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Jurassic: Pangea breakup and birth of the Atlantic Ocean

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Crustal extension across the Triassic-Jurassic boundary at *c.* 201 Ma marked the beginning of the breakup of the Pangaea supercontinent, leading to the formation of shallow-marine basins and the opening of ocean gateways. In NW Europe the Jurassic Period is characterised by extension between the Laurentian, Baltic and Avalonian shields to form a series of fault-bounded sedimentary basins that ultimately culminated in sea-floor spreading and the creation of the North Atlantic Ocean. These rift basins formed between Europe and North America/Greenland with variable links to the Tethyan and Arctic Oceans. Throughout, the Scottish mainland together with the Orkney and Shetland Islands and the Central North Sea High, formed a divide in the evolving North Atlantic rift system (Fig. 12.1). This separates an eastern 'Arctic' branch of North Sea basins that extend southwards towards Denmark and central Europe from a western 'Atlantic' branch trending through the Inner Hebrides to the Rockall Basin and basins west of Ireland, and ultimately south towards Portugal and north-west Africa. Roberts *et al.* (1999) and Doré *et al.* (1999) suggest that the Arctic and proto-Atlantic rift systems remained separate until at least the Late Jurassic or even Mid-Cretaceous, with only earlier fragmentary and discontinuous connections. In contrast, a number of authors (Ziegler 1992; Coward *et al.* 2003; Pharaoh *et al.* 2010) consider that a fully connected rift system developed much earlier, from the Permian onwards. Jurassic sediments in these rift basins subsequently provided key source and reservoir rocks developing significant hydrocarbon resources.

Based on decades of detailed onshore mapping and a large volume of offshore hydrocarbon exploration data we have a comprehensive understanding of Scotland's Jurassic rocks and fossils. Outcrops are confined in the west to the islands of the Inner Hebrides and nearby mainland and in the east to the coast of the Moray Firth. The deposits are dominated by fossiliferous siliciclastic deposits with subordinate but key horizons of carbonates and ironstones. Offshore, Jurassic sediments are widespread and extensively explored with intrusive and extrusive volcanic rocks proven in the Central North Sea (Fig. 12.1).

Information about marine flooding events and palaeo-oceanic connections between the various basins and their correlation onshore is primarily based on precise ammonite chronostratigraphy and offshore, where ammonites are more rare, mainly on micropalaeontology. As a result, diachronism of marine flooding events can be demonstrated in the Hebrides and in the Moray Firth basins and is confirmed in Jurassic successions elsewhere, including East Greenland, Denmark and Sweden (Surlyk & Ineson 2003).

During the Early Jurassic there is clear evidence for faunal connections between the Arctic and Atlantic branches. For example, Late Sinemurian ammonite faunas occur in the Hebrides (Hesselbo *et al.* 1998), the west Shetland basins (Page in Andrews *et al.* 2018) and the Moray Firth Basin (Trewin 2004) extending east and southwards to the Cleveland Basin and linking to central and southern England and beyond (Simms *et al.* 2004). Later in the Early to Middle Jurassic (latest Toarcian and Aalenian) volcanism and uplift of the Mid North Sea Dome (Underhill & Partington 1994) resulted in erosion and north-south faunal isolation across the Dome, and later east-west across the Scottish landmass during the Middle Jurassic (Aalenian and Bajocian). Subsequently, during the Late Bajocian immigration of Boreal ammonite faunas into the East Shetland Basin and Beryl Embayment indicate an Arctic (East Greenland) connection (Morton *et al.* 2020). In the Hebrides, ammonite faunas related to those of western and southern Europe continued until the late Bajocian before marginal to non-marine environments were established, also with faunal connections to the English Midlands (Morton & Hudson 1995). Reopening of Arctic – Europe ammonite faunal links date to the Early Callovian (Koenigi Zone) during a phase of renewed extensional tectonics in the northern North Sea (Underhill *et al.* 1997; Morton *et al.* 2020). There is no evidence that Jurassic seas ever covered the entire Scottish landmass but in both the Hebrides and Moray Firth basins sediment provenance and extensive fossil remains including marine faunas, land plants, vertebrate fossils and dinosaur footprints indicate a palaeoenvironment of forested riverine landscapes with significant relief, coastal lagoons and shallow warm seas.

Building on the excellent summary and description of the Jurassic strata in the 4th edition of this volume by Hudson & Trewin (2002) in this account we describe the strata using a regional basin approach and highlight recent advances in research and interpretation. These include, refinement of ammonite stratigraphy, for example, supporting the formal international definition of the *Global Stratotype Section and Point* (GSSP) for the Kimmeridgian Stage on Skye, new dating and use of isotope proxies for climate and environmental conditions, major discoveries of vertebrate fossils on the Isles of Skye and Eigg, and hydrocarbon exploration on the NW continental shelf which has improved our understanding of basin evolution and tectonics linked to opening of the Atlantic.

Stratigraphical Framework

Jurassic rocks were first recognised in Scotland in the 18th Century, and described by several authors including Macculloch (1819) and Judd (1873, 1878). World-famous Scottish fossils from that era include *Ammonites (Uptonia) jamesoni* (J. de C. Sowerby 1827) from Carsaig, Mull, *Ammonites (Ludwigia*) *murchisonae* (J.de C. Sowerby 1829) from Bearreraig, Skye, (both names used for international standard zones), and *Ostrea (Praeexogyra) hebridica* (Forbes 1851), from Trotternish. In the late 19th to early 20th centuries the Jurassic was documented in the maps and memoirs of the Geological Survey of Scotland (Lee & Pringle (1932); Arkell (1933)) and some of this information has yet to be superseded. For details of key localities the reader is referred to the summaries and references contained in the volumes of the Geological Conservation review Series (Simms *et al.* (2004); Cox & Sumbler (2002); Wright & Cox (2001)) and excursion guides (Trewin 1991; Trewin & Hurst, 1993).

Offshore, seismic interpretations integrated with well logs form the basis for recognition of seismic stratigraphical units and the definition of the structural architecture of sedimentary basins. In the North Sea, Jurassic early lithostratigraphic schemes (e.g., Deegan & Scull (1977)) were revised and simplified by Richards *et al.* (1993) and subsequently reviewed by Underhill (1998). In the West Shetland Basin, the lithostratigraphical framework has been revised by Ritchie & Varming (2011) and is followed in this account. The eastern flank and north-east sector of the Rockall Basin (also referred to as the Rockall Trough) (Fig. 12.1) includes extensive Paleogene or older lavas that obscure the underlying strata on seismic records (Stoker *et al.* 2017). There are several basins offshore Ireland with proven, and documented Jurassic, although their total extent remains speculative (Hitchen *et al.* 2013).

As a result of a long history of geological investigations and different data sets, the stratigraphy of the Jurassic can be complicated to grasp. Onshore lithological units have traditionally been given local names unless they can be confidently related to those in other basins (e.g., the Lower Jurassic Blue Lias Formation and the Upper Jurassic Kimmeridge Clay Formation). Ammonite biostratigraphy has been used onshore to correlate individual successions which can be linked to isotopically defined numerical ages to result in a time scale (Fig. 12.2) of Series, Stages and Zones. Each Stage is defined by reference to a precise point in an outcrop (*Global Stratotype Section and Point* or GSSP) where the key ammonite (for Jurassic) taxa and other relevant data to enable correlation with other localities are available. In contrast, ammonites are rarely available offshore so microfossil biostratigraphy, especially dinoflagellates, is used with assemblages linked and dated by reference to Standard Stages and Ammonite Zones defined onshore (e.g., Kelly *et al.* 2015 for eastern Greenland). Of note for Scotland, the GSSP for the base of the Kimmeridgian Stage, confirmed by the International Union of Geological Sciences (Wierzbowski *et al.* 2023) is located on the foreshore at Flodigarry, Staffin Bay, Isle of Skye (see below).

In offshore areas, the techniques of sequence stratigraphy linked to microfossil biostratigraphy have been widely applied (Partington *et al.* 1993) and more recently evolved with the identification of progressive and regressive systems tracts related to sea-level change and tectonic events. This approach requires the recognition of maximum flooding surfaces that describe a single progradational package that can be correlated across each basin (Underhill & Partington 1994; Stephen & Davies 1998) and thus define correlatable genetic sequences. A revised and fully documented scheme of the Jurassic genetic sequence has been published by Copestake & Partington (2023), with 36 recognised sequences in 11 stages, compared with 71 standard ammonite chronozones (Fig. 12.2). In this account we follow Simms (2004) and Copestake & Partington (2023) for onshore and offshore stratigraphical nomenclature.

Structural Framework

Fault controlled sedimentation is a significant feature throughout the Jurassic and relates in a wider context to the evolution of the Central North Sea Dome (Ziegler 1992; Underhill & Partington 1993) and, increasingly with time to the opening of the Atlantic Ocean. The main bounding faults (Fig. 12.3) are often aligned along NE-SW Caledonian trends and separate uplifted blocks of older rocks. The degree of influence and reactivation of older faults along basin margins and elsewhere to provide a locus for the formation of new faults during Mesozoic extension remains a subject of debate (see below). In the 'western branch' the West Shetland-Faroe and Rockall basins are controlled again by tilted fault blocks aligned along Caledonian trends (Fig. 12.3). A review by Schofield *et al.* (2018) and recent work by Dodd (2018) and Andrews *et al.* (2018) has shown that a simple tectonic model which invokes a continuous, extensive marine environment throughout the whole of the Jurassic is probably an over simplification. These authors instead envisage a more complex tectonic history with significant periods of localised uplift, erosion, and deposition that varies across individual basins and sub-basins often in relatively close proximity.

Onshore, in the Hebrides Basin Jurassic rocks occur in a series of westerly tilted fault blocks. The western limit of the basin is formed by the Minch Fault which separates the emergent basement of the Outer Hebrides in the hanging wall from the sedimentary Inner Hebrides and Minch Basins to the east (Fig. 12.3). In contrast, the eastern limit is unfaulted and its location probably varied through time. The presence of Torridonian and Lewisian clasts (Hudson 1962) indicates that adjacent to northern Skye and Raasay the eastern margin was west of the Moine Thrust. The Skerryvore-Camasunary Fault divides the southern Hebrides area into two separate westerly-dipping blocks (Fig. 12.3). With one exception there are no Jurassic rocks immediately west of the fault and this has led to interpretations that there were two separate basins. However, on the north-west side of the Isle of Rum Emeleus & Bell (2005) describe a thick succession of conglomerates, sandstones and calcretes identical to the Stornoway Formation in Skye and Raasay. In addition, in the SE corner of Rum, the Main Ring Fault complex of the volcanic centre incorporates down-faulted blocks of metamorphosed limestones, sandstones, mudstones and rare ironstone that can be correlated with the Lower Jurassic of the Broadford area (Emeleus & Bell 2005). These indicate that Rum was part of the same basin and that the Skerryvore-Camasunary Fault was intermittently active during the Jurassic.

In the eastern (Arctic) branch subsidence and sedimentation in the Moray Firth Basin was again strongly influenced by normal displacements on NE-SW trending faults (Fig. 12.3). Onshore, whilst the role of the Great Glen Fault is unproven, the related Helmsdale Fault was demonstrably a major feature defining the north-western margin of the Moray Firth Basin. Offshore, in the Inner Moray Firth main bounding faults include the Wick Fault in the north and the Banff Fault in the south and between these a series of parallel faults define the sub-basins and intervening highs. In the Outer Moray Firth, during the late Middle to early Late Jurassic a complex of NE-SW and N-S "Viking" fault trends dominated. During the Kimmeridgian renewed crustal extension replaced these with a NW-SE "Witch Group" trend (Boldy & Brealey 1990).

Extending out in the North Sea, the Moray Firth Basin, the Central Graben and the Viking Graben form the radiating arms of a trilete rift system that developed early in the Middle Jurassic (Fig. 12.3). The main structural elements and distribution of the component basins and sub-basins are primarily controlled by the relative motions of three palaeoplate boundaries centred on the Central North Sea (Crowder *et al.* 2019) (See Fig. 1.12 in Smith *et al*. 2024a Ch. 1 this volume). Here, uplift of the Central North Sea Dome in the latest Toarcian to early Aalenian resulted in the widespread Mid-Cimmerian unconformity with erosion of Lower Jurassic and older sediments, while in the centre volcanism developed during the Bathonian and early Callovian (Fig. 12.1). Fig. 12.4 shows an example of the relations between ammonite subzones, sequence stratigraphical boundaries and the extent of erosion. Subsequent collapse and subsidence in the three main rift arms occurred at varying rates during the Middle and Late Jurassic.

Rifting in the North Sea commenced at least by Triassic times although evidence is complicated by later events especially salt tectonics (halokinesis) and basin inversion. Basin geometries and normal fault activity were spatially and temporally variable and are highlighted by a change in basin profiles from symmetrical graben in the north to asymmetrical in the south. Multiple rifting events led to a westward migration of rifting and re-orientation of stress axes with time (Erratt *et al.* 1999). During the early stages of the Late Jurassic gravitational collapse and slumping is an important process on key faults in the northern North Sea (e.g., in the Statfjord and Brent fields, Underhill *et al.* 1997; Hesthammer & Fossen 1999). Evidence of the influence of pre-existing fault controls on basin margins and syn-rift depocentres is largely subjective. Based on 3D seismic reflection and borehole data, Claringbould *et al.* (2017) argue for example, that many older faults in the East Shetland Basin were buried and inactive and that rift narrowing was a response to thermal evolution in the underlying lithosphere. In contrast, in the Norwegian sector, accumulating evidence indicates that reactivation of major Devonian shear zones initially influenced fault location and basin development but diminished with time (e.g., Phillips *et al.* 2019).

Faroe-West Shetland and Northern Rockall basins

Interpretation of the stratigraphy and sedimentology of the Jurassic rocks in the Rockall-West Shetland-Faroe basins (Fig. 12.25a) is key to our understanding the development of the proto-NE Atlantic rift system. However, a paucity of data with only 12 exploration wells drilled in the Rockall Basin since 1980 (Broadley *et al.* 2020), has resulted in a high degree of uncertainty and opposing views about the basin model remain unresolved (Schofield *et al.* 2018; Scotchman *et al.* 2018). Since the 4th edition new well data have become available which improve the picture but poor biostratigraphical control limits confidence in any basin-wide correlation.

Based largely on evidence from a single well (206/05-1), Lower, Middle and Upper Jurassic sediments were originally described by Haszeldine *et al.* (1987) as being deposited in or proximal to relatively deep marine environments suggesting a long-established rift system. In contrast, Verstralen *et al.* (1995) interpret Upper Jurassic sandstones in the Faroe-Shetland Basin as being deposited in a variety of environments that pass transitionally from sub-aerial fan delta into shoreface/shallow marine, and finally deeper-marine, in response to Late Jurassic rifting and regional transgression. According to Vestralen *et al.* (1995), deposition of the shallower coarse clastic facies was mainly controlled by marine transgression of residual islands, probably elevated by footwall uplift along fault bounding highs such as the West Shetland, Rona and Judd highs (Fig. 12.5a). In contrast, further south and extending into the Celtic Sea Middle Jurassic strata are widely developed throughout the Porcupine Basin and are also predicted over much of the Rockall region (Naylor *et al.* 1999) and were probably deposited in a broad thermal sag basin superimposed on minor, narrower Late Triassic–Early Jurassic rifts (Roberts *et al.* 1999).

Active extension during Late Jurassic to Early Cretaceous resulted in a fully marine linkage of the Arctic and Atlantic rifts, creating a continuous rift which is now represented by the Faroe–Shetland and Rockall Basin (Figure 12.3). The Arctic rift was mainly active during Oxfordian to Tithonian. Within the Atlantic rift, Mid and Late Jurassic extension may have been modest, but was sufficient to create restricted marine environments in which organic-rich petroleum source beds were deposited for example, in the Irish Sector (Jeanne d'Arc, Porcupine) and Faroe-Shetland basins, and possibly also the Rockall Basin (Roberts *et al.* 1999; Cole & Peachey, 1999). In the Irish sector, along the western margin of the Erris Trough, footwall uplift associated with a Mid to Late Jurassic rifting event induced uplift and erosion, implying Late Jurassic rifting within the Rockall Basin (Chapman *et al.* 1999). Basin modelling also supports the hypothesis of a significant rift episode linking the Arctic and Tethyan seas, there in Late Jurassic times (e.g., Shannon *et al.* 1999).

Lower Jurassic

In the Faroe-Shetland region proven instances of Lower Jurassic material are scarce due to significant uplift and erosion in the Mid and Late Jurassic (Fig. 12.5b). Apatite fission track analysis by Booth *et al.* (1993) suggests that for example, across much of the Solan Basin more than 1.5 km of Lower Jurassic material was removed. An exception is in the West Solan Basin (Fig. 12.5a,b) where 770 m of Lower Jurassic sediments assigned to the Stack Skerry Formation and overlying Sule Skerry Formation are proven in the well 202/03a-3. Ritchie & Varming (2011) interpret these sediments as shallow marine inner shelf deposits. In contrast, Dodd (2018) has re-interpreted them as deposited in a marine, shelfal environment with the presence of turbiditic sands indicating a period of lowstand during deposition. This is confirmed by the presence of a Raricostatum Zone ammonite fauna (Late Sinemurian) that is only found in fully marine basins. The presence of deep marine sediments albeit in only isolated, preserved locations supports the theory that there was active extension in the Early Jurassic (Dean *et al.* 1999). The presence of Raricostatum Zone ammonites in particular suggests a significant connection between the Arctic, proto-Atlantic and Tethyan regimes.

The lower section of the Stack Skerry Formation comprises two intervals hemi-pelagic, dark-grey, moderate to intensely bioturbated mudstones and thinly interbedded with fine to very fine-grained, parallel to ripple laminated sandstones. These are interpreted as deposits from low-density turbidite flows that were likely sourced from an in-draining river system. The presence of bioturbation (*Cruziana* ichnofacies), (Fig. 12.6a) in the lower section of well core 202/03a-3 supports a sub-littoral setting with a well oxygenated water column. The upper half of the core is composed of thickly bedded, medium to fine grained, well sorted, structureless sandstone beds deposited by a mixture of high-density turbidity flows and hybrid event beds. Hybrid event beds are marked by the presence of clay-rich bed-tops, typically with high concentrations of mud clasts and carbonaceous fragments (Fig. 12.6a). High density turbidites and hybrid event beds suggest an active turbidite fan and the presence of a marine shelf, located to the west of Shetland, during the Early Jurassic. In well

202/03a-3 the overlying *Sule Skerry Formation* comprises a *c.* 36 m thick succession of homogeneous, dark grey to brown coloured, parallel laminated mudstones interpreted as the product of suspension fall-out within the water column (Dodd 2018). The lack of bioturbation or shell material throughout, suggests anoxic bottom waters and a deep marine depositional environment.

Middle Jurassic

Due to a lack of data and evidence within the Faroe-Shetland Basin for the Middle Jurassic strata the amount of rifting and extension that occurred within this time period is unknown. Sandstones proven in various wells previously described as Middle Jurassic strata are now re-interpreted as Upper Jurassic leaving only one well (206/05-1) with purported Middle Jurassic strata. This well contains 3 m of unfossiliferous, relatively mature, well-sorted, sub-rounded, quartz-rich sandstone assigned to the Fair Sandstone Member of the Heather Formation; no evidence was found to age-date accurately the sediments. Sedimentology studies from the one existing core suggest that the most likely depositional environment is a high-density turbidite flow deposited in a deep marine setting, although a deep lacustrine setting may be possible (Dodd 2018).

There are no well penetrations of Lower Jurassic strata or proven Middle Jurassic strata in the Northern Rockall Basin (Schofield *et al.* 2018).

Upper Jurassic

Upper Jurassic strata are relatively widespread across the Faroe-Shetland Basin and rest unconformably on earlier Mesozoic strata or basement. The strata are assigned to the Kimmeridge Clay Formation and are subdivided into three units; the Rona (R1-5 facies) and Solan Sandstone members, and the Ridge Conglomerate Member (Fig. 12.5b). These were deposited in a variety of environments that record a transition from sub-aerial fan deltas into shoreface/shallow marine, and finally deeper-marine environments with time (Verstralen *et al.* 1995; Dodd 2018). In particular, detailed studies of the facies of the Rona Sandstone Member by Dodd (2018) provide a useful illustration of this transition and are described below.

As recorded in core recovered from exploration wells, the R1 facies of the Rona Sandstone Member sediments comprise thickly bedded (0.5-1.5 m), fine- to coarse-grained, graded and trough cross-bedded, arkosic sandstones with subordinate mudstones with brown wood and plant material. Sandstone bases are typically erosional, displaying pebble-grade basal lags, composed of granitic and mixed lithic clasts indicating subaerial conditions and deposition within a laterally avulsing fluvial system. In general, sediment maturity is low, suggesting the fluvial system was being sourced from an actively eroding hinterland, composed of granitic/igneous terranes. Dinoflagellate cyst fragments (well 205/26a-6) tentatively indicate a Late Jurassic to Early Cretaceous age and some marine influence (Dodd 2018).

The Rona R2 facies includes fine to coarse-grained, matrix and clast-supported conglomerates and very fine to medium-grained, structureless, occasionally parallel-laminated, normally-graded sandstones, occasionally with evidence for pedogenic texturing. Matrix supported conglomerates, particularly those with immature clasts and no matrix grading are interpreted by Dodd (2018) to represent primary debris flow deposits whereas clast-supported conglomerates represent water-winnowed debris flow deposits. These are commonly overlain by moderate to well-sorted, fine to medium-grained sandstones, representing sheet-flow deposits. The presence of immature, clast-rich debris flows deposited in a fan delta setting, suggests developing relief, potentially linked to fault activation in the Late Jurassic, West of Shetland. The Rona R3 facies is identified by Dodd (2018) as marginal marine with deposition in a barrier-beach and back barrier/lagoon depositional environment. Sediments comprise moderate to well-sorted, very fine to coarse-grained, reversely graded, low inclined and parallel-laminated to planar cross-bedded, quartz-rich sandstones and interbedded mudstones. Both the sandstones and mudstones display abundant, weak to intense bioturbation throughout (Fig. 12.6a). Towards the top of the logged core, coarser-grained successions document a progressively increasing energy (wave/tidal), evidenced by the occurrence of storm-generated, shell-rich beds. In addition, the interbedded mudstone successions show an increasing pyritic content. Together, these observations suggest a progressive rise in relative sea level and inundation of the Solan/North Rona Basin area. In well 202/09-1 the uppermost sample contains dinoflagellate cyst assemblages *Oligosphaeridium patulum* and *Perisseiasphaeridium pannosum* indicating a Kimmeridgian to Early Tithonian (Mutabilis to Pectinatus zones) age (Riding & Thomas 1992).

Rona R4 facies is characterised as a fine to coarse grained, moderate to well-sorted, sand-prone succession rich in lithic clasts. A coarsening upward trend to trough cross-bedded and parallel-laminated sandstones indicates an overall shallowing consistent with deposition through both wave and tidal processes in a shoreface/littoral environment (Fig. 12.6b). The dinoflagellate cyst assemblage indicates Late Jurassic (Kimmeridgian to Mid Tithonian) marine conditions and is supported with macrofossils including, crinoid ossicles, solitary corals, belemnites, and the bivalve *Pinna sp.* and *Skolithos* trace fossils (well 205/20-2). In well 204/27a-1 the basal deposits of the Rona R5 facies are represented by a coarsening-upwards, fine- to medium-grained, trough cross-bedded to parallel-laminated sandstone succession, deposited in an inner to outer proximal shelf environment. These are in turn overlain by low-density turbidites, interbedded with asymmetrically ripple laminated sandstones, representing deposition of an offshore/inner shelf. The uppermost deposits comprise dark grey to black-coloured, parallel-laminated, ripple cross laminated, silt-grade mudstones deposited in an offshore, outer shelf to bathyal environment. In addition, the dark grey colouration of the mudstones, along with a decrease in the amount of bioturbation in this interval, suggests the development of bottom water anoxia at the top of the Rona R5.

In the Solan sub-basins (Fig. 12.5a) the Solan Sandstone Member comprises very fine to medium-grained quartz-rich, structureless sandstone beds amalgamated in sedimentary units up to 16 m thick. In wells 205/26a-4 and 205/26a-5Z individual event beds display loaded bases, normal grading, parallel and asymmetrical ripple laminated bed tops and dish structures. Bed tops are commonly clay-rich and contain concentrations of broken shelly material and carbonaceous fragments and mud clasts, interpreted as the product of hybrid event beds (Haughton *et al.* 2009). Deposition occurred through successive high-density turbidite flows. The presence of the dinoflagellate cysts *Cribroperidinium globatum* and *Cyclonephelium hystrix* indicates a Late Jurassic (Kimmeridgian) age or younger age (Riding

& Thomas 1992) and confirms that the Solan Sandstone and the Rona Sandstone are likely coeval as proposed by Ritchie *et al.* (2011).

Finally, the Ridge Conglomerate Member is recorded in well 206/05-1 where it comprises a succession of well sorted, fine to medium grained, sub-angular to sub rounded structureless sandstones, interpreted as high-density turbidite deposits (Dodd 2018). These are interbedded with coarse-grained, clast-rich, argillaceous sandstones and matrix-supported conglomerates, with thin, parallel laminated, hemi-pelagic mudstones. This facies association is characteristic of deposition within a subaqueous debris cone or scree perhaps sourced from an intra-basinal high with the high density turbidite fans of the contemporaneous Solan Sandstone Member, being sourced from the shelf.

Whilst the syn-rift Kimmeridge Clay deposits of the North Sea were not developed west of Scotland, on the eastern flank of the Rockall Basin the Benbecula gas discovery and similar finds in the Irish Sector indicate the presence of a working hydrocarbon system with likely Jurassic source rocks at depth. A major transgression is indicated as Bathonian to Oxfordian lacustrine–fluvio-deltaic–marginal marine shales pass up into Kimmeridgian marine shales. Although fully marine, a restricted depositional environment with a stratified water column, probably due to hypersalinity is suggested by Scotchman *et al.* (2018).

Hebrides basin

Outcrops of Jurassic rocks extend from Arran in the south to the Shiant Isles in the north (Fig.12.7a) and are often found underlying a protective cover of Paleogene volcanic rocks (Bell & Williamson 2024, Ch. 15 this volume). Adjacent to the major volcanic centres in Ardnamurchan, most of Mull, Rum and southern Skye the Jurassic rocks are thermally metamorphosed (Thrasher 1992); but in Applecross, Lochaline, Raasay and the Strathaird area of Skye thermal effects are limited and the sediments here are thermally immature (Fyfe *et al.* 2021) and preserve detail of both sedimentary structure and fossil assemblages.

The depositional history of the Hebrides Basin was controlled by two principal factors – tectonically controlled subsidence and eustatic sea-level change (Hesselbo & Jenkyns 1998). These produced three distinct depositional phases defined by lateral facies variations and thickness changes (Fig. 12.8). The first extensional phase in the Lower Jurassic is dated from Late Triassic to early Sinemurian (Bucklandi Zone). Differential subsidence resulted in Mesozoic sediments deposited unconformably and unevenly on mainly Torridonian and Moinian basement. However, basement rocks in southern Skye and especially the Durness Group were not overlapped until the Sinemurian. The basal conglomerate, mainly of Triassic age, is overlain by limestones that date the early Jurassic transgression to Planorbis Zone (western Mull only), the Liasicus Zone (Raasay only) and Angulata Zone (other areas) with Bucklandi Zone (sandstones in southern Skye) (Fig. 12.7b). Combined, these data document the diachronous nature of the early Jurassic transgression. The subsequent Sinemurian strata record rifting with large lateral variations of thickness and a change of facies to a broad range of sandstones, siltstones and ironstone, with the incoming of detrital mica suggesting uplift and a change in source material in the hinterland. In almost all localities the abrupt incoming of dark fine-grained shales in the Pabay Shale Formation (Late Sinemurian to Early Pliensbachian) and coarsening up into siltstone and sandstone of the Scalpay Sandstone Formation (Pliensbachian to early Toarcian) indicate sea level rise and post-rift thermal sag phase. Above, the change to thinner successions and development to condensed sequences of ironstones records reduced subsidence and widespread basin stabilisation.

A second phase of extension and rifting commenced in the Middle Jurassic, documented by the Bearreraig Sandstone Formation (Late Toarcian to Middle Bajocian). This is characterised by great variability in thickness and facies indicating subsidence with block tilting (Fig. 12.7c). By the Late Bajocian crustal extension and basin-wide marine flooding deposited mudstone in a series of basins and lagoons with reduced salinity followed by basin stabilisation and marine transgression in Late Bathonian to Early Callovian times. The third and final phase of extension (Middle Callovian to early Kimmeridgian) is well documented in other regions, but in the Hebridean basins is limited to outcrops of shale and sandstone on Skye and Eigg.

Lower Jurassic

Outcrops of Lower Jurassic strata are widespread. In the south on Arran where small blocks of Hettangian mudstone and decalcified 'limestones' occur within the caldera of the Central Ring Complex and are recorded as far north as the Shiant Isles where black metamorphosed mudstones intruded by thick dolerite sills have remarkably yielded ammonites of Lower to Middle Jurassic age (Penn & Merriman 1978). The application of sequence stratigraphy and a reinterpretation of the Lower Lias by Hesselbo & Jenkyns (1998) and Hesselbo *et al.* (1998) led to a major revision of the stratigraphy with the adoption of a tri-fold subdivision into the Breakish, Ardnish and Pabay Shale Formations (Morton 1999). The classic area for the lowest Jurassic strata is on the east side of Broadford Bay where facies and palaeontological differences identify two units.

The lower Breakish Formation is dominated by alternating beds of limestone and mudstone. In the type section on the headland west of Ob Lusa (Morton 1999) the lowest bed seen is a red pebbly calcareous sandstone of the Stornoway Formation conformably overlain by calcareous sandstones interbedded with limestones with oysters (*Liostrea*) in the basal beds and an uppermost soft green calcareous sandstone, locally pebbly. Elsewhere in the region sandstones are either rare (Applecross) or absent (Raasay). Ammonites are rare in the Breakish Formation but distinctive colonies of *Heterastraea* and *Thecosmilia* corals and oolitic limestones suggest shallow warm seas (Gretz *et al.* 2013). Further south in Morvern and Mull, usage of the term "Blue Lias" is more appropriate and reflects a more offshore facies with ammonites. South-west of Gribun in western Mull the oldest Jurassic strata (Planorbis Zone) with various species of *Psiloceras* in typical Blue Lias facies occur (Oates 1978, Morton 2004). Here, they are underlain by Ostrea Beds and bioturbated sandstones of the Penarth Group of Rhaetian age. This locality is unique in being the only in situ outcrop in Scotland of fossiliferous strata spanning the Triassic/Jurassic boundary. On the mainland in Morvern, in stream sections in the area around Loch Aline the Blue Lias Formation comprises alternating beds of mudstone and limestone with shell beds which extend from Hettangian (Angulata Zone) to the Lower Sinemurian (Bucklandi Zone) described by Oates (2004a). In Ardnamurchan, the oldest Jurassic sediments are best exposed at Swordle on the north coast and are mainly carbonates including a coral bed with "*Thecosmilia*", and calcareous sandstones, similar to the Breakish Formation.

In the Broadford-Loch Eishort area and Raasay the base of the upper Ardnish Formation is marked by a facies change from siliceous sandstone to micaceous siltstone. Shales and sandstones with incoming of beds crowded with the bivalve mollusc *Gryphaea* and two ironstone beds are overlain by a coarsening-up silty sandstones. The uppermost observed unit is a thick bed (>20 m) of ferruginous sandstone and sandy limestone with trough cross-bedding assigned to the Semicostatum and Turneri zones (Morton & Hudson 1995; Hesselbo *et al.* 1998; Oates 2004b). In the southern Hebrides on Ardnamurchan, Morvern and Mull, complexities of structure and thermal metamorphism together with limited outcrops hinder a full interpretation.

The base of the Pabay Shale Formation marks a major and abrupt change in the pattern of sedimentation with the incoming of dark-coloured mudstone indicating deeper, offshore water, locally coarsening up with increasing clastic content into siltstone and sandstone (Hesselbo *et al.* (1998); Oates (2004)). The most complete outcrop and type section is on the north coast of Loch Eishort, where the base is marked by an erosion surface overlain by thin beds of siltstone and sandstone with ammonites of the Obtusum Zone and dark-coloured mudstone of the Oxynotum Zone. The main part of the Formation is in the Raricostatum Zone with mudstone and siltstone followed by a 30 m thick body of sandstone (the Suisnish Sandstone Member). This sandstone is also present on Pabay and Raasay but is much reduced in thickness. This increase in coarser sand content, recorded in a number of Jurassic units (Breaknish to Bearreraig formations) may be related to displacements on the Moine Thrust and the westward extension of sub-Moine structures in SE Skye.

In south-west Raasay, south-east of Suisnish Point the lowest beds of the Formation are dark grey fissile mudstones in which Brittain *et al.* (2010) found the dinoflagellate cyst *Liasidium variabile*, characteristic of the Oxynotum Zone. Together with unpublished evidence of both *Obtusum* and *Oxynotum* Zonal ammonites in the lowest parts of the Pabay Shale Formation (K Page 2022 pers. comm.), these indicate that the hiatus previously presented by Morton (1992) is incorrect. In Carsaig Bay on the Ross of Mull the lower beds contain abundant ammonites of the Jamesoni Zone including the holotype of *(Ammonites) Uptonia jamesoni* (J. de C. Sowerby), collected here by Murchison in 1824.

A particular feature of the Pabay Shale Formation is the great thickness of the Raricostatum Zone, especially in the Borereaig (central Skye) and Allt Fearns (Raasay) sections. This was commented on by Hesselbo *et al.* (1998) who suggested an episode of increased faulting. However, this is more than just a local phenomenon restricted to the Hebrides Basin, and correlates more widely with the first marine flooding in the Moray Firth Basin (Lady's Walk Member at Dunrobin (Trewin 2004)) and in Lossiemouth (Berridge & Ivimey-Cook 1967). In the Faroe-Shetland Basin in well 202/03a ammonites of the same age have been found in the Stack Skerry Formation (Andrews *et al.* 2018).

The transition from the predominantly mudstone-siltstone facies of the Pabay Shale Formation to the sand-dominated Scalpay Sandstone Formation can be placed at different zonal levels in different localities and is therefore diachronous. The formation comprises a prominent *c.* 30 m thick massive sandstone with low-angle cross-bedding and large sideritic concretions ('doggers'). The ammonite *Pleuroceras spinatum* indicates the Pliensbachian Spinatum Zone and the uppermost thinly-bedded ferruginous sandstones contain

Dactylioceras indicating the basal Toarcian Tenuicostatum Zone. Near the ironstone opencast mine on Raasay there is a layer of thinly-bedded berthierine (chamosite) oolitic ironstone at the top of the Scalpay Sandstone Formation (Morton & Hudson 1995). On Raasay, Trotternish and Strathaird on Skye and Ardnamurchan there is a sharp boundary with the overlying dark shale and ironstone of the Portree Shale Formation which has also been identified from ammonites as far north as the Shiant Isles (Penn & Merriman 1978). The Portree Shale Formation in central Raasay was recently sampled in detail by Chen *et al.* (2021) providing the first identification of the early Toarcian Oceanic Anoxic Event in Scotland.

The discovery of ironstone on the Isle of Raasay was first announced in 1893 and was initially thought to be equivalent to the Upper Pliensbachian Cleveland Ironstone of Yorkshire, but it was soon recognised as being significantly younger. The ironstone was mined from 1913 till 1919 (from 1916 by German prisoners of war), first by opencast working then from a horizontal shaft into the hill (Draper & Draper 1990), (Fig. 12.9). The type section for the Raasay Ironstone Formation is at the opencast Ironstone workings east of the mine entry. Here, the Formation (2.40 m thick) comprises thinly-bedded layers of berthierine oolitic ironstone, shelly in places. At the base there are black shales with berthierine ooliths, *Dactylioceras* spp. and abundant belemnites with no preferred orientation. Overall the sediments suggest slow intermittent deposition in an offshore environment giving rise to condensed sequences probably with several hiatuses. At Dun Liath, Strathaird the Raasay Ironstone Formation contains thin (12-18 cm) beds with internal cross-bedding, and when traced south the upper layers are progressively eroded suggesting uniquely an unconformity at this level.

Middle Jurassic

After the Toarcian hiatus, tectonic tilting of basement blocks which renewed subsidence in the Hebrides Basin and rejuvenated hinterland topography in the Scottish Highlands is dated to the latest Toarcian (Aalensis Zone) (Morton 1965; Mellere & Steel 1996; Archer *et al.* 2019). In the Hebridean Basin the Middle Jurassic comprises two distinct units. The older Bearreaig Sandstone Formation characterised by thick marine sandstones is overlain by more varied non-marine strata of the Great Estuarine Group. Middle Jurassic sediments have also been proved near the western basin margin by the shallow BGS borehole (88/6), 6.6 km SE of Renish Point, Outer Hebrides, (Fig. 12.7a).

Bearreraig Sandstone Formation: Originally termed the “Inferior Oolite” the Bearreraig Sandstone Formation is recorded on Skye north of Portree, around the Strathaird Peninsula and on Raasay, with lesser and more complex outcrops further south on Ardnamurchan and Mull (Morton & Hudson 1964). Varying in thickness from 38 m to 480 m it is the thickest unit of sandstone in Jurassic Britain. Lateral facies variation and changes in palaeocurrent orientations between the different areas indicate differential subsidence and hinterland uplift and permit subdivision into local members (Hudson & Trewin 2002). In the type section at Bearreraig Bay, Trotternish (Fig. 12.10), there are three coarsening-up cycles of mudstone or siltstone to sandstone. Calcareous and sideritic nodules and concretions (‘doggers’) occur throughout the succession. Wilkinson (1993) has proposed that the large ‘doggers’ formed from meteoric-derived waters during diagenesis, beneath the sea floor, whilst the small nodules often preserving fossils formed during early marine diagenesis. An exploration well drilled by Pentex Oil (Upper Glen 1) 22 km west of Bearreraig provides a detailed comparison from the almost linear coastal sections towards the deepening centre of the basin (Archer *et al.* 2019) (Fig. 12.10).

Most of the succession is richly fossiliferous especially with belemnites, ammonites, bivalves, foraminifera and palynomorphs (Gregory 1991; Riding *et al.* 1991; Morton 1994). The ammonites enable precise dating to the level of subzones (Morton & Hudson (1995) and particularly famous are the ammonite beds of the Murchisonae – Bradfordensis zones. These preserve unusual features of the ammonite faunas including, high proportions of juveniles, pathological deformity of some specimens and preservation with probable paired jaw parts (aptychi) in situ (Morton 1973) (Fig. 12.11). Previously, over collecting of this key locality has been an issue and it is now protected. NatureScot (formerly Scottish Natural Heritage) recommend that sampling is only from loose blocks on the foreshore. One outcrop (in the Udairn Shale Member) is internationally recognised (Pavia & Enay 1997) as the Auxiliary Stratotype for the base of the Bajocian Stage. The main international marker for the base of the Bajocian Stage is the first appearance of *Hyperlioceras mundum* in the GSSP at Cabo Mondego (Portugal) (Hesselbo *et al.* 2020). At Bearreraig, this species occurs in bed U10 and an ancestral species, *Hyperlioceras incisum* occurs in bed U9 (Fig. 12.10), which until recently, was unknown elsewhere.

Permineralised drifted land plant material is also common. At Bearreraig Bateman *et al.* (2000) identified at least two plant communities in the hinterland; a coastal/deltaic community dominated by conifers and an inland community dominated by ferns (frequently preserved as charcoal). Cell structures in specimens from both communities show features associated with xeromorphic adaptation to environmental stress, such as seasonal aridity. The flora includes one horsetail, four ferns, one cycad, two bennettites, one czekanowskialien and at least two conifers. Subsequent detailed work by Dower *et al.* (2004) on the cycadophyte leaves and on the conifers by Spencer *et al.* (2015) led to naming a new genus and species of conifer seed cone *Scitistrobus duncaanensis* from the Opalinum Zone (Fig. 12.12). The significance of the latter find is that it influences interpretation of the evolutionary history of conifers, including extending the known range of the Cupressaceae back to the beginning of the Middle Jurassic. The combination of the land plant features indicates a land area with significant topographic relief and periodic (seasonal) aridity. This is supported by the observation that fern leaves are mostly preserved as charcoal, indicating periodic wild-fires. It is envisaged that seasonal rivers transported large quantities of coarse sand and plant debris to the shore where tidal long-shore currents dispersed the sediment. As the floating plant debris sank to the sea-floor it was rapidly calcified by redistribution of calcium carbonate from the abundant marine shell debris present in the sediment.

More recently, the abundance of well-preserved belemnites has enabled detailed documentation of the evolution of carbon and oxygen isotopes through latest Toarcian to Early Bajocian times (Korte *et al.* 2015). The most striking feature is a major shift during the early Aalenian, of both oxygen ($\partial^{18}O$) and carbon ($\partial^{13}C$) isotope ratios, indicating an abrupt change in palaeotemperature from warm to cool at approximately the base of the Murchisonae Zone. This is interpreted by Korte *et al.* (2015) as recording the influence of cold Arctic waters reaching the Hebrides. However, at this time the close faunal connections between the Hebrides and basins to the south at species level do not support such a marine connection. Also, recent exploration north of the Hebrides in the Faroes and Shetland Basin confirms an absence of Middle Jurassic sediments (Andrews *et al.* 2018).

In the Strathaird Peninsula on Skye the base of the Bearreraig Sandstone Formation, resting on the underlying Raasay Ironstone Formation comprises an unnamed fossiliferous basal limestone, 6 m thick, with sand and shale partings (Morton & Hudson 1995). A small ammonite ?*Leioceras* and brachiopods similar to those found in Mull suggest a Scissum Zone age. Above, a thick (247 m) unit of cross-bedded sandstones and sandy limestones, are interbedded with massive whitish quartz sandstones. Planar cross-sets are mainly north dipping with a minor south-dipping component. 6 km to the south at Kilmarie, the succession thickens to 336 m but with fewer massive sandstones and here cross-bedding is bimodal with both north and south dips. In southern Strathaird, at Glasnakille, the Formation thickness has increased to 488 m. In the lower half of the Formation cross-bedding dips are almost entirely to the south but in the upper part of the Formation south of Elgol, the sediments have lower proportions of shell debris and large-scale trough cross-bedding dipping north (Morton 1983), indicating a major change of sand input and transport direction. The top bed of the Druim an Fhuarain Sandstone Member, seen south of Elgol, is a grey crinoidal limestone indicating an abrupt end to terrigenous sediment input to the basin.

The quartz-rich sandstones of the Druim an Fhuarain Sandstone Member indicate sediment delivery from at least two source areas including a neighbouring land area with topography and climate resulting in coarse sand and an environment in which sessile benthos could flourish resulting in marine shell debris, mainly of crinoid origin, with bivalves, bryozoans, locally rhynchonellids and belemnites. The fossil remains are mainly broken into sand size grains and larger fossils are rare. An exception are sparse ammonite shells which floated, rather than rolled. The presence of cross-bedding and the widespread occurrence of marine shell debris indicates tidal-influenced environments (Morton 1983; Mellere & Steel 1996; Archer *et al.* 2019). These require a hinterland climate with periodic wet periods so that drainage and sediment supply are concentrated in time and strongly tidal seas to redistribute and mix the two sediment components. On Raasay, the cross-bedding directions are mainly towards east of north and matched by an increase in the proportion of shell debris in that direction. In the south of Strathaird, southerly-dipping cross-bedding in the lower half of the Formation contrasts with more bimodal directions in the centre and north-dipping in the north. Here there is a higher proportion of massive sandstones in the north and the proportion of shell debris increases to the south.

The marked changes in sedimentation and palaeocurrent directions within the Bearreraig Sandstone Formation have been interpretated by Mellere & Steel (1996) to indicate a change from predominantly regressive, pro-delta settings in the lower half of the formation, to transgressive tidal estuarine environments in the upper part. Currents were probably channelled along narrow sub-basins formed by differential movement on faults oblique to the basin margins.

Great Estuarine Group

The Great Estuarine Group was named (as a ‘Series’) by Judd (1878) and in contrast to the Bearreraig Sandstone Formation, is of similar thickness and duration throughout the basin.

Despite being predominantly deposited in a lagoonal environment, stratigraphical subdivisions even down to the scale of some individual beds (e.g., a cyanobacterial stromatolite in the Kildonnan Member) are recognised basin-wide. Based on lithological character and depositional environments the strata are classified into seven formations (Fig. 12.7b).

At Port na Cullaidh, Elgol, overlying the marine Garantiana Mudstone Member there is a dark fissile organic-rich shale formerly called the “Oil Shale”, with TOC values up to 15.3%, now known as the Cullaidh Shale Formation (Fyfe *et al.* 2021). The shales are sparsely fossiliferous with non-marine mytilid bivalves, conchostracans, freshwater ostracods and fish scales. In the upper part, thin beds of siltstone appear gradually becoming coarser and thicker, grading into the basal beds above. The overlying Elgol Sandstone Formation forms the cliff on the north side of the bay and in most areas throughout the Hebrides forms a prominent scarp. It displays cross-bedding, mainly south-dipping, coarsening-up and towards the top are some *Unio* bivalves in life-position. In Strathaird the Elgol Sandstone Formation is interpreted as forming a lobate delta (Hudson & Trewin 2002), (Fig. 12.13), but elsewhere, in Raasay and Trotternish, different delta morphologies are found (Harris 1989). The formation is unique in the Great Estuarine Group by the lack of calcareous concretions. At the top there is a granule-conglomerate as a result of wave-winnowing of the delta top.

There is a sharp junction at the base of the Lealt Shale Formation marking a significant change of environment, one consequence of which is that most succeeding formations are more fossiliferous. The Formation is divided into two Members. The best (and type) section of the Kildonnan Member is on the east coast of Eigg and includes Hugh Miller’s “reptile” (plesiosaur) bed (Miller 1858, see below). The palaeocology of the type section has been described by Hudson *et al.* (1995) and the excellent preservation of *Praemytilus* shell beds and fish ear bones (otoliths) has enabled detailed oxygen and strontium isotope studies of temperature and salinity. These indicate that the lagoons had fresh-water input with salinity controlled by evaporation rather than mixing with seawater (Holmden & Hudson 2003). At the top of the Kildonnan Member a distinctive basin-wide stromatolite (algal limestone with pseudomorphs after gypsum) indicates an episode of desiccation. The overlying Lonfearn Member comprises shale with thin limestones, mainly shelly but some oolitic. In the lower part, the fauna of bivalves and ostracods is brackish-marine, but the main part has mainly conchostracans (Chen & Hudson 1991). At the type section immediately south of Rubha nam Brathairean (Cox 2002) the strata are mainly shales with thin beds of marly limestone or ooidal limestone and until recently were infrequently visited. This changed when ostracod and conchostracan rich faunas (Chen & Hudson 1991) and the first dinosaur footprint in Scotland was discovered (Andrews & Hudson 1984). The site, which is protected, has since been visited regularly by large teams who have collected a diversity of material (see below).

Towards the top of the Lonfearn Member silty and sandy beds with the bivalve *Neomiodon* increase in frequency reflecting a coarsening-up gradation into the Valtos Sandstone Formation. The formation is characterised by the presence of numerous very large calcareous sandstone concretions or doggers that formed prior to Paleocene volcanism. Initial geochemical and isotopic studies on these concretions by Wilkinson (1993 and references therein) suggested growth was post-compaction of the host sediment and preburial by Paleocene lavas with meteoric waters interacting with aragonite in the *Neomiodon* shells to release calcite. Recently, the application of clumped isotope data, combined with traditional stable isotope and trace element data by Paxton *et al.* (2023) have allowed an improved understanding of cementation chronology. These data show the Valtos Sandstone concretions to preserve an early record of Paleocene Hebridean meteoric water but with increasing compaction, further growth was affected by hydrothermal or basinal fluid temperatures of between 50°C and 100°C linked to the overlying Paleocene lava pile. Their formation and final compaction was completed in no more than 2.6 myr. (Paxton *et al.* 2023). Unlike the Elgol Sandstone Formation which was deposited as a single prograding system, the Valtos Sandstone Formation was built by several successive deltas building into lagoons, so that the sequence in any section is highly variable in thickness and sand content (Harris 1992). Differences in the detrital feldspar content and in heavy minerals, suggest varying hinterland source geologies from mainly Moine in Eigg to Lewisian/Torridonian in Trotternish.

The top of the Valtos Formation is characterised by an abundance of the non-marine bivalve *Neomiodon* and this is immediately replaced in the basal beds of the Duntulm Formation by marine bivalves *Placunopsis* and *Modiolus* and then the oyster *Praeexogyra hebridica* which became dominant, often in monospecific shell beds. First named by Forbes (1851) in Skye, this oyster species is widespread in southern England, confirming biogeographic links southwards. The Duntulm Formation is characterised by thin interbeds of shale, siltstone, limestone and sandstone (Fig. 12.14a); fewer sandstones occur further south in Strathaird, Eigg and Muck. Most beds are very fossiliferous with fossils ranging from species that are almost fully marine (e.g. rhynchonellids and *Modiolus*) to those that represent more brackish episodes. The limestone layers are often nodular cyanobacterial (algal) stromatolites, described in detail in Hudson & Trewin (2002), while others are laminated and some are *Praeexogyra* shell beds. Dessication cracks and gypsum pseudomorphs are evidence of periodic evaporation. The sandstones were deposited by fresh-water floods (with plant debris) or storms (Hudson & Trewin 2002).

The upper boundary is marked by an abrupt faunal change from oysters in the top Duntulm Formation beds to ostracods and conchostracans in the basal bed of the Kilmaluag Formation. In Strathaird the lower part of the Kilmaluag Formation (Fig. 12.14b) is mainly shales with upwards increasing limestones with numerous surfaces displaying desiccation cracks. These are overlain fresh-water hard blue-grey limestones with irregular bases interbedded with siltstones and shales, some with calcareous nodules. These yielded early mammal remains (Waldman & Savage 1972) and were labelled the “Vertebrate Beds” (Andrews 1985) and have since proven rich in microvertebrate fauna (see below).

Vertebrate Fossils

Some of the richest vertebrate fossil deposits in Scotland are found in the Middle Jurassic Great Estuarine Group of the Inner Hebrides, on shoreline exposures on the Isles of Skye and Eigg. These fossils are found where wave-action has removed the overlying Paleogene basalts to reveal Middle Jurassic sediments beneath. While body fossils from larger vertebrates are less common and usually fragmentary, extensive fossil trackways are present on the Trotternish Peninsula, Skye. By far the most exceptional fossils are found in the microvertebrate-bearing beds near Elgol, which are proposed to be considered a Konzervat Lagerstätte due to their exceptional preservation (Benson *et al.* 2023).

The first Jurassic vertebrate fossils in the Hebrides were found on the Isle of Eigg (Miller 1858) and comprised fish and marine reptile bones (plesiosaur) from the thin, iron-rich limestone of the Kildonnan Member of the Lealt Shale Formation, now known as 'Miller's Reptile Bed' (Hudson 1962). The 'fish bed' is part of the same formation, and contains a large concentration of scales and teeth including those belonging to the sharks *Hybodus* and *Acrodus*. Some of these are also known from the Valtos Formation on Eigg, and the Duntulm and Kilmaluag Formations on the Isle of Skye, and altogether at least eight hybodont shark taxa are known from the two islands (Rees & Underwood 2005). The first dinosaur bone on the Isle of Eigg was found only recently: a probable stegosaur fibula from the onshore exposures of the Valtos Formation near Camas Sgiotaig (Panciroli *et al.* 2020a) (Fig.12.15). This is a rare example of terrestrial input into what are predominantly shallow marginal marine facies. Tooth marks on the bone indicate post-mortem scavenging by marine reptiles, suggesting that after death the carcass was swept out of a deltaic environment and offshore where it was disarticulated.

The presence of vertebrate fossils on neighbouring Skye was first noted on the Strathaird Peninsula by Peach (1910), but it was not until 1971 that major discoveries were made in this locality. A near-complete large marine reptile was found on the Trotternish Peninsula in 1962, and other scattered marine reptile finds include vertebrae, a humerus and a pterygoid (Brusatte *et al.* 2015a). More recently, the global significance and scientific importance of the Kilmaluag Formation, which outcrops near the village of Elgol, have been more widely recognised (Panciroli *et al.* 2020b), see also Topic Box below. These so called 'vertebrate beds' (as named by Andrews 1985) yield the most complete fossils - but almost no plant material. Riding *et al.* (1991) as part of a wider study recorded low palynological diversity dominated by gymnosperm pollen (up to 87 %), with <24 % pteridophyte spores. The beds also contain abundant freshwater ostracods and represent a freshwater lagoon environment, making them unique among the predominantly brackish to saline Great Estuarine Group (Andrews 1985; Barron *et al.* 2012).

Topic Box: **Skye - a thriving Jurassic ecosystem**

The Middle Jurassic Kilmaluag Formation on the Isle of Skye is composed of beds of pale blueish dolomitised argillaceous limestone with smooth millimetre-scale lamination and stromatolitic domed laminations, alternating with mud-cracked horizons and breccias. The Formation was initially recognised for its exceptional microvertebrates in the 1970s, with the discovery of Scotland's first Mesozoic mammal fossil, the docodont *Borealestes serendipitus* (Waldman & Savage 1972). Many finds have been made subsequently, particularly in the last decade, including the new species *Borealestes cuillensis* (Panciroli *et al.* 2021), named after the iconic Cuillin mountain range. The mixed autochthonous and allochthonous fauna comprises one of the richest relatively undisturbed Mesozoic vertebrate fossil assemblages in the British Isles. Taxa include fish (Rees & Underwood 2005), salamanders such as *Marmorerpeton* (Jones *et al.* 2022), choristoderes (Evans & Waldman 1996), lepidosaurs like *Bellairsia* (Tałanda *et al.* 2022) (Fig.12.16TP1), a new species of turtle, *Eileanchelys waldmani* (Anquetin *et al.* 2009; Anquetin 2010), crocodylomorphs and dinosaurs (Wills *et al.* 2014; Young *et al.* 2016), pterosaurs (Martin-Silverstone *et al.* 2022), non-mammalian cynodonts and early mammals such as *Stereognathus* and *Wareolestes* (Panciroli *et al.* 2020b). Studied principally using x-ray computed tomography (Fig. 12.16TP1) the exceptional preservation, with partial and near-complete skeletons preserved with minimal deformation or compression, is providing information on the early evolution of modern animal groups, particularly salamanders, lizards and mammals (Panciroli *et al.* 2020b; Jones *et al.* 2022; Tałanda *et al.* 2022).

Elsewhere on Skye a pterosaur specimen was uncovered from the Lealt Shale Formation on the Trotternish Peninsula, representing a new species of unusually large non-pterodactyloid pterosaur, named *Dearc sgiathanach* (Jagielska *et al.* 2022). The first dinosaur tooth from Scotland, belonging to a sauropod, was found in the Kilmaluag Formation on Skye (Barrett 2006), and teeth are now known from numerous locations, representing theropod and sauropod dinosaurs (Young *et al.* 2019). Dinosaur bones include partial limb bones and vertebrae, many from the Valtos Sandstone Formation on the Trotternish Peninsula (Clark 2018). A theropod limb bone is also known from the Broadford Beds in southern Skye, found in a limestone boulder in a stream (Benton *et al.* 1995), and some unpublished skeletal material was found in the Kilmaluag Formation (Panciroli *et al.* 2020b). Finally, Skye has become well known for its dinosaur trackways (Fig. 12.17 (TP2)), the first discovered in the Lealt Shale Formation at Rubha Nam Braitherean in 1984 (Andrews & Hudson 1984). Extensive dinosaur trackways have since been described from Rubha Nam Braitherean (de Polo *et al.* 2020), as well as An Corran (Clark *et al.* 2004), and Duntulm (Brusatte *et al.* 2015b). The purported smallest dinosaur track in the world, measuring ~2 cm in length, comes from a sandstone layer in the clastic facies of the Kilmaluag Formation outcropping just south of Duntulm, and likely represents a juvenile theropod (Clark *et al.* 2005). Most of these prints come from near-shore brackish to marine environments, and have been used as evidence that sauropod dinosaurs in particular habitually spent time in lagoons in the Middle Jurassic (de Polo *et al.* 2020).

In summary, the combined sedimentological and palaeontological research of the Kilmaluag Formations on Skye over the past two decades provides a greatly improved interpretation of an ancient Jurassic environment that supported a diverse and thriving animal and plant ecosystem. A depositional low-salinity environment of closed lagoons or marginal coastal lakes, fed by small rivers which transported siliciclastic sediments and plant material is envisaged (Panciroli *et al*. 2020a). Multiple layers of desiccation cracks, and reworked desiccation breccias infilling mud-cracks, suggest a seasonal climate with periodic drying out followed by wetter periods of lagoon expansion.

The uppermost part of the Great Estuarine Group consists mainly of unfossiliferous red/green (or purple where metamorphosed) mottled silty mudstones of the Skudiburgh Formation deposited in a floodplain environment (Andrews 1985) with some calcareous nodules formed as calcretes. In north Trotternish the marls are interbedded with fluvial sandstone beds, some in cut channels. The top bed is locally a dark clay with plant remains overlain by a thin shell bed with *Neomiodon*.

The Skudiburgh Formation is overlain by the Staffin Bay Formation with contrasting successions (Fig. 12.7b). In Trotternish two members can be recognised. Where the uppermost shale bed of the Skudiburgh Formation is overlain by dark shales and shell beds with oysters grading up into siltstones this marks the Upper Ostrea Member of the Staffin Bay Formation and represents a major transgressive flooding event that is recorded across much of Europe and beyond. The upper part of the Staffin Bay Formation is characterised by siltstone and limestone of the Belemnite Sand Member which hosts a more diverse bivalve fauna often preserved in pristine but delicate aragonite and some ammonites (Koenigi Zone) passing upwards into sandstones and limestone beds with abundant belemnites. The Member is interpreted as an offshore bar deposit with the 'Belemnite Battlefield' of Doyle & Macdonald (1993) representing shoreface deposition on the seaward side of the barrier (see Fig. 11.23 in Hudson & Trewin 2002). In contrast, in Strathaird there is an abrupt change to a coarse-grained marine sandstone (the Carn Mor Sandstone Member) which disconformably rests on the Skudiburgh Formation and is dated by ammonites from near the top to the Koenigi Zone. The marine strata above the Skudiburgh Formation are dated from palynology by Riding (1992) and Riding & Thomas (1997) as Lower Callovian. This applies to all the onshore and offshore Callovian of Scotland, dating a major transgression and the establishment of fully marine environments with ammonite faunal connections from the Arctic Realm south into Scotland and the North Sea (Morton *et al.* 2020).

Upper Jurassic

In Strathaird, Skye, the *Staffin Shale Formation* succession is dominated by two thick sandstone units and thermal metamorphism is significant. The older Camasunary Siltstone and Scaladal Sandstone Members comprise blue siltstones and bioturbated and ripple-drift coarse-grained sandstones with ammonites indicating a Middle (Densiplicatum Zone) to Late Oxfordian (Rosenkrantzi Zone) age. The overlying Camasunary Sandstone and Tobar Ceann Siltstone Members comprise respectively, a thick (91.4 m) fine-grained sandstone unit and bioturbated sandy silts, muddy sandstone and clays with TOC values up to 7.8%. Largely unfossiferous, rare ammonites indicate a Lower (Cordatum Zone) to Late Oxfordian age.

In contrast, in North Skye at various localities in Staffin Bay between Digg and Kildorais the Staffin Shale Formation is entirely argillaceous and is divided on the basis of grain-size variations, silt content and bio-facies into five Members (Sykes 1975; Sykes & Callomon 1979; Hudson & Trewin 2002). Bentonitic clays occur at intervals, indicating distant volcanic activity to the west from mid-Callovian to early Oxfordian times. For detailed descriptions the reader is referred to Wright (2001) and Page in Cox (2002). The structure is complex because of displacement by faults and rotation of blocks at the base of the Quirang landslip, but the abundance and quality of preservation of fossils makes this one of the most important Upper Jurassic (especially Oxfordian) sections in the UK. In particular, the zonal scheme for the Boreal Middle and Upper Oxfordian introduced by Sykes & Callomon (1979) is of global significance because of the co-occurrence of Boreal and Subboreal ammonites. The section includes the type localities for many of the zones and subzones and recently it has been selected and approved as the site for the GSSP of the base of the Kimmeridgian Stage (Wierzbowski & Coe 2021; Wierzbowski *et al.* (2023).

The Kimmeridgian Global Stratotype Section and Point (GSSP)

Standard definitions for all chronostratigraphical units (Stages) globally are by reference to a specific Global Stratotype Section and Point or GSSP. A GSSP outcrop must provide the detailed chronostratigraphcal data to enable precise correlation (for the Jurassic mainly using ammonites) as widely as possible. Staffin Bay, Skye, was selected as a candidate for the Kimmeridgian GSSP and was confirmed by the IUGS in 2023. It is unique in having a full assemblage of Boreal ammonites, a Rhenium-Osmium radiometric date of 154.1+/-2.2 Ma and a full range of other relevant data. The precise definition is that the GSSP is placed in the upper part of bed 35 of the Staffin Shale Formation, 1.25 +/- 0.01 m below the base of bed 36 in block F6 in the foreshore at Flodigarry, Staffin Bay, Isle of Skye, Scotland (Fig. 12.18a-c). The prime information on this boundary definition is shown on the range chart of ammonite species with first occurrence of the key species *Pictonia flodigarriensis* (Fig. 12.18d).

Moray Firth basin

On the east side of the Scottish Highlands the Moray Firth Basin displays a markedly different character from the Hebrides Basin. Whilst there are limited, but nevertheless significant, onshore outcrops with a long history of investigation, the full extent of the Moray Firth Basin was not uncovered until hydrocarbon exploration in the 1980s (Fig. 12.19a). This proved a thick Jurassic succession offshore (Underhill 1998) which subsequently became a key area for the application of seismic and sequence stratigraphy.

Lower Jurassic

Onshore outcrops of Lower Jurassic rocks are confined to a single locality at the western edge of the Moray Firth near Brora and are also proven in a borehole on the south coast near Lossiemouth. The equivalent strata offshore are comparable, but with some differences. In the Inner Moray Firth basin in Quadrants 11, 12, 17 and 18 (e.g., in the Beatrice Field) increasing thicknesses reflect changes from margin to centre of the basin. In the Outer Moray Firth, nearer the Central North Sea Dome area of uplift, there is no evidence for Lower Jurassic strata (Boldy & Brealey 1990).

In localities onshore and offshore, overlying an erosion surface cut into the Triassic Lossiemouth Formation (Hartley & Watson 2024, Ch. 11 this volume), there is a sequence of sediments up to 180 m in thickness of distinctly different character. These sediments assigned to the Dunrobin Bay Formation comprise four members (Fig. 12.19b). The oldest rocks are of the Dunrobin Pier Conglomerate Member (> 32 m thick), a succession of conglomerates and sandstones interpreted as deposited in an alluvial fan environment in response to tectonic uplift of the Scottish landmass (Trewin 2004). Palynomorphs and land plant debris indicate a climate change to more humid subtropical conditions (Batten *et al.* 1986, Hudson & Trewin 2002) and comparison with successions in the Lossiemouth area. In the Inner Moray Firth offshore, the equivalent strata are represented by the Golspie Member (Fig. 12.19b) which rests on calcretes and mudstones (Stotfield Calcrete Member) or sandstones (Lossiemouth Member). Here, pebbles occur only at the base and there is a higher proportion of mudstones (*c.* 60 m), sometimes bituminous and with rootlet horizons, becoming increasingly sand-prone towards the south-east. At Dunrobin there follows a thick sequence (73 m) of shales and siltstones (Carbonaceous Siltstone and Clay Member) deposited in alluvial plain to lagoonal environments. These are in turn overlain by marginal marine sandstones (22 m thick). Offshore the equivalent strata are represented by the

White Sandstone Unit/Mains Member up to 60 m of interbedded white coarse-grained and cross-bedded, sandstones fining-up to mudstones with plant and root horizons.

The Lady's Walk Member is the only unit that is definitively recognised offshore as well as onshore. It is dominated by upward-fining non-marine sandstone-siltstone units (undated at base) with dark to medium grey calcareous shelly mudstones and limestones hosting bivalves and ammonites (see Trewin 2004 for detailed succession). Proven ages from ammonites are top Sinemurian (Raricostatum Zone) for the lower part and basal Pliensbachian (Jamesoni Zone) for the upper 30 m. This part of the succession, also identified offshore, is confirmed by Raricostatum Zone ammonites in well 12/27-1 (SE of Beryl Field) just below a maximum flooding surface. A similar upward transition from non-marine to marine strata is also observed in the Lossiemouth borehole, also dated to the Raricostatum Zone (Berridge & Ivimey-Cook 1967). The top unit of the Lower Jurassic, the Orrin Member is only preserved offshore where it is variably unconformable on the underlying sediments. Two main coarsening-up siltstone to sandstone units are recognised and overlain by a persistent fossiliferous mudstone capped by a thick (up to 60 m) cross-bedded sandstone.

Middle Jurassic

At the beginning of the Middle Jurassic the palaeogeography of the North Sea region was influenced by the uplift of the Central North Sea Dome (Underhill & Partington 1993). Throughout the Moray Firth Basin the Middle Jurassic stages (Aalenian to Bajocian), so well-developed in the Hebrides Basin, are missing (Fig. 12.4).

The oldest Middle Jurassic strata in the Moray Firth Basin are represented by the Brora Coal Formation with the type section cropping out on the coast at Brora and at Cadh'-an-Righ, Ballintore (Cox 2002). The formation is presumed to be mainly Late Bathonian in age and onshore is divided into a lower Doll Member and an upper Inverbrora Member. Offshore in the Inner Moray Firth the Formation is penetrated in boreholes of the Beatrice Field (Fig. 12.b-c) but individual members have not been recognised. In the lower part of the Doll Member cross-bedded sandstones with foreset dips indicating transport from west or north-west represent deposition in a predominantly fluvial environment. These are overlain by grey mudstones, interpreted as overbank fines, with sandy channels and siderite-cemented "cementstones" (palaeosols), and containing non-marine palynofloras and non-marine ostracods; the freshwater bivalve *Unio* has been recorded from the top bed (Neves & Selley 1975); giving an estimated age range of Middle to Late Bathonian.

The overlying Inverbrora Member is mainly composed of laminated black carbonaceous shales (some parts bituminous with up to 20% TOC) with lenses of coal and two main coal beds, including at the top the Brora Coal Bed, mined intermittently from the 16th until the 20th Century, (Smith *et al.* 2024b, Ch. 17 this volume). The Inverbrora Member is internationally famous for the diversity of drifted land plants, (e.g., Stopes (1907); Harris & Rest (1966)). There are also two thin green shell beds with *Neomiodon* and *Isognomon* which, together with finds of marine microplankton including dinoflagellate cysts (Maclennan & Trewin 1989) and benthic foraminifera (Trewin & Hurst 1993), indicate episodic marine incursions; while on lower bedding surfaces *Euestheria* indicates freshwater or brackish-water episodes. The stratigraphical age of the Member is stated to be Upper

Bathonian to basal Callovian, based mainly on the occurrence of a diagnostic dinoflagellate cyst in the upper shell bed (Lam & Porter 1977), but the position of the Bathonian-Callovian boundary at the top of the Brora Coal Bed or below is uncertain.

Offshore, the Brora Coal Formation is thickest in the western part of the Inner Moray Firth and thins rapidly towards the east. It comprises interbedded, dark grey carbonaceous waxy mudstones and greenish grey sandy mudstones, sandstones and coals. Cyclicity can be recognised with the sandstones having a sharp base and grading up into mottled bioturbated and veined mudstones with rootlets and coaly zones. The Brora Coal bed also occurs further offshore e.g., in the Beatrice Field although the underlying mudstones are more limited in thickness.

The Callovian part of the Middle Jurassic outcrops at two onshore localities in the Inner Moray Firth, at Brora and at Cadh'-an-Righ, south of Balintore. The classic shore and river cliff sections at Brora were originally described by Murchison (1829) and Judd (1873), and others with more recent updates of the lithostratigraphy, ammonite identifications and chronostratigraphy by Page (2002) and Barron & Riding (2014). Although the two outcrops are today only *c.* 30 km apart the striking change of facies and thickness between the successions has been ascribed to post-Jurassic dextral movement along the Great Glen Fault system (Sykes 1975). However, as the lithostratigraphy of the two outcrops does not easily compare or correlate and an alternative terminology has been proposed by Barron & Riding (2014).

At Brora the strata are divided into two formations. The older Strathsteven Mudstone Formation (formerly part of the Brora Argillaceous Formation), comprises *c.* 55 m of mudstone and siltstone with some silty sandstone layers and is divided into four members. The Brora Roof Bed at the base is an intensely bioturbated sandstone with some pebbles and an erosional base, dated by Lower Callovian ammonites of the Koenigi Zone. The overlying Brora Shale Member of silty sand grading up to dark organic-rich shale with thin seams of sand contains shell beds and ammonites of the Calloviense Zone and possibly *Jason* Zone (Page 2002). The Glauconitic Sandstone Member consisting of muddy glauconitic silty sandstones with thin shale beds and phosphatic nodules, in five coarsening-up cycles, contains ammonites of the Middle Callovian Jason Zone. The Brora Brick Clay Member, with five rhythms of bituminous sandy silts and muddy siltstones grading up to clays and belongs to the Middle Callovian Coronatum Zone and the Upper Callovian *Athleta* Zone (Page 2002). Offshore in the Inner Moray Firth the Strathsteven Mudstone Formation correlates with the lower part of the Louise Member of the Beatrice Formation (Richards *et al.* 1993).

The upper Clynekirkton Formation (formerly part of the Brora Argillaceous Formation, the Brora Arenaceous Formation and the Balintore Formation (sensu Sykes (1975)). Consists mainly of sandstones, with variable cementation and sandy siltstone with some carbonaceous or calcareous beds and is over 500 m thick. It is divided into: Fascally Siltstone Member (33.5 m) at the base comprising coarse siltstone passing up to fine sandstone. It is poor in ammonites but an age range of Athleta Zone to Lamberti Zone has been identified (Page 2002). The Fascally Sandstone Member, composed of bioturbated sandstones with common ammonites belongs to the uppermost Callovian Lamberti Zone. The uppermost Clynelish Quarry Sandstone Member is a well-sorted cross-bedded sandstone. Previously interpreted as tidally influence bar deposits, Surlyk & Bruhn (2020) have reinterpreted as deposited by flood-generated density flows and implying a relatively steep basin margin marking the onset of rifting in the Inner Moray Firth to the latest Callovian.

At Port'-an-Righ south of Balintore the Middle to Upper Jurassic succession is thinner and shows an increase in mudstone compared with the equivalent strata at Brora. The Balintore Formation is dominated by fossiliferous sandstones and sandy siltstones with some bituminous mudstone and a total thickness of *c.* 68 m. It is divided into four Members (Wright 2001). The Cadh'-an-Righ Shale Member, with the Brora Roof Bed at its base comprises bituminous shales with thin beds of glauconitic sand with a prominent band of calcareous concretions marking a hiatus between a lower part with ammonites of the Middle Callovian (Jason Zone) and an upper part with ammonites of the Middle-Upper Callovian Coronatum – Athleta zonal boundary (Page 2002). The Shandwick Clay Member, consists of fossil-rich grey-green clay in the lower part and sandy siltstone in the upper part. Callovian Ammonites occur 3.5 m above the base extending for 9.7 m into the top Callovian (Lamberti Zone). At 12.3 m ammonites are of basal Oxfordian and this bed documents the Middle to Upper Jurassic Series boundary. This detailed ammonite stratigraphy permits a correlation across the Scottish landmass to the Hebrides Basin (Fig. 12.20) highlighting contrasts in stratigraphy and depositional environment (Wright 2001).

The change in facies to sandstones in the offshore sections in the western part of the Moray Firth Basin (e.g., the eastern parts of Quadrant 11, including the Beatrice oilfield) has resulted in different lithostratigraphical terminology (Fig. 12.19b). The Beatrice Formation is dominated by fine- and medium-grained, upward-coarsening sandstones with dark grey micaceous and carbonaceous mudstone, locally shelly, passing up through ripple-laminated silty sandstone to clean sandstone. The lower Louise Member, up to 25 m thick, has a higher proportion of sandstones with coarsening-up cycles and calcite and limonite cements, shell debris and sponge spicules throughout except in the lower part; the base is an unconformity that cuts down eastwards. The overlying Carr Member has a basal 15 m a unit of dark grey calcareous and micaceous mudstone with belemnites and marine bivalves which coarsens up into bioturbated sandstone with calcareous ooliths, bivalves and belemnites at the top of the bed. In the Outer Moray Firth the oldest Middle Jurassic Fladen Group volcanic (Rattray Volcanics Formation) and sedimentary (Pentland Formation) rocks of the Central North Sea Dome, are absent except for the southern parts of Quadrant 15 (Boldy & Brealey 1990) where there may be several volcanic vents, sources to a thick sequence of lavas.

Upper Jurassic

Oxfordian strata outcrop on the banks of the River Brora and on the shore at Ardassie Point where fine-grained sandstone over 30 m thick, with occasional lenses of conglomerate and large-scale cross-bedding occur. Although poorly fossiliferous it is thought to contain the Lower Oxfordian Mariae and Cordatum Zones (Wright 2001). The maximum flooding surface which defines the base of a genetic stratigraphic sequence is in the underlying mudstone.

The overlying Ardassie Limestone Member marks a sharp change to muddy carbonaceous sandstone alternating with richly fossiiferous sandy limestone with bivalves and ammonites of the Middle Oxfordian Densiplicatum Zone. The Achrimsdale Sandstone (formerly Clynekirkton sandstone) Member estimated to be 400 m thick was named and described by

Barron & Riding (2014) as calcareous or siliceous sandstone with thin mudstone layers. The age is uncertain, presumed to be Middle to Upper Oxfordian, perhaps extending into the Kimmeridgian. Three km south of Balintore at Port-an-Righ and Cadh'-an-Righ two outcrops of Oxfordian strata assigned to the upper part of the Balintore Formation, are exposed at low water (Wright 2001). The Shandwick Siltstone Member consists of alternating calcareous siltstones above a basal sandy siltstone, both Lower Oxfordian Cordatum Zone. Above, the Port-an-Righ Ironstone Member is divided into an upper part (0.5 m) of sandy clay with red-weathering nodular ironstone and a lower part (1.7 m) of sandy clay with bands of red-weathering berthierine-siderite nodules, both belonging to the Middle Oxfordian Densiplicatum Zone. The youngest strata of the Port-an Righ Ironstone Member consist of coarse, dark, bituminous siltstone with rhythmically bedded units each coarsening-up to fine, argillaceous sandstone, ammonites indicate the Middle Oxfordian Tenuiserratum Zone (21.7 m thick).

Offshore the stratigraphical unit of the Heather Formation is widely used in the northern North Sea for strata ranging in age from Bathonian to Oxfordian. In the Inner Moray Firth the Heather Formation is mainly composed of medium to dark grey or brownish mudstones and siltstones, with occasional thin sandstone stringers, or calcareous concretions. These sediments are restricted to the Oxfordian and the lower boundary is within the Callovian Beatrice Formation. The most distinct unit is a distinctive sandstone (Alness Spiculite Member*)* up to 90 m thick containing variable proportions of spicules derived from the siliceous sponge *Rhaxella*. It contains two coarsening-up cycles and one fining-up cycle at the top.

In the Outer Moray Firth sediments of Oxfordian age rest unconformably on older, usually pre-Jurassic rocks and are transgressive in character (Fig. 12.4). They evolve from a non-marine paralic facies of coal-bearing sandstone and carbonaceous shale and mudstone (Sgiath Formation) thinning eastwards via an important transgressive event to marine environments with sandstones of the Piper Formation. The latter were deposited in marine-dominated deltaic coastal plain and shoreface environments that extended from the late Oxfordian into the early Kimmeridgian (Boldy & Brealey. 1990). Harker *et al.* (1987) defined these strata as a pre-rift succession, influenced by pre-existing fault systems.

One of the most famous outcrops of Kimmeridgian rocks in Britain is situated on the north-western coast of the Moray Firth. The "Helmsdale Boulder Beds" consist of large blocks of older rocks in a black fossiliferous mudstone matrix (Fig. 12.21), providing evidence for syn-sedimentary movement and gravity collapse along the Helmsdale Fault. The coastal outcrop, averaging 1 km in width, extends over 17 km from Kintradwell in the south to Dun Glas north-east of Helmsdale. The relevance to offshore oil exploration was recognised in the mid-70s (Neves & Selley 1975) and a detailed description and interpretations are given by Wignall & Pickering (1993) and McArthur *et al. (*2013). With the apparent exception of the basal Kimmeridgian Baylei Zone the complete Kimmeridgian sequence of ammonite zones can be identified along the coast (Cox 2001), the only locality outside Dorset where this is possible. Stable isotope ($\delta^{18}O$, $\delta^{13}C$) and geochemical data from belemnites (Nunn & Price 2010) indicate a cooling event with palaeotemperatures of up to 24^{o}C in the Early Kimmeridgian falling to 11^{o}C in the Mid-Tithonian. Interestingly, this cooling may be contemporaneous with a change in sedimentation rates and from siliclastic to carbonate and linked to increased aridity in the hinterland and a global sea level rise (McArthur *et al.* 2013).

The Helmsdale succession is divided into a southern Kintradwell Boulder Beds Formation which is geographically isolated from the sandy Allt na Cuile Formation in the centre at Lothbeg Point which is in turn overlain by the thick Helmsdale Boulder Beds Formation to the north. The Kintradwell Boulder Beds Formation with a thickness of c. 85 m consists of lenticular masses of matrix-supported conglomerate interbedded with finely laminated, siltstone and thin sandstone. Sedimentary structures include syn-sedimentary compaction and soft sediment deformation features and sand dykes. The boulders, composed of pale sandstone, are derived from older Jurassic formations (Pickering 1984) and are very variable in size (up to 7 m), ranging from angular to rounded. Ammonites indicate age as Lower Kimmeridgian Cymodoce Zone. North of Kintradwell there is a gap with no outcrops until *c.* 2 km south of Lothbeg Point where scattered outcrops predominantly of sandstones of the Allt na Cuile Sand Formation are interbedded with a 25 m thick unit of coarse breccia, also dated to the Cymodoce Zone. Towards the north the sandstones pass up into siltstone dated as Mutabilis Zone. The total thickness is *c.* 120 m. The occurrence of such a thick sandstone unit between boulder beds to south (Kintradwell) and north (Helmsdale) coincides with a unique break and lateral displacement of the Helmsdale Fault which may have resulted in a canyon controlling sediment transport from the hinterland (Pickering 1984; McArthur *et al.* 2013) (Fig. 12.22). North-east of Helmsdale from Westgarty north-eastwards to Dun Glas, conglomeratic beds crop out over a distance of *c.*16 km with only one small gap in the middle, giving an estimated thickness of about 800 m of strata. Individual bed thicknesses, generally 0.5 to 1.0 m, locally range from a few centimetres up to tens of metres. Most beds contain spectacular subangular to subrounded clasts of Devonian Caithness Flagstones, the largest, at *c.* 45 m by 27 m, being the "fallen stack" of Bailey & Weir (1932) at Portgower.

The boulders were embedded into a unlithified matrix of interbedded thin layers of fine sands and silts with some slightly thicker sands, giving the distinctive "tiger-stripe" facies, deposited by deep marine turbidity currents. The layers show evidence of distortion by the weight of the boulders and also by down-slope slippage. Debris of Jurassic origin, mainly silicified wood and coral fragments also occur while in the matrix some layers are rich in plant fragments, others with diverse bivalves (oysters, pectinids, thick-shelled *Isgnomon* with lithophagid borings, trigoniids), gastropods, belemnites, crinoids and brachiopods and rare blocks of the "reef-building" coral *Isastraea* are evidence of a rich shallow marine fauna west of the fault cliff. The occurrence of *Isastraea* is the only evidence for corals in the Jurassic of east Scotland. In the Hebridean Basin similar corals are also recognised. Although ammonites are not abundant, all the Lower and Upper Kimmeridgian zones, except Baylei at the base, and the Albani Zone have been identified (Wignall & Pickering 1993).

The major change in the tectonic environment during the Kimmeridgian evident from the onshore outcrops is even more pronounced offshore with the development of a new rift pattern dominated by NW – SE fault trends that overprinted the previous Caledonian structural trends (Boldy & Brealey 1990). With active extension the Kimmeridge Clay Formation was deposited on the down-thrown sides of faults while active erosion occurred on the crests of fault blocks, creating a complex mosaic of basins and horsts. The juxtaposition of an important source rock (the Kimmeridge Clay Formation) adjacent to clastic reservoirs (various sandstone formations) resulted in the creation of many economically important oil fields in the Moray Firth Basin, both in the Inner Moray Firth (e.g., Beatrice and Ross Fields – Burns Sandstone Member) and especially in the Outer Moray Firth (e.g., Claymore, Piper, Rob Roy and Scott Fields – Claymore Sandstone Member). The complexity of the tectonic structure, which evolved during deposition of the Kimmeridgian sediments, resulted in great lateral variations in facies and thickness of sediments and hence in the nomenclature of the sandstone units.

The Piper Sandstone Formation ranges in age from Upper Oxfordian to Lower Kimmeridgian (see also Fig. 12.19c). There is an abrupt facies change from the non-marine Piper Sandstone Member to the fully marine Mid Shale Member, marking an important sea-level rise and a second major transgression event. Using ammonites found in the well cores Boldy and Brealey (1990) assign this unit to the Baylei and Cymodoce Zones (base Kimmeridgian), although identification of the Baylei Zone is questioned by Morton *et al.* (2020). The Mid Shale Member coarsens-up gradually into a higher sandstone unit (Supra Piper Sandstone Member) composed of medium-fine grained sandstones, but with increased proportion of detrital felspar grains suggesting a different source. Above, there is a sharp junction between the underlying sandstones and a shale unit (Transgressive Unit) which has a thin glauconitic layer at the base in the Moray Firth Basin. As elsewhere in the North Sea the overlying Kimmeridge Clay Formation, (of Kimmeridgian and later age), is dominated by dark-grey brown to black mudstones, commonly non-calcareous and moderately to highly organic-rich with local thin streaks of siltstone or sandstone interpreted as derived from short-lived slumps or turbidity current flows. In some areas, mainly near tectonic highs subject to erosion, sandstones and even conglomerates are interbedded with mudstones. If these are sufficiently large and extensive they may be identified as named members of the formation, especially if they prove to be producing petroleum reservoirs. Examples include the Burns Sandstone Member in the Inner Moray Firth, the well-sorted medium-grained structureless sandstones with occasional interbedded mudstone of the Claymore Sandstone Member in Block 14/19 Quadrants 14 and 15, and in the same area, very fine to medium-grained sandstones separated by a distinctive mudstone unit of the Dirk Sandstone Member.

CENTRAL AND NORTHERN NORTH SEA BASINS

The volume of borehole and seismic data acquired over many decades has made the North Sea one of the most intensively studied failed rift systems in the world. As a result, the Jurassic succession of the Central and Northern North Sea (Fig. 12.23) is relatively well understood and is described in the large volume of papers contained in the memoirs of the Geological Society along with summaries by Richards *et al.* (1993); Underhill (1998); Evans *et al.* (2003); Johnson *et al.* (2005) and Underhill & Richardson (2022). The offshore Jurassic rocks can be correlated in part with the onshore sections around the Moray coast and with major transgression and sea-level change represented in the more distant basins north and west of Scotland. Only a brief summary of the Jurassic succession is presented here and the reader is referred to Geostrat (2017) and Copestake & Partington (2023) and references therein for up to date details on the lithostratigraphy and current interpretations.

Lower Jurassic

Due to uplift, doming and erosion in the Central North Sea Early Jurassic rocks are only recorded in the North Viking Graben (including the Beryl embayment) (Figs. 12.3, 12.23), and in the small Fiskebank sub-basin east of the Central Graben in the Norwegian Sector.

The oldest strata comprise conglomerates and sandstones of the Skagerrak and Cormorant Formations of Triassic (Rhaetian) to Hettangian age which are interpreted as alluvial fan and fluvial sediments shed off the Scottish mainland (Fig. 12.25a) and the uplifting Fennoscandian Shield. The regional pattern of subsequent marine incursions and the progressive onlap of marine strata northwards with time has been interpreted by Ryseth (2001) to indicate southerly dipping palaeoslopes and drainage systems at this time. The overlying sediments are divided into two groups. The older Banks Group (Fig. 12.23) comprises a lower Statfjord Formation (in part Rhaetian) of interbedded sandstones, siltstones, mudstones with caliche soil profiles near the base attesting to arid terrestrial conditions. These are overlain by cross-bedded sandstones locally pebbly, with rip-up mud clasts deposited in cyclical sequences which fine up into red and grey mudstones. The upper parts of the formation, characterised by grey mudstones with rootlet beds and thin coals indicate a major climate change (Nystuen *et al.* 2014). The base of the overlying Nansen Formation is marked by a transgressive flooding surface and is overlain by pale coloured, well-sorted carbonate cemented sandstones. These were deposited in shallow marginal marine and fan delta environments and onlap onto the East Shetland Platform. They may in part be synchronous with the Statfjord Formation.

The younger Dunlin Group of Late Sinemurian to Aalenian in age, is dominated by dark to black argillaceous shales with marginal sandstones. In the northern Viking Graben it is divided into four formations (Fig. 12.25a) with facies representing deposition in a variety of wave-dominated shelf, to tidally-dominated shoreline and estuarine systems (Marjanac & Steel 1997). The Amundsen Formation is a coarsening up sequence of bioturbated calcareous mudstone, siltstone and fine-grained sandstone and recognised over most of the East Shetland Basin extending eastwards into the Viking Graben. The Burton Formation is dominated by carbonaceous, non-calcareous marine mudstones sparsely bioturbated with sandy laminae and ripples and horizons of iron and phosphate indicating restricted sediment supply and low energy shelf conditions (Hudson & Trewin 2002). In the East Shetland Basin the Cook Formation is dominated by grey siltstones and silty mudstones, recording a return to shallow prograding marine sands and bioturbated muds deposited in coarsening and cleaning-upward cycles. These sands have been variously interpreted as prograding shelf sands, marine shoal sands and redeposited (turbidite) sands (Copestake & Partington 2023). Above, the Toarcian Oceanic Anoxic event which marks a major global climate change associated with a warm climate and low sedimentation rates, is represented in the North Sea by the Drake Formation. Although often eroded out, this formation is recorded in the North Viking Graben and East Shetland Basin where it contains calcareous mudstones and sandstones with thin oolitic sideritic ironstones and shales interpreted as a stacked succession of progradational and retrogradational events (Copestake & Partington 2023).

Middle Jurassic

Middle Jurassic rocks were deposited during a prolonged period of relative sea-level fall associated with uplift of the Mid North Sea Dome, followed by regional flooding as the dome subsided and North Sea rifting commenced. The base of the Middle Jurassic succession is marked by exhumed and eroded Lower Jurassic and Triassic rocks that form a series of composite unconformities collectively referred to as the 'Mid-Cimmerian Unconformity' (Davies *et al.* 1999). The earliest deposits are confined to the North Viking Graben area (Fig. 12.23) and are represented by the Brent Group – a large fluvial-deltaic system up to 300 m thick that was initially fed from the eroding margins of the East Shetland Platform and Viking Graben areas, and prograded rapidly northward. The interaction of flooding events due to relative sea level rise associated with extension, subsidence and sediment supply give rise to widespread variation in facies and depositional environments.

Based on correlative flooding events the Brent Group is formally sub-divided into five formations (Fig. 12.23). The Broom Formation (Aalenian) comprises up to 50 m of coarse, occasionally pebbly, massive to cross-bedded sandstones with mudstones and conglomerates, deposited directly on the Mid-Cimmerian Unconformity surface. They are generally interpreted (e.g., Scott 1992) as low-stand fan delta deposits derived locally from the basin margins and deposited in marine conditions. The overlying Rannoch Formation consists of a lower shale-dominated unit grading upwards through bioturbated and often structureless sandstones, into cross-bedded sandstones at the top of the succession. Løseth & Ryseth (2003) interpret these as wave-dominated middle to lower shoreface and offshore marine sediments, deposited in a shallowing-upward, progradational delta-front environment. The Etive Formation consists of medium to coarse-grained sandstones with occasional mudstones and siltstones. Sandstones range from ripple or wave laminated, to massive and structureless, and generally form fining upward packages with erosional bases and channel lag deposits. They are interpreted as upper shoreface sediments, representing deposition in a delta-front or barrier island system.

The Ness Formation consists of a highly varied succession of interbedded sandstones, siltstones, mudstones, and thin coals. A lower unit of marginal marine and lagoonal sediments indicating deposition in a swampy, back-barrier or delta-top environment is overlain by a laterally extensive, organic-rich claystone unit commonly referred to as the 'Mid Ness Shale'(Cannon *et al.* 1992). Deposited in open lagoonal conditions; this shale represents a regionally significant marine flooding surface and is commonly used to sub-divide the Brent Group into an older unit characterised by stacked, northward-prograding delta systems deposited as the coastline regressed during Aalenian to Bajocian times, from a younger retrogradational stack of delta systems that retreated southward during the subsequent Late Bajocian transgression as determined by ammonite finds in the East Shetland Basin and Beryl embayment (Morton *et al.* 2020) (Fig. 12.24). Above, the Tarbert Formation consists of fine to medium-grained, highly-bioturbated sandstones, siltstones, mudstones and thin coals probably derived from reworking of the underlying succession and marks the eventual drowning of the delta system (Cannon *et al.* 1992). The formation is highly diachronous, representing the rapid landward retreat of the coastline and delta plain environments and a return to shallow marine deposition.

In the Central North Sea and Beryl Embayment areas, the Brent Group passes laterally into deposits of the Fladen Group (Fig. 12.23). The Pentland Formation, up to 500 m in thickness and Bajocian to Bathonian in age, comprises a mixed succession of sandstones, siltstones, and coals, interbedded with volcaniclastic and tuffaceous deposits of the Rattray Volcanics Member (Deegan and Scull 1977; Richards, 1992). Deposition took place on extensive coastal plains, with sandstones developing in fluvial-dominated aggradational delta-top environments (Richards 1992). Previously, around the North Sea Dome correlation of these paralic sequences has proved problematic and was eventually resolved with the recognition of Maximum Flooding Surfaces (Underhill 1998) and refinement of the sequence stratigraphic framework (Copestake & Partington 2023). The earliest deposits are preserved in the Beryl Embayment area and are coeval with deposits of the Broom Formation described above. Further south, Pentland Formation strata sit unconformably upon Early Jurassic or older rocks and correlate with the middle and upper parts of the Ness Formation. The informally named ‘Bruce B/C Coal’ (Beckly *et al.* 1993) has been correlated with the ‘Mid Ness Shale’ unit in the Brent Group.

Around the North Sea triple junction in the Outer Moray Firth and Central North Sea, fluvial-deltaic sediments interfinger with basaltic lava flows of the Rattray Volcanics Member (Figs. 12.23, 25b). This unit, now well constrained by a wealth of core data, petrophysical logs and 3D seismic reflection data, reaches a total cumulative thickness of up to 1,500 m in the Witch Ground Graben and has an estimated eruptive volume of *c.* 3,000 km^3 (Quirie *et al.* 2019, 2020). Coeval lava deposits to the south in the West Central Graben area, are assigned to the Ron Volcanics Member. Two main phases of volcanism separated by an eruptive hiatus are recognised with sub-aerial lava flows sourced from linear fissure eruptions and small cinder cones onto large lakes. The lavas were subjected to significant weathering and erosion, with the eroded products reworked into the surrounding Pentland Formation sediments (Fig. 12.26). Algal blooms within inferred hyaloclastite deposits suggest increased volcanic related nutrient activity in fresh water (Quirie *et al.* 2020). The lavas comprise undersaturated porphyritic alkali-olivine basalts and whilst the presence of more evolved alkaline intrusions is uncertain they likely exist within the volcanic pile. Geochemistry suggests derivation from enriched lithospheric mantle sources with a possible asthenospheric contribution. Underhill & Partington (1993, 1994) have attributed the volcanism to a short-lived mantle plume head source impacting beneath the triple junction and affecting an area up to 1,000 km wide (Fig. 12.1). Volcanic activity is estimated to have continued from Bajocian-Bathonian through to Callovian times, and prior to the main phase of Late Jurassic extension. However, attempts to date the deposits accurately using radiometric (^{40}Ar–^{39}Ar and K-Ar) dating and biostratigraphical analysis have yielded contradictory results (Howitt *et al.* 1975; Ritchie *et al.* 1988; Husmo *et al.* 2002; Quirie *et al.* 2019).

The youngest Middle Jurassic strata comprise the Heather Formation, a thick succession of marine claystones interspersed with numerous marine sandstone members. The formation ranges from latest Bajocian to middle Oxfordian in age. Deposits younger than Callovian in age are described below. The oldest sediments, assigned to the Hugin Sandstone Member, are bioturbated and cross-bedded sandstones with carbonaceous mudstones and thin coals (Copestake & Partington 2023). In basinal areas these pass laterally into claystones. The Hugin Sandstone Member is interpreted as a succession of shoreface sandstones deposited as the coastline migrated southward during flooding of the Mid North Sea Dome.

Upper Jurassic

In the early Callovian a major marine transgression with rising sea levels led to the establishment of open marine environments and was accompanied by a renewed phase of extension. Rifting and footwall uplift spanned the Mid-Oxfordian to Early Kimmeridgian and continued into the Cretaceous and was superimposed upon a background of regional thermal subsidence. As a result, erosion and the eventual subsidence of the Mid North Sea Dome delivered an increased sand component into the shallower basins and proximal to rift margin faults whilst in the deeper basins anoxic conditions and poor water circulation facilitated deposition of black shales and mudstones characteristic of the Kimmeridge Clay Formation. Upper Jurassic strata are widespread across the North Sea basins (Johnson *et al.* 2005) often forming a blanket to previously faulted basin margins and uplifted ridges and spurs. The thickest accumulations developed in graben areas, where up to 3000 m of marine mudstones and siltstones are preserved (Fig. 12.25b).

The Humber Group comprises all the Upper Jurassic sediments above the Brent Group in the Northern North Sea up to the base of the Cretaceous. It comprises a range of sediments including sandstones, mudstones and shales that reflect responses to rifting, long-term sea-level rise and the movement of salt controlling subsidence. The group is divided into four formations (briefly described below) and up to 24 sandstone members (Copestake *&* Partington 2023). Collectively these are subdivided into transgressive-regressive depositional sequences and define two megasequences (Sansom 2010 and references therein).

The oldest formation includes the upper parts of the Heather Formation and comprises grey, silty, weakly bioturbated mudstones recording deposition offshore and below wave base, and is variously overlain by the Brae and Kimmeridge Clay formations. In the Central Graben and West Central Shelf areas, laterally equivalent sandstones sourced from Triassic platforms are assigned to the Fulmar Sandstone Member (Copestake & Partington 2023), and are dominated by fine- to medium-grained bioturbated sandstones indicating shallower water and low to moderately high energy environments. This mainly transgressive formation has an extended age range from the Callovian to the Tithonian and is thus also equivalent to the Kimmeridge Clay Formation. Individual sandstone bodies are laterally continuous and interpreted to reflect sea level change as supported by trace fossil assemblages indicating changes in water depth and substrate (Hudson & Trewin 2002). The sandstones of the Fulmar Formation are distinct in preserving exceptionally high porosities as a result of early oil charging that inhibited the growth of clay cements and chemical compaction (Wilkinson & Haszeldine 2011). In graben areas, sandstones of shallow marine origin have been shown by biostratigraphical studies to pre-date the Fulmar sandstones; recent correlation studies have proposed the term Frigate Formation to refer to these. In the East Shetland Basin, shallow marine sandstones derived from the adjacent platform are included in the Emerald Sandstone Member. In basinal areas, Heather Formation mudstones are punctuated by sandstones of deep marine and turbiditic origin. These include the Freshney Sandstone Member which is well developed in parts of the East Central Graben, the Ling Sandstone Member recognised in the South Viking Graben, and the Bruce Sandstone Member in the Beryl Embayment. Further localised sandstone deposits are commonplace and are informally referred to as the Intra-Heather Sandstones.

In the Central North Sea the Piper Formation of late Oxfordian to Kimmeridgian age, comprises up to 300 m of coarse to fine-grained quartz and subarkosic sandstones. Arranged in both upward coarsening and upward fining cycles, individual sand bodies are often laterally continuous and thus form key hydrocarbon reservoirs. The sands were derived from regional highs with both progradational and retrogradational phases in response to shortlived regressive pulses. Two major depositional cycles are recognised. The lower part is a marine influenced channel complex with low diversity of trace fossil (ichnofauna) that passes upwards into shoreface sandstones that in turn grade landward to deltaic and fluvial succession and basinward into submarine fans. In the Outer Moray Firth the overlying Brae Sandstone Member is absent and the Piper Formation is overlain by deep marine sandstones of the Kimmeridge Clay Formation.

The overlying Kimmeridge Clay Formation is a key source rock for oil and gas fields and the development of hydrocarbon resources in the Scottish offshore sector. The formation is dominated by marine organic-rich shales that were deposited in anoxic bottom waters during periods of high sea level with low sedimentation rates (Fig. 12.25c). Near to the basin margins (e.g. Moray Firth and Witch Ground graben) depositional rates were higher leading to interfingering bodies of turbiditic sandstone (see Brae Sandstone Member below) that form important productive reservoirs. During periods of high salinity uranium enriched shales accumulated (Cooper *et al.* 1995) and more recent investigations into petroleum migration pathways using Re-Os isotopic studies (Finlay *et al.* 2010) suggest that the rift bounding faults extend to sufficient crustal depths to allow interaction of oil with mantle derived fluids.

Numerous individual and often coeval sandstone members are recognised within the Kimmeridge Clay Formation. In the Outer Moray Firth and Peterhead Basins, the earliest sandstones include the Buzzard Sandstone Member sourced from the eroding Scottish mainland to the west, and the Ettrick Sandstone Member sourced from the south west (Copestake & Partington 2023). Equivalent deposits in the Witch Ground Graben are represented by deep marine sandstone deposits including the Galley Sandstone Member, the Claymore Sandstone Member, and Dirk Sandstone Member, which were sourced from the East Piper High and fed to the south and east, where they ponded against the Renee Ridge and Fladen Ground Spur. The synrift deposits of the Brae Sandstone Member of the South Viking Graben were largely sourced from the faulted margin of Fladen Ground Spur to the west. Proximal to the bounding faults the deposits are conglomeratic and pass down the palaeoslope into sand-rich turbiditic flows that form vertically- and laterally-stacked lobe elements and ultimately distally interfinger with organic hemipelagic shales of the Kimmeridge Clay Formation. Hudson & Trewin (2002) note this setting is analogous to the Helmsdale Boulder Bed and Allt na Cuile Sandstone deposits adjacent to the Helmsdale Fault as described above. To the north, in the East Shetland Basin and Magnus Basin areas, channelised turbidite deposits derived from platform areas to the west and north are represented by the Home Sandstone Member, Magnus Sandstone Member, and Ptarmigan Sandstone Member.

Summary

The sedimentary basins formed by crustal extension during the Jurassic Period although tectonically related, demonstrate significant evolutionary differences between the western

Faroe—Shetland and Hebrides basins and the eastern Moray Firth, Central and Northern North Sea basins. These differences can be traced back to the breakup of Pangea and the formation of seaways heralding opening of Atlantic and rifting links to Europe.

A flooding event marks the Triassic/Jurassic boundary and is diachronous across the Scottish region. The oldest sediments are identified on western Mull although confirmation of the record of *Psiloceras erugatum* (Planorbis Zone) is required. The Lower Jurassic was deposited throughout, although presumably subsequently eroded in the Central North Sea. Apart from carbonates in the Hebrides, sediments were siliciclastic with the distribution of ammonites supporting open marine faunal connections. By latest Toarcian to Aalenian times uplift and erosion in the eastern basins is marked by the Mid-Cimmerian unconformity. In contrast, in the west renewed subsidence and hinterland uplift resulted in highly variable successions deposited in marine tidal-dominant environments with "Tethyan" ammonites indicating continued faunal connections to the south. The absence of late Bajocian and Bathonian sediments in the West Shetland area suggests a barrier existed to the north of the Hebrides Basin. In contrast, in the Northern North Sea marginal to marine sedimentation continued through the Middle Jurassic and the presence of Boreal late Bajocian and Bathonian ammonites supports connections to the Arctic and a barrier to the south. By Callovian times marine transgressions and the migration of Boreal ammonites into the Hebrides, Moray Firth, Northern North Sea basins and further south into Europe proves the widespread linkage of former marine basins. In the Late Jurassic (Kimmeridgian and Tithonian) rifting and differential subsidence/uplift formed complex fault structures (horsts and grabens) and variable facies development, with juxtaposition of sandstones (reservoirs) and organic-rich mudstones. In the Hebrides Basin inversion occurred after the early Kimmeridgian and before the Middle Cretaceous (Cenomanian) with faults uplifting ridges of basement separating tilted blocks of Jurassic sediment.

Since publication of the 4th edition a resurgence in palaeontological research with the discovery of vertebrate footprints and fossils on Eigg and Skye providing new insights into the evolutionary development of early mammals and reptiles. Also on Skye, exceptionally-preserved, land plants in the Bearreraig sandstone have enabled interpretation of climate, hinterland topography and evolution of some major taxa. The national and international importance of ammonites from the Scottish Jurassic continues to be recognised. Following years of investigation by an international team led by Polish and British researchers the GSSP for the Kimmeridgian Stage is now established at Flodigarry on Skye. The abundance of coastal outcrops many with well-preserved fossils thus continues to attract attention from enthusiastic amateur and professional fossil collectors. Some localities have been adversely affected and fieldwork and collecting are subject to supervision by NatureScot with fossil collection only permitted from loose blocks.

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Figure captions

Fig. 12.1: General map of distribution of Jurassic strata in Northern Britain including onshore outcrops, the main offshore rift basins and the extent of influence of the Mid North Sea Dome. Onshore locations cited in the text are shown. Source: Modified from original diagram provided by Matthew Wakefield for forthcoming Jurassic Correlation Chart, with data from Morton *et al.* 2020. BGS © UKRI 2023.

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Fig. 12.3: Simplified map of offshore Scotland Mesozoic (including Jurassic) basins, structural highs and main faults. Line of transect in Fig. 12.4 indicated. Source: Contains data obtained via OIL AND GAS AUTHORITY (OGA, now NSTA) & LLOYDS REGISTER (LR), 2019. UKCS Merged Regional Geological Maps (Open Source version). UK Continental Shelf Mapping Project (2016–2019). Published online 31st July 2019. Available at: https://hub.arcgis.com/documents/NSTAUTHORITY:-nsta-and-lloyds-register-ukcs-merged-regional-geological-maps-open-source-version/about' BGS © UKRI 2023.

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Fig. 12.19: (a) Generalised map of Moray Firth basin showing main faults and locations described in the text. (b) Simplified onshore to offshore stratigraphic scheme for the Lower, Middle and part of the Upper Jurassic in the Inner Moray Firth. (c) cross-section across Inner Moray Firth along line shown in (a). Source: Reproduced from Hudson & Trewin (2002). © Geological Society of London.

Fig. 12.20: Cartoon of stratigraphic correlation across Scottish mainland after Wright & Cox (2001). Source: Nature England released under Open Government Licence 3.0 (nationalarchives.gov.uk).

Fig. 12.21: Helmsdale Boulder Bed on foreshore near Gartymore, 1.6 km. south-west of Helmsdale, Sutherland. Rock-fall breccia consisting of angular blocks and boulders, varying in diameter from cm to metres, of Devonian sandstone sitting in bedded shelly limestone and mudstone of Jurassic age. Taken in 1914. Source: British Geological Survey Photo P002200 © UKRI. BGS images available from BGS Geoscenic.

Fig. 12.22: Cartoon of sedimentation and faulting during early Kimmeridgian adjacent to the Helmsdale Fault between Kintradwell and Port Gower. Source: Reproduced from Hudson & Trewin (2002). © Geological Society of London.

Fig. 12.23: Lithostratigraphical and chronostratigraphical scheme for the North Sea and Moray Firth areas. Source: after Copestake & Partington (2023), showing second and third order sequences. © Geological Society of London.

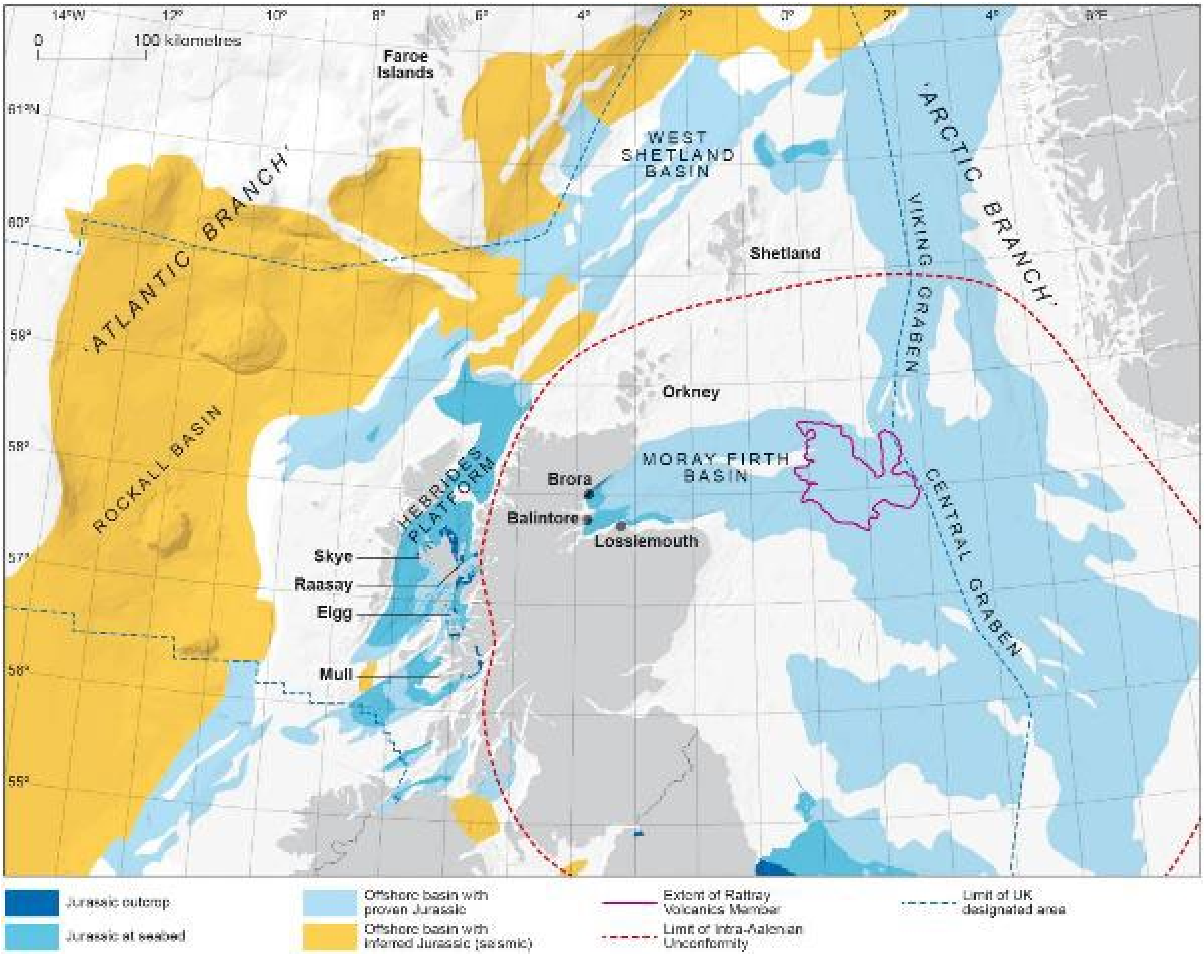
Fig.12.24: example of 'Arctic' ammonite *Arctocephalites* cf. *arcticus* recovered from borehole core at depth of 3,283.35 m. Mobil well 9/13b-51, Beryl Field, Viking Graben. Location shown in Fig. 12.3. Scale in mm. Source: Photo image © N. Morton.

Fig. 12.25: Distribution and depositional facies of Jurassic deposits in offshore Scotland based on regional mapping by Lloyds Register and the Oil and Gas Authority (OGA). (a) Early

Jurassic (Hettangian-Toarcian); (b) Callovian; (c) Kimmeridgian. Source: Contains information provided by the OGA. [Open source, Available at: https://hub.arcgis.com/documents/NSTAUTHORITY::-nsta-and-lloyds-register-ukcs-merged-regional-geological-maps-open-source-version/about].

Fig. 12.26: Schematic cross-section across the Rattray Volcanic Province with the possible subvolcanic stratigraphy as interpreted by Quirie *et al.* (2019). Evidence for fissure-fed volcanism and a lack of central volcanoes in the Witch Ground Graben and Fisher Bank Basin indicates that a large non-intruded sedimentary gross rock volume is present beneath the Rattray Volcanic Province. Source: Modified after Quirie *et al.* (2019) © Geological Society of London.

Chapter 12 Jurassic Figures



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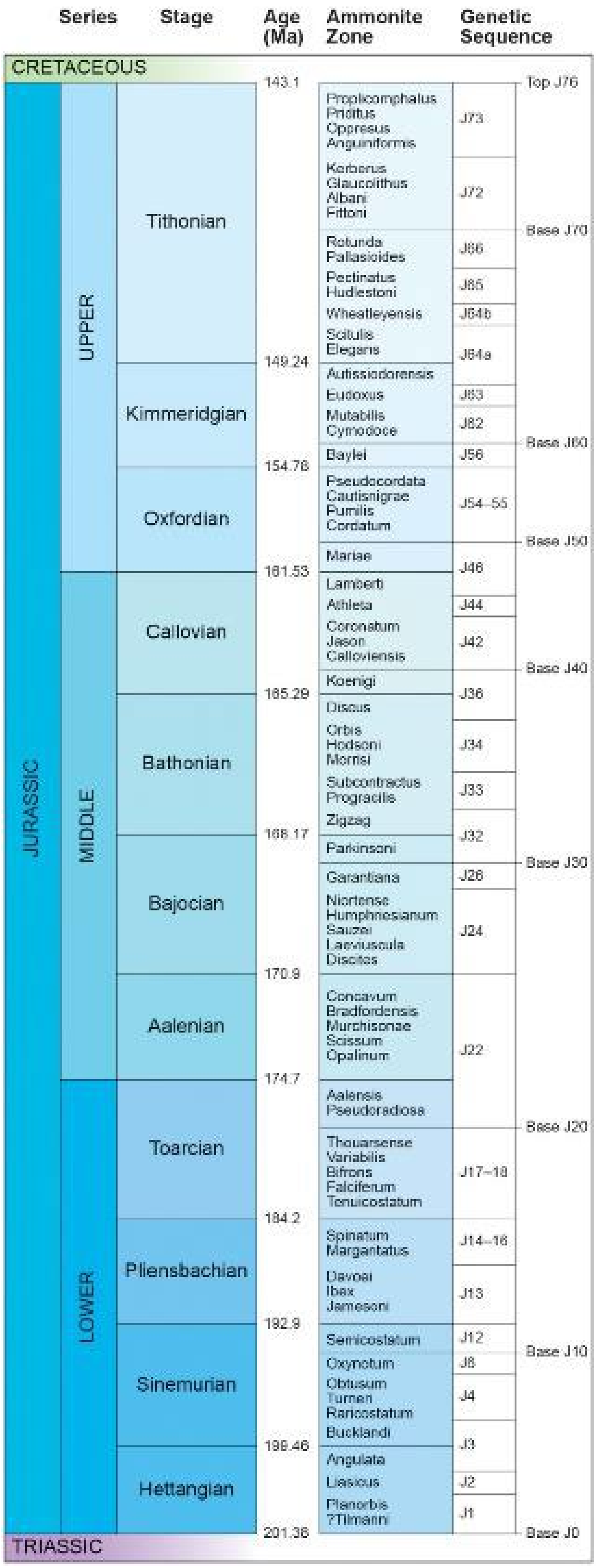

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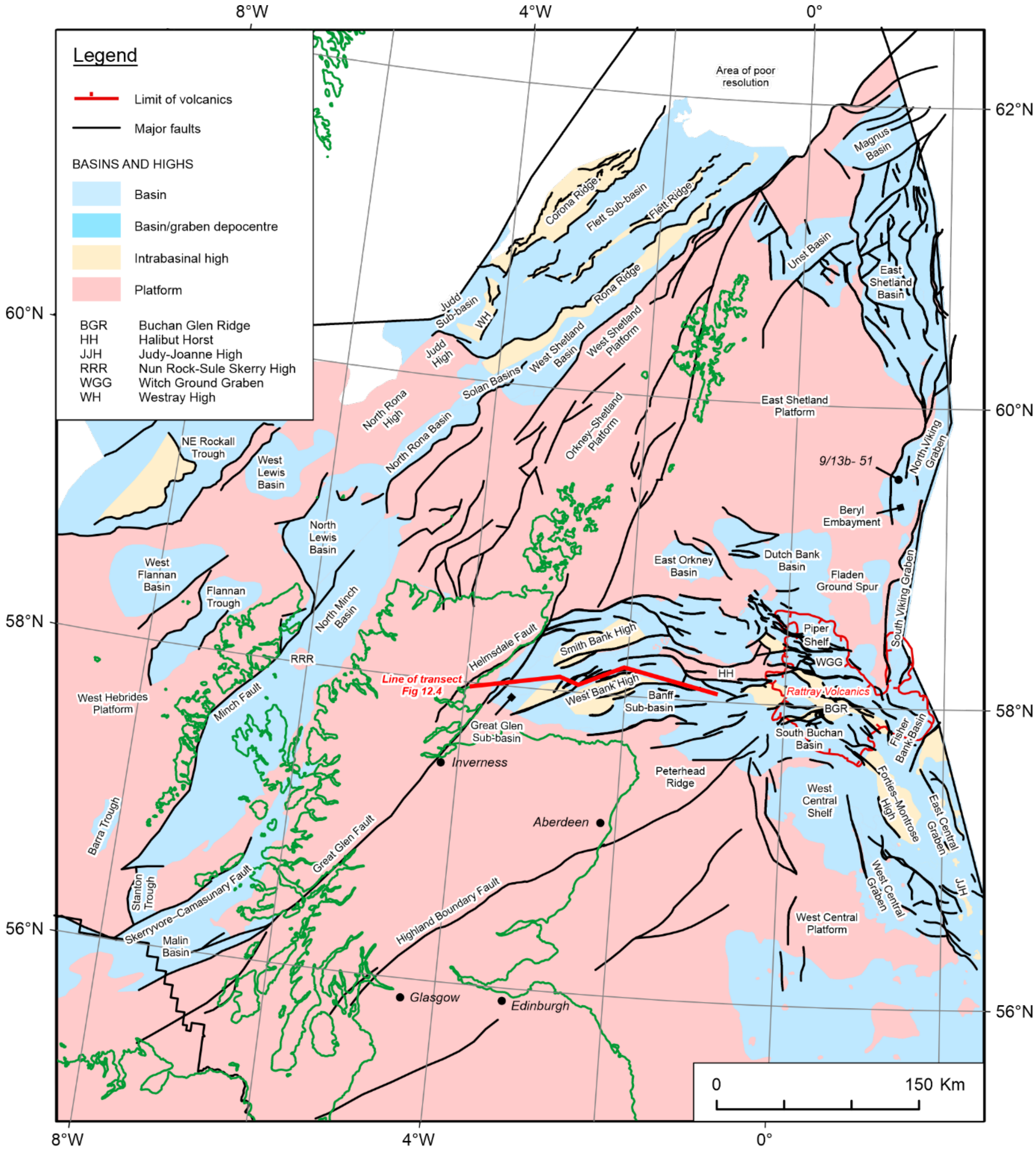

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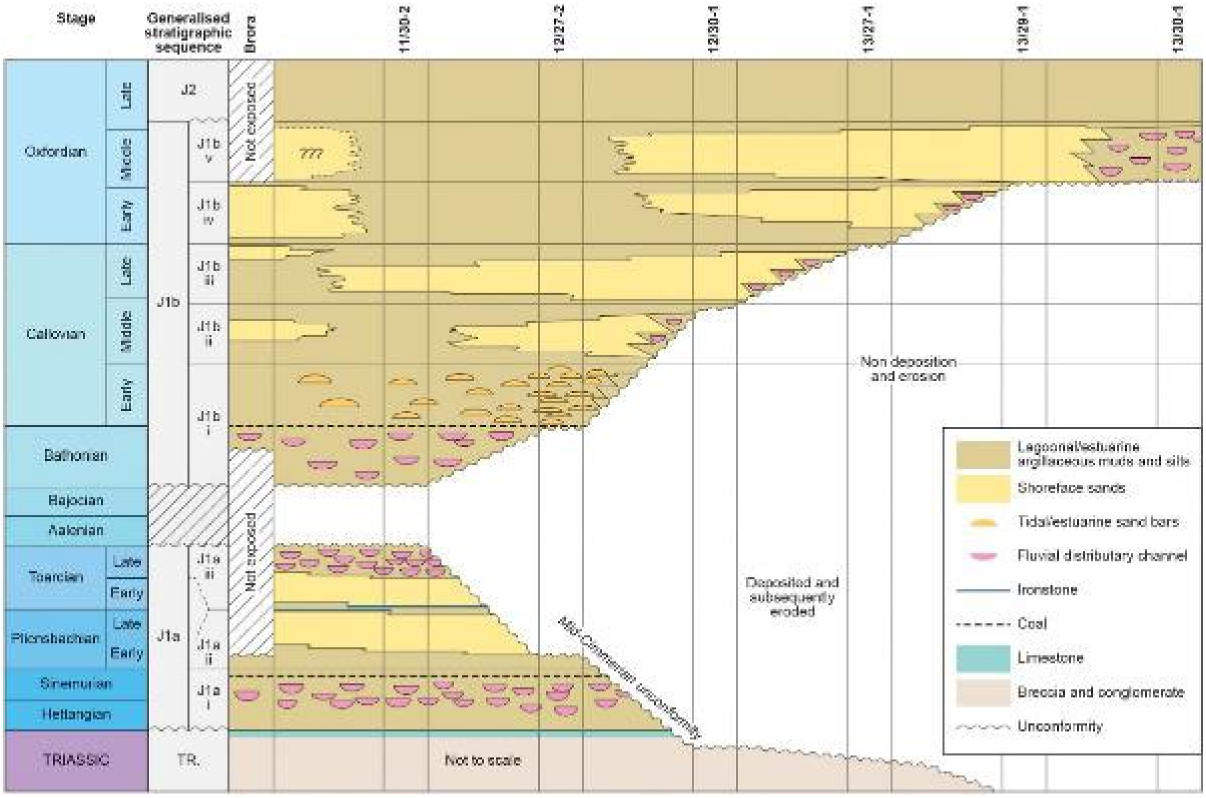

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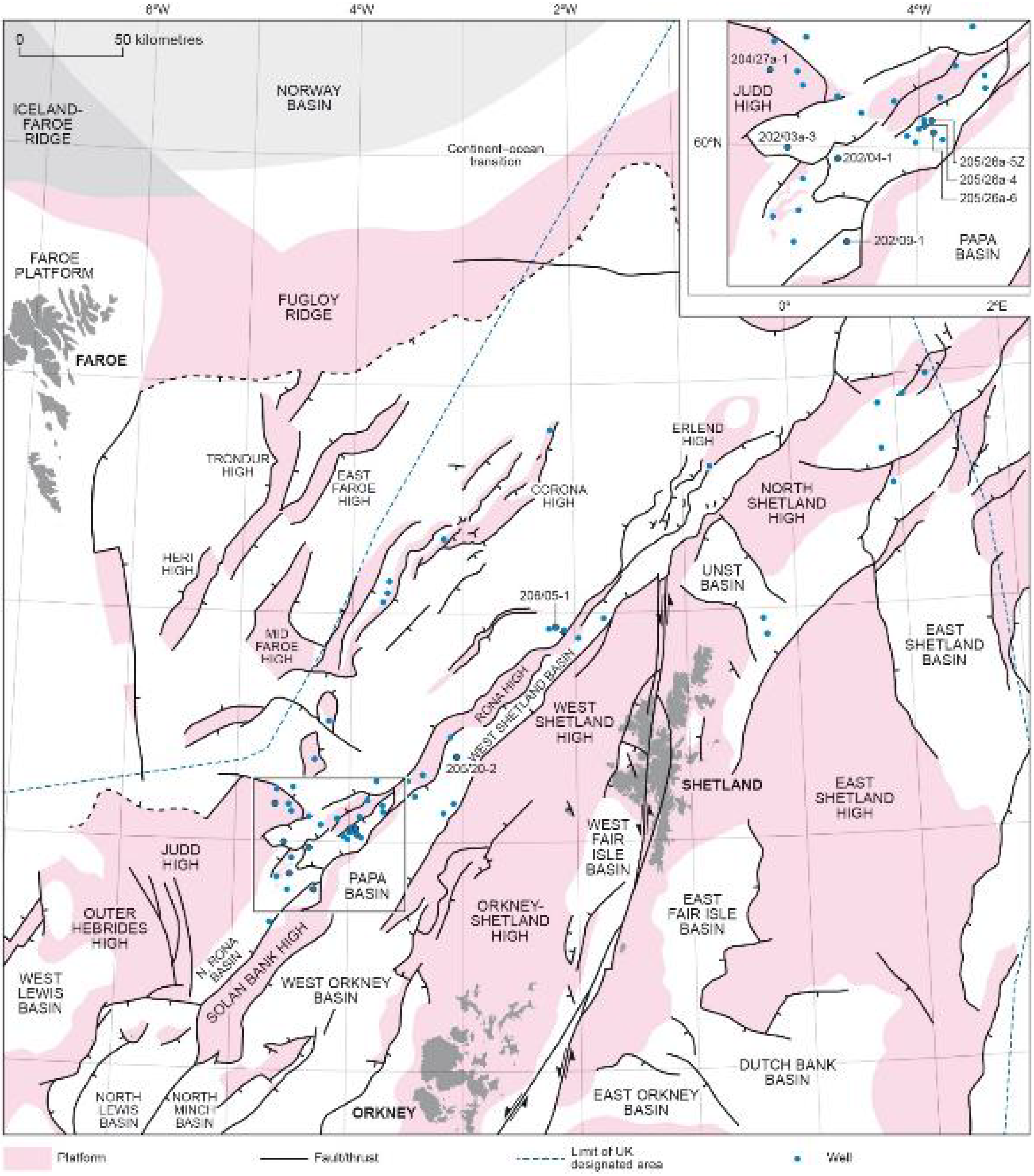
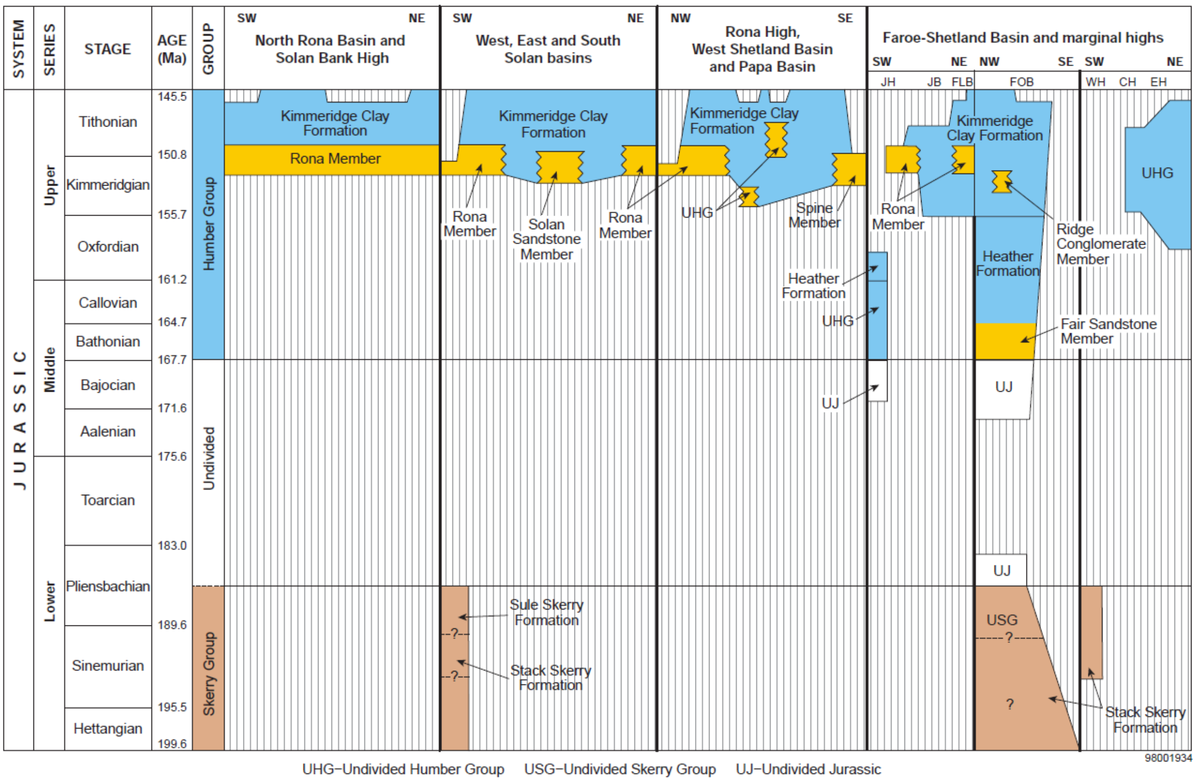


6°W
4°W
2°W
0°
2°E
63°N
62°N
61°N
60°N
59°N
0
50 kilometres
ICELAND-FAROE RIDGE
NORWAY BASIN
Continent–ocean transition
FAROE PLATFORM
FUGLOY RIDGE
FAROE
TRONDUR HIGH
EAST FAROE HIGH
CORONA HIGH
HERI HIGH
MID FAROE HIGH
ERLEND HIGH
NORTH SHETLAND HIGH
UNST BASIN
EAST SHETLAND BASIN
206/05-1
RONA HIGH
WEST SHETLAND BASIN
WEST SHETLAND HIGH
200/20-2
SHETLAND
EAST SHETLAND HIGH
JUDD HIGH
PAPA BASIN
WEST FAIR ISLE BASIN
EAST FAIR ISLE BASIN
OUTER HEBRIDES HIGH
N. RONA BASIN
SOLAN BANK HIGH
ORKNEY-SHETLAND HIGH
WEST LEWIS BASIN
WEST ORKNEY BASIN
NORTH LEWIS BASIN
NORTH MINCH BASIN
ORKNEY
EAST ORKNEY BASIN
DUTCH BANK BASIN
204/27a-1
202/03a-3
202/04-1
205/26a-5Z
205/26a-4
205/26a-6
202/09-1
Platform
Fault/thrust
Limit of UK designated area
Well



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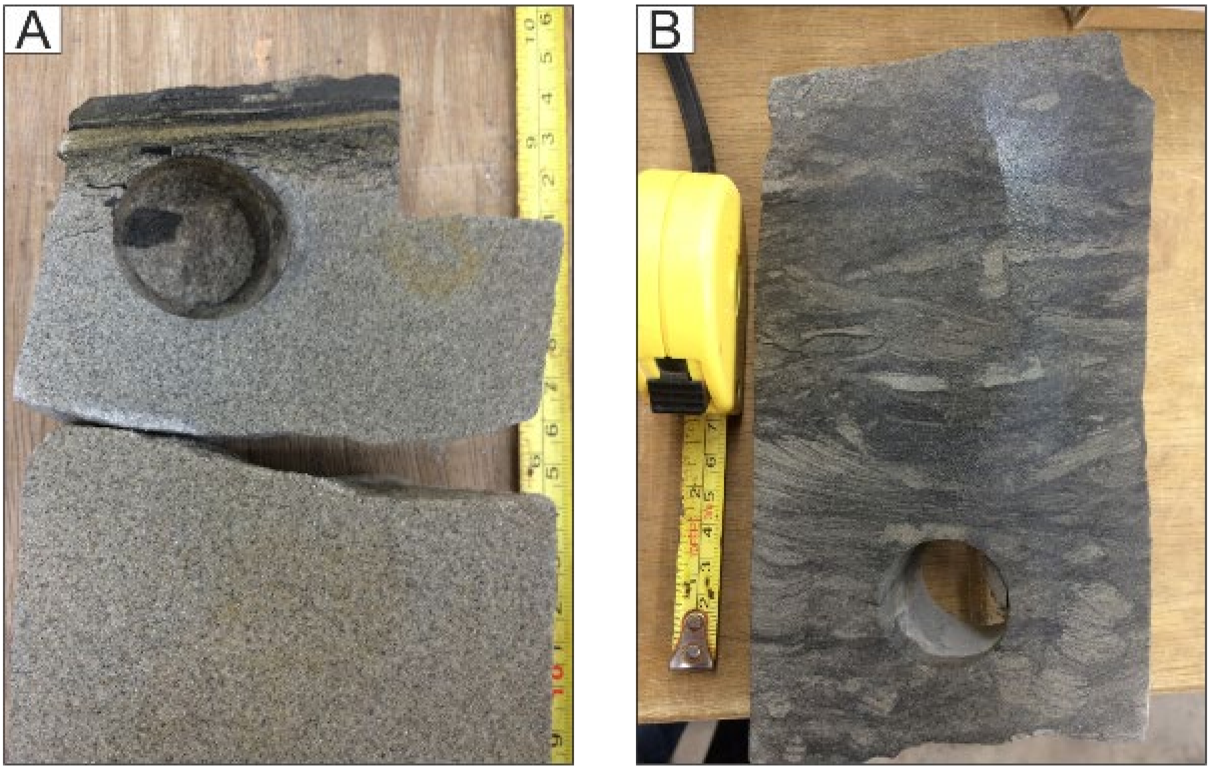

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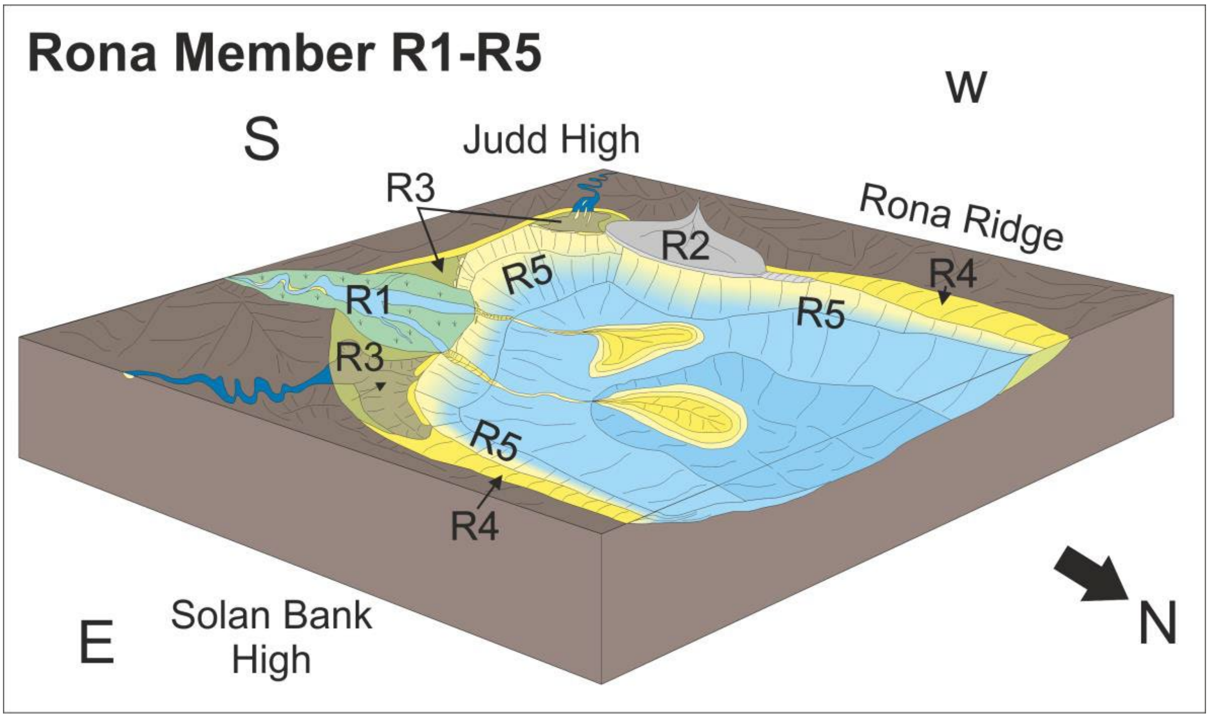

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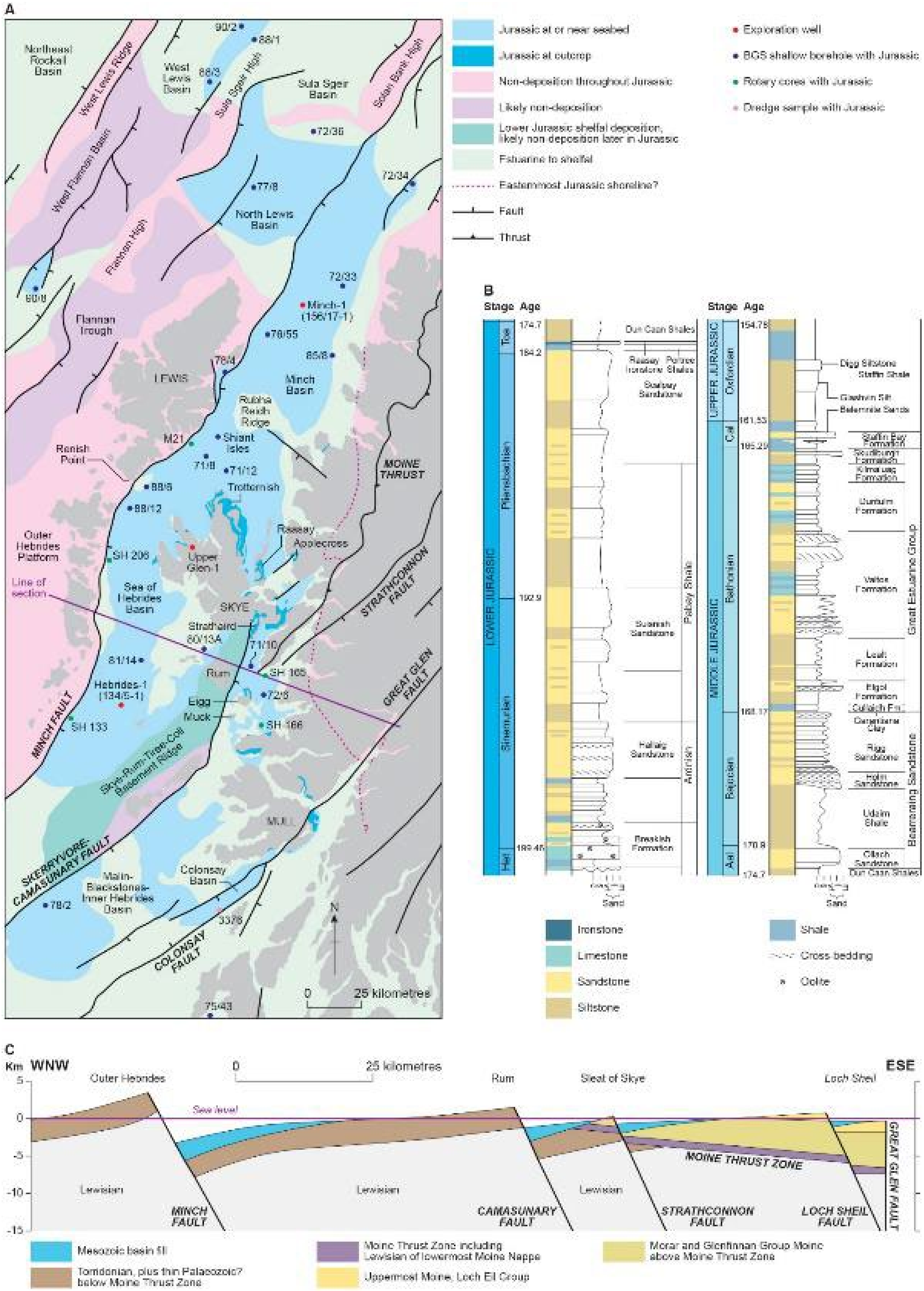

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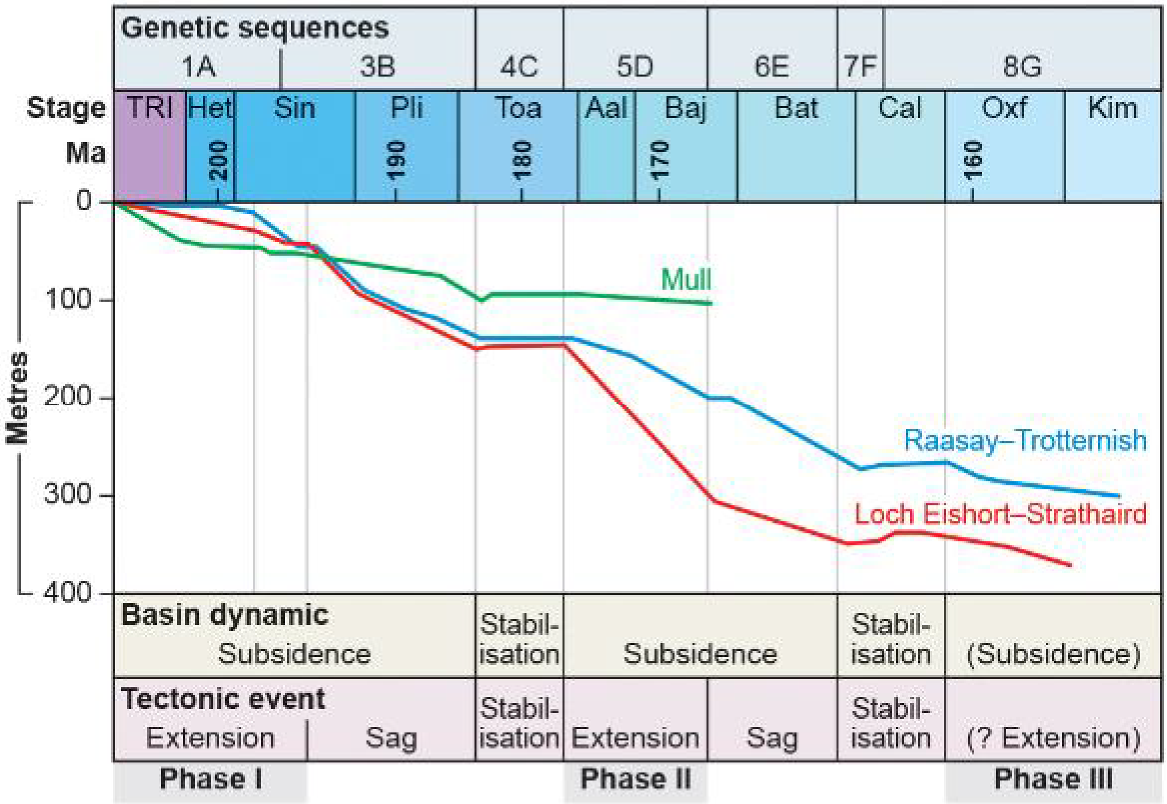

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Bearreraig.pdf

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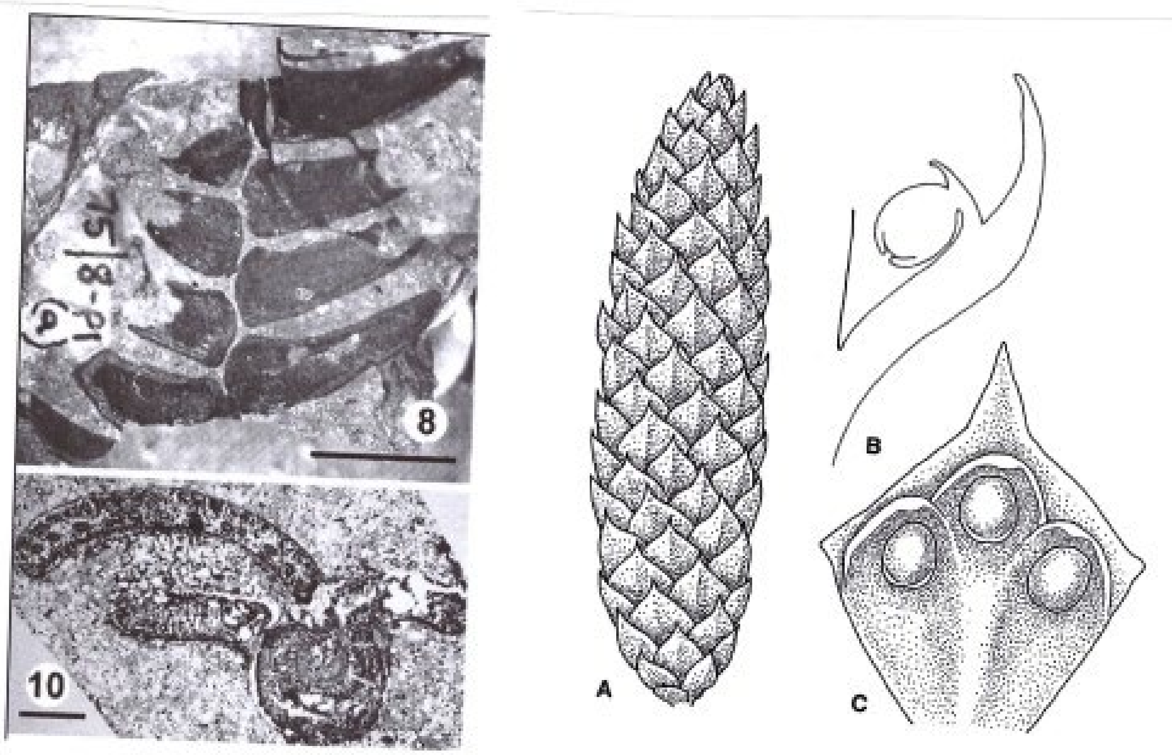

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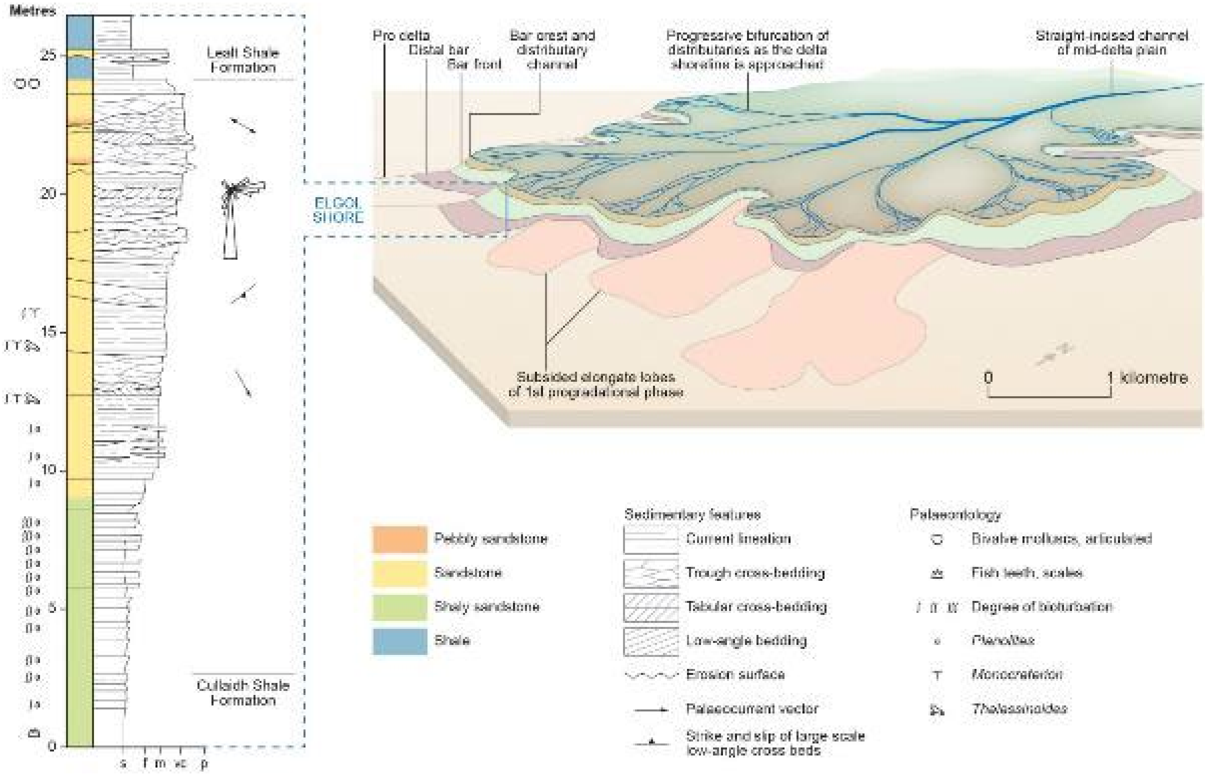

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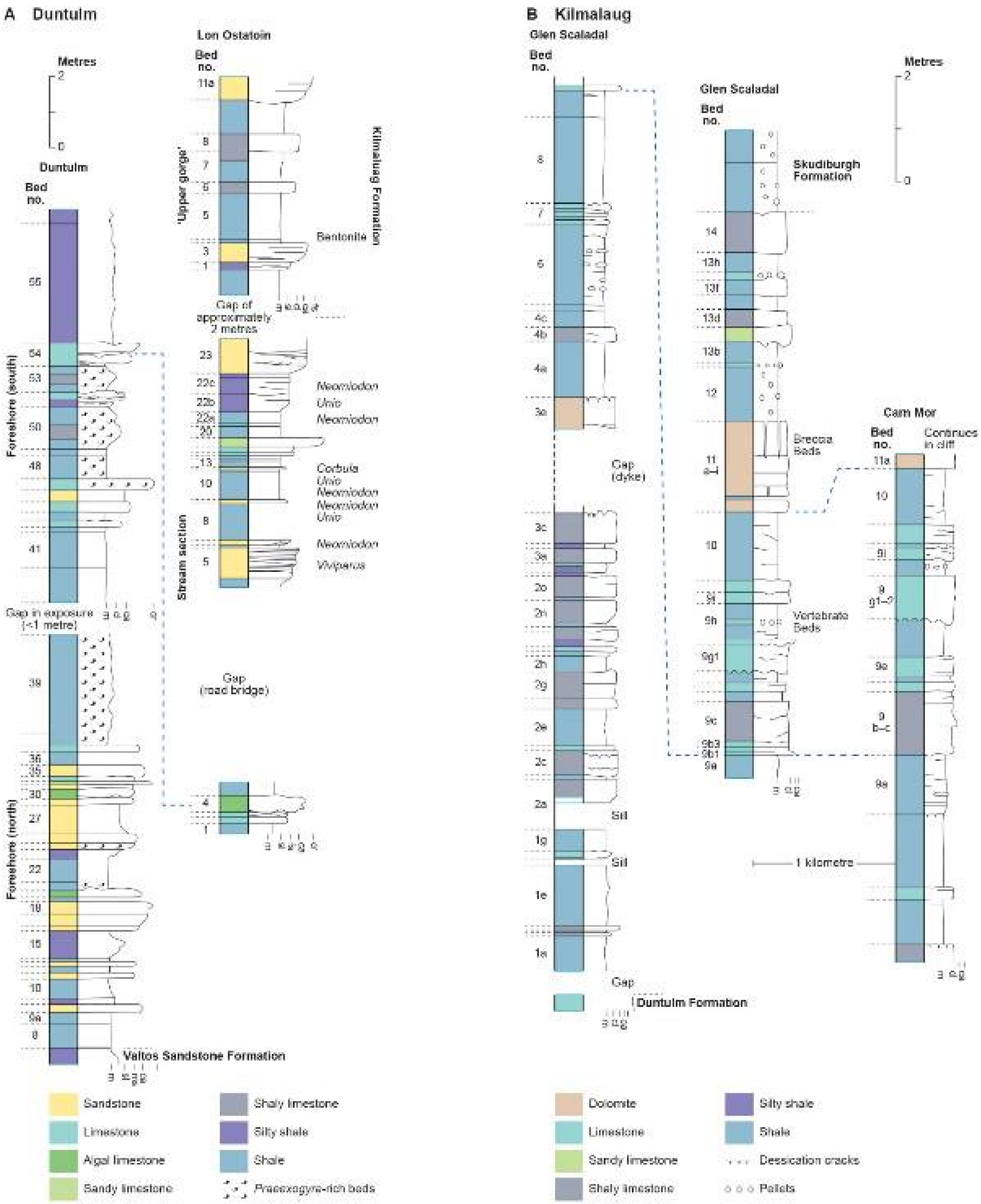

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Fig. 12.15: probable stegosaur fibula, Isle of Eigg. Scale bar in cm. [reproduced with permission from E Panciroli]

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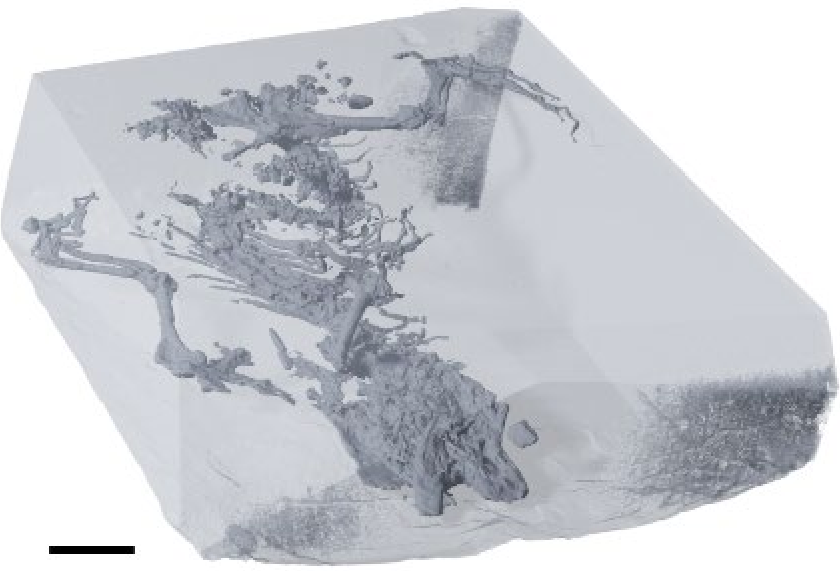

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Fig. 12.17(TP2): dinosaur footprint, Isle of Skye reproduced with permission Jason Gilchrist


A
B
C
Bed 36
Bed 35

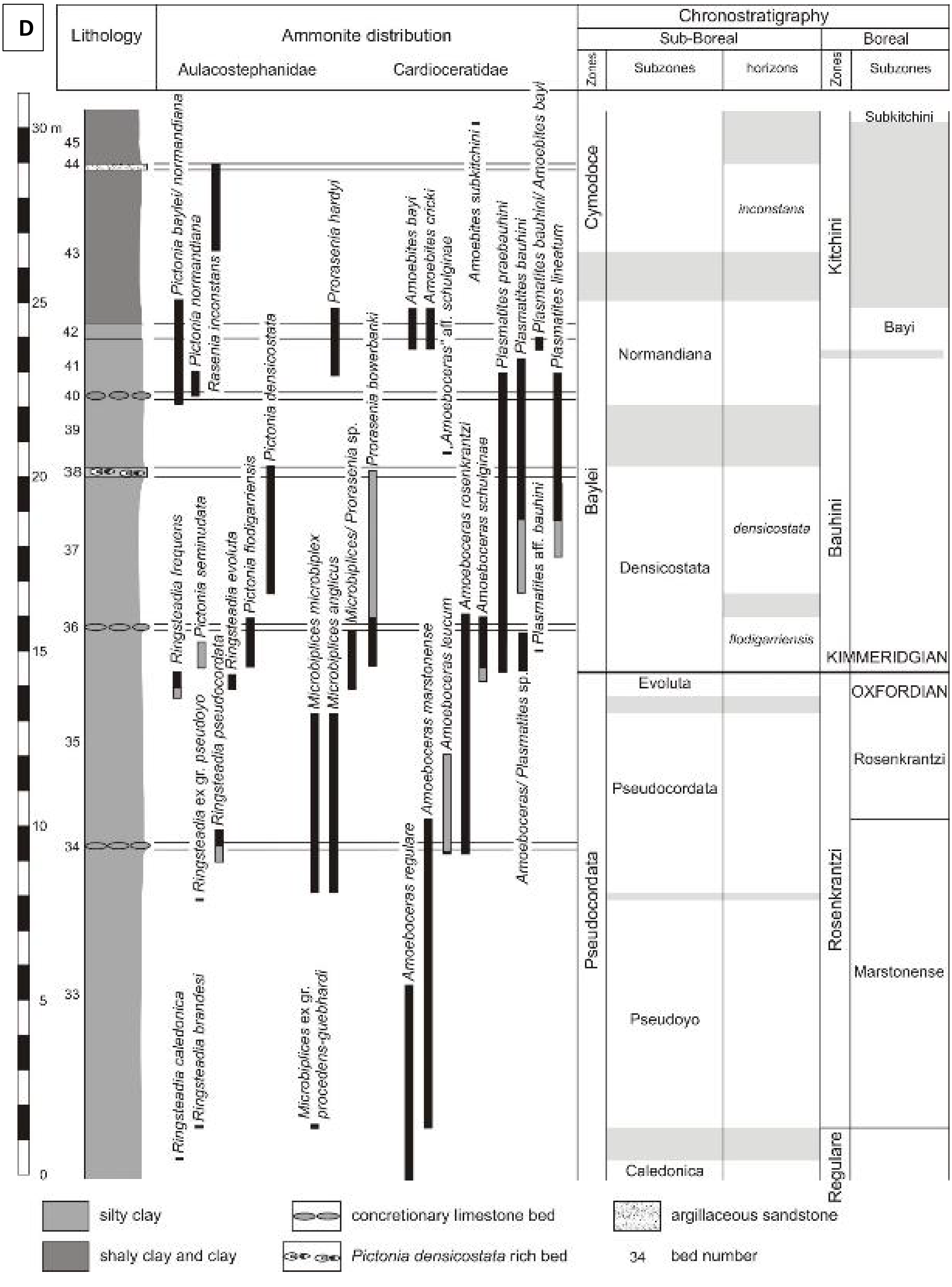

Fig. 12.18: (a) General view along the foreshore at Flodigarry, Staffin Bay, Isle of Skye note the large dolerite boulder, for location; (b) Looking north along beach showing marker bed 36; (c) Detail of beds 36 and 35 showing position of Oxfordian/Kimmeridgian boundary; (d) Detail of stratigraphic

distribution of ammonites in the Flodigarry section, across the Kimmeridgian GSSP. The ammonites are located to the nearest centimetre. Ammonite distribution column – black lines denote the first, last and intervening recorded occurrence of the key species; grey bars denote cf. species; chronostratigraphy column – grey blocks indicate intervals where no ammonites were found. Reproduced from Wierzbowski *et al.* (2023) [copyright IUGS, Creative Commons 4.0]

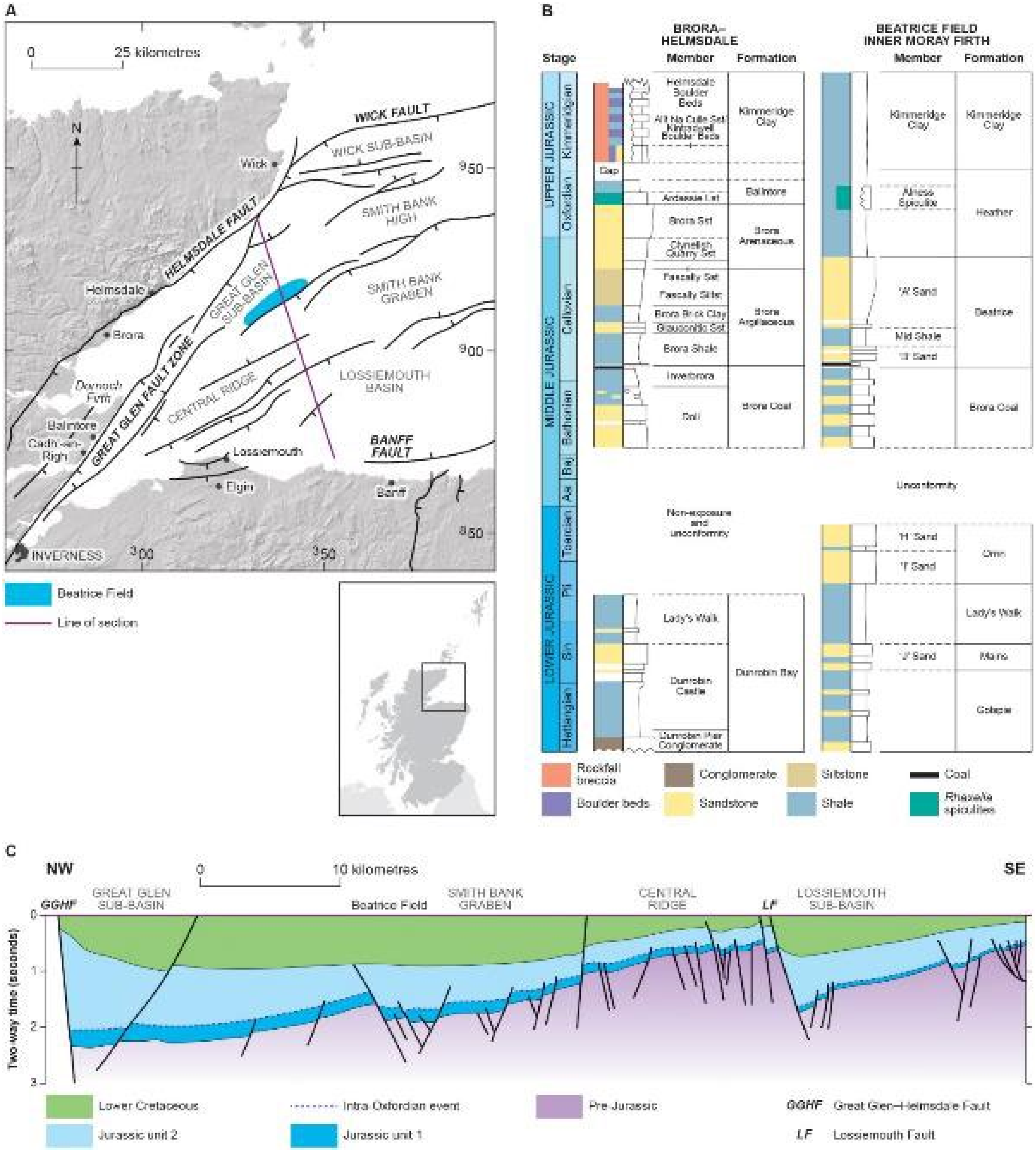

Fig. 12.19: (a) Generalised map of Moray Firth basin showing main faults and locations described in the text. (b) Simplified onshore to offshore stratigraphic scheme for the Lower, Middle and part of the Upper Jurassic in the Inner Moray Firth. (c) cross-section across Inner Moray Firth along line shown in (a). Reproduced from Hudson & Trewin (2002) [copyright Geological Society]

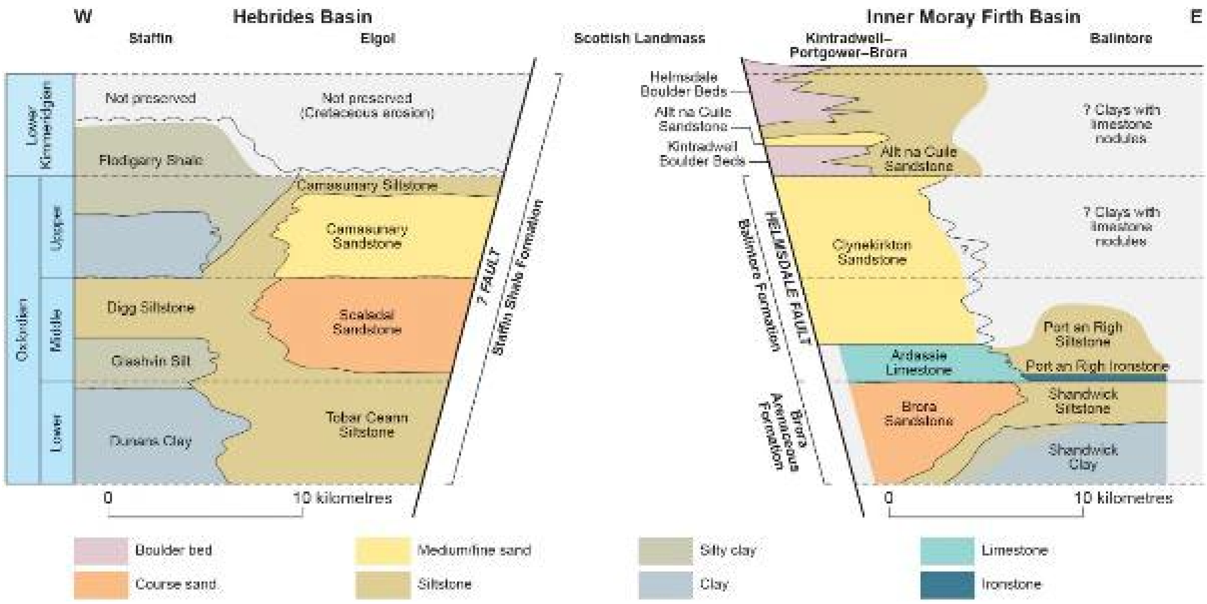

Fig. 12.20: cartoon of stratigraphic correlation across Scottish mainland after Wright & Cox 2001. [copyright Open Government Licence 3.0].

Fig. 12.21: Helmsdale Boulder Bed on foreshore near Gartymore, 1.6 km. south-west of Helmsdale, Sutherland. Rock-fall breccia consisting of angular blocks and boulders, varying in diameter from cm to metres, of Devonian sandstone sitting in bedded shelly limestone and mudstone of Jurassic age. BGS photo P002200 taken in 1914. [BGS © UKRI]

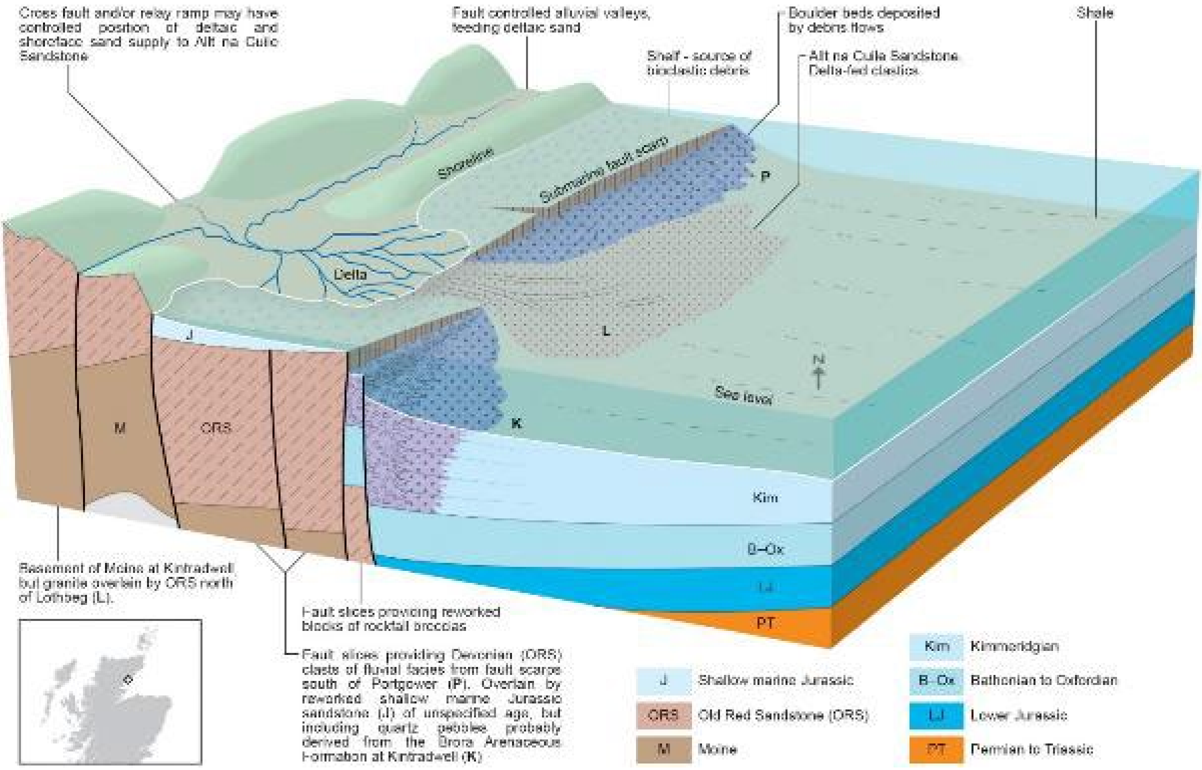

Fig. 12.22: Cartoon of sedimentation and faulting during early Kimmeridgian adjacent to the Helmsdale Fault between Kintradwell and Port Gower. Reproduced from Hudson & Trewin (2002). [copyright Geological society].

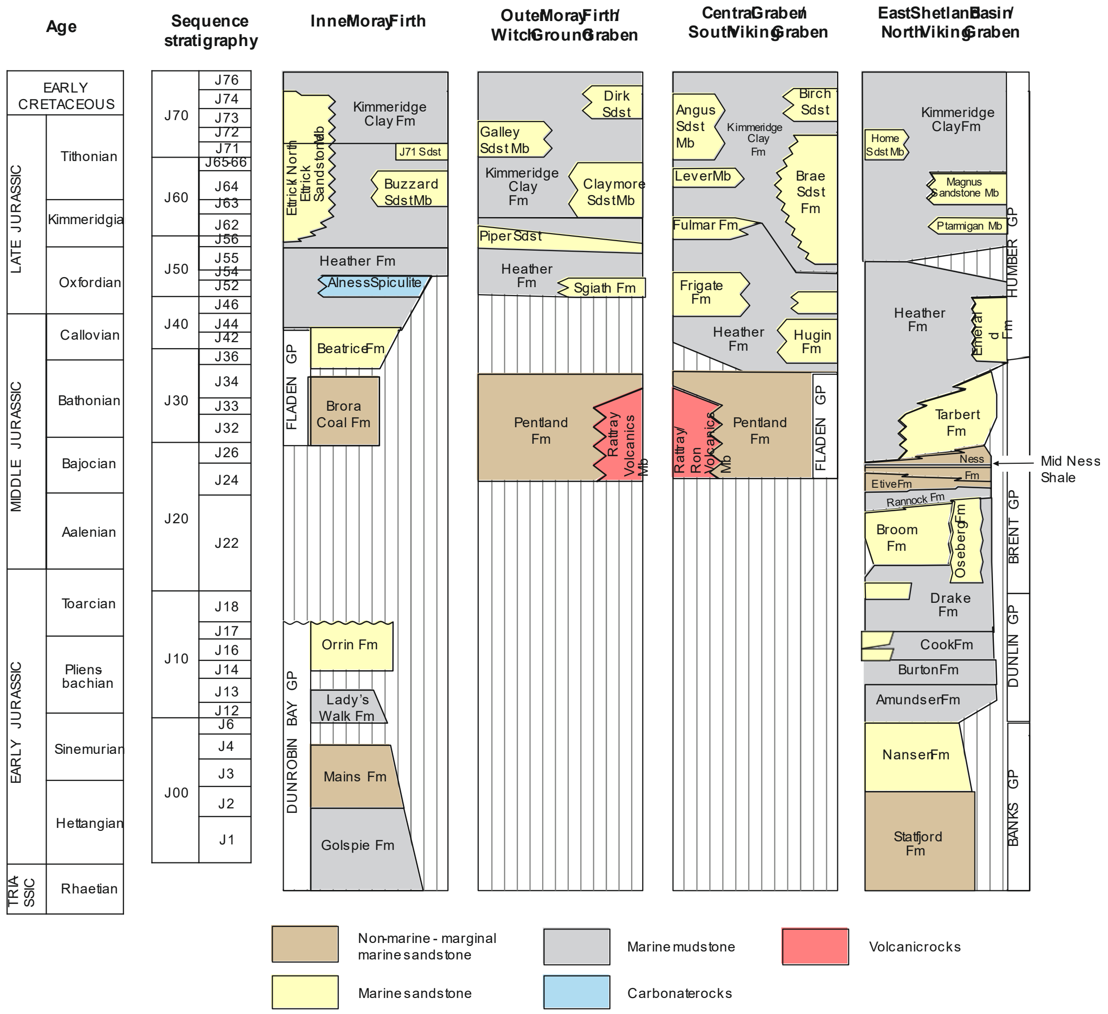

Fig. 12.23: Lithostratigraphical and chronostratigraphical scheme for the North Sea and Moray Firth areas, after Copestake & Partington (2023), showing second and third order sequences. [copyright Geological Society].

Fig. 12.24: Example of ‘Arctic’ ammonite *Arctocephalites* cf. *arcticus* recovered from borehole core at depth of 3,283.35 m. Mobil well 9/13b-51, Beryl Field, Viking Graben. Location shown in Fig. 12.3. Scale in mm. Photo by N. Morton [copyright N Morton].

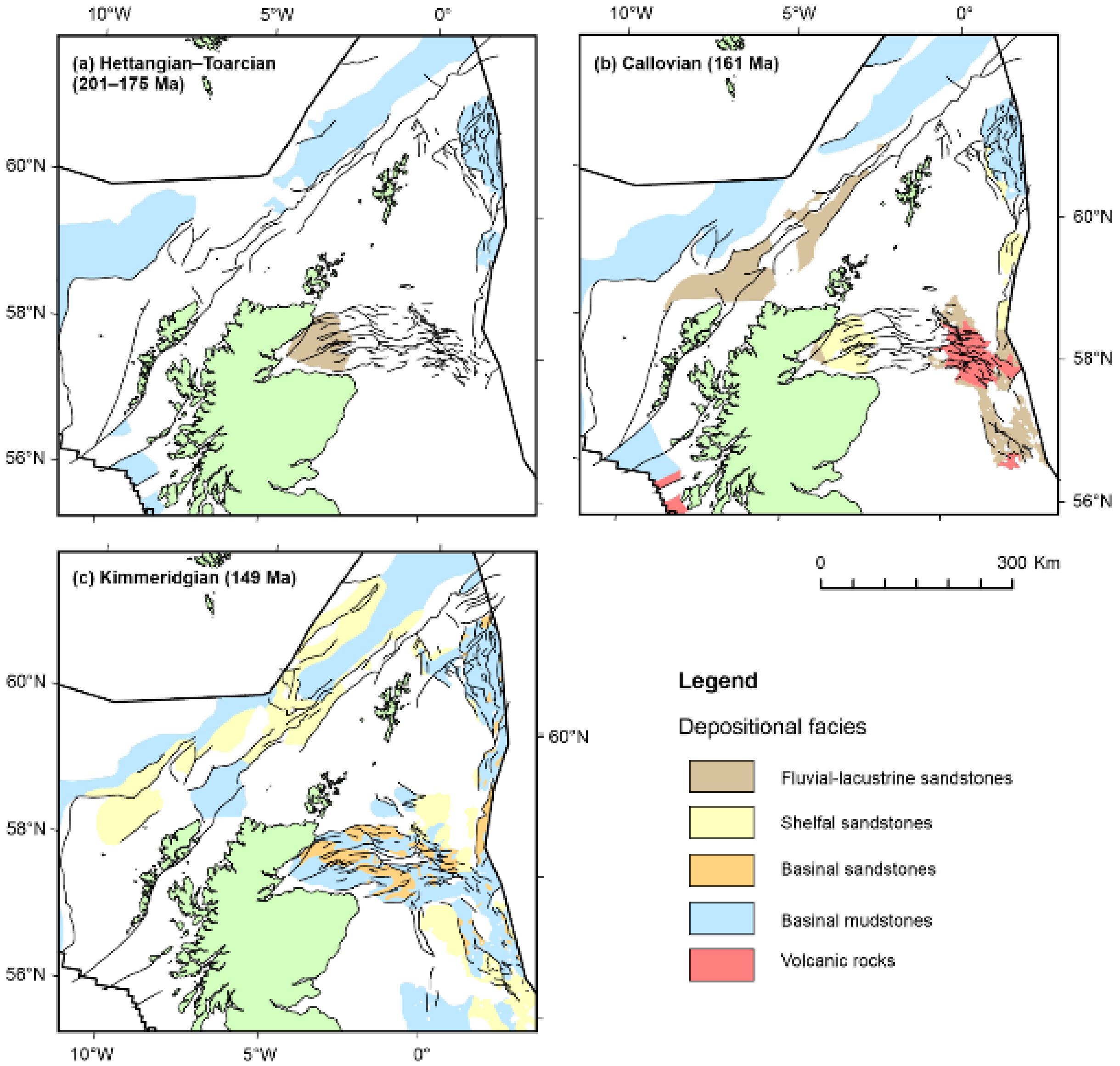

Fig. 12.25: Distribution and depositional facies of Jurassic deposits in offshore Scotland based on regional mapping by Lloyds Register and the Oil and Gas Authority (OGA). (a) Early Jurassic (Hettangian-Toarcian); (b) Callovian; (c) Kimmeridgian. Contains information provided by the OGA. [Open source, Available at: https://hub.arcgis.com/documents/NSTAUTHORITY::-nsta-and-lloyds-register-ukcs-merged-regional-geological-maps-open-source-version/about].

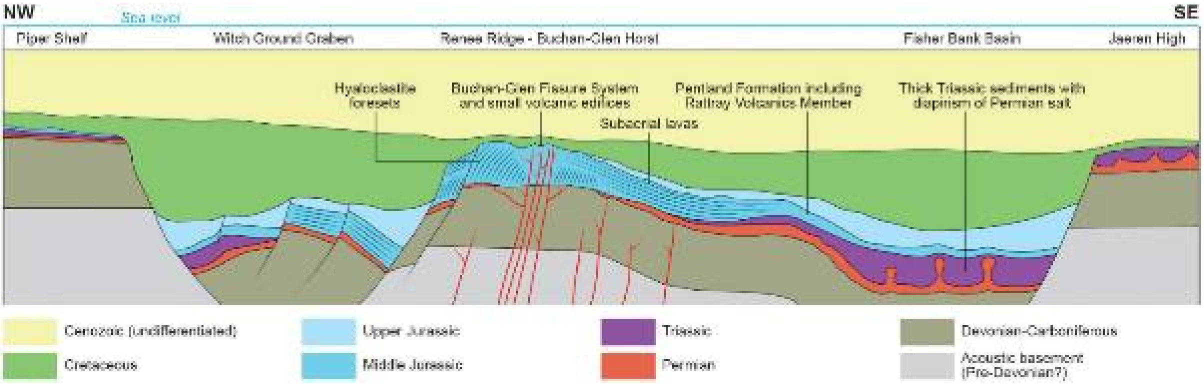

Fig.12.26: Schematic cross-section across the Rattray Volcanic Province with the possible subvolcanic stratigraphy as interpreted by Quirie *et al.* (2019). Evidence for fissure-fed volcanism and a lack of central volcanoes in the Witch Ground Graben and Fisher Bank Basin indicates that a large non-intruded sedimentary gross rock volume is present beneath the Rattray Volcanic Province. Simplified from Quirie *et al.* (2019). [copyright Geological Society].