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Foraminiferal, calcareous algal and problematica assemblages from the Mississippian Lower Limestone Formation in the Midland Valley, Scotland

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ABSTRACT: Foraminiferal, algal and problematica assemblages from the Mississippian (late Viséan and early Serpukhovian) Lower Limestone Formation have been studied in order to validate lithostratigraphical correlations of limestones within the central and western parts of the Midland Valley of Scotland. Analysis of more than 100 outcrops allows recognition of four calcareous microfossil assemblages, which span the late Brigantian and early Pendleian, and enables a detailed correlation to be made within the Central Coalfield (north Lanarkshire) and with the thinner sequences to the west (north Ayrshire), to the south (Douglas area, south Lanarkshire), and to the east (Bathgate area, West Lothian). The age of the Lower Limestone Formation is modified because the upper part of this formation is now assigned to the Pendleian (due to the first occurrences of new foraminiferans and the co-occurrence with the Namurian goniatites), and some individual limestone horizons within the formation are repositioned, or their precise correlation with other limestones is established. A refined stratigraphical framework is proposed for the above noted areas, and a correlation between them and the Pennine region in northern England is proposed, passing through the Archerbeck Borehole sequence in the Scottish Borders.

KEY WORDS: Biostratigraphy, microfossils, Mississippian, Late Viséan, Brigantian, Early Serpukhovian, Pendleian

In the Midland Valley in Scotland, the Mississippian (late Viséan and early Serpukhovian) Lower Limestone Formation (formerly Lower Limestone Group; see Browne *et al.* 1999), the basal formation of the Clackmannan Group, crops out around the margins of a number of basins, separated by areas of older Pre-Mississippian rocks. In the western part of the Midland Valley, three main areas can be distinguished based on their lithological content (Fig. 1): the Central Coalfield (including the Glasgow area and extending southeast by Calderwood Glen to Birkwood Burn); the North Ayrshire area (including the ground between Roebank Glen and Ardrossan); and the Douglas area (including the area south of the River Nethan, and extending west to Sorn). The Lower Limestone Formation is composed of several Yoredale-type cyclothemic sequences (Browne *et al.* 1999, fig. 3; Read *et al.* 2002), similar to those described by Ramsbottom (1974) and George *et al.* (1976) in northern England. Although individual limestones are of wide lateral extent, geographic isolation led, during economic exploitation (for coal, limestone and ironstone) during the 19th Century, to a proliferation of local names. Correlation of limestone beds between basins was complicated by lateral changes in thickness, facies and faunas.

Also included in this study are outcrops in the Bathgate area of West Lothian, which contains a distinct lithological succession, composed of thick volcanic rocks interbedded with sparse shales, siltstones, sandstones and limestones. This sequence has been interpreted as representing the eastern border of the Central Coalfield Basin flanking the Burntisland High (Francis 1991; Read *et al.* 2002) (Fig. 1). This unusual succession led Browne *et al.* (1999) to include these rocks as a separate lithological unit, the Bathgate Group, which is, in part, laterally equivalent to the Strathclyde and Clackmannan groups (Fig. 2).

Foraminiferans and problematica of the limestone beds in these sequences have been analysed in order to validate the local and regional correlations proposed by previous authors (e.g. Burgess 1965; Holliday *et al.* 1975; George *et al.* 1976; Wilson 1979; Cameron & Stephenson 1985; Francis 1991; Browne *et al.* 1999). The destructive dolomitisation observed in several limestone horizons has prevented the preservation of the microfossil communities.

For a general comparison with the microfaunal and microfloral changes occurring in the Lower Limestone Formation, limestone and shell band horizons in the uppermost part of the underlying Strathclyde Group (within the Lawmuir Formation) have also been analysed (Fig. 2).

In comparing the successions in the Midland Valley with those in northern England, two reference sections have been

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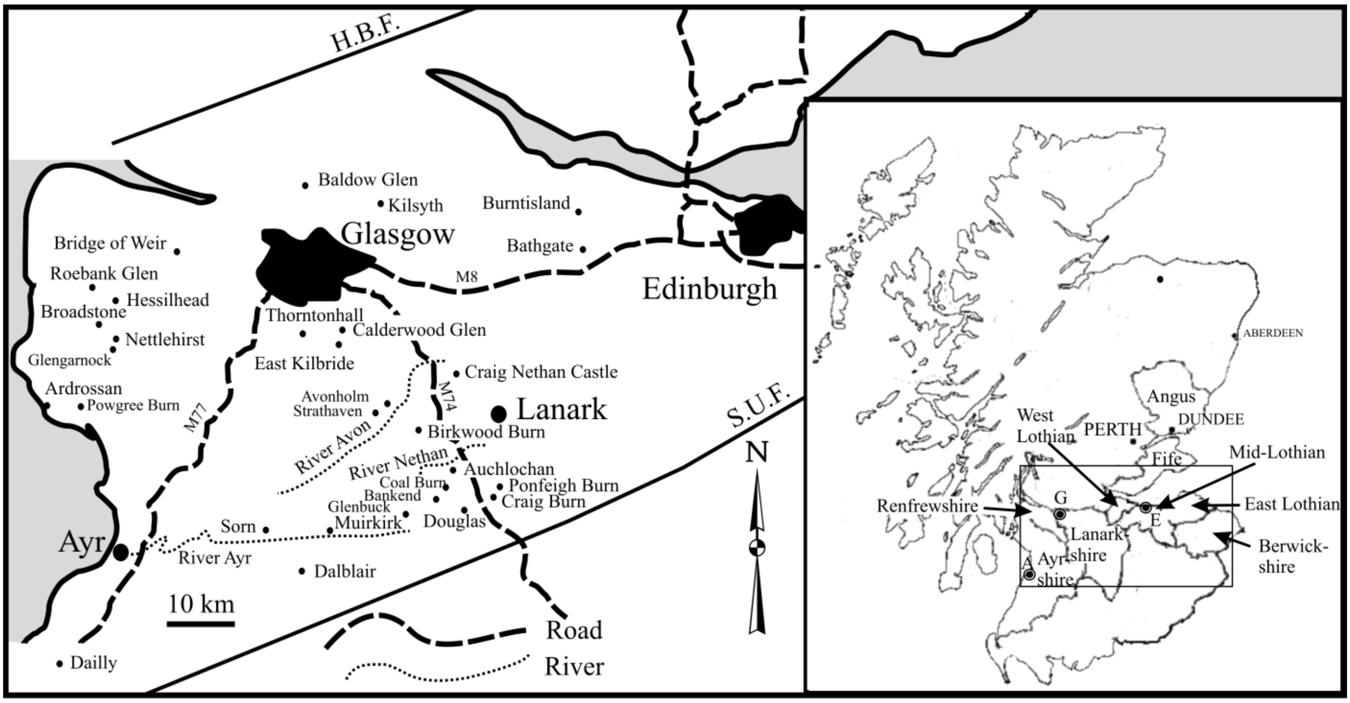

Figure 1 Counties of the Midland Valley of Scotland, with locations of the main localities documented in the text and in Appendix 1 (Supplementary Material online). H.B.F. = Highland Boundary Fault; S.U.F. = Southern Uplands Fault. In inset map G = Glasgow; E = Edinburgh; A = Ayr.

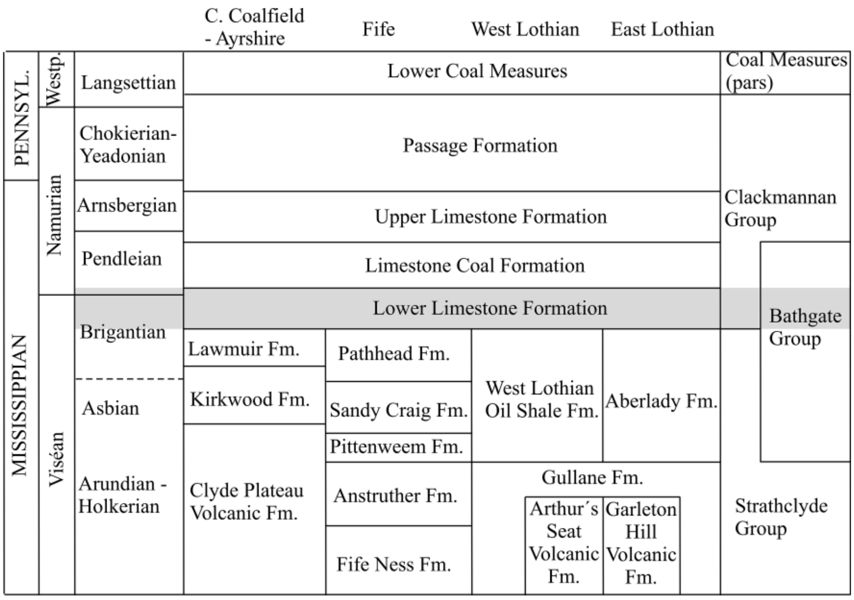

Figure 2 Lithostratigraphy of the Carboniferous in the Midland Valley (modified from Browne *et al.* 1999). NB: the Inverclyde Group is not represented, and only the basal part of the Coal Measures Group is included. PENNSYL. = Pennsylvanian; Westp. = Westphalian; Fm. = Formation.

used, the Glasgow district (selected by Browne *et al.* 1999 as the standard succession for the Central Coalfield Basin; see Fig. 3) and the Archerbeck Borehole (Lumsden & Wilson 1961; Cummings 1961) in Dumfriesshire, close to the border of Scotland and northern England. Unfortunately, the currently available foraminiferal database from the Archerbeck Borehole cannot be used with confidence because, despite various studies (Cummings 1961; Conil *et al.* 1980; Strank 1981), bed-by-bed details have been never published in an adequate form for this type of comparison to be achieved. Taxonomic names, foraminiferal zones and their stratigraphic ranges documented by Cummings (1961) were considered as confusing (e.g. Strank 1981), and the present authors' own survey of these data could not clarify sufficiently enough the problems detected in the foraminiferal lists recorded by Cummings (1961). Furthermore, because of the lack of illustrated material in the study by Cummings, it seems to be impossible to use his foraminiferal and algal/problematica assemblages (FZ1–9) for precise biostratigraphic correlations. Some data were extracted from the assessment and illustrations in Conil *et al.* (1980) and Strank (1981), but correlations presented in Figure 3 have to be considered as tentative, and are based mostly on the work of Holliday *et al.* (1975), and detailed correlation of many limestone horizons could not be corroborated precisely. Holliday *et al.* (1975) used the occurrence of *Falsocalcifolium punctatum* and *Calcifolium okense* as one of the main tools for the correlation of these limestones. However, those problematica do not occur in each laterally equivalent limestone of the Midland

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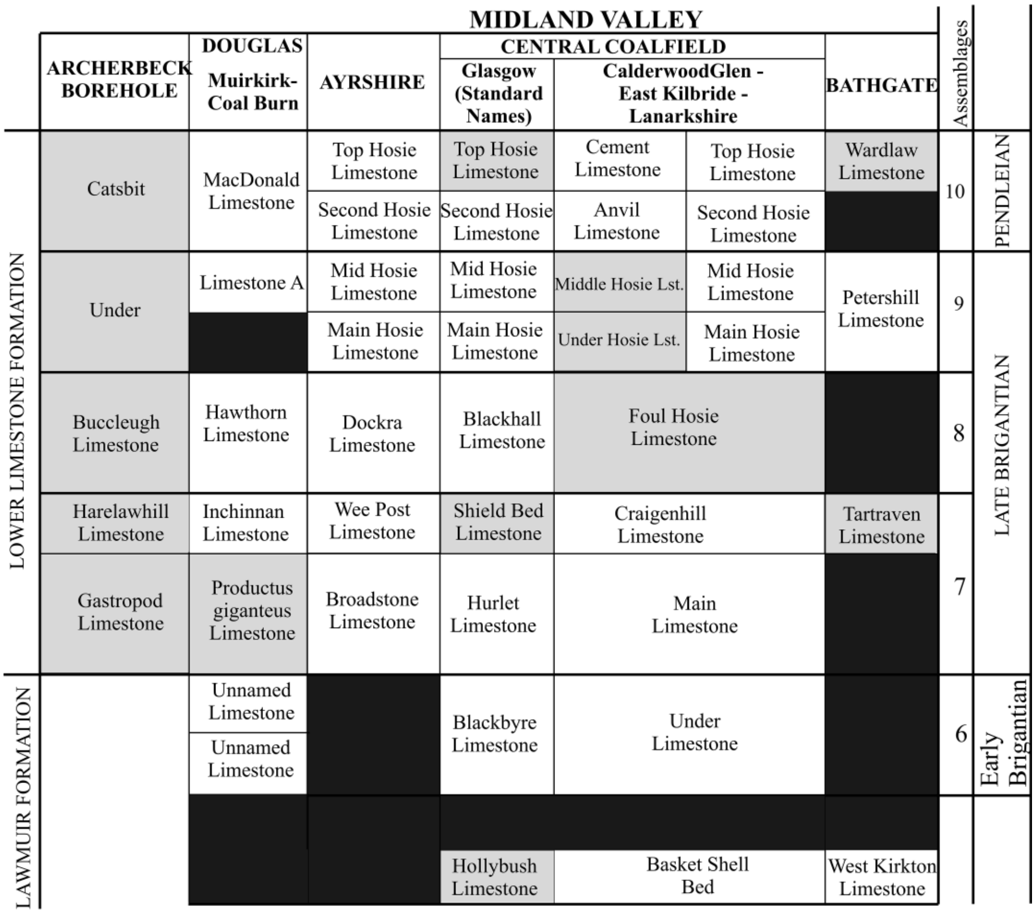

Figure 3 Biostratigraphical correlation of the limestone horizons included in the Lower Limestone Formation. Black areas represent non-depositional sequences, limestone names in grey areas represent the limestone horizons that were not sampled for this study. The Archerbeck Borehole column is modified from Holliday *et al.* (1975).

Valley, and the use of foraminiferal assemblages became necessary for establishing this kind of detailed correlation.

The microfossil database presented herein is not only useful for an intra-basin correlation within the designated areas in the Midland Valley, but it is also a tool for extra-basin correlations with the Pennine region, where the British Dinantian stratotypes for the Asbian and Brigantian stages (now substages according to Heckel & Clayton 2006) were selected and described by George *et al.* (1976). Moreover, the basal Namurian Stage also has its stratotype section in the Pennines (Ramsbottom *et al.* 1978). As recognised by numerous authors, cyclic sedimentations in the Midland Valley and in the Pennines show many aspects in common. Within this present study, this close relationship is tested using foraminiferal, calcareous algal and problematical assemblages. The database used for the comparison with the Pennines is that for the assemblages described by Cózar & Somerville (2004), with the same quantification of the specimens and taxonomy for the species being adopted in the present paper.

1. Materials

More than 600 large thin sections of limestones were prepared by one of the authors (IB), as part of his postgraduate research while based at the University of Glasgow (1958–1961). The samples were collected from diverse localities within the Midland Valley, and the thin sections correspond to *circa* 550 different calcareous horizons, mostly situated in Muirkirk and Coal Burn, Bathgate, Calderwood Glen, East Kilbride, the Glasgow district and Ayrshire (Fig. 3). This material is labelled as IB-, and is housed in the British Geological Survey Collection at Edinburgh. Unfortunately, several of the quarry sites are now filled in and collecting is no longer possible.

In addition, 10 limestones horizons were recently sampled from Bathgate (Petershill Limestone), of which, *c.* 50 thin sections were prepared. These thin sections are numbered with a prefix Pc- and are held in the Department of Palaeontology, Universidad Complutense de Madrid (Spain).

All the productive limestones sampled in each locality are presented in Appendix 1 (in Supplementary Material), and the most significant localities are highlighted in Figure 1. Foraminiferal, algal and problematica taxa are documented in Tables 1 to 11 (in Supplementary Material).

2. Foraminiferal, calcareous algal and problematica assemblages

In the northern Pennines, eight calcareous microfossil assemblages were recognised for the stratigraphic interval spanning the late Asbian 'Basement Group' of the Alston Block to the Pendleian Little Limestone (Cózar & Somerville 2004). Most assemblages from the Midland Valley can be correlated with assemblages 7 and 8, of which Assemblage 7 is observed in the Brigantian Scar and Five Yard limestones, and Assemblage 8 in the Three Yard, Four Fathom and Great limestones of late Brigantian to Pendleian age. However, only scarce material of the Pendleian Great and Little limestones was studied, which lacked precise definition by Pendleian markers. On the other hand, in the Midland Valley, new taxa have been recorded in the upper part of the Lower Limestone Formation succession (Cózar *et al.* 2008a), which allows the proposal of two new assemblages, Assemblages 9 and 10 (described below).

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2.1. Limestones in the upper part of the Strathclyde Group

In the Midland Valley, sampled limestones included in the Strathclyde Group are the Blackbyre and Under limestones, the Basket Shell Bed, and two unnamed limestones below the Main Limestone in the Muirkirk Syncline (Douglas area) (Fig. 3), which can all be assigned to the Lawmuir Formation (Fig. 2).

2.1.1. Blackbyre Limestone. This limestone, occurring in Renfrewshire, shows a poor microfossil assemblage (Table 1 in Supplementary Material (SM)) where the occurrence of the problematicum *Draffania biloba* suggests possibly an Assemblage 6 age (Fig. 3), because *Draffania* is commonly recorded in the 'middle' Brigantian (Johnson & Nudds 1996; Cózar & Somerville 2004). However, no diagnostic foraminiferans are recognised in this limestone unit, where destructive dolomitisation has preserved only a limited suite of foraminiferans.

2.1.2. Basket Shell Bed. This unit in the Calder River, Lanarkshire is mostly dolomitised and contains a very poor assemblage (Table 1, SM). Only one horizon containing preserved microfauna has been recognised, including *Archaediscus* at *angulatus* stage and *Neoarchaediscus*. These taxa can occur from Assemblage 2 in northern England and, thus, they lack significance for a detailed comparison, and the age of this unit is assigned questionably to the latest Asbian to early Brigantian.

2.1.3. Under Limestone. This limestone is located in Lanarkshire and contains a more diverse suite of foraminiferans (Table 1, SM), although the most representative are the occurrence of *Loeblichia paraammonoides* and *Euxinita efremovi*, which are only recorded in Assemblage 5 or younger assemblages in northern England. These taxa are representative of the middle part of the early Brigantian. The Under Limestone is laterally equivalent to the Blackbyre Limestone, which has been assigned to Assemblage 6 (Fig. 3), and thus, the former can be included also in Assemblage 6.

The two unnamed limestones below the Main Limestone in Coal Burn, Lanarkshire have no diagnostic foraminiferans (Table 1, SM), except for species of *Neoarchaediscus*, *Euxinita efremovi* and the problematicum *Fasciella crustosa*. These taxa suggest an Assemblage 5 or younger age. However, according to their stratigraphic position, they are laterally equivalent to the Under and Blackbyre limestones (Fig. 3) and, thus, probably included also in Assemblage 6, of probable Early Brigantian age, at least for the upper unnamed limestone.

2.2. Limestones in the Lower Limestone Formation (Clackmannan Group)

Above these rare carbonate beds from the Strathclyde Group, limestone horizons become more common in the Lower Limestone Formation in the Central Coalfield Basin (Fig. 3), and four successions are classically described, in Ayrshire, Glasgow, Calderwood Glen/East Kilbride and Douglas.

2.2.1. Broadstone Limestone. In Ayrshire, the oldest limestone of the Lower Limestone Formation is the Broadstone Limestone, in which the assemblage is characterised by common *Archaediscus* at *angulatus* stage, *Falsocalcifolium punctatum* (Fig. 4i), *Neoarchaediscus* species, *Euxinita efremovi* (Fig. 4p) and *Endostaffella* species (Table 2 in Supplementary Material (SM)). The acmes of all these taxa, although first occurring in the Asbian, are representative of a Brigantian age. Furthermore, *Howchinia* species (particularly *H. gibba*; Fig. 4d–f), *Draffania biloba* and *Loeblichia paraammonoides* (Fig. 4n) are relatively common. Also noted are rare occurrences of *Asteroarchaediscus baschkiricus*, *Asteroarchaediscus rugosus* (Fig. 4k), *Endothyranopsis sphaerica*, possible *Climacammina* sp. and *Planospirodiscus* spp. (Fig. 4g). The occurrence of this latter group of taxa permits the assemblage to be assigned to the late Brigantian. In addition to the above-mentioned taxa, there are other common genera, such as *Endothyra*, *Earlandia*, *Eostaffella* (Fig. 4j), *Omphalotis*, *Pseudoammodiscus* and *Tetrataxis*. However, their abundance is not biostratigraphically significant, because they show acmes from Asbian rocks or even older strata. This rich and diverse suite of foraminiferans and problematica is correlated with Assemblage 7 of the Pennines (Cózar & Somerville 2004). There is an unusual outcrop assigned to the Broadstone Limestone, in the Ardrossan Harbour area (IB-1458 to 1466; Table 2, SM), because it contains *Asteroarchaediscus* and *Tubispirodiscus cornuspiroides* (Fig. 4h), but lacks the problematicum *Falsocalcifolium punctatum*. The rest of the assemblage is similar to that in other outcrops of this limestone. These features suggest that *F. punctatum* did not colonise this area.

2.2.2. Hurlet Limestone. The assemblages of the Hurlet Limestone in the Renfrew and Lanarkshire areas are characterised by common *Archaediscus* at *angulatus* stage *Tubispirodiscus* sp. (Fig. 4r), *Falsocalcifolium punctatum*, *Neoarchaediscus* species and *Euxinita efremovi* (Table 3 in Supplementary Material). Furthermore, species of *Howchinia* (Fig. 4q) and *Loeblichia paraammonoides* are relatively common. Noteworthy, are the occurrences of *Asteroarchaediscus baschkiricus*, *Endothyranopsis sphaerica* (Fig. 4u), *Climacammina* sp., *Parabradyina pararotula* (Fig. 4s) and *Planospirodiscus* sp., and the alga *Archaeolithophyllum lamellosum* (Fig. 4t). The occurrence of the latter group of taxa permits the assemblage to be assigned also to Assemblage 7 in northern England, of late Brigantian age (Cózar & Somerville 2004), and it is readily correlatable with the Broadstone Limestone in Ayrshire and the Main Limestone (see below), each with over 30 foraminiferal genera.

2.2.3. Main Limestone. This limestone is located in Lanarkshire and contains common *Archaediscus* at *angulatus* stage, as well as primitive *Tubispirodiscus cornuspiroides* (Fig. 5d), *Falsocalcifolium punctatum* (Fig. 5e), and *Neoarchaediscus* species. This rich and diverse suite of foraminiferans, algae and problematica is very similar to the Broadstone and Hurlet limestones (Table 4 in Supplementary Material). However, a highlight of the Main Limestone is the relatively common large *Archaediscus* at *angulatus* stage of the *A. karreri* group, *Endothyranopsis sphaerica* (Fig. 5h), *Howchinia* species and *Euxinita efremovi*. Also noteworthy are the occurrences of *Asteroarchaediscus baschkiricus*, *Pseudoglomospira* sp. (here considered as belonging to the class Fusulinata with a microgranular wall, but assigned to the class Miliolata by some authors) and *Climacammina* (Fig. 5b), and the first occurrence of the problematicum *Praedonezella* sp. in the Midland Valley (Fig. 5g). The assemblage is correlated with Assemblage 7 in the northern Pennines (Cózar & Somerville 2004), of late Brigantian age.

2.2.4. Wee Post Limestone. This unit has been sampled rarely in Ayrshire (see Appendix 1), and the foraminiferans are not representative enough for accurate age determination, and only suggest a correlation with Assemblage 5 or younger of the Pennines (Table 5 in Supplementary Material (SM)).

2.2.5. Craigenhill Limestone. This limestone exposed at Calderwood, southeast of Glasgow (Fig. 3), is laterally equivalent to the Wee Post Limestone horizon. Although the assemblage is very poor (six foraminiferal and two problematica genera), it contains *Tubispirodiscus* sp. and common *Falsocalcifolium punctatum* (Table 5, SM). These taxa suggest an Assemblage 7 age and, thus, the Wee Post Limestone can be confidently assigned also to Assemblage 7.

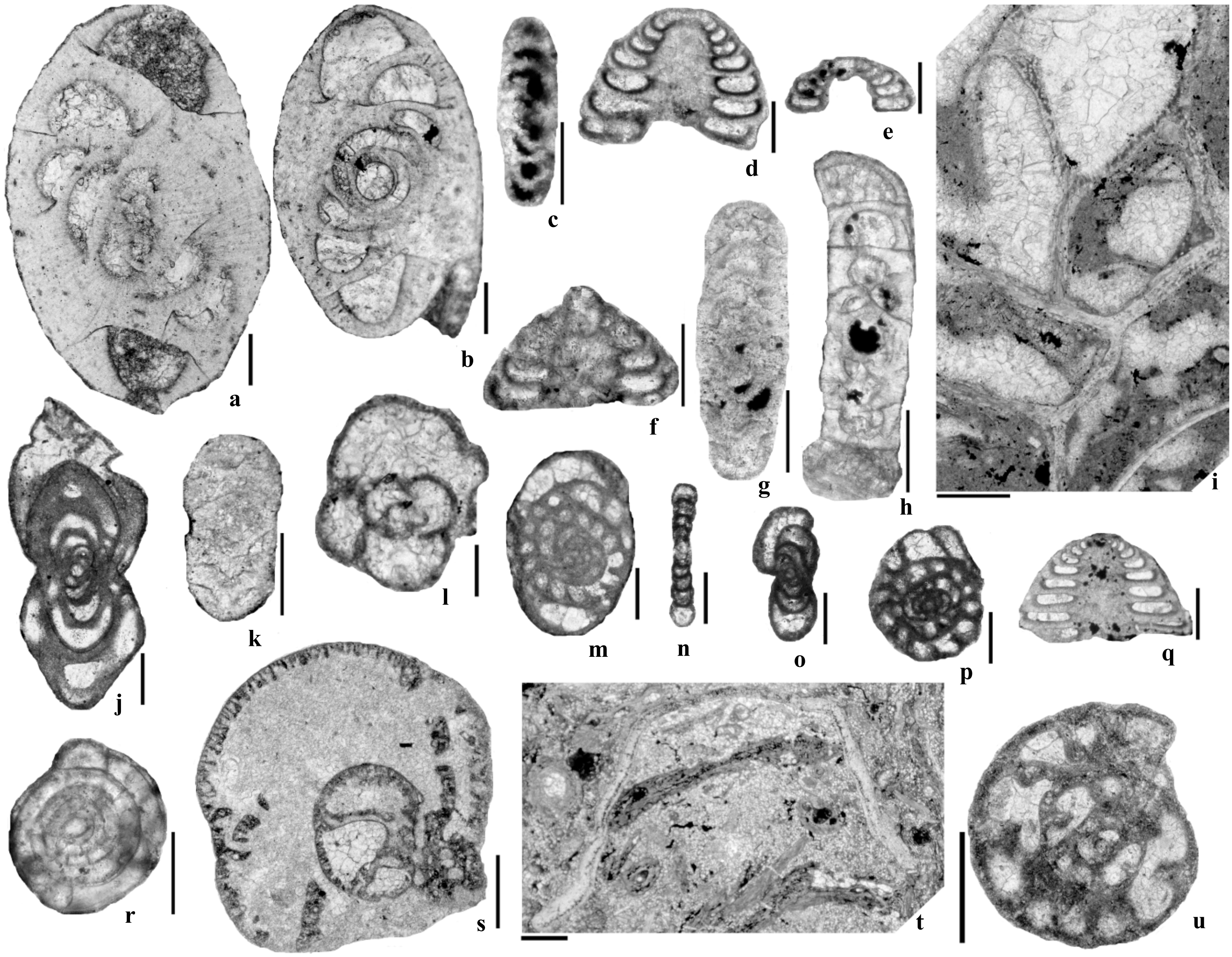

Figure 4 Foraminiferans, calcareous algae and problematica from limestones at the top of the Strathclyde Group: Lawmuir Formation (a–c), and from the overlying Lower Limestone Formation (Clackmannan Group): Broadstone Limestone (d–p), and Hurlet Limestone (q–u) (Scale bar = 100 μm; except for (i), (s), (t) and (u) = 500 μm). (a) *Archaediscus gigas*, IB-171/2519–1, first limestone below Main Limestone. Note the retro-sigmoidal coiling which distinguish this taxon from the typical sigmoidal coiling of the *A. karreri* group. In order to see the great variety of forms in those large *Archaediscus* in the British Isles, see Conil *et al.* 1980 and Cózar & Somerville 2004. (b) *Archaediscus* sp., IB-309/2532–13, Under Limestone. Note that the coiling is not perfectly sigmoidal. (c) *Neoarchaediscus*? sp., IB-850/2534–37, Blackbyre Limestone. Shape of the specimen is similar to *Planospirodiscus*, but in contrast to this genus, occlusion of their initial whorls is limited. Compare with Figure 4g. (d) *Howchinia gibba*, IB-911/2535–6. (e) *Howchinia* sp., IB-974/2535–25. (f) *Howchinia* sp., IB-965/2535–19. (g) *Planospirodiscus* aff. *gregorii*, IB-1029/2536–7. (h) *Tubispirodiscus* ex. gr. *cornuspiroides* IB-1466/2538. (i) *Falsocalcifolium punctatum* in erect growth position, IB-971/2530–8. (j) *Eostaffella parastruvei*, IB-962/2535–17. Note that the final whorl is crushed. (k) *Asteroarchaediscus rugosus*, IB-1013/2536–2. (l) *Koktjubina* sp., IB-1462/2537–34. (m) *Euxinita*? sp. B, IB-1013/2536. (n) *Loeblichia paraammonoides*, IB-971/2535–21. (o) *Endostaffella*? sp., IB-972/2535–24. (p) *Euxinita efremovi*, IB-971/2535–22. (q) *Howchinia gibba*, IB-1324/2537–19. (r) *Tubispirodiscus* sp., IB-847/2534–30. (s) *Parabradyina pararotula*, IB-1087/2530–15. (t) *Archaeolithophyllum lamellosum*, covering fragments of *Falsocalcifolium punctatum*, IB-1324/2530–31. (u) *Endothyranopsis sphaerica*, IB-1088/2530–19.

2.2.6. Inchinnan Limestone. This unit crops out in the Douglas area and also contains peaks of *Falsocalcifolium punctatum*, together with rare, questionable *Climacammina* and *Endothyranopsis sphaerica*, and common *Euxinita efremovi* (Table 5, SM). This more diverse suite of microfossils allows it to be to assigned to Assemblage 7, as well as its lateral equivalents, the Wee Post and the Craigenhill limestones.

2.2.7. Dockra Limestone. This limestone in Ayrshire shows common *Archaediscus* at *angulatus* stage and *Neoarchaediscus* species (Table 6 in Supplementary Material). Other taxa, relatively common, are: *Asteroarchaediscus baschkiricus*, *A. rugosus*, *Biseriella parva* (Fig. 6n, p, q), *Biseriella* sp. (Fig. 6o) and *Euxinita efremovi*. Rare elements of these assemblages are: *Climacammina* sp., *Endothyranopsis sphaerica* (Fig. 6s), *Planospirodiscus* species (Fig. 6k), *Tubispirodiscus* and *Draffania biloba*, as well as the first occurrence of Miliolata foraminiferans, *Calcivertella* (Fig. 6u) and *Calcitornella* (Fig. 6v) (see also Cózar *et al.* 2008b). This diverse suite of foraminiferans and problematica, as well as their abundance, correlates reasonably well with Assemblage 8, despite the lack of *Calcifolium okense* (typical in northern England). In particular, the local peaks of *Asteroarchaediscus* and *Biseriella* suggest an upper level within Assemblage 8 recognised in the Pennines, as well as the first occurrence of the Miliolata. The absence of *Calcifolium okense* together with that of the closely related *Falsocalcifolium punctatum*, from stratigraphically older limestones demonstrates the lack of Calcifoliales in the western part of the Midland Valley area.

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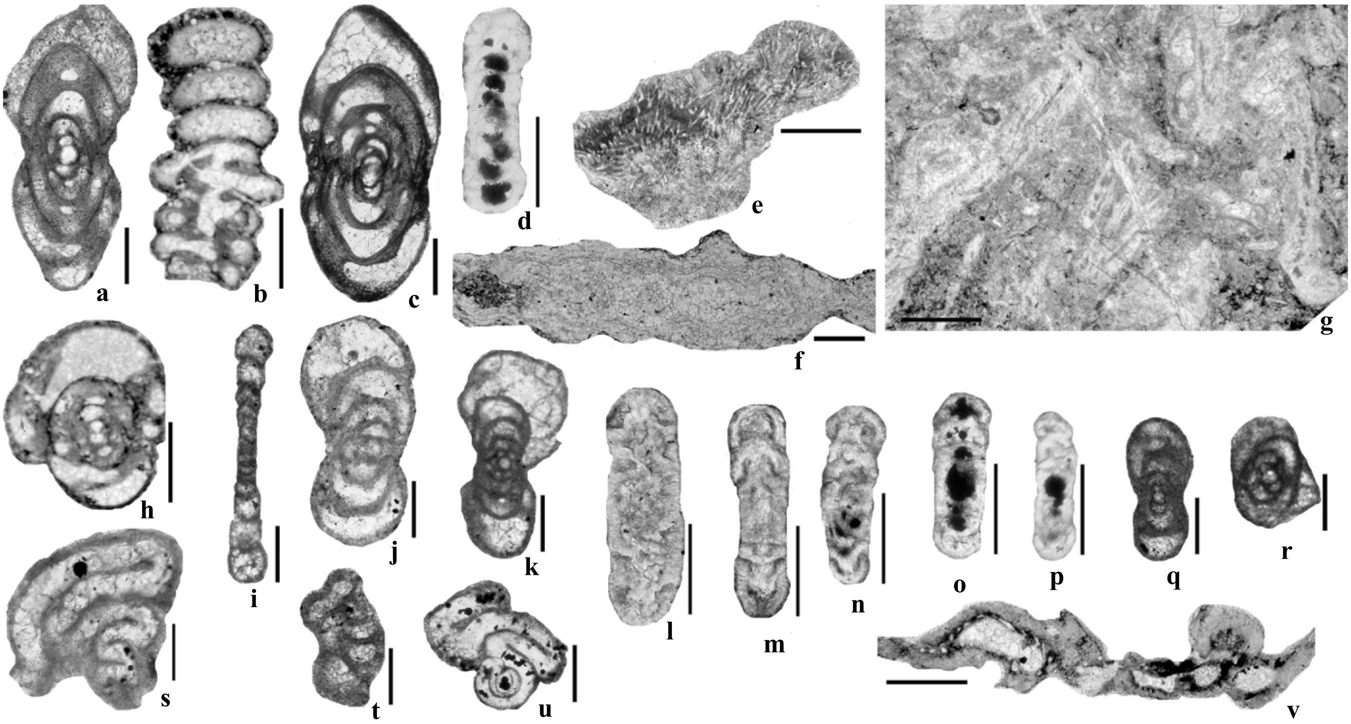

Figure 5 Foraminiferans and problematica from the Lower Limestone Formation: Main Limestone (a–h), and Hawthorn Limestone (i–v) (Scale bar = 100 μm; except for (b), (e), (f), (g), (h) and (v) = 500 μm). (a) *Eostaffella parastruvei*, IB-616/2533–12. (b) *Climacammina* sp., IB-263/2518–18. (c) *Eostaffella mosquensis*, IB-616/2533–13. (d) *Tubispirodiscus cornuspiroides*, IB-313/2532–11. (e) *Falsocalcifolium punctatum*, IB-618/2529–26. (f) *Fasciella crustosa*, IB-234/2518–9. (g) *Praedonezella caespiformis*, IB-330/2529–3. (h) *Endothyranopsis sphaerica*, IB-172/2518–2. (i) *Loeblichia paraammonoides*, IB-274/2519–31. (j) *Eostaffella* ex gr. *postmosquensis*, IB-677/2534–3. (k) *Eostaffella* ex gr. *pseudostruvei*, IB-670/2533–38. (l) *Planospirodiscus minimus*, IB-197/2519–11. (m) *Tubispirodiscus* sp., IB-517/2533. (n) *Neoarchaediscus postrugosus*, IB-275/2519–33. (o) *Tubispirodiscus* sp., IB-275/2519–36. (p) *Tubispirodiscus attenuatus*, IB-275/2519–34. (q) *Eostaffella* ex gr. *postmosquensis*, IB-615/2533–10. (r) *Euxinita*? sp. B, IB-197/2519–15. (s) *Ammovertella inversa*, IB-662/2533–20. (t) *Calcitornella* sp., IB-665/2533–25. (u) *Ammovertella inversa*, IB-677/2534–7. (v) *Calcifolium okense*, IB-615/2529–15.

2.2.8. Blackhall Limestone. Located in the Glasgow area, the Blackhall Limestone is characterised by common *Archaediscus* at *angulatus* stage and *Neoarchaediscus* species (in particular the first occurrence of *N. postrugosus*), as well as relatively common *Asteroarchaediscus* (Fig. 6c), *Calcifolium okense* (Fig. 6a), *Loeblichia paraammonoides* (Fig. 6g–i), *Euxinita efremovi* and species of *Planospirodiscus* (Table 7 in Supplementary Material). It also records the questionable occurrence of *Biseriella* and *Climacammina*, and the first occurrence of *Tubispirodiscus attenuatus* (Fig. 6e) [= *Betpakodiscus*, see taxonomic discussion in Cózar *et al*. 2008a]. This assemblage is readily correlated with Assemblage 8 in northern England, of latest Brigantian age, identified by the marked development of *C. okense*. In this area, *Falsocalcifolium punctatum* occurs locally.

2.2.9. Hawthorn Limestone. Common *Archaediscus* at *angulatus* stage, *Euxinita efremovi*, and *Neoarchaediscus* species are present in the Hawthorn Limestone of the south Lanarkshire (Douglas) and south Ayrshire areas, as well as relatively common *Endothyranopsis sphaerica*, *Planospirodiscus* species (Fig. 5l), and some local peaks of *Calcifolium okense* (Fig. 5v) (Table 8 in Supplementary Material). In addition, rare occurrences of large *Archaediscus* sp. of the *A. karreri* group, *Asteroarchaediscus baschkiricus*, *A. rugosus*, *Tubispirodiscus* sp. (Fig. 5m, o), and *Climacammina*, as well as the first occurrence of *Tubispirodiscus attenuatus* (Fig. 5p) in this area can be highlighted.

Additional taxa that first occur are: Miliolata such as *Ammovertella* (Fig. 5s, u), *Eostaffella* ex gr. *postmosquensis* (Fig. 5j, q) and *Eostaffella* ex gr. *pseudostruvei* (Fig. 5k), as well as the occurrence of *Neoarchaediscus postrugosus* (Fig. 5n), previously only recorded in the Blackhall Limestone. This rich and diverse suite of microfossils is compared to that of Assemblage 8. *Archaeolithophyllum lamellosum* is locally common in Polquhirter Burn. In general, the diversity of the calcareous algae and problematica is similar to that of the Blackhall Limestone of the Glasgow area.

2.2.10. Main Hosie and Mid Hosie limestones. These limestones of north Ayrshire are generally poor in microfossils, and they mostly exhibit representatives of *Archaediscus* at *angulatus* stage, *Asteroarchaediscus* and *Euxinita efremovi* (Table 9 in Supplementary Material (SM)). These foraminiferans cannot be used to distinguish the Main and Mid Hosie limestones from the underlying Dockra Limestone. In Powgree Burn, another limestone horizon was sampled (IB-1471 to IB-1476), situated above the Dockra Limestone. It probably corresponds to the Main Hosie band. In this limestone, in addition to the previously mentioned taxa, is recorded the occurrence of *Planospirodiscus* (Fig. 7o, u), *Tubispirodiscus* spp. (Fig. 7n, t), *Tubispirodiscus simplicissimus* and *Pseudoglomospira*. The first *T. simplicissimus* is only recorded in the upper part of this limestone. These features allow the proposal of a new Assemblage 9, described in detail later and complemented with additional foraminiferal taxa.

The Main and Mid Hosie limestones at Glengarnock, are relatively faunally poor (Table 9, SM), but record the first occurrence for north Ayrshire of *Endostaffella parva*, and species of *Tubispirodiscus* (Fig. 7p, q, s), particularly *Tubispirodiscus simplicissimus* (Fig. 7r). The latter is considered as a significant taxon for their inclusion in Assemblage 9. Noteworthy is the first occurrence of a new genus of Archaediscidae, characterised by (1) the occurrence of septation

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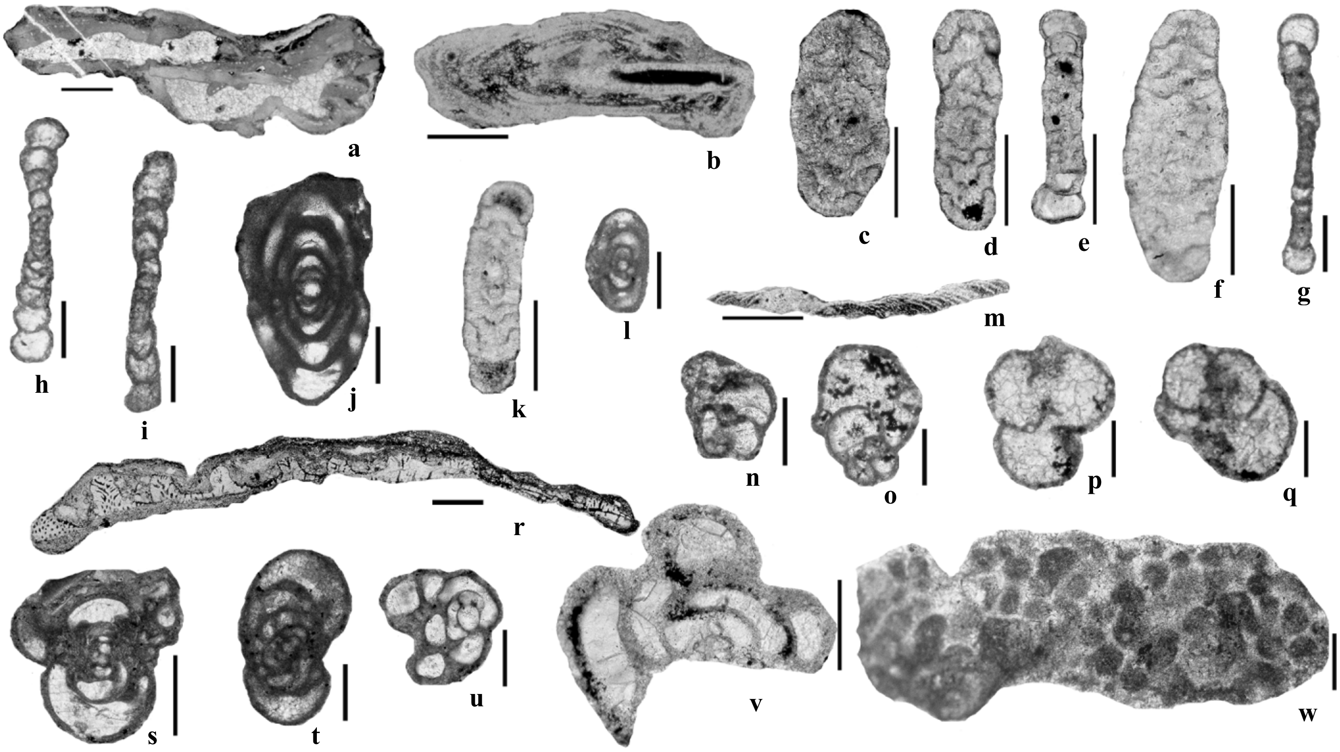

Figure 6 Foraminiferans, problematica and calcareous algae from the Lower Limestone Formation: Blackhall Limestone (a–i) and Dockra Limestone (j–w) (Scale bar = 100 µm; except for (a), (b), (m), (r) and (s) = 500 µm). (a) *Calcifolium okense*, IB-1305/2530–29. (b) *Chuvashovia* sp. and *Nanopora anglica* in the core, IB-1347/2531. (c) *Asteroarchaediscus rugosus*, IB-1523/2537–21. (d) *Planospirodiscus* sp. aff. *P. taimyricus*, IB-1522/2538–10. (e) *Tubispirodiscus attenuatus*, juvenile, IB-1523/2538–12. (f) *Planospirodiscus gregorii*, IB-1522/2538–10. (g) *Loeblichia paraammonoides*, IB-1522/2538–7. (h) *Loeblichia paraammonoides*, IB-1301/2537–18. (i) *Loeblichia paraammonoides*, IB-1301/2537–17. (j) *Eostaffella mosquensis*, IB-1139/2536–32. (k) *Planospirodiscus* sp., IB-985/2535–37. (l) *Euxinita*? sp. B, IB-985/2535–38. (m) *Eflugelia johnsoni*, IB-985/2530–9. (n) *Biseriella parva*, IB-730/2534–18. (o) *Biseriella* sp., IB-730/2534–19. (p) *Biseriella parva*, IB-1115/2536–19. (q) *Biseriella parva*, IB-1115/2536–20. (r) *Paraepimastopora noetschensis*, IB-743/2529–32. (s) *Endothyranopsis sphaerica*, IB-1139/2530–23. (t) *Praeostaffellina macdonaldensis*, IB-1149/2537–4. (u) *Calcivertella* sp., IB-739/2534–23. (v) *Calcitornella* sp., IB-739/2534–23. (w) *Palepimastoporella espielensis*, IB-985/2535–30.

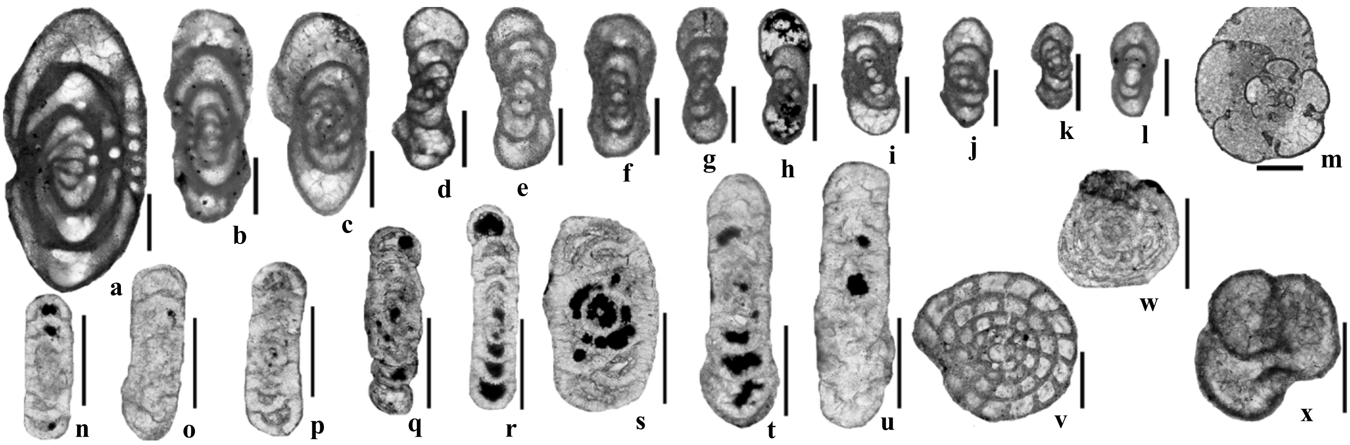

Figure 7 Foraminiferans from the Petershill Limestone (a–m, x), Main Hosie Limestone (n, o, t, u, w), and Mid Hosie Limestone (p–s, v) (Scale bar = 100 µm). (a) *Eostaffella mosquensis*, Pc-2967/2716–19. (b) *Eostaffella* ex gr. *pseudostruvei*, Pc-2968/2716–28. (c) *Eostaffella* ex gr. *pseudostruvei*., Pc-2962/2716–18. (d) *Endostaffella*? sp. A, Pc-2967/2716–23. (e) *Eostaffella* ex gr. *postmosquensis*, Pc-2967/2716–19. (f) *Eostaffella* ex gr. *pseudostruvei*, Pc-2971/2716–28. (g) *Zellerinella*? sp., IB-776/2534–27 (see Cózar *et al*. 2008b). (h) *Endostaffella*? sp. A, Pc-2967/2716–20. (i) *Chomatomediocris* sp., Pc-2971/2716–27. (j) *Endostaffella*? sp. B, Pc-2967/2716–22. (k) *Endostaffella*? sp. B, Pc-2967/2716–25. (l) *Eostaffella* ex gr. *pseudostruvei*, Pc-2962/2716–17. (m) *Parajanischewskina brigantiensis* Pc-2972. (n) *Tubispirodiscus* aff. *cornuspiroides*, IB-1473/2538–1. (o) *Planospirodiscus minimus*, IB-1473/2538–3. (p) *Tubispirodiscus* sp., IB-1575/2724–16. (q) *Tubispirodiscus hosiensis*, IB-1575/2724–20. (r) *Tubispirodiscus simplicissimus*, IB-1575/2538–24. (s) *Tubispirodiscus* aff. *cornuspiroides*, oblique section, IB-1575/2538–25. (t) *Tubispirodiscus cornuspiroides*, IB-1473/2538–1. (u) *Planospirodiscus minimus*, IB-1473/2538–2. (v) *Loeblichia ammonoides*, IB-1531/2538–15. (w) Archaediscidae new genus, IB-1575/2927–3. (x) *Biseriella parva* Pc-2962/2716–18.

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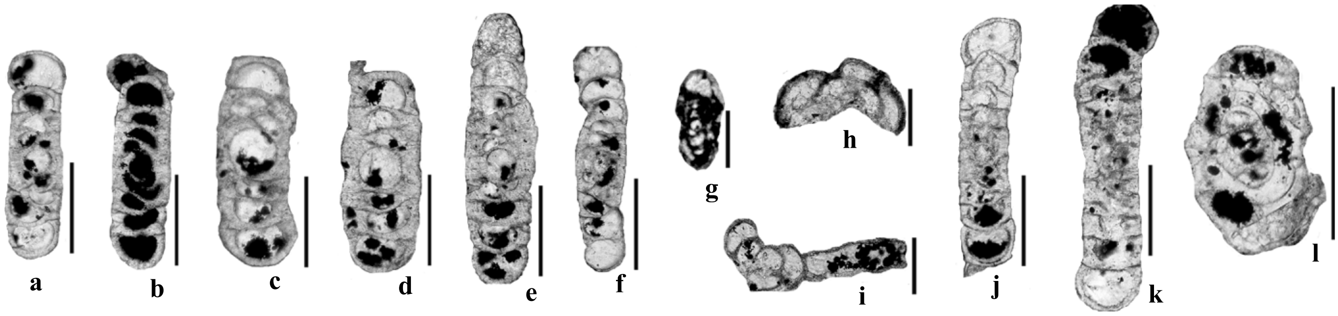

Figure 8 Foraminiferans from the Second Hosie Limestone (a–i), and Top Hosie Limestone (j–l) (Scale bar = 100 μm). (a) *Tubispirodiscus cornuspiroides*, IB-1571/2723–11. (b) *Tubispirodiscus cornuspiroides*, IB-1572/2724–9. (c) *Tubispirodiscus absimilis*, IB-1574/2724. (d) *Tubispirodiscus absimilis*, IB-1571/2723–5. (e) *Tubispirodiscus hosiensis*, IB-1574/2724–7. (f) *Tubispirodiscus hosiensis*, IB-1574/2724–6. (g) *Eostaffella mutabilis*, IB-1573/2723–29. (h) *Calcitornella* sp., IB-1571/2723–3. (i) *Calcitornella* sp., IB-1573/2723–30. (j) *Tubispirodiscus attenuatus*, IB-1569/2722–22. (k) *Tubispirodiscus attenuatus*, IB-1569/2722–19. (l) *Archaediscus* sp. at *tenuis* stage, IB-1569/2722–23.

(a feature only recorded within the family Archaediscidae in the genus *Tournarchaediscus*), and (2) a reduced microgranular wall (in a similar stage to the *Archaediscus* at *angulatus* stage). At present, only a few specimens have been recorded (Fig. 7w), which hamper its formal diagnosis, but these features allow its unique properties to be recognised. Moreover, this new genus is currently considered as endemic to the Midland Valley, and no other taxon in the literature of NW European basins can be compared with it.

These limestones in the Glasgow area contain rich assemblages (Table 9, SM), although the most significant taxa recorded in these horizons are common *Archaediscus* spp. at *angulatus* stage and *Eostaffella* of the *E. parastruvei* and *E. mosquensis* groups. No biostratigraphically significant taxa occur, although their correlation with the Main and Mid Hosie limestones of north Ayrshire is well established in the literature, and thus, they are assigned to Assemblage 9.

2.2.11. Limestone A. This limestone occurs in the Douglas area, south Lanarkshire, and is equivalent to the Mid Hosie Limestone (Fig. 3). It does not contain many diagnostic foraminiferans in Coal Burn and Garpel Water, except *Tubispirodiscus simplicissimus* (Table 9, SM).

2.2.12. Second Hosie Limestone. In Glengarnock section, north Ayrshire, this limestone contains a relatively poor foraminiferal assemblage, limited to ten genera (Table 10 in Supplementary Material (SM)), some of which are also abundant in older rocks, such as *Archaediscus* at *angulatus* stage, *Endothyra*, *Eostaffella*, *Koskinobigenerina* and *Tetrataxis*. Several features are noted: (1) lack of *Asteroarchaediscus baschkiricus*; (2) scarcity of *Biseriella*; (3) common *Tubispirodiscus* species (Fig. 8a–f), (although present in older rocks, they never occur in such numbers and with such diversity); (4) relatively common *Tubispirodiscus simplicissimus* and *Eostaffella* ex gr. *postmosquensis*; and (5) first occurrence of *Eostaffella mutabilis* (Fig. 8g). An additional characteristic is the first occurrence of *Archaediscus* at *tenuis* stage with a poorly developed to virtually absent microgranular layer and the fibrous-radial wall, achieving an appearance of the typical wall of the eosigmoilinids, with only a relict of the microgranular inner layer. These assemblages are not comparable with previous assemblages, and they are also more evolved, and here referred to a new Assemblage 10 (described later).

2.2.13. Top Hosie Limestone. This limestone is similar to the Second Hosie Limestone horizon, although it exhibits poorer assemblages, with only six foraminiferal genera. However, a similar richness in *Tubispirodiscus* (Fig. 8j–k) and *Archaediscus* at *tenuis* stages (Fig. 8l) is observed and, thus, it is assigned to Assemblage 10.

2.2.14. Anvil Limestone. In this limestone of north Lanarkshire, *Tubispirodiscus* is common, but never in such large numbers, whereas specimens of *Archaediscus* at *tenuis* stages (Fig. 9b) are more common. A rich and diverse assemblage is recorded, with 19 foraminiferal genera (Table 10, SM). Highlighted are *Tubispirodiscus simplicissimus* and *Endostaffella shamordini* (Fig. 9k–l). Also noteworthy is the occurrence of *Euxinita* which, although rarely recorded in the Second and Top Hosie limestones, becomes relatively common in the Anvil Limestone. It first occurs as a larger species than the typical *E. efremovi* (Fig. 9f), denominated as *Euxinita pendleiensis* (in Cózar *et al*. 2008a), together with *Praeplectostaffella*. Another important first occurrence is *Endothyranopsis plana* (Fig. 9a), characterised by its flattened, small test without an umbilicus. In addition, *Rectocornuspira regularis* first occurs, being relatively common. The genus *Eostaffella* is well represented, with common *E.* ex gr. *postmosquensis* (Fig. 9c–d), and the first occurrence of *E.* aff. *proikensis*, and *E. angusta* (Fig. 9e). Some specimens of *Calcitornella* sp. are also identified in the Anvil Limestone. This assemblage, although with some differences, is comparable to the assemblages recorded in the Second and Top Hosie limestones, and assigned to Assemblage 10.

2.2.15. Cement Limestone. This is entirely dolomitised.

2.2.16. MacDonald Limestone. This limestone of south Lanarkshire contains a high foraminiferal diversity, with 25 genera recorded, and the taxa are well-preserved. The MacDonald Limestone is equivalent to the Second and Top Hosie horizons. The diversity in the limestone is also increased by the occurrence of rare calcareous algae and problematica (*Kulikia*, *Paraepimastopora*, *Kamaena*, *Mametella* and *Draffania*; Table 10, SM). Several foraminiferal features can be highlighted: (1) occurrence of miliolid-walled foraminiferans, *Calcivertella* sp. (Fig. 9n) and *Rectocornuspira regularis* (Fig. 9v–w) previously documented in the Anvil Limestone; (2) a diverse suite of evolved *Eostaffella* (*E. mutabilis*, *E. proikensis*, *E. constricta*, *E. mosquensis*, *E.* ex gr. *pseudostruvei* and *E.* ex gr. *postmosquensis*) (Fig. 9m, r, s), *Eostaffellina*? sp. (Fig. 9o), *Neoarchaediscus* and *Planospirodiscus* (particularly the first occurrence of *P. taimyricus*); (3) large species of *Euxinita pendleiensis* (Fig. 9t–u); (4) relatively common *Tubispirodiscus* and *Archaediscus* at *tenuis* stages. The first occurrence of *Millerella*? sp. (Fig. 9g) is controversial, and its determination is exclusively based on the presence of convex septa directed toward the aperture, although no well-oriented axial section has been recorded. The assemblage is similar to the newly recognised Assemblage 10 recorded from the Top Hosie, Second Hosie and Anvil limestones.

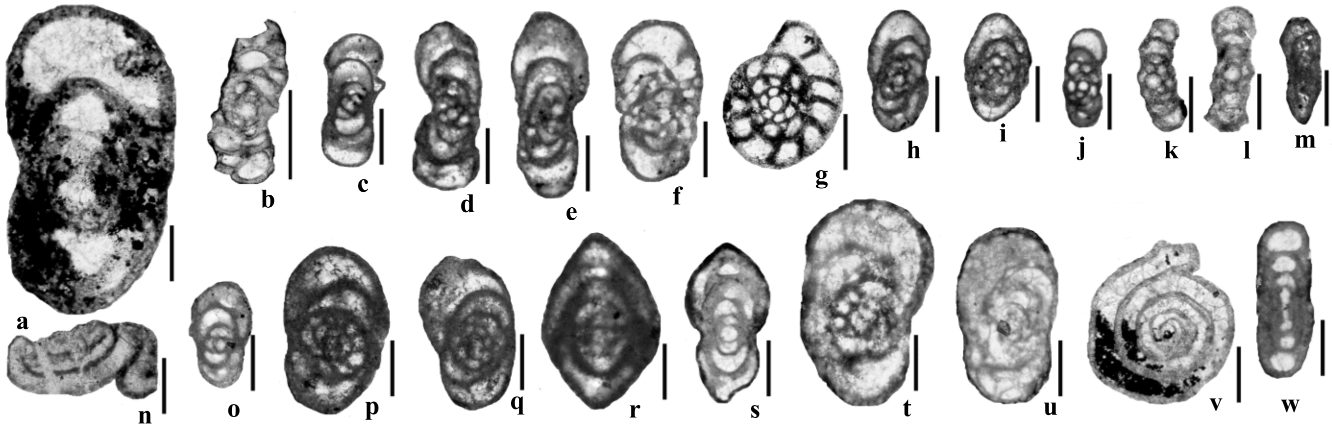

Figure 9 Foraminiferans from the Anvil Limestone (a–l, except for g) and MacDonald Limestone (g, m–w) (Scale bar = 100 µm). (a) *Endothyranopsis plana*, IB-1516/2721–30. (b) *Archaediscus* sp. at *tenuis* stage, IB-1517/2722–12. (c) *Eostaffella* ex gr. *postmosquensis*, IB-1514/2721–12. (d) *Eostaffella* ex gr. *postmosquensis*, IB-1515/2721–26. (e) *Eostaffella* ex gr. *pseudostruvei*, IB-1515/2721–17. (f) *Euxinita efremovi*, IB-1514/2721–13. (g) *Millerella*? sp., IB-363/2719–12. (h) *Praeplectostaffella anvilensis*, IB-1515/2721–21. (i) *Praeplectostaffella anvilensis*, IB-1514/2721–27. (j) *Endostaffella delicata*, IB-1514/2721–14. (k) *Endostaffella shamordini*, IB-1516/2722–1. (l) *Endostaffella shamordini*, IB-1516/2722–2. (m) *Eostaffella mutabilis*, IB-538/2720–3. (n) *Calcivertella* sp., IB-724/2721–2. (o) *Eostaffellina*? sp., IB-364/2719–14. (p) *Praeostaffellina macdonaldensis*, IB-541/2720–13. (q) *Praeostaffellina macdonaldensis*, IB-541/2720–11. (r) *Eostaffella proikensis*, IB-541/2720–10. (s) *Eostaffella* sp., IB-374/2719–25. (t) *Euxinita pendleiensis*, IB-546/2720–34. (u) *Euxinita pendleiensis*, IB-546/2720–37. (v) *Rectocornuspira regularis*, IB-186/2719–7. (w) *Rectocornuspira regularis*, IB-538/2720–5.

2.3. Limestones in the Lower Limestone Formation (Bathgate Group)

The succession in the Bathgate district is quite different from most of the successions in the Midland Valley, due to the occurrence of thick intervals of volcanic rocks (Fig. 3). The succession includes the West Kirkton, Tartraven, Petershill and Wardlaw limestones, although it was only possible to sample the West Kirkton and Petershill limestones.

2.3.1. West Kirkton Limestone. This limestone does not contain diagnostic foraminiferans for accurate age determination (Table 11 in Supplementary Material (SM)), with only three of the twelve thin-sections recording *Archaediscus*, *Earlandia* and *Endothyra*.

2.3.2. Petershill Limestone. This limestone on the other hand contains a rich assemblage, comprising 26 foraminiferal genera (Table 11, SM), with common *Archaediscus* at *angulatus* stage, *Asteroarchaediscus*, *Climacammina* and *Parajanischewskina* (Fig. 7m) (cf. Cózar & Somerville 2006). In addition, the occurrences of *Tubispirodiscus*, *Calcitornella*, *Biseriella* (Fig. 7x), *Janischewskina*, diverse species of *Eostaffella* (Fig. 7a–c, e–g, l), *Endostaffella*? sp. (Fig. 7d, h, j–k) and *Chomatomediocris*? sp. (Fig. 7i) are biostratigraphically significant. Due to its isolated stratigraphic position in between volcanic rocks, the precise correlation of the Petershill Limestone with other limestones in the Midland Valley was not definitively established. The foraminiferal assemblage recorded in this present study, however, suggests an Assemblage 9 age, and thus, is probably correlatable with the Main and Mid Hosie limestones and their lateral equivalents (cf. Browne *et al.* 1999, table 4; Fig. 3).

3. Characterisation of the assemblages

Most of the limestone beds and shell bands in the Lower Limestone Formation have been assigned to assemblages 7 and 8 based on comparison of their microfauna and microflora to those in northern England, although the stratigraphic ranges of some taxa can be more precisely constrained in the Midland Valley to the Assemblage 8 interval. This interval has now been subdivided into a lower Assemblage 8, succeeded by two new assemblages, 9 and 10. These assemblages allow a correlation throughout the area (Fig. 3), and can be summarised as follows (Fig. 10):

Assemblage 7 is characterised (in comparison with northern England) by (i) common *Neoarchaediscus* and *Endostaffella* species, *Falsocalcifolium punctatum*, *Howchinia gibba*, and also *Euxinita efremovi*; (ii) first occurrence of rare *Endothyranopsis sphaerica*, *Biseriella*, *Planospirodiscus*, *Pseudoglomospira*, *Tubispirodiscus* sp., *Tubispirodiscus cornuspiroides*, and in younger strata within the assemblage, *Climacammina* and *Janischewskina*, which also first occur in northern England; (iii) rare *Asteroarchaediscus*, (although its first occurrence is situated in the uppermost part of Assemblage 6); (iv) in the upper part, near the top, the first occurrences of rare *Calcifolium okense* is recorded in northern England.

The typical Assemblage 8 is characterised by (i) common *Calcifolium okense* and *Asteroarchaediscus* species; (ii) local peaks of *Biseriella*, are also observed; and (iii) first occurrences of *Eostaffella* ex gr. *postmosquensis*, *E.* ex gr. *pseudostruvei*, and the Miliolata foraminiferans *Tubispirodiscus attenuatus* and *Neoarchaediscus postrugosus*.

Assemblage 9 is quite similar to Assemblage 8, and the observed differences might be only of regional interest, confined to the Midland Valley. This assemblage is characterised by the first occurrence of *Tubispirodiscus simplicissimus* (and more common primitive *Tubispirodiscus* sp.), *Tubispirodiscus hosiensis* (in Cózar *et al.* 2008a), *Endostaffella shamordini*, *Endostaffella*? sp. A and *Endostaffella*? sp. B. Other common taxa are species of *Tubispirodiscus* and *Pseudoglomospira*. However, another notable characteristic is the marked decrease in foraminiferal diversity, and particularly in the problematica, where *Calcifolium* and *Falsocalcifolium* virtually disappear, a feature that is distinct from northern England (see Cózar & Somerville 2004).

The correlation exclusively using algae suggests major concerns about the strong influence of palaeoecological factors on the assemblages, and some aspects have to be clarified. This case would be the same also for the problematica, commonly related to the algae. Thus, the occurrence of the biostromes of *C. okense* and *F. punctatum*, previously proposed as markers for correlation in Britain (e.g. Holliday *et al.* 1975) needs to be carefully assessed. *Falsocalcifolium punctatum* shows a

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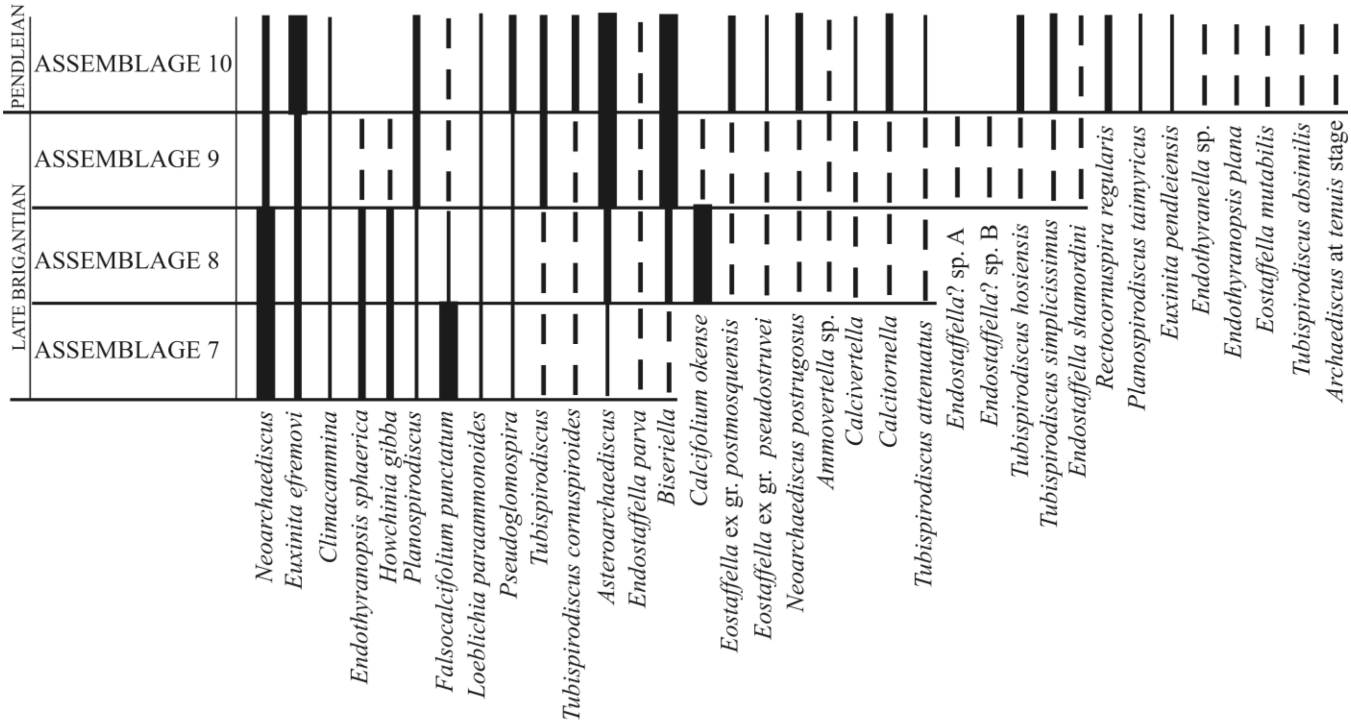

Figure 10 Main biostratigraphical markers of the Assemblages 7 to 10 in the Central Coalfield and Douglas areas. Relative abundance based on combined data in Tables 1–11 (Supplementary Material). Thick solid line = high abundance; thin solid line = low abundance; dashed line = rarity.

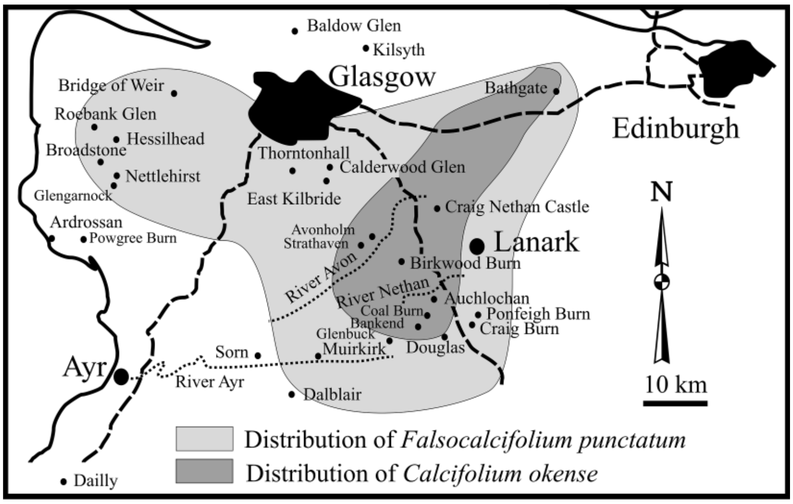

Figure 11 Geographical distribution of *Falsocalcifolium punctatum* and *Calcifolium okense* in the Central Coalfield, North Ayrshire and Douglas areas.

widespread distribution, not only in Britain, but also in the entire western Palaeotethys (see Vachard & Cózar 2005), and it also occurs in high numbers in samples up to and including the Pendleian limestones (Cózar & Somerville 2004). In the Central Coalfield Basin, *F. punctatum* is not distributed throughout the entire basin (Fig. 11), and thus, its occurrence cannot be universally used as a marker. However, its acme seems to be a reliable datum.

On the other hand, *Calcifolium okense* is much more restricted in its distribution (Fig. 11), and clear differences are observed between areas of the Midland Valley, e.g. compare the Blackhall and Dockra limestones, with correlation being possible only using foraminiferans. Higher in the succession, *C. okense* is apparently absent in the Hosie limestones and their lateral equivalents, whereas it is common in the Great Limestone from northern England (Johnson 1958; Burgess 1965; Hallett 1970; Holliday *et al.* 1975; Johnson & Nudds 1996; Cózar & Somerville 2004; Vachard & Cózar 2005). Nevertheless, its acme in the late Brigantian, following that of *F. punctatum* (Fig. 10), can be also used as a reliable marker.

Palaeoecological constraints have not only had an influence on algal and problematica distribution, but can be also observed in foraminiferans. One clear case is the distribution of *Biseriella*. It is usually rare during the late Brigantian, although some local peaks can be recorded, usually in beds equivalent to Assemblage 9. However, these local peaks are also observed in the Midland Valley in assemblages 7 and 8 (Captains Bridge and Castlehill, south Ayrshire). In those outcrops, impure sandy limestones, locally cross-bedded, occur, in a near-shore marginal facies of the basin.

Assemblage 10 is characterised by several features and the following can be highlighted as being representative for these younger limestone units (Fig. 10): (1) first occurrence of *Tubispirodiscus absimilis*, as well as other unusual species of the

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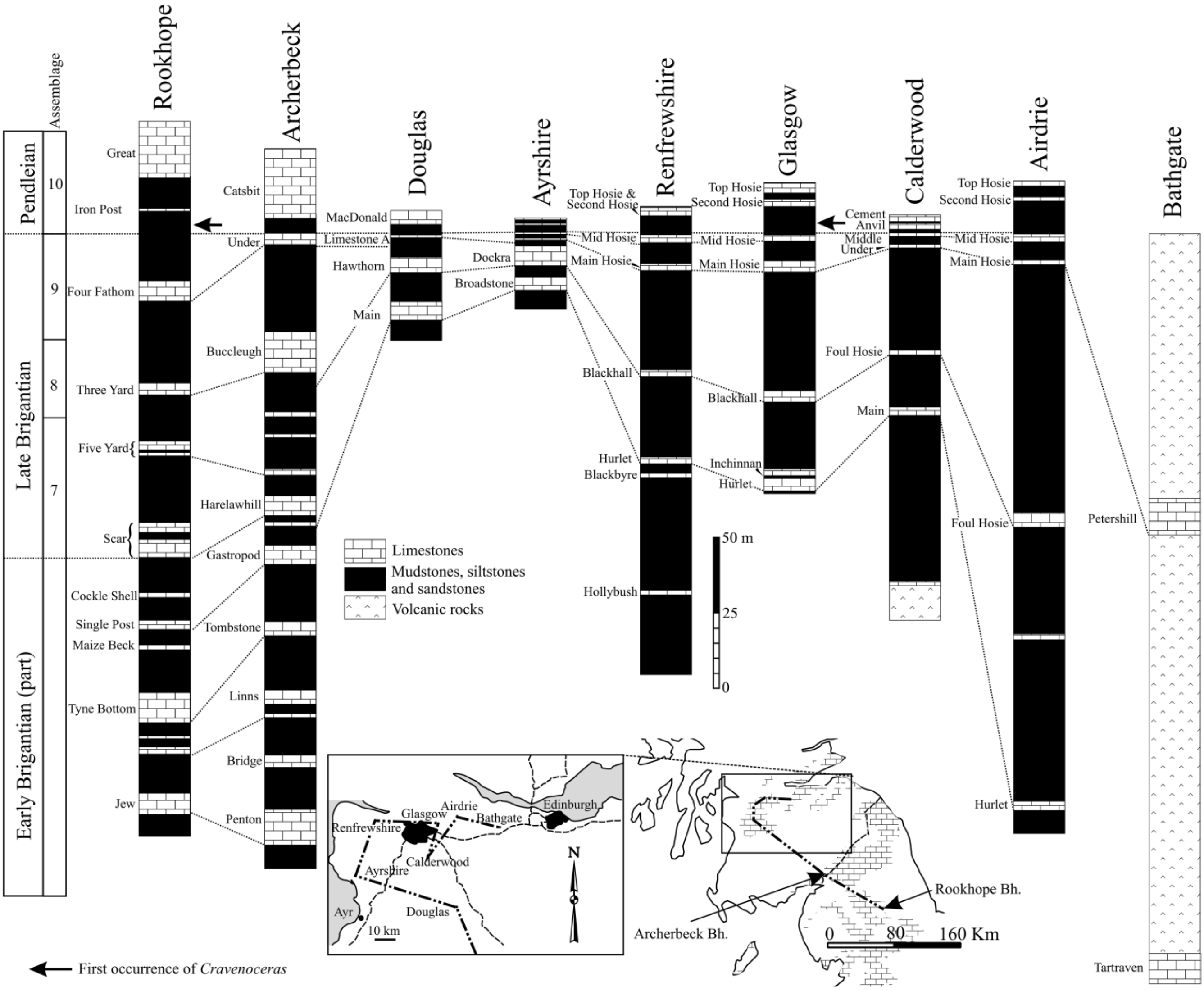

Figure 12 Correlation between the Central Coalfield Basin, Midland Valley and Northern England.

genus; (2) first occurrence of *Archaediscus* at *tenuis* stage; (3) first occurrence of *Endothyranella*; (4) first occurrence of *Endothyranopsis plana*; (5) first occurrence of *Eostaffella mutabilis*; (6) first occurrence of *Euxinita pendleiensis*; and (7) first occurrence of *Rectocornuspira regularis*. In addition to the latter first occurrences, the assemblages can be also characterised by common: (7) *Tubispirodiscus*; (8) *Eostaffella* ex gr. *postmosquensis* and *E.* ex gr. *pseudostruvei*; (9) *Euxinita efremovi*; (10) *Endostaffella* species; (11) *Praeplectostaffella anvilensis* (in Cózar *et al*. 2008a); (12) *Praeostaffellina macdonaldensis* (in Cózar *et al*. 2008a); and (13) calcitornellids.

Biostratigraphical correlation of the central and western parts of the Midland Valley presented in this present study has both assigned new and confirmed existing stratigraphical correlations for some limestone horizons, distinct from data observed in previous correlations (Burgess 1965; Holliday *et al*. 1975; George *et al*. 1976; Wilson 1979; Cameron & Stephenson 1985; Francis 1991; Browne *et al*. 1999):

The main change is the age attributed to the Lower Limestone Formation. This was previously considered as exclusively late Brigantian (latest Viséan), but the top of this formation clearly ranges up into the Pendleian (early Serpukhovian) (Figs 2, 3).

The West Kirkton Limestone is not included in the Lower Limestone Formation, and its age cannot be precisely determined; it could be Asbian or early Brigantian.

The Broadstone Limestone correlation with the Main and Hurlet limestones is confirmed, as is the correlation of the Hawthorn Limestone with the Blackhall and Dockra limestones (cf. Wilson 1979; Fig. 3).

The Petershill Limestone shows an assemblage considered here to be equivalent to the Main and Mid Hosie limestones (and their lateral equivalents) (cf. Browne *et al*. 1999, table 4; Fig. 3).

4. Correlation with northern England

It is difficult to correlate directly individual limestones from the Midland Valley with those in northern England, due to variations in cyclothemic sedimentation for equivalent intervals. Moreover, differences in the limestone facies observed within the limestones in the Midland Valley, are also recorded in northern England. Consequently, biostratigraphical assemblages previously described (Cózar & Somerville 2004) are considered as a reliable tool for undertaking this kind of correlation (Fig. 10). The assemblages suggest that the common early Brigantian limestones in northern England are limited to a reduced number of cycles in the Midland Valley; the lower early Brigantian interval seems to be represented mostly by siliciclastic rocks in the Lawmuir Formation, which

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hamper a detailed bed-by-bed correlation. Within the upper part of this formation, the Blackbyre or Under limestones are probably correlatable with the Tyne Bottom Limestone (Figs 3, 12). These limestone bands are only represented in the north-western areas of the Midland Valley (Glasgow and Renfrewshire), where the Lawmuir Formation is thickest.

In contrast to the early Brigantian, the late Brigantian in the Midland Valley is represented by more numerous cycles than in northern England (Fig. 12). Assemblage zones can be correlated, and generally, four limestones horizons from northern England (Scar, Five Yard, Three Yard, Four Fathom) can be traced across to the Central Coalfield with up to five or six limestone horizons in the Midland Valley (Fig. 12). However, for a precise correlation of the cycles, marine shell bands also have to be acknowledged. The Assemblage zone 7 is recognised in northern England in the Scar and Five Yard limestones, of early late Brigantian age, and no significant differences between them can be proposed, but this pair is generally correlated with pairs of limestones in the western part of the Midland Valley: Broadstone/Wee Post, Hurlet/Shield Bed and the Main/Craigenhill limestones (Fig. 3). In an intermediate geographic position, the Scar Limestone is correlated with the Harelawhill Limestone of the Archerbeck Borehole in Dumfriesshire (115 km southeast of Glasgow and 65 km northwest of the Rookhope Borehole on the Alston Block; Fig. 12).

The Assemblage zone 8, attributed to the Three Yard Limestone in northern England, of middle late Brigantian age, is a different case from the previous assemblage; it corresponds to a single bed in most parts of the Midland Valley: the Dockra, Blackhall and Hawthorn limestones (Fig. 12). This horizon is correlated with the Buccleugh Limestone in the Archerbeck Borehole.

The Four Fathom Limestone from northern England, formerly attributed to Assemblage 8, can now be reassigned to Assemblage 9, of latest Brigantian age, and equates to pairs of limestones in the Midland Valley: Main Hosie/Mid Hosie, except around Douglas, where only one bed, Limestone A, is present (Fig. 12). This horizon is correlated with the Under Limestone in the Archerbeck Borehole and the Petershill Limestone of the Bathgate area.

The Great/Main Limestone of the Northern Pennines can now be assigned to Assemblage 10, correlating with the Second/Top Hosie limestones, Anvil/Cement, and the equivalent MacDonald Limestone, and with the Catsbit Limestone of the Archerbeck Borehole (Fig. 12).

The base of the Pendleian Sub-stage (early Serpukhovian) is defined in northern England on goniatite evidence (*Cravenoceras*), and has been located at a level just above the top of the Four Fathom Limestone (Arthurton *et al.* 1988), confirming the Pendleian age of Assemblage 10. This implies that in Scotland, the base of the Pendleian lies within the clastic rocks between the Mid Hosie and Second Hosie limestones and their correlatives, probably just above the top of Mid Hosie Limestone (Fig. 12).

5. Conclusions

Analysis of the foraminiferal, algal and problematica assemblages of the Lower Limestone Formation in the Central Coalfield and Douglas outlier allow its stratigraphical range to be extended higher from the late Brigantian (latest Viséan) up to the Pendleian (early Serpukhovian), and the Second/Top Hosie, Anvil/Cement and MacDonald limestones are all considered now as Pendleian in age. In addition, the stratigraphical positions of some horizons are modified or confirmed (e.g., West Kirkton, Petershill, Broadstone, Hawthorn).

Local biozonation of the Central Coalfield Basin allows four assemblages to be proposed, numbered 7 to 10, for comparison with the assemblages defined for the late Brigantian to Pendleian interval in northern England. Assemblage 7 is equivalent in both areas, but Assemblage 8 in northern England is subdivided into three assemblages in the Central Coalfield, a lower Assemblage 8 (middle part of the late Brigantian), succeeded by Assemblage 9 (uppermost late Brigantian) and Assemblage 10 (Pendleian). Those assemblages allow correlation with the standard limestones from the Alston Block (Fig. 12).

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7. Supplementary Material

Appendix I and Tables 1–11 are published as Supplementary Material with the on-line version of this paper. This is hosted by the Cambridge Journals Online service and can be viewed at http://journals.cambridge.org/tre

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