

Recycled acritarchs as provenance indicators:  
Implications for Caledonian terrane reconstruction

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Abstract

Silurian successions deposited on the margins of the Iapetus Ocean in the English Lake District, Southern Uplands of Scotland and Ireland contain recycled Ordovician acritarchs. These include taxa known only from Avalonia and Gondwana, with other recycled acritarchs possibly derived from Baltica. There is no palynological evidence to indicate that Laurentia constituted a source area. The data presented herein suggest that provinciality in derived microfossils may be profitably exploited in provenance studies.

1. Introduction

The precise nature and timing of the closure of the Iapetus Ocean and the history of the terranes that bounded it have been areas of intense research and debate ever since the concept of the Iapetus Ocean was first mooted (Wilson, 1966). The British section of Iapetus was finally destroyed in the late Lower Devonian Acadian Orogeny, as Eastern Avalonia (southern Britain, and adjacent continental Europe to the east) was sutured onto the southern Laurentian margin (McKerrow, 1988). The relative importance of the circum-Iapetus terranes (Fig. 1) as sediment sources during this late history has always remained

uncertain as they are difficult to distinguish using most provenance techniques (e.g. neodymium isotope studies, Thorogood, 1990). Such knowledge is invaluable, however, if evolving terrane configurations are to be modelled with any degree of confidence.

Organic walled microfossils are common in Lower Palaeozoic rocks. They are robust, easily transported, and are frequently recycled. The study of provinciality in recycled microfossils offers a new way of characterizing sediment sources. We present the results of a pilot study to ascertain the usefulness of recycled acritarchs in Silurian rocks of the Windermere Group of the English Lake District, and assess the significance of other known occurrences of recycled acritarchs around the Iapetus suture.

## 2. Recycled acritarchs as provenance indicators

The application of recycled acritarchs to provenance studies has certain prerequisites. Their original distributions must show an adequately constrained provinciality, and their preservation must permit confident identification. Furthermore, it is necessary to show that the recycled acritarchs were transported with their host sediments. Alternative possibilities include ocean current and/or aeolian transportation prior to incorporation into hemipelagic sediments. In the latter case we envisage exposures of unconsolidated marine sediments enclosing acritarchs being eroded by the wind. In turbidite sequences care should be taken to avoid sampling hemipelagite interbeds.

The recycled acritarchs recorded in this study are Ordovician. Although no provinces are defined, it is possible to pick out differences at a generic level between the contemporary terranes of Avalonia/Gondwana, Baltica and Laurentia. Early Ordovician (Tremadoc) assemblages from Avalonia and Gondwana are dominated by diacromorph acritarchs, principally species of *Acanthodiacrodium*, and forms with large polar openings closed by an operculum, such as *Caldariola*, *Cymatiogalea* and *Stelliferidium* (for example Elacquad-Debbaj 1988; Martin 1972;

Molyneux and Rushton 1985; Rasul 1979). Early Ordovician data from Laurentia are limited to the Tremadoc assemblages from the Wilcox Pass, Alberta (Dean and Martin 1982; Martin 1984). These are less diverse, and lack the species of *Cymatiogalea* and *Stelliferidium* characteristic of Avalonian/Gondwanan microfloras. Their absence, and the low assemblage diversity may be related to the shallow conditions of deposition postulated for the Wilcox Pass sequence (Dean and Martin 1982) or to provincialism. This needs to be tested by further examination of Laurentian assemblages of Tremadoc age. There are, however, positive differences, namely the presence in Wilcox Pass assemblages of *Aryballomorpha*, *Athabascaella* and *Corollasphaeridium*. Tremadoc assemblages from Baltica closely resemble Avalonian/Gondwanan assemblages in composition (Welsch 1986), with the addition of *Aryballomorpha* and *Abathascaella* in assemblages from Öland, Sweden (Bagnoli *et al.*, 1988).

More data are available for comparison from the middle Ordovician (Llanvirn-Caradoc). Avalonian/Gondwanan assemblages contain a variety of polygonomorph acritarch genera, such as *Arkonina*, *Frankea*, *Marrocanium* and *Striatotheca*; heteropolar diacromorph acritarchs, for example *Arbusculidium*, *Dicrodiacrodium* and *Stephanodiacrodium*; *Stelliferidium*, which persists from early Ordovician into Llandeilo and possibly Caradoc strata; and *Coryphidium* which occurs in Arenig strata and may persist into the Caradoc (Vavrdová 1974, 1977; Deunff and Massa 1975; Colbath 1990; Molyneux 1990; Downie 1984 and Turner 1982). None of these genera occur in coeval assemblages from Laurentia or Baltica. Laurentian assemblages from the Bromide Formation of Oklahoma (Loeblich and Tappan 1978 and references therein), the Kope Formation of Indiana (Colbath 1979) and the Clays Ferry Formation of Kentucky (Jacobson 1978), all of Llandeilo or Caradoc age, contain a number of apparently indigenous genera, including *Anomaloplaisium*, *Cleithronetrum*, *Comptaluta*, *Dicommopalla*, *Petaloferidium* and *Rhiptosococheerma*. Legault (1982) has indicated that similar assemblages occur in the Labrador Sea and on Baffin Island. None of the

Avalonian/Gondwanan or Laurentian genera are known from Baltica, where middle Ordovician (Viruan) assemblages from Sweden (Kjellström 1976 and references therein, Górka 1987) are dominated by more cosmopolitan genera including *Baltisphaeridium*, *Goniosphaeridium*, *Multiplicisphaeridium*, *Orthosphaeridium* and *Peteinosphaeridium*.

### 3. Recycled acritarchs in the Windermere Group

The Windermere Group of northwest England (Fig. 2) is a late Ordovician to late Silurian marine succession deposited on the leading edge of eastern Avalonia in a peripheral foreland basin, *sensu* Ingersoll 1988 (Kneller 1991). Five samples from the upper Wenlock Birk Riggs Formation and thirteen from the lower Ludlow Coniston Subgroup (formerly known as Lower Coldwell Beds and Coniston Grits, respectively) were collected for palynological analysis. These coarse clastic formations record the earliest major ingress of turbidity currents into the main Windermere Group basin.

Samples are registered in the series MPA 30344 - 30362, and together with the palynological residues and slides are held in the collections of the Biostratigraphy and Sedimentology Group of the British Geological Survey, Keyworth, Nottingham.

Recycled Ordovician acritarchs were recorded from the Coniston Subgroup in sections from the A6 road near Shap summit (MPA 30352, MPA 30353, Table 1 columns 1 and 2), from Dillicar Quarry, (MPA 30354, MPA 30355, Table 1 columns 3 and 4) and from Allen Knott Quarry (MPA 30357, Table 1 column 5). Spaced samples through individual turbidite beds were taken at Dillicar and Allen Knott Quarries. In both cases recycled taxa were recorded from the base of the beds (samples MPA 30354, MPA 30357) suggesting recycling within the coarsest fraction. At Dillicar Quarry one sample yielding recycled acritarchs was collected from the middle of the bed (MPA 30355). Hemipelagite interbeds were sampled at both localities, but no recycled taxa were recorded.

Preservation of both *in situ* Silurian material and recycled Ordovician acritarchs is poor, but firm identifications are possible at least to generic level. The presence of *Stelliferidium* seems certain from careful examination of the six specimens recorded. Records of *Stelliferidium* are from Avalonia and Gondwana, where the genus ranges from Tremadoc to Llandeilo and possibly into Caradoc strata, and from the early Ordovician of Baltica (Bagnoli *et al.*, 1988; Welsch 1986). There are no records from Laurentia. The other taxa recorded are either cosmopolitan (*Acanthodiacrodium*, *Orthosphaeridium*?) or have insufficiently documented biogeographical distributions (e.g. *Uncinisphaera*? sp. *sensu* Booth 1979) to help in determining possible source areas.

#### 4. Recycled acritarchs in the Silurian rocks of Ireland and the Southern Uplands

Recycled acritarchs have been reported from the Silurian rocks of the Slievenamon and Slieve Aughty inliers of Ireland (Colthurst and Smith 1977; Emo and Smith 1978) and from localities in the Southern Uplands of Scotland (White *et al.*, in press; this paper). The samples in which they occur were collected for biostratigraphy, and a different sampling strategy to that adopted for the Windermere Group was employed, involving the preferential collection of fine grained clastic sedimentary rocks. This strategy allows the possibility of acritarch transportation by ocean currents or by wind, particularly in the case of acritarchs extracted from mudstones.

##### 4.a. Southern Ireland

The Slievenamon Inlier (Fig. 2) lies south of the Navan-Silvermines Fault, the trace of the Iapetus Suture in Ireland (McKerrow and Soper 1989), and is therefore assumed to be sited on Avalonian crust. Recycled Ordovician acritarchs occur in the late Llandovery Ahenny Formation and the late Llandovery to early Wenlock Rathclarish Formation (Smith, 1980; 1981, Colthurst and Smith,

1977). Samples from the Ahenny Formation, comprising grey and blue-black slates, have yielded specimens of *Stelliferidium* (recorded as *Priscogalea* cf. *striatula* by Colthurst and Smith, 1977), *Striatotheca*, *Coryphidium*? and other recycled taxa including a specimen compared with the upper Cambrian species *Trunculumarium revinium* (Table 2, column B). The Rathclanish Formation comprises "grey turbidites", though the sample prepared by Colthurst and Smith (1977, prep. no. 52) is described as a grey silty slate. This sample has also yielded recycled Ordovician acritarchs (Colthurst and Smith, 1977, table 2; this paper Table 2, column B), including species of *Striatotheca*, *Coryphidium* and *Stelliferidium*.

The possible significance of *Stelliferidium* is discussed above. Equally important in this case are the records of *Striatotheca*, *Coryphidium* and *Trunculumarium* cf. *revinium*. None of these taxa is known from Laurentia, and *Striatotheca* and *Coryphidium* are, in the context of circum-Iapetus terranes, known only from Avalonia and Gondwana (Table 2). The other recycled taxa are cosmopolitan.

#### 4.b, Central Ireland

The Slieve Aughty Inlier (Fig. 2) lies immediately to the north of the Navan-Silvermines Fault, and so is probably sited on Laurentian crust. Recycled Tremadoc-Arenig acritarchs have been reported from the upper Llandovery to lower Wenlock Killanena Formation (Emo and Smith, 1978). This formation consists of both 'proximal and distal turbidites' (Emo and Smith, 1978), although the sample yielding recycled Ordovician taxa is described as a black slate. Ordovician taxa include species of *Striatotheca*, *Coryphidium* and *Stelliferidium*. Their distributions exclude Laurentia and, in the case of *Striatotheca* and *Coryphidium*, Baltica. Other taxa, such as *Acanthodiacrodium convexum*, *A. ignoratum* and *A. cf. ubui* have distributions that encompass Gondwana, Avalonia and, in some cases, Baltica but not Laurentia (Table 2). Many of these taxa

have not been illustrated, however, and the preservation of those that are figured is poor. The identification of *Stelliferidium* is probably correct, judging from those species figured by Emo and Smith (1978, plate 1, fig. 1), but identification of the other taxa requires verification.

#### 4.c. The Southern Uplands of Scotland

Recycled Ordovician acritarchs, including *Acanthodiacrodium* sp., *Baltisphaeridium* sp., *Cymatiogalea cristata*, *Peteinosphaeridium trifurcatum* and *Stelliferidium* spp., have been recovered from turbiditic facies in the southwest Southern Uplands (White et al., in press, Fig. 4, Locs. 99, 101, 113, 119, 120 and 136). Samples collected in this area comprise turbidite mudstones from the late Llandovery Gala Group, turbidite sandstones and siltstones from the late Llandovery to early Wenlock Carghidown Formation (Hawick Group), turbidite sandstones from the early Wenlock Ross Formation (Hawick Group) and turbidite siltstones from the mid to late Wenlock Raeberry Castle Formation (Riccanton Group). To the northeast, in the Galashiels area, turbidite mudstones and siltstones of the late Llandovery Gala Group have also yielded recycled Ordovician acritarchs (MPA 27541, MPA 27538 and MPA 27539, Table 1 columns 6, 7 and 8; these samples and the slides derived from them are held in the palynological collection of the Biostratigraphy and Sedimentology Group, British Geological Survey, Keyworth).

Some of the recycled taxa, for example *Acanthodiacrodium*, *Baltisphaeridium*, *Goniosphaeridium*, *Peteinosphaeridium* sp. and possibly *Stellechinatum* are cosmopolitan (Table 2). Others, including *Stelliferidium* and *Peteinosphaeridium trifurcatum* (Hawick and Gala Groups), have distributions which, in the context of circum Iapetus terranes, are restricted to Avalonia/Gondwana and Baltica.

## 5. Conclusions

### 5.a. Summary of acritarch evidence

Late Llandovery to early Wenlock sediments deposited south of the Iapetus suture in the Slievenamon Inlier contain recycled acritarchs which permit derivation from Avalonia/Gondwana, possibly supplemented by a Baltican source. Precisely the same constraints apply to coeval sediments deposited north of the suture in Ireland in the Slieve Aughty inlier. Late Llandovery to late Wenlock sediments deposited north of the suture in the Southern Uplands contain recycled acritarchs which could have been sourced in either of Avalonia/Gondwana or Baltica, as do early Ludlow sediments deposited south of the suture in northwest England. There is no evidence for reworking of diagnostic Laurentian taxa into any of the sequences considered in this paper.

### 5.b. Interpretation of acritarch evidence

Hutton and Murphy (1987) argue that during the Llandovery in Ireland, microconglomerates transported towards the Iapetus Suture from both north and south failed to cross it in either case, but that during the Wenlock, coarse, siliclastic marine turbidites overstepped the suture from north to south. The acritarch evidence from the Ahenny and Rathclarish formations supports the inference that some sediments in the Silurian inliers located south of the suture were derived from the south in the Llandovery. Gondwana was probably too remote to have constituted a significant source. Alternatives include Pretannia, a landmass which Cope and Bassett (1988) infer to have been emergent in the region of the Bristol Channel, and the uplifting impact zone between Eastern Avalonia and Laurentia, inferred to be located to the west of the Irish inliers (Soper and Woodcock 1990), where uplift and erosion of Avalonian rocks may have supplied Avalonian microfossils. Similarly, the recycled acritarchs reported in the upper Llandovery to early Wenlock immediately north of the suture (Killanena Formation) suggest an Avalonian source. Although their



deposition just predates the effective demise of Iapetus as a barrier to sediment dispersal (Hutton and Murphy 1987), the possibility that these sediments were derived from the Avalonian terrane to the south cannot be ruled out. Soper and Woodcock (1990, fig. 4b), however, infer regional sediment dispersal eastwards from the uplifting impact zone between Eastern Avalonia and Laurentia into the inliers north of the suture. This could account for the presence of recycled Avalonian acritarchs north of the suture.

If the preponderance of southwestward directed palaeoflow indicators in upper Llandovery to Wenlock sediments of the Southern Uplands (Kelling *et al.* 1987) provides a reliable indication of principal sediment dispersal directions (Soper and Woodcock 1990; *c.f.* Kneller and McCaffrey 1992), the uplifting Avalonian/Laurentian impact zone is unlikely to be their source. On the other hand, Baltican underthrusting of the eastern Laurentian margin, and the subsequent generation of Baltoscandian nappes (Harland and Gayer 1972; Stephens and Gee 1985; Dallmeyer 1988) would have created a contemporary source of predominantly Baltican material to the northeast.

Soper and Woodcock (1990) raise the problem of whether the easterly derived palaeoflow in northern England in the late Wenlock and Ludlow was delivering sediment from the Scandian Orogen, or sediment diverted axially from the Southern Uplands. They suggest that Scotland (Laurentia) must have been the source of the large volume of northwest-derived flows. It is worth reiterating that there is no evidence for reworking of diagnostic Laurentian taxa into the Windermere Group. Had the large volume of apparently southeastward dispersing Ludlow sediment been derived from Scotland, it would require that the sequences which sourced them, and also any from which they may have picked up material *en route* (e.g. the Ordovician of the Southern Uplands) were devoid of diagnostic Laurentian microflora. The acritarch evidence suggests either an Avalonian or a Baltican source, but cannot be used to distinguish between them.

## 6. Summary

This paper highlights some of the strengths and weaknesses of using recycled acritarchs and other microfossils as provenance indicators. Their strength lies in their potential to indicate source areas accurately - although this requires that their biogeographical distributions are fully documented, which in turn requires further work on acritarch provincialism. In some cases, however, it may not be possible to discriminate between sources, to eliminate the possibility of more than one episode of reworking or to elucidate the transport mechanism. Although the study of derived microfloras constitutes a useful way of determining provenance, it should be used in conjunction with other provenance techniques when attempting to resolve ancient terrane configurations.

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Figure 1, Probable early Wenlock configuration of Eastern Avalonia, Baltica and Laurentia. Adapted from Scotese and McKerrow (1990) and Soper and Woodcock (1990).

Figure 2, Location of the Silurian of the Windermere Group, the Slievenamon and Slieve Aughty inliers, and the Southern Uplands terrane with respect to the Iapetus Suture (dashed line - from McKerrow and Soper, 1989). G = Galashiels area. In Ireland the Iapetus suture is taken to lie along the Navan-Silvermines Fault

Table 1, Windermere Group stratigraphic nomenclature (after Kneller *et al.*, 1992).

Table 2, Recycled Ordovician acritarchs in the Silurian of Northern England and the Southern Uplands (new data), 1, Sample number MPA 30352 [National Grid Reference NY 5553 0543] 2, MPA 30353 [NY 5553 0543] 3, MPA 30354 [SD 6149 9880] 4, MPA 30355 [SD 6149 9880] 5, MPA 30357 [NY 4151 0130] 6, MPA 27541 [NT 3370 3800] 7, MPA 27538 [NT 5338 5396] 8, MPA 27539 [NT 402 409],

Table 3. Ordovician taxa recycled into the Silurian of A,the Windermere Group, B,Southern Ireland, C,Central Ireland and D,the Southern Uplands, and occurrences in Ordovician successions; 1,Dean and Martin, 1978, 2,Martin and Dean, 1981, 3,Molyneux and Rushton, 1985, 4, Molyneux and Rushton, 1988, 5,Rushton and Molyneux, 1989, 6,Cooper and Molyneux, 1990, 7,Molyneux, 1987, 8,Molyneux and Dornig, 1989, 9,Rasul, 1979, 10,Martin, 1972, 11,Martin, 1975, 12, Wolf, 1980, 13,Mette, 1989, 14,Albani, 1989, 15,Elaouad-Debbaj, 1988, 16,Martin and Rickards, 1979, 17,Turner,1984, 18,Turner, 1985, 19,Welsch, 1986, 20,Bagnoli, Stouge and Tongiorgi, 1988, 21,Kjellström, 1976, 22,Tynni, 1975, 23,Dean and Martin, 1982 and Martin 1984, 24,Martin, 1983, 25, Jacobson, 1978, 26,Jacobson and Achab, 1985, 27,BGS unpublished data, Corsewall and Fortpatrick formations, Rhins of Galloway, Southern Uplands.