

# Late Ordovician brachiopod faunas from Pomeroy, Northern Ireland: a palaeoenvironmental synthesis

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**ABSTRACT:** Comparisons of the Caradoc assemblages with North American biofacies indicate that the Bardahessiagh Formation was deposited during a transgressive regime, which peaked with the presence of a typical *Sericoidea* association (member (II)). These diverse and exceptionally preserved faunas lived below the storm-wave base. The assemblages also contained a shallower water brachiopod component typical of transition zone environments or above, which may have been transported during periods of instability. A deep-water regime (BAs 4 to 4–5) through the Rawtheyan occurs with the deposition of the Killey Bridge Formation, which yielded a diverse brachiopod fauna including *Bimuria*, *Chonetoidea* and *Christiania*. The Rawtheyan assemblage also contains a shallower water component. Representatives of the deep-water *Proboscisambon* assemblage occur in middle parts of the Tirnaskea Formation. This distinctive low-diversity assemblage yields small, thin-shelled brachiopods including *Dedzetina*, *Sericoidea*, *Protozyga* and *Proboscisambon*. The upper parts of the Tirnaskea Formation yielded the low diversity, shallow water (BA 3) *Hirnantia* fauna, which is characterised by the presence of *Eostropheodonta*, which is a key form of the fauna, *Dysprosorthis* and the absence of *Hirnantia*. As a whole the changing brachiopod biofacies monitor environmental fluctuations, on part of the Laurentian margin, driven mainly by eustatic and tectonic events.

**KEY WORDS:** Ashgill, biofacies, Brachiopoda, Caradoc, palaeoecology, palaeoenvironments

Following work by Portlock (1843), Fearnside *et al.* (1907) and Reed (1952), Mitchell (1977) undertook a modern description of the brachiopod faunas from the Bardahessiagh, Killey Bridge and Tirnaskea formations involving the description of an exhaustive and diverse collection including abundant new species, as well as the palaeogeographical and palaeoecological interpretation of the different faunas. The Caradoc brachiopod faunas have been documented more recently by Candela (2003), based on material collected *in situ*. This new material was collected in stratigraphically higher horizons than the older material from the Bardahessiagh Formation collected and described by Mitchell (1977).

## 1. Caradoc Faunas

Mitchell (1977) analysed the brachiopod faunas from the Bardahessiagh Formation from what is now known as members (I) to (III) (Candela 2002). The fauna from member (I) was collected from *in situ* material, whereas the fauna from member (III) was collected from loose blocks, all within 0.5 km south of Craighbardahessiagh. Mitchell's (1977) material from member (I) was also obtained from loose blocks, which were widely used as building material, deriving from a local quarry, also known as the 'Old Quarry' or more anciently as the 'Flagstone Quarry', filled at the beginning of the 20th Century. Member (II) was not recognised then. Subsequent field work, during 1992, by a team from the Ulster Museum (Belfast) permitted the collection of *in situ* material that has been described by Candela (2003). The brachiopod fauna from member (I) described from the latter was collected from younger horizons than the fauna described by Mitchell (1977).

In this study the horizon from which Mitchell (1977) collected his material is called member (0) to differentiate it from the stratigraphically younger horizon from which the

later material was obtained. Table 1 compares the relative abundance of genera collected from members (0) to (III). The Caradoc brachiopod faunas from Pomeroy were compared to the eastern North American brachiopod Biofacies of Patzkowsky (1995) (Table 2). Although a similar study of members (I) to (III) has been published (Candela 2001), the input of new critical data will allow previous conclusions to be refined. The data was analysed using cluster analysis and the Chord index of similarity (abundance data). The resulting dendrograms are displayed on Figures 1 to 3. The brachiopod faunas member (0), members (I) and (III) of the Bardahessiagh Formation clearly show a mixing of taxa, with a shallower [mbr x/1] and a deeper [mbr x/2] water component of the assemblage (with  $x=0, 1$  or  $3$ ).

The dendrogram (Fig. 1) shows that [mbr0/1] groups with an undifferentiated cluster composed of a combination of samples from Patzkowsky's (1995) clusters C, D and E, whereas [mbr0/2] groups with samples more typical of Patzkowsky's (1995) cluster D. Nevertheless, these two can be grouped into a single cluster. Sub-assemblage [mbr0/1] is characterised by *Sowerbyites*, *Rostricellula* and *Campylorthis* which represent 38%, 14% and 13.5% of the total sub-assemblage, respectively. *Sowerbyella* accounts for 12% of the sub-assemblage. On the other hand, sub-assemblage [mbr0/2] is dominated by *Salopina* and *Glyptorthis* that represent 20% and 16% of the sub-assemblage. *Bimuria* (8%), *Isophragma* (7.5%) and *Colaptomena* (7%) are also present in the sub-assemblage. Patzkowsky's (1995) clusters C and D are characterised by the abundance of the plectambonitoid *Sowerbyella*, which ranges over 15% (and more commonly 39% for cluster D) of the total abundance of the samples in which it is present. The strophomenoids *Oepikina* and *Strophomena* and the orthoid *Hesperorthis* are abundant taxa in collections from cluster C. The orthoids *Multicostella*, *Mimella*, *Glyptorthis* and



**Table 1** List of the genera collected from members (0) to (III); relative abundance in (%); total shows absolute abundance of specimens for each formation; data from Mitchell (1977) and Candela (2003)

	mbr0/1	mbr0/2	mbr1/1	mbr1/2	mbr2	mbr3/1	mbr3/2
<i>Acanthocrania</i>	0	0	0	0	0	0.5	0
<i>Anisopleurella</i>	0	0.2	0	5.6	1.1	0	9.7
<i>Anoptambonites</i>	0	0	0	0	0	0	0.4
<i>Apatomorpha</i>	0	0	0	0	0	0	0.2
<i>Bicuspina</i>	0	0	0	0	0	2.7	0
<i>Bilobia</i>	0	4.9	0	1.6	0.6	0	10.1
<i>Bimuria</i>	0	8	0	23.2	2.3	0	5.1
<i>Caeroplecia</i>	0	0	0	0	0	3.2	0
<i>Camerella</i>	0.3	0	0	0	0	0	0
<i>Campylorthis</i>	13.7	0	26.5	0	0	1.1	0
<i>Cathrynina</i>	0	0	0	0	4.3	0	0
<i>Christiania</i>	0	3.2	0	10.4	0	0	2.5
<i>Colaptomena</i>	0	7.2	0	3.2	0	0	0.6
<i>Cremnorthis</i>	0	0.9	0	0.8	0	0	0
<i>Cyclospira</i>	0	0.2	0	0	1.2	0	0
<i>Cyrtonotella</i>	1.4	0	2	0	0	0	0
<i>Dactylogonia</i>	0	1.3	0	0	0	0	3.4
<i>Dalmanella</i>	0	0	0	8	2.7	0	4.9
<i>Diambonia</i>	0	1.8	0	0.8	0.6	0	14.4
<i>Dicoelosia</i>	0	0	0	0	0.6	0	0.4
<i>Dinorthis</i>	0	0	2	0	0	7.1	0
<i>Doleroides</i>	1.1	0	0	0	0	0	0
<i>Dolerorthis</i>	0	0.3	0	0	0	0	1.5
<i>Drepanorhyncha</i>	0.5	0	0	0	0	0	0
<i>Eochonetes</i>	0	0	0	0	1.2	0	1.7
<i>Eodinobolus</i>	0	0.7	0	0	0	0	0
<i>Eoplectodonta</i>	0	2.9	0	4	0	0	3.2
<i>Eridorthis</i>	0.5	0.4	0	0	0	0	0
<i>Fascifera</i>	0.3	0	0	0	0	1.6	0
<i>Foliomena</i>	0	0	0	0	0.6	4.8	0
<i>Glyptambonites</i>	0	0	0	0	0	0	2.3
<i>Glyptomena</i>	0.5	0	0	0	0	1.6	0
<i>Glyptorthis</i>	0	16.1	14.3	0	0.6	6.4	0
<i>Gunnarella</i>	0	0	0	0	0	0	0.4
<i>Hesperorthis</i>	1.6	0	6.2	0	0	24.6	0
<i>Hisingerella</i>	0	0	0	0	1.2	0	0
<i>Idiospira</i>	1.9	0	2	0	0	2.1	0
<i>Isophragma</i>	0	7.4	0	12.8	0	0	1.9
<i>Laticrura</i>	0	0	0	0	0	0	0.8
<i>Leptaena</i>	0	0	0	0	0	0	2.3
<i>Leptellina</i>	0	0.7	0	2.4	0.6	0	2.5
Leptellinae gen. et sp. indet.	0	0	0	0	0	0	1.9
<i>Leptestiina</i>	0	0	0	0	0.6	0	3.2
<i>Lingulella</i>	0.8	0.7	0	0	0	0	0
<i>Mimella</i>	2.5	0	0	0	0	2.7	0
<i>Mjoesina</i>	0	0	0	0	0	0.5	0
<i>Multispinula</i>	0	0	0	0.8	0	0	0
<i>Nicolella</i>	0	0	0	0.8	0	0	0
<i>Oanduporella</i>	0	0	0	0.8	2.7	0	2.7
<i>Oepikina</i>	0.3	0	6.2	0	0	6.4	0
<i>Orbiculoidea</i>	0	0.4	0	0	0.6	0	0
<i>Oxoplecia</i>	0.3	0.2	0	0	0	0	0
<i>Pachyglossa</i>	0	0	0	0	0.6	0	0
<i>Palaeostrophomena</i>	0	0	0	0	1.6	1.6	0
<i>Paterula</i>	0	0	0	0	0.6	0	0
<i>Paucicrura</i>	0	0	0	0	0	0	2.5
<i>Paurorthis</i>	0	1.3	0	7.2	0	0	0.2
<i>Petrocrania</i>	0	0.4	0	0	0	0	0
<i>Pionodema</i>	7.4	0	2	0	0	1.6	0
<i>Plaesiomys</i>	0	0	0	0	0	1.6	0

Table 1 Continued

	mbr0/1	mbr0/2	mbr1/1	mbr1/2	mbr2	mbr3/1	mbr3/2
<i>Platymena</i>	0	0	0	0	0	1.6	0
<i>Plectorthis</i>	0.3	0	0	0	0	1.6	0
<i>Protozyga</i>	0.8	0	2	0	0	0.5	0
<i>Pseudolingula</i>	0	0	0	0	0	0.5	0
<i>Ptychoglyptus</i>	0	0	0	0	0	0	0.6
<i>Ptychopleurella</i>	0	0	2	0	0	2.7	0
<i>Reuschella</i>	0	0	0	0.8	0	0	0
<i>Rostricellula</i>	13.9	0	8.3	0	0.6	1.1	0
<i>Rugosowerbyella</i>	0	0	0	0.8	0.6	0	0.2
<i>Salopina</i>	0	20.1	0	11.2	0	0	1.7
<i>Scaphorthis</i>	0	0	0	0	0	0	0.2
<i>Schizotreta</i>	0	0	0	0	0.6	0	0
<i>Sericoidea</i>	0	0	0	0	68.8	0	8.9
<i>Skenidioides</i>	0	3.8	0	1.6	1.6	0	7.3
<i>Sowerbyella</i>	12.6	10.3	0	0	2.3	17.1	0
<i>Sowerbyites</i>	38.2	0	16.3	0	0	1.1	0
<i>Strophomena</i>	0.8	0	0	0	0.6	3.7	0
<i>Sulevorthis</i>	0	6.2	0	3.2	0.6	0	2.3
<i>Thaerodonta</i>	0	0	10.2	0	0	0	0
<i>Titanambonites</i>	0.3	0.2	0	0	0	0	0
<i>Triplesia</i>	0	0.2	0	0	0	0	0
Total	366	448	49	125	190	187	474

*Hesperorthis* with the strophomenoids *Strophomena* and *Oepikina* constitute minor elements in assemblages from cluster D. The dominant elements from cluster E are *Sowerbyella* and the enteletoid *Paucicrura*. These occur with minor elements such as *Eoplectodonta* and *Bilobia*. Samples grouping in cluster E clearly show a mixing of elements from Patzkowsky's (1995) cluster II and III, ranging from storm-influenced shoreface to transition zone environments. [mbr0/1] and [mbr0/2] group in the same cluster, which indicates that the depositional environment of [mbr0] was stable overall. The taxonomic composition of assemblage [mbr0] can be compared to those of the *Sowerbyella* and the *Paucicrura*-plectambonitacean biofacies (Patzkowsky 1995, tables 5 and 6) and, although not equating with either of these two, appears to be an intermediate, 'deeper', lower energy type of the *Sowerbyella* biofacies. The *Sowerbyella* biofacies is overwhelmingly dominated by *Sowerbyella*, but also possesses abundant *Multicostella* and *Glyptorthis*. The *Paucicrura*-plectambonitacean biofacies is dominated by *Paucicrura* and small plectambonitoid brachiopods such as *Sowerbyella*, *Eoplectodonta* and *Bilobia*. Although *Sowerbyella* is abundantly present in [mbr0] it does not represent the majority of the sample. [mbr0], contains small plectambonitoids such as *Eoplectodonta* and *Bilobia*, and also *Christiania*.

Assemblages [mbr1/1] and [mbr1/2] are more differentiated than [mbr0] sub-assemblages (Fig. 2). The former groups with samples having affinities with cluster D, in which *Glyptorthis* is present at a significant level. These form a small cluster that groups at low level with a cluster comprising samples of clusters C, D and E, as did [mbr0/2]. The taxonomic composition of [mbr1/1] is also similar, being dominated by *Campylorthis*, *Sowerbyites*, *Glyptorthis* and *Thaerodonta*, which account for 26%, 16%, 14% and 10% of the sub-assemblage respectively. Although *Sowerbyella* is absent from the sub-assemblage, its taxonomic identity is very similar to the *Sowerbyella* biofacies (although there are some slight regional differences). This biofacies represents environments within the transition zone. On the other hand, [mbr1/2] groups with

samples describing cluster F. It is characterised by low diversity samples, including *Eoplectodonta*, *Paucicrura*, *Christiania* and *Bilobia*. Assemblage [mbr1/2] is characterised by *Bimuria* (23%), *Isophragma* (13%), *Salopina* (11%), *Christiania* (10%), *Dalmanella* (8%), *Paurorthis* (7%), *Anisopleurella* (5%) and *Eoplectodonta* (4%). Cluster F is distinguished from cluster E, with which it forms the *Paucicrura*-plectambonitacean biofacies, by the absence of *Sowerbyella*. Cluster F is composed only of genera belonging to cluster III, which are deeper water taxa than those of cluster II which compose part of cluster E. The *Paucicrura*-plectambonitacean biofacies is typical of offshore environments, below storm influence.

Assemblage [mbr2] is dominated by the small plectambonitoid brachiopod *Sericoidea*, which represents 68% of the total assemblage. Other elements include *Cathrynina*, *Dalmanella*, *Oanduporella*, *Bimuria* and non-articulate brachiopods, which together represent less than 15% of the assemblage. This assemblage is better compared to the *Sericoidea* association of Lockley (1980) from the Bala area, even though it is more diverse than its Welsh counterpart (Candela 2001). *Sericoidea* associations are environmentally controlled. They have been recognised as characteristic of deep-water/distal clastic settings around the Caradoc-Ashgill boundary in the Anglo-Welsh area, Baltica, Gondwana and in Laurentia from the middle-late Caradoc.

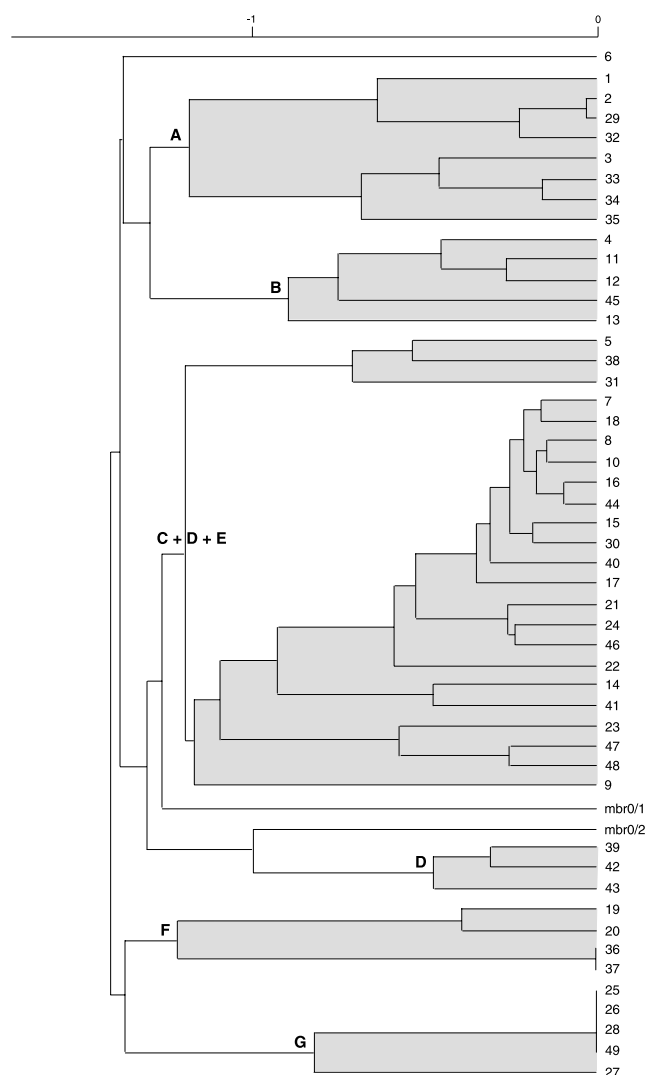
The highest Caradoc rocks in Pomeroy have yielded a rich and diverse fauna, with over 650 specimens identified as belonging to over 60 different species. Assemblage [mbr3] yielded 31 species in common with [mbr1] and although its taxonomic composition is different to that of [mbr2], 21 species have been recognised in common. The [mbr3] brachiopod assemblage is characterised by a relatively high proportion of specimens belonging to the Plectambonitoidea that represent 52% of the total number of specimens and 31% of the number of genera (Candela 2003). Notable differences in taxonomic content between [mbr1] and [mbr3] include deep-water genera such as *Diambonia*, *Bilobia*, *Anisopleurella*, *Sericoidea* and *Oanduporella* that were absent or poorly represented in [mbr1];

**Table 2** Locality list for Patzkowsky's (1995) samples used in the statistical analysis (Figs 1 to 3)

	Samples	Formation	Locality	
1	89-MW-1	Maxwell Formation	Maxwell	Virginia
2	89-TV-1	Wardell Formation	Thompson Valley	Virginia
3	89-HA-2	Hagan	Virginia	
4	89-HA-5	Hagan	Virginia	
5	89-EF-1	Benbolt Formation	Evan's Ferry	Tennessee
6	89-EF-2	Benbolt Formation	Evan's Ferry	Tennessee
7	89-EF-3	Benbolt Formation	Evan's Ferry	Tennessee
8	89-EF-4	Benbolt Formation	Evan's Ferry	Tennessee
9	89-RCBC-1	Benbolt Formation	Rye Cove Brick Church	Virginia
10	89-RCMS-1	Benbolt Formation	Rye Cove Memorial School	Virginia
11	89-BF-300	Wardell Formation	Blackford	Virginia
12	89-BF-2	Wardell Formation	Blackford	Virginia
13	88-LS-22	Benbolt Formation	Lay School	Tennessee
14	89-LS-17	Benbolt Formation	Lay School	Tennessee
15	89-LS-14	Benbolt Formation	Lay School	Tennessee
16	89-LS-11	Benbolt Formation	Lay School	Tennessee
17	89-LS-9	Benbolt Formation	Lay School	Tennessee
18	89-LS-4	Benbolt Formation	Lay School	Tennessee
19	89-CC46-2	Oranda Formation	Colley Block Road	Virginia
20	89-CC46-1	Oranda Formation	Colley Block Road	Virginia
21	89-TR-1	Lantz Mills and Liberty Hall facies	Tumbling Run	Virginia
22	89-TR-2	Lantz Mills and Liberty Hall facies	Tumbling Run	Virginia
23	89-TR-3	Lantz Mills and Liberty Hall facies	Tumbling Run	Virginia
24	89-TR-4	Lantz Mills and Liberty Hall facies	Tumbling Run	Virginia
25	89-RTL-1	Liberty Hall facies	Read Trilobite Locality	Virginia
26	89-CV-1	Liberty Hall facies	Catawba Valley	Virginia
27	89-WR-2AB	Whitesburg Formation	Warrensburg Road	Tennessee
28	90-BG-1	Whitesburg Formation	Bull's Gap	Tennessee
29	90-HK-1	Moccasin Formation	Heiskell	Tennessee
30	90-WWR-10	Lebanon Formation	Whippoorwill Road	Tennessee
31	90-WWR-2	Lebanon Formation	Whippoorwill Road	Tennessee
32	90-WWR-1	Lebanon Formation	Whippoorwill Road	Tennessee
33	90-SV64-3	Lebanon Formation	Shelbyville	Tennessee
34	90-SV64-2	Lebanon Formation	Shelbyville	Tennessee
35	90-SV64-1	Lebanon Formation	Shelbyville	Tennessee
36	89-RSHB-2	Oranda Formation	Harrisburg	Virginia
37	89-RSHB-3	Oranda Formation	Harrisburg	Virginia
38	89-TH-1	Benbolt Formation	Thorn Hill	Tennessee
39	89-TH-3	Benbolt Formation	Thorn Hill	Tennessee
40	89-TH-4	Benbolt Formation	Thorn Hill	Tennessee
41	88-TH-1	Benbolt Formation	Thorn Hill	Tennessee
42	88-TH-5	Benbolt Formation	Thorn Hill	Tennessee
43	88-TH-7	Benbolt Formation	Thorn Hill	Tennessee
44	88-EF-9	Benbolt Formation	Evan's Ferry	Tennessee
45	88-EF-15	Benbolt Formation	Evan's Ferry	Tennessee
46	89-I75-1	Lantz Mills facies	Interchange 75	Virginia
47	89-TR-6	Lantz Mills and Liberty Hall facies	Tumbling Run	Virginia
48	89-TR-5	Lantz Mills and Liberty Hall facies	Tumbling Run	Virginia
49	89-ST275-1	Liberty Hall facies	Staunton	Virginia

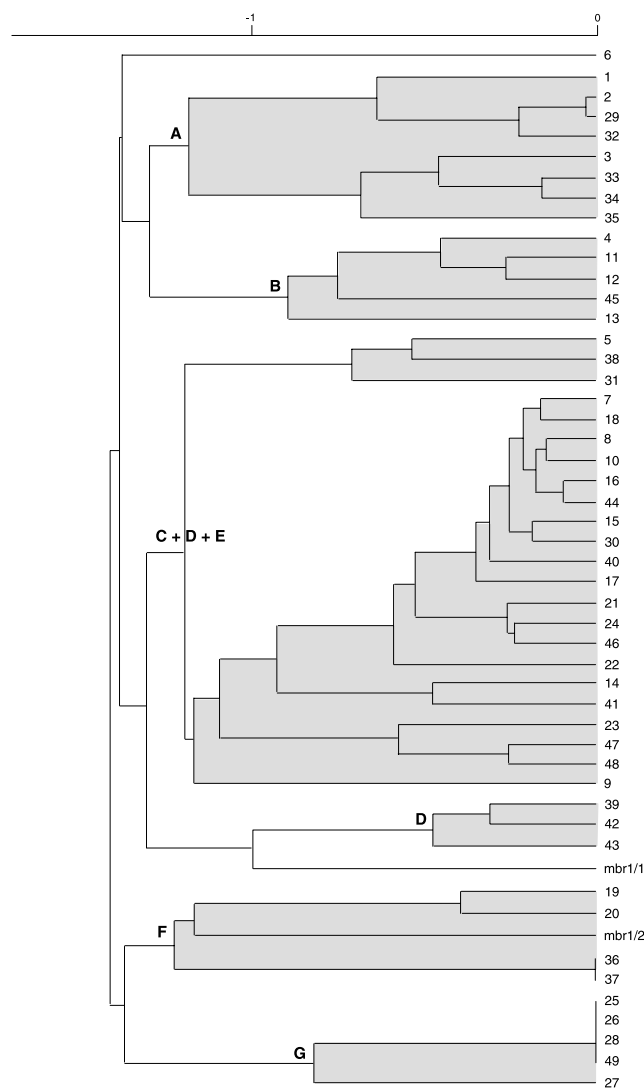
they represent 10%, 7%, 7%, 6% and 2% respectively of the total assemblage. Sub-assemblage [mbr3/1] groups, within the cluster comprising samples from Patzkowsky's (1995) clusters C, D and E, at high level with elements from cluster C (Fig. 3), which are part of the *Strophomena* biofacies. These are low-diversity samples dominated by *Strophomena*, *Hesperorthis*, *Pionomena* and *Sowerbyella*. Sub-assemblage [mbr3/1] associates with these samples because of their low diversity ([mbr3/1], being more diverse, is more likely to have common elements with these than with more diverse samples) and the relative proportion of their common elements. *Hesperorthis* and *Sow-*

*erbyella* are the dominant genera of [mbr3/1], representing 25% and 17% of the sub-assemblage respectively, whereas *Strophomena* represents less than 5% and *Pionomena* is absent. The taxonomic composition of [mbr3/1] is intermediate between the *Strophomena* and the *Sowerbyella* biofacies. These occur in the high energy shoreface to transition zone environments in eastern North America. The genus *Foliomena* is also present in the sub-assemblage, representing about 5% of the number of specimens. The specimens are the largest ever collected, with an average length of about 9 mm and an average width of about 15 mm (Candela 2003). However, the taxa associated



**Figure 1** Cluster analysis (Q-mode) of data from Patzkowsky (1995) with data from the 'Bardahessiagh Formation' *sensu* Mitchell (1977): Chord index of similarity, abundance data; samples 1 to 49 refer to Patzkowsky's (1995, table 1 and Appendix p. 179) collections; reference to these samples in Table 2.

with *Foliomena* (i.e. *Sowerbyella*, *Mimella*, *Hesperorthis* ...) imply that they cannot be assigned to the *Foliomena* Fauna. They are similar to brachiopod faunas encountered from mid-Ashgill strata in the Jiangxi–Zhejiang border areas on the Zhe-Gan Platform, where similar shallow water taxa were recovered (Rong & Zhan 1996). These may have lived in level-bottom environments of middle to upper BA3 (Zhan & Rong 1995). Sub-assemblage [mbr3/2] clusters with samples from Patzkowsky's (1995) cluster F, which represents the *Paucicrura*-plectambonitacean biofacies and is characterised by assemblages containing taxa such as *Bilobia*, *Christiania* and *Eoplectodonta*. Sub-assemblage [mbr3/2] is composed of *Diambonia*, *Bilobia*, *Anisopleurella*, *Sericoides* and *Skenidioides* which represent 10%, 7%, 7%, 6% and 5% of the total number of specimens respectively. Although sub-assemblage [mbr1/2] also groups with samples from cluster F (Fig. 1), sub-assemblage [mbr3/2] possesses a different taxonomic composition, which unfortunately does not appear in the cluster analysis. [mbr3/2] possesses deeper water genera that are either absent or very rare in [mbr1/2]; notably the small plectambonitoid *Sericoides* is absent from [mbr1/2] and other plectambonitoids such as *Diambonia*, *Bilobia*, *Eoplectodonta* and the small enteletoid *Oanduporella* are abundant at a more signifi-

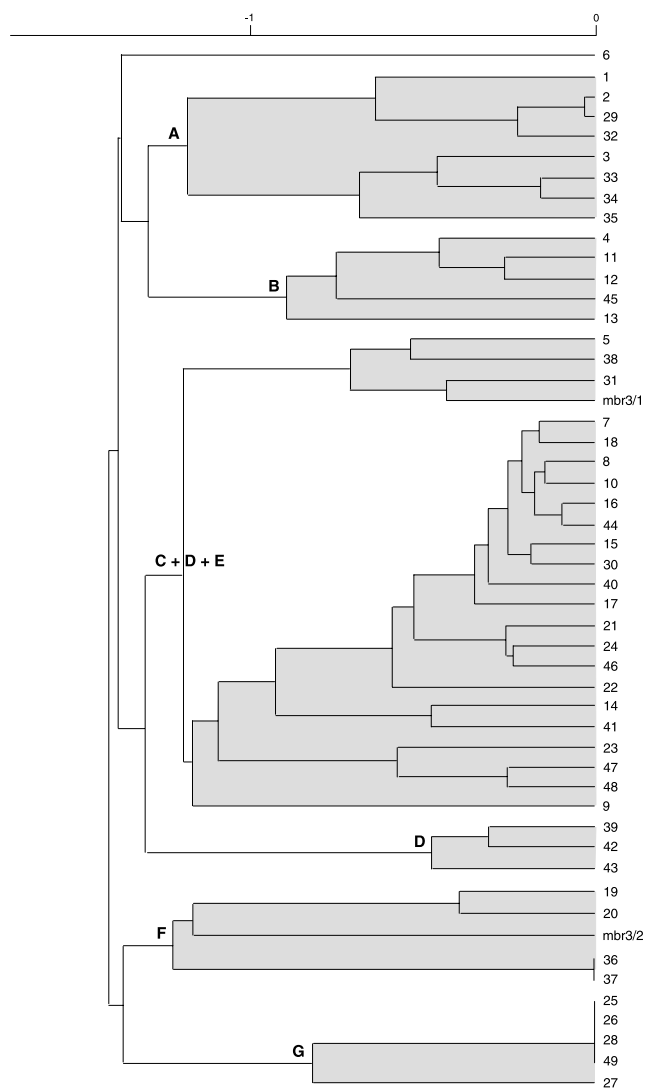


**Figure 2** Cluster analysis (Q-mode) of data from Patzkowsky (1995) with data from member (I) of the Bardahessiagh Formation (Candela 2003): Chord index of similarity, abundance data; samples 1 to 49 refer to Patzkowsky's (1995, table 1 and Appendix p. 179) collections; reference to these samples in Table 2.

cant level in [mbr3/2]. Assemblage [mbr3/2] may have occupied a more offshore position than [mbr1/2].

## 2. Ashgill Faunas

The Killy Bridge Formation consists mainly of chloritic and micaceous flaggy mudstones and siltstones with thin calcareous bands. A lens of coarse sandstone (3 m thick) is interbedded in this sequence (Mitchell's (1977) locality 4b) and the thrust-faulted section in the Tirnaskea River reveals a quartzitic sandstone (Mitchell 1977). Potter & Boucot (1992) have investigated brachiopod communities of North America for the middle and late Ordovician. Communities were grouped along a shoreline to deep-water transect according to five depth-related benthic assemblages (BAs). Late Ordovician brachiopod faunas were extracted from Potter & Boucot's (1992) locality list (Table 3). This data was compared with the data obtained from the diverse, coeval Killy Bridge Formation in Pomeroy. Cluster analysis using the Dice coefficient on presence-absence data was chosen to discriminate any palaeoenvironmental gradient (Fig. 4). The dendrogram shows two broad groups: the first group includes assemblages typical of BAs 2 to 3, whereas the second group include BAs 4 to 4–5



**Figure 3** Cluster analysis (Q-mode) of data from Patzkowsky (1995) with data from member (III) of the Bardahessiagh Formation (Candela 2003): Chord index of similarity, abundance data; samples 1 to 49 refer to Patzkowsky's (1995, table 1 and Appendix p. 179) collections; reference to these samples in Table 2.

faunas. The Pomeroy assemblage has been separated into two on the basis of the difference in lithology: assemblages from localities 1 to 4a were grouped together as they were collected from the mudstone and siltstone horizons, whereas the collection from locality 4b, which represents the coarser sandstone lens, has been separated. Nevertheless, these two assemblages group closely together and then cluster with three North American assemblages typical of BAs ranging from 3–4 to 4–5. The closeness of the Pomeroy assemblage to a cluster including a mixture of environmental provenance indicates that they have, more than likely, a mixed origin. The assemblage possesses genera typical of BAs 2 to 3 (for example *Hypsitycha*, *Leptaena*, *Plaesiomys* and *Skenidioides*) but also of deeper BA 4 to 4–5 (for example *Bimuria*, *Chonetoidea*, *Christiania*, *Sampo* and *Tyronella*). Assemblages with BAs 4 and 4–5 do not form a tight cluster. The Pomeroy assemblages group closely with North American assemblages from the Percé area (Québec) and Newfoundland, whereas the other cluster is composed of assemblages collected from western North America (Alaska, Yukon, California). Deeper water, moderate to high diversity assemblages appear to be confined to extracratonic areas (Potter & Boucot 1992).

The Tirnaskea Formation consists of calcareous siltstones lacking obvious sedimentary structures, hence deposited below

the storm wave base (Harper *et al.* 1994). The formation has not yielded abundant fossil data. Portlock (1843) thoroughly investigated the Ordovician rocks around the Pomeroy area but did not find any fossils (“... on the Tirnaskea or small river there are thin calcareous layers of three or four inches thick mixed with quartzose bands, no fossils, however, occurring in them ...”). Mitchell (1977) collected a single species, *Eostropheodonta* aff. *siluriana* (Davidson), from the Tirnaskea Formation (see Faunal list in Mitchell 1977, p. 7–10). Harper *et al.* (1994) undertook field work in the same area. They collected sparse brachiopod faunas from new exposures of the middle and upper parts of the Tirnaskea Formation. These comprised species of *Dedzetina*, *Sericoidea*, *Proboscisambon* and *Protozyga?* from the middle part of the Tirnaskea Formation, whereas the upper part yielded species of *Eostropheodonta* and *Dysprosorthis*.

The Tirnaskea Formation also yielded *Mucronaspis mucronata olini* and a cyclopygid (Owen 1986) and an undetermined deep-water bivalve form of nuculoid (Tunnichliff 1982). *Mucronaspis* was collected from the upper part of the formation. It is the most common genus within Hirnantian trilobite faunas, known from over 30 sites worldwide (Owen *et al.* 1991), and this eurytopic taxon has been recorded from deep-water (BA 6) environments at Percé, Canada (Lespérance *et al.* 1987) to shallow water environments in the Oslo Region (Brenchley & Cullen 1984). The stratigraphic positions of the cyclopygid trilobite and the nuculoid bivalve are not known. The former may either be associated with the deep-water *Proboscisambon* assemblage or represent a rare deep-water Hirnantian trilobite biofacies in the upper part of the formation.

Harper *et al.* (1994) discussed the palaeoecology of the brachiopod assemblage from the middle part of the Tirnaskea Formation. The taxonomy indicates strong affinities with the *Proboscisambon* fauna, which is closely related to the *Foliomena* fauna. This genus is only known from the upper Rawtheyan of the Prague area in Czechoslovakia. It colonised depths between the deeper parts of BA 5 and shallower part of BA 6 (Havlíček & Vanek 1990).

The brachiopod assemblage collected in the upper part of the Tirnaskea Formation is indicative of a variant of the *Hirnantia* fauna. It is characterised by the absence of the eponymous genus and the presence of key form *Eostropheodonta*. This assemblage shows affinities in composition with the brachiopod fauna of the High Mains Formation in Girvan, Scotland, described and discussed by Harper (1981, 1988, 2001). Two associations of the *Hirnantia* fauna developed through a regressive sequence occur within the formation (Harper 2001). The assemblage from the Tirnaskea Formation is more similar to the lower assemblage: it is low-diversity (four taxa) and high dominant (two genera, *Eostropheodonta* and *Hindella*, representing over 80% of the total). The brachiopod and trilobite data suggest a shallow shelf environment (Owen 1986) in the deposition of the High Mains Formation representing a local regression (Harper 1981). *Eostropheodonta* (and its synonym *Aphanomena*) is a common Rawtheyan–Wenlock cosmopolitan genus and key member of the latest Ashgill *Hirnantia* fauna. The *Hirnantia* fauna is characterised by many of such widespread forms which also include *Hirnantia*, *Dalmanella*, *Cliftonia*, *Paromalomena* and *Hindella* (Rong & Harper 1988). *Eostropheodonta* and *Dysprosorthis* are geographically distributed between mid to high latitudes. The former is characteristic of upper BA 3 (Rong & Harper 1988), whereas the latter is common in lower BA 3 occurring in *Hirnantia* faunas in NW England, Ireland, Morocco, Hubei and Tibet. *Dysprosorthis* is a new opportunistic form in the Hirnantian and, like other genera, it flourished in this crisis

**Table 3** Locality list for Potter & Boucot's (1992) samples used in the statistical analysis (Fig. 4)

	Formation	Locality	
46	Horseshoe Gulch unit	Yreka terrane	California
47	Montgomery Limestone	Northern Sierra terrane	California
48	Unit uOll	Nixon Fort terrane	Alaska
49	Jones Ridge Limestone	Yukon Territory	Canada
50	Mount Kindle Formation	Northwest Territories	Canada
51	Hanson Creek Formation	central Nevada	Nevada
52	Saturday Mountain Formation	southern Lemhi Range	Idaho
53	Upper Bighorn Formation	Wyoming	
54	Stony Mountain Formation	Manitoba	Canada
55	Red River Formation	Manitoba	Canada
56	Maquoketa Group	Iowa	
57	community transect of cycle 1	Kentucky, Indiana and Ohio	
58	community transect of cycle 1	Kentucky, Indiana and Ohio	
59	community transect of cycle 1	Kentucky, Indiana and Ohio	
60	community transect of cycle 2	Kentucky, Indiana and Ohio	
61	community transect of cycle 2	Kentucky, Indiana and Ohio	
62	community transect of cycle 2	Kentucky, Indiana and Ohio	
63	upper Reedsville Formation	Tennessee and Virginia	
64	upper Reedsville Formation	Virginia and Pennsylvania	
65	upper Reedsville Formation	Virginia and Pennsylvania	
66	Vaureal Formation	Anticosti Island	Québec
67	Pabos Formation	Percé Area, Gaspé Peninsula	Québec
68	Pabos Formation	Percé Area, Gaspé Peninsula	Québec
69	Pyle Mountain Argillite	Aroostook County	Maine
70	Samson Formation	New World Island, Newfoundland	Canada

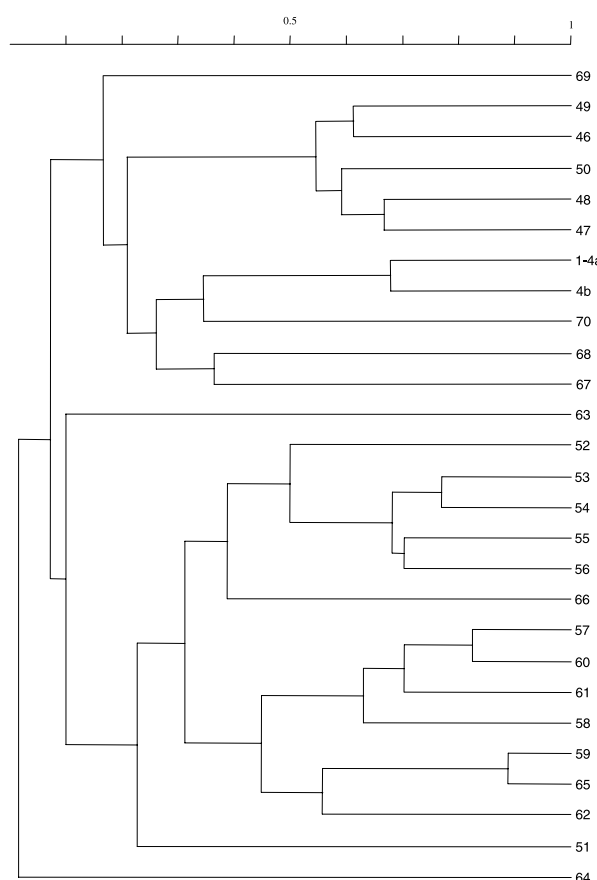
interval into the ecological vacuum left by the mid-Ashgill fauna (Rong & Harper 1999; Harper 2001).

### 3. Conclusions

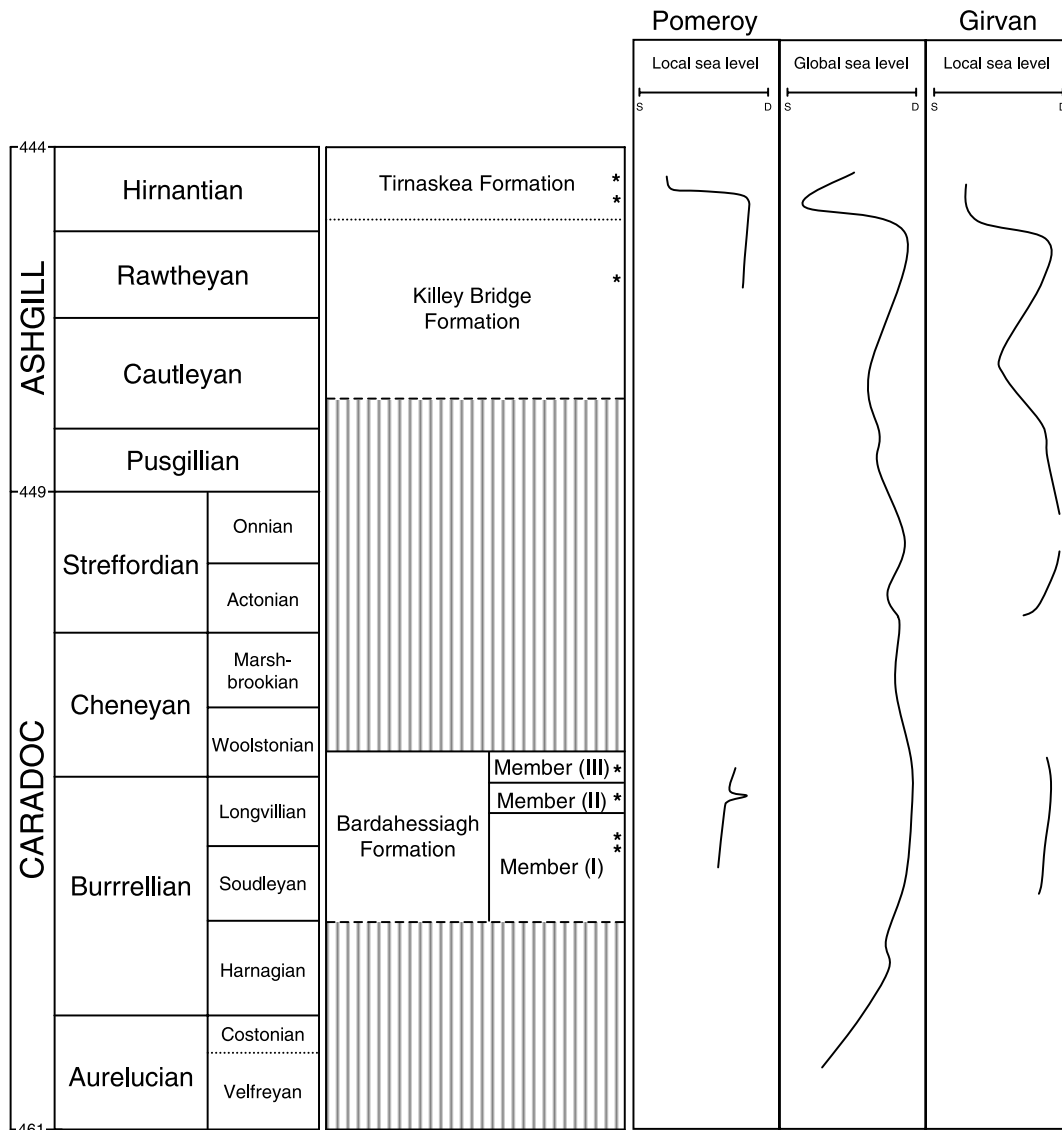
The Caradoc assemblages from the Bardahessiagh Formation yielded a mixture of relatively shallow water (BA 3) and deep-water brachiopod assemblages with typical BAs equal to or in excess of BA 4–5. Comparisons with eastern North American brachiopod biofacies indicate that the deep-water assemblages lived below the storm wave base, in deep ramp to slope environments. [mbr2] is faunally very different from the older [mbr0] and [mbr1] and the younger [mbr3], yielding a typical *Sericoidea* association indicative of at least BA 5. Except for this peak in water depth, the curve indicates a transgressive regime which conforms to deep-water facies in Girvan.

The Ashgill assemblages from the Killey Bridge and Tirnaskea formations yielded varied brachiopod faunas. The former fingerprints deep-water brachiopod assemblages (BA 4–5). A transgressive trend is continued through the overlying Tirnaskea Formation with the presence of a *Proboscisambon* fauna, which indicates BAs ranging between 5 and 6. The upper part of the Tirnaskea Formation has yielded a local variant of the shallower *Hirnantia* fauna indicative of BA 3 type of environment.

The sea-level curves for Girvan and global were redrawn from Harper (2001), with addition for the Caradoc made by the present author and Ross & Ross (1995) respectively, and are tentative. The Caradoc curve from Pomeroy (Fig. 5) is roughly similar to the global eustatic gradient, showing a broad deepening towards the end of the Burrellian. However, the global curve does not record the sharp and sudden deepening occurring during the deposition of member (II) of the Bardahessiagh Formation, which may account for local



**Figure 4** Cluster analysis (Q-mode) of data from Potter & Boucot (1992) with data from the Killey Bridge Formation (Mitchell 1977); Dice index of similarity, presence-absence data. Samples 1–4a and 4b refer to locality numbers used by Mitchell (1977); samples 46 to 70 refer to Potter & Boucot (1992, table 3 and pp. 315–316) collections; reference to these samples in Table 3.



**Figure 5** Stratigraphy of the Ordovician rocks in Pomeroy; sea-level curved for the Pomeroy and Girvan areas and the Laurentian platform as a reference for global eustatic sea-level change; data from Ross & Ross (1995), Harper (2001); asterisks represent fossil horizons.

tectonic history. The Ashgill curve from Pomeroy broadly conforms to the global eustatic trend, indicating that tectonic movements were less important than eustatic processes.

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