The palynology of the Pabay Shale Formation (Lower Jurassic) of southwest Raasay, northern Scotland

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Synopsis

A thermally mature palynomorph assemblage containing significant proportions of the characteristic dinoflagellate cyst *Liasidium variabile* Drugg 1978 was recovered from the Lower Jurassic Pabay Shale Formation of southwest Raasay. This is the first record of this biostratigraphically important species from the Jurassic of onshore Scotland. *Liasidium variabile* is a zonal index for the Late Sinemurian in northwest Europe, and this occurrence allows a correlation to the Oxynotum Zone of this substage. This is the first evidence for this chronozone on Raasay. Furthermore, the presence of morphotypes A and B of *Liasidium variabile* indicates a probable correlation to the Oxynotum Subzone of the Oxynotum Zone. This interpretation is not consistent with a hiatus within the Upper Sinemurian succession on Raasay.

Introduction

The Jurassic outcrops of western Scotland are the most northwesterly in Britain, and are exposed from the Shiant Isles in the north to Mull in the south (Riding *et al.* 1991; Morton and Hudson 1995). They occur in westerly-tilted fault blocks in a major half-graben structure that is one of a system of basins on the margins of the North Atlantic formed during early extensional phases of the Atlantic Ocean (Morton 1992). Southwest Raasay is situated on a small block, approximately 10 km wide, which is bound to the west by the Screapadal Fault, and to the east by the Applecross Fault (Mellere and Steele 1996). The Jurassic strata have been intruded by Palaeogene basalts and granites.

The Lower and Middle Jurassic strata of southwest Raasay have been preserved largely due to an overlying sheet of intrusive granophyre, which has caused limited thermal alteration to this succession. The strata are Hettangian to Late Bajocian in age and the succession is approximately 600 m thick (Cope, Duff *et al*. 1980; Cope, Getty *et al*. 1980; Cox and Sumbler 2002; Simms *et al*. 2004). It comprises six formations which are, in ascending stratigraphical order, the Breakish Formation, the Ardnish Formation, the Pabay Shale Formation, the Scalpay Sandstone Formation, the Portree Shale Formation, the Raasay Ironstone Formation and the Bearreraig Sandstone Formation (Lee 1920; Howarth 1956; Morton 1965; 1976; Getty 1973; Page 1992; Morton and Hudson 1995; Hesselbo *et al*. 1998; Morton 1999a, b; Cox and Sumbler 2002; Fig. 1). This study is on the palynology and the stratigraphical implications of two samples from the lower part of the Pabay Shale Formation in Suisinish, southwest Raasay (Fig. 2). In this paper, the zones and subzones are treated as chronostratigraphical subdivisions of stages. They are given the name of the respective ammonite species and written with an initial capital and in Roman font (Cox and Sumbler, 2002, p. 6).

Previous Research

The Pabay Shale Formation crops out in various locations in the Inner Hebrides, notably along the east coasts of Skye and Raasay (Morton and Hudson 1995; Hesselbo *et al*. 1998, fig. 3). Most of the previous biostratigraphy on the Pabay Shale Formation of Raasay has been done on the succession at Hallaig on the east coast of the island. Ammonite faunas indicate that the Pabay Shale Formation in the Skye area is Sinemurian to Pleinsbachian in age, ranging from the Semicostatum Zone (Lyra Subzone) to the ?Middle Ibex Zone (?Valdani Subzone) (Hesselbo *et al*. 1998, figs. 3, 12, 13). However not all of the ammonite-based zones and subzones have been recorded and the absence of much of the Upper Sinemurian, notably the Obtusum and Oxynotum zones, was noted by Oates (1978) and Hesselbo *et al*. (1998, fig. 3). This was thought to be due to outcrops being obscured by landslip. Hesselbo *et al*. (1998, p. 38, 39) also observed that, in southwest Raasay, “The Oxynotum zone is unconfirmed but is likely also to be present”. Other authors, such as Richey (1961) and Sellwood (1972), have however suggested there may be a non-sequence in the Late Sinemurian succession on Raasay.

Previous studies on the Jurassic palynology of the Hebrides Basin include Bradshaw and Fenton (1982), Riding (1984, 1992a), Riding *et al*. (1991) and Riding and Thomas (1997). This report represents the first palynological evidence for Upper Sinemurian strata in the Hebrides Basin.

Palynology

Two dark grey mudstone samples, JMB1 and JMB2, were collected for palynological analysis from the Pabay Shale Formation in Suisinish, southwest Raasay. These samples were collected from an extensive outcrop of a uniform parallel-laminated black shale at Grid References [NG 55353 34600] and [NG 55198 35026], respectively (Fig. 3). The bed sampled has been intruded by numerous Palaeogene basalt dykes, and is capped by the Raasay Granite.

The samples were processed using standard palynological laboratory techniques which comprised digestion using hydrochloric acid and 49% hydrofluoric acid followed by oxidation with Schultze's solution and sieving using a 10 µm mesh to concentrate the 11 to 200 µm fraction (Wood et al., 1996). The raw organic residues from both samples were dark brown to black in colour. This relatively high level of thermal maturity is due to the proximity of the basalt dykes and the Raasay Granite. Hence they were oxidised using Schultze's solution for 5 to 6 hours to render the palynomorphs sufficiently light for study.

The two samples yielded abundant organic particulate matter, mainly terrestrially-derived plant fragments, pollen and spores with relatively low proportions of marine microplankton (acritarchs and dinoflagellate cysts). Both samples proved relatively low in palynomorph diversity. Sample JMB1 was the richest, with 11 species of gymnosperm pollen and pteridophyte spores recorded. These miospores comprise *Cerebropollenites macroverrucosus* (Thiergart 1949) Schulz 1967, *Classopollis classoides* (Pflug 1953) Pocock & Jansonius 1961, *Cyathidites minor* Couper 1953, *Gleicheniidites senonicus* Ross 1949, *Ischyosporites variegatus* (Couper 1958) Schulz 1967, *Osmundacidites wellmanii* Couper 1958, *Perinopollenites elatoides* Couper 1958, *Podocarpidites* spp., *Protopinus scanicus*

Nilsson 1958, *Retitriletes austroclavatidites* (Cookson 1953) Döring *et al*. 1963 and *Todisporites major* Couper 1958. These taxa are all relatively long ranging, however the absence of the characteristic pollen genus *Callialasporites* is indicative of an Early Jurassic age (Riding *et al*., 1991).

Marine palynomorphs comprise 5-8% of the palynomorph assemblages. These are overwhelmingly dominated by the dinoflagellate cyst *Liasidium variabile* Drugg 1978 and small acanthomorphic (spine-bearing) acritarchs referable to *Micrhystridium* (Fig. 4). *Liasidium variabile* is the most biostratigraphically significant palynomorph in the entire microflora. This species is confined to the Late Sinemurian of northwest Europe. Bucefalo Palliani and Riding (2000, fig. 5A,B) recognised two morphotypes of this taxon from North Yorkshire. Morphotype A is characterised by relatively short polar horns, whereas Morphotype B is distinguished by a prominent apical horn, a rounded left antapical protuberance and a pronounced right lateral 'shoulder' on the hypocyst. In the two Pabay Shale Formation samples, both morphotypes of *Liasidium variabile* were recorded, although Morphotype A is significantly more common than Morphotype B. However, Morbey (1978) and Van de Schootbrugge et al. (2005, p. 82) observed more than two discernible morphotypes of *Liasidium variabile.* A systematic treatment of *Liasidium* and *Liasidium variabile* is presented as Appendix 1.

Biostratigraphy

The previously recorded stratigraphical ranges for *Liasidium variabile* are presented in Fig. 5; the total reported range is Hettangian to Early Pliensbachian. The oldest recorded occurrences are Hettangian by Brenner (1986) from southwest Germany and Rauscher and Schmitt (1990) from northeast France. Both these studies are not based on samples correlated to ammonite zones. Likewise, there are two records from the Pliensbachian Stage; these are Fauconnier (1995) and Williams et al. (1990). The report of Fauconnier (1995) is from a borehole drilled in northeast France and the range top is apparently within the earliest Pliensbachian Jamesoni Zone. Williams et al. (1990) represents the first non-European report of *Liasidium variabile*. The species was identified from four wells in the Scotian Basin, offshore eastern

Canada; there is no explanation of the Late Sinemurian-Early Pliensbachian age assigned to the *Liasidium variabile* Zone of Williams et al. (1990, fig. 3.8).

As is evident from Fig. 5, the overwhelming majority of records of this species are from the Late Sinemurian (for example Woollam and Riding, 1983; Feist-Burkhardt and Wille, 1992; Poulsen, 1996; Lund, 2003). Furthermore the Late Sinemurian records with ammonite control indicate that the majority of these occurrences are centred on the Oxynotum Zone (both the Simpsoni and Oxynotum subzones). The key records from the Oxynotum Zone are Drugg (1978), Riding (1987), Dybkjær (1988) and unpublished data. These unpublished data are records of *Liasidium variabile* from two British Geological Survey cored boreholes drilled in eastern England. These are the Cockle Pits Borehole, east Yorkshire ([NGR SE 9323 2865]; see Gaunt et al., 1980) and the Copper Hill Borehole ([NGR SK 9787 4265]; see Berridge et al., 1999). Abundant *Liasidium variabile* were recorded at 57.32 m, within the Oxynotum Zone, in the Cockle Pits Borehole (Woollam and Riding, 1983, p. 25). In the Copper Hill Borehole, *Liasidium variabile* was found in significant proportions (up to 17.4% of the palynoflora at 177.00 m) in 11 samples from the Brant Mudstone Formation, all of which are referable to the Oxynotum Zone between 182.00 to 172.00 m (Riding, 1992b).

Weiss (1986) recorded *Liasidium variabile* from the Lower/Upper Sinemurian boundary beds (Turneri and Obtusum zones) in Germany. Other reports from the Obtusum Zone include Riding (1987), Bucefalo Palliani and Riding (2000) from eastern England and Van de Schootbrugge et al. (2005) from west Wales. Despite the relatively restricted range of *Liasidium variabile*, the spread of records is interesting and may represent differing recovery of ammonites and/or the quality of ammonite interpretations.

Bucefalo Palliani and Riding (2000) found that *Liasidium variabile* Morphotype A, with short polar horns, first appears in the Late Sinemurian Obtusum Zone (Denotatus Subzone) and extends into the overlying Simpsoni Subzone of the Oxynotum Zone. By contrast *Liasidium variabile* Morphotype B, with a prominent apical horn, is typically confined to the Oxynotum Subzone (Bucefalo Palliani & Riding 2000, p. 5, 10). Hence, the presence of *Liasidium variabile* morphotypes A and B in the two samples from Raasay indicates that this part of the Pabay Shale Formation is of Late Sinemurian age and referable to the Oxynotum Zone (and probably the Oxynotum Subzone).

Conclusions

The prominent occurrence of the dinoflagellate cyst *Liasidium variabile* within a thermally-mature palynomorph association in the Pabay Shale Formation of southwest Raasay is the first record of this biostratigraphically important Late Sinemurian species in Scotland. This record unequivocally confirms the presence of Upper Sinemurian strata within the Pabay Shale Formation in the southwest part of Raasay. This occurrence is strongly indicative of the Oxynotum Zone, and the presence of *Liasidium variabile* morphotypes A and B strongly suggests the Oxynotum Subzone of the Oxynotum Zone. The Oxynotum Zone has not previously been identified on Raasay. The presence of the Upper Sinemurian is not consistent with the Late Sinemurian hiatus on Raasay proposed by Richey (1961) and Sellwood (1972).

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APPENDIX 1

Appendix 1 is a systematic section and comprises a review of the stratigraphically important genus *Liasidium* Drugg 1978, and lists the previously published illustrated occurrences of the single species, *Liasidium variabile* Drugg 1978.

Systematic Palaeontology

Division DINOFLAGELLATA (Bütschli 1885) Fensome *et al*. 1993
Subdivision DINOKARYOTA Fensome *et al*. 1993
Class DINOPHYCEAE Pascher 1914
Subclass PERIDINIPHYCIDAE Fensome *et al*. 1993
Order PERIDINIALES Haeckel 1894
Suborder HETEROCAPSINEAE Fensome *et al*. 1993
Family HETEROCAPSACEAE Fensome *et al*. 1993

Genus *Liasidium* Drugg 1978, p. 69.
Type: *Liasidium variabile* Drugg 1978, pl. 5, fig. 9; Fensome *et al*. 1995, p. 1881, fig. 4.
Remarks: In phylogenetic terms, *Liasidium* is a highly significant monotypic dinoflagellate cyst genus. It is part of a relatively low-diversity plexus of apparently relatively primitive genera which characterise the Mid-Late Triassic and Early-earliest Mid Jurassic interval. These forms preceded the major evolutionary radiation of the Order Gonyaulacales which started during the Bajocian Stage of the Mid Jurassic (Fensome et al., 1996, fig. 1). The characteristic biconical shape of *Liasidium* and the presence of polar horns are similar to those of Mid-Late Triassic genera such as *Heibergella* Bujak & Fisher 1976, *Rhaetogonyaulax* Sarjeant 1966 emend. Below 1987 and *Sverdrupiella* Bujak & Fisher 1976. Drugg (1978, p. 70) remarked that *Liasidium* appears to have peridiniinean affinities, probably due to the prominent anterior intercalary archaeopyle. Bujak and Davies (1983, p. 56, fig. 22) and Evitt (1985) also commented that the genus may be one of the earliest representatives of the peridinioid lineage. Below (1987, p. 128, fig. 68a,b) also discussed this question and interpreted the shape of the type I_{2a} archaeopyle as heptagonal. The shape of the archaeopyle (i.e. the 2a plate) is hence not typical of the Family Peridiniaceae

Ehrenberg 1831 because it has a geniculate anterior margin. Below (1987, p. 128) commented that, because of this, *Liasidium* appears to be closely related to *Rhaetogonyaulax*.

Van de Schootbrugge et al. (2005) commented that the presence of younger genera of the Family Heterocapsaceae such as *Parvocysta* Bjaerke 1980 and *Reutlingia* Drugg 1978 emend. Below 1987 in the Toarcian-Aalenian. *Liasidium* was thus considered by these authors to be a 'missing link' between the Mid-Late Triassic and latest Early-earliest Mid Jurassic *Rhaetogonyaulax* and *Parvocysta/Susadinium* suites respectively. Van de Schootbrugge et al. (2007) commented on the severe extinction of dinoflagellate cysts at the Triassic-Jurassic boundary. The presence of abundant *Liasidium variabile* in the late Sinemurian, during the Hettangian to late Pliensbachian interval which was otherwise largely devoid of dinoflagellate cysts, is intriguing. It is possible that it was an opportunistic taxon which thrived briefly, perhaps in response to a major palaeoecological event. It is also possible that *Liasidium variabile* may have been a heterotrophic species (S. Feist-Burkhardt, personal communication, 2009), and hence was adapted to particular nutritional circumstances.

Van de Schootbrugge et al. (2005, p. 87-88) speculated that *Liasidium* was associated with late sea level highstands, and that this genus migrated from the palaeo-Pacific into the Tethys during the Late Sinemurian as a result of changes in ocean circulation. This is consistent with the interpretation of *Liasidium variabile* as a warm water taxon by Riding and Hubbard (1999). However, there are no reports of this species from the palaeo-Pacific region, except for the unsubstantiated occurrence of cf. *Liasidium variabile* from the Lower Jurassic of Mexico by Rueda-Gaxiola et al. (1999).

Species *Liasidium variabile* Drugg 1979 (Fig. 4.1-4.12)

Full synonymy:

1978 *Liasidium variabile* Drugg, p. 69, 70, pl. 4, fig. 10, pl. 5, figs 1-9.

1978 "*Liassogonyaulax complexa*" Morbey, figs. 2.2-2.12, pl. 1, figs. 10-29.

1978 Dinoflagellate sp. 2 Morbey and Dunay, pl. 1, figs. 7-13.

1983 *Liasidium variabile* Drugg 1978. Bujak and Davies, fig. 22.

1983 *Liasidium variabile* Drugg 1978. Woollam and Riding, pl. 1, fig. 5.

1984 *Liasidium variabile* Drugg 1978. Riding, pl. 1, fig. 4.

1986 *Liasidium variabile* Drugg 1978. Brenner, p. 159, fig. 8.25.

1986 *Liasidium variabile* Drugg 1978. Weiss, p. 318-320, figs. 1, 2.

1987 *Liasidium variabile* Drugg 1978. Below, figs. 68a,b.

1987 *Liasidium variabile* Drugg 1978. Riding, fig. 6.1.

1988 *Liasidium variabile* Drugg 1978. Dybkjær, p. 26, 27, pl. 13, fig. 6.

1990 *Liasidium variabile* Drugg 1978. Rauscher and Schmitt, pl. VI, fig. 12.

1991 *Liasidium variabile* Drugg 1978. Dybkjær, p. 30, pl. 16, figs. 3, 6.

1992 *Liasidium variabile* Drugg 1978. Riding and Thomas, pl. 2.1, figs. 2-4, 8.

1996 *Liasidium variabile* Drugg 1978. Poulsen, pl. 41, figs. 3-5.

1996 *Liasidium variabile* Drugg 1978. Fensome et al., pl. 4, fig. 3.

1996 *Liasidium variabile* Drugg 1978. Stover et al., pl. 1, fig. 9, pl. 2, fig. 10.

2000 *Liasidium variabile* Drugg 1978. Bucefalo Palliani and Riding, figs. 5A-B, 6A-6H.

2003 *Liasidium variabile* Drugg 1978. Lund, pl. 2, fig. 6.

2003 *Liasidium variabile* Drugg 1978. Riding et al., fig 3E.

Remarks. In the above synonymy list, all the previous illustrated records of *Liasidium variabile* are listed in chronological order. This species has also been reported, but not figured by, for example, Riding and Sarjeant (1985), Ainsworth *et al*. (1987; 1989), Williams *et al*. (1990), Feist Burkhardt and Wille (1992), Partington *et al*. (1993), Feist Burkhardt (1994), Fauconnier (1995; 1997), Poulsen & Riding (2003) and Van de Schootbrugge *et al*. (2005). *Liasidium variabile* has been reported from the Hettangian to the Early Pliensbachian of Europe (Denmark, England, France, Germany, offshore Ireland and Wales) and offshore eastern Canada. The numerous records of this species, however, indicate that it is normally confined to the Late Sinemurian (Oxynotum Zone) (Fig. 5). The report of this form from the Toarcian of Romania by Moldovanu (1987) is not substantiated. A specimen of *Liasidium variabile* reworked into Late Devensian (Late Quaternary) glaciolacustrine sediments of Norfolk was illustrated by Riding *et al*. (2003, fig. 3E).

Figure captions:

FIG. 1. The Lower and Middle Jurassic lithostratigraphy of Raasay, and the ammonite biostratigraphy of the Pabay Shale Formation. The Oxynotum Zone is asterisked to indicate that this has been identified by this study.

FIG. 2. The position of the outcrop sampled between Suisnish Point and Inverarish in southwest Raasay, and the location of the Isle of Raasay.

FIG. 3. Annotated photographs of the sampling points along the road cutting between Suisnish Point and Inverarish, southwest Raasay showing the sampling points, faulting in the Pabay Shale Formation, intrusive dykes cutting through the Pabay Shale Formation and the overlying Raasay Granite.

FIG. 4. Selected marine microplankton from the Pabay Shale Formation of southwest Raasay. All photomicrographs were taken using plain transmitted light. The specimens are curated in the palaeontological collections of the Department of Geology, University College Cork, Ireland. Note the relatively high thermal alteration level of these palynomorphs.
(1-12) *Liasidium variabile* Drugg 1978. Note the relatively squat, biconical outline, the polar horns which are somewhat variable in size, the large anterior intercalary archaeopyle and the prominent laevorotatory cingulum. Some specimens, for example figures 10-12 have a pronounced right lateral 'shoulder' on the hypocyst.
(1) Sample JMB 1, slide 4, England Finder coordinate F23.
(2) Sample JMB 1, slide 5, England Finder coordinate J31.
(3) Sample JMB 1, slide 5, England Finder coordinate O28.
(4) Sample JMB 1, slide 3, England Finder coordinate P26.
(5) Sample JMB 2, slide 1, England Finder coordinate M20.
(6) Sample JMB 1, slide 3, England Finder coordinate N37.
(7) Sample JMB 1, slide 4, England Finder coordinate D21.
(8) Sample JMB 1, slide 4, England Finder coordinate L12.
(9) Sample JMB 1, slide 1, England Finder coordinate L19.
(10) Sample JMB 1, slide 5, England Finder coordinate R20.
(11) Sample JMB 1, slide 1, England Finder coordinate K21.
(12) Sample JMB 1, slide 1, England Finder coordinate J23.

(13-16) *Micrhystridium* spp. These are representatives of an important acanthomorphic acritarch genus.

(13) Sample JMB 1, slide 3, England Finder coordinate D22.

(14) Sample JMB 1, slide 1, England Finder coordinate H13.

(15) Sample JMB 1, slide 5, England Finder coordinate R40.

(16) Sample JMB 1, slide 4, England Finder coordinate P19.

FIG. 5. A compilation of the published records of the range of *Liasidium variabile* from northwest Europe and eastern Canada. Reports in generic compilations such as Stover et al. (1996) are not included because they merely repeat previously published ranges. If the surnames of the authors are in upper case font, the respective study is based on specified geological materials e.g. a borehole section. If the surnames of the authors are in initial capitals and lower case font, the respective study did not specify the sample database. Records with square symbols indicate that the samples are positively correlated to the ammonite zonation. The circular symbols indicate that the samples have no ammonite control. One, two or three symbols indicate that *Liasidium variabile* is present, common and abundant respectively.