 38.35 m depth. Light coloured evaporite wisps are rare but present above around 28.5 m depth, and at the very top of the studied interval, centimetre-scale white calcite nodules are present in the material of BHM4CAN122.

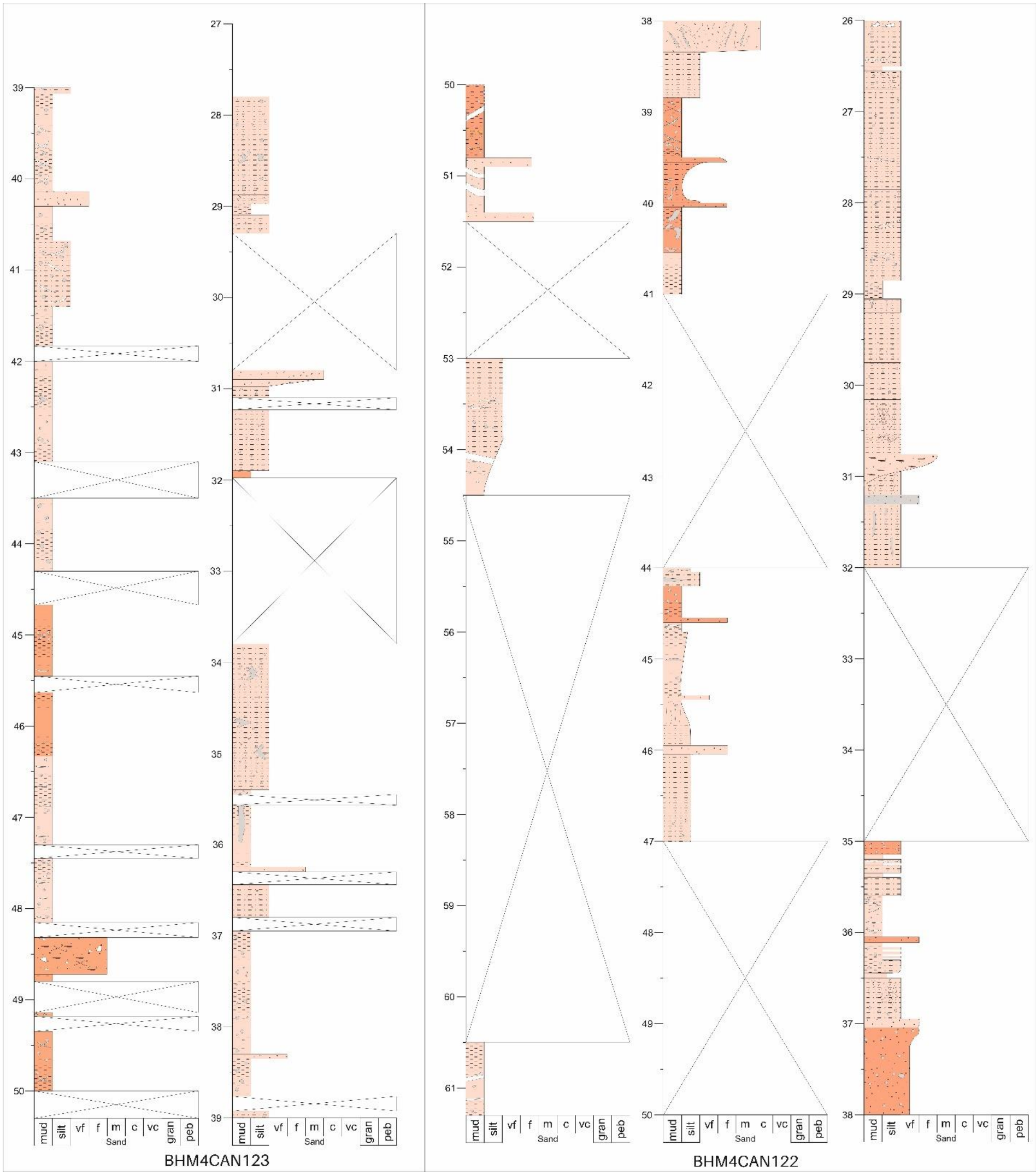

Figure 12. The sedimentary logs collected from the BHM4CAN122 and BHM4CAN123 drillcore. The locations of the boreholes from which this core was extracted is shown in Figures 2 and 3, and the legend of symbols in Figure 5.

4.2.2 Twyning

The BGS National Geological Repository holds tray samples collected from the Twyning borehole, forming a discontinuous record of the material. The samples are likely to have been selectively collected or retained according to their recovery and preservation potential, as well as the aims of the original drilling, introducing some bias. The relatively coarse-grained beds representing the Arden Sandstone Formation have been preferentially retained. The interval studied in this work is within that also studied by Milroy *et al.,* (2019). Images of selected samples from the studied interval are presented in Figure 13.

The Arden Sandstone Formation is present in the Twyning core from around 315.2 to 312.3 m depth (Figure 13A). Below the Arden Sandstone, the core of the Sidmouth Mudstone Formation is generally a deep red, well to moderately sorted, massive claystone with a waxy, shiny lustre (Figure 13B), though there are intervals which are mottled grey and white or lighter red in colour (Figure 13C). Gypsum veins, commonly around 2 mm thick, though up to 1 cm thickness, are present (Figure 13C). Between around 315.17 m and 312.30 m, the Arden Sandstone Formation is present in its more typical Worcester/Knowle Basin character: interbeds of siltstone to fine sandstone with sand drapes, hummocky cross-stratification and coarse sand lenses (Figure 13A; Howard *et al*., 2008). Above the Arden Sandstone Formation, the Branscombe Mudstone Formation was studied from 222.50 to 312.30 m. The Branscombe Mudstone Formation has a different character to the Sidmouth Mudstone Formation beneath, with a generally duller lustre and lighter colour (Figure 13D), though mid-red (Figure 13E) and shiny beds are present, particularly toward the base of the Formation. Reduction spots and zones up to around 8 mm diameter are also present within the Branscombe Mudstone Formation (Figures 13E and F), as well as blotchy, poorly-defined reduction zones of grey-blue colour (Figure 13D), gypsum veins up to 2 cm thick (Figure 13E), and nodules up to 7 cm diameter, though commonly of millimetre-scale (Figure 13F).

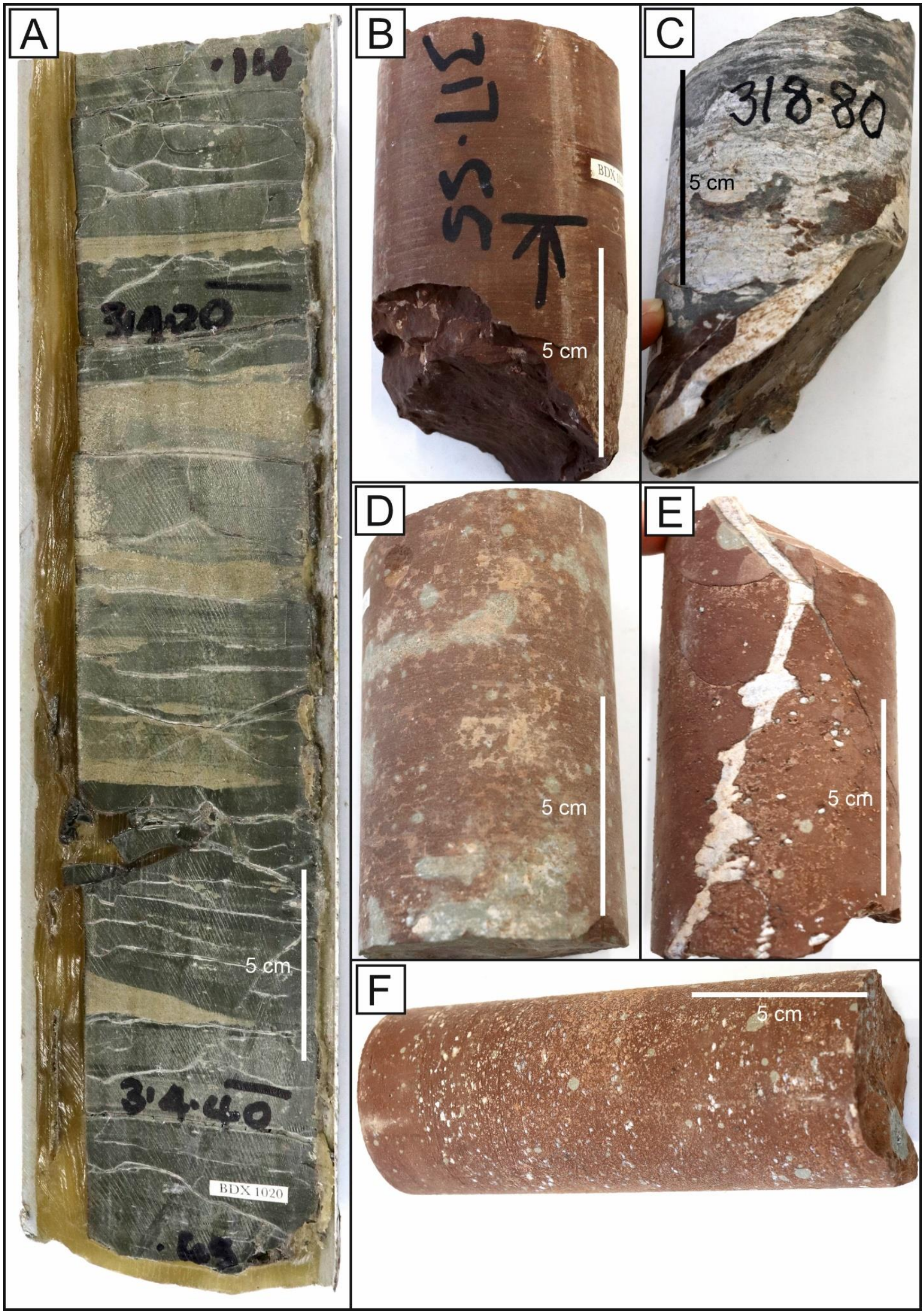

Figure 13. Selected samples of Twyning borehole drillcore. A) Millimetre-scale interbedded blue-grey siltstone and sandstone of the Arden Sandstone Formation, its typical Worcester Basin character. Sample from 314.14-314.45 metres. B) The deep red, slightly greasy character associated by Milroy *et al*. (2019) with the Sidmouth Mudstone Formation. Sample from 317.60-317.51 metres. C) A white-grey mottled and disturbed claystone bed with gypsum nodules and an inclined gypsum vein of around 1 centimetre thickness. Sample from 318.84-318.73 metres. D) Poorly-defined blue-grey mottled regions within a dull, dusty pink-red silt-rich mudstone typical of the Branscombe Mudstone Formation (Milroy *et al*., 2019). Sample from 307.12-307.22 metres. E) Dull mid-red mudstone with silt and gypsum nodules up to 3 millimetres in diameter and blue-grey reduction spots commonly up to 2 millimetres in diameter with a few larger instances up to 1 centimetre in diameter. An inclined gypsum band is present which is distorted and nodular in appearance, and is up to around 1 centimetre in width. Sample from 244.40-244.50 metres. F) Dull mid-red siltstone with reduction spots commonly up to 5 millimetres in diameter with dark-cored outliers up to 1.5 centimetres in diameter, gypsum nodules up to 2 millimetres diameter throughout and abundant platy detrital grains up to 2 millimetres in size. Sample from 178.50-178.65 metres.

5 Discussion

5.1 THE MILROY *ET AL*. (2019) FACIES ASSOCIATIONS AND FORMATION IDENTIFICATION SCHEME

5.1.1 Palaeoenvironment of the facies associations of Milroy *et al*. (2019)

The two main facies associations identified by Milroy *et al.* (2019) – the 'blocky claystone' facies association and the 'silty mudstone' facies association – and their characteristic features are indicative of particular palaeoenvironmental processes.

The sedimentology of the 'blocky claystone' facies association indicates a relatively low-energy terrestrial environment where wind-blown detrital clay and subordinate silt-sized grains could accumulate to create, on the whole, primary structure-less monotonous claystone beds of relatively uniform texture, colour, and sorting. The structures which are seen in the 'blocky claystone' facies association, such as desiccation cracks, vertic slickensides and pseudoanticlines (Figures 6C and F) are suggestive of a seasonal wet-dry climate (Jones *et al*., 2025), allowing for vertisol development in a semi-arid continental environment.

One exception to the monotony of these beds is the presence of relatively hard, well-cemented blue-grey coloured beds comprised of predominantly silt to fine sand sized grains (Figure 6B). These beds may be dolomitised, which may further explain their relative hardness, and they have the appearance of pseudogley – a bleaching which develops due to the redistribution of iron in a clay-rich but relatively permeable soil under waterlogged conditions which result from increased pluvial input as opposed to the elevation of the groundwater table. This increase in surface-water is a seasonal phenomenon, with the soil unsaturated for the majority of the year, becoming waterlogged where an underlying less permeable layer prevents further downward percolation (PiPujol & Buurman, 1994) – further evidence for cyclic wet-dry conditions. Similar features are described and attributed to a similar climatic cyclicity by Jones *et al*. (2025) in a study of borehole material from Cropwell Bishop, Nottinghamshire, which lies on the East Midlands Shelf (Figure 2). Drab-haloed root traces (Figure 6E) indicate that the soils were colonised by plants episodically, whose survival will likely have relied on seasonally increased soil moisture. The thick successions of this facies in the Sidmouth Mudstone Formation with well-developed features suggest formation over a relatively long period of time, in a distal setting with little coarse sediment input (Milroy *et al.,* 2019). The relatively high quantity of gypsum in this facies (Figure 8), compared to the 'silty mudstone' facies association, suggests the existence of drier periods which resulted in the evaporation of saline groundwater (Andeskie *et al.,* 2018). Climatically wetter intervals are reflected by the presence of sediments which exhibit bedforms indicative of deposition by alluvial sheet flows (Figure 6B).

The laminated horizons in the 'silty mudstone' facies association record deposition in relatively shallow, hypersaline waters. In wetter intervals with high groundwater levels, airborne silts may have been adhered to the damp saline mudflats to form weakly stratified material (Jefferson *et al.,* 2002; Mao *et al.,* 2021). Fluctuating groundwater levels within the saline mudflats would have allowed for the repeated interstitial growth and dissolution of evaporites, overwriting any depositional features present and creating new features such as collapse breccias, as seen at Newnham (Figure 6G) and in the BH4CAN122 and BH4CAN123 drillcores (Figure 12 – BHM4CAN122 log, 38-38.3 m). Cyclic alternations between massive, weakly stratified and stratified sediments suggest the repeated growth and contraction of ephemeral playa lakes through time (Figure 9; Allison & Wright, 2005; Andeskie *et al*., 2018).

The observed transition from predominantly 'blocky claystone' facies in the Sidmouth Mudstone Formation to predominantly 'silty mudstone' facies in the Branscombe Mudstone Formation reflects a transition from, earlier, more alluvially-controlled conditions to less arid conditions during and, to a lesser extent, following the Carnian Stage (Milroy *et al.,* 2019). The 'Carnian Pluvial Episode' or 'Event' interrupted this transition, as a period of greater humidity and

terrestrial precipitation allowed for the formation of the potentially widespread 'Lake Arden' lacustrine system and therein the deposition of the Arden Sandstone Formation (Simms & Ruffell, 2018; Baranyi *et al*., 2021; Burley *et al*., 2023).

5.1.2 Evaluating the facies scheme of Milroy *et al.* (2019)

Milroy *et al.* (2019) divide the Mercia Mudstone Group at Formation level by dividing material that is predominantly the 'blocky claystone' facies association, interpreted as the Sidmouth Mudstone Formation, from material that is predominantly the 'silty mudstone' facies association that is interpreted as the Branscombe Mudstone Formation. Following their facies interpretations, we identify the same characteristics in exposure and core to produce a stratigraphic correlation across the Severn Basin area (Figure 14), from Garden Cliff in the east to Newport in the west. This correlation has been made on the approximate time surface which is understood to separate the Sidmouth and Branscombe Mudstone formations: the time of the deposition of the Arden Sandstone Formation. This horizon may represent the Carnian Pluvial 'Event' or 'Episode' (Simms & Ruffell, 2018), which occurred during the late Julian to early Tuvalian Substages (mid-Carnian Stage) according to palynological evidence (Baranyi *et al*., 2021), though may be slightly later than this (Barclay *et al*., 1997; Burley *et al*., 2023).

In relating palaeosol structures to Formation characteristics, Milroy *et al.* (2019) assume that the palaeoenvironmental conditions which led to the formation of these structures were persistent across the study area during broadly the same period. This enables the linkage of palaeosol structures observed in exposure and core in the modern to geological time, and therefore geological Formation. On a regional scale (i.e. intra-basin) this appears to be possible, however at a national level (i.e. inter-basin) there are certainly lateral variations in depositional environment, environmental conditions, therefore diagenetic processes and their resultant palaeosol structures which challenge the application of this scheme over broader areas. One such example of this is the deposition of the Preesall Halite Member in West Lancashire and the Northwich Halite Member in the Cheshire Basin during part of the Anisian Stage, contemporaneous with the deposition of a thick evaporite-free Sidmouth Mudstone Formation in the Stafford and other basins (Howard *et al*., 2008).

5.1.3 Applying the scheme at exposure and in core

At exposure scale at the sites in the Severn Basin we have visited during this work, the facies associations identified by Milroy *et al.* (2019) provide a method to divide the succession at Formation level. Similar facies associations are visible in core, but even though the material of core samples is typically cleaner than those seen at exposure, the smaller sample size and more discontinuous record makes it harder to identify the facies present. When logging at a finer scale in core than is typically possible at exposure, with cleaner samples, more variations in facies become apparent.

In the Twyning core rock samples, while the Branscombe Mudstone Formation is predominantly comprised of material of the 'silty mudstone' facies association, there is a significant proportion that could be described as the 'blocky claystone' facies association (Table 4). The Sidmouth Mudstone Formation is harder to identify using the Milroy *et al*. (2019) scheme, with a greater length of retained samples identified as the 'silty mudstone' than the 'blocky claystone' facies association (Table 4). While this may reflect bias in the core samples that were chosen to be retained, similar variation in facies is also seen in the drillcores of BH4CAN122 and BH4CAN123 (Figure 12).

There is an increase in the proportion of core samples that belong to the 'silty mudstone' facies association toward the top of the Sidmouth Mudstone Formation. The base of the Branscombe Mudstone Formation also contains proportionally more material belonging to the 'blocky claystone' facies association than towards the top. The facies scheme is, on the whole, suitable for identifying the Formation present, but the facies immediately either side of the Arden Sandstone Formation appear to be more transitional, thus less diagnostic. Where the Arden Sandstone Formation is absent, this would make placing the stratigraphic boundary between the Sidmouth and Branscombe Mudstone Formations difficult. Since the character of the uppermost Sidmouth Mudstone Formation appears transitional with the lowermost Branscombe Mudstone Formation, even where a siliciclastic unit which could be described as the Arden

Sandstone Formation is present such as in the Twyning drillcore, it could be suggested that the currently accepted tripartite stratigraphic classification for this interval of the Mercia Mudstone Group (in ascending order: Sidmouth Mudstone Formation, Arden Sandstone Formation, Branscombe Mudstone Formation *sensu* Howard *et al*., 2008) may not be entirely fit for purpose (see Newell, 2024).

Table 4. The proportion of the Twyning drillcore which is classed as Sidmouth Mudstone, Arden Sandstone, and Branscombe Mudstone Formation, within which the proportion represented by each of the facies identified by Milroy *et al.* (2019), as well as sedimentary lithology, is shown both as a proportion of the length of the core interval and as a proportion of the total number of logged beds within that Formation interval. Numbers are given to the nearest percent and therefore may not add to 100%. One bed of gypsum recorded in the Branscombe Mudstone Formation is not represented in the table.

	Whole core		Sidmouth Mudstone Formation		Arden Sandstone Formation		Branscombe Mudstone Formation	
Depth interval	222.50-323.09 m		323.09-314.76 m		314.76-312.30 m		312.30-222.50 m	
	% of beds recorded	% of core length	% of beds recorded	% of core length	% of beds recorded	% of core length	% of beds recorded	% of core length
Core not retained	47%	92%	47%	85%	45%	67%	48%	93%
Blocky claystone facies association	10%	1%	32%	6%	0%	0%	7%	1%
Silty mudstone facies association	38%	6%	21%	9%	0%	0%	45%	6%
Claystone	34%	6%	42%	13%	0%	0%	36%	5%
Siltstone	16%	2%	11%	<1%	27%	27%	16%	2%
Sandstone	2%	<1%	0%	0%	27%	6%	0%	0%

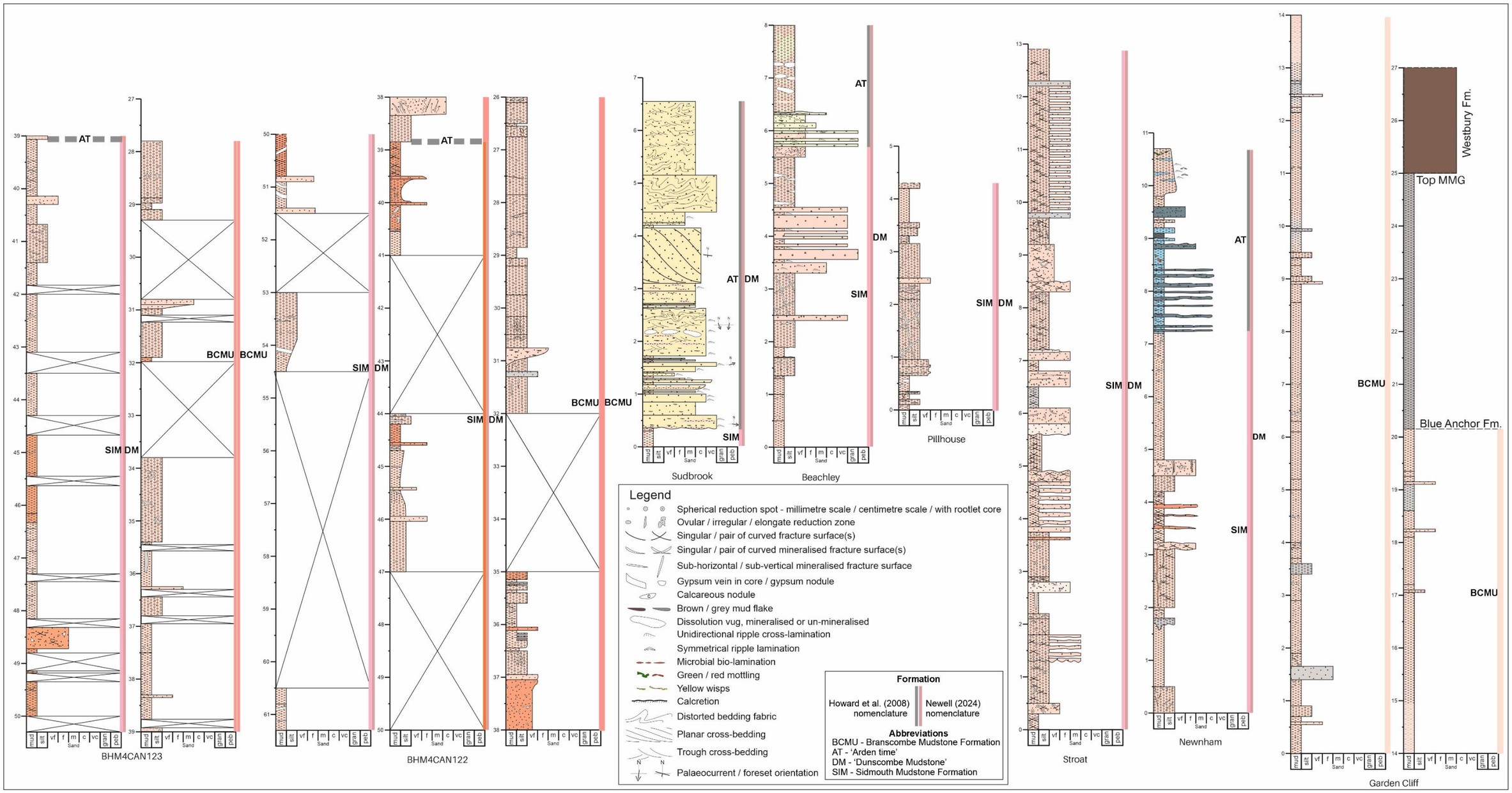

Figure 14. The application of Howard *et al.* (2008) and Newell (2024) stratigraphy to logged Mercia Mudstone Group exposures and cored boreholes in the Gloucester-Newport area. 'Arden Time' broadly corresponds to part of the late Carnian during which the Carnian Pluvial Event is thought to have occurred.

5.2 THE 'SANDSTONES'

5.2.1 The Arden Sandstone at Newnham

This locality features the most typical Arden Sandstone succession seen in the Severn Basin during this study. It could be either that similar successions were once present in other parts of the region and have since been removed by erosion, are rarely exposed, or that the environment in which the strata at Newnham were deposited was not widespread. A combination of the latter two possibilities seems favourable since the absence of this unit at exposures such as Aust Cliff where time-equivalent strata are thought to be present (Milroy *et al*., 2019) suggests that the depositional environment had a spatially restricted nature, regardless of the erosion that may have taken place. Burley *et al*. (2023) publish a possible extent of the 'Lake Arden' environment in which these strata are thought to have been deposited based on their proposed extent of the Arden Sandstone unit. This 'Lake Arden' encompasses the Newnham area as a lake-marginal setting, though Burley *et al.* (2023) acknowledge that the system is more likely to have been comprised of numerous variably connected water bodies. It is almost certain that these sand-rich beds are not exactly time-equivalent across the entire region but are nonetheless the result of the same broad climatic deterioration. Our sedimentological analysis of the Newnham section (Figure 4A – Newnham log) supports the hypothesis of a non-marine littoral palaeoenvironmental setting for this site. Understanding the extent and architecture of, and lateral variability in both thickness and sedimentology within this unit at subcrop in the Severn Basin area will require further research in conjunction with research into the geological expression of the Carnian Stage elsewhere in the UK and its continental shelf.

5.2.2 The 'Sudbrook Sandstone' at Sudbrook

The arenaceous beds at Sudbrook are, according to Milroy *et al*. (2019), at a similar stratigraphic level to the Arden Sandstone Formation at Newnham but have very different characteristics. The medium to coarse-grained sandstones that dominate the succession at Sudbrook, displaying common centimetre-scale outsized clasts (Figure 11B), decimetre-scale cross-beds and metre-scale inclined bedding (Figures 11A and 4B – Sudbrook log, 1.7-6.5 m), differ from the succession of thinly (millimetre- to centimetre-scale) interbedded sandstones and siltstones of the Arden Sandstone Formation at Newnham (Figure 10C), in the Twyning drillcore (Figure 13; Table 4) and at Shrewley (Figures 10A and B).

At the base of the succession at Sudbrook, thinly-interbedded claystones and siltstones interspersed with medium-coarse sandstones (Figures 11E and 4B – Sudbrook log, 1-1.7 m) suggest deposition in standing water rather than under sustained flow conditions or in settings which received constant agitation. The interbedded nature of the sediment suggests that the lithology and grain-size of material the system received was liable to marked variation on relatively short timescales, changing from fine muds and silts to coarse sands and pebbles. It is likely that these changes result from marked shifts in the volume and size of sediment being transported from source (likely the flanks of the Welsh and Cornubian massifs) to sink (the Severn Basin) by rivers. These shifts are themselves likely to be resultant of changes in precipitation in the catchment, similar to the pseudocyclic nature of energy within the system observed within the Arden Sandstone section at Newnham. The inclusion of mud clasts within sandstone beds indicates that water travelled over muddy ground which was prone to drying and cracking ephemerally, painting a picture of flash flooding and overland sheet flow. In the presence of water these hydrophobic mud flakes are easily remobilised, though have relatively short transport potential, thus are likely to be locally sourced, travelling tens to hundreds of metres from their loci of entrainment (Li *et al*., 2017). It seems plausible that these strata represent deposition in the littoral region of a sort-lived shallow pond occupying an ephemerally damp subdued depression within the desert plain.

Higher up in the succession at Sudbrook (Figure 4B – Sudbrook log, above 1.7 m), medium- to coarse-grained sandstone dominates the succession, typically bedded on a decimetre to metre-scale with cross-bedding and inclined bedding common (Figure 11A). Palaeocurrent measurements from cross-beds in this interval are strongly indicative of a southerly flow (Figure 4B – Sudbrook log). Inclined surfaces between 3.1-4.1 m also dip toward the south. The strata

at the top of the succession (Figure 4B – Sudbrook log, uppermost 2 m) appear distorted (Figures 11C and D), likely as a result of dewatering, suggesting rapid burial and high sedimentation rates.

During the deposition of the sediment which now comprises the Mercia Mudstone Group there are few recognised sources of significant terrestrial freshwater input. The period of increased precipitation responsible for the emplacement of the Arden Sandstone Formation, the Carnian Pluvial Event (Simms & Ruffell, 2018; Baranyi *et al*., 2021; Burley *et al*., 2023), may also be responsible for depositing the conspicuous sandstone beds at Sudbrook. The Arden Sandstone Formation is known to be laterally heterogeneous, perhaps representing a network of lakes and flashy fluvial systems rather than a single large lake (Burley *et al*., 2023).

Perhaps the 'Sudbrook Sandstone' represents the terminus of a basin-marginal fluvial system similar to those interpreted by Burley *et al*. (2023) to be present in Arden Sandstone Formation successions in the Knowle and Worcester Basins. It seems plausible that the periodically damp depression or pond which had previously collected pulses of sheet flow-derived siliciclastics alongside fines-dominated background sedimentation could become a deeper (at least ~1 m) lake which received input from a well-developed fluvial channel system due to its topographically low position. In this case, relatively thick inclined beds (3.1-4.1 m; Figure 4B – Sudbrook log) and dewatered medium to very coarse sand above 4.1 m (Figure 4B –Sudbrook log) containing cobbles (Figure 11D) could possibly represent the progradation of a small delta mouth bar into a ~1 m deep lake setting, thus recording the approximate margin of the late Carnian lacustrine system in this region at this time. Burley *et al*. (2023) propose a deltaic origin for decimetre-scale cross-beds toward the top of sections at Rowington, Henley and Shrewley in the Knowle Basin. The periodic nature of discharge and sand inputs from high ground to the north, as well as fluctuations in lake water level, thus lake size, drove the migration of facies significant distances across this dynamic low-gradient environment over time, recorded as significant changes in depositional style within single exposures.

Alternatively, the inclined beds between 3.1-4.1 m may represent point bar deposits emplaced by the lateral migration of a river channel across a mud-rich floodplain, and although there is neither an obvious erosion surface at the base of this package, nor obvious current ripples on the inclined bed surfaces to support this hypothesis, this possibility warrants further field investigation. The variable and localised nature of these facies contributes significant heterogeneity to this interval, though it is worth reiterating that it is very unlikely that these beds are exactly time-equivalent across the entire region since the late Carnian lasted for several million years.

Though the southerly-directed palaeocurrents and mouth bar progradation surfaces observed at Sudbrook suggest that this fluvial channel system may not have been directly feeding the lake systems which occupied the Worcester Basin which lay to the north-east (as depicted in Burley *et al*., 2023), it is likely that a lake was present in the area immediately to the south or south-east of Sudbrook at some point during the late Carnian. What is evident, is that runoff and material was derived from the flanks of the Welsh Massif to the immediate north-west (Figure 2), and this proximity may explain the significantly greater grainsizes and bed thicknesses observed here compared with outcrops in the Knowle and Worcester basins presented by Burley *et al*. (2023).

5.2.3 How do 'Arden times' manifest where the Arden Sandstone Formation and its potentially time-equivalent arenaceous deposits are not present?

The deposition of the Arden Sandstone Formation is associated with deposition of arenaceous material in freshwater lakes (e.g. Burley *et al*., 2023). The mobilisation of this sediment, as well as the freshening of previously saline desert pools, is attributed to an increase in precipitation – perhaps the Carnian Pluvial Episode (Simms & Ruffell, 2018; Baranyi *et al.*, 2021; Burley *et al*., 2023). In regions where no sediment accumulation took place during this period, overland flow, and therefore erosion, would be expected to be widespread. Evidence for overland flow in lake-proximal environments is provided by the presence of mud clasts, up to tens of centimetres in diameter, preserved within the Arden Sandstone Formation at Newnham and sandstone beds at Sudbrook (Figures 11B and D). Where the Arden Sandstone Formation and its likely laterally equivalent formations (e.g. the 'Sudbrook Sandstone') are absent, this period of time would be

expected to be marked by an erosion surface, or relatively thin accumulations of reworked detrital material deposited in local topographic lows. This hypothesis may assist in explaining the coarsening of grainsizes observed toward the uppermost Sidmouth Mudstone Formation (Figure 4A – Newnham log, 3-5 m; Figure 4B – Beachley log, 2.4-6.4 m; Figure 4C – Stroat log, all depths) which results in a transition of character from blocky claystone to silty mudstone thus, according to Milroy *et al*. (2019), a gradational boundary between the Sidmouth Mudstone and Branscombe Mudstone formations. Due to the nature of this transition in character, it has been suggested that this existing stratigraphic framework may not accurately reflect the heterogeneity of the deposits in this interval (Newell, 2024). Increased meteoric groundwater flow during this time may also have resulted in the dissolution of evaporite nodules within these strata, creating voids as seen at Beachley (Figures 11G and 4B – Beachley log, 6.75-7.3 m) and Sudbrook (Figures 11F and 4B – Sudbrook log, around 2.2 m), and the precipitation of calcite, quartz and perhaps other mineral deposits within these cavities. Deciphering the geological signal of the late Carnian in non-depositional regions or those which lack prominent arenaceous beds is of critical importance to the development of a stratigraphic framework for the Group as a whole. On the other hand, localities where multiple arenaceous beds are preserved within the succession present their own challenges where both basin-wide and inter-basin correlation is concerned. Further work in both types of setting will greatly benefit scientific understanding of Carnian palaeoclimate and subsurface heterogeneity.

5.3 APPLICATION OF THE NEWELL (2024) STRATIGRAPHIC FRAMEWORK TO THE SEVERN BASIN EXPOSURES

According to the stratigraphic framework proposed by Newell (2024) the Arden Sandstone Formation should no longer be recognised as a Formation-level subdivision within the Mercia Mudstone Group. Instead, this interval, in addition to strata formally recognised as the uppermost Sidmouth Mudstone Formation, should be included within the ‘Dunscombe Mudstone Formation’ (Figure 1; Newell, 2024). The boundary between this unit and the underlying Sidmouth Mudstone Formation should, at exposure, be placed where relatively homogeneous red brown claystones give way upward to red brown and grey mottled mudstones which may contain common gypsum, laminated or cross-laminated siltstone or sandstone, cross-bedded sandstone units of up to several metres’ thickness which exhibit bioturbation and convolute bedding, and grey laminated mudstone.

The presence of sandstone interbeds (Figure 6E), pervasive gypsum veining, grey mottling within mudstone successions interpreted to lie within the Sidmouth Mudstone Formation at Pillhouse and Stroat (Figure 4C), and ripple cross-laminated sandstones at Beachley (Figure 4B), suggests that these strata could be considered to make up part of the ‘Dunscombe Mudstone Formation’. Indeed, Jones *et al*. (2025) note the marked similarity in the sedimentology of the uppermost Sidmouth Mudstone Formation and Branscombe Mudstone Formation, particularly with regard to the presence of evaporite minerals and relatively coarse horizons hosting sedimentary structures such as cross-lamination. The strata described at Sudbrook also match the descriptive criteria of this Formation, containing many of the sedimentological features described above in addition to metre-scale inclined beds (Figure 11A) and convoluted bedding (Figure 11C) above 3 metres within the logged section (Figure 4B). However, identification of the contact between this unit at the Sidmouth Mudstone Formation in logs of the exposures visited is challenging due to the limited stratigraphic thickness which can be viewed in the exposures. It may be that this contact is not present in any of the logged sections presented in this work. What is clear is that this interval, if described as the ‘Dunscombe Mudstone Formation’, is markedly heterogeneous within this region. Separating this interval from those which surround it using formal stratigraphic boundaries not only aids the correlation of formation-bounding surfaces in geophysical logs as is demonstrated by Newell (2024), but is useful from an applied perspective, since the most significant known sedimentological heterogeneity within the Mercia Mudstone Group is therefore confined within this rather complex unit rather than being encompassed by both the topmost Sidmouth Mudstone Formation, the Arden Sandstone Formation where present, and its broadly time-equivalent arenaceous units. Relegating the Arden Sandstone to Member status better communicates its lateral discontinuity and probable time-transgressive nature, and the

discontinuity of similar broadly time-equivalent sandstone horizons (e.g. the ‘Sudbrook Sandstone’), on regional to national scales.

6 Conclusion

The facies scheme of Milroy *et al*. (2019) provides a method for dividing the Mercia Mudstone in the Severn Basin using the differing characteristics of the ‘blocky claystone’ and ‘silty mudstone’ facies associations, which are linked to the Sidmouth Mudstone Formation and Branscombe Mudstone Formation respectively. However, this scheme relies on the assumption that the palaeoenvironmental conditions which were responsible for the generation of palaeosol features and sedimentary or pedogenic structures associated with these facies were widespread and coincidental, occurring at the same time everywhere. While this appears to broadly hold true at a basin scale, it is likely that the successful application of this scheme inter-basinally will be restricted to more basin-marginal areas which have experienced similar environmental conditions. Cross-basin analysis will also rely on the assumption that the basins have similar diagenetic histories, otherwise this may impact the application of the scheme. We find that while a single facies does dominate both the Sidmouth and Branscombe Mudstone formations, variations in facies on a smaller, sub-formation scale may present issues in applying the scheme of Milroy *et al*. (2019), particularly to short or discontinuous sections of drillcore where relative stratigraphy (based upon easily recognised unit boundaries) cannot be established.

This study has highlighted the heterogeneity around the stratigraphic horizon of the Arden Sandstone Formation, commonly associated with the late Carnian Stage. Difficulty differentiating between the ‘blocky claystone’ and ‘silty mudstone’ facies associations appears to increase toward the top of the Sidmouth Mudstone Formation and into the base of the Branscombe Mudstone Formation. This heterogeneity could perhaps better be accommodated within the ‘Dunscombe Mudstone Formation’ of Newell (2024), within which the Arden Sandstone becomes a laterally discontinuous Member. The exposure most reminiscent of the typical Knowle/Worcester Basin manifestation of the Arden Sandstone Formation in the Severn Basin is that at Newnham, represented by thinly interbedded siltstones, sandstones and claystones of blue grey colour, ripple cross-lamination and symmetrical ripples, reflecting a shallow littoral environment sensitive to fluctuations in non-channelised (overland sheet flow-dominated) sediment input and driven by precipitation episodes. Elsewhere, such as at Sudbrook, coarse cross-bedded sandstone beds, in some cases featuring dewatering structures and cobbles, are present atop cm-scale interbeds of mud and coarse sandstone with pebbly outsized clasts. We suggest that this sandstone is likely to reflect a significant fluvial channel transporting material southward from the upstanding Welsh Massif, perhaps similar to channels seen by Burley *et al*. (2023) in the Knowle and Worcester Basins. The upper beds of the Sudbrook succession may record the termination of this channel in a standing body of water. The heterogeneity observed within this horizon in particular, if present elsewhere at depth, may have significant impacts on the unit’s ability to act as a seal for CO_2 storage or as a host rock for a radioactive waste geological disposal facility (Jones *et al*., 2025) among other applied uses. Further research into how the late Carnian Stage climatic deterioration manifests in the rock record in different areas of the UK and its continental shelf is crucial to gain greater understanding of palaeogeography, palaeoclimate, sedimentary processes and subsurface heterogeneity, improving our stratigraphic framework for the Mercia Mudstone Group as a whole.

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