Chapter 8 The Hebrides Basin

Introduction

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Geological setting

The Hebrides Basin is one of a series of Mesozoic extensional basins, extending from Spitzbergen and Greenland in the north to Portugal in the south, which evolved during the early stages of opening of the North Atlantic Ocean (Trueblood and Morton, 1991; Morton, 1992a). These were mainly half-grabens, with alternating polarity of faulted margin on the west (including Hebrides) or east. The Hebrides Basin ceased being part of the system after the Jurassic Period, with basin inversion in Early Cretaceous times, when the main tilted fault-block structures were formed. It then became part of the Thulean volcanic province during Palaeocene times so that most of the Jurassic sequence is intruded by dykes and sills. These caused only local baking, but near the main plutonic centres of central Skye, Ardnamurchan and Mull, thermal metamorphism has occurred.

Lower Jurassic rocks crop out on various islands of the Inner Hebrides and on some neighbouring parts of the western coast of the Scottish mainland (Figure 8.1), in part preserved because of an overlying protective cover of Palaeogene plateau basalt lavas. More spectacularly, two small isolated outcrops, on Rum and Arran, owe their preservation entirely to large-scale downward movements within or on the margins of Tertiary igneous complexes. On a regional scale the rocks form a series of westerly- to north-westerly-tilted fault-blocks cut by two main sets of faulting. Both are downthrown predominantly to the east, with a small number of very large NNE–SSW-trending faults of mainly Early Cretaceous age (Morton, 1992b), and a large number of generally smaller NNW–SSE- to NW–SE-trending faults which are of Palaeogene age.

In some areas, particularly near the Palaeocene plutonic igneous centres, the Jurassic succession has been thermally metamorphosed, posing problems of interpretation in Ardnamurchan and parts of Mull and of Skye. The extent and effects of the Skye plutonic centre are shown by Thrasher (1992) and Taylor and Forester (1971). Elsewhere there are fewer such problems and in Mull, Morvern, Skye, Pabay, Raasay and Applecross there are excellent outcrops of Lower Jurassic sediments with normal diagenetic alteration, enabling reasonable syntheses of the stratigraphy, although there remain unresolved problems (Morton, 1989; Hesselbo *et al.*, 1998).

Previous work

The first discovery of a Hebridean Jurassic sequence is attributed to Pennant (1774) and early descriptions include Faujas de Saint-Fond (1797), Macculloch (1819), Boué (1820) and Necker-de-Saussure (1821). However the most important early contributions were by Murchison (1829, more important are the ammonites collected during his expedition which became Sowerby types), Geikie (1858), Miller (1858), Bryce (1873), Judd (1878) and others, sometimes in correspondence for presentation to meetings of the Geological Society of London or the British Association in the early part of the 19th century.

During the early 20th century the [British] Geological Survey produced a series of geological maps and descriptive memoirs, which gave details of the stratigraphy and palaeontology (Peach *et al.,* 1910, 1913; Lee, 1920; Lee and Bailey, 1925; Tyrrell, 1928; Richey and Thomas, 1930; the delayed North Skye Memoir by Anderson and Dunham, 1966, contributed little new information on the Lower Jurassic succession). Some of the memoirs included reports by S.S. Buckman on the ammonites collected by the [British] Geological Survey officers (most notably in Lee, 1920). The results were summarized by Lee and Pringle (1932). Other publications from these decades were by Woodward (1914), Spath (1922b,c, 1924), and Trueman (1942). Arkell's (1933) descriptions were based on some of these publications.

The next phase of investigation on the Lower Jurassic sequence of the Hebrides began in the 1950s with the work of various research students, including MacLennan (1954), Howarth (1956, 1958; his brachiopod collections were used by Ager, 1956a) and Hallam (1959). Subsequent research students' work has been published only in part, including Amiri-Garoussi (1977), Oates (1978) and Searl (1989, 1992, 1994). Unpublished doctoral theses which relate wholly or partly to the Lower Jurassic Series of the Hebrides include Clark (1970), McCallum (1971), Getty (1972), Oates (1976), Amiri-Garoussi (1978), Corbin (1980), Phelps (1982), and Smith (1996). Other recent contributions on the Hebridean Lower Jurassic sequence include Nicholson (1978), Hesselbo *et al.* 1998), Morton (1999a,b) and Farris *et al.* (1999).

These established the Hebrides as a significant area to be included in European or even global syntheses of Lower Jurassic stratigraphy, for example Hallam (1967a), Sellwood (1972), Getty (1973), Phelps (1985), Donovan (1990), Howarth (1992), Page (1992), Dommergues *et al.* (1994) and Hesselbo and Jenkyns (1998).

Syntheses and summaries of the Hebrides Jurassic System are given by Hudson and Morton (in Hemingway *et al.,* 1969 — field guide), Cope *et al.* (1980a — on correlations), Hudson (1983), Morton (1987, 1989, 1992b on basin evolution), Hallam (1991), Bradshaw *et al.* (1992 — on palaeogeography), and Morton and Hudson (1995 — field guide). The setting and stratigraphical evolution of the Hebridean Lower Jurassic succession was described by Morton (1990) and in the broader context of British Lower Jurassic sequence stratigraphy by Hesselbo and Jenkyns (1998).

Stratigraphical framework

The Lower Jurassic rocks of the Hebrides are predominantly siliciclastics and the stratigraphical evolution of the area was different from that of Yorkshire, Somerset or Dorset. Therefore a different scheme of lithostratigraphical nomenclature (Figure 8.2) has been developed. Many of the names (now called formations) derive from Judd (1878), Woodward (1897) or other 19th century authors and were used by the [British] Geological Survey. The more recent revisions concern mainly the lower part of the Lower Jurassic succession or revision of spelling of place-names, and these are incorporated in the following summary.

1. For the Triassic (to lowermost Jurassic in the north) 'New Red Sandstone' continental red-beds, wider use of the name Stornoway Formation (Steel and Wilson, 1975) was suggested by Morton and Hudson (1995). The type section is near Stornoway and the best Inner Hebridean section, at Rubha na' Leac on Raasay, is described by Morton and Hudson (1995).
2. The marine 'Rhaetic' (only in the south) was identified with and named the Penarth Group (e.g. Cope *et al.*, 1980a). The type section lies outside the Hebrides, but the best Hebridean section is in Gribun, western Mull, included in the Aird na h-Iolaire GCR site report.
3. The Hettangian to Lower Sinemurian succession of Mull and Morvern, previously classified with the Broadford Beds, is developed in alternating limestone–mudstone facies identical to the Blue Lias Formation of south-west England Oates (1978) proposed using the same name, Blue Lias Formation, and this has been generally, though not universally, accepted. The Blue Lias Formation passes laterally through intermediate sandy limestones and shales, seen in northern Ardnamurchan, south-west Raasay and Sconser in Skye into the lithologically varied unit traditionally called the 'Broadford Beds'. The type section lies outside the Hebrides, but details of the best Hebridean section are given in the Allt Leacach GCR site report: see also Hesselbo *et al.* (1998).
4. The name 'Broadford Beds' has been applied to the lower part of the Lower Lias since the 19th century, and subdivision into a lower more calcareous unit and a higher more siliciclastic unit widely used. Restriction in use of the name 'Broadford Formation' to only the lower unit was proposed by Hesselbo *et al.* (1998), but to avoid confusion the new name Breakish Formation was introduced and defined by Morton (1999b). The type section east of Broadford is described in the Ob Lusa to Ardnish Coast GCR site repoxt.
5. The upper unit of the former Broadford Beds was included within an expanded Pabay (see below) Shale Formation by Hesselbo *et al.* (1998). However, Morton (1999a) argued that there is a basin-wide mappable lithological distinction (cf. Hesselbo *et al.,* 1999) between the traditional 'Pabba Shales' and the upper unit of the 'Broadford Beds' and suggested the name Ardnish Formation for the latter. This has been adopted by the [British] Geological Survey in the revised Broadford and Raasay 1:50 000 maps. The most important sections of the formation are described in the Ob Lusa to Ardnish Coast and Boreraig to Carn Dearg GCR site reports. The Hallaig Sandstone Member designated by

Hesselbo *et al.* (1998) is used for the upper more sandy part of this formation. The type section of the member lies outside the GCR sites, but is described by Morton and Hudson (1995) and Hesselbo *et al.* (1998).

6. The 'Pabba Shale' was named after the Isle of Pabay, but the anglicized names used by the original authors were the versions then current. The original spelling has been used more recently by the Ordnance Survey (and other official bodies) and adopted as appropriate for lithostratigraphical nomenclature as Pabay Shale Formation. The type section has not been defined, but is likely to be designated in the Boreraig to Carn Dearg GCR site. More sandy units within this formation are recognized by Hesselbo *et al.* (1998) as the Suisnish Sandstone Member (Skye, Raasay) and the Torosay Sandstone Member (Mull). The classic Allt Fearns section on the Isle of Raasay (Getty 1973; Page, 1992) is not included in a GCR site, but is described in Morton and Hudson (1995), while the section on Pabay is described by Hesselbo *et al.* (1998).
7. Similarly, the 'Scalpa Sandstone', named after the Isle of Scalpay, has been amended to Scalpay Sandstone Formation, but the most appropriate type section is on the Isle of Raasay; see Howarth (1956) and the Rubha na' Leac, Cadha Carnach and Hallaig Shore GCR site reports.
8. The lower shaly part of the Upper Lias was named 'Portree Shales' in Lee (1920) after the capital town of the Isle of Skye (Portree, from Gaelic *Port-an-Righ* = King's harbour). This is retained as Portree Shale Formation and the type section is defined and described in the Prince Charles' Cave to Holm GCR site report.
9. The shales pass up into the 'Raasay Ironstone', named after the Isle of Raasay, almost everywhere in the Hebrides where the strata are exposed, justifying recognition of a Raasay Ironstone Formation even though it is frequently less than 1 m thick. The type section at the opencast mine on the Isle of Raasay is not included in any of the GCR sites, but is described in Morton and Hudson (1995).
10. The uppermost Lower Jurassic succession is classified lithostratigraphically as part of the Bearreraig Sandstone Formation, notably the Dun Caan Shale Member. This unit is described in the Middle Jurassic GCR volume under the Gualann na Leac and Bearreraig GCR site reports (Cox and Sumbler, 2002), and included here in the Cadha Carnach GCR site report.

The standard ammonite zonal and subzonal scheme for the Liassic of north-west Europe (Dean *et al.,* 1961; modified in Cope *et al.,* 1980a; and revised by Page, 2003) Is readily applicable to the Lower Jurassic sequence of the Hebrides, as shown by Hesselbo *et al.* (1998). Indeed two index species have their type localities in the Hebrides. Except for the middle and upper Toarcian successions, nearly all zones and subzones can be recognized in at least one locality. Some localities yield detailed faunal sequences and are of international significance for Lower Jurassic ammonite biostratigraphy, as indicated in the next section.

Locality descriptions

Only brief descriptive notes on the most important features or potential of the various localities are given here, for further details see the appropriate [British] Geological Survey memoir, or other references indicated. All the localities are shown on (Figure 8.1).

Arran

The island of Arran is not strictly part of the Hebrides, but is included here for completeness. Two small poorly exposed outcrops of Lower Lias shales and decalcified mudstones are known, preserved by spectaculaz accident in Palaeocene vent agglomerates as a result of collapse of caldera walls. Ammonites of the Planorbis (Trueman, 1942) and Angulata zones occur in separate places, and elsewhere marine 'Rhaetic' shales and limestones and Upper Cretaceous chalk, thermally metamorphosed (Tyrrell, 1928). Comparisons may be made with Antrim in Northern Ireland where Lias up to Valdani Subzone is known in *situ* under Upper Cretaceous strata, and derived fragments from the Spinatum Zone and Lower Toarcian Substage are known from the Cretaceous basal conglomerate (Wilson and Robbie, 1966; 'Wilson and Manning, 1978). A greater lateral extent of at least Lower Liassic rocks than might otherwise be expected is proved here.

Mull

Outcrops of Lower (and the lower part of Middle) Jurassic rocks are mostly along the southern and eastern coasts of Mull, but in many areas, especially around Loch Don, the rocks are thermally metamorphosed to varying degrees. Exceptions include the remote outcrops of basal Lias in Gribun (Aird na h-Iolaire GCR site) and the important Upper Sinemurian to Lower Pliensbachian shore sections of Carsaig Bay (the original type locality of *Ammonites Jamesoni* Sowerby) (Oates, 1976; Hesselbo *et al.,* 1998). Middle and upper parts of the Lias (and up to Upper Bajocian) occur in the Loch Don area (Lee and Bailey, 1925), but structural complications and thermal metamorphism sometimes make interpretation difficult. Higher parts of the Jurassic sequence are cut out by unconformity beneath the Upper Cretaceous sediments and Palaeocene basalt lavas (except for a surprising outcrop of Lower Kimmeridgian shales, see Morton, 1989). Isolated small outcrops of Lias occur in northern Mull.

Morvern

Lower Lias (up to Upper Sinemurian) occurs on both sides of Loch Aline on Movern, but the best sections are in streams to the east (MacLennan, 1954; Oates, 1976; Hesselbo *et al.,* 1998), including the Allt Leacach GCR site. The Hettangian and Lower Sinemurian (to Lyra Subzone) successions are developed in classic Blue Lias Formation facies with spectacular *Gryphaea* beds, overlain unconformably by the Upper Sinemurian Pabay Shale Formation. Jurassic rocks above the Oxynotum Zone are missing beneath the Upper Cretaceous unconformity (Lee and Bailey, 1925).

Ardnamurchan

There are excellent Lower Jurassic outcrops on both the northern and southern coasts of Ardnamurchan, but thermal metamorphism has limited the stratigraphical value of some. A transitional 'sandy Blue Lias' facies is noteworthy on the northern coast (Oates, 1976) and coral beds correlated with Skye. Outcrops in the Kilchoan area of Pabay Shale and Scalpay Sandstone formations are generally too metamorphosed to be informative, but there are important small outcrops of Toarcian strata on the coast, including the only recorded evidence for possible post-Bifrons Zone ammonites in the Raasay Ironstone Formation (Richey and Thomas, 1930).

Rum

No in-situ Jurassic sequence occurs on Rum because it forms part of a central basement ridge uplifted during Early Cretaceous times (the westward dip results in an outlier of Trias in the north-west). However a sliver of metamorphosed Jurassic limestones, presumably of the Blue Lias or Breakish formations, occurs in the ring-fault of the Palaeocene granophyric and ultrabasic plutonic complexes (Emeleus in Craig, 1983) and proves former continuity across the Camasunary Fault (see Morton, 1992b).

Skye

Outcrops of Lower Jurassic rocks occur in several parts of Skye, the most extensive forming a broad stretch between Broadford and Loch Eishort. The oldest beds dated by ammonites in this part of the Hebrides belong to the Angulata Zone, and are underlain by transitional 'Passage Beds' and the continental red-beds of the Stornoway Formation. This has been re-interpreted (Morton, 1999b) as suggesting that the uppermost parts of the 'New Red Sandstone' in this area probably belong to the Hettangian Stage. There are extensive excellent outcrops of the Breakish and Ardnish formations east of Broadford, especially in coastal sections including the Ob Lusa to Ardnish Coast GCR site, and north of Loch Eishort, including the Boreraig to Carn Dearg GCR site, which are important for the Hettangian to Sinemurian stratigraphy of the Hebrides. Outcrops of the Pabay Shale Formation are less good around Broadford, but there are significant excellent stream and cliff sections on the north side of Loch Eishort, in the Boreraig to Carn Dearg GCR site (Peach *et al.,* 1910; Spath, 1922b; Trueman, 1942; Hallam, 1959; Oates, 1976, 1978; Hesselbo *et al.,* 1998). From Loch Eishort northwards to Loch Slapin the Ardish Formation overlaps older Mesozoic strata to rest unconformably on the Ordovician Durness Limestone at Camas Malag and Torrin (Nicholson, 1978; Farris *et* ed., 1999), but the Breakish Formation again occurs north of Torrin east of the head of Loch Slapin. On the west coast of Loch Slapin outcrops of the higher parts of the Lower Jurassic succession occur on the east coast of the Strathaird Peninsula (Morton and Hudson, 1995). Outcrops of Breakish Formation (in transitional 'sandy Blue Lias' facies), Ardnish Formation and the lower part of the Pabay Shale Formation occur south of Loch Sligachan, south-west of Sconser, but the rocks are slightly metamorphosed and strongly faulted. Smaller outcrops of Blue Lias (or Breakish) Formation occur locally under the Upper Cretaceous and Palaeocene unconformity west of the basement ridge on the north shore of Soay Sound and west of Camasunary, while the Breakish, Ardnish and Pabay Shale formations crop out north of Camasunary. Higher parts of the Lower Jurassic succession are also well exposed in excellent coastal cliff exposures on the eastern coast of the Trotternish Peninsula in northern Skye, south and north of Portree, the latter in the Prince Charles' Cave to Holm GCR site.

Pabay

The low island of Pabay gives its name to the Pabay Shale Formation, but in fact only the upper part of the formation is exposed in the excellent coastal outcrops (Sellwood, 1972; Oates, 1976; Hesselbo *et al.,* 1998). The locality is internationally significant as the type locality of *Platypleuroceras brevispina* (see Spath, 1922b).

Scalpay

The coastal outcrops of the 'name locality' of the Scalpay Sandstone Formation and of part of the Pabay Shale Formation on the south-east coast of the island of Scalpay have not been studied recently and only limited information is available (Peach *et al.,* 1910).

Applecross

The faulted Jurassic outlier in the remote village of Applecross is stratigraphically restricted to the Hettangian to lowermost Sinemurian Breakish Formation, mainly in sedimentologically unusual carbonate facies, exposed in stream and coastal sections (Lee, 1920; Hallam, 1959; Searl, 1989, 1992, 1994; Hesselbo *et al.,* 1998; Morton, 1999b).

Raasay

The renowned Jurassic outcrops in the southern half of the Isle of Raasay owe their preservation, at least in part, to an overlying intrusive sheet of granophyre, but thermal metamorphism from this and other minor intrusions is fortunately limited. There are several superb stream, cliff and coastal exposures of all parts of the Lower Jurassic sequence. The contrast between the carbonate Breakish Formation and siliciclastic Ardnish Formation (with sandy Hallaig Sandstone Member) Is well illustrated at Hallaig on the east coast (Hallam, 1959; Morton and Hudson, 1995; Hesselbo *et al.,* 1998; Morton, 1999b) and transitional 'sandy Blue Lias' facies at Suisnish in the south-west (Morton and Hudson, 1995). The Allt Fearns section in the Pabay Shale Formation is of international importance for biostratigraphy, especially in the very thick Raricostatum Zone (Getty, 1972, 1973; Oates, 1976; Donovan, 1990; Page, 1992; Dommergues *et al.,* 1994; Morton and Hudson, 1995). Important cliff sections in the Scalpay Sandstone Formation were described by Howarth (1956) and yielded data on Lower Pliensbachian ammonites (Phelps, 1985), Upper Pliensbachian ammonites (Howarth, 1958) and brachiopods (Ager, 1956a): see also Morton and Hudson (1995) and Hesselbo *et al.* (1998). These are included in the Cadha Carnach, Hallaig Shore and Rubha na' Leac GCR site reports, the latter proposed as the type section for the Scalpay Sandstone Formation. Data on the Toarcian succession is more limited (Lee, 1920; Morton, 1965; Morton and Hudson, 1995). Outcrops of Portree Shale Formation are rare (see Cadha Carnach GCR site report) but the Raasay Ironstone Formation is well exposed in the type section at the old opencast workings north-east of Inverarish (Morton and Hudson, 1995), and marginal-facies outcrops are included in the Cadha Carnach and Rubha na' Leac GCR site reports.

Gruinard Bay

From the south side of Gruinard Bay to Loch Ewe there is a narrow strip of faulted Mesozoic rocks, but only limited outcrops of Lower Jurassic carbonates, presumed to be Breakish Formation (Peach *et al.*, 1913).

Shiant Isles

The isolated Shiant Isles are composed mainly of dolerite intrusions, but baked Jurassic shales with Toarcian ammonites (Portree Shale Formation?) also occur (Penn and Merriman, 1978).

Stratigraphy

Two approaches to stratigraphical analysis of the Jurassic System of the Hebrides Basin have been employed by Morton (1987, 1989) and Hesselbo (Hesselbo and Jenkyns, 1998; Hesselbo *et al.,* 1998), genetic stratigraphy and sequence stratigraphy. These were used to emphasize, respectively, tectonic and sea-level controls of stratigraphical evolution. These are generally complementary, but there are significant differences of interpretation (Figure 8.2).

Genetic stratigraphy

Analysis in terms of genetic stratigraphical sequences (Morton, 1989) has resulted in the recognition of three major sequences, plus a fourth which begins with the Aalensis Zone at the top of the Lower Jurassic succession but is mainly Middle Jurassic. Sequence boundaries were defined at major changes of facies, sometimes associated with a hiatus, and each sequence was found to be characterized by a distinctive style of stratigraphical architecture (thickness and facies variation through the basin). Integration of this data with information from analysis of the subsidence history (Morton, 1987) has enabled interpretation of the dynamic stratigraphical evolution of the basin. The results for the Lower Jurassic succession are summarized below and in (Figure 8.2).

Sequence A began with an episode of lithospheric extension causing fault-controlled (especially on the western margin) differential subsidence resulting in the deposition of continental red-beds (Stornoway Formation) which onlap pre-Mesozoic basement. Continued subsidence and sea-level rise resulted in marine transgression in the south (Arran, Mull) during the latest Trias (Penarth Group) continuing northwards (Morvern, Ardnamurchan, Raasay) during early Hettangian times (Blue Lias Formation, Breakish Formation). Marine sedimentation did not begin in some areas in the north (Skye, Applecross) until middle or late Hettangian times (Breakish Formation) (Morton, 1999b). Renewed transgression and onlap also occurs at the base of the (Lower Sinemurian) Semicostatum Zone, most notably with the Ardnish Formation overlapping the older Mesozoic strata to rest unconformably on the Durness Limestone of the Loch Slapin area (Camas Malag–Torrin). The stratigraphical architecture of this sequence is characterized by great lateral variability of facies and thicknesses (see Morton, 1989, 1990 for details). These features are consistent with deposition during an episode of lithospheric extension resulting in differential subsidence at the surface.

Sequence B begins with a hiatus which can be identified but is of different ages in the various localities, although Morton's (1989) interpretation of a cliachronous hiatus is questioned by Hesselbo *et al.* (1998). In Mull, Morvern and Ardnamurchan parts of the Semicostatum and Turneri zones are missing below the Pabay Shale Formation. In southern Skye (Loch Eishort) biostratigraphical evidence for the age of the Hallaig Sandstone Member is poor but possibly parts of the Turneri and Obtusum zones may be absent. On Raasay, especially at Hallaig, there is better evidence, with the top of the Hallaig Sandstone Member of Birchi Subzone age and the base of the Pabay Shale Formation of Oxynotum Zone (probably also subzone) age so that the Obtusum Zone and part of the Oxynotum Zone are missing. Above the hiatus there is a sharp reduction of grain size, and in most areas deposition begins with fine-grained organic-rich days at the base of the Pabay Shale Formation. Onlap above a minor unconformity is also seen in Morvern (Oates 1976, 1978). The variations in facies and thickness seen in Sequence B are very much less than in Sequence A. Minor coarsening-up shale to sandstone cycles occur within an overall coarsening-up succession which includes the Pabay Shale and Scalpay Sandstone formations, but lateral variation in the shale–sandstone cycles has meant that the boundary between the two formations is drawn earlier in the north (Raasay and Skye) than in the south (Mull). The changes in stratigraphical architecture, after a submarine hiatus, sharp reduction of the grain size of sllici-clastic input, and onlap, are interpreted as resulting from a change in tectonic regime. Lithospheric extension and differential subsidence during deposition of Sequence A were replaced by broader and more uniform subsidence across the basin as a result of thermal and loading sag.

Sequence C is marked at the base by a sharp change of facies to dark organic-rich shales, the Portree Shale Formation. There does not appear to be a significant hiatus, at least at zonal level. The boundary is dated as at or close to the base of the Serpentinum Zone wherever ammonite faunas have been found, so that it appears to be isochronous throughout the basin. The Portree Shale Formation passes up gradationally into the Raasay Ironstone Formation, and the lateral extent and uniformity of facies in two such thin formations is remarkable. The Raasay Ironstone Formation shows evidence of condensation, with stromatolitic hardgrounds, and is succeeded by a major hiatus in which most of the Middle and Upper Toarcian sequence is missing. There is no apparent tectonic reason for the sequence boundary at the base of this sequence, and its isochronous nature together with precise correlation with similar deepening events in many other areas (Hallam, 2001) suggest that it was caused by a eustatic rise of sea level. The low thicknesses and hiatus development indicates that this sequence corresponds to a phase of basin and hinterland stabilization when subsidence and uplift were reduced, limiting accommodation space availability and siliciclastic sediment supply. Careful assessment of likely eustatic sea-level trends, compaction and other factors (Morton, 1987) suggests that there may even have been slight uplift of the basement during most of the Toarcian Stage. However, there is no evidence of emergence and only very local erosion of the Raasay Ironstone Formation.

Sequence D is mainly a Middle Jurassic sequence, so outside the scope of this volume. It is characterized by being very thick and highly variable in facies as well as thickness, indicating a new episode of renewed differential subsidence as a result of lithospheric extension. This began in very latest Early Jurassic times, because sediment accummulation recommenced with the top Toarcian Aalensis Zone, which is itself extremely variable; for example the thickness on Raasay increases from 9.1 m to 38.2 m over a distance of 3 km (Morton, 1965).

Sequence stratigraphy

Hesselbo *et al.* (1998) re-measured and restudied a number of the best Lower Jurassic sections in the Hebrides, publishing the first detailed measured successions for several decades. The stratigraphy was interpreted in the context of a wider study by Hesselbo and Jenkyns (1998) of Lower Jurassic secions in the Wessex, Bristol Channel and Cleveland basins as well as the Hebrides.

Four large-scale (second-order) transgressive–regressive cycles were recognized by Hesselbo *et al.* (1998), with boundaries in the Hallaig Sandstone Member, the Suisnish Sandstone Member and the Scalpay Sandstone Formation (see (Figure 8.2)). Hesselbo and Jenkyns (1998) interpreted the Hebrides Basin as exemplifying a proximal pattern of sedimentation, with expanded sections corresponding to sea-level rise or high-stand, and condensed sections corresponding to relative sea-level fall or lowstand. The key medium-scale (third-order) sequence surfaces identified by Hesselbo and Jenkyns (1998) are shown on (Figure 8.2). Two types are identified — candidate sequence boundaries, defined at unconformities or intervals of minimal accommodation space, and maximum flooding surfaces, recognized at condensed intervals in distal settings and maximum accommodation space in proximal settings. In each case major, medium or minor expressions can be distinguished, and these are shown on (Figure 8.2).

Palaeogeographical evolution

Onshore evidence proves that subsidence in the Hebrides Basin started in the Triassic Period, and highly irregular topography resulted in deposition of conglomerates and breccias, mostly of local derivation, in a series of alluvial fans and mass-flow deposits. These pass laterally into fluvial sandstones and floodplain mudstones, and development of caliche in semi-arid conditions was widespread and frequent (Steel, 1977). There is no direct evidence for dating, but a late Triassic (?Norian) age is likely. Arran was at this time part of a separately evolving sedimentary basin, with evidence of lacustrine deposition in a more varied environment. During the latest Trias (Rhaetian) the marine transgression spread northwards from the south-west of the British Isles, to give marine conditions in Arran and as far north as Mull.

Dating events at the beginning of the Jurassic Period is hampered by limitations of biostratigraphical evidence — no Planorbis Zone ammonites are known north of Mull, and Liasicus Zone ammonites (*Franziceras*) only from eastern Raasay (Morton, 1999b). Ammonites from the Angulata Zone (*Schlotheimia*) are rare but more widespread (Applecross, Skye, Ardnamurchan, Morvern, Mull). Integrating facies and biostratigraphical evidence from other fossil groups (e.g. bivalves) with the ammonite dating indicates that renewed transgression spread marine conditions farther north, to Morvern, Ardnamurchan and Raasay during early Hettangian times, and to Applecross probably in mid-Hettangian times.

However, in southern Skye (Broadford area) an Angulata Zone ammonite occurs not far above the base of the Breakish Formation. On the basis of correlations based on biostratigraphical and lithostratigraphical markers, Morton (1999b) interpreted a diachronous transgression and facies change from continental Stornoway Formation to marine Breakish Formation in the Skye area. Therefore the Penarth Group passes laterally into the Stornoway Formation, while the Blue Lias Formation in offshore areas (e.g. Mull, Morvem; Oates, 1976, 1978) passes laterally through a transitional more sandy facies (Ardnamurchan, south-west Raasay and Sconser; Oates, 1976; Morton, 1999b), or into Breakish Formation carbonates/shales (eastern Raasay), then near-shore Breakish Formation carbonates/ sandstones (Applecross, southern Skye) and into the non-marine Stornoway Formation (Morton, 1999b). The sandstones represent offshore sandbars, sometimes with wave-, tide- and possibly storm-action evident. The carbonates vary from oolites to coral beds (small patch reefs), *Liostrea* coquinas and calcilutites which may represent shallow lagoonal deposits, and there is diagenetic evidence for several periods of emergence near the basin margins at Applecross (Searl, 1989).

During the Semicostatum Zone there was a major change in the depositional environment, and final onlap of the topographic high related to the area of Cambro-Ordovician carbonates in the area north of Loch Slapin. In Raasay, Broadford, Loch Eishort, Mull and possibly Ardnamurchan, carbonate-dominated facies were replaced abruptly by ferrugineous association (Hallam, 1975) sandstones, siltstones and shales (Ardnish Formation) with at least one ironstone bed (Broadford) and *Gryphaea* beds. In the Broadford area three coarsening-up cycles from siltstone to sandstone to ironstone (or at least goethite ooliths present) can be recognized (Taylor, Cointet, unpublished reports; see Morton and Hudson, 1995). In the Skye and Raasay area a thicker sandstone (Hallaig Sandstone Member) was deposited in the Turneri Zone, while in Morvern slight tilting (presumably near the basin margin) resulted in the subsequent development of a local angular unconformity (Oates, 1976).

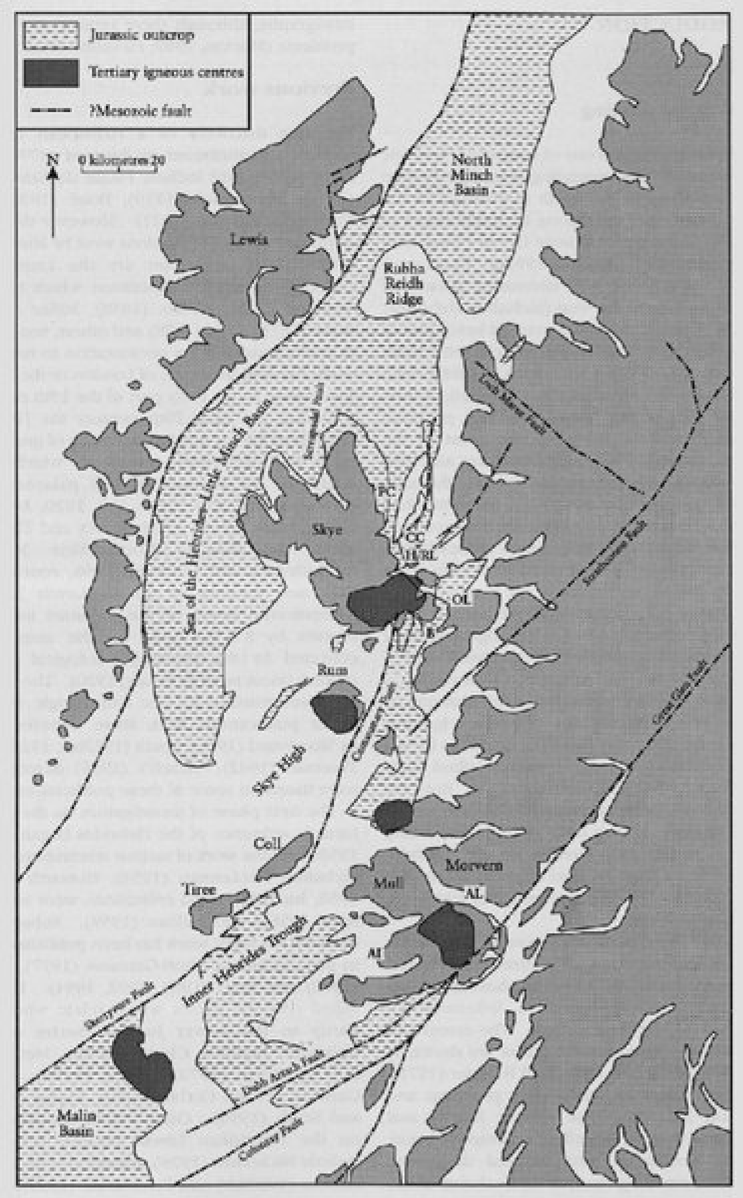
During Late Sinemurian times more uniform depositional environments occurred throughout the basin. The sediments were deposited on a mud- or silt-dominated shelf with local sand-bars (Pabay Shale Formation), and similar conditions continued into Early Pliensbachian times. Upward shallowing in Late Pliensbachian times resulted in the spread across the basin of extensive offshore sand-bars and sheet sands (Scalpay Sandstone Formation), influenced by tidal and storm activity (MacCallum, 1971; Oates, 1976). This continued into earliest Toarcian times.

The deepening event of the Early Toarcian Serpentinum Zone caused the establishment of deposition of shales (Portree Shale Formation) in partially anaerobic conditions below wave-base. This is the local expression of the widespread early Toarcian anoxic event Oenkyns, 1988). Analysis of the subsidence history and stratigraphical architecture indicates that this rise of sea level postponed the development of 'basin-fill' conditions of stabilization in the Hebrides Basin, probably in a continuing marine environment, achieved during Early Toarcian times, with deposition of the Raasay Ironstone Formation.

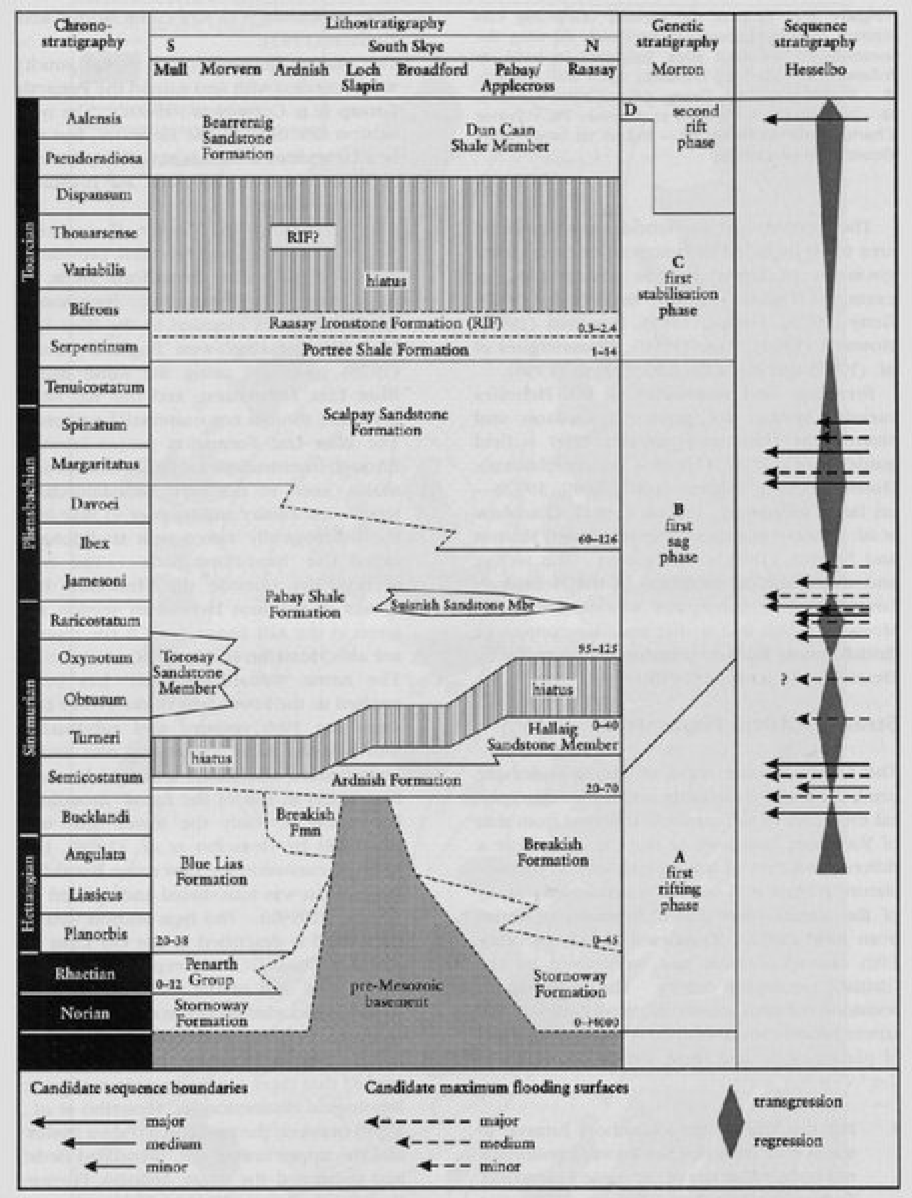
There is no evidence from outcrops for any deposition having occurred during middle and most of late Toarcian times. Conversely there is evidence for only limited erosion in a few localities (e.g. Strathaird; see Morton, 1989), because the overlying Bearreraig Sandstone Formation rests everywhere on the Raasay Ironstone Formation even though this is very thin.

The top of the Lower Jurassic succession in the Hebrides is genetically part of the Middle Jurassic Series, with a lithospheric extension event beginning in latest Toarcian times (Morton, 1987) resulting in renewed subsidence in the Hebrides Basin and rejuvenation of hinterland topography resulting in influx of large quantities of coarse siliciclastic sediment to form the Bearreraig Sandstone Formation, partly in tidal sand-wave environments (Morton, 1983).

References



(Figure 8.1) Map of the Jurassic (including Lias Group) outcrop in western Scotland, showing the locations of the GCR sites, indicated in bold, as follows: AI — Aird na h-Iolaire; AL — Allt Leacach; B — Boreraig to Cam Dearg; CC — Cadha Carnach; H — Hallaig; OL — Ob Lusa to Ardnish; PC — Prince Charles' Cave to Holm; RL — Rubha na Leac. After Hesselbo et al. (1998).



(Figure 8.2) Chronostratigraphical (stages) and lithostratigraphical nomenclature of the Lower Jurassic Series in the Hebrides, with genetic stratigraphical sequences (after Morton, 1989) and sequence stratigraphy (based on Hesselbo and Jenkyns, 1998; and Hesselbo et al., 1998).