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Strike-slip influenced stratigraphic and structural development of the Foula Sandstone Group, Shetland: implications for offshore Devonian basin development on the northern UK continental shelf

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Abstract: The island of Foula, located 25 km SW of Shetland, preserves a gently folded, 1.6 km thick sequence of Middle Devonian sandstones spectacularly exposed in kilometre-long cliff sections >350 m high. These rocks unconformably overlie likely Precambrian-age amphibolite facies basement rocks that are intruded by sheeted granites. The onshore succession is similar in age to the nearby Lower Clair Group offshore to the west. New mapping, incorporating the use of drone imagery in the inaccessible cliff sections, uses down-plunge projections to show that growth folding and faulting on Foula were contemporaneous with sedimentation during basin filling. The large-scale structural geometry is consistent with the regional constrictional strain due to the sinistral transtension associated with movements along the Walls Boundary–Great Glen fault zone system during the Mid-Devonian. Detrital zircon provenance studies indicate that the Devonian sequences of Foula (and nearby Melby in western Shetland) show similarities with the Clair Group and Orkney successions. We suggest that NE–SW transtensional fold development contemporaneous with regional subsidence in the Devonian basins of Scotland may be more widespread than previously realized. Large, kilometre-scale folds previously interpreted to be related to Permo-Carboniferous inversion may therefore have initiated earlier in the basin evolution sequence than previously realized.

Supplementary material: Appendices A, Methodologies; B, Regional stratigraphic correlation table; C, Heavy mineral data; D, Detrital zircon data; and E, 3D virtual outcrop models are available at https://doi.org/10.6084/m9.figshare.c.6442552

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Onshore 'analogue' outcrops of strata are commonly studied during hydrocarbon exploration in offshore settings to better understand the stratigraphic, sedimentological and structural character of potential or actual reservoir units in the subsurface (e.g. Tamas *et al.* 2022). These rocks are typically deemed to be equivalent based on similarities in their age, proximity or geological character. The Clair Field (Fig. 1a, c), located 75 km west of Shetland, is the largest known hydrocarbon resource on the UK continental shelf, with a closure of *c.* 250 km^2 and an estimated 7–8 billion barrels of oil equivalent in place (Witt *et al.* 2010; Ogilvie *et al.* 2015). It comprises naturally fractured Devonian–Carboniferous sandstones of the Clair Group, which unconformably overlie an up-faulted ridge of fractured Precambrian (Neoarchean) metamorphic basement (Coney *et al.* 1993; Holdsworth *et al.* 2019*a*) (Fig. 1c). The Devonian sequences that crop out in mainland Scotland and Orkney are widely used as analogues for the Clair Group, but lie >200 km to the south.

This paper details the stratigraphy, provenance, structure and tectonic evolution of little-studied Devonian rocks that unconformably overlie a ridge of Precambrian metamorphic basement on the island of Foula. These outcrops lie <70 km SE of the Clair Field and, given their proximity and the close similarities in their scale (see Fig. 1a, inset), geology and structural setting, we explore whether these outcrops might be used as an onshore analogue for the Devonian rocks in the Clair Field. We also show that the structural development of the Foula basin-fill shares common features with the transtensional Devonian basins of Shetland and western Norway. This implies that existing tectonic models for the development of offshore Devonian basins around Scotland may require revision and reappraisal.

Regional framework

The Orcadian and Clair basins belong to a series of Devonian continental sedimentary depocentres that formed in the North Atlantic region (Friend 1981; Friend *et al.* 2000) following the collision of Laurentia, Baltica and Avalonia and the subsequent collapse of the Caledonian mountain belt (Fig. 1b). Several kilometres of siliciclastic sediments and smaller volumes of volcanic rocks were deposited in a series of rift basins from the

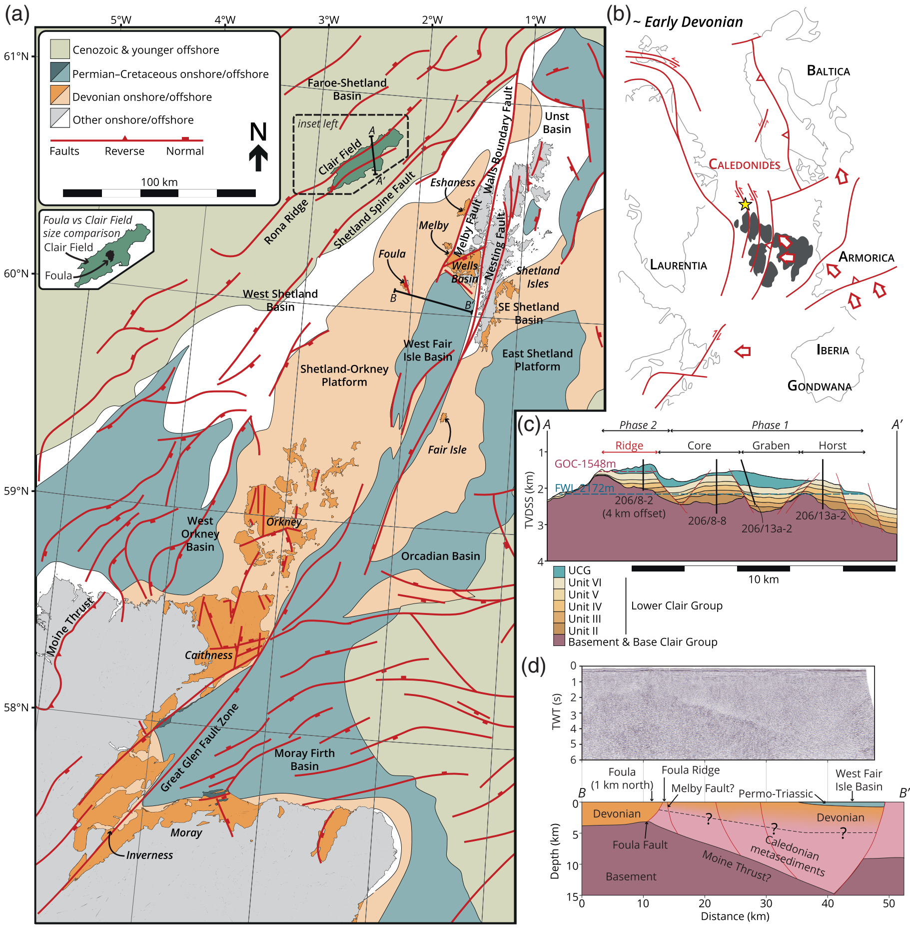

Fig. 1. (**a**) Regional map of the Orcadian Basin study area highlighting the Clair Field. Inset shows a simple map comparing the known extent of the Clair Field (green) in comparison with the size of the island of Foula (black). (**b**) Devonian palaeogeography and simplified reconstruction of the North Atlantic region; the approximate location of Shetland is shown by the yellow star. (**c**) North–south cross-section through the Clair Field; location of section shown in part (a). (**d**) WNW–ESE seismic reflection section (upper panel) and interpretation (lower panel) through the Foula Ridge and West Fair Isle Basin; location of section shown in part (a). Source: part (a) modified after Dichiarante *et al.* (2016) and Oil and Gas Authority (2019); part (b) modified after Dewey and Strachan (2003); part (c) modified after Barr *et al.* (2007) and Ogilvie *et al.* (2015).

late Silurian to early Carboniferous in eastern Greenland, northern Scotland and western Norway (Friend *et al.* 2000).

The Orcadian Basin occurs both onshore and offshore in the Shetland, Orkney, Caithness and Moray Firth regions of NE Scotland (Fig. 1a). In mainland Scotland, Lower Devonian synrift alluvial fan and fluvial–lacustrine deposits are mostly restricted to the fringes of the Moray Firth region (Rogers *et al.* 1989; Tamas *et al.* 2021) and parts of Caithness (Holliday *et al.* 1994), occurring in a number of small fault-bounded basins. These are partially unconformably overlain by Middle Devonian synrift alluvial, fluvial, lacustrine and, locally, marine sequences that dominate the onshore sequences exposed in Caithness and Orkney (Marshall and Hewett 2003). Upper Devonian post-rift fluvial and marginal aeolian sedimentary rocks (Friend *et al.* 2000) are only found as small fault-bounded outliers in Caithness and Orkney.

The north–south-orientated Shetland Islands, part of the extensive Shetland Platform (Fig. 1a), predominantly comprise highly deformed and metamorphosed Precambrian rocks (Mykura *et al.* 1976*a*). These were intruded by a suite of granitic plutons and associated volcanics during the Ordovician–early Devonian Caledonian Orogeny and were later flanked and overlain by Mid-Devonian (Mykura *et al.* 1976*a*) and later Mesozoic sedimentary basins, which now lie predominantly offshore. The Shetland archipelago is cut by large, subvertical strike-slip faults initiated during the Caledonian Orogeny, including the Walls Boundary Fault (WBF), the proposed northward continuation of the Great Glen Fault (Fig. 1a; Flinn 1979, 1992; McGeary 1989; Ritchie and Hitchen 1993; McBride 1994; Watts *et al.* 2007). The exact amount of strike-slip motion along the WBF and associated structures has been a topic of debate, but is generally accepted as being in the region of several tens or hundreds of kilometres of sinistral motion during the Silurian–Devonian, followed by subsequent dextral motion of 20–30 km during the Carboniferous and Permian and a further 15 km in the Mesozoic (Watts *et al.* 2007; Armitage *et al.* 2021). To the west of the Melby Fault, Devonian sedimentary and volcanic rocks are exposed at Melby, Eshaness and on the islands of Foula and Papa Stour (Fig. 1a). They are juxtaposed to the east against thermally mature and more deeply buried and folded Devonian sedimentary and volcanic rocks that form a large part of the Walls Peninsula (Melvin 1985), into which granites are emplaced, bounded to the east by the WBF. East of the Nesting Fault, in the SE Shetland Basin, Devonian sedimentary rocks are exposed in a strip along the eastern coast from Lerwick to Sumburgh Head, on nearby offshore islands and, further to the south, on Fair Isle (Fig. 1a).

The Clair Basin lies on the eastern margin of the Mesozoic–Cenozoic Faroe–Shetland Basin, forming a large half-graben flanking an up-faulted NE–SW-trending ridge of Precambrian basement: the Rona Ridge (Fig. 1a; Ritchie *et al.* 2011; Holdsworth *et al.* 2019*b*). Blackbourn (1987) termed the Devonian–Carboniferous basin-fill the Clair Group. This succession is both faulted against, and unconformably overlies, the Precambrian basement and both of these are overlain by Cretaceous marine mudstones of the Shetland Group, which form a regional seal (Fig. 1b). The Devonian–Carboniferous fill records a general upwards increase in sediment maturity from basal alluvial fans, through mainly braided streams in the Lower Clair Group (Mid- to Upper Devonian) and up into the higher sinuosity rivers and lake deposits of the Upper Clair Group (Lower Carboniferous) (Allen and Mange-Rajetzky 1992; Schmidt *et al.* 2012).

Geology of Foula

The 13 km^2 island of Foula (Fig. 2) lies 25 km SW of Shetland and *c.* 70 km SE of the Clair Field (Fig. 1a). A 1.6 km thick sequence of gently folded and fractured continental clastic deposits unconformably overlies, and is locally faulted against, fractured metamorphic basement and granite, which are exposed on the low-lying eastern side of the island (Mykura *et al.* 1976*a*, *b*) (Figs 2, 3a, b). Foula lies at the southern end of the Foula Ridge, one of several NE–SW-trending basement structural highs in this region (BGS 1988). The Foula Ridge forms a positive gravitational anomaly and a positive topographic feature on geophysical and bathymetric surveys and in regional 2D seismic reflection data (Fig. 1d). It is bounded to the west by the Foula Fault, which may truncate or link to the Moine Thrust at depth (Figs 1d, 2). Andrews (1985) postulated that the northwards continuation of the Moine Thrust Zone subcrops to the west of Foula and continues north, passing to the east of Ve Skerries, where supposedly Lewisian-type basement is exposed. To the east of Foula, the Melby Fault forms a relatively steep structure with little vertical offset of reflectors within the West Fair Isle Basin, which is bounded to the east by the WBF (Fig. 1d).

Mykura *et al.* (1976*a*) suggested correlation of the sedimentary rocks of Foula with the Old Red Sandstone (Devonian) succession observed on mainland Shetland at Melby (Fig. 1a). The most recently published regional correlation confirms this linkage and assigns an Eifelian age to the Foula and Melby successions (Marshall and Hewett 2003). They are slightly older than the Devonian rocks of the Walls and SE Shetland basins (Marshall and Hewett 2003) and probably equivalent to the Lower Clair Group (Fig. 1a), which, on the basis of wells drilled in the Clair Field, accumulated during the Givetian to Frasnian or later (Allen and Mange-Rajetzky 1992). However, these authors report abundant sporomorphs of late Eifelian to early Givetian age within a Kimmeridgian conglomerate penetrated in well 206/5-1, drilled a little to the north of the Clair Field, indicating that deposition of the Devonian in the area had commenced by the Eifelian and so may overlap with that of Foula. Despite the slight age difference, it has been long recognized that the sandstones on Foula are a suitable analogue to those of the Clair Group based on their proximity and the similarity of the predominantly fluvial sedimentary sequences (Blackbourn 1981*c*). To date, no comprehensive account of the sedimentological, stratigraphic or structural evolution of Foula has been published.

Geological mapping of the island by Blackbourn (1981*c*) at a scale of 1:10 000, building on earlier work by Mykura *et al.* (1976*b*), has been revised by Blackbourn to create the new

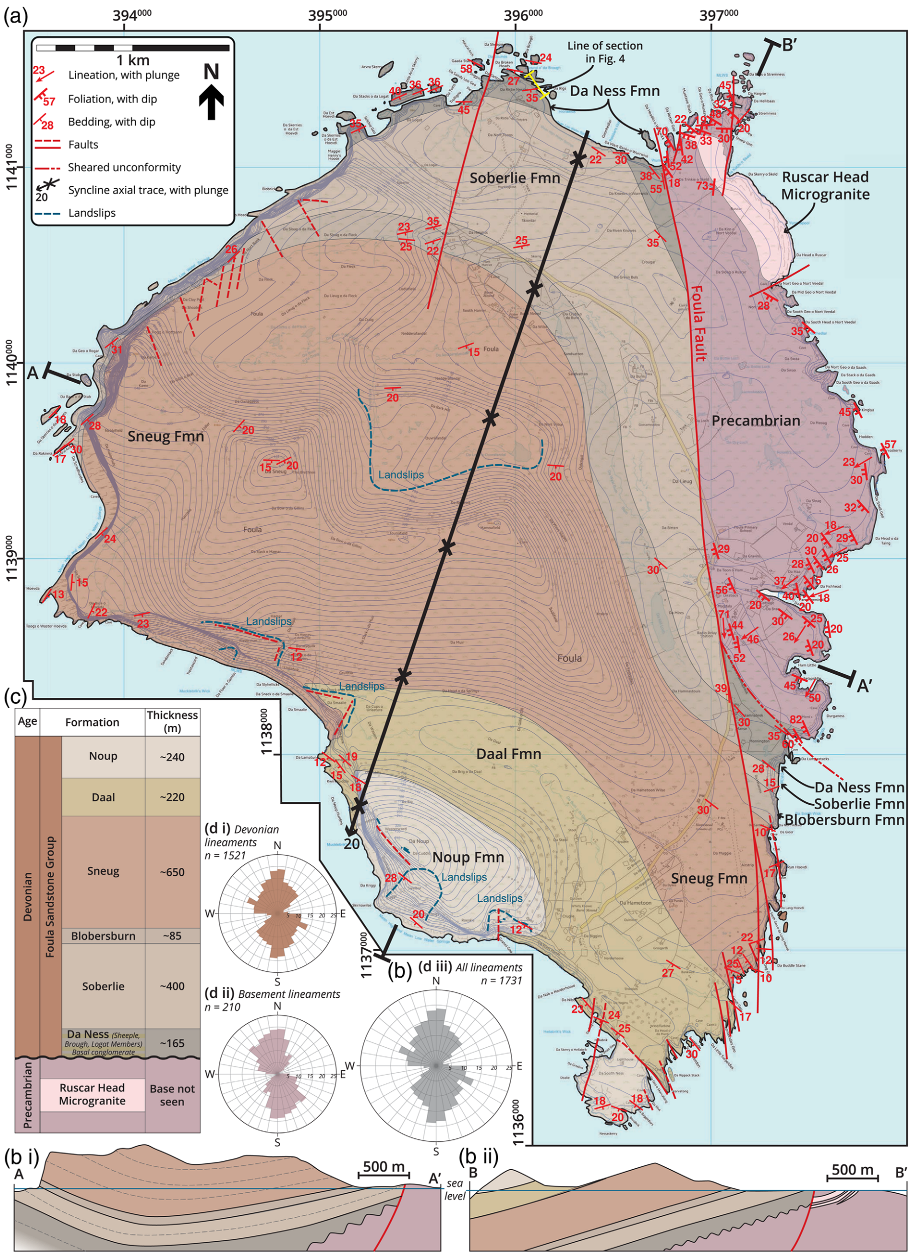

Fig. 2. (**a**) Updated geological map of Foula compiled from primary field observations, remote sensing data and existing maps. Grid references are prefixed by OS National Grid Reference HT. Contour interval is 10 m. The location of the sedimentary log shown in Figure 4a is shown at the northern end of the island. (**b**) Schematic cross-sections (**i**) A–A′ and (**ii**) B–B′; location of section lines are shown in part (a). (**c**) Stratigraphy of the Foula Sandstone Group (see also Table 1). (**d**) Rose diagrams of lineaments interpreted from Ordnance Survey aerial images for (**i**) the basement, (**ii**) the Foula Sandstone Group and (**iii**) all rocks. Source: base map in part (a) courtesy of the Ordnance Survey.

Table 1. *Stratigraphy of the Foula Sandstone Group*

Definition	Description	Depositional Environments
Noup Sandstone Formation *Type section*: in cliffs of The Noup *Lower boundary*: top of the highest laterally extensive dolomitic sandy siltstone in cliffs NW of The Noup *Thickness*: 240 m+ (top not seen)	Lithology and structure are similar to the Soberlie and Sneug formation sandstones. Discontinuous siltstone and mudstone intercalations are common. Palaeocurrent indicators are poor on The Noup owing to almost ubiquitous disorientation resulting from slippage of the sediments on the flaggy siltstones at the top of the Daal Fomation. On South Ness, tabular and trough cross-beds indicate currents flowing consistently to the south and SE	Wide sandy fluvial plain, with currents flowing mainly towards the southern quadrant
Daal Formation *Type section*: in cliffs NW of The Noup *Lower boundary*: base of the lowest dolomitic siltstone bed at Smallie; the position is difficult to define in the field as a result of considerable slippage and collapse of cliffs in SW Foula *Thickness*: *c.* 220 m	The formation appears not to change significantly in thickness across its outcrop. It consists largely of medium-grained cross-bedded sands with scattered pebbles forming beds up to 50 cm thick, but with laterally extensive interbeds of buff yellow dolomitic siltstone and grey green mudstone, mostly only a few centimetres thick, but with some up to 60 cm. Silts and interbedded fine sands display horizontal and ripple cross-lamination, with slumping and collapse structures. Carbonized plant fragments are common in places. The Daal Formation appears more 'flaggy' than the Sneug Formation; trough cross-bedding is less prevalent and there are many more well-defined flat bedding surfaces. The top of the Daal Formation is marked by a 2–3 m thick laterally extensive unit of interbedded dolomitic silts and sands with horizontal or low-angle cross-bedding. The yellow–orange weathering of the dolomitic silts forms a distinctive marker wherever this horizon outcrops	Similar to the formations above and below, but with more extensive fluvial overbank areas. Active half-graben subsidence had slowed or stopped, reducing the sediment supply and allowing an increased area of deposition. Distinctive dolomitic silts and sands at the top of the formation were deposited in an area dominated by interchannel deposits and ephemeral lakes
Sneug Sandstone Formation *Type section*: in cliffs along west coast of Foula *Lower boundary*: base of the lowest cross-bedded pebbly sandstone in cliffs of SW North Bank *Thickness*: thins NW to SE from *c.* 650 to *c.* 220 m over 3.5 km	Similar to the Soberlie Formation, comprising fine- to coarse- (mainly medium-) grained pebbly sandstones, which thin considerably from *c.* 650 m in central and western Foula to 220 m in the SE. Low in the formation are a few thin interbedded carbonaceous siltstones like those of the Blobersburn Formation. The only good exposures of the Sneug Formation occur close to the top, comprising red and buff, medium-grained pebbly sandstones with a variety of cross-bedding types with sets averaging *c.* 50 cm thick. Trough cross-bedding dominates. Convolute beds of red mudstone with abundant sand-infilled desiccation polygons are also present. Elsewhere in the formation, palaeocurrent indicators are sparse. Cross-bed foresets and trough axes generally indicate currents flowing towards the south or SW, although five readings from Wester Hoevdi indicate consistent flow towards the east	Wide sandy fluvial plain within subsiding half-graben. Similar to, but more extensive than, the Soberlie Formation environment
Blobersburn Formation *Type section*: in cliff tops of North Bank *Lower boundary*: base of the lowest carbonaceous siltstone exposed in North Bank *Thickness*: thickens NW to SE from *c.* 45 to *c.* 85 m	Well-exposed in the banks of Blobersburn, in the north of Foula. A succession of interbedded fine sandstones, dark grey micaceous siltstones and thin calcisiltites, varying from about 85 m thick in the SE of Foula to 45 m in the NW. The facies are similar to lacustrine facies 1, 2 and 3 of Allen (1981*a*, *b)* from SE Shetland Mainland. These are: (1) fine-grained sandstones with horizontal bedding, low-angle planar cross-bedding and ripple cross-lamination, convolute bedding (suggesting downslope movement towards the SE at Blobersburn), with common slump and load structures; (2) ripple cross-laminated and horizontally laminated siltstones with plant remains, syneresis cracks and convolute lamination, irregular indistinct and questionable crawling traces; and (3) calcisiltites and shaly limestones, which on Foula form only rare beds up to 10 cm thick of very-fine-grained calcareous and slightly ankeritic siltstones	Shallow freshwater lake; sub-environments represented by three facies types (after Allen 1981*a*, *b*): Facies 1: lacustrine shoreline subject to wave activity, with recumbent folding indicating downslope movement Facies 2: shallow lake bed (3–10 m) subject to wave activity Facies 3: lake floor below wave base (5–10 m+)

Table 1. *Continued*

Definition	Description	Depositional Environments
Soberlie Sandstone Formation *Type section*: in cliffs NW of Soberlie Hill *Lower boundary*: top of the highest red mudstone bed in the cliffs of East Hoevdi, NW Foula *Thickness*: thins NW to SE from *c.* 400 to *c.* 35 m	A uniform succession of buff to yellow, medium- (occasionally fine-) grained sandstones with scattered pebbles. The pebbles, which mostly occur separately, scattered through the sediment, are up to 7 cm across, although most are 1–2 cm. They are generally well-rounded and comprise quartz, quartzite, pink granite and granite gneiss. The dominant sedimentary structure is trough cross-bedding, often with superimposed convolute bedding. Tabular beds are more common in the upper half of the formation, averaging 15–20 cm thick, some with pebbly basal lags. Although foreset dip directions are difficult to measure in the mainly small, weathered exposures, currents appear to have flowed almost exclusively towards the SE, apart from occasional SW-directed currents to the east of the Foula Fault	Wide sandy fluvial plain within NE–SW-trending half-graben. At first, major rivers with prograding 3D dunes transported sediment from the NW. Later, tabular cross-beds may have been deposited by straight-crested dunes, perhaps in more extensive shallow streamflow conditions. Downstream, rivers diverted to flow along the basin axis towards the south or SW, possibly with some sediment sourced from the NE
Da Ness Formation *Type section*: in low cliffs and adjacent stacks of Da Ness, northernmost Foula *Lower boundary*: unconformity with metamorphic basement *Thickness*: Logat Mbr *c.* 100 m, Brough Mbr *c.* 15 m, Sheepie Mbr 50 m+; total 165 m+; apparent slight NW to SE thinning	Three members are distinguished in the type locality, from the top down *Logat Member*: an interbedded sequence of sandstones and mudstones, superficially like those of the Brough Member below, although the maximum thickness of sandstone units is greater here; the basal sandstone unit is up to 5 m thick and comprises trough cross-bedded sets up to 1 m thick. Sandstones are yellow-weathering, slightly to non-calcareous, and only slightly micaceous. The trough cross-sets are far more numerous than the tabular sets and they were deposited in currents flowing uniformly towards the SE quadrant. Irregular and convolute bedding of the sandstones is very common, in places on a large scale. Interbedded mudstones, siltstones and fine sandstones are similar to those of the Brough Member, but dominantly red. Large polygonal desiccation cracks are abundant. In the upper part of the Logat Member, fine-grained interbeds become less common and thinner, with thicker interbedded sandstone units *Brough Member*: Forms the Brough sea stack and adjacent low cliffs. It is a succession of dark grey, calcareous and micaceous sandstones and mudstones with the base below sea-level. Individual sand bodies are up to 3 m thick, comprising fine- and medium-grained packages of planar-tabular and trough cross-bedded sets averaging *c.* 50 cm thick, with horizontal-bedded and cross-laminated intervals. Scoured hollows up to 1 m deep and 6 m wide occur, draped by overlying sands and muds. Cross-bedded foresets and cross-lamination indicate consistent currents flowing towards the west. Sandstone bodies, although continuous within the outcrop, are not of constant thickness, and probably wedge out laterally. They are enclosed within a sequence of grey, green and red mudstones with thin siltstones and very fine to fine-grained sandstones. These sandstone and siltstone beds are horizontally or cross-laminated. Mudstones contain abundant pseudo-nodules of the interbedded sandstones; sand-filled desiccation polygons are abundant and well developed. Convolute bedding is very common *Sheepie Member*: forms the large outlying stacks of Sheepie, Gaada and probably Arva Skerry. Inaccessible from land, but comprising yellow-weathered 'massive' sandstones with only rare and thin fine-grained beds. Only about 15 m are exposed above sea-level, but the unit appears to be at least 50 m thick. In SE Foula a basal breccia up to 2.4 m thick overlies metamorphic basement. The overlying sandstones here are inaccessible in cliff exposures	*Logat Member*: Shoals of forward-migrating 3D dunes within the sandy channels of an extensive fluvial system sourced from the NW. Muddy overbank areas underwent alternating periods of flood and desiccation *Brough Member*: Low-relief floodplain with frequent desiccation. Fluvial channels containing a variety of bedforms. Abundant plane bedding and compositional immaturity indicate frequent floods originating from nearby upland source area to east. Probably no well-established flow regime *Sheepie Member*: basal breccia is a ?residual weathering deposit from a period of no net deposition. Overlying sandstones are probably fluvial or alluvial fan deposits

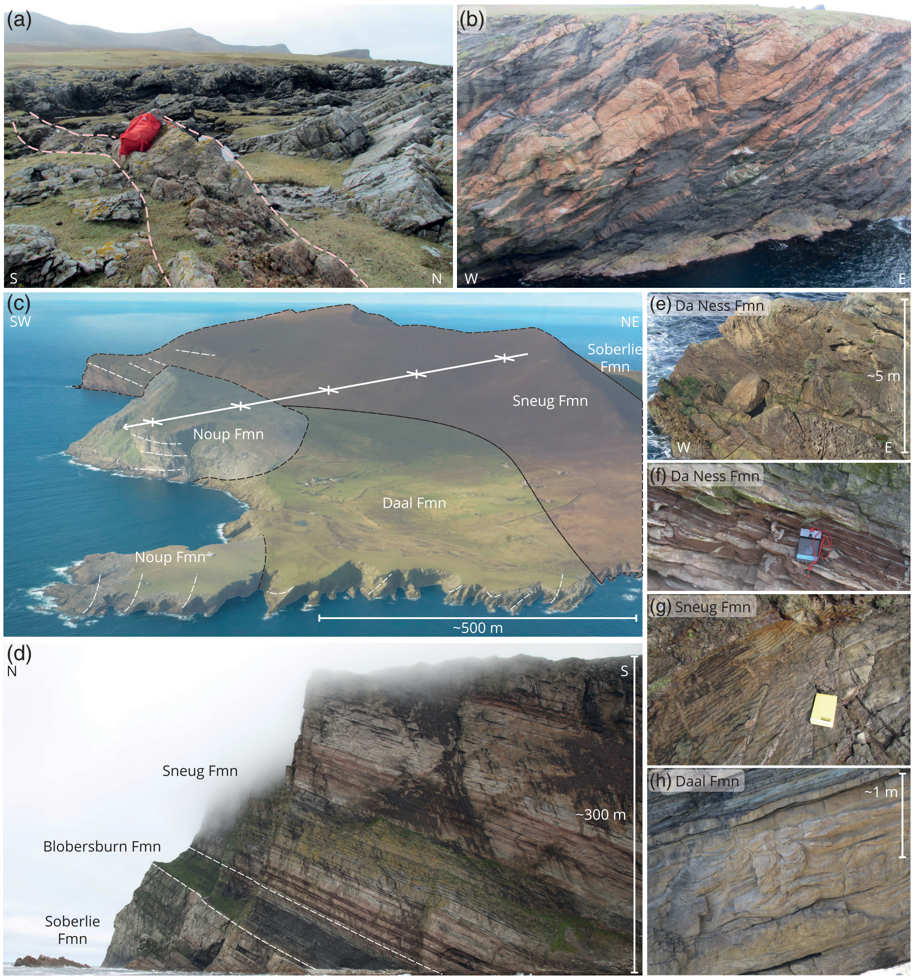

Fig. 3. Field photographs of examples of the basement and Foula Sandstone Group. (**a**) South-dipping, well-foliated and fractured basement cut by granite vein (delimited by pink dashes) at Stremness; rucksack and notebook for scale [HT 397013 1141160]. (**b**) Sheets of Ruscar Head Microgranite cutting the basement in a 20 m high cliff section [HT 396868 1141157]. (**c**) Oblique aerial image showing the gently SW-plunging Foula Syncline. (**d**) Cliffs at Wester Hoevda [HT 393746 1138832] showing the organic-rich Blobersburn Formation and highly fractured sandstones of the Sneug and Soberlie formations. (**e**) Soft sediment deformation and fluid-escape structures in the Sheepie Member and (**f**) sand-filled desiccation cracks in mudstones of the Logat Member (compass for scale) of the Da Ness Formation. (**g**) Well-developed symmetrical ripples in the Sneug Sandstone at Da Doon Banks (HT 397153 1136918); notebook for scale. (**h**) Multi-storey sandstone bed of the Daal Formation, displaying planar to low-angle inclined bedding overprinted in a middle storey by soft sediment deformation and overlain by darker unit of horizontal- to ripple-laminated siltstones and sandstones [HT 395047 1137999]. Source: image in part (c) courtesy of Canmore, Historic Scotland; photo in part (d) courtesy of Jim Henderson.

stratigraphy for the Foula Sandstone Group presented here (see Fig. 2c; Table 1). A new geological map and cross-sections (Fig. 2a, b) integrate this mapping and stratigraphy with the findings of new fieldwork (Utley 2020). As a result of poor inland outcrops and the inaccessible coastal nature of many of the exposed cliff sections, which are up to 376 m high, new fieldwork was supplemented by the use of aerial and drone-based imagery and photogrammetric 3D models interpreted in Virtual Reality Geological Studio to extract geological information and structural measurements (Burnham and Hodgetts 2019). Lineament analysis of aerial photographs (Fig. 2d) was carried out at a scale of 1:500 in ArcGIS. Lineament and structural data were analysed using Stereonet 9.5 (Allmendinger *et al.* 2011). Palaeocurrent measurements were made where possible, mostly from the dip direction of cross-bedding foresets, although the poor or inaccessible exposure, combined with an abundance of soft sediment deformation, impeded precise measurements in many locations. It was, however, often possible to determine the general foreset dip direction even where exact measurements could not be made. Sampling was undertaken for thin section, microstructural, heavy mineral provenance analysis and detrital zircon geochronology. Detailed methodologies for these techniques and the full results of our analysis can be found in Appendix A of the Supplementary Material.

Metamorphic basement and minor intrusions

Metamorphic basement rocks form a *c.* 1 km wide strip along the eastern side of the island (Fig. 2a), comprising metasediments and a suite of microgranite sills and dykes (Fig. 3a, b) (Mykura *et al.* 1976*b*). The basement is dominated by interbanded psammitic and semi-pelitic paragneisses (Fig. 3a), with subordinate metabasic intrusions. The basement is lithologically comparable with the early Neoproterozoic Yell Sound Group on mainland Shetland (deposited at *c.* 1019–941 Ma; Jahn *et al.* 2017). Flinn *et al.* (1979) reported K–Ar hornblende and biotite ages of 443 ± 14 to 426 ± 20 Ma, respectively, from Foula, indicating that the basement here was most recently metamorphosed during the Caledonian Orogeny. In NE Foula (Fig. 2a), a pink microgranite (the Ruscar Head Microgranite) forms part of a little deformed, laccolith-like complex of sills and feeder dykes with most contacts sub-parallel to the basement foliation (Fig. 3a, b). South of Ruscar Head, on the coast east of Da Swaa [HT 397486 1140048], a second thick sill (10–15 m) is exposed within inaccessible cliff sections (Fig. 2a). An age for these intrusions is undetermined, but it is likely to be pre-Mid-Devonian because lithologically identical granite clasts are preserved in sedimentary breccias in the basal part of the Foula Sandstone Group immediately overlying the basement.

Devonian Foula Sandstone Group

The succession that outcrops through most of the island, apart from the northeastern coastal strip, is subdivided into six formations (Fig. 3d–h), comprising three major subarkosic sandstone units separated by more mixed shale-dominated units (Table 1). In total, it is *c.* 1.6 km thick and comprises fluvial, floodplain, lacustrine and possible alluvial fan sedimentary rocks.

The Da Ness Formation is at least 165 m thick in the north of Foula, where the base is not seen. It is subdivided into three members, with a 3–5 m thick localized basal breccia exposed on the coast at Shoabill in the SE [HT 397390 1138110] resting unconformably on an irregular basement surface. Overlying the basal breccia, the Sheepie Member (at least *c.* 50 m thick in the north) is only exposed in an inaccessible cliff section and sea stacks. It comprises massive yellow sandstones with rare, thin (centimetre to decimetre), finer grained beds (Fig. 3e). Above this, the Brough Member comprises *c.* 15 m of grey mudstones and sandstones. Unlike most of the sedimentary rocks on Foula, the Brough Member is both calcareous and mica-rich. Fine- to medium-grained sand bodies up to 3 m thick display cross-laminations and planar or trough cross-bedding. Scoured hollows up to 1 m deep and 6 m wide are draped by sandstone and mudstone; the thicker sandstones are enclosed in a sequence of grey, green and red siltstones and laminated fine- to very-fine-grained sandstones. Soft sediment deformation is widespread, with concentric laminated slump balls and convolute bedding, and sand-filled desiccation cracks are well developed in the mudstones (Fig. 3f). The overlying Logat Member, *c.* 100 m thick, is broadly similar to the Brough Member, but with sandstone beds up to 5 m thick that are less micaceous and dominated by trough cross-bedding.

The Da Ness Formation is interpreted as comprising mainly fluvial channel deposits, with finer grained material representing fluvial overbank and floodplain deposits that underwent prolonged periods of desiccation. Figure 4a is a sedimentological log of a well-exposed and accessible section of the upper Brough Member and lower Logat Member. Palaeocurrent data based on the dips of cross-bedding foresets demonstrate an abrupt switch in current direction from flow towards the westerly quadrant in the Brough Member to a southeasterly quadrant in the Logat Member (Fig. 4b). The relatively immature, micaceous nature of the Brough Member is thought to indicate a local sediment source lying to the east. Tabular cross-bedded sets, most abundant in the Brough Member, may represent sheetflood deposits, possibly formed on the toes of alluvial fans. The Sheepie Member may represent less well-organized alluvial fan sands, although this is speculative owing to their inaccessibility. The more compositionally mature, thicker sandstones of the Logat Member may have been deposited in a larger scale fluvial system sourced from the NW.

The Soberlie Formation forms a uniform succession of buff to yellow, medium- to fine-grained sandstones with occasional scattered pebbles, reaching 400 m thick in the west of Foula (Fig. 3c, d). The pebbles are up to 7 cm in size, but most are 1–2 cm, well-rounded and consist of quartz, quartzite, pink granite and granitic gneiss. The dominant sedimentary structures are trough cross-bedding and convolute bedding. Towards the top of the sequence, tabular beds up to 15–20 cm thick with pebbly lags are more common. Palaeocurrents measured across most of the island flowed consistently towards the southeastern quadrant (Fig. 4b). The Soberlie Formation is poorly exposed and much thinner in the centre and SE of the island, reducing to <200 m west of the Foula Fault in the SE (Fig. 2b i), and only *c.* 35 m east of the fault, where it comprises fine- to coarse-grained sandstones with rare pebbles and intraclasts of siltstone and mudstone. Occasional cross-bedding foresets here indicate generally SW-directed palaeocurrents (Fig. 4b). The depositional environment of the Soberlie Formation is similar to that of the Da Ness Formation, but it is distinguished by the presence of thicker sandstones and by less frequent and thinner floodplain and fluvial overbank facies.

The Blobersburn Formation is up to *c.* 85 m thick immediately to the west of the Foula Fault in the SE of Foula, and possibly a little thinner to the east of the Foula Fault, where is it poorly exposed or inaccessible. It is clearly distinguished from the underlying Soberlie sandstone by its distinctive darker colour and relative susceptibility to erosion. It is well-exposed, but inaccessible, in the cliffs on the west of the island, although it can be seen to have reduced in thickness here to *c.* 45 m (Fig. 3d). Poor exposures in the stream bed at Blobersburn [HT 395540 1140636] show that it is composed of interbedded fine-grained sandstones, dark grey micaceous siltstones and thin calcareous siltstones. It provides a key marker horizon due

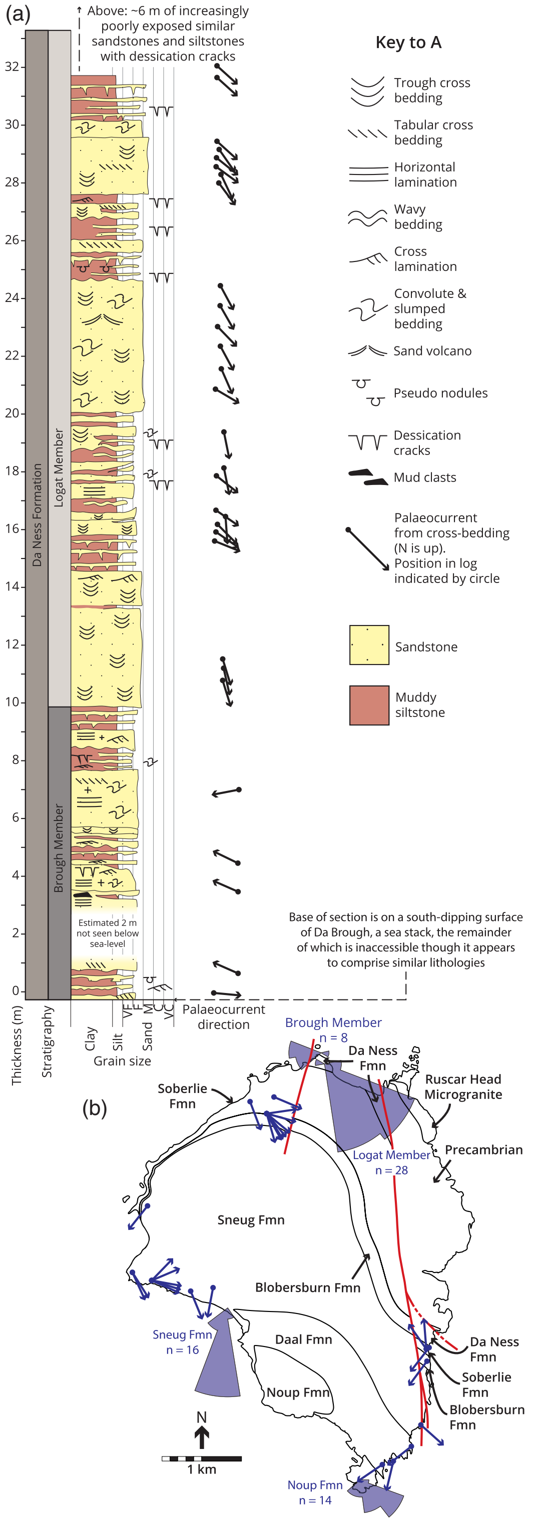

Fig. 4. (**a**) Sedimentological log of a well-exposed section of the Da Ness Formation on the coast at the northern tip of Foula (see Fig. 2a for location) covering parts of the Brough and Logat members and illustrating an abrupt change in palaeocurrent direction between the two units. (**b**) Map of the palaeocurrent directions inferred from sedimentary structures, mostly cross-bedding foresets. Arrows are used for a single or small number of readings and rose diagrams for larger sample sets.

to its distinctive lithology and it exhibits facies types similar to those reported in the lacustrine successions of SE Shetland (e.g. Allen 1979, 1981*a*, 1982; Allen and Marshall 1981; Table 1).

The total organic carbon values are generally <0.5%, but this is the most organic-rich unit on the island and the only unit to contain amorphous organic matter within the kerogens (Marshall *et al.* 1985). The preservation of this form of organic material, derived from algal matter, indicates that anoxic conditions prevailed for a time, but did not become established for long periods as in the fish-bearing units of Caithness and Shetland (Marshall *et al.* 1985). A single probable *Asmussia (Estheria)*, a small freshwater branchiopod, has been discovered in the Blobersburn Formation on Foula (Donovan *et al.* 1978).

The Blobersburn Formation is interpreted to have been deposited in a shallow freshwater lake with variable water depth, probably no greater than 10 m. Well-developed sedimentary cyclicity, as seen in Caithness (Andrews *et al.* 2016), is not evident, but overall it is similar to other lacustrine units in the Orcadian Basin, such as the Achnarras Horizon in Caithness and Orkney, and the Melby Formation and Exnaboe Fish Beds in Shetland.

The Sneug Formation has a maximum thickness of *c.* 650 m in the west of the island, where it forms the greater part of the cliffs (Fig. 3d, g). It comprises red- to buff-coloured, fine- to coarse-grained, locally pebbly sandstones, which thin considerably to 220 m in the east. This thinning, much like that seen in the Soberlie Formation, can be attributed to deposition in a developing half-graben bounded by the Foula Fault. Sedimentary structures include trough cross-bedding (sets averaging *c.* 50 cm) and symmetrical ripples with predominant SSW-directed palaeocurrents (Fig. 4b). Floodplain and fluvial overbank deposits are preserved as thin red mudstone beds, which contain some convolute bedding and sand-filled desiccation cracks. This depositional environment of the Sneug Formation is interpreted to be similar to that of the Soberlie Formation, representing a fluvial system with axial flow through the basin.

The Daal Formation*,* with a fairly uniform thickness of *c.* 220 m, is largely composed of medium-grained sandstones with scattered pebbles (Fig. 3h) and laterally extensive interbeds of buff yellow dolomitic siltstones and grey green mudstones. Sedimentary structures include well-defined planar beds, with less common trough cross-bedding. The interbeds are usually only a few centimetres thick, although some reach 0.5 m and include horizontal and ripple cross-lamination, with some soft sediment deformation structures (Fig. 3h). Plant material is also common. This unit is interpreted as having been deposited on an extensive floodplain, possibly largely submerged, crossed by fluvial channels with fine-grained overbank and crevasse-splay deposits, and with possible sheetflood deposits. Relatively poor exposure and soft sediment deformation leads to sparse reliable palaeocurrent data, but there are indications of generally southwards-directed currents. The rate of deposition, and therefore possibly of subsidence, appears to have been slower than during the deposition of the under- and overlying formations.

The Noup Formation is the youngest formation outcropping on Foula (Fig. 3c). It has a minimum thickness of 240 m, with the top unseen. The lithology and sedimentary structures are like those of the underlying Soberlie and Sneug formations, especially the latter, which, together with a dominant southwards palaeocurrent direction (Fig. 4b), suggests a similar tectonic and sedimentary setting, with fluvial systems being channelled along the basin axis. Some discontinuous overbank silts and muds occur and yield occasional plant remains.

Structural geology

The structure of Foula is dominated by a regional-scale north–south- to NNW–SSE-striking, steeply west-dipping normal fault known as the Foula Fault (Fig. 2a). This splays into a series of fault branches, which can be observed in numerous steep-sided, narrow geos (local term for gullies) (Hansom 2003) along the coastline to the south. The underlying geology has a strong control on the present day topography. Landslips and subsidence/sinkholes pick out both north–south- and east–west-orientated faults and fracture zones, such as at Da Sneck o Da Smaalie [HT 395044 1138286]. Here, a relatively recent landslip on a seawards-dipping bedding plane has opened a narrow chasm almost down to sea-level. Recent glaciation and landslips are also thought to have taken advantage of these pre-existing weaknesses to generate geomorphological features, such as the corries at Ouvrandal, Da Fleck and Netherfandal (Fig. 2a) (Finlay *et al.* 1926; Mykura 1976; Mykura *et al.* 1976*b*; Flinn 1977).

Structures in the basement

The basement on Foula is strongly foliated and records multiple phases of ductile and brittle deformation. The gneissic to schistose basement foliation is folded into a large-scale open synform plunging SW sub-parallel to the metamorphic mineral lineations (Fig. 5a, e). The basement is highly fractured and dominated by north–south-orientated, east-dipping normal faults and lesser north–south-orientated fracture zones and brittle shear zones (Fig. 5a, b); this is reflected by a dominance of north–south lineaments in areal images (Figs 2d, 5b). In addition to these major structures, three well-defined joint/fracture sets trend NNE–SSW to NE–SW, east–west to ENE–WSW and NNW–SSE to north–south (Fig. 5e).

Most normal faults in the basement dip moderately to the east (Fig. 5c) and have measurable throws of a few tens of centimetres to several metres; their orientation appears to be significantly influenced by the similarly orientated basement foliation. They are associated with epidote, quartz feldspar, base metal sulfide mineralization and are significantly iron-stained as a result of weathering. The mineralization and associated alteration appear to predate the emplacement of the Ruscar Head Microgranite and deposition of the Foula Sandstone Group. Some faults have normal to sinistral-normal slickenlines preserved, with local drag folds (Fig. 5d) and mineralized en echelon tension-gash arrays with a sinistral sense of shear. Some of the NE–SW faults exhibit faint slickenlines with dextral kinematics and appear to form antithetic structures to the major north–south faults with sinistral movement components. The fractures and faults within the granites are largely barren of mineralization.

Basement–cover relationships and associated deformation

The Foula Fault is exposed on the coastline at the northern end of the island in Rotten Geo, Wurrwick [HT 396749 1140994] as a west-dipping normal fault zone (Fig. 6a, b and i). Foliated basement with abundant granite sheets in the footwall are juxtaposed against interbedded sandstones and siltstones of the Da Ness Formation. A throw of *c.* 100 m is estimated on the basis of the stratigraphy omitted. On the principal slip surface, a thin (3–8 mm thick) layer of blue grey, clay-rich fault gouge is developed, underlain by 20–30 cm of mullioned, chaotic microbreccia (Fig. 6b) that has been folded by a series of centimetre-scale open, south- to SSW-plunging fold hinges (Fig. 6c). In the hanging wall, the Da Ness Formation is folded and cut by sub-parallel conjugate curviplanar faults and fracture corridors (Fig. 6a, d, i). Some shale-rich units are locally folded into tight chevron folds plunging SW (Fig. 6f). Further to the west are several shallow, subhorizontal, roughly bedding-parallel faults that appear to have acted as slip zones to accommodate differential displacement between the bedded units and subordinate fracture corridors and faults (Fig. 6g). The beta axes of the folded bedding, foliation and curviplanar faults all plunge south to SW (Fig. 6h).

On the southeastern coast of Foula at Shoabill [HT 397390 1138110], a 3–5 m zone of sheared basal conglomerate is in contact with a SW-dipping undulating, erosional basement unconformity surface, above which the bedding of the Da Ness Formation is sub-

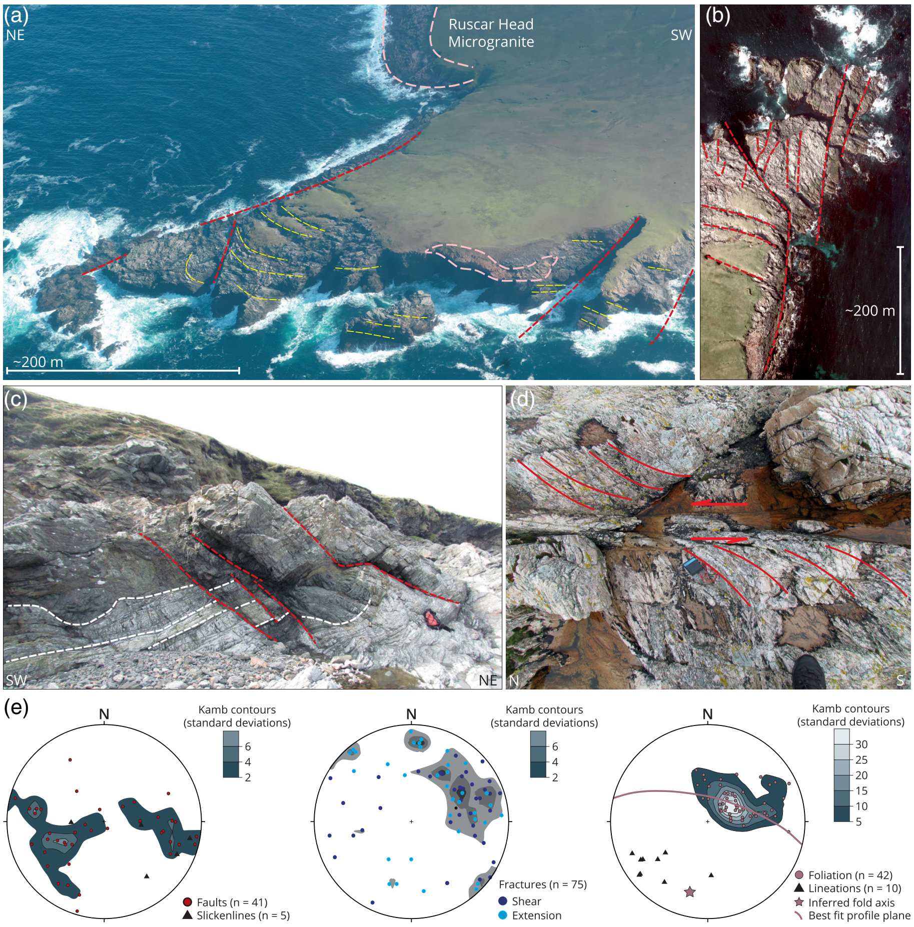

Fig. 5. Basement structures on Foula. (**a**) Oblique aerial image of NE Foula showing subtle folding of the foliation and major faults. (**b**) Aerial image showing major north–south fracture corridors. (**c**) East-dipping normal faults within the basement at Da Head o Da Taing; rucksack for scale [HT 397802 1139275]. (**d**) North–south fault with sinistral drag folds, Ruscar Head Granite [HT 397331 1140687]. (**e**) Stereonets of basement foliation, lineation, faults and slickenlines, and fractures. Plotted as contoured poles to planes with mean planes shown as great circles. Source: part (a) courtesy of Canmore, Historic Scotland; part (b) courtesy of the Ordnance Survey.

parallel (Fig. 7a–d). This sedimentary breccia covers an irregular unconformity surface. In the zone of shearing, the long axes of the clasts are orientated parallel to the SW-dipping fabric and exhibit well-developed asymmetrical boudinage with a top-to-the-SW sense of shear (Fig. 7b, c). The clasts comprise basement material set in a matrix of coarse- to medium-grained sand. Minor synsedimentary NE-dipping normal faults can be seen cutting through this zone and can be traced into the basement units below (Fig. 7c). Collectively, these indicate top-to-the-SW/SSW extension coeval with slip along this unconformity surface. Open brittle fractures of unknown age trending NW–SE and north–south occur locally in the basement, particularly within more granitic and pegmatite-rich units. Rare, small-scale millimetre- to centimetre-scale sediment-filled fractures are present, which are infilled with fine- to medium-grained sand- and clay-rich silt. These fractures are interpreted to have formed in proximity to the base-Devonian unconformity during deposition.

Structures in Devonian rocks

The entire Devonian sequence on the island is folded into a broad open structure (the Foula Syncline), which plunges *c.* 20° to the SSW (Figs 2a, b and 3c). Field data were supplemented by data derived from virtual outcrop models (Fig. 8a and b(i), b(ii)) and remote sensing to include orientation data from the largely inaccessible cliffs that follow the western limb of the fold. The basement foliation is folded in a similar manner (Figs 5e, 8b(iii)). A down-plunge projection of the Foula Syncline reveals an upwards-opening fold with interlimb angles increasing upwards from 129° to 168° (Fig. 8c). Major thickness changes are apparent within the Soberlie and Sneug sandstones, consistent with mapped changes in thickness in these units over the Foula Fault (Fig. 2a, b). These relationships are interpreted to show that the Foula Syncline was initiated and progressively tightened during sedimentation – that is, like the Foula Fault, it is interpreted to be a growth structure. Smaller scale, more localized folds, which also have south- to SSW-orientated fold hinges, are observed in the western cliff section (Fig. 9g).

The earliest brittle structures in the Devonian strata are NE–SW- to north–south-orientated deformation bands (granulation seams) and fractures (Fig. 9a, i) with rare quartz cement fills. These structures increase in number with proximity to major faults and are the likely precursor structures to the major north–south-orientated normal to sinistral oblique normal faults, which also increase in number closer to the Foula Fault in the east. North–south-orientated normal faults (Fig. 9a–c) are the dominant structures seen, and are widely eroded to form distinct geos (Fig. 2a). There is minor brecciation and the development of small (<5 mm) vuggy fractures in the footwalls of these faults. Unlike in the basement, these major north–south faults do not contain significant mineralization and form clean breaks that preserve rare sinistral oblique to sinistral strike-slip slickenlines and dextral oblique slickenlines on antithetic Reidel shears. Subvertical, en echelon north–south and east–west discrete fracture corridors (Fig. 9c, d) with limited normal offsets are common and decrease in frequency away from the Foula Fault. Viewed in cross-section, these left-stepping en echelon arrays have a flower structure-like geometry (Figs 6i, 9b, c).

In a small quarry near to Hamnabrek [HT 397101 1138331], a *c.* 15 m wide fault zone juxtaposes the sandstones and siltstones of the Soberlie Formation against the sandstones of the Da Ness Formation (Fig. 9e, f). The fault zone comprises steeply west-dipping north–south-orientated faults and antithetic east-dipping shear fractures with abundant tensile fractures, sigmoidal tension gashes with a sinistral sense of shear and small open tensile fractures with some rare quartz fills. Shale-rich units close to the faults have a well-developed cleavage and their brittle deformation has contributed to

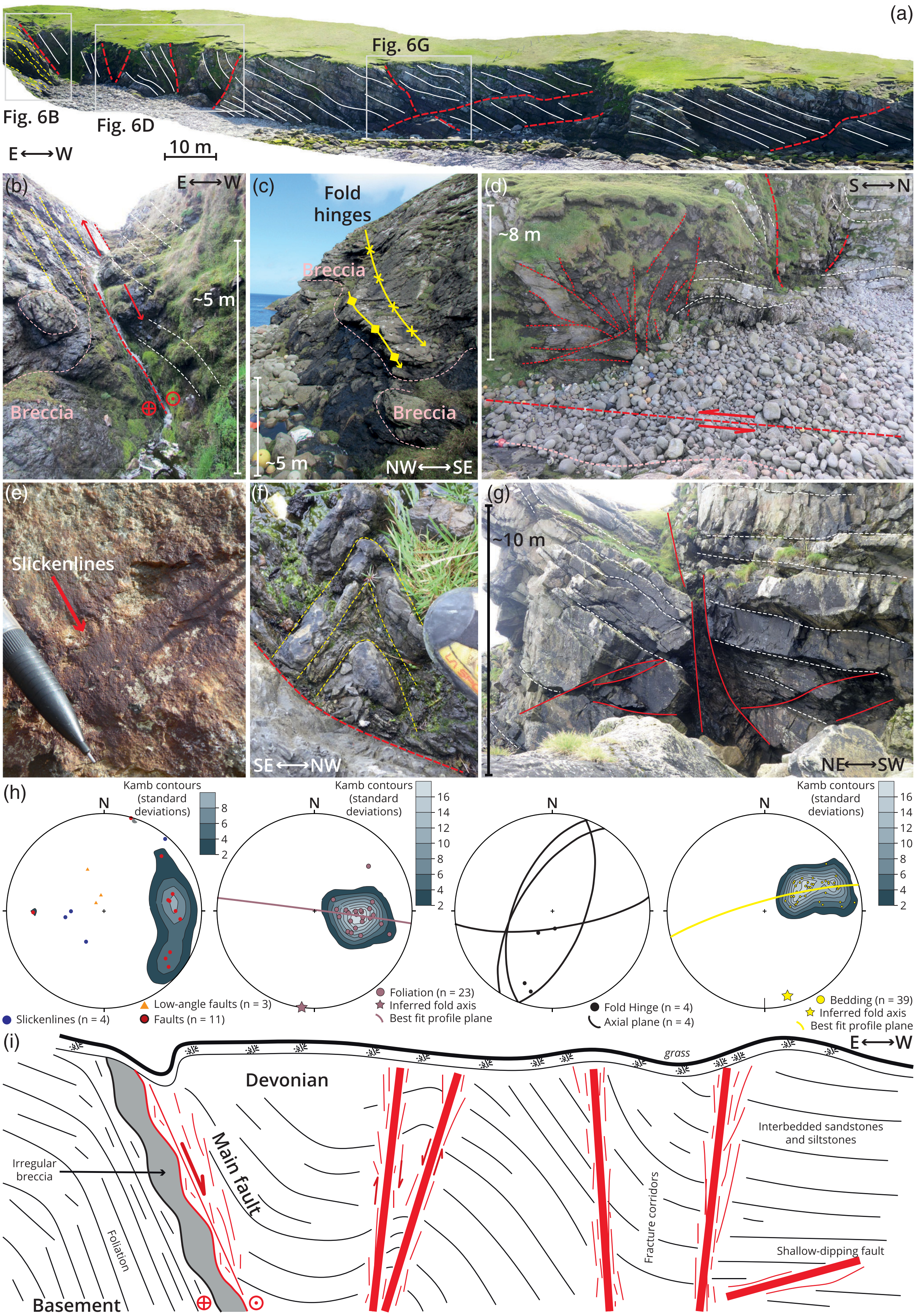

Fig. 6. Basement–cover relationships at Wurrwick [HT 396749 1140994]. (**a**) Annotated Virtual Outcrop Model of cliffs at Da Wast Banks o Wurrwick. (**b**) Principal slip surface of the Foula Fault with location of breccias. (**c**) SW-plunging folds in the footwall fault breccia. (**d**) SW-plunging folds and fractures in the hanging wall. (**e**) Close-up of fault plane showing sinistral oblique slickenlines. (**f**) Minor small-scale chevron folds within siltstones/mudstones in the hanging wall. Folds plunge steeply SW. (**g**) Fault zone in the hanging wall showing complex geometries and interaction of steeply dipping faults/fracture corridors and shallow bed-parallel faults. (**h**) Stereonets of major faults, foliation, fold axial planes and hinges, and bedding. Plotted as (Kamb) contoured poles to planes and mean planes shown as great circles. (**i**) Schematic summary diagram of the fault zone structure at Wurrwick covering the cliff section shown in part (a).

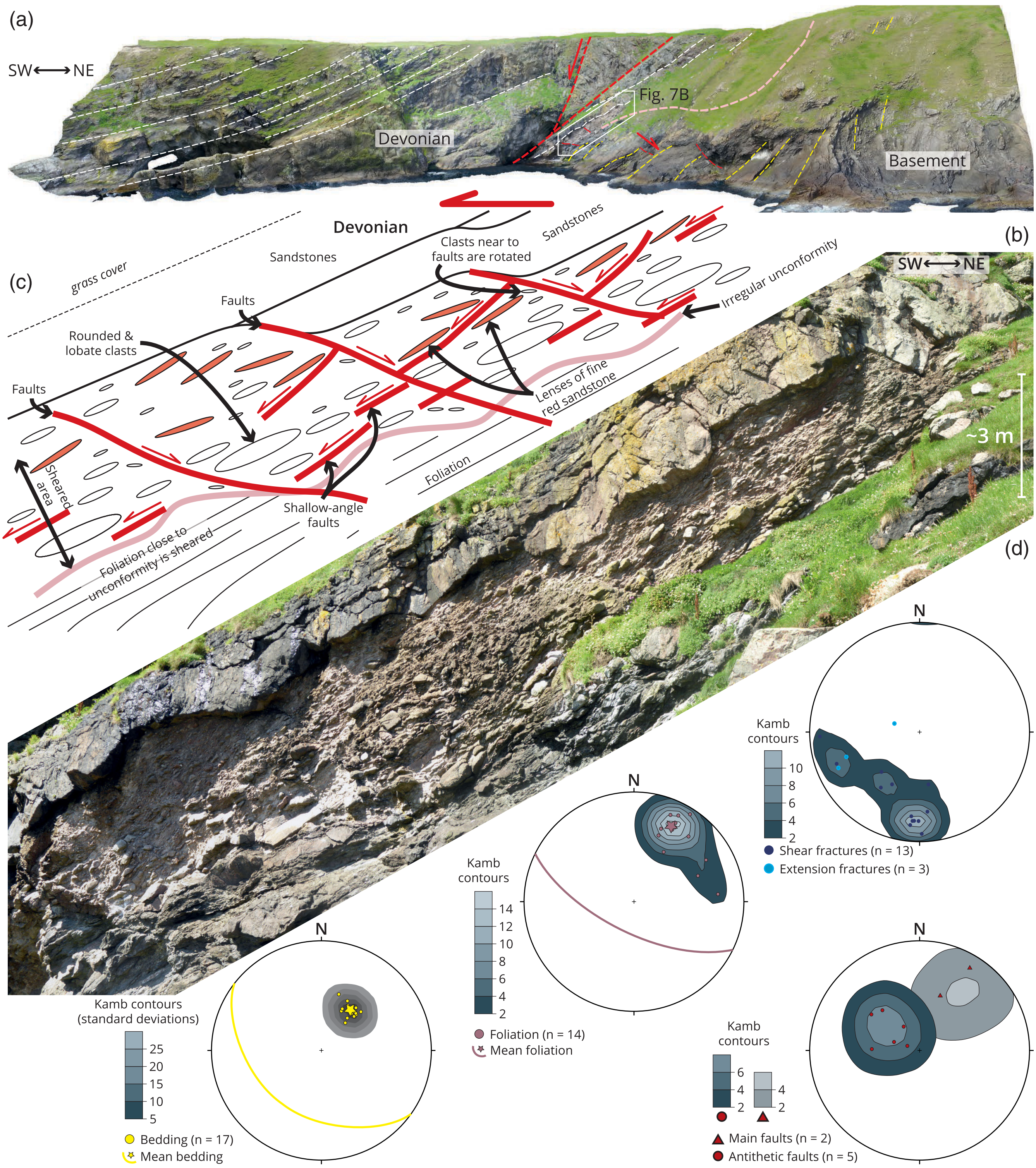

Fig. 7. Basement–cover relationships at Shoabill [HT 397390 1138110]. (**a**) Interpreted ortho-rectified image of a Virtual Outcrop Model of the cliffs at Shoabill. Faults are shown in red, bedding in white and the foliation in the basement in yellow. (**b**) Close-up section image of sheared basal breccia. (**c**) Schematic diagram of the sheared unconformity and associated faults at Shoabill. (**d**) Stereonets of bedding, foliation and faults plotted as contoured poles to planes with mean planes shown as great circles where appropriate.

the development of 1–2 cm thick clay-rich fault gouge along the main fault plane. In the hanging wall, a crackle/crush breccia is developed with clasts of *c.* 0.5 mm.

Even in regions well away from larger faults, the Devonian sequences are heavily fractured and have an overall polymodal fracture pattern with a dominant north–south trend (Fig. 9c, i) and small normal to strike-slip offsets (Fig. 9a, b, h) with mutually cross-cutting and abutting relationships (Fig. 9c). Many of the smaller faults have a scissor-like style of offset, with faults tipping out over short distances. The fractures are commonly open with small apertures (<2 mm) with no fracture fill or mineralization. Some faults preserve minor quantities of fine angular fault breccia or green–red gouge <2 mm thick that is partially cemented with quartz.

The generally barren clean break nature of the faults means that relatively few faults preserve slickenlines. Fault-slip slickenline data measurements from 10 faults (Fig. 10a) were used to carry out a conventional stress inversion. The results of this analysis

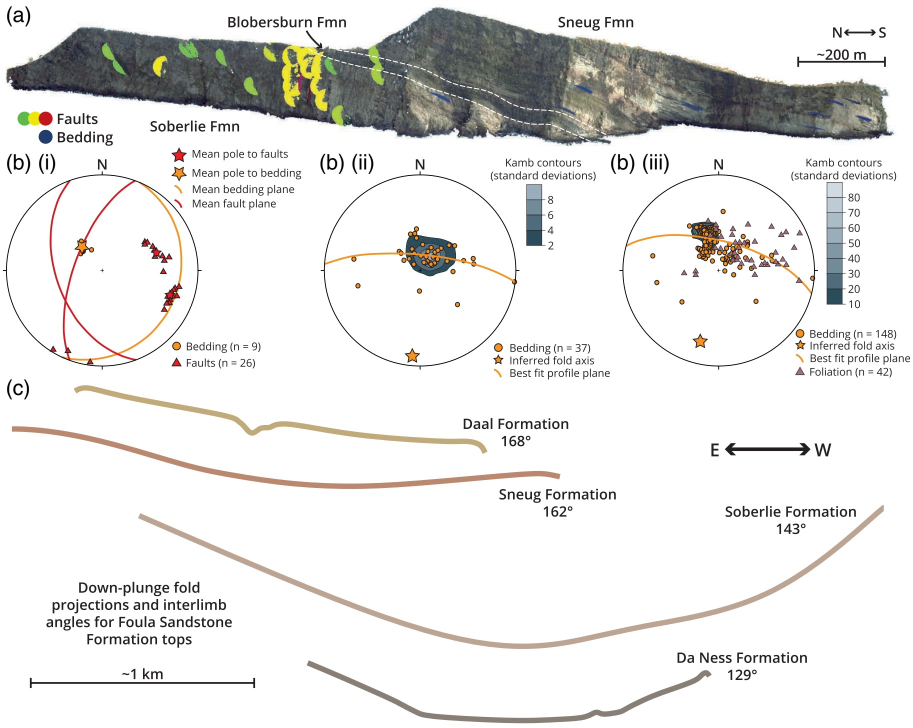

Fig. 8. (**a**) Virtual Outcrop Model of Da Kame, Foula. (**b**) (**i**) Stereonet of data shown on the model in part (a) with mean pole and planes as appropriate. (**ii**) Field and remotely sensed bedding data from the Foula Sandstone Group and (**iii**) with poles to basement added. Best-fit great circles and the beta axis (the plunge of the Foula Syncline) are also shown. (**c**) Down-plunge projection with interlimb angles for the Foula Sandstone Group formation tops. Note the subtle changes in hinge location and the opening-upwards geometry, as indicated by the increasing interlimb angle up the stratigraphy. Horizontal scale = vertical scale. Source: model in part (a) built in Agisoft Photoscan from archive helicopter-based imagery courtesy of BP and analysed in the Virtual Reality Geological Studio courtesy of David Hodgetts, University of Manchester, UK.

(Fig. 10b, c) show that the minimum principal stress (σ_3) was orientated NE–SW (09/240). The shape ratio ($ø = 0.4$) (Fig. 10c, d) indicates that local faulting represents an extension-dominated transtension (Fig. 10e), consistent with regional sinistral transtension along the north–south basin-bounding structures, including the Foula Fault (Fig. 10f).

Summary and local synthesis for the Foula Sandstone Group basin

Based on the field observations and analysis of structures, a schematic basin development model for the Foula Sandstone Group (Fig. 11) illustrates how the depositional systems and changes in palaeocurrent (e.g. Fig. 4a, b) may have evolved in response to changes in tectonics and climate in this part of the regional Orcadian Basin. The local basin may have initiated as a half-graben, with sediments being shed off regional highs to the north and west and from more localized features, such as the Foula Ridge (Fig. 11a, b) to the NE. With progressive subsidence and periods of active faulting, the basin began to fill. During lacustrine highstands, a broad alluvial plain was flooded, forming units such as the Blobersburn Formation (Fig. 11c) and other more minor lacustrine intervals elsewhere in the succession. Very widespread soft sediment deformation structures and water-escape structures are preserved throughout the succession on Foula (e.g. Fig. 3e, h) and are most evident within the interbedded sandstones and siltstones of the stratigraphically lower units. These are indicative of high sedimentation rates, rapid burial (Leeder 1987), synsedimentary deformation and the expulsion of high-pressure pore fluids. Their extensive development, together with major changes in thickness across the Foula Fault, indicate an active tectonic environment with growth faulting and gentle folding during deposition. The upwards-opening of the Foula Syncline seen in the down-plunge cross-section (Fig. 8c) implies that low-angle erosional unconformities (discordances <5°) should exist within the succession (e.g. as shown schematically in Fig. 11f). However, the limited and often inaccessible coastal exposures on the island did not allow unequivocal identification of such features in the field.

Spore colours in the Foula Sandstone Group are mid- to dark brown with a vitrinite reflectance between 1.2 and 1.8% (Hillier and Marshall 1992), considerably lower than values from the Walls Group, eastern Shetland and Fair Isle. The values on Foula appear to be closer to those obtained from Melby, Orkney and Caithness (Marshall *et al.* 1985; Hillier and Marshall 1992), although they are higher than at Melby, which has vitrinite reflectance values of 0.8–1.0% (Hillier and Marshall 1992), suggesting slightly deeper burial. Thus the burial history of the Foula succession seems to have closer affinities to that of the main part of the Orcadian Basin in Orkney–Caithness rather than Shetland. This leads to broader questions concerning the age and affinities of the Foula Sandstone Group relative to the other Devonian sequences in northern Scotland, issues that we explored using new heavy mineral analyses and detrital zircon geochronology.

Age, provenance and detrital zircon geochronology

A Mid-Devonian Eifelian age has been proposed for the Foula Sandstone Group (Marshall and Hewett 2003). The distinctive lacustrine facies of the Blobersburn Formation have been correlated with the so-called Fish Bed horizons in western Shetland (Melby), Orkney (Sandwick) and Caithness (Achanarras) (see Supplementary Materials, Appendix B).

Palaeocurrents in the Foula Sandstone Group (Figs 4a, b and 11a–f) show material initially being shed from palaeohighs immediately to the north and east (the Da Ness and Soberlie formations), evolving to more distally derived material transported from the NW as the basin began to fill (the Sneug Formation and younger units). Heavy mineral analyses and detrital zircon geochronology of sandstones were undertaken (for methodology, see Supplementary Material, Appendices C and D) to learn more about the provenance of the Foula Sandstone Group and the nearby Melby Formation.

Heavy mineral data (Supplementary Material, Appendix C) show that samples from Foula and Melby overlap with those from the Lower Clair Group and the Late Devonian sequences in the Orcadian Basin, suggesting that these sandstones were sourced from similar source areas. The ratios of the key heavy minerals (Fig. 12)

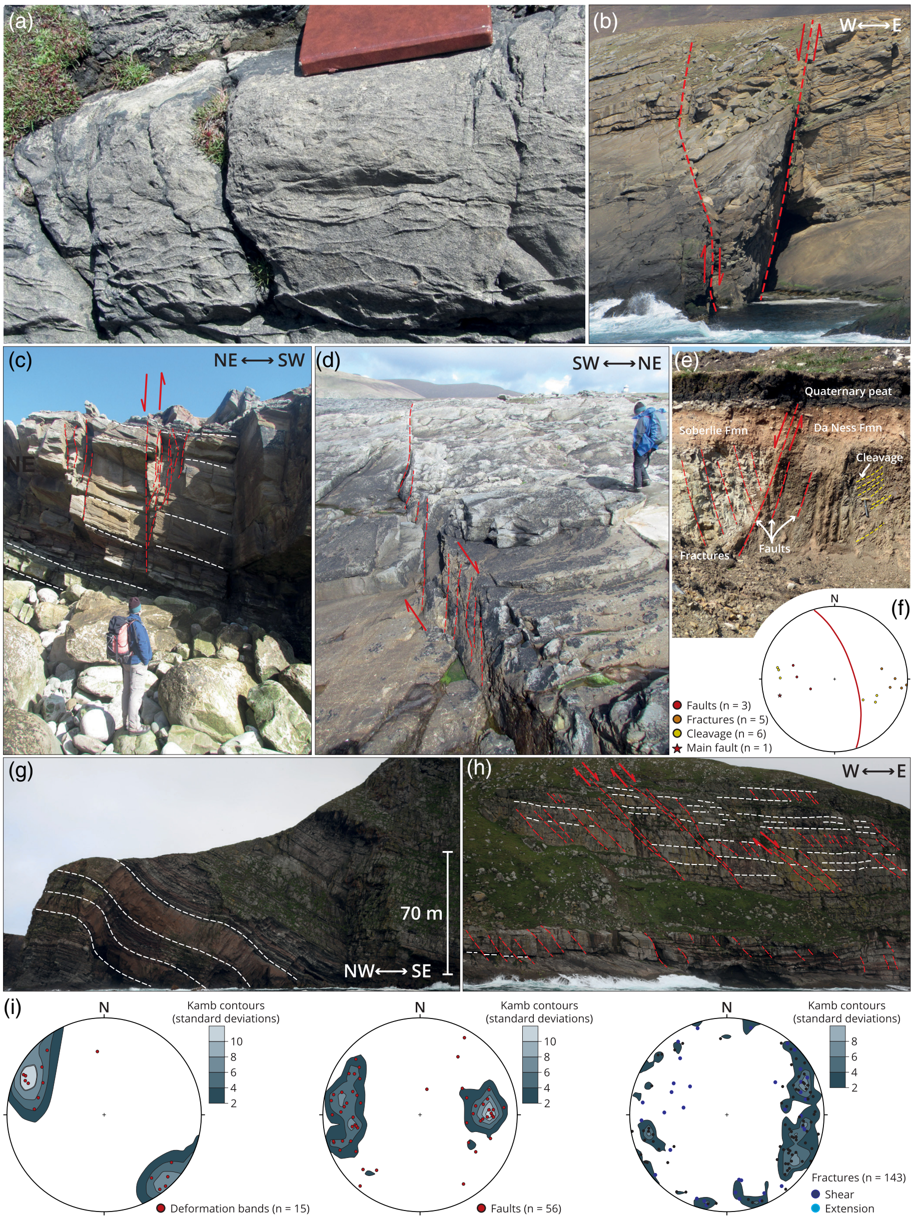

Fig. 9. Devonian structures. (**a**) Deformation bands in sandstones adjacent to north–south normal fault [HT 396980 1136560]. (**b**) Conjugate north–south normal faults in geo at Da Ness [HT 396405 1136695]. (**c**) Oblique view looking NNE of a north–south fracture corridor with polymodal fractures close to Da Rippack Stack [HT 367760 1136350]. (**d**) Oblique view of fracture corridor showing en echelon arrangement of fractures at Da South Ness [HT 396499 1136199]. (**e**) Exposure of the major Foula Fault in small quarry near Hamnabrek [HT 397000 1138320]. (**f**) Stereonet of plane of major fault and poles to planes of cleavage and shear fractures in quarry. (**g**) Minor folding at Da Est Hoevdi [HT 395188 1141176] forming a natural sea arch. These minor folds have variable hinges that plunge gently towards the south to SW. (**h**) Multiple minor normal faults exposed in the cliffs at Da Noup [HT 3953325 1137240]. (**i**) Stereonets of Devonian deformation bands, faults and fractures plotted as contoured poles to planes with mean planes shown as great circles.

confirm the similarity in provenance between sandstones from Foula, Melby, Hoy and the Lower Clair Group. The garnet to zircon ratios are highly variable within samples from Foula (Fig. 12) and may reflect diagenesis due to garnet dissolution (Morton and Hallsworth 1999). Higher garnet to zircon ratios in the samples from Melby may indicate shallower burial and would be consistent with the lower vitrinite reflectance values reported by Hillier and Marshall (1992) for this succession (0.8–1.0) compared with Foula (1.0–1.8). The higher proportion of garnet in the Melby and Soberlie formations may also reflect proximity to local basement source rocks. The lower apatite to tourmaline ratios in some Foula samples are interpreted to be the result of weathering leading to apatite dissolution.

U–Pb laser ablation inductively coupled plasma mass spectrometry detrital zircon geochronology was carried out on five samples (four from Foula and one from Melby) to determine the age and provenance of sediment source regions and enable comparison with published detrital zircon data obtained from the Clair Group and other Devonian sequences of the Orcadian Basin, as well as the Neoproterozoic metasedimentary rocks of the East Mainland Succession that underlies much of Shetland (Fig. 13a–d). The results are displayed as kernel density estimation and multi-dimensional scaling plots (Fig. 13a–d). A total of 476 grains were considered to be reliable, with zircon ages falling in the range 366.1 ± 3.7 to 3483 ± 6.7 Ma, with zircons showing ±10% discordance being discarded. Data tables are presented in the Supplementary Materials, Appendix D.

The kernel density estimation plots suggest that the zircons in the Foula Sandstone Group and Melby Formation reflect a diversity of sediment sources, with the zircon ages falling into three or four main groups: Phanerozoic, Proterozoic (with broad age peaks at *c.* 1200–1000 and 1800–1500 Ma) and Neoarchean (Fig. 13a). These groups are also identifiable within the other Devonian samples from the Clair Group, Shetland and Orkney. The Proterozoic and Neoarchean groups are present within the East Mainland Succession (Fig. 13). The multi-dimensional scaling plots indicate a more variable provenance for the Clair–Foula–Shetland samples compared with the Orkney samples (Fig. 13d). The Foula Sandstone Group and the Melby Formation appear to be intermediate between the Clair Group and Orkney samples.

It is debatable whether the detrital zircon grains are first or second cycle (or more). Within the Foula and Shetland Devonian samples, the Phanerozoic grains are most likely relatively proximal first-cycle detritus because the grade of Caledonian (Ordovician) metamorphism on Shetland was sufficiently high to crystallize new zircon (Cutts *et al.* 2011) and the basement rocks there are intruded by

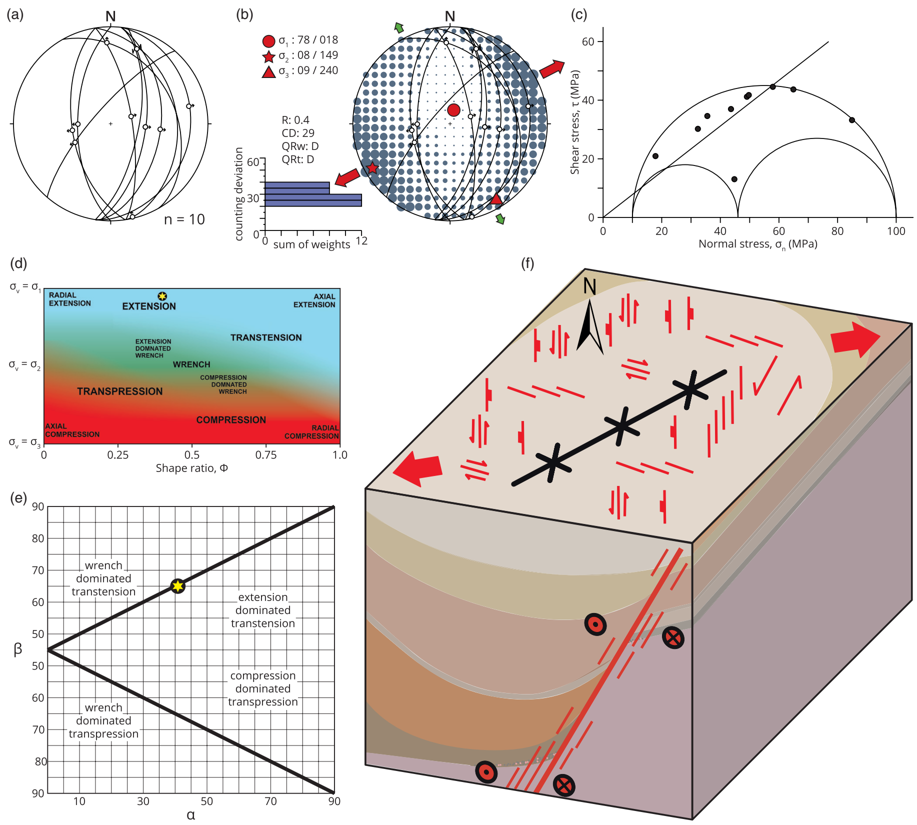

Fig. 10. (**a**) Lower hemisphere equal-angle stereonet plot of analysed faults and slickenlines with fault kinematics. (**b**) r-Dihedron stress inversion analysis. (**c**) Mohr circle diagram for the data shown in part (b). (**d**) Stress regime diagram. (**e**) α v. β plot, where β and α are the angles between the boundary fault and the infinitesimal maximum extension axis and transport direction, respectively. (**f**) 3D structural model for the Foula Fault, the Foula Syncline and associated minor structures. Devonian sequence and basement coloured as in Figure 2.

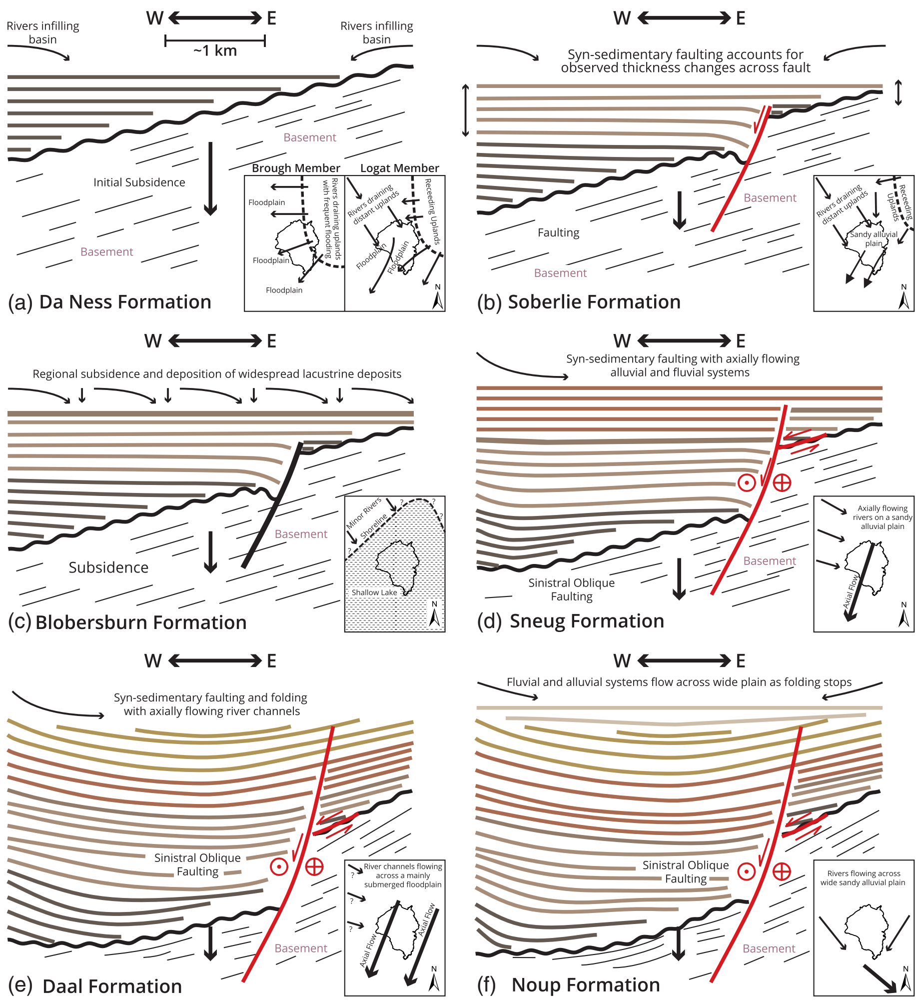

Fig. 11. Integrated basin development model for the Foula Sandstone Group with inset maps of palaeocurrent directions split by formation. Source: based on Blackbourn (1981*c*) supplemented by the new palaeocurrent data shown in Figure 4b.

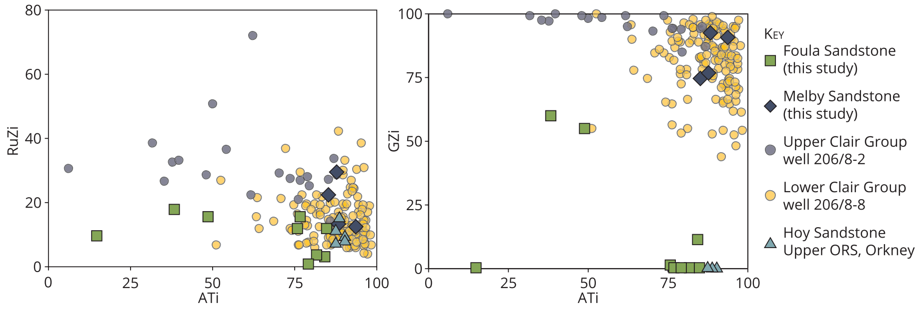

Fig. 12. Heavy mineral provenance relationships between the Foula Sandstone Group, the Melby Formation of Shetland, the Hoy Sandstone of Orkney, and the Lower and Upper Clair Groups of the Clair Field. ATi, apatite:tourmaline index; RuZi, rutile:zircon index; GZi, garnet: zircon index. Source: Morton and Hallsworth (1994); Clair Field data from Morton *et al.* (2010).

Ordovician–Devonian granitic plutons (Lancaster *et al.* 2017). More problematic is whether the older zircon grains are first- or second- (or greater) cycle detritus. There are no exposed proximal basement sources that fall within the age ranges of *c.* 1200–1000 and 1700–1500 Ma within this sector of the North Atlantic. Given the probability that the Phanerozoic grains were proximally derived, it therefore seems likely that at least some of the Proterozoic grains are second-cycle (at least) material derived from reworking of the East Mainland Succession, although sources further afield in East Greenland could also have contributed detritus (Schmidt *et al.* 2012; Saßnowski 2015). By contrast, the Neoarchean grains are plausibly a mix of second-cycle detritus also derived from reworking of the East Mainland Succession and first-cycle material eroded from the basement of this age that underlies much of the Faroe–Shetland terrane west of Shetland (Holdsworth *et al.* 2019*b*) and crops out onshore in North Rona/Uyea (Kinny *et al.* 2019).

The youngest detrital zircons within the Foula Sandstone Group and the Melby Group conflict with the currently accepted Eifelian age for these successions (Marshall and Hewett 2003). Within the Foula Sandstone Group, an average of the three youngest zircons that overlap in age at 2σ gives a maximum depositional age (Dickinson and Gehrels 2009) of *c.* 386 Ma, indicating a Frasnian or younger age. Moreover, the youngest detrital zircon from the Sneug Sandstone gives an Upper Devonian Fammenian age of 366.1 ± 3.7 Ma. The youngest detrital zircon within the Melby Formation yields a Mid-Devonian Givetian to Late Devonian Frasnian age of 382.2 ± 7.7 Ma. The significance of these ages is uncertain given the small sample size and the possibility that the analysed grains may have suffered post-depositional Pb loss: further work is therefore needed to assess their reliability.

Discussion

Regional tectonics and palaeogeography

The Foula Sandstone Group records a dynamic and evolving depositional environment (Table 1). Figure 14 presents a generalized Devonian palaeogeographical map of the Orcadian and Clair basins with post-Devonian, mainly dextral movements along regional strike-slip structures restored, including the Melby, Walls Boundary and Nestings faults. In line with the provenance data, the reconstruction places Foula and the Clair Basin in closer proximity to Orkney and mainland Scotland and separates these areas from the Walls, East Shetland and Fair Isle basins, which lay further to the north.

The opening-upwards, growth folding geometry of the Foula Syncline and the presence of sinistral-normal faults and fracture corridors, orientated sub-parallel and perpendicular to the hinge of the Foula Syncline, are consistent with syndepositional folding and faulting related to sinistral transtension (Figs 10f and 11a–f; Fossen *et al.* 2013) during the Devonian and the development of the Orcadian Basin. This is supported by the results of the stress inversion analysis of slickenline data on Foula (Fig. 10a–e) and is also consistent with observations made by Seranne (1992) from

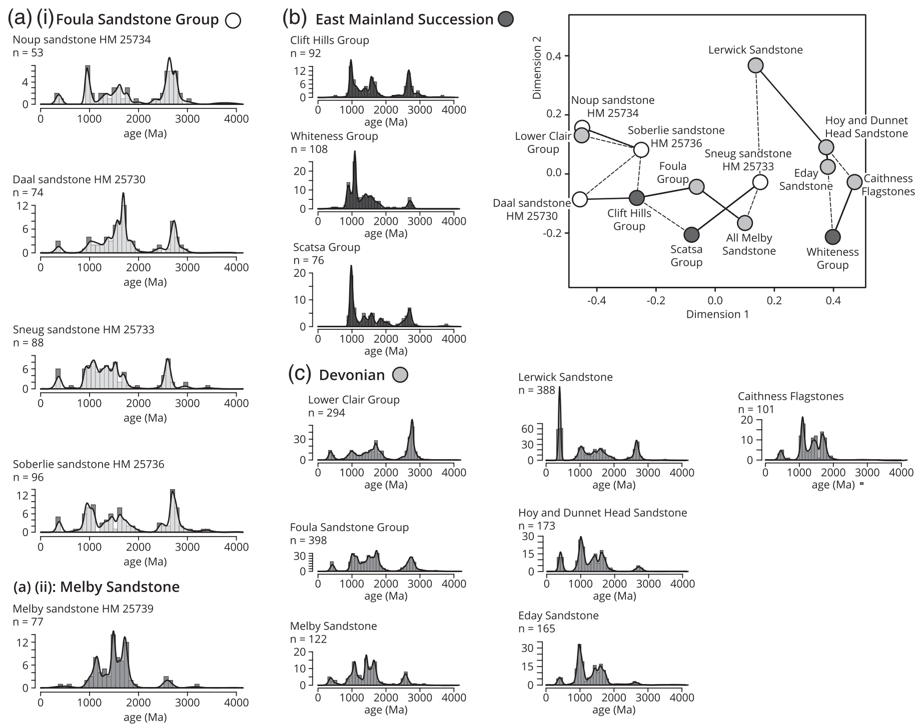

Fig. 13. Kernel density estimation plots of samples analysed for detrital zircon geochronology for samples within: (**a**) this study, including (**i**) the Foula Sandstone Group and (**ii**) the Melby Sandstone; (**b**) published data from the East Mainland Succession of Shetland; and (**c**) the Lower Clair Group, Middle and Upper Devonian of Caithness and Orkney, the Middle Devonian Melby Formation and the Middle Devonian Lerwick Sandstone of Shetland. Data grouped by area and age; *n* is the number of concordant data between −10 and 10% discordance of all data. Note the close similarity in zircon distributions between the Lower Clair Group and the Foula Sandstone Group. (**d**) Multi-dimensional scaling plot of samples showing degree of similarity between analysed and published samples. The solid and dashed lines link the two most similar samples and next most similar samples, respectively. Source: modified after Schmidt *et al.* (2012) and Saßnowski (2015).

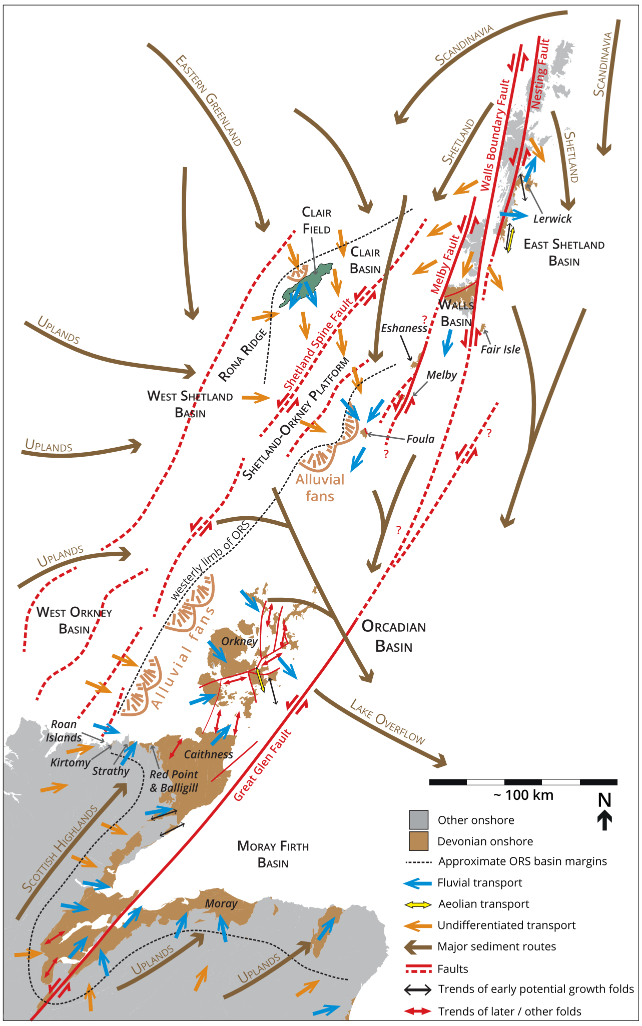

Fig. 14. Devonian palaeogeographic map of the Orcadian and Clair basins showing the major structures, sediment sources and major palaeocurrents. Major sinistral transcurrent faults separate the different Devonian sub-basins, partitioning deformation and the associated structures that controlled basin development. This reconstruction places Foula and Melby in a position between Clair and Orkney, reflecting the new provenance data and integrating them with the observations of Allen and Mange-Rajetzky (1992), Blackbourn (1981*a*, *b*, *c*), Donovan *et al.* (1976), Duindam and van Hoorn (1987), Mykura *et al.* (1976*a*, *b*), Saßnowski (2015), Schmidt *et al.* (2012), Smalley (2011) and Trewin and Thirlwall (2002). ORS, Old Red Sandstone.

Shetland. It is also commensurate with recent models for the transtensional development of the Orcadian Basin as a whole due to sinistral shearing along the Great Glen Fault–WBF system and associated structures (Fig. 14; Dewey and Strachan 2003; Wilson *et al.* 2010; Dichiarante *et al.* 2020; Tamas *et al.* 2021). Similar fold and strike-slip structures are also observed in the Inner Moray Firth (Clarke and Parnell 1999), Greenland (Hartz 2000), the East Shetland Platform (Patruno and Reid 2017) and the Devonian basins of Norway (Seranne and Seguret 1987; Séguret *et al.* 1989; Krabbendam and Dewey 1998). Collectively, all are thought to be related to sinistral oblique transtension and collapse following the sinistral oblique collision of Laurentia and Baltica (Dewey and Strachan 2003; Fossen 2010; Dewey *et al.* 2015).

More generally, the folding seen on Foula is similar in geometry to the low-amplitude, long-wavelength fold structures common throughout Devonian sequences onshore and offshore around northern Scotland, many of which have previously been attributed to Carboniferous or younger inversion events (e.g. Coward *et al.* 1989). This raises the possibility that not all the fold structures in the Orcadian Basin are necessarily solely inversion-related, compressional structures. It is possible that, in at least some cases, Devonian-age transtensional folds have been reactivated and tightened, forming some of the more substantial fold structures, such as the Eday Syncline in Orkney (Mykura *et al.* 1976*a*) and folds associated with the Brough Fault in Caithness (Dichiarante *et al.* 2020). Further work is needed regionally to clarify this possibility.

Implications for offshore basins

The large-scale structural setting of Foula resembles that of the Clair Field in that it comprises Devonian sandstones that overlie a NE–SW-orientated up-faulted ridge of metamorphic basement. The stratigraphy of Foula has strong similarities to that of the Lower Clair Group due to the presence of thick sequences of fluvial and alluvial sediments (Blackbourn 1981*c*, 1987; Table 1). The physical size of Foula is comparable in scale to the Clair Field (Fig. 1a, inset) and may provide a particularly good analogue for the unconformable and fault relationships seen around the Clair Ridge (Fig. 1b). This raises the possibility that models of the Clair Basin require reassessment to determine whether there is evidence for regional sinistral transtension and growth folding during the Devonian, a significant departure from the more traditional extensional models that are generally applied to this basin (e.g. Barr *et al.* 2007; Ogilvie *et al.* 2015; Robertson *et al.* 2020). It is important to add that, on Foula, the absence of definitive post-Devonian deformation contrasts with the Clair Field, where most of the important structures are Permian or younger (Holdsworth *et al.* 2019*a*; Robertson *et al.* 2020). Thus the Devonian rocks of Caithness, where the effects of Permian faulting related to the development of the West Orkney Basin are widespread (see Dichiarante *et al.* 2016, 2020), probably continue to represent a better analogue for the Clair Field in terms of the fracture systems that it displays in the subsurface.

Folds and trapping geometries that developed early in the Devonian basins, and not during later reactivation and/or inversion, could have important implications for modelling the petroleum systems of the offshore West Orkney Basin and East Shetland Platform, together with basins SE of the Great Glen Fault in the Central North Sea and Moray Firth regions (e.g. Whitbread and Kearsey 2016). Potential growth-fold-related hydrocarbon-trapping geometries may have developed in Devonian reservoir sequences during basin formation and in proximity to potential Devonian lacustrine source rocks, which, in the Orcadian Basin, were mature during the Carboniferous (Astin 1985, 1990; Marshall *et al.* 1985; Hillier and Marshall 1992; Parnell *et al.* 1998; Vane *et al.* 2016). Potential scenarios of this kind have been recorded onshore in Caithness by Baba *et al.* (2018) and in parts of Scandinavia (Rønningen 2015). Offshore Devonian lacustrine source rocks are also known to contribute to the Beatrice, Oseberg, Judy and Embla oilfields (Stevens 1991). Fold traps may therefore have initiated across a wide region of the UK continental shelf prior to Permo-Carboniferous (or younger) basin inversion and exhumation and would have remained available for later reactivation and/or hydrocarbon charge.

Conclusions

The Devonian rocks of Foula (and nearby Melby) show sedimentological, heavy mineral and detrital zircon characteristics that are intermediate between those of the lower part of the Clair Basin fill to the NW and the Orcadian Basin to the SE. Faulting and folding on Foula were contemporaneous with sedimentation during basin filling and can be related to regional constrictional strain due to sinistral transtension associated with movements along the Walls Boundary–Great Glen fault zone system during the Mid-Devonian. Transtensional fold development contemporaneous with regional subsidence may be more widespread than previously realized in the onshore and offshore Devonian basins of Scotland, meaning that kilometre-scale folds previously interpreted to be related to later inversion may therefore have initiated much earlier in the evolution of the basin.

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Author contributions **TAGU**: data curation (lead), formal analysis (lead), investigation (lead), visualization (lead), writing – original draft (lead), writing – review & editing (supporting); **REH**: conceptualization (lead), funding acquisition (lead), investigation (supporting), project administration (lead), supervision (lead), writing – original draft (supporting), writing – review & editing (lead); **GAB**: investigation (supporting), supervision (supporting), writing – original draft (supporting), writing – review & editing (supporting); **ED**: data curation (equal), investigation (supporting), supervision (supporting), writing – review & editing (supporting); **RAS**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **KJWM**: supervision (supporting), writing – review & editing (supporting); **ACM**: data curation (equal), formal analysis (supporting), investigation (supporting), writing – original draft (supporting), writing – review & editing (supporting); **AFB**: data curation (supporting), formal analysis (supporting), investigation (supporting), writing – review & editing (supporting); **RRJ**: data curation (supporting), methodology (supporting), supervision (supporting); **AS**: data curation (supporting), formal analysis (supporting), investigation (supporting); **RJW**: visualization (supporting), writing – review & editing (supporting).

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Data availability All data generated or analysed during this study are included in this published article (and if present, its supplementary information files).

References

Allen, P.A. 1979. *Sedimentological Aspects of the Devonian Strata of SE Shetland*. PhD thesis, University of Cambridge.

Allen, P.A. 1981*a*. Devonian lake margin environments and processes, SE Shetland, Scotland. *Journal of the Geological Society, London*, **138**, 1–14, https://doi.org/10.1144/gsjgs.138.1.0001

Allen, P.A. 1981*b*. Wave-generated structures in the Devonian lacustrine sediments of SE Shetland and ancient wave conditions. *Sedimentology*, **28**, 369–380, https://doi.org/10.1111/j.1365-3091.1981.tb01686.x

Allen, P.A. 1982. Cyclicity of Devonian fluvial sedimentation, Cunningsburgh Peninsula, SE Shetland. *Journal of the Geological Society, London*, **139**, 49–58, https://doi.org/10.1144/gsjgs.139.1.0049

Allen, P.A. and Mange-Rajetzky, M.A. 1992. Devonian–Carboniferous sedimentary evolution of the Clair area, offshore north-western UK: impact of changing provenance. *Marine and Petroleum Geology*, **9**, 29–52, https://doi.org/10.1016/0264-8172(92)90003-W

Allen, P.A. and Marshall, J.E.A. 1981. Depositional environments and palynology of the Devonian South-East Shetland Basin. *Scottish Journal of Geology*, **17**, 257–273, https://doi.org/10.1144/sjg17040257

Allmendinger, R.W., Cardozo, N. and Fisher, D.M. 2011. *Structural Geology Algorithms: Vectors and Tensors*. Cambridge University Press.

Andrews, I. 1985. The deep structure of the Moine Thrust. *Scottish Journal of Geology*, **21**, 213–217, https://doi.org/10.1144/sjg21020213

Andrews, S.D., Cornwell, D.G., Trewin, N.H., Hartley, A.J. and Archer, S.G. 2016. A 2.3 million year lacustrine record of orbital forcing from the Devonian of northern Scotland. *Journal of the Geological Society, London*, **173**, 474–488, https://doi.org/10.1144/jgs2015-128

Armitage, T.B., Watts, L.M., Holdsworth, R.E. and Strachan, R.A. 2021. Late Carboniferous dextral transpressional reactivation of the crustal-scale Walls Boundary Fault, Shetland: the role of pre-existing structures and lithological heterogeneities. *Journal of the Geological Society, London*, **178**, https://doi.org/10.1144/jgs2020-078

Astin, T.R. 1985. The palaeogeography of the Middle Devonian Lower Eday Sandstone, Orkney. *Scottish Journal of Geology*, **21**, 353–375, https://doi.org/10.1144/sjg21030353

Astin, T.R. 1990. The Devonian lacustrine sediments of Orkney, Scotland; implications for climate cyclicity, basin structure and maturation history. *Journal of the Geological Society, London*, **147**, 141–151, https://doi.org/10.1144/gsjgs.147.1.0141

Baba, M., Parnell, J., Muirhead, D. and Bowden, S. 2018. Oil charge and biodegradation history in an exhumed fractured reservoir, Devonian, UK. *Marine and Petroleum Geology*, **101**, 281–289, https://doi.org/10.1016/j.marpetgeo.2018.12.024

Barr, D., Savory, K.E., Fowler, S.R., Arman, K. and McGarrity, J.P. 2007. Pre-development fracture modelling in the Clair field, west of Shetland. *Geological Society, London, Special Publications*, **270**, 205–225, https://doi.org/10.1144/gsl.sp.2007.270.01.14

BGS 1988. *Foula Sheet 60 N–- 04 W Solid Geology 1:250000 Series*. Ordnance Survey, for the British Geological Survey.

Blackbourn, G.A. 1981*a*. Correlation of Old Red Sandstone (Devonian) outliers in the Northern Highlands of Scotland. *Geological Magazine*, **118**, 409–414, https://doi.org/10.1017/S0016756800032283

Blackbourn, G.A. 1981*b*. Probable Old Red Sandstone conglomerates around Tongue and adjacent areas, north Sutherland. *Scottish Journal of Geology*, **17**, 103–118, https://doi.org/10.1144/sjg17020103

Blackbourn, G.A. 1981*c*. *Red Bed Successions on the Western Seaboard of Scotland*. PhD thesis, Strathclyde University.

Blackbourn, G.A. 1987. Sedimentary environments and stratigraphy of the Late Devonian–Early Carboniferous Clair Basin, west of Shetland. *In:*Miller, J., Adams, A.E. and Wright, V.P. (eds) *European Dinantian Environments*. Wiley, Chichester, 75–91.

Burnham, B.S. and Hodgetts, D. 2019. Quantifying spatial and architectural relationships from fluvial outcrops. *Geosphere*, **15**, 236–253, https://doi.org/10.1130/GES01574.1

Clarke, P. and Parnell, J. 1999. Facies analysis of a back-tilted lacustrine basin in a strike-slip zone, Lower Devonian, Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **151**, 167–190, https://doi.org/10.1016/S0031-0182(99)00020-6

Coney, D., Fyfe, T.B.B., Retail, P. and Smith, P.J.J. 1993. Clair appraisal: the benefits of a co-operative approach. *Geological Society, London, Petroleum Geology Conference Series*, **4**, 1409–1420, https://doi.org/10.1144/0041409

Coward, M.P., Enfield, M.A. and Fischer, M.W. 1989. Devonian basins of Northern Scotland: extension and inversion related to Late Caledonian–Variscan tectonics. *Geological Society, London, Special Publications*, **44**, 275–308, https://doi.org/10.1144/GSL.SP.1989.044.01.16

Cutts, K.A., Hand, M., Kelsey, D.E. and Strachan, R.A. 2011. P–T constraints and timing of Barrovian metamorphism in the Shetland Islands, Scottish Caledonides: implications for the structural setting of the Unst ophiolite. *Journal of the Geological Society, London*, **168**, 1265–1284, https://doi.org/10.1144/0016-76492010-165

Dewey, J.F. and Strachan, R.A. 2003. Changing Silurian–Devonian relative plate motion in the Caledonides: sinistral transpression to sinistral transtension. *Journal of the Geological Society, London*, **160**, 219–229, https://doi.org/10.1144/0016-764902-085

Dewey, J.F., Dalziel, I.W.D., Reavy, R.J. and Strachan, R.A. 2015. The Neoproterozoic to Mid-Devonian evolution of Scotland: a review and unresolved issues. *Scottish Journal of Geology*, **51**, 5–30, https://doi.org/10.1144/sjg2014-007

Dichiarante, A.M., Holdsworth, R.E. *et al.* 2016. New structural and Re–Os geochronological evidence constraining the age of faulting and associated mineralization in the Devonian Orcadian Basin, Scotland. *Journal of the Geological Society, London*, **173**, 457–473, https://doi.org/10.1144/jgs2015-118

Dichiarante, A.M., Holdsworth, R.E., Dempsey, E., McCaffrey, K.J.W. and Utley, T.A.G. 2020. The outcrop-scale manifestations of reactivation during multiple superimposed rifting and basin inversion events: the Devonian Orcadian Basin, northern Scotland. *Journal of the Geological Society, London*, **178**, jgs2020-089, https://doi.org/10.1144/jgs2020-089

Dickinson, W.R. and Gehrels, G.E. 2009. Use of U–Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic database. *Earth and Planetary Science Letters*, **288**, 115–125, https://doi.org/10.1016/j.epsl.2009.09.013

Donovan, R.N., Archer, R., Turner, P. and Tarling, D.H. 1976. Devonian palaeogeography of the Orcadian Basin and the Great Glen Fault. *Nature*, **259**, 550–551, https://doi.org/10.1038/259550a0

Donovan, R.N., Collins, A., Rowlands, M.A. and Archer, R. 1978. The age of sediments on Foula, Shetland. *Scottish Journal of Geology*, **14**, 87–88, https://doi.org/10.1144/sjg14010087

Duindam, P. and van Hoorn, B. 1987. Structural evolution of the West Shetland continental margin. *In:* Brooks J. and Glennie K.W. (eds) *Petroleum Geology of Northwest Europe*. Graham and Trotman, 765–773.

Finlay, T.M., Woodward, A.S. and White, E.I. 1926. The Old Red Sandstone of Shetland. Part I. South-eastern area. With an account of the fossil fishes of the Old Red Sandstone of the Shetland Islands. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **54**, 553–572, https://doi.org/10.1017/S0080456800016094

Flinn, D. 1977. The erosion history of Shetland: a review. *Proceedings of the Geologists' Association*, **88**, 129–146, https://doi.org/10.1016/S0016-7878(77)80023-0

Flinn, D. 1979. The Walls Boundary fault, Shetland, British Isles. *United States Geological Survey, Open File Reports*, **79**, 181–200.

Flinn, D. 1992. The history of the Walls Boundary fault, Shetland: the northward continuation of the Great Glen fault from Scotland. *Journal of the Geological Society, London*, **149**, 721–726, https://doi.org/10.1144/gsjgs.149.5.0721

Flinn, D., Frank, P.L., Brook, M. and Pringle, I.R. 1979. Basement–cover relations in Shetland. *Geological Society, London, Special Publications*, **8**, 109–115, https://doi.org/10.1144/GSL.SP.1979.008.01.09

Fossen, H. 2010. Extensional tectonics in the North Atlantic Caledonides: a regional view. *Geological Society, London, Special Publications*, **335**, 767–793, https://doi.org/10.1144/SP335.31

Fossen, H., Teyssier, C. and Whitney, D.L. 2013. Transtensional folding. *Journal of Structural Geology*, **56**, 89–102, https://doi.org/10.1016/j.jsg.2013.09.004

Friend, P.F. 1981. Devonian sedimentary basins and deep faults of the northernmost Atlantic borderlands. *Memoirs of the Canadian Society of Petroleum Geologists*, **7**, 149–165.

Friend, P.F., Williams, B.P.J., Ford, M. and Williams, E.A. 2000. Kinematics and dynamics of Old Red Sandstone basins. *Geological Society, London, Special Publications*, **180**, 29–60, https://doi.org/10.1144/GSL.SP.2000.180.01.04

Hansom, J.D. 2003. Foula. *In:* May, V.J. and Hansom, J.D. (eds) *Coastal Geomorphology of Great Britain*. Geological Conservation Review Series, **28**. Joint Nature Conservation Committee, Peterborough, pp. 76–81.

Hartz, E. 2000. Early syndepositional tectonics of East Greenland's Old Red Sandstone basin. *Geological Society, London, Special Publications*, **180**, 537–555, https://doi.org/10.1144/GSL.SP.2000.180.01.28

Hillier, S. and Marshall, J.E.A. 1992. Organic maturation, thermal history and hydrocarbon generation in the Orcadian Basin, Scotland. *Journal of the Geological Society, London*, **149**, 491–502, https://doi.org/10.1144/gsjgs.149.4.0491

Holdsworth, R.E., McCaffrey, K.J.W. *et al.* 2019*a*. Natural fracture propping and earthquake-induced oil migration in fractured basement reservoirs. *Geology*, **47**, 700–704, https://doi.org/10.1130/G46280.1

Holdsworth, R.E., Morton, A. *et al.* 2019*b*. The nature and significance of the Faroe–Shetland terrane: linking Archaean basement blocks across the North Atlantic. *Precambrian Research*, **321**, 154–171, https://doi.org/10.1016/j.precamres.2018.12.004

Holliday, D.W., Holmes, D.C. and the Joint Interpretation Team. 1994. *The geology of the region around Dounreay: Report of the Regional Geology*. UK Nirex Limited.

Jahn, I., Strachan, R.A., Fowler, M., Bruand, E., Kinny, P.D., Clark, C. and Taylor, R.J.M. 2017. Evidence from U–Pb zircon geochronology for early Neoproterozoic (Tonian) reworking of an Archaean inlier in northeastern Shetland, Scottish Caledonides. *Journal of the Geological Society, London*, **174**, 217–232, https://doi.org/10.1144/jgs2016-054

Kinny, P.D., Strachan, R.A. *et al.* 2019. The Neoarchaean Uyea Gneiss Complex, Shetland: an onshore fragment of the Rae Craton on the European plate. *Journal of the Geological Society, London*, **176**, 847–862, https://doi.org/10.1144/jgs2019-017

Krabbendam, M. and Dewey, J.F. 1998. Exhumation of UHP rocks by transtension in the Western Gneiss Region, Scandinavian Caledonides. *Geological Society, London, Special Publications*, **135**, 159–181, https://doi.org/10.1144/GSL.SP.1998.135.01.11

Lancaster, P.J., Strachan, R.A., Bullen, D., Fowler, M., Jaramillo, M. and Saldarriaga, A.M. 2017. U–Pb zircon geochronology and geodynamic significance of 'Newer Granite' plutons in Shetland, northernmost Scottish Caledonides. *Journal of the Geological Society, London*, **174**, 486–497, https://doi.org/10.1144/jgs2016-106

Leeder, M. 1987. Sediment deformation structures and the palaeotectonic analysis of sedimentary basins, with a case-study from the Carboniferous of northern England. *Geological Society, London, Special Publications*, **29**, 137–146, https://doi.org/10.1144/GSL.SP.1987.029.01.12

Marshall, J.E.A. and Hewett, A.J. 2003. Devonian. *In:*Evans, D., Graham, C., Armour, A. and Bathurst, P. (eds) *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*. Geological Society, London, 65–81.

Marshall, J.E.A., Brown, J.F. and Hindmarsh, S. 1985. Hydrocarbon source rock potential of the Devonian rocks of the Orcadian Basin. *Scottish Journal of Geology*, **21**, 301–320, https://doi.org/10.1144/sjg21030301

McBride, J.H. 1994. Structure of a continental strike-slip fault from deep seismic reflection: Walls Boundary fault, northern British Caledonides. *Journal of Geophysical Research: Solid Earth*, **99**, 23985–24005, https://doi.org/10.1029/94JB00902

McGeary, S. 1989. Reflection seismic evidence for a Moho offset beneath the Walls Boundary strike-slip fault. *Journal of the Geological Society, London*, **146**, 261–269, https://doi.org/10.1144/gsjgs.146.2.0261

Melvin, J. 1985. Walls Formation, Western Shetland: distal alluvial plain deposits within a tectonically active Devonian basin. *Scottish Journal of Geology*, **21**, 23–40, https://doi.org/10.1144/sjg21010023

Morton, A.C. and Hallsworth, C. 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. *Sedimentary Geology*, **90**, 241–256, https://doi.org/10.1016/0037-0738(94)90041-8

Morton, A.C. and Hallsworth, C.R. 1999. Processes controlling the composition of heavy mineral assemblages in sandstones. *Sedimentary Geology*, **124**, 3–29, https://doi.org/10.1016/S0037-0738(98)00118-3

Morton, A.C., Hallsworth, C.R., Kunka, J., Laws, E, Payne, S. and Walder, D. 2010. Heavy mineral stratigraphy of the Clair Group (Devonian) in the Clair Field, west of Shetland, UK. *SEPM Special Publications*, **94**, 183–199, https://doi.org/10.2110/sepmsp.094.183

Mykura, W. 1976. *Orkney and Shetland*. British Regional Geology, Institute of Geological Sciences, Edinburgh.

Mykura, W., Flinn, D. and May, F. 1976*a*. *British Regional Geology: Orkney and Shetland*. HMSO.

Mykura, W., Phemister, J. and Sabine, P.A. 1976*b*. *The Geology of Western Shetland: Explanation of One-Inch Geological Sheet Western Shetland, Comprising Sheet 127 and Parts of 125, 126 and 128*. HMSO.

Ogilvie, S., Barr, D., Roylance, P. and Dorling, M. 2015. Structural geology and well planning in the Clair Field. *Geological Society, London, Special Publications*, **421**, 197–212, https://doi.org/10.1144/SP421.7

Oil and Gas Authority 2019. *Oil and Gas Authority Open Data*, http://data.ogauthority.opendata.arcgis.com/

Parnell, J., Carey, P. and Monson, B. 1998. Timing and temperature of decollement on hydrocarbon source rock beds in cyclic lacustrine successions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **140**, 121–134, https://doi.org/10.1016/S0031-0182(98)00035-2

Patruno, S. and Reid, W. 2017. New plays on the greater east Shetland platform (UKCS quadrants 3, 8–9, 14–16)—part 2: newly reported Permo-Triassic intra-platform basins and their influence on the Devonian–Paleogene prospectivity of the area. *First Break*, **35**, 59–69, https://doi.org/10.3997/1365-2397.2016017

Ritchie, J.D. and Hitchen, K. 1993. Discussion on the location and history of the Walls Boundary fault and Moine thrust north and south of Shetland. *Journal of the Geological Society, London*, **150**, 1003–1008, https://doi.org/10.1144/gsjgs.150.5.1003

Ritchie, J.D., Ziska, H., Johnson, H. and Evans, D. 2011. *Geology of the Faroe–Shetland Basin and adjacent areas*. BGS Research Report RR/11/01.

Robertson, A., Ball, M. *et al.* 2020. The Clair field, blocks 206/7a, 206/8, 206/9a, 206/12a and 206/13a. UK Atlantic margin. *Geological Society, London, Memoirs*, **52**, 931–951, https://doi.org/10.1144/M52-2018-76

Rogers, D.A., Marshall, J.E.A. and Astin, T.R. 1989. Short paper: Devonian and later movements on the Great Glen fault system, Scotland. *Journal of the Geological Society*, **146**, 369–372, https://doi.org/10.1144/gsjgs.146.3.0369

Rønningen, A. 2015. The first attempt to correlate the migrated bitumen from the Helgeland Basin cores to Devonian source rocks and oils from the UK Orcadian Basin – is there a Devonian Orcadian type basin offshore Norway? Unpublished Masters thesis, University of Oslo, http://hdl.handle.net/10852/45554

Saßnowski, A. 2015. *Palaeogeographic Implications of Heavy Mineral and Detrital Zircon Provenance of Devonian–Carboniferous Sedimentary Rocks in the North Atlantic Region*. PhD thesis, Royal Holloway University of London.

Schmidt, A.S., Morton, A.C., Nichols, G.J. and Fanning, C.M. 2012. Interplay of proximal and distal sources in Devonian–Carboniferous sandstones of the Clair Basin, west of Shetland, revealed by detrital zircon U–Pb ages. *Journal of the Geological Society, London*, **169**, 691–702, https://doi.org/10.1144/jgs2011-148

Séguret, M., Séranne, M., Chauvet, A. and Brunel, A. 1989. Collapse basin: a new type of extensional sedimentary basin from the Devonian of Norway. *Geology*, **17**, 127–130, https://doi.org/10.1130/0091-7613(1989)017<0127:CBANTO>2.3.CO;2

Seranne, M. 1992. Devonian extensional tectonics versus Carboniferous inversion in the northern Orcadian basin. *Journal of the Geological Society, London*, **149**, 27–37, https://doi.org/10.1144/gsjgs.149.1.0027

Seranne, M. and Seguret, M. 1987. The Devonian basins of western Norway: tectonics and kinematics of an extending crust. *Geological Society, London, Special Publications*, **28**, 537–548, https://doi.org/10.1144/GSL.SP.1987.028.01.35

Smalley, A. 2011. Fluvial paleotransport derived from trough cross-bedding: example from the Lower Clair Group, west of Shetland, using oriented whole-core images. *SEPM Special Publications*, **97**, 153–166, https://doi.org/10.2110/sepmsp.097.153

Stevens, V. 1991. The Beatrice field, block 11/30a, UK North sea. *Geological Society, London, Memoirs*, **14**, 245–252, https://doi.org/10.1144/GSL.MEM.1991.014.01.30

Tamas, A., Holdsworth, R.E. *et al.* 2021. New onshore insights into the role of structural inheritance during Mesozoic opening of the Inner Moray Firth Basin, Scotland. *Journal of the Geological Society, London*, **179**, jgs2021-066, https://doi.org/10.1144/jgs2021-066

Tamas, A., Holdsworth, R.E. *et al.* 2022. Correlating deformation events onshore and offshore in superimposed rift basins: the Lossiemouth Fault Zone, Inner Moray Firth Basin, Scotland. *Basin Research*, **34**, 1314–1340, https://doi.org/10.1111/bre.12661

Trewin, N.H. and Thirlwall, M.F. 2002. Old Red Sandstone. *In:* Trewin, N.H. (ed.) *The Geology of Scotland*. 4th edn. Geological Society, London, 213–249.

Utley, T.A.G. 2020. *Basement–Cover Relationships and Regional Structure in the Transtensional Orcadian Basin*. PhD thesis, Durham University.

Vane, C.H., Ugana, C., Kim, A.W. and Monaghan, A.A. 2016. *Organic Geochemistry of Palaeozoic Source Rocks, Orcadian Study Area, North Sea, UK*. British Geological Survey, Commissioned Report **CR/16/037**.

Watts, L.M., Holdsworth, R.E., Sleight, J.A., Strachan, R.A. and Smith, S.A.F. 2007. The movement history and fault rock evolution of a reactivated crustal-scale strike-slip fault: the Walls Boundary Fault Zone, Shetland. *Journal of the Geological Society, London*, **164**, 1037–1058, https://doi.org/10.1144/0016-76492006-156

Whitbread, K. and Kearsey, T. 2016. *Devonian and Carboniferous Stratigraphical Correlation and Interpretation in the Orcadian Area, Central North Sea, Quadrants 7–22*. British Geological Survey, Commissioned Report **CR/16/032**.

Wilson, R.W., Holdsworth, R.E., Wild, L.E., McCaffrey, K.J.W., England, R.W., Imber, J. and Strachan, R.A. 2010. Basement-influenced rifting and basin development: a reappraisal of post-Caledonian faulting patterns in the North Coast Transfer Zone, Scotland. *Geological Society, London, Special Publications*, **335**, 795–826, https://doi.org/10.1144/SP335.32

Witt, A.J., Fowler, S.R., Kjelstadli, R.M., Draper, L.F., Barr, D. and McGarrity, J.P. 2010. Managing the start-up of a fractured oil reservoir: development of the Clair field, west of Shetland. *Geological Society, London, Petroleum Geology Conference Series*, **7**, 299–313, https://doi.org/10.1144/0070299