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Lower Carboniferous ostracods from the Ballagan Formation, Midland Valley, Scotland: analysis of the Spilmersford Borehole; improved analysis of the Glenrothes Borehole; and a review of stratigraphical and palaeoecological ostracod data from key sections.

Midland Valley Project

Internal Report IR/02/194

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/02/194

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Mark Williams

Key words

Ballagan Formation, ostracods, biostratigraphy, palaeoecology, Carboniferous, Tournaisian, Visean

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Parent Body

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Foreword

The micropalaeontological results and interpretations presented in this report are part of a regional study within the 'Geology and Tectonic Evolution of the Midland Valley Terrane' project, that is part of the programme of geological resurvey of the United Kingdom. The work contributes to the provision of up-to-date geoscientific research for the Central Belt of Scotland.

Acknowledgments Paul Shepherd made the electronic image of Figure 7. Mark Dean supplied additional information about the palaeoecological significance of the bivalve *Modiolus* and, together with Maxine Akhurst, Richard Smith, Alison Monaghan, Sarah Arkley and Mike Stephenson, made many useful improvements to the text.

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Figure 5. Improved stratigraphical and biofacies resolution for the ostracods of the Ballagan Formation, Glenrothes Borehole [NGR NO 25615 03142].

Figure 6. Stratigraphical ranges of key ostracod species in the Lower Carboniferous of the Midland Valley, Scotland. The ranges are plotted against the palynomorph biozones and are reconstructed from data presented in figures 2 to 5. Numbers on the ranges denote data from: 1, Spilmersford Borehole; 2, Ayrshire; 3, East Dron Borehole; 4, Glenrothes Borehole. The thin dotted lines indicate a longer range recorded by Robinson (1978). Thick dotted lines denote an uncertain range

Figure 7. Sediment infilling mud cracks at depth 802.85 m below Ordnance Datum in the Spilmersford Borehole. The sediment infill includes specimens of *Sulcella* cf. *affiliata.*

Overview

This report details ostracod distribution in the Ballagan Formation (Lower Carboniferous) of the Spilmersford Borehole [NGR NT 4570 6902], provides an improved biostratigraphical and biofacies analysis of the Glenrothes Borehole [NGR NO 25615 03142] ostracod faunas and summarises knowledge about ostracod biofacies and biostratigraphy in the Lower Carboniferous of the Midland Valley. A summary ostracod biostratigraphical range chart for the Ballagan Formation is presented, calibrating the total ranges of key individual species with the palynomorph biozones. Several species emerge as potential proxies for the palynomorph biozones: *Shemonaella* cf. *scotoburdigalensis* may indicate the PC Biozone; the widespread *Cavellina coela* and *C. incurvescens* indicate the CM Biozone; and *Sulcella* cf. *affiliata* indicates the uppermost CM Biozone and succeeding Pu Biozone. In terms of palaeoecology, the ostracod assemblages suggest as many as four recurrent biofacies for the Ballagan Formation, indicative of quasi-marine, brackish and freshwater habitats. The Ballagan Formation may yield some of the earliest freshwater ostracods.

1. Introduction

The Ballagan Formation is a widespread lithostratigraphical unit of the Lower Carboniferous of the Midland Valley of Scotland (Browne et al. 1999). Eastwards from the Ayrshire coast exposures, the formation is known from numerous inland localities and several boreholes extending across central Scotland to Fife. The widespread occurrence of evaporite minerals, desiccation cracks, and a restricted ('*Modiolis* phase') bivalve fauna suggest that much of the formation was deposited in marginal marine coastal floodplains and lagoons, in a semi-arid climate (Andrews et al. 1991; Andrews and Nabi 1998).

Throughout central Scotland, much of the Ballagan Formation yields palynomorph assemblages assigned to the CM Biozone of the Tournaisian (see Stephenson et al. 2003; Stephenson 2002a, 2002b, 2002c, 2002d). Recent detailed work has greatly refined earlier palynomorph-biostratigraphies and indicates that the Ballagan Formation may, in some areas, be as old as the PC Biozone (see Stephenson 2002a). Stephenson (2002b) has also identified problems with the positioning of the CM/Pu biozonal boundary in the upper part of the Ballagan Formation and helped to distinguish assemblages which can be used for local correlation in Ayrshire (Stephenson et al. 2003).

In tandem with the palynomorph and field mapping work, the ostracods of the Ballagan Formation have been studied in an attempt to quantify their biostratigraphical ranges and their application to biofacies analysis. This report summarises progress with the ostracods thus far. It provides a stratigraphical and biofacies analysis of the Spilmersford Borehole, a much refined biostratigraphical analysis of the Glenrothes Borehole (see Williams 2001) and applies biofacies analysis to the East Dron borehole (see Williams 2002) and Ayrshire sequence (Williams and Taylor 2001; Stephenson et al. 2003). The geographical position of these four studied sections is shown in Figure 1 (see page 15).

2. Ostracod biostratigraphy of the Spilmersford Borehole – and comparison with other key sections in the Midland Valley

The Spilmersford borehole yields ostracods from the Ballagan Formation at 56 horizons between 700 and 896 m below Ordnance Datum (OD). Ostracod stratigraphical distributions in the Spilmersford Borehole are shown in Figure 2, plotted against the palynological biozonation of Neves et al. (1973), Neves and Ioannides (1974) and Stephenson (2002b). Ostracod distributions at three other key sections in the Midland Valley are shown in Figures 3-5.

The ostracod *Sulcella* cf. *affiliata* (Jones and Kirby) has an extensive range between 718.13 m and 832.11 m below OD and, based on the palynomorph biozonation for this borehole produced by Neves et al. (1973), Neves and Ioannides (1974), and Stephenson (2002b), would appear to range through the top of the Tournaisian CM Biozone and into the succeeding Visean Pu Biozone. *S.* cf. *affiliata* also occurs above an horizon (at 832.88 m below OD; 2732.5 feet) from which a CM Biozone 'Upper Ballagan' palynomorph assemblage is identified. *Sulcella* cf. *affiliata* has previously been recorded from the Ballagan Formation in Ayrshire (Williams and Taylor, 2001; see Figure 3). There it occurs in the interval of the uppermost part of the 'Lower Ballagan' palynomorph assemblage and the succeeding 'Upper Ballagan' palynomorph assemblage. These are regarded as most likely representative of the CM Biozone (Stephenson et al. 2003). This suggests that *S.* cf. *affiliata* is an ostracod proxy for the upper CM Biozone and for much of the succeeding Pu Biozone. *Sulcella affiliata* has been recorded from Holkerian horizons of the Visean by Robinson (1978).

Acutiangulata aequalis is recorded at depth 877.42 m below OD in the Spilmersford Borehole, at a level below that from which an 'Upper Ballagan' palynomorph assemblage of the CM Biozone was recovered (i.e. at 832.88 m below OD, 2732.5 feet, Figure 2). This ostracod species is also recorded from the East Dron Borehole (see Figure 4) and from the Ayrshire coast (Figure 3), at levels equated to the CM Biozone. The absence of *A. aequalis* from younger (Visean) horizons contrasts with the reported range of this species by Robinson (1978). However, Robinson does report the very similar (conspecific?) *Acutiangulata quadrata* from Tournaisian horizons; its relationship to *A. aequalis* needs further investigating.

Shemonaella sp. A occurs at several horizons in the Spilmersford Borehole between 713.46 m and 793.45 m below OD (Figure 2), a range which equates to the Pu palynomorph Biozone according to Neves and Ioannides (1974) and Stephenson (2002b). In the East Dron and Glenrothes boreholes (Figures 4, 5), and on the Ayrshire coast (Figure 3), this species also ranges through the CM Biozone (Williams and Taylor, 2001; Williams, 2001, 2002).

Many of the characteristic Ballagan Formation ostracods of the western Midland Valley in Ayrshire, have not been recovered in the Spilmersford Borehole. These forms, which appear to range through the CM palynomorph Biozone in Ayrshire, include *Knoxiella* sp. A, *Cavellina coela* and *C. incurvescens*. With the exception of *C. coela*, these ostracod taxa appear to be rare in the Ballagan Formation of the eastern Midland Valley (see also Williams, 2002).

3. Ostracod biostratigraphy of the Ballagan Formation: summary ranges of key species

The temporal distribution of ostracods in the Ballagan Formation at the four key sections illustrated here (Figures 2-5) can be used for a provisional reconstruction of the ranges of individual taxa relative to the palynomorph biozones (see page 20, Figure 6). Notwithstanding lithofacies controls on the distribution of species (for which, see below), several species emerge as useful proxies for the Lower Carboniferous palynomorph biozones. Thus, *Shemonaella scotoburdigalensis* may indicate the PC Biozone, whilst *Knoxiella* sp. A, *Cavellina coela* and *C. incurvescens* appear to indicate the CM Biozone. *Glyptolichvinella* cf. *spiralis* (Jones and Kirkby) and *Beyrichiopsis glyptopleuroides* Green (see Figures 4, 5) appear well above the base of the CM Biozone, as does *Sulcella* cf. *affiliata*, which ranges into the succeeding Pu Biozone. *Shemonaella* sp. A emerges as a long-ranging proxy for the CM and Pu biozones.

4. Ostracod biofacies of the Ballagan Formation

The ostracod biofacies associations (biotopes) identified in the Ballagan Formation at outcrop in Ayrshire (Williams and Taylor, 2001; Stephenson et al. 2003), and from boreholes at Glenrothes (Williams, 2001; and new information in this paper), East Dron (Williams, 2002) and Spilmersford (herein) are summarised below as Associations 1 to 4. The associations are not entirely exclusive and some species occur in more than one biotope. Further work on the Ballagan Formation from new field collections and from the East Linton and Blairmulloch boreholes will test the validity of these associations. Lithofacies information is gleaned from Turner (1991) and Stephenson et al. (2003).

Association 1. 'Tidal flat, supratidal or marginal marine'

This is characterised by abundant *Cavellina coela* together with *Cavellina incurvescens, Knoxiella* sp. A and *Paraparchites* sp. 1. It is best developed between *c.* 230 to 270 m above the base of the Heads of Ayr section in Ayrshire (horizons MW1 and ASB100-102 of Figure 3). Other ostracods occurring exclusively in this association are *Acratia*? sp. and cf. *Bairdia jakutika*, which suggest some marine influence (see Robinson 1978). *Beyrichiopsis glyptopleuroides* and *Shemonaella* sp. A also occur, but both of these taxa are present in other associations. In Ayrshire the assemblages are associated with lithofacies interpreted as tidal flat, supratidal or marginal marine (Williams and Taylor, 2001; Stephenson et al. 2003).

Poorly developed Association 1 assemblages may be signalled in the East Dron Borehole by *Knoxiella* sp. A at depth 46.96 m below OD and by *Cavellina coela* and *C. incurvescens* at depth 191.63 m below OD (Figure 4).

In the Glenrothes Borehole Association 1 may be signalled by *C. coela*, which is intermittently abundant between 244.90 m and 310.05 m below OD (Figure 5). The quasi-marine bivalve *Modiolus* is not typical of this association, but does occur occasionally with *C. coela,* for example, around depth 302 m below OD in the Glenrothes Borehole. *C. coela* appears to be associated with Turner's (1991) Lithofacies 1 (cementstones deposited on mudflats in brackish water conditions) and Lithofacies 2 (alternations of mudrock and low Mg-calcite limestones, specifically at 310-311m below OD) identified in the Glenrothes Borehole. It may have been euryhaline. It was probably also tolerant of raised salinity as evidenced by its occurrence in the rock-sequence just below Lithofacies 3 of Turner (Evaporite lithofacies at 300 m below OD). However, the absence of *Acratia*, *Bairdia* and *Knoxiella* from Association 1 in this borehole suggests little or no marine influence (cf. Stephenson et al. 2003).

Stephenson (2002e) notes a general absence of autochthonous algal palynomorphs in the Ayrshire rock sequence with Association 1 ostracods: elsewhere these palynomorphs (e.g. *Botryococcus*) occur in non-marine (e.g. lower salinity) aquatic environments (see Association 2 below).

Association 2. 'Brackish water or quasi marine'

Association 2 is dominated by *Shemonaella* sp. A, together with *Acutiangulata aequalis*. In Ayrshire it occurs between *c.* 320 to 330 m above the base of the Heads of Ayr section (horizons SAR15, SAR16 and SAR43 of Figure 3), where the associated lithofacies suggest a lagoonal environment, possibly with fluctuating salinity (Stephenson et al. 2003).

Association 2 is most fully developed in the East Dron Borehole, where *Shemonaella* sp. A is the most common ostracod (Figure 4). Association 2 is also well developed in the Spilmersford Borehole between about 754 m and 762 m below OD (Figure 2). It is typically associated with the bivalve *Modiolus*, and with plant debris, suggesting it to be an indicator of brackish or quasi-marine facies (see Wilson in Lumsden et al. 1967, p. 90; Wilson, 1989, p. 103). The common occurrence of *Shemonaella* sp. A with *Acutiangulata aequalis* suggests a similar ecology for the latter (though see below). In the East Dron Borehole, Association 2 dominates the interval from 43.01 m to 92.02 m below OD and the intermittent occurrence of *Shemonaella* sp. A to depth 218.8 m below OD suggests similar facies are developed throughout the lower Ballagan Formation in this borehole.

Although *Shemonaella* sp. A and *A. aequalis* commonly co-occur, some horizons of the East Dron Borehole and Ayrshire are dominated by an abundance of one species to the apparent exclusion of the other: these are identified as 2a (*Shemonaella* absent) and 2b (*Acutiangulata* absent) on the range diagrams (Figures 2-5). Possibly this relates to slight fluctuations in the ambient environment, such as changes in salinity, which favoured one species (see Williams, 2002, p. 15). In part though, for example in the upper part of the Ballagan Formation in the Spilmersford Borehole sequence, the absence of *A. aequalis* might also be related to temporal constraints on its stratigraphical range.

Stephenson (2002e) has noted the similar lithofacies occurrence of *Leiosphaeridia*- and algal-dominated palynomorph assemblages with ostracod associations 2 and 3, suggesting that both the ostracod and palynomorph fossil assemblages may be used to indicate brackish or low salinity aquatic environments. This is supported by the occurrence of zygnematacean algae and *Botryococcus* in these assemblages, both of which, in modern ecologies, are restricted to freshwater and brackish water settings.

Association 3. 'Low salinity or freshwater'

This is dominated by *Sulcella* cf. *affiliata*. In Ayrshire it occurs at several horizons between *c.* 360 to 410 m above the base of the Heads of Ayr section (Stephenson et al. 2003; horizons SAR4-6, SAR21 and SAR42 of Figure 3). Other associates include *Glyptolichvinella* cf. *spiralis* and a 'robust ?cavellinid'. There are few co-occurrences of Association 3 ostracods with those of the other associations. In Ayrshire, associated lithofacies suggest a lagoonal environment possibly with fluctuating salinity, but the co-occurrence of the *Leiosphaeridia* palynomorph assemblage with *S.* cf. *affiliata* suggests the latter may have tolerated low salinity or was freshwater (see Stephenson et al. 2003).

Faunas representative of Association 3 also occur in the Spilmersford Borehole, often in sandy infillings of mud cracks in mud rocks (Figure 7). These suggest an ephemeral aquatic system, perhaps lacustrine or overbank river deposits on a mudflat: land derived 'millet seed' wind blown sand grains are associated with the mud crack fills. *S.* cf. *affiliata* occasionally occurs with *Shemonaella* sp. A in the Spilmersford Borehole, suggesting that the latter, like *A. aequalis*, may have been euryhaline.

Association 4. 'Brackish or freshwater'

In the Glenrothes Borehole, at depth 357.8 m and 358.2 m below OD *Shemonaella* cf. *scotoburdigalensis* dominates the ostracod fauna (Figure 5). Its associates include plant fragments, fish fragments and small gastropods. According to Turner (1991, p. 113), between 362 m and 329 m below OD in the Glenrothes Borehole the environment may have been a distal alluvial fan type setting, so a brackish water setting - suggested by the abundance of paraparchitaceans - or even a freshwater setting seems likely. In some respects, the dominance of paraparchitaceans in this fauna resembles that of Association 2, and Association 4 might be its temporal precursor.

Ostracods, evaporites and proximal fluvial facies

There is some indication that ostracods may also have tolerated evaporitic environments. Thus, ostracods are recorded adjacent evaporite horizons in the Glenrothes and East Dron boreholes (Figures 4, 5). The ostracods tend to be diminutive and indeterminate, though possible *Shemonaella* is associated with evaporites at one horizon in East Dron. These impoverished faunas probably represent ostracods existing at the absolute limit of their salinity tolerance.

Ostracods are absent from certain parts of the Ballagan Formation rock-sequence. For example, they appear to be absent from successions associated with more proximal fluvial facies at Lindsayston Burn (collections of Alison Monaghan). The absence of ostracods from certain terrestrial facies of the Ballagan Formation provides additional information about the range of environments Carboniferous ostracods had colonised.

5. Testing the ostracod biofacies model

In order to further test the validity of the ostracod associations, the following work should be undertaken.

- Analysis of C and O stable isotopes from the ostracod shells to assay marine salinity and provide a test of ostracod biotopes independent of associated sedimentary facies or palynomorph biofacies.
- Integration of ostracod and palynomorph biotope data: this is already being undertaken with Dr. Stephenson and will involve facies modelling and statistics.
- Comparative examination of Eric Robinson's Carboniferous ostracod collections, newly donated to the Natural History Museum, London.
- Study of the ostracod faunas from the Ballagan Formation of the East Linton and Blairmulloch boreholes and other relevant sections discovered by the field mapping team.

6. Summary and conclusions

Spilmersford Borehole The Spilmersford borehole yields ostracods from the Ballagan Formation at 56 horizons between 700 and 896 m below Ordnance Datum (OD). *Sulcella* cf. *affiliata* has an extensive range within this borehole between 718.13 m and 832.11 m below OD and, based on the palynomorph biozonation for this borehole produced by Neves et al. (1973), Neves and Ioannides (1974), and Stephenson (2002b), would appear to range through the top of the Tournaisian CM Biozone and into the succeeding Visean Pu Biozone. *S.* cf. *affiliata* also occurs above an horizon (at 832.88 m below OD; 2732.5 feet) from which a CM Biozone 'Upper Ballagan' palynomorph assemblage is identified. *Acutiangulata aequalis* occurs at depth 877.42 m below OD, below the level at which the 'Upper Ballagan' palynomorph assemblage was recorded. *Shemonaella* sp. A occurs at numerous horizons between 713.46 m and 793.45 m below OD, a range which appears to place it entirely within the Pu Biozone (see Neves and Ioannides, 1974), though it occurs at levels within the CM Biozone elsewhere.

Ostracod biotopes A review of ostracod assemblages from the Ballagan Formation suggests four recurrent biofacies associations: **(1)** the *Cavellina coela* (Rome), *C. incurvescens* (Jones and Kirkby), *Paraparchites* sp. 1, *Knoxiella* sp. A and cf. *Bairdia jakutika* sensu Robinson, 1978 association occurring in a **tidal flat, supratidal or marginal marine** setting; **(2)** the *Shemonaella* sp. A and *Acutiangulata aequalis* Association, often occurring with the bivalve *Modiolus*, and suggesting **brackish water or quasi marine conditions**; **(2a)** this association without *Shemonaella* sp. A, **(2b)** this association without *A. aequalis*; **(3)** the *Sulcella* cf. *affiliata* Association, possibly associated with **low salinity or freshwater**; **(4)** the *Shemonaella scotoburdigalensis* (Hibbert) Association, possibly indicative of **brackish or freshwater**. Associations 1-3 are well developed in Ayrshire, whilst the East Dron Borehole sequence is dominated by Association 2. Thus far, Association 4 is found only in the lower part of the Ballagan Formation in the Glenrothes Borehole, where it may be a temporal precursor of Association 2. Association 3 is present in the Spilmersford Borehole and Ayrshire, but not in the Glenrothes sequence. There are strong ties between freshwater/brackish water *Leiosphaeridia*- and algal-dominated palynomorph assemblages and ostracod associations 2 and 3. In contrast, the more 'marine' sequences yielding ostracod Association 1 are characterised by the absence of aquatic algal-palynomorphs.

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Appendix: Samples wet-processed for calcareous micropalaeontology from the Ballagan Formation in the Spilmersford Borehole

Borehole Registration no.	Depth below OD (feet and inches)	Fauna (if any)
BEA3933	2204'	none
BEA4052	2474' 9''	none
BEA4062	2497' 6''	none
BEA4075	2523' 6''	none
BEA4119	2604' 6''	none
BEA4144	2607'	none
BEA4124	2631' 6''	none
BEA4178	2730'	ostracods
BEA4272	2865' 1''	ostracods (rare), *Spirorbis* sp.
Other horizons that bear ostracods (assessed from rock slabs)		
BEA4128	2634'	ostracods
BEA4217	2794' 6''	ostracods (rare)

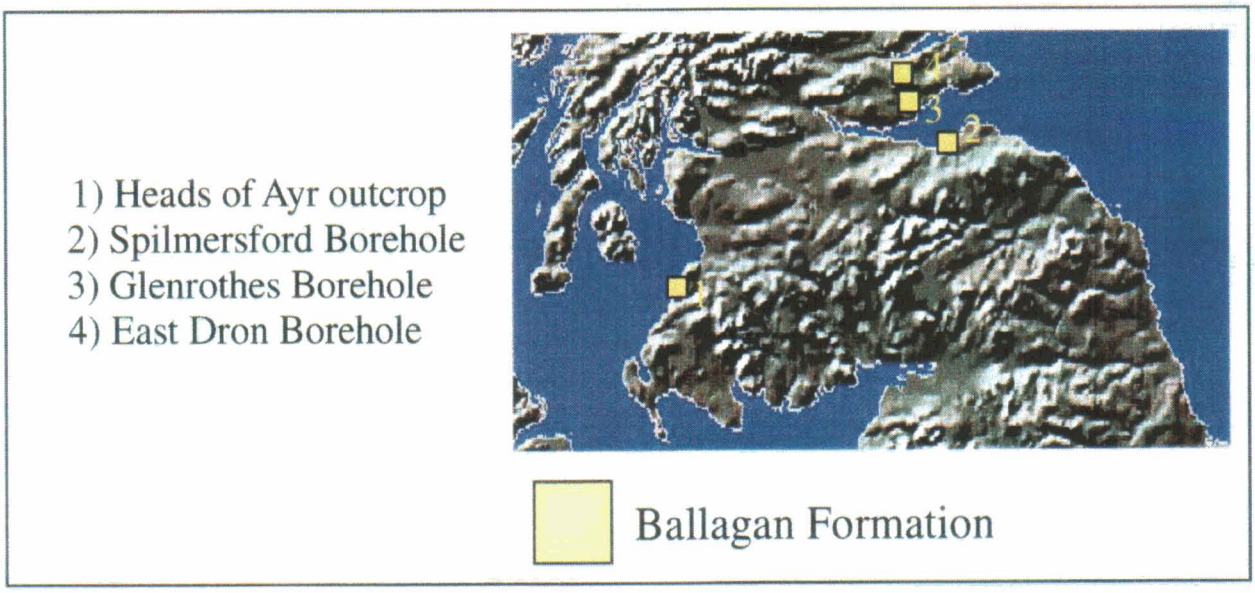

Figure 1. Studied sections for the Ballagan Formation documented in this report: boreholes at Spilmersford, Glenrothes and East Dron; and the Ayrshire coastal section.

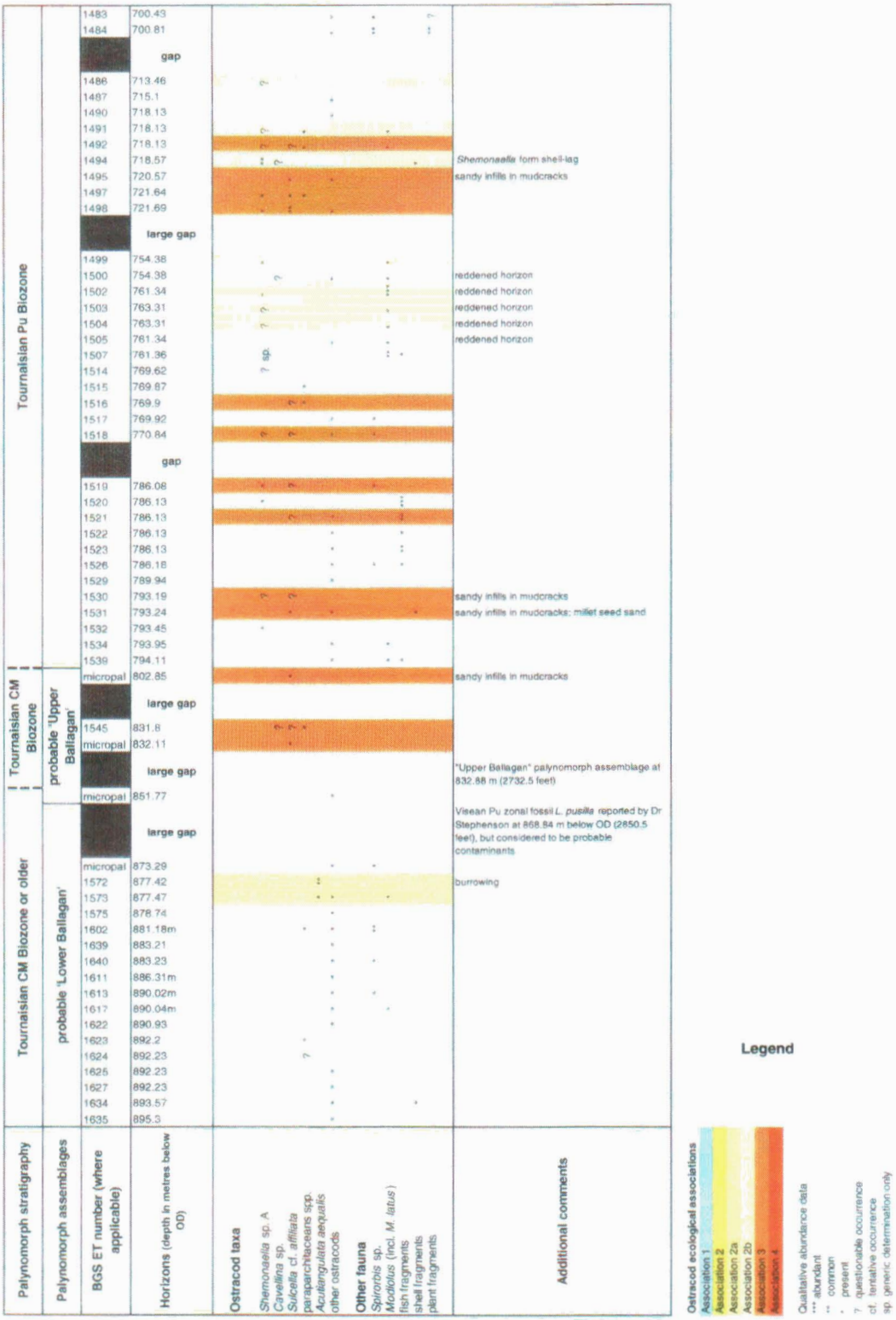

Figure 2. Stratigraphical and ecological distribution of ostracods in the Ballagan Formation of the Spilmersford Borehole [National Grid Reference NT 4570 6902].

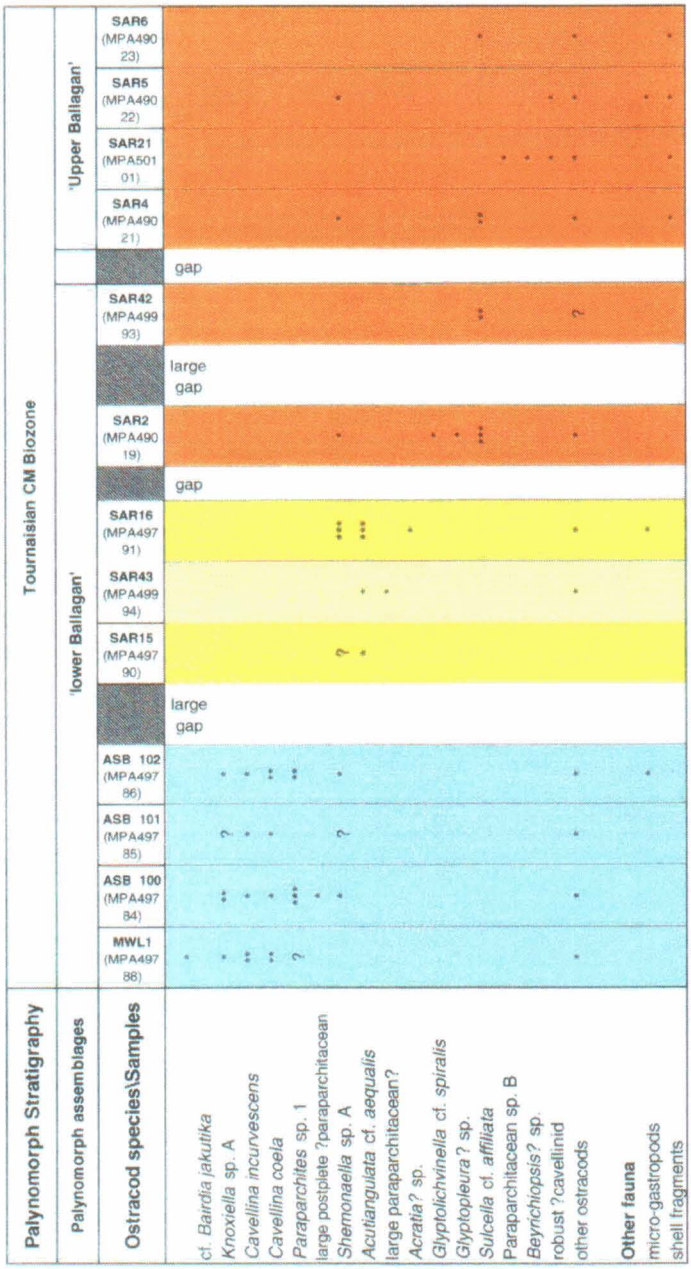

Figure 3. Stratigraphical and ecological distribution of ostracods in the Ballagan Formation of the Ayrshire coast. For Legend see Figure 2.

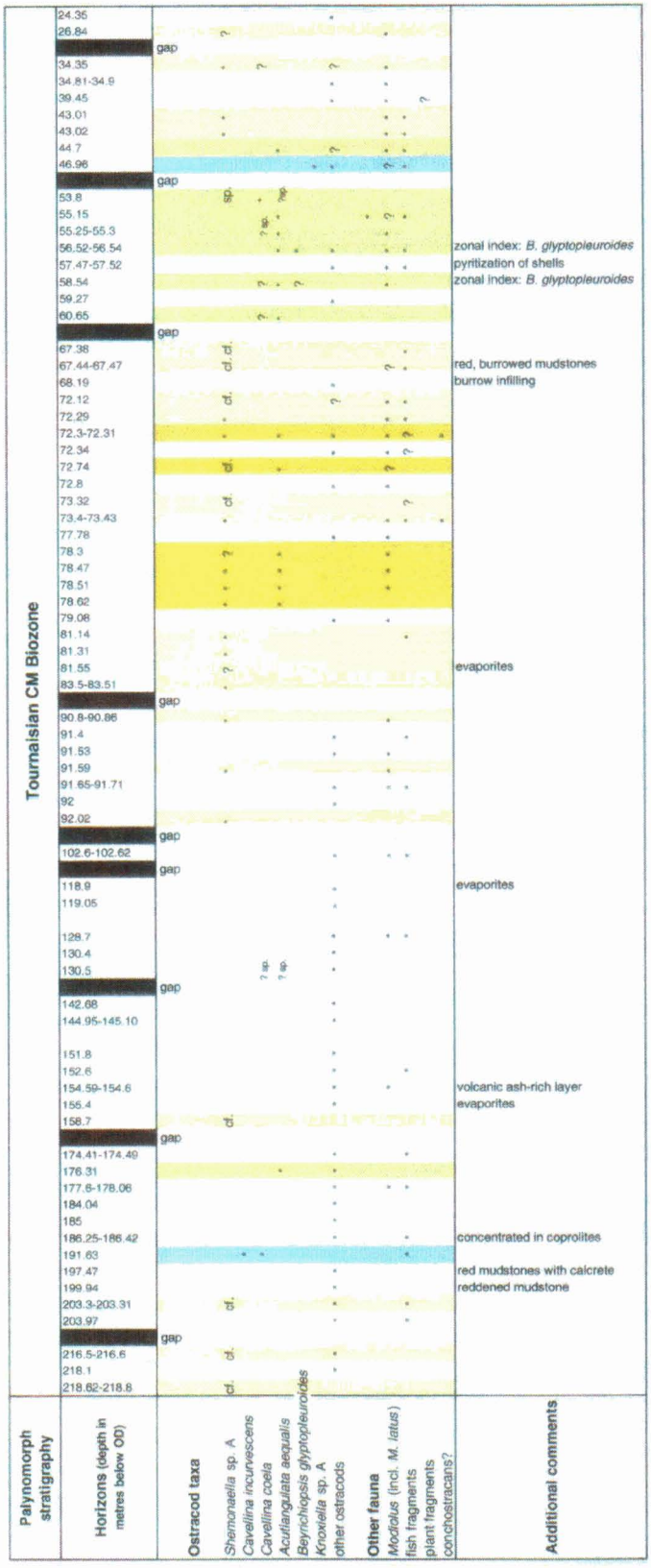

Figure 4. Stratigraphical and ecological distribution of ostracods in the Ballagan Formation of the East Dron Borehole [NGR NO 1360 1572]. For Legend see Figure 2.

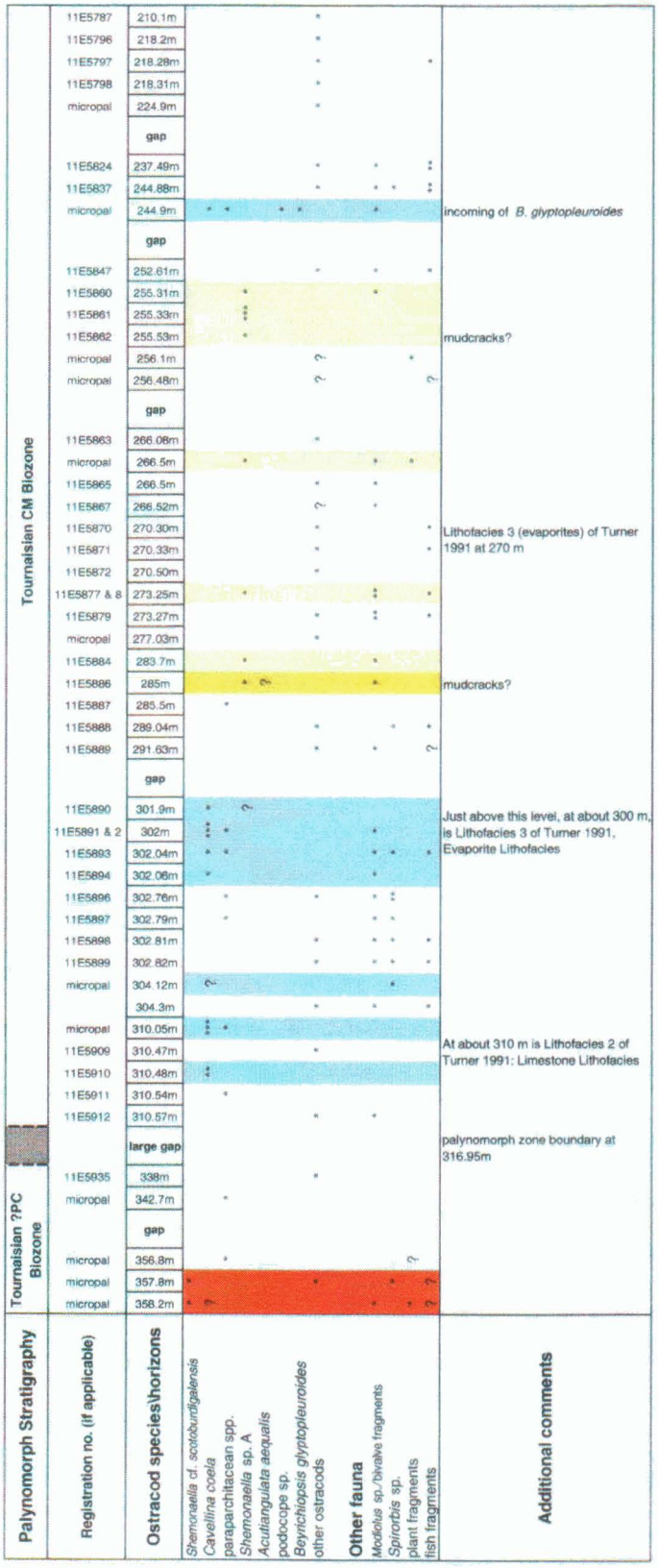

Figure 5. Improved stratigraphical and ecological resolution for the ostracods of the Ballagan Formation, Glenrothes Borehole [NGR NO 25615 03142]. For Legend see Figure 2.

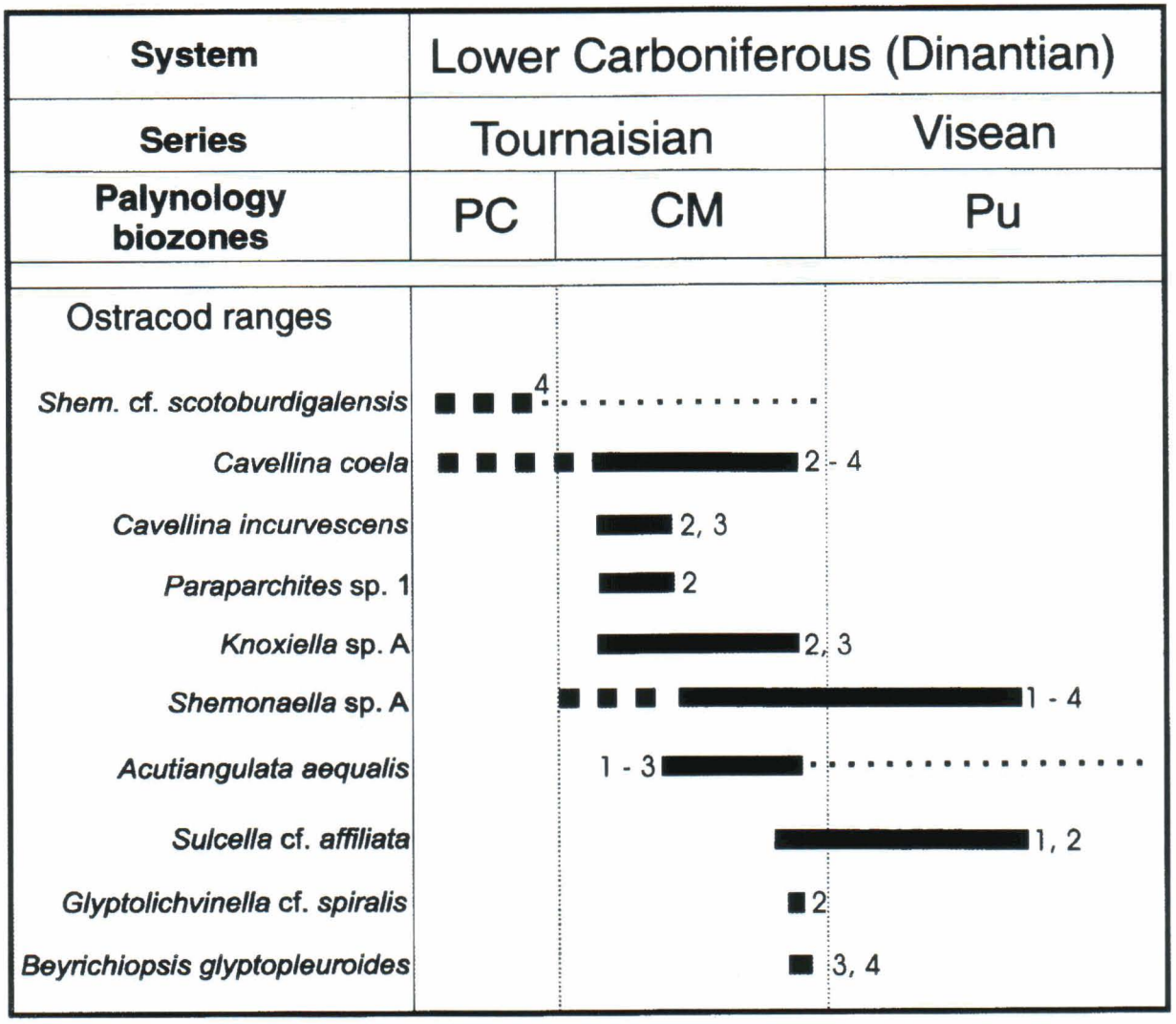

Figure 6. Stratigraphical ranges of key ostracod species in the Lower Carboniferous of the Midland Valley, Scotland. The ranges are plotted against the palynomorph biozones and are reconstructed from data presented in Figures 2 to 5. Numbers on the ranges denote data from: 1, Spilmersford Borehole; 2, Ayrshire coast; 3, East Dron Borehole; 4, Glenrothes Borehole. The thin dotted lines indicate a longer range recorded by Robinson (1978). Thick dotted lines denote an uncertain range.

Figure 7. Lighter coloured sandy sediment infilling mudcracks at depth 802.85 m below Ordnance Datum in the Spilmersford Borehole (BGS core slab BEA 4128). The sediment infill includes specimens of *Sulcella* cf. *affiliata* (just above centre of picture). Field of view *c.* 2 cm.