# Jurassic sequences of the Hebrides Basin, Isle of Skye, Scotland

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## INTRODUCTION

The hebridean area is well known for the spectacular Palaeocene igneous rocks (plutons, dykes, sills and flood basalts) that form part of the North Atlantic large igneous province. The exposures of Mesozoic sedimentary strata of the Hebrides have been less widely appreciated, partly because they are perceived as having been extensively altered by thermal metamorphism. Whilst this is undoubtedly true locally, the bulk of the succession remains only weakly affected, and much of significance has been learned from it of Jurassic palaeoenvironments, biostratigraphy and magnetostratigraphy. Additionally, because of recent hydrocarbon exploration in the Mesozoic basins offshore west of Scotland and Ireland (Trueblood & Morton, 1991; Fyfe *et al.*, 1993; Stoker *et al.*, 1993; Scotchman & Thomas, 1995) these succession have assumed a new importance as the nearest easily accessible outcrop analogues.

There are already a number of excellent field guides to the geology of the Skye; e.g. Bell & Harris (1986) and Morton & Hudson (1995), and we strongly recommend that interested readers consult these works for details of access and background information. Elaborated graphic logs, summaries of previous work, and tables of strata are provided particularly in Morton & Hudson (1995) and a few other works cited below. Space here does not allow reproduction of these measured sections, which provide an essential framework for accurate sample collection. In the present guide, instead, we set out to provide an up-to-date summary of Jurassic successions in the Skye area of the Hebrides Basin, including new summary diagrams, and we highlight a selection of localities that illustrate the salient features of the succession. (The locality list is ordered stratigraphically: each locality has to be accessed as tides and weather conditions allow.) Along the way, we suggest sequence stratigraphic interpretations for the successions, and present a history of relative sea-level change implied on this basis.

The Hebrides Basin was subsident through the Triassic and Jurassic and the overall geometry is a

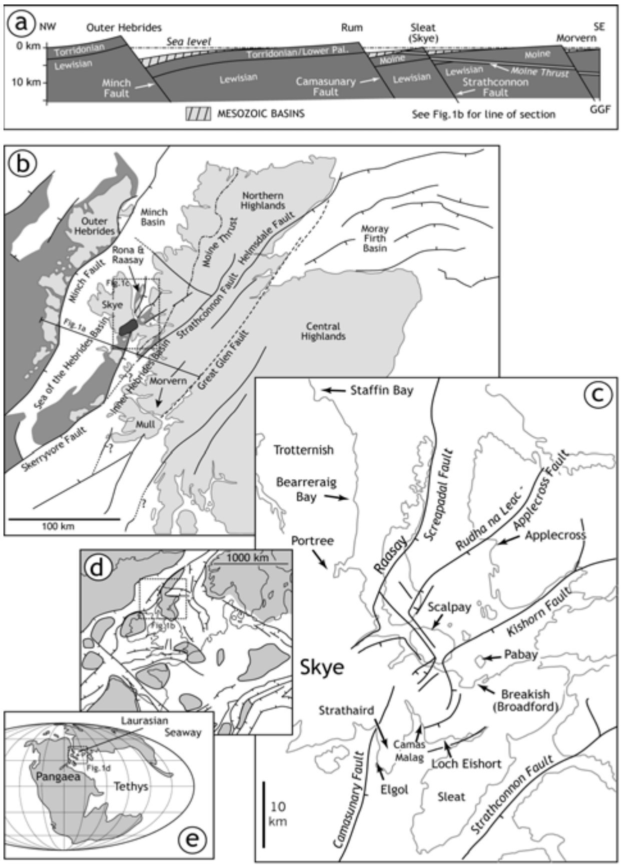



**Fig. 1.** Palaeogeography, structural setting and geological cross-sections of the Hebrides Basin. (a) Schematic Jurassic cross-section from the Outer Isles to the mainland SE of Skye, showing structural disposition of the main Mesozoic sedimentary basins (modified from Roberts & Holdsworth, 1999). (b) Structural map for the Hebrides basin and surrounding region basins (data from Fyfe *et al.*, 1993; Roberts & Holdsworth, 1999). Dark stipple indicates areas of pre-Mesozoic basement forming probable footwalls in extensional fault blocks; light stipple indicates present-day land areas. Very dark stipple indicates the Skye Palaeocene igneous centres. (c) Major structures in the vicinity of Skye and Raasay and their possible sense of motion in the Jurassic according to Butler & Hutton (1996). Many of these faults may in fact have been inactive in the Jurassic, and their affect on Jurassic sedimentation only passive by control of basement character. (d) Regional context of the Hebrides Basin; dark stipple indicates likely Jurassic land areas; Early Jurassic palaeogeography (Ziegler, 1990a). (c) Global context of the basins of the Laurasian seaway (Toarcian palaeogeography; Smith *et al.*, 1994). In all maps north is towards the top of the page.

NNE-SSW oriented half-graben delimited in the WNW by the Minch Fault (e.g. Binns *et al.* 1975; Stein, 1988; Figs 1a, b). However, the timing of fault

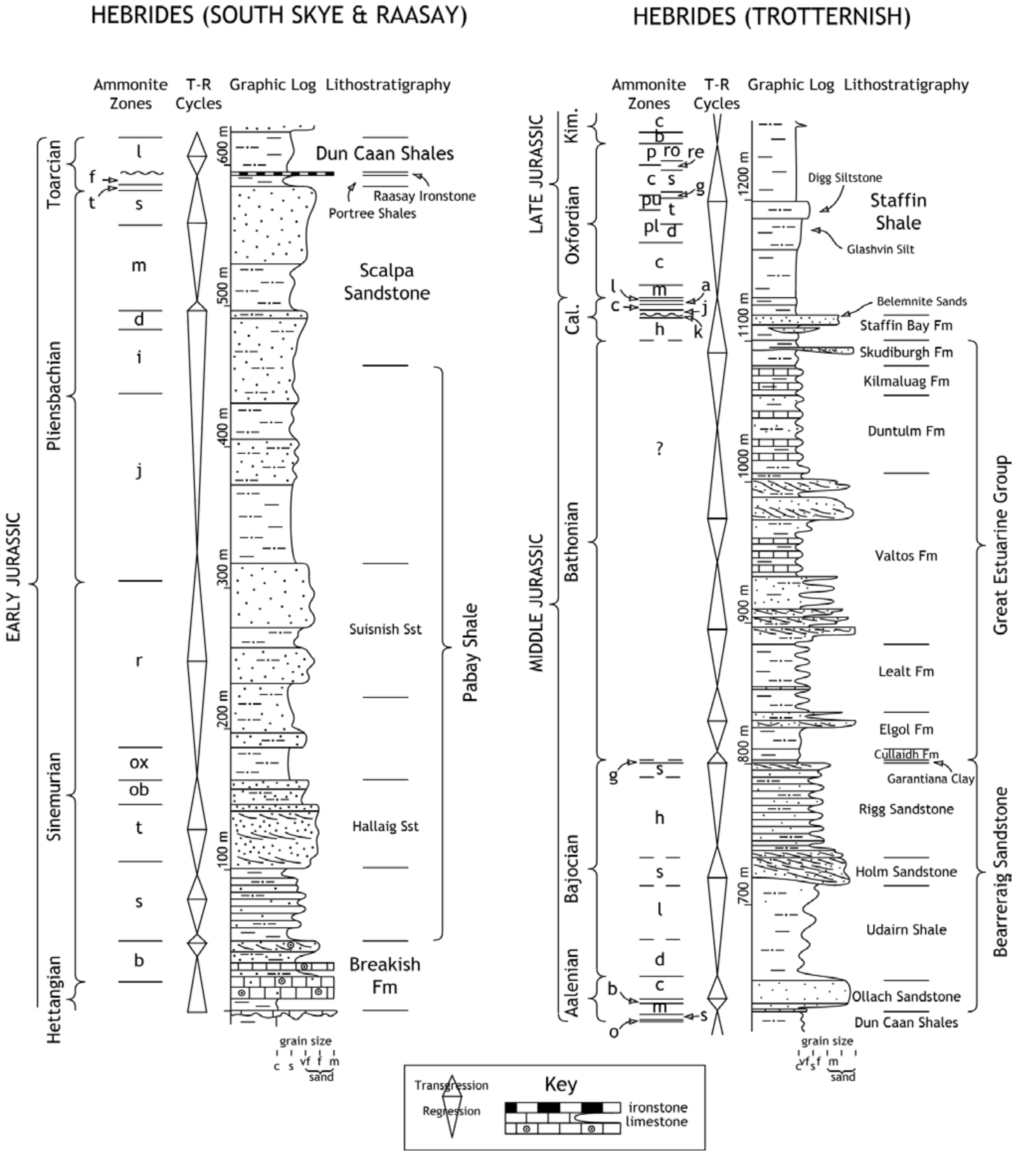
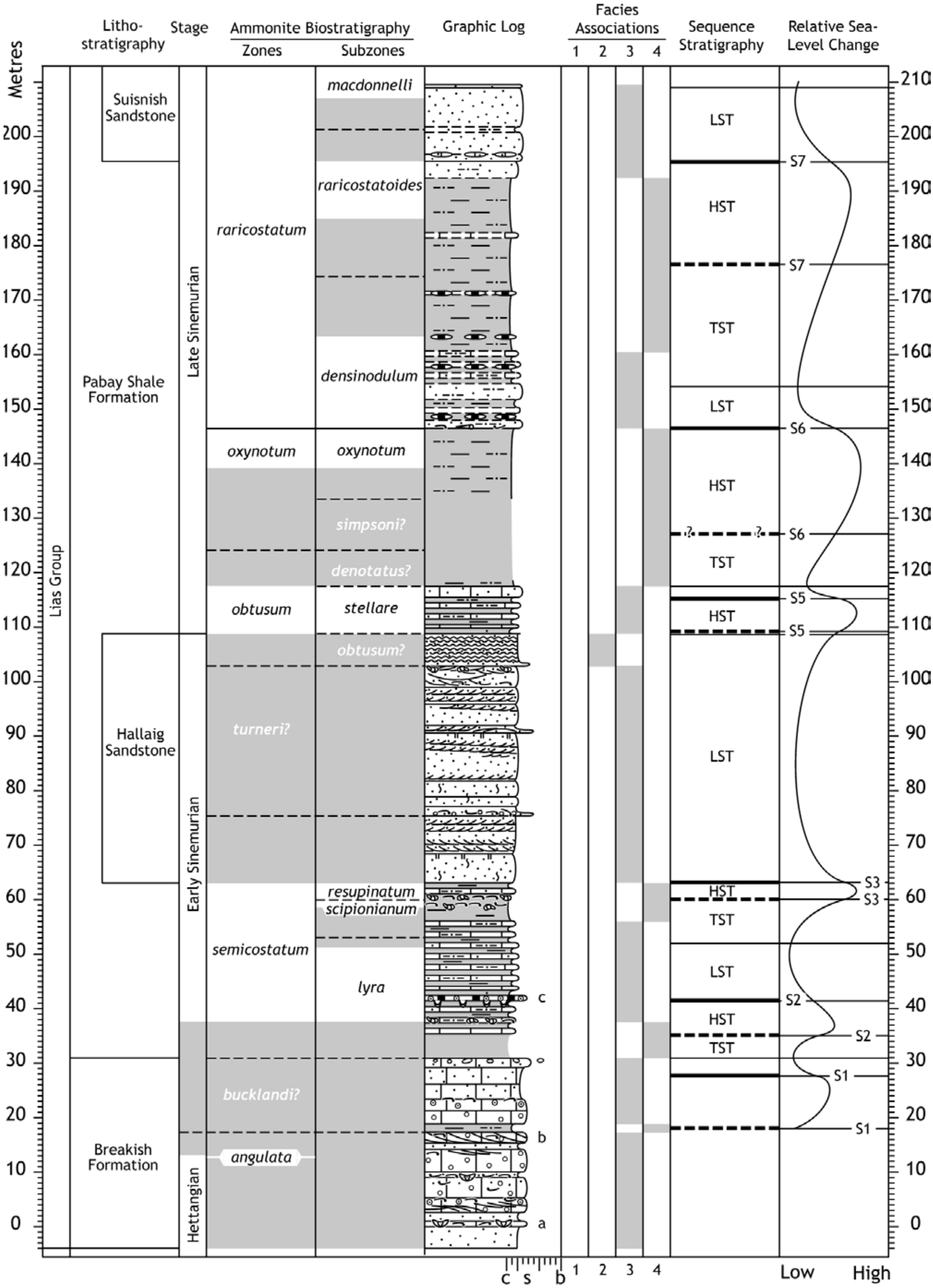



**Fig. 2.** Summary graphic logs for the Jurassic of the Hebrides Basin. See Figs. 3, 6, 9 & 12 for names of ammonite zones. Hettangian–Early Pliensbachian from Hesselbo *et al.* (1998); Late Pliensbachian from Howarth (1956); Aalenian–Bajocian from Morton in Morton & Hudson (1995) and own observations; Bathonian from Harris & Hudson (1980) and Harris (1989, 1992); Callovian–Kimmeridgian mainly from Sykes & Callomon (1979), Wright (1989), Hudson & Morton (1969), as summarized in Morton & Hudson (1995) and own observations.

**Fig. 3.** Summary graphic log for the Hettangian–Sinemurian of the Syke-Raasay area. Data sources and locations: -5–31 m, Ob Lusa, Skye, Hesselbo *et al.* (1998); 31–52 m, Ardnish, Skye, Hesselbo *et al.* (1998); 52–63 m, Hallaig Waterfall, Raasay, Hesselbo *et al.* (1998); 63–209 m, Loch Eishort, Skye, Hesselbo *et al.* (1998). a = Ob Lusa Coral Bed; b = Ob Breakish Coral Bed; c = Ardnish Ironstone. Summary log continued as Fig. 6. Dark shading in biostratigraphy columns indicates lack of age-diagnostic fossils.

movements within the basin is not yet well understood. Some authors, for example Butler & Hutton (1994) and Roberts & Holdsworth (1999) interpret the Mesozoic structure of the basin to comprise a series of active NNE–SSW aligned half-graben which, in the Inner Hebrides area, were defined by the Strathconnon, Camasunary and Skerryvore faults (Fig. 1b, c). Hence the basin is commonly subdivided into a western Sea of the Hebrides (– Little Minch) Basin and an eastern Inner Hebrides Basin (or Trough); and Middle Jurassic sedimentary facies and sequence development have been interpreted within this structural framework (e.g. Harris, 1989, 1992; Mellere & Steel, 1996). However, because clear evidence for thickness




Hebridean Basin, Loch Eishort, Skye, and Hallaig, Raasay changes at outcrop across these faults is not forthcoming, their synsedimentary status has been also been challenged, particularly for Early and Late Jurassic times (Morton & Hudson, 1995; Morton, 1999a). On the basis of gravity and seismic data, O'Neill & England (1994) interpret the Jurassic succession to have been accommodated largely by thermal subsidence.

In a wider palaeoceanographic context, the Jurassic seas of the Hebrides Basin form part of a network of narrow waterways that connected Tethys in the south to the Boreal ocean in the north (e.g. see Ziegler 1990a, 199b; Hesselbo, 2000; Fig. 1d), the whole recently named the Laurasian Seaway (C.J. Bjerrum, pers comm.; Fig. 1e). The marine connections between polar and equatorial water masses through the seaway were established and broken several times during the Jurassic.

Contrasts and comparisons with North Sea basins can be instructive. The Hebrides Basin is dissimilar to the North Sea in that the footwalls of Mesozoic faults have not been buried by Late Cretaceous and Cenozoic sediment, and instead remain upstanding as topographic highs. This pattern is explained by Brodie & White (1994) as produced partly by igneous underplating below the hebridean region. Kinematically, development of the Hebrides Basin has been linked to coeval development of the Moray Firth Basin in the north-eastern North Sea (Underhill, 1991, 1994; Thompson & Underhill, 1993; Wignall & Pickering, 1993, 1994) through activity on major faults exposed onshore in Scotland, particularly the Strathconnon Fault (Roberts & Holdsworth, 1999; Fig. 1b). A major influence on stratigraphic patterns in the North Sea area was domal or rift-related uplift associated with central North Sea igneous activity in the Middle Jurassic (Ziegler, 1990a, b; Underhill & Partington, 1993). Although it has been suggested that features of hebridean stratigraphy are explicable in the context of the same domal uplift (development of shallow-water sandstones in the Early–Middle Jurassic: Underhill & Partington, 1993), similar facies occur widely across northern and western Europe at these times, indicating the importance of mechanisms operating over even wider areas (e.g. Nielsen, 2000).

In the area of Skye and Raasay, deposition occurred through most Jurassic stages. Depositional rates were demonstrably highest in two phases – the Sinemurian to Pliensbachian and the Bajocian to Bathonian – with the intervening intervals being relatively thin (Fig. 2). Condensation in the Toarcian and from the Callovian onwards may be explained by regional sediment starvation that occurred as the basin continued to deepen. Condensation during the Aalenian, in contrast, may be related to regional shallowing because the basal sandy facies of the Bearreraig Sandstone are of shallow-water origin (e.g. Mellere & Steel, 1996). The Jurassic succession is truncated near the base of the Kimmeridgian strata by the overlying Palaeocene igneous rocks.

**Fig. 4.** Keystone vugs in limestone from the Breakish Formation, Borreraig, Loch Eishort, south Skye (from the top of Bed 3, Loch Eishort section; Hesselbo *et al.*, 1998, p.34, probable Hettangian age). Early gravity cements and geopetal micrite ponds are clearly visible in fenestrae that occur between aggregate grains bound together by dark meniscate cements. Field of view = 2 mm.

**Fig. 5.** Lowest beds of the Pabay Shale Formation, Borreraig, Loch Eishort (Beds 1–6 of Hesselbo *et al.*, 1998, p.34). The prominent dark shale interval is of early Sinemurian age, probably belonging to the *lyra* Subzone (*semicostatum* Zone) and it represents an important phase of rapid regional relative sea-level rise in the UK area (e.g. see Hesselbo & Jenkyns, 1998).

There is no evidence for Tithonian sediments from the outcrops on Skye, but there is a small isolated pocket of Cretaceous- rocks on the Strathaird peninsular.

## EARLY JURASSIC

### Summary

The earliest Jurassic deposits of the Skye–Raasay area are mixed carbonate and siliciclastic sediments of shallow-water origin. These make up the Breakish Formation and are Hettangian to earliest Sinemurian age (Morton, 1999b; cf. Hesselbo *et al.*, 1998; Morton, 1999a; Fig. 3). Evidence for deposition between storm-wave base and the backshore is present in the form of features such as hummocky cross-stratification in the sandstones

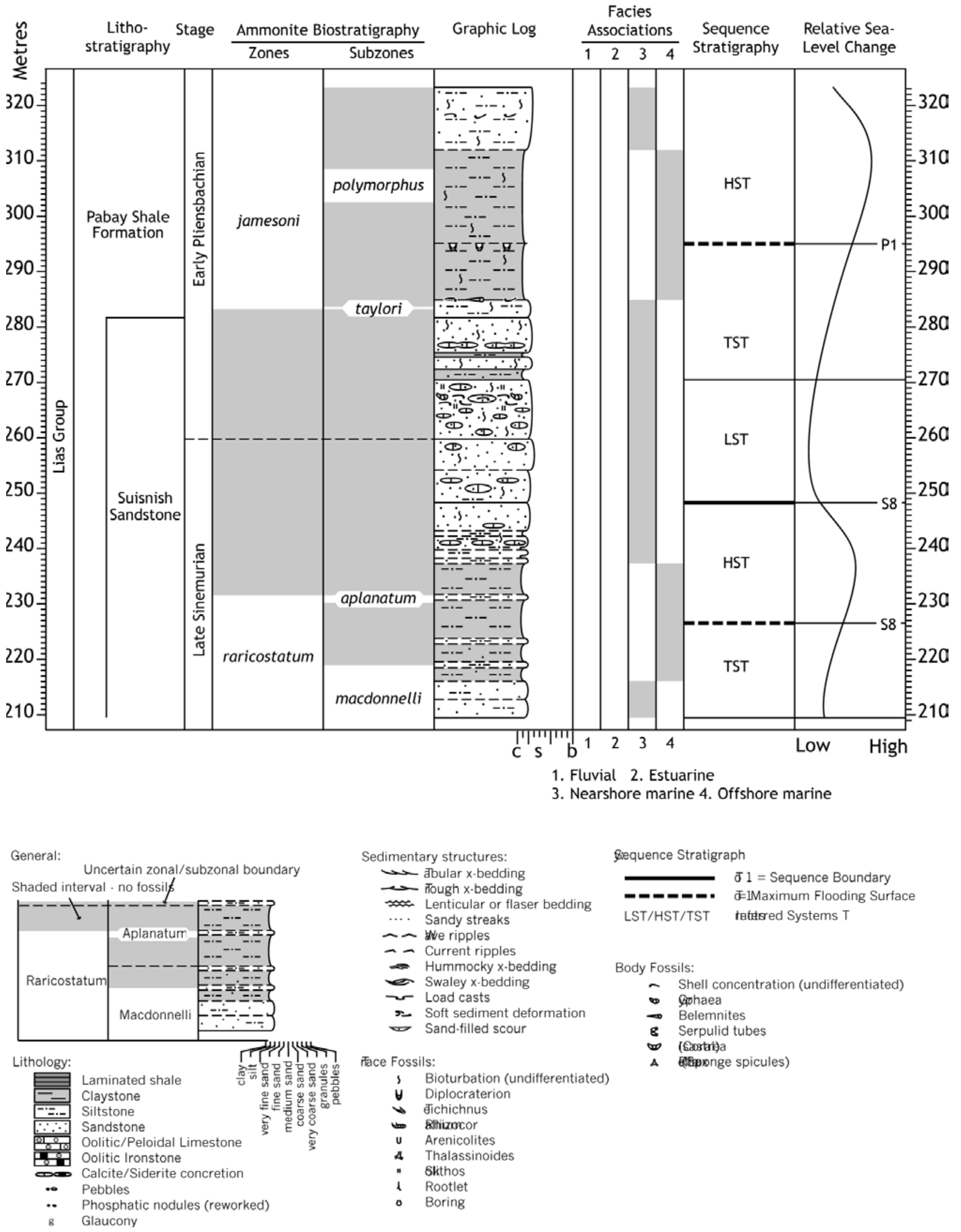



**Fig. 6.** Continuation from Fig. 3. Summary of the Sinemurian–Pliensbachian boundary section at Rubha Suisnish between Loch Eishort and Loch Slapin, and in the mountainside at Allt Cul an Dùin, above Loch Eishort (sections J and K of Hesselbo *et al.*, 1998). Dark shading in biostratigraphy columns indicates lack of age-diagnostic fossils.

and keystone vugs in oolitic and peloidal limestones (Fig. 4; cf. Searl, 1992, 1994); well developed coral beds are also known and have proved useful for correlation (Fig. 3). The occurrence of these littoral facies is localized, and they may be viewed as shallow-water fringes developed around basement highs, much as is the case in other basins further to the south of Britain (e.g. Trueman, 1922). Alternations between carbonate and quartz-sand occur through the succession, which may signify either climatic changes, or sea-level fluctuations that influenced sediment supply. A widely correlatable argillaceous interval within the upper part of the succession is interpreted as a response to relative sea-level rise within the *bucklandi* Zone, and the upward termination of the formation in pebbly coarse-grained facies is interpreted to signify relative sea-level fall at the end of the *bucklandi* Zone (Hesselbo & Jenkyns, 1998; Fig. 3). Shallow-water facies of the Breakish Formation pass southwards into offshore-marine limestone–marl interbeds of the Blue Lias Formation (Oates, 1978; Hesselbo *et al.*, 1998; Morton, 1999a).

The abrupt transition to deeper water argillaceous facies at the base of the Pabay Shale Formation is the local expression of a major regional deepening that took place in the early Sinemurian, *semicostatum* Zone (Fig. 3 & 5; Hesselbo & Jenkyns, 1998). At this time, local basement highs, such as the Ordovician-age Durness Limestone at Camas Malag, were permanently submerged beneath the Jurassic sea (e.g. Farris *et al.*, 1999). With this major relative sea-level rise the dominant siliciclastic character of the basin was established, and it persisted for the remainder of the Jurassic. Although the Pabay Shale is predominantly mudstone, commonly rather silty, in the Skye-Raasay area sand deposition occurred in two phases: in the mid Sinemurian manifested as the tidally influenced and possibly estuarine Hallaig Sandstone; and at about the Sinemurian–Pliensbachian boundary, evident as the bioturbated fully marine Suisnish Sandstone (Fig. 3). Additionally, less pronounced coarsening–fining sedimentary cycles occur; these are interpreted as depositional sequences as shown in Figure 3. In general, the strata making up the Pabay Shale are well dated on the basis of ammonites (Oates, 1978; Hesselbo *et al.*, 1998).

It should be noted that the lithostratigraphic nomenclature for this mid-Sinemurian part of the succession is unsettled. It has been proposed (Hesselbo *et al.*, 1998) that the Pabay Shale Formation should encompass all strata formerly called Pabba Shale, and also strata formerly called "Upper Broadford Beds". Sand bodies, of various ages, sandwiched within offshore mudstones could then be assigned to local members within the formation (e.g. the Hallaig and Suisnish members of the Skye–Raasay area). Hesselbo *et al.* (1998) proposed this scheme because the top of the "Upper Broadford Beds" could only be recognized in the Skye–Raasay area and the unit is useless when applied to exposures in the south of the basin, around Mull and Morvern (Fig. 1). However, Morton (1999a) prefers simply to replace the name "Upper Broadford Beds" with "Ardnish Formation". Nevertheless, in the present work we persevere with the revised scheme of Hesselbo *et al.* (1998), slightly modified as suggested by Morton (1999b), in the belief that it will be workable over a larger geographic area.

Following on from deposition of the Suisnish Sandstone, a mud-dominated marine environment was again established at the beginning of the Pliensbachian which persisted through the Early Pliensbachian (Phelps, 1985; Fig. 2). These facies are similar to older Pabay Shales in comprising ammonite-bearing silty mudstones with rather low organic content. The Pabay Shale is terminated abruptly with deposition of the Scalpa Sandstone (more abruptly in the south of the basin than in the north). The age of this regionally extensive shallow-marine unit is Late Pliensbachian (Howarth, 1956). Both the major deepening phase at the beginning of the Pliensbachian, and the later shallowing in the Late Pliensbachian are effectively synchronous over a remarkably wide region within the Laurasian seaway (Sellwood, 1972; Howarth, 1956); they betoken a significant tectonic–eustatic sequence of events that are not obviously linked to movements on individual fault systems (Hesselbo & Jenkyns, 1998).

As a response to global events, a major change took place in the Hebrides Basin at the start of the

**Fig. 7.** Top of Susinish Sandstone Member and mudstones of the basal *jamesoni* Zone, Pabay Shale Formation, Allt Cul an Dùin (Hugh Jenkyns [arrowed] for scale, upper right).

Toarcian. The succession of strata that make up the Toarcian section comprises organic-rich shale of the Portree Shales, oolitic ironstone of the Raasay Ironstone, and silty shale and mudstone of the Dun Caan Shale (Fig. 2). Although the Dun Caan Shale is sometimes grouped with the overlying Bearreraig Sandstone, because of its age and lithology it is better regarded as part of an argillaceous Toarcian lithostratigraphic package. There are a number of records of ammonites through these units that show that the succession is highly incomplete, particularly in the mid Toarcian to late Toarcian (Smith, 1996, and references therein).

Organic-rich shales occur globally at the start of the Toarcian (*tenuicostatum* to *falciferum* zones) and characterize the Early Toarcian oceanic anoxic event – a palaeoceanographic happening of unique severity in the Jurassic which coincided with the formation of the southern hemisphere Karoo–Ferrar large igneous province, possible massive dissociation of methane-hydrate in continental margin sediments, a palaeotemperature maximum, and mass extinction (Jenkyns, 1988; Hesselbo *et al.*, 2000; Pálfy & Smith, 2000).

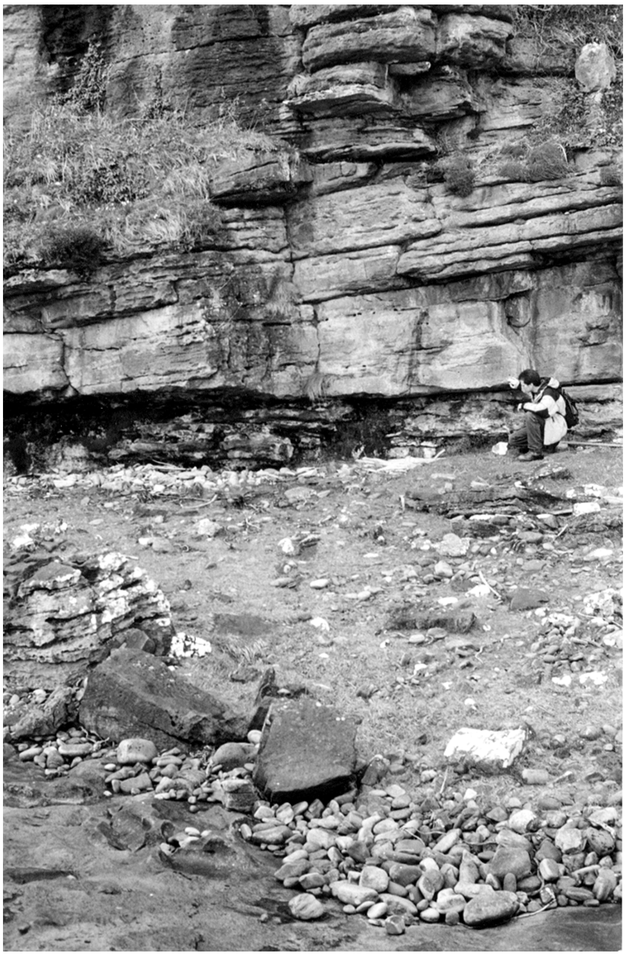


**Fig. 8.** Pliensbachian to Aalenian succession, close to Dun Liath, Strathaird. Christian Bjerrum marks the position of the Raasay Ironstone, and his right hand rests on the base of the Bearreraig sandstone. Rock in the bottom left of the picture is uppermost Scalpa Sandstone.

## Localities

### *Borereraig, Loch Eishort*

Hettangian–Sinemurian rocks are well exposed along the shore and in stream sections along the north side of Loch Eishort, south Skye. The abandoned village of Boreraig, is reached from Kilchrist (NG 620 208) via a rugged 3.5 km long hill-track, through the former Skye Marble workings, and then alongside the Allt na Pairte and Allt na Peighinn. Early Jurassic rocks are exposed in faulted blocks on the shore and in cliffs between NG 626162 and NG 605158. Detailed measured sections and precise locality data are given in Hesselbo *et al.* (1998). The sections are repeated several times by faults, which are not always obvious. Hence, previous accounts have tended to overestimate the thicknesses of the various units. Of particular note are good exposures of the Breakish Formation on the small headland between NG 625160 and NG 624162; the *semicostatum*-Zone transgressive phase at the base of the Pabay Shale Formation at NG 623163 (Fig. 5), and the tidally influenced facies of the Hallaig Sandstone at NG 605158. On the basis of comparisons with age-equivalent sections at Broadford and on Raasay, Hesselbo *et al.* (1998) suggested that the Hallaig Sandstone at Loch Eishort may fill an incised valley, but exposure of the base of the unit is too poor to allow more than speculation from the outcrop geology.

A further two kilometre walk along the coast path westwards allows examination of the Suisnish Sandstone at Rubha Suisnish. Access to the cliff exposures at low tides can be achieved to the south of Stac Suisnish a couple of hundred metres north of the point itself (having first ascended the path up the hillside below Càrn Dearg), or along the foreshore from the east below Càrn Dearg. The thoroughly bioturbated sandstone here is locally crinoidal, and the better-cemented horizons have been quarried.

Return to Kilchrist is possible via a 5-km-long high-level path from Suisnish, or directly from Boreraig if the section at the point is omitted.

### *Camas Malag, Loch Slapin*

The basal Lias and its relationship to the basement are seen south of Camas Malag, on the NE side of Loch Slapin. Access is on foot along a rough road from Camas Malag which can be reached in vehicles from the road junction at NG 594 202. Exposures here have been extensively described and discussed by Steel *et al.* (1975), Nicholson (1978) and Farris *et al.* (1999). The strata are strongly metamorphosed in the aureole of the Palaeocene Beinn an Dubhaich granite. Red-coloured siliciclastic sediments occur in large pods within the metamorphically mobilized Durness Limestone at NG 584 186 and these may be of a modified karst-fill origin. Further south, at NG 585 183 a bored limestone breccia of Jurassic age sits within and above a karst surface on the Durness limestone. This breccia is the age of the Breakish Formation elsewhere (cf. Farris *et al.*, 1999). It is unlikely that exposures here were separated from those at Loch Eishort by any significant Jurassic synsedimentary fault

*Dun Liath, Strathaird*

Some small-scale roadside exposures of the Pliensbachian–Toarcian rocks occur along the eastern side of the Strathaird Peninsula (see Morton & Hudson (1995) for details), but the Scalpa Sandstone to basal Bearreraig Sandstone succession is also relatively well exposed on the shore and raised beach below Drinan (Fig. 8; NG 5486 1488 to 5467 1466). The Scalpa Sandstone here is generally well bioturbated and contains marine fossils such as belemnites and pectiniid bivalves. The raised-beach platform exploits the easily eroded Portree Shales, which is here very thin (about 1.5 m). The Raasay Ironstone, a chamositic ooidal ironstone <1 m thick, occurs here in a cross-bedded facies; it contains the ammonite *Dactylioceras* and, particularly at the top, abundant belemnites. Lying erosionally

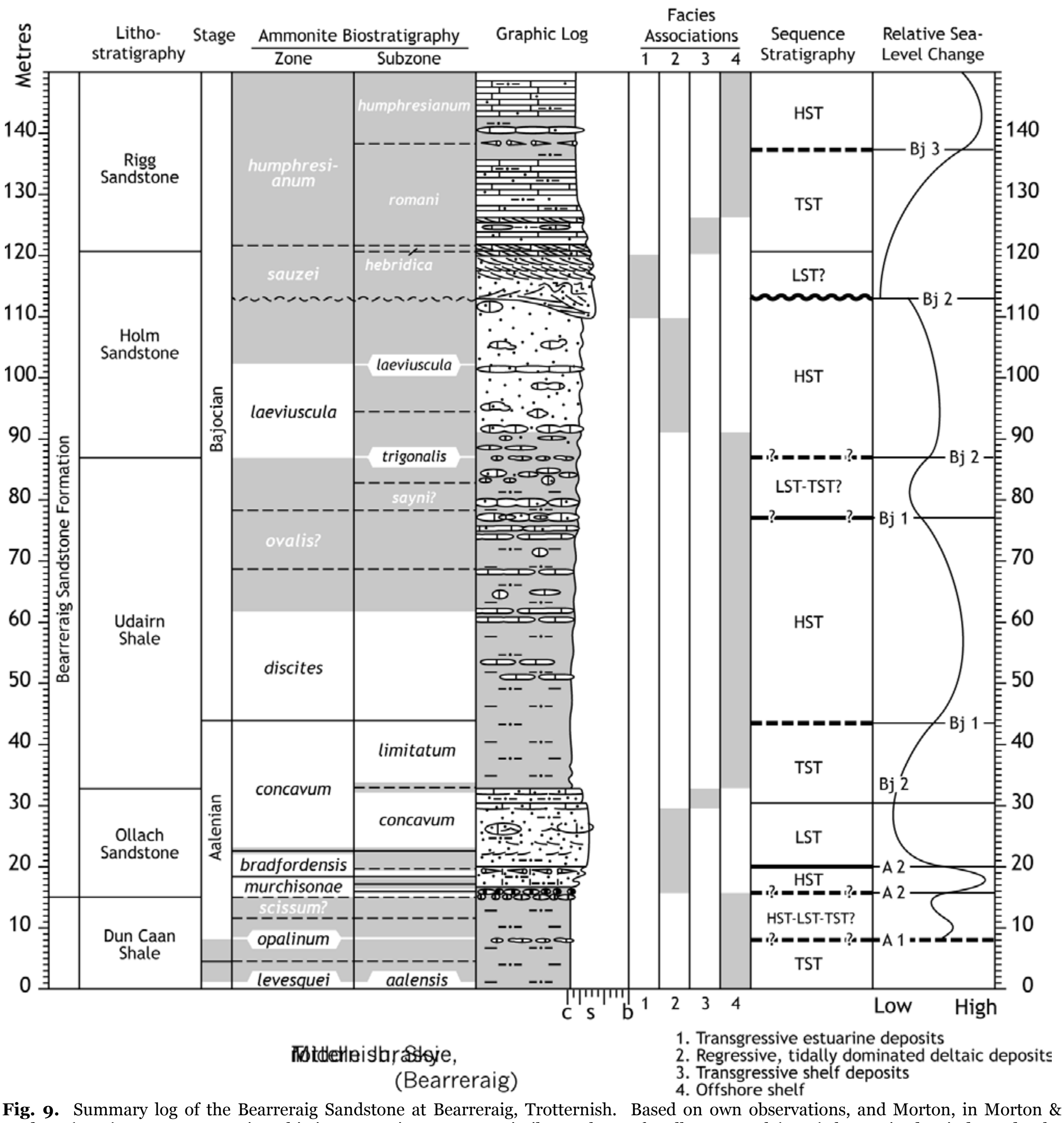



**Fig. 9.** Summary log of the Bearreraig Sandstone at Bearreraig, Trotternish. Based on own observations, and Morton, in Morton & Hudson (1995). Sequence stratigraphic interpretations are very similar to those of Mellere & Steel (1996), but arrived at independently. Dark shading in biostratigraphy columns indicates lack of age-diagnostic fossils in this section (upper parts are dated from nearby localities: N. Morton, pers comm., 1998).

above the Raasay Ironstone is cross-bedded sandstone of the basal Bearreraig Sandstone. The cross bedding here is of tidal sand-wave origin and shows approximate N-S transport directions (Morton, 1983; Mellere & Steel, 1996).

*Ob Lusa, Broadford*

At the headland of the small bay of Ob Lusa (NG 697 251) the apparently gradational transition is exposed from the Triassic Stornoway Formation to the Jurassic Breakish Formation. Here the Ob Lusa coral bed is well developed.

*Ardnish, Broadford*

The Ardnish peninsula can be approached from the end of the road at Waterloo (NG 666 239). The most easily understood exposures are at the western end of the peninsula from NG 680 243 to NG 683 251. Here there occurs an almost continuous succession of basal Pabay Shale Formation (*sensu* Hesselbo *et al.* 1998). Non-exposure in the inlet of Ob Breakish is equivalent to the shaly level at the base of the *semicostatum* Zone seen at Boreraig, and a less prominent exposure gap may correspond to a shaly level in the *scipionianum* Subzone. A well-developed ooidal ironstone occurs here at NG 680 240, the Ardnish Ironstone ("c" in Fig. 3). The transition into the Hallaig Sandstone is also visible and here occurs gradationally in the upper part of the *semicostatum* Zone.

**Fig. 10.** Dune-scale cross-bedded sandstone in the lower Bearreraig Sandstone, Strathaird. This facies is typical of the Bearreraig sandstone in the south of Skye. Christian Bjerrum for scale.

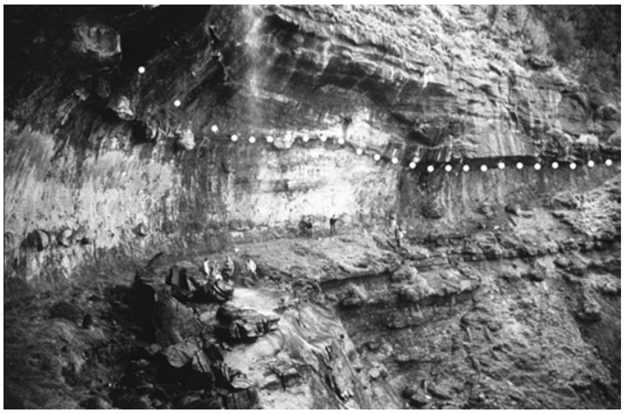


**Fig. 11.** Photograph of the Holm Sandstone within the Bearreraig Sandstone, Bearreraig Burn, Trotternish. White dots mark out a major erosion surface that cuts down into bioturbated marine sands (interpreted as pro-deltaic by Mellere & Steel, 1996) and which is overlain with large-scale cross-bedded tidal sands at the base of a transgressive facies sequence (see also Fig. 9).

## MIDDLE JURASSIC

### Summary

Middle Jurassic deposits of the Skye–Raasay area fall mostly into two distinctive lithostratigraphic groups: the Bearreraig Sandstone of late Aalenian to late Bajocian age, and the Great Estuarine Group of late Bajocian to Bathonian age (Figs 2 & 9). Whilst the Bearreraig Sandstone is largely of marine origin and well-dated by ammonites, the Great Estuarine Group represents a complex of lagoonal, deltaic and fluvial environments of quite varied salinity and lithology (Morton & Hudson, 1995).

Sedimentary facies making up the Bearreraig Sandstone are variable and differ significantly in separate half graben (Morton, 1965, 1983; Morton & Hudson, 1995; Mellere & Steel, 1996). The range of facies, and their arrangement into depositional sequences is well illustrated by the type section at Bearreraig, Trotternish, where the facies succession is in a relatively distal setting (Fig. 9). A striking feature of many of the coarse-grained facies is their strongly cross-bedded character indicative of significant tidal influence during deposition: typical dune-scale cross-bedding is well displayed throughout group in more proximal setting of Strathaird, for example (Fig. 10). Overall, two major transgressive phases are evident in the Bajocian; one in the earliest Bajocian *discites* Zone and one in the mid–late Bajocian *humphesianum* Zone, separating regressive maxima in the late Aalenian (*concavum* Zone) and mid Bajocian (*laeviuscula–sauzei* zones) (Figs 9 & 11). Both of these transgressive phases are evident in neighbouring basins such as the Cleveland Basin in Yorkshire (Knox *et al.*, 1991).

The transition from the Bearreraig Sandstone through to the Great Estuarine Group is not well exposed. Apparently, marine shales of the *garantiana* Zone give way upwards to non-marine shales of the Cullaidh Formation (Fig. 2). The Great Estuarine Group then shows evidence of two main phases of sand deposition (in the form of small deltas) separated by intervals of more argillaceous character. At the top of the group is a red-grey mottled fluvial mudstone with calcretes and channel sandstones, the Skudiburgh Formation.

Age diagnostic fossils are absent from the Great

Estuarine Group, but fossils indicative of various salinities are abundant and have been the focus of close investigation over many years (Hudson *et al.*, 1995, and references therein). A model for the palaeogeographic evolution represented by the group is presented by Harris (1989, 1992). Deltas which make up the Elgol Formation prograded roughly from north to south in both the Sea of the Hebrides – Little Minch Basin (Trotternish) and the Inner Hebrides Basin (Strathaird). The deltas differed in type depending on the salinity and wave or tidal energy conditions of the receiving waters (Harris, 1989). Sandbodies of the Valtos Formation represent deltaic and lagoonal shoreline deposits and show evidence of two phases of progradation, also from north to south (Harris, 1992).

The environments represented by the argillaceous facies of the Great Estuarine Group varied widely, although they were all to some extent lagoonal (some of these units have hydrocarbon-source potential: Vincent & Tyson, 1999). Broadly, the Lealt Shale represents intermediate (brackish) conditions, whereas the Duntulm Formation approaches normal marine salinities, and the Kilmaluag Formation is predominantly freshwater (Fig. 2; Hudson, 1963, 1970, 1980, 1983; Andrews & Walton, 1990). In detail, rapid and abrupt salinity changes undoubtedly occurred (Hudson *et al.*, 1995). The regressive termination of the group that led up to deposition of the fluvial Skudiburgh Formation has been described by Andrews (1985) who also pointed out similarities with late Bathonian successions in other UK basins.

Transgressive-regressive cyclicity in the Great Estuarine Group has previously been interpreted principally in terms of climatic change, and changes in the character of the source regions (e.g. Harris, 1989), but interpretations are also plausible in which regional relative sea-level changes play a key role. Certainly, there can be no doubt that the transgression at the Bathonian–Callovian boundary that terminated Great Estuarine group deposition, resulted from relative sea-level rise of very wide extent. In the Hebrides area, an offshore marine environment was established by the Middle Callovian (top of the Belemnite Sands: Fig. 12). In the Sea of the Hebrides Basin (Trotternish area) mudstones with a variable amount of both marine and non-marine organic-carbon dominated deposition throughout the remainder of the exposed Jurassic (Figs 2 & 12), whilst deposition in the Inner Hebrides Basin (e.g. Strathaird) was dominated by marine sandstones

## Localities

*Bearreraig, Trotternish*

Access to the section at Bearreraig (Fig. 9) is from a small car park at Storr Lochs hydroelectric power plant (NG 517 524). Morton, in Morton & Hudson (1995), provides a full account of the section with copious location detail. The strata below the middle Ollach Sandstone are only accessible at low tide. The remainder of the succession can be accessed along a path that ascends the burn, and an exit is usually possible by a ravine (fault) to the south of the burn, having first circuited below the waterfall at the level of the Holm Sandstone (Fig. 11). There are some exposure gaps affecting the lower part of the Udairn Shale, and a little uncertainty in correlations from one side of the burn to the other that stem from non-exposure of the ravine fault at low levels.

Noteworthy features of the succession include the following: the condensed and ammonitiferous beds of the mid-Aalenian which sit at the base of the Ollach Sandstone (the "Black Bed of Bearreraig" of S.S. Buckman); the expanded shaly interval in the earliest Bajocian; the abundant sand and associated erosion surface in the mid Bajocian, and; the return to relatively shaly belemnite-rich beds in *humphresianum* Zone (exposed below the higher of the two waterfalls in the burn).

*Elgol, Strathaird*

Around Elgol, Strathaird, good exposures of the late Bajocian to Bathonian strata occur although they are considerably affected by thermal metamorphism. On the shore to the south of Elgol, Strathaird, good exposures of Bearreraig sandstone occur (NG 515 134 to NG 513 1280) which display large-scale trough cross bedding of tidal current origin. The bay below Elgol itself (Port na Cullaidh) is formed by erosion of the Cullaidh Formation shale which is visible between boulders on the beach.

On the coast north of Elgol is a fine succession through most of the Great Estuarine Group. A full account based on the work of J.E. Andrews and J.D. Hudson is provided in Morton & Hudson (1995) and additional detailed sedimentological logs are presented by Harris (1989, 1992) and Andrews & Walton (1990). Immediately north (NG 517 138) of Port na Cullaidh is a coarsening upward succession of Elgol Formation sandstone formed by delta progradation – careful mapping and section measurement has shown that the more than one coarsening upwards cycle makes up the member, but only a single cycle is usually evident at any one locality (Harris, 1989). The argillaceous Lealt Shale member is well displayed in the bay north of the Elgol Formation headland (NG 516 140 to NG 516 144). Abundant fossils (bivlaves, gastropods, ostracods and conchostracans) give evidence of brackish water lagoonal conditions. Stomatolitic limestones also occur, and some beds show faunal evidence of higher salinities.

Exposures of the Valtos Formation are discontinuous and separated by faults: the formation is much less sandy here than it is at Trotternish, being probably not greater than 24 m (cf. Fig. 2). North of the Valtos Formation

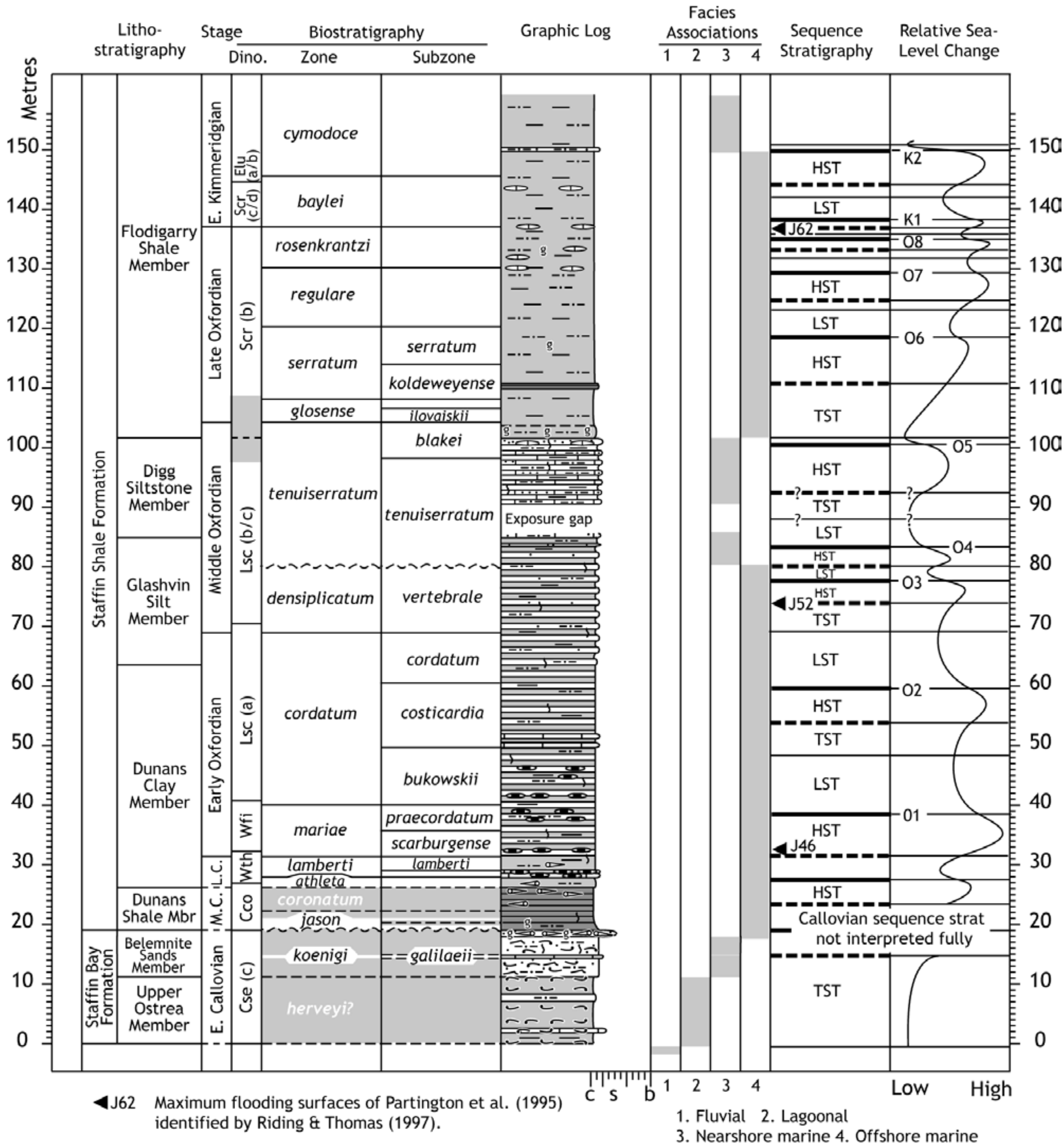



**Fig. 12.** Callovian – early Kimmeridgian succession, Staffin Bay, Skye. Data sources: 0–156 m, Staffin Bay, Trotternish, Morton & Hudson (1995), Riding & Thomas (1997), Coe (unpublished). Biostratigraphy: Sykes (1975), Sykes & Callomon (1979), Callomon in Morton & Hudson (1995). Dark shading in biostratigraphy columns indicates lack of age-diagnostic fossils.

exposures (NG 516 145), the Duntulm Formation (mudstones and limestones) is locally well seen and contains the distinctive oyster *Praeexogyra hebridica* and cyanobacterial limestones.

At the top of the Great Estuarine Group, the Kilmaluag and Skudiburgh Formation are also relatively well exposed on this stretch of coast, but the Kilmaluag Formation is best seen north of Glen Scaladal (NG 519 165) via a path that avoids the shore. However, the basal Kilmaluag Formation (mudstone–limestone alternation containing a freshwater fauna) and the Skidiburgh Formation (mottles mudstone with calcretes) can be studied at NG 516 146 – NG 517 147 and NG 517 147 – NG 518 152, respectively.

### *Staffin, Trotternish*

Callovian strata are well exposed in the wave-cut platform north of Staffin (e.g. NG 473 708; see also Late Jurassic locality descriptions). The most easily recognized unit is the well-cemented and very belemnite-rich bed at the top of the

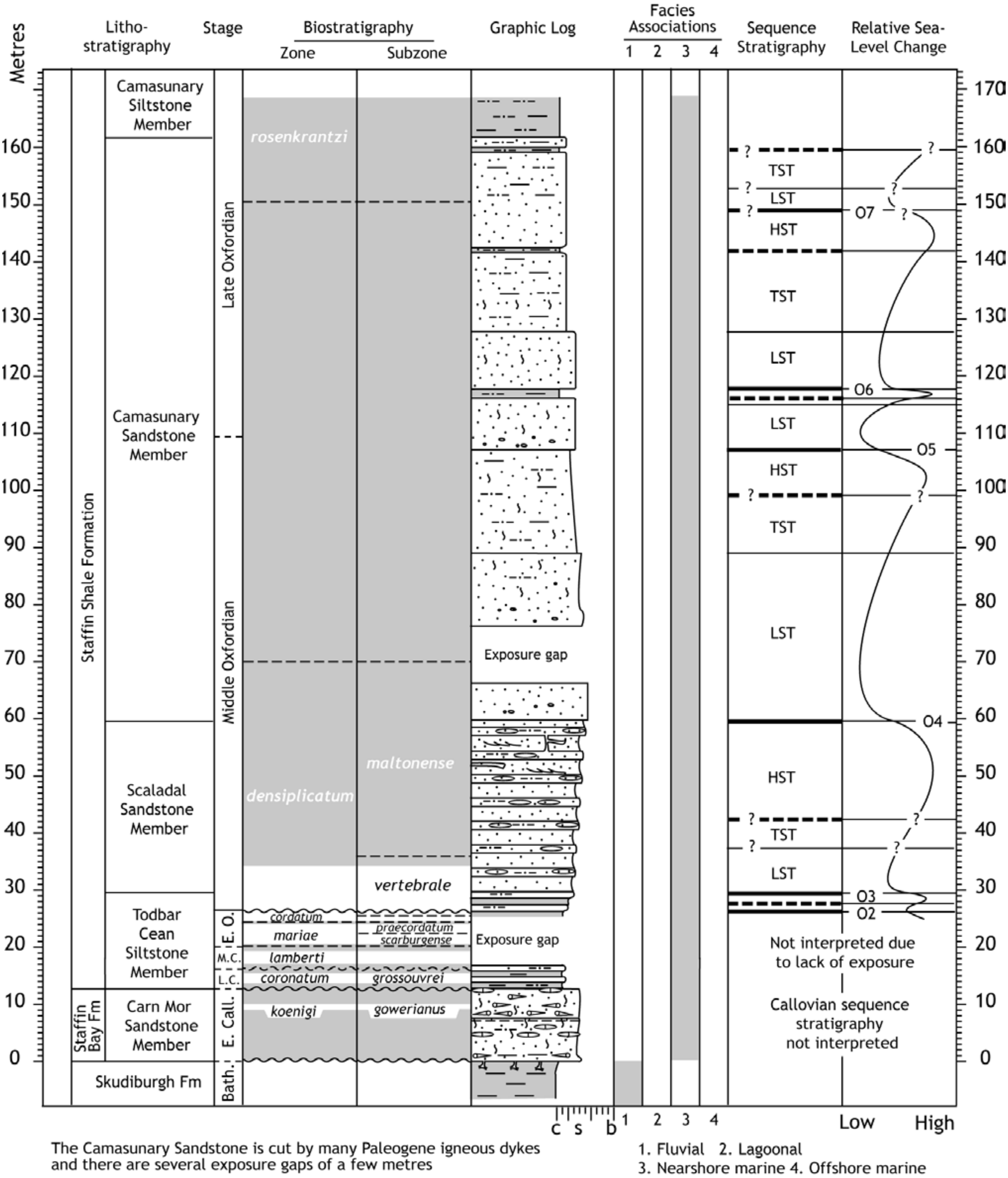



**Fig. 13**. Callovian – late Oxfordian, Rubha na h-Airighe Bàine, near Camasunary, Strathaird, Skye. From Coe (unpublsihed work). Biostratigraphy: Sykes (1975), Page (1989).

Belemnite Sands Member, Staffin Bay Formation. The Belemnite Sands forms a prominent feature near low-water mark, and then again nearer high-water mark due to repetition by a bedding-parallel fault. This unit is underlain by the Upper Ostrea Member which comprises mainly shales with abundant oysters and some well-preserved cross-lamination and represents the youngest preserved sediment deposited in the lagoons that characterized the Great Estuarine Group. The Belemnite Sands Member is overlain by the marine, organic-rich shales of the Dunans Shale Member. These shales are distinctive because they are dark in colour, tend to weather slightly proud compared to the overlying mudstones, and they are the only true shales in the Staffin Shale. They are

**Fig. 14.** Carn Mor Sandstone (Callovian) just south of Rubha na h-Airighe Bàine, near Camasunary, Strathaird. The lowest arrow indicates the erosion surface at the top of bed 5 and the upper two arrows mark belemnite beds within bed 6. Rucksack for scale. The base of Fig. 17 is the exposure in the near distance.

**Fig. 15.** Decimetre-scale asymmetric mudstone cycles in the Dunans Clay Member, near Staffin. Each cycle has a maximum of three parts. At the base of the photograph is the medium-grey mudstone which forms the top of a cycle. In the middle is the dark-grey silty mudstone which forms the lowest unit of the cycle. The middle part of the cycle is the medium-dark-grey mudstone shown in the top third of the photograph. Mixing of the layers by bioturbation is clearly shown. Rule = 20 cm.

equivalent to the most organic-rich interval in the Oxford Clay in southern England and probably represent a significant regional transgressive event. The late Callovian is represented by the Dunans Clay Member, which continued to be deposited well into the early Oxfordian and is described in the Late Jurassic section below.

*Glen Scaladal to Rubha na h-Airighe Bàine, Strathaird*

Strata on the Strathaird peninsular represent about half of the Callovian; the rest is lost in unconformities. The most continuous and easily accessible exposure is in the small bay between Glen Scaladal and the point called Rubha na h-Airighe Bàine (NG 507 169). The exposure is about 1.5 km away from the Palaeocene igneous complex that forms the Cuillin Hills, so the sedimentary strata are contorted, baked and cut by several dykes. The lowest unit is the Carn Mor Sandstone (*gowerianus* Subzone of the *koenigi* Zone; Page, 1989; Sykes, 1975; Fig. 13). The base is taken at the sharp *Thalassinoides*-burrowed contact with the underlying mottled clays of the Skudiburgh Formation. The sandstone is medium to coarse-grained and generally poorly sorted with sub-rounded to sub-angular grains; it is pervasively bioturbated, though occasional cross-lamination and planar bedding is preserved. The fauna is dominated by belemnites with subordinate bivalves and brachiopods. A distinct erosion surface occurs 4.5 m below the top of the Carn Mor Sandstone (top of Bed 5; Fig. 14) associated with a lag of quartz pebbles and vertical burrows (escape burrows?). The overlying sandstones are rich in belemnites. The member probably represents vertically stacked offshore sandbodies, and is overlain by the Todbar Cean Siltstone Member (*grossouvrei* Subzone to *lamberti* Zone?) which comprises grey, bioturbated, marine siltstones with carbonate nodules and belemnites.

## LATE JURASSIC

### Summary

Late Jurassic strata are exposed at Staffin Bay, Trotternish, where they are mainly mudrock (Oxfordian and earliest Kimmeridgian age), and on the Strathaird peninsular (Oxfordian), where they are siltstone and sandstone. These strata are grouped into the Staffin Shale Formation, a unit that is largely equivalent to the better known Oxford Clay Formation (Callovian and Oxfordian), Corallian Group (Oxfordian), and Kimmeridge Clay Formation (Kimmeridgian) of the English Jurassic basins. Indeed, the shallow-water English Corallian finds its shadow in the relatively coarse-grained Glashvin Silt and Digg Siltstone near Staffin, and the Scaladal Sandstone and basal part of the Camasunary Sandstone at Strathaird. Once again, we have a demonstration of regional control on the timing of deposition of shallow-water and deep-water sediment (Figures 2, 12 and 13). The exposures around Staffin have been of considerable importance in defining the Oxfordian Boreal–Sub-boreal zonal scheme (Sykes, 1975; Sykes & Callomon, 1979; Birkelund & Callomon, 1985; Fig. 12). More recently, the Staffin sections have been used for the construction of a high-resolution palaeomagnetic timescale for the Oxfordian (Ogg and Coe, submitted). The Staffin section is important because it represents the most stratigraphically complete Oxfordian section in the UK, despite the fact that it is difficult to reconstruct from the poor foreshore exposures.

Depositional sequences are not simply determined in these strata because of both condensation and stratigraphic gaps (Callovian) or mudrock facies (Oxfordian–Early Kimmeridgian) at Staffin, and because of thermal metamorphism in Strathaird (Oxfordian). Nevertheless, identifications can be made for parts of the succession based on the relative spacing of decimetre-scale fining-upwards cycles, large-scale changes in sediment type, the occurrence of organic–rich mudstones, fossiliferous horizons and nodule beds (Coe, unpublished). Additionally, on the basis of relative proportions of marine microplankton in the Staffin section, Riding & Thomas (1997) suggested stratigraphic positions for maximum flooding surfaces, which they correlated to those recognized by Partington *et al.* (1993) from the North Sea (Fig. 12).

## Localities

### *Staffin, Trotternish*

The 2-km stretch of foreshore to the north of Staffin Bay consists of a number of small rotated fault blocks composed of Oxfordian and early Kimmeridgian strata. Just inland, Palaeocene flood basalts overlie the Jurassic rocks but, except for contact metamorphism within decimetres of individual intrusions, the sediments have remained thermally immature (Thrasher, 1992; Bishop & Abbott, 1995). Seven points provide geographic markers that relate to slight promontories along the foreshore and help one to identify position in the section (see summary in Morton & Hudson, 1995). However, the individual rotated blocks are difficult to piece together in the boulder-strewn foreshore, and the quality of the exposure varies according to the abundance of seaweed and the state of the pebble beach. Most of the section is repeated at least twice.

The dominant sedimentary features of the Oxfordian mudrocks are asymmetrical decimetre-scale cycles (Figs 15 & 16), and prominent bands of nodules composed of either siderite or calcite. In the lower two members (Dunans Clay and Glashvin Silt; Sykes, 1975) the cycles range in thickness from <10 cm to about 1 m. Each cycle comprises a sharp-bottomed dark-grey silty mudstone in beds ~1 cm thick containing abundant plant fragments, grading up abruptly into medium-dark-grey calcareous mudstone of variable thickness, which in turn grades up into medium-grey calcareous mudstone also of variable thickness. The bases of most cycles show *Thalassinoides*, *Planolites* and *Chondrites burrows* (Fig. 15), and a few are associated with scours filled with shell debris. Some cycles do not have the dark-grey silty mudstone at the base. The boundary between the Dunans Clay and the Glashvin Silt is

**Fig. 16.** Cycles in the Flodigarry Shale Member (Kimmeridgian) at Point 7, north of Staffin. Photograph taken from on top of the large 3-m diameter basalt boulder. Beds in the foreground are dipping at about 85°. The silty mudstone base of each cycle forms a dark rib on the foreshore. The prominent bed on the right is a Palaeocene dyke.

taken at a gradational change from the predominance of thick, medium-grey mudstone beds, into mostly darker, more closely spaced mudstone beds. In the overlying Digg Siltstones, the cycles are similar to those of the Dunans Clay and Glashvin Silt members except that they are generally lighter coloured (reflecting an increase in carbonate content) and more closely spaced, thus making the member slightly coarser-grained in general. The Flodigarry Shale is dark- to medium-grey and slightly greenish in colour due to the presence of glaucony; it also contains subtle cycles, the base of each marked by a slightly siltier bed typically < 1 cm thick (which forms a rib in the weathered foreshore; Fig. 16) overlain calcareous mudstone. The Dunans Clay contains distinct bands of orange-weathering septarian siderite nodules and the Digg Siltstone, Flodigarry Shale and Dunans Clay members all contain bands of calcite nodules that are correlatable between the different rotated blocks. The Dunans Clay and Glashvin Silt members both contain thin bentonitic ash layers.

Intervals of closely-spaced cycles are interpreted as sequence boundaries (lack of accommodation) a clear example of which can be seen in the upper part of the *praecordatum* subzone at Point 3 (NG 474 698); conversely the maximum flooding surfaces are marked by the most widely spaced cycles (e.g. *costicardia* Subzone at point 3; NG 474 698) and in some instances an abundance of fossils (e.g. ammonite–rich horizon in the *vertebrale* Subzone at Point 5 (NG 473 707)). Long-term regression is marked by the gradual upward decrease in cycle spacing and consequential coarsening upward trend between the Dunans Clay and the Digg Siltstone. The rapid facies change from calcareous silty mudstones at the top of the Digg Siltstone into the glauconitic mudstones and thin organic–rich shale of the Flodigarry Shale Member marks the start of a long-term transgression. Individual sequence


**Fig. 17.** Oxfordian sandstones at Rubha na h-Airighe Bàine, near Camasunary, Straithaird. D = Tertiary dyke, TCS= Todbar Cean Siltstone Member, S = Scaladal Sandstone Member, C = Camasunary Sandstone Member. Field of view is c. 300 m.

**Fig. 18.** Rough and smooth weathering pattern in the Scaladal Sandstone Member at Rubha na h-Airighe Bàine, near Camasunary, Strathaird. The cross-sectional face exposed is the contact where a Tertiary igneous dyke has weathered away. Vertical face is c. 1 m high.

boundaries within this transgression are again marked by closely spaced cycles. Long-term regression in the early Kimmeridgian is marked by the return of more significant amounts of silt and fine-grained sand to the succession just above the Kimmeridgian sequence boundaries (*baylei* and *cymodoce* zones). There is a total of eight depositional sequence cycles in the hebridean Oxfordian, all of which can be correlated using magnetostratigraphy and biostratigraphy to sequence cycles in Yorkshire, Dorset and Switzerland (Gygi *et al.,* 1998; Ogg & Coe, submitted; Coe, unpublished).

*Rubha na h-Airighe Bàine, near Camasunary, Strathaird*

Access to the section at Rubha na h-Airighe Bàine can be gained either by the coastal footpath from Elgol, or from the track between Kilmarie and Camasunary. The section is mainly exposed in the boulder-strewn foreshore from Rubha na h-Airighe Bàine northwards (NG 517 170 – NG 517 178; Fig. 17). The exposures are very close to the Palaeocene gabbroic igneous complex of the Cuillin Hills and, thus, the sediments are strongly baked and cut by many dykes; this makes the different sedimentary facies difficult to distinguish. The earlier Oxfordian (*mariae* Zone to *bukowskii* Subzone of the *cordatum* Zone) is represented in the foreshore by the poorly exposed Todbar Cean Siltstone. The lowest 1 m of strata represent the top of the *bukowskii* Subzone and base of the *costicardia* Subzone and forms the more prominent vertical exposure in the foreshore at the point. A sharp change in grain size marks an unconformity at which most of the *costicardia* Subzone and all the *cordatum* Subzone is missing; this is interpreted to be due to the combination of a *cordatum*-Subzone sequence boundary and overlying transgressive surface. The uppermost 3-m of the Todbar Cean Siltstone contains phosphatized ammonites encrusted with serpulids; it is directly correlatable with the *vertebrale*-Subzone surface that also shows an abundance of ammonites near Staffin which is interpreted as a maximum flooding surface.

The base of the overlying Scaladal Sandstone is marked by a slight increase in grain size, and a change in the character of the sandstones to regularly interbedded smooth and rough weathering beds and lenses (Fig. 18). The smooth beds weather proud and are more poorly sorted and slightly muddier than the rough beds that form layers or ovoid lenses reminiscent of carbonate-concretions. Thus, the beds show the reverse weathering pattern to that commonly found in Jurassic sandstones (e.g. Bridport Sands, Dorset; Lower Calcareous Grit, Yorkshire) with proud-weathering carbonate-cemented nodule layers and beds. The pattern at Camasunary is interpreted to be a result of the thermal metamorphism dissolving the carbonate and baking the clay minerals. The Scaladal Sandstone gradually coarsens upwards to a medium- to coarse-grained sandstone and it also contains ammonites, belemnites, wood, and a few cross-stratified units. It is interpreted to represent a shelf sand body.

The Scaladal Sandstone is sharply overlain by the Camasunary Sandstone, which is a massive, coarse-grained, to very coarse-grained sandstone in the lowest 6 m. This unit represents the peak of a long-term regression and a *maltonense* Subzone sequence boundary. The remainder of the Camasunary Sandstone is variable in grain-size and contains mudstone-rich intervals, some ghost carbonate-coated clasts, and intensely bioturbated layers. In general, the member fines upwards into the overlying Camasunary Siltstone representing the overall long-term transgression of the late Oxfordian, superimposed on this trend are smaller-scale sequence cycles (Coe, unpublished work).

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