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A rift-to-drift record of vertical crustal motions in the Faroe–Shetland Basin, NW European margin: establishing constraints on NE Atlantic evolution

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Abstract: The Upper Paleocene–Eocene rock record in the Faroe–Shetland Basin is punctuated by a series of unconformities that reflect a persistent tectonic instability throughout the syn- to early post-breakup period, a duration of about 20 myr. A particular focus is on a Late Paleocene subaerial unconformity, herein termed the Flett unconformity, which has been argued to have formed in response to a transient pulse of mantle convective uplift associated with a proto-Iceland plume. However, ambiguity over its presumed correlation with the Faroe Islands Basalt Group combined with stratigraphic and palaeogeographical analysis of the Upper Paleocene–Eocene succession indicates that it is just one of a series of subaerial unconformities that are spatially linked to the same part of the Faroe–Shetland Basin. Most of these Late Paleocene–Eocene unconformities post-date volcanism, and their formation coincides with vertical motions associated with phases of uplift, inversion and compressional deformation linked to the growth of structures, such as the Wyville Thomson and Munkagrunnur ridges, and the Judd Anticline. These deformation phases are broadly coeval with intraplate and plate-boundary events in the wider NE Atlantic region. The possibility that the Flett unconformity had a similar tectonic origin should not be discounted.

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Vertical crustal motions are an integral part of the plate-tectonic paradigm. According to Dewey (1982), they occur primarily as a response to the extension and contraction of the lithosphere, that is, a secondary response to lateral movements (e.g. plate-tectonic-related processes), although other mechanisms, including mantle thermal anomalies (e.g. mantle plumes), are locally important. Using vertical motions to compare plate- and plume-related processes against one another may be difficult as they both predict uplift and subsidence (Foulger 2010). On the Atlantic continental margin of NW Europe, the Faroe–Shetland Basin (Fig. 1) provides one such example where the interpretation of the early Paleogene history of vertical motions has resulted in two contrasting geodynamic models of plate breakup and post-rift shaping of this margin. In a number of studies, Late Paleocene syn-breakup vertical crustal movements have been linked to uplift induced by a mantle plume (Shaw Champion *et al.* 2008; Hartley *et al.* 2011), followed by post-breakup subsidence and tectonic quiescence attributed to the loss of thermal support as seafloor spreading commenced (Jones *et al.* 2002; Smallwood & Gill 2002). An alternative view based on plate-tectonic mechanisms ascribes the syn-breakup movements and volcanism to rifting processes as part of the natural response to plate breakup (Ziska & Varming 2008; Ellis & Stoker 2014; Mudge 2015), whereas a complex post-breakup history of compressional tectonics and uplift has been linked to intraplate shortening controlled primarily by plate boundary forces (Holford *et al.* 2009; Stoker *et al.* 2010).

Advocates of the mantle plume model interpret a Late Paleocene subaerial unconformity, herein referred to as the Flett unconformity (Fig. 2; Table 1), at the southern end of the Faroe–Shetland Basin as the surface expression of plume-generated maximum uplift (Smallwood & Gill 2002; Shaw Champion *et al.* 2008; Lovell 2010; Hartley *et al.* 2011). A key element of this model is the assumption that the formation of the unconformity coincided with peak volcanic activity at the time of breakup in the NE Atlantic region (Shaw Champion *et al.* 2008, fig. 2). However, this correlation remains ambiguous. In the Faroe–Shetland region, breakup-related volcanism is represented by the Faroe Islands Basalt Group, part of the North Atlantic Igneous Province, which comprises a *c.* 6.6 km thick succession of predominantly subaerial basalt lava flows (Passey & Jolley 2008). Other indicators of volcanic activity include intrusive magmatism, such as the Faroe–Shetland Sill Complex (see Passey & Hitchen 2011) and tuffaceous beds (Mudge 2015; Watson *et al.* 2017). Whereas the intrusion of the Faroe–Shetland Sill Complex spanned most of the Paleocene–earliest Eocene interval (Schofield *et al.* 2017), and tuffaceous activity began in the Selandian (T22 – 35, 61.6 – 59.2 Ma) (Mudge 2015; Watson *et al.* 2017), a persistent lack of consensus has surrounded the chronology of the Faroe Islands Basalt Group for almost two decades. There are currently two schools of thought (Fig. 3), as follows.

(1) On the basis of biostratigraphic data alone, a number of researchers (e.g. Jolley *et al.* 2002; Passey & Jolley 2008; Jolley 2009) have proposed that the extrusion of the entire Faroe Islands Basalt Group occurred exclusively during chron C24r (latest Thanetian–earliest Ypresian time, *c.* 57 – 54.5 Ma), which Schofield & Jolley (2013) recently assigned to the interval 56.1 – 54.9 Ma.
(2) A combined radiometric, magnetostratigraphic and biostratigraphic dataset (e.g. Riisager *et al.* 2002; Waagstein *et al.* 2002; Storey *et al.* 2007; Mudge 2015; Wilkinson *et al.* 2017) implies a longer stratigraphic range for the Faroe Islands Basalt Group spanning Selandian–earliest Ypresian time (chron C26r–C24r, *c.* 61 – 54.9 Ma).

As long as this debate remains unresolved any correlation between the Faroe Islands Basalt Group, either in part or whole, and

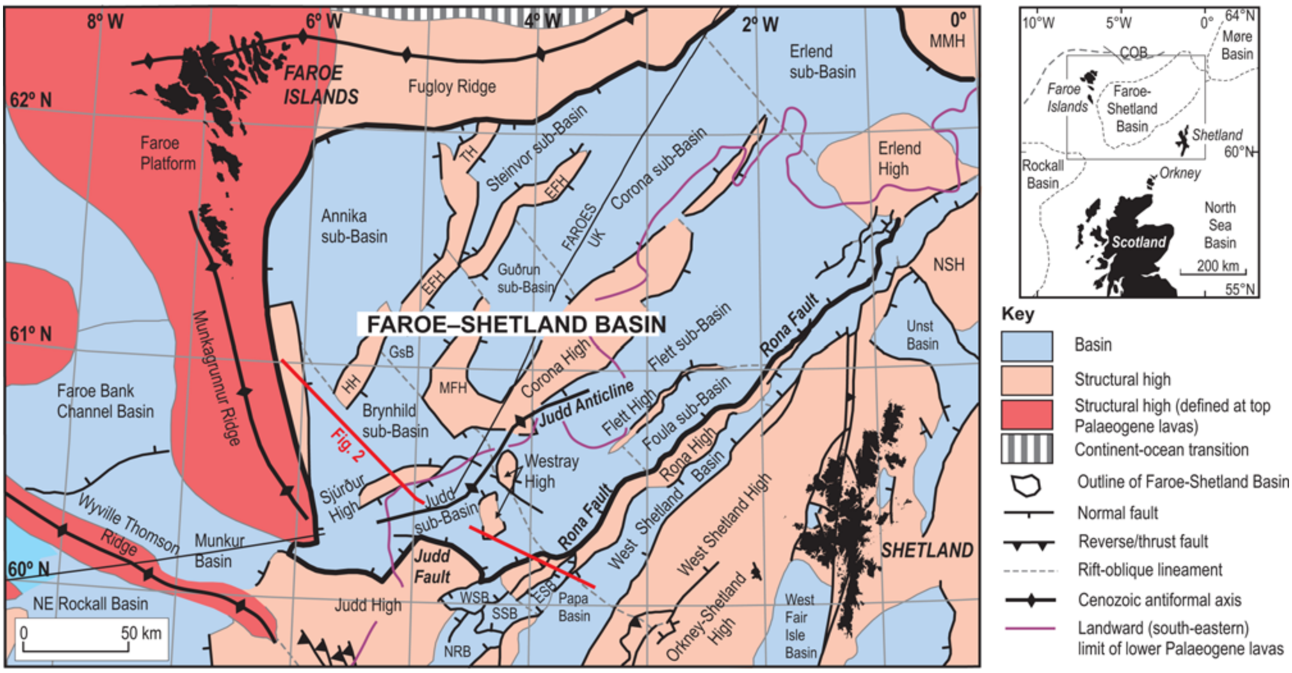

Fig. 1. Map showing location and structural setting of study area, together with position of geoseismic section in Figure 2. Structural elements are based on Ritchie *et al.* (2011*b*) and Stoker (2016), to which the reader is referred for more detailed information. Inset shows regional setting of Faroe–Shetland Basin. COB, continent–ocean boundary; EFH, East Faroe High; ESB, East Solan Basin; GsB, Grimhild sub-Basin; HH, Heri High; MFH, Mid Faroe High; MMH, Møre Marginal High; NRB, North Rona Basin; NSH, North Shetland High; SSB, South Solan Basin; TH, Tróndur High; WSB, West Solan Basin.

the Flett unconformity remains subjective. An alternative, more prolonged model of breakup-related volcanic eruption has been presented by Mudge (2015) (Fig. 3), and comprises several phases of volcanism and sedimentation linked to early Paleogene basin formation, uplift and the development of multiple unconformities, including the Flett unconformity. In this scenario, magmatic activity is interpreted to be a more passive process, following extension by the exploitation of pre-existing structural weaknesses (Ziska & Varming 2008).

Context is also an important consideration, both spatial and temporal. Pre-rift Late Cretaceous and Paleocene and post-rift Eocene and later Cenozoic uplifts and deformations are spatially linked to the same part of the Faroe–Shetland Basin as the inferred plume-generated uplift, and are equally co-extensive (Ritchie *et al.* 2008; Stoker *et al.* 2013; Tassone *et al.* 2014; Stoker 2016). Moreover, the structural disposition of the Paleocene–Eocene succession displayed in Figure 2 more closely resembles that of a mildly inverted basin-fill; that is, the configuration of the original basin at depth is retained whilst its shallower parts are gently deformed and arched upwards, and ultimately expressed as the Judd anticline in this part of the basin.

In view of these conflicting ideas on the early Paleogene history of vertical motions, this paper presents an appraisal of the Late Paleocene–Eocene succession at the southern end of the Faroe–Shetland Basin. Here, we address the issue of the origin of the Flett

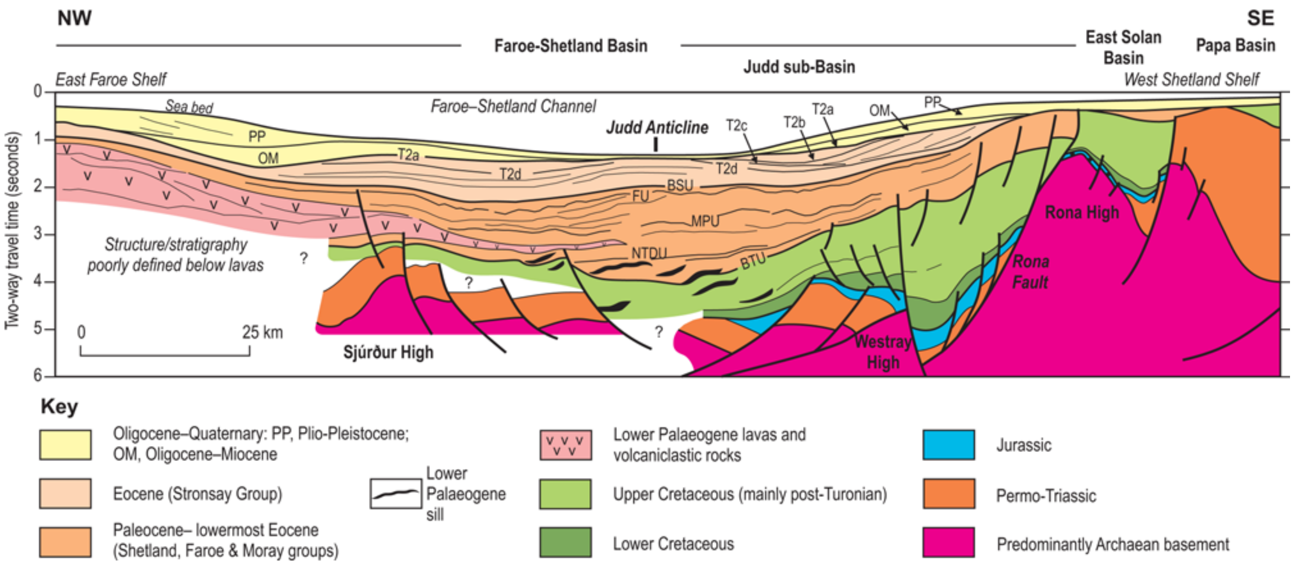

Fig. 2. Geoseismic section (location shown in Fig. 1) showing the structural and stratigraphic framework of the southern Faroe–Shetland Basin, with a focus on the Paleocene–Eocene succession in the Judd sub-Basin, and its key unconformities (modified after Lamers & Carmichael 1999). (See Table 1 for key to unconformities.) BSU, Base Stronsay unconformity; BTU, Base Tertiary unconformity; FU, Flett unconformity; MPU, Mid-Paleocene unconformity; NTDU, Near-Top Danian unconformity.

Table 1. *Summary of key Paleocene and Eocene unconformities in and adjacent to the southern Faroe–Shetland Basin*

Unconformity	Age	Description
T2a	Late Priabonian–early Rupelian (essentially 'Top Eocene')	Tilted and folded surface eroded and onlapped by younger strata on both flanks of the basin
T2b	Late Bartonian–Priabonian	Onlap surface onto southeastern slope of basin; possible subaerial erosion on adjacent shelf
T2c	Mid- to late Bartonian	Downlap surface progressively buried beneath younger prograding Eocene strata
Intra-FSP-2c (i2c)	Late Lutetian	Irregular erosion surface with channels 80 – 200 m deep incised into older Eocene strata
T2d	Mid-Lutetian	Incised subaerial erosion surface truncating Ypresian succession
Base Stronsay (BSU)	Early Eocene	Downlap surface progressively buried beneath younger prograding Eocene strata
Flett (FU)*	Late Thanetian	Irregular subaerial erosion surface with channels up to 200 m deep incised into older Paleocene strata
Mid-Paleocene (MPU)	Late Selandian	Onlap surface on basin flank; erosion surface on adjacent shelf
Near-Top Danian (NTDU)	Late Danian–early Selandian	Maximum flooding surface downlapped by Selandian strata
Intra-Danian (IDU)	Mid- to late Danian	Erosion surface on shelf
Base Tertiary (BTU)	Latest Cretaceous–earliest Paleocene	Regional erosion surface over much of the West Shetland region

Paleocene terminology and details are from Mudge (2015), Stoker (2016) and this study; Eocene terminology and details are from Stoker *et al.* (2013). Additional descriptive information is derived from Ebdon *et al.* (1995), Smallwood & Gill (2002) and Robinson *et al.* (2004).
*Informal term used in this study: broadly correlates with intra-Upper Thanetian to near-Top Paleocene hiatus of Mudge (2015).

unconformity by comparing the palaeogeographical setting around the time of its formation with a set of reconstructions that cover the subsequent Eocene rift-to-drift transition and early post-rift development of the Faroe–Shetland Basin, when volcanic activity associated with the Faroe Islands Basalt Group had ceased. This represents a duration of about 20 myr after the instigation of breakup (Fig. 4). By focusing on the observational evidence for a series of major Eocene regressions and their connection to a set of key unconformities, we demonstrate a commonality in the stratigraphic and structural evolution across this critical syn- to early post-breakup period, and discuss their implications for the general process of plate breakup and passive margin development in the Faroe–Shetland and wider NE Atlantic region.

Geological setting

The structural framework illustrated in Figure 1 is a legacy of a prolonged history of episodic rifting in the Faroe–Shetland region from the Late Paleozoic until the early Cenozoic plate breakup (Ritchie *et al.* 2011*b*). The general structural grain of the various basins and structural highs (mainly Archaean basement) reflects the interaction of long-lived NE- and NW-trending lineaments, which

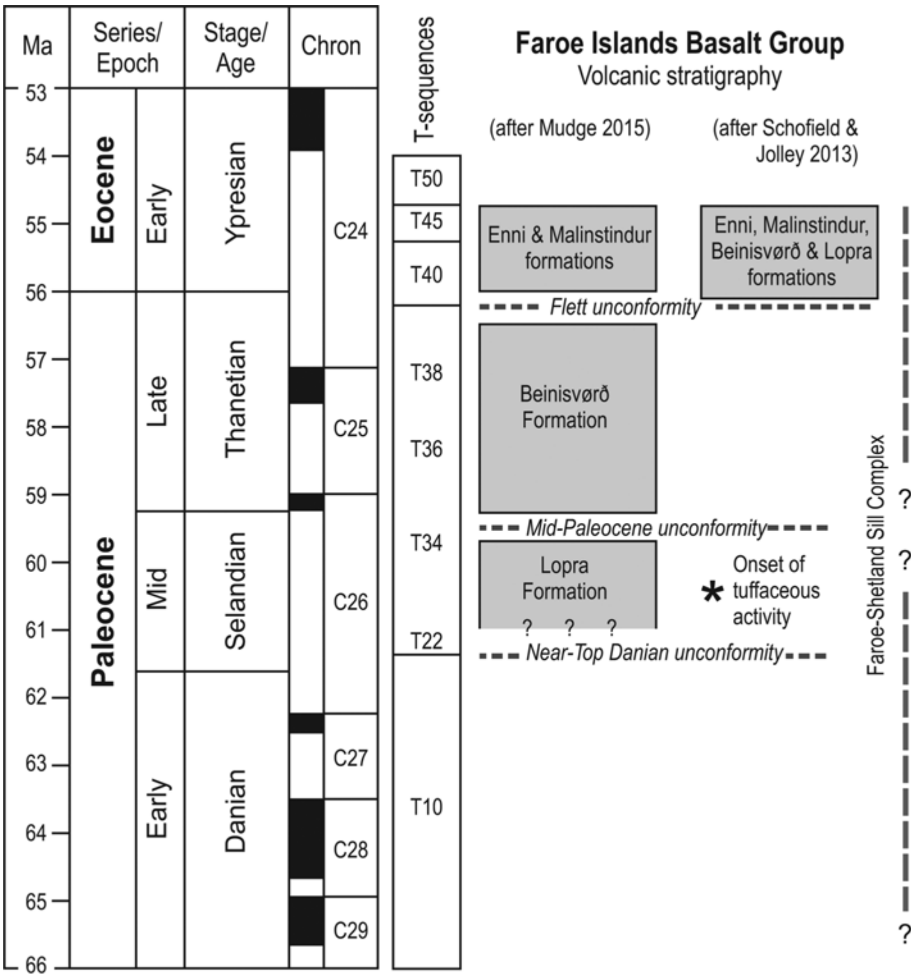

Fig. 3. Stratigraphic-range chart illustrating conflicting age models for the Faroe Islands Basalt Group as recently summarized by Schofield & Jolley (2013) and Mudge (2015). Information on other indicators of volcanic activity is derived from the following sources: Faroe–Shetland Sill Complex from Schofield *et al.* (2017); onset of tuffaceous activity from Mudge (2015) and Watson *et al.* (2017). Timescale is based on Gradstein *et al.* (2012); T-sequences are after Mudge (2015).

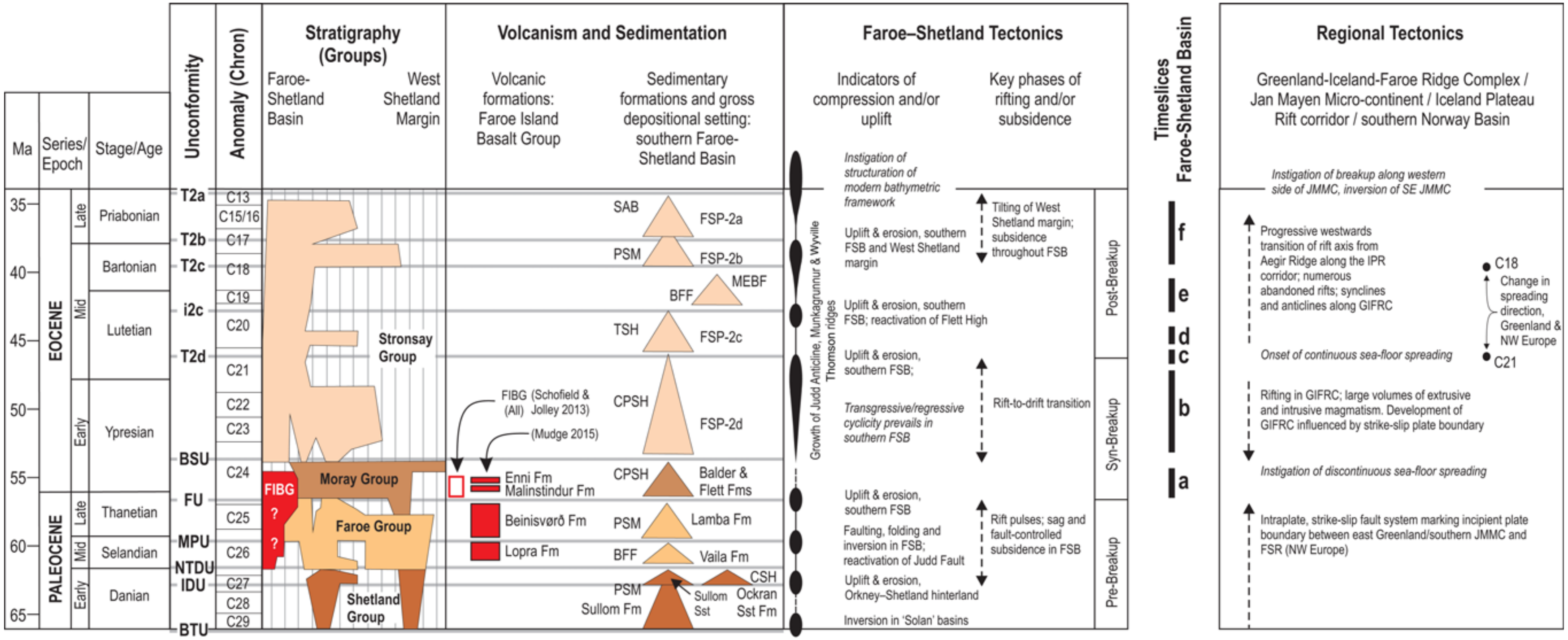

Fig. 4. Paleocene–Eocene tectonostratigraphical framework for the Faroe–Shetland Basin. The compilation of the stratigraphy, volcanism and sedimentation, and Faroe–Shetland tectonics is based mainly on Stoker *et al.* (2013), Mudge (2015) and this study. Additional information is derived from the following sources: under the 'Volcanism and Sedimentation' column, volcanic formations data are from Schofield & Jolley (2013) and sedimentary facies data are from Ebdon *et al.* (1995) and Goodwin *et al.* (2009); under the 'Faroe–Shetland Tectonics' column, information is from Dean *et al.* (1999), Robinson *et al.* (2004), Ritchie *et al.* (2008), Shaw Champion *et al.* (2008), Stoker *et al.* (2012), Ólavsdóttir *et al.* (2013) and Ellis & Stoker (2014). The 'Regional Tectonics' column is based on information derived from Gaina *et al.* (2009), Gernigon *et al.* (2012), Guarnieri (2015), Blischke *et al.* (2017) and Hjartarson *et al.* (2017). BFF, basin-floor fans; CPSH, coastal plain–shallow-marine shelf (includes deltaic); CSH, clastic shallow-marine shelf; FIBG, Faroe Islands Basalt Group; FSB, Faroe–Shetland Basin; FSR, Faroe–Shetland region; GIFRC, Greenland–Iceland–Faroe Ridge Complex; IPR, Iceland Plateau Rift; JMMC, Jan Mayen Microcontinent; MEBF, Mid-Eocene basin-floor fans; PSM, prograding shelf-margin (shelf, slope and basin); SAB, slope apron–basinal; TSH, transgressive shelf. The timeslice notation (a–f) relates to the palaeogeographical maps illustrated in Figure 5. (See Table 1 for key to unconformities.) Timescale is based on Gradstein *et al.* (2012).

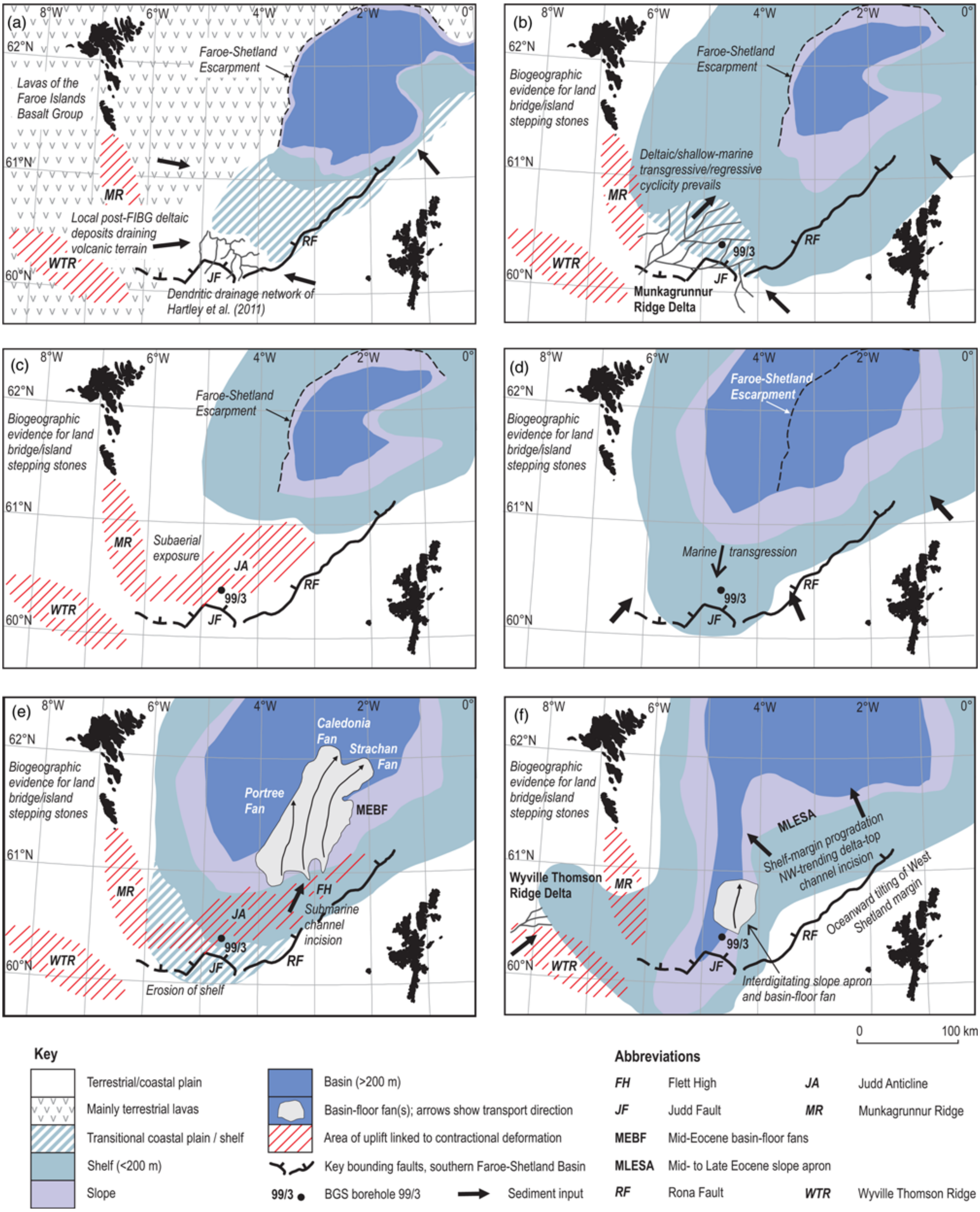

Fig. 5. Series of schematic palaeogeographical maps showing the inferred spatial and temporal development of the Faroe–Shetland Basin during Late Paleocene–Eocene times: (**a**) late Thanetian–early Ypresian; (**b**) mid- and late Ypresian–earliest Lutetian; (**c**) early and mid-Lutetian; (**d**) mid-Lutetian; (**e**) late Lutetian; (**f**) late Bartonian–Priabonian. Palaeogeographical information in map (**a**) is derived from Ritchie *et al.* (2008), Hartley *et al.* (2011), Stoker & Varming (2011), Ólavsdóttir *et al.* (2013) and Mudge (2015); maps (**b**–**f**) are modified after Stoker *et al.* (2013). The positions of the main bounding faults on the southern margin of the Faroe–Shetland Basin, and the key Eocene borehole (BGS borehole 99/3) are shown for reference points. FIBG, Faroe Islands Basalt Group.

were periodically and variably reactivated throughout the rifting process. Within this framework, the Faroe–Shetland Basin is a collective term for a complex amalgam of predominantly NE-trending sub-basins and intra-basinal highs, which were subject to a major phase of 'Mid'- to Late Cretaceous extension; this resulted in increased connectivity between, and a general subsidence of, the sub-basins from which the Faroe–Shetland Basin acquired its larger regional expression (Larsen *et al.* 2010; Stoker

2016). Analysis of the Cretaceous succession, which is punctuated by episodes of uplift, erosion and compressional deformation, has established that the reactivation of basement fabrics played a major role in determining the structural framework at this time (Dean *et al.* 1999; Stoker 2016). The interaction of the fault sets created a rectangular framework, including the southern limit of the Faroe–Shetland Basin, which was controlled by the Judd and Rona faults (Fig. 1).

During the Paleocene pre-breakup rifting phase (late Danian–Thanetian, *c.* 63 – 56 Ma), these faults continued to have a major influence on the development of the Faroe–Shetland Basin by controlling sedimentation in a series of sag and fault-controlled sub-basins, such as the Judd, Foula and Flett sub-basins (Dean *et al.* 1999; Lamers & Carmichael 1999). Coeval uplift and erosion of the hinterland throughout this rifting phase led to an influx of coarse clastic sediment in the Sullom and Ockran Sandstone formations (Shetland Group) and the Vaila and Lamba formations (Faroe Group), all of which are characterized by unconformity-bounded cyclical accumulations of shelf, shelf-margin and basinal deposits (Ebdon *et al.* 1995; Goodwin *et al.* 2009; Mudge 2015) (Fig. 4). The sediment forming these units was fed into the sub-basins through established entry points, such as the Judd Fault–Rona Fault intersection (Ebdon *et al.* 1995). During the deposition of the Sullom, Ockran Sandstone and Vaila formations, the shelf–slope break on the southern flank of the Faroe–Shetland Basin was largely controlled by this fault system; however, the Lamba Formation represents a large prograding shelf-margin system that significantly advanced the position of the shelf edge northwards into the basin. Throughout the pre-breakup rifting phase, the Faroe–Shetland Basin also deformed internally in response to contemporary compressional tectonics, including the reactivation of extensional faults, development of synclines and monoclines, and transpressional pop-up structures (Dean *et al.* 1999). An angular unconformity between the Moray Group and underlying Paleocene and older rocks on the Corona High confirms the action of pre-breakup compressional deformation (Dean *et al.* 1999, fig. 12). According to Mudge (2015), rifting and extension was accompanied by volcanism associated with the Lopra and Beinisvørð formations of the Faroe Islands Basalt Group, which are envisaged to have erupted coevally with the Vaila and Lamba formations (Faroe Group), respectively (Fig. 4).

The Late Paleocene uplift, erosion and formation of the Flett unconformity at about 56 Ma marked a major regressive interval that, in the southern part of the Faroe–Shetland Basin, was characterized by the change from predominantly marine to coastal plain and terrestrial depositional environments of the Flett Formation (Moray Group) (Ebdon *et al.* 1995; Mudge 2015) (Fig. 4). This change was coeval with the extrusion of flood basalts of the syn-breakup Malinstindur and Enni formations between about 55 and 56 Ma (Mudge 2015), although Schofield & Jolley (2013) correlated the entire Faroe Islands Basalt Group with this interval (Figs 3 and 4). Whereas the first indication of seafloor spreading offshore NW Britain and the Faroe Islands is generally correlated to chron C24r (early Ypresian, 55 – 54 Ma), along with the deposition of tuffs of the Balder Formation (Moray Group) (e.g. Passey & Jolley 2008), the first continuous spreading anomaly was not achieved until chron C21 (late Ypresian–early Lutetian, about 48 – 46 Ma) (Stoker *et al.* 2012; Ellis & Stoker 2014) during the early stage of deposition of the Stronsay Group. Prior to this, the chron C24r–C21 record is fragmented and discontinuous along the length of the continental margin (Kimbell *et al.* 2005; Elliot & Parson 2008), and has been interpreted by Stoker *et al.* (2012) as a rift-to-drift phase of about 8 myr. Thus, the tectonostratigraphic development of both the Moray and Stronsay groups is integral to understanding the process of plate breakup. Further details on this Upper Paleocene–Eocene succession are presented below.

Upper Paleocene–Eocene tectonostratigraphic framework

Figure 5 presents a series of six schematic palaeogeographical maps that illustrate the syn- to early post-breakup development of the Faroe–Shetland Basin. The maps are based upon the vast wealth of geological and geophysical information acquired and published by the British Geological Survey (BGS) over the last 50 years as part of their regional offshore mapping programme (see Ritchie *et al.* 2011*a*), integrated with data from other published sources. BGS borehole 99/3 is a key Eocene stratigraphic site (Stoker *et al.* 2013), and provides an important control point in the Faroe–Shetland Basin. The six timeslices depicted are as follows: (1) late Thanetian–early Ypresian; (2) mid- to late Ypresian–earliest Lutetian; (3) early to mid-Lutetian; (4) mid-Lutetian; (5) late Lutetian; (6) late Bartonian–Priabonian. These six intervals reflect the punctuated sedimentary record preserved within the Moray and Stronsay groups (Fig. 4), and, as such, can be utilized as a sensitive recorder of the processes involved in basin development across the rift-to-drift transition. The maps are summarized below, with a focus on the southern part of the Faroe–Shetland Basin and adjacent margin.

Late Thanetian–early Ypresian

The Faroe–Shetland Basin was a narrow, semi-enclosed basin at this time, bounded by faults on its southern and eastern margins, and with its NW margin delimited by the contemporary volcanic terrain, including the Faroe–Shetland Escarpment (Fig. 5a). The latter represents a hyaloclastite delta that formed along the marine margin of the basin (Passey & Hitchen 2011). A dendritic fluvial drainage network incised into the underlying marine deposits of the Lamba Formation at the southern end of the basin formed a branching network of valleys with a maximum relief of 200 m (Smallwood & Gill 2002; Shaw Champion *et al.* 2008). This irregular surface represents the Flett unconformity, and the valleys were subsequently backfilled by paralic and deltaic deposits of the Flett and Balder formations (Moray Group), which formed an extensive coastal plain on the uplifted and emergent southern part of the Faroe–Shetland Basin. This coastal plain was periodically inundated by shallow-marine incursions from the adjacent shelf, the southern limit of which was controlled by the Judd Fault, and beyond which a terrestrial setting prevailed (Ebdon *et al.* 1995; Mudge 2015). The oscillatory nature of relative sea-level throughout this interval is further highlighted by westerly-derived deltaic deposits (equivalent to the Balder Formation) that prograde and downlap onto the transgressive shelf sequence (Ólavsdóttir *et al.* 2013). The instigation of the anticlinal Wyville Thomson and Munkagrunnur ridges on the southern margin of the Faroe–Shetland Basin may have occurred in the latest Paleocene (Boldreel & Andersen 1993; Johnson *et al.* 2005; Ritchie *et al.* 2008). Extensive tuffs in the Balder Formation probably mark the instigation of seafloor spreading north of the Faroe Islands during chron C24r (Passey & Jolley 2008).

Mid- and late Ypresian–earliest Lutetian

This interval represents the rift-to-drift transition. An alternating succession of deltaic and shallow-marine sediments accumulated as part of unit FSP-2d of the Stronsay Group (Fig. 4), largely derived from the southern margin of the Faroe–Shetland Basin (Andersen *et al.* 2000; Stoker *et al.* 2013). The Munkagrunnur Ridge Delta was a prominent depocentre that prograded northwards into the basin (Fig. 5b); its lower bounding surface, represented by a downlap horizon, corresponds to the Base Stronsay Unconformity. The formation of this delta has been attributed to episodic uplift of the Munkagrunnur Ridge (Ólavsdóttir *et al.* 2010, 2013); the Wyville

Thomson Ridge also continued to grow at this time (Ritchie *et al.* 2008; Tuitt *et al.* 2010). These structures maintained the semi-enclosed character of the Faroe–Shetland Basin, and actively contributed to the development of the extensive terrestrial region that formed the North Atlantic 'land bridge' between Greenland and Scotland (Denk *et al.* 2011; Stoker *et al.* 2013) (Fig. 5b–f). This terrain persisted and developed on the western flank of the basin throughout the Eocene as a consequence of the development of the Greenland–Iceland–Faroe Ridge Complex (see Discussion). The deeper NE part of the basin remained largely delimited by the Faroe–Shetland Escarpment.

Early and mid-Lutetian

A major regression partially exposed the Faroe–Shetland Basin during this interval. The top of the deltaic succession, as observed in BGS borehole 99/3, was subaerially eroded forming the T2d unconformity (Stoker *et al.* 2013) (Fig. 4). The extent of the exposed area remains uncertain, but probably included much of the southern half of the basin (Fig. 5c). The early growth of inversion domes within the Faroe–Shetland Basin, such as the Judd Anticline (Fig. 2), is generally interpreted to have been instigated in the early and mid-Lutetian, accompanied by the continued growth of the Wyville Thomson Ridge on the basin margin (Smallwood 2004; Ritchie *et al.* 2008).

Mid-Lutetian

The southern Faroe–Shetland Basin was transgressed during the mid-Lutetian, and a lower shoreface to shallow-marine environment prevailed in the area of BGS borehole 99/3, preserved as unit FSP-2c of the Stronsay Group (Stoker *et al.* 2013). The Faroe–Shetland Escarpment increasingly lost expression within the basin as it was overlapped by younger strata (Robinson 2004). The main source of sediment input remained the southern flank of the Faroe–Shetland Basin (Andersen *et al.* 2000; Stoker *et al.* 2013).

Late Lutetian

A fall in relative sea-level in the late Lutetian resulted in renewed erosion and incision of the shelf deposits (unit FSP-2c of Stoker *et al.* 2013) on the southern margin of the Faroe–Shetland Basin by channels 80 – 200 m deep (Robinson 2004; Robinson *et al.* 2004), forming the i2c unconformity (Fig. 4). These channels formed part of a shelf-edge system that linked into northerly-trending submarine canyons, which, in turn, fed a series of deep-water fans: the Mid-Eocene basin-floor fan complex (Fig. 5e). 3D seismic evidence in the area of the Flett High suggests that channel morphology and trend were controlled by its topographic relief, possibly as a consequence of relative uplift or faulting, although a eustatic fall in sea-level was not discounted (Robinson *et al.* 2004). As the southern margin of the Faroe–Shetland Basin remained the main source of sediment at this time, it is not inconceivable that erosion might have been a response to further growth of the Judd Anticline, Munkagrunnur Ridge and Wyville Thomson Ridge (Ritchie *et al.* 2008). The Faroe–Shetland Escarpment no longer influenced depositional patterns in the basin.

Late Bartonian–Priabonian

A shelf-margin wedge prograded northwestwards from the West Shetland region (Fig. 5f). This correlates with unit FSP-2b of Stoker *et al.* (2013), and its lower bounding surface, represented by a downlap horizon, corresponds to the T2c unconformity that partially buried the Mid-Eocene basin-floor fan complex (Fig. 4). The scale of the prograding clinoforms indicates basinal water depths of between 350 and 500 m. A stacked series of subaerial–deltaic channels, several tens of metres deep, is preserved in the topset deposits (Robinson *et al.* 2004). The T2b unconformity represents an onlap surface that is overlain by slope-apron and basinal deposits of unit FSP-2a following a brief hiatus (Fig. 4). The occurrence of units FSP-2b and 2a in BGS borehole 99/3 (Fig. 5f) represents the first indication, since the Mid-Paleocene, of major subsidence and deepening of the southern part of the Faroe–Shetland Basin beyond shelfal water depths. However, the basin remained largely enclosed at its southern end where it was fed, in part, by northward-draining deltas, including the Wyville Thomson Ridge Delta, sourced and offloaded from the northern flank of the ridge in response to uplift and continued growth of this anticline (Stoker *et al.* 2013). Moreover, a late Mid- to Late Eocene hiatus on the western flank of the Faroe–Shetland Basin (Waagstein & Heilmann-Clausen 1995) implies continued exposure of this region. Thus, despite the marine embayment and relative deepening of the southern basin margin, there is much evidence of a major regression in late Mid- to Late Eocene times.

Discussion

The Late Paleocene–Eocene palaeogeographical maps presented in Figure 5 provide an observational basis upon which to assess the influence of vertical crustal motions on the syn- to early post-breakup development of the southern Faroe–Shetland Basin. Collectively, the maps reveal the sedimentary response to a *c.* 20 myr record of near-continual vertical crustal motions. Figure 5a broadly depicts the palaeogeographical setting at the time of formation of the Late Paleocene Flett unconformity, when volcanic activity associated with the Faroe Islands Basalt Group dominated the western part of the Faroe–Shetland region. In contrast, intra-Eocene basin development highlighted in Figure 5b–f post-dates the emplacement of the Faroe Islands Basalt Group, but the area remained tectonically active through the rift-to-drift transition and into the early post-breakup stage. Throughout this period, the frequency of change is about 2 – 3 myr, albeit possibly higher in the rift-to-drift transition when a transgressive–regressive cyclicity prevailed.

In all of the reconstructions that highlight uplift and erosion, the vertical crustal motions are spatially linked to the same (southern) part of the basin. Despite this spatial coincidence, the Late Paleocene Flett unconformity has been interpreted to represent the incised subaerial surface expression of a proto-Iceland mantle plume (Smallwood & Gill 2002; Shaw Champion *et al.* 2008; Hartley *et al.* 2011), whereas the subsequent intra-Eocene phases of uplift and associated unconformities (including subaerial erosion surfaces) are linked to tectonic activity. This includes compressional deformation and the generation of fold structures, such as the Wyville Thomson and Munkagrunnur ridges, and the Judd Anticline (Smallwood 2004; Ritchie *et al.* 2008; Ólavsdóttir *et al.* 2013; Stoker *et al.* 2013), and reactivated structural highs (Robinson *et al.* 2004) (Fig. 4). In the same area, a series of vertical movements in the pre-breakup Paleocene succession is generally linked to rift pulses, including periodic reactivation of the Judd–Rona fault system that bounds the southern margin of the Faroe–Shetland Basin (Ebdon *et al.* 1995; Dean *et al.* 1999; Lamers & Carmichael 1999) (Fig. 4). Rifting and extension during the Paleocene was accompanied by volcanism associated with the Faroe Islands Basalt Group (Ziska & Varming 2008; Mudge 2015). In the following text, we assess the likely processes that are responsible for these observations and interpretations, and consider the implications in terms of plate breakup and passive margin development in the Faroe–Shetland and wider NE Atlantic region.

In the last decade, much significance has been placed on the Late Paleocene Flett unconformity, which has been interpreted to have formed during a phase of rapid transient mantle convective uplift ahead of plate breakup (Shaw Champion *et al.* 2008; Hartley *et al.* 2011). This model assumes a correlation between the timing of formation of the Flett unconformity and the emplacement of the entire Faroe Islands Basalt Group; however, the conflicting interpretations of the chronology of the breakup-related volcanic succession (Fig. 3) cast some doubt over its presumed association with this single unconformity. A further degree of uncertainty over the role of transient mantle convective uplift in the formation of the Flett unconformity is provided by our observations regarding the transition from the Moray Group into the Stronsay Group. According to Smallwood & Gill (2002), deep marine conditions were re-established rapidly across the Faroe–Shetland Basin early in the deposition of the Stronsay Group. This is a major factor in the mantle convective model, as it is utilized to convey a transient process of rapid uplift and decay (within 3 myr) of the southern Faroe–Shetland Basin (Shaw Champion *et al.* 2008). There is no doubt that the fluvial drainage network of the Flett unconformity was backfilled by paralic and shallow-marine deposits of the Moray Group, but our observations provide no indication whatsoever that the southern Faroe–Shetland Basin deepened beyond shelfal depths until the Late Eocene (Fig. 5). Terrestrial or coastal plain sedimentation with periodic shallow-marine incursions dominated in this area throughout the deposition of the Moray Group and unit FSP-2d (Ypresian–mid-Lutetian) of the Stronsay Group, which included the development of the Munkagrunnur Ridge Delta. Our observations indicate that episodic exposure of the southern Faroe–Shetland Basin prevailed until the late Bartonian. Deeper-water marine conditions throughout all of this time were restricted to the northern Faroe–Shetland Basin (Mudge 2015). Thus, our maps indicate that the transition from the Moray Group into the Stronsay Group in the southern part of the basin was not marked by any significant (nor rapid) deepening. The comparable stratigraphic and sedimentological development of both these groups during the Ypresian–Lutetian does not support the passage of a transient thermal anomaly.

In assessing the importance of tectonics in the Late Paleocene–Eocene development of the southern Faroe–Shetland Basin, our observations are considered together with data from the wider NE Atlantic region (Figs 4 and 6), which allow us to speculate on the potential correlation between phases of uplift in the Faroe–Shetland Basin and the timing of key regional intraplate and plate boundary events. Our maps (Fig. 5) show a close association between the locations of long-established sediment entry points into the Faroe–Shetland Basin (a pattern also previously established by Ebdon *et al.* (1995) for the Paleocene Shetland and Faroe group deposits), and the cluster of compressional structures (growth folds), and the strongly rectilinear southern margin of the basin bounded by the Judd and Rona faults. Such a linkage has been proposed for the Cretaceous development of the Faroe–Shetland region, where compressional deformation, especially along the southern margin of the Faroe–Shetland Basin, has been attributed to intraplate strike-slip tectonics as rifting intensified within the Laurasian continent (Dean *et al.* 1999; Stoker 2016). The continuation of this tectonic regime into the Paleocene would also be consistent with the observations (described above) for coeval extension and compression (Dean *et al.* 1999; Lamers & Carmichael 1999), including the frequent activity recorded for the Judd Fault (Ebdon *et al.* 1995). The persistence of tectonic activity in the same area through the Early Eocene rift-to-drift transition might suggest a long-lived structural control on basin development driven by the episodic reactivation of its underlying basement fabric, including its major bounding faults (Ziska & Varming 2008; Holford *et al.* 2016). The NE-trending Rona Fault displays a close affinity to major Caledonian lineaments, such as the Great Glen Fault, whereas the Judd Fault is considered to form part of the Judd Lineament, one of several NW-trending regional lineaments identified in this region,

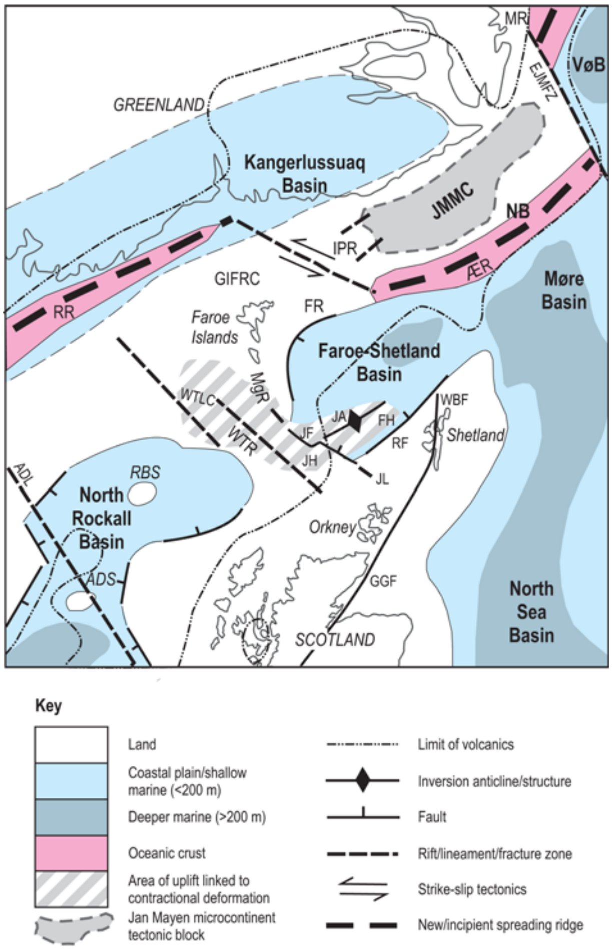

Fig. 6. Location and gross tectonic setting of the Faroe–Shetland region in the context of the Late Paleocene–Early Eocene reconstruction of the SE Greenland–Faroe–Shetland corridor as Laurasia begins to break up. The reconstruction is modified after Ellis & Stoker (2014), and also includes information derived from Kimbell *et al.* (2005), Guarnieri (2015) and Blischke *et al.* (2017). ADL, Anton Dohrn Lineament; ADS, Anton Dohrn seamount; ÆR, Ægir Ridge; EJMFZ, East Jan Mayen Fracture Zone; FH, Flett High; FR, Fugloy Ridge; GGF, Great Glen Fault; GIFRC, Greenland–Iceland–Faroe Ridge Complex; IPR, Iceland Plateau Rift system; JA, Judd Anticline; JF, Judd Fault; JH, Judd High; JL, Judd Lineament; MgR, Munkagrunnur Ridge; MR, Mohns Ridge; NB, Norway Basin; RBS, Rosemary Bank seamount; RF, Rona Fault; RR, Reykjanes Ridge; VøB, Vøring Basin; WBF, Walls Boundary Fault; WTLC, Wyville Thomson Lineament Complex; WTR, Wyville Thomson Ridge.

which also includes the Wyville Thomson Lineament Complex (Kimbell *et al.* 2005) (Fig. 6). These NW-trending lineaments may have a pre-Caledonian history; during the Mesozoic, they are interpreted to have acted as transfer faults, with the Wyville Thomson Lineament Complex reactivated as part of a ramp anticline complex during the Paleogene albeit with an element of rifting and strike-slip faulting (Kimbell *et al.* 2005; Lundin & Doré 2005; Ziska & Varming 2008). These pre-existing structural weaknesses were also exploited by magmatic activity, at least locally, during the breakup process (Ziska & Varming 2008; Schofield *et al.* 2017).

That this reactivation process might be part of a plate-wide system is supported by a recent analysis of the palaeostress state along the conjugate SE Greenland margin (Guarnieri 2015). This study has revealed that Paleocene intraplate deformation in the Kangerlussuaq area was driven by strike-slip tectonics along a shear margin bordering the Faroe–Shetland region (Fig. 6), which induced the reactivation of old lineaments and the localized formation of pull-apart basins. According to Guarnieri (2015), oblique rifting in this area during the Selandian–Thanetian heralded the onset of breakup. As the Faroe–Shetland region was juxtaposed with Kangerlussuaq during this interval, and preserves an identical record of Paleocene palaeostress state (Guarnieri 2015: fig. 8), it seems inherently sensible that the same tectonic system may have been responsible for reactivating similarly old lineaments on the Faroe–Shetland side of the shear margin. In such a scenario, deformation generated by intraplate push–pull stresses, superimposed upon a structural framework dominated by NE- and NW-trending faults, would be accommodated by strike-slip displacements and pull-apart structures in some areas, and penecontemporaneous uplift and erosion in others; a pattern of structural development that seems compatible with the Faroe–Shetland region.

The abundant evidence of Mid- to Late Eocene compressional structures (i.e. Wyville Thomson and Munkagrunnur ridges; Judd Anticline), unconformities (i.e. T2d, i2c, T2c and T2b) and associated forced regressions demonstrates that tectonic instability in the southern Faroe–Shetland region continued into the early post-breakup stage (Figs 2, 4 and 5). In the wider NE Atlantic region, instability at this time was driven by a complex process of rifting, rift transfer (rift jumps) and ocean spreading in this part of the NE Atlantic during the Eocene, where plate separation between Greenland and NW Europe remained only partial (Ellis & Stoker 2014; Blischke *et al.* 2017). Observational evidence has been reported in support of Eocene rifting and plate reorganization along the developing Greenland–Iceland–Faroe Ridge Complex, and within the Norway Basin as the Jan Mayen Microcontinent began to separate from East Greenland (Gaina *et al.* 2009; Gernigon *et al.* 2009, 2012, 2015; Blischke *et al.* 2017; Hjartarson *et al.* 2017) (Fig. 6).

The development of the Greenland–Iceland–Faroe Ridge Complex was strongly influenced by the shear margin separating SE Greenland and the Faroe–Shetland region, and rifting and rift jumps accompanied by large volumes of extrusive and intrusive magmatism dominated its early (rift-to-drift transition) development (Blischke *et al.* 2017; Hjartarson *et al.* 2017). On the Greenland–Iceland–Faroe Ridge Complex, evidence for formerly active and abandoned rifts is preserved as a series of synclines and anticlines (Hjartarson *et al.* 2017). Whereas continuous spreading along the Ægir Ridge was established in chron C21 (*c.* 48 – 46 Ma) it did not connect with the Reykjanes Ridge; instead, a progressive westwards transition of the southern tip of its rift axis throughout the Mid- to Late Eocene resulted in numerous abandoned rifts, collectively termed the Iceland Plateau Rift system, in the basin (Blischke *et al.* 2017) (Fig. 6). Two major phases of extension and fragmentation occurred on the southern part of the Jan Mayen Microcontinent during chrons C21 and C18 (*c.* 41 – 39 Ma) with a change in spreading direction between Greenland and NW Europe, as well as a certain amount of counter-clockwise rotation of the microcontinent as rifting (and ultimately ocean spreading) developed between the Jan Mayen Microcontinent and Greenland. This rotation has been coupled to local compression on the eastern side of the Jan Mayen Microcontinent and the southwestern part of the Norway Basin (Gaina *et al.* 2009; Gernigon *et al.* 2012). The significance of all these tectonic movements and plate boundary reconfigurations to the development of the Faroe–Shetland region remains uncertain. However, inspection of Figure 4 might invite speculation concerning a broad correlation between these regional events, the reactivation of structural weaknesses and the formation of the Eocene unconformities, particularly T2d and T2c during C21 and C18 times respectively, as far-field effects of the rifting process between the Jan Mayen Microcontinent and Greenland (Ziska & Varming 2008; Stoker *et al.* 2013).

Although the detail remains to be worked out, a general correlation of all tectonic events in the Faroe–Shetland and wider NE Atlantic region (Fig. 4) suggests that the transmission of stresses into the plate interior related to these rifting and plate boundary processes cannot be ignored in consideration of the control of vertical motions across the Faroe–Shetland region (Holford *et al.* 2009, 2016). It is interesting to note that the general pattern of uplift, subsidence and compression that prevailed throughout the Mid-Paleocene–Eocene development of the Faroe–Shetland Basin is remarkably similar to results from studies of Neogene plate-boundary development in the outer continental borderland offshore southern California. In this predominantly strike-slip setting, a pattern of uplift, followed by subsidence and later folding and basin inversion has been documented, with vertical displacements of up to 3 km having occurred in as little as 1 myr (e.g. Nicholson *et al.* 2007, 2011; de Hoogh *et al.* 2009). In this context, the overall geometry of the Paleocene–Eocene succession, which is deformed and arched upward and is manifested by the Judd Anticline (Fig. 2), is consistent with the southern part of the Faroe–Shetland Basin having been partially folded and inverted during the early Paleogene. A history of Eocene compression is well established for this structure (Smallwood 2004; Ritchie *et al.* 2008). However, the nearby Wyville Thomson and Munkagrunnur ridges are interpreted to have been actively growing since the Late Paleocene (Boldreel & Andersen 1993; Johnson *et al.* 2005). This might lead to speculation as to whether the early growth phase of the Judd Anticline was similarly rooted in the Late Paleocene, and whether or not the Flett unconformity might simply be a consequence of pre-breakup compression as continental rifting developed along the SE Greenland and Faroe–Shetland shear margin.

Following breakup, this tectonic signature can also be linked to the end-Eocene–Early Miocene process of structuration that accentuated structures, such as the Wyville Thomson and Munkagrunnur ridges, as well as the Fugloy Ridge (Fig. 1), and helped to create the contemporary bathymetry of the Faroe and West Shetland shelves, separated by the Faroe–Shetland Channel (Stoker *et al.* 2005) (Fig. 2). It may be no coincidence that this deformation coincided with the interval bracketed by the instigation of breakup along the western side of the Jan Mayen Microcontinent (chron C13, *c.* 35 – 33 Ma) and the onset of full spreading as the newly formed Kolbeinsey Ridge (between Jan Mayen Microcontinent and SE Greenland) and the Reykjanes Ridge became conjoined (chron C7–C6, 25 – 19 Ma) (Ellis & Stoker 2014; Blischke *et al.* 2017).

All of these data suggest that the persistence of vertical movements throughout the pre-, syn- and early post-breakup development of the Faroe–Shetland region reflects a predominantly structural control on the shaping of the southern Faroe–Shetland Basin. The preservation of a sedimentary succession that is punctuated by episodes of uplift, erosion and compressional deformation throughout the Paleocene–Eocene interval represents a sensitive record of this structural history. In our view, this is consistent with an overall regional pattern of coeval extension and compression as proposed by the model of Guarnieri (2015) of oblique rifting along a SE Greenland and Faroe–Shetland shear margin during the process of breakup, and further modulated by rift- and plate-boundary-related stresses as breakup remained only partial until the Jan Mayen Microcontinent and Greenland separated in the Early Miocene (Blischke *et al.* 2017). The significance of thermal uplift during Mid- and Late Paleocene–earliest Eocene time remains uncertain given the conflict of thought surrounding both the chronology (and thus duration) of the Faroe Islands Basalt Group and its process of emplacement. Thus, we consider that the proposed link between the Flett unconformity, the Faroe Islands Basalt Group and a transient pulse of mantle convective uplift remains subjective. Our stratigraphic and palaeogeographical observations on the Late Paleocene–Eocene succession provide evidence for comparable uplift and erosion of the same part of the Faroe–Shetland Basin long after the cessation of volcanism in this region, including into the early Neogene.

Conclusions

An appraisal of the Upper Paleocene–Eocene succession has revealed a history of vertical movements in the southern Faroe–Shetland Basin that spans the rift-to-drift transition. By focusing specifically on the spatial and temporal distribution of the preserved depositional packages within the Moray and Stronsay groups it has been possible to identify the large-scale pattern of sedimentation and basin development throughout the process of plate breakup. In particular, the following should be noted.

(1) The preserved rock record indicates that the development of the Faroe–Shetland Basin during plate breakup was not a simple two-stage process whereby syn-breakup uplift was followed by post-breakup subsidence and tectonic quiescence. Instead, the syn- to early post-breakup record is characterized by long-term tectonic instability and vertical motions that persisted throughout the Late Paleocene–Eocene, long after the cessation of volcanism in the Faroe–Shetland region.

(2) A series of prominent unconformities resulting from the vertical motions punctuate the Upper Paleocene–Eocene sedimentary succession. Several of these were formed by subaerial processes that incised the southern part of the Faroe–Shetland Basin, which was episodically uplifted, inverted and exposed during the rift-to-drift transition. This includes the Late Paleocene Flett unconformity, which is commonly assumed to have formed in response to a pulse of transient mantle convective uplift; however, its correlation with the Faroe Islands Basalt Group remains ambiguous, and palaeogeographical considerations do not support the case for rapid subsidence and a return to deep-water conditions during the Early Eocene, as proposed by this model.

(3) The majority of the unconformities that developed during the syn- to early post-breakup interval post-date volcanism. They are most probably linked to vertical movements associated with compressional deformation, which was particularly focused along the southern margin of the basin. The possibility that the Flett unconformity had a similar tectonic origin should not be discounted, especially considering the overall structural disposition of the Paleocene–Eocene succession.

(4) The process of breakup and passive margin development in the Faroe–Shetland region is underpinned by a long history of vertical crustal motions that arguably extended from the Paleocene to the Early Miocene. This long-ranging tectonic signature most probably reflects the protracted process of breakup in the wider NE Atlantic region, instigated during the Late Paleocene but not completed until the Early Miocene, when the Jan Mayen Microcontinent finally separated from Greenland and the Reykjanes and Kolbeinsey spreading ridges became linked. From a consideration of the position of the Faroe–Shetland Basin within the NE Atlantic during Late Paleocene–Eocene time, and the broad correlation between local and regional tectonic events, it is likely that basin development was modulated by rift- and plate-boundary processes linked strongly to the tectonic evolution of the adjacent oceanic basin.

It is clear that the long-running conflict surrounding the issue of the chronology of the Faroe Islands Basalt Group continues to hinder our understanding of the process of NE Atlantic breakup, and urgently needs resolution. Nevertheless, we feel that there is scope for the development of a new and more comprehensive model of NE Atlantic rifting and breakup across the SE Greenland and Faroe–Shetland conjugate margin, which takes into account the stratigraphic and structural information presented in this paper set against the complex kinematics of breakup that are being increasingly reported from the wider NE Atlantic region. Further work should focus on assessing how the preserved Cenozoic succession in the Faroe–Shetland and SE Greenland regions can be utilized as a sensitive recorder of the processes involved both in plate breakup (testing the nature of the plate boundary) and in passive-margin basin development.

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