A potential global chronostratigraphic boundary for the base of the middle Viséan

Pedro Cózar[1]*, Ian D. Somerville[2], Mark W. Hounslow[3,4]

Author Affiliations

[1] Instituto de Geociencias (CSIC-UCM), Madrid, Spain; p.cozar@igeo.ucm-csic.es
[2] UCD School of Earth Sciences, University College Dublin, Ireland; ian.somerville@ucd.ie
[3] Lancaster Environment Centre, Lancaster University, Lancaster, UK. LA1 4YW; mark.w.hounslow@gmail.com
[4]Earth, Ocean and Ecological Sciences, University of Liverpool, Jane Herdman Building, Liverpool, L69 3GP

Abstract: High-resolution foraminiferal biostratigraphy of carbonates immediately below and near the base of the Holkerian Substage in three sections of the South Cumbria Shelf allows the recognition of the Cf5α and Cf5β subzones. The most complete section at Grubbins Wood is almost free of dolomitisation. At the White Scar Quarry and Barker Scar sections, minor faunal gaps are inferred at the base of one or both subzones, respectively. The Grubbins Wood section has the most limited exposure, whereas White Scar Quarry has extensive exposure of this interval, especially the basal horizons of the subzones, compared to Barker Scar. The Grubbins Wood section, because of its exceptional foraminiferal record is more suitable for the establishment of a coincident boundary stratotype for the mid Viséan and Holkerian boundary at the base of the Cf5β subzone. However, the Barker Scar section should be retained as the Holkerian unit stratotype for Britain, with the base of the Holkerian repositioned lower in the section, at the base of the Cf5β subzone. White Scar is a suitable unit-parastratotype, filling data gaps due to possible faunal gaps and dolomitisation at Barker Scar. The rich foraminiferal assemblages allow good global correlation with other regional zonations, which if refined in other countries, would allow a more affirmative global chronostratigraphic basal boundary for the middle Viséan.

Keywords. biostratigraphy; foraminifers, middle Viséan; Mississippian; Britain

1. Introduction

The establishment of globally applicable chronostratigraphical levels within the Viséan is an emerging trend in the geological community (e.g., Poty et al. 2014, Lucas 2021, Pointon et al. 2021). This is because the Viséan Stage is the second longest stage in the Phanerozoic, at 15.8 or 16.39 Myr (sensu Davydov et al. 2012 and Aretz et al. 2020, respectively), which contrasts with shorter international Carboniferous stages of 6.94, 8.25, 8.13, 3.34 and 4.79 Myr for the Serpukhovian, Bashkirian, Moscovian, Kasimovian and Gzhelian, respectively (Aretz et al. 2020). The Tournaisian Stage (at 12.57 Myr), the second longest stage in the Carboniferous, has also been proposed for formal subdivision (e.g., Poty et al. 2014). Formal intermediate subdivisions of longer international stages are desirable for more precise global chronostratigraphic correlations.

Regional substages are also an important component of Carboniferous chronostratigraphy (Heckel and Clayton 2006), but to redefine each regional substage of the Viséan formally is not viable, because of the long time necessary between undertaking the detailed studies and formal ratification (Lucas 2021). Dated bentonites in Belgium at the base of the Livian Substage (base of mid Viséan in Belgium) suggest ages of ca. 340 Ma and 342 Ma (Pointon et al. 2021). This is not exactly a mid-position within the Viséan, but an internationally consistent substage boundary at about this age would create a lower stage of about 6 Myr, and an upper one of almost 10 Myr—a first step in achieving a more equitable subdivision.

1.1. The British Holkerian Substage

The Holkerian Substage is a well-established chronostratigraphical interval in Britain, recognizable by a general suite of microfossils and macrofossils over northern England (e.g., Waters et al. 2021). The base of the Holkerian Substage was established at Barker Scar (near the village of Holker) by George et al. (1976). In 2004, the IUGS International Subcommission on Carboniferous Stratigraphy recognised the Viséan as the formal international stage, and thus, the Holkerian became a formal regional substage (Heckel and Clayton 2006). As with many other British substages of the Viséan since their definition in 1976, subsequent revision of stratotypes have raised problems and inconsistencies (Simpson and Kalvoda 1987, Riley 1993, 1994, Cózar and Somerville 2004, Aretz and Nudds 2005, Waters et al. 2011, McLean et al. 2018). The base of the Holkerian at Barker Scar represents the last of the Viséan stratotype sections to be investigated and revised (Cózar et al. 2022).

The original definition of the Holkerian was strongly bound to the mesothem concept of Ramsbottom (1973). In the South Cumbria Shelf (SCS) the body of rock thought to represent the Holkerian Substage was the Park Limestone Formation (Ramsbottom 1973, Riley 1990), which was linked to mesothem D4 of Ramsbottom (1973, 1981). In essence, the interval represented by the Holkerian was in part expressed within the concepts which define unit stratotypes (e.g., Hilgen et al. 2006, 2020). The binding of the Holkerian Substage to the lithostratigraphy was emphasised by choosing the base of the Holkerian to be the Dalton Fm-Park Limestone Fm boundary at the Barker Scar section (Fig. 1). Also, over much of northern England, the limestones that are inferred to belong to the Holkerian are largely weakly bedded grainstones with relatively minor lithological variation (Waters et al. 2021), emphasizing the regional utility of this unit as a recognisable body of limestone (but not everywhere). However, lithostratigraphical revisions and new biostratigraphy (Waters et al. 2021, Hounslow et al. 2022) has shown that the boundaries of the Holkerian and Dalton Formation in the SCS cannot be precisely recognised using the prior criteria, and a revision of the base of the Holkerian is needed.

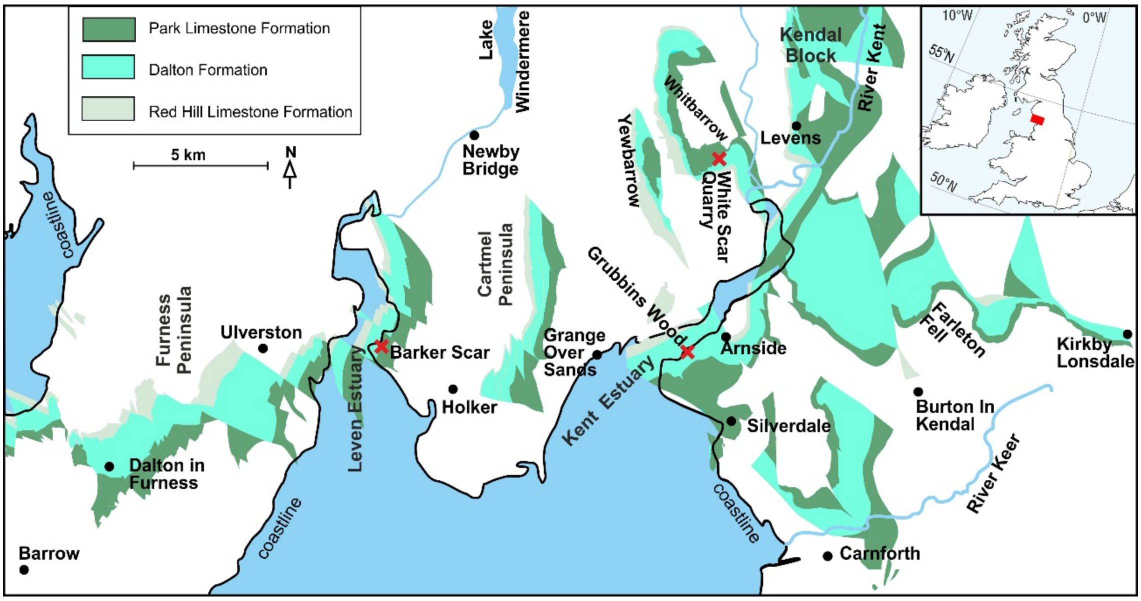

Fig. 1. Map of the studied stratigraphic sections in south Cumbria and north Lancashire (South Cumbria Shelf, SCS), overlain on the distribution of the Arundian (Red Hill Limestone Formation, Dalton Formation) and Holkerian (Park Limestone Formation) units. Map based on Digimap data. Red crosses=sections mentioned in text, black filled circles=towns and villages. Inset shows location in Britain. Rivers-lakes in blue. Coastline in black.

The Holkerian, as mentioned above, is indirectly based on the 'sequence' stratigraphy defined by Ramsbottom (1973), where mesothems were subdivided by widely distributed unconformities, or on diagenetic boundaries (often commonly associated with dolostones), thus also marking abrupt faunal and lithofacies changes (e.g., Simpson and Kalvoda 1987, Riley 1993, Waters 2011). In practice, the inferred unconformities are not commonly observed in the field, except in the shallowest-water platform successions. Such implied hiatuses in the faunal and lithological record also questions the precision of the British substage boundaries as useful global correlation markers. Likewise, these supposed surfaces provide imprecise methods for regional and local correlation, which are difficult to apply without clear contrasting lithologies and strong biostratigraphic guides. Such difficulties are not an exclusive problem of the British Viséan substages. The coeval Belgian substages are also based on dolomitic boundaries or nearly-azoic intervals (e.g., stromatolitic horizons; Poty et al. 2002, 2014). The Russian substage boundaries also use contrasting lithological changes (carbonates to sandstones) or palaeokarsts (e.g., Alekseev 2009, Kulagina 2022), and consequently both present similar problems.

Unfortunately, alternative sections in deep-water basins in Britain are not available, and hence the British Viséan substages are defined in shallow-water carbonate successions. Deeper-water facies, such as those in the Craven Basin, are principally zoned on goniatites, but cannot be precisely correlated, due to the rarity of goniatites in the adjacent carbonate platforms. However, goniatites do provide high-resolution zonations in the upper Viséan and younger strata in Britain (Waters et al. 2011, Cózar and Somerville 2014). Conodonts in Britain present a similar problem for this interval, since apart from the basal *Pseudognathodus homopunctatus* Zone (Chadian and lowermost Arundian), most of the Arundian, Holkerian and early Asbian are represented by the *Lochriea commutata* Zone (Varker and Sevastopulo 1985) and hence lack the necessary high-precision biostratigraphy (Barrick et al. 2022).

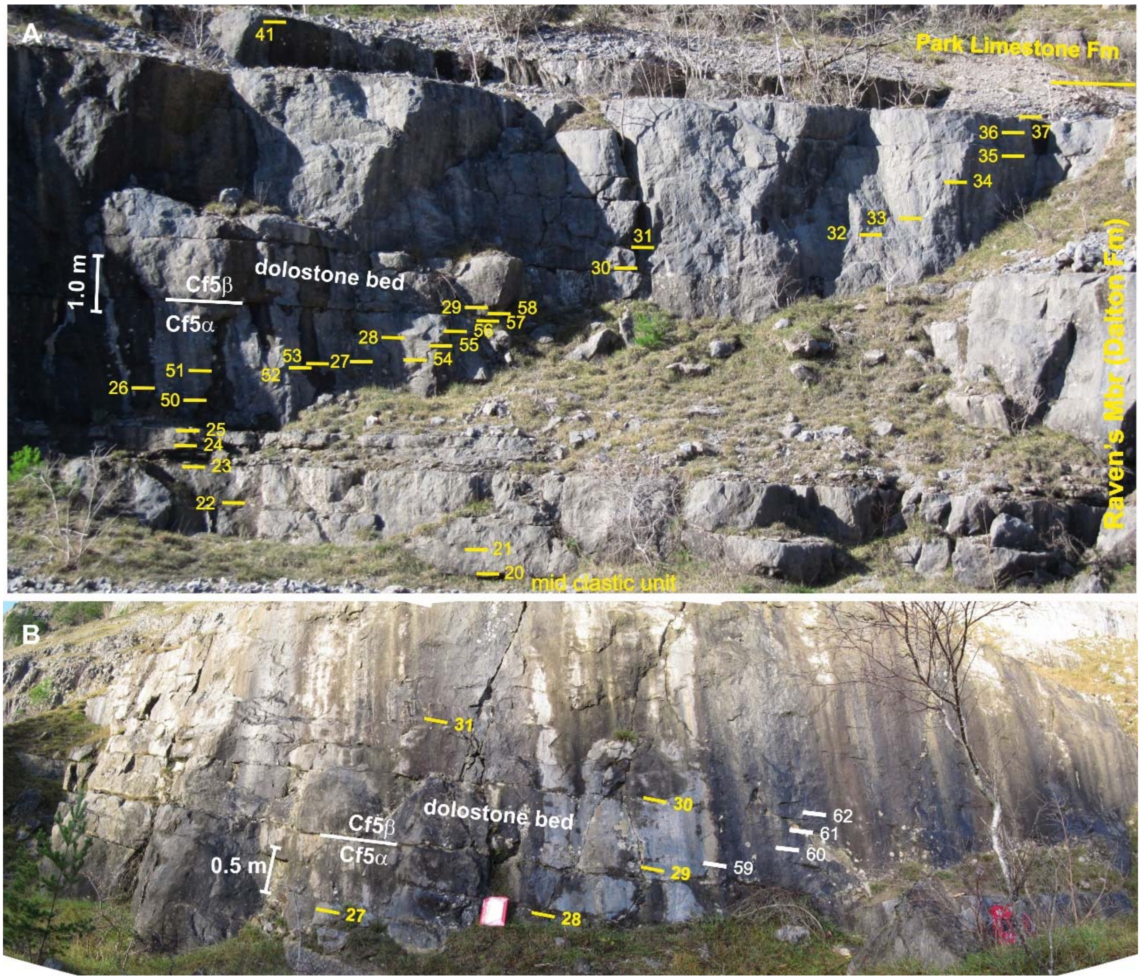

Fig. 2. White Scar Quarry. **A**. Sample positions in subsection 2. **B**. sample positions in subsection 4a (in B yellow labelled samples are extrapolated from subsection 2 using the dolostone bed for correlation).

1.2. Issues with the biostratigraphy of the Barker Scar section

At Barker Scar, the horizon originally selected as the base of the Holkerian by George et al. (1976), was between beds J and K of Rose and Dunham (1977). However, the faunal details provided in Ramsbottom (1981) do not permit a detailed boundary recognition outside of the type section. This is exacerbated by the strong dolomitization of these key levels and beds in the section (Cózar et al. 2022). The Holkerian Substage interval was supposedly characterised and defined by the occurrence of the Cf5 Zone or *Pojarkovella nibelis-Koskinotextularia* Zone (Conil et al. 1977, 1980), subsequently renamed as MFZ12 or *Pojarkovella nibelis* Zone (Poty et al. 2006). However, both foraminiferal taxa have been recorded in older levels at Barker Scar (Cózar et al. 2022). For Barker Scar to maintain biostratigraphic consistency, the base of the Holkerian, needs to be relocated at lower levels, which contain key foraminifera taxa representative of either the Cf5α or Cf5β foraminiferal subzones (Cózar et al. 2020a). However, due to the presence of much dolomitisation, it is not clear if the lowest presence of these taxa at Barker Scar represents their actual first occurrence, as there are some faunal gaps in the section where beds are strongly dolomitised, and largely lack foraminifers.

Foraminiferal assemblages are here analysed in additional coeval sections from the type region of the Holkerian Substage, focussing on the basal boundary interval (Fig. 1). Our aim is to validate and propose new stratotype and parastratotype sections for the base of the Holkerian to allow better international correlation. These sections have also been investigated as part of an ongoing work of the authors in the region, to establish a detailed biostratigraphic-base for magnetostratigraphic work (presented elsewhere).

2. Investigated sections

Three sections were selected here as yielding the important Arundian/Holkerian boundary interval: White Scar Quarry at the southern end of the Whitbarrow escarpment [N54º15’27’’/W2º50’04’’] (Figs. 1, 2), Grubbins Wood 1 (abbreviated as Grubbins Wood) at Arnside [N54º11’37’’/W2º51’12’’] (Figs. 1, 3), and the current stratotype at Barker Scar [N54º11’50’’/W3º1’28’’] (Figs. 1, 4). In general, dolomitisation of the Arundian-Holkerian limestones in the South Cumbria Shelf (SCS) is strongest westwards from the Holker region (Fig. 1), whereas it is less intense to the north-east, around Yewbarrow, and less significant in the Arnside to Silverdale region in the south-east (Fig. 1).

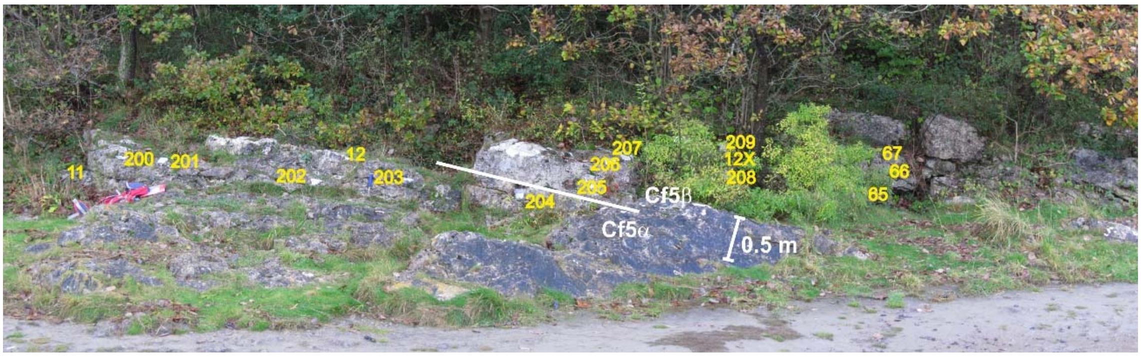

Fig. 3. Sample positions for the mid part of Grubbins Wood-1 section containing the base of the Cf5β subzone.

Details of the facies analysis and sedimentological interpretation of these and other sections can be found in Hounslow et al. (2022), as well as analysis of zircons and apatite for U-Pb geochronology from bentonitic levels in the White Scar section.

The base of the Cf4δ foraminiferal subzone (late Arundian) is located at a horizon much lower down in the SCS successions than examined here (within the underlying Red Hill Limestone Formation; Hounslow et al. 2022). It is estimated that the base of the Cf4δ subzone is ca. 17 m below the Grubbins Wood section (Fig. 5), using lithostratigraphic correlation of the clastic unit in the middle of the Raven's Member (upper Dalton Formation to adjacent sections; Hounslow et al. 2022). The base of the Cf4δ subzone has only an approximate correspondence with the MFZ11 Zone defined in Belgium, correlating with its upper part (MFZ11γ subzone as defined in Cózar et al. 2020a).

Fig. 4. Sample positions in the Barker Scar section containing the base of the Cf5β subzone. Base of Park Limestone Formation based on Hounslow et al. (2022).

3. Foraminiferal subzones at the Arundian-Holkerian boundary

Detailed analysis of samples from the sections in the SCS demonstrates that foraminiferal taxa used previously for this boundary may not be appropriate, because their first occurrences are earlier than previously expected and/or new taxa have been distinguished. That is: (i) primitive species of *Koskinotextularia* occur at lower horizons than the classically well-known species (*K. cribriformis* Eickhoff); (ii) a primitive species of *Endothyranopsis s.s.* occurs in the upper part of the early Viseán; (iii) the first occurrences of *Pojarkovella nibelis* (Durkina) and the well-known species of *Koskinotextularia* do not follow a single pattern; and (iv) there are several species of *Pojarkovella* relatively similar to *P. nibelis* that have been recognised, and thus, it would be necessary to revise specimens from the literature to understand better all the involved species for the definition of the Cf5 Zone.

The problematic use of *Pojarkovella* species is possibly derived from the redefinition of *P. nibelis* by Simonova and Zub (1975), which restricted those specimens usually larger than 600 μm in diameter to *P. nibelis*, whereas rather similar forms, less than 500 μm, were included under the new species *P. honesta* Simonova and Zub. In addition, there are numerous examples in the literature where the recognition of a *Pojarkovella* species is not sufficiently clear. For instance, Kimpe et al. (1978, pl. 10, figs. 57, 59) used *Quasiendothyra*(?) cf. *nibelis* and *Q.*(?) ex gr. *nibelis* for specimens which would correspond to the diagnosis of *P. honesta*; Conil and Lys (1967, pl. 4, figs. 37-39) illustrated three *Quasiendothyra nibelis*, of which the first two correspond to *P. honesta* and the only *P. nibelis* belongs to a younger horizon. Also, Zandkarimi et al. (2016, fig. 8.5-8.20) included all the specimens under the name of *Pojarkovella* ex gr. *nibelis*, where there is a clear mixture of species. However, this definition of *P. nibelis* does not correspond to the original definition by Durkina (1959), where type specimens show a diameter < 510 µm. It is beyond the aims of this work to study the systematics of the species, but as proposed by Cózar (2002), both species (*P. nibelis* and *P. honesta*) are likely synonyms. Nevertheless, there is a small stratigraphical difference in the first occurrence (FOD) of both morphotypes. Herein, as a means of distinguishing them, *P. nibelis* morphotype 1 is reserved for those specimens less than 600 µm in diameter, and morphotype 2 for those larger than 600 µm.

Therefore, the Cf5α subzone can be primarily defined on the first occurrence of *Archaediscus* at *concavus* stage cf. Conil et al. (1980) (including species such as *A. pauxillus* Shlykova) and *Pojarkovella ketmenica* Simonova and Zub.

Koskinotextularia (including only the primitive species of the genus with rudimentary characters) is considered the first marker and most important for recognition of the Cf5β subzone. Auxiliary markers for the identification of this subzone (which first occur near or at the base), are *Endothyranopsis compressa* (Rauser-Chernousova and Reitlinger), *Omphalotis minima* (Rauser-Chernousova and Reitlinger) and *Pojarkovella occidentalis* Vachard and Cózar. Close to the base of the subzone (with first occurrence less well constrained), are *Endostaffella*, and some other species of *Pojarkovella* of moderate size (*P. pura* Simonova and Zub and *P. nibelis* morph. 1).

The record of *Pojarkovella nibelis* is not as robust as would be desirable (for its definition and its occurrence), and in general, the distribution of species of *Pojarkovella* are not consistent between sections (Fig. 5). Only *P. occidentalis* is consistently recorded <1 m above the base of the Cf5β subzone in the three sections (Fig. 5). These facts prevent the use of *P. nibelis* as a primary marker for Cf5β (in contrast with many other zonations elsewhere), since depending on the morphotype recognised, it can first occur from 1.0 to 4.25 m above the base of the subzone.

This suggested small enhancement for greater biostratigraphic consistency, does not discredit the classical Cf5 Zone (or MFZ12) of previous authors (Conil et al. 1980, Poty et al. 2006), or the more recent Cf5β subzone. This is because, the first occurrence of both key taxa (*K. cribriformis* and *P. nibelis* morph. 2) are always very close to each other stratigraphically, or when the latter occurs earlier, it is only by some 0.3 m, whereas the first occurrences of primitive *Koskinotextularia* and *P. nibelis* morph. 1 are located between 2.5 and 3 m below *K. cribriformis* and *P. nibelis* morph. 2. Such a small difference is insignificant for many biostratigraphic studies, and only detailed and intense sampling can detect such a stepped occurrence. In many biostratigraphic studies (not related to specific boundaries), the sampling interval is wide and the number of thin-sections prepared is low, and thus such small positional differences are unlikely to be detected.

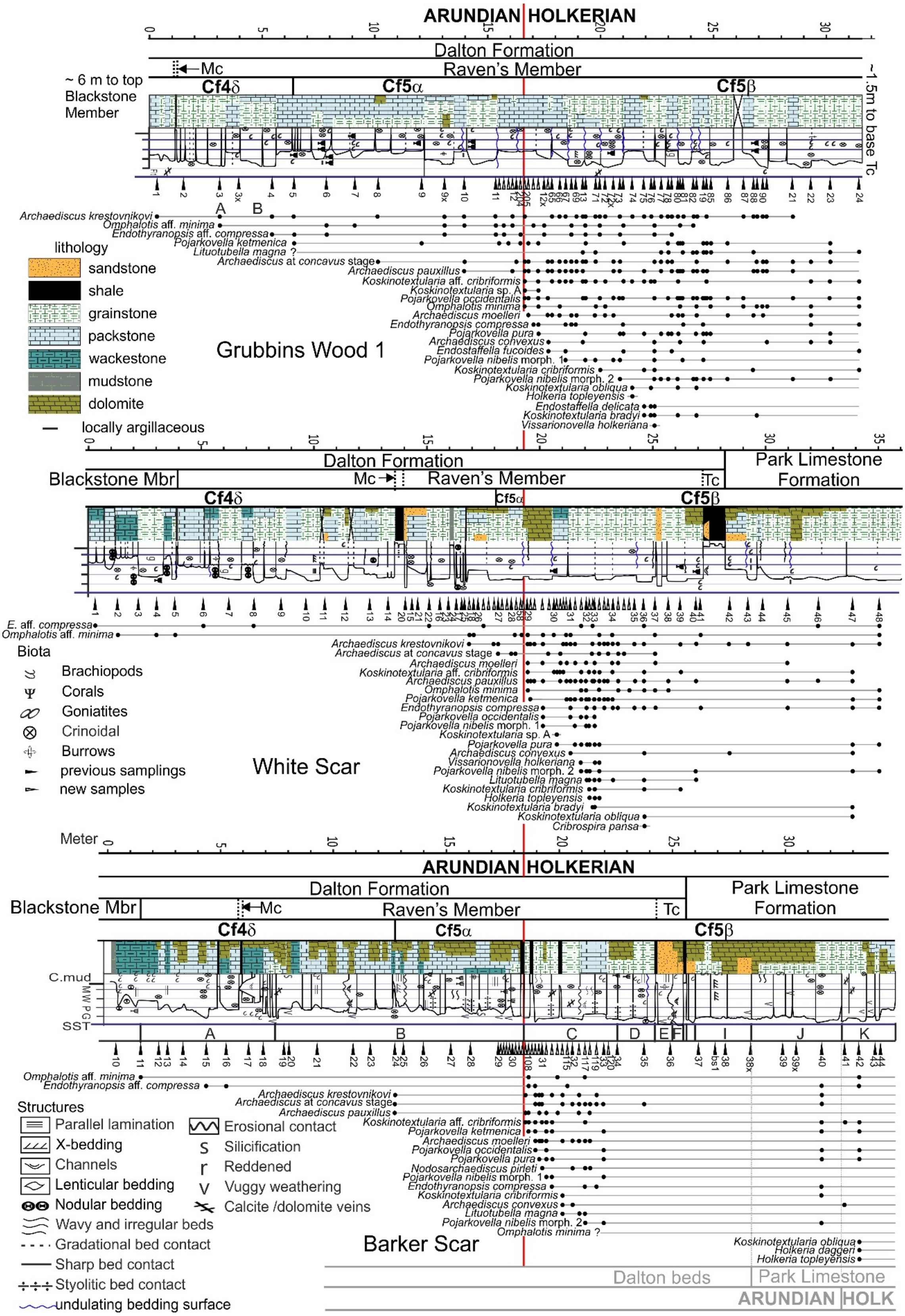

Fig. 5. Stratigraphic range of selected foraminifers. The lithostratigraphical subdivisions in the bottom part of Barker Scar (in greyed text) correspond to that in Johnson et al. (2001). Modified lithostratigraphical and chronostratigraphical units in the top columns of Barker Scar are sensu Hounslow et al. (2022). Bed numbers A to K in Barker Scar follow Ramsbottom (1981) with most representing bed-intervals except at the Dalton-Park Limestone boundary. Abbreviations: HOLK Holkerian, Mc middle

Raven's Member clastic unit, Tc top Raven's Member clastic unit, Mbr Member, *E. Endothyranopsis,* C carbonate muds, M mudstone, W wackestone, P packstone, G grainstone, SST sandstone.

4. Selected foraminiferal occurrences in the SCS

Individual beds and bed-intervals (labelled A-K, up to Z) were defined for the Barker Scar section (Rose and Dunham 1977, Rambottom 1981). A strong stratigraphical correlation within the upper part of the Dalton Formation in all sections is provided by the clastic-rich interval at the top of the Raven's Member. A second more weakly developed clastic-rich interval in the middle part of the Raven's Member (Fig. 5), is in the upper part of bed A at Barker Scar (Hounslow et al. 2022).

4.1. Barker Scar section

This section was studied in detail by Cózar et al. (2022), and the most important foraminifers were illustrated. However, subsequently, a further twenty-one samples were collected, in order to search for foraminifers present in undolomitised levels within the mostly dolomitised bed B interval. Unfortunately, the samples taken from bed B were mostly barren or very poor in foraminifers, with only the topmost sample containing moderately diverse assemblages. However, a sample (BS24), collected from the middle part of bed B, contains *Archaediscus* at *concavus* stage (including *A. pauxillus*), and is assigned to the base of the Cf5α subzone (Fig. 5).

The base of the bed C interval displays much richer assemblages, including *Koskinotextularia* aff. *cribriformis* (from the basal sample), as well as *Pojarkovella ketmenica* (0.25 m above the base), *Archaediscus moelleri* Rauser-Chernousova and *Pojarkovella occidentalis* (0.52 m above the base), *Pojarkovella pura* (0.65 m above the base), *Pojarkovella nibelis* morph. 1 (0.97 m above the base) and *Endothyranopsis compressa* (1.42 m above the base). The base of bed C is considered the base of the Cf5β subzone.

The occurrence of *Koskinotextularia cribriformis* and *Lituotubella magna* Rauser-Chernousova are located 1.67 m above the base of the Cf5β subzone, and *Pojarkovella nibelis* is at 2.48 m above base. Compared to other sections, important taxa such as *Omphalotis minima*, *Koskinotextularia bradyi* (Möller) and *Holkeria* species occur in higher levels (Fig. 5). Samples located at the top clastic interval in the Raven's Member (beds E and F), as well as beds G to most of bed J are barren in foraminifers; an interval of 7.88 m without microfossil information.

A minor refinement to the proposal of Cózar et al. (2022) is warranted, following the incorporation of our new data (see above). The base of the Cf5α subzone is now lowered slightly, to the middle part of bed B, and the base of the Cf5β subzone positioned at the base of bed C (Fig. 5). Despite the inclusion of data from the new samples, it is not until bed K, when more diversified Holkerian markers are recorded. Most taxa do not seem to follow a progressive pattern of occurrences, instead occurring in steps, mostly at the base of bed C, where the sharp contrast between the dolomitised and non-dolomitised carbonates questions the precision of this boundary in the section owing to the apparent faunal gaps due to dolomititisation. Both inferred chronostratigraphic boundaries, Cf5α and Cf5β, occur at positions without evidence of hiatuses.

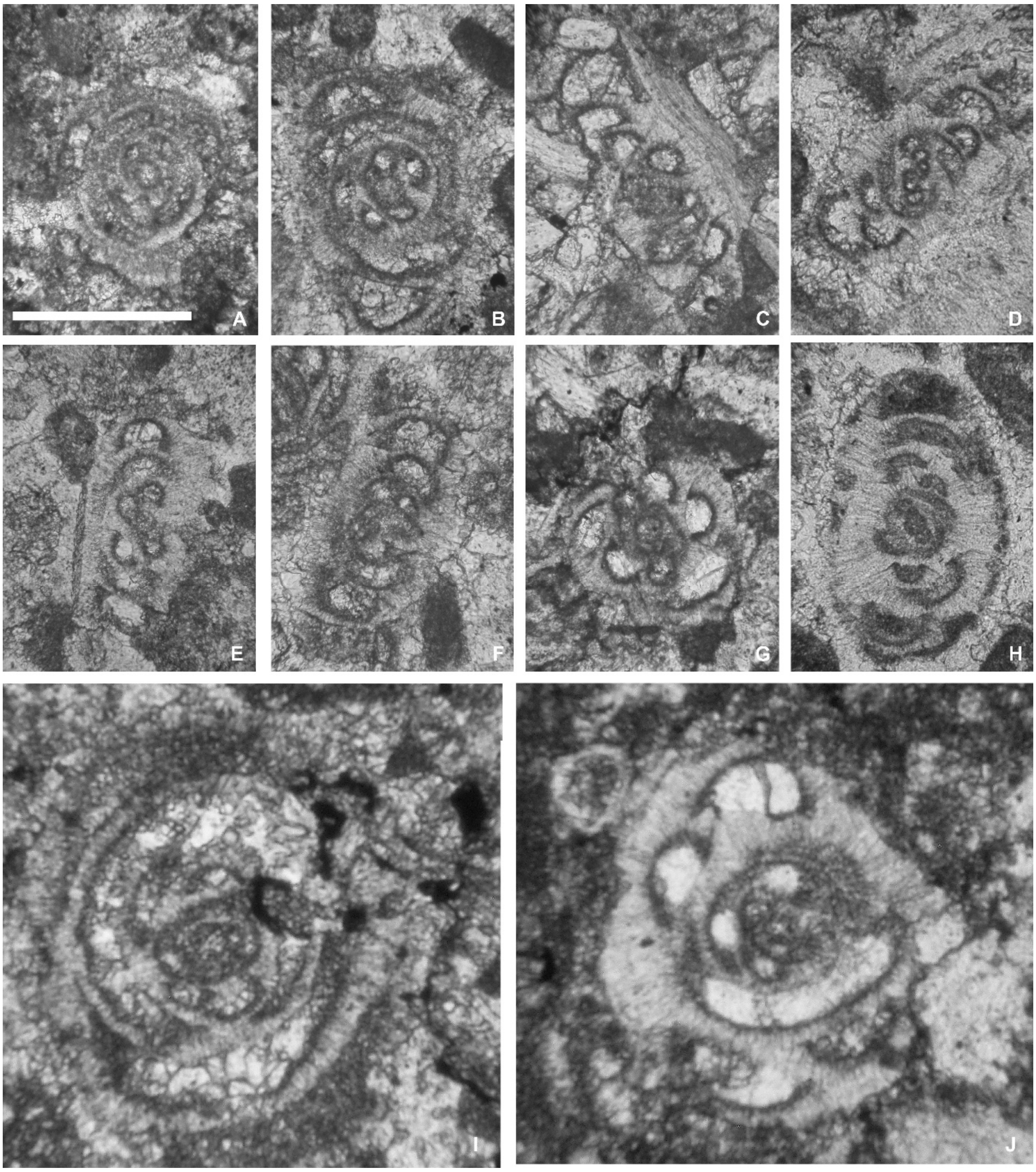

Fig. 6. Selected archaediscids (scale bar = 200 microns). **A–B**. *Archaediscus pauxillus* Shlykova, A WS29, B GW209 (Cf5β). **C–F**. *Archaediscus krestovnikovi* Rauser-Chernousova, C WS53 (Cf4δ), D WS36 (Cf5β), E GW3 (Cf4δ), F, GW11 (Cf5α). **G, I**. *Archaediscus moelleri* Rauser-Chernousova, G GW206, I WS29 (Cf5β). **H, J**. *Archaediscus convexus* Grozdilova and Lebedeva, H WS36, J, GW209 (Cf5β). Scale in A applies to B-J also.

4.2. White Scar Quarry section

The succession at White Scar Quarry shows some lithological similarities with the Barker Scar section (Hounslow et al. 2022). *Archaediscus* at *concavus* stage is recorded from sample WS27, indicating the Cf5α subzone (at 18.2 m in Fig. 5). From sample WS29 (at 19.4 m height) other species of *Archaediscus* at *concavus* stage are recorded, including *A. pauxillus* and *A. moelleri* (Fig. 6A, 6I), as well as *Koskinotextularia* aff. *cribriformis* (Fig. 7A). Also included in the same bed is *Omphalotis minima* (Fig. 7F). This sample, WS29 is 0.13 cm above a bedding plane. Those taxa allow us to interpret this bedding plane as the base of the Cf5β subzone. Close to the base of this subzone, *Pojarkovella ketmenica* (0.16 m above the base), *P. occidentalis*, *P. nibelis* morph. 1 and *Endothyranopsis compressa* have been recorded (0.71 m above the base) (Fig. 7H–L). Higher positions in the Cf5β subzone show the occurrence of another primitive species of *Koskinotextularia* (*K*. sp. A; Fig. 7B, but only in one level), and *Pojarkovella pura* (1.39 m above the base of the bed).

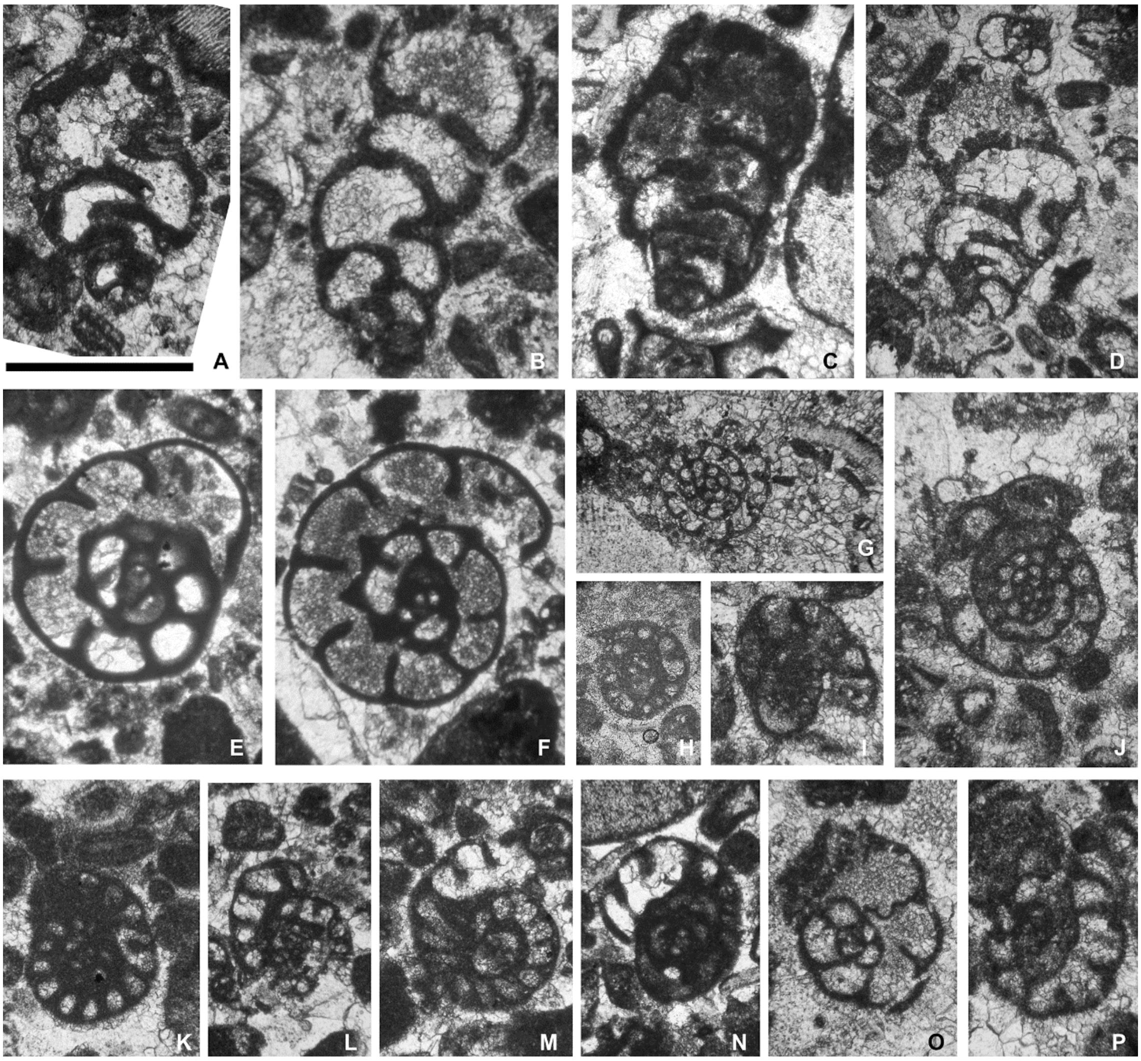

Fig. 7. Selected foraminifers from the White Scar Quarry (scale bar = 500 microns). **A**. *Koskinotextularia* aff. *cribriformis* sensu Cózar et al. (2022), WS29 (Cf5β). **B**. *Koskinotextularia* sp. A, WS63 (Cf5β). **C**. *Koskinotextularia cribriformis* Eickhoff, WS33 (Cf5β). **D**. *Koskinotextularia obliqua* (Conil and Lys), WS36 (Cf5β). **E**. *Omphalotis* aff. *minima* sensu Cózar et al. (2022), WS4 (Cf4δ). **F**. *Omphalotis minima* (Rauser-Chernousova and Reitlinger), WS38 (Cf5β). **G**. *Endothyranopsis* aff. *compressa* sensu Cózar et al. (2022), WS1 (Cf4δ). **H**. *Pojarkovella ketmenica* Simonova and Zub, WS32 (Cf5β). **I**. *Pojarkovella occidentalis* Vachard and Cózar, WS33 (Cf5β). **J**. *Endothyranopsis compressa* (Rauser-Chernousova and Reitlinger), WS33 (Cf5β). **K**. *Pojarkovella pura* Simonova and Zub, WS69 (Cf5β). **L**. *Pojarkovella nibelis* morph. 1 (Durkina), WS67 (Cf5β). **M**. *Pojarkovella nibelis* morph. 2 (Durkina) WS68 (Cf5β). **N**. *Vissarionovella holkeriana* (Conil and Longerstaey), WS 68 (Cf5β). **O**. *Cribrospira pansa*? Conil and Lys, WS36 (Cf5β). **P**. *Holkeria topleyensis* Strank, WS33(Cf5β). Scale in A applies to B-P also.

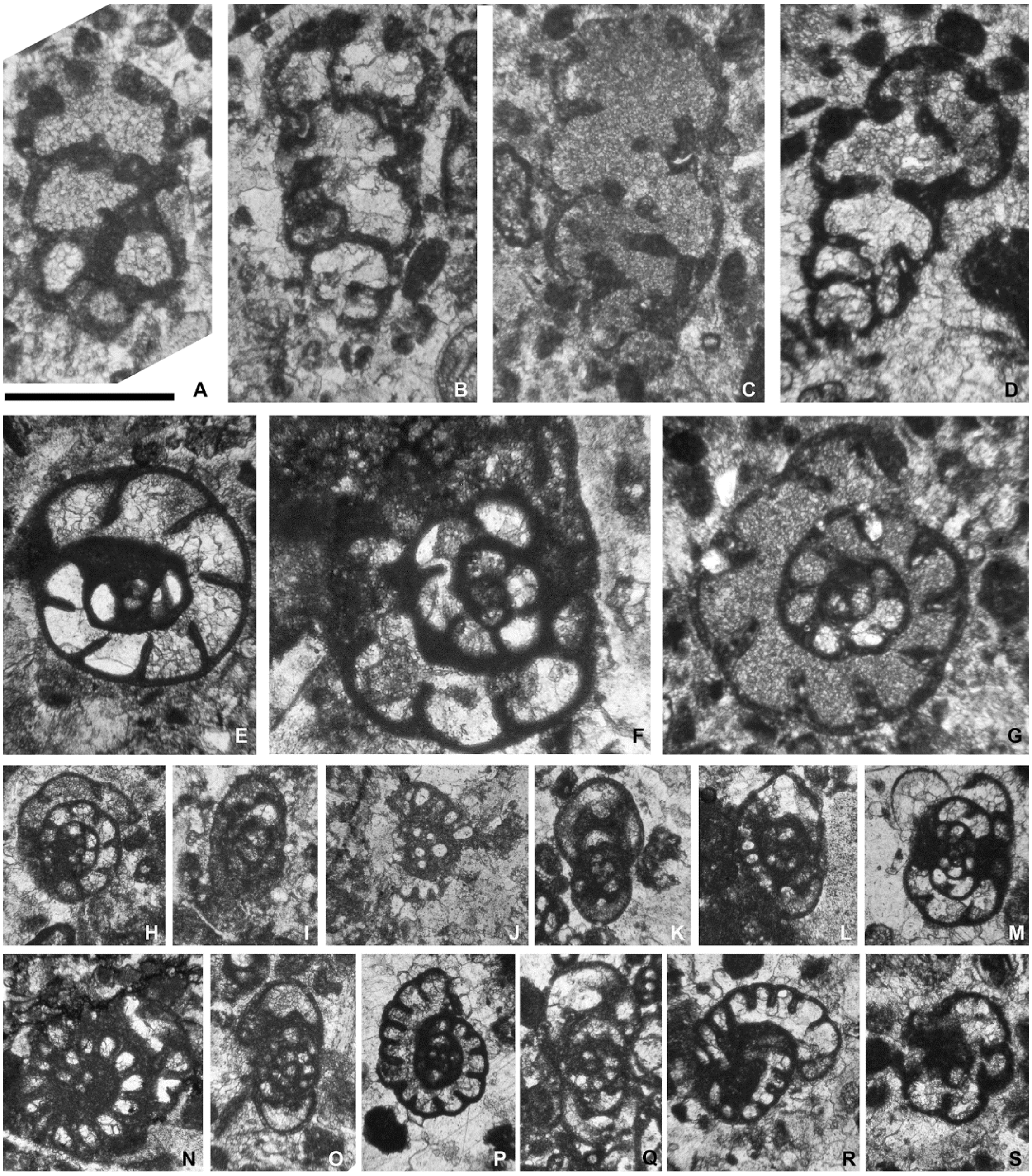

Fig. 8. Selected foraminifers from Grubbins Wood (scale bar = 500 microns). **A**. *Koskinotextularia* aff. *cribriformis* sensu Cózar et al. (2022), GW205 (Cf5β). **B**. *Koskinotextularia* sp. A, GW208 (Cf5β). **C**. *Koskinotextularia cribriformis* Eickhoff, GW14 (Cf5β). **D**. *Koskinotextularia obliqua* (Conil and Lys), GW74 (Cf5β). **E**. *Omphalotis* aff. *minima* sensu Cózar et al. (2022), GW6 (Cf5α). **F**. *Omphalotis minima* (Rauser-Chernousova and Reitlinger), GW68 (Cf5β). **G**. *Endothyranopsis compressa* (Rauser-Chernousova and Reitlinger), GW67 (Cf5β). **H**. *Endothyranopsis* aff. *compressa* sensu Cózar et al. (2022), GW11 (Cf5α). **I**. *Pojarkovella ketmenica* Simonova and Zub, GW9 (Cf5α). **J**. *Pojarkovella occidentalis* Vachard and Cózar, GW206 (Cf5β). **K**. *Pojarkovella eostaffelloides* Simonova in Simonova and Zub, GW19 (Cf5β). **L**. *Pojarkovella ovoides* Simonova in Simonova and Zub, GW19 (Cf5β). **M**. *Vissarionovella holkeriana* (Conil and Longerstaey), GW16 (Cf5β). **N**. *Pojarkovella pura* Simonova and Zub, GW15 (Cf5β). **O–P**. *Pojarkovella nibelis* morph. 1 (Durkina), O. GW73 axial section, P equatorial section GW16 (Cf5 β). **Q–R**. *Pojarkovella nibelis* morph. 2 (Durkina), Q. axial section GW19, R. oblique equatorial section GW73 (Cf5β). **S**. *Holkeria topleyensis* Strank, GW14 (Cf5β). Scale in A applies to B-S also.

Higher up, at 2.5 m above the base of the Cf5β subzone, *Pojakovella nibelis* morph. 2 first occurs, together with *Vissarionovella holkeriana* (Conil and Longerstaey), and *Lituotubella magna* (0.26 m above), *Koskinotextularia cribriformis* and *Holkeria topleyensis* Strank (0.02 m above) (Fig. 7C, M–N, P). *Koskinotextularia bradyi* occurs close to those levels (0.11 m above) and *Cribrospira*? *pansa* Conil and Lys higher up (Fig. 7O). Other evolved species of *Koskinotextularia* and *Pojarkovella* occur in the upper part of the section.

The horizons with the main foraminiferal occurrences do not coincide with bedding planes, although the first level, WS29, is close to the base of a bedding plane but not exactly at the base (0.13 m below the first occurrence of markers). However, in this first sample, the occurrence of *Archaediscus moelleri*, together with a slightly more primitive form, *A. pauxillus* (that should first occur earlier), suggests a small faunal gap in this part of the succession. The base of the bed assigned to the Cf5β subzone therefore might contain a small faunal gap, as at Barker Scar.

4.3. Grubbins Wood Section

An important foraminiferal change is recognised at sample GW205 (at 16.64 m; Fig. 5), by the first occurrence of *Koskinotextularia* aff. *cribriformis*, *Koskinotextularia* sp. A, *Pojarkovella occidentalis*, *Omphalotis minima* and common *Archaediscus pauxillus,* as well as oblique sections of *Archaediscus* at *concavus* stage (Figs 6B, 8A–B, 8J, 8F). Similar taxa from the Cf5β subzone, are recorded in the White Scar Quarry and Barker Scar sections (Fig. 5). Furthermore, *Archaediscus moelleri* is recorded nearly from the base (0.33 m higher; Fig. 6G) and *Endothyranopsis compressa* (0.46 m above the base) (Fig.8G). In addition, *Pojarkovella pura* and *P. nibelis* morph. 1 are also recorded from slightly higher levels (0.6 m and 1.84 m, respectively) (Fig. 8N–P).

The Cf5α subzone is recognised much lower down in the section (c. 10 m below the base of Cf5β subzone), at the first occurrence of *Pojarkovella ketmenica* (Fig. 8I) and *Lituotubella magna*? Subsequently, at higher levels and with rare occurrences are recorded *Archaediscus* at *concavus* stage and *A. pauxillus* (Fig. 5).

Higher up in the succession, the occurrence of *Koskinotextularia cribriformis* is at 3 m above the base of the Cf5β subzone (at 19.64 m), whereas *Pojakovella nibelis* morph. 2 is recorded a further1.25 m above (Fig. 8C, Q–R). As in Barker Scar, *K. cribriformis* occurs earlier than *P. nibelis* morph. 2. Between 1.8 and 2.8 m above the previous horizon, *Koskinotextularia obliqua* (Conil and Lys), *K. bradyi, Holkeria topleyensis,* and *Vissarionovella holkeriana* are recorded (Fig. 5) (Fig. 8D, 8M).

5. Diversity of the Foraminiferal record

Barker Scar records a lower number of foraminiferal first occurrences in their expected or inferred positions, whereas the number of first occurrences in their inferred positions are rather similar between White Scar and Grubbins Wood (Table 1). In the lower part of the Grubbins Wood section, the Cf5α subzone is particularly thick and better preserved than in the other sections (Fig. 5).

Taxa	**Inferred position**	**Barker Scar**	**White Scar**	**Grubbins Wood**
Cribrospira? *pansa*	<5 m above the base Cf5β		X	
Vissarionovella holkeriana	<5 m above the base Cf5β		X	X
Koskinotextularia obliqua	<5 m above the base Cf5β		X	X
Holkeria topleyensis	<5 m above the base Cf5β		X	X
Koskinotextularia bradyi	<5 m above the base Cf5β		X	X
Pojarkovella nibelis morph. 2	<5 m above the base Cf5β	X	X	X
Koskinotextularia cribriformis	<5 m above the base Cf5β	X	X	X
Pojarkovella nibelis morph. 1	nearly at the base Cf5β	X	X	X
Pojarkovella pura	nearly at the base Cf5β	X	X	X
Endostaffella fucoides	nearly at the base Cf5β			X
Omphalotis minima	base Cf5β	X	X	X
Endothyranopsis compressa	base Cf5β	X	X	X
Archaediscus moelleri	base Cf5β	X	X	X
Pojarkovella occidentalis	base Cf5β	X	X	X
Koskinotextularia sp. A	base Cf5β		X	X
Koskinotextularia aff. *cribriformis*	base Cf5β	X	X	X
Archaediscus pauxillus	Cf5α	X		X
Archaediscus at *concavus* stage	Cf5α	X	X	X
Lituotubella magna?	Cf5α			X
Pojarkovella ketmenica	Cf5α			X
Archaediscus krestovnikovi	lower Cf4δ			X

Table 1. First occurrences of selected foraminifers in their inferred positions.

Using the Margalef richness index with the foraminiferal assemblage data, indicates the diversity in the Grubbins Wood section is, on average, five to six times larger than that at Barker Scar (Fig. 9). The White Scar Quarry section showing intermediate richness values, closer to the high values at Grubbins Wood. These differences are more pronounced during the Cf5α subzone, a factor which probably explains the more frequent occurrence of the ancestral forms in Grubbins Wood compared to the other sections. The intense sampling of beds in the lower metres of the Cf5β subzone in the three sections produces more similar diversity values between the sections, but Grubbins Wood remains higher.

There are two main factors which could control the foraminiferal diversity, firstly dolomitisation. Levels with moderate to strong dolomitization are rather common at Barker Scar from bed B interval to bed J, although the bed C interval shows lower levels of dolomitisation (Fig. 9). Dolomitisation is less significant at White Scar, but does affect levels below the middle clastic unit in the Raven's Member (upper Dalton Fm) and particularly the basal levels assigned to the Cf5β subzone. Only sparse low-level dolomitisation is observed at Grubbins Wood (Fig. 9).

Secondly the assemblages seem to respond to palaeoenvironmental differences. The lower 16 m in the Grubbins Wood section mostly contain intertidal facies, whereas in the lower 19 m in White Scar there are many intervals interpreted as transitional intertidal/subtidal, as well as intervals influenced by coastal clastics. At Barker Scar, in beds A and B, there is a predominance of subtidal facies (Hounslow et al. 2022). From the base of Cf5β subzone upwards, the palaeoenvironmental influences are similar in the three sections with dominantly intertidal facies.

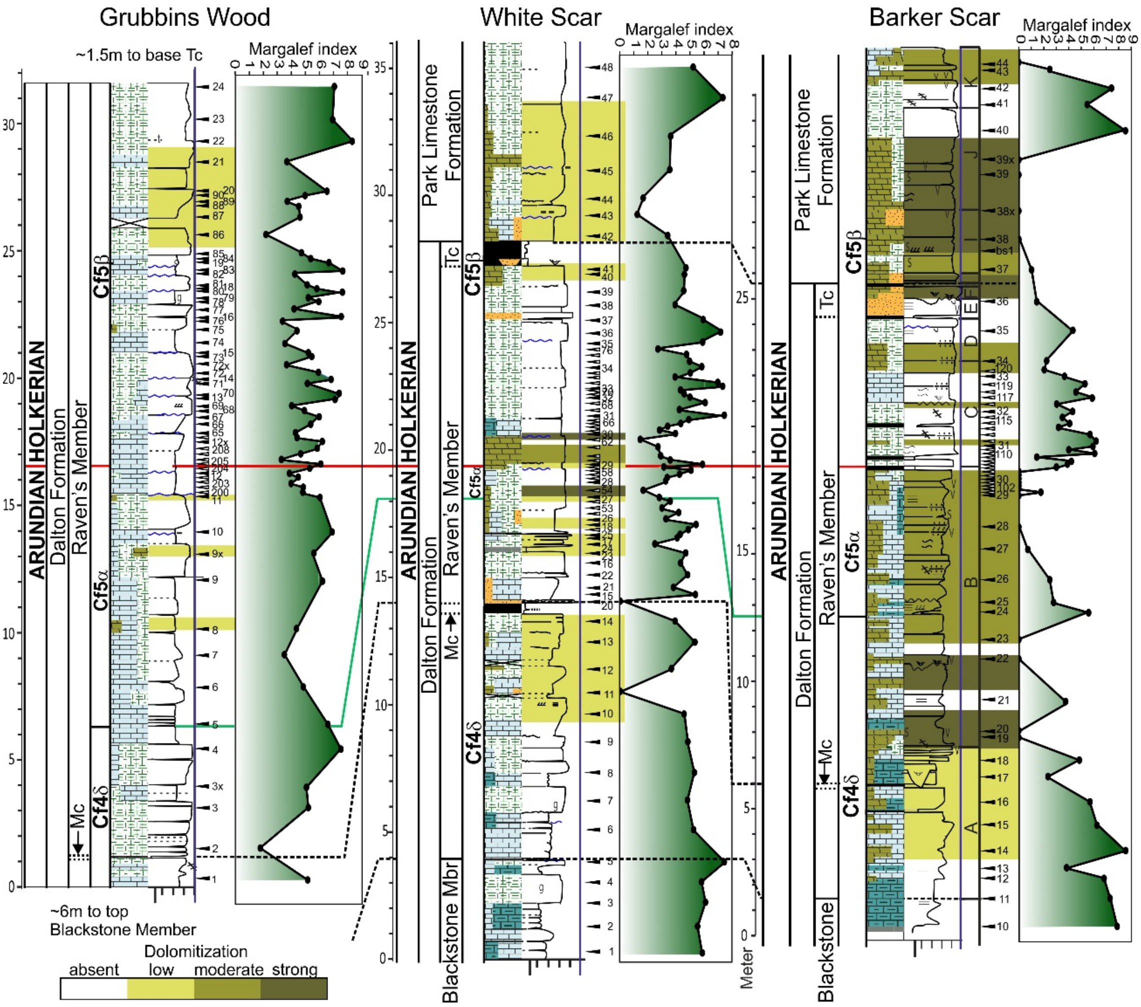

Fig. 9. Correlation of the sections showing the degree of dolomitization and the Margalef index of foraminiferal diversity. Legend as in Fig. 5.

6. Quality of exposure in the sections

An important factor in the proposal and designation of stratotypes is the amount of exposure and ease of access. All three sections have similar ease of access and are protected nature reserve sites. Larger exposures greatly facilitate micropalaeontological sampling and the potential for macrofaunal investigation. Unfortunately, the three sections examined contain sparse macrofossils which are often poorly preserved and fragmented (Fig. 5). However, specialists could potentially expand the list of macrofossils, particularly in the Grubbins Wood section. A list of brachiopods and rugose corals were summarised from the Holker area based on the recognition of individual beds (see George et al. 1976), but not specifically for material from Barker Scar. However, apart from the occurrence of the coral *Lithostrotion araneum* (M'Coy) from bed P in Barker Scar (20 m above the base of the Park Limestone Fm) other macrofossils recorded in the sections are not particularly representative (Cózar et al. 2022). *Lithostrotion araneum* is also an informal marker for the late Holkerian (Waters et al. 2021). Relevant preserved macrofauna have not been recorded at White Scar Quarry or Grubbins Wood, although Garwood (1913, 1916) listed rich late Arundian macrofaunas in the outcrops along the Arnside shore. The White Scar Quarry section is a disused quarry (a local nature reserve). The Barker Scar section is an old sea cliff (1 to 15 m high, fronted by marsh, and in places formerly quarried, probably in the 1850's). These two sections together show the most bed-exposures in the boundary interval and particularly in the overlying Park Limestone Formation (Figs. 2, 4). However, at Barker Scar, the position of the Cf5β boundary interval coincides with an interval with the most limited exposure (Fig. 4). The exposure at Grubbins Wood is, like Barker Scar, a sea cliff (but only 1-3 m high), fronted by marsh, and has limited (~10 m width) exposure of each bed, but nevertheless, has continuous outcrop like the other two sections, but with complete exposure of both the Cf5α and Cf5β boundaries (Fig. 3). Grubbins Wood does not show the transition into the Park Limestone Formation, but a 7 m section within the wood to the north, shows some of the lowest part of the Park Limestone. However, here the base of the formation, as well as the clastic interval at the top of the Raven's Member, are covered, representing a gap of ca. 3 m.

7. The Holkerian redefined

This work proposes that the Grubbins Wood section should be considered as the Holkerian boundary stratotype, at the base of the Cf5β subzone. This section contains the most complete faunal succession without apparent hiatuses, as well as the richest and most characteristic assemblages of the Cf5α and basal Cf5β subzones, allowing global correlation. The existing boundary stratotype for the Holkerian at Barker Scar is inadequate for the following reasons.

Firstly, the regional assessment of the boundary of the Dalton Fm-Park Limestone Fm, indicates that the clastic-rich interval at the top of the Raven's Member is more easily recognizable as a robust lithostratigraphical boundary (Hounslow et al. 2022). This represents a better criterion than the colour change of limestones and style of bedding, as described by Johnson et al. (2001) at Barker Scar (for the base of the Holkerian). Secondly, this former interval is also strongly dolomitised.

Thirdly, the biostratigraphy at Barker Scar, has no foraminiferal markers which could characterize bed K (perhaps the evolved species of *Holkeria* only), and more importantly the bases of the Cf5α and Cf5β subzones are much lower in the section than previous data suggested.

Fourthly, if the base of the Holkerian substage is to be correlated with international and non-British regional units, then the Barker Scar section is not the ideal boundary stratotype, since it lacks many important foraminiferal guides (or they occur in slightly younger positions).

7.1. The Holkerian as a body of rock

This work proposes to retain the Barker Scar section as the Holkerian unit-stratotype (in the sense of Hilgen et al. 2006, 2020), with the White Scar Quarry as a Holkerian unit-parastratotype. This designation recognises the utility of the Holkerian regionally as lithologically a rather similar body of rock. This is based on the following criteria.

1) Both sections are excellent representatives of most of the Holkerian in the region. Both sections are rather similar to each other in terms of the amount of exposure of beds, and both cover the lower parts of the Dalton Formation to mid parts of the Park Limestone Formation. Exposure is also excellent in both. The so-far unstudied remainder of the Park Limestone Formation at White Scar Quarry is exposed in outcrops overlying the studied section, and in the west of the quarry.
2) The base of the Holkerian unit-stratotype at Barker Scar should be repositioned to the base of bed C, where well-constrained foraminiferal markers of the Cf5β subzone occur (Fig. 5). The Holkerian unit therefore now includes the upper part of the Dalton Fm.
3) The White Scar Quarry section allows the filling of foraminiferal absences from the lowest part of the Holkerian, due to the dolomitisation at Barker Scar.
4) The Raven’s Member of the Dalton Formation, which contains the base of the Cf5β subzone, has its type section at White Scar Quarry.

8. Global correlation of the base of the revised Holkerian

The precise correlation of the new Holkerian boundary with the Livian in the French-Belgian basin, is imprecise, because:

1) The concept of *P. nibelis* is not clear in the Belgian sections, and it could represent a regrouping of some species of the genus.
2) Implicit in the definition of the markers in Belgium, is that the basal Livian and MFZ12 are primarily based on the first occurrence of *Pojarkovella nibelis*, with a subsidiary marker of *Koskinotextularia* (occurring later than *P. nibelis;* Poty and Hance, 2006). As has been demonstrated in Britain, *Koskinotextularia* first occurs earlier than *P. nibelis*.
3) The base of the Cf5β subzone is questionably correlated with the base of the MFZ12 zone, because the latter shows the first occurrence of taxa (e.g., *Consobrinellopsis*, *Lituotubella*, *Archaediscus* at *concavus* stage and *Nodosarchaediscus*) that occurs in the late Cf4δ to Cf5α interval.
4) In Belgium, typical markers of the Cf5β subzone first occur ‘too late’, i.e. within the lower part of Cf5β, since it is usual to see the coexistence of taxa typically also seen in the Cf4δ subzone. This ‘mixture’ of fauna is not observed in Belgium in the Dinant-Namur Basin (Poty et al. 2006). These typical ‘early Viséan foraminifers’ occurring in the Holkerian are recorded in the Grubbins Wood section, up to 6.5 m above the base of Cf5β, 2.72 m in White Scar, and up to 18 m above the base at Barker Scar. Thus, as well as the apparent absence of foraminiferal taxa seen from the upper part of Cf4δ and the entire Cf5α, the MFZ12 zone and the Livian stratotype also display a faunal gap in the lowest part of the Cf5β subzone (Fig. 10).

5) The definition of the MFZ12 Zone based on the FOD of *P. nibelis* implies that the MFZ11 Zone is defined as an interval zone whose top in theory (representative of the Moliniacian) extends through the base of the Livian.

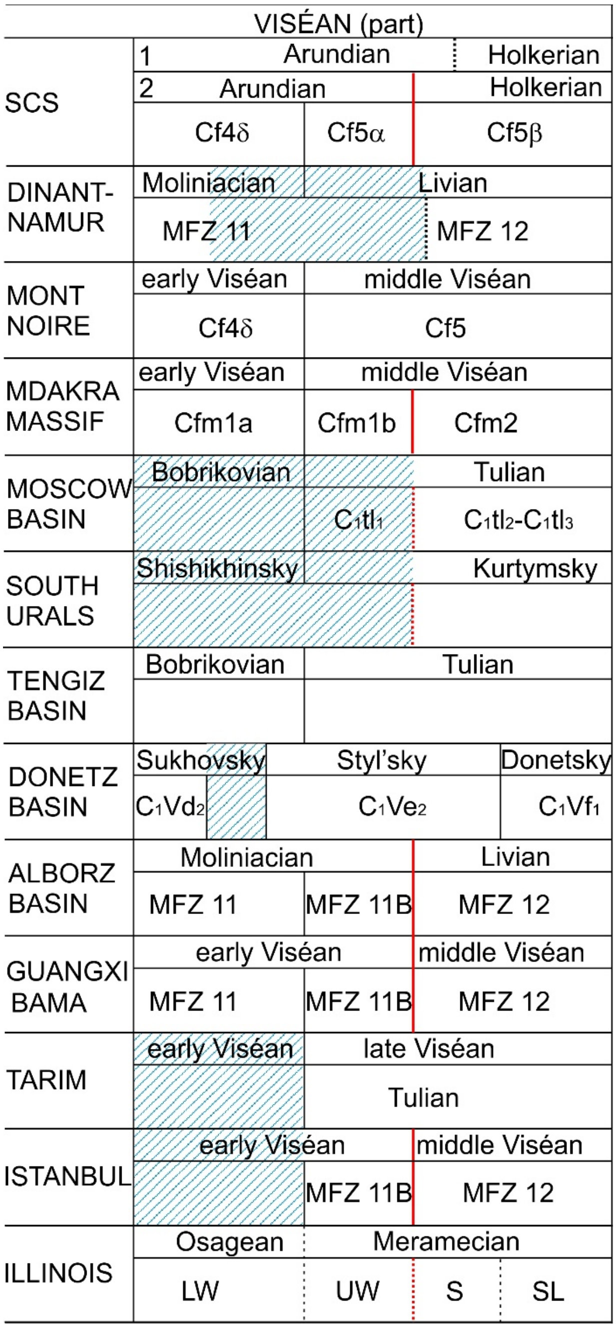

Fig. 10. Worldwide correlation of selected regional chronostratigraphic and foraminiferal biozones. Units and biozones described in the text. Illinois row shows lithologic units. The Arundian, Moliniacian, early Viséan, late Viséan, MFZ11, Donetsky and Osagean are only represented in part in the figure. The base of the traditional Holkerian (SCS 1 row) is repositioned, as proposed here, at the base of the Cf5β subzone (SCS 2 row). Diagonal hatching are important hiatuses and dotted lines are questionable lines of correlation. Abbreviations: MONT Montagne, LW Lower Warsaw, UW Upper Warsaw, S Salem.

Therefore, owing to all these issues, only a crude correlation of the Holkerian and Livian is plausible, where the lower barren 14.3 m in the Lives section might represent the Cf5α. Above this interval the Cf5β subzone is represented, but any correlation does not define a precise relationship between the base of both substages. According to the U-Pb dating of Pointon et al. (2021), the likely gap at the base of the Livian stratotype is about 1.25 Myr, spanning the interval from the base of the Lives Formation up to the first occurrence of *P. nibelis* (Durkina), 14.3 m above the base of the formation.

In southern France (Montagne Noire), the early occurrence of *Archaediscus* at *concavus* stage and primitive *Pojakovella* are recognised in the Valuzière, Combe Roland and Colonnes formations (Cózar et al. 2020a) before the typical *Pojarkovella occidentalis*, *P. nibelis*, primitive *Cribrospira* and *Endothyranopsis compressa* (Vachard et al. 2018), with *Koskinotextularia*, *Vissarionovella and Lituotubella magna* first occurring in slightly younger levels. These assemblages allow the distinction of both the Cf5α and Cf5β subzones at Montagne Noire.

In Morocco, the early Viséan is rather poorly represented (Cózar et al. 2020b), although sections in the Mdakra Massif allow identification of the Cf5α subzone (biozone Cfm1b; Fig. 10). Other sections containing more typical middle Viséan foraminifers of the Cf5β subzone correspond to local biozone Cfm2 (Fig. 10). However, in most sections, rare limestones interbedded in largely siliciclastic units do not allow recovery of continuous foraminiferal records.

Most classical markers of the Tulian Substage of the Moscow Basin, as described by Rauser-Chernousova (1948), Lipina and Reitlinger (1970), Makhlina et al. (1993) and Einor (1996), are recorded from the Cf5β subzone. This is also for the Kurtymsky Substage of the southern Urals in Kulagina and Klimenko (2014) and Kulagina (2022). In the Viséan, the substages defined in the Moscow Basin have their counterparts in the Western Urals, and their bases are equivalent (Alekseev et al. 2022). Unfortunately, most of the traditional studies summarised the foraminifers in intervals or by substages, and it is not possible to know if there could be a significant difference, in a bed-by-bed recognition of the boundaries of the Cf5α subzone. In the Russian Platform, the co-occurrence of ‘early Viséan foraminifers’ at the base of the Tulian is also a shared feature (e.g., Einor 1996), which indicates a more robust correlation with the Cf5α-Cf5β subzones in Britain.

At the Tengiz Platform, Kazakhstan, the occurrence of *Archaediscus pauxillus* from the top of the early Viséan (Brenckle and Milkina, 2003) suggests the Tengiz succession has both the Cf5α and Cf5β foraminiferal subzones, which could be identified with more detailed studies. It would be necessary to locate the base of the Cf5α subzone, whereas the base of the Cf5β subzone is well characterised as the Tulian Substage by the presence of *Endostaffella*, *Endothyranopsis compressa*, *Koskinotextularia* sp., *Cribrostomum*, *Palaeotextularia*, *Pojarkovella nibelis*, *Vissariotaxis exilis* (Vissarionova), and *Pseudoendothyra.* At Tengiz there is also a clear co-occurrence with typically early Viséan forms in the rocks assigned to the Tulian.

In Ukraine, similar foraminifers to those of the middle Viséan in Western Europe are described from the Microfaunistic Horizon XIIa of Brazhnikova et al. (1967) or the C_1Ve_2–C_1Vf_1 biozones of Brazhnikova and Vdovenko (1973), characterised by the

Vissariotaxis exilis-Ammarchaediscus eospirillinoides-Lituotubella magna Zone (Cf10), and corresponding to the Styl'sky and the lower part of the Donetsky substages. Vdovenko (1973) considered as distinctive the *Ammarchaediscus eospirillinoides* (Brazhnikova) and the *Vissariotaxis exilis-Lituotubella magna* zones, which seem to correspond to the Cf4δ–Cf5α boundary. However, the occurrence of *Vissariotaxis* is questionably earlier than in Western Europe because Poletaev et al. (1991) suggested that the taxon occurs in the upper part of the Cf10 zone. However, the other taxa suggest that this zone includes the Cf5α-Cf5β subzones, and thus, the existing gap in foraminifers corresponds to the upper part of the Sukhonsky Substage, equivalent to the middle part of the Arundian (Fig. 10).

In Iran (Alborz) an interval of about 1 m is observed between the first occurrence of primitive *Pojarkovella*, and the *Pojarkovella nibelis* morph. 2 (although many of them were included under a generic identification as "ex group", forms only present from sample MZ87; see Zandkarimi et al., 2016, figs, 3 and 8). However, at Alborz, the first representative of the genus *Koskinotextularia* occurs a few metres above this datum. All of the taxa were assigned to the MFZ12 zone, which can be correlated with the Cf5β subzone (Fig. 10). Hence, both Cf5α-Cf5β subzones seem to be present at Alborz, and the earlier occurrence of *Archaediscus* at *concavus* stage would permit the recognition of the Cf5α subzone below the base of the MFZ12 (see Zandkarimi et al. 2017).

The Chinese standard substages do not coincide with those in Europe, because the base of the Holkerian, Tulian or Livian, are correlated with the middle part of the Jiusian (Davydov et al. 2004), middle-upper part of the Jiusian (Aretz et al. 2020, Lucas et al. 2022) and top Jiusian (Davydov et al. 2012). However, the MFZ12 or *Pojarkovella nibelis* Zone is readily recognisable in the Guanxi Province of South China (e.g., Hance et al. 2011, Sheng and Wang 2015). There are also primitive *Pojarkovella* and *Koskinotextularia* and a basal interval with mixed faunas of the early Viséan in Guanxi, Bama platform and Tarim Basin (Hance et al. 2011, Liu et al. 2015, Brenckle 2004 respectively). These were used to define the MFZ11B of Hance et al. (2011). In addition, Brenckle (2004) recognised much older occurrences of *Pojarkovella* sp. (>100 m below the classical *P. nibelis*), although these were included in all the interval assigned to the Russian Tulian Substage. This subzone suggests that a detailed correlation between China and Europe is plausible (i.e., recognizing the Cf5α–Cf5β subzones), but enhancement of research in this interval in China is needed to calibrate possible synchronous events.

In the Istanbul Terrane of Turkey, the MFZ11B Zone was also recognised. The occurrence of *Archaediscus* at *concavus* stage (*A.* aff. *pauxillus*) (Okuyucu et al. 2013, fig. 8CC) from the basal sample of this subzone, allows correlation with the Cf5α subzone in Britain, whereas the Cf5β subzone should be represented in higher levels of the shaley Kartaltepe Member.

Correlation of these foraminiferal subzones with the American zonal schemes is difficult, due to the absence of the most important markers. The base of the Meramecian Substage has been correlated with the base of the Livian or Holkerian (Davydov et al. 2004, 2012, Brenckle 2004, Lane and Brenckle 2005, Lucas et al. 2022), but also, with the middle part of the Arundian or Moliniacian (Heckel and Clayton 2006, Aretz et al.

2020). Foraminifers do not seem to be the best group for calibration of the intercontinental correlation of the Meramecian. Foraminifers from the Upper Warsaw and Salem formations in Illinois are typically recorded in the upper part of the Arundian in Western Europe. Also, typical mid Viséan foraminifers (e.g., *Archaediscus convexus* Grozdilova and Lebedeva, *Endostaffella*) are only recorded from the younger St Louis Formation, a formation which is traditionally considered equivalent to the Asbian of the late Viséan (see Lane and Brenckle 2005). Hence, there are no clear foraminiferal criteria to correlate the Holkerian and Asbian with the American Realm.

These comparisons highlight that further research on the base of the Cf5α–Cf5β subzones could produce a consistent global chronostratigraphic boundary, suitable for defining the basal mid Viséan. Although the Cf5α occurs with hiatuses, or unfavourable facies in some regions, the Cf5β subzone seems to be well represented worldwide, particularly within Palaeotethys.

9. Conclusions

High-resolution foraminiferal biostratigraphy of beds at the boundary interval for the base of the Holkerian Substage in the type region of south Cumbria includes rich associations which have been used to precisely define the base of the Cf5α and Cf5β foraminiferal subzones. This work has involved detailed sampling at Barker Scar (current boundary stratotype), White Scar Quarry and Grubbins Wood sections. The base of the Cf5α subzone is primarily defined by the presence of *Archaediscus* at *concavus* stage (including *A. pauxillus*) and *Pojarkovella ketmenica*. The base of the Cf5β subzone is defined by the appearance of several species of *Koskinotextularia* and also by common *Archaediscus* at *concavus* stage (e.g., *A. moelleri*), *Endothyranopsis compressa*, *Omphalotis minima*, and small and moderate-sized species of *Pojarkovella* (*P. occidentalis*, *P. pura*, *P. nibelis* morph. 1). The overlying part of the Cf5β subzone is characterised by the first occurrences of large *Pojarkovella* (e.g., *P. nibelis* morph. 2) and other species of evolved *Koskinotextularia* (*K. bradyi*, *K. obliqua*).

The most complete succession of foraminiferal taxa is recorded in the Grubbins Wood section, whereas at White Scar Quarry and Barker Scar, short faunal gaps are inferred to be present at the base of the Cf5α and Cf5β subzones. Furthermore, the Grubbins Wood section is almost free of dolomitisation and contains the richest and most diverse foraminiferal assemblages. The White Scar Quarry section has intermediate diversities compared to Barker Scar, which is most strongly affected by dolomitization, consequently having the lowest richness and diversity. However, the Grubbins Wood section has the smallest lateral exposure of beds, compared to White Scar Quarry, which shows the best exposures of the Cf5α and Cf5β subzones in any of these sections.

The higher quality and diversity of foraminifers recorded in Grubbins Wood section indicates this should be the new Holkerian boundary stratotype. The utility of the Holkerian as an interval encompassing a viable lithostratigraphic unit that can be correlated regionally, suggests the Barker Scar section should be retained as a Holkerian unit stratotype, with its base repositioned to the base of bed C, at the base of the Cf5β subzone. The White Scar Quarry section could act as a Holkerian unit parastratotype, to fill the common absences of taxa in the Barker Scar section in the basal Holkerian.

The rich foraminiferal assemblages in the studied interval suggest a close correlation with other regional substages or local foraminiferal zones elsewhere internationally, particularly within the Palaeotethys. Further investigation in other countries could facilitate the establishment of a chronostratigraphic horizon at the base of the 'mid Viséan'.

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