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Relocate the base of the Arundian?: a re-evaluation from south Cumbrian sections and implications for British and Irish Lower Carboniferous successions

Abbreviated Title: The Arundian base in Britain & Ireland

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Abstract: The largely ice-free world of the 'Chadian'-Arundian (early Visean) is investigated in two successions in south Cumbria, in order to help better understand the relationships between transgression, hiatus and the position of the basal Arundian. A detailed foraminiferal biostratigraphy is used to age constrain the transition from the late 'Chadian' to early Arundian. This demonstrates a good synchronous relationship between the sequence stratigraphy of the two successions and the first occurrence of key species (mostly primitive archaediscids, rapidly followed by more evolved forms of the same family), suggesting there is no significant hiatus, and a closely comparable record of faunal changes in key successions. A synthesis of other 'Chadian'-Arundian boundary successions in Britain and Ireland indicates some key failings of the current Arundian boundary stratotype, in practical usage. We propose a stratigraphically higher position for the Arundian boundary in the stratotype, which is easier correlated to the Bobrikian and Moliniacian substages of eastern Europe and Belgium, respectively, and tied to foraminifera first occurrences, allowing more robust age assessments, free from the confounding factors of inferred lithological or sequence stratigraphic changes.

Keywords: Stratigraphy; boundary-stratotype; foraminifers; Mississippian; Britain; Ireland

The impact of eustatic sea-level changes has long been considered to have exerted a fundamental control on Carboniferous successions (Ramsbottom 1973; Ross and Ross 1985). In the Carboniferous, this is largely seen through the waxing and waning of polar ice buildups, particularly from the middle of the Mississippian, associated with the Late Paleozoic Ice Age (e.g., Montañez 2022). In Britain, the inference of sea-level change (expressed in transgressive and regressive successions) is the primary component of the mesothem concept of Ramsbottom (1973), which was fundamental in defining formal British regional stages (George *et al*. 1976; Ramsbottom 1977), now considered as Carboniferous regional substages (Heckel and Clayton 2006). These substages are widely used and supported in Britain and Ireland. For the focus of this work in the early Visean (Middle Mississippian), there is little or no evidence globally of ice buildups in low palaeolatitudes (e.g., Fielding *et al*. 2023), even though a substantial eustatic sea-level drop has been inferred in many European regions (Poty 2016; Herbig 2016), around the Chadian-Arundian boundary. An assumed near synchronous facies change associated with the initial Arundian transgression (D3 mesothem; Fig. 1) was also fundamental to the definition of the base of this substage (George *et al*. 1976; Ramsbottom 1981).

However, with the advent of ever finer-scale palaeoclimatic and environmental studies, the utility of the substages erected by George *et al*. (1976), which were built on the inherently diachronous transgressive-regressive facies concepts of Ramsbottom (1973), have been questioned (Davies *et al*. 1989; Riley 1993). As a result, some of these British Visean boundary stratotypes have been criticized (Fewtrell *et al*. 1981; Simpson and Kalvoda 1987; Davies *et al*. 1989; Riley 1993, 1995; Cózar and Somerville 2004; Aretz and Nudds 2005; Cózar *et al*. 2022a). Overall, the problems imply: (i) that the characteristic biota are recorded below the basal boundary stratotypes, such as in the Holkerian, Asbian and Brigantian (Cózar and Somerville 2004; McLean *et al*. 2018; Cózar *et al*. 2022a, 2022b); (ii) or in contrast, characteristic biota are recorded far above the basal boundary (Fewtrell *et al*. 1981; Riley 1995); (iii) there are common hiatuses in the successions (Riley 1993, McLean *et al*. 2018); (iv) faunal gaps are present due to dolomitized intervals (Simpson and Kalvoda 1987; Cózar et al. 2022a); and (v) there are a lack of good markers for international correlation with other regional substages or international stages (Cózar and Somerville 2021a, 2021b; Cózar *et al*. 2022b).

The general preference has been to retain the British substage chronostratigraphy (e.g., Davies *et al*. 1989; Riley 1993; Waters *et al*. 2011b), but to reposition the base of the substages in the stratotypes. There is reticence to radical major changes in stratotypes or to adopt new stratotypes and/or provide better characteristics of the substages, thereby hampering more precise chronostratigraphic correlation, both regionally and internationally. The key aspect of modern boundary stratotypes is they should contain a clear, detailed and robust biostratigraphy, thereby allowing precise chronostratigraphic relationships for correlation. Recently, progress has been made on a new Holkerian boundary stratotype, as well as a late Asbian unit and boundary stratotype (Fig. 1), using sections with more continuous biota than previous data, and thus, defining chronostratigraphical units which allow more precise international correlations (Cózar *et al*. 2022b, 2023).

In the early Visean, the most important chronostratigraphic change compared to the original proposal of George *et al*. (1976), concerns the Chadian, where the foraminifer, *Eoparastaffella,* considered as diagnostic for the base of the Chadian, was recorded 300 m above the proposed base (Riley 1990). To revise the Chadian, the proposed options are to: (i) move the base of the Chadian to the first occurrence of *Eoparastaffella* (Riley 1990), and thus, to extend the Courceyan into the early Chadian (e.g., Somerville 2008; Waters 2011); (ii) replace the Chadian Stage in favour of a new stage, recognised by a different "diagnostic" fauna (Riley 1990), or to use a currently unnamed lithological unit for the Visean part (Sevastopulo and Wyse-Jackson 2009); (iii) use early and late Chadian divisions (e.g., Riley 1990, 1993, 1995; Aitkenhead *et al*. 1992; Jones and Somerville 1996); or (iv) to replace the British substage for the Belgian Hastarian-Ivorian substages for the Tournaisian, and retain the Chadian only for the Visean part (e.g., Ramsbottom and Mitchell 1980; Waters *et al*. 2011b; Dean *et al*. 2011). On the other hand, foraminifers recorded near the base of the Chadian stratotype by Riley (1995) are closely comparable with assemblages recorded in the Ivorian upper MFZ6 and MFZ7 biozones from Belgium (e.g., *Eotextularia*, *Pseudotaxis*, *Endothyra*, *Omphalotis*, *Florennella* and *Brunsia*), and thus, the base of the Chadian can be correlated approximately with the base of the Ivorian. Thus, due to the poor definition of the 'Chadian', it is better to avoid the term or to use it with inverted commas until a proper redefinition of the unit or a new lithostratigraphical unit is proposed.

The proposal of early and late 'Chadian' intervals was based on the first occurrence of *Eoparastaffella* by Riley (1990), when comparing with the first occurrence of the taxon in Belgium in the Cf4α2 subzone (in Conil *et al*. 1989). However, as demonstrated by Hance *et al*. (1994) and Devuyst *et al*. (2006), specimens recorded in the former Moliniacian stratotype (at Bastion) and the current stratotype (at the Salet road section) belong to *Eoparastaffella simplex* (markers of the Visean base or MFZ9 zone; Devuyst *et al*. 2003), whereas other species of the genus are recorded in the upper part of the Tournaisian. Thus, the first occurrence of the genus *Eoparastaffella* is representative of the MFZ8 zone in the uppermost Tournaisian (Devuyst *et al*. 2003). In some successions in Britain, the first occurrence of the genus *Eoparastaffella* is used to recognise the late 'Chadian' or the Cf4α2 subzone, whereas in others, the first occurrence of the species *Eoparastaffella simplex* is used to define the base of the late Chadian or 'Cf4α2' (e.g., Aitkenhead *et al*. 1992). However, the position of *E. simplex* in the classical stratotype section at Chatburn is unknown, and possibly the best option is to select a new stratotype coinciding with the base of the Visean.

The base of the Arundian in the stratotype section at Hobbyhorse Bay (south Pembrokeshire, south Wales; Supplementary Material Fig. S1) was defined at the "first lithological change occurring below the entry of Archaediscidae" (George *et al*. 1976). This event was located at the boundary of the Hobbyhorse Bay Limestone (its upper part is dolomitized) and the succeeding Pen-y-holt Limestone (both now considered as formations; Waters *et al*. 2007). We refer to this as the 'classical definition' of the base Arundian. The boundary is situated below the first *Ammarchaediscus* (base of the Cf4β subzone), which occurs at 17.5 m (Simpson and Kalvoda 1987), or *Glomodiscus* sp. (Strank in Ramsbottom 1981), whereas more evolved forms of *Glomodiscus* are recorded at 23 m, and *Archaediscus* at *involutus* stage (base of Cf4γ subzone) at 27 m (Strank in Ramsbottom 1981). It was assumed that there was a major transgression at the base of the Arundian, coinciding with the base of mesothem D3 of Ramsbottom (1973, 1977) (Fig. 1). Thus, some authors use the transgressive surface (or hiatus) below the first occurrence of archaediscids coinciding with a lithological change, as the base of the Arundian (e.g., Davies *et al*. 1989; Kalvoda *et al*. 2014). However, using a lithological change for correlating a substage boundary is a weak and imprecise concept for defining a chronostratigraphic level.

One aim for this study is to assess the current use of the Arundian in Britain and Ireland, and to rationalize the criteria to achieve a regionally recognisable base with more consistency. A second aim is to examine in detail strata of early Visean age in South Cumbria, which were thought previously to contain a hiatus at the 'Chadian'-Arundian boundary (e.g., Rose and Dunham 1977; Johnson *et al*. 2001; Dean *et al.* 2011; Waters *et al.* 2011c). This uses the transition between the Martin Limestone and Red Hill Limestone formations in the Furness Peninsula and Kent Estuary areas, at the Dunnerholme Point and Meathop Fell outcrops (Fig. 2). This region contains well-exposed mostly continuous successions suitable for high-resolution biostratigraphy (e.g., Rose and Dunham 1977; Johnson *et al*. 2001), which here focuses on foraminifera, which provide the highest resolution biostratigraphy in the early Visean of carbonate platform successions.

Stratigraphical context

The Martin Limestone Formation (MLF) of Johnson *et al*. (2001) (Martin Limestone of Rose and Dunham 1977) is composed of calcareous mudstones, peloidal and bioclastic limestones and ooidal limestones. The formation was included within the late 'Chadian', together with the underlying siliciclastic red-beds (the Marsett Formation; Fig. 2) by Johnson *et al*. (2001), but was considered as top Courceyan and 'Chadian' by Waters *et al*. (2011c). The Marsett Formation is particularly thick in the Duddon Estuary area (Fig. 2), and very thin to absent in the area east of the Cartmel Peninsula. The formation was assigned by miospores to the *Schopfites claviger- Auroraspora macra* Zone of late Courceyan age (Rose and Dunham 1977; Waters *et al*. 2011c) and is, perhaps, laterally equivalent to the lower part of the MLF to the east of the Cartmel Peninsula. Overlying the Martin Limestone Formation is the Red Hill Limestone Formation (RHLF) of Johnson *et al*. (2001) (Red Hill Oolite of Rose and Dunham 1977). The RHLF typically comprises medium to coarse grainstones with abundant micritized bioclasts, and has been assigned to the top of the late 'Chadian' and early Arundian (Johnson *et al*. 2001), or early Arundian in Waters *et al*. (2011c). Modern biostratigraphic age assignments for these units are largely based on the coral faunal zones of Mitchell (1989), which in south Cumbrian sections contains the richest and most diverse British Arundian coral faunas, but these formations have not been studied in detail for foraminifera.

Despite having divergent 'typical' lithologies for each formation, the base of the RHLF is either seen as:

- A pronounced disconformable boundary in sections in the Leven Estuary area (at Ashes Point and Skelwith Hill sections; Fig. 2), marked by 'algal nodules and beds of breccias' (Nicholas 1968; Adams and Cossey 2004). Adams and Cossey (1981) demonstrated that most of the so-called algal nodules were nodular calcretes due to subaerial exposure, associated with rhizoliths, laminated micrites and palaeosol breccias.

- Outside of the Leven Estuary area, the formation boundary is transitional in lithologic character, such as at Dunnerholme Point (Adams and Cossey 1981). Here, Rose and Dunham (1977) defined the top of the Martin Limestone at their 'Algal Band'– a bed with markedly abundant oncoids, brachiopods and gastropods. In contrast, Nicholas (1968) used a position for the formational boundary some ~15 m lower in the section.

- Later, Johnson *et al*. (2001) placed the base of the Red Hill Limestone Formation at the base of the Algal Band, and considered that there was a hiatus between both formations, likely 'expanding' the evidence from the Leven Estuary outcrops, as similarly inferred by Ramsbottom (1973). Moreover, Leviston (1977) also inferred a level of breccia in the basal RHLF at Meathop Quarry, although this was later shown by Adams and Cossey (1981) to be erroneous. Despite this, a hiatus was accepted by Dean *et al*. (2011) and Waters *et al*. (2011c), who considered that the top 'Chadian' was not present in the region.

Certainly, the formational boundary is more complex than either of these current concepts and locally includes biostromes, as noted by Nicholas (1968), in outcrops in the Furness Peninsula. Nicholas (1968) recognised two episodes of development of small reefs, one in the upper part of the Martin Limestone and the second with thicker biostromes in the upper part of the Red Hill Limestone, with the latter biostromes studied in detail by Adams (1984).

Meathop Quarry (southwest side of Meathop Fell; Fig. 2; SM Fig. S2) is currently the best reference section for the Martin Limestone Formation (Johnson *et al*. 2001;

Adams and Cossey 2004). Here, the base of the Red Hill Limestone Formation has been placed near the top of the outcrop at the base of Garwood's '*Spirifer furcatus* Band' (Garwood 1913; Leviston 1979; Adams and Cossey 2004), a level utilised by Ramsbottom (1973, 1977) for the base of his mesothem cycle D3. Only the upper part of the Meathop Quarry section is shown here, our data from the lower part will be discussed elsewhere. The extension of these formations is also recorded in sections in west Limegarth Wood and around and west of the hamlet of Sunnyside on the south side of Meathop Fell (SM Fig. S2), sections which cover the boundary interval and the lower part of the RHLF. This work examines the detailed biostratigraphy of these sections plus that at Dunnerholme Point, briefly described by Rose and Dunham (1977) and Nicholas (1968). More precise sub-section details are in Supplementary Material Figs. S2, S3 and the geographic coordinates are included in SM Table S1.

In the light of the relationship between the basal Arundian and transgressive events, a sequence stratigraphic division has been applied to the studied sections using the basic principles of Tucker *et al*. (1993) and Catuneanu *et al*. (2011), using the genetic sequence labelling. Principally, this has attempted to determine regressive intervals by identifying, 1) rootlets and birdseyes in micrite limestones in the underlying regressive facies, 2) laminated mudstones, likely of peritidal origin, and 3) erosional events and channelling, indicating a low stand, or falling stage events close to the overlying transgressive surface. The associated maximum flooding surfaces are less easy to define, but are likely associated with wackestones, and sometimes more argillaceous levels. The sequence stratigraphy divisions are based on investigation of thin sections from 272 samples, plus those from intermediate positions, based on field analysis from additional sampling.

Biostratigraphy and sequence stratigraphy

Biostratigraphy at Dunnerholme Point

The Dunnerholme Point succession has been studied using four subsections: two sections within the abandoned quarry (the quarry section and SE section), and two coastal cliff sections (SW and NE sections), separated by a NW-SE trending fault (SM Fig. S3). The SE subsection (the shortest) contains the Algal Band illustrated in Rose and Dunham (1977, plate 3). The oldest levels are from the topmost part of the Marsett

Formation, from the NE subsection, whereas the SW subsection overlaps the previous sections. Following the definition of Johnston *et al*. (2001), the base of the Red Hill Limestone Formation is positioned at the base of the Algal Band.

The lower part of the succession contains common species of *Bessiella*, *Spinobrunsiina*, *Spinochernella*, *Lysella* (mostly *L. gadukensis*), relatively common *Brunsia*, and rare *Eoparastaffella* (including *E. simplex* and *E. evoluta*), *Eosinopsis*, *Pseudoammodiscus*, *Eotextularia* and *Urbanella*. The assemblage is interpreted as Visean, within the foraminiferal zones MFZ9 or Cf4α2, corresponding to the late 'Chadian' (Fig. 1).

In the upper part of the NE subsection and lower part of the SW subsection, the previous assemblage with a predominance of loeblichiids changes and some of the common taxa become rarer or even disappear. However, the assemblages are now composed of common *Brunsia* and *Eoparastaffella* (rather abundant and diversified), and taxa such as *Eoendothyranopsis* ex gr. *donica*, *Bogushella*, *Alticonilites* and *Eblanaia* are first recorded. They are noteworthy for the first occurrence of evolved species of *Eoparastaffella*, such as *E. iniqua* and *E. restricta* (samples 61 and 2, respectively; Figs. 3-4). These species are considered here as some of the large species of *Eoparastaffella* (e.g., *E. pseudochomata*, *E. lacionosa*, *E. asymmetrica* M2 and *E.* ex gr. *simplex* evolved). These evolved forms of *Eoparastaffella* are usually first recorded in the upper part of MFZ9 (e.g., Devuyst 2006; Kalvoda *et al*. 2012; Zandkarimi *et al*. 2019). Approximately at the same levels, the first representatives of the genus *Eostaffella* are recorded (Figs. 3-4), included under the taxon *E.* ex gr. *nalivkini* (Conil *et al*. 1991; Poty *et al*. 2006; Hance *et al*. 2011). For some authors, this latter species is considered as a transitional form between *Eostaffella* and *Eoparastaffella* (Kalvoda *et al*. 2012, 2014).

Kalvoda *et al*. (2012) already suggested that the above-mentioned species of evolved *Eoparastaffella* have the potential to subdivide the upper part of the MFZ9, although their first occurrences need to be further tested, and the systematics of the illustrated specimens needs to be revised.

The upper part of the Dunnerholme Point sections contains similar assemblages as the underlying interval. However, of great significance, is the first occurrence of primitive archaediscids (Figs. 3, 5). Within these earlier forms, there is a predominance of the genus *Planoarchaediscus* (samples 17, 72, 83, 96), although *Ammarchaediscus* also occurs (sample 90), as well as specimens with a thicker development of the pseudofibrous layer. These latter taxa can be classified as primitive *Glomodiscus* and *Uralodiscus* (samples 17 and 94), although for some authors, they might be still included under *Ammarchaediscus* and *Planoarchaediscus* (see specimens illustrated from the base of the MFZ10 in Zandkarimi *et al*. 2017). The assignment of those primitive specimens to one or more genera is controversial.

The first occurrence of archaediscids are widely used as markers for the base of the Cf4β or MFZ10 zones (e.g., Conil *et al*. 1980, 1991; Poty *et al*. 2006; Hance *et al*. 2011; Kalvoda *et al*. 2014). These horizons also coincide with abundant bilaminar dasycladacean alga *Koninckopora* (e.g., *K. tenuiramosa* and mostly *K. inflata*) (Fig. 3).

Rose and Dunham (1977) described some macrofauna (corals and brachiopods) from the section, but none of them are biostratigraphically significant.

Biostratigraphy in the Meathop – Sunnyside sections

The upper part of the Meathop Quarry contains an assemblage with a predominance of *Eoparastaffella* species, although in contrast with Dunnerholme Point, many of the common genera recorded from older levels, are still relatively common, such as *Bessiella*, *Lysella*, *Eotextularia*, *Spinobrunsiina* and *Spinochernella*.

Within the genus *Eoparastaffella*, species with angular peripheries are common, including *E*. ex gr. *simplex*. The large and evolved species of *Eoparastaffella* and *Eostaffella* are first recorded in the upper part of the quarry section (samples MQ47-49; Fig. 6). The assemblage is assigned to the upper part of MFZ9. Beds in the upper part of the quarry can be approximately traced along strike to the West Limegarth Wood section, which shows a direct bed-for-bed correlation with the lower part of the Sunnyside sections (SM Fig. S2; Fig. 6).

In the west Sunnyside section, the foraminiferal assemblage is similar to that in Meathop Quarry, presenting a mixed assemblage with *Eoparastaffella*, loeblichiids and spinobrunsiids. In the lower part is recorded *Eostaffella* (sample SS10; Fig. 6), although large species of *Eoparastaffella* are not recorded. At sample SS19 is recorded a primitive *Planoarchaediscus*. Therefore, the lower half of the subsection is assigned to the upper Cf4α2 or upper MFZ9, whereas the upper half is assigned to the MFZ10 or Cf4β.

At the Sunnyside section, dolomitization is more destructive, and those preserved horizons that have escaped dolomitization contain poor foraminiferal assemblages. Despite this rarity of specimens, the lower part mostly contains *Lysella* and *Paralysella*. Very rare *Eoparastaffella* ex gr. *simplex* is recorded, which allows assignment of this section to the Cf4α2 or MFZ9. Primitive *Planoarchaediscus* and *Uralodiscus* are recorded in samples 74 and 83 respectively (Fig. 6), representatives of the Cf4β or MFZ10. In these levels, common *Koninckopora inflata* are also recorded (from sample 80X), as well as a late first occurrence of *Eostaffella* and large *Eoparastaffella* (Fig. 6).

Macrofauna recently collected from Sunnyside

Solitary rugose corals recorded from the Martin Limestone in the lower part of the Sunnyside section include *Axophyllum simplex*?*, Sychnoelasma konincki, Amygdalophyllum* cf. *sudeticum, Clisiophyllum* sp.*, Haplolasma*? and the tabulate coral *Syringopora* cf. *reticulata.* Higher beds in the section assigned to the Red Hill Limestone include *Clisiophyllum* cf. *multiseptatum.* The latter taxon is similar to *Clisiophyllum multiseptatum*, whose holotype is from the overlying Dalton Fm of late Arundian age, but is much smaller, and is likely to be an ancestor. For the most part, the coral assemblage compares with fauna A of Mitchell (1989) and equates with rugose coral zone RC4β1-β2 of Poty *et al*. (2006).

Sequence stratigraphy

Transgressive surfaces (TS) were numbered from the base of each composite section. Lowstand system tracts (LST) at Dunnerholme are mostly shown as more reddened argillaceous intervals with common channelling and oncoids (e.g. below TS1, TS4), well seen just below the Algal Band. Whereas at Meathop Fell, the LST are mudstones with bird-eyes (e.g. below TS4), with some well-developed laminated peritidal mudstones and occasional rootlets in the Martin Limestone Fm (below TS2). The LST below TS3 at Sunnyside is well-characterised by much channelling and a shale-filled channel. Transgressive surfaces are typically grainstones, sometimes with erosional boundaries, the most pronounced of which is TS1 at Meathop Quarry. This is the only substantive down-cutting boundary seen in the figured sections and is recognised as a sequence boundary. The Algal Band is inferred to mark TS4 at Dunnerholme, and a very similar bed with an erosive lower boundary may be an overlying TS5(?) in the Quarry and SW subsections at Dunnerholme (Fig. 3). However, the hummocky-cross-stratified grainstones in the upper parts of the Dunnerholme Quarry and SW sub-sections may be the highstand system tract (HST) of TS4, since it does not have a well-defined underlying LST. Highstand system tracts (HST) are typically represented by grainstones relatively rich in macrofauna, and sometimes ooids. Also, by biostromes in the Meathop Fell sections.

There is good consistency with the position of the foraminifera markers, such that TS3 and TS4 are inferred to be near synchronous between both composite sections (marked in blue in Figs. 3, 6). The upper Cf4α2 or upper MFZ9 markers occur in the TST or HST above TS3, and the markers for the base of MFZ10 or Cf4β occur in the TST and HST of TS4 (Figs. 3, 6). The underlying TS1 and TS2 surfaces could also match between the composite sections, which would make the TS1 surface at Meathop Fell equivalent to the TS1 surface at Dunnerholme, ~ 3 m above the top of the Marsett Formation.

Where is the base of the Arundian?

Simpson and Kalvoda (1987), regard the dolostone interval in the Hobbyhorse Bay Limestone as diagenetic in origin, and therefore the current base of the Arundian is a diagenetic boundary. In south Cumbria, based on detailed examination of the consistent biota and additions of minor new taxa, we consider it unlikely there is a major biostratigraphic hiatus in the studied sections (Figs. 3, 6). Likewise, facies changes are transitional between the Martin Limestone and Red Hill Limestone formations at these sections, without evidence of a major hiatus. Hence, the palaeosols in the sections in the Leven Estuary area, marking the presumed based Arundian, are features local to that area only (Fig. 2). The base of TS4 is the closest transgressive surface below the first record of archaediscids, with lithologies immediately above and below rather similar, so it could be a place to position the classical base Arundian (Fig. 3). Similarly, at Meathop Fell, TS4 is recognized 0.2–5 metres below the first archaediscids, and so is a suitable position for the base for the classical base Arundian (Fig. 6). However, it could correspond to the top of the Meathop Quarry, where questionable *Planoarchaediscus* are recorded in the grainstones just above the biostrome. Thus, positioning the base of the Arundian located on a transgressive surface is inevitably ambiguous.

Likewise, there is no certainty that a horizon with Cf4β foraminifers above a transgressive surface corresponds clearly to any level in Hobbyhorse Bay, since any sequence stratigraphy in Hobbyhorse Bay has not been fully tested. The Arundian, as it is currently defined, can be approximated (i.e. it lies within a hiatus interval) in regions such as south Wales to Bristol, where the mid-Avonian unconformity occurs (e.g. Kalvoda *et al*. 2014), but applying this to other regions of Britain and Ireland is ambiguous. Inherently, any such unconformity or transgressive surface will be diachronous between basinal and shelf successions and only correlative conformities (onset or end of relative sea level fall, at the boundary of HST/LST) are likely to be the least diachronous (Catuneanu *et al*. 2011), and these are not currently defined at Hobbyhorse Bay.

Use of the Arundian in Britain and Ireland

The 'Chadian'-Arundian boundary is recorded in many regions of England, Wales, Northern Ireland and the Republic of Ireland (Fig. 7), although it is not present in Scotland (SM Fig. S1). Most of these data were compiled by Waters *et al*. (2011a), and the most important successions yielding this boundary are summarized (some of them are modified here) in the Supplementary Material and in Tables 1 and 2.

Subdivisions of the Arundian

Using foraminifers, which give us the highest resolution in carbonate platforms during the early Viséan, six foraminiferal subzones were included in the classical sense of the Arundian, the top of Cf4α2, Cf4β, Cf4γ, Cf4δ (Conil *et al*. 1980, 1991) and the Cf5α and lower part of Cf5β1 (Cózar *et al*. 2020, 2023) (Fig. 1). More recently, the Cf4δ has been also subdivided into lower, middle and upper foraminiferal assemblages (Hounslow *et al*. 2022), although the isochronous character of those assemblages needs to be further tested elsewhere. These subzones and assemblages can be informally grouped as the classical early Arundian (top Cf4γ2 and Cf4β), mid Arundian (Cf4γ) and late Arundian (Cf4δ- lower Cf5β1). A similar subdivision into early, mid and late Arundian was recognised in brachiopods and rugose corals (Riley 1993) or coral zones B, C and D of Mitchell (1989); subdivisions that are approximately coeval with those in the foraminifers. The lower Cf5β1 is now part of the Holkerian following the proposal of a new Holkerian stratotype (Cózar *et al*. 2023).

Other fossil groups are less precise in recognising the Arundian. Conodont assemblages are mostly represented by the *Lochriea commutata* Zone of Varker and Sevastopulo (1985), although the base of this zone does not correspond with the base of the Arundian. Other detailed studies on Arundian conodonts did not achieve much more precision (e.g., Stone 1989). In miospores, the *Lycospora pusilla* (Pu) Zone embraces part of the 'Chadian' (or even Courceyan, depending on the author) and part of the Arundian (Riley 1993).

Practical determinations of the 'Chadian'-Arundian boundary in British and Irish successions

Generally, five main types of criteria have been used to position the basal Arundian boundary in British and Irish successions (Fig. 7; Tables 1 and 2):

1. An important lithological change below the first occurrence of archaediscids (or Arundian macrofauna).

2. An important lithological change or hiatuses implying the beginning of a transgressive phase below the first occurrence of archaediscids (or early Arundian macrofauna). These lithological criteria are rarely documented in regions with some important hiatuses, such as south Wales, Bristol and east Dublin Basin (Skerries-Lane).

3. At the first occurrence of primitive archaediscids representative of the Cf4β subzone, coinciding or not with a lithological change.

4. An approximate position between 'Chadian' biota and Cf4β, Cf4γ or even Cf4δ subzones without any lithological change. This is the most common type of criteria for establishing the base of the Arundian.

5. Successions with poor biostratigraphic control, with the Arundian base inferred between 'Chadian' and Holkerian faunas, without supporting lithological change.

Not classified here are regions in Britain and Ireland (not included in Fig. 7 and Tables 1-2), where the base of the Arundian is within a long-ranging hiatus below Arundian biota, such as in the south Askrigg Block or Bowland sub-basin.

Discussion

Primary and secondary markers for the Arundian

A common theme emerging from practical determination of the basal Arundian shown in Figure 7 and Tables 1 and 2, is that the biostratigraphic markers for the base of the Arundian are being used as the primary marker (corresponding to the Cf4β subzone or early Arundian macrofauna) at or near the base, and that any transgressive event (or lithological change) is a secondary marker for repositioning the base. Without faunal primary markers, any secondary markers (e.g. the classical base of the Arundian) are little more than an approximation, since the detailed context of the sequence stratigraphy in the stratotype is poorly known and can only be inferred from the up-dip successions (e.g. Wright 1986). Of the 40 studies listed in Tables 1 and 2, corresponding to successions encompassing this boundary interval, only this one and seven others utilise the combination of a foraminiferal primary marker (i.e. archaediscids, primitive or otherwise) and secondary lithological change to correlate to the stratotype (i.e. mostly classified as inferred type-1 and -2). The reasons for this are probably two-fold:

A) Lack of significant transgressive/lithological changes inferred or observed (inferred types 3 and 4), perhaps through insufficiently detailed studies to identify them.

B) The absence of clear transgressive-regressive phases in the distal ramp settings of some of these study areas. In many successions the transgressive phase starts in the 'Chadian' or late 'Chadian' and continues through to the Holkerian or even Asbian. As Wright (1986) concluded for the south Wales 'Chadian'-Arundian ramp succession, none of the shallowing phases seen in the inner and mid- ramp zones can be detected in the outer ramp sequence, where the stratotype is located. Hence, the secondary marker of transgression/lithology change seems to be widely absent, in outer-ramp settings or requires other kinds of methods to identify it.

The studies classified as inferred type 3 are inconsistent with the current definition and position of the primary Arundian biostratigraphic marker in Hobbyhorse Bay. Authors using this approach are recognising biozones, but not the proper chronostratigraphy, thus they are not recognising the 'true' primary marker. Naturally, there is often additional uncertainty, in some studies, where biostratigraphy is scarce and the primary markers are not found, such as inferred types 4 and 5 (Fig. 7). Thus, in those cases, they lack precision in the identification of the Cf4α2 and Cf4β subzones, but the correlation inference could be approximately consistent with the stratotype boundary.

Classifications of the early Archaediscidae

Riley (1993) first proposed to reposition the base of the Arundian in the Hobbyhorse Bay section at the first occurrence of archaediscids (inferred type 3), and to consider the lower ~16 m of the Pen-y-Holt Limestone as 'Chadian' in age. However, specimens of *Planoarchaediscus/Ammarchaediscus* are rarely documented in the assemblages elsewhere in Britain and Ireland, and it is necessary to clarify how much later the first primitive *Glomodiscus/Uralodiscus* occur in suitable sections (which in many cases are more commonly documented). At Hobbyhorse Bay, it is also necessary to test if the recorded foraminifers really correspond to *Ammarchaediscus/ Planoarchaediscus* and the first most primitive *Glomodiscus/Uralodiscus.* These later taxa, likely correspond to the basal levels of the Cf4β subzone, but have been never illustrated. The 1.5 m of measured stratigraphic difference between the first occurrence datum (FOD) of *Ammarchaediscus* and primitive *Glomodiscus* in Hobbyhorse Bay is rather similar to the 2-4 m observed in south Cumbria, although these taxa are not recorded in each section (Figs. 3, 6), mostly due to the scarcity of specimens.

In the hypothetical classifications of the Archaediscidae, the stratigraphic distance between the first occurrences of *Planoarchaediscus/Ammarchaediscus* and *Glomodiscus/Uralodiscus* is often small, but can depend on the morphological criteria used to define the genera. Pirlet and Conil (1974) and Conil *et al*. (1980) considered the family Archaediscidae a polyphyletic group arising from two separate genera, *Pseudoammodiscus* (planispiral forms) and *Brunsia* (non-planispiral forms), with *Planoarchaediscus* first appearing from the base of the Cf4β and *Glomodiscus* slightly later. However, these authors considered *Ammarchaediscus* and *Uralodiscus* as mostly occurring first from the upper Cf4β, and questionably from lower levels in the subzone. These apparently diachronous occurrences are likely an artefact of the studied sections. In western Europe, it seems that the non-planispiral forms are more common than the planispiral forms. However, in middle Asia, i.e. Afghanistan and Iran, the planispiral forms are more common (e.g., Vachard 1980; Zandkarimi *et al*. 2016). Consequently, in the classification proposed by Vachard (1988), the first genus to be recorded is *Ammarchaediscus*, rapidly followed by *Planoarchaediscus* and *Uralodiscus*. The ancestral stock for the Archaediscidae is thought to be *Lapparentidiscus*, and thus, considered as a monophyletic family, with Zandkarimi *et al*. (2017) coming to similar conclusions. In addition to this small difference between the first occurrence of these key genera, the classification of some specimens is questionable, since transitional forms make identifications difficult. For example, *Ammarchaediscus* passing into *Viseidiscus*, ammarchaediscid indet, Viseinid indet. in Zandkarimi *et al*. (2017) or *Ammarchaediscus* (cf. *Rectodiscus*) sp. [= *Uralodiscus*] in Hance (1988), which was later refined as *Ammarchaediscus* sp. in Hance *et al*. (1994) and Devuyst *et al*. (2006) (see also Fig. 5). In addition, the validity of the genus *Ammarchaediscus* is not universally admitted, and these forms were included under the genus *Viseidiscus* (Brenckle et al., 1987).

A revision of those primitive forms is necessary to establish more robust criteria for correlation of the finer scale biostratigraphic units.

International correlation of the basal Arundian

At the Arundian stratotype in Hobbyhorse Bay, the specimens recorded 1.5 m above *Ammarchaediscus* were identified as Archaediscidae and *Glomodiscus* sp. by Strank (in Ramsbottom 1981), whereas Simpson and Kalvoda (1987) only recorded *Ammarchaediscus* at those levels. In south Cumbria, the difference between stratigraphic levels first recording *Ammarchaediscus*-*Planoarchaediscus* and those with primitive *Glomodiscus*-*Uralodiscus* are less than 3 m, but the specimens are very rare, and in some sections they occur together.

In the Moliniacian stratotype in the Salet road section, *Planoarchaediscus* and *Glomodiscus* first occur together in bed 215, whereas forms questionably assigned to *Ammarchaediscus* or *Uralodiscus* are first recorded from bed 216 (only some tens of cm above). This near-coincident first occurrence is not observed in other sections from Belgium, such as at the Ciney section, which only contains *Planoarchaediscus*; the Halloy section, which only contains *Uralodiscus* and *Glomodiscus*, Ivoir section that only contains *Uralodiscus*, and the first archaediscid in the Braibant section is *Archaediscus* (Cf4γ) (Hance 1988; Hance *et al*. 1994). Thus, this rarity is shared between the Belgium and Britain sections, but in both regions, the most primitive archaediscids can be used as primary markers for the recognition of the MFZ10 and the Cf4β subzone respectively (Fig. 8).

In Russia, the widely accepted lateral equivalent of the Arundian base is the base of the Bobrikian (e.g., George *et al*. 1976; Conil *et al*. 1977; Riley 1995; Davydov *et al*. 2004, 2010; Poty *et al*. 2014; Lucas *et al*. 2022). However, this substage in its type area is composed of fluviatile sandstones and shales, subdivided by miospore zones. The base of this substage usually corresponds to a large gap in the East European Platform (EEP), with the Radaevkian substage being commonly absent, which makes comparison difficult. Thus, the foraminiferal Bobrikian zonations in Russia are mostly based on data from the Urals (and Ukraine). Some of the early foraminiferal zonations are those of Lipina and Reitlinger (1970), who proposed the *Planodiscus primaevus–Uralodiscus rotundus* Zone for the Bobrikian ("and lateral analogues"). The genus *Planodiscus* has also been considered as an *Ammarchaediscus* (e.g., Vdovenko *et al*. 1990), but from our point of view, *Planodiscus* is a transitional form to *Uralodiscus*. More recently, this zone was referred to as the *Uralodiscus rotundus* Zone (Kulagina *et al*. 2003; Davydov *et al*. 2010; Alekseev *et al*. 2022).

Davydov *et al*. (2012) used a lower *Uralodiscus primaevus* (named as Mf9) and an upper *U. rotundus* (Mf10) zones. The Uralian zones *U. primaevus* and *Ammarchaediscus eospirillinoides* are representative of the Ilychian and Burlian substages, which are correlated with the lower part of the Bobrikian (Alekseev *et al*. 2022). Above, and equivalent to the upper part of the Bobrikian and part of the Tulian in the EEP, are the Druzhininian and Ustgrekhovkian substages, which are marked by the occurrence of *U. rotundus* (Alekseev *et al*. 2022). Both zones in the Urals of *U.*

primaevus and *U. rotundus*, were correlated with the *U. rotundus* Zone in the EEP by Alekseev (2008).

Generally, authors recognizing the Bobrikian Substage documented numerous species of Archaediscidae, a fact which raises a question if the occurrence of the above British-Belgian taxa are really the first archaediscids. In fact, Lipina and Reitlinger (1970) documented that the first isolated Archaediscidae are recorded from the *Dainella chomatica – Eoendothyranopsis transita* Zone (located in the underlying Radaevkian Substage), but with rare occurrences. Thus, the basal Bobrikian, Ilychian and Burlian seem to correspond more correctly with the record of primitive *Uralodiscus* in Britain, slightly younger than *Planoarchaediscus/Ammarchaediscus* (Fig. 8).

In Ukraine, the equivalent to the Bobrikian corresponds to the *Uralodiscus rotundus – Paraarchaediscus* Zone (named as Cf9 zone by Poletaev *et al*. 1991), or $C_1^v d_2$ Horizon and the hiatus represented by the $C_1^v e_1$, although, the underlying $C_1^v d_1$ Horizon contains the first *Ammarchaediscus* (Poletaev *et al*. 2011). Thus, the Donets region seems to show a similar positioning of the Shukhonsky Substage as in parts of Russia, based on slightly evolved forms of archaediscids (Fig. 8).

Other regions are much more poorly studied, and thus, biozonations are not as detailed, such as in Uzbekistan, where the possible equivalent to the Bobrikian (upper part of the Pskem Substage) corresponds to the *Planoarchaediscus spirillinoides* Zone (Mikhno *et al*. 2007). In Kazakhstan, Gibshman (1997) first recorded an informal *Uralodiscus rotundus* – Planoarchaediscinae zone, although a more detailed subsequent study by Brenckle and Milkina (2003) recognized this zone as belonging to the Bobrikian Substage, in which these authors considered *Glomodiscus*, *Uralodiscus* and *Viseidiscus* as suitable markers.

In other countries a proper lithostratigraphical framework with regional substages has not been defined, and European biozonations and schemes are used, such as in Iran, where *Ammarchaediscus* first occurs together with the transitional forms in the lower 10 m of the succession assigned to the MFZ10, using the Belgian zonal scheme (Zandkarimi *et al*. 2017).

More distant regions are more difficult to correlate. In the type Mississippian succession in the USA, the Osagean-Meramecian boundary does not coincide with any regional substages in Europe, and it is interpreted that the base of the Keokuk

Limestone corresponds to the basal Visean (e.g., Wang *et al*. 2019). Certainly, primitive forms of archaediscids are recorded in the middle part of the Keokuk Limestone, *Viseidiscus* (possibly an *Ammarchaediscus*) (Lane and Brenckle, 2005), which suggest a potential level of correlation with the basal Arundian (Fig. 8). In addition, the first *Archaediscus* (as *Paraarchaediscus* sp.) are recorded in the lower Warsaw Formation, whereas the first forms with nodes (such as *Kasachstanodiscus* spp.) are recorded from the upper Warsaw Formation, which suggest a possible correlation with the Cf4γ and Cf4δ subzones in the upper Arundian (Fig. 8).

In contrast, in south China, the Tangbagouan-Jiusian boundary coincides with the basal Visean (Fig. 8), although the Jiusian Substage includes the early and mid Visean. Nevertheless, foraminiferal zonations in the region are closely comparable to the Belgian zonation, and defined as the basal *Eoparastaffella simplex* Zone (at the base of the Visean), and the *Viseidiscus monstratus* Zone (considered as an *Ammarchaediscus* by Hance *et al*. 2011), correlated with the MFZ10 from Belgium (Wang *et al*. 2019). This zone was previously named as *Viseidiscus/Ammarchaediscus* Zone by Hance *et al*. (2011). Thus, although it would be necessary to clarify which archaediscid genera first occurs, a similar subdivision to Western Europe seems to be the case, and the ability to distinguish the equivalent to the Arundian (Fig. 8).

Taking into consideration the above distributions of archaediscids in Western and Central Palaeotethys, it is unclear that the base of the Bobrikian Substage corresponds exactly with the base of the Arundian Substage in Britain and Ireland (as it is classically correlated). Rarely, the base of the Bobrikian has been correlated with the uppermost 'Chadian', possibly based on the first occurrence of Archaediscidae (e.g., Poletaev *et al*. 1991; Jones and Somerville 1996). The basal Bobrikian best corresponds to the first occurrence of primitive *Uralodiscus* (some metres above the first *Ammarchaediscus* and *Planoarchaediscus*), and thus, the top of the Radaevkian substage should be correlated with the lowest part of the Arundian (e.g., Makhlina 1996). In most regional successions, the difference in measured levels between the first occurrences of *Planoarchaediscus-Ammarchaediscus* and the primitive *Uralodiscus-Glomodiscus* are usually negligible (Fig. 8), whereas there is a substantial interval within which *U. rotundus* first occurs.

Nevertheless, the first occurrence of archaediscids is a rather consistent guide to establish global correlations, their main handicap is their rarity in samples. This rarity is a more pronounced problem in successions from China and U.S.A., where these earliest genera of Archaediscidae are mostly absent or first occur much later (e.g., Devuyst *et al*. 2003; Lane and Brenckle 2005; Hance *et al*. 2011; Liu *et al*. 2015).

A proposal to move the base of the Arundian

In consequence, the base of the Arundian Substage, as it is currently defined, is at a level which cannot be correlated with any precision both within Britain and Ireland or internationally, and there is no real benefit to retain it. Even in Britain and Ireland, many different ways of inferring correlation to the Arundian stratotype section in south Wales have been used (Fig. 7), which likely utilise rather different chronostratigraphic levels. The most pragmatic option is to fully adopt the proposal of Riley (1993), and use primarily biostratigraphic criteria, to define the base of the Arundian at options of:

- The first occurrence of *Ammarchaediscus* in Hobbyhorse Bay (16 m above the current base; also valid for the first *Planoarchaediscus*), to be coincident with the base of the Moliniacean Substage in Belgium, or

- Use the first occurrence of primitive *Glomodiscus/Uralodiscus* (at 17.5 m above the current base in Hobbyhorse Bay; Fig. 1). This makes it closely correlated to the base of the Bobrikian Substage of Russia and equivalents in Ukraine. A systematic revision of these forms may help to establish a more precise horizon, making the base of all the regional substages isochronous. Since although the first occurrences of *Planoarchaediscus*/*Ammarchaediscus* and *Glomodiscus*/*Uralodiscus* differ slightly in level these may relate to minor sampling issues.

Taking into account the record in Hobbyhorse Bay, it is better to select option 1 above, since it is a more robust Arundian base for the following reasons. 1) In successions in Britain and Ireland where the primitive *Glomodiscus*/*Uralodiscus* are only recorded, the real chronostratigraphic horizon will be located a close distance below, which is a much more precise approach than is currently used (Fig. 7). 2) The variable sequence stratigraphy and imprecise former boundaries recorded in south Cumbria, together with the faunal archaediscid succession support the relocation of the Arundian base to this more consistent boundary, based on biostratigraphy. 3) This archaediscid succession is like that recorded in Belgium, as well as in some regions from Britain and Ireland where high-resolution biostratigraphy is available (e.g., Ogmore, Galway). 4) To select the first occurrence of archaediscids avoids the problems in the distinct classification of some transitional forms, such as primitive *Uralodiscus* versus *Ammarchaediscus* and primitive *Glomodiscus* versus *Planoarchaediscus*.

The Hobbyhorse Bay stratotype also contains the first *Archaediscus* at *involutus* stage, 9 m above *Ammarchaediscus*, which is an important horizon to correlate rocks belonging to the overlying Cf4γ subzone in Britain. Unfortunately, at Bobby Horse Bay there is no record of *Uralodiscus rotundus*, which has been recorded by us more or less consistently close to and below the first *Archaediscus* at *involutus* stage elsewhere in south Cumbria, which would allow correlation with the base of the MFZ11 in Belgium. The rarity of some of the discussed genera and the poor availability of published data, makes it difficult to recognise this new base Arundian widely across Britain and Ireland. Many successions need to be revised and the Arundian base repositioned to coincide with the first occurrence of archaediscids, because these taxa are the only consistent guides to subdivide the early Visean in this sector of the Western Palaeotethys, These taxa allow a robust correlation with successions in Western and Central Palaeotethys, and potentially, possibilities to correlate with more distant basins in Eastern Palaeotethys and North America (Fig. 8). The foraminiferal succession recorded in Hobbyhorse Bay match perfectly with that in south Cumbria sections, where most of the highlighted levels and subzones defined for the Arundian are recognisable, allowing a much higher-resolution subdivision of the early Visean in these regions.

Conclusions

A detailed examination of the 'Chadian'-Arundian boundary at two regions in south Cumbria has allowed a revision of the foraminiferal biostratigraphy. This has highlighted the lack of a probable hiatus at this boundary, as previously suggested. This divergence of views is likely due to the rather more complex regional changes in the successions at around this boundary. A detailed sequence stratigraphy of the successions highlights that key foraminiferal first occurrences consistently relate to the transgressive and highstand parts of the system tracts. This may be useful for longer term inter-regional comparisons.

A review of how the 'Chadian'-Arundian boundary has been inferred in many studies in Britain and Ireland indicates much inconsistency in correlation to the Arundian stratotype, which in part relates to the gaps in our upstanding of the sequence stratigraphy of the Hobbyhorse Bay section, being in an outer-ramp setting. However, the current practical identification of the early Arundian is linked to using the first occurrence of archaediscids as the primary foraminiferal indicator for proximity to this boundary. We propose the current classical definition of the base of the Arundian should be abandoned in favour of a higher stratigraphic position, marked by the first occurrence of archaediscids, which was immediately followed by overlying primitive *Glomodiscus/Uralodiscus*. Adoption of this approach allows a clear and precise correlation to the regional Moliniacian Substage of Belgium and is nearly coincident with substage definitions in Russia and Ukraine, as well as possible correlation with similar records in North America and China.

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Captions

Fig. 1. British regional substages, including the mesothems defined by Ramsbottom (1973) (left column, D1c to N3), foraminiferal zones (Cf3 to Cf7) defined by Conil *et al*. (1980, 1989) and modifications introduced by Cózar *et al*. (2022a, 2023). The right margin of the figure shows the stratotypes (in black italics) defined by George *et al*. (1976) to separate the substages, and the most suitable sections (in blue) and positions for the substages (blue arrows) to obtain a better consensus with other international substages. The red arrow highlights the suggested change of position in the stratotypes. Time scale based on Aretz *et al*. (2020).

Fig. 2. Map of the 'Chadian'- lower Arundian outcrop in south Cumbria showing the outcrops of the Martin Limestone and Red Hill Limestone formations, with location in Britain marked in inset map in red. Based on Digimap data.
Geological Map Data BGS © UKRI 2024.

Fig. 3. Stratigraphic sections at Dunnerholme Point (see SM Fig. S3 for location of the sections). First occurrences of key foraminiferal taxa for the latest 'Chadian' and Arundian marked in purple and red. Transgressive surfaces TS3 and TS4 are inferred to be coeval with TS3 and TS4 at Meathop Fell. C.mud= clastic mudstone, M=mudstone, W=wackestone, P=packstone, G=grainstone, B/R/F= boundstone/rudstone/floatstone. Sample numbers (at arrows) are preceded by site code DP. MF Marsett Formation.

Fig. 4. Selected *Eostaffella* and *Eoparastaffella* first occurring below the Arundian base. (**a-c**) *Eostaffella* ex gr. *nalivkini*, A. MQ-70, B. MQ-70, C. DP-2. (**d-e**) *Eoparastaffella restricta*, D. MQ-76, E. DP-95. (**f**) *Eoparastaffella iniqua*, DP-71. (**g**) *Eoparastaffella simplex* evolved, DP-18.

Fig. 5. Selected primitive archaediscids. (**a**) *Planoarchaediscus* sp., a thin pseudofibrous layer is only observed in the two inner whorls (arrow), DP-90. (**b**) *Glomodiscus* sp. or *Planoarchaediscus* sp., DP-17. (**c**) *Planoarchaediscus* sp., a thin pseudofibrous layers is observed in the inner whorls (arrow), DP-96. (**d**) *Planoarchaediscus* sp., DP-17. (**e**) *Glomodiscus rigens*, DP-17. (**f**) *Ammarchaediscus* sp., a thin fibrous layer is observed only in the inner whorl (arrow), DP-90. (**g**) *Ammarchaediscus* sp., DP-17. (**h**) *Uralodiscus* sp. or *Ammarchaediscus* sp., DP-94. (**i**) *Uralodiscus* sp., DP-17. (**j**) *Uralodiscus* sp., SS-83, the pseudofibrous layer is only well observed in the side of the test (the specimen is micritized).

Fig. 6. Stratigraphic sections at Meathop Fell (see SM Fig. S2 for location of the sections). Legend and details as in Figure 3. The base of the Red Hill Limestone Fm in the Limegarth Wood and Sunnyside sections, is based on the correlation from the Meathop Quarry section.

Fig. 7. Revision of the main successions (all the included names are formations, except for some members) in Britain and Ireland (after Waters *et al*. 2011a with modifications herein) (see SM Fig. 1 for location of the successions). The upper two rows show the classical position of the Arundian base in the stratotype. Type explained in text. Change of background colours implies a change of formations. Hatching shows small hiatuses. Thick lines at the base of the Cf4β, Cf4γ or Cf4δ are the confirmed biostratigraphy (based on: B=brachiopod, F=foraminifera, C=coral). The confirmed Cf4δ biota is only highlighted when no older Arundian markers are known in the successions. Red squared boundaries are the selected base for the Arundian in the classical sense. A question mark is included in those successions where the boundary was not precisely located. When the Arundian base is coincident with a lithological change without any supporting biostratigraphy, this formational boundary is located artificially coinciding with the position of the Arundian base in the stratotype, although this could not be proved. Successions which include a large hiatus are not shown.

Fig. 8. Correlation of the main regional schemes for the substages in Britain including the foraminiferal zones defined by Conil *et al*. (1980, 1989) and modifications introduced by Cózar *et al*. (2022a, 2023), with the dashed line showing the approximate position of the 'Chadian'-Arundian boundary at Hobbyhorse Bay. Belgium column shows the foraminiferal zones defined by Poty *et al*. (2006) (MFZ6 to MFZ12). The East European Platform (EEP), W and E Urals of Russia columns based on Alekseev *et al*. (2022). The Donets column of Ukraine includes the horizons and is based on Poletaev *et al.* (2011), with D. = Donetsky. Illinois (USA) column shows the type Mississipian subdivisions in the Illinois Basin based on Lane and Brenckle (2005). South China column is based on Wang *et al*. (2019). *1 is the position where the *Planoarchaediscus/Ammarchaediscus* are used for regional subdivisions; *2 position where *Planodiscus/Uralodiscus* are used for regional subdivisions. Dotted lines are questionable levels of correlation.

Table 1. Summary of the classical Arundian base and markers in Britain (modified from Waters et al. 2011a).

Table 2. Summary of the classical Arundian base and markers in the Republic of Ireland (modified from Waters et al. 2011a).

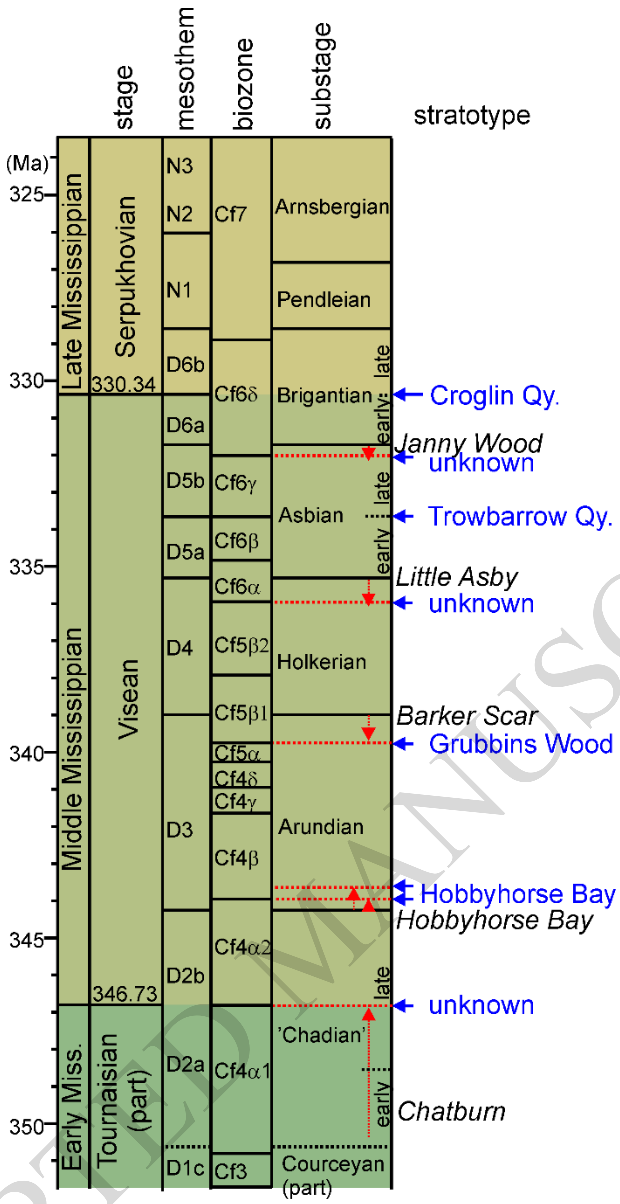
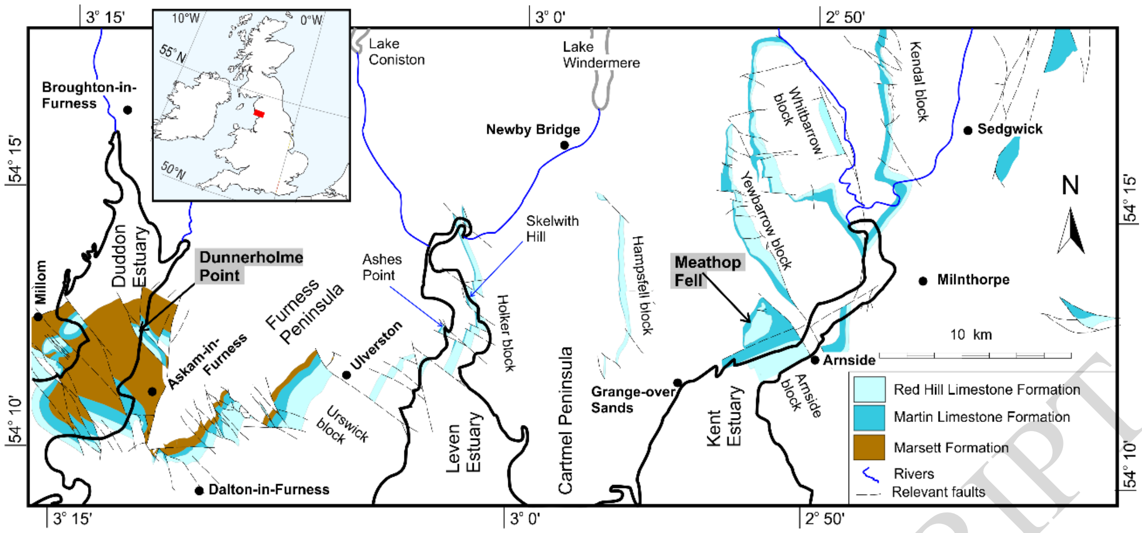
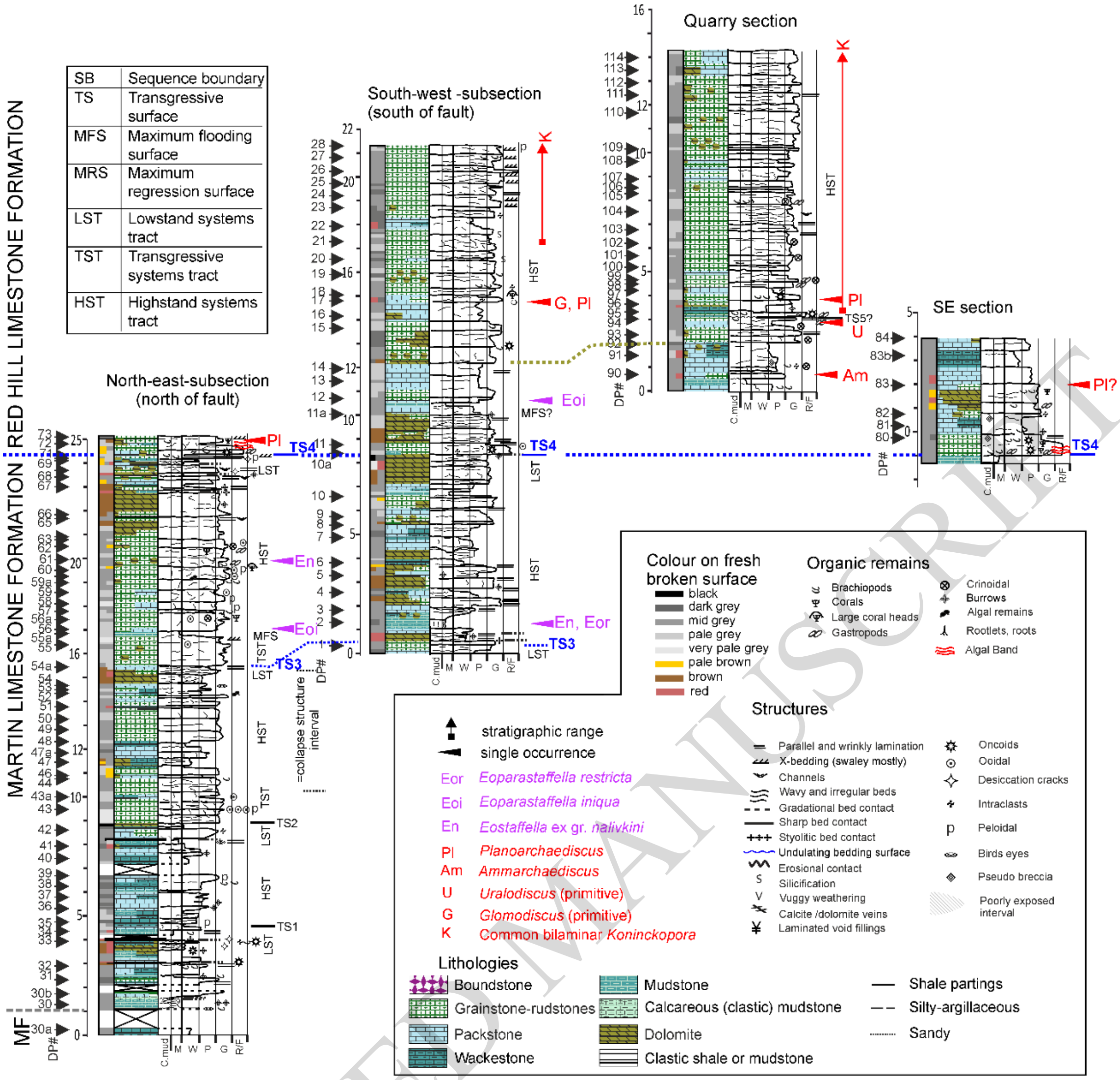

stage
mesothem
biozone
substage
stratotype
(Ma)
325
330
335
340
345
350
Late Mississippian
Middle Mississippian
Early Miss.
Serpukhovian
330.34
Visean
346.73
Tournaisian (part)
N3
N2
N1
D6b
D6a
D5b
D5a
D4
D3
D2b
D2a
D1c
Cf7
Cf6δ
Cf6γ
Cf6β
Cf6α
Cf5β2
Cf5β1
Cf5α
Cf4δ
Cf4γ
Cf4β
Cf4α2
Cf4α1
Cf3
Arnsbergian
Pendleian
Brigantian
late
early
Asbian
late
early
Holkerian
Arundian
late
'Chadian'
early
Courceyan (part)
Croglin Qy.
Janny Wood
unknown
Trowbarrow Qy.
Little Asby
unknown
Barker Scar
Grubbins Wood
Hobbyhorse Bay
Hobbyhorse Bay
unknown
Chatburn

Figure 1



3° 15'
3° 0'
2° 50'
54° 15'
54° 10'
10°W
0°W
55°N
50°N
Lake Coniston
Lake Windermere
Broughton-in-Furness
Newby Bridge
Sedgwick
Kendal block
Whitbarrow block
Yewbarrow block
Skelwith Hill
Ashes Point
Hampsfell block
Holker block
Meathop Fell
Milnthorpe
Duddon Estuary
Dunnerholme Point
Millom
Furness Peninsula
Ulverston
Askam-in-Furness
Urswick block
Dalton-in-Furness
Leven Estuary
Cartmel Peninsula
Grange-over Sands
Kent Estuary
Arnside block
Arnside
10 km
N
Red Hill Limestone Formation
Martin Limestone Formation
Marsett Formation
Rivers
Relevant faults

Figure 2



MARTIN LIMESTONE FORMATION RED HILL LIMESTONE FORMATION
SB Sequence boundary
TS Transgressive surface
MFS Maximum flooding surface
MRS Maximum regression surface
LST Lowstand systems tract
TST Transgressive systems tract
HST Highstand systems tract
North-east-subsection (north of fault)
South-west -subsection (south of fault)
Quarry section
SE section
TS1
TS2
TS3
TS4
TS5?
MFS
MFS?
LST
TST
HST
MF
DP#
C.mud M W P G R/F
=collapse structure interval
Pl
Pl?
En
Eoi
En, Eor
G, Pl
Am
U
K
Colour on fresh broken surface
black
dark grey
mid grey
pale grey
very pale grey
pale brown
brown
red
Organic remains
Brachiopods
Corals
Large coral heads
Gastropods
Crinoidal
Burrows
Algal remains
Rootlets, roots
Algal Band
Structures
stratigraphic range
single occurrence
Eor Eoparastaffella restricta
Eoi Eoparastaffella iniqua
En Eostaffella ex gr. nalivkini
Pl Planoarchaediscus
Am Ammarchaediscus
U Uralodiscus (primitive)
G Glomodiscus (primitive)
K Common bilaminar Koninckopora
Parallel and wrinkly lamination
X-bedding (swaley mostly)
Channels
Wavy and irregular beds
Gradational bed contact
Sharp bed contact
Styolitic bed contact
Undulating bedding surface
Erosional contact
Silicification
Vuggy weathering
Calcite /dolomite veins
Laminated void fillings
Oncoids
Ooidal
Desiccation cracks
Intraclasts
Peloidal
Birds eyes
Pseudo breccia
Poorly exposed interval
Lithologies
Boundstone
Grainstone-rudstones
Packstone
Wackestone
Mudstone
Calcareous (clastic) mudstone
Dolomite
Clastic shale or mudstone
Shale partings
Silty-argillaceous
Sandy

Figure 3

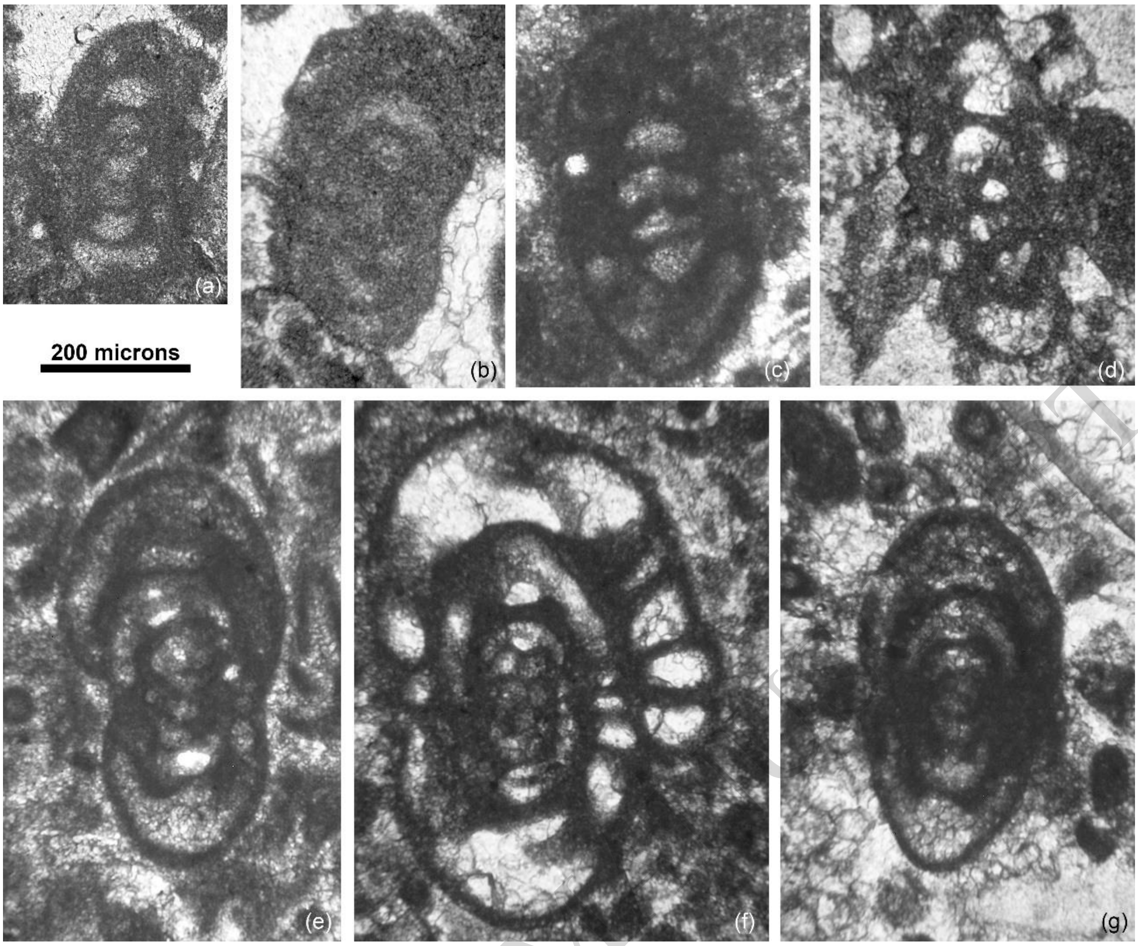


Figure 4

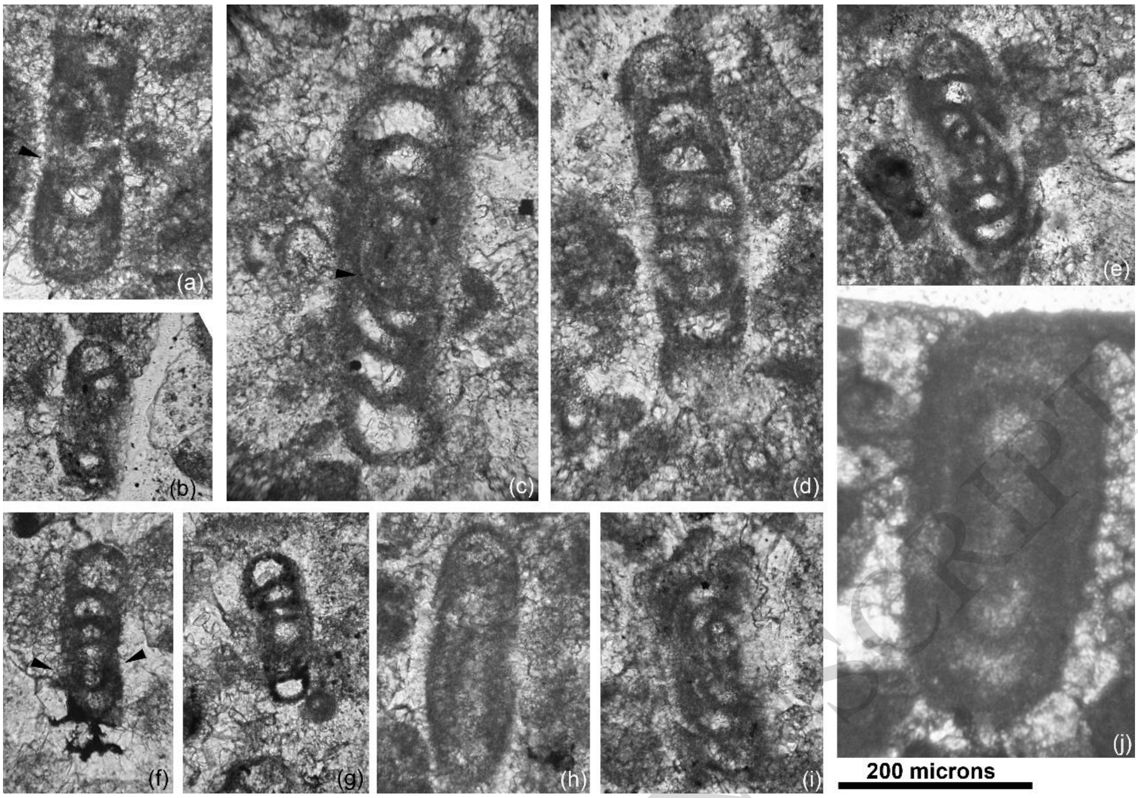
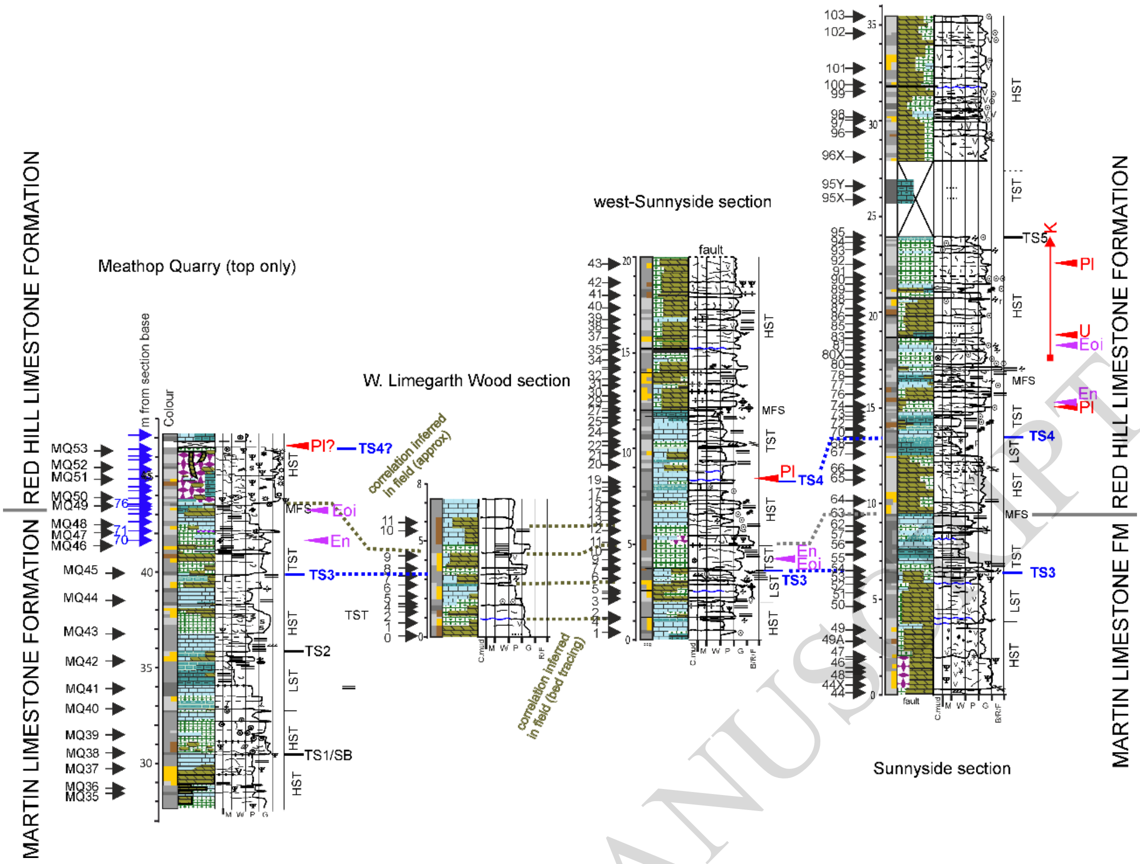


Figure 5



Meathop Quarry (top only)
W. Limegarth Wood section
west-Sunnyside section
Sunnyside section
RED HILL LIMESTONE FORMATION
MARTIN LIMESTONE FORMATION
MARTIN LIMESTONE FM
correlation inferred in field (approx)
correlation inferred in field (bed tracing)
m from section base
Colour
fault
TS1/SB
TS2
TS3
TS4?
TS4
TS5
MFS
HST
TST
LST
Pl?
Pl
Eoi
En
U
K

Figure 6

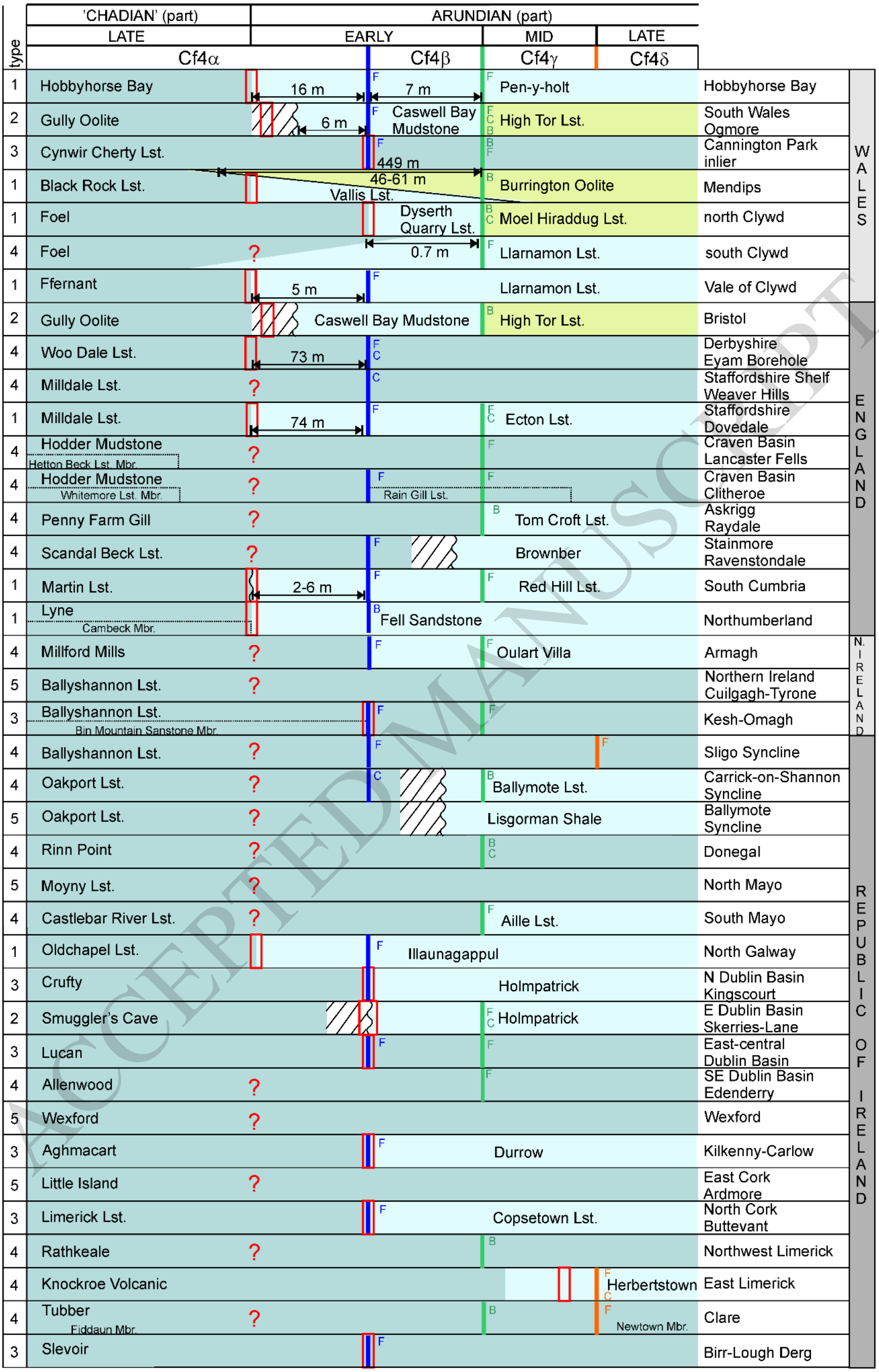

'CHADIAN' (part)
ARUNDIAN (part)
LATE
EARLY
MID
LATE
type
Cf4α
Cf4β
Cf4γ
Cf4δ
1 Hobbyhorse Bay 16 m 7 m Pen-y-holt Hobbyhorse Bay
2 Gully Oolite 6 m Caswell Bay Mudstone High Tor Lst. South Wales Ogmore
3 Cynwir Cherty Lst. 449 m Cannington Park inlier
1 Black Rock Lst. 46-61 m Vallis Lst. Burrington Oolite Mendips
1 Foel Dyserth Quarry Lst. Moel Hiraddug Lst. north Clywd
4 Foel 0.7 m Llarnamon Lst. south Clywd
1 Ffernant 5 m Llarnamon Lst. Vale of Clywd
2 Gully Oolite Caswell Bay Mudstone High Tor Lst. Bristol
4 Woo Dale Lst. 73 m Derbyshire Eyam Borehole
4 Milldale Lst. Staffordshire Shelf Weaver Hills
1 Milldale Lst. 74 m Ecton Lst. Staffordshire Dovedale
4 Hodder Mudstone Hetton Beck Lst. Mbr. Craven Basin Lancaster Fells
4 Hodder Mudstone Whitemore Lst. Mbr. Rain Gill Lst. Craven Basin Clitheroe
4 Penny Farm Gill Tom Croft Lst. Askrigg Raydale
4 Scandal Beck Lst. Brownber Stainmore Ravenstondale
1 Martin Lst. 2-6 m Red Hill Lst. South Cumbria
1 Lyne Cambeck Mbr. Fell Sandstone Northumberland
4 Millford Mills Oulart Villa Armagh
5 Ballyshannon Lst. Northern Ireland Cuilgagh-Tyrone
3 Ballyshannon Lst. Bin Mountain Sanstone Mbr. Kesh-Omagh
4 Ballyshannon Lst. Sligo Syncline
4 Oakport Lst. Ballymote Lst. Carrick-on-Shannon Syncline
5 Oakport Lst. Lisgorman Shale Ballymote Syncline
4 Rinn Point Donegal
5 Moyny Lst. North Mayo
4 Castlebar River Lst. Aille Lst. South Mayo
1 Oldchapel Lst. Illaunagappul North Galway
3 Crufty Holmpatrick N Dublin Basin Kingscourt
2 Smuggler's Cave Holmpatrick E Dublin Basin Skerries-Lane
3 Lucan East-central Dublin Basin
4 Allenwood SE Dublin Basin Edenderry
5 Wexford Wexford
3 Aghmacart Durrow Kilkenny-Carlow
5 Little Island East Cork Ardmore
3 Limerick Lst. Copsetown Lst. North Cork Buttevant
4 Rathkeale Northwest Limerick
4 Knockroe Volcanic Herbertstown East Limerick
4 Tubber Fiddaun Mbr. Newtown Mbr. Clare
3 Slevoir Birr-Lough Derg
WALES
ENGLAND
N. IRELAND
REPUBLIC OF IRELAND

Figure 7

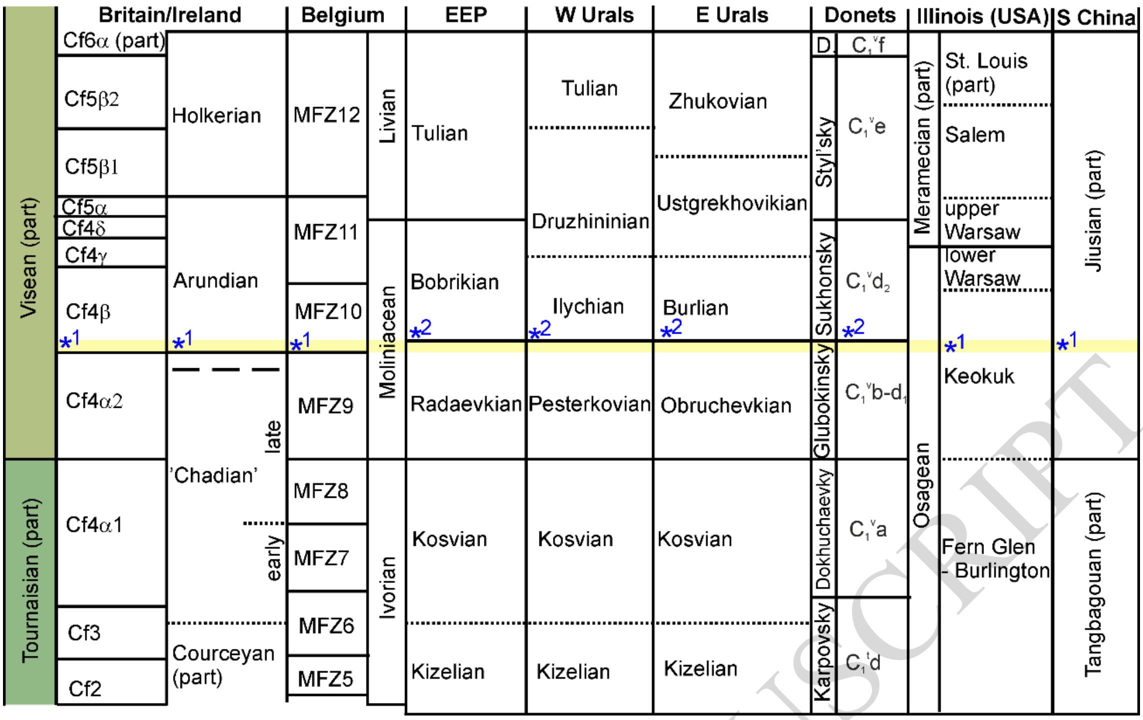

Britain/Ireland
Belgium
EEP
W Urals
E Urals
Donets
Illinois (USA)
S China
Visean (part)
Tournaisian (part)
Cf6α (part)
Cf5β2
Cf5β1
Cf5α
Cf4δ
Cf4γ
Cf4β
Cf4α2
Cf4α1
Cf3
Cf2
Holkerian
Arundian
late
'Chadian'
early
Courceyan (part)
MFZ12
MFZ11
MFZ10
MFZ9
MFZ8
MFZ7
MFZ6
MFZ5
Livian
Moliniacean
Ivorian
Tulian
Bobrikian
Radaevkian
Kosvian
Kizelian
Tulian
Druzhininian
Ilychian
Pesterkovian
Kosvian
Kizelian
Zhukovian
Ustgrekhovikian
Burlian
Obruchevkian
Kosvian
Kizelian
D
Styl'sky
Sukhonsky
Glubokinsky
Dokhuchaevky
Karpovsky
Meramecian (part)
Osagean
St. Louis (part)
Salem
upper Warsaw
lower Warsaw
Keokuk
Fern Glen - Burlington
Jiusian (part)
Tangbagouan (part)
*1
*2

Figure 8

Table 1. *Summary of the classical Arundian base in continuous successions and markers in Britain (modified from Waters et al., 2011a)*

Locality	**Arundian base**	**biostratigraphic point**	**subzone**	**markers**	**type**	**source**
Hobbyhorse	base Pen-y-holt	16 m above base Pen-y-holt	Cf4β foraminifers	*Ammarchaediscus*	1	Ramsbottom (1981; Simpson and Kalvoda (1987)
south Wales/Bristol	base Caswell Bay Mudstone	base High Tor Lst.	Cf4γ foraminifers + mid Arundian brachiopods	*Archaediscus, Delipinea carinata*	2	Waters and Lawrence (1983)
south Wales	base Caswell Bay Mudstone	base High Tor Lst.	Cf4β foraminifers	*Glomodiscus, Uralodiscus*	2	Kalvoda et al. (2012)
Ogmore	base Caswell Bay Mudstone	midde part Caswell Bay Mudstone	Cf4β foraminifers	*Planoarchaediscus, Ammarchaediscus, Glomodiscus, Uralodiscus*	2	Kalvoda et al. (2014)
Cannington Park Inlier	at 449 m in the Cynwir Cherty Lst.	at 449 m in the Cynwir Cherty Lst.	Cf4β foraminifers	*Ammarchaediscus, Glomodiscus*	3	Mitchell et al. (1982)
Mendips	base Burrington Oolite	46-61 m above Burrington base	Cf4γ brachiopods	*Delepinea carinata*	1	Whitaker and Green (1983)
north Clwyd	base Dyserth Quarry Lst.	base Moel Hiraddug Lst.	mid Arundian corals, brachiopods	*Koninckophyllum carlyanense, Michelinia* cf. *tenuisepta, Delepinea carinata*	1	Somerville et al. (1986)
Vale of Clwyd	base Llanarmon Lst.	5 m above base Llanarmon Lst.	Cf4β foraminifers	*Uralodiscus*	1	Davies et al. (1989)
south Clwyd	base Llanarmon Lst.	0,7 m above base Llanarmon Lst.	Cf4γ foraminifers	*Archaediscus*	4	Davies et al. (2004)
Derbyshire	middle Woo Dale Lst.	1240, 1216 m	early Arundian corals, Cf4β foraminifers	*Haplolasma subibicina, Uralodiscus, Glomodiscus*	4	Strank (1985)
Stafforshire shelf	middle Milldale Lst.	knoll-reef facies	early Arundian corals	*Clisiophyllum multiseptatum*	4	Aitkenhead et al. (1985)
Dovedale	base Ecton Lst.	74 above base Ecton Lst.	Cf4β foraminifers	*Uralodiscus*	1	Aitkenhead et al. (1985)
Lancaster Fells	top Hetton Beck Lst. Mbr.	168.9 m, SD65/SW25 Bh.	Cf4γ foraminifers	*Archaediscus*	4	Brandon et al. (1988)
Clitheroe	top Phynis Mudstone Mbr., or between Whitemore Lst. and Rain Gill Lst. Members	9 m above base Embsay Lst. In Skipton	Cf4β foraminifers	*Planoarchaediscus, Ammarchaediscus, Glomodiscus, Uralodiscus*	4	Riley (1990)
Raydale Bh.	base Tom Croft Lst.	base Tom Crotf Lst.	mid Arundian brachiopods	*Delepinea carinata*	4	Dunham and Wilson (1985)
Ravenstondale Bh.	base middle Scandal Beck Lst.	top Scandal Beck Lst.	Cf4β foraminifers	archaediscids	4	George et al. (1976)
south Cumbria	base Red Hill Lst.	2-5 m above base Red Hill Lst.	Cf4β foraminifers	*Planoarchaediscus, Ammarchaediscus, Glomodiscus, Uralodiscus*	1	this work, Jonhson et al. (2001)
Northumberland	base Fell Sandstone	base Fell Sandstone	early Arundian brachiopods	*Rugosochonetes cumbriensis*	1	Day (1970)
Cuilcagh to Tyrone	middle Ballyshanon Lst.		no biostratigraphic support		5	Legg et al. (1998)
Kesh-Omag	top Bin Mountain Sandstone	top Bin Mountain Sandstone	Cf4β foraminifers	*Planoarchaediscus, Glomodiscus, Uralodiscus*	3	Mitchell (2004)
Armagh	upper Milford Mills	base Oulart Villa	Cf4β foraminifers	*Viseidiscus, Glomodiscus*	4	Somerville et al. (2001)

Table 2. *Summary of the classical Arundian base in continuous successions and markers in the Republic of Ireland (modified from Waters et al., 2011a)*

Locality	Arundian base	biostratigraphic point	subzone	markers	type	source
Sligo	middle Ballyshanon Lst.	middle Ballyshanon Lst.	Cf4β foraminifers	*Uralodiscus*	4	George et al. (1976)
Carrick-on-Shannon	middle Oakport Lst.	5 m below Oakport Lst.	early Arundian corals	phacelloids colonies	4	Macdermot et al. (1996)
Ballymote	middle Oakport Lst.		No biostratigraphic support		5	Macdermot et al. (1996)
Donegal	middle Rinn Point	35 m above base Rinn Point	early Arundian corals	*Lithostrotion*	4	Hubbar and Pocock (1972)
North Mayo	middle Moyny		No biostratigraphic support		5	Graham (1996)
South Mayo	middle Castlebar River	base Aille Limestone	mid Arundian foraminifers	"foraminifers"	4	Long et al. (2004)
North Galway	base Illuanagappul	20 m above base Illaunagappul	Cf4β foraminifers	*Uralodiscus*	1	Zandkarimi et al. (2024)
Kingscourt	base Holmpatrick	base Holmpatrick	Cf4β foraminifers	*Glomodiscus, Planoarchaediscus, Uralodiscus*	3	Nolan (1986)
Skerries-Lane	base Holmpatrick	base Holmpatrick	Arundian corals	*Clisiophyllum multiseptatum, Haplolasma subibicinum, Siphonodendron martini*	2	Somerville and Waters (2011)
Dublin Basin	middle Lucan	middle Lucan	Cf4β foraminifers	*Planoarchaediscus, Glomodiscus*	3	Strogen et al. (1990)
Edenderry	middle Allenwood	upper part Allenwood	Cf4γ foraminifers	*Uralodiscus, Archaediscus*	4	Gatley et al. (2005)
Wexford	middle Wexford		No biostratigraphic support		5	Nagy et al. (2005)
Kilkenny-Carlow	base Durrow	base Durrow (at 468 m)	Cf4β foraminifers	*Glomodiscus, Uralodiscus*	3	Nagy (2003)
Ardmore	middle Little Island				5	Sleeman and McConnell (1995)
Buttevant	base Copsetown	close to the base Copsetown	Cf4β foraminifers	"foraminifers"	3	Clipstone (1992)
NW Limerick	middle Rathkeale	mid Rathkeale	mid Arundian brachiopods, conodonts	*Delepinea carinata, Lochriea commutata*	4	Somerville and Strogen (1992), Austin et al. (1970)
E Limerick	close to base Herbertstown	Cf4δ foraminifers, late Arundian corals	close to base Herbertstown	*Archaediscus, Siphonodendron sociale*	4	Somerville et al. (1992)
Clare	middle Fiddaun Mbr.	upper Fiddaun Mbr.	mid Arundian brachiopods	*Delepinea carinata*	4	Sevastopulo and MacDermot (1991)
Birr-Lough Derg	middle Slevoir	middle Slevoir	Cf4β foraminifers	*Uralodiscus*	3	Gatley et al. (2005)

Journal of Geological Society
Supporting Material for

Relocate the base of the Arundian?: a re-evaluation from south Cumbrian sections and implications for British and Irish Lower Carboniferous successions

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The supporting materials contain the following.

1. Details of the recognition of the base of the Arundian in Britain and Ireland (Section 1 and Fig. S1, Table S1)
2. Details of the sections at Meathop Fell (Figs. S2, S3, Table S2)
3. Details of the sections at Dunnerholme Point (Figs S4, S5, Table S2)

1. Details of the recognition of the Arundian in Britain and Ireland

The ‘Chadian’-Arundian boundary is recorded in many regions of England, Wales, Northern Ireland and the Republic of Ireland (Fig. S1), although it is not present in Scotland. Most of the data were summarized in the compilation by Waters et al. (2011a) and biota markers for Britain described by Riley (1993a). Details of the biota used as guides for the recognition of the zones and subzones in each succession are included in Tables 1 and 2 in the main text.

Fig. S1. Localities mentioned in the text from Britain and Ireland.

1.1 Foraminiferal subdivisions of the Arundian

Within the foraminifers, five foraminiferal subzones were included in the classical sense of the Arundian, the top of Cf4α2, Cf4β, Cf4γ, Cf4δ (Conil et al. 1980, 1991) and the Cf5α and lower part of Cf5β1 (Cózar et al., 2020, 2023a) (main text Fig. 1). More recently, the Cf4δ has been also subdivided in lower, middle and upper foraminiferal assemblages (Cózar et al., 2023b), although the isochronous character of these assemblages needs to be tested in other regions. These subzones and assemblages can be informally grouped as the classical early Arundian (top Cf4γ2 and Cf4β), mid Arundian (Cf4γ) and late Arundian (Cf4δ-Cf5α). A similar subdivision into early, mid and late Arundian was recognised in brachiopods and rugose corals (Riley, 1993a) or zones B, C and D of Mitchell (1989); subdivisions that are approximately coeval with those in the foraminifers. The lower Cf5β1 is now part of the Holkerian following the proposal of a new Holkerian stratotype (Cózar et al., 2023a).

1.2 Wales

Other regions in South Wales, apart from Hobbyhorse Bay, include the classical Gully Oolite, Caswell Bay Mudstone and High Tor Limestone succession of Tenby and the Gower peninsula. Traditionally, the High Tor Limestone contains foraminiferal assemblages of the Cf4γ (e.g., Waters and Lawrence, 1987), whereas the Gully oolite contains 'Chadian' foraminifers (e.g., Conil and George, 1973). Using sequence stratigraphy criteria, the base of the Caswell Bay Mudstone and its underlying sequence boundary, was assigned to the base Arundian. More recently, Kalvoda et al. (2012) recognised that the upper part of the Gully Oolite contains Viséan foraminifers of the MFZ9, and Kalvoda et al. (2014) recognized the MFZ11 in the High Tor Limestone, whereas the first archaediscids occur in the upper half of the Caswell Bay Mudstone, so justifying assignment of the base of the Caswell Bay Mudstone as the classical base Arundian.

In north Wales, in the north Clwyd region, Somerville et al. (1986) assigned the base of the Arundian to the Dyserth Quarry Limestone Formation, whereas the overlying Moel Hiraddug Limestone Formation (at least), contains mid Arundian corals. Thus, here, the Arundian boundary was selected at the lithological change below the Arundian corals. In the south Clwyd region, Davies et al. (1989) recorded primitive *Uralodiscus* 5 m above the base of the Llarnamon Limestone Formation. They interpreted that the base of the Llarnamon Limestone was a transgressive event, and thus, they used this event below the first archaediscids to locate the base of the Arundian. In the Vale of Clwyd, the situation might be a diachronous boundary (see Davies et al., 2011), because in some sections the situation is similar to that in south Clwyd, with a basal part containing only ‘Chadian’ foraminifers, whereas at the River Clywedog section, foraminifers of the Cf4γ subzone occur 0.7 m above the base of the formation (Davies et al., 2004).

1.3 England

Sections closer to Bristol, are similar to most parts of south Wales, where there is a disconformity below the Castwell Bay Mudstone Formation, and thus, the transition is not in a continuous succession.

In the Cannington Park inlier (close to the Mendips), the basal Arundian occurs within the continuous succession of the Cynwir Cherty Limestone, and thus, there is no lithological change, nor sequence stratigraphy defined. The ‘Chadian’ (485-449.5 m in the Knap Farm Borehole) was based on the record of the conodont *Gnathodus homopunctatus*, whereas the Arundian (449.5-7.57 m) was based on the first archaediscids. In addition, Mitchell et al. (1982) also recorded in this interval mid Arundian brachiopods. The base of the Arundian however, is ambiguous, because these authors only documented it in the interval between 449.5 and 417 m, where the first archaediscids occur, but the assemblage includes genera of the Arundian Cf4β and taxa of the Cf4γ subzones. It is not clear in this study if all the taxa occur together from the base (in which case, the horizon at 449.5 m would represent the base of the mid Arundian), nor which genera occur first. The authors located the base of the Arundian at the first occurrence of archaediscids.

In the Mendips, the situation is more complicated, because the formations are diachronous, and the base of the Arundian is inferred by the occurrence of mid Arundian brachiopods in the upper part of the Vallis Limestone (Black Rock Limestone subgroup) and Burrington Oolite Subgroup (Whittaker and Green, 1983; Kellaway and Welch, 1993) with a Courceyan-‘Chadian’ dating of the Black Rock Limestone Subgroup.

In Derbyshire, the Arundian interval is included in the Woo Dale Limestone Formation, and the base follows biostratigraphic criteria. The base of the Arundian, at 1313.38 m in the Eyam Borehole, seems to have been defined based on the absence of archaediscids and *Koninckopora* (Strank, 1985), although the first *Uralodiscus* and *Glomodiscus* were recorded at 1216 m. Below, at 1240 m, she recorded the coral *Haplolasma subibicina* (at 1240 m), which was considered originally as an Arundian marker (Mitchell, 1989). Thus, there is no lithological change at the base of the Arundian, and it is difficult to understand why the base Arundian is located nearly 100 m below the record of the first archaediscid and Arundian corals.

In Staffordshire, early Arundian corals (Aitkenhead et al., 1985) are recorded in the knoll-reef facies of the Milldale Limestone Formation, but, it is a continuous formation from the Courceyan to the late Holkerian, and the base of the Arundian is inferred, but the horizon was not precisely established. Further south, at Dovedale, the Milldale Limestone Formation passes into the Ecton Limestone Formation, which is considered as the base of the early Arundian. However, the corals and foraminiferal assemblages described from the lower 74 m levels are only representative of the late 'Chadian', whereas the first archaediscids are recorded from the overlying 18 m of limestones (Aitkenhead et al., 1985). The first important lithological change is at 74 m, with shales. Assuming a scenario similar to the Caswell Bay Mudstone in south Wales, maybe a transgressive event could be located at 60 m above the base of the formation.

In the Craven Basin, the base of the Arundian was located in the Hodder Mudstone Formation, between assemblages of the Cf4α2 and Cf4γ at Lancaster Fells (Brandon et al., 1988), and the Arundian base is inferred at the change into the basal Hetton Beck Limestone Member. In Clitheroe, the Arundian base is located above hemipelagic mudstones of the Phynis Mudstone Member of the Hodder Mudstone Formation. In this region, Riley (1990) published a detailed analysis of the biota in the succession, including the foraminiferal markers for the Cf4α2 to lower Cf5 subzones within the Hodder Mudstone Formation. Thus, a lithological change below the Arundian fauna was selected as the boundary. In other regions in the Craven Basin (e.g. at Skipton), after a hiatus, the succession starts directly with Arundian biota (Riley, 1990, 1993b).

In South Askrigg, in the Silverdale Borehole, the Chapel House Limestone Formation contains late Arundian foraminifers (Cf4δ) (Waters et al., 2017), and below, there is a large hiatus with the underlying Courceyan age Stockdale Farm Formation.

In North Askrigg, e.g., Raydale Borehole, the biostratigraphy for the lower part of the succession is based on macrofauna (e.g., Dunham and Wilson, 1985), and the boundaries in this region classically coincide with formational boundaries (lithological changes). The most significant data are recorded in the Tom Croft Limestone Formation, where mid Arundian brachiopods occur. The underlying Penny Farm Gill Formation was attributed to the 'Chadian' to Arundian due to the occurrence of the Pu miospore Zone. However, Waters et al. (2011b) questioned this biostratigraphy, and reinterpreted the miospore assemblage as representative of the Arundian-Holkerian interval. These authors questioned if the base of the Arundian should be located within the Penny Farm Gill Formation, but they do not suggest any precise level.

In the Stainmore Trough- Ravenstonedale area, the lower part of the succession between the late 'Chadian' and Arundian contain two hiatuses. The Arundian base can be located within the Scandal Beck Limestone, where George et al. (1976) recorded archaediscids in its upper part.

There are few relevant biostratigraphic data in the lower part of the succession in the Northumberland Trough, and the base of the Arundian is mostly inferred to occur at the base of the Fell Sandstone Formation due to the presence of the brachiopod *Rugosochonetes cumbriensis* (Day, 1970). However, within the brachiopod assemblage, is *Punctospirifer scabricosta*, which is generally regarded as an Asbian brachiopod (Riley, 1993a). The underlying Cambeck Member at the top of the Lyne Formation, contains a brachiopod-coral assemblage typical of the late 'Chadian'-early Arundian (Day, 1970). Thus, the base of the Arundian is rather questionable in Northumberland, and although it is widely accepted at the base of the Fell Sandstone Formation, it could also lie in the Cambeck Member. In both cases, the Arundian base would mark important lithological changes below the first occurrence of Arundian biota.

1.4 Northern Ireland

In Northern Ireland, in counties Fermanagh and Tyrone, the Arundian base is included within the Ballyshannon Limestone Formation, which is informally subdivided into lower and middle members with a 'Chadian' microfauna, and an upper member with mid Arundian foraminifers (Legg et al., 1998), but a precise horizon for the base of the Arundian was not determined. In the Kesh-Omagh region, the succession is slightly different with a thinner Ballyshannon Limestone Formation passing laterally to the Bin Mountains Sandstone Formation. At the base of the Ballyshannon Limestone Formation are late 'Chadian' foraminifers, whereas foraminifers of the Cf4β and Cf4γ are recorded higher up (Mitchell, 2004). Thus, the boundary is simply biostratigraphic in the middle of the formation. In County Armagh, the Arundian base is located within the Milford Mill Formation, which contains the Pu miospore Zone at the base, whereas the overlying Oulart Villa Limestone Formation contains early to mid Arundian foraminifers from its base (Somerville et al., 2001). Thus, the Arundian base is a biostratigraphically inferred position.

1.5 Republic of Ireland

In the northwest Irish Lough Allen Basin, in the Sligo syncline, the Ballyshannon Limestone Formation is also recorded, with late 'Chadian' algae in the lower part the formation (MacDermot et al., 1983) and late Arundian foraminifers near the top (MacDermot et al., 1996), although George et al. (1976) documented *Uralodiscus* from the middle part of the formation. Thus, the Arundian base is inferred between both assemblages, but not at any precise level. In the Carrick-on-Shannon and Ballymote synclines, the Arundian base was located within the upper part of the Oakport Limestone Formation which shows evidence of a palaeokarst at the top. Early Viséan ('Chadian') corals were recorded by Caldwell (1959) in the middle part of the formation, whereas in the upper 5 m of the formation (below the palaeokarst), MacDermot et al. (1996) recorded Arundian corals, and thus, the Arundian base was inferred below this horizon. In Donegal, the Arundian base is located within the Rinn Point Formation due to the record of mid Arundian brachiopods and Arundian corals in its upper part (Hubbard and Pocock, 1972; Sevastopulo and Wyse Jackson, 2009). This formation is considered as laterally equivalent to the Moyny Limestone Formation in the coastal region of north County Mayo (Somerville and Waters, 2011a), whereas Sevastopulo and Wyse Jackson (2009), inferred the base of the Arundian would lie within the Moyny Limestone. However, there is no supporting biostratigraphy to test the possible Arundian base, only late Arundian miospores and foraminifers in the overlying Mullaghmore Sandstone Formation (Graham, 1996).

In south County Mayo, the Arundian base is located within the upper part of the Castlebar River Limestone Formation (Somerville and Waters, 2011b), although there is only indirect biostratigraphic evidence provided by the presence of mid Arundian foraminifers from the overlying Aille Limestone Formation (Long et al., 2004). In north Galway, the Arundian base is located in the upper part of Oldchapel Limestone Formation (Somerville and Waters, 2011b), due to the occurrence of late 'Chadian' (Cf4α2) foraminifers in the underlying Cregg Limestone Formation (Long et al., 2004) and late Arundian foraminifers from the lower levels of the Illaunagappul Formation (Long et al., 2004; Pracht et al., 2004). These formations are currently under investigation (Zandkarimi et al., 2024), which suggests that the base of the Arundian might be situated at the base of the Illaunagappul Formation.

In the north of the Dublin Basin, the Arundian base is located between the Crufty and Holmpatrick formations or the Smuggler's Cave and Holmpatrick formations because the Crufty Formation contains foraminifers and corals of the early Viséan (Pickard et al., 1992; Somerville et al., 1992a; Somerville 1994), whereas the Holmpatrick Formation contains common mid and late Arundian corals and foraminifers (Pickard et al., 1992; Gatley et al., 2005). Nevertheless, primitive archaediscids were recorded at the base of the Holmpatric Formation in the type region (Nolan, 1986), as well as from the top of the Crufty Formation (Rees, 1987), and thus, the Arundian base should be located within the Crufty Formation. In most parts of the basin, the Arundian base is located within the Lucan Formation, which contains numerous outcrops with late 'Chadian' to Asbian foraminiferal zones, including detailed foraminiferal subzones Cf4α2 and Cf4β which provide outstanding biostratigraphic precision of the boundary (Mamet, 1969; Strogen et al., 1990, 1996; Somerville et al., 1992a, 1996; Morris et al., 2003). In the southeast of the basin, the lateral equivalent is the Allenwood Formation, where the Arundian boundary is located between late 'Chadian' and late Arundian foraminifers (Gatley et al., 2005).

In south-central Ireland, there are two types of positioning for the base of the Arundian, within intermediate positions of long-ranging formations and at formation boundaries based on biostratigraphy. Within the long-ranging formations, in Co. Wexford, the interval is represented by the Wexford Formation, the base of the Arundian is located in an intermediate position, at the base of the 'Lime Mudstone and Dolomite Unit' due to the occurrence of bilaminar *Koninckopora* (a fact that could be questioned because these forms are first recorded from the 'Chadian'), whereas in the upper 'Skeletal Limestone Unit', there are foraminifers of Holkerian and Asbian age (Nagy et al., 2005). The closest confirmed biostratigraphy is recorded from the underlying Ballysteen Formation, with late Courceyan spores and conodonts. Thus, the boundary is rather imprecise. In East Co. Cork, the Arundian interval occurs within the Little Island Formation, which is inferred to range from the late 'Chadian' to the Asbian (Sleeman and McConnell, 1995), but there is no supporting biostratigraphy. In Co Clare, the Arundian base is located between the first occurrence of *Eoparastaffella simplex* (Cf4α2, in the lower part of the Fiddaun Member; Pracht et al., 2004) and the brachiopod *Delepinea carinata* and archaediscid foraminifers (in the upper part of the Fiddaun Member; Sevastopulo and MacDermot, 1991), within the Tubber Formation. In northwest Co. Limerick, the Arundian base is located within the Rathkeale Formation, between 'Chadian'-Arundian conodonts at the base of the formation (Austin et al., 1970) and mid Arundian brachiopods higher up in the formation (Somerville and Strogen, 1992). In Birr-Lough and Derg, the Arundian base is located between the Cf4α2 foraminifers and corals, and Cf4β foraminifers within the Slevoir Formation (Gatley et al., 2005).

On the other hand, localities where a formational boundary was selected are recorded in North Co. Cork, where the Arundian base is located between the Limerick Limestone and Copsetown Limestone formations due to the occurrence of archaediscids close to the base, as well as rich brachiopods and corals (Hudson and Philcox, 1965; Clipstone, 1992). In counties Kilkenny and Carlow, the Arundian base is located between the Aghmacart and Durrow formations, because the latter contains early Arundian foraminifers from the base (Nagy, 2003; Gatley et al., 2005). In East Limerick, the base of the Arundian is located at the base of the Herbertstown Limestone Formation due to the occurrence of late Arundian corals and foraminifers (Somerville et al., 1992b). This implies that probably, the real Arundian base should be located within the underlying Knockroe Volcanic Formation.

Section 2. Details of studied section in South Cumbria

Sections	Latitude	Longitude
NE Dunnerholme Point	N54º12’30.5’’	W3º12’38’’
SW Dunnerholme Point	N54º12’28.5’’	W3º12’42.5’’
Quarry at Dunnerholme Point	N54º12’27.6’’	W3º12’38.5’’
SE Dunnerholme Point	N54º12’23.6’’	W3º12’32.3’’
Meathop Quarry	N54º12’18’’	W2º52’21’’
West Limegarth Wood	N54º12’18.5’’	W2º52’6.6’’
West Sunnyside	N54º12’21.2’’	W2º51’56.8’’
East Sunnyside	N54º12’30.2’’	W2º51’31.6’’

Table S1. Geographic coordinates (Google Earth locations) of the studied sections in South Cumbria.

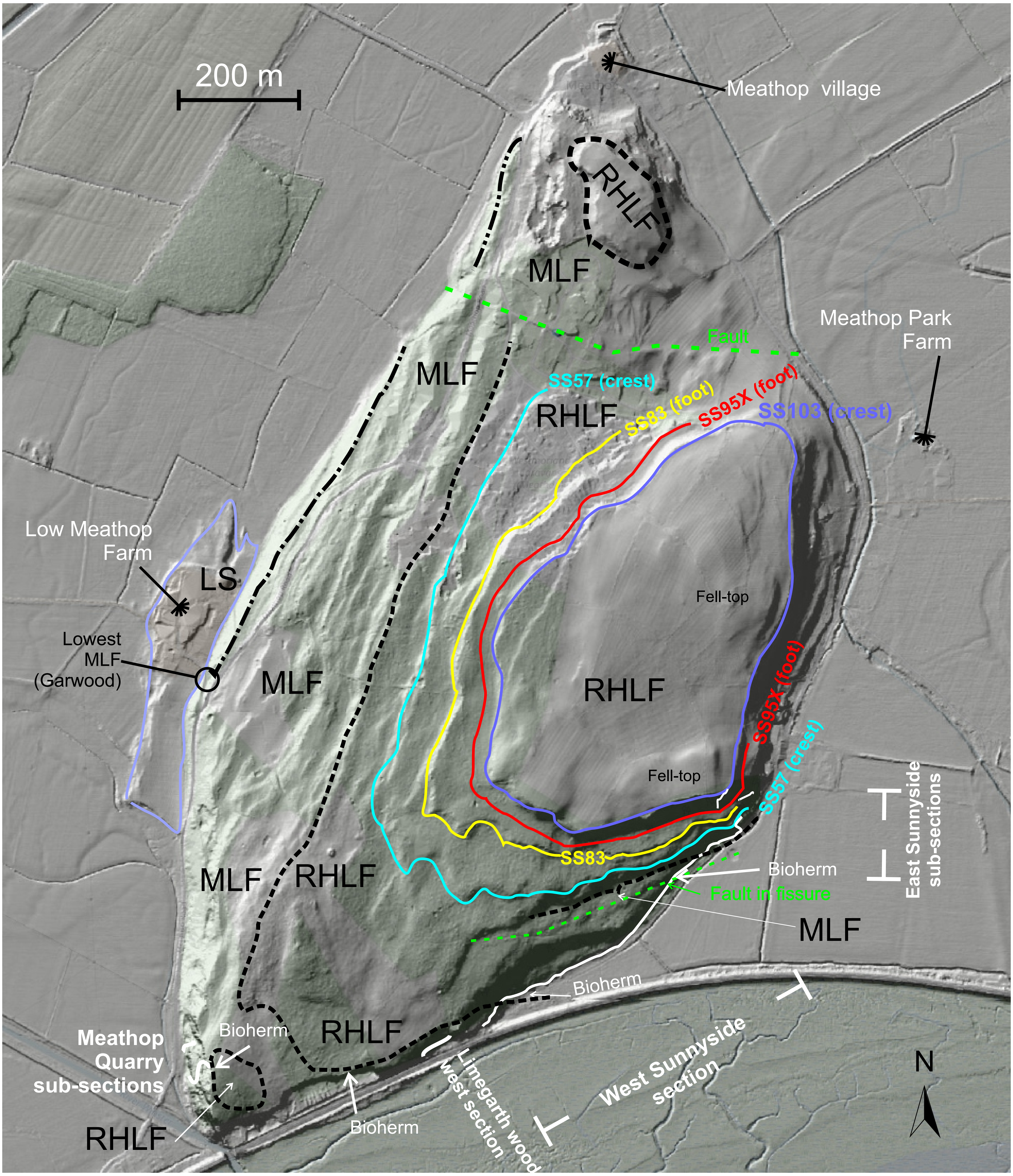
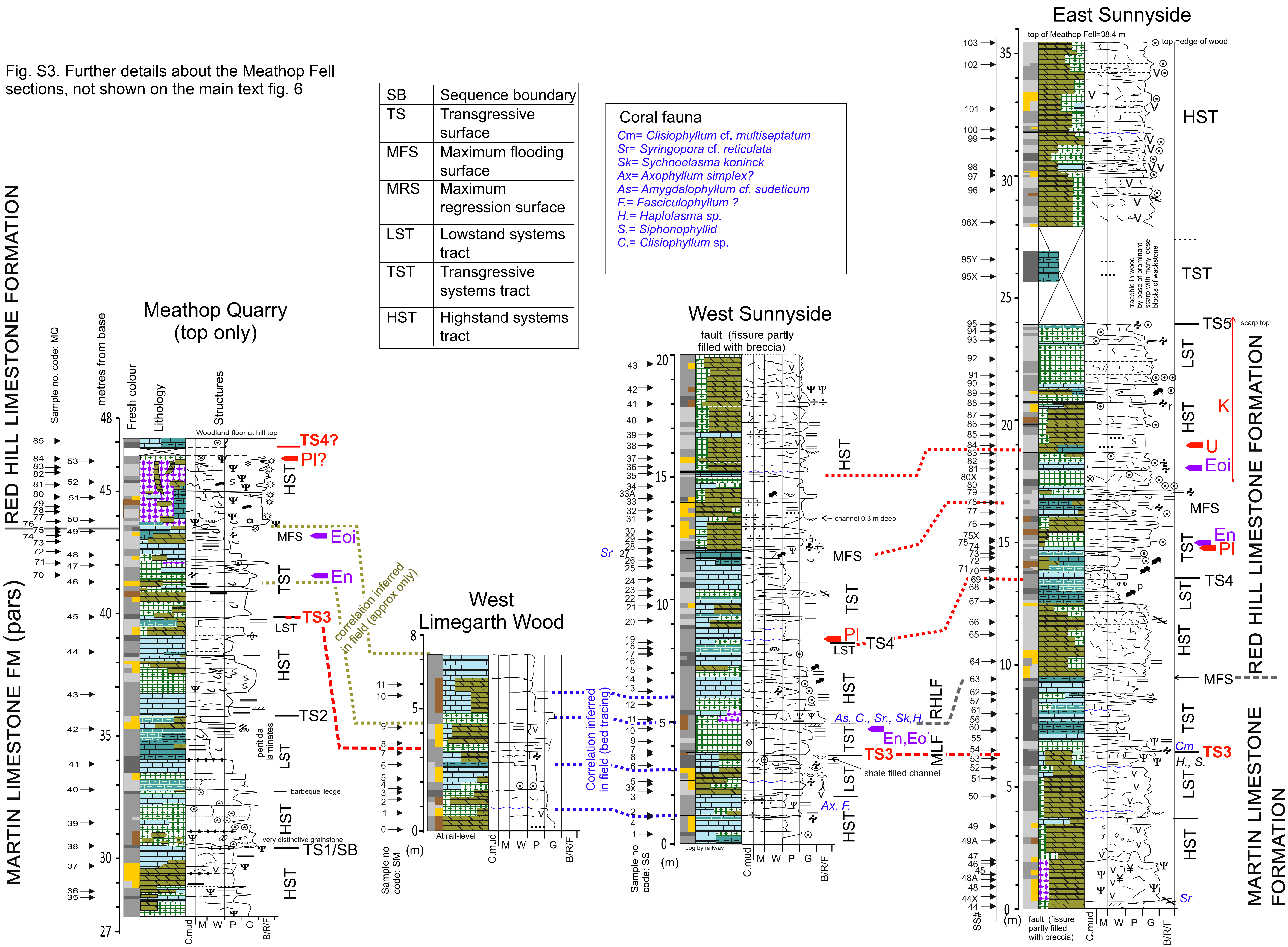


Figure S2. Base LIDAR map of Meathop Fell, with buildings and vegetation cover removed (downloaded from https://www.archiuk.com/), overlaid with the sub-sections measured for this work. The LIDAR map particularly shows well the scarp-slope topography typical of the Red Hill Limestone Fm (RHLF), when not covered with drift, due to the repetitions of grainstones and wackstone/mudstones. The approximate positions of the foot and crest of scarps with respect to the sampling codes for the key ones are shown as coloured lines. The Martin- Red Hill boundary is shown dashed, and the dot-dash lines shows the lowest unit of the Martin Limestone Fm (MLF), referred to by Garwood (1913) as the Solenopora Subzone, which rests unconformably on the Late Silurian (LS) basement. The described Meathop Quarry section is the upper-most sub-section in Meathop Quarry (upper part of southerly white track). Two further, sub-sections, not described here are present (lower 1/2 of south white-track, and N-white track). The positions of visible bioherms are marked with the most southerly one high in the old quarry face. The east sunnyside section consists of several sub-sections, comprising slope and crag outcrops to near the top of the fell (disconnected white tracks).

Fig. S3. Further details about the Meathop Fell sections, not shown on the main text fig. 6



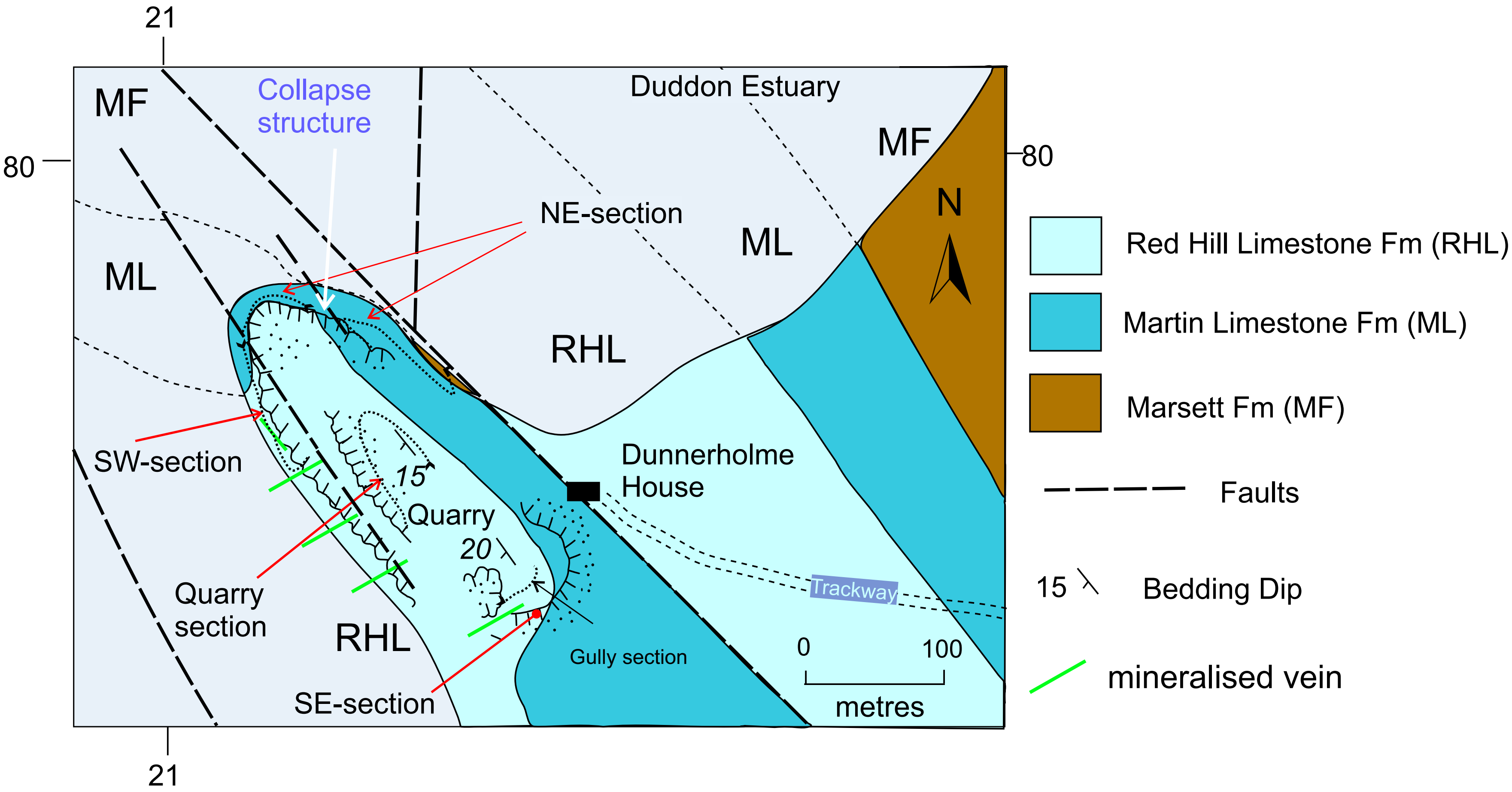


Figure S4. Geological sketch map of Dunnerholme Point (without the superficial deposits shown), slightly modified from that of Rose and Dunham (1977), with the sub-sections sampled indicated with red arrows (and dotted lines). The SE section is the type locality of the Algal Band. An additional section (the Gulley section) is shown, but is not figured in this work. The top of the Marsett Formation is assumed to be present at the very base of the NE section, based on the map of Rose and Dunham. The grey area represents modern beach sand and Duddon Estuary mudflats.

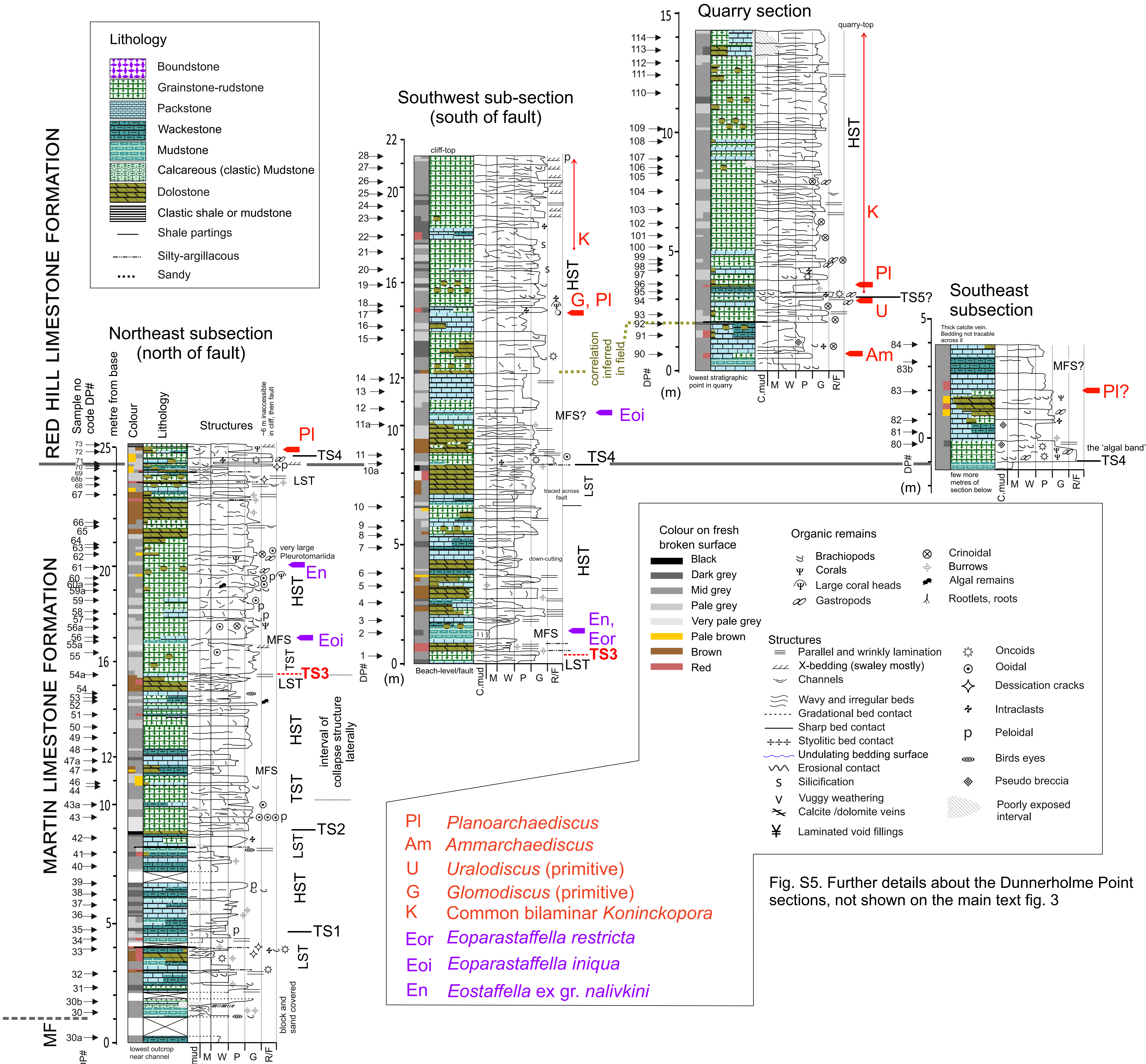


Fig. S5. Further details about the Dunnerholme Point sections, not shown on the main text fig. 3

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