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Dynamic Evolution of the Faroe–Shetland Region

Energy and Marine Geoscience Programme

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BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

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Dynamic Evolution of the Faroe–Shetland Region

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Columnar-jointed Streymoy Sill cross-cutting the Sneis Formation, Hundsarabotnur quarry, Streymoy, Faroe Islands. (Photographer Martyn Stoker; P910291)

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Foreword

This report is the result of a study by the British Geological Survey (BGS) and Jarðfeingi in the Late Mesozoic–Cenozoic geological development of the Faroe–Shetland region. The report is centred on a series of twenty palaeoenvironment maps with descriptions that depict the evolution of the region, highlighting the stratigraphic framework, depositional environments, volcanism and contemporary deformation. The maps combine observational information derived from previous and new work undertaken by the BGS and Jarðfeingi – on behalf of the Faroe-Shetland Consortium: FSC – with published material from the scientific press to provide an up-to-date synthesis. In addition to the palaeoenvironment maps, the report also presents a summary of the structural and stratigraphic frameworks of the Faroe–Shetland region, as developed throughout phases 1 and 2 of the FSC. All of these data have been used to construct a tectonostratigraphic chart that displays the general stratigraphic framework, including key unconformity surfaces, together with the gross sedimentary architecture and key tectonic characteristics of the Faroe–Shetland succession, and places all of these elements within the wider context of European and North Atlantic plate tectonics, with a view to better understanding the dynamic evolution of the Faroe–Shetland region.

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Responsibilities of individual authors during the production of the report have been as follows:

M S Stoker	Summary; chapters 1, 3, 4 (Late Jurassic–Cretaceous and Oligocene–Plio-Pleistocene maps) 5 and 6; and task management
K Smith	Major contribution to chapters 4 (Paleocene–Eocene maps) and 5
G S Kimbell	Chapter 2
M F Quinn	Chapter 2
J Ólavsdóttir	General contribution to understanding of Faroese sector
Ó Eidesgaard	General contribution to understanding of Faroese sector
H Johnson	General contribution to understanding of UK sector; project management
H Ziska	General contribution to understanding of Faroese sector

In compiling this report, the authors readily acknowledge the assistance of several BGS colleagues, including Robert Gatliff for his review of this report, and Sandy Henderson for constructing the accompanying GIS. The authors are especially grateful to Andrew Alderson of Ichron Limited for supplying non-proprietary Ichron biostratigraphy reports throughout the duration of the FSC phases 1 and 2.

The GSHHS/World Vector Shoreline used in this report is courtesy of National Geophysical Data Center (NGDC)/US Geological Survey (Wessel and Smith, 1996).

The report contains public sector information licensed under the Open Government Licence v3.0. This consists of well locations based on information provided by DECC (the Department of Energy and Climate Change), which is available online at https://www.gov.uk/oil-and-gas-offshore-maps-and-gis-shapefiles.

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Summary

This report presents a series of twenty palaeoenvironment maps that span the interval between the Late Jurassic and the Quaternary, and which form the basis of a generalised reconstruction of the late Mesozoic–Cenozoic development of the Faroe–Shetland and adjacent region. The database behind this study is firmly grounded within the portfolio of existing FSC stratigraphic reports (Cretaceous to Eocene), though it also includes new work that has extended the stratigraphic time series back to the Kimmeridgian (Late Jurassic), and forward to the Mid-Pleistocene. A synthesis of the main structural elements – basins, highs, faults, folds – is also included as these features provide a reference framework on the maps, as well being indicators of contemporary deformation spanning the pre-, syn- and post-breakup stages of NE Atlantic development in this region. By considering the palaeoenvironment maps (our observations) we identify the following key stages in the late Mesozoic–Cenozoic 'dynamic evolution' of the Faroe–Shetland region:

- Intermittent and localised rifting in the Late Jurassic (mid-Kimmeridgian–earliest Berriasian) and Early Cretaceous (late Berriasian–Hauterivian).
- Early Cretaceous (Aptian–Albian) instigation of rifting in the Faroe-Shetland Basin with maximum extension and basin widening in the Late Cretaceous (Coniacian–Maastrichtian). Localised uplift, compression and folding in various basins, particularly in Cenomanian–Turonian.
- The Paleocene onset of major extrusive volcanism initiated close to Danian/Selandian boundary; growth of major basaltic shield of Selandian–Thanetian age overlying continental crust in the vicinity of the Faroe Platform; plate breakup and associated volcanism in the earliest Eocene north and west of the Faroe Islands.
- Eocene (post-breakup) episodic uplift and erosion along the southern and eastern flanks of the Faroe-Shetland Basin; this was followed by a period of major compressive structuration across the entire Faroe–Shetland region spanning the end-Eocene/Oligocene–Mid-Miocene interval; this set the template for the shape of the modern-day continental margin, including the formation of the deep-water Faroe Conduit which facilitated the transfer of intermediate- and deep-water masses across the Greenland-Scotland Ridge.

By comparing the timing of these key phases of geological development of the Faroe–Shetland region with European and North Atlantic plate tectonics we identify a first-order correlation between the pattern of deformation that we observe and established changes in intraplate and/or plate boundary stresses. This raises the possibility that additional forces, including those postulated to be related specifically to the internal dynamics of a mantle plume, may not be a prerequisite to the evolution of the Faroe–Shetland region.

1 Introduction

The Faroe–Shetland region is an area of complex bathymetry located between the Faroe and Shetland islands on the outer part of the NW European continental margin, bounding the oceanic Norwegian Basin and Iceland-Faroe Ridge (Figure 1). On the continental margin, the shallow-water shelf areas that surround these islands are separated by the deeper-water basins of the Faroe-Shetland and Faroe Bank channels; these, in turn, are separated from the Rockall Trough – to the SW of the Faroe–Shetland region – by a series of shallower ridges and banks, including the Wyville Thomson Ridge and Faroe Bank. To the north of Shetland and the Faroe Islands, the continental margin slopes into the oceanic Norwegian Basin; in contrast, the shelf area to the NW of the Faroe Islands is juxtaposed against the Iceland-Faroe Ridge, which forms a major bathymetric high extending north-westwards from the Faroe Islands to Greenland (*via* Iceland). This complex bathymetry is ultimately a reflection of crustal thickness variations due initially to extension and magmatism linked to the evolution of the NE Atlantic rift system, followed by post-rift compressional deformation of the developing ocean margin.

The structural framework of the area is dominated by the Faroe-Shetland Basin, which is one of a series of NE–SW trending Cretaceous–Cenozoic depocentres between Ireland and Mid Norway, including the Rockall Basin and the Møre and Vøring basins, which developed as precursors to continental breakup between NW Europe and Greenland (Doré et al., 1999; Roberts et al., 1999). The main phase of extension in the Faroe-Shetland Basin occurred during the Cretaceous (Dean et al., 1999; Lamers and Carmichael, 1999; Larsen et al., 2010), though continental breakup – to the north and west of the Faroe Islands – was not achieved until the Early Eocene (54.8–54.5 Ma) (Passey and Jolley, 2009). Breakup was accompanied by extensive volcanism, which exploited weak spots in the increasingly thinned and rifted lithosphere of the NW European plate, including the Faroe–Shetland region (Passey and Hitchen, 2011).

In common with passive margins throughout the NE Atlantic region, it is becoming increasingly apparent that the Faroe–Shetland region has experienced tectonic movements during the post-breakup Cenozoic interval, manifest as significant departures from the expected post-rift pattern of decaying subsidence due to cooling (e.g. Steckler and Watts, 1978), including episodes of accelerated subsidence and uplift that were, at least in part, coeval (e.g. Andersen et al., 2000; Praeg et al., 2005; Ritchie et al., 2011). The most visible consequences of these tectonic episodes are the Fugloy, Munkagrunnur and Wyville Thomson ridges, all of which form major present-day bathymetric highs (Figure 1). The disposition of the Eocene succession, which is folded about the axes of these uplifts, implies that this major phase of folding and/or uplift occurred during late Palaeogene/early Neogene times (Boldreel and Andersen, 1993; Andersen et al., 2000; Johnson et al., 2005; Stoker et al., 2005c, 2013; Ritchie et al., 2008; Ólavsdóttir et al., 2010). Concomitant subsidence and the instigation of the deep-water Faroe-Shetland and Faroe Bank channels is revealed by the onlapping character of the overlying Oligocene and Miocene basinal sequences.

Aspects of the Cretaceous to Eocene stratigraphic record covering the pre-, syn- and post-breakup development of the Faroe–Shetland region have already been addressed within the framework of the Faroe-Shetland Consortium (FSC) (e.g. Stoker et al., 2010, 2012; Smith et al., 2013, 2014). At the specific request of consortium members, the present study was commissioned with a view to summarising this stratigraphic record through a time-series of palaeoenvironmental maps, designed to illustrate the development of the Faroe–Shetland region during this dynamic period of its history. To this end, this project presents a synthesis of much of the work undertaken on behalf of the FSC during phases 1 and 2 (2008–2015), representing a culmination to the phase 2 work.

1.1 SCOPE AND OBJECTIVES

The project was designed to present both a temporal and spatial representation of the Late Mesozoic–Cenozoic development of the Faroe–Shetland region based on the preserved stratigraphic record. The area of study extends north-westwards from the West Shetland Shelf to the Iceland-Faroe Ridge, with a south-western boundary essentially marked by the Wyville Thomson Ridge and an eastern boundary marked by the UK/Norwegian median line in the North Sea (Figure 1). Whereas the main focus of the FSC work lies in the area between the Shetland and Faroe islands, this entire map area was considered in all of the reconstructed maps.

The major objective of this study is to produce a set of maps that are intended to provide a generalised palaeoenvironmental reconstruction of the Faroe–Shetland and adjacent regions for a number of allocated time intervals (timeslices). The dataset behind this work is firmly grounded within the portfolio of reports previously produced for the FSC phases 1 and 2. However, following detailed discussion with the FSC sponsors, it was agreed to extend the time series back to the Late Jurassic (mid-Kimmeridgian) and forward to the Mid-Pleistocene; consequently, this required new work – beyond the existing set of FSC products – in order to produce maps for the Late Jurassic, Oligocene and Neogene–Quaternary intervals.

A secondary objective of the study is to construct a Late Mesozoic–Cenozoic tectonostratigraphic chart that is intended to highlight key events within the Faroe–Shetland region, and to examine their significance (if any) with regard to the evolution of the wider NE Atlantic region.

1.2 DATA SOURCES

There are four main sources of information:

1. Published scientific literature, including the BGS regional reports, the Millennium Atlas, and the UKOOA lithostratigraphic atlases.
2. BGS 1:250 000 and 1:500 000 offshore map series.
3. The portfolio of FSC reports produced by the BGS and Jarðfeingi between 2008 and 2014.
4. An updated version of the structural element map of Quinn et al. (2014), which is included as ‘supplementary information’ (a separate PDF document[1]) attached to the digital version of the current report.

1.3 METHODOLOGY

The palaeoenvironment maps have been constructed largely on the basis of observational data derived from the preserved stratigraphic record, i.e. outcrops, BGS boreholes, released commercial wells and seismic data; we have strived to keep ‘inference’ to a minimum. The intention is to produce a set of maps that is based on an honest appraisal of the data available for every specific time interval considered in the study.

The maps primarily display sedimentary environments, ranging from terrestrial/paralic to muddy basinal marine. The maps also include lithostratigraphic information, as well as attempting to depict areas undergoing contemporary deformation. The structural elements (basins, sub-basins, highs and faults) that underpin the Late Mesozoic and Palaeogene maps are based on a revision[1] of the framework presented by Quinn et al. (2014). The timescale used in this study is based on Gradstein et al. (2012).

More specific details on the methodology of map production are presented in Chapter 4.

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[1] See ‘Supplementary Information’ attached to digital version of this report

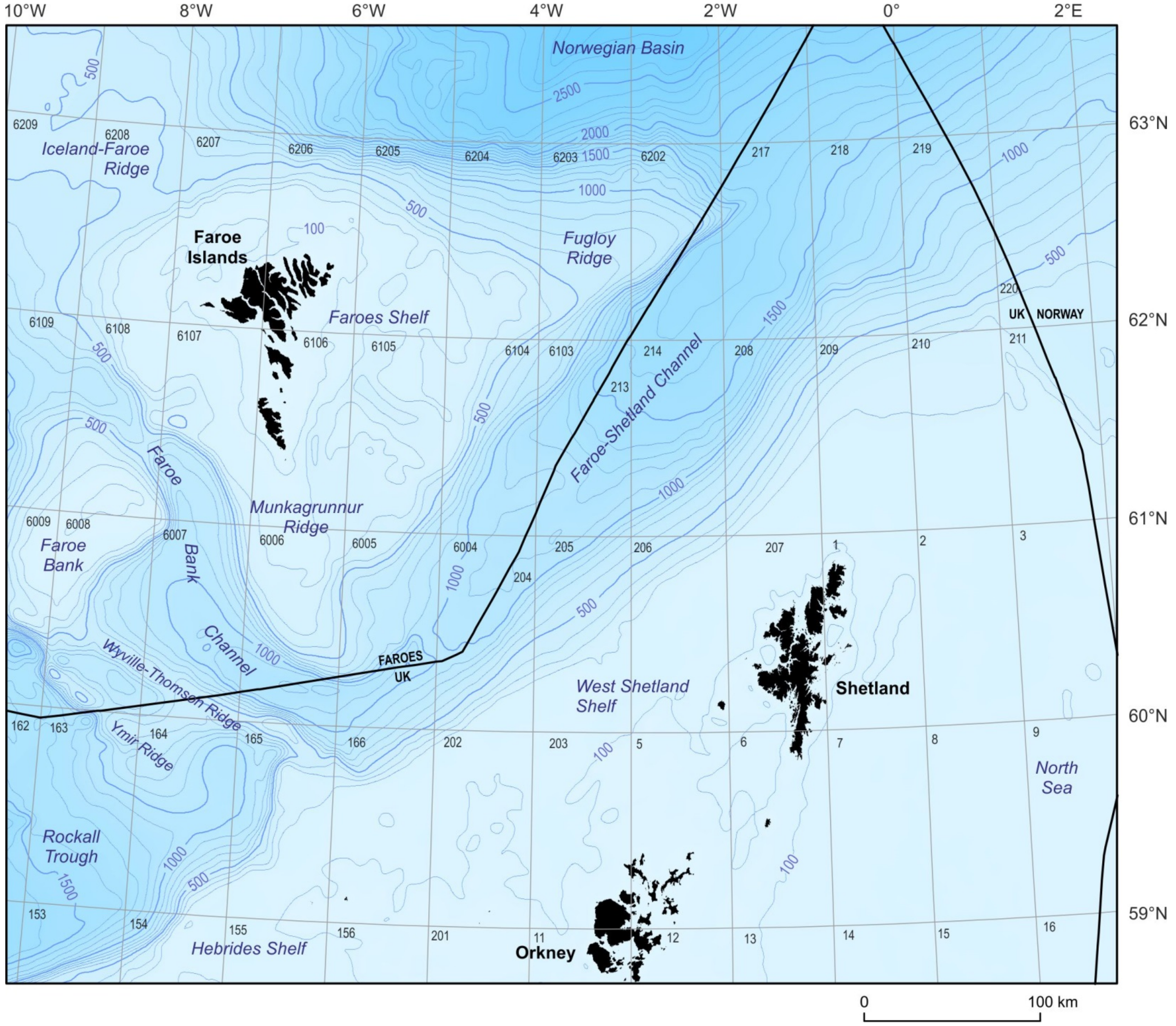

Figure 1 Location of study area showing main bathymetric features, EEZ median line, and licence quadrant numbers for UK and Faroese areas. Bathymetric contours in metres below sea level. Based on BGS marine surveys, released Faroese data provided by Jarðfeingi, and contours from the GEBCO digital atlas (IOC, IHO and BODC, 2003).

2 Structural Framework

The structural elements map of the Faroe-Shetland region shown in Figure 2 is used as a reference framework for the palaeoenvironmental time-slices displayed in Chapter 4. The present version is based on the map and nomenclature of Ritchie et al. (2011), modified as a result of a reassessment undertaken on behalf of the FSC (Quinn et al., 2014). Interpretations over the Corona, Flett and Erlend highs and a reviewed set of published fold axes form the main components of the revised map, and these new interpretations and other revisions are fully described in Quinn et al. (2014). The interpretation of the Erlend High and adjacent area was further refined for the Atlas template, details of which can be found elsewhere (see section 1.2). The structural elements – excepting fold axes – have been extended beyond the Faroe–Shetland region, within the limits of the study area, using published information for the northern Rockall Basin (Ritchie et al., 2013), Northern North Sea (Johnson et al., 1993) and Norwegian sector (Blystad et al., 1995).

A brief description of the structural framework is presented below.

2.1 STRUCTURAL FRAMEWORK MAP

The Atlas template (Figure 2) shows the NE-trending Faroe-Shetland Basin and its various sub-basins in the context of surrounding structure. The Faroe-Shetland Basin is bounded to the north by the Fugloy Ridge, an east- to east-northeast-trending Mesozoic and older structure (cf. Ritchie et al. 2011) that has been affected by later compression during the Eocene to Miocene. The Fugloy Ridge separates the Faroe-Shetland Basin from the Continent Ocean Transition, oceanic crust and the Iceland-Faroe Ridge (Figure 2). The Faroe Platform and Munkagrunnur Ridge form the western boundary to the Faroe-Shetland Basin and together with the Faroe Bank High, Wyville Thomson and Ymir ridges form thick Palaeogene-lava-covered highs that are located largely within the Faroese sector. The south-west and south-east boundaries to the Faroe-Shetland Basin are marked by the bounding faults of the crystalline basement-cored Judd and Rona highs respectively, beyond which are located a number of marginal basins, including the West Shetland Basin and the North Rona, South Solan, West Solan and East Solan basins, which are collectively referred to as the ‘SE Marginal Basins’. To the north-east, re-interpretation of the Erlend High and adjacent areas for this project has resulted in a change in the boundary to the Faroe-Shetland Basin compared to Ritchie et al. (2011) and Quinn et al. (2014), such that the Erlend High is now incorporated within the basin, and separated from the West Shetland and North Shetland highs by the Yell and Muckle sub-basins. Farther to the north-east, the Faroe-Shetland Basin boundary is marked by the Møre Marginal High containing the Brendan Igneous Centres, and Møre Basin.

Within these bounding highs and basins, the Faroe-Shetland Basin comprises 12 sub-basins generally separated from one another by north to north-east trending crystalline basement cored highs. Where sub-basins are juxtaposed, their boundaries are somewhat equivocal (grey dashed lines on Figure 2); either defined by the locations of possible rift-oblique lineaments (Ritchie et al., 2011) (see section 2.1.1) or inferred by continuations of the general trend of bounding basement highs.

Whereas this structural framework is largely a legacy of Late Palaeozoic–early Cenozoic extension, eventually leading to plate breakup to the north and north-west of the Faroe Islands in the earliest Eocene, much of the Faroe–Shetland region has been affected by compression, particularly since plate breakup, and synclines and anticlines of various scales are evident (Figure 2). Further details are presented in section 2.1.2.

2.1.1 NW-trending lineaments

Ritchie et al. (2011) attempted to rationalise the rift-oblique lineaments identified and described by previous authors (e.g. Duindam and van Hoorn, 1987; Rumph et al., 1993; Dore et al., 1997; Keser Neish, 2003) and show twelve NW-trending lineaments on their structural elements map. However, a study by Moy and Imber (2009) based on the interpretation of 3D seismic data volumes, questioned the influence that three of the lineaments – specifically the Judd, Corona and Clair features (naming from Rumph et al., 1993 and Ritchie et al., 2011), and by analogy other rift-oblique lineaments – might have had on Cenozoic sediment distribution. In addition, no unequivocal evidence for the influence or effects that these structures may have had on the present-day structural configuration could be recognised during the compilation of the revised structural map (Quinn et al., 2014). Thus, it was decided that inclusion of these lineaments on the structural map would place undue emphasis on these structures and might 'draw the eye' away from other possible structural trends in the area. For these reasons, none of these lineaments were shown on the revised structural map of Quinn et al. (2014), and this decision has been followed for the structural template used in this study. However, in order to retain the existing structural nomenclature, particularly for the sub-basins within the Faroe-Shetland Basin, the location of NW-trending lineaments of Ritchie et al. (2011) have been used to infer the probable position of sub-basin boundaries. The grey-dashed lines are used on Figure 2 to mark their inferred boundaries.

2.1.2 Fold axes

Figure 3 shows the location of a revised set of anticlinal and synclinal axes within the Faroe–Shetland region; those within the Faroe-Shetland Basin and on the bounding highs, e.g. Munkagrunnur, Fugloy and Wyville Thomson ridges and More Marginal High, are rationalised from a number of published sources and following the methodology as described in Quinn et al. (2014). Fold axes are also shown from the northern Rockall Trough, within the limits of the study area, and are based on Tuitt et al. (2011). Whereas many of the anticlines are inferred to have originated during contractional deformation, others, such as the Munkagrunnur Ridge, might have formed initially as simple drape structures between synclines, though some tightening of the structure in response to compressive stress is also considered likely.

Within the Faroe-Shetland Basin, the majority of the anticlinal axes have a NE–NNE trend and are located within the sub-basins (Figure 3); they have been identified on a number of structure maps generated from the interpretation of stratigraphic horizons within the Palaeogene and Neogene successions (Johnson et al., 2012). On the basis of the relationship between the folds and the established seismic stratigraphy it has been possible to chart the timing of initiation and subsequent history of movement of all of the axes in the Faroe-Shetland Basin (Figure 4). A chart has also been constructed for the Faroe Bank Channel and NE Rockall Basin area (Figure 5). Inspection of these charts suggests that whereas compressive stress, in general, might be an ongoing, low-level, background phenomenon, this stress regime was punctuated by 'instances (pulses) of accentuated compression' that coincide with major structuration (e.g. Ritchie et al., 2003, 2008; Johnson et al., 2005). Both charts document the source(s) of the data used in their construction.

For the most part, the folds were generated subsequent to plate breakup (Eocene–Pleistocene); however, Cretaceous and Paleocene folds have also been reported, e.g. the Flett Syncline, Flett High Anticline and Foula Syncline (Grant et al., 1999; Stoker et al., 2010; Quinn et al., 2014).

In relation to the palaeoenvironment maps presented in Chapter 4, we have attempted to show which of the folds indicated in Figure 3 might have been actively developing at specific times, primarily during the post-breakup interval (Eocene–Pleistocene).

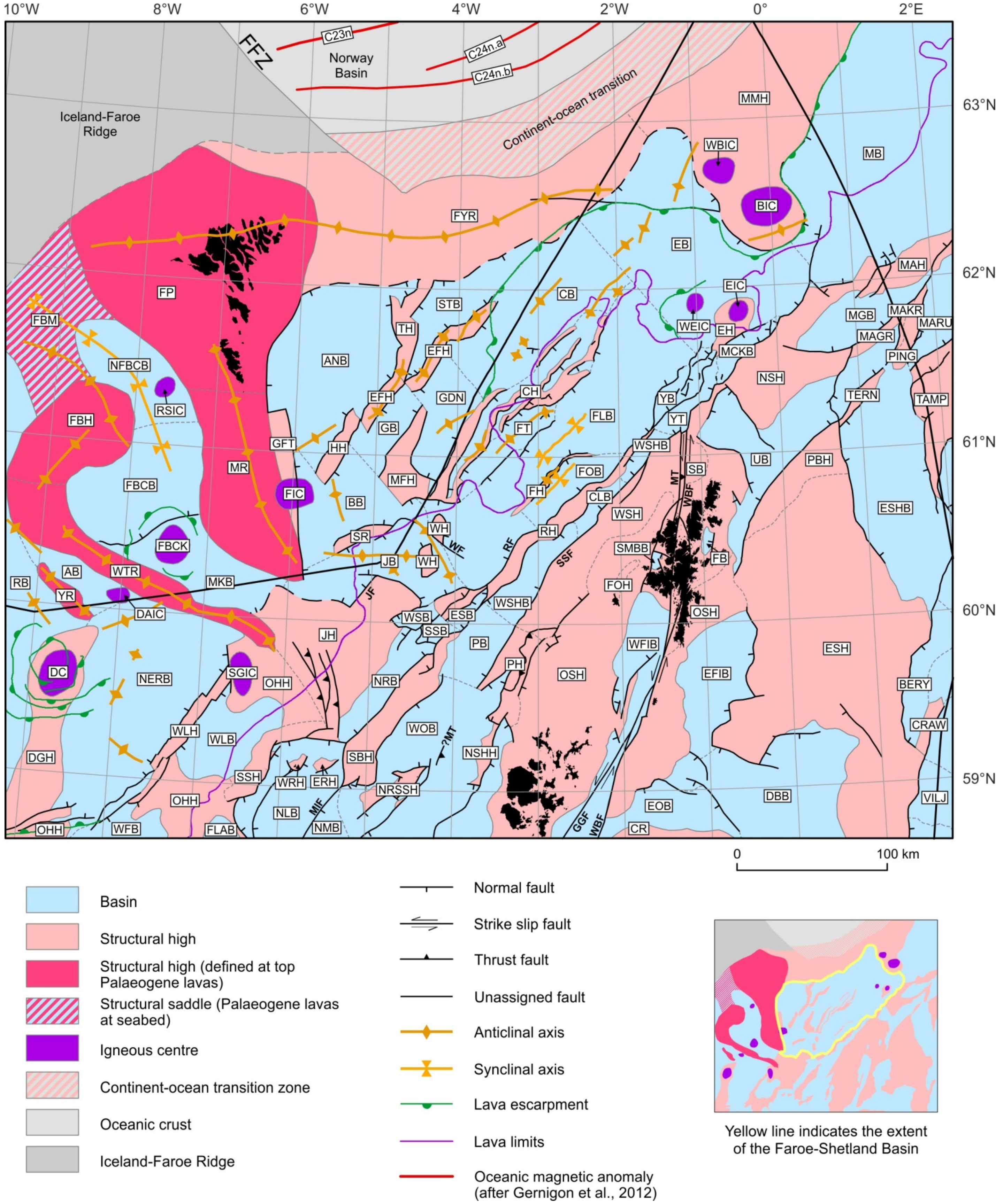

Figure 2 Structural element map of the Faroe-Shetland area, based on Ritchie et al. (2011), Quinn et al. (2014) and this study, with information on peripheral areas from Johnson et al. (1993), Blystad et al. (1995) and Ritchie et al. (2013). The grey dashed lines represent inferred structural boundaries (see text for details). For details of the fold axes, see Figure 3; for key to structural element abbreviations, see Table 1. Inset map shows delineation of the Faroe-Shetland Basin.

AB	Auðhumla Basin	NERB	NE Rockall Basin
ANB	Annika sub-Basin	NFBCB	North Faroe Bank Channel Basin
BB	Brynhild sub-Basin	NLB	North Lewis Basin
BERY	Beryl Embayment	NMB	North Minch Basin
BIC	Brendan Igneous Centre	NRB	North Rona Basin
CB	Corona sub-Basin	NRSSH	Nun Rock-Sule Skerry High
CH	Corona High	NSH	North Shetland High
CLB	Clair Basin	NSHH	North Shoal High
CR	Caithness Ridge	OHH	Outer Hebrides High
CRAW	Crawford Spur	OSH	Orkney-Shetland High
DAIC	Drekaeyga Igneous Centre	PB	Papa Basin
DBB	Dutch Bank Basin	PBH	Pobie High
DC	Darwin	PH	Papa High
DGH	Darwin-Geikie High	PING	Penguin Ridge
EB	Erlend sub-Basin	RB	Rockall Basin
EFH	East Faroe High	RH	Rona High
EFIB	East Fair Isle Basin	RSIC	Regin Smidur Igneous Centre
EH	Erlend High	SB	Sandwick Basin
EIC	Erlend Igneous Centre	SBH	Solan Bank High
EOB	East Orkney Basin	SGIC	Sula Sgeir Igneous Centre
ERH	East Rona High	SMBB	St. Magnus Bay Basin
ESB	East Solan Basin	SR	Sjúrður Ridge
ESH	East Shetland High	SSB	South Solan Basin
ESHB	East Shetland Basin	SSH	Sula Sgeir High
FB	Fetlar Basin	STB	Steinvør sub-Basin
FBCB	Faroe Bank Channel Basin	TAMP	Tampen Spur
FBCK	Faroe Bank Channel Knoll	TERN	Tern-Eider Horst
FBH	Faroe Bank High	TH	Tróndur High
FBM	Faroe Bank Margin	UB	Unst Basin
FH	Flett High	VILJ	Vilge sub-Basin
FIC	Fraenir Igneous Centre	VOLV	Volve sub-Basin
FLAB	Flannan Basin	WBIC	West Brendan Igneous Centre
FLB	Flett sub-Basin	WEIC	West Erlend Igneous Centre
FOB	Foula sub-Basin	WFB	West Flannan Basin
FOH	Foula High	WFIB	West Fair Isle Basin
FP	Faroe Platform	WH	Westray High
FT	Flett Terrace	WLB	West Lewis Basin
FYR	Fugloy Ridge	WLH	West Lewis High
GB	Grimhild sub-Basin	WOB	West Orkney Basin
GDN	Guðrun sub-Basin	WRH	West Rona High
GFT	Grani Fault Terrace	WSB	West Solan Basin
HH	Heri High	WSH	West Shetland High
JB	Judd sub-Basin	WSHB	West Shetland Basin
JH	Judd High	WTR	Wyville Thomson Ridge
MAGR	Magnus Ridge	YB	Yell sub-Basin
MAH	Margarita High	YR	Ymir Ridge
MAKR	Makrell Horst	YB	Yell Terrace
MANE	Manet Ridge	*Faults:*	
MARU	Marulk Basin	GGF	Great Glen Fault
MB	Møre Basin	JF	Judd Fault
MCKB	Muckle sub-Basin	MIF	Minch Fault
MFH	Mid Faroe High	MT	Minch Fault
MGB	Magnus Basin	RF	Rona Fault
MKB	Munkur Basin	SSF	Shetland Spine Fault
MMH	Møre Marginal High	WBF	Walls Boundary Fault
MR	Munkagrunnur Ridge	WF	Westray Fault

Table 1 Structural element abbreviations for Figure 2

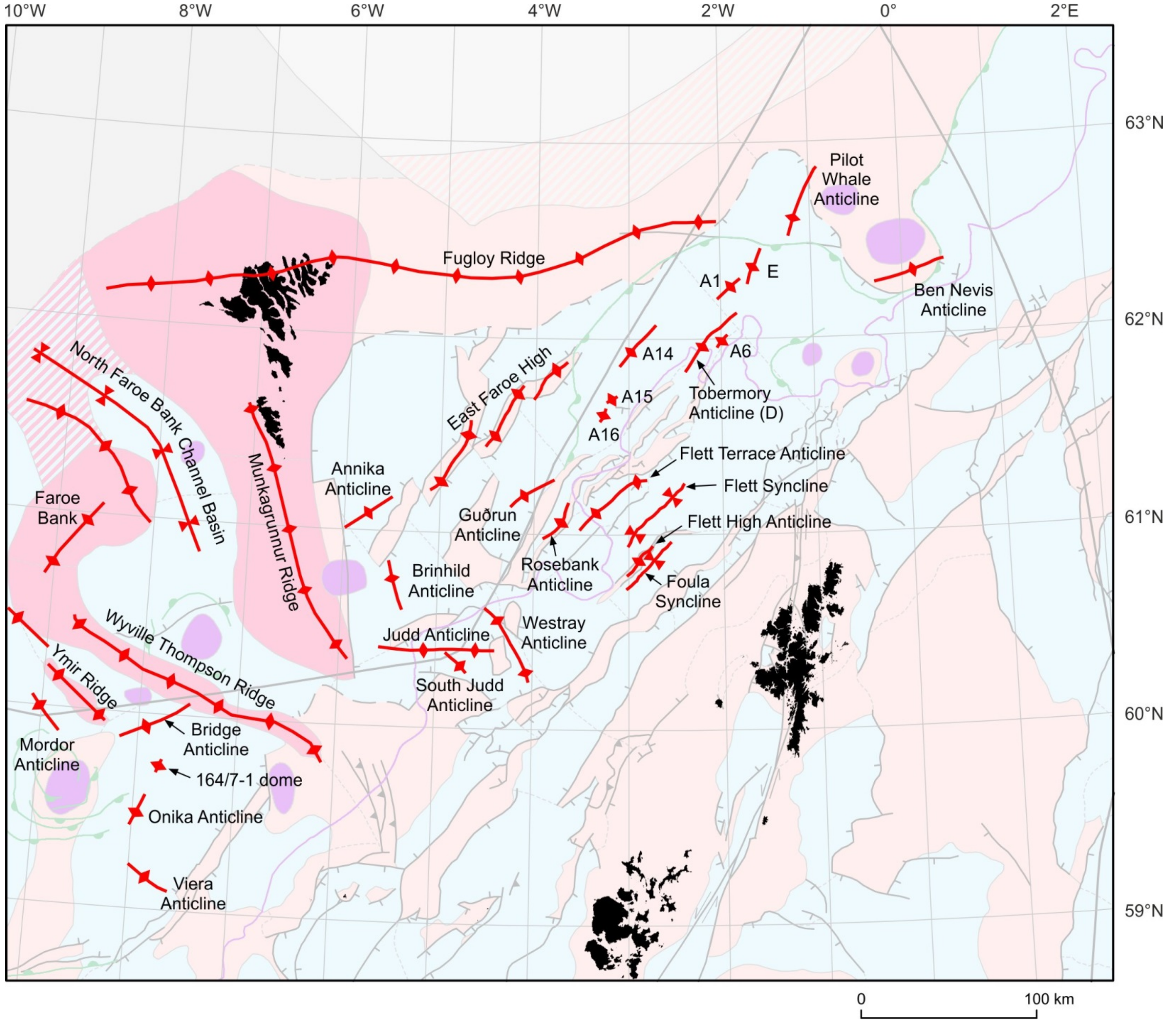

Figure 3 Fold axes in the Faroe-Shetland area. The backdrop is a masked version of the structural element map (Figure 2).

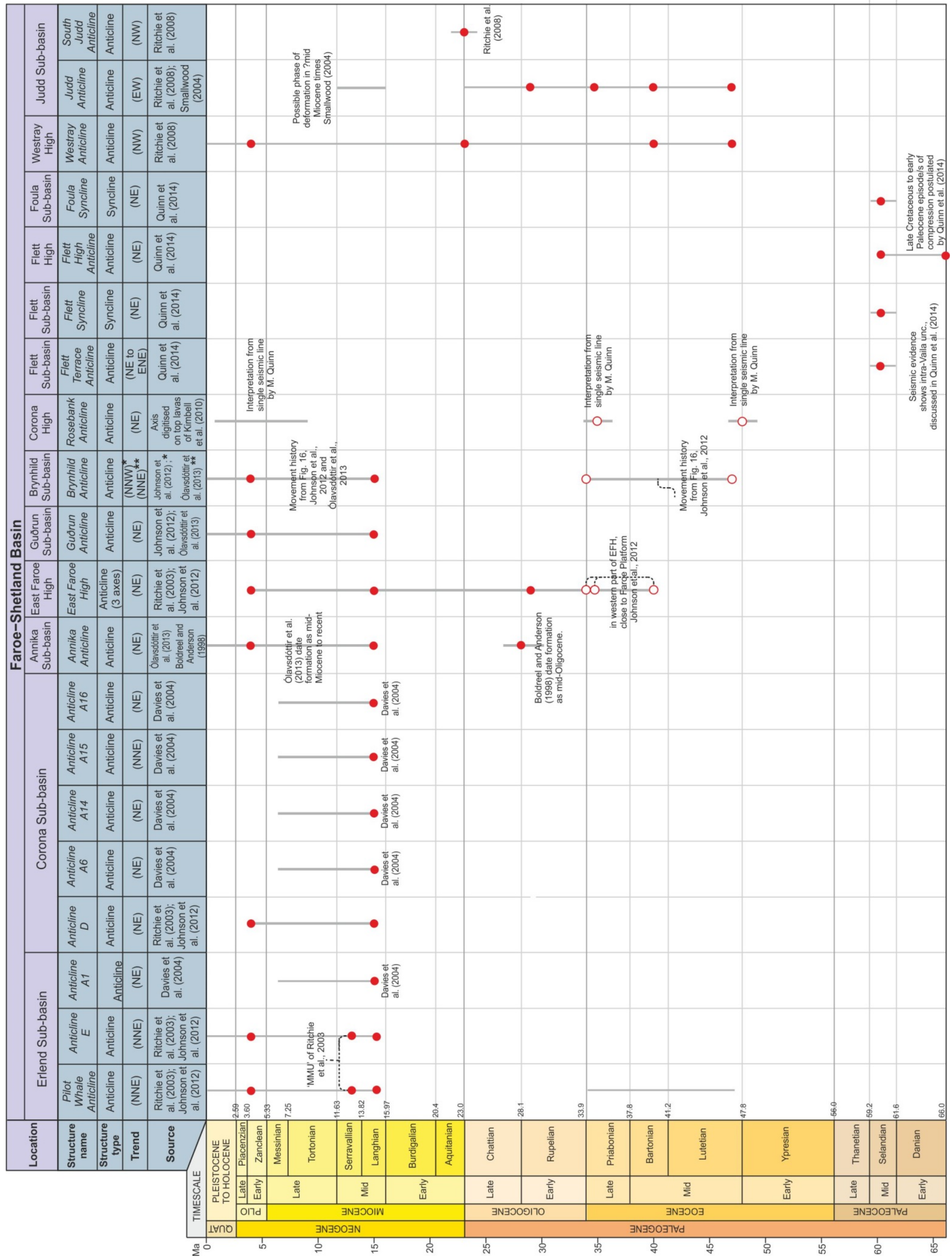

Figure 4 Chart summarising the timing of growth of Cenozoic anticlines and synclines within the Faroe-Shetland Basin. Key pulse of growth indicated by red dot; tentative pulse of growth indicated by open circle; grey bar shows inferred range of low-level background growth of structure. Growth ranges are from Johnson et al. (2012), unless otherwise indicated. All fold axes are described in detail in Quinn et al. (2014), except for the Rosebank Anticline. Timescale is based on Gradstein et al. (2012).

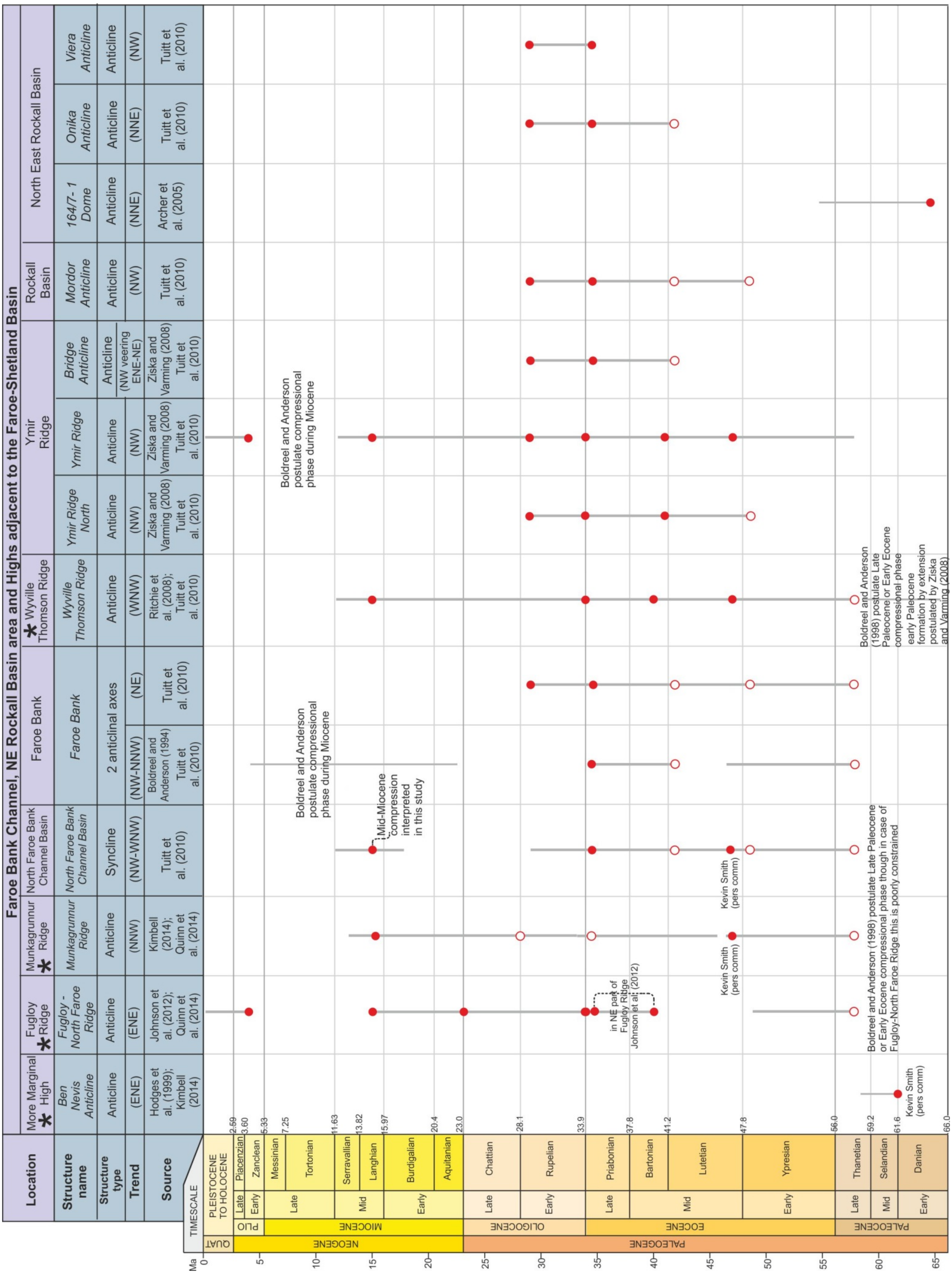

Figure 5 Chart summarising the timing of timing of growth of Cenozoic anticlines and synclines in the NE Rockall Basin–Faroe Bank Channel area, and on structural highs bounding the Faroe-Shetland Basin. Key pulse of growth indicated by red dot; tentative pulse of growth indicated by open circle; grey bar shows inferred range of low-level background growth of structure. Structures marked by an asterisk are described in detail in Quinn et al. (2014). Timescale is based on Gradstein et al. (2012).

3 Stratigraphic Framework

The upper Mesozoic–Cenozoic stratigraphic framework for the Faroe–Shetland region is summarised in Figure 6, and the present structural disposition of the various units is shown in Figure 7. The widespread distribution and masking effect of the early Palaeogene volcanic rocks across the outer continental margin – essentially the Faroese sector – means that the proven Jurassic to Cretaceous rock record in the Faroe–Shetland region is largely restricted to the area west of Shetland, including the eastern part of the Faroe-Shetland Basin (Ritchie and Varming, 2011; Stoker et al., 2010; Stoker and Ziska, 2011). The occurrence and distribution of these rocks to the west of the Corona and Sjurður highs is unknown (Figure 7).

In general terms, the Jurassic–Cretaceous succession records an increasing marine influence across the Faroe–Shetland region, which was probably at its most expansive during the Late Cretaceous, as indicated by the widespread distribution of the Upper Cretaceous sequence within the Faroe-Shetland Basin (Figure 7b, d). However, the rock record shows that this development was not a gradual trend as the Jurassic–Cretaceous succession is punctuated by a series of unconformities, especially in the Mid-Jurassic; in the Berriasian (earliest Cretaceous: base of the Cromer Knoll Group); in the ‘mid’ Cretaceous (Albian/Cenomanian); as well as in the early Late Cretaceous (probably Turonian) (Figure 6). The latter unconformity was termed the ‘near-base Upper Cretaceous’ boundary by Stoker et al. (2010), and is prominent on seismic profiles as a pre-Coniacian folded surface, which defines the Foula and Flett synclines (Figures 3 and 7). A major unconformity separates Cretaceous and Paleocene rocks, and was followed by a series of Paleocene–earliest Eocene unconformities linked to the widespread intrusion and extrusion of igneous and volcanic rocks, and marking the process of continental breakup (Passey and Hitchen, 2011; Smith et al., 2013). The post-breakup Eocene–Pleistocene succession reflects the development of the Faroe–Shetland region as a divergent margin; however, the episodic nature of sediment accumulation, with sequences commonly bounded by unconformities, is a reflection of the interaction between sedimentation and post-breakup deformation (Stoker et al., 2005a, 2005b, 2012b, 2013; Stoker and Varming, 2011; Smith et al., 2014).

A fuller appraisal of the upper Mesozoic–Cenozoic stratigraphic framework is beyond the scope of this report, and the reader is referred to the references cited above for more detail. However, there remain a number of general issues that continue to impart a degree of uncertainty on any interpretation of the stratigraphic succession, and these are briefly highlighted in the following section.

3.1 UPPER MESOZOIC–CENOZOIC STRATIGRAPHIC UNCERTAINTIES AND THEIR IMPLICATIONS

There are four main areas of uncertainty where better resolution of the stratigraphic framework is required in order to improve our understanding of the late Mesozoic–Cenozoic development of the Faroe–Shetland region: 1) Facies interpretation of Upper Jurassic coarse clastic rocks; 2) Age and facies interpretation of basal Cretaceous rocks; 3) Chronology of Paleocene–earliest Eocene breakup succession; and, 4) Chronological resolution of post-breakup succession. Each of these is briefly highlighted below.

3.1.1 Facies interpretation of Upper Jurassic coarse clastic rocks

The Upper Jurassic Kimmeridge Clay Formation includes a basal coarse clastic unit around the marginal areas to the south and east of the Faroe-Shetland Basin assigned to various members, e.g. Ridge Conglomerate, Rona, Spine and Solan Bank members (Verstralen et al., 1995; Ritchie and Varming, 2011). There are two contrasting models to explain the origin of these deposits: 1) Haszeldine et al. (1987) and Hitchen and Ritchie (1987) suggest that the coarse-grained deposits, currently assigned to the Ridge Conglomerate Member, were derived from an active fault scarp

(Rona Fault: see Figure 2), and are cited as evidence for the Late Jurassic or older inception of a deep-marine seaway in the Faroe–Shetland region; and, 2) Verstralen et al. (1995) presented a wider perspective of the distribution of this facies (including the Rona and Spine members) within the SE marginal basins, and concluded that footwall uplift on the Rona, Judd and Shetland Spine faults (Figure 2) generated the supply of coarse-grained material to isolated, subaerial to shallow-marine fan deltas. The significance of these two models is that they present a contradictory view of the status of basin development and general sedimentary environment in this area in the Late Jurassic.

3.1.2 Age and facies interpretation of basal Cretaceous rocks

A new appraisal of the stratigraphic framework of the Cretaceous rocks in the Faroe–Shetland region is presented in Figures 8 and 9. These charts are based on the stratigraphic-range charts previously published by Stoker et al. (2010) and Stoker and Ziska (2011), but instead of presenting individual wells and their lithologies, they summarise the stratigraphic range that is preserved within each basin/sub-basin, and on each structural high. Moreover, they present the rock record in terms of the sedimentary environment. A more specific update – in terms of this report – concerns the age of the basal rocks in the Judd and Flett sub-basins and on the southern Westray High, and shows a revised Barremian/Aptian onset of deposition as previously noted by Stoker et al. (2010).

Inspection of the revised stratigraphic framework shown in Figures 8 and 9 reveals a more consistent view of the timing of Cretaceous basin instigation, with a slightly older, albeit punctuated, record of sedimentation (from the late Berriasian) preserved in the West Shetland Basin and SE Marginal Basins compared to the Faroe-Shetland Basin (predominantly Aptian–Albian).

One further area of uncertainty concerns the genetic interpretation of the basal coarse clastic rocks that comprise the Neptune, Royal Sovereign and Commodore formations, and which fringe the Judd, Flett and Foula sub-basins. These are interpreted to include basal conglomerates that overlie Jurassic and older rocks, as well as mass-flow deposits (Ritchie et al., 1996; Harker 2002). Whereas well-logs provide important information on sand-body geometry, it is suggested that caution be exercised in the interpretation of their sedimentary environment. For example, Ritchie et al. (1996) have assigned both shallow- and deep-marine environments to the Neptune Formation, solely on the basis of its gamma-ray signature. It is unclear to the present authors how water depth can be derived solely from well-log data.

3.1.3 Chronology of Paleocene–earliest Eocene breakup succession

Pollen from Lopra 1A, the deepest borehole in the Faroe Islands, has been used to suggest that the volcanic pile in the area is almost entirely post-Paleocene in age (Ellis et al. 2002; Schofield and Jolley, 2013). Accepting this restricted age range for the Faroe Islands Basalt Group means that the older radiometric age dates measured on Faroese lavas, the magnetostratigraphic interpretations of the succession (Riisager et al., 2002; Kimbell, 2014) and the early Palaeogene tectono-stratigraphy of Smith et al. (2013) (Figure 10) must be largely discarded in favour of the biostratigraphic data.

An independent re-appraisal of the biostratigraphic and radiometric evidence was carried out to help resolve this conflict of interpretation (Harrington and Riding, 2015). The preliminary results of the biostratigraphic review appear to support Aubry et al.'s (2003) claim that elements of the early Palaeogene flora are wide-ranging and do not have the chronological significance originally attributed to them by Jolley (1997).

The accompanying review of the radiometric age determinations proved more inconclusive, mainly questioning the applicability of the Ar^{40}/Ar^{39} method to the dating of low potassium volcanic rocks and proposing that a search be carried out in the basalt succession for minerals more suited to dating by alternative methods. It was suggested that U/Pb method, applied to mineral separates obtained from interbedded tuffs or the late differentiates of dolerite sills, in boreholes or at outcrop, might yet provide better radiometric ages from the area.

A review of existing chronostratigraphic reports submitted as part of the Sindri programme did reveal that the final 'preferred' age dates for the Faroe Island Basalt Group were selected from a wide ranging set of radiometric age determinations largely because they were judged to support the regional biostratigraphic interpretations of Jolley and his co-workers (Jolley, 1997; Ellis et al., 2002). It follows that the handful of selected age dates cannot be taken as an independent confirmation of the biostratigraphic analysis.

The results of these reviews undermine the repeated assertion that the apparent narrow range of ages indicated by the biostratigraphic data is a better indication of the true age of the Faroe Islands Basalt Group. However, further work may be required to construct a more firmly established chronological scheme for the area.

In summary, nothing has yet emerged from the expert review process to conflict with the decision to construct the series of timeslice maps for the early Palaeogene on the assumption that the Faroe Island Basalt Group and associated volcanic rocks in the Faroe–Shetland region have had a more prolonged geological history than that claimed by Jolley and his co-workers. Accepting the magnetostratigraphic interpretation of Riisager et al. (2002), in particular, means that much of the Beinsvørđ Formation must be of pre-Thanetian age and this clearly has potential implications for the nature and distribution of Selandian and older reservoirs, especially in the Faroese sector.

3.1.4 Chronological resolution of post-breakup succession

It is well established that the Eocene–Pleistocene succession comprises a series of unconformity-bounded units, and several key unconformities have been recognised and mapped regionally within the Faroe–Shetland region, incuding: Top Palaeogene unconformity (TPU), Intra-Miocene unconformity (IMU), and the Intra-Neogene unconformity (INU) (Stoker et al., 2005a, b; Stoker and Varming, 2011) (Figures 6 and 7). However, issues of stratigraphic resolution remain, with the main uncertainties as follows:

- Progress has been made recently in the subdivision of the Eocene succession (e.g. Stoker and Varming, 2011; Stoker et al., 2012b, 2013; Smith, 2014) (Figure 11); however, the recognition of the Eocene/Oligocene boundary – labelled T2a – within the Faroe-Shetland Basin is problematic. Whereas the eroded top of the Eocene succession is commonly defined by angular truncations at a composite basal Neogene unconformity (IMU/INU) on the flanks of the Faroe-Shetland Basin, its boundary with the Oligocene can be very difficult to identify in wells, and especially on seismic data from the centre of the basin. Within the basin, reflector T2a often occurs in the vicinity of a conspicuous cross-cutting reflector formed by a diagenetic opal transition horizon (Davies and Cartwright, 2002), and is also masked locally by 'V-bright' reflectors linked to polygonal faults; all of which obscure this part of the stratigraphic succession on seismic profiles (Johnson et al., 2012; Smith et al., 2014).
- Subdivision of the Oligocene succession remains problematic. There are indications, regionally, for a mid-Oligocene unconformity (e.g. in the North Sea; on the Hebrides margin), and an 'intra-Oligocene unconformity' was tentatively inferred by Johnson et al. (2012) within the Faroe–Shetland region. However, the lack of biostratigraphic precision available from Oligocene borehole and well data (e.g. Stoker, 1999), as well as issues of seismic resolution that include the diagenetic reflection described above, all conspire to hinder our understanding of this succession. Where observed on the flanks of the Faroe-Shetland Basin, an angular unconformity – the TPU (sometimes composite with the IMU and INU) – commonly separates the Oligocene from the overlying Neogene–Quaternary succession.

- The stratigraphy of the Neogene–Quaternary succession is fairly well established, including the key regional unconformities of the IMU and INU (e.g. Stoker, 1999, 2002; Johnson et al., 2005; Stoker et al., 2005a, b; Stoker and Varming, 2011). Nevertheless, one aspect that requires improvement is the biostratigraphic resolution of the Miocene sandstone-dominated succession – the Muckle Ossa Sandstone – preserved on the West Shetland margin. Available data currently only provide a long-ranging late Early to Late Miocene age for this unit (Stoker, 1999; Stoker and Varming, 2011). Improved stratigraphic resolution would enable better correlation to the well-established Miocene successions in the North Sea.

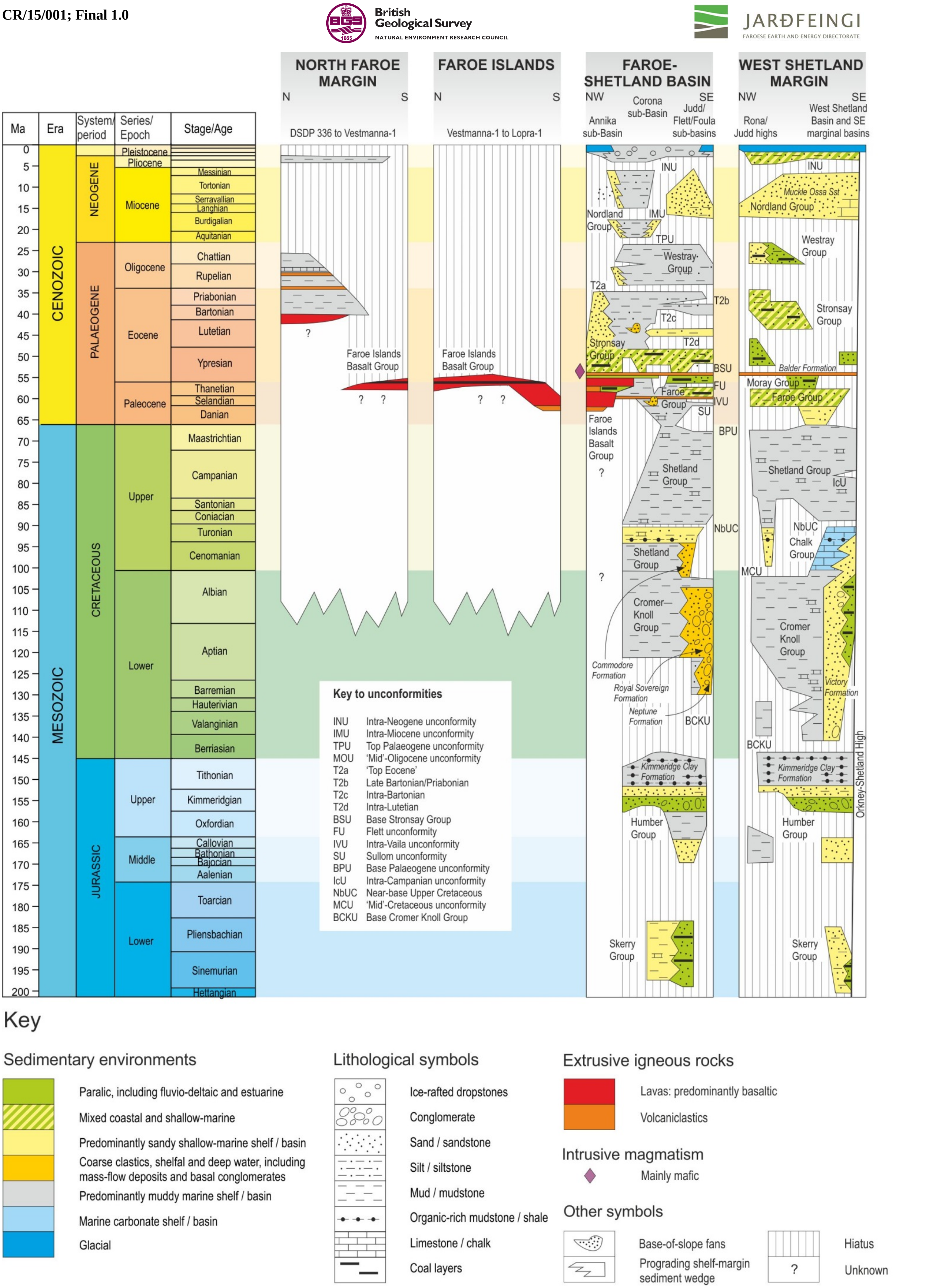

Figure 6 Generalised late Mesozoic–Cenozoic stratigraphic columns for the Faroe–Shetland region showing the stratigraphic range and general facies characteristics of the preserved (and known) rock record, and key unconformities. Timescale is based on Gradstein et al. (2012).

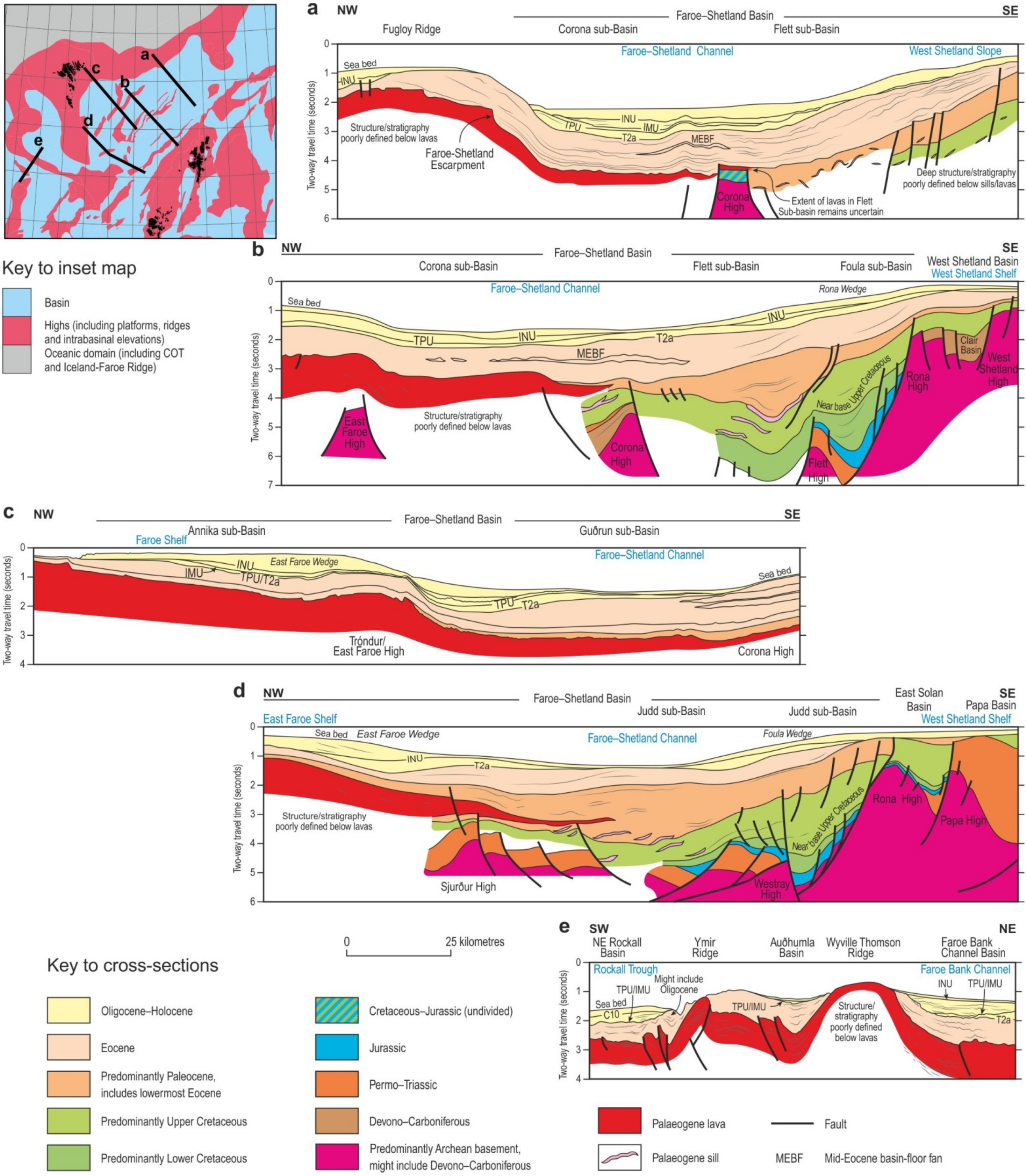

Figure 7 Geoseismic profiles from the Faroe–Shetland region showing the general tectonostratigraphic architecture of the preserved rock record (modified after Stoker et al., 2014a). Structural elements labelled in black font; bathymetric elements labelled in blue font. Abbreviations/notation: IMU, Intra-Miocene Unconformity; INU/C10, Intra-Neogene (Pliocene) Unconformity; MEBF, Middle Eocene basin-floor fans; TPU, Top Palaeogene Unconformity; T2a, Top Eocene. Inset map shows location of profiles.

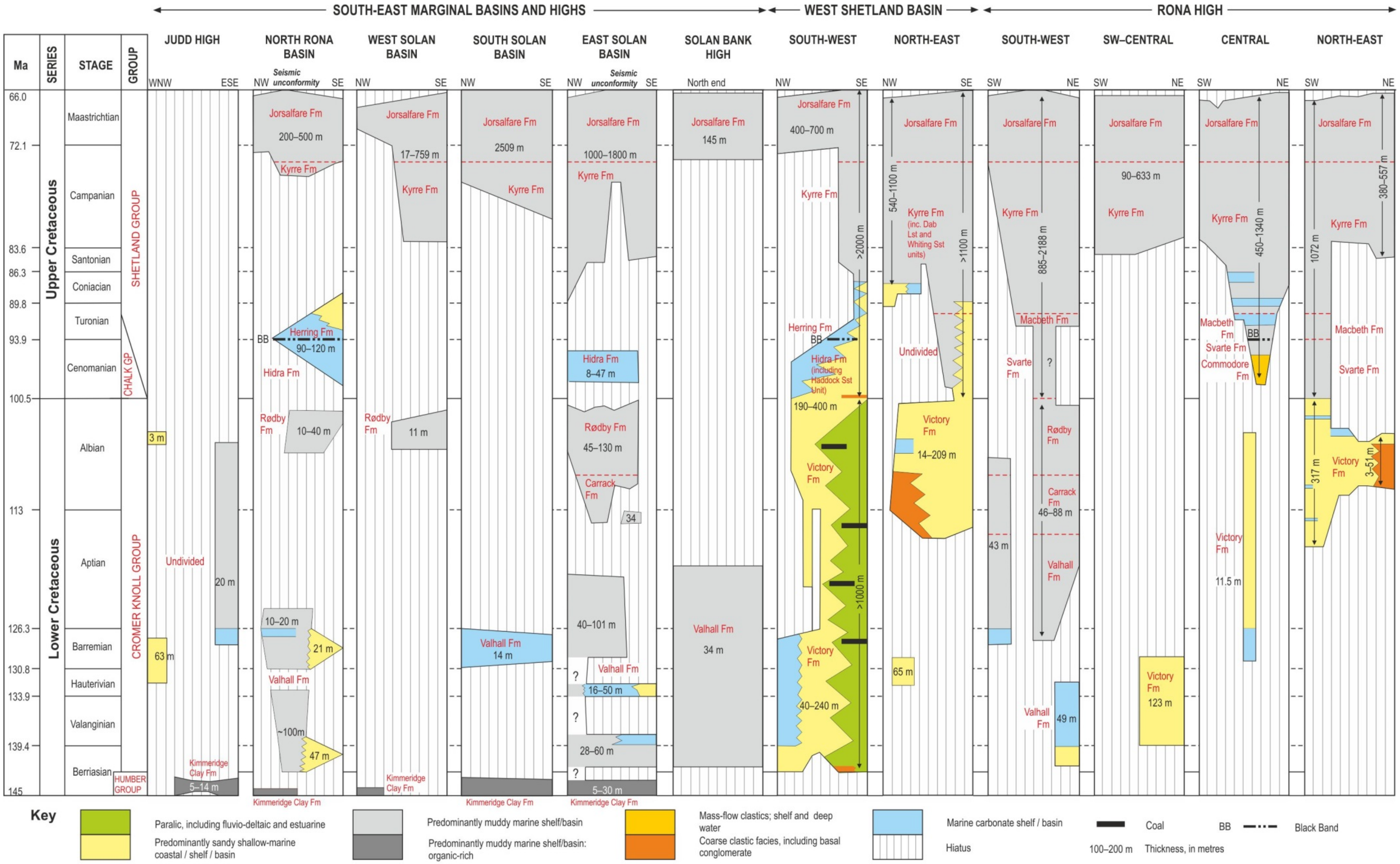

Figure 8 Cretaceous stratigraphy of the SE Marginal Basins, West Shetland Basin and Rona High, indicating stratigraphic range, thickness and sedimentary environment of the preserved rocks (modified after Stoker et al., 2010a). Timescale is based on Gradstein et al. (2012).

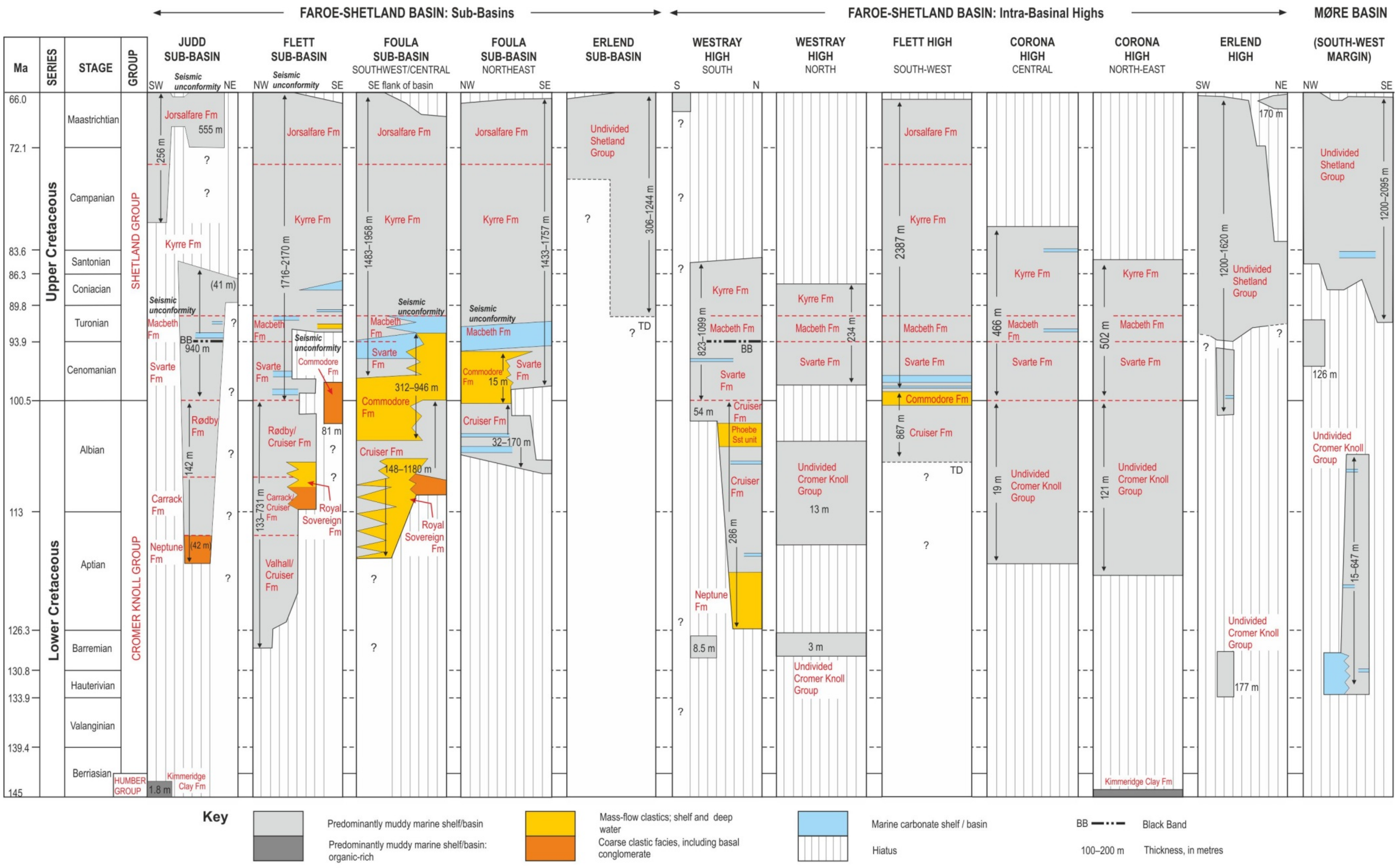

Figure 9 Cretaceous stratigraphy of the Faroe-Shetland Basin and south-west margin of the Møre Basin, indicating stratigraphic range, thickness and sedimentary environment of the preserved rocks (modified after Stoker et al., 2010a). Timescale is based on Gradstein et al. (2012).

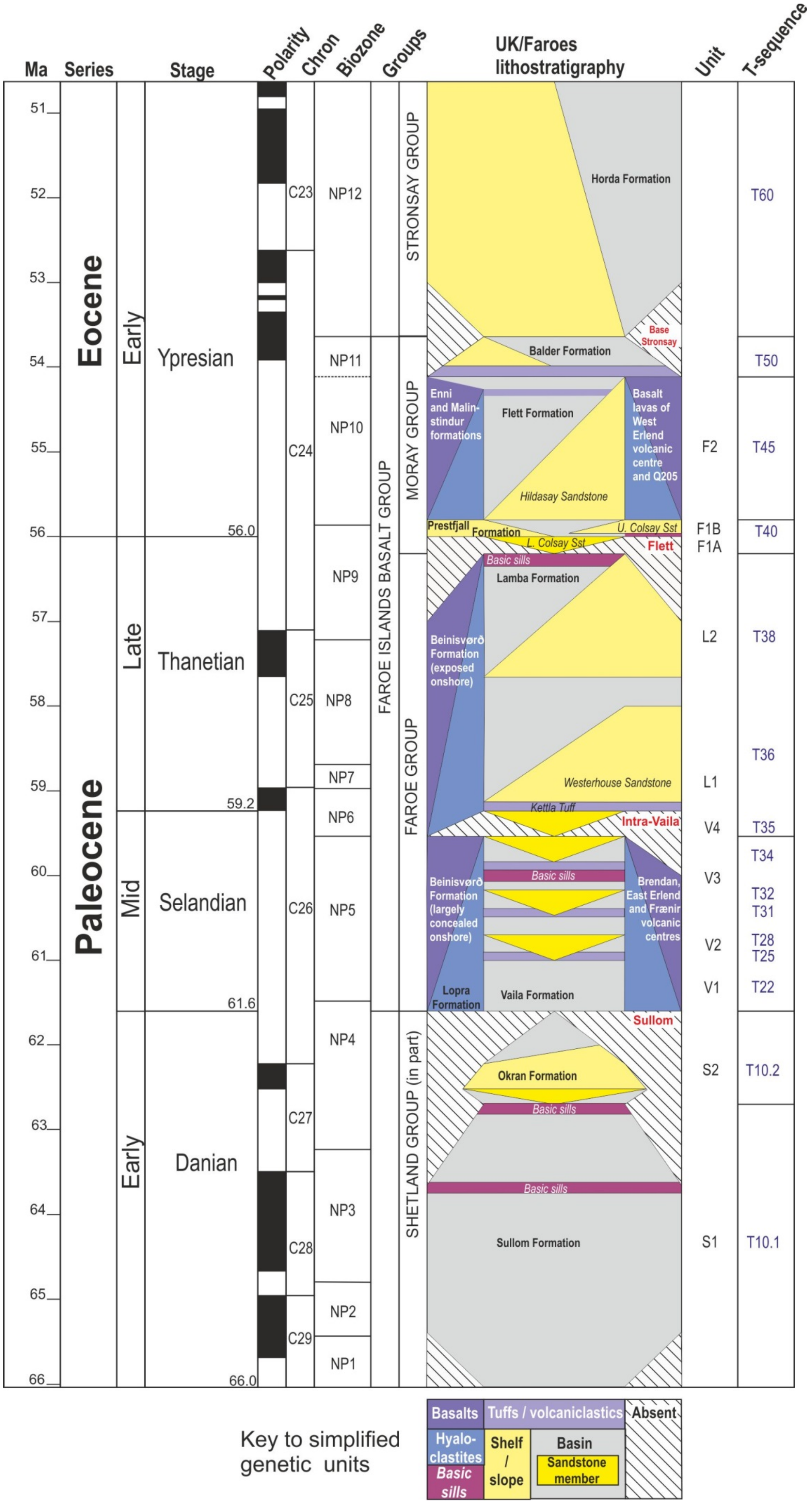

Figure 10 Paleocene–earliest Eocene stratigraphic chart for the Faroe-Shetland Basin (modified after Smith et al., 2013). Timescale is based on Gradstein et al. (2012).

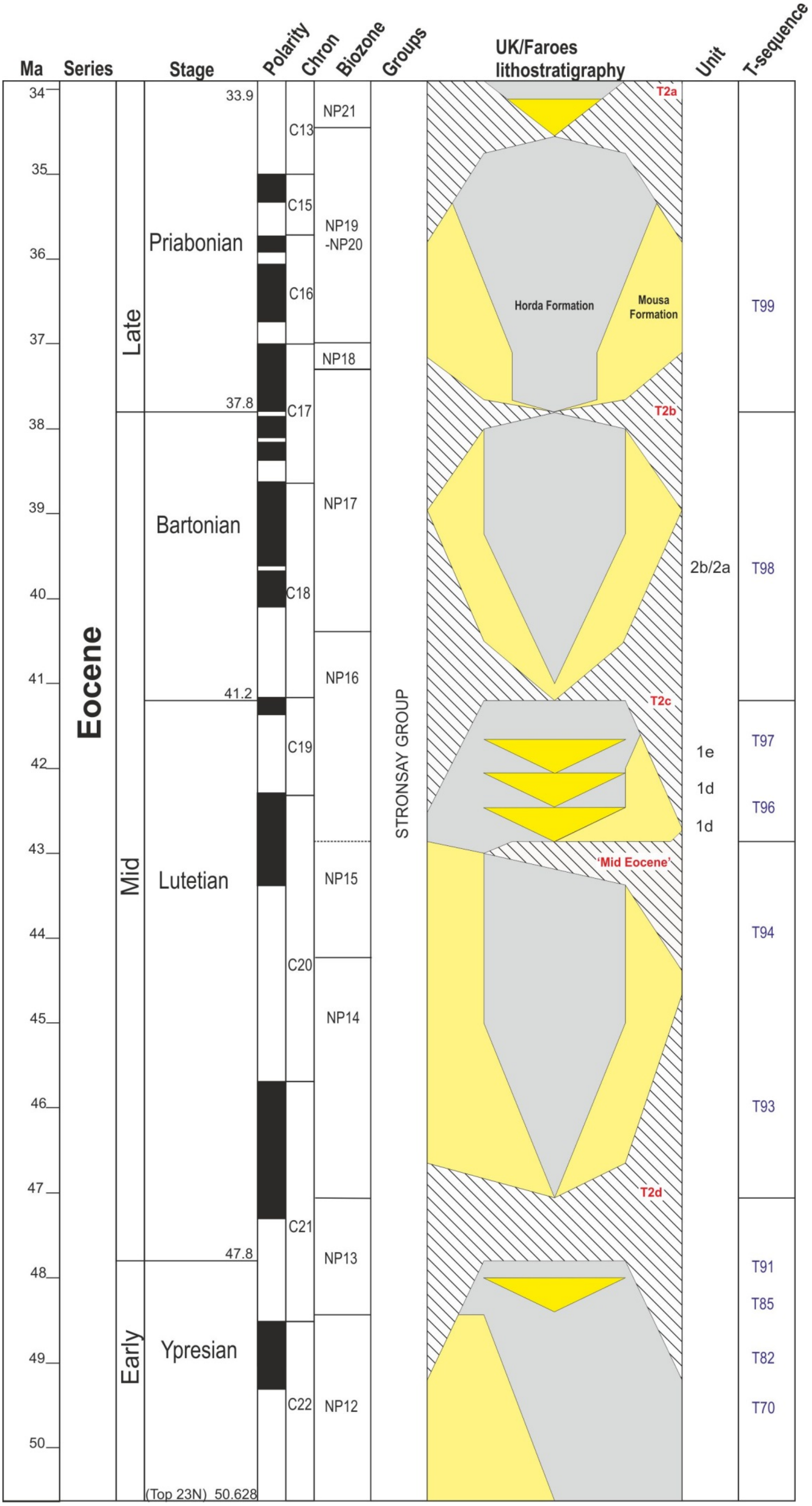

Figure 11 Eocene stratigraphic chart for the Faroe-Shetland Basin (modified after Smith et al., 2014). Timescale is based on Gradstein et al. (2012). See Figure 10 for key to colours.

4 Palaeoenvironment Maps

The palaeoenvironment maps form the main focus of this study. In this chapter, we present a set of twenty maps for the following time periods:

Late Jurassic–earliest Cretaceous

- Mid-Kimmeridgian–early Berriasian

Cretaceous

- Late Berriasian–Hauterivian
- Aptian–Albian
- Albian/Cenomanian boundary
- Cenomanian–Turonian
- Coniacian–Santonian
- Campanian–Maastrichtian
- Maastrichtian/Danian boundary

Palaeogene

- Danian (T10)
- Selandian (T22–T34)
- Late Selandian–mid-Thanetian (T35–T38)
- Late Thanetian–early Ypresian (T40)
- Ypresian (T45–T91)
- Early to mid-Lutetian (T93–T94)
- Late Lutetian (T96–T97)
- Bartonian–Priabonian (T98–T99)
- Oligocene

Neogene

- Early Miocene
- Mid-/Late Miocene
- Late Early Pliocene–early Mid-Pleistocene.

The timeslices represented by these maps are illustrated graphically in Figure 12, and the maps are presented as Figures 13–32.

The rationale behind the selection of these specific time periods reflects the punctuated character of the late Mesozoic–Cenozoic succession, with – in most cases – the sequences specific to a particular time interval separated from preceding and succeeding intervals by a hiatus (i.e. unconformity-bounded packages).

The maps are intended to provide generalised representations of sedimentary environments for the time periods concerned. In any one area, local palaeoenvironmental changes might have occurred during the extended time period being represented; thus, use of the maps at anything other than regional scale is discouraged. In particular, the location of basin margins and the coastline, the extent of sedimentation over structural highs that were subsequently eroded, as well as over intrabasinal highs, and the environment shown in undrilled regions are all interpretations based on a regional appraisal of the data available to this project, as outlined in section 1.2. In an effort to retain, as far as possible, an impartial observational dataset – within the limits of the available information – we have refrained from overly speculative reconstruction.

In the following pages, the maps are presented sequentially, in ascending stratigraphic order. Each map is accompanied by a short text describing the key points of the reconstruction, with a focus on the Faroe–Shetland region, but also including information from surrounding areas within the limits of the study area, i.e. the NE Rockall Basin, SE Greenland, the SW Møre Basin and the northern North Sea. Whereas an extensive literature has contributed to the overall content of the maps, as indicated by the key references in the text, important general sources of information used in the construction of the various maps, e.g. limits of sedimentary environments, area of hinterland, etc., are listed in Table 2.

STRATIGRAPHIC INTERVAL	SOURCE OF GENERAL MAPPING INFORMATION
Late Jurassic	Evans, 2013 Fraser et al., 2003 Hudson and Trewin, 2002 Ritchie and Varming, 2011
Cretaceous	Copestake et al., 2003 Harker, 2002 Johnson et al., 1993 Larsen et al., 1999b Smith, 2013 Stoker and Ziska, 2011 Stoker et al., 2010
Paleocene–Eocene (Ypresian)	Kimbell, 2014 Knox and Holloway, 1992 Knox et al., 1997 Mudge, 2014 Ólavsdóttir et al., 2013 Shaw Champion et al., 2008 Smith et al., 2013 Stoker and Varming, 2011 Ziska and Varming, 2008
Eocene (Lutetian–Priabonian)	Knox and Holloway, 1992 Ólavsdóttir et al., 2013 Stoker et al., 1994 Stoker et al., 2012b Stoker and Varming 2011 Smith et al., 2014
Oligocene / Miocene / Plio-Pleistocene	Andersen et al., 2000 Fyfe et al., 2003 Johnson et al., 1993 Johnson et al., 2012 Ólavsdóttir et al., 2013 Stoker, 1999 Stoker, 2013 Stoker and Varming, 2011 Stoker et al., 1993

Table 2 Key general sources of data consulted during the construction of the palaeoenvironment maps. See ‘References’ for full citation.

The structural framework template presented and described in Chapter 2 is included on the Late Jurassic to Oligocene maps, both as a general reference guide to aid location within the study area, as well as providing a possible indication as to which parts of the underlying structural framework might have been active – in a general sense – at any given time. The structural framework is not included on the Neogene–Quaternary maps as the shaping of the ocean margin through this time period became more controlled by the effects of plate boundary compression, which is ultimately manifested, in a large part, by the present-day bathymetry. Instead, these maps include the present-day bathymetric contours (at 200 m, 500 m, 1000 m, 1500 m, 2000 m and 2500 m) albeit unlabelled as a guide to the developing structure and morphology of the Faroe–Shetland region.

A consistent set of colours representing sedimentary environments has been used as far as possible on all of the maps, though there is some customisation that simply reflects changing environments through time. The consequence of erosion throughout the late Mesozoic–Cenozoic period means that the landward edge of any preserved sequence does not necessarily reflect the former position of the contemporary coastline. This problem has been addressed on all maps by using a red diagonal-stripe colour-fill that provides a zone of uncertainty with regard to determining the former extent of the land area. In most cases, the erosion responsible for the creation of this zone of uncertainty post-dates the deposition of the sedimentary sequence; however, in several maps there are indications of contemporary deformation, and these locations are highlighted by annotated notes on the relevant maps. In areas of no data, or where there is too much uncertainty, the map remains white. In addition to the accompanying text, a few annotated notes are presented on each map in order to provide extra information where necessary. Lithostratigraphic information is also included, where available.

On a number of the Paleocene and Eocene maps, thicknesses have been depicted by graduated colour fill and by contours. The former technique is utilised to provide an impression of the relative thickness of the developing volcanic shield, whereas contour lines are utilised to show quantifiable thicknesses of the contemporary sedimentary successions.

On some of the Late Cretaceous and Cenozoic maps, an attempt has been made to indicate contemporary deformation, primarily with respect to pulses of contractional deformation and/or uplift. This aspect of structural development features mostly on the Eocene to Pleistocene maps, and is based primarily on the history of growth of anticlines and synclines as proposed on the charts presented in Figures 4 and 5. It should be noted that in order to transfer the information on the charts to the maps, we have focused primarily on those times where very definite pulses of growth are envisaged to have occurred. In other words, whereas compressive stress might be a general, ongoing, background phenomenon, the placement of structures on the maps reflects those instances where we envisage accentuated contractional deformation to have occurred. On the charts (Figures 4 and 5), the timing of the key pulses of growth of anticlines and synclines are indicated by the red dots; the more tentative chronology (represented by the open circles) is not included on the maps. It should be further noted that only those fold axes that have been described as part of the structural study within the Faroe–Shetland region (i.e. Quinn et al., 2014) – together with some of the structures in the NE Rockall Basin – are included on the maps; for aspects of contemporary deformation in the other peripheral areas (within the limit of the study area) the reader is referred to the notes that accompany the maps.

The general implications of the environmental development of the region, as depicted in this series of maps, will be discussed in Chapter 5 (Dynamic Evolution).

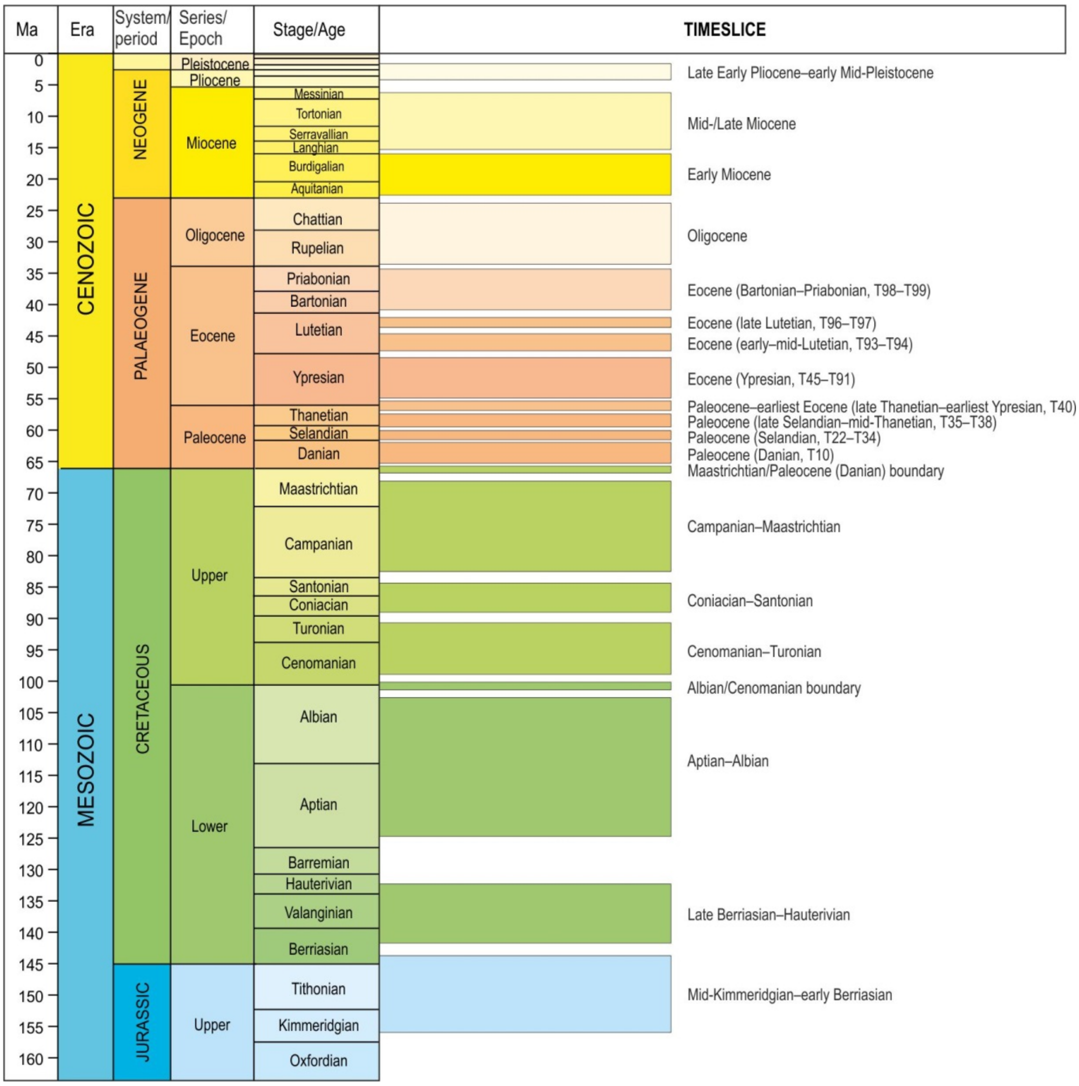

Figure 12 Graphic representation of timeslices represented by the palaeoenvironment maps in Figures 13–32. Timescale is based on Gradstein et al. (2012).

4.1 MID-KIMMERIDGIAN–EARLY BERRIASIAN

West of Shetland, Upper Jurassic rocks – predominantly of Kimmeridgian–Turonian age – have been recovered in numerous wells, albeit mainly within the SE Marginal Basins; in contrast, few wells have penetrated Jurassic rocks within the Faroe-Shetland Basin (Ritchie and Varming, 2011) (Figure 13). In the SE marginal basins, the Upper Jurassic rocks largely comprise the Kimmeridge Clay Formation of the Humber Group, which extends into the earliest Cretaceous.

The Kimmeridge Clay Formation is characteristically associated with dark grey to black organic-rich mudstone and minor siltstone; however, in the North Rona, West Shetland, East Solan and West Solan basins, this formation includes a basal coarse clastic unit (assigned to various members, e.g. Ridge Conglomerate, Rona, Spine and Solan Sandstone members) (Verstralen et al., 1995; Ritchie and Varming, 2011). These coarse clastic deposits and the facies they represent (debris flow, turbidite and shoreface deposits) are considered typical of fan delta deposition, initially in a subaerial environment and later under progressively more marine conditions (Verstralen et al., 1995; Ritchie and Varming, 2011). According to Hudson and Trewin (2002), the local palaeogeographic framework consisted of a Scottish landmass, which was generally emerged, including the Orkney-Shetland high and vicinity of variable extent depending on relative sea level and tectonic events. Vestralen et al. (1995) has proposed that the deposition of the coarse clastic facies, west of Shetland, was mainly controlled by marine transgression of residual islands, which were probably elevated by footwall uplift along controlling faults bounding highs, such as the West Shetland, Rona and Judd highs. The gradual transition from subaerial to submarine deposits reflects an overall transgressive succession, which culminated with the extensive deposition of the finer-grained, hemipelagic mudstone that characterises the Kimmeridge Clay Formation. The high organic content of the mudstone implies that the bottom waters were oxygen-starved. This transgressive model of Late Jurassic sedimentation over an irregular topographic surface contrasts with previous rift-related models, imported from the North Sea, which imply a Late Jurassic instigation of the Faroe-Shetland Basin (e.g. Haszeldine et al., 1987; Hitchen and Ritchie, 1987; Meadows et al., 1987). Indeed, Doré et al. (1999) report that there is very little evidence of Late Jurassic syn-rift sedimentary expansion in the Faroe–Shetland region.

General observations from the wider region include:

- There is no information from the Faroese sector of the Faroe-Shetland Basin. Further to the NW, the conjugate SE Greenland margin – specifically the Kangerlussuaq–Blosseville Kyst region – was probably exposed at this time (Bjerager et al., 2014).
- SW of the Faroe–Shetland region, Upper Jurassic sandstone was deposited in a nearshore marine environment in the West Flannan Basin (Hitchen and Stoker, 1993), and shallow-marine shale crops out on Skye (Morton et al., 1987). In general, Kimmeridgian–Tithonian rocks are absent from the Hebridean region (Evans, 2013).
- The palaeogeography of the area east of Shetland was linked to the development of the Viking Graben, which records the progressive evolution and decay of Late Jurassic to earliest Cretaceous rifting (Underhill, 1998; Fraser et al., 2003). In the Viking Graben, intense rifting in the Kimmeridgian to early Tithonian gave way to thermal subsidence during the mid-Tithonian to early Berriasian. Initially, rift-related bathymetric deepening resulted in the transfer of coarse clastic detritus, derived from the Orkney-Shetland/East Shetland highs, directly into the deep-water basin, where it accumulated as mass-flow sandstones deposits (e.g. Magnus Sand Member; Brae Formation). As regional extension diminished, the rift basin was gradually drowned and former Kimmeridgian shelf areas (e.g. Beryl Embayment, East Shetland Basin) were flooded.
- To the NE of the Faroe–Shetland region, the Late Jurassic–earliest Cretaceous development of the Møre Basin is interpreted as contiguous with the North Sea rift system (Brekke, 2000). Swiecicki et al. (1998) infer shallow-marine sandy and muddy shelf to basinal environments on the NW flank of the Møre Basin. This might reflect the shelf of the conjugate SE Greenland margin, where the More Basin was juxtaposed with the Jurassic Jameson Land Basin (Bjerager et al., 2014; Stoker et al., 2014b).

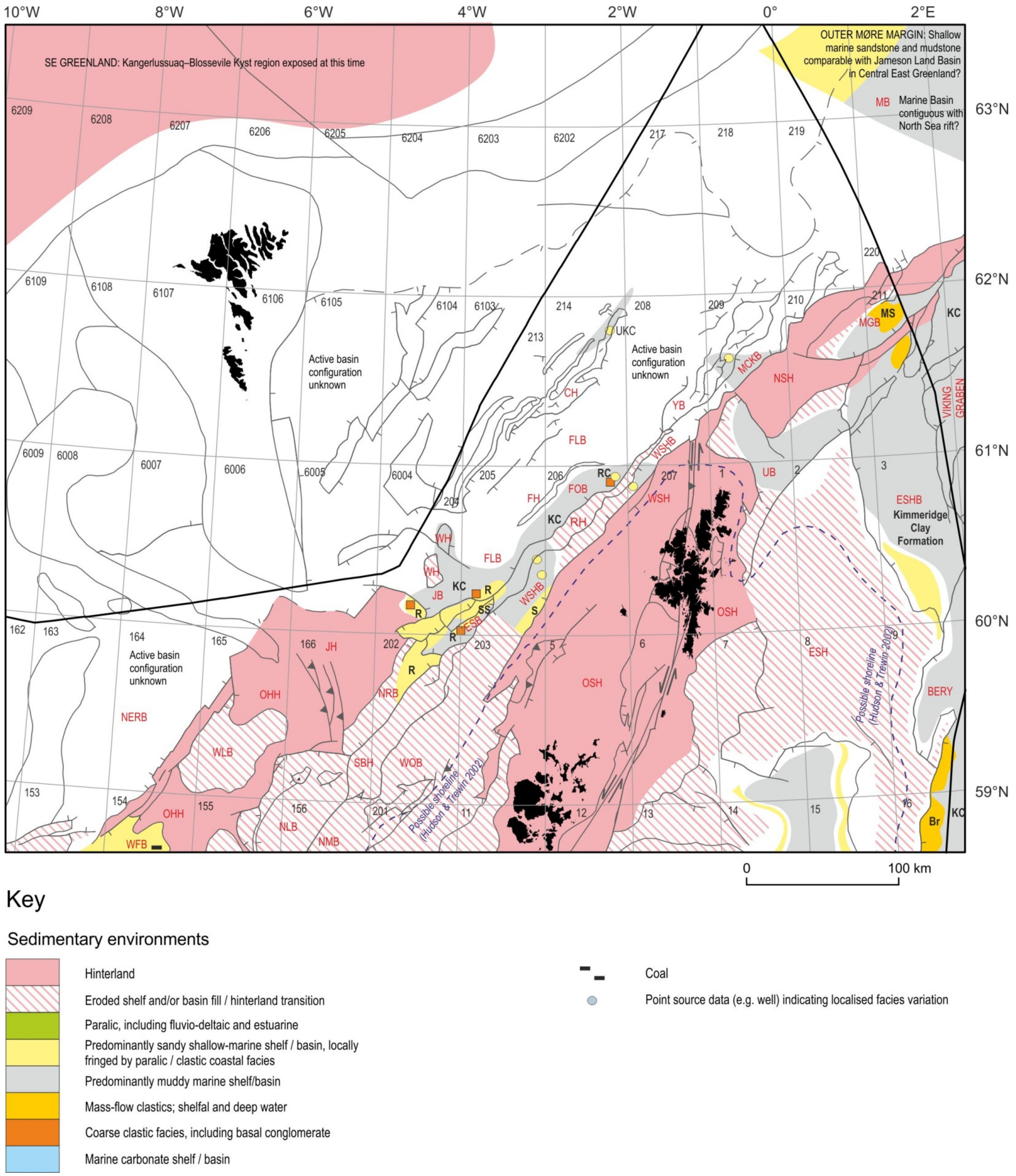

Figure 13 Gross palaeoenvironment map for the mid-Kimmeridgian–early Berriasian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Lithostratigraphic abbreviations: Br, Brae Formation; KC, Kimmeridge Clay Formation; MS Magnus Sand Member; R, Rona Member; RC, Ridge Conglomerate Member; S, Spine Member; SS, Solan Sandstone Member.

4.2 LATE BERRIASIAN–HAUTERIVIAN

During the late Berriasian–Hauterivian, proven active basin development in the Faroe–Shetland region is restricted to the SW West Shetland, East Solan and North Rona basins, which form part of the SE Marginal Basin domain (Figure 14). The SW West Shetland Basin accumulated paralic and sandy shallow-marine deposits of the Victory Formation, up to several hundred metres thick, adjacent to the Shetland Spine Fault (Ritchie et al., 1996; Harker, 2002; Stoker et al., 2010a; Stoker and Ziska, 2011). In contrast, the North Rona and East Solan basins preserve a thinner record of sandy and muddy shallow-marine deposition, assigned to the Valhall Formation (Ritchie et al., 1996), which is punctuated by intra-Valanginian and Hauterivian hiatuses. These paralic to shallow-marine basins appear to be relatively isolated within a hinterland that extends across much of the Hebrides–West Shetland region. In particular, the Orkney-Shetland High, Rona High, West Shetland High and North Shetland High might have acted collectively as a barrier (perhaps even a watershed) between the SE Marginal Basins and the larger, active, North Sea domain. West of Orkney, the exposed area extends at least as far west as the Judd High–Outer Hebrides High–West Lewis Basin region, which imparts a marked offset in the palaeogeography of the hinterland. In consideration of the likely provenance of marine connections to these SE Marginal Basins, the following observations must also be considered:

- The southern and eastern flanks of the Faroe-Shetland Basin, including the Judd sub-Basin, the SE margin of the Flett and Foula sub-basins, and the Yell and Muckle sub-basins were emergent, as were the intra-basinal Westray and Corona highs, and possibly the Flett High (Larsen et al., 2010; Stoker et al., 2010a). The possibility of pre-Aptian rocks in the deeper axial parts of the Foula and Flett sub-basins cannot be discounted, though information on pre-Aptian Cretaceous rocks is lacking from these locations.

- Farther to the NW, there is no information from the Faroese sector of the Faroe-Shetland Basin. However, the conjugate SE Greenland margin – specifically the Kangerlussuaq–Blosseville Kyst region – was juxtaposed with the NW margin of the Faroe–Shetland region, and was exposed at this time (Larsen et al., 1999a, b; Bjerager et al., 2014).

- SW of the Faroe–Shetland region, a hiatus in the Inner Hebridean basins, including the North Lewis and North Minch basins, as well as the West Lewis Basin, suggests that there was no connection to the Erris or southern Rockall basins, which were open at this time (McDermott and Shannon, 2014; Stoker et al., 2014a, b). Moreover, the central and northern/NE Rockall basins were probably not active until the late Barremian/early Aptian (Musgrove and Mitchener, 1996; Smith, 2013).

- The area east of Shetland (mostly the East Shetland High) has been interpreted as a mixed clastic and carbonate shelf, flanking the semi-emergent western margin of the Viking Graben by Copestake et al. (2003), though Harker (2002) has proposed a shoreline position much further to the east. It should be noted that the most of the East Shetland High lacks Lower Cretaceous strata.

- To the NE of the Faroe–Shetland region, available information suggests that the south-western part of the Møre Basin was not actively accumulating sediment until the late Hauterivian (Stoker and Ziska, 2011). This is consistent with the adjacent Magnus Basin, where the ‘End of the world’ sands, also of Hauterivian age, represent mass-flow deposits that might be linked to increasing tectonic instability in this region at this time (Copestake et al., 2003).

According to Ritchie et al. (1996), the mudstones of the Valhall Formation in the Faroe–Shetland region were deposited in a predominantly aerobic environment, which implies a relatively open water circulation; however, in the central and northern North Sea equivalent rocks preserve evidence of intermittent anoxic conditions and restricted circulation (Johnson and Lott, 1993). From the available evidence, the degree of connectivity between the Faroe–Shetland and adjacent areas remains unclear.

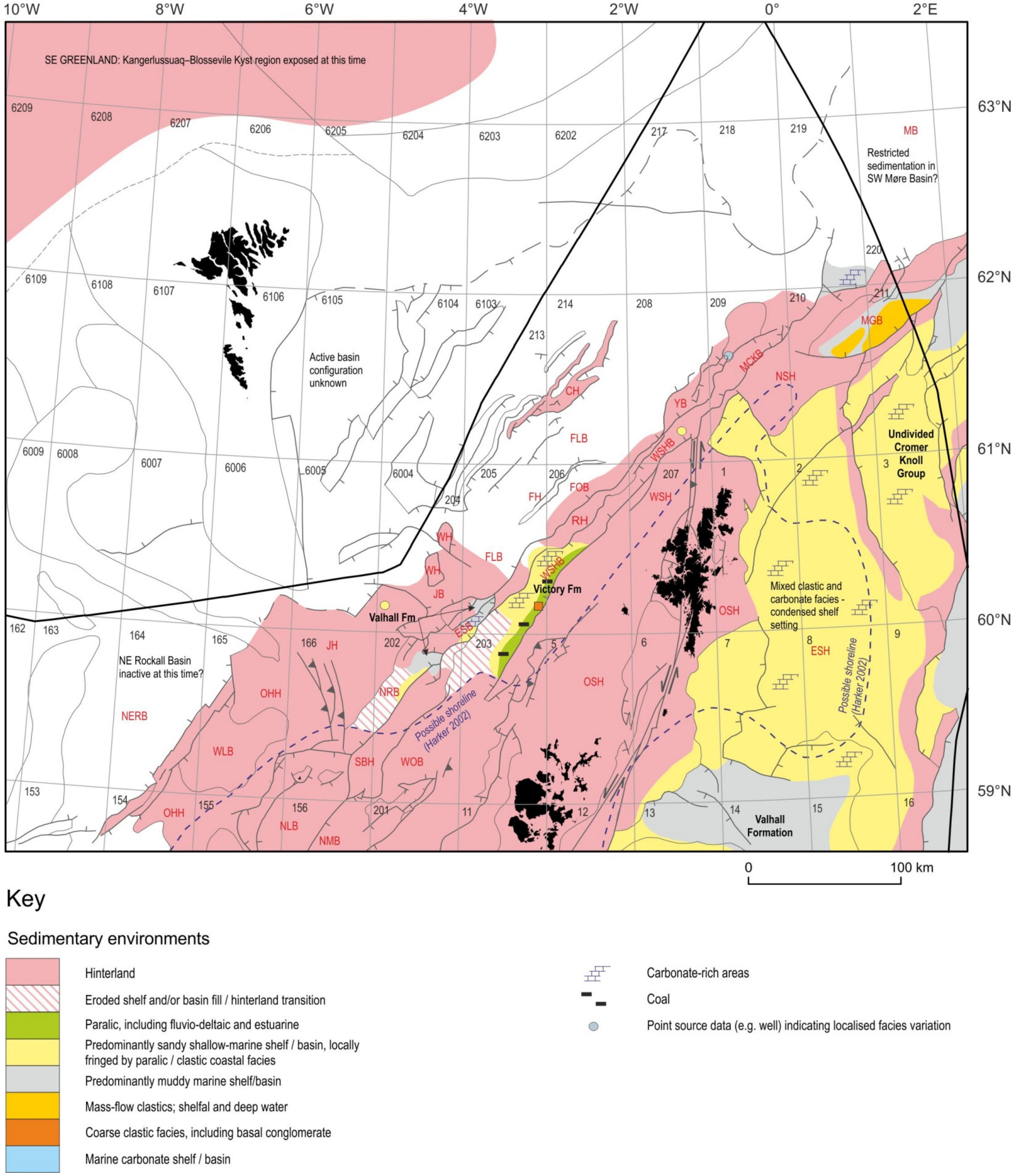

Figure 14 Gross palaeoenvironment map for the late Berriasian–Hauterivian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.3 APTIAN–ALBIAN

This interval marks the onset of a significant change in the basinal development of the Faroe–Shetland region, as the Faroe-Shetland Basin becomes a larger, integrated depocentre (Figure 15). The Judd, Foula and Flett sub-basins accumulated predominantly marine mudstones of the Valhall, Carrack, Cruiser and Rødby formations, fringed by coarse clastic deposits, including basal conglomerate and mass-flow sandstones, of the Commodore, Royal Sovereign and Neptune formations (Ritchie et al., 1996; Harker, 2002; Stoker et al., 2010a; Stoker and Ziska, 2011) (Figure 9). The previously emergent Corona and Westray intra-basinal highs were drowned and buried beneath a cover of marine mudstone. The NE and SW ends of the Rona High also record a sediment cover at this time; however, the bulk of the high remained exposed. On the NE flank of the Faroe-Shetland Basin, the Yell and Muckle sub-basins were probably also instigated at this time (Larsen et al., 2010), along with the NE West Shetland Basin. To the SW, paralic to shallow-marine deposition persisted within the SW West Shetland Basin, and marine mudstone accumulated in the SE Marginal Basins, though the preserved record in the North Rona, West Solan, South Solan and East Solan basins is sporadic and commonly punctuated with hiatuses (Figure 8).

General observations from the wider region include:

- SW of the Faroe–Shetland region, the hiatus in the Inner Hebridean basins persisted (Harker, 2002); thus, there was no connection via this area to the active depocentres of the Erris Basin and southern Rockall Basin (McDermott and Shannon, 2014).
- Marine mudstone accumulated in the West Lewis Basin (Stoker et al., 2014a), but it is unclear whether or not there was any connection to the North Rona Basin, to the NE, or to the central and northern/NE Rockall basins, to the west. The latter were probably instigated by this time (Musgrove and Mitchener, 1996; Smith, 2013), but are separated from the West Lewis Basin by the exposed West Lewis High.
- On the conjugate margin of SE Greenland, the Kangerlussuaq Basin was instigated and preserves a record of late Aptian–Albian paralic sedimentation and subsequent marine transgression (Larsen et al., 1999a, b; Nohr-Hansen, 2012; Bjerager et al., 2014). Fluvio-deltaic and estuarine sandstone wedges of the Watkins Fjord Formation were transgressed by marine mudstone deposits of the Sorgenfri Formation. Sediment transport direction was from west to east.
- East of Shetland, a shallow, tidally-influenced shelf is envisaged to have existed over much of the map area, flanking the Viking Graben, though there is ambiguity in the possible location of the coastline (Harker, 2002; Copestake et al., 2003). There is no obvious connection across the Orkney–Shetland hinterland.
- Restricted sedimentation may have prevailed on the SW flank of the Møre Basin, with intrabasinal highs locally exposed (Brekke, 2000).

According to Ritchie et al. (1996), the marine mudstones of the Valhall, Carrack, Cruiser and Rødby formations were deposited under fluctuating oxic/anoxic conditions, which suggest that marine connections between the Faroe–Shetland region and adjacent areas were restricted to some degree.

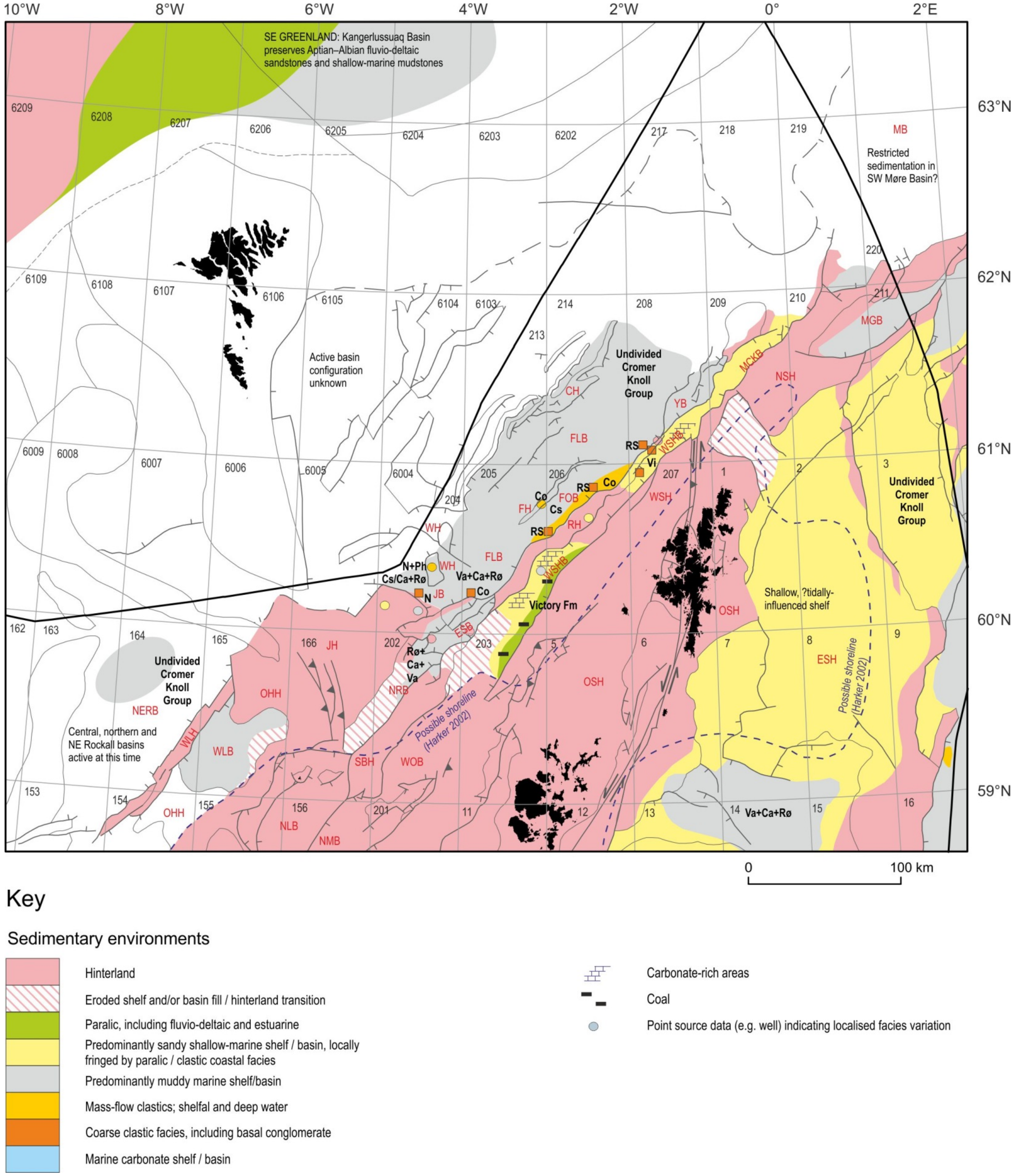

Figure 15 Gross palaeoenvironment map for the Aptian–Albian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Lithostratigraphic abbreviations: Ca, Carrack Formation; Co, Commodore Formation; Cs, Cruiser Formation; N, Neptune Formation; Ph, Phoebe Sandstone unit; Rø, Rødby Formation; RS, Royal Sovereign Formation; Va, Valhall Formation; Vi, Victory Formation.

4.4 ALBIAN/CENOMANIAN BOUNDARY

The significance of this map (Figure 16) is that many of the SE Marginal Basins, together with the Rona High and NE West Shetland Basin, record an erosional hiatus at the Albian/Cenomanian boundary (Figure 8), which implies a widespread uplift of the Orkney–Shetland hinterland. The SW margin of the Møre Basin also records an unconformity, as does the northern Westray High, within the Faroe-Shetland Basin (Figure 9). In contrast, the SW West Shetland Basin apparently continued to accumulate paralic–shallow-marine deposits of the Victory Formation (Ritchie et al., 1996), though it is unclear whether or not this basin became land-locked at this time. Marine mudstone deposition associated with the Cruiser and Rødby formations prevailed in the Faroe-Shetland Basin.

General observations from the wider region include:

- The continued deposition of transgressive, shallow-marine, mudstone of the Sorgenfri Formation in the Kangerlussuaq Basin of SE Greenland (Larsen et al., 1999a, b; Bjerager et al., 2014).
- The continued deposition of marine mudstone in the central, northern and NE Rockall basins (Musgrove and Mitchener, 1996; Archer et al., 2005; Smith, 2013; Stoker et al., 2014a).
- Marine mudstone is also recorded from the West Lewis Basin (Stoker et al. 2014), though marine connections with this basin, at this time, are uncertain.
- Tectonic activity in the Inner Hebrides region has been regarded by Mortimore et al. (2001) and Emeleus and Bell (2005) as a precursor to the deposition of the Upper Cretaceous Inner Hebrides Group. Perhaps the instigation of this tectonic activity is concomitant with the uplift of the Orkney–Shetland region.
- In the North Sea region, the deposition of marine mudstones of the Rødby Formation is widespread beyond the East Shetland High (Johnson et al., 1993). It remains uncertain to what extent the area east of Shetland was affected by the uplift observed to the west.
- Despite the uplift of the SW margin of the Møre Basin, sedimentation prevailed throughout most of the basin (Brekke, 2000).

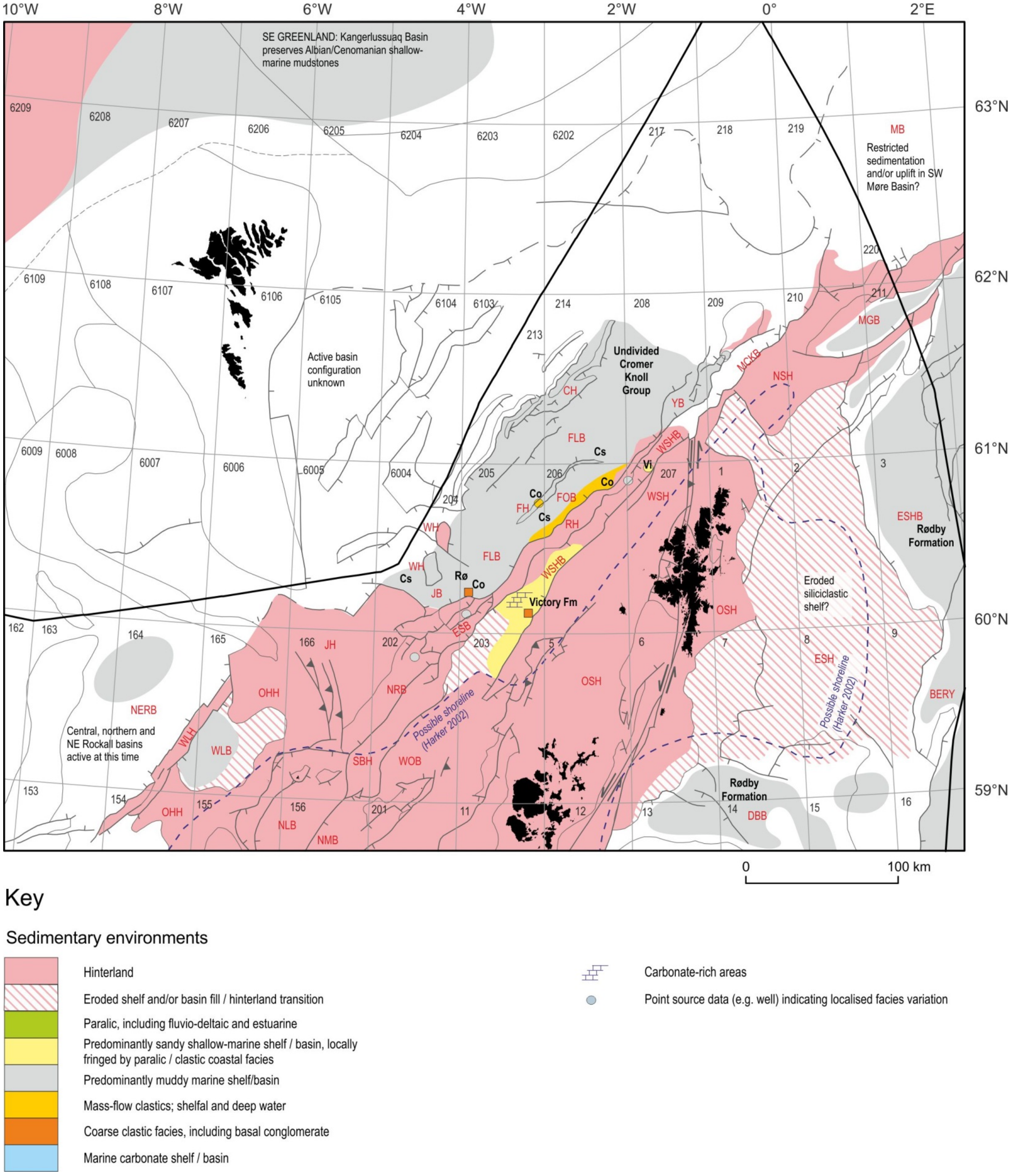

Figure 16 Gross palaeoenvironment map for the Albian/Cenomanian boundary. Facies distribution and facies characteristics based on top-Albian distribution. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Lithostratigraphic abbreviations: Co,Commodore Formation; Cs, Cruiser Formation; Rø, Rødby Formation; Vi, Victory Formation.

4.5 CENOMANIAN–TURONIAN

In the Late Cretaceous, the Faroe–Shetland region was located at the northern limit of deposition of the Chalk Group (Figure 17). Whereas limestone of the Hidra and Herring formations have been reported from the SW West Shetland, North Rona and East Solan basins, the bulk of the Cenomanian–Turonian sequence comprises calcareous mudstone of the Svarte and Macbeth formations of the mudstone-dominated Shetland Group (Ritchie et al., 1996; Harker, 2002; Stoker and Ziska, 2011) (Figures 8 and 9). Localised coarse clastic rocks are associated with the Haddock Sandstone unit (part of the Hidra Formation) adjacent to the Shetland Spine Fault, and the mass-flow deposits of the Commodore Formation, on the eastern flank of the Faroe-Shetland Basin. The Orkney–Shetland hinterland continues to remain expansive, though a developing link between the SE Marginal Basins and the Inner Hebridean region (see below) during the Turonian has been suggested (Harker, 2002).

The clastic facies' associated with the Haddock Sandstone unit and the Commodore Formation might be indicative of Cenomanian fault activity adjacent to the West Shetland and Rona highs, respectively. Evidence of contemporary tectonics is also supported by examples of compression, including:

- Turonian folding in the Foula and Flett sub-basins (Grant et al., 1999), which formed the 'near-base Upper Cretaceous unconformity' (cf. Stoker et al., 2010), and latest Cenomanian–Turonian inversion (flower structure) in the East Solan Basin (Booth et al., 1993).
- Folding and erosion of Albian–Turonian sediments in the North Rona and West Solan basins (Stoker et al., 2010a), though the timing of deformation is less precise (pre- or intra-Campanian).

General observations from the wider region include:

- SW of the Faroe–Shetland region, shallow-marine clastic rocks of the Morvern Greensand and Lochaline White Sandstone formations were deposited in the Inner Hebridean region (Harker, 2002; Emeleus and Bell, 2005; Waters et al., 2007); however, it remains uncertain whether or not there was a marine connection – via the North Lewis and West Orkney basins – with the SE Marginal Basins.
- The continued deposition of marine mudstone in the central, northern and NE Rockall basins (Musgrove and Mitchener, 1996; Archer et al., 2005; Smith, 2013; Stoker et al., 2014a).
- The Kangerlussuaq Basin of SE Greenland continued to accumulate shallow-marine mudstone of the Sorgenfri Formation (Larsen et al., 1999a, b; Bjerager et al., 2014).
- The northern North Sea region reflects the northward transition from carbonate-rich to mudstone rich deposits: the Chalk Group to Shetland Group transition. According to Harker (2002), the East Shetland High might have been largely a terrestrial to coastal setting, with a transition to a deeper-marine muddy shelf or basin coinciding with the East Shetland Basin/Beryl Embayment/Vilge sub-Basin.
- According to Brekke (2000), the intrabasinal highs within the southern More Basin were largely submerged by this time. Connectivity with the NE Faroe-Shetland Basin remains uncertain.

Sedimentation throughout the region occurred largely under oxic conditions; however, the Black Band (a high gamma pyritic mudstone), at the base of the Herring Formation, represents an interval of oceanic euxinia.

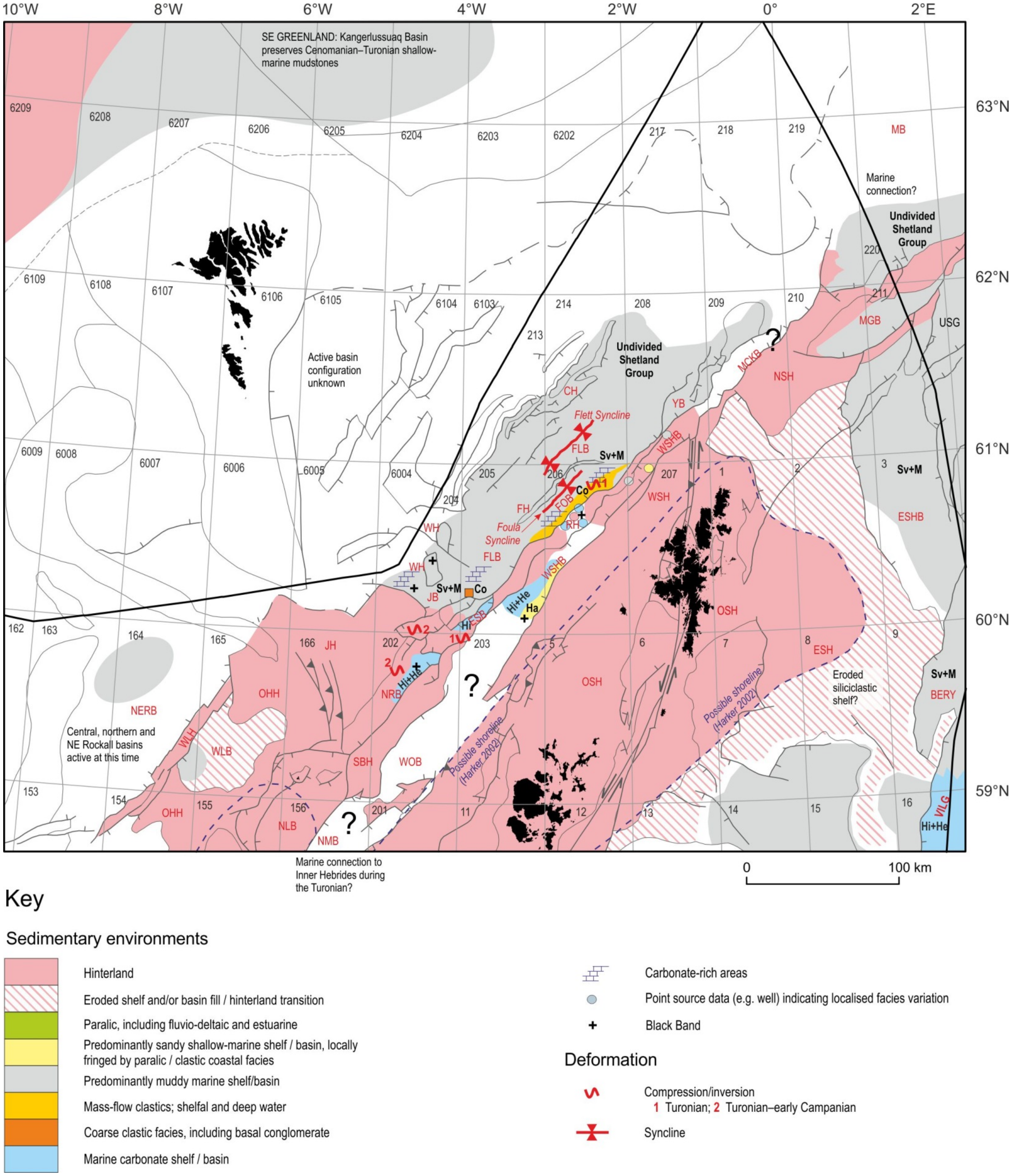

Figure 17 Gross palaeoenvironment map for the Cenomanian–Turonian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Lithostratigraphic abbreviations: Co, Commodore Formation; Ha Haddock Sandstone Member; He, Herring Formation; Hi, Hidra Formation; M, Macbeth Formation; Sv, Svarte Formation.

4.6 CONIACIAN–SANTONIAN

A major uncertainty with this reconstruction is the extent of the hinterland (Figure 18). Various authors (e.g. Hancock and Rawson, 1992; Harker, 2002; Cope, 2006) have suggested that regionally only remnants of the Scottish Highlands and Southern Uplands remained subaerially exposed during the Coniacian to Maastrichtian, i.e. the Orkney–Shetland region was wholly submerged. This interpretation is largely predicated on the basis of a high eustatic sea level during this interval. However, this contradicts evidence from wells in the area of the SE Marginal Basins and the Rona High (Stoker et al., 2010a; Stoker and Ziska, 2011). In both the North Rona and West Solan basins, Albian to Turonian rocks were deformed and eroded prior to Campanian sedimentation; the SW West Shetland Basin was also partially exposed (Figure 8). Whereas some parts of the Rona High were accumulating sediment, a large tract of the high remained exposed. Collectively, these data suggest that the Orkney–Shetland region, and extending into the Judd High–Outer Hebrides High region, might have remained as hinterland, albeit potentially reduced in area due to the higher sea level.

The Faroe-Shetland Basin remained the focus of sedimentation, and was dominated by the deposition of shallow-marine to basinal mudstone of the Kyrre Formation (Ritchie et al., 1996; Harker, 2002; Stoker and Ziska, 2011) (Figure 9). The Kyrre Formation is also recorded from the West Shetland Basin, including the NE part of the basin which was active at this time. In this basin, as well an on the adjacent Rona High, the Dab Limestone and Whiting Sandstone units (of the Kyrre Formation) reflect a mixed clastic-carbonate inner shelf facies.

General observations from the wider region include:

- SW of the Faroe–Shetland region, a mixed clastic-carbonate shallow marine succession, including the Gribun Chalk Formation, was deposited as part of the Inner Hebrides Group (Harker, 2002; Emeleus and Bell, 2005; Hopson, 2005; Waters et al., 2007). It remains unclear whether or not there was a marine connection to the SE Marginal Basins, especially as the SW West Shetland Basin was exposed at this time.

- In the Kangerlussuaq Basin of SE Greenland, shallow-marine mudstone deposition, associated with the Sorgenfri Formation, prevailed during the Coniacian; however, a major unconformity marks the Coniacian/Santonian boundary (Larsen et al., 1999a, b; Larsen et al., 2005a; Nøhr-Hansen, 2012; Bjerager et al., 2014). Uplift and erosion of the basin during the Santonian might have provided a north-westerly provenance for sediment input into the Faroe-Shetland Basin at this time (Nøhr-Hansen, 2012).

- Whereas the central Rockall Basin continued to accumulate marine mudstone, the northern and NE Rockall basins might have been increasingly subjected to uplift and erosion, though the absence of Santonian and younger Cretaceous rocks makes timing of this event difficult to establish (Smith, 2013; Stoker et al., 2014a). Conglomerates of uncertain age, reported from the adjacent West Lewis High, have been assigned to the Coniacian–Santonian (Smith, 2013), and might be related to tectonic activity at this time.

- The area east of Orkney continued to mark the northern limit of the Chalk Group, with the carbonate rocks of the Mackerel Formation in the Dutch Bank Basin passing northwards into the marls and mudstones of the Flounder and Kyrre formations, respectively, of the Shetland Group (Harker, 2002). As noted above, an increasing eustatic sea level might have been responsible for (at least partial) submergence of the Orkney–Shetland hinterland; this in turn might have enabled increased marine connectivity between the North Sea and the Faroe-Shetland Basin.

- In the Møre Basin, Coniacian–Santonian rocks form an increasingly expansive basinal drape (Brekke, 2000), and it seems probable – from the available well evidence – that a marine connection to the Faroe-Shetland Basin was fully established at this time (Stoker et al., 2010a; Stoker and Ziska, 2011).

Sedimentation throughout the region occurred largely within an aerobic, open marine environment (Ritchie et al., 1996; Harker, 2002), which is most probably a reflection of the higher eustatic sea level coupled with an increasing connectivity between the basins to the east and west of the Orkney–Shetland hinterland.

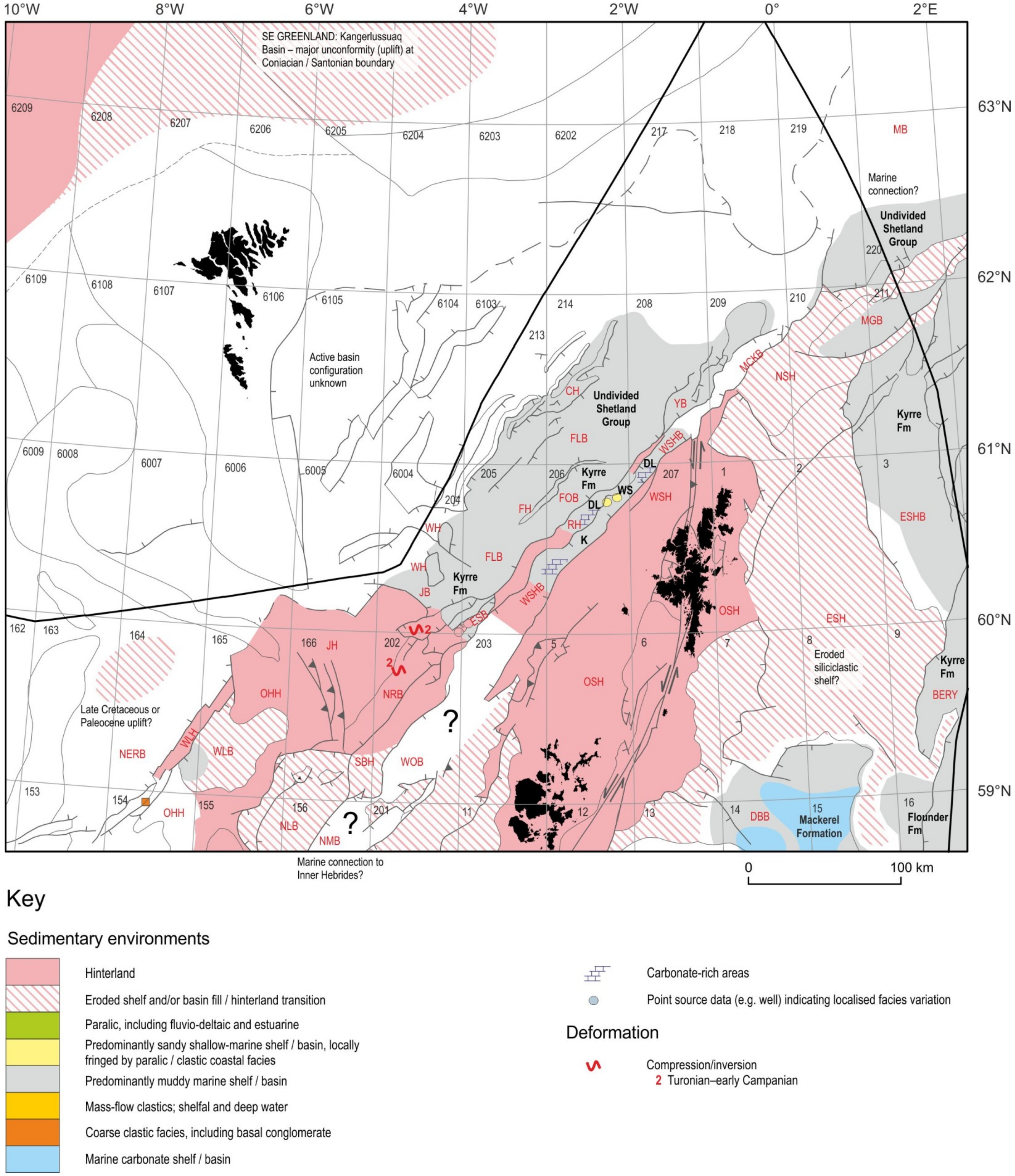

Figure 18 Gross palaeoenvironment map for the Coniacian–Santonian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Lithostratigraphic abbreviations: DL, Dab Limestone unit; Kyrre Formation; WS, Whiting Sandstone unit.

4.7 CAMPANIAN–MAASTRICHTIAN

The Campanian–Maastrichtian interval is characterised by the widespread deposition of marine mudstones of the Kyrre and Jorsalfare formations across the Faroe-Shetland and SE Marginal basins, as well as many of the adjacent highs (Figures 8, 9 and 19). Of particular significance is the total submergence of the Rona High. In general terms, despite the prevailing high eustatic sea level it remains uncertain whether or not the entire region was submerged at this time, as has been suggested (e.g. Hancock and Rawson, 1992; Harker, 2002; Cope, 2006). Active tectonics occurred in the Campanian that resulted in local basinal readjustments, such as within the NE West Shetland Basin where folding created a late Campanian unconformity (Goodchild et al., 1999). It has previously been noted (cf. Figures 17 and 18) that the folding, uplift and erosion observed in the North Rona and West Solan basins might also have occurred during the Campanian, which would imply local exposure of the hinterland. The absence of Campanian–Maastrichtian rocks from the Westray and Corona highs might also reflect contemporary uplift of intrabasinal highs within the Faroe-Shetland Basin, though latest Cretaceous/Early Paleocene uplift cannot be discounted.

General observations from the wider region include:

- SW of the Faroe–Shetland region, the Strathaird Limestone Formation of the Inner Hebrides group is of Campanian age (Mortimore et al., 2001; Hopson, 2005; Waters et al., 2007); however, Maastrichtian rocks are largely absent (uplift?) – the Beinn Iadain Mudstone Formation has been variably assigned an age of Maastrichtian and Early Paleocene. The nature of any marine connection to the SE Marginal Basins remains uncertain.
- The Rosemary Bank volcano – situated in the northern Rockall Basin, just west of the study area – was instigated in the Maastrichtian (Morton et al. 1995; Hitchen and Johnson 2013). Maastrichtian marine mudstone accumulated in the West Lewis Basin and southern part of the NE Rockall Basin, but Campanian–Maastrichtian rocks are absent from the northern part of this basin (Archer et al., 1995; Smith, 2013; Stoker et al., 2014a).
- In SE Greenland, the Kangerlussuaq Basin was transgressed by marine mudstones of the Christian IV Formation (Larsen et al., 2005a; Nøhr-Hansen, 2012; Bjerager et al., 2014).
- The area east of Orkney continued to mark the northern limit of the Chalk Group, with the carbonate rocks of the Mackerel and Tor formations in the Dutch Bank Basin and Vilge sub-Basin of the central Viking Graben, passing northwards into the marls and mudstones of the Flounder and Kyrre formations, respectively, of the Shetland Group (Harker, 2002). As noted above, a high eustatic sea level might have been responsible for (at least partial) submergence of the Orkney–Shetland hinterland.
- In the Møre Basin, there was widespread deposition of Campanian–Maastrichtian rocks (Brekke, 2000).

Sedimentation throughout the region continued under aerobic, open marine conditions (Ritchie et al., 1996; Harker, 2002).

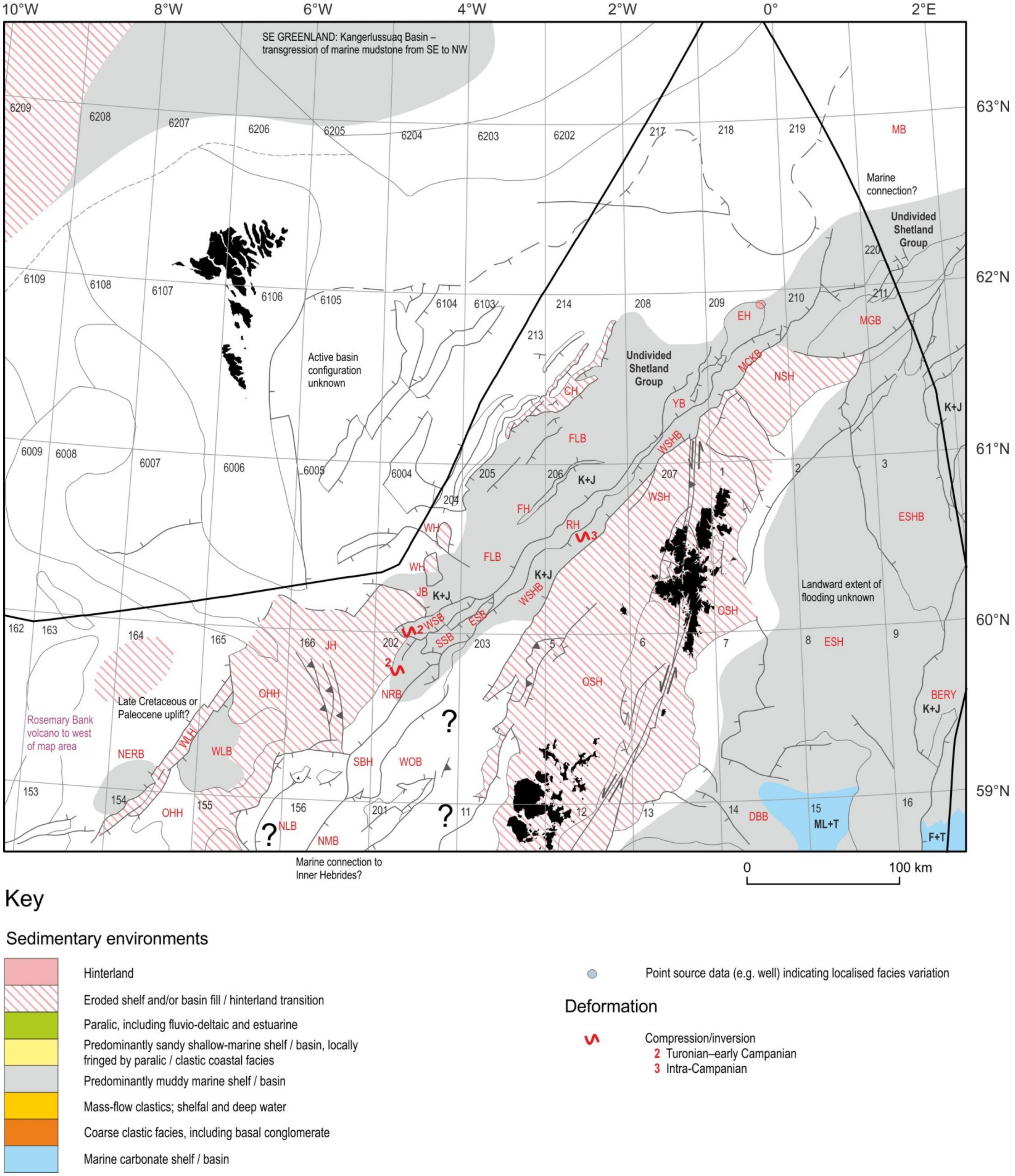

Figure 19 Gross palaeoenvironment map for the Campanian–Maastrichtian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Lithostratigraphic abbreviations: F, Flounder Formation; J, Jorsalfare Formation; K, Kyrre Formation; ML, Mackerel Formation; T, Tor Formation.

4.8 MAASTRICHTIAN/DANIAN BOUNDARY

The top of the Cretaceous succession in the Faroe–Shetland region is commonly marked by an unconformity that is overlain by Danian and younger Paleocene rocks (Figures 8 and 9). On this basis, regional uplift of the hinterland is inferred (Figure 20). This unconformity is generally recorded both in well and seismic data (Stoker et al., 2010a). Seismic profiles across the Faroe-Shetland Basin commonly display the top of the Upper Cretaceous succession as being truncated below a high-amplitude reflection, which is onlapped by Paleocene deposits. This relationship is also observed within the SE Marginal Basins, including the West Solan and East Solan basins, where Booth et al. (1993) describe an angular unconformity linked to latest Cretaceous/earliest Paleocene inversion, which shows folded Upper Cretaceous rocks onlapped by Paleocene deposits. On the eastern flank of the Faroe-Shetland Basin, the Flett High Anticline is interpreted to have been active at this time, causing uplift, folding and erosion of the Mesozoic succession (Quinn et al., 2014). However, the regional extent of subaerial exposure remains unclear. In the Solan basins, there is an absence of any obvious erosion of the anticlines generated by the folding, which suggests that they probably developed in a submarine (albeit shallow-water) setting. The unconformity in the deeper-water Faroe-Shetland Basin might also have developed in a submarine environment. It should be noted that there are wells in all of these basins that indicate conformity between the Maastrichtian and Danian rocks; however, the validity of the contact relationship in these wells remains uncertain.

In the SE Marginal Basins, the top-Cretaceous unconformity is locally overlain by the Ockran Sandstone Formation, which was deposited in an inner shelf setting during the Danian (Knox et al., 1997) (see Figure 21); whereas it remains uncertain how proximal the deposition of this shelf facies was to the Orkney–Shetland hinterland, its coarse clastic character suggests a relatively close proximity. Thus, in comparison to the preceding (Campanian–Maastrichtian) interval, the Maastrichtian/Danian boundary appears to coincide with a relative fall in sea level.

Support for this scenario from the wider region includes:

- SW of the Faroe–Shetland region, paralic sediments of Danian age are reported from the Outer Hebrides High (Stoker, 2013). In the Inner Hebrides, Mortimore et al. (2001) describe palaeovalleys cut at the end of the Cretaceous in response to faulting, uplift and erosion prior to the onset of Paleocene volcanism.
- All wells in the NE Rockall Basin, as well as on the basin-marginal West Lewis High, record a major Maastrichtian/Paleocene unconformity. In well 164/7-1, the earliest Paleocene intrusion of basic sills into Late Cretaceous mudstones created a domal uplift, which might have had subaerial expression in the Danian (Archer et al., 2005).
- In SE Greenland, the Maastrichtian/Danian boundary is marked by a major erosional unconformity that is attributed to an abrupt fall in relative sea level (Larsen et al., 2005a; Nøhr-Hansen, 2012). It has been postulated that the erosion of the Kangerlussuaq Basin at this time might have contributed sediment to the Faroe–Shetland region (Nøhr-Hansen, 2012).
- East of Orkney and Shetland, the latest Cretaceous rocks of the Chalk and Shetland groups are represented by the Tor and Jorsalfare formations, respectively. In early Danian time, these groups are represented, respectively, by the Ekofisk Formation and laterally equivalent (un-named) mudstones in the East Shetland Basin (Johnson and Lott, 1993; Johnson et al., 1993). However, the Maastrichtian and Danian units are separated by a break in sedimentation linked to a fall in relative sea level; this resulted in a seaward shift of the shoreline towards the eastern edge of the East Shetland High (Knox, 2002).

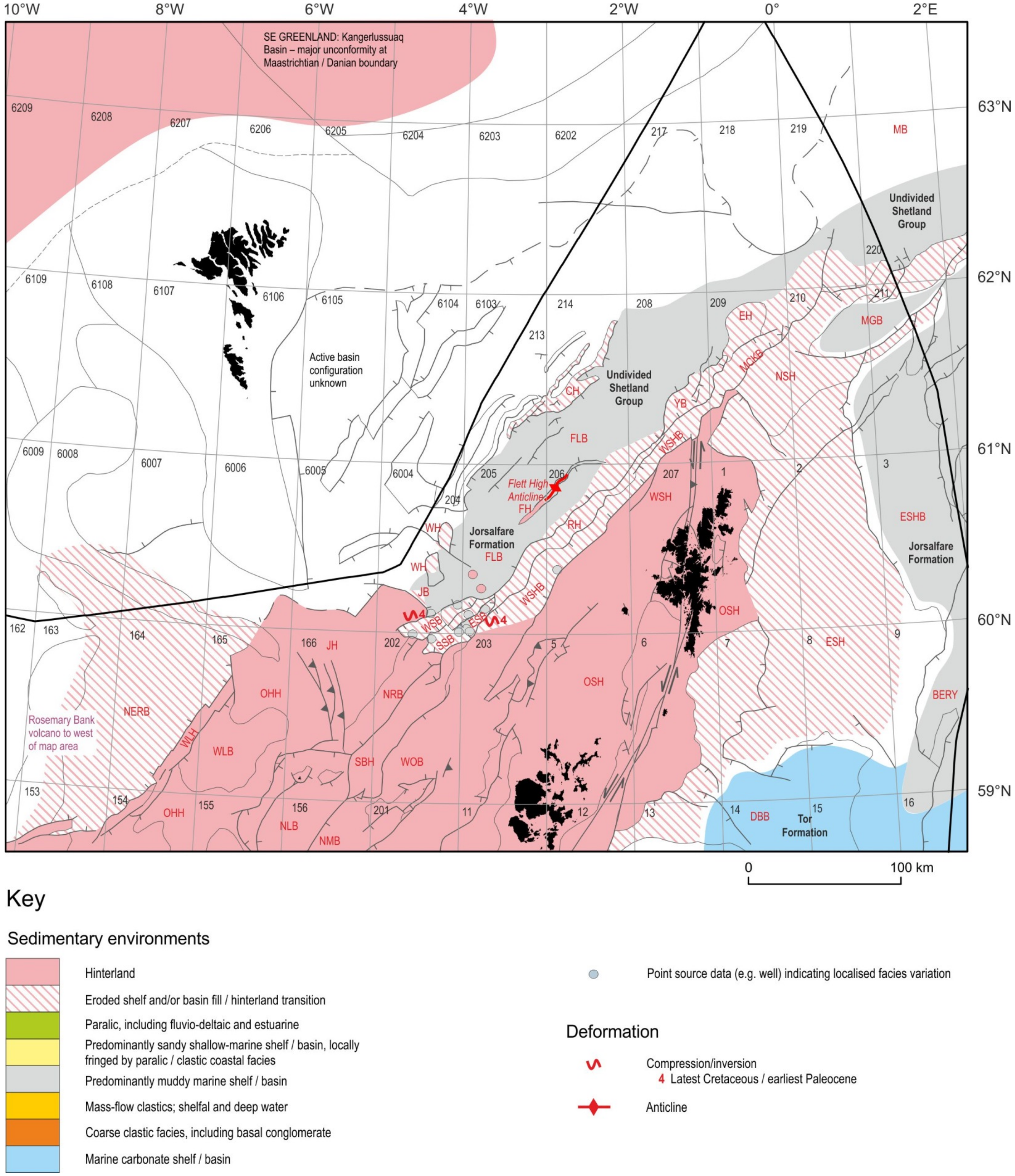

Figure 20 Gross palaeoenvironment map for the Maastrichtian/Danian boundary. Facies distribution and facies characteristics based on top-Maastrichtian distribution. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.9 DANIAN (T10)

Well data largely from the UK sector show that the Faroe-Shetland Basin consists of the Foula, Flett and Judd sub-basins at the start of the Danian (Figure 21). Other contemporaneous early Palaeogene depocentres, subsequently concealed by volcanic rocks, may lie east and west of the East Faroe High in the Faroese sector. The existence of these potential pre-volcanic basins is currently unproven and is simply inferred from the subsequent reactivation of their bounding faults. Together they form a fan-like zone of extension, which broadens northwards as it approaches the incipient oceanic margin. Biostratigraphic data suggest that the Danian basinal succession can be divided into two sequences – T10.1 and T10.2 (Figure 10) – which are separated by an unconformity at the basin margins (Smith et al., 2013). Across most of the Faroe-Shetland Basin, Danian deposition is dominated by the basinal mudstones of the Sullom Formation (Knox et al., 1997), but a more sand-rich succession is preserved in the hanging wall of the Judd Fault along its southern margin. Rare occurrences of shelfal sandstones in the same area have been assigned to the Ockran Sandstone Formation (Knox et al., 1997); however, subsequent uplift has largely removed traces of equivalent sandstones from the basin flanks elsewhere. Danian successions generally thicken towards the northern part of the study area, where active faults may include the easterly-trending Fugloy-Brendan Fault and a fault at Palaeogene level bounding the western margin of the North Shetland High. These faults may have helped to accommodate strike-slip or transtensional movement between the Faroe–Shetland region and the Jan Mayen Microcontinent (Peron-Pinvidic et al., 2012a, b). An episode of basic sill intrusion near the end of the Danian marks the beginning of early Palaeogene magmatism. Tectonically-related structures possibly initiated at this time include the Ben Nevis Anticline in Q218 and Q219, where the Danian is absent above a dome at top Cretaceous level (Hodges et al., 1999). Seismic and well data suggest that the dome was densely intruded by basic sills before its later re-burial by basaltic lavas associated with the Brendan Volcanic Centre on its northern limb. Thick, possibly contemporaneous, dolerites are especially common in the Danian claystones of the Erlend area.

General observations from the wider region include:

- In the Central North Sea, the Danian Ekofisk Formation consists of a thin series of chalk-rich debris flows and rests unconformably on the Upper Cretaceous Chalk Group. Similar facies continue to dominate the lower part of the overlying Maureen Formation, which is also of Danian age (Knox and Holloway, 1992).
- The boundary between the northern part of the Faroe-Shetland Basin and the contemporaneous Møre Basin, which adjoins the eastern edge of the study area, lies at the western end of the Møre-Trøndelag Fault Zone (in the area of the Margarita High) (Kimbell et al., 2005) (Figure 2). This major ENE-trending lineament probably originated as a strike-slip fault in the Palaeozoic basement (Gabrielsen et al., 1999; Fossen, 2010). Along strike to the east, it also separates the Møre Basin from the Northern North Sea (Mudge, 2014).
- Close to the margin of the NE Rockall Basin, well 164/27-1 proved 10 m of Sullom Formation sandstones resting (unconformably?) upon Upper Cretaceous claystones in which the well terminated. Elsewhere in the basin, the Danian is absent above the igneous domal feature tested by well 164/7-1. This structure compares closely with the Ben Nevis Dome in Q218 and Q219 (Hodges et al., 1999). Danian basic sills within the underlying Cretaceous succession have been dated at 63–64 +/- 0.5 Ma, by the $^{40}Ar/^{39}Ar$ method (Archer et al., 2005). More complete Danian sedimentary successions may be preserved in intervening structural lows.
- In the Kangerlussuaq area of SE Greenland, most of the Lower Danian is missing at the contact between the Paleocene and the underlying Christian IV Formation (Maastrichtian). This interval marks a change in the basin configuration and corresponds to a reduction in marine species diversity and abundance in the area. Nøhr-Hansen (2012) assigns the overlying, unconformable Upper Danian proximal turbidites to the Fairytale Valley Member of the Sediment Bjerge Formation, which correlates with the upper part of the Sullom Formation (T10.2) in the Faroe-Shetland Basin.

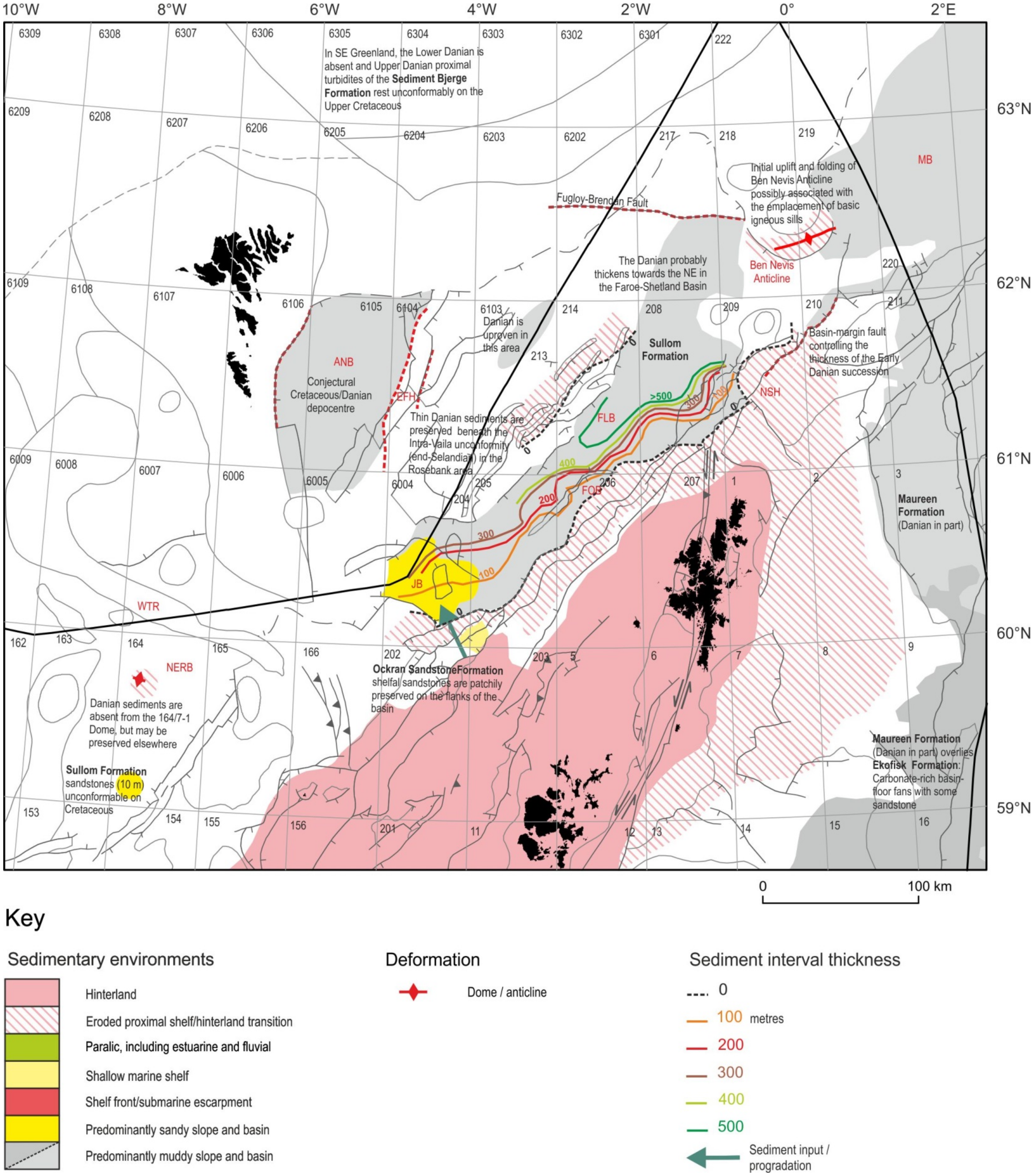

Figure 21 Gross palaeoenvironment map for the Danian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.10 SELANDIAN (T22–T34)

The onset of major extrusive basaltic shield volcanism close to the Danian/Selandian boundary in the Faroe–Shetland region probably indicates a reversion to a more extensional tectonic regime, with the earliest lavas and volcaniclastics resting unconformably upon a truncated Danian and Upper Cretaceous succession dominated by mudstones and basic sills. The largest outpouring of basalt took place in the vicinity of the Faroe Platform (Figure 22), where the Lopra Formation and the lower part of the Beinisvørð Formation must have added a significant isostatic load to the incipient continental margin. Elsewhere, contemporaneous basaltic shield volcanism is linked to smaller local volcanic centres, including East Erlend, Brendan and Frænir. The distribution and thickness of the Selandian part of the Faroe Islands Basalt Group is poorly defined regionally and the main focus and mode of the eruptions at this time has yet to be identified (Waagstein, 1988). However, much of the basal part of the basalt succession probably consists of prograding hyaloclastite facies similar to that proven at the base of the Lopra 1A well in the Faroe Islands (Chalmers and Waagstein, 2006). Its distribution may be partly controlled by extensional structures bounding the Annika sub-Basin. There is independent evidence that the Judd sub-Basin was an active westerly-dipping half-graben around this time (Ebdon et al., 1995). Sandstones of the Vaila Formation, largely derived from the Scottish hinterland, were deposited contemporaneously across a wide area of the Faroe-Shetland Basin (Knox et al., 1997) and consist predominantly of turbidites, which were laid down in a series of overlapping basin-floor fans. Throughout the Selandian, regional uplift continued to rejuvenate the Scottish hinterland along a NE-trending axis, while the Faroe-Shetland Basin deformed as a sub-parallel structural syncline flanked by contemporaneous basin inversions in the Flett Terrace, East Erlend and Ben Nevis Anticline areas.

General observations from the wider region include:

- Selandian turbidite successions in the North Sea are incorporated in parts of the Maureen and Lista formations (Knox and Holloway, 1992). In the Maureen Formation, the Maureen Sandstone Member overlies Danian carbonate-dominated clastics, which indicates the progressive removal of the former Cretaceous carbonate shelf and the continuing degradation of the Scottish hinterland. The overlying Lista Formation includes distal basinal claystones, widespread turbiditic sandstones and a broad area of dissected shelf and slope facies preserved landward of the later Moray Group shelf. Knox and Holloway (1992) assigned Lista Formation sandstones to the Heimdal and Mey Sandstone members; the latter including the Andrew Sandstone Unit. Interbedded tuffs provide some evidence of contemporaneous volcanism.

- A thin succession of shale-dominated deep marine facies at the centre of the Møre Basin is equivalent to the Maureen, Ty and Våle formations in the Northern North Sea (Ahmadi et al., 2003). The Møre Marginal High has a fringe of sand-dominated shallow marine facies, according to Sweicicki et al. (1998).

- Selandian basinal sandstones probably entered the NE Rockall Basin in Q153, where the T25–T28 sequences can be mapped west of the West Lewis High. Younger turbidites may lie basinward, but are absent above the 164/7-1 dome (Archer et al., 2005). Thick overlying tuffaceous successions indicate that the growth of the volcanic Hebridean Escarpment around the Geikie Volcanic Centre possibly curtailed other clastic deposition later in the Selandian (Evans et al.1989). Paleocene sediments are preserved in a half graben in the West Lewis Basin, similar to the structural setting of the Vaila Formation in the Judd sub-Basin along strike to the north-east (Ebdon et al., 1995). A thin volcanic interval resting directly on metamorphic basement shows that the West Lewis High formed a contemporaneous intra-basinal feature. Its associated structures include reverse 'pop-up' type faults at top basalt level (Tuitt et al., 2010) similar to those that bound the East Faroe High in the Faroese sector (Smith et al., 2013). It remains unproven whether or not sediment derived from the uplifts in Q166 (Earle et al., 1989) are interbedded with contemporaneous volcanic rocks in the adjoining Wyville Thomson Ridge area (Smith et al., 2009).

- In SE Greenland, the oldest pre-break-up basaltic lavas north of Kangerlussuaq, are assigned to the Urbjerget Formation and dated as 61.0 +/- 1.1 and 61.6 +/- 1.3 Ma by the ^{40}Ar/ ^{39}Ar method (Hansen et al., 2002). Elsewhere along the Blosseville Kyst, basaltic lavas up to 1100 m thick belong to the Nansen Fjord Formation, which is equivalent to the Beinisvórđ Formation in the Faroe Islands (Pedersen et al., 1997; Larsen et al., 1999). Landward of the main lava outcrop, Selandian sediments in the upper part of the Sediment Bjerge Formation correlate with the top of sequence T20 or the lower part of T30 (equivalent to the Vaila Formation) (Nøhr-Hansen, 2012).

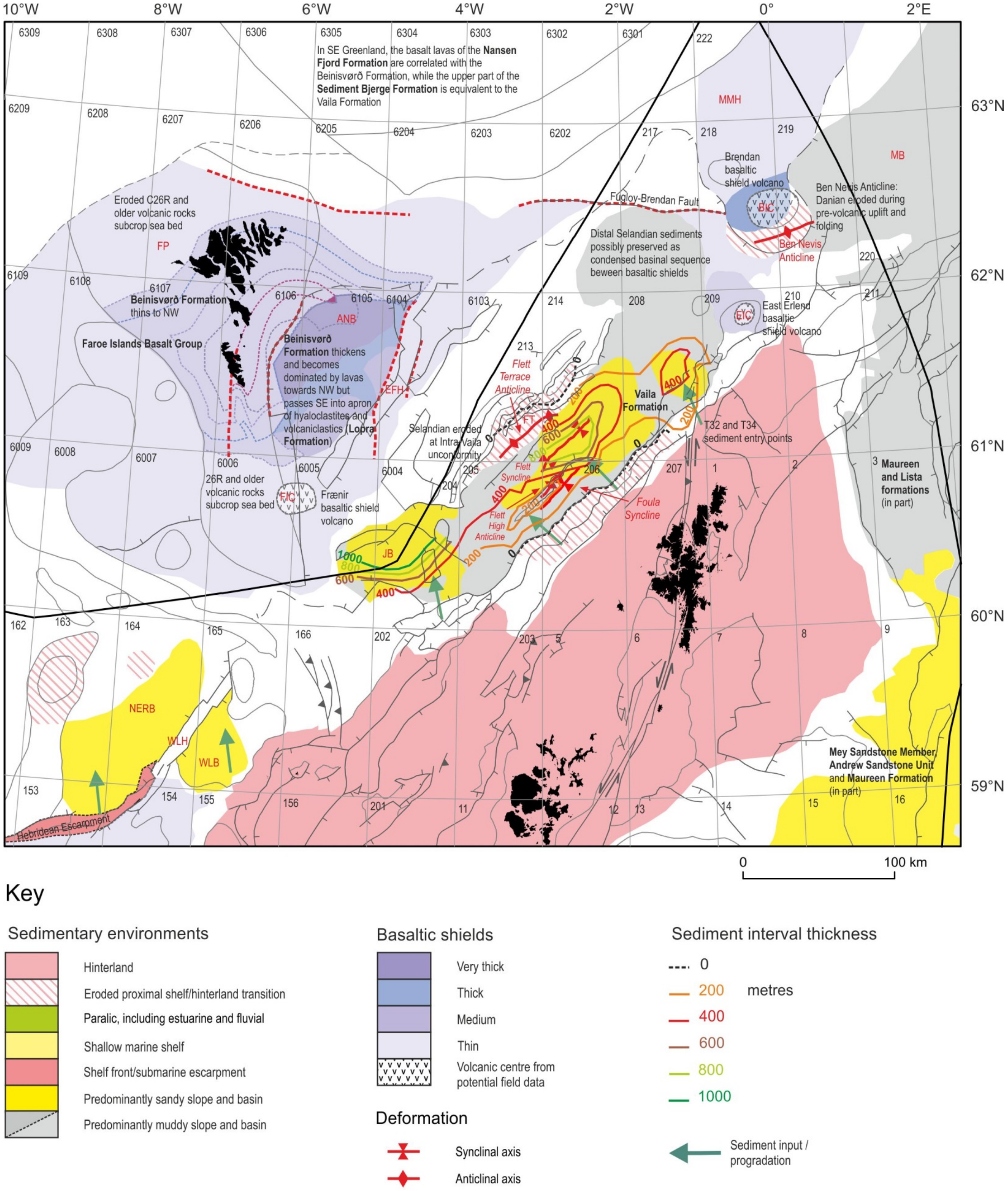

Figure 22 Gross palaeoenvironment map for the Selandian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.11 LATE SELANDIAN–MID-THANETIAN (T35, T36, T38)

By definition, the top of the Selandian stage is tied to the base of the C26n magnetochron (Gradstein et al. 2012). It follows that the 900-1000 m thick succession of basalt lavas between the base of C26n and the top of C25n exposed onshore in the Faroe Islands (Riisager et al., 2002) (Figure 23) is of Thanetian age. Kimbell (2014) shows that the limits of this magnetically-defined unit of the Beinisvørð Formation can be mapped both onshore and offshore around the Faroe Islands, although its thickness variation is poorly constrained by the magnetic data. For mapping purposes, it is assumed that the offshore thickness of the putative Thanetian volcanic rocks is broadly comparable to the onshore Faroese succession, with most of the thickness variation of the Beinisvørð Formation attributed to the older part of the shield. A resurgence of uplift and erosion at the Intra-Vaila unconformity (T35) was possibly accompanied by the lateral-injection of sills from the former focus of Selandian melting. Some evidence for more prolonged retention of magma at depth in the crust may be provided by the development of crustal melting, acidic volcanism and caldera collapse at the East Erlend and Darwin volcanic centres near the start of the Thanetian (cf Gatliff et al., 1984). Biostratigraphic data (Jolley and Bell, 2002) suggest that the related volcaniclastic-rich sequence (including ignimbrites and welded tuffs) on the flank of the East Erlend Volcanic Centre is of Thanetian (or older) age. Recognition of the Intra-Vaila unconformity at the edge of the basaltic shield in the Rosebank area provides an additional indication that the overlying (?Thanetian) part of the Beinisvørð Formation extends beyond the limits of the older fault-bound basalt succession in places. Linked to this series of explosive events, the Kettla Tuff Member is a widespread tuffaceous/volcaniclastic unit that marks the base of the northerly-prograding Lamba Formation in more distal successions. In the Foula and Flett sub-basins, overlying shelfal and basinal sediments belonging to the T36 sequence of the Lamba Formation advanced across the underlying structural syncline at Vaila Formation level and included the Westerhouse Sandstone Member of Knox et al. (1997). The distribution of the Lamba Formation shelf is well defined in the SE of the Faroe-Shetland Basin (Ebdon et al., 1995), where its upper part (?T38) prograded in a more westerly direction (Shaw-Champion et al., 2008). This might indicate that a tectonic shift between E–W and SW–NE-trending uplifts of the Scottish hinterland occurred during the Thanetian. In the Faroese sector, magnetic signatures east of the Annika magnetic anomaly are consistent with the suggestion that the Thanetian lavas probably pass basinwards into a prograding apron of volcaniclastics west of the Faroe-Shetland Escarpment (Smith et al., 2013; Kimbell, 2014).

General observations from the wider region include:

- In the North Sea, the Balmoral Tuffite is a direct correlative of the Kettla Tuff and forms a chronostratigraphic link with the Faroe–Shetland region (Knox and Holloway, 1992; Knox et al., 1997). In areas where the tuffite is recognised, the overlying sandstones within the Mey Sandstone Member are assigned to the Lower and Upper Balmoral Sandstone units and together, these successions are equivalent to the Lamba Formation (T36/T38) (Knox and Holloway, 1992).
- On the Vøring Marginal High, ODP site 642 proved 400 m of dacitic lavas and ignimbrites in a normal polarity succession of possible C25n (Thanetian) age (Planke and Eldholm, 1994; Swiecicki et al., 1998). This sequence closely resembles the more acidic explosive volcanic rocks of the East Erlend and Darwin volcanic centres in chemistry and age, so raising the possibility that these widely-spaced areas had a common tectonic and volcanic setting before oceanic opening.
- In the NE Rockall Basin, Thanetian breccias and tuffaceous interbeds near the Hebridean Escarpment could indicate continuing or resurgent volcanic activity at the Geikie Volcanic Centre or otherwise a reworking of the existing Selandian volcanic margin into younger shelf facies. In well 164/27-1, 114 m of basinal Lamba Formation-equivalent sediments consist of claystones, thin interbedded limestones and a trace of sandstone, which rest upon 68 m of Vaila Formation claystones possibly equivalent to the T35 sequence (Figure 10).
- In SE Greenland, a Late Selandian unconformity at the base of the Vanfaldsalen Formation (Blosseville Group) might correspond to the Intra-Vaila event in the Faroe-Shetland Basin (Larsen et al., 2005b; Nøhr-Hansen, 2012; his Fig. 6), but the full relationship between the overlying sedimentary units and volcanic successions elsewhere in the Blosseville Kyst area has yet to be established.

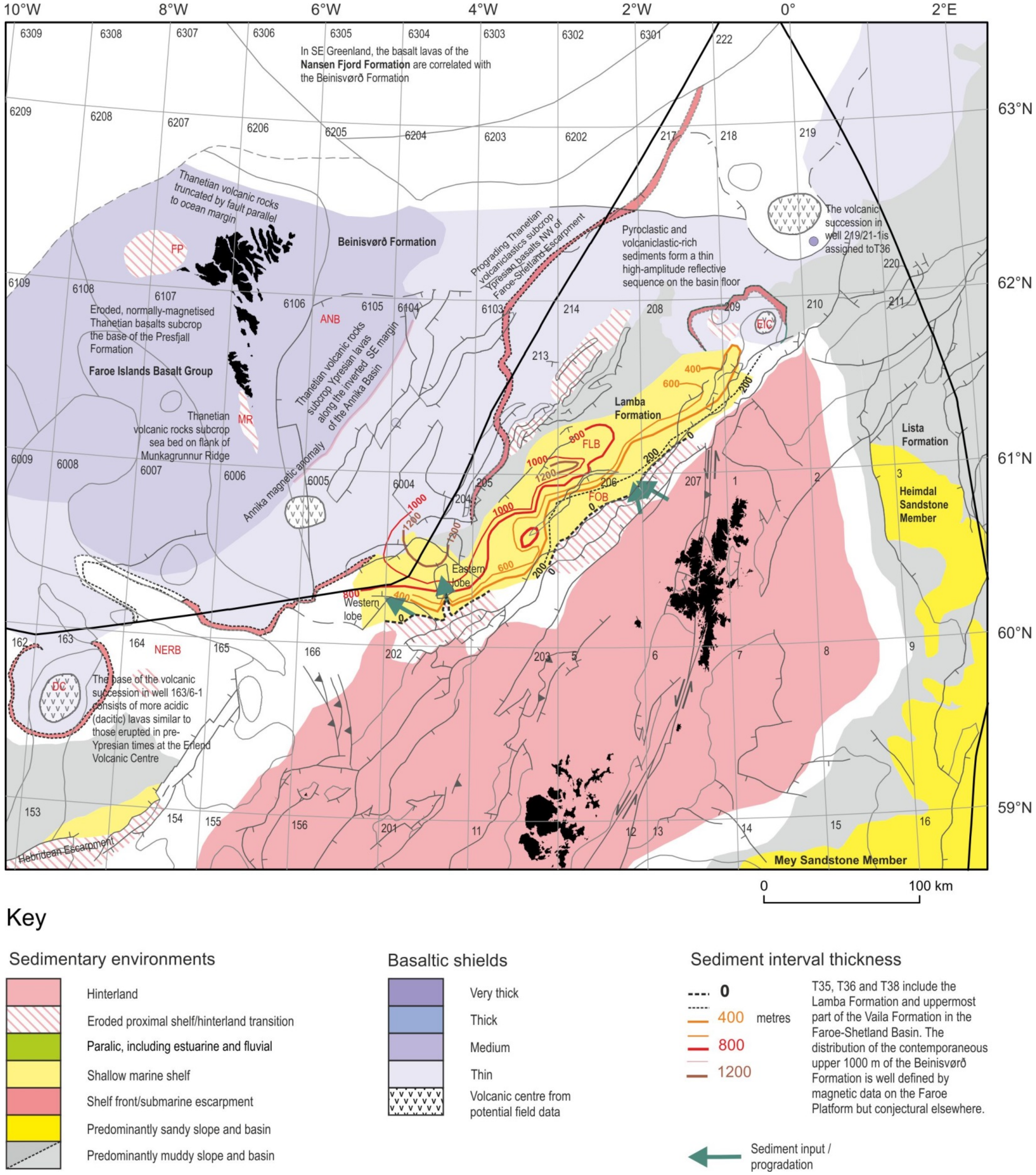

Figure 23 Gross palaeoenvironment map for the late Selandian–mid-Thanetian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.12 LATE THANETIAN–EARLY YPRESIAN (T40)

Coeval subsidence probably allowed the Faroe Platform to remain close to sea-level during the construction of the Beinisvørð Formation basaltic shield (Figure 24). At the end of the Thanetian, local uplift along the SE margins of the Faroe-Shetland Basin and the Annika sub-Basin resulted in the erosion of Lamba Formation shelf sediments and the top of the Beinisvørð Formation basalts at the Flett unconformity (Smith et al., 2013). Evidence for the uplift and truncation of the lavas of the Beinisvørð Formation offshore is provided by the NE-trending Annika magnetic anomaly (Kimbell, 2014), which is provisionally linked to the erosive south-eastern limit of normally magnetised Thanetian lavas associated with the C25n and C26n magnetochrons. At the same time, the southern flank of the Faroe-Shetland Basin was deeply dissected, leaving a wide area marked by a pattern of dendritic drainage cut into the top of the former Lamba Formation shelf (Smallwood and Gill, 2002). Onlap of this erosive surface began during the deposition of the T40 sequence, which partly backfills the deepest of the dendritic channels (Shaw-Champion et al., 2008). Additionally, fluvial and lignitic sediments of the Prestfjall Formation (Passey and Jolley, 2009) onlapped the unconformity surface on the Faroe Platform. In the Faroe-Shetland Basin, the shelf sediments of the lower Flett Formation responded to the uplift by prograding along the axis of a structural syncline that obliquely transects deeper structures in the area. The subsequent progradational limit of the lower Flett Formation shelf in Q214 defined the southern flank of the later Eocene depocentre (Smith et al., 2014). Volcaniclastic fans derived from the erosion of the edge of basaltic shield in the Faroese sector might have floored the northern part of the basin at this time. Evidence of local small-scale eruptions of basaltic lava around the junction of the upper and lower Flett formations in wells 205/8-1 and 205/9-1 (Smallwood and Kirk, 2005), and possibly in the Rosebank area, might be associated with contemporaneous basic sill intrusion.

General observations from the wider region include:

- The base of the Lower Dornoch Formation shelf and a change in shale facies at the base of Sele Formation formerly marked the base of the T40 sequence in the North Sea (Knox and Holloway, 1992). More recently, Schiøler et al. (2007) have included the basal (S1a) unit of the Sele Formation in the Lista Formation (T30), making the overlying S1b unit solely equivalent to the T40 sequence. This unit includes basinal turbidite sandstones of the Forties and Teal sandstone members that are characterised by the abundant presence of the dinocyst *Apectodinium augustum*. The acme occurrence of this dinocyst is a regional marker for the Paleocene Eocene Thermal Maximum (PETM), the base of which currently defines the base of the Eocene. Accepting these revisions places the main Forties Sandstone Member entirely within the Eocene (Kender et al., (2012) and has implications for the interpretation of the Moray Group succession in the Faroe–Shetland region. A tectonic synthesis suggests that an episode of uplift and erosion of the Scottish hinterland at the Paleocene/Eocene boundary displaced the Lower Dornoch Formation shelf basinward of its Lista Formation equivalent in the Central North Sea. In the Faroe-Shetland Basin, this relationship is reflected in the juxtaposition of the Lamba and lower Flett Formation shelves.

- In the NE Rockall Basin, the complex relationship between normal and reversely-magnetised basalt lava units near the Drekaeyga Volcanic Centre has some similarities with the structure of the Thanetian Beinisvørð Formation and younger lavas that explains the origin of the Annika magnetic anomaly in the Faroese sector (Kimbell, 2014). Although the areas lie approximately along strike, firmer structural connections cannot yet be established across the Wyville Thomson Ridge.

- In SE Greenland, the horizon corresponding to the T40 sequence lies between the Nansen Fjord and Milne Land formations and forms a correlative datum with the base of the Prestfjall Formation in the Faroe Islands (Larsen et al., 1999). Offshore in the Faroese sector, this junction is an unconformity marked by a widespread planar reflector within the Faroe Islands Basalt Group (Smith et al., 2013).

- In the NE of the area, Sweicicki et al. (1998) show the Møre Marginal High with a conjectural fringe of sand-dominated shallow-marine facies. In their interpretation, an area of shale-dominated marine facies at the centre of the Møre Basin lies to the east of an uplifted emergent volcanic high focused upon the Brendan Volcanic Centre.

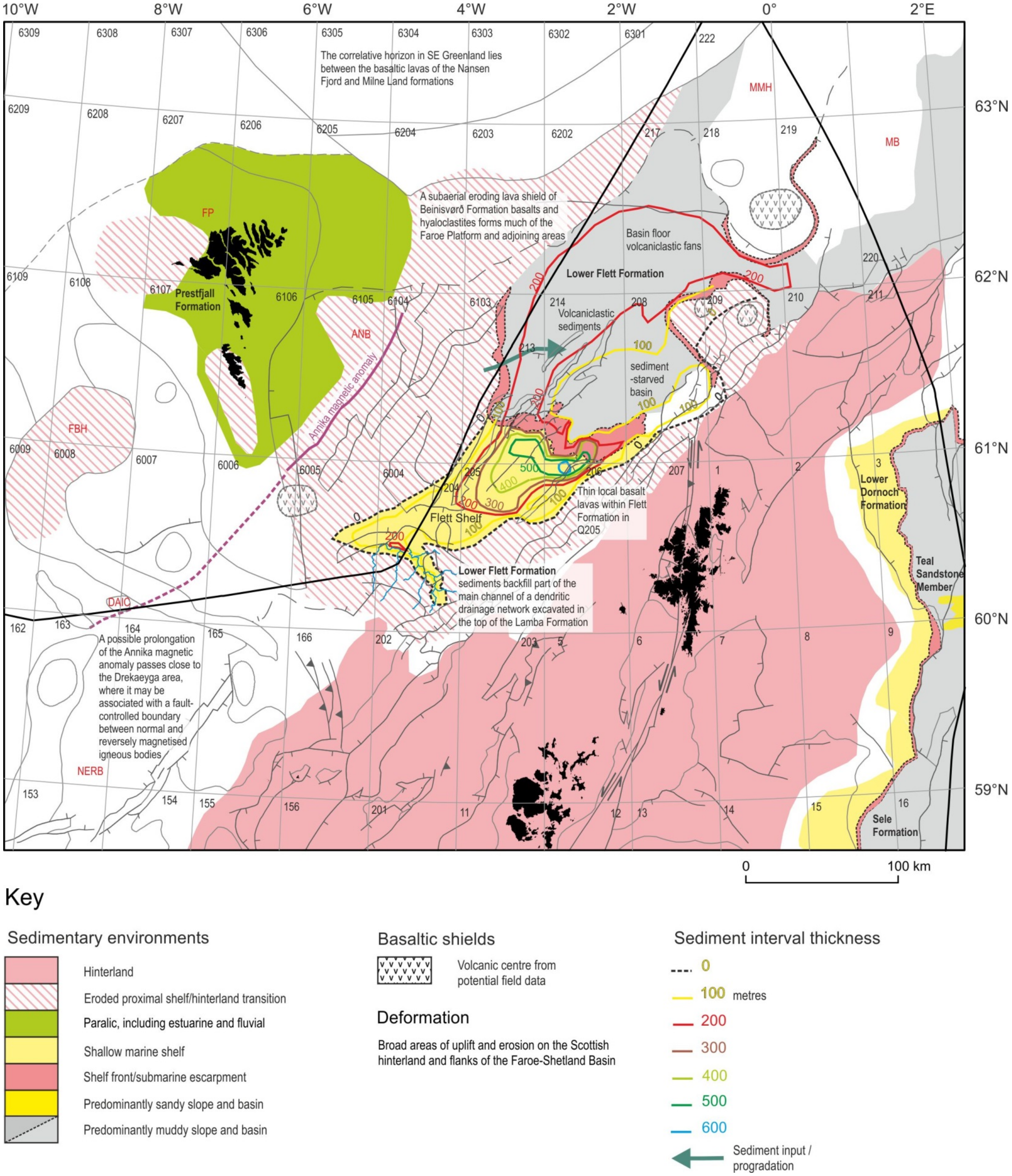

Figure 24 Gross palaeoenvironment map for the late Thanetian–early Ypresian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.13 YPRESIAN (T45, T50, T60–T91)

The period of relative uplift at the end of the Paleocene was rapidly followed at the start of the Eocene by a coastal onlap on both flanks of the Scottish hinterland, as well as on the Faroe Platform (Figure 25). Following the erosion at T40 level, sediments of fluvial and paralic facies continued to onlap the southern margins of the Faroe-Shetland Basin during the remainder of the Ypresian in a sustained period of relative subsidence (and/or sea level rise), possibly associated with the onset of closely focused extension at the incipient oceanic margin. Eruption of more than 2300 m of terrestrial basaltic lavas in the Malinstindur and Enni formations kept pace with the subsidence of the Faroe Platform, while prograding hyaloclastites built up the submarine, mainly aggradational, Faroe-Shetland Escarpment along the marine margin of the Faroe-Shetland Basin. Associated reversely magnetised volcanic rocks form part of the sea-ward-dipping reflector sequence (Kimbell, 2014), which, by analogy with the deep structure of East Greenland (Quirk et al., 2014), is possibly controlled by a breakup fault and a series of other landward-dipping shallow detachments at the continent-ocean transition. The focus of intra-plate volcanism elsewhere possibly shifted to the major basaltic shield volcanoes of Regin Smiđur and the Faroe Bank Channel Knoll in the Faroe Bank Channel area. The increase in volcanism in this area contrasts with the minor contemporaneous activity recorded at existing centres in the UK sector, including the thin succession of basaltic lavas proven in wells around the West Erlend Volcanic Centre (Unit D of Jolley and Bell, 2002). With the relative rise in sea level, onlap of the upper Flett Formation (T45) completed the infilling of the fluvial channels in the former area of dendritic drainage along the southern margin of the Faroe-Shetland Basin, and other coeval sediments were probably trapped on the shelf above the top of the Faroe-Shetland Escarpment. A minor basin-floor thick possibly developed in the axis of the northern part of the Faroe-Shetland Basin, which otherwise remained largely starved of sediment between volcanic escarpments during the Early Eocene. Although tuffaceous sediments are widely developed within the T45 sequence, it is the younger, more extensive onlapping tuffs and volcaniclastic sediments of the Balder Formation (T50) that probably mark the onset of oceanic spreading along the Aegir Ridge during the C24r magnetochron (Gernigon et al., 2012). After oceanic opening, onlap continued with the development of thin, backstepping and prograding wedges on the basin margins and flanks of the Munkagrunnur Ridge. In the main depocentres, a condensed sequence of partly tuffaceous sediments at the base of the Stronsay Group was deposited on the top of the Balder Formation.

General observations from the wider region include:

- In the Central and Northern North Sea, the Dornoch Mudstone overlies the Lower Dornoch Sandstone Unit and marks the onset of aggradation on the Upper Dornoch shelf. At the same time, the volume of turbidites reaching the basin floor was reduced, which is consistent with a relative rise in sea-level. Minor turbidite units in the upper (T45) part of the basinal Sele Formation include the Cromarty, Flugga and Hermod sandstone members of Knox and Holloway (1992). The thick lignites of the Beauly Member record the ongoing process of subsidence and coastal onlap during sequence T50 and are contemporaneous with the more basinal tuffaceous claystones of the Balder Formation.

- In the NE Rockall Basin, the Ness Escarpment (Tate et al., 1999), which marks the southern extent of the Ypresian terrestrial basalt lavas proven by well 164/7-1 (Archer et al., 2005), forms a hyaloclastite delta analogous to the Faroe-Shetland Escarpment. In well 164/27-1, to the south of the Ness Escarpment, the basinal succession of the Flett Formation only consists of 17 m of claystones. Outside the study area, on the eastern flank of the Rockall High, Eocene successions comparable to those in the Faroe-Shetland Basin are proven by BGS shallow boreholes 94/02 and 94/03 (Stoker, 2013). These boreholes show unconformity surfaces within the Ypresian, equivalent to the base of the Stronsay Group (?intra-NP12).

- Larsen et al. (1999) considered the Milne Land Formation in SE Greenland to be an equivalent of the syn-breakup lavas of the Faroe Islands Basalt Group, and went on to argue that the overlying lavas of the Geikie Plateau, Rømer Fjord and Skrænterne formations on the Blosseville Kyst are not preserved in the Faroe Islands. The subsequent recognition of only thin representatives of these later formations near the top of the Faroes basalt pile (Søager and Holm, 2009) is still consistent with the original observation that the focus of volcanism migrated away from the Faroe Islands during breakup.

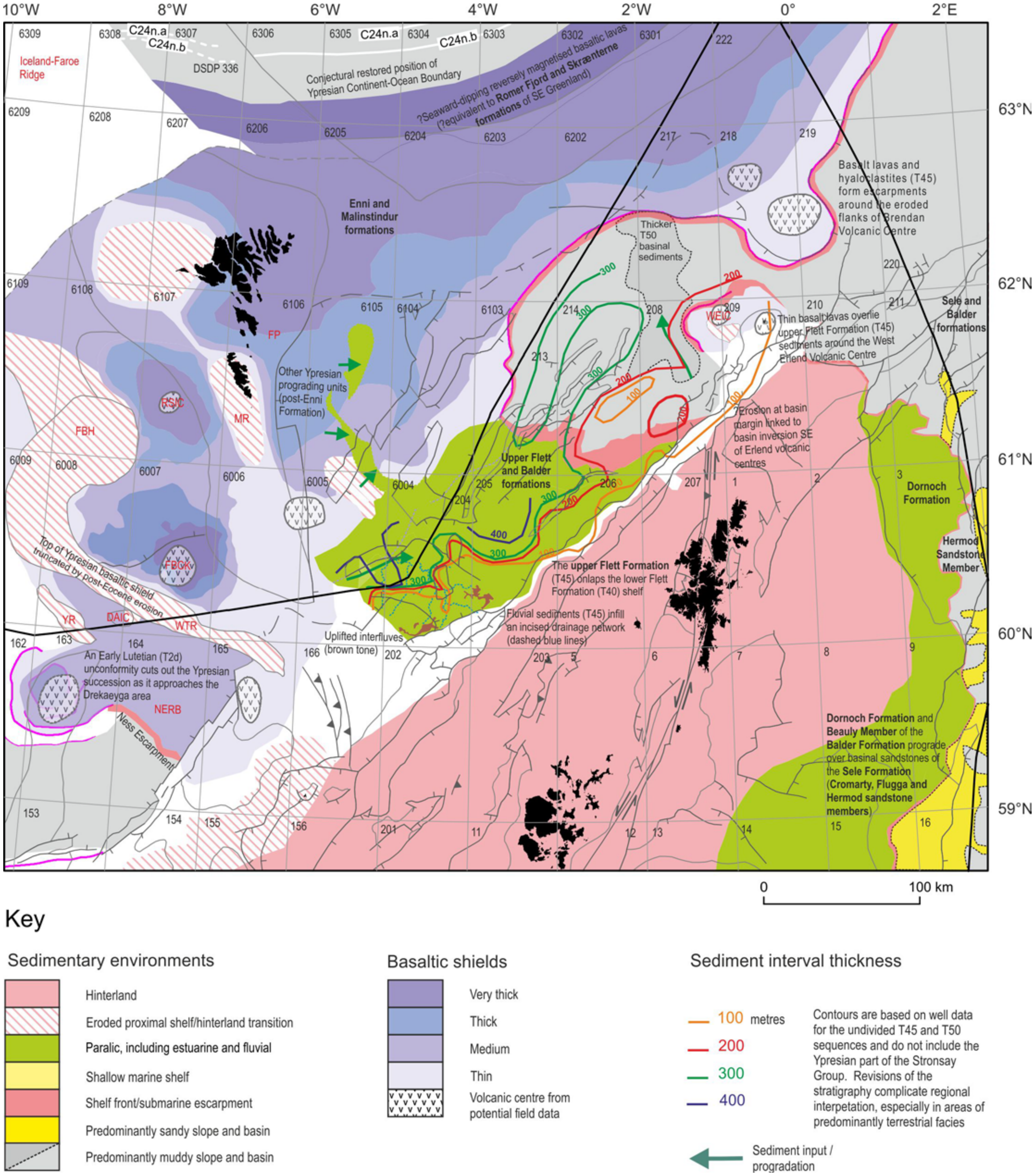

Figure 25 Gross palaeoenvironment map for the Ypresian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.14 EARLY TO MID-LUTETIAN (T93–T94)

Landward of the oceanic margin, the effects of subsidence and volcanism diminished towards the end of the Ypresian and a widespread unconformity (T2d) truncates the fluvial and paralic successions along the southern flank of the Faroe-Shetland Basin (Stoker et al., 2013) (Figure 26). Contemporaneous deformation probably contributed to the uplift of the Wyville Thomson Ridge and the development of a syncline in the north Faroe Bank Channel area. It might also have enhanced the anticlinal structure of the Munkagrunnur Ridge, which might have been initiated by differential subsidence of its flanking basins during the previous (Ypresian) episode of extension (ocean opening). It is likely that the whole continental margin landward of the line of Ypresian breakup was affected by a relative fall in contemporary sea level at this time. As a result, the early to mid-Lutetian shelf (T93/T94) in the Faroe-Shetland Basin was displaced northwards to rest unconformably on a truncated Ypresian succession. There is evidence in the magnetic data of Gernigon et al. (2012) of a normally-magnetised unit within the seaward-dipping reflectors of C24r age on the northern flank of the Fugloy Ridge (Kimbell, 2014). The normally-magnetised unit currently forms a curvilinear feature parallel to the continental margin, which is affected by a series of NW-trending fault offsets (Gernigon et al., 2012), the largest of which corresponds to the Faroes Fracture Zone of Kimbell et al. (2005). It is possible that this unit was associated with the emplacement of basic sills and other intrusions into the reversely magnetised lavas at continental margin after breakup. The magnetic unit is inferred to post-date C24r, but its age is otherwise poorly constrained. An equivalent succession of effusive basalts on the northern flank of the Iceland-Faroe Ridge might include those currently dated at about 43–40 Ma, which are proven at the base of the DSDP 336 borehole (Ellis and Stoker, 2014). Since these are vintage K-Ar radiometric age determinations (Talwani et al. 1976), which are generally superseded by Ar/Ar-based dates elsewhere, the true age of the DSDP 336 volcanic rocks may be older. In the same area, a normal-polarity basaltic shield and shallow volcanic escarpment on the flanks of the Faroe Platform is attributed to a minor episode of post-breakup volcanism, and other normal-polarity basalts and intrusions are associated with the predominantly reversely magnetised volcanic centres in the Faroe Bank Channel (Kimbell, 2014). If the normally magnetised basalt lavas and related intrusions were emplaced during the C22n or C21n magnetochrons near the end of the Ypresian, at the same time as the tectonic episode responsible for the formation of the T2d unconformity, it would provide evidence that contemporaneous magmatism might have extended at least 200 km from the area of active melting at the mid-ocean Aegir Ridge. Supporting evidence for intra-plate volcanism distant from the active plate boundary at this time is preserved on the conjugate continental margin in the Kap Dalton area of E Greenland (see below).

General observations from the wider region include:

- In the North Sea, the Mousa Formation forms a patchily preserved proximal shelf. Other widespread Middle–Upper Eocene sandstones are assigned to the Grid Sandstone Member of the Horda Formation or more specifically to the Caran Sandstone Unit, in cases where a prograding shelfal association is more firmly identified (Knox and Holloway, 1992).
- Along the southern edge of the NE Rockall Basin, early to mid-Lutetian shelf sediments probably make up part of the marginal succession in the area of the Geikie and Hebridean escarpments (Evans et al., 1989; Stoker et al., 1994). On the opposite side of the basin, near the Drekaeyga Volcanic Centre, a composite reflector, partly equivalent to the T2d unconformity, truncates a parallel-bedded Ypresian unit so that the Lutetian succession rests directly upon the eroded top of the early Ypresian basalts approaching the southern flank of the Wyville Thomson Ridge. Outside the study area, on the eastern margin of the Rockall High, Eocene successions comparable to those in the Faroe-Shetland Basin are proven by BGS shallow boreholes 94/02 and 94/03 (Stoker, 2013). These boreholes show closely-spaced unconformity surfaces within the Lutetian, equivalent to the T2d and Mid-Eocene (?intra NP14–15) reflectors.
- In the Kap Dalton area of E Greenland, 300 m of basaltic lavas of the Igtertivâ Formation overlie 7 m of sediments, which rest unconformably upon the eroded top of the Ypresian Skrænterne Formation (Larsen et al., 1999, 2014). Age dates of 49.09 +/- 0.46 Ma obtained from the Igtertivâ Formation suggest firstly that there is an interval of about six million years between the two basalt successions during the Ypresian, and secondly that the base of the interbedded sedimentary unit probably corresponds with the T2d unconformity at the base of the early Lutetian in the Faroe–Shetland region.

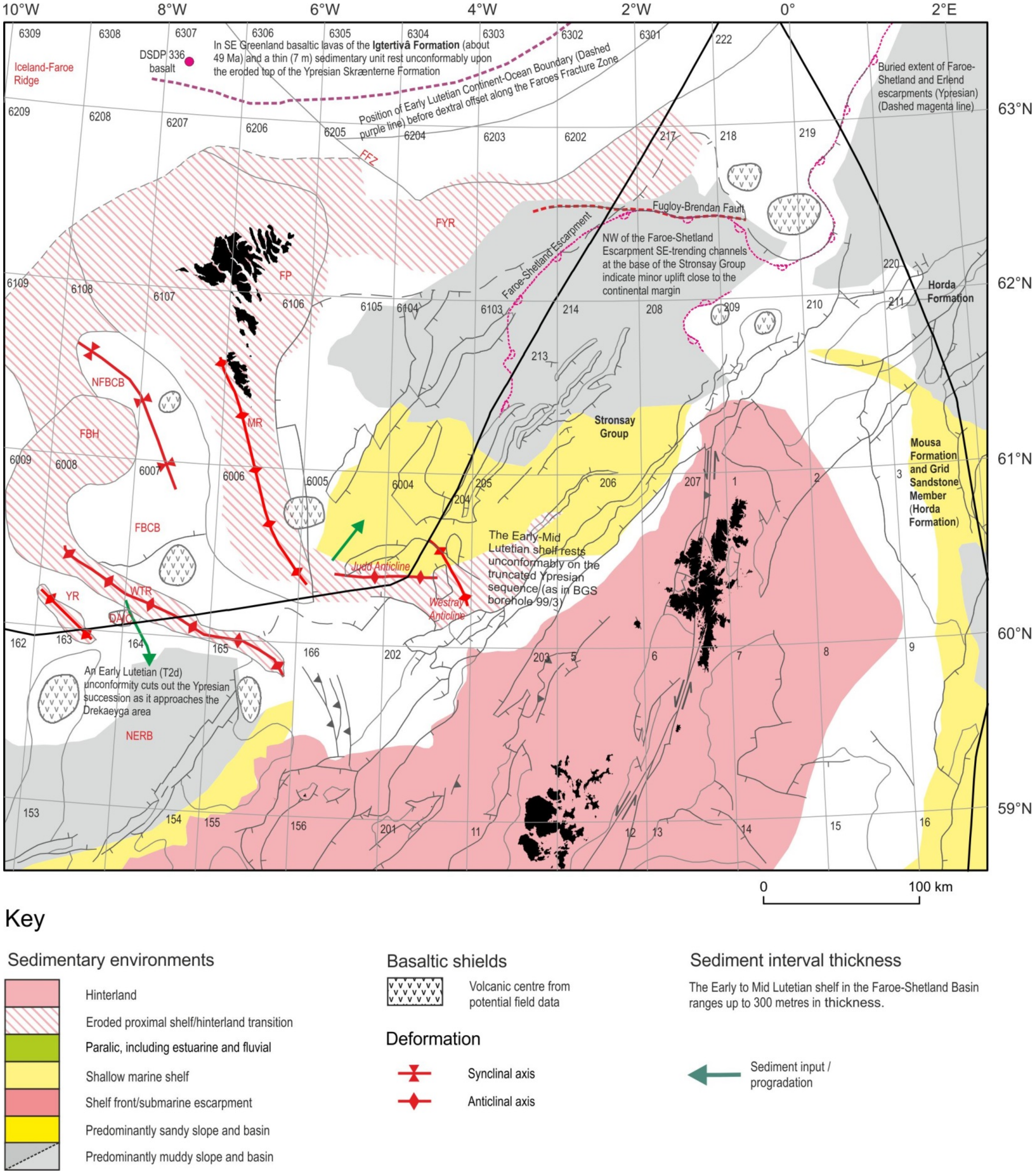

Figure 26 Gross palaeoenvironment map for the early to mid-Lutetian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.15 LATE LUTETIAN (T96–T97)

During the late Lutetian, there was a significant period of basin-floor fan deposition in the Faroe-Shetland Basin, which can be linked to the relative uplift of the SE flank of the basin and adjacent Scottish hinterland (Figure 27). With an apparent slight change of provenance, the fans largely entered the basin through a series of northerly-trending channels that dissected the front of the preceding early to mid-Lutetian shelf, before spreading out in the Eocene depocentre and onlapping the area above the Faroe-Shetland Escarpment in the Faroese sector (Davies et al., 2004; Robinson et al., 2004)). The resurgence of uplift might be tectonically linked to an episode of strike-slip faulting along the Faroes Fracture Zone that offset existing intrusions, magnetic stripes and related curvilinear structures at the new oceanic margin, possibly at the start of the late Lutetian. The minor dextral strike-slip displacements on a series of faults sub-parallel to the Faroes Fracture Zone, mapped by Gernigon et al. (2012), might have also occurred at this time. It is suggested that the landward area responded to this deformation by uplift along a NE-trending axis within the Scottish hinterland, with a corresponding enhanced influx of coarse clastic detritus to the adjoining basin floors. Towards the end of the Lutetian, there was a short period of relative sea-level rise as the upper part of sequence T97onlapped the margins of the Faroe-Shetland Basin and basin-floor fan deposition was largely curtailed. This change in the pattern of regional uplift and subsidence might have been a precursor to subsequent Bartonian–Priabonian tectonism (see section 4.16). Although the upper part of the Eocene succession is currently largely absent from the crest of the Fugloy Ridge, restoration of seismic profiles by flattening on the top of the basalt shield indicates that a continuous cover of Ypresian basalts and Lower to Middle Eocene sediments probably once extended across the ridge towards the developing area of oceanic crust. In a synoptic view, before the main episode of post-Eocene uplift at the Fugloy Ridge, the whole of the preceding volcanic and sedimentary succession of Eocene age in the Faroe-Shetland region probably consisted of a wedge-like offlapping unit that thickened northward towards the subsiding oceanic margin, as its southern flanks were episodically uplifted and eroded.

General observations from the wider region include:

- In the North Sea, sparsely distributed Middle–Upper Eocene basinal sandstones are assigned to the Grid Sandstone Member of the Horda Formation or more specifically to the Brodie Sandstone Unit, in cases where a turbidite association is firmly identified (Knox and Holloway 1992).
- In the NE Rockall Basin, a channel or proximal basin-floor fan of undifferentiated Eocene age is identified on 3D seismic data in Block 164/27 (Promote UK, 2012). Basinward, to the south of Rosemary Bank in the northern parts of Quadrants 151 and 152, a major Eocene basin-floor fan complex, at least 95 km long and up to 18 km wide, has been identified on 2D seismic data to the west of the current study area, but its precise age remains poorly constrained (Promote UK, 2012). Comparison with the Faroe-Shetland Basin suggests that these fans could also be related to the late Lutetian uplift of the Scottish hinterland.

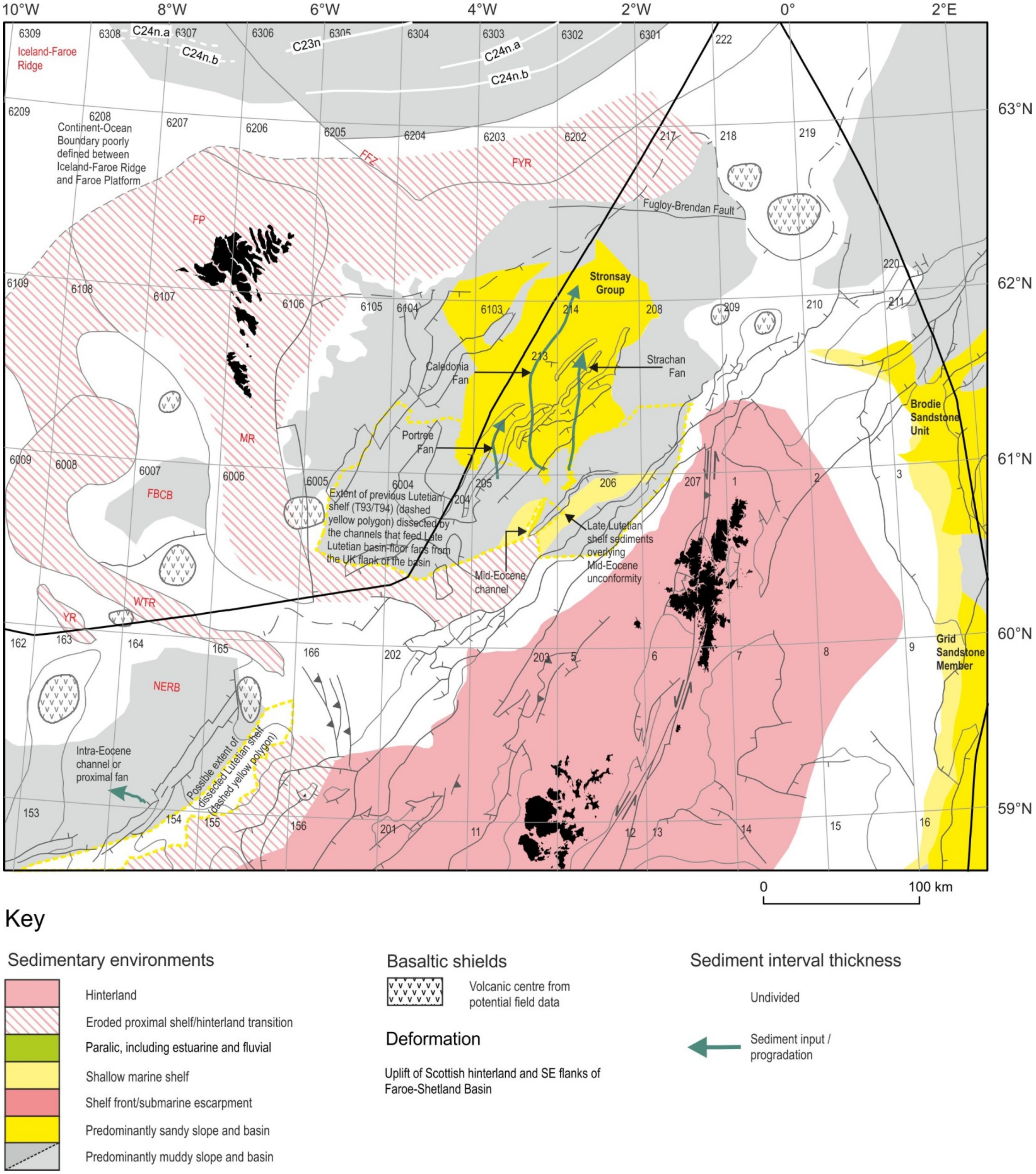

Figure 27 Gross palaeoenvironment map for the late Lutetian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.16 BARTONIAN–PRIABONIAN (T98–T99)

A Bartonian shelf, which rested with slight unconformity (T2c) on late Lutetian basinal sediments, prograded into the south-eastern part of the Faroe-Shetland Basin and advanced over an attached slope-apron consisting of base-of-slope fans (Stoker et al., 2013) (Figure 28). A smaller, analogous shelf prograded eastwards from the eastern flank of the Faroe Platform (Ólavsdóttir et al., 2013).The position of the south-eastern shelf, landward of the underlying early–mid-Lutetian shelf in the UK sector, and its association with base-of-slope – rather than basin-floor – fans, both indicate a relative rise in sea-level in this part of the Faroe-Shetland Basin in the Late Eocene. The top of the base-of-slope fans is marked by the T2b seismic reflector (Stoker and Varming, 2011; Stoker et al., 2013). Distal basinal sediments are most thickly developed along the synclinal axis of the Faroe-Shetland Basin, especially between the volcanic escarpments in the north of the area. In some areas, the Late Eocene interval on seismic sections is uniform and largely unreflective; in others however, it consists of a thick succession of short wavelength, high amplitude reflections, which is cut by a dense network of polygonal faults. The main deformation and uplift of the Fugloy Ridge, which eventually resulted in the removal of most of its former cover of Eocene sediments at the continental margin, may have been initiated towards the end of this period. Anticlines in the Faroe Bank Channel–Wyville Thomson Ridge area were also growing at this time. This deformation marked the onset of a protracted phase of contractional deformation across the Faroe–Shetland region, which persisted until the Mid-Miocene and instigated the topographic shaping that characterises the present-day continental margin (see sections 4.17 and 4.18). As a result of the onset of this tectonism, areas of more continuous deposition at the end of the Eocene were focused in structural synclines within the Faroe-Shetland Basin. Transitional sedimentary successions with an element of structural control may include those assigned to the ‘marginal fan’ unit of Stoker et al. (2012), and a possible slump body characterised by fluid injection structures, which overlies the Flett Shelf in Quadrants 213 and 214. It is suggested that there was a change in regional structural controls at the end of the Eocene as a period dominated by ‘Pyrenean’ tectonics during the Late Eocene and Early Oligocene (with an inferred NNE-trending direction of maximum horizontal stress) reverted to one more influenced by ‘Alpine’ tectonics (with a NW- to NNW-trending direction of maximum stress) during the Late Oligocene. The origin of local depocentres at the Eocene/Oligocene transition elsewhere within the wider uplifted margin is generally attributed to the development of pull-apart structures. These are commonly filled with terrestrial sediments in the parts of the onshore UK and its adjoining continental shelf and show a close relationship with sets of sinistral NE-trending faults and dextral NW-trending faults that offset early Palaeogene basic dykes and other intrusions (Quinn, 2006; Cooper et al., 2012).

General observations from the wider region include:

- Late Eocene environments in the North Sea are modified from Jones et al. (2003). In wells in the UK and Norwegian sectors, sequence T98 ranges between 10-80 metres in thickness and broadly corresponds to sequences T98 and T99 (Figure 11) in the Faroe–Shetland region. Contemporaneous lithostratigraphic units of the Stronsay Group in the North Sea include the shelfal Mousa Formation on the flanks of the East Shetland High and the more extensive, basinal Horda Formation.

- NE Rockall Basin environments are modified from McInroy et al. (2006), who infer that parts of the nearby Hatton High, Rosemary Bank Seamount and Rockall High formed sources of sediment comparable to the Faroe Platform at this time. To the west of the Faroe–Shetland region, the Lousy and Bill Bailey highs formed contemporaneous nearshore marine areas (Vanneste et al., 1995), similar to the Fugloy Ridge. In all these places, the former cover of Upper Eocene sediments has been deeply truncated by subsequent, more prolonged, uplift of the continental margin.

- Part of a former Late Eocene prograding shelf is preserved on the SE margin of the NE Rockall Basin (McInroy et al., 2006; Stoker et al., 2012), while within the basin, NW of well 164/7-1, Upper Oligocene and Miocene sediments rest unconformably on an uplifted Eocene succession at the axis of the Bridge Anticline (Tate et al., 1999; Archer et al., 2005; Tuitt et al., 2010).

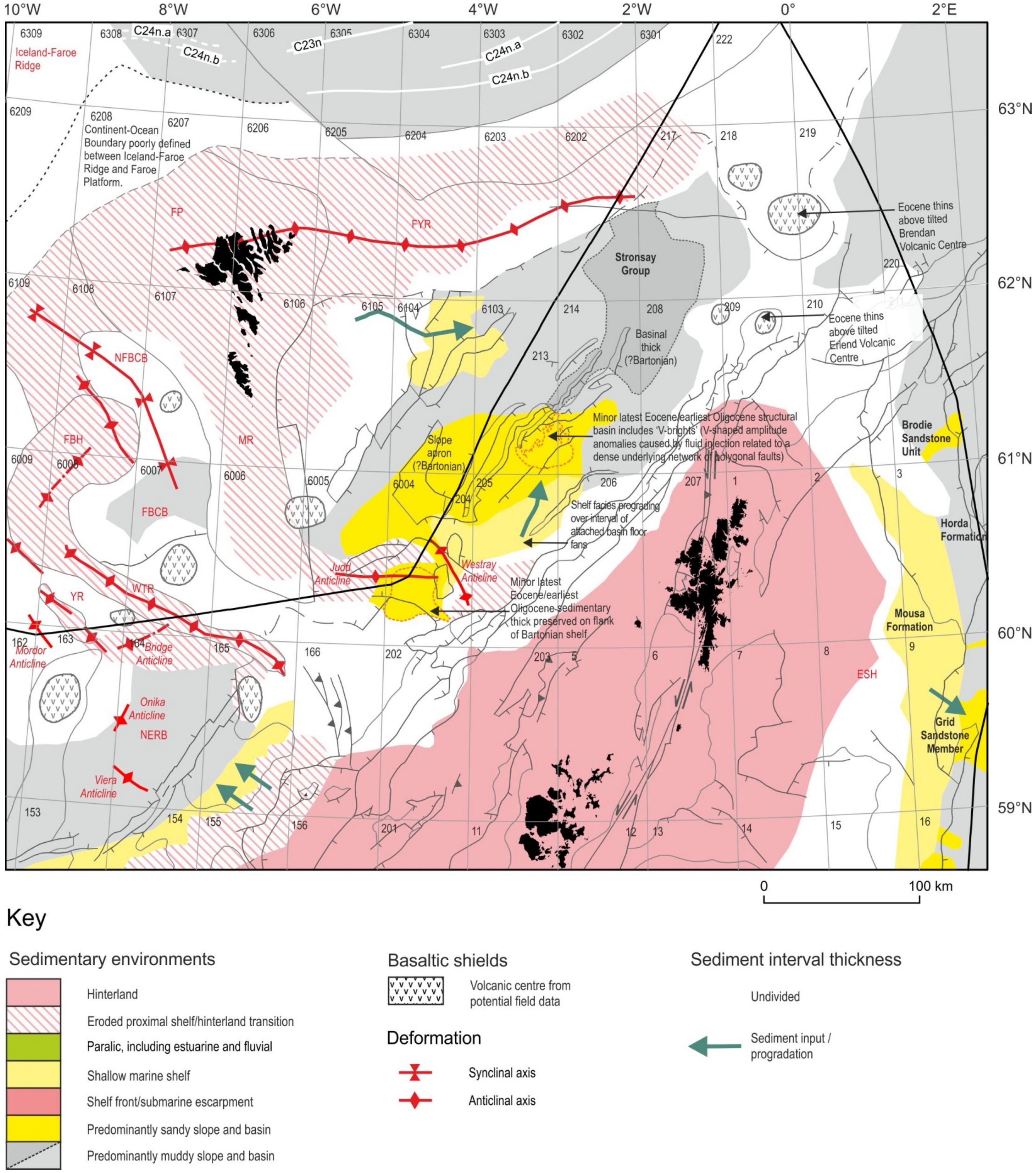

Figure 28 Gross palaeoenvironment map for the Bartonian–Priabonian. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.17 OLIGOCENE

The Late Eocene–Mid-Miocene topographic adjustment across the Faroe–Shetland region marks a period of major change in the shape and structure of the continental margin. Understanding the response to this change in the Oligocene is hindered by the overall poor stratigraphic resolution of this series in this area. However, there are a number of key points that are pertinent to the palaeoenvironment map depicted in Figure 29; these include:

- The input of coarse clastic material into the Faroe-Shetland Basin persisted during the Oligocene.
- On the SE margin of the Faroe-Shetland Basin, the transition from shallow-marine sandstone and mudstone deposits into predominantly muddy basinal marine sediments coincides approximately with the Late Eocene shelf-edge, though the latter was slightly tilted and eroded prior to the Early Oligocene (Stoker, 1999).
- East of the Faroe Islands, the shelf-edge might have been controlled by the Heri–East Faroe–Tróndur high, which separates the shallower Annika sub-Basin from the main Faroe-Shetland Basin. Lower Oligocene shallow-marine sandstones are present in the Annika sub-Basin (Waagstein and Heilmann-Clausen, 1995). North of the Faroe Islands, Oligocene marine mudstone has been proved on the flank of the Iceland-Faroe Ridge (Talwani et al., 1976), part of an Eocene–Oligocene shelf-margin system (Nielsen and van Weering, 1998). All these sediments were derived from the Faroe Platform, probably in response to the uplift of the Fugloy Ridge (Andersen et al., 2000; Ólavsdóttir et al., 2013).
- In the Faroe-Shetland Basin, mudstone, siltstone and sporadic sandstone, up to 300 m thick, thickens to the NE (Damuth and Olsen, 1993; Davies and Cartwright, 2002; Stoker and Varming, 2011). Along the NW margin of the basin, these deeper-water rocks onlap tilted Eocene rocks on the flank of the Fugloy Ridge.
- Evidence for lowstand conditions include intra (mid?)-Oligocene incisions (canyons?) up to 100 m deep on the East Faroe High (Johnson et al., 2012), and Upper Oligocene paralic rocks on the south-eastern margin of the Faroe-Shetland Basin (Evans et al., 1997).
- The ‘SE Faroes drift’ of Davies et al. (2001) is herein re-interpreted as a Late Oligocene mass-flow slump deposit (cf. Johnson et al., 2012) derived from the Fugloy Ridge.
- The Annika, East Faroe High, Judd and Westray anticlines, and the Fugloy Ridge might have been actively deforming (Figures 4 and 5).

General observations from the wider region include:

- Evidence for low relative sea level at various times during the Oligocene includes: Lower Oligocene lowstand-fan deposits in the NE Rockall Basin (Egerton, 1998); a Lower Oligocene fringing carbonate reef built upon tilted and eroded Eocene shelf-margin deposits on the Outer Hebrides High (Stoker et al., 1994; Stoker, 2013); Upper Oligocene terrestrial/paralic rocks preserved in the Inner Hebrides region (Evans et al., 1979, 1991); Late Oligocene delta progradation (Skade Formation) from the Orkney-Shetland High into the northern North Sea Basin (Fyfe et al., 2003); Oligocene lowstand progradation of the SW Norwegian margin into the Møre Basin (Martinsen et al., 1999).
- The Wyville Thomson Ridge, Ymir Ridge and Bridge anticlines, as well as the Mordor, Onika and Viera anticlines in the NE Rockall Basin, might have been actively growing (Figure 5). The Oligocene sediments onlap the flanks of these folds (Tuitt et al., 2011).
- Biogeographic evidence suggests that a subaerial link persisted across the Greenland–Scotland Ridge throughout the Oligocene (Denk et al., 2011).

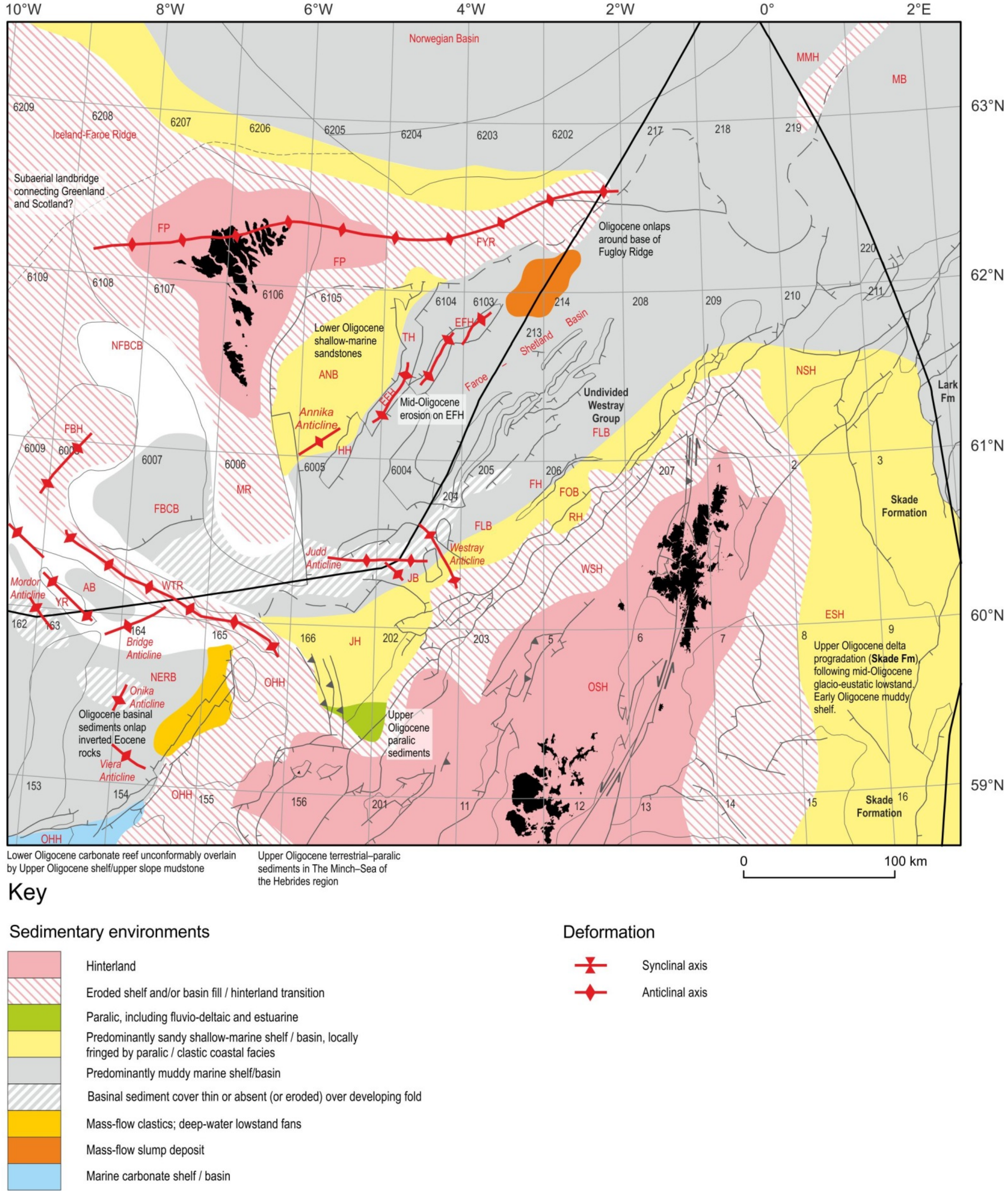

Figure 29 Gross palaeoenvironment map for the Oligocene. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map.

4.18 EARLY MIOCENE (INCORPORATING MID-MIOCENE TECTONIC EVENTS)

The Early to early Mid-Miocene interval witnessed an intensification of contractional deformation across the Faroe–Shetland region (Johnson et al., 2005; Stoker et al., 2005c) (Figure 30). The culmination of this period of deformation is well dated in the north-eastern part of the Faroe-Shetland Basin where the deposition of Lower Miocene sediments is bracketed by the formation of the TPU and IMU (Stoker and Varming, 2011). The Lower Miocene sediments onlap folded Oligocene rocks (TPU), but are themselves deformed and onlapped by Middle–Upper Miocene rocks (IMU) (Figure 7). This deformation activated a number of folds within the Faroe-Shetland Basin (Figures 4 and 29), which created undulating basin-floor topography; however, its most significant effect was the differential topographic adjustment – possibly up to 1 km – between the Faroe-Shetland and Faroe Bank Channel basins and adjacent highs, such as the Fugloy, Munkagrunnur and Wyville Thomson ridges (Figures 5 and 7). The scale of this shaping might have been cumulative between the Late Eocene and Mid-Miocene, and essentially created the modern-day topographic framework of shelves and channels that characterise the Faroe–Shetland region. A particular consequence of Early to Mid-Miocene differential movement was the creation of the *Faroe Conduit* – comprising the Faroe-Shetland and Faroe Bank channels – that provides a passageway for the exchange of intermediate- and deep-water masses across the Greenland-Scotland Ridge. This important development was one of a series of concomitant NE Atlantic–Arctic-wide tectonically-forced adjustments to the palaeobathymetry that facilitated a change in global palaeoceanographic circulation (Stoker et al., 2005a).

A major impact of this change on Early Miocene sedimentation in the Faroe–Shetland region is that the continental slopes bordering the West Shetland and Faroe margins were bathed by southerly-flowing intermediate- and deep-water masses derived from the Norwegian-Greenland Sea. At the inception of the Faroe Conduit, these currents were strong and much of the channel floor at the shallower south-west-end of the conduit was an erosive zone. In places, such as the Judd Deeps (Stoker et al., 2003), the sea bed is highly sculpted into a series of deep hollows. In the deeper NE Faroe-Shetland Channel, Lower Miocene diatomaceous mud was deposited from contour-following bottom currents on a muddy basin floor (Stoker, 1999; Stoker and Varming, 2011). On the adjacent West Shetland Slope, coarser clastic facies derived from the adjacent shelf are preserved beneath the current mid-slope region (Stoker and Varming, 2011). These include stacked deltaic bodies that backstep upslope; an indication of a generally rising relative sea level. Comparable lowstand fan deposits are described from the East and SW Faroe margins (Stoker and Varming, 2011; Ólavsdóttir et al., 2013), whereas a transgressive shelf-margin system is reported from the north Faroe margin (Nielsen and van Weering, 1998). It seems probable that the West Shetland and Faroe shelves were, for the most part, exposed (Stoker, 1999; Andersen et al., 2000).

General observations from the wider region include:

- The NE Rockall Basin was largely a zone of erosion due to the presence of strong, southerly-derived bottom currents (Stoker et al., 2005a, b; Stoker, 2013). Most of the late Palaeogene inversion domes were inactive at this time (Tuitt et al., 2011) (Figure 5).
- East of Shetland, the Skade Formation continued to prograde eastwards into the northern North Sea (Fyfe et al., 2003). The occurrence of both glauconitic and lignite in these rocks suggests an interplay between shallow-marine and terrestrial environments due to fluctuations in relative sea level. In the late Early Miocene–Mid-Miocene, the shelf east of Shetland was uplifted and eroded. A dendritic drainage pattern is described by Martinsen et al. (1999) from the northern flank of the North Sea, with Middle–Upper Miocene rocks infilling incisions cut into Oligocene strata.
- The SW Norwegian margin continued to prograde westward into the area underlain by the Móre Basin (Martinsen et al., 1999). It remains uncertain whether or not the Møre Marginal High was locally exposed at this time (Brekke, 2000).

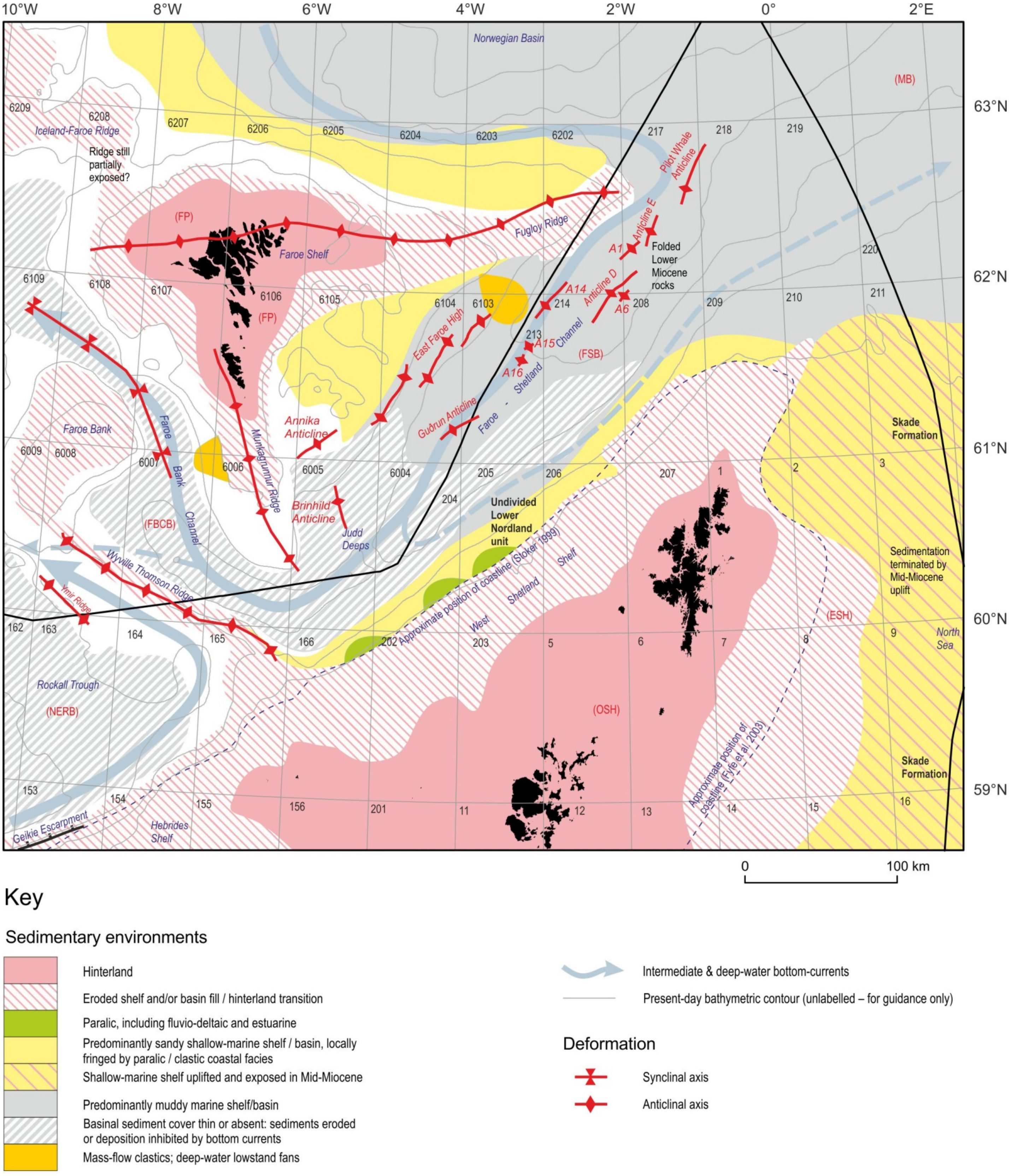

Figure 30 Gross palaeoenvironment map for the Early Miocene (incorporating Mid-Miocene tectonic events). See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Bathymetric features labelled in blue font. Present-day bathymetric contours intended as a guide (only) to the developing shape of the continental margin.

4.19 MID-/LATE MIOCENE

Middle and Upper Miocene rocks are more widely preserved across the Faroe–Shetland region, both on the shelves and in the adjacent deep-water basins (Figure 31). The irregular palaeobathymetry (the IMU surface) created by the early Mid-Miocene culmination of folding in the NE part of the Faroe-Shetland Basin resulted in differential sedimentation, with basinal mudstone 'thicks' preferentially accumulating by onlap within the synclines that separate the Mid-Miocene anticlines (Figures 30 and 31). These fine-grained contourite sediments were transported into the area by, and deposited from, bottom currents generated by the intermediate- to deep-water masses. Although the narrow SW part of the Faroe Conduit remained largely a zone of erosion, the wider distribution of contourite deposits within the basin indicates a generally more stable deep-water depositional system. Elongate depositional 'thicks' with positive relief – elongate sediment drifts – that developed locally in the Faroe Bank Channel reflect the interaction between local topography and reduced intensity of the current system away from the core of the current.

On the West Shetland Shelf, the glauconite- and bioclastic-rich Muckle Ossa Sandstone was deposited during a marine transgression of the shelf, though there are indications (reduced glaucony and sporadic lignites and mudstones) of coastal/paralic facies towards the top of the unit (Stoker, 1999). The West Shetland Shelf was subsequently tilted eastwards during the latest Miocene/earliest Pliocene, which resulted in the erosion of the Muckle Ossa Sandstone, and the transfer of sediment onto the adjacent slope apron where it was deposited as a mass-flow clastic deposit (Stoker, 1999). On the north Faroe margin, a shelf-margin system continued to build out into the Norwegian Basin, which largely comprises a series of stacked wedges that backstep upslope; this implies an overall transgressive setting (Nielsen and van Weering, 1998). These deposits were tilted basinward in Late Miocene/Early Pliocene time (Andersen et al., 2000). Equivalent deposits are inferred to have accumulated east of the Faroe Islands, in the area of the Annika sub-Basin, including the sporadic transfer of coarser clastic material from the Munkagrunnur Ridge into the Faroe-Shetland Basin (Ólavsdóttir et al., 2013).

General observations from the wider region include:

- The Iceland-Faroe Ridge was fully submerged by the Mid-Miocene (Thiede and Myhre, 1996).
- Middle–Upper Miocene glauconitic sandstone deposited on the upper Hebrides Slope is laterally equivalent to the Muckle Ossa Sandstone (Stoker, 2013).
- Muddy sediment drift deposits accumulated in the NE Rockall Basin, though erosion prevailed around the northern flank of the basin (Stoker, 2013).
- East of Shetland, the Mid-Miocene is marked by a hiatus throughout the northern North Sea (Fyfe et al., 2003). This was followed by the deposition of the Upper Miocene–lowest Pliocene Utsira Formation – predominantly a glauconite- and bioclastic-rich sandstone – and the Hutton Sands. The former were derived from the Norwegian North Sea margin, whereas the latter were sourced from the East Shetland Platform. The Mid-Miocene hiatus may have been formed, in part, in response to uplift of the Orkney-Shetland Platform and the Fennoscandian High, from where the succeeding sandstone units were derived (Fyfe et al., 2003). Although the North Sea sandstone units are lithologically comparable to the Muckle Ossa Sandstone, their relationship might be diachronous. The Muckle Ossa Sandstone might have been deposited (at least in part) at the same time that the northern North Sea was uplifted and eroded (Mid-Miocene); in contrast, the latest Miocene/earliest Pliocene uplift and erosion of the Muckle Ossa sandstone occurred at a time that the North Sea units continued to be deposited. This might indicate tilting of the areas east and west of Shetland, in a see-saw manner, about an axis defined by the Orkney-Shetland Platform.
- The SW Norwegian margin continued to build a slope system that prograded across the underlying Møre Basin (Martinsen et al., 1999).

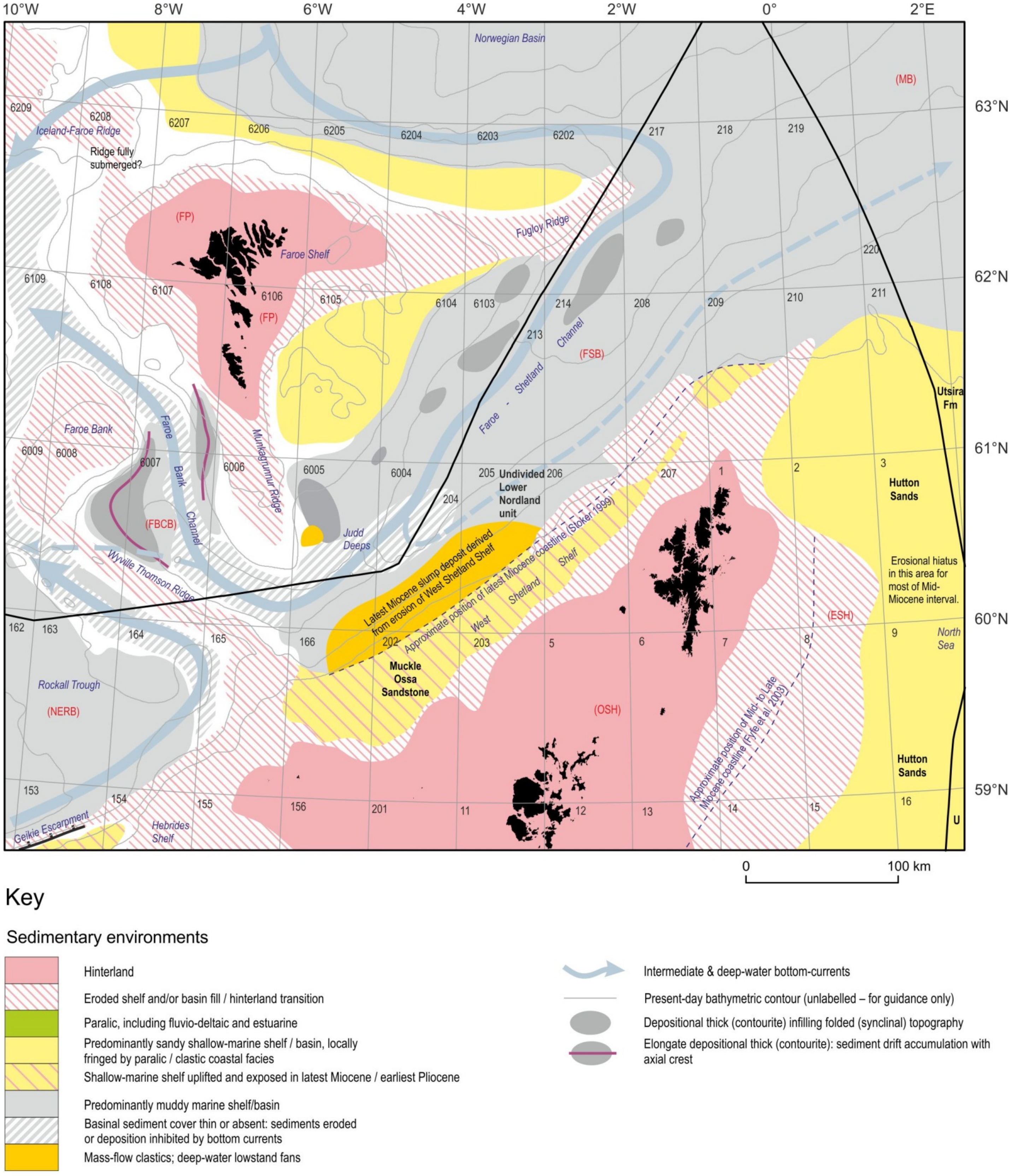

Figure 31 Gross palaeoenvironment map for the Mid- to Late Miocene (incorporating latest-Miocene/earliest Pliocene erosion of the West Shetland Shelf). See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Lithostratigraphic abbreviation: U, Utsira Formation. Bathymetric features labelled in blue font. Present-day bathymetric contours intended as a guide (only) to the developing shape of the continental margin.

4.20 LATE EARLY PLIOCENE–EARLY MID-PLEISTOCENE

This reconstruction (Figure 32) covers the interval between 4 Ma and 0.5 Ma, thereby pre-dating the expansive Mid- to Late Pleistocene glaciations that – at their maximum – were shelf-wide in extent.

The intra-Neogene unconformity (INU), dated at about 4 Ma (late Early Pliocene), marks the onset of the most recent large-scale change in the development of the Faroe–Shetland region (Stoker, 2002). The INU can be traced from the West Shetland and east Faroe shelves into the adjacent deep-water basins (Figure 7). This unconformity formed by a combination of large-scale tilting of shelf areas and bottom-current-induced submarine erosion in the deeper-water basins. Evidence for tilting is observed on the West Shetland margin, where the eroded surface of the Muckle Ossa Sandstone has been rotated westwards towards the Faroe-Shetland Basin (Stoker, 2002), as well as the north Faroe margin, where the Miocene shelf-margin deposits dip towards the Norwegian Basin (Nielsen and van Weering, 1998). At about the same time, an Early Pliocene reorganisation of deep-water currents reflects both the global evolution of oceanographic circulation at this time (cf. Stoker et al., 2005a, and references therein) and modifications (due to the large-scale tilting) to local bathymetric thresholds; the latter resulted in locally intensified current flow and hence submarine erosion within the Faroe–Shetland region. The sedimentary response to these changes in the Faroe–Shetland region can be illustrated by the following:

- Along the margins of the Faroe-Shetland and Faroe Bank Channel basins, the INU surface is downlapped by prograding clinoforms of major clastic sediment wedges, such as the Rona, Foula, East Faroe and West Faroe wedges (Stoker, 1995; Nielsen et al., 2007; Stoker and Varming, 2011). These discrete depocentres, which locally exceed 500 m thick, were instigated in the Late Pliocene in response to the uplift of the Orkney-Shetland and Faroe platforms, and are associated with advances of the shelfbreak in excess of 50 km, around these platforms, by the Mid-Pleistocene. During Mid- to Late Pleistocene glaciation, recurrent shelf-wide glaciation resulted in major erosion of the shelves, and delivered glacially-derived material directly to the shelf-margin wedges (Stoker and Varming, 2011).
- Within the Faroe-Shetland and Faroe Bank Channel basins, the INU is overlain by fine-grained deep-water contourite sediments, deposited in association with the bottom-current system derived from the Norwegian Basin, but also including a strong return flow (to the NE) along the West Shetland margin (Stoker, 2002; Stoker and Varming, 2011). Basinal thicknesses are generally less than 200 m thick, though in areas of enhanced deposition, e.g. West Shetland Drift, the sediments are up to 400 m thick. The INU is locally enhanced and/or deformed by reactivation of several anticlines.
- On the north Faroe margin, contourite deposits accumulated on the upper to mid continental slope (above 2000 m water depth), whereas the lower slope has underwent significant mass failure (Nielsen and van Weering, 1998; Stoker and Varming, 2011).

General observations from the wider region include:

- In the NE Rockall Basin–Hebrides Shelf region, the overlapping relationship between the prograding Sula Sgeir Fan and sediment drift deposits in the NE Rockall Basin confirms the general synchroneity of these sedimentary patterns off NW Britain (Stoker, 2013).
- East of Shetland, the Upper Pliocene–Middle Pleistocene sediments, including the Pleistocene Shackleton Formation, represent a predominantly sandy, prograding shelf that becomes increasingly muddy as water depths increased within the North Sea Basin (Johnson et al., 1993).
- The North Sea Fan built out for hundreds of kilometres from the Norwegian North Sea margin into the Norwegian Basin, and accumulated up to 1 km of Late Pliocene–Mid-Pleistocene sediment (as well as a further 800 m during Mid- to Late Pleistocene glaciation). The shelfbreak offshore Mid-Norway advanced by up to 100 km. The pre-glacial growth of this wedge is attributed to erosion due to uplift of the Fennoscandian High (Martinsen et al., 1999; Rise et al., 2005).

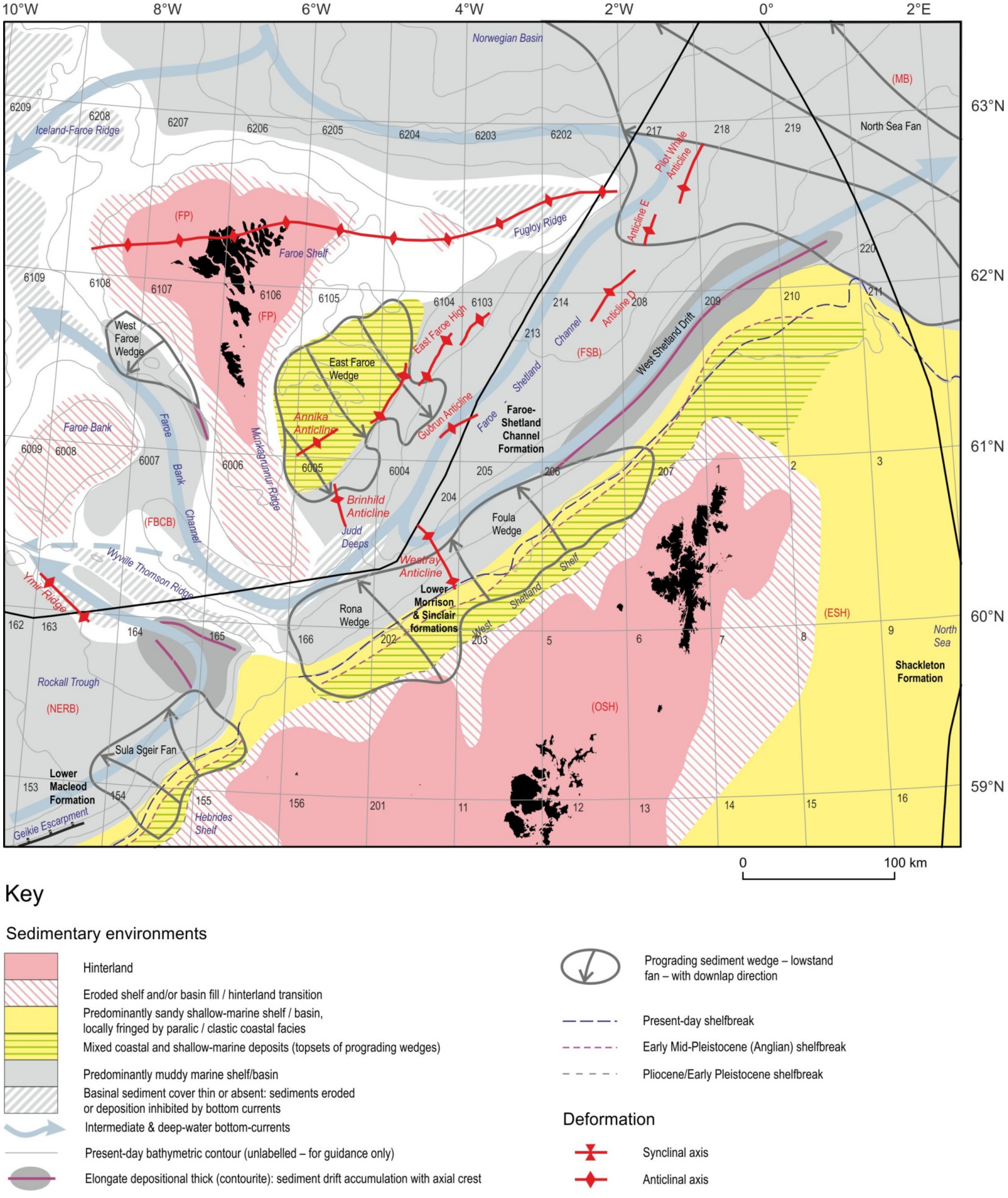

Figure 32 Gross palaeoenvironment map for the late Early Pliocene–early Mid-Pleistocene. See Table 1 for key to structural labels (red font) used on this map; see Table 2 for main sources of data consulted during the compilation of the map. Bathymetric features labelled in blue font. Present-day bathymetric contours intended as a guide (only) to the developing shape of the continental margin.

5 Dynamic Evolution

On the basis of the palaeoenvironment maps presented in chapter 4, the late Mesozoic–Cenozoic evolution of the Faroe–Shetland region – as we currently understand it – is summarised in a tectonostratigraphic chart (Figure 33). This chart displays the general stratigraphic framework, including the key unconformity surfaces, which bound the depositional packages. The chart also depicts the gross sedimentary architecture and key tectonic characteristics of the Faroe–Shetland succession, and places all of these elements within the wider context of European and North Atlantic plate tectonics. In the following sections we (1) summarise the key phases of the late Mesozoic–Cenozoic development of the Faroe–Shetland region, and (2) consider some wider implications of the preserved record.

5.1 TECTONOSTRATIGRAPHIC SUMMARY

The Faroe–Shetland region preserves a punctuated record of late Mesozoic–Cenozoic sedimentation that can be directly related to the latter stages of the breakup of Pangaea, the earliest Eocene onset of ocean spreading, and its subsequent development as a divergent margin. Key phases in this development are as follows:

- The base of the Upper Jurassic Humber Group represents a marine transgression across, for the most part, a hinterland comprising Triassic and older strata (Ritchie and Varming, 2011). Localised rifting, especially associated with the West Shetland Basin and SE Marginal Basins, might have controlled the deposition of subaerial to shallow-marine fan deltas in response to footwall uplift (Verstralen et al., 1995); however, Upper Jurassic sediment accumulation rates (8.5 m Ma^{-1}) are low, and there is very little evidence of widespread rifting in the Faroe–Shetland region at this time (Doré et al., 1999). The extent of rifting in the Faroe-Shetland Basin remains ambiguous.
- In the earliest Cretaceous, a phase of intra-Berriasian uplift and erosion is marked by the formation of the base Cromer Knoll Group unconformity. This was followed by the renewal of rifting in the West Shetland Basin and the SE Marginal Basins during the late Berriasian–Hauterivian/Barremian interval, accompanied by paralic to shallow-marine deposition, though the low sediment accumulation rate (7 m Ma^{-1}) and common intra-basinal unconformities (Figure 8) implies that this was localised and intermittent. The extent of rifting (if any) in the Faroe-Shetland Basin remains unknown at this time.
- In the late Early Cretaceous, the Aptian–Albian record includes evidence of rifting along the eastern and southern borders of the Faroe-Shetland Basin. In addition to the active West Shetland and SE Marginal basins, the instigation of the Faroe-Shetland Basin might be indicative of an increasingly interactive fault array and expanding system of basins (e.g. Larsen et al., 2010). An increase in the sediment accumulation rate (11 m Ma^{-1}) is consistent with this scenario. Paralic and shallow-marine sedimentation prevailed in the West Shetland Basin, whereas muddy marine deposition characterises the Faroe-Shetland Basin.
- 'Mid'-Cretaceous (late Albian/early Cenomanian) uplift resulted in exposure and erosion (Mid-Cretaceous unconformity) of much of the area flanking the eastern and southern margins of the Faroe-Shetland Basin, whereas the latter became increasingly the main focus of rifting and sedimentation in the Late Cretaceous. A concomitant increase in sediment accumulation rate (up to 58 m Ma^{-1} by the Campanian/Maastrichtian) across all of the Faroe–Shetland sub-basins – by almost an order of magnitude compared to the lower stages of the Early Cretaceous – is consistent with a major expansion of the rift system in the Late Cretaceous.

- The Late Cretaceous also witnessed compression across the Faroe–Shetland region. The Turonian 'near-base Upper Cretaceous' unconformity is associated with the development of synclines in the Foula and Flett sub-basins, as well as folding/inversion in the North Rona, West Solan and East Solan basins. A phase of intra-Campanian folding is also recorded (intra-Campanian unconformity) in the NE West Shetland Basin.
- Late Cretaceous deposition was dominated by marine mudstone of the Shetland Group in the Faroe-Shetland Basin, whereas the Chalk Group locally prevailed in the SW West Shetland Basin and SE Marginal Basins in the Cenomanian–Turonian stages before being replaced by marine mudstone in the Coniacian. By the Campanian, most of the basins – as well as the Rona High – were submerged, and accumulating marine mudstone; however, some intrabasinal highs, such as the Corona and Westray highs, might have been emergent.
- The base Palaeogene unconformity marks a phase of late Maastrichtian/early Paleocene uplift and erosion across much of the Faroe–Shetland region, as well as across the wider region, including the Hebrides–NE Rockall area, SE Greenland, and the western flank of the North Sea. In the Faroe–Shetland region, evidence of contractional deformation is preserved in the East Solan and West Solan basins, as well as the Flett High Anticline.
- Claystone-dominated Danian basins appear to form a fan-like zone of extension in the Faroe–Shetland region, which broadens towards the incipient oceanic margin in the north. An episode of basic sill intrusion near the end of the Danian marks the beginning of early Palaeogene magmatism.
- Major extrusive basaltic shield volcanism was initiated close to the Danian/Selandian boundary at the Brendan, East Erlend and Frænir volcanic centres. In the Faroese sector, much of the basal part of the basalt succession probably consists of prograding hyaloclastite facies (Lopra Formation), overlain by terrestrial lavas of the Beinisvørđ Formation. Basin-floor turbidite sandstones of the Vaila Formation, largely derived from the Scottish hinterland, were deposited across a wide area of the Faroe-Shetland Basin, which evolved as a structural syncline – incorporating the Flett and Foula synclines – flanked by sub-parallel inversions of former basins in the Flett Terrace, East Erlend and Ben Nevis Anticline areas.
- A resurgence of hinterland uplift and erosion during the late Selandian was accompanied by the progradation of the Lamba Formation shelf into the Faroe-Shetland Basin. Coeval subsidence in the Faroese sector allowed the Faroe Platform to remain close to sea-level as the Beinisvørð Formation basaltic shield increased in extent during the Thanetian.
- Uplift along the SE margins of both the Faroe-Shetland Basin and the Annika sub-Basin resulted in local erosion of the Lamba Formation shelf and Beinisvørð Formation shield at the end of the Thanetian. The lower Flett Formation shelf migrated basinwards, before the fluvial and lignitic sediments of the Prestfjall Formation onlapped the unconformity surface on the Faroe Platform.
- Paralic and fluvial sediments of the Moray Group onlapped the southern margins of the Faroe-Shetland Basin as extension became focused in an area of seaward-dipping reflectors at the incipient oceanic margin during the Ypresian. Eruption of the associated terrestrial basalts of the Malinstindur and Enni formations kept pace with the subsidence of the Faroe Platform and the lavas pass eastwards into prograding hyaloclastites in the Faroe-Shetland Basin. Away from the oceanic margin, the focus of basaltic shield volcanism shifted to the Regin Smiđur and Faroe Bank Channel Knoll volcanic centres in the Faroe Bank Channel area. The widespread tuffs and volcaniclastic sediments of the Balder Formation, which mark the onset of oceanic spreading along the Aegir Ridge, were onlapped by similar sediments at the base of the overlying Stronsay Group.

- The Wyville Thomson Ridge is deformed towards the end of the Ypresian and the axis of the Munkagrunnur Ridge begins to develop as an area of reduced subsidence between flanking basins. Related uplift along the southern flank of the Faroe-Shetland Basin displaces the early to mid-Lutetian shelf sequence northwards to rest on a folded (by Judd Anticline) and truncated Ypresian succession. Unconformable basalt lavas and intrusions were possibly emplaced at the new continental margin at the same time.
- Renewed uplift of the Scottish hinterland during the late Lutetian is indicated by a series of basin-floor fans that entered the Faroe-Shetland Basin through northerly-trending channels cut into the front of the former early to mid-Lutetian shelf. A short period of relative sea-level rise curtails basin-floor fan deposition before the end of the Lutetian.
- In the SE of the Faroe-Shetland Basin, a Bartonian shelf advanced over a slope-apron of base-of-slope fans, and rests with slight unconformity on late Lutetian basinal sediments. A similar shelf prograded eastwards from the Faroe Platform. Fine-grained successions of polygonally-faulted Upper Eocene basinal sediments, which thicken oceanward, were eroded during Late to post-Eocene uplift and deformation along the Fugloy Ridge.
- The Late Eocene–Mid-Miocene interval encompasses a period of major change in the shape and structure of the Faroe–Shetland region, which resulted in a topographic adjustment across the continental margin of up to 1 km between structural highs and adjacent basins—a response to contractional deformation and/or differential uplift and subsidence. The Faroe Conduit – a deep-water passageway that combines the Faroe-Shetland and Faroe Bank channels – was generated by these tectonic forces, which probably culminated in the late Early/early Mid-Miocene. The changing palaeobathymetry generated by this general instability (including numerous folds within the deep-water basin), together with fluctuations in relative sea level, both combined to create a series of shelf-to-deep-water unconformities, including the mid-Oligocene, top Palaeogene, and intra-Miocene unconformities.
- Mid-/Late Miocene–Early Pliocene deep-water deposition (contourite drifts) was controlled by intermediate- and deep-water oceanic currents, which were generated in the oceanic basins beyond the Faroe–Shetland region, but circulated within the continental margin *via* the Faroe Conduit. In the latest Miocene/Early Pliocene, the West Shetland Shelf was uplifted and eroded.
- The intra-Neogene (late Early Pliocene) unconformity (INU) marked the onset of the most recent large-scale change in the development of the Faroe–Shetland region. The INU was instigated by basin-margin uplift, and resulted in the growth of prograding sedimentary wedges on the West Shetland and Faroe margins.
- In the Mid- to Late Pleistocene, the West Shetland and Faroe shelves were extensively glaciated – with ice streams extending to the shelf-edge – on several occasions.

5.2 IMPLICATIONS FOR THE TECTONIC DEVELOPMENT OF THE FAROE–SHETLAND REGION

Any consideration of regional controls on the tectonostratigraphic development of the Faroe–Shetland region must also take account of the wider tectonic setting, notably the major deformation events at the most proximal plate boundaries, i.e. the Alpine collisional zone and the North Atlantic rift/ridge system. Figure 33 places the local tectonic phases that we recognise across the Faroe–Shetland region against published regional European and North Atlantic tectonic events. Inspection of the chart in Figure 33 might invite speculation concerning a broad correlation between the local (Faroe–Shetland) responses to regional tectonic events; however, it also provides constraints on established ideas concerning the evolution of the Faroe–Shetland region. In the following sections, we consider the following three main issues – in terms of controls and constraints – that are fundamental to understanding the development of this part of the NW European plate: 1) Jurassic–Cretaceous rifting; 2) Early Palaeogene plate breakup; and, 3) Post-breakup 'passive' margin development. It should be noted that aspects of these themes have been addressed more fully in the series of FSC reports that focused specifically on the Cretaceous, Paleocene and Eocene tectonostratigraphies (Stoker et al., 2010, 2012; Smith et al., 2013, 2014), and the history of Pre- and Post-Cenozoic Compression (Johnson et al., 2012). The summaries presented below are built upon these earlier FSC reports, albeit enhanced through the process of synthesis that underpins this study.

5.2.1 Jurassic–Cretaceous rifting

On the basis of a series of speculative palaeogeographic reconstructions (e.g. Ziegler, 1988; Cope et al., 1992; Coward et al., 2003; Pharoah et al., 2010) it has been commonly assumed that a through-going rift system has prevailed in the Faroe–Shetland region since the Permian, and that this formed part of a marine connection linking the Arctic/Norwegian/Greenland and central Atlantic domains since the Jurassic, and throughout the Cretaceous. This has led to several major contradictions in the literature concerning Late Jurassic–Early Cretaceous palaeogeography and tectonics, including: 1) palaeogeographic reconstructions that show a rift system hosting conflicting shelf (Roberts et al., 1999) and deep marine (Knott et al., 1993; Coward et al., 2003) settings for this interval, with the latter presented as a continuation from the Late Jurassic; and, 2) whether or not Late Jurassic–Early Cretaceous rifting was a single event or two separate events.

Arguably, the premise for much of this confusion has been driven by the import of a North Sea rift model into the Faroe–Shetland region; this is despite the fact that the proven Upper Jurassic to Lower Cretaceous rock record in this region is sparse and of limited extent (Ritchie and Varming, 2011; Stoker and Ziska, 2011; this study) (Figures 6 and 7). Our study has confirmed the presence of a major hiatus between the Upper Jurassic Humber Group and the Lower Cretaceous Cromer Knoll Group, which does not support the concept of a single rifting event. It may be no coincidence that this hiatus broadly coincides with a phase of hinterland (NW Scotland) uplift as proposed by Holford et al. (2010). Whereas there is no doubt that the deposition of both the Humber and Cromer Knoll groups was controlled – to some extent – by faulting, with a particular focus on the West Shetland Basin and other SE Marginal Basins (Figures 13 and 14), the restricted (proven) distribution of these rocks combined with generally low sediment accumulations rates (Figure 33) suggests that extensional tectonic activity was limited, both in magnitude and extent.

This observation has implications for developing our understanding of the Late Jurassic–Early Cretaceous tectonic setting of the proto-North Atlantic margin. According to Ziegler (1988) and Doré et al. (1999), tectonic activity on the future Atlantic margin switched from a system dominated by N–S Tethyan rift propagation during the Late Jurassic, driven by seafloor spreading in Tethys, to one dominated by NE–SW rifting as Atlantic spreading propagated northwards during the Cretaceous. The rotation of the regional extension vector from E–W to NW–SE led Doré et al. (1999) to propose a model of migrating, rather than repeating, rifts. In their model, some areas of the Atlantic margin – the existence of which is largely the result of later tectonics – are largely devoid of Late Jurassic extension (including the Faroe–Shetland region; cf. Doré et al., 1999, their Figure 6), whereas the Early Cretaceous instigation of an extension vector (NW–SE) that was maintained intermittently through to plate breakup resulted in a broad zone of stretching from the south-western Rockall Basin to the western Barents Sea. Upper Jurassic rocks are present in the Faroe–Shetland region (Figure 13); however, the environment of deposition, degree of syn-sedimentary extension, and connectivity to the Arctic–North Sea rift remain ambiguous (see section 4.1).

In terms of Cretaceous rifting, various authors have previously described multiple phases of Early Cretaceous rifting, spanning the Valanginian to Cenomanian stages (e.g. Booth et al., 1993; Turner and Scrutton, 1993; Dean et al., 1999; Doré et al., 1999; Goodchild et al., 1999;

Grant et al., 1999; Lamers and Carmichael, 1999; Roberts et al., 1999; Coward et al., 2003; Larsen et al., 2010). It has also been proposed that the Late Cretaceous interval was a thermal sag phase (cf. Roberts et al., 1999, and references therein), though many of the previously cited author's envisaged extension persisting throughout this interval. Moreover, phases of compression were also described as part of the evolution of the region (e.g. Booth et al., 1993). To some extent, the lack of a consensus in the timing of Early Cretaceous extension is a reflection of the restricted areas of study of individual groups, but the spread of ages does reveal something about the character of the tectonic activity in the Faroe–Shetland region, at this time. As stated by Dean et al. (1999), the locus of fault activity, and hence depocentres, varied with time, from which they concluded that 'uplift and subsidence within the Cretaceous period was thus highly variable and a single, discrete rift model (that implies a predictable subsidence history throughout the basin) is inappropriate'. Whilst our present study, together with the precursor FSC work of Stoker et al. (2010a), would agree with the sentiment expressed by Dean et al. (1999), the pattern of co-eval extension and compression is consistent with regional model of oblique-slip associated with transtension and/or transpression (Roberts et al., 1999). A process of progressive basin enlargement interspersed with compressional deformation is apparent from the Cretaceous rock record summarised in Figure 33, and the marked increase in sediment accumulation rates argues for a rift climax in the Late Cretaceous. The transition from intermittent and localised rifting (SE Marginal Basin region) during the late Berriasian–Hauterivian stages, through the instigation of the Faroe-Shetland Basin in the Aptian–Albian as fault connectivity increases, and towards maximum integration of all of the Faroe–Shetland basins in the Late Cretaceous is supportive of the model of basin development proposed by Larsen et al. (2010), albeit interspersed with phases of compression.

Given the location of the Faroe–Shetland region relative to the developing North Atlantic spreading centre as well as the Alpine collisional zone (Figure 33), it is not surprising that this area developed as a zone of oblique-slip motion. From inspection of Figure 33, it is interesting to consider the possibility that the increased connectivity between basins in the Faroe–Shetland region, during the Aptian–Albian, might have been a response to stresses generated by the onset of Alpine orogenesis and/or ridge-push forces derived from the opening of the Bay of Biscay and the area west of Iberia (Doré et al., 1999; Sibuet et al., 2004). It is also worth noting that the interval bracketed by the 'mid'-Cretaceous and near-base Upper Cretaceous unconformities coincides with a prolonged phase of hinterland (NW Scotland) uplift (Holford et al., 2010). Rift climax in the Campanian–Maastrichtian interval appears to be coincident with rifting in the Labrador Sea (Doré et al., 1999). The high sediment accumulation rate that accompanies the climax of the rifting provides another contradiction to established views of palaeogeography in the Late Cretaceous (Campanian–Maastrichtian), i.e. that land area at this time was minimal (e.g. Hanock and Rawson, 1992; Harker, 2002; Cope, 2006). If this was the case, it begs the question of the provenance of the thick siliciclastic infill.

As is evident from the Late Jurassic–Cretaceous palaeoenvironment maps (Figures 13–20) significant uncertainties in the reconstructions remain, in particular the degree of connectivity between basins in the Faroe–Shetland region and the adjacent areas, including the Arctic–North Sea rift. This is largely due to the lack of information from the Faroese sector. Thus, whether or not a pervasive pre-Cretaceous rift system transected the Faroe–Shetland–North Rockall–SE Greenland region remains ambiguous. On the conjugate SE Greenland margin, no Phanerozoic rocks older than Aptian/Barremian have – to date – been found in the Kangerlussuaq or Ammassalik basins (Bjerager et al., 2014). Moreover, a recent Late Jurassic plate reconstruction of the NE Atlantic region indicated that the Jurassic succession in the Jameson Land Basin of central East Greenland – which was positioned north of the Faroe-Shetland region – correlated with the Møre–North Sea Basin, as part of the Arctic–North Sea rift (Stoker et al., 2014b). A connection to the Faroe–Shetland region has not been established, at the present time.

5.2.2 Early Palaeogene plate breakup

The conflicting chronological results of biostratigraphic and radiometric age dating remain unresolved. In the current synthesis, the early Palaeogene timeslices have been constructed on the basis that the volcanic history of the region, and of the Faroe Islands Basalt Group in particular, is more prolonged than commonly supposed (cf. Ellis et al., 2002; Schofield and Jolley, 2013 and references therein). As a result, maps that show the presence of a major basaltic shield of Thanetian and Selandian age overlying continental crust in the vicinity of the Faroe Platform differ significantly from some published reconstructions of the palaeogeography and structure of this part of the developing Atlantic margin (cf**.** Goodwin et al., 2009; their Fig. 10).

As part of the revised tectonic interpretation, it is suggested that isostatic subsidence allowed the Beinisvørđ Formation volcanic shield in the Faroe Islands to remain close to sea level during the Selandian and thus act as one of the dominant controls on the morphology of the whole Faroe–Shetland Basin during the deposition of the potential hydrocarbon reservoirs of the turbidite-dominated Vaila Formation. The thickness and extent of the volcanic shield and its apron of volcaniclastics increased further during the Thantetian, while detritus derived largely from the adjoining Scottish hinterland fed the contemporaneous NW progradation of the Lamba Formation shelf. When the main locus of volcanism and continental extension shifted during the Ypresian, subsidence along the developing oceanic margin became the main control on subsequent Eocene sedimentation in the Moray and Stronsay groups. As in the Paleocene, the supply of non-volcanic detritus from the Scottish hinterland was supplemented by the local erosion of contemporaneous intra-basinal uplifts.

This tectonic interplay between uplift, phases of volcanism and episodes of enhanced clastic sedimentation is one of the fundamental observations that underpins the interpretation of the NE Atlantic as the site of a pulsing mantle plume (White and Lovell, 1997; Shaw-Champion et al., 2008). Unusual V-shaped structures, which are best imaged on regional gravity data along the Reykjanes Ridge, possibly indicate the continued influence of a pulsing plume in the NE Atlantic during the Neogene. According to some workers, these structures, which converge to the SW of Iceland, form when periodic variations in magma production at the site of the plume give rise to linear ridges of enhanced crustal thickness (Poore et al., 2009, 2011; Parnell-Turner et al., 2014). Others, however, have argued that V-shaped ridges originate in the spreading ocean as a type of propagating rift structure that is not necessarily linked to a plume (Hey et al., 2010; Benediktsdøttir et al., 2012). Their alternative proposal adds weight to previous attempts to question the plume model, some of which relate the development of excess magmatism in the NE Atlantic to shallow lithospheric structures and the distal effect of larger scale plate movements, including those associated with the Alpine and Pyrenean orogenies (Lundin and Doré, 2005, and references therein).

Structures revealed by multibeam survey in the Inner Hebrides link uplift and igneous activity in the Hebridean part of the North Atlantic Igneous Province with contemporaneous strike-slip deformation and rift propagation (Smith, 2012). Other tectonic evidence from the Faroe–Shetland region suggests that the relationship of extensional- and contractional-dominated magmatism varies throughout the structural evolution of the NE Atlantic margin, with episodes of sill intrusion and deep emplacement of magma (underplating) possibly alternating with periods of basaltic shield volcanism and dyke intrusion during plate breakup (Smith et al., 2013). Future development of an integrated alternative to the plume model that incorporates these observations should focus upon finding a common link between early Palaeogene tectonics at the continental margin and the processes of rift propagation and related deformation in the ocean basins after plate breakup.

5.2.3 Post-breakup 'passive' margin development

Following plate breakup, it has been previously assumed that the dominant process affecting vertical movement of the Faroe-Shetland Basin was post-rift thermal subsidence accompanied by a decrease in sediment flux (Turner and Scrutton, 1993; Jones et al., 2002). However, it has been demonstrated that about 80% of the total Cenozoic sediment volume was deposited in Eocene and later time (Stoker et al., 2010b) (Figure 33). Thus, in common with passive margin basins throughout the NE Atlantic region (e.g. Rockall, Norway and Vøring basins), the post-rift structural development and sediment flux of the Faroe–Shetland region has been considerably influenced by tectonic activity at various stages since breakup, including:

- In the Eocene, several phases of post-rift uplift and erosion of the Munkagrunnur Ridge (Ólavsdóttir et al., 2010, 2013) and the West Shetland–Orkney-Shetland High (Stoker and Varming, 2011; Stoker et al., 2012b, 2013; Smith et al., 2014) led to the progradation of sedimentary wedges and basin-floor fans into the Faroe-Shetland Basin, which were locally deformed by early growth on compressional domes, including the Judd and Westray anticlines and the Wyville Thomson Ridge (Ritchie et al., 2003, 2008; Davies et al., 2004; Smallwood, 2004; Johnson et al., 2005, 2012; Stoker et al., 2005c). This clastic input was primarily a response to episodic uplift and erosion of the eastern and southern flank of the Faroe-Shetland Basin and the Munkagrunnur Ridge, and expressed by the development of unconformities, i.e. T2b–T2d (Figure 33).
- Towards the end of the Eocene, and spanning the Oligocene to Mid-Miocene interval, the area was subjected to enhanced contractional deformation, which resulted in folding, inversion and/or uplift of the Wyville Thomson, Munkagrunnur and Fugloy ridges (Boldreel and Andersen, 1993; Johnson et al., 2005, 2012; Stoker et al., 2005a,b,c; Ritchie et al., 2011) as well as numerous intra-Faroe-Shetland Basin anticlines (Ritchie et al., 2008) (Figures 29 and 30), together with the general uplift of the Faroe and West Shetland platforms and/or subsidence of the Faroe-Shetland Basin (Andersen et al., 2000; Ritchie et al., 2011; Stoker and Varming, 2011; Stoker et al., 2013; Smith et al., 2014), which were, at least in part, coeval. The formation of unconformities, including T2a, ‘MOU’, TPU, and IMU (Figure 33), are a result of this phase of instability.
- In the Early Pliocene, the West Shetland Shelf was tilted to the northwest (basinwards) by <1°, which generated uplift of the shelf and hinterland, created accommodation space along the West Shetland margin, and initiated the deposition of large-scale Pliocene-Pleistocene prograding sediment wedges (Stoker 2002; Praeg et al. 2005; Stoker et al. 2005a,b). The INU is a widespread subaerial to submarine unconformity formed at this time.

Without a doubt, the Late Eocene to Mid-Miocene phase of tectonic activity had the strongest influence on the post-rift shaping of the Faroe–Shetland region, with the Fugloy, Munkagrunnur and Wyville Thomson ridges all forming major present-day bathymetric highs (Figure 7). The disposition of the Eocene succession, which is folded about the axes of these uplifted areas (Ritchie et al., 2011; Stoker and Varming, 2011; Johnson et al., 2012), indicates that prior to this re-structuring, the morphology of the outer continental margin might have been more subdued, in terms of relief; as there are few indications of significant sedimentary input from the Faroe region during the Eocene (Andersen et al., 2000; Smith et al., 2014) (Figures 25–27). Concomitant differential subsidence resulted in a deepening of about 1 km across the Faroe-Shetland region, which ultimately configured the present-day underfilled deep-water basins of the Faroe-Shetland and Faroe Bank channels (Stoker et al. 2005a, b). This created the Faroe Conduit, the deep-water passageway, which has enabled the transfer of intermediate-and deep-water masses across the south-eastern-end of the Greenland-Scotland Ridge since the early Neogene (Stoker et al., 2005c).

From a regional perspective, several potential mechanisms have been suggested to drive contractional deformation, including NE Atlantic ridge push (Boldreel and Andersen 1993), Alpine tectonism (Hibsch et al., 1995; Sissingh, 2001), and the body forces associated with the growth (from the Miocene onwards) of the Iceland Insular Margin (Doré et al., 2008). Several recent regional tectonic studies have highlighted a major, complex reorganisation of the North

Atlantic seafloor spreading system during the mid-Cenozoic, possibly instigated at C21/C18 (Mid-Eocene), and intensified between C13 to about C6 (i.e. Oligocene to Mid-Miocene), and the effect of this reorganisation on post-rift compressional deformation along the margin (Gaina et al., 2009; Gernigon et al., 2012). Significant components of this plate boundary reorganisation include the cessation of spreading in the Labrador Sea and along the Aegir Ridge in the Norway Basin; the shift from an orthogonal to an oblique spreading direction in the NE Atlantic at about C18 (Kimbell et al., 2005; Stoker et al., 2012a); the separation of the Jan Mayen Microcontinent from Greenland (Gaina et al., 2012); and the eventual linkage of the Reykjanes and Kolbeinsey ridges at about C6 resulting in a single spreading system linking the Arctic and Atlantic Oceans (Doré et al., 2008; Gernigon et al., 2012). Based on palinspastic reconstructions of the North Atlantic seafloor, Le Breton et al. (2012), suggested that left-lateral reactivation (i.e. opposite to the sense of movement suggested in section 4.15) of northwest trending transfer zones sub-parallel to the Faroe Fracture Zone probably initiated the compressional deformation of the Fugloy Ridge during the Eocene/Oligocene. This also coincides with the dominant timing of major strike-slip reactivation of the Great Glen Fault bisecting onshore Scotland (Le Breton et al., 2013) and exhumation of NW Scotland, including the Faroe–Shetland region (Holford et al., 2010; Tassone et al., 2014).

Many of the above events have been plotted on Figure 33. It should not be any surprise that there is a broad correlation between the timing of plate reorganisation events and the post-breakup structuration of the Faroe–Shetland region, bearing in mind the proximity of the Faroe–Shetland region to the oceanic Norwegian Basin, and its protracted history of Palaeogene breakup. For example, it may be no coincidence that the Mid-Eocene T2b and T2c unconformities correlate with two major phases of deformation linked to the separation of the nearby (a few hundred kilometres at this time) Jan Mayen Microcontinent from east Greenland (Stoker et al., 2013). With regard to the end-Eocene/Oligocene–Mid-Miocene restructuring, there are various orogenic and plate tectonic candidate mechanisms for the origin of the compressional deformation, and multiple causes are probable. According to Tassone et al. (2014), the spatial and temporal variations in the mid-Cenozoic differential movements in the Faroe–Shetland region represent the variable responses of a complexly structured continental margin to fluctuating intraplate stress magnitudes and orientations. These stresses might be primarily governed by the dynamics of the adjacent oceanic spreading system, though the contribution of orogenic stress associated with the culmination of the Pyrenean and Late Alpine collisions cannot be discounted.

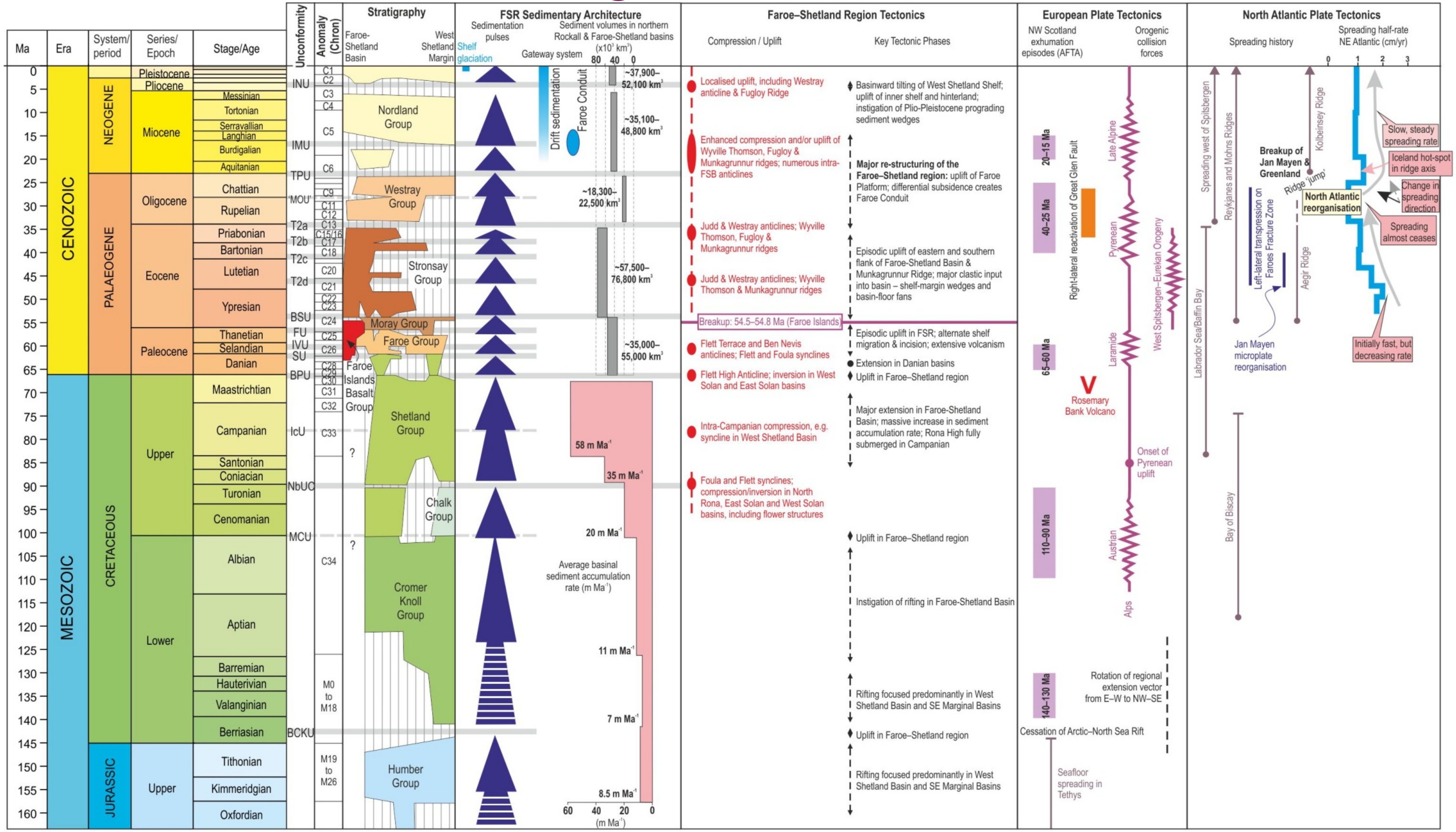

Figure 33 Late Mesozoic–Cenozoic Tectonostratigraphy for the Faroe–Shetland region (FSR). The compilation of the FSR Stratigraphy, Unconformities, Sedimentary Architecture and Tectonics is based on this study (see chapters 2–4 for details). Additional information is derived from the following sources: FSR Sedimentary Architecture — Sediment volumes and sediment accumulation rates – Stoker et al. (2010a, b). European Plate Tectonics: NW Scotland exhumation – Holford et al. (2010); Reactivation of Great Glen Fault – Le Breton et al. (2013); Orogenic forces – Doré et al. (1999, 2008), Sibuet et al. (2004), Ziegler (1988); Rosemary Bank volcano – Morton et al. (1995); Tethys, North Sea, extension vectors (Doré et al. (1999). NE Atlantic Plate Tectonics: Spreading history – Lundin and Doré (2005); Faroes Fracture Zone – Le Breton et al. (2012); Jan Mayen reorganisation – Gaina et al. (2009). Spreading half-rate – Mosar et al. (2002). See Figure 6 for explanation of abbreviations for unconformity surfaces. Timescale is based on Gradstein et al. (2012).

6 Conclusions

A set of twenty gross palaeoenvironment maps has been established for the upper Mesozoic–Cenozoic succession in the Faroe–Shetland region. In addition to stratigraphic and facies information, these maps also highlight contemporary deformation, particularly since plate breakup. On the basis of this synthesis, our key conclusions are as follows:

- Aspects of the stratigraphic framework require better resolution and understanding, in particular:
  - Facies interpretation of Upper Jurassic coarse clastic rocks—there are currently contrasting views on the Late Jurassic depositional model in the Faroe–Shetland region, with consequences for the prevailing tectonic setting.
  - Chronology of Paleocene–earliest Eocene breakup succession—following an independent review of biostratigraphic and radiometric evidence related to the age of the Faroe Islands Basalt Group, as published in the scientific press as well as a series of Sindri reports, it is concluded that the age range of this group might be greater than that claimed by Jolley and his co-workers. This has major implications with respect to the timing and process of plate breakup.
- The time series depicted by our maps reveals an Upper Jurassic–Pleistocene succession that is punctuated by numerous unconformities. The tectonic regime responsible for this stratigraphic architecture comprises episodes of extension and compression prior to, during and subsequent to plate breakup. Key stages in the development of the Faroe–Shetland region are as follows:
  - Late Cretaceous—main extension in Faroe-Shetland Basin.
  - Paleocene—major extrusive volcanism initiated close to Danian/Selandian boundary.
  - Earliest Eocene—plate breakup to the north and west of the Faroe Islands.
  - Late Eocene–Mid-Miocene—major compressive structuration across the Faroe–Shetland region and shaping of modern-day continental margin.
- The maps also highlight the fact that Late Jurassic/earliest Cretaceous, ‘mid’-Cretaceous, latest Cretaceous/earliest Paleocene, Late Paleocene and (various) Eocene uplifts are co-extensive and spatially linked to the southern and eastern margin of the Faroe-Shetland Basin. This observation provides some support for a common tectonic origin for these episodes of uplift, and indicates a process that has been active for at least 90 My prior to plate breakup. We would suggest that the patterns of sedimentation depicted on the palaeoenvironment maps were most probably controlled by changing patterns of tectonically-controlled uplift and subsidence. The correlation between key unconformities and changes in intraplate and/or plate boundary stresses raises the possibility that additional forces, including those postulated to be related specifically to the internal dynamics of a mantle plume, may not be required. Indeed, our observations suggest that there is nothing anomalous or unique about the uplift(s) in the Paleocene, implied by others to be a direct consequence of temperature variations within a radiating mantle plume. In our view, it is the volcanism that is anomalous, albeit a consequence of a long history of rifting and lithospheric thinning as part of Pangaean plate breakup, which culminated in passive upwelling of magma in the Faroe–Shetland region during the Paleocene/earliest Eocene, exploiting weak spots in the thinned and rifted lithosphere.
- The persistence of post-breakup deformation across the Faroe–Shetland region – most likely linked to the dynamics of the adjacent oceanic spreading system – throughout the

Eocene–Mid-Miocene interval is a reflection of the protracted process of North Atlantic plate reorganisation, which was not fully completed until the Reykjanes and Kolbeinsey ridges conjoined in the area of SE Greenland and offshore Kangerlussuaq, and Iceland and its associated upper mantle anomaly came into being.

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