

Early Carboniferous (Late Tournaisian–Early Viséan) ostracods from the Ballagan Formation, central Scotland, UK

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ABSTRACT – The Ballagan Formation (Late Tournaisian–Early Viséan) of central Scotland yields an ostracod fauna of 14 species in ten genera, namely *Beyrichiopsis*, *Cavellina*, *Glyptolichvinella*, *Glyptopleura*, *Knoxella*, *Paraparchites*, *Sansabella*, *Shemonaella*, *Silenites* and *Sulcella*. The ostracods, in combination with palynomorphs, are important biostratigraphical indices for correlating the rock sequences, where other means of correlation, especially goniatites, conodonts, foraminifera, brachiopods or corals are absent. Stratigraphical distribution of the ostracods, calibrated with well-established palynomorph biozones, identifies three informally defined intervals: a sub-CM palynomorph Biozone interval with poor ostracod assemblages including *Shemonaella scotoburdigalensis*; a succeeding interval within the CM palynomorph Biozone where *Cavellina coela*, *Cavellina incurvescens*, *Sansabella amplexans* and the new species *Knoxella monarchella* and *Paraparchites discus* first appear; and, an upper interval, in the upper CM Biozone, marked by the appearance of *Sulcella affiliata*. At least locally in central Scotland, *S. affiliata* permits a level of resolution equivalent to a sub-zonal upper division of the CM Biozone. The fauna, flora, sedimentology and stable isotope composition ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of carbonate minerals in the Ballagan Formation suggest the ostracods inhabited brackish, hypersaline and ephemeral aquatic ecologies in a coastal floodplain setting. *J. Micropalaeontol.* 24(1): 77–94, May 2005.

KEYWORDS: Carboniferous, Tournaisian, ostracods, biostratigraphy, palaeoenvironments

INTRODUCTION

During Dinantian times, central Scotland underwent a change from terrestrial semi-arid conditions that prevailed during the Devonian and earliest Carboniferous, and gradually became affected by widespread marine transgressions (Wilson, 1989), which reached their maximum effect during deposition of the Lower Limestone Formation (Fig. 1). This history is reflected in the palaeontology of the Inverclyde Group, which is largely barren of biostratigraphically useful marine macrofossils. Even the upper, more marine parts of the Strathclyde Group contain few biostratigraphically useful marine macrofossils (Wilson, 1989). However, spores of land plants and crustacean ostracods are abundant in the Dinantian succession and a scheme of Carboniferous palynomorph biozones, in ascending order the CM, Pu, TS, TC, NM and VF biozones, was proposed by Neves *et al.* (1972, 1973), to deal with successions mainly from eastern Scotland and northern England (Fig. 1).

The Ballagan Formation is the second unit of the Dinantian sequence in Scotland (Fig. 1) and was established by Young (1867a, b) for the mudstone and ‘cementstone’ sequence at Ballagan Glen, north of Glasgow [National Grid Reference NS 572 800]. The base of the formation is positioned at the boundary with the underlying, mainly Old Red Sandstone facies, Kinnesswood Formation (Fig. 1). The upper boundary is placed at the change from mudstone and ‘cementstone’ of the Ballagan Formation to the arenaceous Clyde Sandstone Formation (Browne *et al.*, 1999). Its maximum thickness is 900 m (Mitchell & Mykura, 1962, p. 38).

The Ballagan Formation is exposed in coastal outcrops of Ayrshire, East Lothian and Fife and is known also from

numerous inland localities and several boreholes extending across central Scotland (Stephenson *et al.*, 2003, 2004a, b; Fig. 2). It contains an ostracod fauna of 14 species, including those described in open nomenclature. As part of an ongoing British Geological Survey Mapping Project in the Midland Valley of Scotland, the ostracods have been used as a tool for correlating Tournaisian–Early Viséan rock sequences. The focus of this paper is threefold: to record the biostratigraphical distribution of these ostracods in five key sections through the Ballagan Formation, where other means of biostratigraphical correlation – except palynomorphs, are rare; to make a provisional assessment of their ecological setting; and to provide modern illustrations of the Scottish material, much of which has not been illustrated since the 1890s. The ostracod fauna comprises species of *Beyrichiopsis*, *Cavellina*, *Glyptolichvinella*, *Glyptopleura*, *Knoxella* (*K. monarchella* sp. nov.), *Paraparchites* (*P. discus* sp. nov.), *Sansabella*, *Shemonaella*, *Silenites* and *Sulcella*. New records from Scotland extend the biostratigraphical ranges of several species, enabling a revision of the stratigraphy of British Carboniferous ostracods presented by Robinson (1978).

KEY SECTIONS AND MATERIAL

Ballagan Formation ostracods from coastal and inland sections in Ayrshire and from several boreholes were assessed (Fig. 2). These provide coverage of the Ballagan Formation across the Midland Valley of Scotland. Over 350 ostracod-bearing horizons were examined, yielding several thousand specimens. Micropalaeontology residues and picked material from these samples are housed at the British Geological Survey,

Subsystem	Series	Lithostratigraphical Units					Groups
		Formations					
		Central Coalfield	Ayrshire	Fife	West Lothian	East Lothian	
Dinantian	Viséan	Lower Limestone Formation					Clackmannan Gp.
		VF	Lawmuir Formation	Pathhead Fm.	West Lothian Oil-Shale Fm.	Aberlady Fm.	Strathclyde Group
		NM	Kirkwood Formation	Sandy Craig Fm.			
		TC	Clyde Plateau Volcanic Formation	Pittenweem Fm.	Gullane Formation		
		TS		Anstruther Fm.	Arthur's Seat Volcanic Formation	Garleton Hills Volcanic Formation	
		Pu		Fife Ness Fm.			
	Tourmaisian	Clyde Sandstone Formation				Ballagan Formation	
		CM	Ballagan Formation				
			Kinnesswood Formation				
		PC					

Fig. 1. Stratigraphical setting of the Ballagan Formation within the Early Carboniferous rock succession of central Scotland. Also shown is the palynomorph biozonation of Neves *et al.* (1972, 1973).

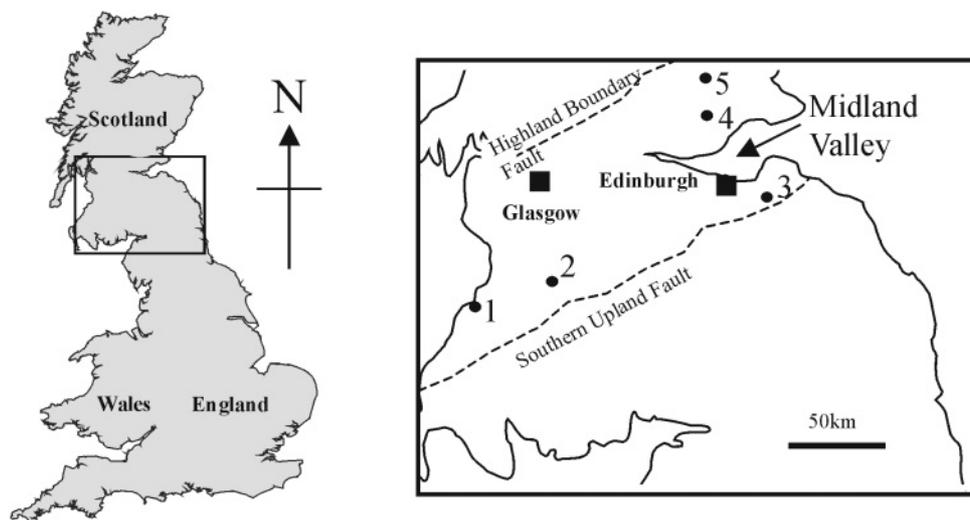


Fig. 2. Key ostracod-bearing sections in the Ballagan Formation in central Scotland. 1, Heads of Ayr coastal section (see Stephenson *et al.*, 2003, fig. 1); 2, Blairmulloch Farm Borehole [National Grid Reference (NGR) NS 56050 28200]; 3, Spilmersford Borehole [NGR NT 4570 6902]; 4, Glenrothes Borehole [NGR NO 25615 03142]; 5, East Dron Borehole [NGR NO 1360 1572].

Nottingham (Kingsley Dunham Centre). Figured specimens are registered with the prefix MPK, whilst faunal slides are prefixed MPA. Rock slab material from the boreholes is stored at BGS Edinburgh (Murchison House). Registration numbers for the borehole rock slabs mentioned in the text are identified by the prefix EV, ET, 11E, 15E or 16E. Where rock slab specimens were accessioned into the Type and Stratigraphical collections they are stored in the museum at Nottingham and are identified by the prefix GSE. BGS Technical Reports on the ostracods in each borehole (Glenrothes, East Dron, Spilmersford, Blairmulloch Farm) and in the Ayrshire coastal section are available through the BGS library at Nottingham: [http://](http://www.bgs.ac.uk)

www.bgs.ac.uk and <http://geolib.bgs.ac.uk> (reports IR/01/031, IR/01/063, IR/02/110, IR/02/194, IR/03/026).

PALAEOENVIRONMENTAL SETTING

Sedimentology

The Ballagan Formation was deposited in low-lying coastal floodplains in a semi-arid environment (Andrews *et al.*, 1991; Turner, 1991; Andrews & Nabi, 1998; Stephenson *et al.*, 2003, 2004a). It is dominated by grey mudstones and siltstones with fine-grained carbonate cements and shelly material. Nodules and thin (generally up to 30 cm thick) beds of ferroan dolostones

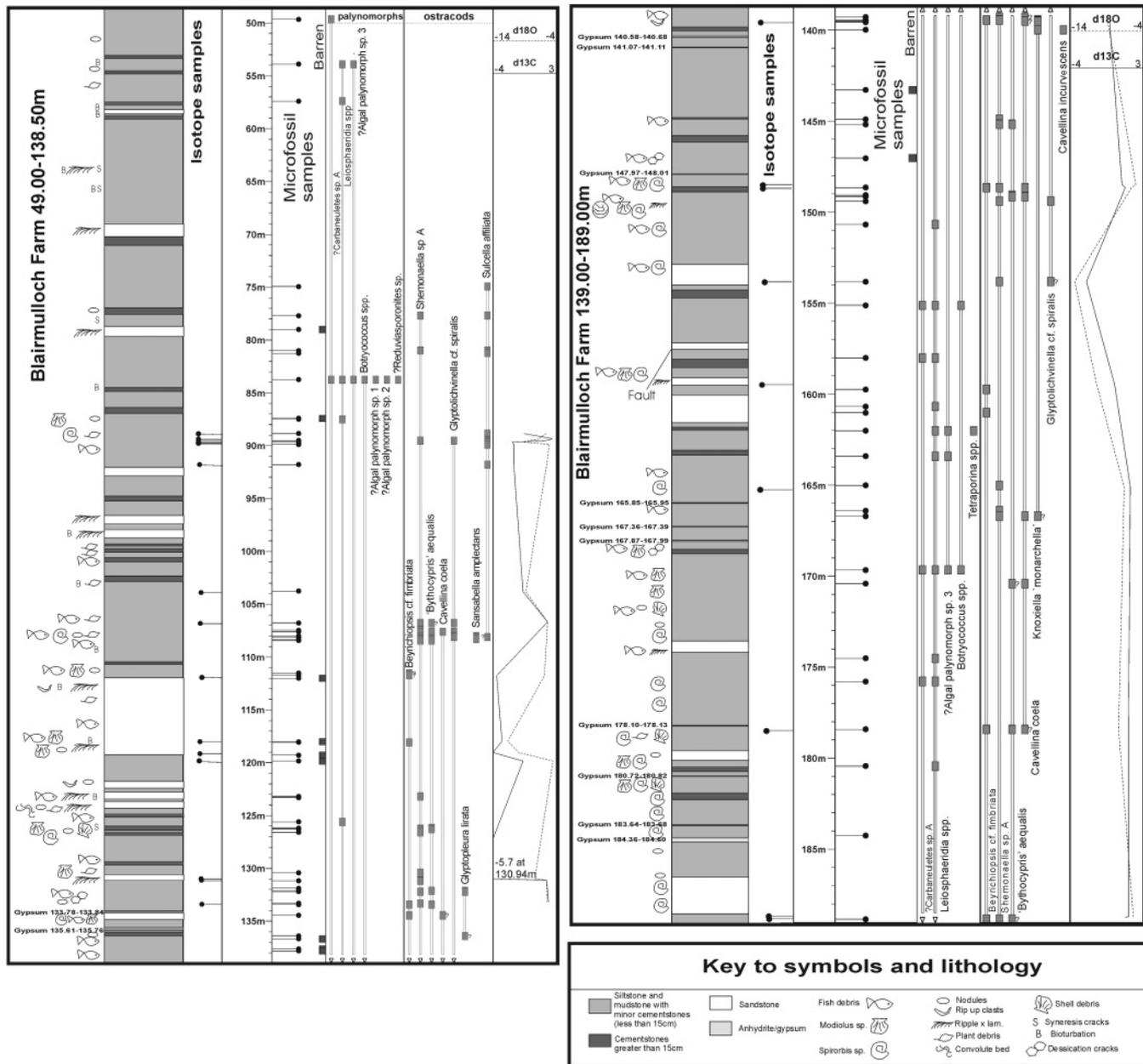


Fig. 3. Sedimentology of the Ballagan Formation in the Blairmulloch Farm Borehole. Further details about the fauna and flora of this borehole can be sourced from Dean (1998) and Stephenson *et al.* (2004a). The temporal variation in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopes is too coarse to resolve any clear stratigraphical trends (spaced at *c.* 4 m intervals), though the ratios are indicative of carbonates deposited in brackish (mixed marine+fresh water) salinities (see Fig. 4). Also shown are key palynomorphs.

(the ‘cementstones’ of earlier terminology) occur. Thin sandstones are widespread geographically. Rootlet beds, thin evaporite horizons (gypsum, anhydrite) and pseudomorphs of halite are associated sometimes with the mudstones (Fig. 3). These finer-grained sediments, which are characterized by desiccation cracks, were probably deposited on a low energy coastal plain in lakes, ponds and lagoons, subject to periodic aridity (Turner, 1991; Stephenson *et al.*, 2003). Sharp-based and ripple-laminated sandstones probably represent distal crevasse splay deposits that were supplied across the floodplain during periodic fluvial flood events.

The thinly bedded calcareous dolostones represent primary dolomite deposited during arid phases, causing conditions of fluctuating salinity and periods of desiccation. Evidence from the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotope values (below), indicate that lakes and ponds were subject to evaporation and to fresh water input by run-off and rainfall. Incursions of water with normal marine salinity are probably responsible for the rare marine fauna present, such as foraminifer test-linings and brachiopod debris (see also Stephenson *et al.*, 2004a, b).

In the Ayrshire sequence, at the Heads of Ayr (Fig. 2, locality 1), Stephenson *et al.* (2003) distinguished lithofacies of a tidal

Blairmulloch Farm Borehole BGS borehole horizon no.	Depth below OD (m)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
15E 5079	88.9	-5.7	-0.6
5083	89.3	-6.7	2.4
5084	89.4	-6.7	2.5
5089	89.5	-8.6	1.6
5090	89.7	-9.2	-1.9
5091	89.9	-5.2	-1.7
5810	91.8	-5.6	-1.7
5846	103.8	-8.8	-0.7
5865	106.7	-5.4	2.0
5919	111.8	-5.9	-3.6
5952	118.0	-11.7	-3.0
5961	119.0	-10.0	-4.0
5970	119.8	-4.6	-0.7
6043	130.9	-7.4	-5.7
6044	131.1	-5.6	1.9
8931	133.2	-5.5	2.1
9060	139.6	-8.8	-0.2
9134	148.5	-5.0	1.0
9144	148.7	-5.6	1.3
9231	153.8	-13.3	-2.4
9249	159.5	-10.3	0.3
9387	165.1	-6.6	1.8
9770	178.4	-7.3	1.6
16E 134	188.7	-5.3	1.6
136	188.8	-5.5	1.3
Other samples			
15E 5877	Diagenetic calcite	-12.5	-3.0
ASB100	Diagenetic calcite	-11.1	-2.6
15E 5919	Orthocone	-13.2	-5.2

Note: three examples of diagenetic calcite from this sequence are also analysed.

Table 1. Stable isotope data ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) for carbonates from 25 mudstone samples in the Ballagan Formation of the Blairmulloch Farm Borehole (see Fig. 4).

flat setting, with halite pseudomorphs, mud cracks and carbonaceous (plant) material, succeeded upwards by more lagoonal facies characterized by mudstone–dolostone interbeds. At the top of this sequence are sandstones thought to be of fluvial origin (Stephenson *et al.*, 2003, p. 98). Both the tidal flat and lagoonal facies are ostracod bearing. Elsewhere in the Midland Valley (Fig. 2, localities 2–5) ostracods occur dominantly in mudstone and dolostone sequences, probably deposited in lagoons or brackish lakes on a coastal plain with fluctuating salinities.

$\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ stable isotopes

Analysis of calcium carbonate for carbon and oxygen isotope ratios (expressed as $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) from 25 carbonate-bearing mudstone samples spread through 100 m of strata, between depths 88.85 m and 188.75 m below Ordnance Datum (OD) in the Blairmulloch Farm Borehole (Fig. 3), provide evidence for the aquatic environment of deposition for the Ballagan Formation (Table 1; see Fig. 4 for methodology). The sequence in this borehole is characterized by interbedded muds, silts and dolostones, with occasional evaporite and sandstone beds. These indicate a quiescent lagoon or lacustrine setting, with fluctuating salinity and periodic desiccation.

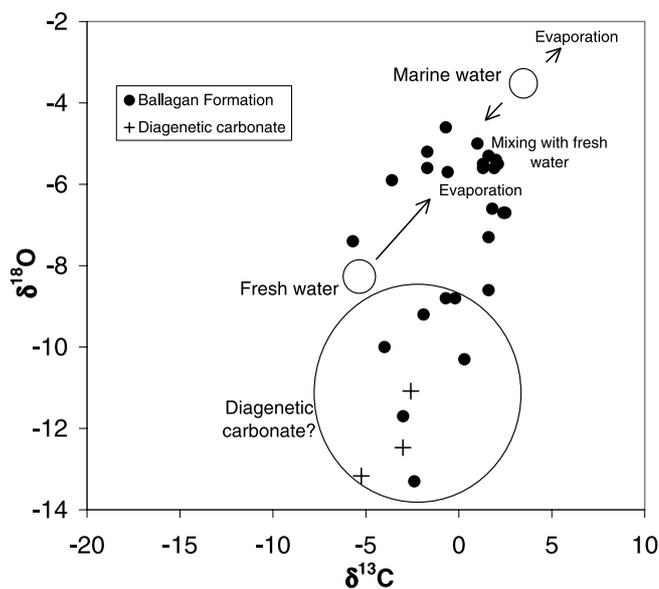


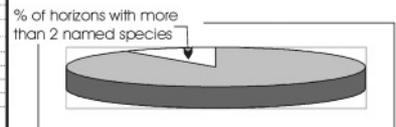
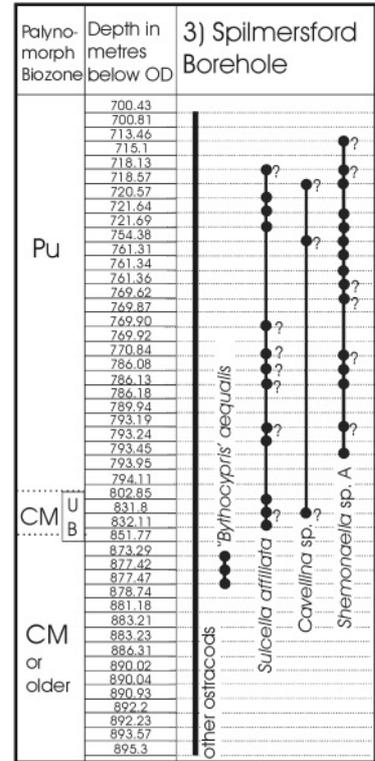
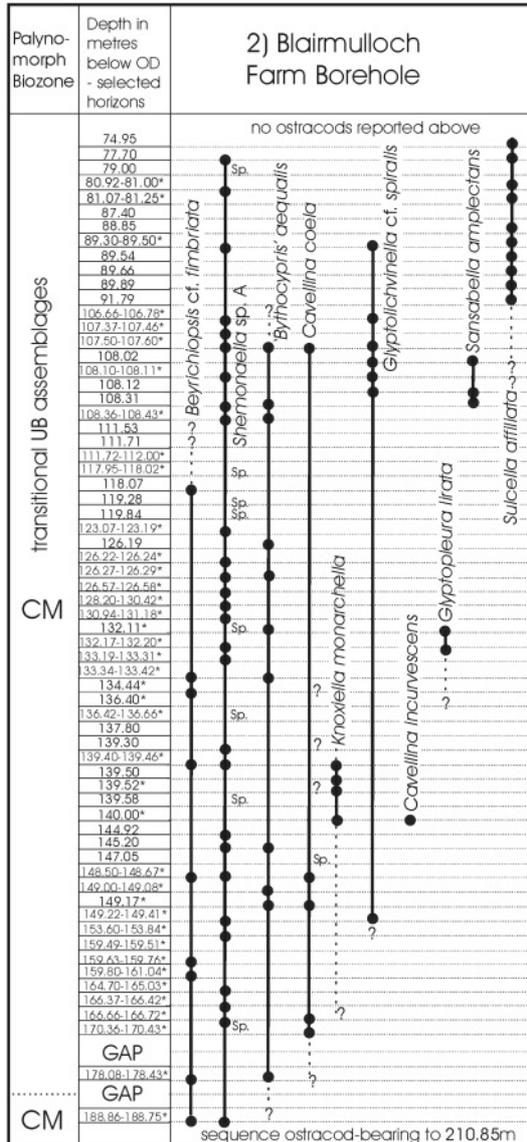
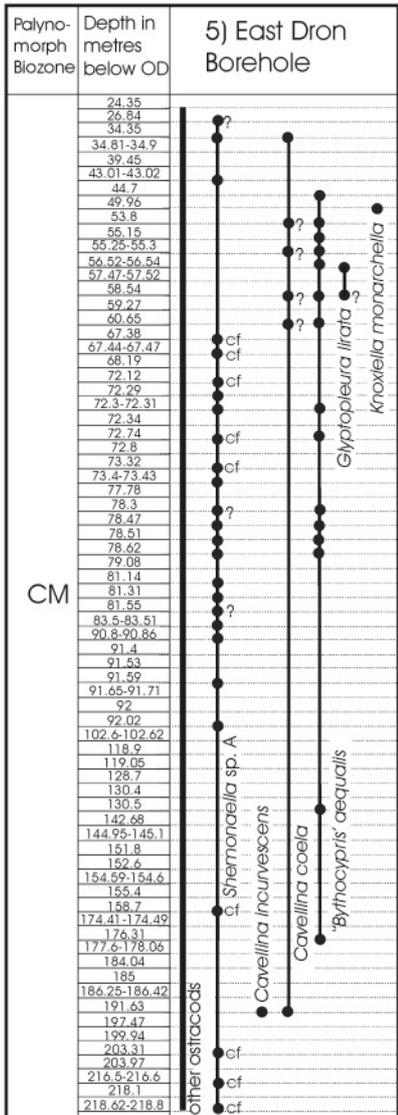
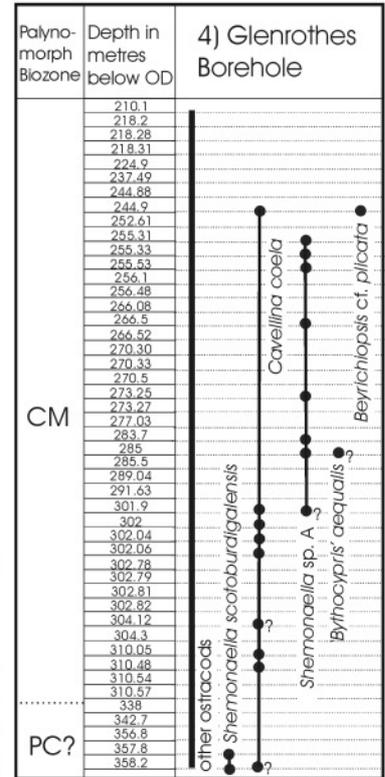
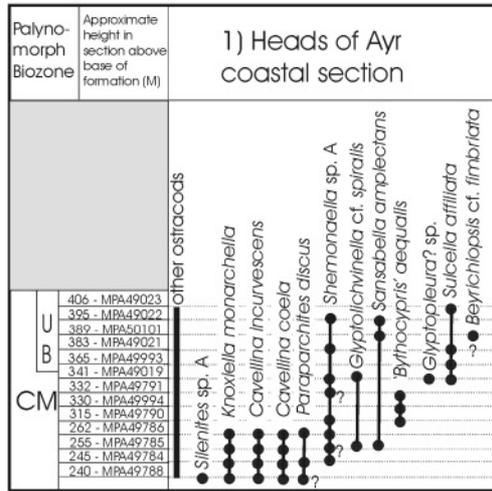
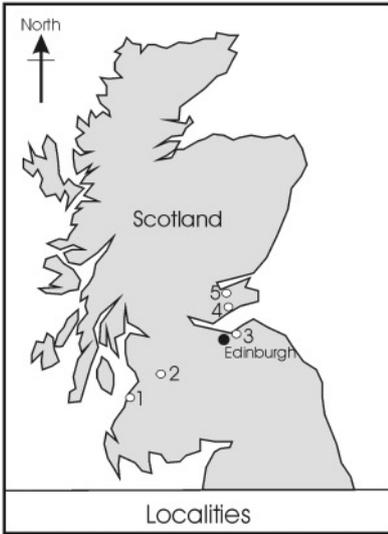
Fig. 4. Stable isotope ratios ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of carbonates in 25 mudstone samples from the Ballagan Formation, through about 100 m of the strata in the Blairmulloch Farm Borehole. Although some of the carbonates yield values in the range of diagenetic carbonate (determined from a recrystallized orthocone test and ostracods with calcite overgrowths; see Table 1), most values suggest evaporated fresh water or a mixture of marine and fresh water (i.e. brackish). There is no normal marine salinity signature ($\delta^{18}\text{O} \approx -4\text{‰}$ to -3‰ ; see Bruckschen *et al.*, 1999) for any of the carbonates analysed. The fields for marine water and fresh water are explained in the text. For stable isotope analysis, mudstones without obvious diagenetic calcite – and avoiding shelly fragments – were ground to a powder and reacted with anhydrous phosphoric acid *in vacuo* overnight at a constant 25°C. The CO_2 liberated was separated from water vapour under vacuum and collected for analysis. Measurements were made on a VG Optima mass spectrometer. Overall, analytical reproducibility for these samples is normally better than 0.1 for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ (2s). Isotope values ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) are reported as per mille deviations of the isotopic ratios ($^{13}\text{C}/^{12}\text{C}$, $^{18}\text{O}/^{16}\text{O}$) calculated to the VPDB scale using a within-run laboratory standard calibrated against NBS standards.

The $\delta^{18}\text{O}$ values (to Vienna Pee Dee Belemnite standard, VPDB) of the Ballagan Formation carbonates span a large range from -13.3‰ to -4.6‰ . The average European Lower Carboniferous marine carbonate signature is $\approx -4\text{‰}$ to -3‰ (Brand, 1989; Bruckschen *et al.*, 1999; Veizer *et al.*, 1999). All the oxygen isotope data from the Ballagan Formation are lower than this sea water value, suggesting the sediments analysed were deposited in aquatic settings that did not have normal marine salinity, assuming that sea water was not at a higher temperature or had a lighter $\delta^{18}\text{O}$ and there was no significant recrystallization during burial (cf. Tucker *et al.*, 2003). There are no unequivocal published estimates for Early Carboniferous fresh water $\delta^{18}\text{O}$ in Scotland, although Scotland was part of Pangaea close to the equator (see Mississippian reconstruction of the North Atlantic region by R. C. Blakey available through <http://www4.nau.edu/geology/blakey.html>) and sea water $\delta^{18}\text{O}$ (the initial source of all fresh water) was much lower than today and at a higher temperature (Bruckschen *et al.*, 1999). These factors suggest meteoric water was probably much lower than current equatorial rainfall $\delta^{18}\text{O}$ (Yurtsever & Gat, 1981). Indeed, Devonian calcretes thought to have precipitated from



Explanation of Plate 1.

Faunal elements of the Ballagan Formation: **1**, ostracods associated with a rare orthocone (GSE15210), colonized by *Spirorbis* sp. and displaced from its original marine setting prior to burial ($\times 3$); **2**, *Cavellina coela* associated with rare brachiopod debris (GSE15217) ($\times 14$); **3**, fish debris (GSE15213) ($\times 7$); **4**, *Shemonaella* sp. A and *Modiolus latus* (GSE15212) ($\times 4$); **5**, well-preserved valves of *Shemonaella* sp. A (GSE15207) ($\times 6$).



evaporated soil water have been found to have $\delta^{18}\text{O}$ values between -9.0‰ and -8.0‰ (Andrews *et al.*, 1991; Turner, 1991), suggesting that the Early Carboniferous fresh water $\delta^{18}\text{O}$ might have been lower than this. Thus, carbonate $\delta^{18}\text{O}$ values of around -9‰ to -8‰ are probably typical of evaporated fresh waters from rivers entering the coastal environment. Fresh water and marine carbonates are thus thought to have $\delta^{18}\text{O}$ around -9‰ and -3‰ , respectively. Values between -9‰ and -3‰ are, therefore, either evaporated fresh water (which increases $\delta^{18}\text{O}$) or a mixture of fresh water and sea water ($\delta^{18}\text{O}$ c. -3‰). There are no samples that have $\delta^{18}\text{O}$ values around the expected value for sea water. However, there are some samples with $\delta^{18}\text{O}$ values that are very low. Two samples of diagenetic calcite overgrowths adhering to ostracod carapaces (see Table 1) and also a sample of recrystallized orthocone gave low $\delta^{18}\text{O}$ (-13.2‰ to -11.1‰), suggesting that the carbonate with low $\delta^{18}\text{O}$ ($< -9\text{‰}$) in the sediments may have had secondary fluids passing through them which precipitated calcite via dissolution and re-equilibration during burial and diagenesis. These low values may be a function of recrystallization at higher temperatures during burial, although there is no evidence for low-grade metamorphism.

The $\delta^{13}\text{C}$ values (to VPDB) of the Ballagan Formation carbonates analysed span a range between -5.7‰ to $+2.5\text{‰}$ (Fig. 4), lower than Early Carboniferous sea water, which had a $\delta^{13}\text{C}$ value of $+3\text{‰}$ to $+4\text{‰}$ (Bruckschen *et al.*, 1999). Fresh water $\delta^{13}\text{C}$ tends to be derived from CO_2 via soils and has low $\delta^{13}\text{C}$. Modern groundwaters in Europe have $\delta^{13}\text{C}$ of -10‰ to -15‰ (Andrews *et al.*, 1997). This can be modified to higher values by a number of processes (Leng & Marshall, 2004), including exchange with atmospheric CO_2 in evaporating waters and mixing with heavier marine $\delta^{13}\text{C}$. In localized environments – for example, in organic-rich environments – oxidation of organic matter can lead to low $\delta^{13}\text{C}$. In the Ballagan Formation the preservation of large amounts of organic matter in the sediments analysed suggests that there may have been preferential utilization of the lighter isotope, thus causing the resultant carbonate minerals precipitating to have high $\delta^{13}\text{C}$. All of these processes might have been occurring during deposition of the Ballagan Formation, although the $\delta^{18}\text{O}$ data suggest that the sediments analysed were deposited in evaporating fresh water or a mixed fresh water–marine (i.e. brackish) environment.

Palaeontology

The ostracod fauna of the Ballagan Formation is dominated numerically by paraparchitaceans, though platycopes, palaeocopes and podocopes are well represented. Ostracod assemblages with this range of taxonomic groups are known from brackish water, supratidal and shelf environments in the Carboniferous (Dewey *et al.*, 1990). Although ostracods occur in the dolostones (Turner, 1991), most ostracod-bearing horizons are grey-green mudstones and silty mudstones. The overall environment of deposition, dominated by muds, suggests low energy (Fig. 3). This notion is supported by the size distribution

of the ostracods in the assemblages, which often encompass juveniles and adults (particularly in paraparchitacean-dominated assemblages), and the preservation of the valves and carapaces – some in ‘butterfly’ orientation – which also suggests that many assemblages preserve original biocoenoses (Pl. 1, figs 4, 5). Nevertheless, in the East Dron Borehole the ostracods often occur in thin shell lags in mudstone sequences, suggesting that they have been transported, though the size distribution (adults and juveniles), good preservation of the ostracod valves and occurrence of the same ostracods more thinly scattered on adjacent mudstone laminae, suggests that this was only local. Some assemblages, for example those of *Cavellina coela* occurring with rare brachiopod debris, suggest wider transport and are dominated by adult and sub-adult valves, suggesting sorting (Pl. 1, fig. 2).

The co-occurrence of the bivalve *Modiolus* with the ostracods (Pl. 1, fig. 4; Fig. 3), the low-diversity of the assemblages – typically one to five species per horizon – though about 90% of horizons have no more than two named species (Fig. 5), the absence of normal marine salinity faunas such as corals or echinoderms, and the associated sediments all suggest aquatic settings that were not normal marine salinity. At many horizons the ostracods, particularly *C. coela* and the paraparchitaceans *Shemonaella* and *Paraparchites*, are associated with halite pseudomorphs, calcretes and mud-cracks, suggesting that they tolerated elevated salinity (hypersaline) environments in ephemeral bodies of water (Stephenson *et al.*, 2003, 2004a). Some ostracod-bearing horizons are reddened, suggesting post-depositional subaerial oxidation. Diminutive ostracods sometimes occur in calcrete-bearing horizons and in mudstones adjacent evaporites. A quasi-marine or brackish water setting is also suggested by the common occurrence of plant fragments – sometimes several centimetres long, calcareous worm tubes of *Spirorbis*, conchostracans and *Naiadites* trace fossils. Very rare (four horizons from several hundred studied) co-occurrences of ostracods (*Cavellina coela*) with fragmentary brachiopod valves and orthoconic nautiloids (some colonized by *Spirorbis*) indicate limited normal marine influence (Pl. 1, figs 1, 2), possibly through flooding of coastal floodplains and lagoons by sea water during storm events. Nevertheless, there is no evidence for marine bands with a normal marine salinity fauna at any level in the Ballagan Formation that the authors have examined. Most telling in this respect is the absence of corals, echinoderms, goniatites, *in situ* (i.e. complete and undisturbed) brachiopods or conodonts. The absence of typical stenohaline marine ostracods such as *Bairdia* and *Amphissites*, which characterize open marine biotopes (Becker & Bless, 1990; Dewey & Puckett, 1993), also concurs with the sedimentological interpretation of the Ballagan Formation as a coastal floodplain. Beyrichiaceans, reported from nearshore Early Carboniferous environments in Atlantic Canada (Tibert & Scott, 1999), are also absent from the Ballagan Formation. Furthermore, palynological evidence from the Ballagan Formation also supports brackish-water settings (e.g. Fig. 3). There are no marine acritarchs in the Ballagan

Fig. 5. Stratigraphical distribution of ostracods in the Ballagan Formation at five key sections (localities as Fig. 2). The ranges are calibrated with the palynomorph biozones (see Stephenson *et al.*, 2003, 2004b). ‘UB’ denotes ‘upper Ballagan’ palynomorph assemblages of Stephenson *et al.* (2003). *Sulcella affiliata* has a consistent late CM Biozone first occurrence in three sections (1–3). Several species have earlier ranges than recorded previously (Robinson, 1978), including ‘*Bythocypris aequalis*’ and *Glyptopleura lirata*. Some of the ‘horizons’ are composites of several adjacent laminae.

Ostracod species	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1 <i>Glyptopleura lirata</i>											X		X	
2 <i>Cavellina coela</i>			X	?	X	X	X	X	X	X	X	?	X	X
3 <i>Cavellina incurvscens</i>		X				X	X			X	X			X
4 <i>Sulcella affiliata</i>		?			X		?				X	X		X
5 <i>Glyptolichvinella cf. spiralis</i>		X		X			X				X			X
6 <i>Knoxiella monarchella</i>		X	X					X		X	X			X
7 <i>Sansabella amplexans</i>		X	X	?	X			X			X		X	
8 <i>Beyrichiopsis cf. fimbriata</i>		X				X	X				X		X	
9 ' <i>Beyrichiopsis plicata</i> '		X												
10 <i>Paraparchites discus</i>		X	X			X					X			X
11 <i>Shemonaella</i> sp. A	X	X	X	X	X	X	X	X		X			X	
12 <i>Shemonaella scotoburdigalensis</i>		?		X										
13 ' <i>Bythocypris</i> ' <i>aequalis</i>	X	X					X	X			X			
14 <i>Silenites</i> sp. A		X	X	X	X	X				X				

Certain species, particularly *Shemonaella* sp. A and *Cavellina coela*, occur with a spectrum of faunal associates and may have been eurytopic.

Table 2. Co-occurrence of ostracods in the Ballagan Formation.

Formation (Stephenson *et al.*, 2004a). Instead, the microflora is dominated by the spores of land plants from the hinterland and by indigenous aquatic algae such as *Botryococcus*. These algae include non-hapotypic taxa that suggest low salinity ecologies (Stephenson *et al.*, 2004a).

Although most of the ostracod species of the Ballagan Formation co-occur (Table 2) and, therefore, may have possessed overlapping ecologies, or at least were transported into adjacent ecologies, certain ostracods may have favoured particular aquatic settings during deposition of the Ballagan Formation, perhaps influenced by fluctuating salinity (from brackish to hypersaline). Some taxa, such as *Cavellina coela* and *Shemonaella* sp. A occur across a spectrum of ostracod assemblages and may have been eurytopic (Fig. 5, Table 2). In the Early Carboniferous of Atlantic Canada, Tibert & Scott (1999) were able to distinguish five marginal marine through coastal marsh assemblages, four of which are ostracod bearing. Their assemblages include shallow nearshore glauconite-bearing mudstones and hummocky cross-stratified sandstones, fully marine facies that are not present in the Ballagan Formation. In a provisional study of the Ballagan Formation fauna and flora, Stephenson *et al.* (2003) identified three ostracod assemblages in Ayrshire, based on presence–absence data and a semi-quantitative assessment of the most common elements of the ostracod faunas at each horizon. Their assemblages occupy lithofacies of supratidal–tidal flat ecologies, and brackish and low-salinity lagoons. These assemblages can also be recognized in Ballagan Formation sequences across the Midland Valley (Williams, 2002). The supratidal–tidal flat assemblage of Stephenson *et al.* (2003) is associated with halite pseudomorphs and mud-crack horizons in Ayrshire and forms the most diverse assemblages with up to five species occurring at some horizons. It comprises *Cavellina coela*, *C. incurvscens*, *Knoxiella monarchella* sp. nov., *Paraparchites discus* sp. nov., *Silenites* sp. (referred to as *Bairdia* cf. *jakutika* by Stephenson *et al.*, 2003) and *Shemonaella* sp. A. Paraparchitaceans and cavellinids are dominant. The identification by Stephenson *et al.* (2003) of *Acratia* sp. in this assemblage is based on a fragmentary valve, which is indeterminate. These ostracods sometimes occur with *Spirorbis* worm tubes, modern representatives of which are regarded as eurytopic (Hantzschel 1975, *vide* Tibert & Scott, 1999).

Stephenson *et al.* (2003) also identified a possible brackish-water lagoonal ostracod assemblage in the Ballagan Formation of Ayrshire, characterized by '*Bythocypris*' *aequalis*. This environmental interpretation is supported by the occurrence of zygmematacean algae and *Botryococcus* in these assemblages, both of which, in modern ecologies, are restricted to fresh- and brackish-water settings, and by the associated sediments, which comprise mudstone–dolostone interbeds. In the East Dron Borehole this assemblage is recognized by bispecific assemblages of '*B.*' *aequalis* and *Shemonaella* sp. A, associated with the bivalve *Modiolus latus* at more than 15 horizons (see Pl. 1, fig. 4). The latter is regarded generally as having wide environmental tolerance from marginal marine to brackish-water (Wilson *in* Lumsden *et al.*, 1967, p. 90; Wilson, 1989, p. 103). *Beyrichiopsis* cf. *fimbriata* is also sometimes associated with these assemblages (Fig. 5) and can crowd lamination surfaces, for example in the Blairmulloch Farm Borehole. In his analysis of ostracod faunas from Maritime Canada, Dewey (1983) considered '*B.*' *aequalis* to be associated with brackish marine water. *Shemonaella* sp. A. often dominates horizons in the Ballagan Formation of the East Dron Borehole to the exclusion of other ostracods. It may have been able to withstand raised salinities or water chemistries that excluded other ostracods: low-diversity 'paraparchitacean assemblages' are often associated with hypersaline ecologies (Dewey, 1987, 2001; Dewey & Puckett, 1993).

Stephenson *et al.* (2003) noted a third ostracod assemblage in Ayrshire, characterized by the platycope *Sulcella affiliata*, often in monospecific assemblages (Fig. 5). This assemblage is possibly a temporal successor to the brackish-water/lagoonal faunas dominated by '*B.*' *aequalis* and *Shemonaella* sp. A earlier in the sequence and occurs, for example, in the upper part of the Ballagan Formation of the Blairmulloch Farm Borehole (Figs 3, 5). *Sulcella affiliata* occurs with algal palynomorphs, including *Botryococcus*, which signal low-salinity (brackish?) conditions (Stephenson *et al.*, 2003, 2004a). This species also occurs with *Sansabella amplexans* and *Glyptolichvinella* cf. *spiralis*. Both of these species were accorded a brackish 'carbonaceous facies' tolerance by Robinson (1978). Dewey *et al.* (1990) and Dewey & Puckett (1993) also record *Sansabella* in nearshore and brackish-water environments, where it is a representative of the 'kloedenellacean assemblage', influenced by lower salinity

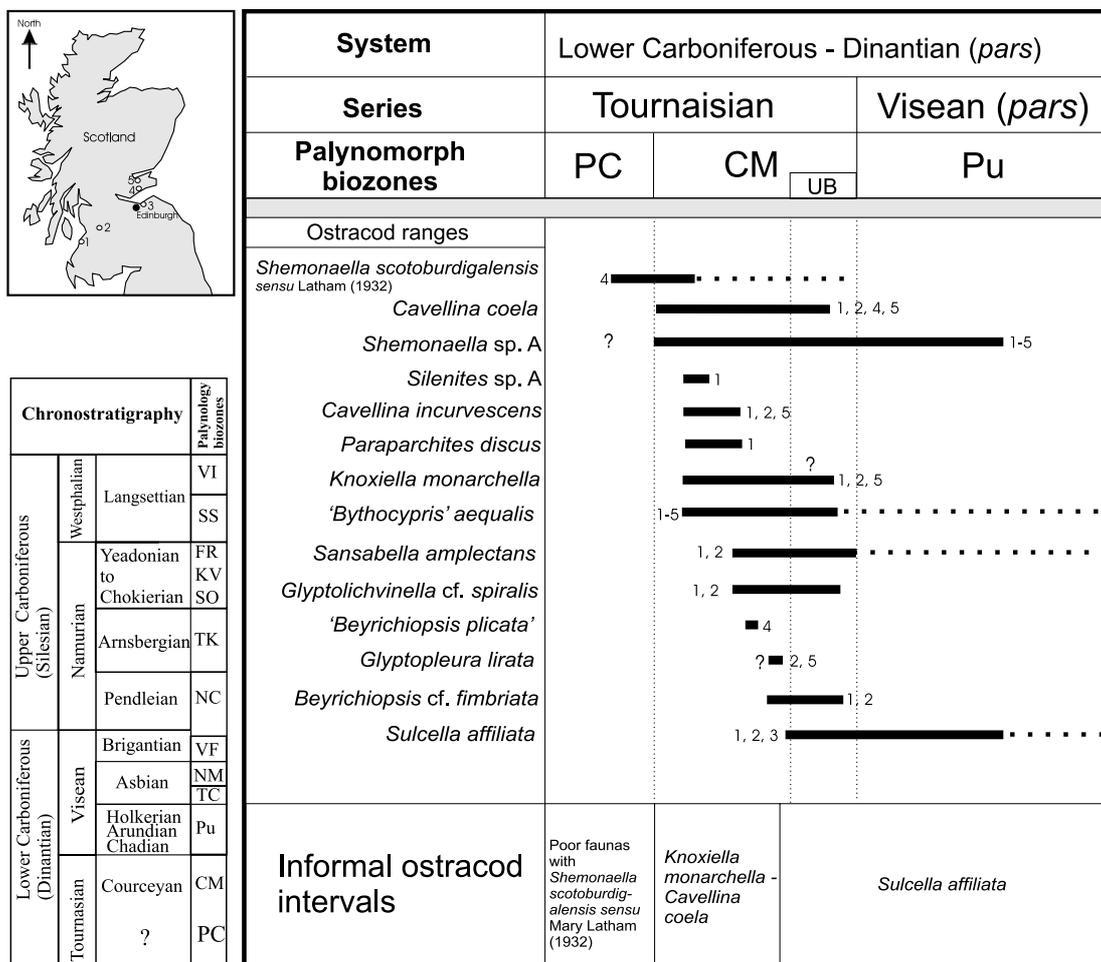


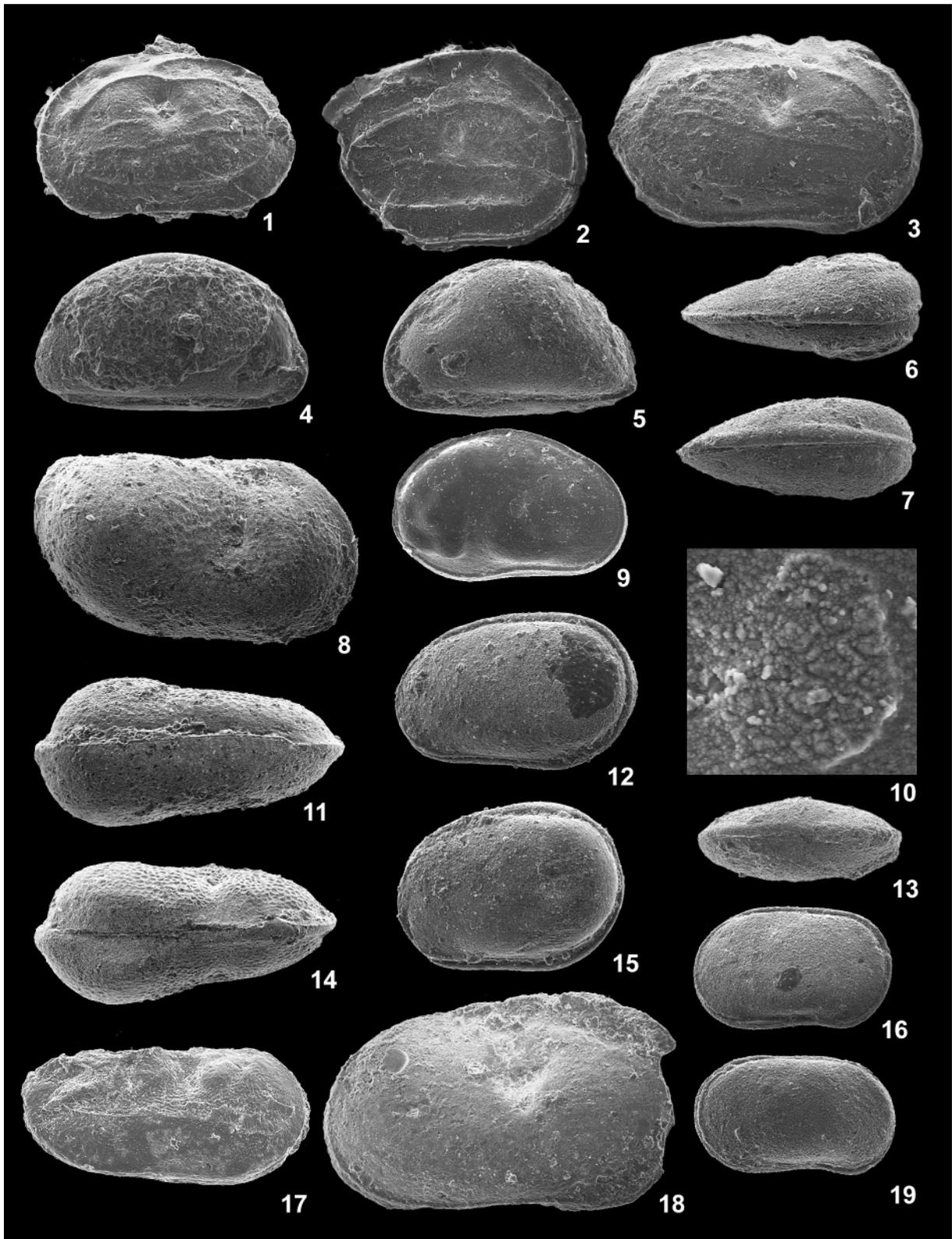
Fig. 6. Composite range chart for ostracods of the Ballagan Formation, reconstructed from data in Figure 5. The numbers against each range indicate the locality source of the data. The inset time-scale shows the position of the studied sequence within the Carboniferous. A dotted line on the range chart indicates that a species has a longer recorded range elsewhere. 'UB' denotes 'upper Ballagan' palynomorph assemblages of Stephenson *et al.* (2003).

(Dewey, 2001). In Ayrshire and in the Spilmersford Borehole, faunas with *S. affiliata* often occur within the sandy infillings of mud cracks – many bearing wind-blown 'millet-seed' sand grains, suggesting colonization of ephemeral water bodies.

BIOSTRATIGRAPHY

Throughout the Midland Valley of Scotland much of the Ballagan Formation yields palynomorph assemblages of the CM Biozone of the Tournaisian (e.g. Stephenson *et al.*, 2003, 2004b and references therein), though in some areas the formation may be of earliest Carboniferous PC Biozone age, and elsewhere extends into the Pu Biozone of the Early Viséan (Stephenson *et al.*, 2003, 2004b). The stratigraphical distribution of ostracods in the Ballagan Formation is reconstructed from assemblages at five key sections (Fig. 5) and is calibrated with the established palynomorph biostratigraphy (Stephenson *et al.*, 2003, 2004b and references therein). The overall ranges of species appear to be controlled by factors other than long duration changes in palaeoenvironment, such as a switch from coastal floodplain to shallow-marine shelf, a transition that only occurred later in the Dinantian of Scotland (Lower Limestone Formation; see

Fig. 1). Some ostracod species emerge as useful local proxies for the palynomorph biozones (Fig. 6). *Shemonaella scotoburdigalensis sensu Latham (1932)* appears early in the sequence, possibly in the PC Biozone. However, the biostratigraphical utility of this species is limited, as *S. scotoburdigalensis* is recorded from younger strata elsewhere (e.g. see Robinson, 1978) and, in addition, specimens referred to this species show a range of shape variation that might encompass more than one species. The new species *Knoxiella monarchella* has an overall stratigraphical range similar to the CM palynomorph Biozone in the Midland Valley and is a useful proxy for that interval, though its stratigraphical occurrence is intermittent. Also appearing in the lower part of the CM Biozone are *'Bythocypris' aequalis*, *Cavellina coela*, *C. incurvscens*, *Sansabella amplexans* and *Shemonaella sp. A*. The new species *Paraparchites discus* may be limited to the lower-middle part of the CM Biozone, though it is so far known only from the Heads of Ayr section in Ayrshire. *Sulcella affiliata* appears consistently near the top of the CM Biozone and its first appearance is not associated with a change in facies (Fig. 3). It enables a local upper subdivision of the CM Biozone, particularly as the incoming of *S. affiliata*



appears to correlate closely with 'Upper Ballagan' palynomorph assemblages from Ayrshire (Stephenson *et al.*, 2003). This provides for a more precise correlation of rock sequences over several tens of kilometres in central Scotland (Stephenson *et al.*, 2004b).

The ranges of many ostracod species are consistent with those depicted by Robinson (1978). However, the new records refine the distribution of several Carboniferous ostracod species, such that '*B. aequalis*', *S. affiliata*, *G. lirata* and *S. amplexans* are confirmed for the first time from pre-Viséan horizons in Britain (Fig. 6).

TAXONOMIC NOTES

Many Scottish Carboniferous ostracod species have remained unstudied since the work of Mary Latham in 1932. Most have not been redescribed or figured since the 1890s, and the type material of early workers such as T. R. Jones & J. W. Kirkby (e.g. 1879, 1886a, b, 1896) remains to be re-evaluated. A detailed taxonomic study of this material is beyond the scope of this paper, but this section provides taxonomic notes with illustrations in Plates 2 and 3 of all the key species. Formal descriptions of *Knoxiella monarchella* sp. nov. and *Paraparchites discus* sp. nov. are given in the Systematic Palaeontology section. Registered specimens in the BGS collections for the ostracods are given in Table 3. Podocopa is used in the sense of Horne *et al.* (2002). Higher taxonomic groups largely follow the usage of Olempska (1999). References for suprafamilial taxa are not included.

Platycopida Sars

Four species of platycopids are present in the Ballagan Formation, *Cavellina coela* (Rome, 1973), *C. incurvescens* (Jones & Kirkby, 1896), *Sulcella affiliata* (Jones & Kirkby, 1886a) and *Glyptolichvinella* cf. *spiralis* (Jones & Kirkby MS, in Jones, 1885).

Heteromorph carapaces of *Cavellina coela* (Pl. 2, figs 6, 7, 9, 10, 12, 15) have the domicilium expanded posteriorly to produce numerous egg receptacles (Pl. 2, figs 6, 7, 9). Internally, heteromorphs have a well-developed limen demarcating the anterior end of the domatium. At least one specimen preserves a well-developed sub-circular muscle scar, situated just anterior of the limen, and comprising numerous (11+) closely set individual scars (Pl. 2, fig. 10). This is similar to the 'primitive' aggregate muscle scar patterns described from other *Cavellina* species (Olempska, 1999). *Cavellina coela* differs from its contemporary, *Cavellina incurvescens*, by its greater size and subovate lateral shape and by the posterior inflation of its carapace in heteromorphs.

Heteromorph carapaces of *Sulcella affiliata* (Pl. 2, fig. 18) are also inflated posteriorly and possess numerous (more than 7) receptacles for eggs (see Stephenson *et al.*, 2004b, fig. 9). These are disposed in a similar manner to that of *C. coela* and the species of *Glyptolichvinella* described by Lundin (1987) and Lundin & Visintainer (1987). Some juveniles of *S. affiliata* resemble *Sulcella* cf. *indistincta* (Tschigova) *sensu* Robinson (1978), a taxon considered typical of the Tournaisian.

Glyptolichvinella cf. *spiralis* (Pl. 2, figs 1–3) has a variable number of costae on the lateral surface of its valves: some specimens have only a single costa ventral of the adductorial sulcus (Pl. 2, figs 2, 3), others possess two (Pl. 2, fig. 1). Sometimes both of these costae are disposed ventral of the adductorial sulcus, and sometimes the upper costa intersects the sulcus at about its mid-height. Unlike typical *G. spiralis* (see Robinson, 1978, pl. 5, fig. 4), and ?*G. annularis* (Kummerow) of Robinson, 1978, the ridge that forms a loop on the lateral valve surface of *G. cf. spiralis* is continuous. The differences in costate morphology between *G. cf. spiralis* and the typical *G. spiralis* may be intraspecific, but this requires examination of more material: Lundin's (1987) detailed description of *G. spiralis* was based on seven available specimens.

Palaeocopida Henningsmoen

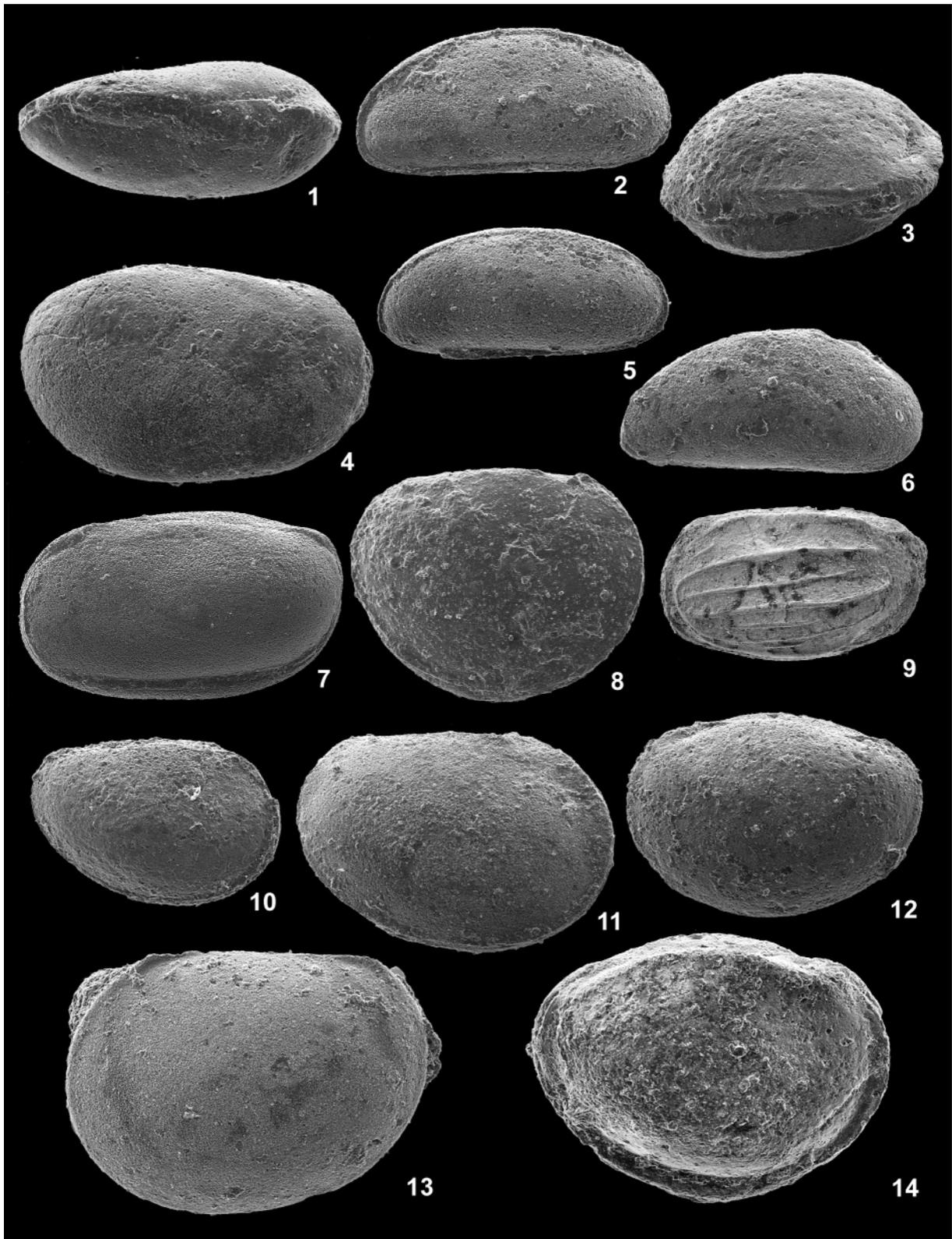
Four species of palaeocopids are present in the Ballagan Formation, *Beyrichiopsis* cf. *fimbriata* Jones & Kirkby, 1886b, *Glyptopleura lirata* Robinson, 1978, *Sansabella amplexans* Roundy, 1926 and *Knoxiella monarchella* sp. nov. Some specimens resembling *Beyrichiopsis plicata* Jones & Kirkby may represent a fifth species (see below). *Knoxiella monarchella* sp. nov. is described in the Systematic Palaeontology section. Although placed here in the Palaeocopida, these straight-hinged taxa may be related closely to the platycopids described above. They all possess domiciliar dimorphism, with posterior inflation of the heteromorph carapace.

The upper size-range of *Beyrichiopsis* cf. *fimbriata* (Fig. 7, Pl. 2, fig. 17) is similar to those *B. fimbriata* figured by Robinson (1978, pl. 3, fig. 2a–d). However, unlike the typical *B. fimbriata*, which possess three costae, in the material from the Ballagan Formation the majority of specimens possess only a single costa, situated below the adductorial sulcus and fully developed in specimens over 1 mm long (Fig. 7). At least one poorly preserved carapace does show two costae, the second developed towards the dorsal margin (Pl. 2, fig. 17). Some of Jones & Kirkby's (1886b, pls 11 and 12) figured specimens of *B. fimbriata* also appear to show a reduced number of costa.

Robinson's (1978, p. 136) figured holotype of *Glyptopleura lirata* (Pl. 3, fig. 9) is 1.39 mm long and the paratype 1.41 mm

Explanation of Plate 2.

Scanning electron micrographs of platycopid and palaeocopid ostracods from the Ballagan Formation. **figs 1–3.** *Glyptolichvinella* cf. *spiralis* (Jones & Kirkby) (all $\times 49$): **1**, right valve, lateral view, MPK13081; **2**, incomplete left(?) valve, lateral view, MPK13085; **3**, carapace, left lateral view, MPK13078. **figs 4, 5.** *Silenites* sp. A: **4**, carapace, left lateral view, MPK12457, $\times 52$; **5**, carapace, left lateral view, MPK12458, $\times 54$. **figs 6, 7, 9, 10, 12, 15.** *Cavellina coela* (Rome, 1973): **6**, heteromorph carapace, ventral view, MPK12453, $\times 51$; **7**, heteromorph carapace, ventral view, MPK12454, $\times 57$; **9, 10**, heteromorph left valve, internal view and close-up of muscle scar, MPK13076 (9, $\times 49$; 10, $\times 500$); **12**, heteromorph carapace, left lateral view, MPK12455, $\times 55$; **15**, heteromorph carapace, left lateral view, MPK12456, $\times 54$. **figs 8, 11, 14.** *Knoxiella monarchella* sp. nov.: **8**, holotype, heteromorph right valve, MPK12455, $\times 55$; **11**, heteromorph carapace, ventral view, MPK12466, $\times 56$; **14**, heteromorph carapace, dorsal view, MPK12477, $\times 55$; **figs 13, 16, 19.** *Cavellina incurvescens* (Jones & Kirkby, 1896): **13**, carapace, ventral view, MPK12460, $\times 55$; **16**, carapace, left lateral view, MPK12459, $\times 52$; **19**, carapace, left lateral view, MPK12482, $\times 52$. **fig. 17.** *Beyrichiopsis* cf. *fimbriata* (Jones & Kirkby, 1886b), right valve, lateral view, BGS MWL7176, $\times 48$. **fig. 18.** *Sulcella affiliata* (Jones & Kirkby, 1886a), left valve, lateral view, MPK13080, $\times 49$.



Early Carboniferous ostracods from Scotland

Ostracod species	Section	Material
<i>Cavellina coela</i>	Ayrshire	MPA49784–49786, MPA49788, MPA49708, MPA49709, MPK12543–12456
	Blairmulloch Farm	GSE15162–15164
	East Dron	horizon EV2685
<i>Cavellina incurvescens</i>	Glenrothes	MPA50237, MPA50231; horizons 11E5910, 11E5890–11E5984
	Ayrshire	MPK12459, MPK12460, MPK12482, MPA49784–49786, MPA49788
	East Dron	horizon EV2685
<i>Sulcella affiliata</i>	Blairmulloch Farm	GSE15165
	Blairmulloch Farm	GSE15166–15181; MPA52105, MPA52106
	Ayrshire	MPA49019, MPA49021, MPA49023, MPA49685, MPA49993, MPK12478–12481, MPK13073, MPK13074
<i>Glyptolichvinella cf. spiralis</i>	Spilmersford	horizons ET1495, ET1497, ET1498, ET1531
	Ayrshire	MPA49019, MPA49785
	Blairmulloch Farm	GSE15178, GSE15182–15191, GSE15224, GSE15225; MPA52105, MPA52109, MPA52112, MPK13078, MPK13079, MPK13081, MPK13085
<i>Beyrichiopsis cf. fimbriata</i>	Blairmulloch Farm	GSE15192–15196, GSE15226–15228, GSE15229, GSE15221, BGS MWL7176, BGS MWL7177
<i>Glyptopleura lirata</i>	Blairmulloch Farm	GSE15198–15200, GSE15209
	East Dron	GSE15236, GSE15197 (seem intermediate between <i>G. lirata</i> and <i>Beyrichiopsis plicata</i>)
<i>Knoxiella monarchella</i>	Ayrshire	MPA 49784–49786, MPA49788, MPK12455–12457
	Blairmulloch Farm	GSE15162, GSE15165, GSE15201–15204
<i>Sansabella amplexans</i>	East Dron	horizon EV2448
	Ayrshire	MPA49022, MPA49685, MPA50101, MPK12475
<i>Paraparchites discus</i>	Blairmulloch Farm	GSE15230, GSE15205; MPA52110, MPK13086
	Ayrshire	MPA49784, MPA49786, MPK12449–12451, MPK12461, MPK12464
<i>Shemonaella scotoburdigalensis</i>	Glenrothes	MPA50237, MPA50641, MPK13082, MPK13083
<i>Shemonaella</i> sp. A	Blairmulloch Farm	e.g. GSE15231–15235
	East Dron	GSE15206, GSE15207, GSE15212 and many more horizons
	Glenrothes	e.g. horizon 11E5861
	Spilmersford	e.g. horizon ET1494
	Ayrshire	e.g. MPA49791, MPA49784, MPA49019, MPA49022, MPK12462, MPK12463, MPK12470–12473, MPK12477
<i>Silenites</i> sp. A	Ayrshire	MPA49788, MPK12457, MPK12458
' <i>Bythocypris</i> ' <i>aequalis</i>	Ayrshire	MPA49790, MPA49791, MPK12465, MPK12466, MPK12468, MPK12469
	Spilmersford	horizon ET1572
	Blairmulloch Farm	MPA52111, MPA52113, MPA52115
	East Dron	GSE15196, GSE15208; horizons EV2476, EV2495, EV2496, EV2498, EV2508, EV2510–2512, EV2641

For further material, see the reports listed in 'Key Sections and Material'.

Table 3. Registered specimens of Ballagan Formation ostracods in the British Geological Survey.

long. The specimens of *G. lirata* in the Ballagan Formation typically bear four costae on the lateral surface of each valve. Their size range (0.8–1.07 mm long), suggests they may be juveniles. Despite this, they clearly bear a smaller number of costae than *G. costata* Hoare, 1991, by which they are readily distinguished. Two small valves from the Glenrothes Borehole (MPA50227, MPK13077; one complete specimen being 0.73 mm long) possess the typical looped costate ridge of *Beyrichiopsis plicata*. However, these specimens are small compared to those figured by Robinson (1978, p. 136), which are up to 1.62 mm long, and it is possible that they are juveniles of *G. lirata*.

Specimens of *Sansabella amplexans* (Pl. 3, figs 1, 4, 7) from the Ballagan Formation are somewhat older than Roundy's (1926) material from Late Carboniferous (Pennsylvanian) shale in the Marble Falls Limestone of Texas (see Sohn, 1975, p. G7). Robinson (1978, pl. 5) records this species from Holkerian to Upper Asbian horizons of the Viséan. The record from the Ballagan Formation indicates that this species extends down into the Late Tournaisian of Britain. Robinson (1978, pl. 5, figs 3a–d) suggested domiciliar and extra-domiciliar dimorphic features in specimens he referred to *S. amplexans*. All of the Ballagan Formation specimens resemble his heteromorphs.

Explanation of Plate 3.

Scanning electron micrographs of palaeocopid, podocopid and paraparchitacean ostracods from the Ballagan Formation. **figs 1, 4, 7.** *Sansabella amplexans* Roundy, 1926: **1**, juvenile carapace, dorsal view, MPK13086, × 62; **4**, carapace, right lateral view, MPK12474, × 54; **7**, carapace, left lateral view, MPK12475, × 56. **figs 2, 5, 6.** '*Bythocypris*' *aequalis* (Jones & Kirkby, 1886a): **2**, carapace, left lateral view, MPK12466, × 52; **5**, carapace, left lateral view, MPK12468, × 53; **6**, carapace, right lateral view, MPK12465, × 54. **figs 3, 12, 14.** *Paraparchites discus* sp. nov.: **3**, carapace, dorsal view, MPK12461, × 52; **12**, juvenile carapace, right lateral view, MPK12450, × 53; **14**, carapace, left lateral view, MPK12449, × 52. **fig. 8.** *Shemonaella scotoburdigalensis* (Hibbert, 1836) *sensu* Latham, 1932, carapace, left lateral view, MPK13082, × 46. **fig. 9.** *Glyptopleura lirata* Robinson, 1978, holotype, left lateral view, specimen NHM OS7370, from Wath Quarry, Lunedale, Westmorland (fig'd Robinson, 1978), × 32. **figs 10, 11, 13.** *Shemonaella* sp. A: **10**, juvenile carapace, left lateral view, MPK12463, × 52; **11**, carapace, left lateral view, MPK12471, × 52; **13**, right valve, lateral view, MPK12473, × 52.

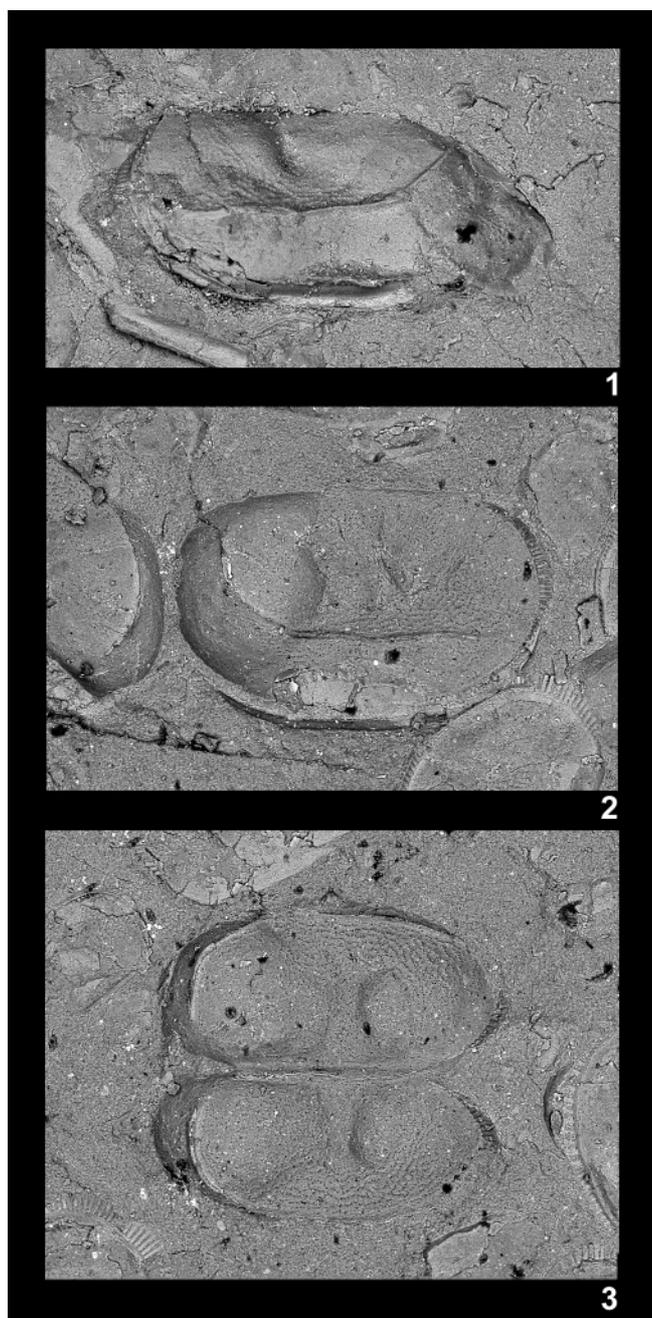


Fig. 7. Scanning electron micrographs of *Beyrichiospis cf. fimbriata* (Jones & Kirkby, 1886b) on rock slab GSE15227 from the Blairmulloch Farm Borehole (depth about 188.7 m below OD). 1, Flattened tectonormorph(?) left valve, partially obscured dorsally by sediment, and posteroventrally by a juvenile carapace. 2, Heteromorph right valve; velum and valve margin obscured by sediment. 3, Small heteromorph carapace preserved in 'butterfly' (valves open) orientation (right valve bottom). Magnification $\times 49$.

Paraparchitacea Scott

Three paraparchitacean species are present in the Ballagan Formation, *Shemonaella scotoburdigalensis* (Hibbert, 1836) *sensu* Latham (1932), *Shemonaella* sp. A and *Paraparchites discus* sp. nov. The latter is described in the Systematic Palaeontology section.

Shemonaella scotoburdigalensis (Hibbert) *sensu* Latham (1932) (Pl. 3, fig. 8) is recorded widely in the British Lower Carboniferous (e.g. see Jones, 1885; Jones & Kirkby, 1886a; Latham, 1932; Pollard, 1985), though the original material of Hibbert (1836), that was poorly figured (see Jones & Kirkby, 1886a, p. 255), has not been restudied. Specimens from the Glenrothes Borehole are identical to those in Mary Latham's (1932) collection (palaeontological collections of BGS Edinburgh) referred to *S. scotoburdigalensis*. They have carapaces that are subovate in lateral shape and subamplete to weakly postplete, show weak dorsal overreach of the left valve over the right valve and have evenly convex smooth valves. Some specimens referred to this species have a more ovate amplete lateral shape, for example, that figured by Robinson (1978, pl. 10, fig. 4a) or that from Atlantic Canada figured by Dewey & Fåhraeus (1987, pl. 7, fig. 5), suggesting a range of variation that might encompass dimorphism and/or more than one species. Jones & Kirkby (1886a, p. 255) certainly considered *S. scotoburdigalensis* to be dimorphic, referring to 'thin and fat' specimens, though there are too few specimens to confirm this in the authors' collection.

Shemonaella sp. A (Pl. 3, figs 10, 11, 13) is the most common ostracod in the Ballagan Formation. In its size and shape, and by possessing valves that show marginal flattening particularly anterodorsally and posterodorsally, it resembles the mid-Tournaisian *Shemonaella?* sp. 66 of Becker & Bless (1974) and may be conspecific. Small specimens of *Shemonaella* sp. A resemble *S. scotoburdigalensis sensu* Latham, 1932 (cf. Pl. 3, figs 8, 10, 11), but adults of *Shemonaella* sp. A are much larger than those *S. scotoburdigalensis* reported by Jones & Kirkby (1886a, p. 255; 1896, pl. 11, fig. 12) or Latham (1932).

Podocopida G. W. Müller

Two species of podocopids are present in the Ballagan Formation, *Silenites* sp. A and '*Bythocypris*' *aequalis* (Jones & Kirkby, 1886a). The small (less than 1 mm long) *Silenites* sp. A (Pl. 2, figs 4, 5) is rare. The younger (Asbian) species *Silenites circumcisa* (Jones & Kirkby, 1879) is much larger: the specimen figured by Robinson (1978, pl. 13, fig. 6a, b) is 1.18 mm long. Compared with the North American Tournaisian *Silenites margaretensis* Crasquin, 1985, which is up to 2 mm long, the Ballagan Formation species is also small. It is also smaller than the type species *S. lenticularis* (Knight; the senior synonym of *Silenites silenus* Coryell & Booth [see Moore, 1961, p. Q387; also see Sohn, 1960, pl. 4, fig. 2]), suggesting that the specimens from the Ballagan Formation are juveniles, or that this is a diminutive new species.

For '*Bythocypris*' *aequalis* (Pl. 3, figs 2, 5, 6) generic identification is made purely on external features – muscle scars and hinge structure are unknown. There are a number of species of *Bythocypris* that bear some similarity, though *Bythocypris* Brady is a 'bag-genus' to which numerous species have been referred (for example, see Moore, 1961, p. Q205). '*B.*' *aequalis* also resembles early *Darwinula* from the Permian and Triassic, although without information on the internal morphology of the carapace, the similarity might be superficial. Jones & Kirkby (1886a) assigned the species to the Mesozoic and younger *Argilloecia*. This bears a characteristically broad inner lamella and wide vestibules, whereas in '*B.*' *aequalis* the inner lamella (seen through translucent carapaces) is moderately broad in the

anterior and posterior (about 0.07–0.1 mm wide), but narrows along the ventral margin and disappears mid-dorsally. Robinson (1978) assigned Jones & Kirkby's species to *Acutiangulata* Buschmina, a Russian bairdiacian genus. *Carbonita acutiangulata* Posner (in Tschigova, 1960) was later chosen by Buschmina (1968) as the type species of *Acutiangulata*. *Carbonita* is a variable genus in terms of shape, but the right valve overlaps the left valve along the free margin (although the left valve may overlap the right valve dorsally) and its characteristic circular adductor muscle pit often has an external representation. The muscle pit is not seen on the Ballagan Formation '*B.*' *aequalis*.

SYSTEMATIC PALAEOLOGY

Class **Ostracoda** Latreille

Subclass **Podocopa** G. W. Müller

Order **Palaecopida** Henningsmoen

Family **Knoxitidae** Egorov, 1950 *nom. correct* Zanina, 1971
(=Geisinidae Sohn in Moore, 1961)

Genus *Knoxiella* Egorov, 1950

Type species. *Knoxiella semilukiana* Egorov, 1950.

Remarks. *Knoxiella* is characterized by its sub-rectangular lateral shape, sub-circular preadductorial node (when well-developed), adductorial sulcus, reticulate ornament in the majority of species, right over left valve overlap, straight ventral overlap contact and domiciliar dimorphism in which the heteromorph carapace is inflated posteriorly. The right valve possesses a straguloid process that overlaps the left valve towards the anterior end of the hinge.

Knoxiella is widespread in the Carboniferous of Europe (e.g. Becker *et al.*, 1974; Robinson, 1978; Coen *et al.*, 1988; Turner *et al.*, 1997) and is also recorded from China (Olempska, 1999).

Knoxiella monarchella sp. nov.
(Pl. 2, figs 8, 11, 14)

2003 *Knoxiella* sp. A Stephenson *et al.*: fig. 9f.

Derivation of name. From the first letters of the surnames of Alison Monaghan and Sarah Arkley of the British Geological Survey, who first collected this species in the rock succession at the Heads of Ayr, Ayrshire, Scotland. Gender feminine.

Diagnosis. *Knoxiella* with the lateral valve margin flattened anteriorly and posterodorsally, an obsolete preadductorial node which is continuous with the gently convex anterior lobe, ventral outline gently concave in lateral view, and fine reticulate ornament in which the reticulae have diameters of between 20 µm and 30 µm.

Holotype. Heteromorph right valve (MPK12455) mistakenly referred to as a 'carapace' by Stephenson *et al.* (2003, fig. 9f). From the Ballagan Formation, just to the north of Heads of Ayr, Ayrshire coast.

Material. See Table 3.

Description. Adult valves longer than 1 mm, elongate and sub-rectangular: valve length about twice the valve height. In lateral view the dorsal outline is essentially straight, the ventral outline weakly concave. Anterior and posterodorsal margin of valves flattened, particularly obvious from a dorsal aspect (Pl. 2, fig. 14). Anterior and posterior lobes gently convex, the latter more inflated in heteromorphs. Adductorial sulcus straight, about one half the valve height and situated about one-third of the valve length from the anterior margin. Posterior part of dorsum weakly epicline in heteromorphs, where the posterior lobe weakly overreaches the dorsum. Straguloid process of larger right valve overreaches the left valve at the anterior end of the hinge (Pl. 2, fig. 14). Right valve overlaps the left valve ventrally; overlap contact straight. Ornament comprises reticulae of diameter between 20 µm and 30 µm, distributed evenly across the valve surface, though often poorly developed in the area of the posterior lobe.

Dimensions. Specimens are 0.83–1.07 mm long and 0.42–0.58 mm high (18 measurements).

Remarks. *Knoxiella monarchella* is characterized by its fine reticulate ornament, in which each reticulum has a diameter of between 20 µm and 30 µm. Of the other described British *Knoxiella* taxa, *K. robusta* Robinson, 1978 is much larger, typically reaching lengths of 1.3 mm, *K. archdensis* (Tschigova) *sensu* Robinson, 1978 appears to be less elongate and has a more arched lateral outline dorsally, and *K. cf. rugulosa* (Kummerow) *sensu* Robinson, 1978 has large reticulae. *Knoxiella* sp. cf. *K. clathrata* (Kummerow) *sensu* Turner *et al.*, 1997 from the Viséan Fell Sandstone of northern England has similar overall shape, but is smaller (adult length 0.79 mm) than *K. monarchella* and also appears to lack ornament. Of the comparably aged continental European taxa referred to *Knoxiella*, *K. clathrata*, *K. rugulosa* and *K. complanata* (all Kummerow, 1939) are small (less than 0.9 mm long). *K. subquadrata* (Kummerow, 1939) is over 1 mm long, but its valves are almost smooth. The small (sub-millimetre length) *Knoxiella* taxa figured by Becker & Bless (1974) have a more well-developed preadductorial node than *K. monarchella* and more evenly distributed reticulo-punctate ornament (Becker & Bless, 1974, pl. 22, figs 4–6; pl. 27, figs 6–8; see also Becker *et al.*, 1974, pl. 7, fig. 2a, b), or a gently convex ventral outline in lateral view and reticulo-striate ornament (Becker & Bless, 1974, pl. 27, figs 1–5; also Becker *et al.*, 1974, pl. 14, figs 7–9), or have smooth valves (Becker & Bless, 1974, pl. 22, fig. 7a–c). In lateral shape and possession of a weakly developed preadductorial node, *K. monarchella* is similar to *K. cf. subquadrata* (Kummerow, 1939) and *K. cf. complanata* (Kummerow, 1939) figured by Becker *et al.* (1974, pl. 14, figs 11, 13, 14), though in both of these taxa the margin of the valves is not flattened in the manner of *K. monarchella*, and their figured specimens are also smaller than the adults of the Ballagan Formation species. *Knoxiella cratigera?* (cf. *subquadrata*) of Coen *et al.* (1988, pl. 9, figs 7, 8) and their *Knoxiella* sp. (Coen *et al.*, 1988, pl. 1, fig. 11a, b) are also smaller and show marked carapace flattening near the anterodorsal margin.

Order **Leiocopa** Schallreuter
Superfamily **Paraparchitacea** Scott, 1959
Family **Paraparchitidae** Scott, 1959

Genus *Paraparchites* Ulrich & Bassler, 1906

Type species. *Paraparchites humerosus* Ulrich & Bassler, 1906.

Remarks. In lateral view the carapace of *Paraparchites* is characterized by its ovate or elongate-ovate shape, rounded anterior and posterior outlines and straight or weakly convex dorsal margin. It has an incised dorsum, but with limited valve overreach over the hinge-line, an absence of spines on the dorsal lateral surface, insignificant free margin valve overlap and non-sulcate valves (see Sohn, 1971, p. A6). Many species of *Paraparchites* are differentiated by means of carapace shape and dimensions (Sohn, 1971, 1972). Some *Paraparchites*, including the type species, show dimorphism, heteromorphs having wider carapaces (see Sohn, 1971; Dewey, 1987).

Paraparchites discus sp. nov.
(Pl. 3, figs 3, 12, 14)

2003 *Paraparchites* sp. 1 Stephenson *et al.*: fig. 9i.

Derivation of name. Resembling a 'discus' in lateral view (see Pl. 3, fig. 14).

Diagnosis. *Paraparchites* with incised dorsum, demarcated by the overreaching margins of the left and right valves, both of which are drawn out to form narrow ridges at the dorsum in larger valves.

Holotype. A carapace, MPK12449 (Pl. 3, fig. 14), from the Ballagan Formation, just to the north of Heads of Ayr, Ayrshire coast [NGR NS 2977 1871].

Material. See Table 3.

Description. Sub-ovate lateral shape: anterior and posterior lateral outlines evenly convex and rounded, anterior outline slightly more tapering, ventral outline evenly convex. Dorsum umbonate: both valves overreach the dorsal margin and meet at about the same height dorsally. Dorsal margin incised, demarcated by the overreaching margins of the left and right valves, both of which are drawn out to form a narrow ridge at the dorsum in larger valves (Pl. 3, fig. 3). Larger valves have well-developed fine punctation and a smooth central muscle spot, which has a diameter about 20% of that of the carapace length. Carapaces show right over left valve overlap. Lateral margins of the valves are flattened both anteriorly and posteriorly.

Dimensions. Valves are 0.5 mm to 1.1 mm long, representing several moult stages (material from Ayrshire).

Remarks. Valves lack spines, indicating that this is not a species of *Shivaella* or *Shishaella* (see Sohn, 1972). Both valves meet at the same height dorsally, their overreach resulting in an epicline dorsum. The latter indicates that this is not a *Shemonaella* or *Chamishaella* species either (Dewey & Fähræus, 1987) and serves to distinguish this species from the similarly-sized *Shemonaella scotoburdigalensis* (Hibbert, 1836).

Paraparchites discus has a more strongly incised dorsum than is typical for the type species *P. humerosus* (see Sohn, 1971, pl. 1) but, in this respect, is similar to taxa such as *Paraparchites* sp. of Sohn, 1971 (pl. 2, fig. 16), *P. gelasinos* Sohn, 1972 and *P. cyclopeus* Girty, 1910 (for which, see Sohn, 1969, pl. 8), though the latter possesses a spine on the right valve and is probably not *Paraparchites* (see Sohn 1971, p. A6). The lateral flattening of the valves anteriorly and posteriorly in *P. discus* is similar to species such as *P. miseri* Sohn, 1972, but *P. discus* differs from that species by lacking indentation along the ventral margin, by which the new species also differs from other *Paraparchites* such as *P. gibbosus* Upson (see Sohn, 1972). The complete shape of *P. discus* serves to distinguish it from postplete forms such as *P. texanus* Delo, 1930 (see Sohn, 1971, pl. 2).

CONCLUSIONS

The Early Carboniferous Ballagan Formation of the Midland Valley, Scotland, contains an ostracod fauna of 14 species in ten genera, including platycopid (*Cavellina*, *Glyptolichvinella*, *Sulcella*), palaeocopid (*Beyrichiopsis*, *Glyptopleura*, *Knoxella*, *Sansabella*), paraparchitacean (*Paraparchites*, *Shemonaella*) and podocopid taxa (*Silenites*, 'Bythocypris'). Two new species are *Knoxella monarchella* and *Paraparchites discus*.

The Ballagan Formation is dominated by ostracod-bearing horizons of low-diversity (one to two species), interpreted as occupying ephemeral aquatic ecologies, with fluctuating salinity (brackish to hypersaline), on a coastal floodplain. Paraparchitacean-dominated assemblages may represent hypersaline conditions. Podocopid-dominated assemblages of 'Bythocypris' *aequalis* may represent brackish-water conditions, which later in the Ballagan Formation were colonized by the cavellinid *Sulcella affiliata*. In Ayrshire, higher diversity assemblages of up to five species (cavellinids, palaeocopids and paraparchitaceans) are associated with lithofacies that are interpreted to be tidal flat environments.

The ostracods are useful biostratigraphical markers. *Knoxella monarchella* and *Cavellina coela* have stratigraphical ranges that are coincident with the CM palynomorph Biozone. *Sulcella affiliata* has a consistent Late CM Biozone occurrence and, thus, affords a local subdivision of that interval in the Midland Valley, which is important for regional correlation.

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