Accepted Manuscript

Proceedings of the Yorkshire Geological Society

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DOI: https://doi.org/10.1144/pygs2023-003

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Received 6 June 2023
Revised 14 August 2023
Accepted 14 August 2023

High-resolution definition and correlation of the Asbian-Brigantian boundary in northern England and the Scottish borders, using foraminiferal diversity and richness

Pedro Cózar[1]*, Ismael Coronado[2], Ian D. Somerville[3] and Mark W. Hounslow[4,5]

[1] Instituto de Geociencias (CSIC-UCM), c/ Severo Ochoa 7, 28040-Madrid, Spain; https//orcid.org/0000-0002-4669-8702

[2] Facultad de Ciencias Biológicas y Ambientales, Universidad de León, Campus de Vegazana s/n, 24071-León, Spain; https//orcid.org/0000-0002-8469-6003

[3] UCD School of Earth Sciences, University College Dublin, Ireland; https//orcid.org/0000-0001-8379-9097

[4] Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YW, UK; https//orcid.org/0000-0003-1784-6291

[5] Earth, Ocean and Ecological Sciences, University of Liverpool, Jane Herdman Building, Liverpool, L69 3GP

* Correspondence: p.cozar@csic.es

Abstract: Foraminiferal diversity and taxa richness from beds transitional between the Asbian and Brigantian substages (Middle Mississippian) show patterns of secular change which allow detailed inter-regional correlations to be established. Foraminifera from the Askrigg Block, Stainmore Trough, Alston Block, South Cumbria Shelf and Solway Basin show similar secular changes (foraminiferal trends, FTs), allowing correlation to be made with the basal Brigantian Stratotype at Janny Wood. Despite the absence of consistent microfossil first occurrence markers for the recognition of the base of the Brigantian, this horizon can be confidently recognised by means of foraminiferal trends. The FTs allow the precise location of the base of the correlated Brigantian in sections where this boundary was questioned or controversial in previous studies, as well as to amend the position of the foraminiferal zones and subzones during the late Asbian and basal Brigantian. This type of analysis when used in combination with foraminiferal zonations, emergent surfaces and lithological cyclicity, together, provide a robust means for high-resolution correlation. This methodology, provides the least uncertainty in sections that have been most densely sampled, whereas for less intensely sampled sections there is more correlation uncertainty.

Sections from northern England and the Scottish borders (Fig. 1) contain the transition between the Asbian and Brigantian substages, in shallow-water facies, with common foraminifers. The Brigantian Substage was defined by George *et al.* (1976) at the base of the Peghorn Limestone (Fig. 2a) in the Janny Wood section (Kirkby Stephen). This is a substage of the British regional scale, representing the uppermost division of the Viséan Stage, which is also ratified as a regional substage by the International Commission on Stratigraphy (Heckel and Clayton 2006). However, the basis for the definition of the Mississippian substages in Britain have been commonly criticised as too strongly dependent on sequence stratigraphic concepts, recognisable by field data, which in most cases lack other stratigraphic and biostratigraphic data to support the wider correlation of the boundaries (e.g., George 1978; Strank 1981; Riley 1993; Cossey *et al.* 2004; Waters 2011). Particularly in the Janny Wood section, Riley (1993) recognised transitional coral and brachiopod faunas between the Asbian and Brigantian substages. Cózar and Somerville (2004), on the other hand, recognised more typical Brigantian foraminiferal assemblages from the Birkdale Limestone, similar to those recorded in the overlying Peghorn Limestone (Fig. 2a). McLean *et al.* (2018) revised the palynology in the Janny Wood section, where they recorded representatives of the VF biozone from shales immediately above the Robinson Limestone (below the Birkdale Limestone; Fig. 2a). This miospore biozone was considered as typical of the Brigantian, but, these authors concluded that the VF biozone is instead first recorded from the Asbian. The first occurrence of the VF biozone in the Asbian, and similar foraminiferal assemblages from the Birkdale Limestone led McLean *et al.* (2018) to suggest that the base of the Brigantian cannot be easily correlated away from the type section.

Above the Birkdale Limestone, the Alston Formation is representative of the Yoredale Group (Dean *et al.* 2011). The definition of the base of the Alston Formation was generally coincident with the limestone that marks the base of the Brigantian, although in some districts, where this boundary cannot be mapped, was taken at the top of the underlying mappable limestone (Dean *et al.* 2011, p. 118). This implies that in these regions, the base of the Alston Formation is Asbian in age, as in Northumberland. In other regions, such as south Cumbria, the base of the Alston Formation was defined at or in the shale below the *Girvanella* nodular Band of Garwood (1913). This formation was previously named the Gleaston Formation by Rose and Dunham (1977) (Fig. 3a), but was later considered as an obsolete term for the Alston Formation by Dean *et al.* (2011, p. 162). However, the Asbian-Brigantian boundary interval can be locally affected by hiatuses, omitting the uppermost part of the Asbian, and questionably, the basal part of the Brigantian (e.g., Waters *et al.* 2021), and in other cases, thick intervals of the late Asbian are missing, such as in Wales (Cózar *et al.* 2022a).

Cózar *et al.* (2022a) have recognised a cyclicity in the foraminiferal diversity of upper Asbian strata, allowing the definition of synchronous foraminiferal trends (FTs) in northern England, Wales and Ireland. Up to 13 FTs were described for the late Asbian, which were calibrated to five foraminiferal assemblages of biostratigraphic significance (Cózar *et al.* 2022b). This composite stratigraphy allows amendments to the mismatches in the first occurrences of key markers in some of the sections and so when used together achieves more precise correlations.

The aim of this study is to analyse the diversity and richness of some foraminiferal taxa during the uppermost Asbian to basal Brigantian of northern England (and in the border region of Scotland). Using this data in combination with other correlation markers allows a better validation and consistency in the recognition of the basal Brigantian in different lithological successions and regions of northern England.

Methodology and studied sections

The Margalef index, D is one of the most popular diversity indices, and is defined as D= (S-1) / ln(n), where S is the number of species and n is the total number of individuals and hence, is basically a measure of species richness (Magurran 2004). The Margalef index responds to basic environmental variables (Li *et al.* 2019), but remains influenced by sampling effort as the main disadvantage (Magurran 2004). Also considered biostratigraphically important for the studied interval are metrics for abundance of identified individuals (SA) (total number of specimens per large thin-section, which is 50 by 80 mm in size, prepared for Janny Wood, Rookhope Borehole, Archerbeck Borehole, Back Scar Borehole and Silverdale Borehole; and total number of specimens every two small thin-sections, 30 by 50 mm in size, prepared for Trowbarrow Quarry), and the richness of selected taxa (RST) (number of specimens for all the species of a genus per thin-section and every two thin-sections for Trowbarrow Quarry). These three indices were calculated, using Past4.05 (https://www.nhm.uio.no/english/research/infrastructure/past/). The FTs of Cózar *et al.*

(2022a) were defined on the basis of marked shifts, peaks or changes in the overall Margalef index, linked to the major emergent surfaces at Trowbarrow Quarry (north Lancashire, South Cumbria Shelf) [SD 4800 7575], which acts as the reference section for the FTs. They also demonstrated quantitative correlation of the 13 FTs was possible between key English and Irish late Asbian sections using sequence slotting with a multivariate set of diversity indices. Thus, as overall features, FT10 is characterised by two maximum peaks in the D-index, one in the upper part, and a second peak in the lower part, but generally with lower D-indices than the upper peak. FT11 is characterised by a declining trend in the D-index, with lower D-indices in its upper part. FT12 show two peaks in D and is increasing weakly throughout, whereas FT13 is characterised by minimum D-indices in the middle part. In spite of differences in the curves for each trend, correlation provides good between-section coherent patterns of diversity changes. In addition, peridograms using the Lomb-Scargle and multi-taper methods in Trowbarrow Quarry showed significant periodicity at around 11 m, which is broadly related to the average spacing of major palaeokarsts, which justifies that FTs are a response to the cyclicity (Cózar *et al.* 2022a).

The aim of this study is to compare and characterise the basal Brigantian stratotype, Janny Wood section [NY7832 0385], using the dataset of foraminiferal associations described in Cózar and Somerville (2004). Additional datasets used for this analysis are the foraminiferal assemblages of the Asbian-Brigantian transition from the Archerbeck Borehole (Dumfriesshire, Solway Basin) [NY 4156 7815], Rookhope Borehole (Weardale, Alston Block) [NY 9375 4278], Back Scar Borehole (North Yorkshire, north Askrigg Block) [SD 8606 6470] and Silverdale Borehole (North Yorkshire, south Askrigg Block) [SD 8435 7143] are from Cózar and Somerville (2004, 2013) and Waters *et al.* (2017) (Fig. 1). The diversity data for some of these borehole records during the late Asbian were published by Cózar *et al.* (2022a; supplementary information fig. S9).

Biostratigraphic constraints on the Cf6γ and Cf6δ foraminiferal subzones

Foraminiferal assemblages of the sections have been previously published (see Methodology Section), and using the foraminiferal assemblages Cf6γ2a to Cf6γ2c, allow some preliminary biostratigraphic control on the sections based on the first occurrence (FO) of key taxa (starred points in Figs. 2, 3).

In the latest Asbian, transitional to the Brigantian, the foraminiferal assemblages Cf6γ2b-Cf6γ2c are more easily recognized, whereas the Cf6δ subzone is not characterized by consistent foraminiferal markers. The latest Asbian assemblages are characterised by the abundance of large *Archaediscus* ex gr. *karreri* Brady 1873, *Bradyina*, *Howchinia* and *Neoarchaediscus*. Particularly noteworthy, is the occurrence of large *Archaediscus karreri karreri*, *Bradyina rotula* (Eichwald 1860), *Howchinia bradyana* (Howchin 1888) emend. Davis 1951 and occluded forms of *Neoarchaediscus*, such as of *Neoarchaediscus incertus* (Grozdilova and Lebedeva 1954) and *N. parvus* (Rauzer-Chernousova 1948b). Evolved *Eostaffella* with a well-differentiated wall (e.g. *E. mosquensis* Vissarionova 1948, *E. parastruvei* (Rauzer-Chernousova 1948a) and *E. ikensis* Vissarionova 1948), as well as *Endothyranopsis crassa* (Brady 1876), which begin to develop wider nautiloid tests, becoming transitional to the younger *E. sphaerica* (Rauzer-Chernousova and Reilinger in Rauzer-Chernousova *et al.* 1936). Small *Archaediscus* spp. at *angulatus* stage (cf. Conil *et al.* 1980), and *Endostaffella* also become abundant. Also useful as indicators for this upper part of the late Asbian, are calcareous algae such as *Ungdarella* which can present an acme, and also large *Saccamminopsis* first occurs (Figs. 2, 3). Most of these taxa generally first appear within the foraminiferal assemblages Cf6γ2b-Cf6γ2c of Cózar *et al.* (2022b), although their FO's develop randomly in this interval (Figs. 2, 3). However, in some sections, they first occur from older levels or in some cases within the Brigantian (Fig. 2a, 2b, 3b).

The occurrence of *Parajanischewskina* never forms large concentrations of specimens, but occurs in a few levels and is of significance. This genus has been confused with *Janischewskina* in Janny Wood and used in most previous zonal schemes from Britain as a marker of the basal Brigantian (see discussion on Cózar and Somerville, 2006), whereas *Janischewskina typica* Mikhailov 1939 has its FO in the late Brigantian or Serpukhovian (Cózar and Somerville 2021). There are rare ancestral forms of *Janischewskina minuscularia* (Ganelina 1956) recorded close to the base of the Brigantian in Silverdale Borehole (Fig. 3b), although the species has not been recorded in any other section, thus, its reliability as potential marker is questionable. On the other hand, the FO of *Parajanischewskina* is located in the latest Asbian, and not at the base of the Brigantian, as in Janny Wood (Fig. 3b; Waters *et al.* 2017).

Other foraminiferal markers traditionally used for the recognition of the Brigantian (e.g., in George *et al.* 1976; Conil *et al.* 1980; Strank 1981; Riley 1993) have been discussed in Cózar and Somerville (2004, 2006), and have been discarded as potential markers because their first occurrences are located far above or below the base of the Brigantian. Therefore, the occurrence of *Asteroarchaediscus* (FO near to the top of the early Brigantian), *Neoarchaediscus* (FO in the late Asbian), *Loeblichia* (FO in the middle of the early Brigantian), *Janischewskina* (usually FO in the late Brigantian), *Warnantella* (FO in the late Brigantian) cannot be used for the recognition of the basal Brigantian. Conil *et al.* (1980) used *Loeblichia*, *Warnantella* and *Janischewskina* as markers for the Cf6δ foraminiferal subzone, and they correlated the base of the Brigantian with the base of the subzone, a concept that has been widely used in subsequent publications. In contrast, Riley (1993), used *Asteroarchaediscus*, *Janischewskina*, *Loeblichia* and *Warnantella* as markers for the Cf6δ foraminiferal subzone, which was located in slightly younger levels than the base of the Brigantian, coincident with the P1c ammonoid subzone, whereas the base of the Brigantian is located at the base of the P1b ammonoid subzone.

Significantly, some calcareous algae (e.g., *Paraepimastopora*, *Claracrusta* and *Fasciella crustosa* Vachard *et al*. 2004) show a more consistent pattern, mostly first occurring from the basal Brigantian (Figs. 2b, 2c, 3a, 3b, 3c) and rarely from the upper part of the Cf6γ2c in Britain (Fig. 2a). Unless the FO of calcareous algae are used as markers, it is clear that the base of the foraminiferal Cf6δ subzone does not coincide with the supposed base of the Brigantian, typically represented by foraminifers of the Cf6γ2c subzone. The FO of typical Brigantian foraminifers occur between 10 and 20 m above the basal boundary (except for Back Scar Borehole, where it occurs ~3 m above; Fig. 3c).

In consequence, after investigating numerous sections through the Asbian-Brigantian transition, there are no unequivocal FO foraminiferal markers that can be used to identify the base of the Brigantian, nor the base of the Cf6δ foraminiferal subzone, only an 'overall suite' of foraminifera commonly associated with the transition interval. For many authors the base of the Cf6δ subzone is pragmatically and approximately coincident with the base of the Brigantian, but certainly there is no definitive marker. Those foraminifera restricted to the Brigantian, first occur in younger levels, e.g. *Loeblichia*, which first occur in the Grain Beck or Gayle limestones (Cózar and Somerville, 2004). Similarly, *Howchinia gibba* (von Möller 1879) first occurs in the

Smiddy Limestone (Cózar and Somerville, 2004), although this foraminifer, like all members of the family Lasiodiscidae, seem to be strongly facies-controlled, only occurring in quiet-water environments (cf. Cózar *et al.*, 2019). This predilection for low-energy environments does not make it suitable as a potential marker in the predominantly higher-energy, shallow-water platform facies such as those in northern England. *Janischewskina minuscularia* has been recorded only in one section. In addition, there are rare forms, identified as *Howchinia* aff. *gibba* and *H. cummingsi* (Hallett 1971) which are recorded closer to the base of the Brigantian (Figs. 2a, 2c, 3a, 3b, 3c), but their occurrence is not as uniform enough to be considered as a good marker.

Hence, with the available data, there are three possibilities: first, to reposition the base of the Cf6δ subzone to a lower horizon, coincident with the base of the Cf6γ2c assemblage at the Robinson Limestone; second, to move it to a higher horizon, coincident with the FO of *H. gibba* at the Smiddy Limestone; or third, to locate it at an even higher horizon, marked by the FO of *Loeblichia* at the Grain Beck Limestone or Gayle Limestone Member. This latter third position is coincident with that proposed by Riley (1993) at the base of P1c ammonoid zone, as well as with the first occurrence of the conodont *Lochriea nodosa* (Bischoff 1957), as recorded by Davies *et al.* (1994), an ammonoid subzone which is recorded in shales above the Gayle Limestone of the Askrigg Block (Dunham and Wilson 1985; Arthurton *et al.* 1988). In all three cases, these levels are located at some distance either above or below the base of the Brigantian. Other rather arduous possibilities are to investigate more intensely the basal Brigantian beds, and so potentially establish a more uniform occurrence of the rare species mentioned above, or test if calcareous algae can be considered consistent enough as markers for the base of the Cf6δ subzone.

Foraminiferal diversity trends and abundance patterns

As discussed above, common biostratigraphic markers for the base of the Brigantian are absent or they first occur in much younger horizons, however, when combined with the foraminiferal trends (FTs), do allow a correction to be made to the imprecise biostratigraphy (Cózar *et al.* 2022a).

The fundamental assumption is that the foraminiferal trends (FTs) are a result of glacioeustasy or Milankovitch-forced cyclicity, which influenced the foraminiferal distribution in upper Viséan strata in northern England, showing an internal ordering within each trend. The FTs permit the correlation of cycles and emergent surfaces over long distances (hundreds of kilometres). The main constraint for the use of the FTs is the density of sampling; closely-spaced samples in sections show more robust changes allowing the establishment of clearer patterns, whereas sparsely sampled sections show more questionable trends, which in some cases are difficult to correlate. The bases of the FTs were selected at the lower emergent surface or prominent lithological changes. Thus, the FO of the key markers for each assemblage is commonly up to a few metres above the base of the FT, or exceptionally, located just at the base. In those cases, where the foraminiferal markers do not coincide with the base of the FTs, the base of the biozonal assemblage should also be displaced to be coincident with the base of the FTs, and therefore coincident with major lithological changes or emergent surfaces (see black columns on the right in Figs. 2, 3). In fact, the FO of markers for the Cf6γ2c assemblage usually occur close to the inferred base of FT12 (Figs. 2a, 3a, 3b, 3c), whereas markers for the Cf6γ2b assemblage first occur in more distal positions from the inferred base of FT10 (Fig. 2a, 2b, 2c, 3a, 3c).

Within the interval represented by assemblage Cf6γ2c, two FTs are recognised, FT12 and FT13, usually separated by a prominent emergent surface. Likewise, for the Cf6γ2b assemblage which contains FT10 and FT11.

From a biostratigraphical point of view, the only distinguishing feature is that the important taxa (discussed above) are much more common in FT13 and the basal Brigantian, than in the underlying FT12 (e.g., Fig. 2a, 2b, 3a, 3b, 3c). Similarly, with respect to the base of the Brigantian, there is no particular FO of foraminifera which allows distinction of FT13 and FT12 confidently, nor between FT10 and FT11.

Secular changes in Margalef diversity

The Margalef index in FT12 shows two positive excursions (Figs. 4, 5). The absence of one of these excursions might suggest that the succession is not complete or poorly preserved in some sections, as observed in the Silverdale Borehole, where FT12 is interrupted by 3 emergent surfaces (Fig. 3b). Nevertheless, the number of diversity excursions present might also be controlled by sampling density. When the number of samples assigned to FT12 is small, both maxima occur in the lower and upper parts of the interval (Figs. 4c, 5b), whereas, if there are more numerous samples, these two maxima are located in the lower and middle part of FT12 (Fig. 5c, 4a). In the most densely sampled section containing FT12 at Janny Wood, these two excursions are located in the middle and upper parts. This variation in the position of the excursions (apart for in densely sampled sections), might correspond to the absence of part of the successions at intervening emergent surfaces.

If the Margalef index are rearranged at a metre-scale (Figs. 2, 3), the FTs can be more difficult to visualize, due to the shaley intervals between limestones (particularly in the Archerbeck Borehole). At an equidistant position for samples, the trends are visually clearer (Fig. 5c).

At Trowbarrow Quarry, foraminiferal trend FT12 starts 7 m below the Humphrey Head Limestone Member and includes the lower part of this member (Fig. 3a). FT12 is between 34 m and 30 m depth in the Silverdale Borehole; between 66.5 m to 60 m depth in the Back Scar Borehole, and occupies the entire Robinson Limestone at Janny Wood and the Rookhope Borehole. FT12 is between 529 m and 547 m depth (lower part of Archerbeck Beds 3) in the Archerbeck Borehole (Figs. 2, 3).

The top of FT13 is critical for the recognition of the base of the Brigantian and changes in D-values are more consistent than for FT12 (except for the sparsely sampled Silverdale Borehole), showing two spikes in D-values (Figs 4,5) in the sections, one in the lower part and other in the upper part of FT13. FT13 is recognised in the Birkdale Limestone at Janny Wood and in the Rookhope Borehole, within the upper Humphrey Head Limestone Member in Trowbarrow Quarry. FT13 is between 529-504 m in the Archerbeck Borehole (upper part of Archerbeck Beds 3 p.p.), at 30-23.5 m depth in the Silverdale Borehole, and 60-55 m in the Back Scar Borehole (Figs. 2, 3). The transition into the Brigantian coincides with a decreasing trend in D-values from the second excursion in D-values in FT13 (Figs. 4, 5). This is valid except for the Archerbeck Borehole, where anomalous assemblages obtained from argillaceous limestones within the shales (samples at 1680’9” and 1710’; Fig. 2c), give an ascending trend. If these anomalous samples are excluded, the diversity-trend from FT13 to the basal Brigantian also becomes decreasing, as in other sections.

Overall, the Margelef index during the basal Brigantian does not show fully consistent patterns. Generally, there are lower diversity values in the basal part, followed by a positive excursion (Figs. 4,5), followed by progressively decreasing values for intervals equivalent to the Peghorn Limestone, up to the *Girvanella* nodular Band (Fig. 5). This diversity trend is not so clearly recognised in the Silverdale Borehole (due perhaps to sparse sampling?) nor in the Rookhope Borehole (since there are no well-preserved limestones in the interval equivalent to the lower Peghorn Limestone; Johnson and Nudds, 1996).

Secular changes in richness of selected taxa

Despite the comprehensive biostratigraphy of the important taxa, it is clear that the richness in *Howchinia* and *Bradyina* is irrelevant in most sections (Figs. 4, 5), since the resulting richness curve is mostly a sum of the specimens of *Archaediscus* ex gr. *karreri*, 'evolved' *Eostaffella* and *Neoarchaediscus,* as well as concentrations of *Endothyranopsis* (Fig. 4, 5). The richness of these taxa shows a consistent pattern of phases in most sections. In general, FT13 is characterised by larger richness-values than in FT12 (Figs. 4, 5), except for the Archerbeck Borehole (Fig. 5c). This pattern of phases (large blue arrows numbered 1 to 6 on the richness curve in Figs. 4, 5) consists of: (1) a progressive increase to larger richness up to FT12, (2) a rather marked decrease in the uppermost part of FT12, (3) a rapid increase in values up to the uppermost part of FT13, usually with an intermediate low richness value, followed by (4) another marked decrease in the lower part of the Brigantian, although there is a more positive shift interrupting this phase, (5) a subsequent increase in richness reaching similar values as in FT13, and finally (6) an overall decrease to the top of the Peghorn Limestone or its lateral equivalents. The inferred base of the Brigantian occurs within the decreasing phase numbered 4 (Figs. 4, 5). In addition, the maximum values for the Margalef diversity (D) are usually mimicked by the taxa richness (RST), as well as specimen abundance (SA), although not in all the cases. Noteworthy, are the high diversity values in some intervals which coincide with relatively low values in richness and specimen abundance. This is observed: (1) in the lower part of the Cf6γ2c assemblage in Trowbarrow, Janny Wood, Rookhope Borehole and Archerbeck Borehole (Figs. 4a, 5a, 5b, 5c); (2) at the base of the Brigantian in Trowbarrow, Janny Wood and Archerbeck Borehole (Figs. 4a, 5a, 5c). Alternatively, in intervals with low diversity, such as that separating both excursion peaks in FT13, locally, the richness and abundance are large, such as at Trowbarrow, Back Scar Borehole, Janny Wood, and Rookhope Borehole (Fig. 4a, 4c, 5a, 5b).

The role of the shales in the richness and abundance changes in foraminiferal assemblages is problematic, and although in the overlying limestones, assemblages rapidly recovered, thicker intervals with shales in the successions show that the succeeding foraminiferal assemblages may display unusual patterns. Certainly, the foraminiferal abundances, show a direct relationship with the amount of shale in the sections (compare the specimens per thin-section in shaley intervals in Fig. 5, with the intervals with scarce shales in Fig. 4). The upper part of the Peghorn Limestone in the Rookhope Borehole is extremely rich in selected taxa, a richness which is usually recorded in lower levels of the Brigantian in other sections (Fig. 5b). Also, the entire Archerbeck Borehole shows a distinctive richness, more so than in the other sections.

Implications of this approach

The combination of the foraminiferal diversity trends (FTs) and phases in the foraminiferal richness gives a set of sound criteria for the identification of the base of the Brigantian, when combined with the foraminifera subzonal assemblages. The precision in identification of the trends and richness phases depends notably on the density of sampling, and thus, by themselves cannot precisely locate and correlate the base of the Brigantian. In such cases, the stratigraphically older prominent lithological change, bedding plane or emergent surface is selected as the base for the Brigantian.

Foraminiferal assemblages from FT12, FT13 and the base of the Brigantian are similar, with no clear independent markers, leading to ambiguous or confounding results. The similarity in markers cause the misidentification of the base of the Brigantian. However, diversity and richness changes help to correlate the position of the base of the Brigantian in other sections (from the stratotype at Janny Wood). Thus, the position of the Brigantian in Trowbarrow Quarry is confirmed at 168 m above the base of the late Asbian (as published in Cózar *et al.* 2022b), amending the previous position at ~160 m, as proposed by Horbury (1987), and that at 187 m, proposed by Dean *et al.* (2011) (Fig. 3a). The base of the Brigantian in the Silverdale Borehole is located at 23 m depth (as already published in Murray 1983), whereas the 'transitional zone' (up to 30 m depth) of Waters *et al.* (2017) corresponds to FT13 (Fig. 3b). The base of the Brigantian in the Back Scar Borehole is modified, with it now being located at 54 m depth, and that previously used by Murray (1983), White (1992) and Cózar and Somerville (2004) at 60 m depth, is now considered as the base of the FT13 (Fig. 3c).

The base of the Callant Limestone in the Archerbeck Borehole (formerly regarded as the base of the Brigantian), as inferred by Lumsden and Wilson (1961), is now, together with the 'unnamed limestone Z' (used by Cummings 1961; Strank 1981) correlated with the upper parts of the Peghorn Limestone or lower Smiddy Limestone (not analysed in detail). In contrast, the base of the Cornet Limestone at 505 m depth (used together with the Callant Limestone as a transitional zone by Cummings (1961) and Strank (1981), or as the base of the Brigantian by Cózar and Somerville (2013)), is now considered as the base of the Brigantian (Fig. 2c).

Conclusions

Foraminiferal diversity and richness of selected taxa in transitional beds between the Asbian and Brigantian substages, mostly from northern England, have been analysed in detail, in order to establish trends and patterns of change which are comparable between regions. Foraminifera from the Askrigg Block, Stainmore Trough, Alston Block, South Cumbria Shelf and Solway Basin show similar trends in diversity and richness and demonstrate that the new combined-strength approach is valid for correlating sections with the basal Brigantian Stratotype at Janny Wood.

In spite of the absence of microfossil FO markers for the recognition of the base of the Brigantian, this horizon can be confidently recognised by means of foraminiferal trends (FTs) and richness of selected taxa. In addition, the FTs allow adjustment of the position of the foraminiferal subzones and assemblages in the late Asbian due to the patchy occurrence of key markers. The FTs allow establishment of the precise base of the Brigantian in some other sections where this boundary was previously questioned or controversial. Cyclical changes in foraminiferal richness supplement this approach. This amends the basal Brigantian boundary in sections that traditionally were incorrectly identified, such as in Back Scar Borehole. This combined methodology, although successful, has the caveat that it provides the most robust results in sections that have been densely sampled, whereas less intense sampling lowers the clarity of the correlations, and could prevent the recognition of the cyclical-changes in diversity and richness.

Acknowledgements We are grateful to the comments by D. McLean, D. Holliday and C. N. Waters which have helped improve this paper. The authors wish to thank M. Howe and M. Dean, British Geological Survey, Keyworth and Edinburgh, who facilitated the examination of thin sections of borehole and outcrop material from northern England and Scotland held in the BGS collections. Natural England, Lancaster City Council and Arnside-Silverdale AONB provided access and permits to collect samples from Trowbarrow Quarry.

Author contributions **PC**: conceptualization (lead), data curation (lead), formal analysis (lead), investigation (lead), methodology (lead), visualization (lead), writing – original draft (lead), writing – review & editing (lead); **IC:** conceptualization (supporting), formal analysis (supporting), writing – review & editing (supporting); **IDS**: conceptualization (supporting), investigation (supporting), writing – review & editing (supporting); **MWH**: conceptualization (supporting), formal analysis (supporting), investigation (supporting), methodology (supporting), writing – review & editing (supporting)

Funding **MWH** was part funded by NERC (grant NE/P00170X/1).

Data availability Datasets were generated or analysed during the current study were already published in the supplementary information in Cózar et al. (2022a, 2022b), and published in Cózar and Somerville (2004).

Competing interests Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Captions

Fig. 1. Main structural features of northern England and southern border of Scotland, with location of the studied sections (red stars) (simplified from Dean *et al.* 2011). South Cumbria is in the Lake District Block.

Fig. 2. Main biostratigraphic foraminifera and calcareous algae (with relative abundance), foraminiferal Margalef diversity (D) and foraminiferal trends (FTs) at scale in stratigraphic sections from Stainmore Trough (Janny Wood), Alston Block (Rookhope Borehole) and Solway Basin (Archerbeck Borehole). At Janny Wood section, the miospores biozones are shown based on McLean *et al.* (2018). Sample numbers indicate the uppermost sample at the top of the foraminiferal trends, and base and top of studied interval. Foraminiferal biozones recognized in the left column are based on the first occurrence of the markers, whereas foraminiferal biozones in the right black column of the diversity curve are repositioned to the inferred position based on the foraminiferal trends. In the Archerbeck Borehole, the position of the Asbian-Brigantian boundary in left columns: 1, sensu Lumsden and Wilson (1961); 2, sensu Cummings (1961) and Strank (1981); 3, sensu Dean *et al.* (2011); and 4, this study. Abbreviations: Co, Cornet; Knipe, Knipe Scar; MS, Melmerby Scar; Rob, Robinson; tran.z., transitional zone; trans., transitional; TLF, Tyne Limestone Formation.

Fig. 3. Main biostratigraphic foraminifera and calcareous algae (with relative abundance), foraminiferal diversity and foraminiferal trends (FTs) at scale in stratigraphic sections from south Cumbria (Trowbarrow Quarry) and Askrigg Block (Silverdale and Back Scar boreholes). At Trowbarrow Quarry, position of the Asbian-Brigantian boundary and formational boundaries and names in left columns are from: 1, sensu Horbury, 1987; 2, sensu Dean *et al.* (2011); 3, sensu Cózar et al. 2022b, and this study. In Silverdale Borehole, position of the Asbian-Brigantian boundary and formational boundaries and names in left columns are: 4, sensu Murray (1983); 5, sensu Waters *et al.* (2017); 6, this study. In Back Scar Borehole, position of the Asbian-Brigantian boundary and formational boundaries and names in left columns are: 7, sensu Murray (1983); 8, this study. Legend and other aspects as in Fig. 2. Abbreviations: Alst., Alston; BRI, Brigantian; Humph., Humphrey Head; trans., transitional.

Fig. 4. Foraminiferal diversity D (total assemblages; Margalef diversity index (ranging from 1 (low) up to 10 (high)), abundance SA (identified specimens per thin-section) and richness RST (number of specimens of selected taxa mentioned in the text) around the Asbian-Brigantian boundary in sections from S. Cumbria and Askrigg Block. Samples in all the sections are placed equidistant, but differ in metre spacing (for metre spacing see Fig. 3). Foraminiferal biozones are repositioned according to the FTs. Large blue arrows numbered 1-6 are phases of change in richness.

Fig. 5. Foraminiferal diversity D, abundance SA and richness RST around the Asbian-Brigantian boundary in sections from Stainmore Trough, Alston Block and Solway Basin. Samples in all the sections are placed equidistant, but differ in metre spacing (for metre spacing see Fig. 2). Other aspects as in Fig. 4. Abbreviations: Birk., Birkdale; M. S., Melmerby Scar; Rob., Robinson; TLF, Tyne Limestone Formation.

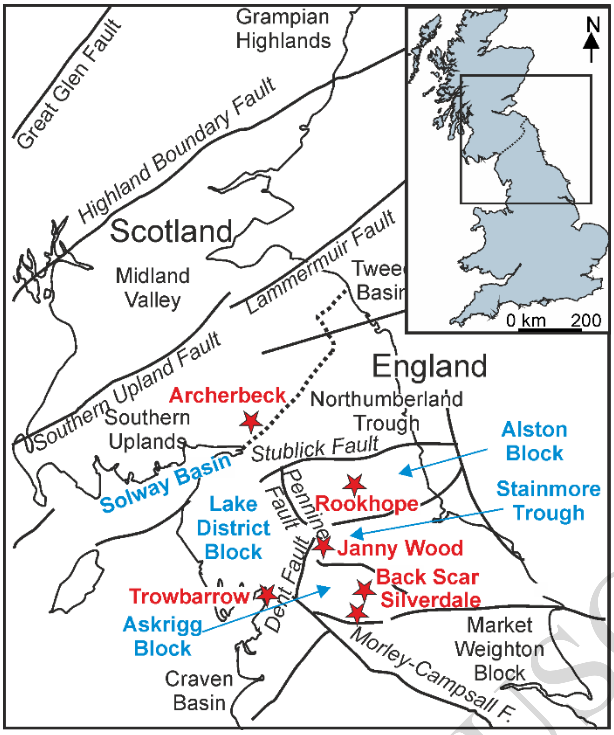
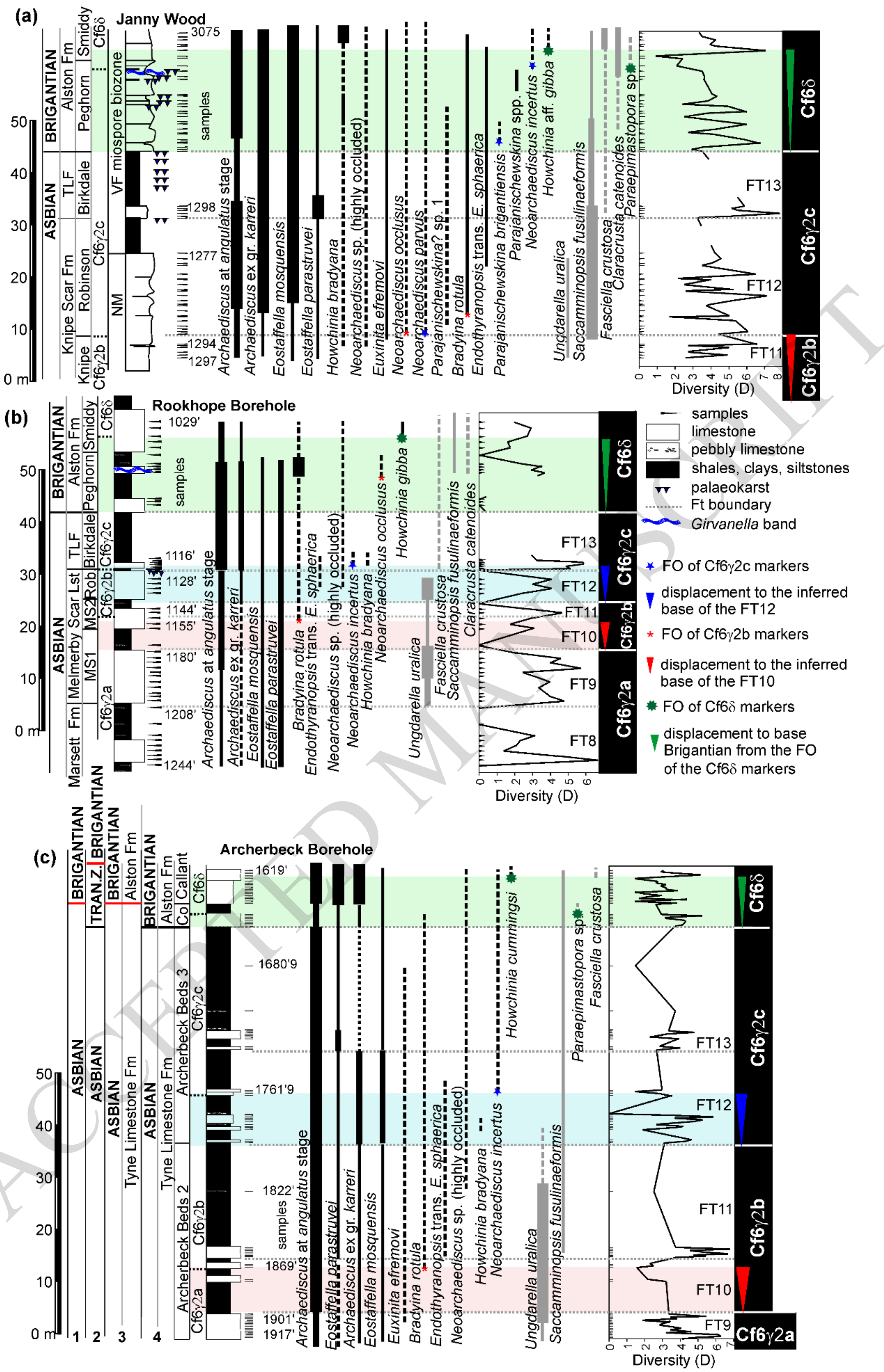

Grampian Highlands
Great Glen Fault
Highland Boundary Fault
Scotland
Midland Valley
Lammermuir Fault
Southern Upland Fault
Archerbeck
Southern Uplands
England
Northumberland Trough
Stublick Fault
Alston Block
Solway Basin
Rookhope
Stainmore Trough
Lake District Block
Pennine Fault
Janny Wood
Back Scar
Silverdale
Trowbarrow
Dent Fault
Askrigg Block
Market Weighton Block
Craven Basin
Morley-Campsall F.
N
0 km 200

Figure 1



(a)
Janny Wood
(b)
Rookhope Borehole
(c)
Archerbeck Borehole
BRIGANTIAN
ASBIAN
Alston Fm
Knipe Scar Fm
Tyne Limestone Fm
VF miospore biozone
samples
Diversity (D)
Cf6δ
Cf6γ2c
Cf6γ2b
Cf6γ2a
FT8
FT9
FT10
FT11
FT12
FT13
Archaediscus at angulatus stage
Archaediscus ex gr. karreri
Eostaffella mosquensis
Eostaffella parastruvei
Howchinia bradyana
Neoarchaediscus sp. (highly occluded)
Euxinita efremovi
Neoarchaediscus occlusus
Neoarchaediscus parvus
Neoarchaediscus incertus
Bradyina rotula
Endothyranopsis trans. E. sphaerica
Parajanischewskina brigantiensis
Parajanischewskina spp.
Howchinia aff. gibba
Howchinia gibba
Howchinia cummingsi
Ungdarella uralica
Saccamminopsis fusulinaeformis
Fasciella crustosa
Claracrusta catenoides
Paraepimastopora sp.
samples
limestone
pebbly limestone
shales, clays, siltstones
palaeokarst
Ft boundary
Girvanella band
FO of Cf6γ2c markers
displacement to the inferred base of the FT12
FO of Cf6γ2b markers
displacement to the inferred base of the FT10
FO of Cf6δ markers
displacement to base Brigantian from the FO of the Cf6δ markers

Figure 2

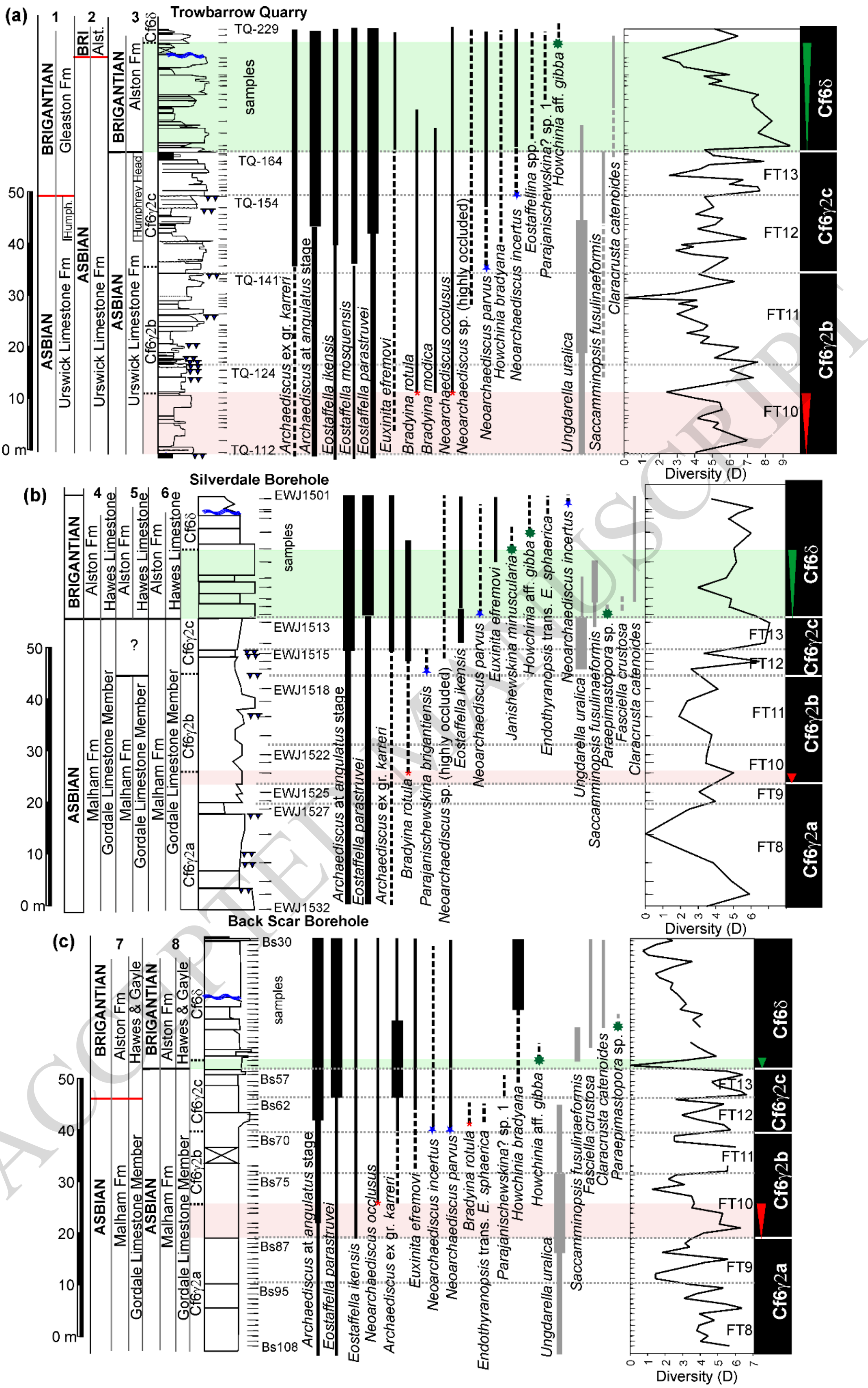
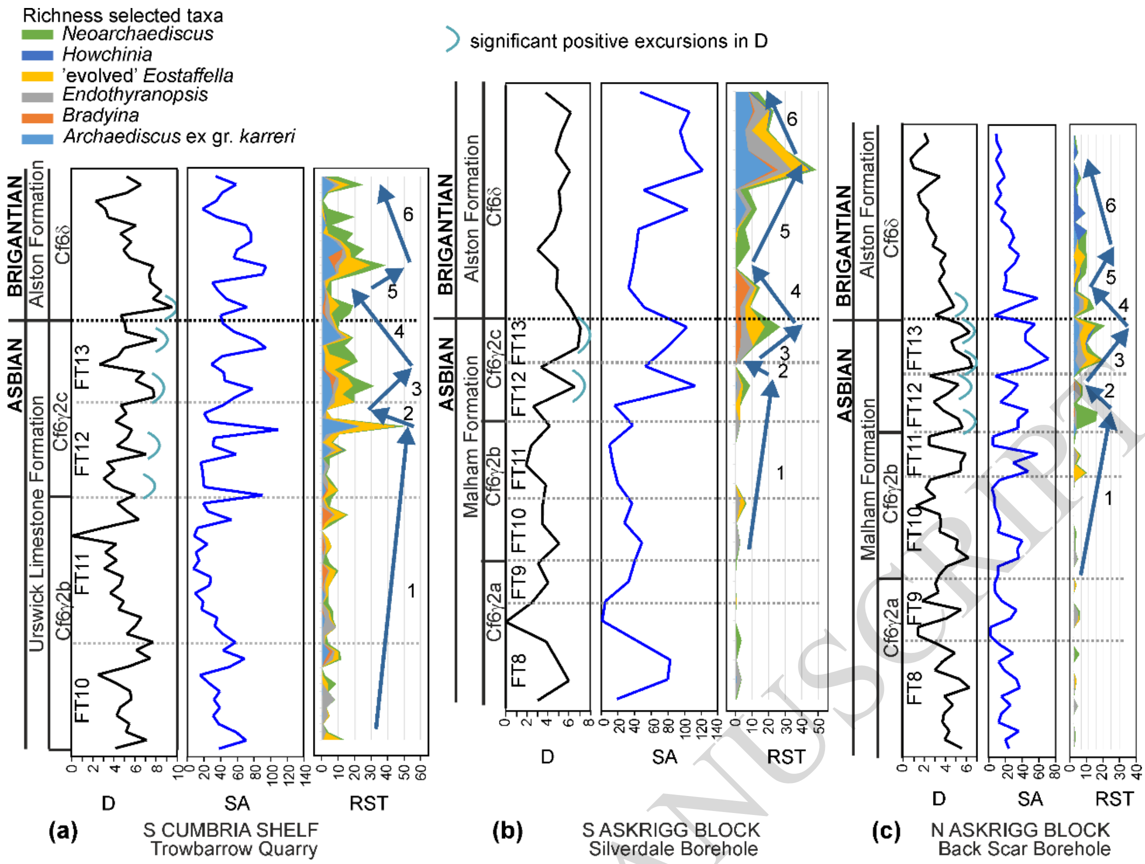

(a)
Trowbarrow Quarry
TQ-229
TQ-164
TQ-154
TQ-141
TQ-124
TQ-112
samples
BRIGANTIAN
ASBIAN
Gleaston Fm
Urswick Limestone Fm
Alston Fm
Humphrey Head
Cf6δ
Cf6γ2c
Cf6γ2b
Archaediscus ex gr. karreri
Archaediscus at angulatus stage
Eostaffella ikensis
Eostaffella mosquensis
Eostaffella parastruvei
Euxinita efremovi
Bradyina rotula
Bradyina modica
Neoarchaediscus occlusus
Neoarchaediscus sp. (highly occluded)
Neoarchaediscus parvus
Howchinia bradyana
Neoarchaediscus incertus
Eostaffellina spp.
Parajanischewskina? sp. 1
Howchinia aff. gibba
Ungdarella uralica
Saccamminopsis fusulinaeformis
Claracrusta catenoides
FT10
FT11
FT12
FT13
Diversity (D)
(b)
Silverdale Borehole
EWJ1501
EWJ1513
EWJ1515
EWJ1518
EWJ1522
EWJ1525
EWJ1527
EWJ1532
Malham Fm
Gordale Limestone Member
Hawes Limestone
Cf6γ2a
Archaediscus at angulatus stage
Eostaffella parastruvei
Archaediscus ex gr. karreri
Bradyina rotula
Parajanischewskina brigantiensis
Neoarchaediscus sp. (highly occluded)
Eostaffella ikensis
Neoarchaediscus parvus
Euxinita efremovi
Janischewskina minuscularia
Howchinia aff. gibba
Endothyranopsis trans. E. sphaerica
Neoarchaediscus incertus
Ungdarella uralica
Saccamminopsis fusulinaeformis
Paraepimastopora sp.
Fasciella crustosa
Claracrusta catenoides
FT8
FT9
(c)
Back Scar Borehole
Bs30
Bs57
Bs62
Bs70
Bs75
Bs87
Bs95
Bs108
Hawes & Gayle
Eostaffella ikensis
Neoarchaediscus occlusus
Neoarchaediscus incertus
Bradyina rotula
Howchinia bradyana
Fasciella crustosa

Figure 3



Richness selected taxa
Neoarchaediscus
Howchinia
'evolved' Eostaffella
Endothyranopsis
Bradyina
Archaediscus ex gr. karreri
significant positive excursions in D
BRIGANTIAN
ASBIAN
Alston Formation
Urswick Limestone Formation
Malham Formation
Cf6δ
Cf6γ2c
Cf6γ2b
Cf6γ2a
FT8
FT9
FT10
FT11
FT12
FT13
D
SA
RST
(a)
S CUMBRIA SHELF
Trowbarrow Quarry
(b)
S ASKRIGG BLOCK
Silverdale Borehole
(c)
N ASKRIGG BLOCK
Back Scar Borehole

Figure 4

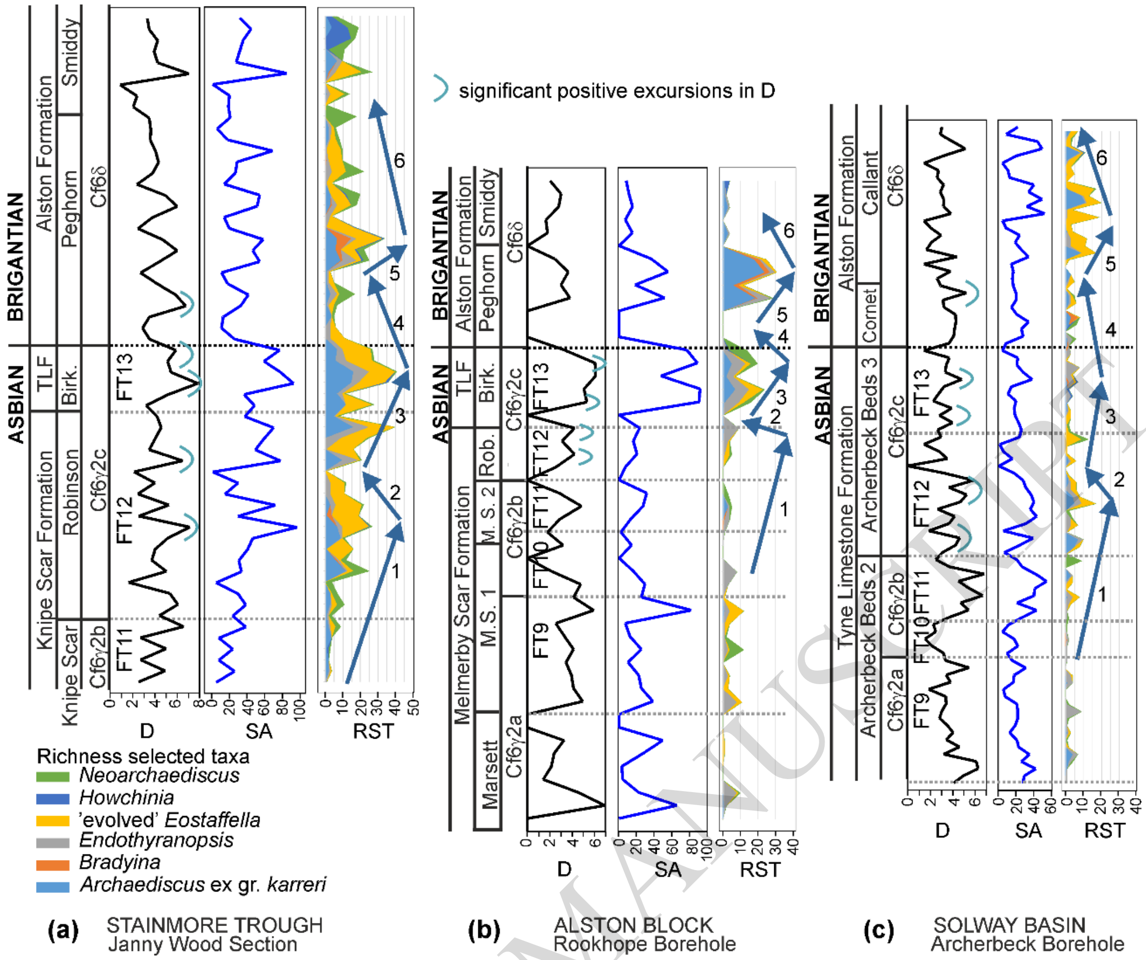

significant positive excursions in D
BRIGANTIAN
ASBIAN
Alston Formation
Knipe Scar Formation
TLF
Smiddy
Peghorn
Birk.
Robinson
Knipe Scar
Cf6δ
Cf6γ2c
Cf6γ2b
FT11
FT12
FT13
D
SA
RST
Richness selected taxa
Neoarchaediscus
Howchinia
'evolved' Eostaffella
Endothyranopsis
Bradyina
Archaediscus ex gr. karreri
(a)
STAINMORE TROUGH
Janny Wood Section
Melmerby Scar Formation
M.S. 1
M. S. 2
Rob.
Marsett
Cf6γ2a
FT9
FT10
(b)
ALSTON BLOCK
Rookhope Borehole
Tyne Limestone Formation
Archerbeck Beds 2
Archerbeck Beds 3
Cornet
Callant
(c)
SOLWAY BASIN
Archerbeck Borehole

Figure 5