Response of Middle Jurassic shallow-marine environments to syn-depositional block tilting: Isles of Skye and Raasay, NW Scotland

Stuart G. Archer¹*, Ronald J. Steel², Donatella Mellere³, Stuart Blackwood⁴ & Brian Cullen⁵

¹ TOTAL Upstream Danmark, Amerika Plads 29, 2100, Copenhagen, Denmark
² Jackson School of Geosciences, University of Texas at Austin, Austin, TX, USA
³ Faroe Petroleum, Badehusgata 37, Stavanger, Norway
⁴ Chevron, 2222 Louisiana St, Houston, TX, USA
⁵ Cairn Energy plc, 50 Lothian Road, Edinburgh, UK

S.G.A., 0000-0002-7927-2628
*Correspondence: stuart.archer@outlook.com

Abstract: The Hebridean Province of NW Scotland provides insight into the interaction between tectonics and shallow-marine and tidal strait depositional environments in the Sea of the Hebrides and Inner Hebrides basins. The study tests the influence of syn-depositional block tilting on gross thickness, sand to mud ratio and the distribution of shallow-marine facies in the resulting succession. New Middle Jurassic palaeogeographical maps and stratigraphic correlations are presented that integrate both outcrop and well data and illustrate the evolution of the deltaic sedimentary system in a broad, semi-regional context.

Results show that distance from the sediment entry point and the syn-rift tectonic geomorphology were the critical controls on gross thickness, sand to mud ratios and facies types. The impact of relative sea-level change is hard to detect in locations proximal to the Scottish hinterland, where sediment supply was large relative to accommodation (Ss > Ac), but becomes more influential in distal locations where eustasy and tectonic subsidence convolved to increase the influence of accommodation over sediment supply (Ac > Ss).

Supplementary material: An outcrop to well log correlation exercise is available at https://doi.org/10.6084/m9.figshare.c.4397858

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The Hebridean Basins offer the most westerly outcrops of Mesozoic strata in NW Europe before the Faroe–Shetland Basin, the Rockall Trough, the Slyne Trough and the wider Atlantic Margin and therefore represent important analogues for these prospective petrolierous basins to the west. The tectonostratigraphic setting and facies types are also analogous to Jurassic syn-rift oil reservoirs of the North Sea (e.g. Brent Group, Fulmar and Ula Formations).

The objective of this work is to provide an up-to-date reservoir analogue study of the Middle Jurassic Bearreraig Sandstone Formation, highlighting the impact of normal faulting and the creation of tilted fault blocks upon shallow-marine sedimentation. Observations from only four representative locations are used for simplification and we place these data points in the context of previously published information. The work provides a synthesis of the subtle interplay that existed between tectonism and eustasy as controls on stratigraphic sequencing and facies distributions.

Methods

Field methods included conventional sedimentological facies logging and the measurement of palaeocurrents through the Bearreraig Sandstone Formation at all locations and the use of photography and photogrammetry to capture larger-scale architectural features. We also utilized data from an oil exploration well, (rock cuttings and wireline logs) to extend the database further to the west and into the subsurface.

Extensive photographic recording of outcrops was useful, but the added benefits of a photogrammetric approach using an airborne unmanned aerial vehicle (UAV) or drone became clear in areas where the outcrop is largely inaccessible cliffs. Video and still images were obtained with a DJI Mavic Pro quadcopter drone, equipped with a 4K video and 12.35 megapixel still image, high quality, stabilized camera system, flown along the main cliff line at Screapadal on Raasay in August 2017. The maximum altitude of the drone, operating within Civil Aviation Association guidelines, was 120 m above the launch point. This provided for an elevated, cliff-orthogonal viewpoint with good representation of the geometry of the outcrop, though this was still some distance below the maximum height of the cliffs. A number of passes were made parallel to the main cliff face, capturing video footage and still images, with sampling every 5 s during the flight.

The results were analysed using Agisoft’s PhotoScan software, from which a 3D virtual outcrop model was constructed. The 3D model is based on 431 camera locations, with 156 203 tie points, generating a high quality, dense point cloud of 33.44 million points over the >750 m of
contiguous outcrop width. The model was georeferenced using the GPS metadata from the drone. The inaccessibility of the upper cliff faces made georeferencing with ground control points difficult; however, the model was cross-checked with a public domain digital elevation model (DEM), namely the OS Terrain 50 Digital Terrain Model from OS Opendata, to ensure a reasonable fit between the 3D model and real-world dimensions. This ensured the resultant georeferenced 3D model was then suitable for measurement of width–thickness relationships of the channels identified on the crestal area of the tilted block at Screapadal on the Isle of Raasay as well as of the overall outcrop dimensions.

**Palaeogeographic overview**

The Jurassic of the Hebridean Province (Fig. 1) has provided a wealth of dynamic stratigraphical understanding over the years, but in the last 50 years through works by Morton (1983, 1987, 1992a, b), Hudson (1983), Harris (1989, 1992), Morton & Hudson (1995), Mellere & Steel (1996), Hesselbo & Coe (2000) and Blackwood (2006).

During the Jurassic, Scotland lay around 40° north of the equator (Callomon 2003) and the climate was humid and sub-tropical (Alexander 1992). Precipitation and therefore run-off is likely to have been perennial but seasonally variable. The landmass would have been well vegetated since drifted wood and plant material is common in these shallow-marine rocks (Bateman et al. 2000). Warm seas promoted significant biological productivity, and preserved flora and fauna are plentiful, such that many of the sandstones are bioclastic in nature (Morton & Hudson 1995).

Fluvial systems would have fed westwards off the Scottish massif to a coastline positioned somewhere east of our Hebridean study area, although the location and exact configuration of the feeder system is not possible to reconstruct due to later erosion (Hudson & Trewin 2002). The facies types present in the study area are subaqueous and fully marine and do not include the fluvial or coastal-plain facies types that are well known from the Middle Jurassic of the Cleveland Basin in Yorkshire (Saltwick, Cloughton or Scalby Formations) or the Middle Jurassic of the North Sea (Ness, Pentland, Sleipner or Bryne Formations).

**Stratigraphic framework**

The Bearreraig Sandstone Formation was deposited during a 6.5 million-year period during the Lower to Middle Jurassic (175–168.5 Ma) (Morton 1965, 1976, 1989; Ogg & Hinnov 2012) (Fig. 2). Ammonite zones have determined the formation to be latest Toarcian to late Bajocian age (Morton 1965, 1976; Morton & Dietl 1989). The field area’s biostratigraphic context is that it is part of the Tethyan (southern) faunal realm and was separated from the Boreal (northern) realm at a time when much of the North Sea region was experiencing restricted, or even blocked, marine connectivity due to the topographic influence of a thermal dome (Underhill & Partington 1993, 1994; Korte et al. 2015).

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**Fig. 1.** Location map and geological map. The Isles of Skye and Raasay are shown, with the route of the ferry transfer from Sconser on Skye to the Isle of Raasay also indicated. The main towns of Portree, Broadford and Kyle of Lochalsh are highlighted. The position of the four localities discussed in this paper are shown using numbers, where 1 = Bearreraig Bay, 2 (UG1) = refers to the location of the Upper Glen 1 exploration well which is treated as locality two, 3 = Screapadal and 4 = Glasnakille. On the geological map the Jurassic section of interest is coloured blue.
The Middle Jurassic successions in the Hebridean Basins are much thicker than their English equivalents (Hudson & Trewin 2002). The Bearreraig Sandstone Formation varies in thickness in outcrop from 36 to 488 m (Morton 1989) and the formation is comparable in thickness to the age-equivalent Brent Group of the Northern North Sea. The Bearreraig Sandstone Formation contains the thickest Jurassic sandstones onshore in the UK, in great lithological contrast to the coeval Inferior Oolite Group further south (Cox et al. 2002).

The Bearreraig Sandstone Formation is defined lithostratigraphically between the Raasay Ironstone Formation (lower Toarcian) below and the Cullaidh Shale Formation (uppermost Bajocian) above (Fig. 2). The Cullaidh Shale Formation (previously termed the Basal Oil Shale) forms the lowest part of the Great Estuarine Group (Morton 1965). The Bearreraig Sandstone Formation includes six informal members that are best identified and characterized at the Bearreraig Bay type locality (Morton 1976). These members (see Fig. 2) can in places be up to 100 m in thickness; however, as this paper demonstrates, it is difficult to perform regional correlation at the member scale due to rapid lateral facies changes, as a consequence of active faulting, and they therefore do not carry formation status.

**Tectonic overview**

The Mesozoic of the Atlantic Margin was dominated by extensional tectonics and multi-phase rifting is believed to have started in the Triassic (Steel 1971). The rift related, non-marine sedimentation patterns in the Hebridean area were outlined by Steel (1974, 1977). During the Triassic, the Atlantic Margin and the North Sea experienced distributed extension over a wide area as Pangaea began to break up. It was the Jurassic Period that hailed the development of marine seaways both east and west of the British landmass due to rising eustatic sea-level (Hallam 2001) and more focused rifting.

The early terrestrial rift phase terminated in the late Triassic, transitioned to a marine thermal sag phase in the early Jurassic and was then followed by a second, more focused rifting phase that started in the Middle Jurassic but climaxed in the late Jurassic. Although rifting ceased at the end of the Jurassic in the North Sea, continued extension on the Atlantic Margin, particularly during the Early Cretaceous, led eventually to Paleocene volcanism, Eocene break up and the production of oceanic crust (Trewin 2002). The Hebridean Basins can be viewed as perched, inboard rift basins in the context of the wider continental margin (McQuillan & Binns 1973). They are the most easterly preserved basins representing the northeastern Atlantic passive margin.

The onset of deposition of the Bearreraig Sandstone Formation in the latest Toarcian (Fig. 2) signalled major palaeo-environmental change, with huge sand influx to the region from around the mid-Aalenian. The rejuvenation of tectonic topography, through the creation of tilted fault blocks during the Middle Jurassic rift episode (Fig. 3), would have generated sediment source areas in the form of uplifted footwall crests. The onset of Middle Jurassic rifting, as outlined in this paper, was a critical development in the Hebrides and the wider Atlantic Margin and is the underlying control behind the large gross thicknesses of the Bearreraig Sandstone Formation observed in the field and in wells (Fig. 4).

More regionally, this stratigraphic evolution to coarser-grained siliciclastic input near the base of the Middle Jurassic has been observed widely (e.g. Cox et al. 2002; Nielsen 2003; Powell 2010; Mellere et al. 2017) and may have larger-scale tectonic or climatic significance (Underhill & Partington 1993; Korte et al. 2015). In addition to the rift-related uplift which is the focus of this paper, the arrival of coarse clastic deposits could be linked to the creation of the Central North Sea thermal dome (and formation of the mid-Aalenian Unconformity, see Fig. 2), mapped in the North Sea by Underhill & Partington (1993) among others (Andsbjerg et al. 2001; Nielsen 2003). Regional-scale doming, centred to the east of Scotland, although distant from the Hebridean Province, could have provided a far field influence, although more work is required to test how transient plume-related
uplift, centred on the North Sea, manifested itself upon and through the thick, post-orogenic Caledonide crust of northern Scotland.

What is clearly observed is a prominent basinward shift of facies into the field area at the start of the Middle Jurassic, contrasting greatly with the relative quiescence of the Lower
Jurassic depositional environments (Hesselbo 2008). This paper synthesizes the stratigraphic evolution across the Lower to Middle Jurassic boundary in the Hebrides and, in doing so, re-frames the interpretive options for allogenic controls: syn-rift tectonics, regional doming, eustatic fall or climate change?

**Structural framework**

The normal faults that became active in the Middle Jurassic are largely NE–SW orientated, dip SE and are believed to have re-used old heterogeneities in the crust (Fig. 5). Stein & Blundell (1990) proposed reactivation of Caledonian lineaments that were previously related to crustal shortening (for example the Outer Isles thrust was re-used by the Sea of the Hebrides Basin-bounding Minch Fault). Clearly this low-angle thrust plane was not utilized along its entire length as a normal fault, but, through the development of steeper angle hanging-wall cut-offs, old crustal weaknesses were exploited by younger normal faults. Later contributions (Roberts & Holdsworth 1999) downplayed the evidence base for the wholesale reactivation of Caledonian thrust structures in the Mesozoic, while building a more robust case for the extension of the Mesozoic fault system onshore, via structures such as the Strathconnon Fault (Fig. 3). One key remaining uncertainty in the evolution of the fault framework is the degree of inheritance from the Triassic to the Middle Jurassic fault systems. The degree of reactivation or otherwise is unclear.

The Strathconnon Fault links broadly along-strike with the Skerryvore Fault, which has Lewisian basement outcrops (the islands of Tiree and Coll) on its footwall side (Fig. 3). To the NE, once beyond the Isle of Eigg, the Skerryvore Fault is re-named the Strathconnon Fault and, along-strike, the Sleat Peninsula becomes the modern expression of the footwall block (Fig. 3). The Strathconnon and Skerryvore faults have NE–SW Caledonian trends, but north of these structures Mesozoic faults tend to swing NNE–SSW, as they were impacted by a tectonic fabric that is related to the orientation of the Moine Thrust. Recognition of this change in the...
basement grain from south to north is important as the tectonic framework ultimately dictates sediment dispersal patterns and the distribution of facies.

Figure 3 is complemented by two structural cross-sections (Fig. 6), which are orientated perpendicular to the main structural grain and reveal the southeastern-dipping character of the normal faults in the region. The Sea of the Hebrides half-graben is the widest basin, where fault spacing is large and is associated with a large throw on the Minch basin-bounding fault to the west. To the east, in the Inner Hebrides Basin, faults are more closely spaced and half-graben are narrower.

Previous studies of the Bearreraig Sandstone Formation (Mellere & Steel 1996) linked the Jurassic faults (e.g. Beinn na Leac Fault on Raasay is linked to the Applecross Fault, and the Camasunary Fault to the Scalpay House Fault, see Fig. 3). However, most of the observed faults are on subtly different trends and in an early syn-rift setting, such as this, they are far more likely to be short, en-echelon fault segments, rather than long and hard linked. Our interpretive preference is to keep these faults short, as separate entities which forced sediment to aggrade up and over the intervening relays, to reach the outer basins far from the Scottish hinterland (compare fault lengths in Fig. 3 to Fig. 7).

Fault length broadly correlates with fault throw (Kim & Sanderson 2005) and, therefore, with the magnitude of footwall uplift. In general, the fault segments in the field area are interpreted to have had subaqueous footwall scarps, but where throws are particularly large (e.g. the Minch Fault and the Camasunary Fault) they are thought likely to have had subaerial footwall crests. A mid-Skye palaeo-high structural element was invoked by Harris (1992) to argue for compartmentalization of the basin into more discrete sub-basins in the later Bathonian stage. Although highly interpretive, it is possible that the early syn-rift Bajocian phase of soft-linked fault segments evolved into a later hard-linked fault system which saw the development of a palaeo-high during the Bathonian.

One complication regarding the structural framework is that Holocene block rotation and slippage is prevalent in the field area (Ballantyne et al. 2014). For example, the Beinn na Leac Fault on Raasay has a slightly curved (3D spoon) shape in outcrop and may be a Holocene listric fault, which may or may not have re-used a Jurassic fault (though in general these younger slips do not re-use Jurassic faults).

Normal faulting and the development of tilted fault blocks was a key feature of Mesozoic syn-rift activity (both east and west of Britain). The scale of the resulting half-graben was dependent on the length scale and spacing of the normal faults. Understanding this structural framework is critical because these faults set the template for the syn-tectonic sedimentation patterns and the resulting Middle Jurassic Hebridean palaeogeography.

**Lines of evidence for Middle Jurassic syn-tectonic sedimentation**

Evidence that supports Middle Jurassic movement on the main faults in the Hebridean region is critical to the
tectonostratigraphic model presented. The Bearreraig Sandstone Formation was previously thought to be a post rift succession related to thermal subsidence, until major thickness changes were mapped and related to the structural configuration of actively subsiding basins (see steepening of subsidence curve in Fig. 4 from Morton 1987). Although there has been a gradual acceptance of the concept of Middle Jurassic syn-tectonic sedimentation, the exact timing and relative importance of the faults in the Jurassic have been controversial (Harris 1992; Morton & Hudson 1995).

We use four criteria to identify syn-sedimentary faulting.

(1) Anomalous thickening of strata into and adjacent to faults (see also Underhill 1991). The inverse of this observation of growth wedges is the thinning of strata, sometimes with marked evidence for erosion, up the hanging-wall dip-slopes on to the fault-block footwall crests.

(2) Sediment dispersal patterns, as indicated by palaeocurrent evidence, running parallel with fault lineaments or being diverted around fault lineaments in the areas of fault tips (see also Ravnás & Steel 1998).

(3) The presence of sand-rich, high-energy tidal facies (dune or compound dune fields, e.g. Olaria et al. 2012) developed in narrow fairways parallel to known structural lineaments. Structures created topographic constrictions and led to the formation of tidal straits (see also Longhitano et al. 2012).

(4) The development of shallow-water transitioning to deeper-water facies trends down the dip-slopes of fault blocks strongly suggests syn-sedimentary tilting of the block, commonly in association with transverse sediment dispersal down from the crestal region (e.g. Ravnás & Steel 1997).
Although thickness changes, the control of faults on palaeoflow, and lateral facies changes can all be observed in the field area, it is the first of these criteria that is arguably the most useful as thicknesses provide direct quantification of the gross subsidence rates when strata are time constrained and decompacted. In addition to field observations, thickening and thinning trends are also observed in well data, providing multiple lines of evidence for differential subsidence patterns.

Using the four criteria above as tests of syn-tectonic sedimentation, our current view supports the division of the Mesozoic Hebridean Province into two clear structural domains, the Sea of the Hebrides and the Inner Hebrides, following the work of Binns et al. (1975), Steel (1977) and Morton (1992b) (Figs 3, 4 and 6).

**Outcrop and well data from the Sea of the Hebrides and Inner Hebrides basins**

The Bearreraig Sandstone Formation crops out in three main belts in the field area: the Trotternish Penninsula (NE Skye); the nearby Island of Raasay; and the Strathaird Penninsula (South Skye)(localities 1, 3 and 4 in Figs 1 and 7b). There are also data from an onshore oil exploration well (Upper Glen 1) that has been given its own locality status (locality 2 in Figs 1 and 7b). These localities illustrate two main palaeogeographical domains:

- a wide-open seaway (The Sea of the Hebrides Basin), in a large half-graben (NE Skye and North Raasay) with broadly transverse sediment delivery (localities 1, 2 and 3 in Fig. 7);
- a tidal strait (the Inner Hebrides Basin), in a narrow fault-controlled half-graben (Strathaird Penninsula) with longitudinal sediment dispersal (locality 4, Fig. 7).

The data from these classic localities can be used to illustrate five stratigraphic themes in time-equivalent strata. They demonstrate how active faulting and block tilting impacted facies, sediment dispersal and sequence stratigraphic subdivisions. These themes are:

1. field evidence to support the interpretation of syn-sedimentary growth in thickness across fault blocks (all 4 localities);
2. basic observations of updip-to-downdip changes in sand/mud ratio and facies on tilted blocks (localities 1, 2 and 3);
3. identification and correlation of progradational to retrogradational siliciclastic wedges, developed on tilted fault blocks (localities 1, 2 and 3);
4. observations of well-exposed, deeply incised submarine channels, present on crestal areas of tilted blocks (locality 3);
5. the identification of extensive submarine dune fields as a result of fast-flowing tidal currents within the narrowest half-graben or ‘straits’ (locality 4).

These five themes are now explored in detail using four key locations. This is the minimum number of datapoints required to illustrate the tectonostratigraphic variability seen in the field area. For more complete documentation of all possible localities, readers are referred to Morton & Hudson (1995).

**Locality 1 – Bearreraig Bay (Trotternish Peninsula, NE Skye): hanging-wall dip-slope (Fig. 7)**

Bearreraig Bay [GR 517 527, Figs 1 and 8] is the type locality for the Bearreraig Sandstone Formation (Morton 1976). The total stratigraphic thickness of the formation is just over 200 m (Fig. 8a) and five of the six members are observable (all except the Garantiana Mudstone Member). The rocks have been described in detail by Morton & Hudson (1995), Mellere & Steel (1996) and Hesselbo & Coe (2000), and we refer to these works for details not included here.

**Dun Caan Shale–Ollach Sandstone Members (Fig. 8a)**

The Dun Caan Shale Member is the lowest unit exposed and is a dark grey, mica-rich, muddy to very fine-grained sandstone with carbonate concretions rather than a shale (as its lithostratigraphic name suggests). The interval is bioturbated (high abundance and diversity of trace fossils) and belemnites are common. Grain size, faunal assemblage and the lack of sedimentary structures suggest deposition near storm wave base in an offshore transition zone. The Dun Caan Shale Member coarsens upwards rapidly into the Ollach Sandstone Member, which forms the main wave-cut cliff face on the modern shoreline and together these two can be viewed as a genetically related shallowing-upward cycle.

The Ollach Sandstone Member (Fig. 8b) is composed of fine-grained sandstone with carbonate concretions, exhibiting structureless, trough cross-stratified and ripple-laminated bed sets. Siltstone and claystone drapes on cross-beds and ripple lamination are particularly common in the lower and middle parts of the unit. These finer-grained components allow the Ollach Sandstone Member to be split into two sub-units, each coarsening upwards, but separated by a deepening event that can be traced as a dark-coloured recessed notch in the outcrop. Intervals of ripple lamination and climbing-ripple lamination become more common towards the top of the unit, usually between low-angle master surfaces, indicating that they were superimposed on larger bedforms or bars.

The macrofauna and flora within the Ollach Sandstone Member includes ammonites, belemnites, bivalves, brachiopods, crinoid ossicles and wood fragments, indicating a marine environment. Lady Murchison, wife of Sir Roderick, collected the type specimen of the zonal index ammonite *Ludwigia murchisonae* close to this locality (Hudson & Trewin 2002). The base of the *murchisonae* ammonite zone is the most obvious position to place the mid-Cimmerian stratal surface (correlative conformity), based on the mid-Aalenian (top *opalinum* ammonite zone) timing of the North Sea thermal dome (Underhill & Partington 1993) and the concomitant grain-size increase at the base of the Ollach Sandstone Member.

A wide range of trace fossils is preserved in the lower sub-unit (*Thallasanoides* and clay-lined *Palaeophycus* are the most common), but these are less abundant in the upper sub-unit where energy levels and sedimentation rates are interpreted to have increased. The Dun Caan Shale and
Fig. 8. Bearreraig Bay photograph montage. (a) Overview of the locality looking from the north of Bearreraig Bay back towards the south. From the water to cliff top is 180 m. The access path is denoted in black, comes from the right and goes behind the house and railway shed at the top of the cliff then down the steep slope to the left (east) of the water pipes and railway. White letters relate to the other photographs in this figure to aid positioning. Four members of the Bearreraig Sandstone Formation are labelled. The logged section on the right provides gross grain-size trends and is taken from Mellere & Steel (1996). (b) Ollach Sandstone Member: an upward-coarsening sequence with a slightly retrogradational, finer-grained and thinner-bedded cap. Note the elliptical calcite-cemented nodules that are more numerous (and larger) towards the top of the unit. Planar, parallel lamination, low-angle planar lamination and cross strata dominate this member. Below the Ollach Sandstone Member the Dun Caan Shale Member can be observed at low tide. Person for scale on the left of the image (circled). (c) Photograph of the southern side of the Bearreraig Burn shows three clear Udairn Shale Member benches (black arrows) with good lateral continuity across the outcrop. Notice the fault throwing down to the SE with a throw of around 3–4 m. Correlation across the fault is facilitated by the three marker beds but is more difficult at higher levels where the contrasting weathering patterns of a white-coloured Lower Holm in the alcove behind the waterfall (footwall to the right) correlates to the same section that lies behind a grass-covered slope in the hanging wall to the left. These sheets of siltstone and very fine sandstone are interpreted to represent distal portions of gravity flows that dispersed down the hanging-wall dip-slope towards the NW (see Fig. 7b). The red arrows show the position of the mid-Holm sequence boundary which represents a major basinward shift of facies. (d) Looking west to the Bearreraig Burn waterfall section, where the Udairn, Holm and Rigg Members can be observed. Outcrop is patchy in the lower reaches of the burn but improves in the middle and upper portions of the Udairn Shale Member where resistant, cemented benches offer a well-exposed step-pool type outcrop pattern in the bedrock stream. Location where photograph (e) was taken is shown. (e) The mid-Holm sequence boundary is depicted by the overhang. Large-scale planar cross-bedding can be seen immediately above the sequence-bounding stratal surface with a broadly northerly palaeoflow, although significant variability exists in these tidally influenced deposits. The set of planar cross-bedding is c. 1 m thick. (f) Close up of the upper section of the Udairn Shale Member. Elliptical calcite-cemented nodules make up the lower benches and these give way to more continuous (and thicker) cemented sheets. The three upper sheets are the marker beds in Figure 8c. Note the presence of a narrow dyke behind the metre stick (marked with a vertical black arrow), possibly utilising the fault plane seen in Figure 8c.
Ollach Sandstone Members reflect an offshore transition zone to lower shoreface and then upper shoreface, though locally delta front, palaeoenvironment. Climbing ripple laminae near the top of the Ollach Sandstone Member are suggestive of uni-directionally accreting mouth-bar deposits at the front of a delta distributary lobe. The uppermost few metres of the Ollach Sandstone Member become finer-grained and thinner-bedded, implying a slight retrogradation (or lateral shift in deposition) before the onset of Udairn Shale Member deposition.

Udairn Shale–Holm Sandstone Members (Fig. 8a)

Although the Ollach–Udairn contact is poorly exposed near the turbine house, this transition is nicely exposed in a gully 300 m to the south of the point (Morton & Hudson 1995) and, in this location, the base of the Udairn Shale Member is interpreted as an important flooding surface of latest Aalenian age. The deepening event is likely to have increased water depth to some tens of metres, at least to below storm wave base. The Udairn Shale Member itself is best observed in the Bearreraig Burn stream bed and in adjacent low cliffs [GR 516 527]. The Aalenian–Bajocian boundary has been placed within the lower part of the Udairn Shale Member based on a change in ammonite genus from Graphoceras to Hyperlioceras (top Aalenian, concavum ammonite zone to base Bajocian discites ammonite zone), accompanied by a change in the composition of the bivalve fauna (Morton & Hudson 1995). The lower part of the Udairn Shale Member is patchily cemented and calcareous nodules give way to siderite nodules that are commonly fossiliferous.

Higher in the stream bed, towards the middle of the Udairn Shale Member, the succession is punctuated by a series of thin siltstones to very fine-grained sandstones that form prominent steps and pools in the stream bed [GR 515 525, Fig. 8c and f]. The resistance to weathering of these beds is largely due to extensive carbonate cementation (Wilkinson 1991). These cemented areas (or doggers) appear relatively tabular, although elliptical concretions are also present and likely formed around fossil-rich parts of the beds. These siltstone and very fine sandstone beds are sharp-based and structureless and are interpreted as the products of sediment-gravity flows (turbidites or hyperpycnites) that dispersed down the hanging-wall dip-slope of the tilted block, from the updip feeder systems. These flows may have been triggered by storms or indeed fault activity along the crest of the tilted block and, if this is the case, then their deposits could be viewed as either tempestite or seismite event beds. These beds become more frequent and thicker upwards towards the Udairn–Holm regressive transition.
The basal part of the Holm Sandstone Member is a thoroughly bioturbated, fine-grained sandstone with ammonite-bearing concretions. In the middle part of the Holm Sandstone Member there is a distinct, sharp but irregular erosion surface (Fig. 8d and e), above which an abrupt increase in grain size is accompanied by the introduction of large-scale planar cross-bedding (Fig. 9). Sediment transport was largely northwesterly, but with enough variability seen in the main cliff face to suggest some bidirectionality and to invoke tidal processes. Above this, large-scale (2–4 m) sigmoidal cross-bedding is observable behind the waterfall [GR 515 525] and is interpreted as reflecting the accretion of large tidal bars. This mid-Holm erosion surface (Fig. 8c–e) is a candidate sequence boundary associated with a clear basinward shift of facies in response to a relative fall in sea-level. This would have induced confinement and the amplification of tidal currents, leading to tidal ravinement and the deposition of large-scale tidal bars.

The Udairn Shale Member grades upwards into the Holm Sandstone Member on the lower slopes of the main cliff [GR 515 525] and the Udairn–Holm pairing represents the second progradational cycle within the Bearreraig Sandstone Formation. The Udairn–Holm progradational cycle (Fig. 8a) portrays a vertical change through time that is interpreted here to represent a change from an offshore setting to a pro-delta clinoform slope with thin turbidite flows, to a shallow-marine, delta-front environment with strongly bioturbated lower shoreface sands, changing abruptly to channels and gullies containing abundant high-energy tidal dunes and bars.

The vertical stacking pattern indicates that aggradation and progradation took place on the half-graben dip-slope as the sequence slowly shoaled upwards. This gradual transition was punctuated by an abrupt reduction in water depth during the mid- to late Bajocian at the mid-Holm candidate sequence boundary (laeviuscula–sauzei zone boundary).

Rigg Sandstone Member (Fig. 9)

The overlying Rigg Sandstone Member shows a tabular interbedding of current-rippled sandstone bed sets (50–100 cm thick) with thinner silty beds (10–30 cm) (Fig. 9). The sandstones are rich in belemnites and are pervasively bioturbated. In the basal 10 m of the Rigg Sandstone Member the beds thin upwards towards a muddier interval that is interpreted as a subtle flooding/deepening event (humphriesianum zone, top romani subzone). This stacking pattern gives the lower Rigg Sandstone Member a retrogradational (backstepping) appearance; then, above the mid-Rigg flooding surface an upwards-thickening package of sandstones suggests renewed progradation of the system. Between the waterfall and the dam [GR 514 524], exposures in the stream bed are of poor quality and have been intruded by a thick igneous sill which can be traced into the adjacent hillside to the north. The top of the Rigg Sandstone Member is a shelly granule and pebble-grade conglomerate (found mainly in loose blocks at GR 512 523), and this conspicuous grain-size increase led some workers to call this interval the Bearreraig Grits (Morton & Hudson 1995). A possible interpretation is that this grain-size increase lies above an unexposed sequence boundary, equivalent to the Vesulian unconformity in the Cotswolds (Barron et al. 2012) and the Paris Basin, however, the grits are interpreted here as a transgressive lag, closely associated with the base of the Garantiana Mudstone Member flooding surface, analogous to the Tarbert Formation of the Northern North Sea (Graue et al. 1987). This is an important stratigraphic surface as it represents the end of coarse-grained sediment supply within the Bearreraig Sandstone Formation. Although not in outcrop at Bearreraig Bay, the Garantiana Mudstone Member has been dated at Brae on Raasay to the Upper Bajocian, Garantiana (ammonite) zone and dichotoma subzone (Morton & Dietl 1989).

In summary, the deposits of Bearreraig Bay indicate sedimentation on a shallow shelfal ramp, where clay and silt-prone pro-delta deposits interdigitated with sandy delta-front prograders, including tidal sand bar facies. Sediment was fed down on to the hanging-wall dip-slope from a shallow-water stagnation area to the east or SE.

In sequence stratigraphic terms, three progradational pulses can be recognized in the Bearreraig Sandstone Formation at the type locality (Dun Caan–Ollach, Udairn–Holm, Upper Rigg). This locality occupies a relatively central position on the Sea of the Hebrides hanging-wall dip-slope and the progradational pulses are clear and separated by marine flooding events; the most pronounced of which appear to be the base Udairn Shale Member flooding event and the base Garantiana Mudstone Member flooding event, which shut off coarse clastic input. The coarser-grained intervals near the top of each cycle represent more proximal, but still subaqueous, delta-front facies and when the three cycles are compared, the second probably reflects the most advanced progradational pulse, with relative sea-level fall and/or high sediment flux triggering the basinward shift of facies and the forestepping of the Holm clastic wedge furthest forward into the half-graben.

Locality 2 – Upper Glen 1 Well (onshore Skye): downdip on hanging wall (Fig. 10)

This exploration well has been given the status of a locality because of its importance as a data point to help build the tectonostratigraphic model (see Fig. 5 for structural context). The well is around 25 km NW of Portree, north of the A850 [GR 298 506, Fig. 1], was drilled in 1989 by Pentex to a depth of 2682 m (8880 ft) and was suspended with gas shows. Cuttings and wireline logs provide a wealth of stratigraphic information.

Beneath thick basalts at the surface, the well intersects two sills in Middle and Lower Jurassic strata and the well terminates in the Upper Triassic. Our interest is in the thickness, lithotypes, sand/shale ratio and wireline stacking patterns of the Bearreraig Sandstone Formation, which is 405 m (1329 ft) thick in the well bore (918–1323 m or 3013–4342′) Measured Depth (MD), including the Garantiana Mudstone and the Dun Caan Shale Members. We make comparisons with the outcrop at the type site of Bearreraig Bay some 22 km away to the east (see Table 1 for thickness comparisons and Fig. 10. for the correlation panel). Net to gross has been computed in the well using a gamma-ray cutoff or threshold and is believed to be similar to the sandstone v. sandstone and shale ratios calculated from outcrop.
Fig. 10. Stratigraphic and lithological correlation panel between the Upper Glen 1 well (locality 2) and the Bearreraig Bay outcrop (locality 1). See Figures 1, 6 and 7 for locations of the two data points. Thicknesses for the Bearreraig Bay strata come largely from Hesselbo & Coe (2000) but also in part from Morton & Hudson (1995). FS, flooding surface; MFS, maximum flooding surface; SB, sequence boundary; GR, gamma-ray log (0–100 API, non-radioactive lithologies kick left); DT, sonic log (140–40 μs/ft, harder lithologies kick right). SB at the base of the Ollach Sandstone Member is interpreted as the mid-Cimmerian Unconformity (or rather correlative conformity) surface. Section datum is the base of the Garantiana Mudstone Member.
### Dun Caan Shale–Ollach Sandstone Members (Fig. 10)

The Bearreraig Sandstone Formation rests on the Raasay Ironstone Formation. The ironstone forms a reliable regional datum, is 27 m (90′) thick in the well, i.e. considerably thicker than at outcrop. The Raasay Ironstone is an important stratigraphic marker as it represents a period of relative quiescence and condensation.

The Dun Caan Shale Member is 5.7 times thicker and much finer-grained in the Upper Glen 1 well than at Bearreraig Bay. The finest grain sizes, interpreted as the deepest-water conditions, occur at 1265 m (4150′) MD and probably represent a flooding surface close to top Toarcian/base Aalenian. Above this, the section begins to ‘clean’ on the gamma-ray log (which measures natural radioactivity) and is interpreted as gradually coarsening upwards towards the Ollach Sandstone Member. The mid-Cimmerian Unconformity (or more likely its correlative conformity) is tentatively placed at the base of the Ollach Sandstone Member.

The Ollach Sandstone Member is sharp-based and consists of micaceous, very fine- to fine-grained sandstones that are locally carbonate-cemented and contain occasional shell fragments. Gamma-ray readings suggest that they are poorly sorted, rather dirty sands or silts, finer-grained and representative of deeper water than their equivalent at Bearreraig Bay. The sandstones clean upwards in two distinct pulses and become sonically ‘faster’, probably due to carbonate cementation (in keeping with the Ollach Sandstone Member outcrop at Bearreraig Bay). The Ollach Sandstone Member is 1.46 times thicker in the well than at Bearreraig Bay. The upper part of the Rigg Sandstone Member fines upwards in several progradational cycles.

### Udairn Shale–Holm Sandstone Members (Fig. 10)

The uppermost part of the Ollach Sandstone Member is slightly finer-grained (see the retrogradational log pattern in Fig. 10) and the base of the Udairn Shale Member is placed at the base of a claystone at 1158 m (3800′) MD, where there is a distinctive gamma-ray spike that is interpreted as a maximum flooding surface associated with the Aalenian–Bajocian boundary. The Udairn Shale Member forms three upward-coarsening cycles, each topped by sandstones. The Udairn Shale Member is 1.69 times thicker in the well than at outcrop. Net sandstone to gross interval thickness is surprisingly high at 49%, using a gamma-ray log-based discrimination of sand v. shale.

The base of the Holm Sandstone Member directly overlies cemented Udairn Shale Member sandstones and there is an obvious change to silstones and claystones associated with a flooding surface forming a high gamma-ray spike. The top of the Udairn Shale Member and base of the Holm Sandstone Member is a distinctive boundary. The Holm Sandstone Member sandstones coarsen upwards in several progradational cycles.

There is a very obvious increase in grain size (marked by a decrease in gamma-ray value) at 1029 m (3375′) MD in the middle of the Holm Sandstone Member, which is a candidate sequence boundary. We suggest that this is likely to correlate with the mid-Holm erosion surface at Bearreraig Bay. Above this, the sandstone is fine- to medium-grained, poorly-sorted and fines upwards in a retrogradational stacking pattern. This is likely to be equivalent to the transgressive interval interpreted above the sequence boundary at Bearreraig Bay by Mellere & Steel (1996). The Holm Sandstone Member is 1.55 times thicker in the well than in outcrop. Net sand to gross interval thickness is 50% in the well.

### Rigg Sandstone Member (Fig. 10)

The top of the Holm Sandstone Member is abrupt, marked by a thin, carbonate-cemented sandstone overlain by claystones (Fig. 10). The Rigg Sandstone Member, a pulsed coarsening-upward unit, has fine grained, moderately to well-sorted sandstones. The member is 1.46 times thicker in the well than in outcrop at Bearreraig Bay. Net sand to gross is 37% in the well.

The upper part of the Rigg Sandstone Member fines upwards gradually and is overlain by a high gamma-ray claystone, 5 m (15′) thick, at 928 m (3045′) MD, which forms the base of the Garantiana Mudstone Member. This is abruptly overlain by a 6 m (18′) thick, very fine- to fine-grained, moderately well-sorted, cemented sandstone that forms the top of the member.

In summary, the Upper Glen 1 well was drilled in a relatively downdip location on the Sea of the Hebrides Basin tilt block (Fig.10). The well data, once correlated to the Bearreraig Bay outcrop, provide a high resolution record of syn-rift extension, block rotation, stratal growth rates, updip–downdip sand/mud ratio and lithology changes in the Hebridean tilt-block province.

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**Table 1. Thicknesses (in feet) of the Bearreraig Sandstone Formation and its members, comparing the Upper Glen 1 exploration well with Bearreraig Bay**

<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>Upper Glen 1 well</th>
<th>Bearreraig Bay Outcrop</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth to top</td>
<td>Thickness</td>
<td>Height to top</td>
</tr>
<tr>
<td>Garantiana Claystone</td>
<td>3013</td>
<td>32</td>
<td>617</td>
</tr>
<tr>
<td>Rigg Sandstone</td>
<td>3045</td>
<td>282</td>
<td>591</td>
</tr>
<tr>
<td>Holm Sandstone</td>
<td>3327</td>
<td>173</td>
<td>397</td>
</tr>
<tr>
<td>Udairn Shale</td>
<td>3500</td>
<td>300</td>
<td>285</td>
</tr>
<tr>
<td>Ollach Sandstone</td>
<td>3800</td>
<td>260</td>
<td>108</td>
</tr>
<tr>
<td>Dun Caan Shale</td>
<td>4060</td>
<td>282</td>
<td>49</td>
</tr>
<tr>
<td>Raasay Ironstone</td>
<td>4342</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Bearreraig Fm thickness</td>
<td>1329</td>
<td></td>
<td>617</td>
</tr>
</tbody>
</table>

Note the gradual, stepwise reduction in the degree of thickening between Bearreraig Bay and the Upper Glen 1 exploration well. The acme of the syn-rift is interpreted to occur early during the deposition of the Bearreraig Sandstone Formation then subsidence rates slowed through time. All figures in feet; compaction is not accounted for.
The thickness of the Bearreraig Sandstone Formation in the well is 405 m (1329′), compared to 188 m (617′) at Bearreraig Bay, thus thickening downdip by 2.15 times (217 m thicker) over some 25 km (8.7 m km⁻¹). There is a clear thickening trend towards the Upper Glen 1 well (Table 1) and we argue that this is clear evidence for syn-rift subsidence, block tilting and the westward growth of strata towards the active Minch Fault. Additionally, as the proportion of thickening diminishes systematically upwards at the scale of each member (Table 1), we can surmise that the rifting may have slowed down through Bearreraig Sandstone Formation time as the fault displacement rates decreased. Intriguingly, the highly prograded clastic wedge of the Upper Holm Sandstone Member appears to be roughly the same thickness in both outcrop and the well. The sandstone/mudstone ratio in the well is lower than all other localities, most likely as a function of deeper palaeo-water depths, palaeo-environmental quiescence and longer distance from sediment source areas.

**Locality 3 – Screapadal (Isle of Raasay): updip reaches of the Sea of the Hebrides tilted block (Fig. 11)**

Locality 3 reveals some key features of the updip, near-crestal reaches of the main Sea of the Hebrides tilted block. This outcrop area is truly spectacular, with greater than 100 m of near-vertical relief, providing outcrop at seismic scale, which is rare indeed for the UK and, as a result, easy access to the cliff section at Screapadal is restricted to the lower slopes.

The sand-prone nature of the Bearreraig Sandstone Formation at this locality (compared to Bearreraig Bay and Upper Glen 1 well) is obvious, even from a distance. Crucially, even though the succession does possess subtle grain-size variations that can be picked out from the vertical weathering profile (Fig. 11a and b), there is no obvious equivalent of the Udairn Shale Member that was so well developed at Bearreraig Bay, only 11 km to the NW. This implies some significant lateral facies change in an updip/down-dip sense. Grain size, palaeocurrents, net to gross, the dominance of cross-bed sets and larger-scale architectural evidence leave no doubt that the Screapadal outcrop is more proximal than that at Bearreraig Bay on the Sea of the Hebrides tilted block.

From a distance, the most spectacular features in the cliffs are the down-cutting channels, seen at multiple levels within the Bearreraig Sandstone Formation [GR 585 429, Fig. 11c/d and e/f]. These have strongly erosional bases, incising from 2 to 10 m into the background facies of mainly planar cross-stratified sandstones (Fig. 11d and f). These channels have been numbered from 10 to 80, from oldest to youngest (Fig. 11f).

This Screapadal outcrop also allows the Bearreraig Sandstone Formation to be examined in detail and the Towers sector of the outcrop is the most easily accessible part. The Towers area also offers an exceptional view of a 5 m deep, U-shaped channel as seen on the SW side of a natural amphitheatre, high on the slope [GR 583 435, Fig. 11i]. The channels are typically lined by a coarse-grained basal lag (with some extra-formational pebbles as well as bioclasts) followed by medium- to coarse-grained sandstones with trough and planar cross-bedding with sets up to 1.5 m thick.

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Fig. 11. (a) An overview of the cliffs at Screapadal, Isle of Raasay. A drone-captured photograph panel, calibrated to a digital elevation model (DEM) of the area to produce a 3D digital outcrop model. (b) An overview of the cliffs at Screapadal, Isle of Raasay with the key erosion surfaces added.
Fig. 11. Continued. (c) Screapadal Main Face (upper section) uninterpreted. These photographs, looking west to the Screapadal locality (locality 3), show spectacularly exposed reservoir-scale outcrop. Cliffs are around 120 m high.
Fig. 11. Continued. (d) Screapadal Main Face (upper section) interpreted. Note large variation in the geometry of the channels. Low in the cliffs the channel forms are open, and chute-like, with high width to depth ratio, whereas the forms tighten into gully-like geometries higher in the section, with lower width to depth ratios. A decimetre numbering system provides a crude chronology of the main incision events.
reflecting the downslope migration of curved and straight crested dunes within the larger channel forms. Muddy drapes and mud rip-up clasts are present but uncommon. Within some channel fills the cross-bedding set heights reduce upwards to become decimetre scale, leading up to laterally extensive sets, less confined by channel walls. The internal structure of the channel fills is commonly disturbed by intensive soft-sediment deformation due to dewatering. The dewatering triggers could be high rates of deposition, seismicity, stress induced on the seafloor by strong currents, or loading from the depositional unit above. Convolution can be large scale, with up to 5 m amplitude ball and pillow structures observed (see the right side of Fig. 11c), but can also result in sandstones that appear structureless where bedding has been disrupted and in some places obliterated.

Channel orientations are broadly towards the NW (Fig. 11g and i), and this is an important observation because the Screapadal Fault (sometimes referred to as the Raasay Fault) lies only 1 km away in this direction. The absence of any fault-parallel channels is good evidence that the down-to-the-SE Screapadal Fault was probably not active at the time of deposition. This is an important re-interpretation and one key area where this account departs from previous work (e.g. Mellere & Steel 1996).

Based on the combined evidence of the NW-directed palaeocurrents and the thickness mapping of the Bearreraig Sandstone Formation (compare the thicknesses at localities 1 and 3 on Fig. 7b), it is unlikely that the Screapadal Fault was active at time of deposition and thus did not partition the area into separate sub-basins. The juxtaposition of Torridonian Sandstones against Middle Jurassic strata across the Screapadal Fault today is thought to reflect post-Middle Jurassic movement (most likely Early Cretaceous based on patchy outcrops but mostly on Atlantic Margin rift timing).

Cross-bedded sandstones of the background facies are especially well exposed in the Towers area (Fig. 11j). The background facies are only slightly finer-grained than the fill of the channels, and consist of well-sorted, stacked sets of mainly planar cross-bedded sandstones. These are interpreted as submarine dune deposits due to the abundance of bioclastic material including scattered molluscan shells. The currents that created the cross strata were clearly strong, as suggested by their medium–coarse grain size and set heights up to 1.5 m high. These may be analogous to the dunes detected in the subaqueous part of the Ganges tidally dominated delta (Kuehl et al. 1997). Tidal currents were the most likely driver, reflected in local bidirectional cross-bedding (dominant to the north and NW) and the rhythmic organisation of foreset thicknesses, suggesting spring-neap tidal bundling (Fig. 11j).

**Geological interpretation for the evolution of channel geometries (Fig. 12)**

The Screapadal outcrop reveals a relatively updip succession, where gross thickness decreases and the sand to mud ratio increases up the hanging-wall dip-slope. In this proximal part...
of the tilted block there was less accommodation, shallower-water depths and stronger tidal currents that encouraged the development of tidal channels. The channelised, erosive forms appear to change their aspect ratio upwards in the succession (wide chutes at the bottom and narrow gullies at the top, see Table 2).

![Photograph looking NW where the channels tend to weather more massively and resistively. The facies type within the channel incisions is thicker bedded and is more homogeneous compared to the background facies, which is more interbedded and heterolithic. Note the steep scour surface cutting down to the left within the channel body. Cliffs around 120 m high.](image)

![Close-up of the internal structure of the lower chutes to demonstrate their thicker-bedded character relative to the background strata. The channel-fill facies are better sorted and are less interbedded because of consistently higher energy, confined tidal current processes (and possibly also dewatering in places). Photograph looking west and cliff in the photograph is around 25 m high.](image)

![A good example of one of the upper channels with a NW palaeoflow (broadly to the right). This channel has a gully-type morphology and is around 18 m thick. The basal fill is less well bedded (possibly due to dewatering and ad-mixing of the contents of the fill). This narrow width to depth gully is representative of the more confined forms towards the top of the succession. Photograph taken looking south. Person for scale on grassy slope.](image)

Fig. 11. Continued. (g) Photograph looking NW where the channels tend to weather more massively and resistively. The facies type within the channel incisions is thicker bedded and is more homogeneous compared to the background facies, which is more interbedded and heterolithic. Note the steep scour surface cutting down to the left within the channel body. Cliffs around 120 m high. (h) Close-up of the internal structure of the lower chutes to demonstrate their thicker-bedded character relative to the background strata. The channel-fill facies are better sorted and are less interbedded because of consistently higher energy, confined tidal current processes (and possibly also dewatering in places). Photograph looking west and cliff in the photograph is around 25 m high. (i) A good example of one of the upper channels with a NW palaeoflow (broadly to the right). This channel has a gully-type morphology and is around 18 m thick. The basal fill is less well bedded (possibly due to dewatering and ad-mixing of the contents of the fill). This narrow width to depth gully is representative of the more confined forms towards the top of the succession. Photograph taken looking south. Person for scale on grassy slope. (j) Rhythmically thicker foresets in trough cross-bedding. Cyclicity is thought to relate to tidal cycles (spring-neap tidal bundles, e.g. Longhitano et al. 2012) and these are especially well preserved in a thin unit three-quarters of the way up the photograph. These sandstones are well sorted, medium and coarse-grained, cross-bedded with pervasive carbonate cementation. The sandstones possess variable amounts of bioclastic material that may be related to the strength and state of the tides (Longhitano et al. 2012). Photograph taken looking NW, with palaeoflow generally to the NNW. Person for scale in bottom left.

Table 2 illustrates the aspect ratio (width to thickness) of each channel in the main face at Screapadal, measured from the 3D outcrop model, chiefly as a half-width of the erosional form, which is then assumed to be symmetrical. These results show a distinctly lower aspect ratio (2.5–5.7) in the upper part of the sequence (channels 50–70). Our interpretation places

<table>
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<tr>
<th>Channel name</th>
<th>Thickness (m)</th>
<th>Bankful half-width (m)</th>
<th>Assumed symmetrical width (m)</th>
<th>Measured full width (m)</th>
<th>Aspect ratio (2hW/T)</th>
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</thead>
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<tr>
<td>70</td>
<td>5.9</td>
<td>16.8</td>
<td>33.6</td>
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<td>4.87</td>
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<tr>
<td>40</td>
<td>8.6</td>
<td>44.6</td>
<td>89.2</td>
<td></td>
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</tr>
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<td>30</td>
<td>6.64</td>
<td>90.9</td>
<td>181.8</td>
<td></td>
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<td>20</td>
<td>11.5</td>
<td>40.4</td>
<td>80.8</td>
<td></td>
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<tr>
<td>10</td>
<td>10.7</td>
<td>54.7</td>
<td>109.4</td>
<td></td>
<td>10.2</td>
</tr>
</tbody>
</table>

Note the general tightening of the channel geometries upwards. Channel thickness was measured from the lowest point of the channel thalweg to the uppermost facies transition (from massive coarse-grained sands to more stratified finer-grained strata). All but one of the width measurements were half-widths (by necessity due to extent of exposure) and these have simply been doubled as an approximation of full widths to compute the width to thickness ratios.
these geometries in a continuum of downslope to upslope channel forms. We believe that the variation in channel form suggests that the channels had a distally flaring planform and were thus most likely excavated by ebb tidal currents. This potentially indicates that the overall system prograded downslope such that the younger, narrower (and presumably more proximal), channels overlie older, shallower channels (which reflect a more distal location, see Fig. 12). The change in form in the section is best illustrated by Figure 11c.

These geometric changes are broadly in keeping with the point of maximum progradation existing high in the succession at Bearreraig Bay (the Holm Sandstone Member). The higher channels with the narrowest aspect ratio at Screapadal are speculated to be the possible time-equivalent section of the Holm Sandstone Member. A notable exception to the basic trend of decreasing width to thickness up-section is channel 30, which has a wide, sheet-like, form with an aspect ratio of 27:1. In addition to the flaring planform model a secondary control on width to thickness ratios is the amount of lateral movement and combing experienced by a channel (e.g. Kumar & Sanders 1974).

Although we favour fully offshore tidal channels with a preferred modern analogue of the offshore part of the mouths of the Yangtze Delta (e.g. Zhang et al. 2018), the channels observed at Screapadal could also be tidal inlet channels, more analogous to those in Anegada Bay, Argentina (Cuadrado & Gomex 2011) or the Carolina Coast (Moslow & Tye 1985). In this model only the basal part of the channel form is preserved, following transgression and erosion (tidal current erosion) of the subaerial barrier bar (see the blue erosion and hiatal surfaces of Fig. 11d and f).

In summary, the Screapadal area, in terms of the background facies types, is interpreted as representing a widespread, sand-rich dune field on the high part of the tilted fault block on the flexural margin of the Sea of the Hebrides Basin. The large dune heights recorded in the background facies suggest that the high-energy tidal dune field existed in a seaway with likely water depths of 10–40 m. This structural position was sensitive to relative sea-level rise and fall where periodic footwall uplift would have reduced water depths and induced incision, promoting the excavation of ebb tidal channels. Following the channel-fill phase, eustatic sea-level rise events may have promoted transgressive erosion of the channel tops in a similar manner as that recognized by Nummedal & Swift (1987).

It is worth emphasizing the exploration significance of the Screapadal channels as they are envisaged to have acted as...
conduits for the rapid delivery of well-sorted sand from this location further down into the half-graben, as seen at Bearreraig Bay and in the Upper Glen 1 well. Large volumes of sand were shed downdip intermittently via these ebb-tide bypass channels, during phases which probably coincided with pulses of footwall uplift. Sand delivery into deeper water could therefore have involved two separate mechanisms: the background dip-slope dune field, transporting a seafloor carpet of sand in a general northwards direction, in addition to the ebb-tidal incision and possibly gravity-enhanced flows towards the west and NW. The channelization and sand transport may have been encouraged by the structural location, triggered by seismic activity and faulting to the east, concomitant footwall uplift and slope over-steepening.

The relatively homogenous sandstone succession at Screapadal means that it is difficult to define the members of the Bearreraig Sandstone Formation (e.g. Ollach Sandstone Member, Udairn Shale Member etc.) or the key stratigraphic surfaces (e.g. the mid-Holm candidate sequence boundary). This is a classic stratigraphic correlation challenge, typical of high net-gross successions that lack clear stratigraphic markers, where sand supply was plentiful relative to accommodation (Ss > Ac).

Locality 4 – Glasnakille (near Elgol on the Strathaird Peninsula): a narrow half-graben and tidal strait (Fig. 13)

The Bearreraig Sandstone Formation outcrops on the eastern and southern coasts of the Strathaird Peninsula. The base of the formation can be observed on the eastern coast and the top is stratigraphically conformable with the Great Estuarine Group close to the village of Elgol. On the southeastern part of the Strathaird Peninsula [GR 531 118], at Glasnakille, the lower part of the Bearreraig Sandstone Formation is dominated by thickly stacked, SSW-accreting sets of planar and trough cross-beds (Fig. 13a–d). Individual sets are up to 4 m thick but more commonly are 1–2 m and are the products of strong, SSW-dominant tidal current-swept coarse sand, granules and uncommon pebbles across a submarine dune field. Locally, cross-strata climb up the stoss surfaces of larger bedforms. Long master bedding surfaces (traceable for 5–10 m) are inclined back at shallow angles to the NW, indicating the presence of large compound dunes. The climbing bedforms indicate high sedimentation rates reflecting the availability of large quantities of sand to this basin.

Uncommon small-scale dunes and ripples generated by a northward-flowing subordinate current indicate bidirectional flow (Fig. 13e), associating closely with the large-scale, dominant-current dunes. A tidal-current interpretation is also supported by evidence of double-drape laminae of silt or fine-grained, black organic matter, especially on dune bottomsets or lower foresets (Mellere & Steel 1996; Blackwood 2006), but these are relatively rare due to the general coarse grain-sizes in the system. Intact ammonites are present but rare, together with belemnites, abundant marine shell fragments and a diverse ichnofauna. Burrows include Diplocraterion and Monocraterion and are best seen on dune foresets and bottomsets where pauses in sedimentation allowed time for traces to be generated.

Critically, the SSW trend of the reconstructed, dominant tidal current is broadly parallel to the basin-bounding fault (Camasunary Fault), which lies only 7 km to the west and is likely to have provided a strong control on subsidence rates (Fig. 13f). Based on preserved thicknesses, the subsidence rates probably increased SW in this basin towards Glasnakille (Fig. 14). The marine basin would have inherited its bathymetry from the geometry of the tilted fault-block. The width of the Inner Hebrides half-graben is narrow and so this relatively confined, long-lived, seafloor dune field has been interpreted as being hosted in a tidal strait. The Sleat Peninsula to the east of this location crudely represents the flexural margin of the Inner Hebridean Basin, although the Strathconnon Fault is largely offshore and is not seen in the immediate area.

The balance between fault-controlled subsidence, eustatic sea-level change and sediment supply appears to have been remarkably steady during the deposition of the Bearreraig Sandstone Formation on the southern tip of the Strathaird Peninsula, where 485 m of tidally generated, cross-bedded sandstones are preserved (Morton 1965; Blackwood 2006). Note that here, in the Inner Hebridean half-graben, there is no equivalent to the fine-grained Udairn Shale Member, presumably due to the persistence of a high, coarse-grained sediment flux, reflecting the relatively close proximity of the source of the sand on the Scottish mainland and the Bearreraig delta.

There are some exceptions to the apparent stability in relative sea-level, and consistent shallow-water depth is recorded on the south coast of the Strathaird Peninsula. Here a possible rooted horizon (Mellere & Steel 1996) suggests very shallow-marine, lagoonal or marsh conditions. This may reflect a short period of shallower water in an estuarine setting; however, the general lack of palaeosols or seat earths suggests that the area never became an exposed, vegetated land surface. The interpreted shallowing of water depth is due to a fall in relative sea-level which may well represent a eustatic fall, but may also reflect a slow-down in subsidence rate due to a diminished rate of slip on the Camasunary Fault to the west.

The consistent southerly palaeocurrents for most cross-strata in the lower part of the Bearreraig Formation at Glasnakille probably reflect the dominance of ebb-tidal currents (Mellere & Steel 1996), on the assumption that sand was supplied from the main delta to the north (Fig. 13f) and the basin was open and connected to the main seaway to the south. However, the Glasnakille outcrop area is not entirely representative of the whole formation since higher in this very thick succession, above the rooted horizon on the shore south of the village of Elgol, the cross-bedding direction is reversed and shows that the dominant current was to the north. This change may have been due to the presence of mutually evasive flood and ebb current fairways changing positions within the strait or, perhaps more likely, a change in the dominant-current direction caused by block-tilting of the hanging wall of the Camasunary Fault, reconfiguring the shape and topography of the Inner Hebridean Basin. The exact stratigraphic position of the change in palaeoflow requires further work but may be correlateable to Bearreraig Bay as the mid-Holm sequence boundary. Immediately below the Garantiana Mudstone Member the top unit is a crinoidal
limestone, indicating that the terrigenous sand supply had been shut down.

In summary, the Glasnakille locality displays a very thick, high sand/mud ratio, coarse sandstone succession apparently dominated by high rates of axial sediment flux, dispersing south through subtidal dune fields that developed in a rapidly subsiding tidal strait between the Camasunary and the Strathconnon faults (Fig. 13f).

Palaeogeography of the Middle Jurassic Hebridean seaway
Many authors have discussed Middle Jurassic depositional processes and palaeogeography (Morton 1983; Hudson 1983; Harris 1989; Mellere & Steel 1996; Hesselbo & Coe 2000; Blackwood 2006). We have modified these interpretations and increased the scale of the palaeogeographical mapping to include regional source-to-sink concepts for the Berreraig deposystem (Fig. 7).
Fig. 14. Stratigraphic correlation panel for the Sea of the Hebrides half-graben. The panel goes from Upper Glen 1 to Bearreraig Bay then up to Screapadal (distal to proximal). The Udairn locality shown in this figure is not included in any detail in this paper, but can be found south of Portree Bay where the northern flank of Ben Tianavaig meets the coast.
The interaction between the allogenic variables of tectonics and eustatic sea-level resulted in a Middle Jurassic palaeogeography that included both open seaways in wide half-graben and tidal straits in narrow half-graben. In the south of the study area, the Camasunary Fault partitions the Hebridean Province into two main basins, the Sea of the Hebrides Basin to the west and the Inner Hebrides Basin to the east. This is in contrast to the north of the study area where the Camasunary Fault transfers throw on to several smaller faults along-strike to create multiple, narrower sub-basins (Figs 5–7). Critical controls on the resulting palaeogeography are fault spacing, fault length, accommodation state (subsidence, eustasy and compaction) and the amount of sediment delivered (catchment area, relief, rainfall and discharge ratio).

The main sediment source area was the Scottish mainland to the east and it is likely that Caledonian lineaments controlled the locations of trunk streams in the fluvial network. We envisage a large catchment area in the North West Highlands that discharged through the NE–SW Loch Carron/Loch Kishorn lineaments (Fig. 7). The erosional engine was strong and supplied large volumes of sediment to the Hebridean margin. The Jurassic coastline is interpreted to have been roughly in the same position as today’s coastline (Hudson & Trewin 2002), but with fewer indentations as today’s sea lochs are a result of Quaternary glacial erosion.

So far as large-scale controls on palaeogeography are concerned, fault-related subsidence rates are believed to have outpaced sedimentation in the region such that marine seaways were maintained. Most fault scarps would have been submarine, but will have been expressed on the sea bed. Only the Minch Fault (the western basin-boundary fault to the Sea of the Hebrides Basin) is thought to have been of a scale large enough to have had a significant subaerial footwall. From the field evidence it is not immediately clear if the Camasunary Fault had a subaerial footwall but we suggest that this is likely, due to the high subsidence rates inferred by the very thick Bearreraig Sandstone Formation strata preserved on the Strathaird Peninsula (nearly 500 m compacted). There must have been a substantial component of footwall uplift (c. 100–200 m) on this fault that may have produced c. 50–150 m of subaerial relief after accounting for water depth. Whether subaerial or not, it was the fault-related geomorphology in this narrow basin that provided bathymetric constriction to the Inner Hebrides Basin and it is this tectonic confinement that differentiates the Inner Hebridean Basin from its outboard counterpart, the Sea of the Hebrides Basin, to the west.

These structural elements (the Minch and Camasunary faults) played an important role in defining the physiography of the region, protecting the Hebridean delta system from storm-wave action and routing tidal currents along-strike to both the north and south (Fig. 6).

The Aalenian–Bajocian-age Hebridean delta system emerging from the Carron and Kishorn lineament was tidally dominated (Morton 1983), with an approximate ratio of 70:20:10 in terms of tidal, river and wave processes, although this no doubt varied in both space and time.

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Fig. 15. Along-strike view (looking to the NW) of the preserved thicknesses of the Bearreraig Formation Sandstone in the hanging wall of the Camasunary Fault. Line of section goes through localities G, K, F and D from SSW to NNE (measured sections from Morton 1965). A highly speculative fault-related subsidence ellipse is shown based on the thickness reduction along-strike to the NE. CF, Camasunary Fault; SF, Strathconnon Fault.
The Sea of the Hebrides Basin

The Sea of the Hebrides Basin was three or four times the width of the Inner Hebrides Basin (Figs 3, 6 and 7) and this contrast in degree of structural confinement between the basins is a critical part of the tectonostratigraphic model. The lack of confinement in the outer basin is manifested in a number of ways in the sedimentary record but most obviously there is a clear grain-size trend to finer-grained materials towards the basin axis (i.e. transversely down the half-graben dip-slope). Lateral changes in facies and sand to mud ratios between updip v. downdip (proximal v. distal) areas of the main tilted-block are best visualized in the cross-section between the Upper Glen 1 well and the Bearreraig Bay locality (see Fig. 6 for structural context and Fig. 14 for details). The relative downdip location of the Upper Glen 1 well offers an invaluable data point for use in correlation, and to assess shallow-marine reservoir continuity on this active tilted fault block. To the south of Bearreraig Bay, outcrops at Torvaig Park and also Udaism (north and south of Portree Bay) continue the trend of thinner gross sections and increased proportions of sand (Fig. 14) updip on the main tilt block.

Coarse-grained sediment supply is likely to have been reduced to this outer basin compared to the Inner Hebrides Basin, due to its greater distance from the Scottish hinterland and a more oblique position relative to the NE-SW (Caledonian) fluvo-deltaic input trend. The sands that did get into the outer basin are likely to have done so through a fill-and-spill delivery system, where the sediment overtopped the inner half-graben (Fig. 6). The most likely locations for the sediment to have spilled through are at fault tips and required oblique aggradation back up the transfer zones. However, once a fault scarp was fully aggraded over, then the feed may have changed from point sourced through relays to more general feed, down the dip-slopes.

The Sea of the Hebrides Basin was dominated by a wide dip-slope or ramp that tilted towards the Minch Fault. The closest locality to the tilted fault-block footwall crest is the Sceapadal location on Raasay (Fig. 14). This palaeogeographical location is dominated by erosive channels that brought sediment down orthogonally on to the dip-slope. The importance of these features in the exploration arena is that they had the capacity to transfer large quantities of sand down into the Sea of the Hebrides Basin in their role as tidally excavated by-pass channels.

The Inner Hebrides Basin

The Inner Hebrides Basin, closer to the Scottish landmass, developed as a narrow fault-controlled marine basin with a vigorous axial sediment delivery system (Figs 6 and 7). We envisage a NE-SW-trending fluviatile system positioned in the NE reaches of the study area, routing down along a catchment system on the Scottish mainland (the palaeo-Loch Carron catchment), feeding directly into the NE-SW-trending half-graben of the Inner Hebrides Basin. Structural alignment on an ancient Caledonian lineament (the Scalpay House to Loch Carron/Kishorn Fault trend in Fig. 3) encouraged the dispersal of sediment axially, into the Inner Hebridean half-graben, leading to a highly efficient delivery system from the terrestrial to the marine environment.

A key feature in the outcrops of the Inner Hebrides Basin is the development of sand-rich tidal dune facies that developed where tidal currents became restricted and fast flowing, along the axis of the ‘straight-like’ half-graben. The largest confinement of tidal currents was between the closely spaced Camasunary and Strathcommon faults (location 4 in Fig. 6), but also in smaller half-graben in the area of SE Raasay. The absence of evidence for significant storm waves in these areas is probably due to the limited wave fetch in the narrow half-graben, allowing these areas to be dominated by river input and, in particular, tidal reworking.

In a strike sense, the Inner Hebridean Basin exhibited variable subsidence along its length, based on the observations of subsidence in the hanging wall of the Camasunary Fault (Fig. 14). The stratigraphy preserved at four localities in the hanging wall of the fault was documented by Morton (1965); the sediment thinning to the NNE suggests a reduction in fault displacement in a NNE direction along the fault profile and the rate of thinning suggests that there was a fault tip to the NNE (Fig. 15). Beyond the Camasunary Fault, displacement reduced and strain is interpreted to have been partitioned into several smaller faults (e.g. the Beinn na Leac and Scalpay House faults, Fig. 6), whereas, to the south, the Camasunary Fault was the most important syn-depositional structure, accommodating large amounts of displacement.

Several faults were active in the northeastern part of the field area, acting together to buffer sediment input from the Scottish hinterland on to the broad ramp slope of the Sea of the Hebrides Basin. Sediment dispersal to the west was highly influenced by structural partitioning of the flexural margin by SE-dipping faults. These would have reduced sediment flux to the outer half-graben relative to inner half-graben, where basins acted as sediment traps for the coarsest grain sizes. The South Raasay (or Fearns) sub-basin is sited in the hanging wall of the Beinn na Leac Fault and is an example of such a sediment trap. This sub-basin represents a more diffuse northern extension of the Inner Hebrides Basin and, in an analogous way, palaeoflows were parallel to the structural elements at this locality. These inner basins exhibit significant sediment thicknesses and a high sandstone/mudstone ratio as large volumes of coarse siliciclastic deposits were spread parallel to faults. The longitudinally developed submarine dune fields were quickly sequestered in this rapidly subsiding syn-rift setting.

Analogue comparison

Sedimentological

The Bearreraig Sandstone Formation has been used extensively as an analogue for the Brent Group of the Northern North Sea (Richards 1992; Mitchener et al. 1992; Husmo et al. 2003). These strata are time-equivalent (Fig. 16) and were deposited in broadly similar settings; both systems being the products of prograding deltas of Middle Jurassic (Aalenian and Bajocian) age.

One obvious limitation of the Skye and Raasay analogues is that fluviatile channels in the style of the Ness Formation of the North Sea are simply not seen in the Hebridean basins.
This difference may be due to retardation of a pseudo-balance between subsidence and sediment supply rates in the Hebrides, whereas supply dominated during the deposition of the Ness Formation in the Northern North Sea. However, the subaqueous portion of the Hebridean deltas may simply have been spatially dominant, or redistribution by tidal currents may also have been a factor in suppressing the progradation of the fluvial system in the Hebrides.

The Bearreraig Sandstone Formation of the Hebridean Basins is also a good first approximation analogue for the shallow-marine sandstone reservoirs of the Upper Jurassic of the Central North Sea area (e.g. Fulmar and Ula Formations, see Husmo et al. 2003). Further afield, the Nukhul Formation in the Gulf of Suez, Egypt, has much in common with the Bearreraig Sandstone Formation due to its syn-rift, tidally influenced, shallow-marine setting (Carr et al. 2003).

Although the Bearreraig Sandstone Formation is much thicker, the formation is strongly analogous sedimentologically with the tidally influenced marine depositional environments of the Middle Jurassic succession of Yorkshire. Here the Eller Beck Formation, the Lebberston Member (of the Cloughton Formation), the Scarborough Formation and a minor part of the Scalby Formation of the Ravenscar Group exhibit tidally influenced facies (Powell 2010) within the Peak Trough, SW of the thermal dome (Cleveland delta in Fig. 17).

Although time-equivalent with the large transverse delta fans of the Broom and Oseberg Formations (Graue et al. 1987), the Ollach Sandstone Member has been used extensively as an analogue for the Rannoch Formation, due to its progradational character and high degree of concretionary cementation. The Ollach Sandstone Member is interpreted here as a mouth bar system, and so could be used as an analogue for more distal parts of the Ness Formation of the Brent Group (Livera 1989). The upper part of the Udairn Shale Member to Lower Holm Sandstone Member is highly cemented and may resemble the deltalic clinoforms of the Rannoch Formation (Matthews et al. 2005). Sub-tidal channels are described in the Etive Formation (Olsen & Steel 2000) and the Bearreraig Bay (especially the Holm Sandstone Member) and Screapadal outcrops provide good analogues for this type of channelized architecture.

**Structural**

Another contrast between the Bearreraig delta system on the Atlantic Margin and its sister Brent delta in the North Sea, is that the Brent system prograded parallel to north-south-trending faults in the Northern North Sea rift arm (Mitchener et al. 1992), whereas the Bearreraig delta system largely prograded westwards towards the active fault planes (Fig. 17). This configuration where sediment input direction was opposed to the dip of the fault planes, and thus the dip of the relays, required sediment to aggrade and prograde up the relay ramps in order to reach the outer half-graben. This relationship between structural configuration and sediment dispersal is unusual in a rifted margin. The Hebridean faults have an antithetic relationship to the main Atlantic Margin basin-bounding fault system, because these faults are related to the reactivation of SE-dipping Precambrian basement thrusts (Stein & Blundell 1990).

The contrasting observations of axial deposition in the Northern North Sea v. transverse depositional systems on the Atlantic Margin is true in general terms, but sediment dispersal was parallel to the fault planes in the Strathaird Field area where the delta fed SW. The higher-energy tidal straits of the Inner Hebridean Basin appear to have time-equivalent counterparts in the Northern North Sea, where there was tectonic confinement (e.g. Wei et al. 2018), and in mid-Norway, where the Bearreraig Sandstone Formation is a direct analogue to the Garm and Ile Formations (Messina et al. 2014) and the Pelion Formation of East Greenland (Engkilde & Surløy 2003). In East Greenland, rifting took place during Middle Jurassic times, generating north-south-trending, east-facing synthetic faults that delimited wide, westwards-tilted fault blocks (Surløy 2003) in a very analogous way to the development of the Hebrides Basins. The key difference between the Hebrides and East Greenland is that rifting started in the Late Toarican in Scotland but in the Late Bajocian in East Greenland, suggesting a northwards diachrony to the rift evolution on this part of the Atlantic Margin.

In terms of analogues for structural traps, tilted fault blocks are the principal trap types in the area studied. Footwall crests are obvious sites where the drilling of exploration wells can be conceptualized. Care must be taken in risking reservoir presence on these footwall crests as syn- and post-depositional crestal erosion may have stripped reservoirs from the succession (if ever deposited). For example, the area west of the Camasunate Fault is a classic footwall crest that lacks Bearreraig Sandstone Formation-age strata, presumably due to Middle and Upper Jurassic tectonism and footwall uplift. The Isle of Raasay is a particularly good analogue area to reconstruct the scale and geometry of the tilted fault blocks as these have geomorphological expression in the current landscape.

The Inner Hebridean region suffered a phase of mass wasting in the Holocene that led to well-known landslides, including the Old Man of Storr (Ballantyne et al. 2014), the Quirang and Ben Tianavaig on Skye (and similar features on SE Raasay). The deformation observed in these landscapes has a great potential as an analogue to understand the processes and geometries of fault-scarp degradation complexes that can be observed seismically on the faulted margins of tilted fault blocks in the Brent Province (e.g. McLeod & Underhill 1999).

**Sequence stratigraphic discussion**

Using the North Sea sequence stratigraphic nomenclature developed by Rattey & Hayward (1993) and built upon at higher resolution by Partington et al. (1993) (Fig. 16), the Bearreraig Sandstone Formation is interpreted as a second-order tectonostratigraphic mega-sequence (J20 age). Within this, three third-order sequences have been recognized in the North Sea by Partington et al. in 1993 (J22, J24 and J26), each separated by a distinctive maximum flooding surface (MFS). We test the robustness of this framework for the Hebridean basins and attempt to rationalize the key similarities and differences below.

**Flooding surfaces**

Within the more distal parts of the field area (Bearreraig Bay and the Upper Glen 1 Well), maximum water depths are
Fig. 16. Sequence stratigraphic framework for the Bearreraig Sandstone Formation, compared to the North Sea sequences and lithostratigraphic formation names of the Brent Group, using Richards (1992), Richards et al. (1993) and Partington et al. (1993). The lithostratigraphy of Mid Norway (Messina et al. 2014) and the speculative position of the Cleveland Basin Formations are also shown for comparison. We recognize the diachronity of the boundaries between these analogous formations and the limitation of 1D lithostratigraphic correlations; however, we do still note the mid-Cimmerian Unconformity (or correlative conformity) at the base of the Ollach Sandstone Member and the Broom Formation and the highly conspicuous coincidence of the mid Holm sequence boundary and the base of the Etive Formation which can also be strongly erosional when observed in core. The ammonite zonation comes from Morton & Hudson (1995). Zones and subzones in bold are observed at Bearreraig Bay and the others have been observed at other localities in the Hebrides.
encountered at the base of each progradational cycle and these stratal surfaces represent the most widespread and significant deepening events. In this list below we suggest the possible age of each of the flooding surfaces based on the published ammonite zonation and speculate about their possible stratigraphic relationship to the North Sea J Sequence stratigraphic surfaces (Fig. 16).

- **Base Garantiana Mudstone Member** – late Bajocian – base *garantiana* (ammonite) zone and base *dichotoma* subzone.
  - J26 MFS
- **Mid-Rigg Sandstone Member** – latest-early Bajocian – intra-*humphresianum* (ammonite) zone and top *romani* subzone.
  - Intra J24 – also detectable in the Upper Glen 1 well.
- **Base Udairn Shale Member** – latest Aalenian – intra-*concavum* (ammonite) zone, at the base of the *limitatum* subzone.
  - Near but not coincident with the J24 *discites* MFS
- **Base Dun Caan Shale Member** – latest Toarcian – base *levesquet* (ammonite) zone, at the base of the *aalensis* subzone.
  - J22 MFS

A flooding surface equivalent to the base of the Garantiana Mudstone Member has been described in the Cotswolds by Buckman (Hudson & Trewin 2002). The base Garantiana Mudstone Member flooding event (J26 *garantiana*) may be correlate with the retrogradation of the Ness Formation fluvio-deltaic system during the formation of the Mid-Ness Shale (Partington et al. 1993).

Correlation is drawn between the Mid-Rigg flooding surface (intra-*humphresianum* (ammonite) zone and top *romani* subzone) at Bearreraig Bay (Hesselbo & Coo 2000) and the marine incursion of the Scarborough Formation in the Cleveland Basin (Hesselbo & Jenkyns 1995) and seen on wireline logs in the Ravenscar Borehole (see Powell 2010, fig. 34). This transgressive phase is unrecognized in the North Sea J sequence stratigraphic scheme of Partington et al. (1993) and may require insertion as an intra-J24 (J25) flooding surface if the correlation to the Scarborough Group is substantiated and interpreted further afield with regional significance. Alternatively this could be deemed a well-defined parasequence within the J24 sequence.

Just south of Bearreraig Bay, the ammonite zonation scheme summarized in Morton & Hudson (1995) offers a comparison between the North Sea’s J24 MFS (base *discites*) definition by Partington et al. (1993) and the age of the important marine flooding event at the base of the Udairn Shale Member. The flooding surface dated near Bearreraig Bay is placed into the Aalenian within the *concavum* zone, at the base of the *limitatum* subzone (Morton & Hudson 1995). The base Bajocian flooding event (J24 MFS *discites*) has been recognized in the North Sea as coincident with the change from the Broom Formation to the Rannoch Formation over the bulk of the Northern North Sea and could also be responsible for the marine incursion that led to the deposition of the Not Shale Formation in Mid Norway (Messina et al. 2014). In the Bearreraig Burn the *discites* event lies wholly within the lower part of the Udairn Shale Member and appears to be related to a change from calcareous to sideritic nodules. The most likely explanation is that the base Udairn surface (base *limitatum* subzone) represents the initial flooding surface that starts the transgression and the J24 (base *discites* zone) surface represents the maximum flooding surface (Hesselbo & Coo 2000). Correlations with the Eller Beck flooding surface in the Cleveland Basin are uncertain but it appears that the timing of the marine incursion of the Eller Beck may support the notion of a widespread *discites* zone flooding event (Hesselbo & Jenkyns 1995).

In the Hebrides the pre-rift to syn-rift transition is thought to occur at the base of the Dun Caan Shale Member. This is based on the hiatus at the top of the Raasay Ironstone Formation, the obvious thickness changes in the Dun Caan shale between localities and the local incursion of coarse-grained clastics, all of which complicate the J22 MFS signal. The tectonic trend to increased subsidence patterns during the syn-rift in the latest Toarcian (*aalensis* zone) is thought to have deepened water depths temporarily, while forcing the basin to reconfigure, rejuvenate sediment source areas whilst ultimately promoting the progradation of coarse clastics.

These increasing water depth events within the Bearreraig Sandstone Formation have four potential origins; eustatic sea-level rise, rapid tectonic subsidence in the half-graben as a response to fault movements, deflation of the North Sea’s thermal dome or rapid reductions in sediment supply (through allogenic or even autogenic responses). As the J26, (±J25), J24 and J22 MFS sea-level rise events have regional correlatives (Partington et al. 1993), we suggest a potential eustatic origin for these flooding events, although close inspection of the eustatic sea-level trends recently published by Haq (2017) failed to reveal an obvious association between these events and interpreted high eustatic sea-level interpretations.

**Sequence boundaries**

Although flooding surfaces deliver a genetic sequence stratigraphic framework (Galloway 1989), full stratigraphic characterization of the Aalenian–Bajocian of the Hebrides also benefits from the identification of sequence boundaries (Mitchum et al. 1977; Vail et al. 1977). Given that tectonic uplift of the thermal dome was likely a key control on sedimentation, a balanced view of both types of stratal surface is important in a holistic analysis.

At Bearreraig Bay and in the Upper Glen 1 well, two abrupt coarsening-upward changes in grain size are interpreted as basinward shifts of facies and therefore sequence boundaries (mid Holm Sandstone and base Ollach Sandstone Members). A third sequence boundary is offered at the boundary of the Garantiana Claystone Member to the Cullaidh Shale Formation, but is not observed at the type site and only characterized by the subtle change upwards from grey-coloured marine claystone to black, bituminous non-marine (brackish water) shale. The fourth sequence boundary represents the base of the J20 megasequence (Rattey & Hayward 1993), which in the field area is the major 5 Ma hiatus seen at the top of the Raasay Ironstone Formation.

- **Base Cullaidh Shale Formation** – latest Bajocian base *parkinsoni* (ammonite) zone
The Jurassic thermal dome(s) of NW Europe have been controversial over the years, with the age, extent, morphology, magnitude of uplift, causal mechanisms and sedimentary responses associated with the dome all having been strongly debated (Whiteman et al. 1975; Hallam & Sellwood 1976; Eynon 1981; Badley et al. 1988; Ziegler 1988, 1990; Latin et al. 1990; Rattey & Hayward 1993; Underhill & Partington 1993, 1994; Jacquin et al. 1998; Andsbjerg et al. 2001; Graversen 2002; Nielsen 2003; Surlýk 2003; Korte et al. 2015).

From a purely tectonic standpoint, it is highly likely that the geodynamic evolution of the thermal dome was more complex in space and time than has been previously published. The detailed nature of the thermal doming process will benefit from numerical modelling and comparisons to modern, high resolution analogues to determine whether the North Sea thermal dome was likely to grow and collapse gradually or if there was a pulsed and more punctuated development. The concepts of multiple, diachronously pulsed and non-circular thermal domes (Nielsen 2003) all need better testing in light of a strongly heterogeneous lithosphere, as does the effects of sediment loading on the dome margins (Underhill & Partington 1993).

The critical debate surrounds the evidence for singular v. multiple allogenic controls on the stratigraphic succession across the mid-Aalenian. Haq et al. (1987) emphasized the importance of the eustatically driven Absaroka–Zuni megacycle sequence boundary in the mid-Aalenian (base murchisonae zone) but the data that this interpretation utilized were biased to Dorset and Yorkshire, both locations within the area of influence of the dome. This analysis was neither globally representative, nor an independent test of eustatic control away from tectonic influence, which prompted Underhill & Partington (1993) to refute the evidence base for eustatic fall, emphasizing the tectonic interpretation for the Central North Sea Dome.

Following a recent reappraisal of Jurassic sea-level trends, Haq (2017) cites global evidence for two major eustatic fall events within the mid-Aalenian (although neither is centred exactly on the opalinum–murchisonae zonal boundary). The largest fall lies within the upper part of the opalinum zone and the other within the lower part of the murchisonae zone (Haq 2017). Although no major cycle boundaries are documented within the Toarcian there is a potentially important sea-level lowering trend from the relative high of the falciferum to bifrons zonal boundary to the relative low in the opalinum zone, which was also recognized by Ogg & Hinnov (2012), and corresponds to Regression R6 of Jacquin et al. (1998) and the J20 SB of Simmons et al. (2007).

A model for the tectonic uplift and deflation signal of the dome needs to be convolved with global eustatic trends to highlight periods of constructive v. destructive interference in a relative sea-level context. The resulting picture of accommodation evolution can then be integrated with variations in sediment supply which are largely a function of the domal topography and climate (and thus runoff and vegetation). The tectonic uplift of the Central North Sea’s triple junction-related thermal dome is unlikely to have been the sole controlling factor on the basinward shift in facies observed in NW Europe at the beginning of the Middle Jurassic.

Sequence stratigraphic work in Arabia has concluded that the most extensive episodes of siliciclastic input correspond to the synchronous combination of tectonic uplift of the
hinterland, wetter climate and major eustatic falls (Davies et al. 2017). Global climatic change could have been an important factor, evidenced by changes in facies in Arabia across the J20 sequence boundary that separates the more arid Marrat Formation of Toarcian age from the more humid Dhruma Formation of Bajocian and Bathonian age (Davies et al. 2017). An obvious feedback loop that could trigger increased amounts of orographic rainfall in our study area is increased elevation as a function of rejuvenated tectonic geomorphology.

Regional changes in oceanic circulation patterns due to the bathymetric barrier provided by the thermal dome may have fed back into the atmospheric climate system (Korte et al. 2015). Interestingly, this climate change event appears to have occurred in the mid-Aalenian according to oxygen isotope proxies (Korte et al. 2015), providing possible support for the idea of increased rainfall and runoff encouraging increased sediment supply at this time. Even if the North Sea dome represented a barrier, further work on Atlantic Margin palaeogeographical reconstructions is required before isolation of Tethys and the Boreal oceans or even the impeded flow of hot low-latitude water can be supported. British, Norwegian and Greenlandic Jurassic strata are centrally placed to better understand the oceanographic linkages of the Tethyan and Boreal realms (Cox et al. 2002).

Although an intriguing possibility, the ‘hothouse v. cold snap’ climate modes of the Jurassic (Simmons 2012) may have other potential drivers. Price (1999) demonstrated that the evidence for Middle Jurassic ice caps was more convincing (tillites and dropstones) than during the Lower Jurassic and,

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**Fig. 17.** A mega-regional ‘source to sink’ palaeogeographical sketch reconstruction of the Hebridean seaway and the Bearraeig delta in the context of other major Middle Jurassic deltas (e.g. Brent, Cleveland, Pentland and Bryne deltas). Huge volumes of sediment dispersed radially from the mid North Sea thermal dome during the Aalenian and Bajocian (this sketch). The main sources are Underhill & Partington (1994), Rawson & Wright (1995), Husmo et al. (2003), Barron et al. (2012) and Mellere et al. (2017). The area of most uncertainty is to the north of the Hebridean seaway where no outcrop and few wells can assist with the reconstruction. Depending on the physiographic expression of the northern end of the Rockall Trough and the southern end of the West of Shetland Trough at the time, it is quite possible that there was little or no actual marine connection north to the Viking straits. This narrow isthmus of land may have connected the southern tip of palaeo-Greenland, through the NW–SE Wyville Thomson Ridge to the palaeo-Orcney Islands, over the East Shetland Platform and Fladen Ground Spur, on to the main part of the well-understood North Sea dome and, then following a Tornqvist trend, down on to the Ringkøbing–Fyn High and linking with the Lower Jurassic volcanic centres of southern Sweden. If validated on the Atlantic Margin, then this NW extension of the Tornqvist lineament could have palaeoceanographic and, therefore, palaeoclimatic importance, as suggested by Korte et al. (2015). This ‘Mid-Cimmerian isthmus’ interpretation would then allow for a southward-opening estuarine model to be developed in the Hebrides rather than an open shelf, which we have elected to promote in contrast to Mellere & Steel (1996). ESP, East Shetland Platform; G.M., Grampian Mountains; H.G.P., Hatton Greenlandic Platform; H.P., Hebridean Platform; H.R.P., Hatton Rockall Platform; I.P., Irish Platform; MNSH, Mid-North Sea High; S.U., Southern Uplands.
with the increased occurrence of glendonites in the Middle Jurassic having been observed by Rogov & Zakharov (2010), with none in the Upper Jurassic, a body of evidence is growing to suggest that glacio-eustatic driven regressions may have been at play in the lower part of the Middle Jurassic at least. Korte & Hesselbo (2011) also agree that glacio-eustatic events are plausible in the Jurassic but demonstrate that cooling likely started in the late Pliensbachian.

In addition to the historical primacy that has been placed on the intra-Aalenian surface (Underhill & Partington 1993), intra-Pliensbachian, intra-Toarcian, intra-Bajocian and intra-Bathonian shallowing events (possible uplift pulses and erosion surfaces) and the interdigitation of flooding surfaces (possible deflation events v. the eventual dominance of eustatic onlap surfaces) still require to be characterized at higher resolution. We now summarize some of the evidence for the key phases of shallowing in chronological order, allowing us to briefly explore other potential factors that could help to account for the increase in coarse-grained sedimentation pulses in the Lower Jurassic and Middle Jurassic, which include: rift-related uplift (this paper); climatic change to a wetter, higher discharge regime (Korte et al. 2015) or indeed eustatic fall (Haq 2017).

Late Pliensbachian shallowing

There is a compelling correlation between the progradational shallow-marine facies of the Scalpa Sandstone Formation in the Hebrides, the Staithes Sandstone Formation in the Cleveland Basin and the Cook Sandstone Formation in the Northern North Sea (Korte et al. 2015). As younger erosional events often excise the Pliensbachian geological record in areas proximal to the dome, the controls on this phase of sedimentation and sediment source areas are difficult to reconstruct. Being within the late Pliensbachian these formations are older than the postulated age of the thermal dome (Underhill & Partington 1993); however, more work is required to consider to what degree these sandstones represent the first response to an early thermal dome or are the depositional products of a late Pliensbachian glacio-eustatic driven lowstand.

Late Toarcian shallowing

In the Hebrides, an important c. 5 Ma hiatus exists between the Raasay Ironstone Formation and the base of the Bearerraig Sandstone Formation from the falciferum to levesquei (ammonite) zones but it is still uncertain whether the unconformity relates to uplift on the pre-to syn-rift transition, or if the North Sea’s thermal dome impacted the Hebrides earlier than its previously published mid-Aalenian timing (Underhill & Partington 1993). Recognition of the omission of this important portion of missing time from Underhill & Partington’s (1993) figure 1 should catalyse renewed discussions and a possible re-interpretation. Although we favour the syn-rift topographic rejuvenation interpretation, new analysis may elevate the importance of a Toarcian-aged precursor dome, at least for the West of Britain and potentially also Greenland (Surylk 2003).

It is clear that the uplift event(s) can be correctly dated only from positions relatively distal from the dome centre and this places huge importance on the Hebridean data. Although the contextual contribution of the Hebridean field area to the debate is unquestionable, its interpretation on the Atlantic Margin is inherently more complex because of syn-rift tectonic signals in the stratigraphic record, i.e. the possibility that increased production of coarse-grained siliciclastic sediments following this Toarcian hiatus is simply related to syn-rift tectonic rejuvenation. Similarly, the base of the sand-prone Pelion Formation in East Greenland (late Bajocian in age) is also most likely associated with rifting (Engkilde & Surylk 2003). An increase in coarse-grained sediment flux is recorded in the late Toarcian of East Greenland (Trefjord Berg Member of the Ostreaelv Formation, Surylk 2003) and this interval probably has more relevance to the mid-Cimmerian debate than the Pelion Formation.

Intriguingly, the stratal position of the main erosion surface in the Cleveland Basin of Yorkshire does appear to be slightly older than the intra-Aalenian event, at the base of the Dogger Formation (base opalinum), opening up the possibility of a slightly earlier start to the uplift event, in some areas. The substratum below the erosion surface is folded (Hesselbo & Jenkyns 1995) and although the kinematic mechanism may not be well understood, the arrival of the dome and its associated deformation was certainly in the Toarcian. The Blea Wyke Sandstone Formation in Yorkshire and the Bridport Sandstone Formation in Dorset are good examples of late Toarcian shallow-marine progradational pulses (Hesselbo & Jenkyns 1995) and are in similar stratigraphic positions to the Dun Caan Shale Member in the Hebrides. The oldest shallowing of water depths (if we discount the late Pliensbachian Staithes Sandstone Formation as eustatically controlled) in Yorkshire appears to be at the base of the levesquei zone of the Toarcian, illustrated by the Blea Wyke Sandstone Formation (Hesselbo & Jenkyns 1995). With a one ammonite zone delay between Yorkshire and Dorset, presumably due to the proximal–distal gradients set up off the radial dome, we can demonstrate the diachronous younging behaviour of dome-related sediments when viewed in high resolution. At a local scale, the Bridport Sands of Dorset themselves young SW (Callomon & Cope 1995) and occupy diachronous stratigraphic positions from the bifrons zone to the levesquei-opalinum zonal boundary (c. 5 Ma) over a distance of 100 km or so. These stratigraphic details may provide the evidence for the lag times associated with dome propagation through the upper crust.

Mid-Aalenian shallowing

Above this, in the Hebrides, the Ollach Sandstone Member sits directly on top of the intra-Aalenian stratal surface, which within most of the field area expresses itself as a correlative conformity. The Ollach Sandstone Member occupies the same stratigraphic position as the Broom and Oseberg Formations in the Northern North Sea (Graue et al. 1987), which at a coarser stratigraphic level, is manifested as the deltaic Brent Group prograding out over the deeper-water Dunlin Group (Underhill & Partington 1993; Husmo et al. 2003). To the south of the dome, the equivalent onshore strata is the Saltwick Formation of Yorkshire (Alexander 1992), which in Figure 17 is termed the Cleveland Delta. The Werkendam Formation is the Dutch lithostratigraphic
equivalent and, like the Hebrides, lies largely beyond the effect of dome-related erosion (Herngreen et al. 2003), with the transition from an unconformity to a correlative conformity lying within Dutch waters. In the Norwegian–Danish Basin the equivalent unit is the Haldager Sandstone Member of the Haldager Formation (Nielsen 2003), which forms part of the proof that the dome had an eastern bulge on to the Ringkøbing–Fyn High and onwards to southern Sweden and eventually the island of Bornholm in the Baltic Sea, where the Bagå Formation overlies the intra-Aalenian correlative conformity (Nielsen 2003). Together, these rocks represent the first coarse-grained depositional response to the uplift of the North Sea’s thermal dome which, at the scale of 700 km north to south and over 1250 km west to east (Ziegler 1990), is best explained by the arrival of a transient plume as a geodynamic precursor to volcanism and rifting in the late Jurassic (Underhill & Partington 1994). Figure 17 illustrates that radial drainage patterns delivered high sediment supply to the dome flanks and led to the deposition of the Pentland Formation in the UK Central North Sea and the Bryne Formation in the Danish Central Graben (Fig.17), although these fluviatile formations are notoriously difficult to age and this is likely to remain a limitation to high resolution studies.

Mid-Bajocian shallowing

A slightly younger case study that comes from the Hebrides is the Holm Sandstone Member of the Bearreraig Sandstone Formation. There is no major eustatic fall event observed by Haq (2017) at the base of the Formation. There is no major eustatic fall event observed is the Holm Sandstone Member of the Bearreraig Sandstone Formation in the Danish Central Graben (Fig.17), although this is likely to remain a limitation to high resolution studies.

The identification and correlation of stratal surfaces of sequence stratigraphic importance within the Hebridean area is a non-trivial problem, largely complicated by changes in the ratio between rates of accommodation generation and sediment supply. Four rather than three progradational cycles are recognized in the Upper Glen 1 well (Fig. 10.) where the Udairn–Holm cycle of Bearreraig Bay can be split into two separate sub-cycles by the distinctive top Udairn Shale Member flooding surface that partitions a heavily carbonate-cemented sandstone. The general conclusion is that the more accommodation, the more flooding surfaces we see in an expanded section and, based on the Upper Glen 1 well, the J24 sequence of Partington et al. (1993), would require to be split into two or even three sequences (or parasequences) pending further sequence stratigraphic hierarchy work. The difficulty of recognizing the top Udairn Shale/base Holm Member flooding surface at Bearreraig Bay is thought to be due to decreased accommodation and increased sediment supply up-dip but the existence of a cryptic erosion surface cannot be ruled out.

Local correlation challenges

The identification and correlation of stratal surfaces of sequence stratigraphic importance within the Hebridean area is a non-trivial problem, largely complicated by changes in the ratio between rates of accommodation generation and sediment supply. Four rather than three progradational cycles are recognized in the Upper Glen 1 well (Fig. 10.) where the Udairn–Holm cycle of Bearreraig Bay can be split into two separate sub-cycles by the distinctive top Udairn Shale Member flooding surface that partitions a heavily carbonate-cemented sandstone. The general conclusion is that the more accommodation, the more flooding surfaces we see in an expanded section and, based on the Upper Glen 1 well, the J24 sequence of Partington et al. (1993), would require to be split into two or even three sequences (or parasequences) pending further sequence stratigraphic hierarchy work. The difficulty of recognizing the top Udairn Shale/base Holm Member flooding surface at Bearreraig Bay is thought to be due to decreased accommodation and increased sediment supply up-dip but the existence of a cryptic erosion surface cannot be ruled out.

Continuing the correlation of stratal surfaces up to the Screapadal locality, no obvious cyclicity in relative sea-level change can be interpreted due to the conspicuous lack of any shales. Depending on whether the erosion surfaces that cap each channel were caused by local autocyclic or allocyclic responses, these could be interpreted as marine flooding surfaces that caused tidal ravinement and truncation (blue surfaces in Fig. 11d and f). One other exception is the Screapadal cliff recession high in the cliff and interpreted decrease in grain size, potentially reflecting flooding and increased water depths, that occurs near the top of the Screapadal cliffs (Fig. 11c). This change is tentatively suggested to represent the base of the Garantiana Mudstone Member equivalent (J26 flooding surface). The Garantiana
Mudstone Member has been detected on the west side of Raasay at Brae (Morton & Hudson 1995), although the lithostratigraphic likeness of this unit and units high in the cliffs have not been tested.

The stratigraphic positions and geometries of the channels in the Screapadal cliff may be the best evidence for water depth reductions and, as previously mentioned, the stacked channel complex in the upper cliff may correlate with the mid-Holm regressive phase (Fig. 14). However, although possibly eustatic in origin, we speculate that the channel incisions are more likely to have been tectonically generated because of their structural setting on the upper part of the hanging-wall dip-slope of the Sea of the Hebrides half-graben. Footwall uplift during an episode of faulting to the east would have impacted the dip-slope by shallowing water depths above the tectonic hinge point. The hinge point (or tilt block fulcrum) defines the switch from subsidence-dominated to uplift-dominated domains in the half-graben (Fig. 12; see also Ravnás & Steel 1998). Although local tectonics could be important, there is an alternative, longer wavelength interpretation of the mid-Holm sequence boundary (at the base of the most pronounced of all the forward-stepping clastic wedges), giving rise to the possibility of the mid-Bajocian representing the acme of uplift on the North Sea’s thermal dome. Given how sand rich many of these successions are, future correlation studies may more successful if heavy mineral stratigraphy or chemostratigraphy is attempted and integrated with the sparse amnoniite stratigraphy.

Conclusions
The Jurassic of Skye and Raasay offers good exposure of hydrocarbon reservoir, source and seal facies and provides superb examples of oil-field-scale tilted fault-block traps, observable in the uplifted and exhumed landscape of the Inner Hebrides. In addition to their obvious relevance to the Atlantic Margin, the strata have much in common with the classic deltoid and shallow-marine reservoirs of the North Sea.

The area is an excellent natural laboratory that has made and, will continue to make, a significant contribution to the understanding of tidally dominated shallow-marine sedimentology, reservoir heterogeneities and architecture. At the type site of the Bearreraig Sandstone Formation we observe three well-exposed upward-coarsening, progradational clastic wedges which transited across the shelfal reaches of the Bearreraig Sandstone Formation we observe the subfurcatum zone of the latest Bajocian, and these regressive minima contrast with transgressive maxima in the discites zone in the earliest Bajocian, the humphresianum zone in the latest, early Bajocian and at the base of the garantiana zone in the late Bajocian.

The impact of relative sea-level change is clear in relatively distal locations where eustasy and tectonism interacted on the dip-slope of a large tilted fault-block to allow accommodation to dominate over sediment supply (Ac > Ss). Signals of relative sea-level change are hard to detect in more proximal locations where sediment supply was large relative to accommodation (Ss > Ac) and the resulting successions are highly sand rich.

The Bearreraig Sandstone Formation offers a test of our ability to correlate at both local and intra-basinal scales and, when scaled up, the strata allow regional and global comparisons. The rocks facilitate valuable discussions regarding the roles and relative importance of tectonics, eustasy and climate in Jurassic sequence stratigraphic models, and are in a critical location to offer valuable insight into the mid-Cimmerian controversy.

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