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

MARK WILLIAMS1, 2, MICHAEL STEPHENSON1, IAN P. WILKINSON1, MELANIE J. LENG3 & C. GILES MILLER4

1British Geological Survey, Keyworth, Nottingham NG12 5GG, UK.
2Current address: British Antarctic Survey, Geological Sciences Division, High Cross, Maddington Road, Cambridge CB3 0ET, UK (e-mail: mwilli@bas.ac.uk).
3NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham NG12 5GG, UK.
4Natural History Museum, Cromwell Road, South Kensington, London SW7 5BD, UK.

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, Knoxiella, Paraparchites, Sansabella, Shemonaella and Sulcella. The ostracods, in combination with palynomorphs, are important biostratigraphical indices for correlating the rock sequences, where other means of correlation, especially goniavites, 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 amplectans and the new species Knoxiella monarchella and Paraparchites discus first appear; and, an upper interval, in the upper CM Biozone, marked by the appearance of Sulcella affinita. At least locally in central Scotland, S. affinita permits a level of resolution equivalent to a sub-zonal upper division of the CM Biozone. The fauna, flora, sedimentology and stable isotope composition (δ13C and δ18O) 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 Lower, Middle and Upper Dinantian biozones (Wilson, 1989; Mitchell & Mykura, 1962, p. 38). 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, Knoxiella (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,
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://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
(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 $\delta^{13}C$ and $\delta^{18}O$ 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
The δ18O 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 c. −4‰ 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 δ18O and there was no significant recrystallization during burial (cf. Tucker et al., 2003). There are no unequivocal published estimates for Early Carboniferous fresh water δ18O 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 δ18O (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 δ18O (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 (× 3); 2, *Cavellina coela* associated with rare brachiopod debris (GSE15217) (× 14); 3, fish debris (GSE15213) (× 7); 4, *Shemonaella* sp. A and *Modiolus latus* (GSE15212) (× 4); 5, well-preserved valves of *Shemonaella* sp. A (GSE15207) (× 6).
Evaporated soil water have been found to have δ18O values between −9.0‰ and −8.0‰ (Andrews et al., 1991; Turner, 1991), suggesting that the Early Carboniferous fresh water δ18O might have been lower than this. Thus, carbonate δ18O 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 δ18O around −9‰ and −3‰, respectively. Values between −9‰ and −3‰ are, therefore, either evaporated fresh water (which increases δ18O) or a mixture of fresh water and sea water (δ18O c. −3‰). There are no samples that have δ18O values around the expected value for sea water. However, there are some samples with δ18O 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 δ18O (−13.2‰ to −11.1‰), suggesting that the carbonate with low δ18O (−< −9‰) 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 δ13C values (to VPDB) of the Ballagan Formation carbonates analysed span a range between −5.7‰ to +2.5‰ (Fig. 4), lower than Early Carboniferous sea water, which had a δ13C value of +3‰ to +4‰ (Bruckschen et al., 1999). Fresh water δ13C tends to be derived from CO2 via soils and has low δ13C. Modern groundwaters in Europe have δ13C 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 CO2 in evaporating waters and mixing with heavier marine δ13C. In localized environments – for example, in organic-rich environments – oxidation of organic matter can lead to low δ13C. 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 δ13C. All of these processes might have been occurring during deposition of the Ballagan Formation, although the δ18O data suggest that the sediments analysed were deposited in evaporating fresh water or a mixed fresh water–marine (i.e. brackish) environment.

**Paleontology**

The ostracod fauna of the Ballagan Formation is dominated numerically by paraparchitaceans, though platycopae, palaeocopae and podocopae 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 biocones (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, calcrites 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 calcrite-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 Spirodiris, onchostracans and Naiadites trace fossils. Very rare (four horizons from several hundred studied) co-occurrences of ostracods (Cavellina coela) with fragmentary brachiopod valves and orthocoon nautiloids (some colonized by Spirodiris) 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 Amphipisites, 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.
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.

<table>
<thead>
<tr>
<th>Ostracod species</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Glyptopleura lirata</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Cavellina coela</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Cavellina incurvescens</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Sulcella afflixi</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Glyptolithvinella cf. spiralis</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Knoxiella monarchella</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Sansabella amplexans</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Beyrichiopsis cf. fimbrriata</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>‘Beyrichiopsis plicata’</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Paraparchites discus</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Shemonaella sp. A</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>Shemonaella scotoburdigalensis</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><em>‘Bythocypris’ aequulis</em></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

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. incurvescens*, *Knoxiella monarchella* sp. nov., *Paraparchites discus* sp. nov., *Silinutes* sp. (referred to as *Bairdia* cf. *jukatika* 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 *Spirotris* worm tubes, modern representatives of which are regarded as eurytopic (Hantzsche 1975, *fide* 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’ aequulis*. This environmental interpretation is supported by the occurrence of zygnematacean 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. aequulis* 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. fimbrriata* 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. aequulis* 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 afflixi*, often in monospecific assemblages (Fig. 5). This assemblage is possibly a temporal successor to the brackish-water/lagoonal faunas dominated by ‘*B. aequulis* 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 afflixi* occurs with algal pseudomorphs, including *Botryococcus*, which signal low-salinity (brackish?) conditions (Stephenson et al., 2003, 2004a). This species also occurs with *Sansabella amplexans* and *Glyptolithvinella 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..."
In Ayrshire and in the Spilmersford Borehole, faunas with *S. affliata* 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 Touraisian (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 incurvescens*, *Sansabella amplexans*, *Glyptolichinella cf. spiralis*, *’Beyrichipros plicata’*, *Glyptopleura lirata*, *Beyrichipros cf. fimbriata* 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 affliata* 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. affliata*.  

---

**Formal ranges of ostracod species, reconstructed from data in Figure 5.**

<table>
<thead>
<tr>
<th>Species</th>
<th>PC</th>
<th>CM</th>
<th>UB</th>
<th>PU</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Shemonaella scotoburdigalensis</em></td>
<td></td>
<td>1, 2, 3, 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Cavellina coela</em></td>
<td></td>
<td>1, 2, 3, 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Shemonaella sp. A</em></td>
<td></td>
<td>1, 2, 3, 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Silanites sp. A</em></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><em>Cavellina incurvescens</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>Paraparchites discus</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>Knoxiella monarchella</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>’Bythocypris’ aequalis</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>Sansabella amplexans</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>Glyptolichinella cf. spiralis</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>’Beyrichipros plicata’</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>Glyptopleura lirata</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>Beyrichipros cf. fimbriata</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>Shemonaella sp. A</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td><em>Paraparchites discus</em></td>
<td></td>
<td></td>
<td></td>
<td>1, 2, 3, 4</td>
</tr>
</tbody>
</table>

**Informal ostracod intervals**

- Poor faunas with *Shemonaella scotoburdigalensis* sensu Latham (1932)
- *Knoxiella monarchella* - *Cavellina coela*
- *Sulcella affliata*
Early Carboniferous ostracods from Scotland

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’ aequulis, 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 redecribed 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 *Pararaphites 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 adductor sulcus (Pl. 2, figs 2, 3), others possess two (Pl. 2, fig. 1). Sometimes both of these costae are disposed ventral of the adductor 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 amplectans* Roundy, 1926 and *Knoxiella monarchella* sp. nov. Some specimens resembling *Beyrichiopsis pilcata* 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 domiciliary 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 adductor 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
Early Carboniferous ostracods from Scotland

<table>
<thead>
<tr>
<th>Ostracod species</th>
<th>Section</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavellina coela</td>
<td>Ayshire</td>
<td>MPA49784–49786, MPA49788, MPA49708, MPA49709, MPK12543–12456</td>
</tr>
<tr>
<td></td>
<td>Blairmulloch Farm</td>
<td>GSE15162–15164</td>
</tr>
<tr>
<td></td>
<td>East Dron</td>
<td>horizon EV2685</td>
</tr>
<tr>
<td></td>
<td>Glenrothes</td>
<td>MPAS0237, MPAS0231; horizons 11E5910, 11E5890, 11E5984</td>
</tr>
<tr>
<td>Cavellina incurvescens</td>
<td>Ayshire</td>
<td>MPK12459, MPK12460, MPK12482, MPA49784–49786, MPA49788</td>
</tr>
<tr>
<td></td>
<td>East Dron</td>
<td>horizon EV2685</td>
</tr>
<tr>
<td></td>
<td>Blairmulloch Farm</td>
<td>GSE15165</td>
</tr>
<tr>
<td>Sulcella affiliata</td>
<td>Ayshire</td>
<td>MPA49019, MPA49021, MPA49023, MPA49685, MPA49993, MPK12478–12481, MPK13073, MPK13074</td>
</tr>
<tr>
<td></td>
<td>Blairmulloch Farm</td>
<td>GSE15166–15181; MPA52105, MPA52106</td>
</tr>
<tr>
<td>Bythocypris cf. spiralis</td>
<td>Ayshire</td>
<td>MPA49019, MPA49785</td>
</tr>
<tr>
<td></td>
<td>Spilmersford</td>
<td>horizons ET1495, ET1497, ET1498, ET1531</td>
</tr>
<tr>
<td>Glyptopleura lirata</td>
<td>Ayshire</td>
<td>MPA49784–49786, MPA49788, MPA49708, MPK12455–12457</td>
</tr>
<tr>
<td></td>
<td>Blairmulloch Farm</td>
<td>GSE15178, GSE15182–15191, GSE15224, GSE15225; MPA52105, MPA52109, MPK12462, MPK12463</td>
</tr>
<tr>
<td></td>
<td>East Dron</td>
<td>horizon EV2448</td>
</tr>
<tr>
<td></td>
<td>Blairmulloch Farm</td>
<td>GSE15192–15196, GSE15226–15228, GSE15229, GSE15221, BGS MWL7176, BGS MWL7177</td>
</tr>
<tr>
<td>Knoxiella monarchella</td>
<td>Ayshire</td>
<td>MPA49784, MPA49788, MPA49708</td>
</tr>
<tr>
<td></td>
<td>East Dron</td>
<td>MPK12469, MPK12470–12473, MPK12477, MPK12478–12481</td>
</tr>
<tr>
<td>Sansabella amplectans</td>
<td>Ayshire</td>
<td>MPA49022, MPAS0641, MPK13082, MPK13083</td>
</tr>
<tr>
<td></td>
<td>Blairmulloch Farm</td>
<td>GSE15220, GSE15207, GSE15212 and many more horizons</td>
</tr>
<tr>
<td></td>
<td>East Dron</td>
<td>GSE15206, GSE15207, GSE15212 and many more horizons</td>
</tr>
<tr>
<td></td>
<td>Glenrothes</td>
<td>e.g. GSE15231–15235</td>
</tr>
<tr>
<td></td>
<td>Spilmersford</td>
<td>e.g. horizon ET1494</td>
</tr>
<tr>
<td></td>
<td>Ayshire</td>
<td>e.g. GSE15231–15235</td>
</tr>
<tr>
<td>Paraparchites discus</td>
<td>Ayshire</td>
<td>MPA49784, MPA49786, MPK12449–12451, MPK12461, MPK12464</td>
</tr>
<tr>
<td>Shemonaella scotoburdigalensis</td>
<td>Glenrothes</td>
<td>MPA50237, MPAS0641, MPK13082, MPK13083</td>
</tr>
<tr>
<td>Shemonaella sp. A</td>
<td>Blairmulloch Farm</td>
<td>e.g. GSE15231–15235</td>
</tr>
<tr>
<td></td>
<td>East Dron</td>
<td>GSE15206, GSE15207, GSE15212 and many more horizons</td>
</tr>
<tr>
<td></td>
<td>Glenrothes</td>
<td>e.g. horizon ET1494</td>
</tr>
<tr>
<td></td>
<td>Spilmersford</td>
<td>e.g. horizon ET1494</td>
</tr>
<tr>
<td></td>
<td>Ayshire</td>
<td>e.g. GSE15231–15235</td>
</tr>
<tr>
<td>Silenites sp. A</td>
<td>Ayshire</td>
<td>MPA49788, MPK12457, MPK12458</td>
</tr>
<tr>
<td></td>
<td>Spilmersford</td>
<td>horizon ET1572</td>
</tr>
<tr>
<td></td>
<td>Blairmulloch Farm</td>
<td>MPA52111, MPA52113, MPK12457</td>
</tr>
<tr>
<td></td>
<td>East Dron</td>
<td>GSE15196, GSE15208; horizons EV2476, EV2495, EV2496, EV2498, EV2508, EV2510–2512, EV2561</td>
</tr>
</tbody>
</table>

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 (MPAS0237, 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 amplectans (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. amplectans. 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 amplectans Roundy, 1926: 1, juvenile carapace, dorsal view, MPK12468, ×56; 4, carapace, right lateral view, MPK12474, ×54; 7, carapace, left lateral view, MPK12475, ×56. figs 2, 5, 6. ‘Bythocypris’ aequis (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.
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 & Fähræus (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

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 tecnomorph(*) 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 × 49.

Paraparchitacaea 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.
Early Carboniferous ostracods from Scotland

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 *Acuitiangulata* Buschmina, a Russian bairdiacian genus. *Carbonita acuitangulata* Posner (in Tschigova, 1960) was later chosen by Buschmina (1968) as the type species of *Acuitiangulata*. *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 PALAEONTOLOGY**

Class Ostracoda Latreille
Subclass Podocopa G. W. Müller
Order Palaeocopida Henningsmoen
Family Knoxitidae Egorov, 1950 nom. correct Zanina, 1971 (=Geisinidae Sohn in Moore, 1961)
Genus Knoxiella 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 monachella* 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 monachella* 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. monachella* 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. subquadra* (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. monachella* 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. monachella* is similar to *K. subquadra* (Kummerow, 1939) and *K. 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. monachella*, and their figured specimens are also smaller than the adults of the Ballagan Formation species. *Knoxiella cratigera*? (cf. *subquadra*) 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 Paraparchitaceae 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 punctuation 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 *Shemonaella* 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 *Chamishiella* species either (Dewey & Fåhraeus, 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 amplete 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*, *Knoxiella*, *Sansabella*), paraparchitacean (*Paraparchites*, *Shemonaella*) and podocopid taxa (*Silenites*, *Bythocypris*). Two new species are *Knoxiella 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 afflita*. 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. *Knoxiella monarchella* and *Cavellina coela* have stratigraphical ranges that are coincident with the CM palynomorph Biozone. *Sulcella afflita* 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.

**ACKNOWLEDGEMENTS**

Maxine Akhurst supported this study through the BGS Midland Valley Mapping Project, Mike Browne selected key sections, and Mark Dean provided information about macrofaunas. Chris Dewey (Mississippi), David Siveter (Leicester), an anonymous reviewer and John Gregory (NHM) made reviews and editorial comments about the higher taxonomy of ostracods, Joanne Green (NIGL) for the isotope analysis, and Paul Shepherd, Grenville Turner and Jim Rayner for help with the SEM and photography. MS, IPW & ML publish with the Permission of the Executive Director, British Geological Survey (NERC).

Manuscript received 25 February 2004
Manuscript accepted 24 December 2004
REFERENCES


