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Upper Triassic and Lower Jurassic stratigraphy from exploration well L134/5-1, offshore Inner Hebrides, west Scotland

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ABSTRACT – A thick (c.1368 m) Upper Triassic to Lower Jurassic sedimentary sequence from exploration well L134/5-1, offshore Inner Hebrides, has yielded a rich and diverse foraminiferal and ostracod microfauna. Many of the taxa have been previously described throughout northwest Europe. Poor preservation (often due to crushing and/or overgrowth) and low numbers preclude a complete taxonomic review of this material, although changes in the faunal composition, rates of faunal turnover and palaeoenvironmental analyses are discussed. This is the first published account of ostracod and foraminiferal assemblages from the Sea of Hebrides and they indicate that the sediments (argillaceous, arenaceous and carbonates) were deposited in a shelf-marine setting with environmental fluctuations that are possibly the result of local relative sea-level changes. *J. Micropalaeontol.* **20**(2): 155–168, December 2001.

INTRODUCTION

Exploration activity in the Hebrides Basin has remained very low compared to other regions within the United Kingdom continental shelf. To date (April, 2001) only three exploration wells have been drilled, one in the North Minch Basin and two within the Sea of Hebrides. A large number (75) of shallow boreholes have, however, been drilled by the British Geological Survey throughout the Hebrides Basin. British Petroleum drilled the first of the three exploration wells (156/17-1) in the North Minch Basin in 1989 (Fig. 1). This was followed by the first of the two Sea of Hebrides wells, the onshore Upper Glen-1 well drilled by Pentex Oil in 1989 on the island of Skye. Chevron UK drilled well L134/5-1 in the Sea of Hebrides, south of Skye and west of Rhum, within the Inner Hebrides, off the west coast of mainland Scotland. Chevron L134/5-1 was spudded in February 1991 and plugged and abandoned in May 1991. It reached a total depth of 2472 m, terminating in Stornoway Formation sandstones of Triassic age.

This paper describes the Upper Triassic and Lower Jurassic sediments and microfaunas (foraminifera and ostracods) from well L134/5-1. Particular emphasis has been placed on the microfossil taxa, because it is the first detailed published study of such faunas from this region. The paper describes the microfaunas and their associated biostratigraphical and palaeoenvironmental implications. Poor preservation due to compaction and heating of the surrounding sediments by igneous intrusions and/or low abundance preclude a complete taxonomic review of this material. Although the palynological dataset for well L134/5-1 has not been used in this study, the authors have had access to the company biostratigraphic report, and have noted that much of the palynomorph biostratigraphic data complements the microfaunal age assignments for the well.

GEOLOGY

The Hebrides Basin can be subdivided into two distinct northeast–southwesterly half-grabens (Fig. 1); to the northwest, the Sea of Hebrides–Little Minch Basin and to the southeast, the Inner Hebrides Trough (Morton, 1983, 1989). Separating these two half-grabens is the Skye High (Morton, 1965; Binns *et al*., 1975; Harris, 1989, 1992; Fyfe *et al*., 1993; Hesselbo *et al*., 1998). The Hebrides Basin is traversed by a number of northeast to southwest/north-northwest to south-southeast trending Caledonian normal faults, which were reactivated during the Triassic. Along the northwest margins of each major basin are two significant faults: the Minch Fault and the Camasunary Fault. The southeast margins of both half-grabens appear, however, to be unfaulted. Numerous rock types occur within the Hebrides Basin, including Proterozoic Torridonian sandstones and Moine Schists, Cambrian Durness Limestone, Devonian Old Red Sandstone, Carboniferous sediments, Triassic New Red Sandstone, Jurassic sediments, Upper Cretaceous chalks, through Palaeogene igneous rocks and finally into Neogene sediments (Fyfe *et al*., 1993). Within the deepest part of the Sea of Hebrides–Little Minch Basin over 2500 m of Permo-Triassic through to Cretaceous sediments are recovered, of which over 1494 m are Jurassic strata.

LITHOSTRATIGRAPHY

Within the Hebrides Basin, thick extensive Lower Jurassic (Lias Group) sequences have been described from the onshore regions, for example Skye has *c.*500 m of exposed Hettangian to middle Pliensbachian sediments. The lithostratigraphical studies of the Lias sequences of the Inner Hebrides commenced in 1897 by Woodward, who subdivided these sediments into a lower Broadford Beds and the overlying Pabba Shales. Since this pioneering work, a large number of publications have discussed these sediments (including Buckman, 1920 (in Lee, 1920); Hallam, 1959; Howarth, 1956; Oates, 1978; Searl, 1992), culminating in the revision of the hebridean Lower Lias Group by Hesselbo *et al*. (1998). The lithostratigraphy for the L134/5-1 well follows Hesselbo *et al*. (1998).

LITHOLOGY

In well L134/5-1, 1368 m of strata were penetrated between the Upper Pliensbachian, Scalpa Sandstone Formation equivalent and the Upper Triassic, Penarth Group (*c.* 494–1890 m depth). One Upper Triassic and six Lower Jurassic lithostratigraphic units are described using wireline log data (gamma ray, resistivity and sonic velocity) and gross lithology (Fig. 2). A

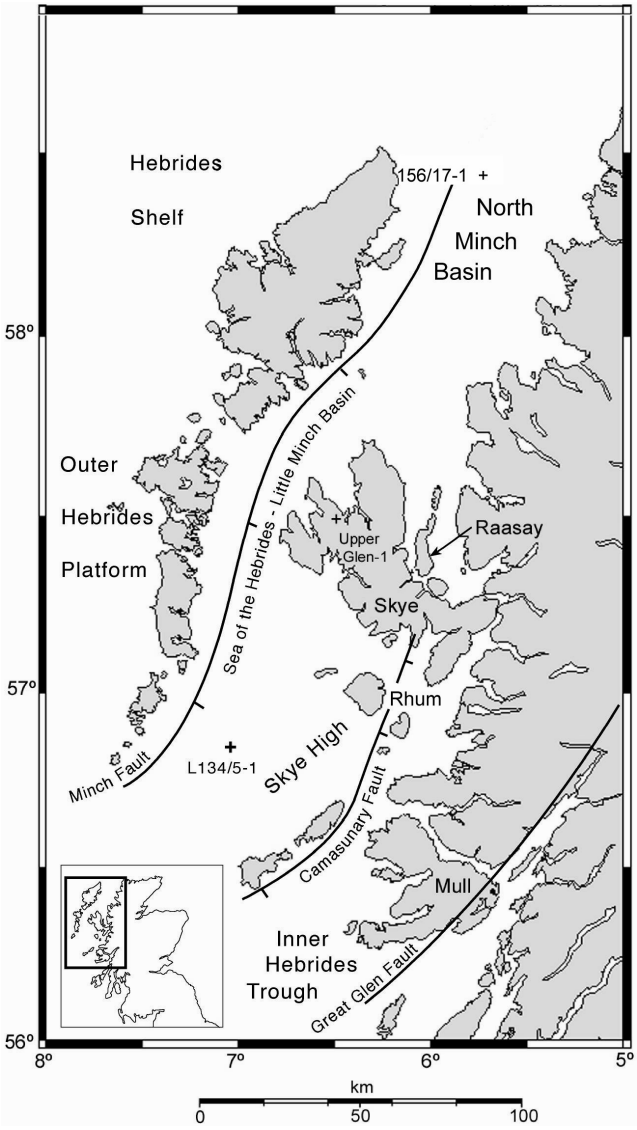

Fig. 1. Location and structure of the Malin–Hebrides area, based on Fyfe *et al*. (1993).

number of thin igneous intrusions are noted at and below 1250 m (the Pabay Shale Formation). All depths discussed below relate to wireline log data.

The Scalpa Sandstone Formation equivalent: (*c*.494 m, top not seen, to 659.5 m, log)

The sediments occurring within this interval in well L134/5-1 are envisaged to be lateral equivalents of the Scalpa Sandstone Formation of mainland west Scotland, differing in their more argillaceous content (silty claystone/argillaceous siltstone) and, where recorded, the sandstones comprise finer-grained lithologies. These lateral equivalent sediments are presumed to have been deposited in a more distal to source setting.

Age. Late Pliensbachian in well L134/5-1. The Pabay Shale/Scalpa Sandstone formational boundary is highly diachronous in mainland west Scotland, ranging in age from mid-early to mid-Late Pliensbachian (mid-*ibex* to upper *margaritatus* Zones) (Howarth, 1956; Oates, 1978; Hesselbo *et al.*, 1998). The Scalpa Sandstone/Portree Shale formational boundary is placed at, or close to, the *tenuicostatum/falciferum* zonal boundary (Howarth, 1992).

Lithology. This formation is dominated by medium grey to dark grey, olive grey, locally silty, non-calcareous to calcareous claystones. Stringers of greyish orange and light olive grey, microcrystalline to sucrosic, dolomite and dolomitic limestone occur throughout. Traces of light olive grey to medium grey, argillaceous siltstone and silty sandstone occur towards the base. Disseminated pyrite occurs throughout this section.

Wireline log characteristics. The lower boundary is moderately sharp; defined by an increase in gamma ray response and an associated increase in sonic velocity values, reflecting a lithological change to claystones. The interval is characterized by slightly serrated wireline log motifs with moderately low gamma ray responses and moderately high sonic velocities. The occurrence of sonic spikes indicates dolomite or dolomitic limestone stringers.

The Pabay Shale Formation: (659.5–1582 m, log)

Age. Early Pliensbachian to Early Sinemurian in well L134/5-1. Onshore west Scotland, the Broadford Beds/Pabay Shale formational boundary is often poorly dated due to the absence of zonal/subzonal marker faunas. It is tentatively placed at the Early Sinemurian, *bucklandi–semicostatum* zone boundary (Hesselbo *et al*., 1998). Similarly the Blue Lias/Pabay Shale formational contact is diachronous. In Morvern (Loch Aline) the junction occurs at the *bucklandi–semicostatum* zonal boundary, while on South Mull the contact is questionably placed within the Early Sinemurian, *semicostatum* Zone.

Lithology. This formation is dominated by argillaceous sediments, comprising medium dark grey to dark grey, olive grey, in part silty, calcareous claystones. Infrequent beds of dark grey, non-calcareous siltstone and off-white, light olive grey, micaceous, calcareous, silty sandstone occur towards the base. Rare stringers of light brownish grey and light olive grey, microcrystalline to sucrosic, limestone and dolomitic limestone are also noted. Disseminated pyrite occurs throughout this section.

Wireline log characteristics. The upper boundary is moderately sharp; defined by an increase in gamma ray response and an associated increase in sonic velocity values, reflecting a lithological change to claystones. The lower boundary of the Pabay Shale Formation is sharp; defined by a decrease in gamma ray response and an associated increase in sonic velocity values, reflecting a lithological change to interbedded limestone and calcareous claystone. The Pabay Shale Formation is characterized by slightly serrated wireline log motifs with moderately low gamma ray responses and moderately high sonic velocities.

The Hallaig Sandstone Member equivalent: (1005–1097.5 m, log)

The sediments occurring within this interval are considered to be a lateral equivalent to the Hallaig Sandstone Member of

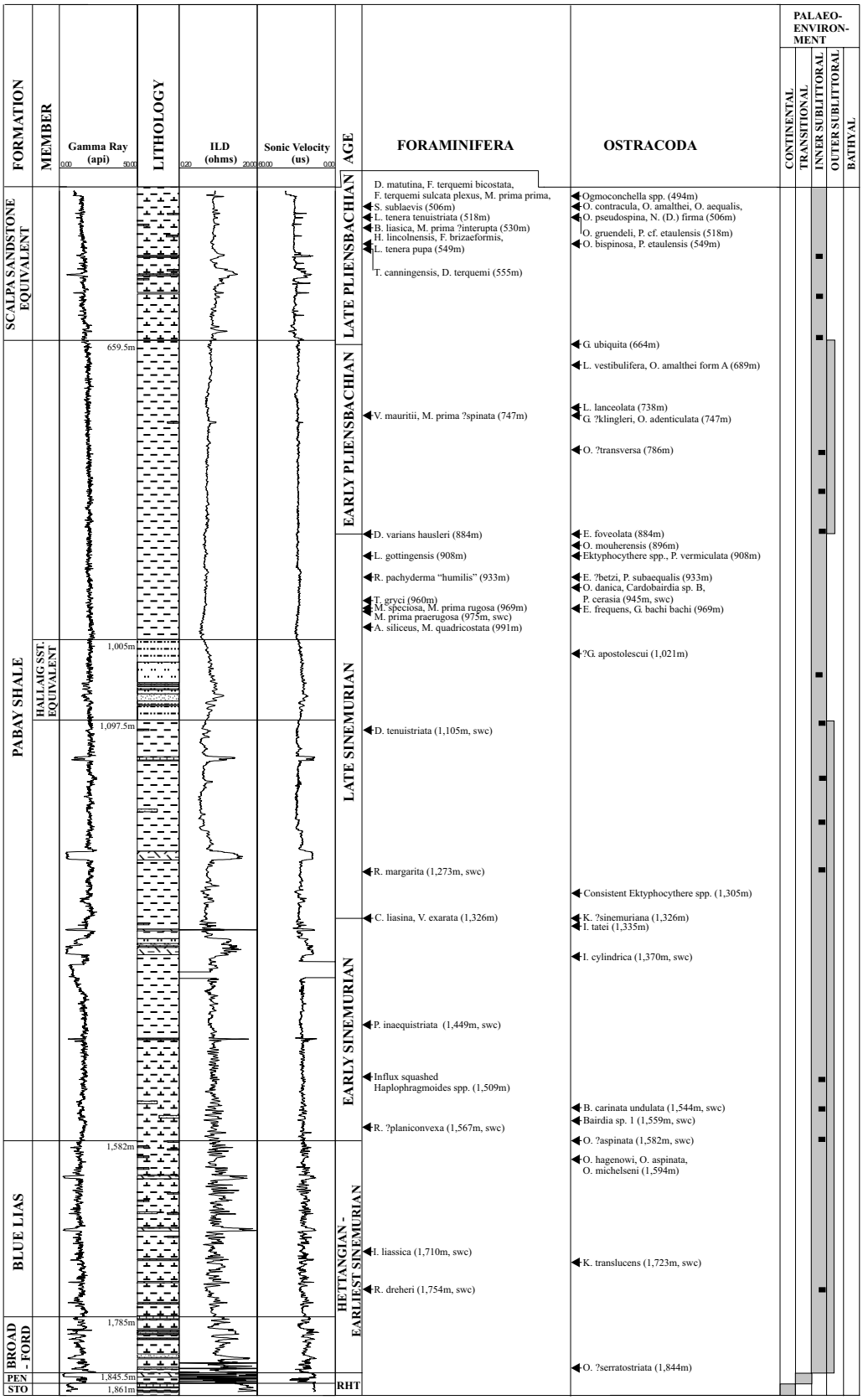

Fig. 2. Wireline log characteristics and stratigraphic summary of the Upper Triassic–Lower Jurassic of exploration well L134/5-1.

Hesselbo *et al*. (1998). The sediments in well L134/5-1 are finer grained than their onshore counterparts, comprising mainly siltstones/silty claystones, with rare fine-grained sandstones. They are considered to represent a more distal equivalent to the onshore Hallaig Sandstone Member *sensu stricto*.

Age. Late Sinemurian in well L134/5-1. In Raasay and Skye, the Hallaig Sandstone Member has a maximum stratigraphic extent of mid-Early to mid-Late Sinemurian (mid-*semicostatum*–lower *oxynotum* Zones; Hesselbo *et al*., 1998).

Lithology. This member is dominated by dark grey-brownish black, non- to slightly calcareous silty claystone and siltstone, while subsidiary off-white to light olive grey, very fine- to fine-grained, micaceous, argillaceous sandstone occurs mid-way through the member. Disseminated pyrite occurs throughout.

Wireline log characteristics. The upper boundary is sharp; defined by a slight decrease in gamma ray response and a marked increase in sonic velocity values, reflecting a lithological change to siltstone. The lower boundary is sharp; defined by a slight increase in gamma ray response and a marked decrease in sonic velocity, reflecting a lithological change to claystones. This member is characterized by a slightly bowed log profile, with the lowest gamma ray response and highest sonic velocity below the midpoint reflecting the most arenaceous part of the section.

The Blue Lias Formation: (1582–1785 m, log)

The Blue Lias Formation interdigitates with the Broadford Formation in many of its more northerly outcrops of west Scotland (e.g. Ardnamurchan), while along its more southerly outcrops (e.g. Mull) it occurs as a lateral equivalent of the Broadford Formation (Hesselbo *et al*., 1998). The Blue Lias Formation is considered to be a deeper-water equivalent of the Broadford Formation.

Age. Earliest Sinemurian to intra-Hettangian in well L134/5-1. Where fully developed onshore west Scotland, the Blue Lias has a maximum stratigraphic range of Hettangian to earliest Sinemurian (*planorbis–bucklandi* Zones).

Lithology. This formation is dominated by an interbedded sequence of claystones and limestones. The former comprise medium dark grey to dark grey, olive grey, locally silty, slightly to very calcareous claystones, while the latter comprise yellowish grey, light olive grey, medium dark grey, microcrystalline and sucrosic limestones. The claystones are increasingly lighter in colour and also more calcareous towards the base of the section. Rare beds of off-white to light olive grey, very fine- to fine-grained, micaceous, argillaceous sandstone are also noted.

Wireline log characteristics. The upper boundary is sharp; defined by a decrease in gamma ray response and an associated increase in sonic velocity, reflecting a lithological change to interbedded limestone and calcareous claystone. The lower boundary is moderately sharp; defined by a decrease in gamma ray response and an associated increase in sonic velocity, reflecting a lithological change to limestone. The Blue Lias Formation is characterized by a regular, serrated 'spiky' log motif, reflecting the limestone–claystone interbeds. The gamma ray response for the Blue Lias Formation is slightly subdued compared to the overlying Pabay Shale Formation.

The Broadford Formation: (1785–1845.5 m, log)

Onshore, this formation has been described as a shallow water equivalent of the Blue Lias Formation. It comprises a succession of littoral carbonate and arenaceous sediments, locally represented by reefs and beach environments (Hesselbo *et al*., 1998). The lower parts of the sequence may yield reduced diversity marine faunas (Hallam, 1959).

Age. Early Hettangian in well L134/5-1. In the Hebrides Basin, the Broadford Formation ranges from the Hettangian through to the earliest Sinemurian (*planorbis–buckl*andi Zones; Hesselbo *et al*., 1998).

Lithology. This formation is dominated by an interbedded sequence of claystones, limestones and sandstones. The claystones are medium dark grey to dark grey, olive grey, locally light brownish grey, in part silty, slightly to very calcareous, while the limestones comprise yellowish grey, light olive grey, medium brown grey, locally sandy, microcrystalline to sucrosic, mudstones. Sandstone beds occur towards the base of the section, comprising off-white to greenish grey, very fine- to fine-grained, slightly argillaceous, calcareous sandstones.

Wireline log characteristics. The upper boundary is moderately sharp; defined by a decrease in gamma ray response and an associated increase in sonic velocity, reflecting a lithological change to limestone. The lower boundary is sharp; defined by a decrease in gamma ray response and an associated decrease in sonic velocity, reflecting a lithological change to non-calcareous claystones. The Broadford Formation is characterized by an irregular, highly serrated log motif, reflecting the limestone, claystone, sandstone interbedding.

The Penarth Group: (1845.5–1861 m, log)

Age. Rhaetian.

Lithology. This interval solely comprises medium light grey, dark grey/olive black, waxy, non-calcareous, claystones. These sediments conformably overlie reddened limestones and calcareous claystones of the Stornoway Formation at 1861 m (log).

Wireline log characteristics. The upper boundary is sharp; defined by a decrease in gamma ray response and an associated decrease in sonic velocity, reflecting a lithological change to non-calcareous claystones. This interval is characterized by serrated wireline log motifs with moderately high gamma ray responses and moderately low sonic velocities.

Intrusives

Palaeogene. A number of thin (<10 m), dusky yellowish green to dark greenish grey, crystalline, fine- to medium-grained dolerite intrusions are noted within the interval between the Penarth Group and the lower section of the Pabay Shale Formation. On wireline log criteria, they are identified by their low gamma

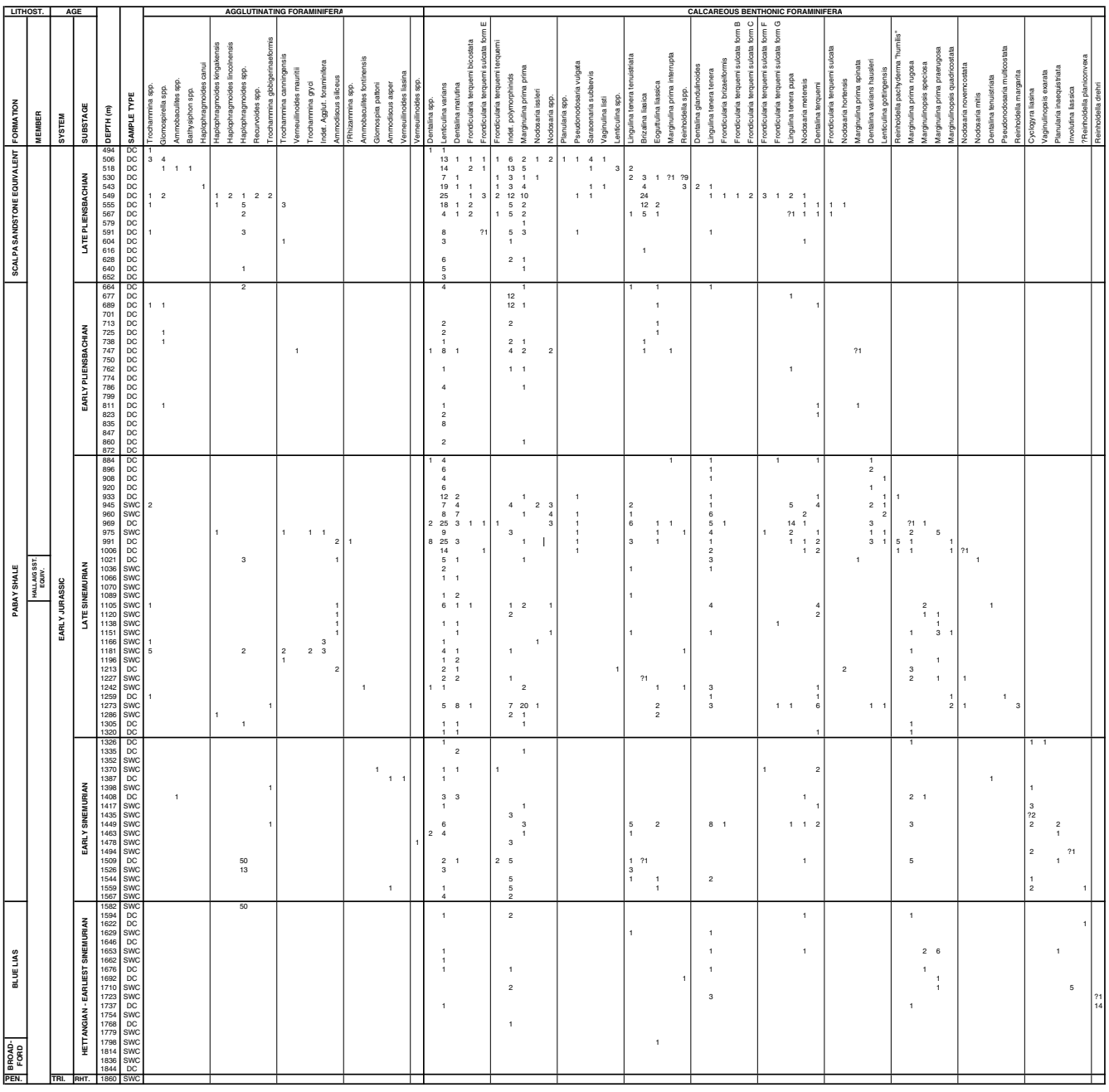

Table 1. Stratigraphical occurrence of foraminifera in well L134/5-1. Samples types are either DC (ditch cuttings) or SWC (sidewall cores). The foraminifera are separated into agglutinating and calcareous benthonic taxa.

ray responses and high sonic velocities, forming blocky log motifs.

BIOSTRATIGRAPHY

A total of 100 taxa, comprising 11 agglutinating and 44 calcareous benthonic foraminifera, in association with 45 species of ostracod were recovered from 104 samples (42 sidewall cores and 62 ditch-cuttings samples). Eight samples were barren of both ostracods and foraminifera. Samples were analysed at approximately 13 m intervals. A number of taxa are considered to be new; however, very poor preservation precludes a complete taxonomic review of this material (Tables 1–2). Since these data are mainly based on ditch-cuttings, emphasis is placed on the highest downhole occurrences (extinctions) of selected microfossil taxa and major fossil assemblage changes. Numerous publications describe the Lower Jurassic microfaunas from the UK and Ireland, and their adjacent offshore areas. These include Ainsworth (1987, 1989a, b, 1990), Ainsworth & Horton (1986), Ainsworth *et al*. (1987, 1989, 1998), Barnard (1950, 1956, 1957, 1960), Boomer (1990, 1991), Boomer & Ainsworth (in

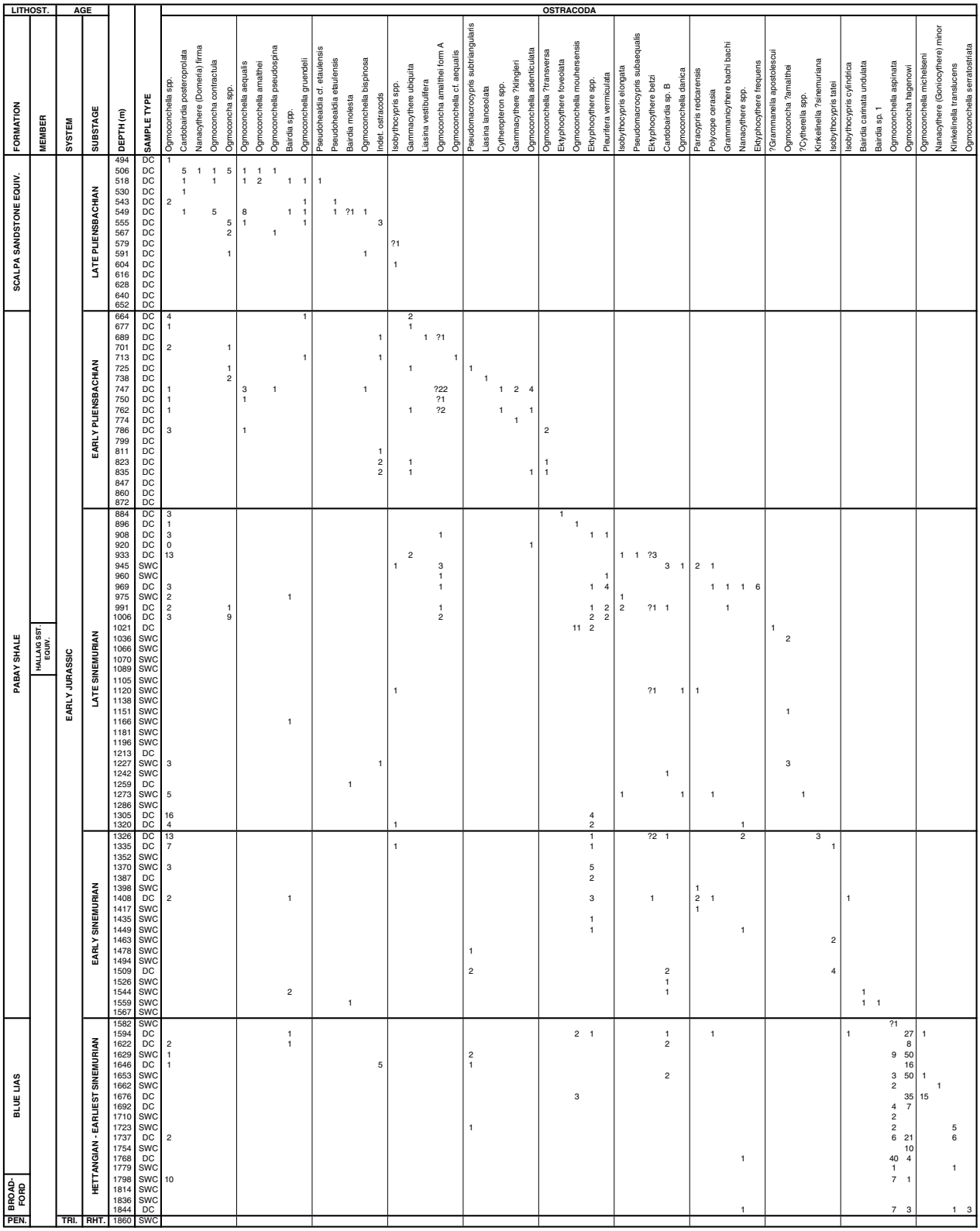

Table 2. Stratigraphical occurrence of ostracods in well L134/5-1. Samples types are either DC (ditch cuttings) or SWC (sidewall cores).

press), Brouwer (1969), Clark (1969), Colin *et al*. (1992), Copestake & Johnson (1984, 1989), Field (1968), Lord (1978), Lord & Bown (1987), Malz & Lord (1976), Park (1987) and Partington *et al*. (1993). Further afield, references are made to France (Apostolescu, 1959; Colloque sur le Lias Français, 1961; Bizon, 1960; Donze, 1967; 1985; Ruget, 1985; Ruget & Sigal, 1967), Germany (Bartenstein & Brand, 1937; Drexler, 1958; Gründel, 1964; Harloff, 1993; Herrig, 1985; Klingler, 1962; Klingler & Neuweiler, 1959; Malz, 1971, 1975), Holland (Brouwer, 1969), Denmark (Norvang, 1957; Bang, 1968, 1971, 1972; Michelsen, 1975), Sweden (Norling, 1972; Sivhed, 1977, 1980), offshore Norway (Malz & Nagy, 1989) and Portugal (Boomer *et al*., 1998; Exton, 1979; Exton & Gradstein, 1984; Ruget & Sigal, 1970).

To date (April, 2001), only Copestake & Johnson (1989) have published records of the Lower Jurassic foraminifera from the Hebrides Basin, from the Loch Aline area of Morvern, Mull (Gribun) and Raasay. The Lower Jurassic ostracod faunas from the west coast of Scotland have been studied by Clark (1969), although, these data remain unpublished. Currently, this material is being re-examined by one of the present authors (NRA).

Late Pliensbachian (494–664 m)

An age no younger than Late Pliensbachian (*margaritatus* Zone) is indicated on the highest downhole occurrence of the calcareous benthonic foraminifera *Dentalina matutina* at (506 m). Confirmation of this age is indicated by the ostracod *Ogmoconcha contractula* Triebel at 506 m and *Haplophragmoides lincolnensis* Copestake at 549 m. The former taxon is restricted to the Late Pliensbachian in the Mochras Borehole (Ainsworth *et al*., 1989; Boomer, 1990), while the latter taxon ranges no higher than the *margaritatus* Zone (Copestake & Johnson, 1989).

Foraminifera. Thirty species of foraminifera – five agglutinating taxa and 25 calcareous benthonic species – occur in the Late Pliensbachian. Highest downhole occurrences include *Haplophragmoides canui* Cushman, *H. lincolnensis* Copestake, *H. kingakensis* Tappan, *Trochammina canningensis* Tappan, *T. globigeriniformis* Parker & Jones, *Brizalina liasica* (Terquem), *Dentalina glandulinoides* Franke, *D. matutina* (d'Orbigny), *D. terquemi* d'Orbigny, *Eoguttulina liassica* (Strickland), *Frondicularia brizaeiformis* Bornemann, *F. terquemi bicostata* d'Orbigny, *F. terquemi sulcata* form B Barnard, *F. terquemi sulcata* form C Barnard, *F. terquemi sulcata* form E Barnard, *F. terquemi sulcata* form G Barnard, *F. terquemi terquemi* d'Orbigny, *Lenticulina varians* (Bornemann), *Lingulina tenera pupa* (terquem), *L. tenera tenera* Bornemann, *L. tenera tenuistriata* (Norvang), *Marginulina prima ?interupta* (Terquem), *M. prima prima* d'Orbignyi, *Nodosaria hortonensis* Terquem, *N. issleri* Franke, *N. metensis* Terquem, *Pseudonodosaria vulgata* (Bornemann), *Saracenaria sublaevis* (Franke) and *Vaginulina listi* (Bornemann).

Many of the above foraminifera possess long stratigraphical ranges, with their documented extinctions in the Toarcian. Only two species have their recorded extinctions within the Late Pliensbachian – *Haplophragmoides lincolnensis* Copestake and *Dentalina matutina* (d'Orbigny) – both of which range no higher than the *margaritatus* Zone (Copestake & Johnson, 1989). In well L134/5-1, seven species are stratigraphically restricted to the Late Pliensbachian. Throughout this interval the foraminiferal assemblages are dominated by calcareous benthonic species, notably the Nodosariidae (*Frondicularia terquemi sulcata* plexus Bornemann, *Lenticulina varians* (Bornemann), *Lingulina tenera* plexus Borneman, *Marginulina prima prima* d'Orbigny), the Polymorphinidae and the Bolivinitidae (*Brizalina liasica* (Terquem)). Agglutinating foraminifera only occur in small numbers and are generally poorly preserved. Approximately mid-way through this interval, there is a marked downhole decrease in both diversity and abundance of the foraminifera. Many of the taxa occurring within this interval have been described throughout northwest Europe (see references listed above).

Ostracoda. Eleven species of ostracod occur in the Late Pliensbachian. Highest downhole occurrences include *Bairdia ?molesta* Apostolescu, *Cardobairdia posteroprolata* Ainsworth, *Isobythocypris* spp., *Nanacythere* (*Domeria*) *firma* Herrig, *Ogmoconcha amalthei* (Quenstedt), *O. contractula* Triebel, *Ogmoconchella aequalis* (Herrig), *O. bispinosa* (Gründel), *O. pseudospina* (Herrig), *Pseudohealdia etaulensis* Apostolescu and *P.* cf. *etaulensis* Apostolescu *sensu* Ainsworth.

Although many of these ostracod species are known to range from the Early through to the Late Pliensbachian, none are thought to range into the Toarcian. Ostracod data from the Fastnet Basin, North Celtic Sea and the Mochras Borehole suggested that only two of these species (*Ogomoconcha contractula* Triebel and *Pseudohealdia* cf. *etaulensis* Apostolescu *sensu* Ainsworth) are stratigraphically restricted to the Late Pliensbachian (Ainsworth, 1987; Ainsworth *et al*., 1989; Boomer, 1990). In well L134/5-1, however, six taxa are restricted to this interval. The Late Pliensbachian ostracod assemblages are not as abundant as the foraminiferal assemblages. Similar to the foraminifera, a marked decrease in abundance occurs below mid-interval, with the earliest part of the Late Pliensbachian barren of ostracods. The assemblages within this interval are dominated by the Healdiidae, notably the genera *Ogmoconcha* and *Ogmoconchella*, with subsidiary Saipanettidae (*Cardobairdia posteroprolata* Ainsworth). No samples contained the latest Pliensbachian to earliest Toarcian 'vallate forms' of *Ogmoconcha* (of Malz, 1975) in this section. From the summary completion log, first returns only began at 494 m, below the setting of the 20 inch casing. The Late Pliensbachian assemblages bear close similarities to those recorded elsewhere in northwest Europe, especially with the dominance of the Healdiidae.

Early Pliensbachian (664–884 m)

An Early Pliensbachian age is indicated by the highest downhole occurrence of the ostracod *Gammacythere ubiquita* Malz & Lord at 664 m and the subsequent downhole occurrence of *Ogmoconcha amalthei* ?form A Michelsen at 889 m.

Foraminifera. Nine species of foraminifera – 1 agglutinating taxon and 8 calcareous benthonic species – occur in the Early Pliensbachian interval. Highest downhole occurrences include

Verneuilinoides mauritii (Terquem) and *Marginulina prima spinata* Terquem.

One taxon is stratigraphically restricted to the Early Pliensbachian (*Verneuilinoides mauritii* (Terquem), while two taxa do not occur below the Early Pliensbachian (*Glomospirella* spp., *Brizalina liasica* (Terquem)). Throughout this interval, foraminifera are generally rare, of low diversity and are comprized almost exclusively of calcareous benthonic taxa, notably the Nodosariidae (*Lenticulina varians* (Bornemann)) and the Polymorphinidae. This marked decrease in foraminiferal diversity within the Early Pliensbachian has also been described from a number of localities throughout England, including Lincolnshire (Brouwer, 1969), Dorset (Barnard, 1950) and the Mochras Borehole (Copestake & Johnson, 1989).

Ostracoda. Fourteen species of ostracod occur in the Early Pliensbachian. Highest downhole occurrences include *Ektyphocythere foveolata* (Michelsen), *Gammacythere ?klingleri* Boomer, *G. ubiquita* Malz & Lord, *Liasina lanceolata* (Apostolescu), *L. vestibulifera* Gramann, *Ogmoconcha amalthei* ?form A Michelsen, *Ogmoconchella adenticulata* (Pietrzenuk), *Ogmoconchella* cf.*aequalis* (Herrig) *sensu* Ainsworth, *O. transversa* (Gründel) and *Pseudomacrocypris subtriangularis* Michelsen.

The occurrence of *Gammacythere ubiquita* Malz & Lord indicates an Early Pliensbachian (*davoei* Zone) age at 664 m. The presence of a tentatively identified specimen of *Gammacythere klingleri* Boomer suggests an Early Pliensbachian (*ibex* Zone) age at 747 m, while the occurrence of a caved specimen (884 m) of *Ektyphocythere foveolata* (Michelsen) indicates the presence of lowermost Pliensbachian (?lower *ibex–jamesoni* Zones) sediments within the well section. *Ogmoconcha amalthei* ?form A Michelsen is also a marker taxon, restricted to the Early Pliensbachian (Michelsen, 1975). From the 14 taxa recorded in this interval, 8 are stratigraphically restricted, while another 4 species do not occur below the Early Pliensbachian. The assemblages are again dominated by the Healdiidae, notably the genera *Ogmoconcha* and *Ogmoconchella*, in association with subsidiary Cytheracea such as *Gammacythere*. The faunas within this section are, however, generally sparser than those occurring in the overlying Late Pliensbachian.

Late Sinemurian (884–1326m)

A Late Sinemurian age is denoted by the highest downhole occurrence of the calcareous benthonic foraminifera *Dentalina varians hausleri* (Schick) at 884 m. Although this taxon has a long stratigraphic range (Lower Sinemurian–Lower Toarcian), it is most commonly recorded from the Late Sinemurian, *raricostatum* Zone (Brouwer, 1969; Copestake & Johnson, 1989). Subsequent confirmation of this age is indicated by the occurrence of the ostracod *Ogmoconchella mouhersensis* (Apostolescu) at 896 m. This taxon has a restricted stratigraphical range (upper *obtusum*–lower *raricostatum* Zones) in the Mochras Borehole (Boomer, 1990).

Foraminifera. Forty-one species of foraminifera – 6 agglutinating taxa and 35 calcareous benthonic species – occur in this interval. Highest downhole occurrences include *Ammodiscus siliceus* (Terquem), *Trochammina gryci* Tappan, *Dentalina tenuistriata* Terquem, *D. varians hausleri* (Schick), *Lenticulina gottingensis* (Bornemann), *Marginulina prima praerugosa* Norvang, *M. prima rugosa* Bornemann, *Nodosaria metensis* (Terquem), *Marginulinopsis quadricostata* (Terquem), *M. speciosa* (Terquem), *Nodosaria mitis* (Terquem & Berthelin), *N. novemcostata* Bornemann, *Pseudonodosaria multicostata* (Bornemann), *Reinholdella margarita* (Terquem) and *R. pachyderma* '*humilis*' Copestake.

Two of the above taxa indicate an age no younger than Late Sinemurian (*raricostatum* Zone) – *Dentalina varians hausleri* (Schick) at 884 m and *Trochammina gryci* Tappan at 960 m – while *Reinholdella pachyderma* '*humilis*' Copestake ranges no younger than mid-*raricostatum* Zone at 933 m (Copestake & Johnson, 1984, 1989). *Reinholdella margarita* (Terquem) is an important marker species in the UK Early Jurassic, ranging no younger than the earliest Late Sinemurian (mid-*obtusum* Zone) to intra-Early Sinemurian (mid-*semicostatum* Zone) (Copestake & Johnson, 1989). In well L134/5-1, its highest occurrence at 1273 m (swc) is taken to indicate an earliest Late Sinemurian (mid-*obtusum* Zone) age. Of the 41 taxa recorded, 12 are stratigraphically restricted, while another 10 species do not occur below the Late Sinemurian. The Late Sinemurian interval is dominated by diverse and rich foraminiferal assemblages, especially with respect to the calcareous benthonic taxa, notably the Nodosariidae (*Dentalina matutina* (d'Orbigny), *D. terquemi* d'Orbigny, *Lenticulina varians* (Bornemann), *Lingulina tenera plexus* Bornemann, *Marginulina prima plexus* d'Orbigny) and the Polymorphinidae. Although present, agglutinating foraminifera (*Ammodiscus*, *Haplophragmoides* and *Trochammina* spp.) are generally very rare throughout the interval, but they do become numerically significant within the middle part of this interval.

Ostracoda. Fifteen species of ostracod occur in the Late Sinemurian. Highest downhole occurrences include *Cardobairdia* sp. B Ainsworth, *Isobythocypris elongata* (Blake), *E. ?betzi* (Klingler & Neuweiler), *E. frequens* (Ainsworth), *Ektyphocythere* spp., *Gramannicythere bachi bachi* (Gramann), *Ogmoconchella danica* Michelsen, *O. mouhersensis* (Apostolescu), *Paracypris redcarensis* (Blake), *Pleurifera vermiculata* (Apostolescu), *Polycope cerasia* (Blake) and *Pseudomacrocypris subaequalis* Michelsen.

The interval is marked by a number of taxa which do not range above the Sinemurian/Pliensbachian boundary. These comprise *Cardobairdia* sp. B Ainsworth, *E. ?betzi* (Klingler & Neuweiler), *E. frequens* (Ainsworth), *Ogmoconchella danica* Michelsen and *O. mouhersensis* (Apostolescu). In the Mochras Borehole, *Ogmoconchella danica* Michelsen is restricted to the latest *oxynotum*–mid-*raricostatum* Zones, while *O. mouhersensis* (Apostolescu) is restricted to the mid-*obtusum*–early *raricostatum* Zones (Boomer, 1990). The occurrence of moderate numbers of *Ektyphocythere* spp. is a diagnostic feature of Sinemurian ostracod assemblages. Of the 15 taxa recorded, 10 are stratigraphically restricted, while 1 species does not occur below the Late Sinemurian. A marked change in the ostracod composition occurs at the Sinemurian/Pliensbachian boundary with the highest downhole occurrence of moderate numbers of the Cytheracea (*Ektyphocythere* spp.), in association with the Healdiidae. The Late Sinemurian interval, is dominated by moderately diverse assemblages, particularly the Cytheracea (*Ektyphocythere* spp. and *Pleurifera vermiculata* (Apostolescu)).

Similar Upper Sinemurian assemblages, dominated by ornate Cytheracea, are recorded throughout northwest Europe (see references listed above).

Early Sinemurian (1326–?1582 m, swc)

A latest Early Sinemurian age is indicated by the highest downhole occurrence of the calcareous benthonic foraminifera *Vaginulinopsis exarata* (Terquem) and the ostracod *Kinkelinella ?sinemuriana* (Ainsworth) at 1326 m. The former taxon is stratigraphically restricted to the late *semicostatum*–early *turneri* Zones in west Scotland (Copestake & Johnson, 1989).

Foraminifera. Twenty-five species of foraminifera – 4 agglutinating taxa and 21 calcareous benthonic species – occur in the Early Sinemurian. Highest downhole occurrences include *Ammodiscus asper* (Terquem), *Verneuilinoides liasina* (Terquem & Berthelin), *Cyclogyra liasina* (Terquem), *?Involutina liassica* (Jones), *Lingulina tenera substriata* (Franke) and *Planularia inaequistriata* (Terquem), *?Reinholdella planiconvexa* (Fuchs) and *Vaginulinopsis exarata* (Terquem).

The latest Early Sinemurian (lower *tuneri* Zone) is denoted by the occurrence of *Vaginulinopsis exarata* (Terquem) at 1326 m. The presence of *Planularia inaequistriata* (Terquem) confirms an Early Sinemurian age at 1449 m (swc). This taxon has a short stratigraphical range (*bucklandi* Zone) in Morvern, west Scotland (Copestake & Johnson, 1989), however, in well L134/5-1 it is envisaged to have a less restricted range, extending into the mid-Early Sinemurian. Of the 25 taxa recovered, 5 species are stratigraphically restricted, while another 11 taxa do not occur below the Early Sinemurian. The Early Sinemurian can be divided into an upper interval (1326–1494 m, swc) characterized by sparse foraminiferal assemblages (some specimens of which are presumed cavings) and a lower interval (1509–1582m, swc) characterized by large numbers of poorly preserved *Haplophragmoides* spp., with subsidiary Nodosariidae (*Lenticulina varians* (Bornemann)) and the Polymorphinidae. No direct faunal comparisons can be made with these Lituolidae-dominated assemblages; however, the calcareous benthonic foraminifera are similar to those described from other sites in northern Europe.

Ostracoda. Thirteen species of ostracod occur in the Early Sinemurian. Highest downhole occurrences include *Bairdia carinata undulata* Herrig, *Bairdia* sp. 1 Ainsworth, *Isobythocypris cylindrica* (Herrig), *I. tatei* (Coryell) and *Kinkelinella ?sinemuriana* (Ainsworth).

All of the above ostracod taxa are envisaged to range later than the Early Sinemurian, with both *Bairdia* sp. 1 Ainsworth and *Isobythocypris tatei* (Coryell) occurring often in profuse numbers throughout the UK offshore (Ainsworth, 1989a, b; Ainsworth *et al*., 1987, 1989, 1998). Of the 13 species recorded, 4 taxa are stratigraphically restricted, while 1 species does not occur below the Early Sinemurian. Two distinct ostracod assemblages are recognized during the Early Sinemurian. The upper interval (1326–1408 m) is composed of moderately diverse ostracod assemblages, comprising smooth-valved taxa such as *Ogmoconchella, Isobythocypris, Cardobairdia* and *Paracypris*, in association with moderate numbers of ornate Cytheracea (e.g. *Ektyphocythere* and *Kinkelinella*). The lower interval (1417–1567 m, swc) is characterized by sparse, low diversity faunas composed entirely of smooth taxa, notably *Bairdia carinata undulata* Herrig, *Bairdia*. sp. 1 Ainsworth, *Cardobairdia* sp. B Ainsworth, *Isobythocypris* spp. and *Pseudomacrocypris subtriangularis* Michelsen.

Similar assemblages have been described by Ainsworth (1989a) and Ainsworth *et al*. (1987, 1989) from a number of wells situated in both the North Celtic Sea Basin and Fastnet Basin. Comparable faunas are also known to occur in the more offshore regions of the English Channel Basin and the Southern North Sea (Ainsworth, pers. obs.).

Earliest Sinemurian–Hettangian (?1582–1844 m)

An age no younger than earliest Sinemurian (*bucklandi* Zone) is indicated on the highest downhole occurrence of the ostracod *Ogmoconchella aspinata* (Drexler) at 1582 m. The subsequent downhole occurrence of *Ogmoconcha hagenowi* Drexler and *Ogmoconchella michelseni* Ainsworth confirm this age at 1594 m.

Foraminifera. Twelve species of foraminifera – 1 agglutinating taxon and 11 calcareous benthonic species – occur in the earliest Sinemurian to Hettangian interval. Notable occurrences include common *Involutina liassica* (Jones) and *Reinholdella dreheri* (Bartenstein).

Involutina liassica (Jones) is a common constituent of the foraminiferal fauna at 1710 m (swc). In the UK Early Jurassic, it is often recorded in abundance within the latest Hettangian–earliest Sinemurian (late *angulata–bucklandi* Zones) (Copestake & Johnson, 1989). In well L1343/5-1 its abundance is thought to represent its earliest stratigraphic occurrence (late *angulata*-Zone). Of these 12 species only one taxon is stratigraphically restricted (*Reinholdella dreheri* (Bartenstein)). The interval is characterized by low diversity assemblages, with localized peak abundance levels of *Haplophragmoides* spp., *Reinholdella* spp. and *Involutina liassica* (Jones). Many of the taxa occurring within this section may be the product of cavings.

Ostracoda. Ten species of ostracod occur in the earliest Sinemurian to Hettangian. Highest downhole occurrences include *Kinkelinella translucens* (Blake), *Ogmoconcha hagenowi* Drexler, *Ogmoconchella aspinata* (Drexler), *O. michelseni* Ainsworth and *O. ?serratostriata* Ainsworth.

The association of *Ogmoconcha hagenowi* Drexler, *Ogmoconchella aspinata* (Drexler), *O. michelseni* Ainsworth indicates an age no younger than earliest Sinemurian (*bucklandi* Zone) at 1594 m. All three taxa can often occur in profuse numbers. The presence of specimens tentatively assigned to *Ogmoconchella serratostriata* Ainsworth at 1844 m suggests an earliest Hettangian age. Six species are restricted to this interval. With the exception of *Ogmoconchella serratostriata* Ainsworth, all of the other nine species decrease in abundance below *c.*1770 m. This is envisaged to be a function of lithology resulting in poor recovery from the indurated limestones of the Broadford Formation. The ostracod assemblages are dominated by large numbers of the Healdiidae (notably *Ogmoconcha hagenowi* Drexler and *Ogmoconchella aspinata* (Drexler)), with subsidiary Cytheracea (*Kinkelinella translucens* (Blake)). The Hettangian to earliest Sinemurian ostracod assemblages recorded in well L134/5-1 are similar to contemporary assemblages described from

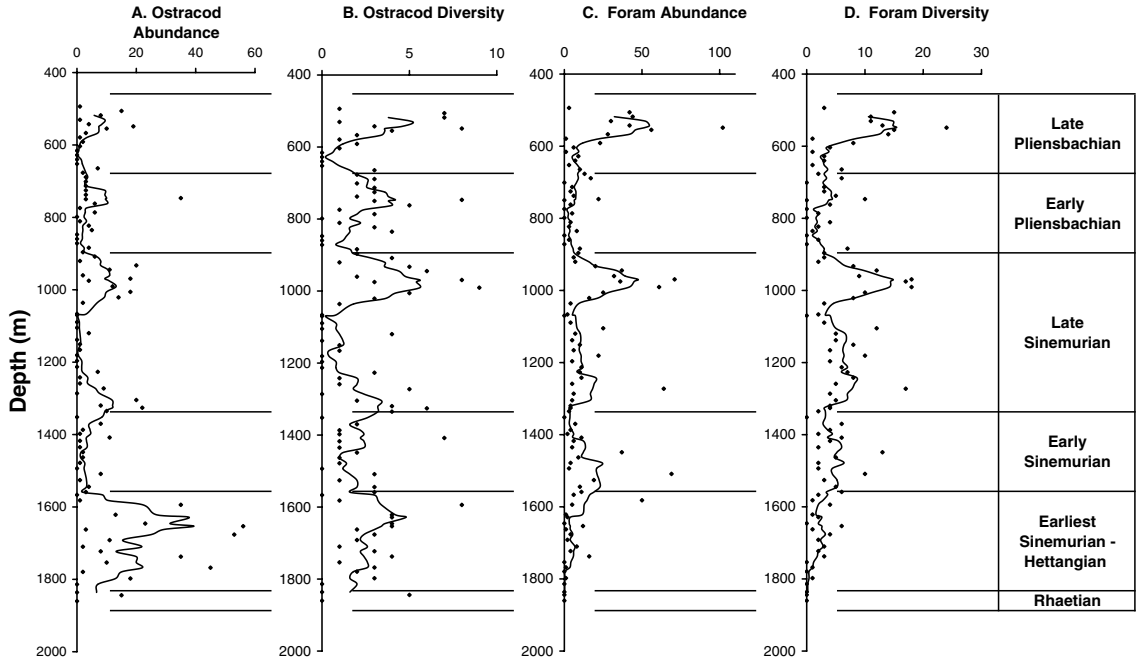

Fig. 3. Changing diversity and abundance of foraminifera and ostracods with depth based on their highest downhole occurrences. (Graph A) Simple species abundance within the ostracods (points) with a 5-point moving mean (line). (Graph B) Simple species diversity within the ostracods (points) with a 5-point moving mean (line). (Graph C) Simple species abundance within the foraminifera (points) with a 5-point moving mean (line). (Graph D) Simple species diversity within the foraminifera (points) with a 5-point moving mean (line).

other regions in northwest Europe, most of which are dominated by the Healdiidae. This faunal assemblage is also characteristic of contemporary horizons in the North Minch Basin (Ainsworth, pers. obs.).

PALAEOENVIRONMENTAL ANALYSIS

The foraminiferal and ostracod assemblages occurring in well L134/5-1 are very similar to contemporaneous records described from other areas in northwest Europe. The palaeoenvironmental reconstruction of the Hebridean area during the Early Jurassic (Hesselbo *et al.*, 1998) places this exploration well at the southern end of a NNE–SSW-trending depositional basin opening seaward to the south, with major detrital sources to the west (Hebrides Platform) and east (Scottish mainland). Given the relatively fine-grained nature of many of the sediments occurring in well L134/5-1, the depositional environment is thought to have been more distal than the correlative sedimentary sequences on Skye to the northwest, typified by a higher incidence of coarser-grained sediments (siltstones and sandstones). The microfossil assemblages support this palaeogeographical interpretation since they are all indicative of fully marine conditions. There is little evidence of proximity to land or marginal marine conditions which would be indicated by the ostracod taxa *Darwinula* or *Lutkevichinella*.

Changes in the faunal composition of both foraminifera and ostracods in well L134/5-1 are illustrated in Figures 3 and 4. From these data, a number of distinct events with characteristic assemblages have been noted. None of the data, however, have taken into account the weight of the unprocessed sample.

The foraminifera display a number of distinct changes. Figure 3 (graphs C and D) illustrates species abundance and simple species diversity, and includes a 5-point moving mean line which highlights the major patterns of change. Foraminiferal abundance is generally higher than the ostracods throughout much of the studied interval, attaining a maximum of 71 specimens at 969 m. However, ostracods are more abundant within the Hettangian–earliest Sinemurian. Likewise foraminiferal diversity is generally higher than the ostracods (with a maximum 24 taxa at 549 m), with a number of distinct cycles clearly visible. Figure 4 (graphs D and E) shows the percentage of agglutinating and calcareous benthonic foraminifera present in each sample. Throughout much of the Early Jurassic, calcareous benthonic taxa are the prevalent group both in diversity and abundance, dominated by the Nodosaridae (*Dentalina, Lenticulina, Lingulina, Marginulina*), the Polymorphidae and, to a smaller extent, the Bolivinitidae (*Brizalina liasica*). Agglutinating foraminifera are less diverse and generally of moderate to rare abundance, dominated by Lituolidae (*Haplophragmoides* spp.). A number of localized peaks of *Haplophragmoides* spp. occur, however, between 1509 m and 1582 m (swc).

The ostracods also exhibit a number of distinct faunal changes throughout the Early Jurassic. Figure 3 (graphs A and B) illustrates species abundance and species diversity, including the 5-point moving mean. Ostracod abundance is highest within the Hettangian–earliest Sinemurian, with numbers reaching 62 specimens, whereas during the Early Sinemurian to Late Pliensbachian interval, totals do not exceed 35 specimens. Ostracod diversity remains relatively low throughout the Early Jurassic (never exceeding 8 taxa), however, again there are clearly a number of cycles. The percentage faunal composition of the ostracod assemblages is illustrated in Figure 4, Graph A

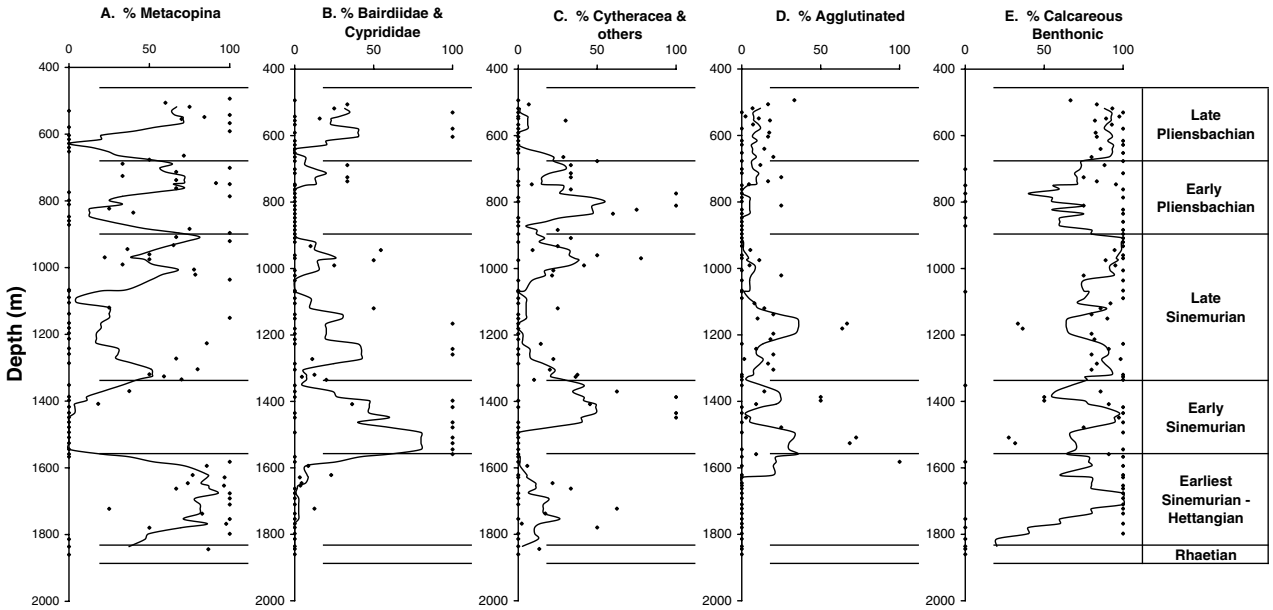

Fig. 4. Changing percentage patterns of foraminifera and ostracods with depth, based on their highest downhole occurrences. (Graph A) Percentage of metacopid ostracods recorded (points) with a 5-point moving mean (line). (Graph B) Percentage of the ostracod families (Bairdiidae and Cyprididae) recorded (points) with a 5-point moving mean (line). (Graph C) Percentage of ostracod superfamily Cytheracea recorded (points) with a 5-point moving mean (line). (Graph D) Percentage of agglutinating foraminifera recorded (points) with a 5-point moving mean (line). (Graph E) Percentage of calcareous benthonic foraminifera recorded (points) with a 5-point moving mean (line).

(Metacopina), Graph B (Bairdiidae and Cyprididae combined) and Graph C (Cytheracea and others) which includes both the Cladocopina and the Platycopina, both groups being extremely rare. The Metacopina graph (*Pseudohealdia, Ogmoconcha* and *Ogmoconchella*) clearly illustrates the dominance of this group in the earliest Jurassic interval (Hettangian to earliest Sinemurian), it should also be noted that the highest abundance of metacopids coincides with the ostracod diversity peaks, illustrating their importance within Early Jurassic ostracod assemblages. Of the 80 samples that yielded ostracods, 56 contained metacopids and in all but 10 of those samples, the metacopids make up more than half of all specimens, while 24 samples comprise more than 80%.

The earliest sediments examined in this study (Rhaetian, Penarth Group) are devoid of microfaunas. From both lithofacies evidence and palynological data (rare acritarchs and abundant miospores) a marginal marine environment is suggested for these uppermost Rhaetian sediments. The succeeding lowermost Jurassic sediments, the Broadford Formation of Hettangian age, yielded only small numbers of metacopid ostracods, in association with rare echinoderm debris. A shallow marine (inner shelf) environment is suggested, with deposition occurring during the continuing marine transgression initiated during the uppermost Rhaetian. The overlying Blue Lias Formation (Hettangian–earliest Sinemurian) yields low diversity foraminiferal and ostracod faunas. The former is dominated by calcareous benthonic taxa, notably the Nodosaridae (*Lenticulina, Lingulina, Marginulina*), with localized peaks of the Involutinidae (*Involutina liassica*) and Epistominidae (*Reinholdella dreheri*). Ostracods are dominated by *Ogmoconcha* and *Ogmoconchella* spp. (albeit in low diversity), with subsidiary Cytheracea (e.g. *Kinkelinella translucens*). Echinoderm debris, microgastropods and bivalves occur in large numbers throughout this interval. A shallow, slightly deeper, low energy, well-oxygenated open marine (inner to middle shelf) environment is envisaged. The occurrence of common specimens of *Reinholdella dreheri* at 1754 m (swc) suggests either a slight shallowing or a period of marine restriction. The high abundance of metacopid ostracods within this interval and the low diversity and abundance of foraminifera (which occurs throughout northwest Europe) has been interpreted as the colonization of a transgressive sea by an opportunistic and successful group of organisms.

The Lower Sinemurian can be subdivided into two units. The lowermost part of the Pabay Shale Formation of intra-Early Sinemurian age is marked by large numbers of agglutinating foraminiferids (squashed *Haplophragmoides* spp.) occurring as three distinct peaks. Calcareous benthonic foraminifera, notably the Nodosaridae and the Polymorphinidae, occur in smaller numbers. This is associated with a marked decline in the ostracod faunas, especially with respect to the Metacopina. Although rare, the ostracod assemblages comprise mainly smooth-walled ostracods of the Bairdiidae and Cyprididae (*Bairdia, Isobythocypris, Pseudomacrocypris* and *Cardobairdia*). This association of faunal elements may suggest localized events of slightly reduced (dysaerobic) oxygen conditions upon the sea floor, within a dominantly shallow marine (inner to middle shelf) environment. Bottom water conditions are envisaged to have ameliorated during the latest part of the Early Sinemurian, denoted by a marked increase in the ostracod faunas, notably the ornate Cytheracea (*Ektyphocythere*). The foraminiferal faunas, however, remain sparse both in diversity and abundance, with no particular group dominating the assemblages. An increase in calcareous benthonic foraminiferal diversity and abundance occurs in the earliest part of the Late Sinemurian,

suggesting moderate to good bottom water conditions, within an inner to mid-shelf environment. The foraminiferal faunas are dominated by the Nodosaridae, notably *Dentalina, Lenticulina, Lingulina* and *Marginulina,* reaching an abundance of 64 specimens at 1273 m. The ostracods mirror this increase in numbers within this early part of the Late Sinemurian, with the assemblages again dominated by *Ektyphocythere,* in association with subsidiary smooth forms, notably *Paracypris* and *Ogmoconchella*. Within the early part of the Late Sinemurian, both diversity and abundance of the calcareous benthonic foraminiferids and ostracods decreases; however, agglutinating foraminifera (*Ammodiscus, Haplophragmoides* and *Trochammina*) achieve numerical significance, indicating some basin restriction within the inner to middle shelf environment. Similarly the macrofaunas (bivalves, microgastropods and echinoderm debris) are only recovered in small numbers, again suggesting dysaerobic bottom waters at this time. Microfaunal recovery within the Hallaig Sandstone Member equivalent is also poor. Deposition is envisaged to have been within a shallow, inner shelf marine environment. The uppermost Sinemurian sediments yield diverse and abundant macro- and microfaunas, with deposition in a well oxygenated inner shelf, shallow marine environment. The foraminiferal assemblages are dominated by calcareous benthonic taxa, notably the Nodosaridae (*Lenticulina, Dentalina, Lingulina* and *Marginulina*), reaching a peak abundance of 71 specimens at 969 m and a peak diversity of 20 species at 991 m. Agglutinating taxa only comprise a tiny fraction of the total fauna. Ostracod faunas also increase in both diversity and abundance towards the Sinemurian–Pliensbachian boundary, with up to 20 specimens. The assemblages are dominated by the ornate Cytheracea (*Ektyphocythere, Pleurifera, Grammanicythere*), in association with smooth forms, notably the Metacopina (*Ogmoconchella*).

Microfaunal diversity and abundance dramatically decline within the earliest Pliensbachian, suggesting restricted water circulation within an inner to mid-shelf environment. This is supported by the occurrence of large numbers of microgastropods within this interval. Midway through the Early Pliensbachian (top Pabay Shale Formation), conditions ameliorated, denoted by an increase in microfaunal recovery. Similar to the Late Sinemurian interval, the foraminiferal faunas almost exclusively comprise calcareous benthonic taxa, dominated by the Nodosaridae (*Lenticulina*, *Marginulina*) and the Polymorphinidae. Although generally rarer than the foraminifera, a marked peak in ostracod abundance (35 specimens) occurs at 747 m. The ostracods are dominated by the Metacopina, notably *Ogmoconcha, Ogmoconchella*, in association with the ornate genus *Gammacythere*. A marked decline in microfauna, associated with large numbers of both echinoderm debris and microgastropods, occurs within the basal part of the Scalpa Sandstone equivalent of earliest Late Pliensbachian age. A shallow marine, partly restricted and/or shallow water environment is suggested. A marked increase in diversity and abundance occurs within the latest Pliensbachian, with the foraminiferal assemblages dominated by rich calcareous benthonic faunas, including the Nodosaridae (*Dentalina*, *Frondicularia*, *Lenticulina, Lingulina*, *Marginulina*, *Saracenaria*) and the Bolivinitidae (*Brizalina liasica*). Although rare, agglutinating taxa are dominated by *Haplophragmoides* and *Trochammina*. Late Pliensbachian ostracods are moderately common, again dominated by smooth-walled taxa, including the Cypprididae (*Cardobairdia*), and the Metacopina (*Ogmoconcha, Ogmoconchella* and *Pseudohealdia*). Deposition of the Scalpa Sandstone equivalent is envisaged to have occurred within shallow (inner shelf) open marine, well oxygenated environments, distal to an arenaceous source.

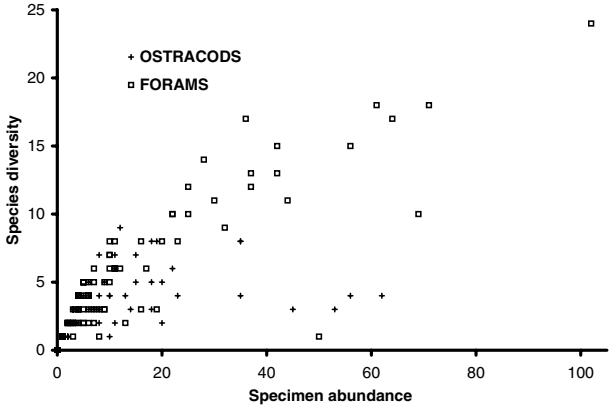

Fig. 5. The number of specimens recorded is plotted against the number of species for both foraminifera and ostracods in each sample. The record for both groups indicates that the small samples investigated do not yield fully representative assemblages. It is commonly accepted that a sample of 300 individuals is required. The ostracods remain at particularly low diversity levels throughout, even in the most abundant samples.

CONCLUSIONS

Exploration well L134/5-1 has yielded an extensive Triassic to Lower Jurassic sequence, which contains a valuable biostratigraphical record permitting correlation with contemporaneous sites throughout much of NW Europe. Although the Rhaetian sediments were barren of microfaunas, the Hettangian to Upper Pliensbachian yields a rich and diverse foraminiferal and ostracod fauna. A total of 100 taxa, comprising 11 agglutinating and 44 calcareous benthonic foraminifera, in association with 45 species of ostracod, are recorded. A number of taxa are envisaged to be new, however, poor preservation precludes a complete taxonomic review of this material. Not surprisingly, many of the microfaunal assemblages possess very strong similarities to those described from the west coast of Scotland, the Mochras Borehole, Fastnet and North Celtic Sea basins, as well as southern England and the various North Sea basins. Faunal comparisons can also be made further afield to those of France, Germany, Portugal and Sweden.

The environment of deposition was entirely marine from the earliest Hettangian through to the Late Pliensbachian, but a combination of local tectonic controls and eustatic changes in sea-level caused a number of abrupt changes in faunal diversity, turnover and assemblage composition. It has not been possible to ascertain the relative impact of each of these dynamic processes upon the microbenthos. Figure 5 indicates that ostracod diversity remains low despite increasing sample size, whereas the foraminiferal diversity increases with abundance.

The Early Jurassic Hebrides microfossil record can be summarized as follows.

- The Hettangian to earliest Sinemurian interval is characterized by relatively high ostracod abundance dominated by the Metacopina; this is a similar pattern to elsewhere in Europe. The single Triassic sample examined is barren of ostracods and foraminifera.
- The Early Sinemurian marks a switch to low abundance Cyprididae/Bairdiidae-dominated assemblages, with relatively high proportions of agglutinating foraminifera. This is followed by a period dominated by cytheracean ostracods.
- The Late Sinemurian witnesses two peaks in diversity and abundance of both foraminifera and ostracods between the depths 1000 m and 1300 m. These peaks are dominated by metacopine ostracods and calcareous benthonic foraminifera.
- The Early Pliensbachian yields poor foraminiferal assemblages, but with a peak in ostracod diversity and abundance at about 750 m; subsequently diversity and abundance of both groups falls sharply.
- The Late Pliensbachian interval is characterized by increasing biodiversity, dominated by metacopine ostracods and calcareous benthonic foraminifera.

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REFERENCES

Ainsworth, N. R. 1987. Pliensbachian Ostracoda from the Fastnet Basin, offshore southwest Ireland. *Bulletin of the Geological Survey of Ireland*, **4**: 41–62.

Ainsworth, N. R. 1989a. Systematic description of new ostracod species, in Rutherford, M. M. & Ainsworth, N. R. Micropalaeontological and stratigraphical recognition of the Triassic/Jurassic boundary in the North Celtic Sea and Fastnet Basins. *In* Batten, D. J. & Keen, M. C. (Eds), *Northwest European Micropalaeontology and Palynology*, 56–65. Ellis Horwood, Chichester.

Ainsworth, N. R. 1989b. Rhaetian, Hettangian and Sinemurian Ostracoda from the Fastnet Basin offshore Southwest Ireland. *Bulletin of the Geological Survey of Ireland*, **4**: 107–150.

Ainsworth, N. R. 1990. Uppermost Rhaetian to lower Bajocian Ostracoda from the Porcupine, Slyne, Erris and Donegal Basins, offshore West Ireland. *Bulletin of the Geological Survey of Ireland*, **4**: 169–200.

Ainsworth, N. R. & Horton, N. F. 1986. Mesozoic micropalaeontology of exploration well Elf 55/30-1 from the Fastnet Basin, offshore southwest Ireland. *Journal of Micropalaeontology*, **5**: 19–29.

Ainsworth, N. R., O'Neill, M., Rutherford, M., Clayton, G., Horton, N. F. & Penney, R. A. 1987. Biostratigraphy of the Lower Cretaceous, Jurassic and uppermost Triassic of the North Celtic Sea and Fastnet Basins. *In* Brooks, J. & Glennie, K. (Eds), *Petroleum Geology of North West Europe*, 611–622. Graham & Trotman, London.

Ainsworth, N. R., O'Neill, M. & Rutherford, M. M. 1989. Jurassic and Upper Triassic Biostratigraphy of the North Celtic Sea and Fastnet Basins. *In* Batten, D. J. & Keen, M. C. (Eds), *Northwest European Micropalaeontology and Palynology*, 1–44. Ellis Horwood, Chichester.

Ainsworth, N. R., Braham, W., Gregory, F. J., Johnson, B. & King, C. 1998. A proposed latest Triassic to earliest Cretaceous microfossil biozonation for the English Channel and its adjacent areas. *In* Underhill, J. R. (Ed.), *Development, evolution and Petroleum Geology of the Wessex Basin*. Geological Society, London, Special Publications, **133**: 87–102.

Apostolescu, V. 1959. Ostracodes du Lias du Bassin de Paris. *Revue de L'Institut Francais du Pètrole*, **14**: 795–826.

Bang, I. 1968. Biostratigraphical investigations of the pre-Quaternary in the Oresund boreholes mainly on the basis of foraminifera. *In* Larsen, G., Buch, A., Christensen, O. B. & Bang, I. (Eds), *Oresund, Helsingor–Halsingborgslinien, Geologisk Rapport*, 86–88. Rapport Danmarks Geologiske Undersøgelse.

Bang, I. 1971. Jura aflejringerne I Ronde Nr1 (2103-2164M). Biostratigrafi pa grundlag af foraminiferen. *Danmarks Geologiske Undersøgelse*, **39**: 74–80.

Bang, I. 1972. Jura biostratigrafi I Novling Nr1 pa grundlag af foraminiferen. *Danmarks Geologiske Undersøgelse*, **40**: 119–123.

Barnard, T. 1950. Foraminifera from the Lower Lias of the Dorset Coast. *Quarterly Journal of the Geological Society of London*, **105**: 347–391.

Barnard, T. 1956. Some Lingulinae from the Lias of England. *Micropaleontology*, **2**: 271–282.

Barnard, T. 1957. Frondicularia from the Lower Lias of England. *Micropaleontology*, **3**: 171–181.

Barnard, T. 1960. Some species of Lenticulina and associated genera from the Lias of England. *Micropaleontology*, **6**: 41–55.

Bartenstein, H. & Brand, E. 1937. Mikropaläontologische Unterschungen zur Stratigraphie des nordwestdeutschen Lias und Doggers. *Abhandlungen Herausgegeben von der Senckenbergischen Naturforschenden Gesellschaft*, **439**: 1–224.

Binns, P. E., McQuillin, R., Fannin, N. T. G., Kenolty, N. & Ardus, D. A. 1975. Structure and stratigraphy of the sedimentary basins in the Sea of the Hebrides and the Minches. *In* Woodland, A. W. (Ed.), *Petroleum and the Continental Shelf of North-West Europe*, 93–102. Applied Science Publishers, Barking.

Bizon, G. 1960. Révision de quelques espèces-types de foraminiféres du Lias du Bassin Parisien de la collection Terquem. *Revue de Micropaléontologie*, **3**: 3–18.

Boomer, I. D. 1990. On *Gammacythere klingleri* Boomer sp. nov. *Stereo-Atlas of Ostracod Shells*, **17**: 77–80.

Boomer, I. D. 1991. Lower Jurassic Ostracod biozonation of the Mochras Borehole. *Journal of Micropalaeontology*, **9**: 205–218.

Boomer, I. & Ainsworth, N. R. in press. Early Jurassic. *In* Athersuch, J., Keen, M. C. & Wilkinson, I. P. (Eds), *A Stratigraphical Atlas of British Ostracoda* 2. British Micropalaeontological Society .

Boomer, I., Ainsworth, N. R. & Exton, J. 1998. A re-examination of the Pliensbachian and Toarcian Ostracoda of Zambujal, west-central Portugal. *Journal of Micropalaeontology.*, **17**: 1–14.

Brouwer, J. 1969. Foraminiferal assemblages from the Lias of N. W. Europe. Verlandelingen der Koninklinjke Netherlandsche (Nederlandse) Akademie van Wetenschappen, Amsterdam. *Afdeeling Natuurkunde*, **25**: 1–48.

Clark, A. R. 1969. *The Ostracoda of the Scottish Lias*. PhD thesis, University of London.

Colin, J.-P., Ionnoides, N. S. & Vining, B. 1992. Mesozoic stratigraphy of the Goban Spur, offshore south-west Ireland. *Marine and Petroleum Geology*, **9**: 527–541.

Colloque sur le Lias Francais 1961. *Memoire du Bureau de Recherche géologiques Miniéres* **4**.

Copestake, P. & Johnson, B. 1984. Lower Jurassic (Hettangian–Toarcian) Foraminifera from the Mochras borehole, North Wales (U. K.) and their application to a worldwide biozonation. *Benthos '83. Second International Symposium on Benthic Foraminifera Pau, April 1983*, 183–184.

Copestake, P. & Johnson, B. 1989. The Hettangian to Toarcian. *In* Jenkins, D. G. & Murray, J. W. (Eds), *Stratigraphical Atlas of Fossil Foraminifera* 2, 129–189. British Micropalaeontology Society/Ellis Horwood Limited, Chichester.

Donze, P. 1967. Les Ostracodes du Sondage de Laneuveville-devant-Nancy (Lotharingen de la region type). *Sciences de la Terre*, **12**: 71–90.

Donze, P. 1985. Lias Inférieur et Moyen. *In* Oertli, H. J. (Ed.), *Atlas des Ostracodes de France*. Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine, Mémoires, **9**: 101–117.

Drexler, E. 1958. Foraminiferen und Ostracoden aus dem Lias von Siebeldingen/Pfalz. *Geologisches Jahrbuch*, **75**: 475–554.
Exton, J. 1979. *Pliensbachian and Toarcian Microfaunas of Zambujal, Portugal: Systematic Paleontology*. Geological Paper, **79**: 1–104 Carleton University, Ottawa.
Exton, J. & Gradstein, F. 1984. Early Jurassic stratigraphy and micropalaeontology of the Grand Banks and Portugal. *Geological Association of Canada Special Paper*, **27**: 13–30.
Field, R. A. 1968. *Lower Jurassic Ostracoda from England and Normandy*. PhD thesis, University of London.
Fyfe, J. A., Long, D. & Evans, D. 1993. *The Geology of the Malin–Hebrides Sea area*. United Kingdom offshore regional report, HMSO for the British Geological Survey, London.
Gründel, J. 1964. Zur Gattung Healdia (Ostracoda) und zu einiger verwandten Formen aus dem unteren Jura. *Geologie*, **13**: 456–477.
Hallam, A. 1959. Stratigraphy of the Broadford Beds of Skye, Raasay and Applecross. *Proceedings of the Yorkshire Geological Society*, **32**: 165–184.
Harloff, J. 1993. Ostracoden des Unter-Pliensbachiums in Baden-Württenberg. *Stuttgarter Beiträge zur Naturkunde, Serie B (Geologie und Paläontologie)*, **191**: 1–215.
Harris, J. P. 1989. The sedimentology of a Middle Jurassic lagoonal delta system: Elgol Formation (Great Estuarine Group), NW Scotland. *In* Whateley, M. K. G. & Pickering, K. T. (Eds), *Deltas: Sites and Traps for Fossil Fuels*. Geological Society, London, Special Publications, **41**: 147–166.
Harris, J. P. 1992. Mid-Jurassic delta systems in the Hebridean basins: thickness and facies distribution patterns of potential reservoir sandbodies. *In* Parnell, J. (Ed.), *Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution*. Geological Society, London, Special Publications, **62**: 111–144.
Herrig, E. 1985. Zur taxonomie und evolution der netzberippten Procytheridea-arten (Ostracoda) im Unteren Jura von Nordwest- und Mittel Europa. *Wiss. Z. Ernst-Moritz-Arndt-Univ. Griefswald, math-nat. wiss Reihe*, **34**: 45–50.
Hesselbo, S. P., Oates, M. J. & Jenkyns, H. C. 1998. The Lower Lias Group of the Hebrides Basin. *Scottish Journal of Geology*, **34**: 23–60.
Howarth, M. K. 1956. The Scalpa Sandstone of the Isle of Raasay. *Proceedings of the Yorkshire Geological Society*, **30**: 353–370.
Howarth, M. K. 1992. *The ammonite family Hildoceratidae in the Lower Jurassic of Britain*. Monographs of the Palaeontological Society.
Klingler, W. 1962. Lias Deutschlands. *Leitfossilien der Mikropaläontologie*. Gebrüder Borntraeger, Berlin-Nikolasse, 73–122.
Klingler, W. & Neuweiler, F. 1959. Leitende Ostracoden aus dem deutschen Lias B. *Geologisches Jahrbuch*, **76**: 373–410.
Lee, G. W. 1920. *The Mesozoic rocks of Applecross, Raasay and North-East Skye*. Memoir of the Geological Survey for Scotland,
Lord, A. R. 1978. The Jurassic, Part 1. (Hettangian–Toarcian). *In* Bate, R. H. & Robinson, J. E. (Eds), *A Stratigraphical Index of British Ostracoda* **1**: 189–212. Seel House Press, Liverpool.
Lord, A. R. & Bown, P. R. 1987. *Mesozoic and Cenozoic Stratigraphical Micropalaeontology of the Dorset Coast and Isle of Wight, Southern England*. Field guide for the Twentieth European Micropalaeontological Colloquium. British Micropalaeontological Society Field Guide, **1**.
Malz, H. 1971. Zur Taxonomie 'glattschaliger' Lias-Ostracoden. *Senckenbergiana Lethaea*, **52**: 433–455.
Malz, H. 1975. Eine Entwicklungsreihe "vallater" Ogmoconchen (Ostracoda) im S-deutschen Lias. *Senckenbergiana Lethaea*, **55**: 485–503.
Malz, H. & Lord, A. R. 1976. *Gammacythere* n.g. (Ostracoda) and its occurrence in the Lower Jurassic of N.W. Europe. *Senckenbergiana Lethaia*, **57**: 249–263.
Malz, H. & Nagy, J. 1989. Lower Jurassic ostracods from North Sea wells in the Norwegian Sector. *Sonderdruck aus CFS-Courier, Forschungsinstitut Senckenberg*, **113**: 61–75.
Michelsen, O. 1975. Lower Jurassic biostratigraphy and ostracods of the Danish Embayment. *Danmarks Geologiske Undersøgelse*, **104**: 1–287.
Morton, N. 1965. The Bearreraig Sandstone series (Middle Jurassic) of Skye and Raasay. *Scottish Journal of Geology*, **1**: 189–216.
Morton, N. 1983. Palaeocurrents and palaeo-environment of part of the Bearreraig Sandstone (Middle Jurassic) of Skye and Raasay, Inner Hebrides. *Scottish Journal of Geology*, **19**: 87–95.
Morton, N. 1989. Jurassic sequence stratigraphy in the Hebrides Basin, N. W. Scotland. *Marine and Petroleum Geology*, **6**: 243–260.
Norling, E. 1972. Jurassic stratigraphy and foraminifera of western Scania, southern Sweden. *Sveriges Geologiska Undersokning, Afhandlingar och Uppsatser*, **47**: 1–120.
Norvang, A. 1957. The Foraminifera of the Lias series in Jutland, Denmark. *Mededelingen Dansk, Geolisch Forening*, **13**: 1–135.
Oates, M. J. 1978. A revised stratigraphy for the western Scottish Lower Lias. *Proceedings of the Yorkshire Geological Society*, **42**: 143–156.
Park, S.-M. 1987. The ostracod Zones and Subzones of the Lower Jurassic in the southern North Sea Basin. *Journal of the Paleontological Society, Korea*, **3**: 44–70.
Partington, M. A., Copestake, P., Mitchener, B. C. & Underhill, J. R. 1993. Biostratigraphic calibration of genetic stratigraphic sequences in the Jurassic–lowermost Cretaceous (Hettangian to Ryazanian) of the North Sea and adjacent areas. *In* Parker, J. R. (Ed.). *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*, 371–386. Geological Society, London.
Ruget, C. H. 1985. Les foraminiferes (Nodosariides) du Lias de l'Europe Occidentale. *Documents de la Laboratoire de geologie de Lyon*, **94**: 1–273.
Ruget, C. H. & Sigal, J. 1967. Les Foraminiferes du Sondage de Laneuveville-devant-Nancy (Lotharingen de la region type). *Sciences de la Terre*, **12**: 33–70.
Ruget, C. H. & Sigal, J. 1970. Le Lias Moyen de Sao Pedro de Muel II. *Communicacoes dos Servicos Geologicos de Portugal*, **54**: 79–108.
Searl, A. 1992. Sedimentology and early diagenesis of the Broadford Beds (Lower Jurassic), Skye, north-west Scotland. *Geological Journal*, **27**: 243–270.
Sivhed, U. 1977. A Lower Jurassic ostracode fauna in the Gantofta brick pit, Skane, southern Sweden. *Sveriges Geologiska Undersokning, Afhandlingar och Uppsatser*, **71**: 1–31.
Sivhed, U. 1980. Lower Jurassic ostracodes and stratigraphy of western Skane, southern Sweden. *Sveriges Geologiska Undersokning*, **60**: 1–84.
Woodward, H. B. 1897. *Annual Report for 1896 of the Geological Survey and Museum of Practical Geology*, **70**.