UK Rockall prospectivity: re-awakening exploration in a frontier basin

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Abstract: The UK Rockall, located to the west of Scotland and the Hebrides, is a frontier petroleum-bearing basin. Exploratory drilling in the basin took place over a quarter of a century (1980–2006), during which time a total of 12 wells were drilled, leading to the discovery of a single, subcommercial gas accumulation. We argue that the basin, which has seen no drilling activity for more than a decade, has not been sufficiently tested by the existing well stock. We examine the reasons for the absence of key Jurassic source rocks in the UK Rockall wells, which are widely distributed elsewhere on the UK Continental Shelf (UKCS), and argue that their absence in the wells does not preclude their existence in the basin at large. An evaluation of the Permian–Early Eocene successions, based upon the seismic interpretation of new 2D seismic data, has been integrated with legacy data and regional evidence to establish the potential for source, reservoir and sealing elements within each interval. Finally, we look at the future for exploration in the UK Rockall and suggest a way forward in the drilling of a new joint governmental–industry test well that may help to unlock the exploration potential of this under-explored, yet prospective, basin.

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The UK continues to undergo rapid change in its domestic oil and gas supply chain, with supermajors (e.g. Conoco-Philips and Chevron) now exiting exploration and production on the UK Continental Shelf (UKCS). This is against an overall decrease in production across the Southern, Central and Northern North Sea (SNS, CNS and NNS) basins. Even with the increased focus within the UK on energy transition to renewables, at current best estimates the global demand for oil and gas will still remain high beyond 2040 (e.g. BP 2019a, 2019b). This coupled with socio-political global uncertainty, it remains important for UK energy security to fully evaluate areas of the UKCS which are under-explored with a view to feeding the funnel of new projects that could yield production and decrease the country’s reliance on oil and gas imports.

The UK Rockall Basin represents a highly under-explored area within the UKCS. To date, only 12 exploration wells (with one discovery) have been drilled in the UK Rockall Basin (Figs 1 and 2), an area comparable in size to the entire developed area of the UK North Sea. However, our knowledge of the UK Rockall stratigraphy is severely lacking, as only four of the 12 wells drilled (132/15-1, 154/03-1, 164/25-12 and 164/25-2) penetrated rocks predating the Cretaceous, and not a single exploration well has found strata of Jurassic age. The results of these four wells have contributed to an informal, but widely held, perception that Jurassic sequences are largely absent from the Rockall Basin. The perceived absence of key stratigraphic intervals has been central to a generally negative industry view of the basin because the Jurassic hosts the main source-rock intervals in the more mature NW European basins, including the prolific North Sea and Faroe–Shetland Basin (FSB). However, the 154/01-1 Benbecula thermal gas discovery not only proved the existence of a source rock but also underlined the fact that a working petroleum system exists in the basin, at least locally.

Associated geochemical analyses indicated that the gas could potentially have been derived from an Upper Jurassic source (Kleingeld 2005). This is further corroborated by analysis of oils from the 164/28-1A well, in which biomarker data from oil shows in the Paleocene-age Vaila Formation indicated multiple sourcing of hydrocarbons, with one component corresponding to a siliciclastic marine source type, suggested to be similar to the Upper Jurassic of the North Sea (Ferriday 2000).

The lack of source-rock penetration in the basin continues to suppress confidence, particularly in the context of the low levels of hydrocarbon industry activity that have persisted in the UKCS for the past 5 years. To compound this, exploration within the UK Rockall remains costly due to the deep water and risky due to poor seismic data quality; biostratigraphy from existing wells is inconsistent, complicating correlation; and the impact of intrusive and extrusive volcanics is manifold, with potential impact not only on seismic imaging but also on migration, trap formation and breaching, maturation or cracking of source rocks, and reservoir diagenesis through fracturing, local heating and enhanced fluid flow (Karvelas et al. 2016; Schofield et al. 2017b).

In this paper, we discuss aspects of the results of a 2 year study of the Rockall Basin conducted at the University of Aberdeen as part of the UK Oil and Gas Authority (OGA) Frontier Basins project. The stimulus for the study was the release of new regional 2D seismic data in the Rockall Basin by the OGA in 2016 to reinvigorate exploration in this frontier basin. We present an overview of the geological background and the exploration history and narrative of the basin. This is followed by a series of well correlations, based on new biostratigraphy carried out in order to place the wells within the widely used T-sequence framework (Fig. 3), established by BP stratigraphers in the 1990s (e.g. Jones and Milton 1994; Ebdon et al.)
Fig. 1. Structure map of UK Rockall, showing main sub-basins, intra-basinal highs, faults and igneous centres. The red boundary marks main area of interest for this study. UK Rockall exploration wells and shallow boreholes, and selected Faroe–Shetland Basin exploration wells are shown. Boreholes mentioned in the text are labelled. WLR, West Lewis Ridge; SSH, Sula Sgeir High; SBH, Solan Bank High; RR, Rona Ridge.

Fig. 2. Graph showing exploration wells drilled in the UK Rockall between 1980 and 2006.
for the Paleogene sequences of the North Sea and the FSB. Palaeogeographies at key intervals are presented, followed by a summary of play concepts. Finally, we consider the main impediments to exploration progress and discuss potential ways forward.

Importantly, we argue, that as it stands, even taking into account regional information from outside of the basin (e.g. Inner Hebrides, Solan Basin and Irish Rockall), insufficient direct subsurface data exist within the UK Rockall, particularly in terms of wells, to make firm conclusions about UK Rockall prospectivity or the lack thereof. We suggest that this impasse can only be broken by the provision of hard data provided by a new stratigraphic test well, similar to the first well drilled within the basin in 1980, which was drilled by a consortium of government and oil companies (to share cost); only then may enough data be potentially available to finally decide on the prospectivity of Rockall, whether positive or negative. Without undertaking such an admittedly bold move, we would argue that questions of the UK Rockall prospectivity are likely to remain for decades to come and exploration interest is likely to remain suppressed.

Geological background and stratigraphy

The detailed geological evolution of the Rockall Basin is still largely unknown, due to the lack of deep well penetrations in the basin and the limited coverage of good quality seismic data; however, its development is thought to be comparable with that of the adjacent FSB (Archer et al. 2005), whilst the Inner Hebrides may provide an insight into the Jurassic development of the basin. A petroleum systems events chart is presented in Figure 4, whilst the lithostratigraphic scheme for the Permian–Eocene of these areas is shown in Figures 4–7.

The basement is likely to comprise two major Caledonian basement terranes, sutured across the Anton Dohrn Lineament (Fig. 1) (Doré et al. 1997b, 1999; Hitchen et al. 2013). The presence of Middle Proterozoic–earliest Devonian sequences is currently largely unknown in the Rockall area; however, the existence of such sequences within the FSB (e.g. Rona Ridge) and, possibly, in the Inner Hebrides (e.g. Minch-1 well; Peacock 1990) infers that they may be present within the UK Rockall. The NE–SW structural grain dominating the rift orientation along the Atlantic margin is an inherited trend, first developed during compression associated with the Caledonides. A Triassic–Early Cretaceous rift phase and Late Cretaceous–Paleogene post-rift phase appear to characterize much of the stratigraphy of the Rockall Basin (Musgrove and Mitchener 1996; Archer et al. 2005). Jurassic rifting is thought to have resulted in a series of restricted north–south-orientated basins that were later overprinted by more widespread Early Cretaceous rifting (Scotchman et al. 2016). The Rockall may have become hyper-extended (Roberts et al. 2018) during this subsequent rifting, potentially leading to highly segmented and discontinuous Jurassic and older sequences towards the centre of the basin (Lundin and Doré 2011).

In the FSB, rifting continued into the Middle and Late Cretaceous, evolving into an initial phase of post-rift subsidence by the latest Cretaceous (e.g. Dean et al. 1999; Doré et al. 1999). Evidence for Late Cretaceous rifting in the UK Rockall is unclear, based on currently available data, and it is argued by Musgrove and Mitchener (1996) that thermal subsidence dominated from the Cenomanian age onwards. The Cenozoic was a period of overall post-rift thermal sag, with accelerated subsidence from the Late Eocene leading to the present-day expression of the Rockall Basin as a single, deep-water basin (Hitchen et al. 2013). Against this backdrop of net subsidence, episodes of inversion during the Thanetian, late Ypresian, Late Eocene, Early Oligocene and Early–Middle Miocene (e.g. Stoker et al. 2005; Ritchie et al. 2008; Tuitt 2009; Tuitt et al. 2010; Hitchen et al. 2013) were widespread along the Northeast Atlantic margin and were important events for the formation of large compressional structures, such as the Wyville–Thomson Ridge (Johnson et al. 2005; Ritchie et al. 2008; Hitchen et al. 2013) and the Ormen Lange Dome in Norway (Lundin and Doré 2002; Tuitt et al. 2010).

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![Fig. 3. Palaeocene and Eocene lithostratigraphy for West of Britain and the Central North Sea, modified from Schofield et al. (2019) and Waters et al. (2007), respectively. The BP T-sequence framework (Edbon et al. 1995) shown over the Palaeocene interval.](image-url)
Exploration history and narrative

To date, only 12 exploration wells have been drilled in the UK Rockall (Figs 1 and 2), comprising 11 dry holes, one with oil shows and a single gas discovery. This in an area of some 180,000 km², comparable in size to that of the developed areas of the UK North Sea hydrocarbon province. Nine of the wells are confined to the Northeast Rockall Basin, with a single well in the adjacent West Lewis Basin and two in the South Rockall Basin (Fig. 1). For a full review of UK Rockall exploration, the reader is referred to Schofield et al. (2017b, 2019), who detail the objectives and results of each well in context. Schofield et al. (2019) summarized the stratigraphy encountered in each well and presented a geological interpretation for each well. They concluded that five of the 12 Rockall wells were drilled on invalid tests and were based on inadequate geological understanding and/or poor seismic data quality. This analysis increases the ratio of exploration successes v. failures to a respectable 1:6 wells, rather than 1:11, similar to early technical success rates quoted for the FSB of one well in every seven wells drilled in the FSB (Loizou 2003). In this section, we present a brief overview of the existing wells and consider the factors that contributed to the negative industry perception of the basin, and whether they can be viewed in a different light. In particular, the four wells that penetrated pre-Cretaceous strata are discussed in more detail, with an emphasis on possible reasons for the absence of Jurassic strata.

Basin opening well – 163/06-1A joint industry and governmental stratigraphic test well

Exploration in the UK Rockall was kicked off in 1980 with the 163/06-1A well. This was a stratigraphic test well, with the objective of testing the stratigraphy of the Rockall Basin and investigating the potential of a set of clinoforms prognosed to be a Mesozoic sedimentary forest succession. However, the well encountered significant losses in the volcanic section, and was first side-tracked and eventually abandoned after problematic drilling through almost 1 km of basalt. Although the occurrence of lavas had been predicted, the thickness of the volcanics was grossly underestimated, and the well was abandoned without having penetrated the base of the volcanics (Morton et al. 1988). With hindsight and knowledge gleaned from the study of volcanic stratigraphy (e.g. Nelson et al. 2009; Davison et al. 2010; Ellefsen et al. 2010; Wright et al. 2012; Rawcliffe 2016), it is considered likely that the original well target was, in fact, a hyaloclastite delta rather than a sedimentary delta (Schofield et al. 2017b).

Although the 163/06-1A well failed to penetrate stratigraphy deeper than the volcanics, it is an interesting case study in UKCS collaboration between the public and private sectors. It was drilled in unlicensed acreage by a consortium of 19 companies and the then Department of Energy (DOE) (Morton et al. 1988; Hitchen et al. 2013), with the DOE and national oil and gas companies (British National Oil Corporation and BG Corporation) splitting 51% of the costs, and 49% apportioned between the remaining private sector companies. This unusual operational model permitted the (many) stakeholders to reduce their cost exposure and financial risk, increasing the ratio of value of information to exploration cost.

Late 1980s–early 1990s: pre-rift play

Following the disappointing 163/06-1A well, there was a hiatus in drilling activity in the UK Rockall. A second planned stratigraphic test well was never drilled and activity did not resume until 1988, which marked the start of the first proper phase of exploration in the basin. This period saw a (relative) burst of activity, with well 164/25-1Z drilled in 1988, 164/25-2 in 1990, and 132/15-1 and 132/06-1).
well to hint at the absence of a Jurassic source rock was 164/25-1Z, which was a test of the West Lewis Sub-basin. The well objective was Middle Jurassic deltaic sands but, instead, the well found Late Albian (latest Early Cretaceous) sandstones and mudstones lying unconformably on Permo-Triassic red beds, with the remainder of the Early Cretaceous and the Jurassic entirely absent.

Two years later, in 1990, well 164/25-2 tested the West Lewis Ridge, prognosed to be a pre-rift fault block capped by a Devonian–Jurassic sedimentary succession. Unfortunately, the well found Lewisian basement directly underlying the Paleocene lavas, with the pre-rift sedimentary succession being markedly absent. Similarly, 154/03-1 was drilled the following year, targeting Paleocene deltaic sands with a secondary objective of Jurassic and Early Cretaceous sands in the pre-rift succession of the West Lewis Ridge. However, the foresets identified on the seismic as the primary deltaic objective proved to be volcanic in origin, and beneath the thick volcanic succession a very thin (<2 m) Cenomanian interval capped a thick breccia of unknown age which, in turn, rested on Paleozoic-aged Basement.

Well 132/15-1, also drilled in 1991, targeted a pre-rift fault block on the eastern margin of the South Rockall Basin, with the expectation that the fault block would be capped by a Permo-Triassic–Jurassic sedimentary succession. Unfortunately, the well found crystalline basement without encountering pre-Cretaceous sediments, the results do not truly test the age of the basin fill due to their position on a structural high. Rather, they demonstrate that the West Lewis Ridge was either emergent and a site of non-deposition or that erosion had stripped the sedimentary cover by Late Cretaceous times. Wells 164/25-1Z and 132/15-1 require more discussion and are revisited later in this paper in order to discuss the possible reasons for the absence of the Jurassic.

Late 1990s–early 2000s: four-way dip closure and forced folds

Following the 154/03-1 well, there was another gap in exploration activity (for 6 years) with no further drilling in the UK Rockall until 1997, at which time the final phase of UK Rockall exploration was launched, with drilling operations commencing on licences awarded during the 17th UK Licensing Round.

The first well to be drilled during this final phase of exploration within the basin was the 164/07-1 well, which targeted a four-way dip closure in the Northeast Rockall Basin, interpreted to be a rollover anticline comprising a sequence of alternating sandstones and shales of Triassic–Cretaceous age. The well was, however, dry and found a thick volcanic sequence underlain by a heavily intruded and mud-prone Late Cretaceous section. Post-well analyses concluded that the structure was, in fact, a result of doming due to the inflation of an underlying laccolith, rather than being linked to extension (Archer et al. 2005; Schofield et al. 2017b, 2019), with significant implications for the timing of structuration.
After the drilling of 164/07-1, the primary focus of exploration in the UK Rockall shifted to the Paleocene plays, probably stimulated by the release of data from, and development sanction of, early to mid-1990s Paleocene discoveries in the FSB, such as Foinaven, Schiehallion and Loyal (Cooper et al. 1999; Leach et al. 1999; Austin et al. 2014; Loizou 2014), in addition to the recognition that Paleocene Vaila Formation sandstones of reservoir quality had been penetrated by the 164/25-1Z well. Unfortunately, only limited success was found during this phase of exploration, with the discovery of gas by the 154/01-1 Benbecula South well and the only evidence for oil in any of the UK Rockall wells found in the form of oil shows in the Vaila Formation of 164/28-1A. However, the wells drilled during this phase of exploration firmly established the presence of thermogenically-derived oil and gas, and the occurrence of reservoir-quality Vaila Formation sandstones in the Northeast Rockall Basin with wells 164/27-1 and 154/01-2, drilled in 2002 and 2006, respectively, also encountering the interval.

A common theme with wells drilled during this phase is that they targeted four-way dip closures. It was shown by Schofield et al. (2017b) that a number of these structures could be linked to underlying sill complexes and were potentially generated as forced folding (e.g. Möller Hansen and Cartwright 2006; Magee et al. 2014) in response to Paleocene intrusion. This interpretation is significant as it has implications for the relative timing of petroleum systems events. A solid understanding of the relationship between networks of sills and overlying forced folds may, furthermore, hold the key to understanding why the 154/01-1 Benbecula well found hydrocarbons whilst other forced folds, presumably generated at a similar time, were found to be dry (Schofield et al. 2017b).

**Reassessment of early exploration wells**

**164/25-1Z – questions raised about source-rock presence**

In a stratigraphic review of 164/25-1Z, Ebdon and Payne (1990) noted that the lack of Jurassic rocks, in conjunction with the absence of shows in the well, raised questions on ‘both the presence and effectiveness of a source in the immediate area’. However, Ebdon and Payne (1990) conceded that the evidence from this well, which is in a marginal location immediately adjacent to the West Lewis Ridge, cannot preclude the existence of source rocks.
of such rocks in the Rockall Basin proper nor even in deeper parts of the West Lewis Basin. In fact, the BGS borehole 88/01, drilled on the eastern margin of the West Lewis Basin at around the same time that 164/25-1Z was approaching TD, proved Middle Jurassic mudstones in the basin; whilst in 1990, shallow boreholes 90/02 and 90/05, also in the West Lewis Basin, found Middle Jurassic sandstones and mudstones, and Ryazanian (earliest Cretaceous) black shales, respectively. Subsequent analyses from these boreholes (Hitchen and Stoker 1993; Isaksen et al. 2000) have established that black shales from well 90/05 were equivalent to the Kimmeridge Clay Formation (KCF) of the North Sea, and that both the Middle Jurassic mudstones and the KCF-equivalent mudstones had good to excellent potential for generating oil or transitional gas to oil, with all samples yielding high total organic carbon (TOC) and potential yield, and intermediate–high hydrogen index. The results from these shallow boreholes are in contrast to those from 164/25-1Z. It is possible that either Jurassic rocks were once present across the West Lewis Basin and were stripped off by erosion prior to the Late Albian or that they were never deposited. Certainly, there is evidence in 164/25-1Z for erosion of Late Jurassic and, to a lesser degree, Middle Jurassic rocks based on reworked fossil assemblages (Ebdon and Payne 1990; Schofield et al. 2019) and mudstones (Fig. 8). However, the observed reworking occurs within the Late Paleocene Vaila Formation and, although there is also some reworking within this interval of Albian and Late Cretaceous fossil assemblages, no reworked Jurassic assemblages are found within the Cretaceous sequence of 164/25-1Z, suggesting that the Jurassic assemblages are derived from elsewhere in the basin, whilst in the vicinity of the well the period is represented by a hiatus. This evaluation is supported by the interpretation of seismic data carried out as part of this study (Fig. 9a), which suggests that the West Lewis Basin is divided into two Permo-Triassic half-graben. The more easterly of these saw a subsequent period of rifting activity, resulting in a synrift succession of Middle Jurassic–earliest Cretaceous, age as proven by the 88/01, 90/02 and 90/05 boreholes. In contrast, the western half-graben, encompassing the 164/25-1Z well, was either inactive until at least the Late Albian or Jurassic sediments were deposited, thickening towards the eastern bounding fault and subsequently stripped away from the western part of the sub-basin as the fault block tilted during further extension. This interpretation reconciles the results from both the exploration well and the shallow boreholes. It should be noted, though, that due to poor data quality, the interpretation is not of high confidence, as it cannot be readily mapped on all lines in the basin. Additional confidence is supplied, however, by depth-to-basement mapping from potential field data (Frogtech Geoscience 2016), which shows a north–south-striking basement high coincident with the fault separating the two sub-basins (Fig. 9b), suggesting that the West Lewis Basin is, indeed, composed of two separate sub-basins.

132/15-1 – missed crest of the pre-rift fault block

The primary objective of well 132/15-1, located in the South Rockall Basin, was to test the hydrocarbon potential of the pre-rift...
succession in a large tilted fault block. However, this well also found Early Cretaceous sediments, predominantly mudstones, directly above Lewisian basement. This could be construed to corroborate the results of 164/25-1Z and confirm that the Jurassic was a period of non-deposition in the UK Rockall. However, an alternative interpretation is provided in Figure 10, which shows an interpreted seismic line through the well, from the OGA 2015 survey. The tilted fault block penetrated by the well is clearly evident on the interpretation, and it can be seen that the well penetrated the bounding fault itself, failing to penetrate what is interpreted as a pre-rift sedimentary succession capping the fault block by c. 1.4 km to the SW. The observation in the post-well reporting that the basement was highly fragmented and fractured (Ebdon et al. 1992; Schofield et al. 2019) is consistent with our interpretation that this is a fault zone. Inspection of the pre-drill interpretation based on the seismic data available at the time (Fig. 10c) illustrates clearly that the target was missed because the structural interpretation differed significantly from that presented here (Fig. 10b). In the pre-drill interpretation faults apparently dip to the SE instead of the NW (Fig. 10b), and the surface that we interpret as a major fault (1 in Fig. 9b) was interpreted in the prognosis as the top of the pre-rift succession (1 in Fig. 10c). The nature of the interpreted pre-rift succession is, of course, unknown, other than that it must predate the Early Cretaceous synrift package that was penetrated by the well. Based on borehole and outcrop data from the Irish Rockall, the Sea of Hebrides and the Isle of Mull (Broadley et al. 2019), it could be any combination of Carboniferous, Permo-Triassic or Early–Late Jurassic. The absence of shows in the 132/15-1 well could indicate that the pre-rift succession in the vicinity of the well does not contain mature source rocks or, alternatively, it may be a symptom of the mudstone-dominated well stratigraphy, with any generated hydrocarbons bypassing the well location via more permeable lithologies.

**Basin modelling, hydrocarbon generation and occurrences in the UK Rockall**

The interpretation of geochemical data from the FSB to the north of the UK Rockall suggests that the primary source rock within the former is the Upper Jurassic–lowermost Cretaceous KCF (Doré et al. 1997a; Gardiner et al. 2019); whilst in the Hebridean basins immediately to the east, Middle Jurassic source rocks are widely documented (e.g. Thrasher 1992; Butterworth et al. 1999). There is evidence to suggest that similar rocks may occur at depth within the Rockall Basin, and this evidence is discussed below.

Whilst source rocks may be present, however, there is a great deal of uncertainty regarding their maturity and, in particular, the timing of maturity relative to trap formation. Vis (2017) identified a large slick cluster along much of the eastern margin of the Rockall Basin, between the Rosemary Bank and Anton Dohrn igneous centres (Fig. 1) and recently-released satellite seepage slick data (OGA CGG UKCS EEZ Seeps data 2019) show a correlation between slick centre points and faults mapped as part of this study (Fig. 11). These data may be an indication of active oil seepage. Published petroleum systems and basin modelling for the UK Rockall (e.g. Isaksen et al. 2001; Karvelas et al. 2016) suggests that charge from a buried Jurassic marine source rock is likely to have commenced post-deposition of Paleocene reservoirs and after trap formation.
However, it is important to note that, historically, models of hydrocarbon generation along the Northeast Atlantic margin have been shown to be troublesome and often incorrect. In the analogous FSB, which possesses a relatively large quantity of subsurface data and direct information to constrain source-rock intervals and sedimentary thicknesses, standard basin models predict early hydrocarbon generation, occurring during the Late Cretaceous, prior to reservoir deposition and trap formation in major fields and discoveries in the FSB (e.g. Lamers and Carmichael 1999). In this respect, if basin models had been adhered to in screening the FSB for prospectivity, the giant Paleocene Schiehallion and Foinaven fields that are estimated to hold >2 (Freeman et al. 2008) and 1.07 Bbbl in place (Carruth 2003), respectively, would be predicted to never have existed.

The quandary of timing was resolved initially by invoking the transient trapping of hydrocarbons in deep Cretaceous reservoirs, which were subsequently breached by hydrofracturing resulting from rapid burial and overpressure development (e.g. Iliffe et al. 1999; Lamers and Carmichael 1999) or by Cenozoic compression (e.g. Doré et al. 1997a). Carr and Scotchman (2003) showed that the onset of hydrocarbon generation could be delayed by sufficient overpressure development, suggesting that the KCF could still be mature for oil generation today despite being buried to a depth of 8 km. More recent studies have highlighted the thickening effects of

Fig. 10. Seismic line OGA 2015 L78 through well 132/15-1. (a) Uninterpreted and (b) interpreted data showing that the well penetrated the bounding fault of a pre-rift fault block, potentially missing a sedimentary pre-rift package capping the fault block. (c) Pre-drill interpretation (modified from Ebdon et al. 1992) of a similarly orientated seismic line through the planned 132/15-1 well location, illustrating the poor data quality available at the time, and the resulting significantly different interpretation; the exact line location is unknown. (d) Index map showing the location of (a) and (b). ‘A’ indicated in both (b) and (c) shows the same surface, interpreted in (b) as a fault and in (c) as the top pre-rift. Lt. Cretaceous, Late Cretaceous. Seismic data in (a) and (b) courtesy of the OGA.
Paleocene intrusives on the Cretaceous of the FSB (Schofield et al. 2017a; Mark et al. 2019), a critical period for petroleum systems development due to the deep burial of the Jurassic source rock thought to have occurred at this time (e.g. Doré et al. 1997a). Mark et al. (2019) estimated that up to 2000 m cumulative thickness of igneous material may be hosted within the Cretaceous section of the FSB. Subsequently, Gardiner et al. (2019) showed that within the FSB, the thickening effects and the long-term change of Cretaceous thermal properties resulting from intrusion, combined with more accurate representation of basement composition, could delay the onset of petroleum expulsion by up to 40 myr.

Similar overthickening of the Cretaceous sequence by intrusives is observed in the UK Rockall. For example, in well 164/07-1, c. 70% of the thickness of the Cretaceous actually comprised igneous material, emplaced during the Paleocene epoch (Schofield et al. 2019). Conversely, isotopic analyses of the Benbecula (154/01-1) gas suggest that the gas comprised oil-associated gas plus additional gas that may have been derived by oil-to-gas cracking (Goodwin 2000; Schofield et al. 2017b), an effect that may have been a result of heating by igneous intrusion. The implications of this are two-fold. First, that the accumulation was originally oil and, secondly, that cracking may originally have taken place in situ, or it may support earlier models of transient accumulations, with both cracking and remigration of hydrocarbons related to later intrusion. Karvelas et al. (2016) made steps towards incorporating intrusives into their 2D Rockall Basin model, which was based on the OGA 2015 seismic dataset, but they only considered the local heating effects of intrusions. In order to build upon these results, proper 3D seismic imaging of the Rockall sill complex and constraints on source-rock type and presence are required.

The preceding discussion illustrates how much variability can be produced in a basin model, based on the input data. We suggest, therefore, that in basins along the Atlantic margin, like the Rockall, where a dearth of subsurface data exists, great care must be exercised when making even a 1D basin model as this could be made to fit virtually any subsurface scenario of generation, based on a current lack of hard data.

Play elements

In this section we consider the elements required for a successful petroleum system by discussing a series of palaeogeography and present-day distribution maps for key intervals in the UK Rockall. The maps were constructed based on review and analysis of well,
borehole and outcrop data; regional data from the literature; and isochrons derived from the regional seismic interpretation carried out as part of this study (Broadley et al. 2019). For each interval, we consider the potential for reservoir, seal and source rocks. It should be noted that the emphasis is on evaluating the potential character of the Mesozoic of the Rockall Basin by looking at evidence from the seismic, and from regional borehole and outcrop data, and therefore these intervals are discussed extensively.

The Cenozoic section, which hosts the Benbecula discovery in Paleocene Vaila Formation reservoir sandstones, is considered to contain important reservoir intervals in the UK Rockall. However, it is relatively well represented by exploration wells, and a more extensive discussion of the Paleocene Vaila Formation play and the Early Eocene Colsay Member play is presented by Schofield et al. (2017b). Instead, we present a brief overview based on our new biostratigraphic re-evaluation.

**Permo-Triassic**

The Permo-Triassic was a time of widespread continental deposition, interrupted by episodes of marine ingress, across much of NW Europe (Doré 1992; Coward 1995; Benton et al. 2002) (Fig. 12). In Britain, alluvial–aeolian deposits of the Early–Middle Permian gave way to marine evaporites and carbonates in the Late Permian (Benton et al. 2002). This Late Permian transgression was followed by a return to predominantly fluvial–alluvial continental conditions during the Early Triassic. The Mid–Late Triassic is an overall transgressive succession with deposition in low-lying playa and sabkha environments punctuated by minor marine incursions and eventually conceding to marginal-marine conditions in the Latest Triassic (Rhaetian), a transgression that continued into the Liassic with the establishment of fully marine conditions (Coward 1995; Benton et al. 2002).

It is unclear how significant these events were in the UK Rockall due to limited dating resulting from poor fossil recovery within the succession and to the limited stratigraphy sampled by shallow boreholes, which provide much of the evidence for the distribution of the Permo-Triassic succession on the Hebrides Shelf and the UK Rockall. However, the periods of relative low sea level and of transgression are widely represented in other areas of the UKCS, such as the North Sea, controlling the deposition of the regionally-important reservoir–seal pairs of the Early–Late Permian Rotliegend and Zechstein groups, and the latest Permian–Triassic Sherwood Sandstone and Mercia Mudstone groups (e.g. Meadows and Beach 1993; Benton et al. 2002).

The Rotliegend–Zechstein reservoir–seal pair is significant in the Southern North Sea (SNS), in particular, with over 80% of production to end 2012 coming from this interval (Gray 2013). Rotliegend-equivalent sandstones are proven in the Irish Rockall, with Early Permian sandstones forming the deepest of the reservoirs in the 12/2-1Z Dooish discovery (Tyrrell et al. 2010). In the discovery well, however, Zechstein-equivalent strata are absent and the Early Permian reservoir is unconformably overlain by Middle Jurassic reservoir sands.

The Triassic-age Sherwood Sandstone, meanwhile, is a key reservoir interval in western UK and Irish offshore basins. Equivalent to the Early Papa and Heron groups (Fig. 6), it forms the principal reservoir interval in sizeable fields, such as the North and South Morecambe fields (combined gas initially in place (GIIP) of 6.7 Tcf) in the East Irish Sea Basin (Meadows and Beach 1993; Bastin et al. 2003; Cowan and Boycott-Brown 2003) and, in Irish

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**Fig. 12.** Permo-Triassic (a) palaeogeography and (b) present-day distribution maps for the UK Rockall; the inset box outlines areas where the Permo-Triassic is interpreted to have been thinned by extension.
waters, the Corrib Field (>1 Tcf GIIP) of the Slyne Basin (Schmid et al. 2004; Corcoran and Mecklenburgh 2005; Tyrrell et al. 2010). Strathmore, in the East Solan Basin located in the FSB is an oil discovery in Triassic-aged sandstones equivalent to the Sherwood Sandstone Group with an estimated 200 MMbbl oil in place (Herries et al. 1999; Morton et al. 2007). In the Donegal Basin, undifferentiated Permo-Triassic sandstones with log porosities in the range 10–20% were found to be overlying an interval tentatively dated as Zechstein equivalent (Odell and Walker 1979) and therefore might potentially be assigned to the Sherwood Sandstone Group equivalent. To the north, the 202/18-1 and 202/19-1 wells in the Papa Basin also proved a Permo-Triassic succession at least 2.9 km in thickness, consisting of a thick presumed Permo-Triassic succession, albeit with poor reservoir potential due to diagenesis (Macchi et al. 2007). In the Donegal Basin, the 202/12-1 well also found presumed Triassic fluvial sandstones, although they were found to have little reservoir potential due to diagenesis (Macchi 1995). Palaeomagnetic dating of the Stornoway Formation exposed on the Isle of Lewis is consistent with a Late Permian age to the Zechstein. Core and log porosities in 202/19-1 are noted to be up to 20%. In the Sula Sgeir Basin, the 202-12-1 well also penetrated a thick presumed Permo-Triassic succession, with fluvial deposits giving way to shallow ephemeral lakes, possibly indicative of subsidence associated with rifting.

Preservation of the Permian and Triassic of the Rockall Basin is difficult to address because of the poor seismic imaging beneath the volcanics. It remains speculative as to whether the entire succession is preserved or was, indeed, deposited in any given location. This is borne out by contrasting the stratigraphies of the 12/2-1Z and 12/2-2 wells that both targeted pre-rift fault blocks in the Irish Rockall; the former encountered only Permian strata, whilst the latter also found a thin veneer of Late Triassic rocks.

One area where it has been possible to pick out likely areas where the succession is thin or absent is that just to the east and SE of the Anton Dohrn Centre (Fig. 12), where the Basement to Base Cretaceous isochron from this study has been interpreted to represent a series of tilted fault blocks (Broadley et al. 2019). The pre-rift succession, including the Permo-Triassic and Jurassic sequences, is interpreted to be thin or absent in the footwalls of faults active during Cretaceous extension due to fault cut out and crestal erosion (Fig. 12). It is likely that other areas exist where the succession is absent or highly thinned due to Cretaceous extension but that these are not readily identified on currently available data.

**Early Jurassic**

The Late Triassic was a period of transgression (Hitchen et al. 1995; Stoker et al. 2016), leading to open-marine conditions that prevailed during the Early Jurassic (Morton 1989; Hesselbo et al. 1998; Hesselbo and Coe 2000). A palaeogeography map has not been constructed for the Early Jurassic of the Rockall Basin because, to date, Early Jurassic strata have not been penetrated by boreholes to
the west of the Hebrides, so no constraining data exist and the sequence cannot be identified within the pre-rift succession on seismic with any confidence.

The Early Jurassic is well represented by shallow boreholes and exploration wells in the Minch and the North Lewis basins, as well as in outcrop at Ardnamurchan, Movem, Skye, Scalpay, Raasay and Mull (e.g. Turner 1966; Morton 1989; Hesselbo et al. 1998). Together, these occurrences prove an overall transgressive Early Jurassic succession of Hettangian–Early Toarcian age in the Inner Hebrides (e.g. Morton 1989; Hesselbo et al. 1998), with a maximum proven thickness of at least 1.3 km in the Sea of Hebrides-1 well.

Of particular note is the occurrence of organic-rich shales of moderate to excellent source-rock potential within the Toarcian and Sinemurian–Pliensbachian in boreholes, exploration wells, and outcrop on Skye and in the Minch Basin. Source-rock evaluation of the Toarcian Portree Shale has yielded TOC values in the region of 3–7%, whilst values in the range 0.5–3.1% are noted in the Sinemurian–Pliensbachian Pabay Shale (Abernethy 1989; Thrasher 1992; Butterworth et al. 1999; Scotchman 2001; Schofield et al. 2016; Broadley et al. 2019). Based on outcrops on Skye and Raasay, reservoir potential within the Early Jurassic may lie within the Pliensbachian Scalpa Sandstone and the Hettangian–Sinemurian Upper Broadford Beds, which consists of sandstones and limestones (Morton 1989; Hesselbo et al. 1998; Hesselbo and Coe 2000). Respectively, these were deposited in a shelf environment and a nearshore marine setting (Morton 1989). In the Solan Basin, Early Jurassic sandstones and shales are found in wells 202/04-1 and 202/03a-3, in which a Pliensbachian–Hettangian-aged sequence of shallow-marine origin is proven. It should be noted, however, that the subsurface equivalents encountered thus far are not encouraging, either comprising unfavourable fine-grained facies (e.g. the Scalpa Sandstone in the Sea of Hebrides-1 and Upperglen-1 wells) or suffering from porosity occlusion due to diagenetic cements (e.g. the sandstone-dominated Broadford Beds in the Minch-1 well).

On the basis of the above observations, it is considered very likely that an Early Jurassic sequence is present in the UK Rockall, and that it contains source rocks and reservoirs, although reservoir quality may be a risk.

Middle Jurassic

The Middle Jurassic is widely distributed in the Inner Hebrides, both onshore and offshore, with the outcrops on the east coast of Skye and Raasay forming one of the most complete Middle Jurassic sections in the British Isles (Barron et al. 2012; Archer et al. 2019) (Fig. 14). Middle Jurassic source rocks of Bathonian and Aalenian age cropping out on Skye are shown to have good to excellent potential for the generation of oil and gas (Thrasher 1992; Vincent and Tyson 1999). Similarly good to excellent source rocks are found in the Aalenian–Bathonian section of the Upperglen-1 well (Pentex Oil Ltd 1989; Scotchman 2001; Schofield et al. 2016). At both outcrop and in the subsurface, the greatest potential is found within the Bathonian Cullaidh Shale and the Aalenian Dun Caan Shale. Critically, the occurrence of Middle Jurassic source rocks is noted in shallow boreholes to the west of the Hebrides, proving that the Middle Jurassic fairway was not confined to the Inner Hebrides basins. The 90/02 and 88/01 boreholes, located NNE of Lewis on the eastern margin of the West Lewis Basin (Fig. 14), found Bathonian organic-rich mudstones interpreted to have been deposited in a lagoonal to lacustrine environment. On the basis of these borehole observations and of seismic interpretation carried out as part of this study, it can be inferred that Middle Jurassic rocks may exist in the Rockall Basin (Figs 14 and 15).
Further north, in the Solan Basin and Rona Ridge area, up to 1.5 km of Middle Jurassic and older rocks were stripped off by peneplanation during the late Middle–early Late Jurassic (Booth et al. 1993). Observations from exploration wells constrain the size of this area on the present-day distribution map (Fig. 14). Where preserved, however, the Middle Jurassic sampled in Solan Basin wells is generally dominated by sandstones.

Middle Jurassic reservoirs remain unproven west of the Hebrides in UK waters, more likely as a function of sparse sampling rather than an actual absence of potential reservoirs. However, the upper
reservoir interval in the Doosh discovery in the Irish Rockall comprises Middle Jurassic fluvial–aeolian to estuarine sandstones (Tyrrell et al. 2010), thus establishing that there is potential for Middle Jurassic reservoirs in the Rockall Basin at large. Evidence from outcrop and well data from the Inner Hebrides suggests that there is reservoir potential at multiple levels through the Middle Jurassic, with a number of sandstone formations occurring within both the Aalenian–Bajocian Bearreraig Sandstone Group and the Bathonian Great Estuarine Group (Pentex Oil Ltd 1989; Hesselbo and Coe 2000; Schofield et al. 2016). Field observations from the Isle of Skye indicate large lateral variations in facies and thickness of the Bearreraig Sandstone, whilst the Great Estuarine Group has greater lateral uniformity of both facies and thickness (Morton 1989; Archer et al. 2019). The Bearreraig Sandstone of the Hebrides contains the thickest Jurassic sandstone succession of any onshore area of the UK and is considered to be an analogue for the Brent Group of the North Sea (Archer et al. 2019). If present in the UK Rockall, it may be an important reservoir interval.

In conclusion, it is likely that any Middle Jurassic section preserved within the pre-rift of the Rockall Basin has good potential for both reservoirs and source rocks.

**Late Jurassic**

In this study, the Late Jurassic is taken to span the interval from the Oxfordian to the earliest Berriasian. This period is largely equivalent to the deposition of the KCF of the North Sea, where deposition extends into the earliest Berriasian (Fraser et al. 2003).

Marine conditions are thought to have resumed to the West of Britain with the advent of the Late Jurassic epoch. This is supported by offshore wells and boreholes, and field studies in the Hebrides (Morton 1989). The palaeogeography map for this interval depicts the UK Rockall as a series of open-marine basins with the palaeo-Outer Hebrides landmass separating an Inner Hebridean seaway from an outer Rockall–Faroe–Shetland trend (Fig. 16).

Deposition in a restricted marine environment is documented in the West Lewis Basin (WLB) and the West Flannan Basin (WFB) by BGS boreholes 90/05 and 90/09, respectively, which found organic-rich shales of earliest Berriasian age, considered equivalent to the KCF and with excellent potential for hydrocarbon generation (Hitchen and Stoker 1993; Isaksen et al. 2000). These rocks are immature at the borehole locations but their presence west of the Hebrides has significance for the UK Rockall, where, if present, it is likely that the rocks have been buried to sufficient depth to reach maturity.

Similar organic-rich, oil-prone shales of earliest Berriasian age are found in a large number of wells in the West of Shetlands, including 202/08-1, 202/02-1 and the Lancaster discovery well, 205/21-1A. The Lancaster Field, with an estimated 1 Bbbl oil in place (Belaidi et al. 2018), is located on the Rona Ridge and is considered to have a KCF source, although it is most likely to be sourced by mature equivalents of the earliest Berriasian buried to sufficient depth in the basins either side of the ridge (Trice 2014) than by the source rocks sampled by the well, which are very thin and likely to be immature by virtue of their location on the Rona Ridge.

In the Solan Basin and on the Rona Ridge, reservoir potential is found in the shallow-marine Rona Sandstone member or the deeper-water turbiditic Solan Sandstone, which forms the main reservoir interval in the Solan Field (78 MMbbl oil in place), charged by oils from the KCF and with an average porosity of ≤27.5% and permeability of ≤185 mD (Herries et al. 1999). The Late Jurassic geology of the Solan Basin is echoed in the WFB, where BGS borehole 90/08 found shallow-marine sandstones assigned a Kimmeridgian–Oxfordian age (Hitchen and Stoker 1993; Isaksen...
The sandstones are roughly age equivalent to the Solan Sandstone and may represent a shallow-marine lateral equivalent. Their occurrence in the WFB is a very important data point, as it represents the most westerly occurrence of Jurassic rocks to the west of Scotland. Younger sandstones are also proven in the WFB by the 90/09 borehole, in which interbedded earliest Berriasian sandstones and mudstones were found to overlie the aforementioned organic-rich shales.

The two control points in the WFB suggest at least two episodes of coarse clastic input to basins west of the Hebrides during the Late Jurassic and earliest Cretaceous. It is envisaged that during this period, a sand-dominated marine shelf may have existed along much of the eastern margin of the Rockall Basin, fed by detritus shed from the Hebridean and Scottish landmasses (Fig. 16). Preservation of the Late Jurassic sequence in the UK Rockall, similar to that of the Permo-Triassic and Middle Jurassic, is uncertain and we propose a similar distribution to that of the Permo-Triassic, as the Late Jurassic largely post-dated the peneplanation event in the Solan Basin–Rona Ridge area (Booth et al. 1993).

Although Late Jurassic rocks remain unproven in the Rockall Basin, the borehole results can be correlated into the basin from the WLB and the WFB on seismic, albeit with varying degrees of confidence. If present, it is highly likely that the sequence contains both rich source rocks and potential reservoir sands.

**Early Cretaceous**

The Early Cretaceous palaeogeography map (Fig. 17) represents the main phase of rifting in the Rockall Basin and its development into a largely deep-water marine basin. The interpretation that the western half of the basin is shallower is based on the Cretaceous isochron, as are the outlines of the deep-water clastics and shelf sand facies bands.

Early Cretaceous sediments are penetrated by just two of the 12 UK Rockall wells. In the 164/25-1Z well, the top c. 177 m of the interval originally assigned entirely to the Permo-Triassic was subsequently found to be Late Albian in age (Plumb et al. 1989; Ebdon and Payne 1990). Ebdon and Payne (1990) interpreted a mid-shelf depositional setting for this section, which comprises red-brown calcareous mudstones, siltstones and sandstones that resemble Albian sediments described from exploration wells in the West of Shetlands area, such as 202/12-1, 204/30-1 and 205/26-1.

Well 132/15-1, in the South Rockall Basin, found a thick Albian–Barremian mudstone-dominated sequence, with fossil assemblages indicating a deep-water marine setting (Ebdon et al. 1992). The mudstone-dominated facies penetrated to date in the Early Cretaceous of the UK Rockall suggest that there is good sealing potential within this interval.

There is regional evidence for sandstones and limestones within the Early Cretaceous, indicating that there may be some reservoir potential in this interval. The 88/01 borehole in the West Lewis Basin found Barremian shallow-marine sandstones (Hitchen and Stoker 1993). The presence of both marine and terrestrial palynomorphs, and of primary carbonate and glauconite mud matrix with the sandstones (Hitchen and Stoker 1993), is indicative of a clastic-dominated continental shelf depositional environment in the West Lewis Basin at this time. Conversely, wells in the Solan and Sula Sgeir basins and in the Rona Ridge area provide evidence of a mid to outer carbonate shelf setting in the Late Berriasian and Barremian, becoming clastic dominated by the Aptian and Albian. The Albian section in 204/30-1 contained an 18 m-thick sandstone unit. In 202/12-1, bioclastic limestones of Late Berriasian–earliest Barremian age are found, although they are noted to lack visible porosity. IRL 12/13-1A in the Erris Basin found a predominantly clastic Lower Cretaceous sequence containing numerous thin
sandstones. Based on the evidence presented, it is considered likely that there is some reservoir potential in the Early Cretaceous of the UK Rockall, particularly in the Northeast Rockall Basin where marine shelf conditions may have prevailed.

It is anticipated that the Early Cretaceous interval is generally preserved throughout the Rockall Basin, although it may be condensed over the crests of fault blocks. The succession is considered to be absent in the Inner Hebrides, where the Early Cretaceous was a time of non-deposition or erosion due to basin inversion (Morton 1987); this is evident by the lack of Early Cretaceous sediments in boreholes and in outcrop in this area.

**Late Cretaceous**

The Late Cretaceous sequence is equivalent to the Shetland Group and is taken to extend from the Cenomanian to the Danian. In the FSB, the Late Cretaceous is interpreted to represent a continuation and intensification of Early Cretaceous rifting followed by an initial phase of post-rift subsidence by the latest Cretaceous (Dean et al. 1999; Doré et al. 1999; Larsen et al. 2011). Evidence from the Irish Porcupine Basin suggests post-rift subsidence from the Cenomanian onwards (e.g. Shannon et al. 1993; Johnston et al. 2001). In the UK Rockall, however, the timing of Cretaceous rifting and subsidence remains uncertain due to the poor seismic imaging and lack of well control (Doré et al. 1999; Hitchen et al. 2013), although Musgrove and Mitchener (1996) proposed that post-rift subsidence occurred from the Cenomanian onwards.

In the Northeast Rockall and South Rockall basins, the interval is interpreted to represent a bathyal setting (Fig. 18), with no shelf area proven adjacent to the West Lewis Ridge nor the eastern margin of the South Rockall Basin (132/15-1). However, the Northeast Rockall Basin wells that sample the Shetland Group (164/07-1, 164/27-1, 164/28-1A, 154/01-1 and 154/01-2) generally TD within the Maastrichtian or Late Campanian, so it is possible that a shelf environment may have prevailed on the margins of the basin during the early stages of post-rift subsidence but is not penetrated by the existing well stock. Further to the NW, wells from the West Lewis Basin through to the Sula Sgeir and Solan basins consistently confirm a mid- to outer-shelf setting.

Relatively speaking, the Late Cretaceous succession is well represented in UK Rockall wells, and is commonly entirely composed of mudstone with subordinate limestones and is commonly heavily intruded by igneous sills. These observations are consistent with observations from the West of Shetlands, where the Late Cretaceous is also well represented in the subsurface record. The abundant mudstones represent good sealing potential within the succession but are thought to have little generative potential as source rocks, based on the overall low TOC of Cretaceous rocks penetrated thus far in the Atlantic margin basins of the UK, Irish and Faroese continental shelves (Scotchman et al. 2016).

164/25-1Z and 132/15-1 are the only UK Rockall wells to have penetrated the base of the Late Cretaceous. In both wells, a relatively complete Cenomanian–Danian section is present (Ebdon and Payne 1990; Ebdon et al. 1992) and, although mudstone dominated, both show evidence of either coarse clastic input or carbonate deposition that could signal the presence of potential reservoirs within this succession. Well 164/25-1Z, found c. 62 m of interbedded Danian sandstone and shale, indicating coarse clastic input at least into the West Lewis Basin at this time. Meanwhile, the Late Cretaceous mudstones of 132/15-1 are interspersed with occasional thin sandstone and limestone interbeds that are generally of insignificant thickness. However, at the base of the section, Late Cenomanian limestones reach a thickness of c. 38 m and, whilst they are noted to have no visible porosity in cuttings, similar limestones within the
Cenomanian may present viable reservoirs if fractured or if secondary porosity has been developed. It is possible that sandstones and limestones may be present in marginal areas of the UK Rockall, representing lowstands within the overall pattern of Late Cretaceous transgression. Outcrop exposures of Cenomanian–Campanian shallow-marine sandstones and limestones on the isles of Skye, Raasay, Eigg and Mull, and on the Movern Peninsula of mainland Scotland (Braley 1990; Broadley et al. 2019), may be analogous to sandstone and limestone members that may be developed within the Late Cretaceous succession on the margins of, at least, the South Rockall Basin and may shed light on their reservoir potential.

**Paleocene–Early Eocene**

This is, arguably, with present knowledge the most important period for reservoir development in the FSB. Numerous sizeable oil and gas discoveries are hosted in sandstones of the Selandian (T22–T35) Vaila Formation, the Ypresian (T40–T45) Flett Formation and, to a lesser degree, the Thanetian (T36–T38) Lamba Formation (e.g. Loizou 2014). The UK Rockall wells, with the exception of 153/05-1 and 163/06-1A, all penetrate the base of the succession and prove the presence of rocks ranging in age from T32 to T50 (Fig. 3). The presence of reservoir rocks within this interval is therefore less speculative than that at earlier stratigraphic levels. The emphasis, therefore, of the work done on the Paleocene–Early Eocene was to improve upon the understanding of the interval by placing the wells within the T-sequence framework (Ebdon et al. 1995) employed in the FSB in order to better define which intervals had been penetrated and proven by each well. For full details of the biostratigraphic analyses conducted and the resulting well correlations, the reader is referred to Broadley et al. (2019).

The Vaila Formation is the only proven hydrocarbon play in the UK Rockall to date. It forms the reservoir interval in the 154/01-1 Benbecula gas discovery in the Northeast Rockall Basin, in which gas, which may have originated from thermally altered oil (Goodwin 2000; Schofield et al. 2017b), is trapped in a four-way closure that is most likely to have formed by the jacking up of strata above an igneous intrusion. However, although wells 154/01-1, 164/28-1A, 164/27-1 and 154/01-2 all targeted and found Vaila Formation sandstones of reservoir quality, belonging to sequences T34 and T35 and in similar four-way closures, 154/01-1 remains the only success case. It has been argued that sills underlying forcing folds may act as baffles or barriers to hydrocarbon migration, diverting hydrocarbons away from some structures, whilst channelling them into others (Rateau et al. 2013; Schofield et al. 2016, 2017a, b). In order to build upon previous basin-modelling work for the UK Rockall (Isaksen et al. 2001; Karvelas et al. 2016) and begin to predict migration patterns, however, 3D seismic data are required, with acquisition parameters and processing designed to improve sub-basalt imaging. This approach has been successful in the FSB, where Mark et al. (2018) were able to carry out detailed mapping of intrusions of the Faroe Shetland Sill Complex on reprocessed 3D data optimized for sub-basalt imaging (Schofield et al. 2017a).

Based on the new biostratigraphic analyses carried out as part of this study, the T36–T38 Lamba Formation is recognized in wells 132/06-1, 132/15-1, 153/05-1, 154/01-1, 154/01-2, 164/27-1 and 164/28-1A (Broadley et al. 2019). In the FSB, the Lamba Formation forms the reservoir interval in a number of discoveries (Loizou 2014). However, in the UK Rockall wells, the formation documents a period of sequence T36 rift flank volcanism, with a series of hyaloclastite deltas prograding westwards from the eastern margin of both the Northeast and South Rockall basins. As a consequence, the sequence comprises volcanic and shale-dominated lithologies, and reservoir potential within the Lamba Formation remains unproven. It does, however, provide an important intra-Paleocene seal, as demonstrated by the 154/01-1 Benbecula discovery in which the hyaloclastites and shale that provide the seal are shown to be of Lamba Formation age (Broadley et al. 2019).

The 164/25-2 well penetrated a 150 m-thick sandstone package, sandwiched between two lava units and assigned to the Lamba Formation at the time of drilling. However, Schofield et al. (2017b) presented evidence that the interval should be assigned to the Colsay Member of the T40 Flett Formation, which forms the reservoir interval in the Rosebank discovery in the FSB. Whilst the Colsay sands in 164/25-2 were water-bearing, they were found to possess excellent reservoir properties, with porosities of up to 34% and multi-Darcy permeabilities. Based on seismic data, Schofield et al. (2017b) correlated the interval with a volcaniclastic package immediately overlying the Cretaceous package in 164/07-1. This interpretation is substantiated by reinterpretation of the 164/07-1 biostratigraphy conducted as part of this study, which indicates that a thin clastic interval between the volcanics and the Late Cretaceous Shetland Group can be assigned to the T40 Colsay Member (Broadley et al. 2019). Whilst the lithology encountered in well 164/07-1 is non-reservoir, this result is important because it confirms that the top of the intra-volcanic package can be recognized on the seismic data.

**Discussion**

**UK Rockall Potential Play Elements: a summary**

Based on the evidence presented thus far, it is clear that the source, reservoir and seal elements required for a successful petroleum system are likely to exist at multiple levels in the UK Rockall (Fig. 19); and the challenge remains to detect where they occur, particularly where source rocks are mature, and how Paleogene sills may have affected hydrocarbon generation and migration. Reservoirs and seals are proven within the Paleocene–Early Eocene megasequence, and are shown to be equivalent to those found in a number of fields in the FSB. Sandstone reservoirs are also likely to exist within the Permo-Triassic, Early, Middle and Late Jurassic, Barremian, Albian, and Danian, whilst carbonate reservoirs may be present within the Cenomanian of the South Rockall Basin. Sealing potential is not seen as a risk, as all proven successions contain intra-formational shales of significant thickness, with hyaloclastites and lavas added to the sealing potential within the Paleocene–Early Eocene megasequence. Potential source rocks are most likely to be of Early, Middle and Late Jurassic age. These elements are summarized in Figures 20 and 21. A variety of trapping geometries may be present: for example, in the form of tilted fault blocks, stratigraphic pinchouts, fault juxtapositions, truncation, forced folding and Cenozoic compression folding.

However, what is equally clear is that much of the evidence for play elements comes from regional observations and inferences. In fact, the only proven elements are reservoirs and seals within the Paleocene and Eocene. Even the Late Cretaceous is only penetrated in its entirety by two wells, from which we cannot extrapolate to the entire basin. Older elements, particularly the pre-rift succession (Permo-Triassic–Late Jurassic), remain highly speculative in the absence of additional well data and an accurate evaluation of source-rock maturity is, we would argue, presently near impossible to conduct successfully.

It is important to note that, although this study has focused on the potential occurrence of Permain and younger rocks, regional evidence from the Irish Rockall (IRL 12/02-1Z and 12/02-2) and from the FSB (e.g. Clair Field) shows that Carboniferous rocks also occur to the West of Britain and Ireland, and there is potential for Carboniferous source rocks and reservoirs to be present in the UK Rockall.
Comparison with the UK North Sea exploration – how many wells are needed to know if a basin is prospective?

The question of whether 12 exploration wells within the UK Rockall is enough to establish if the basin is prospective or non-prospective is open to debate. However, a comparison that can be drawn when evaluating the prospectivity of any part of the UKCS is to the early history and exploration narrative which underlies the world-class North Sea basins, which took considerable investment and drilling before the first commercial oil discovery was made.

The notion that the North Sea might host hydrocarbon resources was born after the discovery of the giant Groningen gas field in the South Permian Basin, onshore Netherlands in 1959 (Stäuble and Milius 1970; Kemp 2012). Groningen comprises a Lower Permian Rotliegend reservoir, sealed by Zechstein evaporates and sourced by Pennsylvanian (Carboniferous) coals (Cook 1965; Stäuble and Milius 1970). By the time of its discovery, onshore evidence from the UK and continental Europe (Kent 1949; Bentz 1958; Visser and Sung 1958) already indicated that the Permian geology of these regions was similar, and there would have been reasonable confidence that this geology was replicated in the SNS. This was confirmed by early gravity and seismic refraction studies in the North Sea, and, despite the shallow water and the presence of salt, it was possible to map the top and base Permian on early seismic reflection data (Cook 1965); so already, arguably prior to drilling, North Sea explorers were able to identify key play elements and understand some of the broad basin stratigraphy far more effectively than was possible in the UK Rockall prior to the first wells drilled in the basin.

In the first year of North Sea exploration, 1965, 10 wells were spudded in water depths averaging c. 33 m, all within the SNS. These initial wells resulted in four gas discoveries, three of which went on to become producing gas fields, opening up the SNS Rotliegend play (Gage 1980; Hillier and Williams 1991; Winter and King 1991; drilling data obtained from the UK National Data Repository https://ndr.ogauthority.co.uk). The drilling rate accelerated over the next few years with continuing high success rates, and exploration was expanded northwards into the Central North Sea (CNS) and the Moray Firth, but it wasn’t until 1969 that the 158th well to be spudded across the SNS and CNS found the first commercial oil accumulation, now known as the Arbroath Field, in CNS Block 22/18 (Kemp 2012). A huge number of wells were drilled before the first commercial oil discovery was made, despite the better-quality seismic data and the ever-increasing well datasets. Whilst it could reasonably be assumed that seismic data quality today is of far better quality than that on which the early North Sea wells were drilled, we argue that current data quality in the Rockall Basin is commonly comparable to this early
North Sea data due to the pervasive volcanics present within the subsurface.

In contrast, when the number of UK North Sea wells drilled to find commercial oil is compared with the exploration history of the UK Rockall (which is the same size as the SNS, CNS and NNS combined), it can be said with some degree of certainty that the latter has not been adequately tested by the 12 wells drilled to date, particularly as only seven of these are considered to be valid tests of the basin (Schofield et al. 2019) and of these, one well reached TD in the late Paleocene and only one well, 164/25-1Z, penetrated below the late Campanian. Interestingly, until the discovery of the Clair Field in 1977, 14 wells were drilled in the analogous FSB without a single discovery. Furthermore, the first well in the basin drilled within the current outline of the Clair Field but missed the accumulation.

Fig. 20. Potential sites for a stratigraphic test well in the Northeast Rockall Basin. (a) Location map, showing locations of (b)–(d) superimposed on the Base Cretaceous Unconformity horizon and faults, both from this study; blue/purple/pink indicates greater depth. (b) OGA 2015 Line 16 passing through Site 1. (c) TWT closure at the Base Cretaceous Unconformity level close to Site 1; the contour interval is 50 ms. (d) OGA 2015 Line 32 passing through Site 2.
Where next for the UK Rockall?

In conclusion, we have argued that a decision cannot yet be made regarding the prospectivity, either positive or negative, of the UK Rockall, as the wells drilled thus far have failed to establish the basin stratigraphy and the sub-basalt seismic imaging is generally too poor to constrain the deep structure of the basin. For these reasons, the basin’s rifting history remains unknown, with rifting episodes prior to the Early Cretaceous remaining unconstrained by well control, despite regional evidence which suggests that Permo-Triassic and Jurassic rifting is likely to have occurred. Furthermore, the fact remains that the UK Rockall remains a high risk but, potentially, a high reward basin to enter – in addition to the geological risk, operating conditions are harsh, water depths and distance to shore can be excessive, and there is no existing infrastructure. All of these factors combine to dictate that any discovery must be of a substantial size, and likely be oil, in order to be deemed commercial. For seismic acquisition contractors, the
impetus to conduct a speculative 3D survey is driven by the perceived appetite (or lack thereof) for exploration, and thus a vicious circle of lack of exploration confidence due to a lack of data continues. So, how to break the deadlock?

In order to increase industry confidence, it is imperative to properly constrain the full basin stratigraphy and, by extension, its structural evolution. This can only be achieved by exploratory drilling. Although seismic data quality in the UK Rockall is still poor, we suggest that it is now of sufficient quality and coverage to identify a number of suitable well locations to test the basin’s full stratigraphy. Moreover, we propose that the time is now ripe for a government–industry collaboration in order to drill one or more stratigraphic test wells, similar to the model employed in drilling the 163/06-1A well in 1980 in the North Rockall. This modus operandi permitted the individual stakeholders to spread the financial risk of the well, so that it was possible, in theory, to conduct an extensive data acquisition programme at very low individual stakeholder cost, whilst retaining full access to all the valuable subsurface data.

Three locations (Figs 20 and 21) have been identified as potential sites for a stratigraphic test well, each with their advantages and disadvantages. Site 1 (Fig. 20) is located in the northernmost part of the Northeast Rockall Basin, close to the Wyville-Thomson Ridge. Our interpretation below the top Cretaceous in this area delineates a number of pre-rift fault blocks capped by a pre-rift succession and overlain by wedge-shaped synrift packages. The eastern end of the seismic line shows the pre-rift succession of the West Lewis Basin, where rich source rocks of Middle and Upper Jurassic age are proven but immature. Seismic data quality is reasonable in this area and there is a good chance that the pre-rift geology observed in the West Lewis Basin is repeated at depth within the pre-rift fault blocks. The pre-rift is also at sufficient depth to increase the likelihood of any source rocks being mature and not post-mature. The top of Fault Block A can be mapped as a structural closure, even on the widely spaced 2D data currently available. However, in our view, targeting Fault Block A in a downdip position, rather than testing the closure in the first instance, would have the greatest benefit from the perspective of constraining the pre-Late Cretaceous stratigraphy, as this is where the pre-rift and synrift successions are observed to be thickest, where there is a lower chance of erosion of the pre-rift succession, and therefore a greater chance of preservation of the complete succession. Another advantage of this site is that it gives the opportunity to evaluate the T40 (Late Paleocene–Early Eocene) Colsay Member, which is correlated on the seismic from 164/25-2 and is a fairly clear pick (Fig. 15). Penetrating this unit to determine the nature of the Colsay Member and whether it is elastic or volcanic would aid in any future delineation of the Colsay play fairway. The disadvantages of this site are that the Late Paleocene succession is most likely thin or absent, based on the seismic data, and the results of wells 164/07-1 and 163/06-1A. The Late Cretaceous, based on our interpretation, is also likely to be incomplete. However, wells further to the south have already proven the Late Paleocene succession, and more limited information on the Late Cretaceous is also available from the 164/25-1Z and 132/15-1 wells.

Site 2 (Fig. 20) is located close to the Benbecula discovery well. This is a low-risk option, as a working petroleum system has already been proven here and operational learnings from the 154/01-1 well could be applied to streamline the planning process. The purpose of the well would be to establish the pre-Paleocene stratigraphy and identify the source rock. Issues with this well location, however, are that it is in currently licensed acreage and that it has less potential to yield new information, as it is already known that Benbecula hydrocarbons are most likely to have originated from a marine source rock (Klingelrad 2005). A cheaper alternative might be to re-drill the Benbecula well itself, if this could be done safely and without compromising the objective of testing the deep, pre-rift stratigraphy.

The final location, Site 3 (Fig. 21), is in the South Rockall Basin, where a complex series of pre-rift fault blocks, similar in form to the Irish Dooish discovery (well IRL 12/02-1Z), can be mapped on the seismic. Targeting one of these structures could establish the extension of the proven geology of the Irish Rockall into UK waters. Water depths here are substantial; however, 132/06-1, close to the proposed drilling location, was drilled to a TD of 4370 m in water depths close to 1900 m, with drilling activities taking 27 days and completion a further 10 days. The top of the pre-rift at the proposed location is slightly shallower than TD of 132/06-1 and at a similar depth in two-way time (TWT) to the Dooish discovery. As with Site 1, a slightly downdip position might ensure penetration of a more complete pre-rift succession. A risk at this location is that it can be argued that any well drilled here may only constrain the pre-rift geology very locally. Comparison of the results from IRL 12/02-1Z (Dooish) and IRL 12/02-2 (Dooish West), located just 7 km apart, demonstrates that the pre-rift stratigraphy of these wells varies significantly, most likely due to complex and highly localized pre-Cretaceous rifting, with the Permian succession penetrated in 12/02-1Z absent in 12/02-2, whilst the Upper Jurassic found in 12/02-2 is not represented in 12/02-1Z.

Our preferred location is Site 1, as we believe that this location offers the highest value of information and could open up an area that has greater potential for commercial success by virtue of its proximity to shore. However, all three sites offer potential to improve our understanding of the pre-Cretaceous evolution of the UK Rockall. It should be noted that a limited amount of speculative 3D seismic data are available in the basin and that the three suggested stratigraphic test well locations each fall within the area of one of these surveys. Whilst the data vintage is around 20–25 years old, a logical first step towards any well planning might be to licence and apply modern reprocessing techniques to one or more of these surveys, similar to those applied by PGS on the Faroe–Shetland Basin (FSB) MegaSurvey Plu. This delivered a substantial improvement in the imaging of the Base Cretaceous Unconformity and of the Paleogene sills (Schofield et al. 2017a; Mark et al. 2018), both of which are important uncertainties that need to be captured for both well-planning and basin-modelling purposes. The interpretation of these data is seen as a step in the decision process on any proposed well location.

It is recognized by the authors that drilling a new stratigraphic test well in deep water and in the challenging conditions of the Northeast Atlantic margin will always be a costly and bold endeavour, and that full technical and commercial justification would be required for any such enterprise. In reality, it is likely that at least part of this justification must come from work done in the more mature, analogous, FSB, where 3D seismic and good well coverage (spatially and stratigraphically) are available. Ongoing research in the FSB is underway to model the impact, or lack thereof, of igneous intrusions upon hydrocarbon migration. If this work can be used to reproduce known accumulations within the basin model, and then be carried forward to successful exploration, this would provide a strong justification for the acquisition of additional data in the UK Rockall, whether this be in the form of 3D seismic or a stratigraphic test well, in order to identify and de-risk prospects with a strong likelihood of hydrocarbon charge.

As the UK transitions to a green future, hydrocarbons, in particular gas, will still need to be an essential part of the energy mix, in particular for electricity generation to enable fuelling of transition to electrified infrastructure. Relying on gas imports degrades the UK’s ability to enable its energy security. In relation to Rockall, a clear forward strategy needs to be developed by government and industry to decide if the area will (or will not) play a part in the future of the UK’s energy and hydrocarbon demands.
Conclusions

On the basis of the work presented in this paper, we conclude that:

- The information available from the existing database of 12 wells in the UK Rockall is insufficient to determine whether or not the basin is prospective.

- Reservoirs are proven within the Paleocene–Early Eocene of the UK Rockall. Whilst the Early and Late Cretaceous successions have been penetrated by UK Rockall wells, their characteristics are not well constrained, as the well evidence is patchy and incomplete. The presence of any rocks older than the Early Cretaceous remains speculative; however, we draw on regional evidence and our new seismic interpretation to demonstrate that there is a strong likelihood that Permio-Triassic and Jurassic rifting occurred in the UK Rockall. It is probable that the associated rock record contains reservoir, seal and, in the case of the Jurassic, restricted marine source rocks, as evidenced by neighbouring basins, such as the Faroe–Shetland Basin and the Inner Hebrides Basin.

- We propose that in order to reboot exploration in the UK Rockall, a bold and different approach must be applied in order to establish the basin’s tectonostratigraphic evolution. We suggest that a government–industry collaboration to drill one or more stratigraphic test wells might succeed in obtaining the requisite information whilst reducing overall risk for the individual stakeholders.

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Author contributions

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JS: conceptualization (supporting), writing
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L.B: data curation (lead), formal analysis (lead), writing – original draft (lead); NS: conceptualization (lead), formal analysis (supporting), project administration (lead), supervision (lead); writing – original draft (supporting), writing – review & editing (lead); DJ: conceptualization (supporting), formal analysis (supporting), supervision (supporting), writing – review & editing (supporting); J.H: conceptualization (supporting), supervision (supporting), writing – review & editing (supporting); J.R.U.: writing – review & editing (supporting).
