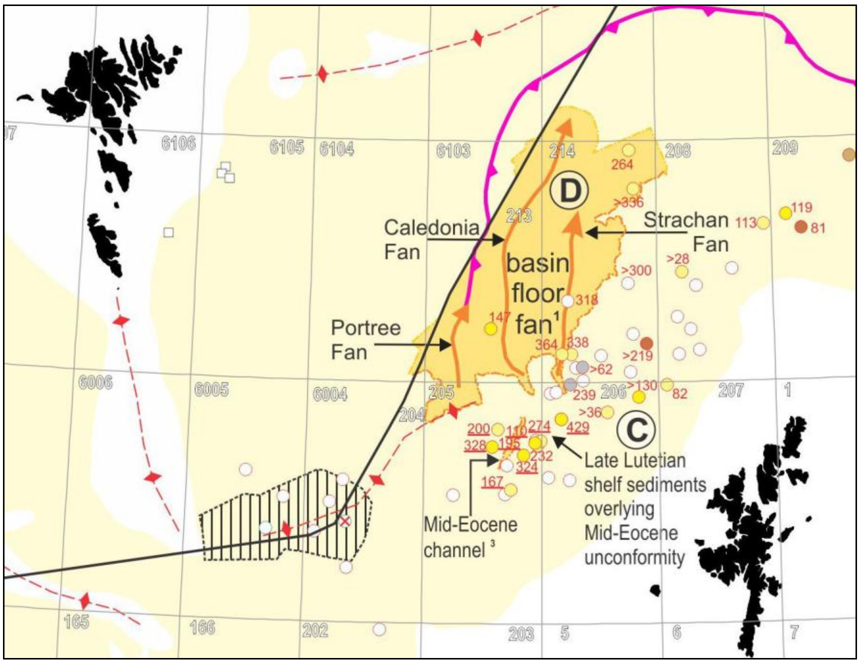
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

JARÐFEINGI

Eocene (Stronsay Group) post-rift stratigraphy of the Faroe–Shetland region

Marine Geoscience Programme

Commissioned Research Report CR/12/009



BRITISH GEOLOGICAL SURVEY

MARINE GEOSCIENCE PROGRAMME

COMMISSIONED RESEARCH REPORT CR/12/009

Eocene (Stronsay Group) post-rift stratigraphy of the Faroe–Shetland region

M Stoker[1], K Smith[1], T Varming[2,3], H Johnson[1] and J Ólavsdóttir[2]

[1] *British Geological Survey, Edinburgh, UK*

[2] *Jarðfeingi, Faroe Islands*

[3] *Bureau of Minerals and Petroleum, Nuuk, Greenland*

Keywords

Faroe–Shetland region; Eocene; Stronsay Group.

Front cover

Part of T96 (Late Lutetian) timeslice map: see Figure 23 for details.

Bibliographical reference

STOKER, M S, SMITH, K, VARMING, T, JOHNSON, H and ÓLAVSDÓTTIR, J. 2012. Eocene (Stronsay Group) post-rift stratigraphy of the Faroe–Shetland region. *British Geological Survey Commissioned Research Report,* CR/12/009.

Copyright in materials derived from the British Geological Survey's work is owned by the Natural Environment Research Council (NERC) and/or the authority that commissioned the work. You may not copy or adapt this publication without first obtaining permission. Contact the BGS Intellectual Property Rights Section, British Geological Survey, Keyworth, e-mail ipr@bgs.ac.uk. You may quote extracts of a reasonable length without prior permission, provided a full acknowledgement is given of the source of the extract.

Maps and diagrams in this book use topography based on Ordnance Survey mapping.

© NERC 2011. All rights reserved

Edinburgh British Geological Survey 2012

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276

email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

This report is the result of a study by the British Geological Survey (BGS) and Jarðfeingi into the Eocene post-rift stratigraphic development of the Faroe–Shetland region. The report presents a stratigraphical analysis of the Eocene Stronsay Group based primarily on a set of released UK commercial wells that have been subjected to a detailed biostratigraphic analysis by Ichron Limited, and made available – in confidence – to the BGS for the purpose of this study. These data have been combined with information from released wells in the Faroese sector, relevant BGS boreholes and other published information for which biostratigraphic information exists, to construct a stratigraphic-range chart for the Eocene succession. This chart forms the basis for a set of timeslice reconstructions based on the rock record. In addition, key seismic sections linked to the stratigraphic-range chart provide a correlation tool for the identification of potential regionally significant intra-Eocene boundaries, thereby forming the basis for a provisional stratigraphic framework for the Stronsay Group. The timing of change recorded by both the rock record and the seismic data is investigated with regard to the tectonic setting of the Faroe–Shetland region in an attempt to better understand the driving mechanisms and controls on the early post-rift development of the Faroe–Shetland region.

Acknowledgements

This report was commissioned by the BGS/Jarðfeingi/Industry Faroe-Shetland Consortium, which consists of the following oil companies: Chevron, ConocoPhillips, Dana, DONG, E.ON UK E&P Ltd, ENI, Faroe Petroleum, Nexen, Shell, Statoil and Total. The funding support and interest of all these companies is gratefully acknowledged.

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

M S Stoker	Summary, chapters 1–6, Appendix 1, and task management
K Smith	General contribution to chapters 1–3; major contribution to chapters 4 and 5, and Appendix 1
T Varming	General contribution to understanding of Eocene of Faroese sector, and provision of Faroese well data
H Johnson	General contribution to understanding and development of Eocene seismic stratigraphy, and project management
J Ólavsdóttir	General contribution to understanding of Eocene of Faroese sector

In compiling this report, the authors readily acknowledge the assistance of several BGS colleagues, including Sandy Henderson for assistance with the database, and Derek Ritchie for his review of this report. The authors are especially grateful to Andrew Alderson of Ichron Limited for supplying two non-proprietary Ichron biostratigraphy reports for this project, as well as discussions concerning the rationale behind the stratigraphic assignment of biozones within the wells. CDA are acknowledged for allowing us access to further released well data for the purpose of this report.

Contents

FIGURES

TABLES

APPENDIX FIGURE (Back pocket)

Summary

A preliminary stratigraphic framework for the post-rift Eocene Stronsay Group succession in the Faroe–Shetland region has been constructed, which incorporates lithological information from over fifty wells, boreholes and dredge sites, biostratigraphic data provided by Ichron Limited, and seismic stratigraphy. A stratigraphic-range chart was compiled using released UK and Faroese commercial well data, together with BGS and other public domain information. This chart details the chronological range, general lithology and correlation of the post-rift Eocene record for each commercial well, BGS borehole and other data point, e.g. DSDP site. This dataset was used to construct a set of timeslice maps utilising the Ichron Limited T-sequence biozonation scheme, which were used to interpret the spatial and temporal variation of Eocene post-rift sedimentation across the region. Seismic profiles further provided an insight into the large-scale stratigraphic architecture of the Stronsay Group which, in combination with the geological database, provides a context for several regional unconformities and other significant surfaces identified in the study.

On the basis of our provisional assessment of the Stronsay Group in the Faroe–Shetland region we have retained the use of the Horda Formation as the main lithostratigraphic unit, as this shelf-margin to basinal unit – defined originally in the North Sea – is consistent with the character of the Eocene succession that we observe preserved offshore NW Britain. Nonetheless, informal subdivision of the Horda Formation is proposed that reflects several discrete phases of sedimentary input into the Faroe-Shetland Basin. Four unconformity-bounded depositional packages have been tentatively identified, and provisionally assigned ages of Ypresian–early Lutetian (phase 1), Lutetian–early Bartonian (phase 2), Bartonian–Priabonian (phase 3), and late Priabonian (phase 4). The phase 1 and 2 depositional packages are separated by the Mid-Eocene (T2d) unconformity which reflects subaerial exposure and channel incision up to 200 m deep during its formation in the Lutetian. The early Bartonian Base-slope-apron (T2c) unconformity separates the phase 2 and 3 depositional packages, and is similarly erosive along the southern and eastern basin margin. Seismic-stratigraphic evidence suggests that synsedimentary deformation may have been active during depositional phases 1 and 2, including growth and uplift of the Munkagrunnur Ridge, and the Judd and Westray anticlines, as well as uplift of the Flett High. The phase 3 depositional package marks a large-scale progradation of the West Shetland margin, which may reflect uplift and rejuvenation of the hinterland. The phase 3 and 4 depositional packages are separated by the Base-marginal-fan (T2b) reflector, which may be a consequence of renewed uplift of the margin and/or further growth of the inversion anticlines during the Priabonian.

This stratigraphic framework provides new insights into the early post-rift tectonic and sedimentary history of the Faroe–Shetland region, identifying a sequence of unconformity-bounded units. Comparison with the wider NE Atlantic region indicates broad coincidence between the timing of formation of the unconformities in the Faroe–Shetland region and plate reorganisation events in the adjacent Norway Basin; as well as orogenic and related compressional deformation in western Europe. This raises the possibility that plate boundary forcing may be a key mechanism in passive margin development. It is hoped that this framework will form a useful foundation for future studies of the tectonostratigraphic development of the Faroe–Shetland region.

1 Introduction

The term Stronsay Group was introduced by Knox and Holloway (1992) for the Eocene sediments of the UK central and northern North Sea that overlie the Balder and Dornoch formations. As these sediments are in direct continuity with deposits of equivalent age on the NW UK margin (Figure 1), the geographical range of the Stronsay Group was expanded by Knox et al. (1997) to include the area to the west of Shetland.

Whereas the Stronsay Group in the central and northern North Sea has been divided on the basis of lithostratigraphic, biostratigraphic and sequence-stratigraphic techniques (Knox and Holloway, 1992; Galloway et al., 1993; Bujak and Mudge, 1994; Jones and Milton, 1994; Mudge and Bujak, 1994, 1996; Jones et al., 2003), it has remained undivided in the Faroe–Shetland region (Knox et al., 1997) (Figure 2), where the main industry focus has been the deep-water Paleocene sandstone play. Although a Mid-Eocene basin-floor fan play has been recognised in the Faroe-Shetland Basin (Davies et al., 2004; Quinn et al., 2011), it has, to date, been largely associated with generally poor hydrocarbon indications.

Academic interest in the Faroe–Shetland region has also been largely focused on its Paleocene–earliest Eocene (pre-Stronsay Group) development, with a number of workers (e.g. White and Lovell, 1997; Jones et al., 2002; Maclennan and Lovell, 2002; Smallwood and Gill, 2002; Mudge and Jones, 2004; Shaw Champion et al., 2008; Hartley et al., 2011) linking an early Palaeogene increase in clastic sedimentation to Iceland plume-related uplift of the British Isles. These studies have tended to emphasise the role of the syn-breakup Iceland plume as the primary tectonic influence on sedimentation patterns during the Palaeogene. Indeed, Jones et al. (2002) have stated that the sediment flux into the northern North Sea and Faroe-Shetland Basin grew through Paleocene time and then decreased into Eocene time. By way of contrast, a recent calculation of sediment volumes along the NW British continental margin, including the Faroe–Shetland region, indicates that ~80% of the total Cenozoic sediment volume was deposited in several pulses during Eocene and later time (Stoker et al., 2010b). This indicates that sedimentation has not declined in any systematic manner since breakup. A stepwise pattern of sedimentation for the Eocene in the central and northern North Sea has been understood for a number of years (e.g. Galloway et al, 1993; Jones and Milton, 1994; Mudge and Bujak, 2004), and this pattern is becoming increasingly apparent for the NE Atlantic margin tied to plate boundary reconfiguration events in the NE Atlantic (Robinson et al., 2004; Praeg et al., 2005; Holford et al., 2009; Stoker et al., 2012).

In order to address the above issues, the Faroe-Shetland consortium of oil companies commissioned this regional study of the Stronsay Group in the Faroe–Shetland region with a view to providing a basis for the establishment of a stratigraphic framework, as well as shedding new light on the early post-rift geological development of this area.

1.1 SCOPE AND OBJECTIVES

The project was designed in order to better define the stratigraphic architecture of the Eocene post-rift Stronsay Group in the Faroe–Shetland region. The area of study extends northwestwards from the West Shetland Shelf to the Iceland-Faroe Ridge, with a south-western boundary essentially marked by the Wyville-Thomson/Ymir Ridge and a north-eastern boundary marked by the UK/Norwegian median line (Figure 1).

The major objective of this study is to develop a preliminary Eocene tectonostratigraphic framework for the Faroe–Shetland region. To achieve this objective, we have mainly used the borehole/well database supplemented by selected seismic profiles. Our stratigraphic framework has built upon the UKOOA lithostratigraphy previously developed for the NW UK margin

(Knox et al., 1997) as well as the adjacent northern North Sea (Knox and Holloway, 1992) (Figure 2a). We have also taken into account the main sequence-stratigraphic schemes developed for the Eocene in the central and northern North Sea (Figure 2b); in particular, the use of the T-sequence scheme of Jones and Milton (1994), which is a basis for biostratigraphical analysis of Faroe-Shetland wells (Figure 3). In addition, there are a number of seismic-stratigraphic schemes (Figure 4) that we have considered during our stratigraphical analysis. As part of the general data gathering process, all stratigraphical information associated with this study will be incorporated into the ArcGIS database that is being created on behalf of the Faroe-Shetland Consortium.

1.2 DATA SOURCES

There are five main sources of information:

1. Published scientific literature, as well as unpublished Ph.D theses.
2. BGS borehole database.
3. Released commercial well-logs.
4. Two non-proprietary Ichron Limited biostratigraphy reports. These reports were supplied by Ichron Limited (2010a, b) in confidence to the BGS as part of this project. They present the results of a biostratigraphic (palynological and micropalaeontological) review of the Paleocene to Eocene interval in 50 exploration and appraisal wells from across the Faroe-Shetland Basin, with the exception of Quadrant 204.
5. Released seismic reflection data contributed by the Faroe-Shetland Consortium members.

1.3 METHODOLOGY

Well-log and core information taken from 54 released commercial wells, two BGS boreholes, one DSDP site and two main areas of sea bed dredge sampling form the main rock-record component of this regional study – a total of 59 key stratigraphic sites (Figure 1 and Table 1). It should be noted that 145 wells in total were investigated; however, the 54 wells used in this study were chosen on the basis of the quality of their biostratigraphic information, of which 45 were included within the Ichron reports. Thus, most of the wells in this study are keyed into the Ichron T-sequence scheme, which is based on the original BP T-sequence framework published by Jones and Milton (1994) (Figure 3). Correlation between the two schemes is detailed in Figure 3. Biostratigraphic data for the remaining nine wells was obtained from CDA (in the UK sector) and from Jardfeingi (in the Faroese sector) (Table 1).

Most of the wells (49) are in the UK sector and show a wide spread of data points along the West Shetland margin. The Faroese wells are located at the south-west end of the Faroe-Shetland Basin, together with the BGS boreholes (Figure 1). The two dredge-site locations are situated as follows: 1) on the east Faroe Shelf; and, 2) on the southern flank of the Ymir Ridge. DSDP site 336 is located on the northern slope of the Iceland-Faroe Ridge. The stratigraphic range of the Eocene sequence at each sample site has been captured on a stratigraphic-range chart (Appendix1; Figure A.1). In addition to the age range, the chart also includes lithology (for the wells this is largely derived from the composite logs), thickness, additional stratigraphical notes where necessary, and a provisional lithostratigraphic subdivision of the Stronsay Group that we are proposing from this study. Inspection of Figure A.1 shows that lithological information for 7 wells (205/10-2, 208/19-1, 214/17-1, 214/19-1, 214/24-1, 214/27a-3, and 214/27a-4) was not available, but the biostratigraphic zonal information was utilised.

This dataset formed by the stratigraphic-range chart underpins the study as it enables a series of timeslice maps, linked to the Ichron T-sequences, to be constructed for the Faroe–Shetland region. Fifteen maps have been produced; these comprise the syn-rift T45 and earliest post-rift T50 intervals (part of the preceding Moray Group), which provide context for the Stronsay

Group, together with the post-rift T60 to T99 intervals. The value of these maps is that they provide an immediate visual appreciation of the spatial and temporal variation in early post-rift sedimentation across the region, based on the actual rock record. The lithological key to the sample sites indicated on the maps is calibrated with the stratigraphic-range chart. Although sandstones and claystones, specifically, are indicated on the logs, many of the recovered sections are reported as interbedded sequences of coarser- and finer-grained clastic deposits. This interbedded lithological character is represented by a gradational colour scheme on the stratigraphic-range chart; however, this subtle colour variation can be difficult to distinguish on the A4-sized hard-copy diagrams. Thus, for best resolution and clarity of the maps the reader is directed to the PDF version of this report, which is included on the CD-ROM attached to the inside cover of the report binder.

A preliminary evaluation of the seismic reflection database has also been undertaken to provide a basis for an appraisal of the Eocene seismic architecture across the continental margin. This work was undertaken alongside, and complemented, the Faroe-Shetland Consortium Project 'Cenozoic pre- and post-breakup compression in the Faroe–Shetland area within the context of the NE Atlantic margin' (Johnson et al., 2012), which is based primarily on regional seismic interpretation. By combining the two methodologies, the stratigraphic and seismic-reflection databases have enabled us to identify a number of provisional key reflectors that might form the basis for the definition of regionally mappable units. This preliminary framework is described and summarised in section 3.

1.4 TIMESCALE AND THE BASE OF THE EOCENE

The timescale used in this study is based on Gradstein et al. (2004) and Ogg et al. (2008) (Figure 3). The base of the Eocene (55.8 Ma) is now defined globally by the onset of the carbon isotope excursion marking the start of the early Eocene thermal maximum (Gradstein et al, 2004; Westerhold et al., 2009 and references therein). In the Faroe-Shetland Basin, this boundary probably occurs within the T40 lowstand sequence (Lower Flett Formation) of the Moray Group. Knox et al. (1997) provisionally correlated the boundary with the top of Flett unit 1B and to the top of the Colsay Sandstone Member (which marks the T40/45 boundary) based on the first downhole occurrence (FDO) of abundant *Apectodinium* spp. (*Apectodinium* spp. acme dinocyst biomarker). This follows a similar assignment by Knox and Holloway (1992) in the North Sea where, on the basis of the same criteria, the Paleocene/Eocene boundary was tentatively placed at the top of the S1b unit of the equivalent Sele Formation. In the Faroe–Shetland region, this would place the Paleocene/Eocene boundary at the T40/T45 sequence boundary. According to Ebdon et al. (1995), however, *A. augustum* is restricted to sequence T40; thus the T40/T45 boundary is arguably associated with the extinction of this dinocyst, which according to the timescale of Gradstein et al. (2004) postdates the Paleocene/Eocene boundary by about one million years (i.e. at 54.8 Ma). Thus defined, the base of the Eocene is probably slightly older than the top F1B and S1b positions provisionally proposed by Knox et al. (1997) and Knox and Holloway (1992) for the Faroe-Shetland Basin and North Sea Basin, respectively (Passey and Jolley, 2009; Passey and Hitchen, 2011). More recently, the Paleocene/Eocene boundary has been placed lower within the Flett Formation, at about the F1A/F1B contact, within the Colsay Sandstone Member (Jolley and Bell, 2002; Jolley et al., 2005).

2 Regional setting

2.1 THE NORTH-EAST ATLANTIC MARGIN

The Faroe–Shetland region forms part of the Atlantic continental margin of NW Europe, which encompasses Norway, Britain, the Faroe Islands and Ireland. The development and shaping of this passive margin is inextricably linked to the evolution and breakup of the NE Atlantic rift system; its complex bathymetry ultimately being a reflection of the crustal thickness variations due to rifting and magmatism that culminated in the separation of Europe and Greenland in the early Eocene (e.g. Skogseid et al., 2000). The final localisation of extension along the continent–ocean boundary took place during an overall northward propagation of seafloor spreading, in the Late Cretaceous along the Labrador Sea axis and in the early Cenozoic along the Greenland–Norwegian Sea axis (e.g. Ziegler, 1988; Doré et al., 1999) (Figure 5a). However, the width of the margin (up to 800 km west of Ireland, 500 km west of Norway) reflects an overall westward displacement of a 'proto-North Atlantic' rift axis through the Mesozoic (Doré et al., 1999), which left a chain of large, Mid-Jurassic to Cretaceous deep-water sedimentary basins, including the Faroe-Shetland Basin, flanked by structural highs and by the inner continental shelf. The Vøring, Møre and Faroe-Shetland basins, in water depths over 1000 m, and the underfilled Rockall and Porcupine basins with water depths >2000 m continued to accumulate sediment throughout the Cenozoic, but contain no tectonostratigraphic evidence of post-Paleocene extension (e.g. Roberts *et al*. 1999).

Additional complexity in margin physiography has resulted from Cenozoic magmatism, which is responsible for the thickened crust of the Greenland-Scotland Ridge (GSR) that flanks the Iceland hot-spot (since the Miocene) and for numerous igneous centres or 'seamounts' (Doré *et al*. 1999) (Figure 5). The development of the GSR is commonly ascribed to the thermal effects from a proto-Iceland plume, the 'arrival' of which is seen by some workers as the decisive factor in causing breakup due to lithospheric weakening (e.g. White, 1988, 1989; Smallwood and White, 2002). This 'plume' is also considered to have influenced high-frequency changes in relative sea level and pulses of sedimentation immediately prior to breakup, with a particular focus on the Faroe–Shetland region (e.g. White and Lovell, 1997; Smallwood and Gill, 2002; Shaw Champion et al., 2008; Lovell, 2010; Hartley et al., 2011). However, the opening of the NE Atlantic Ocean as we see it today, including the development of Iceland and its insular margin, was not a single event in the early Eocene; instead, it represents the final linkage between separate Arctic and North Atlantic rifts, which only occurred in the Miocene when Jan Mayen separated from Greenland, and since when the GSR has developed symmetrically about Iceland (Mosar et al., 2002a; Lundin and Doré, 2005a; Lundin and Sigmond, 2007; Doré et al., 2008). This has led to the alternate view that the Iceland anomaly developed at the plate boundary during breakup and has remained there – fixed – throughout its history (Lundin and Doré, 2005b). The southward- and northward-propagating ridges overlapped in the region of Iceland; thus, conceivably, the Iceland mantle upwelling anomaly is related to the convergence of these ridge tips (Lundin and Doré, 2005a). Therefore, the possibility that the hot spot anomaly is an upper mantle response to plate breakup (i.e. a top-down effect of plate tectonics), of which the volcanism is a by-product of this extension, cannot be discounted (Doré et al., 1999; Foulger and Anderson, 2005). It also raises questions about the mechanism(s) responsible for pre-breakup uplift in the Faroe–Shetland region.

The post-rift development of the NE Atlantic margins is generally classed as passive (tectonically inert). However, the configuration of the NW European margin has been significantly modified by late Palaeogene and Neogene epeirogenic and compressive movements (e.g. Doré *et al*., 1999, 2002; Praeg et al., 2005; Stoker et al., 2005a, b), indicating an evolution that has been anything but passive. Epeirogenic movements have resulted in a series of broad domes along the NW European margin, recording km-scale uplift (Rohrman and van der Beek, 1996; Japsen & Chalmers, 2000), as well as in offshore episodes of rapid differential deepening, also of km-scale (e.g. Cloetingh et al., 1990; Vanneste et al., 1995; Stoker et al., 2005a, b). The domal uplifts include southern Norway and Britain–Ireland (Rohrman and van der Beek, 1996), each of which provides evidence of two main uplift phases, in the early and late Cenozoic (see Doré *et al*., 2002; Holford et al., 2010). The origin of these enigmatic movements remain unclear, and both mantle convective (see Stoker et al., 2005b and Praeg et al., 2005 and references therein) and lithospheric fold (see Japsen et al., 2011 and references therein) processes have been proposed. In the adjacent North Sea Basin, early post-breakup uplift in the northern Scottish–Shetland region is envisaged to have influenced clastic progradational shelf-margin and deep-water fan sedimentation throughout the late Palaeogene (Jones and Milton, 1994; Mudge and Bujak, 1994), though tectonic mechanisms remain unresolved.

Over a comparable period, compressional movements have resulted in the formation of inversion anticlines on parts of the margin, including the Rockall Plateau, Wyville-Thomson Ridge, Faroe-Shetland region and the Norwegian margin (Boldreel and Andersen, 1998; Lundin & Doré, 2002; Johnson et al., 2005; Tuitt et al., 2010). These structures range from 2–4 km in amplitude and are tens of kilometres across, with the axes of some individual structures traced for hundreds of kilometres. The contractional phases are interpreted to record variations in compressive stresses within the European plate, which have been attributed to various causes, such as plate tectonic processes originating from the Pyrenean and Alpine orogenies (Vågnes et al., 1998; Brekke, 2000), changes in seafloor spreading geometries and rates (Boldreel and Andersen, 1993; Mosar et al., 2002b), and ridge-push and mantle drag forces (Doré and Lundin, 1996; Doré et al., 1999; Roberts et al., 1999; Lundin and Doré, 2002). Alternative explanations attribute the formation of the anticlinal structures along the Norwegian margin solely to differential loading by Plio-Pleistocene sediment wedges (e.g. Kjelstad et al., 2003). The ambiguity concerning the causes of compressional tectonism is in part related to uncertainty over the number and age of compressive phases recorded by the anticlinal structures. A compilation of age estimates from a number of studies along the NW European margin implies a record of contractional deformation that was almost continuous from the late Paleocene to the Pleistocene (Boldreel and Andersen, 1998; Vågnes et al., 1998; Lundin and Doré, 2002; Ritchie et al., 2003, 2008, 2011; Johnson et al., 2005; Stoker et al., 2005c, 2011). Common to most age estimates is an intensification of contractional deformation during the Miocene, resulting in the initiation of new structures as well as the reactivation of older (Palaeogene) structures. This prominent period of compressional deformation may coincide with the development of the Iceland Insular Margin, and it has been suggested that the radial body force from the topographic/bathymetric anomaly may have been sufficiently large to cause compressional deformation in the adjacent margins (Doré et al., 2008), particularly in areas of hyperextended and weakened lithosphere (Lundin and Doré, 2011).

2.2 FAROE–SHETLAND REGION

2.2.1 Structural framework

The structural framework of the study area is dominated by the Faroe-Shetland Basin, which is approximately 400 km long and up to 200 km wide and consists of a generally NE-trending complex of sub-basins and intra-basinal highs (Figure 6). The basin has had a long history of development dating back to Late Palaeozoic times (cf. Doré et al., 1999 and Roberts et al., 1999, and references therein) (Figure 7). Basin formation in this region may have been initiated in the Devonian, with additional relatively minor rift phases during the Permo-Triassic and Jurassic. However, the main episode of basin formation occurred during the Cretaceous, with instigation of the Faroe-Shetland Basin during Aptian–Albian times (Dean et al., 1999; Larsen et al., 2010; Stoker et al., 2010a). Differential uplift, subsidence and compressional deformation are all evident in the development of the basin throughout the late Early to Late Cretaceous interval and are probably linked to regional oblique-slip tectonics associated with transtension and transpression in response to the developing North Atlantic rift system (Stoker et al., 2010a).

A widespread unconformity separates the Cretaceous and Palaeogene successions across much of the Faroe–Shetland region. Renewed faulting on some existing faults (e.g. those bounding the Judd, Flett, Westray, Corona and Sjúrður highs: Figure 6) rejuvenated and enhanced an inherited end-Cretaceous fault-induced topography, and resulted in submarine fan development in the adjacent basins (Lamers and Carmichael, 1999; Smallwood and Kirk, 2005). The onset of volcanism, possibly as early as 62 Ma, exploited weak spots in the increasingly thinned and rifted lithosphere of the NW European region, including the Faroe–Shetland region (cf. Passey and Hitchen, 2011 and references therein). This Early Paleocene melting anomaly has been attributed by some authors (e.g. White and Mackenzie, 1989; Saunders et al., 1997; Ritchie et al., 1999) to the arrival, beneath Greenland, of a mantle plume *sensu stricto* (i.e. the proto-Icelandic plume). Indeed, regional dynamic uplift attributable to the proto-Icelandic plume is postulated during the Mid- to Late Paleocene to account for the high rates of sedimentation in the Faroe-Shetland Basin, as well as the earliest Eocene regional unconformity (e.g. White and Lovell, 1997; Jones et al., 2002; Maclennan and Lovell, 2002; Smallwood and Gill, 2002; Mudge and Jones, 2004; Shaw Champion et al., 2008; Hartley et al., 2011). The subsequent onlap of the regional unconformity by the Balder Formation is attributed to the removal of asthenospheric support from the Faroe–Shetland region as anomalously hot asthenospheric mantle flowed into the developing zone of continental rifting to the north and west of the Faroe Islands (Smallwood and Gill, 2002). Whether this melting anomaly is the result of a mantle plume or by some other process is currently a matter of great debate (e.g. Foulger, 2002; Lundin and Doré, 2005a).

Extensive igneous activity accompanied the initiation of seafloor spreading between Greenland and NW Europe at about 56 to 54 Ma, during C24r, in latest Paleocene to earliest Eocene (Ypresian) times (cf. Passey and Hitchen, 2011). North and west of the Faroe Islands, breakup occurred between 54.8 and 54.5 Ma (Passey and Jolley, 2009). Following 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, as noted above, the post-rift structural development of the Faroe–Shetland region has been considerably influenced at various stages by enhanced phases of compression (e.g. Ritchie et al., 2003, 2008, 2011; Davies et al., 2004; Smallwood, 2004; Johnson et al., 2005, 2012; Stoker et al., 2005c), local tectonics (Robinson et al., 2004) and by regional uplift/tilting of the basin margin (e.g. Andersen et al., 2000; Stoker, 2002; Davies et al., 2004; Stoker et al., 2005a, b). Significant (km-scale) post-rift Palaeogene and Neogene uplift and structuring of the Faroe–Shetland region is manifest by the Wyville-Thomson, Munkagrunnur and Fugloy ridges that flank the western margin of Faroe-Shetland Basin, together with the general uplift of the Faroe Platform, the growth of the Judd anticline and various other anticlines that occur within the basin, as well as the progradation and subsequent tilting of Eocene shelf-margin wedges along the eastern side of the basin, flanking the Orkney–Shetland High (Figures 6–8; see also Ritchie et al., 2011, their Figure 2). In combination, these tectonic processes have resulted in the present-day morphology of the Faroe-Shetland Basin – commonly referred to as the Faroe-Shetland Channel (see section 2.2.2).

2.2.2 Regional seismic-stratigraphical architecture of the Stronsay Group

A series of NW–SE-trending geoseismic sections (Figure 7) across the Faroe–Shetland region depicts the gross depositional geometry of the Eocene succession. Figures 7a and b reveal an asymmetry that reflects an overall north to northwesterly progradation of the Eocene Stronsay Group succession, building seawards towards the developing ocean margin, from the Orkney–Shetland High. The syn-rift volcanic terrain – the legacy of breakup in this region – probably influenced the initial morphology of the basin margin, with major volcanic escarpments, such as the Faroe-Shetland and Erlend escarpments, marking former coastlines. Deltas, such as the

Munkagrunnur Ridge delta, provide further constraints on the early post-rift palaeogeography (see section 4.2.1); the development of the Munkagrunnur Ridge delta has been attributed to contemporary uplift at the SW-end on the Faroe-Shetland Basin (Ólavsdóttir et al., 2010). The volcanic escarpments were eventually buried as the shelf-margin prograded to the N/NW across the volcanic landscape. Large-scale clinoforms are evident on the geoseismic and seismic sections in Figures 7 and 8, respectively.

The absence of transported clastic material in Early Eocene limestones recovered from the eastern part of the Faroe Platform has been interpreted as an indication that shallow marine conditions prevailed across the platform for much of the late Ypresian–Lutetian interval (Andersen et al., 2000). It remains uncertain whether or not there was a connection between the Eocene Stronsay Group deposits preserved between the Faroe Islands and Shetland and a thick wedge of assumed Eocene rocks mapped above the continent-ocean boundary, north of the Faroe Islands. Andersen et al. (2000) have inferred that the Fugloy Ridge acted as a watershed separating the two areas; however, the profile in Figure 7b suggests that there is continuity of Stronsay Group rocks across the ridge.

Whilst some degree of contemporary thermal subsidence within the Faroe-Shetland Basin cannot be discounted, the regional disposition of Eocene rocks above the Fugloy Ridge (Figure 7a, b) indicates that their present geometry is primarily a function of later (end- to post-Eocene: see section 2.2.3) compression, basin inversion and uplift of the ridge, which resulted in erosional truncation of the Eocene section alongside and above the ridge. Thus, the present sag-like form of the Eocene Stronsay Group is most probably not a reflection of its original stratigraphical architecture, or of the shape and morphology of the early ocean margin in the Faroe–Shetland region.

2.2.3 Shaping the Faroe-Shetland Channel

The shaping of the Faroe-Shetland Channel was most probably instigated at the end of the Eocene and enhanced during late Palaeogene–Neogene times (Johnson et al., 2012). Although regionally the Eocene/Oligocene boundary is poorly defined on seismic profiles, there is reasonable confidence in the placement of the boundary in the vicinity of well 214/4-1, based on the work of Davies and Cartwright (2002) and Davies et al. (2004) (Figure 7b). From this, it is clear that the overlying Oligocene and Neogene–Quaternary basinal sequences display a broader catenary profile, which implies that post-Eocene basinal sedimentation between Shetland and the Faroe Islands was largely constrained within the limits of the present-day Faroe-Shetland Channel. The shape of the basin was further accentuated by a phase of enhanced compression during the Early to Mid-Miocene, and seaward tilting of the West Shetland Shelf during the Early Pliocene (Johnson et al., 2005; Stoker et al., 2005a–c). Since the late Palaeogene, oceanographic processes have strongly influenced basinal sedimentation, and Pleistocene glaciation of the West Shetland and Faroese shelves and slopes has further modified the basinal profile (cf. Stoker and Varming, 2011 and references therein).

3 Stratigraphy of the Eocene Stronsay Group

In the last twenty years, several stratigraphic methods have been applied to the Eocene succession in the Faroe–Shetland region, including seismic and sequence stratigraphy as well as lithostratigraphy. Seismic-stratigraphic studies have identified a number of key boundaries and major sediment packages of potentially regional extent, whilst the application of sequence-stratigraphic techniques has provided a higher-resolution analysis of Eocene systems tracts. Lithostratigraphical procedure was applied to data recovered from exploration wells as part of the UKOOA/BGS 'Stratigraphic Nomenclature of the UK North West Margin', which followed an earlier study from the UK North Sea. Biostratigraphic data have been used in many of these previous studies to aid correlation and identification of the various seismic, sequence and lithostratigraphic units. More detail on the earlier studies is presented below (section 3.1).

In order to produce a broad regional stratigraphical framework, the resultant scheme is very much a hybrid of all of the stratigraphic methods, utilising the most commonly used subdivisions and nomenclature. However, the hierarchy of lithostratigraphic nomenclature is adopted as the most practicable terminology for describing a succession that is mappable at several levels, is divided by distinctive, regionally-bounding surfaces, and displays significant lithological variation. To date, only group nomenclature has been applied to the Eocene succession in the Faroe–Shetland region; an extension of that used in the North Sea Basin. In this report, we make the case for further extending several formations from the northern North Sea, as well as proposing a number of provisional, informal stratigraphic subdivisions of these formations (Figure 3). It should be noted that a much more detailed, regional mapping programme is necessary before a formal scheme can be presented.

In the following sections we present a summary of previous seismic-stratigraphic, sequence-stratigraphic and lithostratigraphic work, followed by an outline of our proposed provisional stratigraphic framework for the Stronsay Group.

3.1 PREVIOUS WORK

3.1.1 Seismic stratigraphy

Over the last decade, a number of seismic-stratigraphic schemes have been published, together with a plethora of seismic reflector terminology (Figure 4). Correlation between these schemes reveals that there is general consensus that a major change in depositional style occurred at some point in the early Mid-Eocene, with the onset of significant shelf-margin progradation northwards from the West Shetland and north Hebridean platformal areas (e.g. Andersen et al., 2000; Sørensen, 2003; Robinson, 2004; Robinson et al., 2004; Stoker and Varming, 2011). However, the complexity (i.e. the number of named reflectors) of the various schemes is highly variable, and is most probably a function of both the quality of the seismic data and the local vs. regional scope of the studies. The local studies are commonly focused on limited areas, and specific parts of the succession (e.g. the Judd inversion structure, Smallwood, 2004; the Middle Eocene basin-floor fans, Davies et al., 2004), whereas the regional studies (e.g. Andersen et al., 2000, 2002; Sørensen, 2003; Robinson, 2004) concentrated on the broad regional scheme but lacked detail. Robinson (2004) recognised, in particular, that his well ties to seismic data had insufficient biostratigraphic control. None of the studies, including the most recent framework presented by Stoker and Varming (2011), fully integrated the well/borehole and seismic reflection data, nor did they take account of the lateral variations in facies or the regional implications of contemporaneous compression and uplift on the developing shelf-margin succession. The latter, in particular, has led to probable mis-correlations between stratigraphic packages (e.g. compare the column of 'Stoker and Varming, 2011 (FSBRR)' with that of 'This study' in Figure 4). This mis-match arose from the incorrect jump-correlation of a package of submarine fan deposits in block 204 with the Middle Eocene basin-floor fan deposits in blocks 213 and 214; the former have now been identified to be younger than the latter (see section 3.2).

3.1.2 Sequence stratigraphy

A sequence-stratigraphic approach was first applied to the Eocene of the Outer Moray Firth area by BP stratigraphers and subsequently published by Jones and Milton (1994), who subdivided a basinward prograding clastic sediment wedge into a number of seismic stratigraphic sequences: T60 to T98 (cf. Figure 3), which have a resolution of 0.6 Ma to 6.5 Ma. This notation is a continuation of the T10 to T50 subdivision that was developed for the lower Palaeogene succession in this area, and became commonly known as the BP T-sequence scheme (the letter 'T' abbreviated from 'Tertiary'). However, whereas the T10–T50 scheme has similarly developed into common usage in the Faroe–Shetland region by exploration companies investigating the deep-water Paleocene sandstone play, the lack of focus on the Eocene as a hydrocarbon system in this area has resulted in a general lack of stratigraphic analysis, and hence little published material exists for the Eocene T-sequence scheme in this area.

By way of contrast, Ichron Limited have undertaken detailed biostratigraphic analysis of Eocene sections in exploration wells in the Faroe–Shetland region on behalf of oil companies, and have developed an Ichron T-sequence scheme that broadly calibrates with the BP T-sequence scheme (see Figure 3). For the purpose of this study, Ichron Limited have allowed us to use their interpretations and T-sequence scheme for a number of wells in blocks 205, 206, 207, 208, 209, 213, and 214 (Ichron Limited, 2010a, b) (Table 1). The Ichron T-sequence scheme incorporates more biostratigraphic zones, splits the BP T98 into Ichron T98 and T99, and has a resolution ranging from 0.6 Ma to 3.6 Ma.

A higher-resolution 3D sequence-stratigraphic analysis of an intra-Eocene shelf-margin delta that developed adjacent to the Munkagrunnur Ridge was recently published by Ólavsdóttir et al. (2010). This sediment package was divided into nine units that preserve a record of fluctuating relative sea level that the authors' link to contemporaneous uplift of the Munkagrunnur Ridge. Although this shelf-margin deposit was originally assigned a Mid-Eocene age, this study indicates that it correlates in-part with our informal unit A (cf. Figure 3) and spans Ichron T-sequences T60–T85 of Ypresian age.

3.1.3 Lithostratigraphy

As previously noted, the term Stronsay Group was introduced by Knox and Holloway (1992) for the Eocene sediments of the UK central and northern North Sea that overlie the Balder and Dornoch formations of the Moray Group (Figure 2). In the North Sea, the Stronsay Group comprises the Mousa and Horda formations; the former is characterised by a sandstone- and siltstone-dominated shelf succession, whilst the latter is a mudstone-dominated basinal succession. The boundary between the two formations effectively marks the position of the contemporary shelf-edge (Figure 1), though this boundary is not always clear and its position may be taken more arbitrarily where there is a basinward expansion of the argillaceous section. Sandstones within the Horda Formation (e.g. Frigg, Skroo, Tay and Grid (Caran) sandstone members) were largely deposited in complex submarine fan systems, and are separate from the shelf sandstones of the Mousa Formation. In places where the uppermost Grid (Brodie) Sandstone Member can be traced from the basin to the shelf, the boundary between the Mousa Formation and the Horda Formation remains arbitrary (Knox and Holloway, 1992).

The Stronsay Group was extended into the Faroe–Shetland region by Knox et al. (1997), who described a gross SE–NW facies change from sandstone and siltstone in marginal areas to silty mudstone in more basinal areas. Although four reference wells were proposed (214/28-1, 208/15-1A, 206/9-2 and 202/3-2) no subdivision of the group was attempted. Two of these wells

– 214/28-1 and 208/15-1A – have been studied by Ichron Limited, and are included in this study. On Figure 1, the Horda Formation is observed to extend to the eastern limit of the study area, whereas the northwestward extension of the Mousa Formation is less clear.

3.2 A PROVISIONAL STRATIGRAPHIC FRAMEWORK FOR THE EOCENE STRONSAY GROUP

Our provisional stratigraphic framework for the Eocene Stronsay Group of the Faroe–Shetland region as summarised in Figures 3 and A.1 is based upon an integration of lithological information from the sample database at our disposal and the Ichron T-sequence scheme; both linked to the seismic stratigraphy. For reasons outlined below, we propose that most of the succession preserved between Shetland and the Faroe Islands be assigned to the Horda Formation, within which we have identified six informal units, A to F.

Although regional seismic-stratigraphic mapping is beyond the scope of this study, an appraisal of the seismic data indicates that a predominantly shelf-margin to basinal succession is preserved in the study area. Two key profiles are illustrated in this report: Figure 8 is a dip profile that crosses the Eocene shelf margin, whereas Figure 9 provides an axial profile of the basin. In addition, Figure 10 presents a line drawing that further illustrates the shelf-margin succession, especially the stacked nature of successive shelf-margin packages. A number of key seismic reflectors are highlighted, several of which retain (in part) the terminology introduced by Stoker and Varming (2011); these include T2d, T2c and T2b. The full listing of reflectors that we recognise and their provisional age assignment based on calibration with the available sample data (Figure A.1) is as follows, in descending stratigraphic order:

1. Composite TPU/IMU/INU unconformity – a widespread, angular unconformity that separates variably eroded Palaeogene and Lower Miocene rocks from overlying Neogene deposits. In the southern part of the region, the unconformity comprises a composite surface that incorporates the Top Palaeogene (TPU), Intra-Miocene (IMU) and Intra-Neogene (INU) unconformities (Stoker et al., 2005a; Stoker and Varming, 2011) (Figure 8). Farther to the NE, where the upper Palaeogene and Neogene succession expands in thickness, the top Palaeogene and Intra-Neogene surfaces can be separately identified (Figure 9).

2. Base-marginal-fan (T2b) reflector – late Priabonian. In the southern part of the region, this unconformity may define the near-top of the Stronsay Group based on a tie to well 214/4-1 (Figure 9; see also Lamers and Carmichael, 1999 – their Figure 5 – and Davies and Cartwright, 2002). However, the Eocene/Oligocene boundary – previously assigned to reflector T2a by Stoker and Varming (2011), and recognised in well 214/4-1 – generally remains poorly defined regionally on seismic profiles (Johnson et al., 2012).

3. Base-slope-apron (T2c) unconformity – intra-Bartonian. In the southern part of the region, this surface truncates underlying Lutetian and Ypresian deposits.

4. Top-basin-floor-fan reflector – late Lutetian.

5. Mid-Eocene (T2d) unconformity – intra-Lutetian. Includes major channel incisions up to 200 m deep that erode underlying Ypresian–lower Lutetian deposits.

6. Base Stronsay Group – early Ypresian (post-Balder Formation). Ichron Limited (2010a, 2010b) observe missing Early Eocene biostratigraphical zones (representing their T60–T85 sequences) in a number of wells along the margin of the Faroe-Shetland Basin (Figure A1), which is manifest on seismic data as an unconformity marked by onlap or downlap of the overlying Stronsay Group onto the eroded top of the Moray Group. In the more basinal wells, there appears to be conformity between the Moray and Stronsay groups. The way in which this boundary and comparable sequence boundaries within the underlying Moray Group relate to the early Palaeogene lava shield on the Faroe Platform and control the

regional distribution of potential hydrocarbon reservoirs at base Eocene level, will be more fully discussed in a subsequent report describing the pre-Stronsay Group Cenozoic succession.

These reflectors enable the delineation of several depositional packages that stand out on the seismic profiles, notably informal units A, D, E and F (Figures 3, 8–10). The regional applicability of these surfaces remains to be fully tested, though Johnson et al. (2012) have utilised this scheme in their regional study of compression across the Faroe–Shetland region. Unit A includes the Munkagrunnur Ridge Delta of Ólavsdóttir et al. (2010); unit D incorporates the Middle Eocene basin-floor fans of Davies et al. (2004) and DECC (2010); unit E represents the shelf-margin package, including base-of-slope submarine fan deposit, of Stoker and Varming (2011). The mis-correlation between the latter and the Middle Eocene fans is clearly indicated by Figure 9. Unit F is a discrete base-of-slope deposit herein assigned to the Stronsay Group, though an Oligocene (Westray Group) age cannot be discounted. Two other units, B and C, are identified from well data; unit B represents a deep-water sandstone in well 213/23-1, whereas unit C represents a predominantly arenaceous shelf succession in block 205. Collectively, these data are consistent with the Horda Formation as defined by Knox and Holloway (1992), i.e. the shelf-margin to basinal setting and the recognition of deep-water sandstone bodies within an otherwise generally argillaceous succession (as indicated by the stratigraphic-range chart: Figure A.1).

The Ichron T-sequence scheme has enabled us to put the lithological information into a temporal and spatial framework. The temporal correlation between all of the sample data and the Ichron T-sequence scheme is captured in Figure A.1, whereas a combined spatial and temporal representation of the succession, incorporating the key seismic reflectors, is presented schematically in Figure 11.

It is emphasised that this stratigraphic framework is provisional. The informal units A–F have the potential to be ranked as members, but regional seismic-stratigraphic mapping and more detailed lithological assessment, probably incorporating wireline logs, may be necessary to properly define their spatial distribution and genetic interpretation. Moreover, without access to the detailed stratigraphy of the quadrant 204 wells there remains a clear gap in the dataset.

4 Eocene (Stronsay Group) post-rift timeslice reconstruction of the Faroe–Shetland region

In this section, we address the temporal and spatial development of the post-rift Stronsay Group within the Faroe–Shetland region with a series of timeslice maps based on the Ichron T-sequence scheme (Figures 12–26: for highest resolution of the maps the reader should view the PDF version of this report). In order to provide context for the Stronsay Group, we have included information and reconstructions from the earlier Eocene syn-breakup Moray Group. Collectively, these maps present a visual representation of stratigraphical change during the Eocene, with a particular focus on lithology and an introduction to the proposed new lithostratigraphic subdivision. In addition to the sample and seismic data used in this study, we have also drawn upon published material to supplement the timeslice reconstructions wherever necessary. Inspection of the timeslice maps in combination with the seismic-stratigraphic framework has enabled a number of phases to be identified that may define key stages in the Eocene development of the Faroe–Shetland region; these are as follows:

4.1 YPRESIAN (PRE-STRONSAY GROUP)

4.1.1 T40 (upper), T45 and T50 timeslice maps (Figures 12 and 13)

At the start of the Ypresian, before the onset of Stronsay Group deposition, the syn-breakup palaeogeographic setting of the Faroe-Shetland region is partly indicated by the lithological variation of well penetrations of the underlying Moray Group, which includes the Flett and Balder formations of Knox et al. (1997) and encompasses the equivalent BP sequences and Ichron biostratigraphic zones T40, T45 and T50.

Ebdon et al. (1995) interpreted well and seismic data to show that the basal T40 sequence of the Moray Group is absent in Quadrant 204 in the southern part of the Faroe-Shetland Basin. In places, the associated unconformity separates the upper part of the Flett Formation (T45) from the underlying Lamba Formation, which consists of a predominantly marine Palaeocene succession characterised on seismic data by a conspicuous set of prograding foresets (described as T36 by Ebdon et al. 1995; now assigned to T38 by Ichron and BP). At the unconformity, removal of much of the late Paleocene topset interval, during an episode of fluvial downcutting, left a seismically well-defined network of dendritic drainage entrenched within the Lamba Formation. This gently northerly-dipping unconformity surface was subsequently preserved by early Ypresian onlap in parts of quadrants 6004/204 and 205 (Smallwood and Gill, 2002; Shaw Champion et al., 2008; Rudge et al., 2008; Hartley et al., 2011) (Figure 12). In Quadrant 205, the onlapping T45 interval of the Flett Formation is associated with the development of a thin varied succession of interbedded claystones, siltstones and sandstones, which, with its characteristic paralic biostratigraphy and widespread traces of coal and lignite, is indicative of deposition in a coastal plain environment. Similar environments are developed in the Beauly Member at the top of the time equivalent Dornoch Formation deltaic complex in the North Sea (Knox and Holloway, 1992) (Figure 12). In the Faroe-Shetland Basin, Lamers and Carmichael (1999; their Figure 15) supplemented the well lithological data at this level by using a 3D seismic volume to construct a palaeogeographic map based on the extracted pattern of amplitude variation within a 50 ms interval around the top Balder Formation (T50) reflector (Figure 12).

The episode of coastal onlap in the Faroe-Shetland area, which began during the deposition of the upper Flett Formation, continued with the deposition of the Balder Formation (T50). Biostratigraphically, the Balder Formation is usually identified by a downhole influx of abundant *Coscinodiscus* spp 1 and 2 with an associated acme of *Deflandrea oebifeldensis* (Knox and

Holloway, 1992; Knox et al., 1997; Ichron, 2010a,b), though Knox and Holloway (1992) note that *Coscinodiscus* is known to persist into the basal part of the Stronsay Group. Tuffaceous claystones derived from a series of thin airfall tuffs are widely developed in the early part of T50. Later sedimentation is more varied, but lithological data from wells west of Shetland suggest that sandstones are not as widespread as in contemporaneous parts of the northern North Sea (Knox and Holloway 1992) (Figure 13). Following their extensive deposition in the Faroe-Shetland Basin during T45, coal and lignite continued to be deposited locally during T50 (Figure 13), just as the analogous Beauly Member persists into Balder Formation times in the North Sea.

On well logs from the North Sea and the Faroe-Shetland Basin (Knox and Holloway 1992; Knox et al., 1997), the uphole decline in the tuffaceous component of T50 is linked to a marine transgression which divides the Balder Formation into two units (B1 and B2). This intra-Balder Formation horizon (Top B1) is correlated with the main London Clay transgression of southern England by Knox (1996) and may be equivalent to the lower of two downlap surfaces in the basal Eocene of the Faroe-Shetland Basin interpreted by Olavsdottir et al. (2010; their Figure 4, reflector 10). Early Eocene tuffs recovered in dredge hauls from the eastern flank of the Faroe Platform record the transition between largely non-marine environments with spores, pollen, plant fragments and lignite (sites 145, 157 and 158) and more marine-influenced locations (site 161) (Waagstein and Heilmann-Clausen, 1995) (Figure A.1). The top of the Balder Formation in the North Sea is a maximum flooding surface that is widely marked on well logs by a high gamma-spike (Top T50 of Ichron and BP: Top B2 of Knox and Holloway 1992). This event defines the base of the Stronsay Group and in the Faroe-Shetland Basin possibly corresponds with the younger of the basal Eocene downlap horizons recognised by Olavsdottir et al. (2010; their Figure 4, reflector 20).

4.2 YPRESIAN (STRONSAY GROUP)

Ichron Limited (2010a, b) recognise four main biozones (T60, T70, T82 and T85) within the Ypresian (Early Eocene) interval of the Stronsay Group. The well lithology data for each of these intervals are summarised in Figures 14–17, with a composite isopach map in Figure 18. For the most part, these zones are only thinly developed in the Ichron well dataset, where they consist predominantly of fine-grained lithologies, commonly with a tuffaceous component. Equivalent fine-grained basinal sediments in the North Sea are assigned to the Horda Formation (Knox and Holloway, 1992), and it is likely that the deposits of the two basins are laterally continuous around the north of the Shetlands.

4.2.1 T60 timeslice (Figure 14)

The T60 sequence is commonly absent in wells on the south-eastern flanks of the Faroe-Shetland Basin, where the base of the Stronsay Group rests with a slight disconformity on the underlying Moray Group. In adjoining parts of the basin, and possibly including the eastern flank of the Faroe Platform, the conformable T60 interval commonly consists of a thin varied succession of partly tuffaceous sediments, interbedded with siltstones and claystones. Tuffaceous deposits are also recorded from the Ymir Ridge (Jones and Ramsay, 1982). Thicker successions, with a higher proportion of coarse-grained lithologies are developed straddling the median line in Quadrants 6004/204 and 6005, where Ólavsdóttir et al. (2010) recognise an influx of sediment forming the Munkagrunnur Ridge Delta, which we have provisionally included in unit A (of the Horda Formation). Thickness isochrons of this sandstone-dominated area thin rapidly to the north-east, where seismic sections reveal a series of prograding reflectors downlapping onto the Top Balder Formation/Base Stronsay Group event (Ólavsdóttir et al., 2010) (Figure 8). High-amplitude seismic events within the Munkagrunnur Ridge Delta succession probably indicate the local development of a delta-top facies including coal or lignite. The sediments associated with similar shelves on the western flanks of the North Sea are assigned to the Mousa Formation, which was originally defined within the Stronsay Group to incorporate the undifferentiated shelfal equivalent of the more basinal Horda Formation. On a map showing the distribution of the whole Mousa Formation (Figure 1), Knox and Holloway (1992) outline a distinct area of early Eocene sedimentation on the flanks of the northern North Sea, which was deposited at the same time as the Munkagrunnur Ridge Delta (unit A, Horda Formation) (Figure 14) on the opposite margin of the Orkney-Shetland High.

4.2.2 **T70 and T82 timeslices** (Figures 15 and 16)

The contrast established during the T60 interval, between an area of thin sedimentation in the Faroe-Shetland Basin and non-deposition on its flanks, persisted locally during the T70 and T82 intervals, while basin margin onlap resumed in parts of Quadrants 205 and 206. Fine-grained sediments were deposited across most of the basin, as thicker, more arenaceous sedimentation continued in the area of the Munkagrunnur Ridge Delta (unit A) and near the basin margins elsewhere, as in well 209/12-1. In the more basinal well 213/23-1, a 40 m thick turbiditic sandstone unit occurs in Ichron biozone T82 and persists into T85. This sandstone body, which we have provisionally designated as unit B (of the Horda Formation), provides the only evidence in the available Ichron well database for the development of a Lower Eocene basin-floor fan in the Faroe-Shetland Basin, and can be linked to erosion of T60 and older sediments from the basin margins.

4.2.3 **T85 timeslice** (Figure 17)

Tuffaceous sediments become less widespread in the T85 sequence and the proportion of wells proving siltstone increases, possibly indicating the onset of pro-delta deposition on the margins of the basin to the east of the Munkagrunnur Ridge Delta. In a more basinal setting, well 214/4-1 has some thin sandstone beds (with a total thickness of about 7 m) in a claystone-dominated T85 succession. These may be associated with the T82/T85 sandstone turbidite interval in well 213/23-1, which lies updip to the south-west. Several other wells in the UK sector show thin successions of more coarse-grained T85 sediments resting unconformably on the Moray Group, continuing the process of basin margin onlap that started in T70 and T82. In contrast, elsewhere in the basin, the probable absence of the T85 biozone in the BGS borehole 99/3 and its truncation in well 214/26-1 are related to later erosion beneath the Mid-Eocene (T2d) unconformity.

4.2.4 **T60–T85 summary** (Figure 18)

Figure 18 presents a summary isopach map for Stronsay Group sediments of Ypresian age based on well data and the thickness of relevant Ichron T-zones where information is available (Ichron Limited, 2010a, b), as well as generalised from the broad structure of the basin elsewhere. This reveals two depocentres: one which straddles the median line and is related to the influx of sediment associated with the Munkagrunnur Ridge Delta (Ólavsdóttir et al. 2010) (unit A, Horda Formation), and the other is located at the junction of Quadrants 208 and 214 within a part of the Faroe-Shetland Basin that lies beyond the progradational limit of the underlying Paleocene coastal shelf as defined by Lamers and Carmichael (1993) (Figure 12). These depocentres are separated by an area of thinner sediments in the UK sector in which the basal part of the T60–T85 interval is often absent as a result of post-T50 relative uplift of the basin margins followed by onlap during the Ypresian. Although the well evidence is generally sparse, especially from the deeper basinal areas, the thin T82–T85 turbiditic sandstones in well 213/23-1 (unit B, Horda Formation) provide the only strong indication for the development of Ypresian point-sourced basin-floor fans in the Faroe-Shetland Basin analogous to the Frigg, Skroo and Tay sandstone members of the Horda Formation in the North Sea (Knox and Holloway, 1992).

4.3 EARLY TO MID-LUTETIAN

4.3.1 T91 timeslice (Figure 19)

Well lithology data suggest that, in general, Middle Eocene sediments in the UK sector of the Faroe-Shetland Basin rest conformably on the Ypresian and continue to coarsen-up, with sandstone- and siltstone-dominated successions becoming more widespread during the Early Lutetian. Thickness variation remained similar to the upper Ypresian, with the whole interval generally less than 100m thick. The top of biozone T91 may be absent in parts of Quadrants 208 and 209 on the flanks of the Erlend High and similarly may have been removed locally elsewhere by downcutting canyons that sourced the later Mid-Eocene basin floor fans in the north of the basin.

4.3.2 T93 timeslice (Figure 20)

There is strong evidence for the onset of a major change in the structural configuration of the Faroe-Shetland Basin during Ichron biozone T93. The development of thick siltstone- and sandstone-dominated sequences at the base of the interval in the UK sector suggests that a pro-delta succession continued to prograde northwards from the south-eastern flanks of the Faroe-Shetland Basin extending the area of shelf deposition associated with unit A over the former Paleocene depocentres to the north-west of the Rona Ridge. Subsequently, a major Mid-Eocene unconformity truncated the top of this interval in Quadrant 205, redepositing much of the eroded section in an upward-coarsening succession of Mid-Eocene basin floor fans in Quadrants 6103/213 and 214 and marking the instigation of unit D of the Horda Formation (see section 4.4.2) (Figure 9). Well data show that Ichron biozone T93 is also absent from the basin margin near the Erlend High, while to the south of the Rona Ridge, more prolonged Mid-Eocene erosion may have removed much of the shallower part of the contemporaneous shelf. Since the exact timing of the onset of erosion during the T93 interval cannot be established from the available Ichron T zone data, the age of the succession overlying the Lutetian unconformity penetrated by BGS borehole 99/3 becomes of critical importance. Current palaeontological data (cf. Riding, in Hitchen, 1999), indicating the possible presence of biozone NP14 in the onlapping sequence, suggest that the unconformity is older than 46.75 Ma, while the Ichron data alone are consistent with a broader range of dates between 43 and 47 Ma. More detailed biostratigraphical analysis of the 99/3 core may help to constrain the age estimate.

4.3.3 T91-T93 summary (Figure 21)

The summary isopach for Ichron biozones T91–T93 shows a depocentre in the south-eastern corner of Quadrant 214, close to the northern depocentre of the Ypresian Stronsay Group (Figures 18 and 21). This suggests that differential compaction of the underlying Upper Paleocene basinal sequence, which was laid down in the Faroe-Shetland Basin beyond the northern limit of the T45 coastal plain (Figure 12), may have continued to influence Mid-Eocene deposition and controlled the northern limit of shelf progradation. Further to the south-west, the T91–T93 isopach shows the effect of the subsequent partial erosion of T93 sediments beneath the Mid-Eocene (T2d) unconformity.

4.4 MID-LUTETIAN–EARLY BARTONIAN

4.4.1 T94 timeslice (Figure 22)

The Ichron biostratigraphical data show that the T94 biozone is largely absent from wells in Quadrant 205, where the Mid-Eocene (T2d) unconformity is strongly developed and cuts deeply into the older T91 and T93 biozones (Ichron Limited, 2010a,b) in northerly-trending incised channels. The depth of incision ranges from 80 m to 200 m (Robinson et al., 2004). Since these gently sinuous linear features are backfilled by sediments which are characterised by high amplitude reflections, their areal distribution can be mapped by amplitude extraction on 3D seismic data (Robinson 2004; Robinson et al. 2004). Enhanced thicknesses of the T94 interval in Quadrant 214 suggest that redeposition from an eroding shelf in the southern part of the Faroe-Shetland Basin contributed to an increase in coarse-grained sedimentation further north (unit D, Horda Formation: see section 4.4.2). Elsewhere, other wells show that sediments had already begun to onlap the Mid-Eocene (T2d) unconformity during the upper part of the T94 biozone along parts of the basin margin (wells 205/10-4, 208/15-1A and 214/26-1) including the Erlend High (wells 209/6-1 and 209/12-1).

DSDP site 336 indicates that basalt was being extruded subaerially along the northern flank of the Iceland-Faroe Ridge at about this time (dated by K-Ar as 43–40 Ma) (Talwani and Udintsev, 1976; Talwani et al., 1976). The basalt grades into, and is overlain by, a volcanic conglomerate (basaltic rubble), which in turn is overlain by red claystone (Figure A.1). This section is interpreted as a ferruginous lateritic palaeosol formed by the in situ weathering of the basaltic basement (Nilsen, 1978; Nilsen and Kerr, 1978).

4.4.2 **T96 timeslice** (Figure 23)

The Mid-Eocene episode of basin-floor fan deposition, which was instigated during the T93 interval, culminated in parts of the Faroe-Shetland Basin in Ichron biozone T96 during the late Lutetian. The top of the fan is commonly associated with a conspicuous seismic reflector (Figure 9) and 3D seismic interpretation has revealed a mounded basin floor topography with overlapping fan lobes and sinuous northerly-trending sediment thicks linked through incised channels to point sources on the eroded shelf to the south (DECC, 2010). Names for each of the currently-recognised fan lobes in the Faroe-Shetland Basin have been informally adopted in the literature (the Portree, Caledonia and Strachan fans: cf. Davies et al., 2004), which we refer to collectively as unit D of the Horda Formation. Contemporaneous basin-floor fans in the North Sea are generally included in the Grid Sandstone Member, which incorporates Eocene sandstones of various origins. Knox and Holloway (1992) suggest that in areas where a specific Mid-Eocene basin-floor fan origin can be recognised in the North Sea, the sandstones may be assigned to the Caran Sandstone unit. The flooding surface that marked the end of widespread Mid-Eocene basin-floor fan deposition in the Faroe-Shetland Basin may be linked to the return of basin margin onlap in Quadrant 205, where some thick arenaceous shelf successions of T96 age, which we have informally designated as unit C (of the Horda Formation), are preserved above the Mid-Eocene (T2d) unconformity. On the flanks of the basin, the relics of this unconformity-bound shelfal succession of late Lutetian age are closely juxtaposed and overlapped by the prograding deposits of the later (Bartonian–Priabonian) shelf.

Subaerial basalt extrusion and/or palaeosol formation persisted on the Iceland-Faroe Ridge during this time.

4.4.3 **T97 timeslice** (Figure 24)

Thickly-developed basin-floor sandstones in well 213/23-1 show that turbidite deposition in the Caledonia Fan continued locally into Ichron biozone T97 (Figure A.1). This contrasts with well 214/4-1, where fan deposition ceased in T96, and implies that the top basin-floor fan seismic reflector (and thus the top of unit D) is partly diachronous within the Mid-Eocene (Figure 11). Regionally, biostratigaphic interpretation of the T97 sequence is otherwise very poor, largely because many of the late Lutetian and younger successions on the basin margins are commonly penetrated above the depth of first returns, at which well sampling begins. The few analysed intervals are generally arenaceous, but their sparse distribution makes it difficult to assess the limits of the contemporaneous shelf from well data alone (Figure 24). The seismic panels illustrated by Robinson (2004) reveal a pattern of downlapping shelfal reflectors from latest Mid-

Eocene to Late Eocene times on the basin margin in the UK sector, but there is not enough well-constrained thickness information to interpret the full history of the shelf throughout this time.

Subaerial basalt extrusion and/or palaeosol formation persisted on the Iceland-Faroe Ridge during this time.

4.5 BARTONIAN–PRIABONIAN

4.5.1 T98-T99 timeslices (Figure 25)

The T98 and T99 biozones are commonly undifferentiated by Ichron and thickness estimates for the interval are sparse because of poor sample recovery from wells at these levels. The sandstone-dominated intervals in wells from Quadrant 205 provide some indication of the presence of a shelf sequence (unit E of the Horda Formation) whose large-scale depositional geometry can be broadly inferred from the seismic panels of Robinson (2004) and other seismic data (Figures 8 and 9). These profiles show a sequence of downlapping reflectors beneath the Top Palaeogene unconformity, which prograde north-westwards and terminate in a conspicuous shelf margin feature. Basinwards, the steep prograding reflectors pass into a more gently-dipping apron of higher-amplitude events, which is interpreted as a 'slope apron fan' laid down in front of the advancing shelf. The slope apron thins to the north-west, where its limit can be crudely estimated from the regional seismic coverage. In places, the seismic data reveal that the slope apron rests unconformably upon a truncated succession of older sediments probably related to the previous (T96-T97) basin margin. The age of the bounding unconformity – the Base-slope-apron (T2c) unconformity – may be estimated from the Ichron well data, where fossils from biozone T98 are absent from some wells, such as 205/8-1 and 205/9-1, and are generally poorly represented in the well dataset. This would date the unconformity as an early Bartonian event at approximately 39–40 Ma. This age is consistent with the absence of the biozones equivalent to T98 in BGS borehole 99/3. In places, the unconformable early Bartonian–Priabonian shelf sequence may overstep the older Mid-Eocene shelfal deposits to rest directly upon Ypresian sediments originally exposed by the Mid-Eocene (T2d) unconformity. Interpretation of 3D seismic data in Quadrant 205 (Robinson 2004; Robinson et al. 2004) reveals that the shelf sequence includes a stacked series of slightly downcutting north-westerly-trending channel features several tens of metres deep in the area of the shelf/slope transition. In the Central North Sea, undifferentiated shelf deposits of Mid–Late Eocene age are assigned to the Mousa Formation, while the Brodie Sandstone Unit is used to describe the upper, more shelfal deposits of the Grid Sandstone Member, where these can be distinguished (Knox and Holloway 1992).

Subaerial basalt extrusion and/or palaeosol formation may have persisted on the Iceland-Faroe Ridge during the earliest part of T98; however, marine claystones of Bartonian age overlie the palaeosol at DSDP site 336 (Talwani et al., 1976), and represent the first record of marine sedimentation on this part of the ridge. The marine section exceeds 200 m in thickness, and indicates submergence of the northern flank of the Iceland-Faroe Ridge from a subaerial setting in the Mid-Eocene to a neritic to upper bathyal (shelf to upper slope) environment during the Late Eocene (Talwani et al., 1976; Schrader and Fenner, 1976; Berggren and Schnitker, 1983).

4.6 LATE PRIABONIAN

4.6.1 T98–T99 timeslice with marginal fan (Figure 26)

Regionally, the Base-marginal-fan (T2b) seismic reflector, of Late Priabonian age, may define the top or near-top of the Stronsay Group and the base of the onlapping, claystone-dominated Westray Group. However, in Quadrant 204 of the UK sector, there is an additional, locally developed seismic unit at the boundary between the two groups, which is characterised by a pattern of chaotic internal reflections that may indicate an origin as a debris flow alongside the

Late Eocene shelf. This specific unit is not laterally extensive and is provisionally described here as a marginal fan and designated as unit F (of the Horda Formation). Although its distribution has been partly truncated near the present day sea bed by erosion at the Top Palaeogene unconformity (TPU) (Figure 26), seismic sections reveal that it remains >200 ms (~ 200 metres) thick in places. A line drawing based on a seismic profile (Figure 10) shows the stratigraphical relationship between the marginal fan (unit F) and the adjoining Bartonian–Priabonian shelf (unit E) and also displays some of the effects of subsequent Cenozoic folding and uplift. The presence of steeper dips beneath the gently folded Base-marginal-fan reflector may indicate that some of the Cenozoic tectonic movements are of pre-late Priabonian age and are possibly linked to the resurgence of fan deposition on the slope.

BGS borehole 99/3 penetrated 7 m of dark yellowish brown to dark greyish brown, fine-grained, slightly bioturbated mud of Priabonian age, which was deposited in a basinal setting (Hitchen, 1999; Leslie et al., 2010; Stoker and Varming, 2011). This unit was placed above seismic reflector T2b as originally defined by Stoker and Varming (2011); however, the reinterpretation of the seismic data in the present study, and the wider recognition of the Base-marginal-fan (T2b) reflector, casts some uncertainty over their initial interpretation.

5 Discussion

The stratigraphic development of the Stronsay Group records the interrelationship between shelf and basin environments in the Faroe-Shetland Basin in the first 20 million years following the opening of the North-East Atlantic Ocean between Greenland and NW Britain. Using biostratigraphic analyses of well data from the Eocene successions of the Faroe-Shetland region (Ichron Limited (2010a, b) we have divided this time interval into a series of higher-resolution timeslice maps (Figures 12–26) that better constrain the depositional history of the Stronsay Group. Unconformities recognised by the development of missing or truncated biozones have been linked to selected regional seismic profiles, which have confirmed that the Stronsay Group could potentially be divided into a number of informal lithostratigraphic units whose boundaries correspond to regionally significant seismic events (Figure 11); and which themselves may correspond to changes in basin shape and shifts in basin depocentre.

In this section, we summarise the Eocene post-rift geological development of the Faroe–Shetland region by placing our stratigraphic scheme into a provisional tectonostratigraphic framework. As part of this discussion, we also consider the broader-scale elements of the Stronsay Group stratigraphy and their implications for a possible revised understanding of the late syn-rift development of the region.

5.1 EOCENE POST-RIFT GEOLOGICAL DEVELOPMENT

The Eocene post-rift geological development of the Faroe–Shetland region can be described in terms of three main depositional phases, each of which is equivalent (in duration) to a 3rd order sedimentary cycle and linked to progradation of the shelf-margin into the Faroe-Shetland Basin. In the following sections, we present our provisional tectonostratigraphic framework followed by a consideration of the regional controls that may be responsible for this development. The margin-wide applicability of our reconstruction remains to be tested by regional mapping.

5.1.1 A provisional tectonostratigraphy

The informal subdivision of the Stronsay Group that was presented in Figure 11 forms the basis for our provisional tectonostratigraphy, which is summarised in Figure 27. Four main depositional phases are highlighted – phase 1 of Ypresian–early Lutetian age; phase 2 of Lutetian–early Bartonian age; phase 3 of Bartonian–Priabonian age; and, phase 4 of Late Priabonian age – separated by the three intra-Eocene bounding surfaces of the Mid-Eocene (T2d) unconformity, the Base-slope-apron (T2c) unconformity, and the Base-marginal-fan (T2b) reflector. The main characteristics of each phase are summarised below:

5.1.1.1 YPRESIAN TO EARLY LUTETIAN (PHASE 1)

The basal part of the Stronsay Group in the Faroese sector comprises a deltaic succession of Ypresian age (part of unit A), which downlapped the top of the Balder Formation and prograded north-eastwards from the area of the Munkagrunnur Ridge (Ólavsdóttir et al., 2010). Wells from adjoining parts of the UK sector prove contemporaneous Early Eocene successions that consist mainly of thin, commonly tuffaceous sediments, but with sporadic basin-floor sandstone (unit B), which locally rest disconformably on the Balder Formation. Water depths in the Faroe-Shetland Basin were probably between 250 and 350 m, though relative sea level may have fluctuated due to contemporary tectonic movements, e.g. inversion of the Munkagrunnur Ridge and Judd anticline (Smallwood and Gill, 2002; Smallwood, 2004; Ólavsdóttir et al., 2010). The Stronsay Group on the eastern flanks of the Faroe-Shetland Basin appears to coarsen up during the early Lutetian (part of the pro-delta expansion associated with unit A). This phase of shelf-margin progradation and its areal expression is well illustrated by the isopach map based on the combined thickness of the T60–T85 sequences (Figure 18), and has since been revealed in greater detail by Johnson et al. (2012; their Figure 29) on the basis of regional seismic mapping. Any extension of shelf deposition northwards was terminated by the subsequent development of the Mid-Eocene (T2d) unconformity surface.

5.1.1.2 Lutetian to early Bartonian (phase 2)

There is seismic evidence showing that incised channels 80–200 m deep dissect the early Lutetian shelf, in association with the development of the Mid-Eocene unconformity. These channels have yet to be widely mapped in detail (Robinson 2004; Robinson et al. 2004; DECC 2010), but there are indications that they may compare closely in scale, distribution and trend with those formed during a previous episode of basinal uplift at the start of the Eocene (Smallwood and Gill, 2002; Shaw Champion et al., 2008; Rudge et al., 2008; Hartley et al., 2011). Detritus eroded from the Lutetian shelf accumulated in a pile of overlapping fans – the Caledonia, Portree and Strachan fans of unit D – on the Mid-Eocene basin floor (Figures 22–24; see also Johnson et al. 2012, their Figure 30). At the end of the Lutetian, changes in relative sea-level, indicated by flooding surfaces that marked the end of fan deposition, brought about a resumption of shelf progradation, though further deposition on the basin margins was terminated by the development of another local unconformity – the Base-slope-apron (T2c) unconformity – during the early Bartonian.

5.1.1.3 Bartonian to Priabonian (phase 3)

The Middle to Upper Eocene sediments overlying the Base-slope-apron (T2c) unconformity are characterised on seismic data by prograding reflectors (unit E) that define another phase of significant shelf-margin progradation. These reflectors pass basinward into a tapering wedge of more gently-dipping high-amplitude events (Figure 8). This probably corresponds to a slope apron that interdigitates with submarine fan deposits at the base of the slope, in front of the advancing Mid- to Late Eocene shelf (Figure 25; see also Johnson et al. 2012, their Figure 31). The prograding clinoforms indicate water depths of several hundreds of metres. The adjacent shelf preserves much of its depositional topography from this time and the slightly incised courses of north-westerly-trending channels can be traced near the top of its slope on 3D seismic data (Robinson 2004; Robinson et al. 2004) (Figure 25).

5.1.1.4 Late Priabonian (phase 4)

At the southern margin of the Faroe-Shetland Basin, the upper part of the Stronsay Group locally includes a 200-metre thick mounded unit (unit F, the marginal fan) that probably originated as a debris flow abutting the Late Eocene shelf (Figure 10). The pattern of divergent reflectors, possibly related to folding, beneath the base of the unit (Base-marginal-fan T2b reflector) suggests that its deposition may be linked to renewed minor uplift and deformation close to the basin margin. Johnson et al. (2012; their Figure 32) have mapped the seismic-stratigraphic unit that represents this interval over a wider area, and have identified a number of areas with local thickening, including the infill of a contemporary growth syncline in the Guðrun Basin area (Figure 6).

5.1.2 Regional controls on stratigraphic development

Channelized incision of the Ypresian–early Lutetian (phase 1) shelf deposits, up to 200 m deep, occurred during the development of the Mid-Eocene (T2d) unconformity; incision of contemporary shelf deposits also characterises the Bartonian–Priabonian (phase 3) depositional package. In both cases, this reflects a fall in relative sea level. The mechanisms most commonly considered for falls in base level are eustasy, climate and tectonism (including mantle processes).

Inspection of Figure 27 shows that the Mid-Eocene (T2d) unconformity does not appear to coincide with a significant eustatic or glacio-eustatic fall in sea level, though the precise placement of the Mid-Eocene boundary remains to be confirmed. The absolute timing of the Bartonian–Priabonian phase of incision is also uncertain, though there are indications of a fluctuating eustatic curve. Although, eustatic/glacio-eustatic falls in sea level cannot be discounted in terms of accentuating relative sea-level change, the following observations might support tectonic processes as having the primary control on the stratigraphic architecture preserved in the Faroe–Shetland region:

- The deposition of the Munkagrunnur Ridge Delta has been directly linked to contemporary uplift of the Munkagrunnur Ridge (Ólavsdóttir et al., 2010).
- Uplift over a wider area, possibly including the late Ypresian/early Lutetian formation of the Judd and Westray anticlines (Smallwood, 2004; Ritchie et al., 2008; Johnson et al., 2012) (Figure 27) and intra-Lutetian uplift of the Flett High (Robinson et al., 2004), may be a regional response to compression associated with the development of the Mid-Eocene (T2d) unconformity. BGS borehole 99/3, which cored the axial region of the Judd anticline, proved a subaerial erosion surface on this boundary (Leslie et al., 2010), whereas major incisions associated with the Mid-Eocene (T2d) unconformity are developed above the Flett High, whose positive relief at this time influenced the trend of the incisions. The extent of the Mid-Eocene (T2d) unconformity at this time remains unclear, though the above noted areas of uplift incorporate (at least) Quadrants 6006, 6005, 6004/204 and 205 (Figure 22).
- The prograding shelf-margin deposits of unit E, which overlie the early Bartonian Base-slope-apron (T2c) unconformity, appear to be part of a well-defined shelf and slope apron that extends (at least) from Quadrant 204 in the SW, to Quadrant 208 in the NE (Figures 25 and 26). A late Lutetian–Bartonian phase of compression associated with the Judd and Westray anticlines has been reported by Smallwood (2004), Ritchie et al. (2008) and Johnson et al. (2012), which coincides approximately with the change in sedimentation pattern from phase 2 to phase 3 (Figure 27). However, the palaeogeographic reconstruction of the relatively broad shelf margin for the T98–T99 interval (Figures 25 and 26) might be indicative of regional uplift of the West Shetland region. By way of contrast, inspection of Figure 8 also reveals that unit E comprises several cycles of progradation manifest by the interdigitating relationship between the slope apron and the submarine fan deposits; and it is this unit that preserves the stacked series of incised channels on the adjacent shelf. Thus, a link to the eustatic/glacio-eustatic curve in Figure 27, which shows several lowstands in the Bartonian and Priabonian, cannot be discounted.
- Our study has also inferred a phase of uplift prior to the deposition of unit F, which represents depositional phase 4 in the area of Quadrant 204. Johnson et al. (2012) have suggested another phase of compression on the Judd Anticline, as well as uplift of the East Faroe High and the development of a growth syncline in the Guðrun Basin area (Figure 6), at this time.

It remains uncertain as to whether or not the potential intra-Eocene tectonism that we are inferring was restricted primarily to the eastern and southern part of the Faroe–Shetland region. According to Andersen et al. (2000), the Faroe Platform – as a positive feature – was formed at the end of the Eocene, and did not have any significant sedimentary input into the Faroe-Shetland Basin until the Oligocene. However, inspection of Figure 7b reveals a number of SE-dipping and converging reflectors within the Eocene succession on the Fugloy Ridge, which might represent south-easterly progradation but, without regional mapping, it is difficult to assess this issue. The north-westerly extent of these internal reflectors is clearly terminated at the boundary with the overlying Neogene–Quaternary succession. Other areas in the Faroe–Shetland region where Eocene tectonism has influenced deposition include: 1) the Wyville-Thomson Ridge, where small deltaic units derived from the ridge are preserved on its northern slope; and,

2) the Munkur Basin (Figure 6), which is interpreted to have formed as a response to Mid-Eocene inversion (Sørensen, 2003).

Any consideration of regional controls on stratigraphic development in the Faroe–Shetland region must also take account of the wider tectonic setting, notably the development of the Eurasian plate boundary to the north and west of the region, as well as deformation associated with the Pyrenean orogenic zone to the south. The Faroe–Shetland region flanks the southern margin of the oceanic Norwegian Basin (Figures 5b and 6). Whereas conventional kinematic models assume that Greenland and Eurasia moved apart as a two-plate system, new regional geophysical datasets and quantitative kinematic parameters indicate that this rift system underwent several adjustments after its inception, and that additional short-lived plate boundaries existed within certain domains (Gaina et al., 2009; Gernigon et al., 2009). The Norwegian Basin represents one of these domains, and its development is linked to microplate reorganisation since breakup until about 30 Ma (mid-Oligocene) when the Aegir Ridge became extinct, coincident with the formation of the Jan Mayen microcontinent in response to rifting and ridge propagation from the south-west and the north-east (Figure 5b) (Mosar et al., 2002a; Gaina et al., 2009). During the Eocene, two significant phases of extension and fragmentation occurred on the southern part of the Jan Mayen microcontinent during chrons C21 and C18 (Figure 27); both phases are associated with a change in spreading direction between Greenland and Eurasia, as well as a certain amount of counter-clockwise rotation of its southwestern margin as rifting (and ultimately ocean spreading) developed between Jan Mayen and Greenland (Figure 5b). This rotation has been linked to the fan-shaped spreading development of the Norwegian Basin in its later stage, as well as local compression on the eastern side of the Jan Mayen microcontinent and the southwestern part of the Norwegian Basin (Gaina et al., 2009). Whether or not these plate boundary forces exerted during C21 and C18 times extended into the Faroe–Shetland region remains uncertain; however, inspection of Figure 27 might invite speculation concerning a broad correlation between these chrons and the timing of development of the Mid-Eocene (T2d) and Base-slope-apron (T2c) unconformity surfaces, the two main Eocene growth phases of the Judd anticline (latest Ypresian/earliest Lutetian and latest Lutetian times) (Smallwood, 2004), and the relative uplift of the Flett High (Robinson et al., 2004). The pre-C21 growth of the Munkagrunnur Ridge may be indicative that such plate boundary forcing may have been active since breakup and the inception of ocean crust development. Such passive margin tectonic forcing has recently been demonstrated from the Rockall Plateau (Stoker et al., 2012).

Plate boundary deformation was also prevalent in Western Europe, south of the study area, during the Mid- to Late Eocene Pyrenean phase of orogenesis (Figure 27), which was driven by the collision between Eurasia and Iberia. Compressional deformation and inversion have been described from the Iberian, Biscay and southern Rockall margins (Masson et al., 1994; Pereira et al., 2011), from the West Alpine Foreland (Sissingh, 2001), and from the area in and around the southern British Isles (Hibsch et al., 1995). Whether or not these stresses were transmitted as far north as the Faroe–Shetland region is unclear; however, the initiation of spreading to the north and west of the Faroe–Shetland region combined with continental collision to the south would have placed this developing passive margin and intra-plate region in effective compression.

It is interesting to note that the three main clastic progradational phases of the Faroe–Shetland region are largely correlatable with established sandstone members of the Stronsay Group in the North Sea Basin (Figures 2 and 27). The influx of these clastic deposits has been attributed by Jones and Milton (1994) and Mudge and Bujak (1994) to uplift of the western margin of the North Sea Basin. The coincidence in timing of clastic influx between the two basins, together with the depositional symmetry across the Orkney-Shetland High might be indicative of repeated uplift of this platform area. This ‘broad’ uplift contrasts with the more specific, localised, compressional structures, such as the Judd and Westray anticlines in parts of the Faroe–Shetland region. Whilst this suggests that uplift may have occurred at a variety of scales, it also implies that its impact was regional; the apparent synchroneity of the tectonostratigraphic events testifies towards a common geodynamic cause.

5.2 IMPLICATIONS FOR PRE-STRONSAY GROUP (SYN-RIFT) UPLIFT

Immediately before the onset of sea-floor spreading in the Faroe-Shetland area, the widespread unconformity that formed within the earliest Eocene Moray Group can be linked to the development of a dendritic network of deep channels incised into the underlying Lamba Formation. In the southern part of the Faroe-Shetland Basin, this unconformity defines the base of biozone T45 (= base of the Upper Flett Formation), and the preceding uplift has been widely explained as a distant effect of the Iceland mantle plume (Smallwood and Gill, 2002; Shaw Champion et al., 2008; Rudge et al., 2008; Hartley et al., 2011). However, the stratigraphic evolution of the Stronsay Group, with its history of fluctuating shelf development, unconformities and channel incisions, has many features in common with the development of the Moray Group. It is significant that interpretations of seismic reflection data that aim to reconstruct the tectonic history of the Moray Group on the southern flanks of the Faroe-Shetland Basin, must first remove the effects of later Cenozoic deformation in the same area, by using seismic flattening software to restore Moray Group coal horizons to their original horizontal disposition. That this restoration is necessary highlights the fact that the Late Paleocene, Eocene and later Cenozoic deformations are co-extensive and spatially linked to the southern margin of the Faroe-Shetland Basin (Figure 9). This observation provides some support for a common tectonic origin of these features; by the end of the Eocene, however, the North Atlantic Ocean was probably up to 600 kilometres wide, and its axial mantle plume is unlikely to provide a consistent explanation for these repeated episodes of localised deformation. Indeed, the uplift of the Flett High and associated channel incision appears to coincide with a minimum in the influence of the proto-Iceland hotspot (Kimbell et al., 2005) (Figure 27).

6 Conclusions

A provisional stratigraphic framework has been established for the Eocene Stronsay Group succession in the Faroe–Shetland region. The stratigraphic architecture reveals a punctuated record of shelf-margin development and progradation, which we interpret as predominantly reflecting the passive margin response to early ocean spreading. On the basis of this framework our key conclusions are as follows:

- Four main depositional phases are provisionally recognised with sedimentary input – based on available data – mainly from the south and east of the study area. The following pattern of shelf-margin development is proposed:
  1. An initial Ypresian–early Lutetian (T60–lower T93) phase of upwards-coarsening deposition that included the build-out of the Munkagrunnur Ridge Delta into the southern part of the area, as well as an eastern depocentre in the Quadrant 205/208/214 area. Contemporary uplift is manifested by the growth of the Munkagrunnur Ridge. This phase was terminated by the development of the Mid-Eocene (T2d) unconformity, probably a regional response to compression and uplift over a wider area, including the initiation of the Judd and Westray anticlines and uplift of the Flett High.
  2. Major incision and erosion of the Ypresian–early Lutetian shelf deposits in Quadrant 205, and the concomitant deposition of the Lutetian–early Bartonian phase 2 basin-floor-fan sediments extending between Quadrants 205, 213 and 214. Channel incision and initial fan development may have been instigated in T93 times, and largely culminated in the accumulation of the Portree, Strachan and Caledonia fans by T96 times, though the Caledonia fan may have persisted into T97 times. Uplift of the Flett High and growth of the Judd and Westray anticlines continued throughout this interval. This phase of deposition was terminated by the development of the Base-slope-apron (T2c) unconformity.
  3. Renewed shelf-margin build-out characterises the Bartonian–Priabonian phase 3 depositional package, with large-scale clinoforms prograding north-westwards from the West Shetland margin. It is not clear whether this reflects regional or local uplift of this margin. The clinoforms interdigitate with submarine fan deposits at the base of the slope apron. Contemporary incision of phase 3 shelf deposits indicates falling relative sea level, which may or may not relate to eustatic/glacio-eustatic fluctuations.
  4. A localised debris flow deposit that characterises the Late Priabonian phase 3 sediment package at the southern margin of the Faroe–Shetland Basin may be one of a number of responses to renewed uplift of the basin margin, as well as localised uplift of intra-regional highs concomitant with the development of growth synclines elsewhere in the region (Johnson et al., 2012). The influence of eustatic/glacio-eustatic fluctuations cannot be discounted.
- On a wider scale, the boundaries separating phases 1 to 3 (i.e. the Mid-Eocene (T2d) and the Base-slope-apron (T2c) unconformities) appear to broadly correlate with important plate reorganisation events linked to the Jan Mayen micro-continent in the adjacent Norway Basin, as well as general NE Atlantic changes in spreading direction and rates. Moreover, a link to, or interaction with, phases of compressional deformation associated with orogenesis along the southern boundary of the Eurasian plate cannot be discounted. Our phases of shelf-margin progradation also broadly correlate with key phases of clastic input into the North Sea Basin. On this basis, we would suggest that our provisional tectonostratigraphic framework is consistent with a predominantly tectonic control on sedimentation.

Appendix 1 Stratigraphic-range chart

This appendix presents a stratigraphic-range chart for the Eocene Stronsay Group (Figure A1: back pocket) that places the commercial well data, BGS and DSDP boreholes, and seabed dredge sites used in this study into a temporal context. The main source of stratigraphical data was provided by released well-logs, supplemented with biostratigraphic information from Ichron Limited (2010a, b), CDA and Jarðfeingi (Table 1). Log information for DSDP site 336 is mainly from Talwani et al. (1976), whereas information for seabed dredge sites in Quadrants 6009 and 6105 is based on Jones and Ramsay (1982) and Waagstein and Heilmann-Clausen (1995), respectively. The Ichron Limited T-sequence scheme was used primarily for correlation purposes, although BGS, DSDP and dredge site data are linked into the standard Palaeogene calcareous nannofossil (NP) biozones. Additional information includes: 1) general lithological and thickness information; 2) the age and lithostratigraphy (where known) of the sub- and post-Stronsay Group rocks; 3) occasional explanatory notes addressing site-specific issues; and, 4) the provisional subdivision of the Stronsay Group arising out of this study.

(Note: Figure A.1 is located in the back-pocket)

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

JARÐFEINGI

Figure A1 Stratigraphic-range chart showing the generalised lithology, thickness and provisional subdivision of the Stronsay Group in the Faroe–Shetland region. The chart also shows the age of the sub- and post-Stronsay Group rocks. Timescale after Gradstein et al. (2004) and Ogg et al. (2008).

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://envirolib.bgs.ac.uk.

ABREU, V S, and ANDERSON, J B. 1998. Glacial eustasy during the Cenozoic: sequence stratigraphic implications. *American Association of Petroleum Geologists Bulletin*, Vol. 82, 1385–1400.

ANDERSEN, M S, NIELSEN, T, SØRENSEN, A B, BOLDREEL, L O, and KUIPERS, A. 2000. Cenozoic sediment distribution and tectonic movements in the Faroe region. *Global and Planetary Change*, Vol. 24, 239–259.

ANDERSEN, M S, SØRENSEN, A B, BOLDREEL, L O, and NIELSEN, T. 2002. Cenozoic evolution of the Faroe Platform: comparing denudation and deposition. 239–259 in Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. DORÉ, A G, CARTWRIGHT, J A, STOKER, M S, TURNER, J P, and WHITE, N (editors). *The Geological Society, London, Special Publication*, Vol. 196.

BERGGREN, W A., and SCHNITKER, D. 1983. Cenozoic marine environments in the North Atlantic and Norwegian-Greenland Sea. 495–548 in *Structure and Development of the Greenland-Scotland Ridge: new methods and concepts*. BOTT, M H P., SAXOV, S., TALWANI, M., and THIEDE, J. (editors). (New York: Plenum.)

BOLDREEL, L O, and ANDERSEN, M S. 1993. Late Paleocene to Miocene compression in the Faroe-Rockall area. 1025–1034 in *Petroleum Geology of NW Europe: Proceedings of the 4th conference.* PARKER, J R (editor). (London: The Geological Society.)

BOLDREEL, L O, and ANDERSEN, M S. 1998. Tertiary compressional structures on the Faroe-Rockall Plateau in relation to northeast Atlantic ridge-push and Alpine foreland stresses. *Tectonophysics*, Vol. 300, 13–28.

BREKKE, H. 2000. The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and Møre Basins. 327–378 in Dynamics of the Norwegian Margin. NØTTVEDT, A (editors). *Geological Society, London, Special Publications*, No. 167.

BUJAK, J P, and MUDGE, D C. 1994. A high-resolution North Sea Eocene dinocyst zonation. *Journal of the Geological Society, London*, Vol. 151, 449–462.

CLOETINGH, S, GRADSTEIN, F M, KOOI, H, GRANT, A C, and KAMINSKI, M. 1990. Plate reorganization: a cause of rapid late Neogene subsidence and sedimentation around the North Atlantic. *Journal of the Geological Society, London*, Vol. 147, 495–506

DAVIES, R J, and CARTWRIGHT, J. 2002. A fossilized OpalA to Opal C/T transformation on the northeast Atlantic margin: support for a significantly elevated Palaeogeothermal gradient during the Neogene? *Basin Research*, Vol. 14, 467–486.

DAVIES, R, CLOKE, I, CARTWRIGHT, J, ROBINSON, A, AND FERRERO, C. 2004. Post-breakup compression of a passive margin and its impact on hydrocarbon prospectivity: An example from the Tertiary of the Faroe-Shetland Basin, United Kingdom. *American Association of Petroleum Geologists Bulletin*, Vol. 88, 1–20.

DEAN, K, MCLAUCHLAN, K and CHAMBERS, A. 1999. Rifting and the development of the Faeroe-Shetland Basin. 533–544 in *Petroleum Geology of Northwest Europe, Proceedings of the 5th Conference.* FLEET, A J, AND BOLDY, S A R (editors). (London: The Geological Society.)

DECC 2010. *Promote United Kingdom 2011: Petroleum Potential of the United Kingdom*. December 2010 release.

DORÉ, A G and LUNDIN, E R. 1996. Cenozoic compressional structures on the NE Atlantic margin: nature, origin and potential significance for hydrocarbon exploration. *Petroleum Geoscience*, Vol. 2, 299–311.

DORÉ, A G, LUNDIN, E R, JENSEN, L N, BIRKELAND, Ø, ELIASSEN, P E, and FICHLER, C. 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. 41–61 in *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. FLEET, A J and BOLDY, S A R (editors). (London: The Geological Society.)

DORÉ, A G, CARTWRIGHT, J A, STOKER, M S, TURNER, J P, and WHITE, N. (editors). 2002. Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. *Geological Society, London, Special Publications*, No. 196.

DORÉ, A G, LUNDIN, E R, KUSZNIR, N J, and PASCAL, C. 2008. Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas. 1–26 in The Nature of Compression in Passive Margins. *Geological Society, London, Special Publications*, N. 306.

EBDON, C C, GRANGER, P J., JOHNSON, H D, and EVANS, A M. 1995. Early Tertiary evolution and sequence stratigraphy of the Faroe-Shetland Basin: implications for hydrocarbon prospectivity. 51–69 in The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region. SCRUTTON, R A, STOKER, M S, SHIMMIELD, GB, AND TUDHOPE, A W (editors). *The Geological Society, London, Special Publication*, No. 90.

FOULGER, G R. 2002. Plumes, or plate tectonic processes? *Astronomy and geophysics*, Vol. 43, 19–23.

FOULGER, G R, and ANDERSEN, D L. 2005. A cool model for the Iceland hot spot. *Journal of Volcanology and Geothermal Research*, Vol. 141, 1–22.

GAINA, C, GERNIGON, L, and BALL, P. 2009. Palaeocene–Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent. *Journal of the Geological Society, London*, Vol. 166, 601–616.

GALLOWAY, W E, GARBER, J L, XIJIN, L, and SLOAN, B J. 1993. Sequence stratigraphic and depositional framework of the Cenozoic fill, central and northern North Sea basin. 33–43 in *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. PARKER, J R (editor). (London: The Geological Society.)

GERNIGON, L, OLESEN, O, EBBING, J, WIENECKE, S, GAINA, C, MOGAARD, J O, SAND, M, and MYKLEBUST, R. 2009. Geophysical insights and early spreading history in the vicinity of the Jan Mayen Fracture Zone, Norwegian–Greenland Sea. *Tectonophysics*, Vol. 468, 185–205.

GRADSTEIN, F M, OGG, J G, and SMITH, A G. 2004. *A Geologic Time Scale 2004*. (Cambridge: Cambridge University Press.)

HARTLEY, R A, ROBERTS, G G, WHITE, N, and RICHARDSON, C. 2011. Transient convective uplift of an ancient buried landscape. *Nature Geoscience*, Vol. 4, 562–565.

HIBSCH, C, JARRIGE, J-J, CUSHING, E M, and MERCIER, J. 1995. Palaeostress analysis, a contribution to the understanding of basin tectonics and geodynamic evolution. Example of Permian/Cenozoic tectonics of Great Britain and geodynamic implications in western Europe. *Tectonophysics*, Vol. 252, 103–136.

HITCHEN, K. (compiler) 1999. Rockall Continental Margin Project. Shallow Borehole Drilling Programme 1999. Geological Report. *British Geological Survey Technical Report*, WB/99/21C.

HOLFORD, S P, GREEN, P F, DUDDY, I R, TURNER, J P, HILLIS, R R, and STOKER, M S. 2009. Regional intraplate exhumation episodes related to plate-boundary deformation. *Geological Society of America Bulletin*, Vol. 121, 1611–1628.

HOLFORD, S P, GREEN, P F, HILLIS, R R, UNDERHILL, J R, STOKER, M S, and DUDDY, I R. 2010. Multiple post-Caledonian exhumation episodes across NW Scotland revealed by apatite fission-track analysis. *Journal of the Geological Society, London*, Vol. 167, 675–694.

ICHRON LIMITED. 2010a. *Faroe-Shetland Basin Stratigraphic Database (2010 update)*. Ichron Limited 04/722/B, Non-Proprietary Study.

ICHRON LIMITED. 2010b. *Phase 2: Faroe-Shetland Basin Stratigraphic Database (2010 update)*. Ichron Limited 05/857/B, Non-Proprietary Study.

JAPSEN, P, and CHALMERS, J A. 2000. Neogene uplift and tectonics around the North Atlantic: overview. *Global and Planetary Changes*, Vol. 24, 165–173.

JAPSEN, P, CHALMERS, J A, GREEN, P F, and BONOW, J M. 2011. Elevated, passive continental margins: Not rift shoulders, but expressions of episodic post-rift burial and exhumation. *Global and Planetary Change*, in press, doi: 10.1016/j.gloplacha.2011.05.004.

JOHNSON, H, RICHARDS, P C, LONG, D, and GRAHAM, C C. 1993. *United Kingdom Offshore Regional Report: the geology of the northern North Sea*. HMSO for the British Geological Survey, London.

JOHNSON, H, RITCHIE, J D, HITCHEN, K, MCINROY, D B, and KIMBELL, G S. 2005. Aspects of the Cenozoic deformational history of the northeast Faroe-Shetland Basin, Wyville-Thomson Ridge and Hatton Bank areas. 993–1007 in *Petroleum Geology: NW Europe and Global Perspectives: Proceedings of the 6th Conference*. DORÉ, A.G. and VINING, B (editors). (London: The Geological Society.)

JOHNSON, H, QUINN, M F, STOKER, M S, SMITH, K, VARMING, T, ÓLAVSDÓTTIR, J, RITCHIE, J D, KIMBELL, G S, WOODWARD, C, and HENDERSON, A F. 2012. Cenozoic pre- and post-breakup compression in the Faroe–Shetland area within the context of the NE Atlantic margin. *British Geological Survey Commissioned Research Report*, CR/12/017.

JOLLEY, D W, and BELL, B R. 2002. The evolution of the North Atlantic Igneous Province and the opening of the NE Atlantic rift. 1–13 in The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes. JOLLEY, D W, and BELL, B R. (editors). *The Geological Society, London, Special Publication*, Vol. 197.

JOLLEY, D W, MORTON, A, and PRINCE, I. 2005. Volcanogenic impact on phytogeography and sediment dispersal patterns in the NE Atlantic. 969–975 in *Petroleum Geology: North-West Europe and Global Perspectives, Proceedings of the 6th Petroleum Geology Conference*. DORÉ, A G, and VINING, B A (editors). (London: The Geological Society.)

JONES, E, JONES, R, EBDON, C, EWEN, D, MILNER, P, PLUNKETT, J, HUDSON, G, and SLATER, P. 2003. Eocene. 261–277 in *The Millennium Atlas: petroleum geology of the central and northern North Sea*. EVANS, D, GRAHAM, C, ARMOUR, A, and BATHURST, P (editors and co-ordinators). (London: The Geological Society.)

JONES, E J W., and RAMSAY, A T S. 1982. Volcanic ash deposits of early Eocene age from the Rockall Trough. *Nature*, Vol. 299, 342–344.

JONES, R W, and MILTON, N J. 1994. Sequence development during uplift: Palaeogene stratigraphy and relative sea-level history of the outer Moray Firth, UK North Sea. *Marine and Petroleum Geology*, Vol. 11, 157–165.

JONES, S M, WHITE, N, CLARKE, B J, ROWLEY, E, and GALLAGHER, K. 2002. Present and past influence of the Iceland Plume on sedimentation. 13–25 in Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. DORÉ, A G, CARTWRIGHT, J A, STOKER, M S, TURNER, J P, and WHITE, N (editors). *The Geological Society, London, Special Publication*, Vol. 196.

KIMBELL, G S, RITCHIE, J D, JOHNSON, H, and GATLIFF, R W. 2005. Controls on the structure and evolution of the NE Atlantic margin revealed by regional potential field imaging and 3D modelling. 933–945 in *Petroleum Geology: North-West Europe and*

Global Perspectives, Proceedings of the 6th Petroleum Geology Conference. DORÉ, A G, and VINING, B A (editors). (London: The Geological Society.)

KNOX, R W O'B. 1996. Tectonic controls on sequence development in the Palaeocene and earliest Eocene of southeast England: implications for North Sea stratigraphy. 209–230 in Sequence Stratigraphy in British Geology. HESSELBO, S. P. and PARKINSON, D.N. (editors), *The Geological Society, London, Special Publication*, Vol. 103.

KNOX, R W O'B, and HOLLOWAY, S. 1992. 1. Palaeogene of the Central and Northern North Sea. In: *Lithostratigraphic nomenclature of the UK North Sea*. KNOX, R W O'B, and CORDEY, W G (editors). (Nottingham: British Geological Survey.)

KNOX, R W O'B, HOLLOWAY, S, KIRBY, G A, and BAILEY, H E. 1997. *Stratigraphic Nomenclature of the UK North West Margin. 2. Early Palaeogene lithostratigraphy and sequence stratigraphy*. British Geological Survey, Nottingham.

KJELSTAD, A, SKOGSEID, J, LANGTANGEN, H P, BJØRLYKKE, K, and HØEG, K. 2003. Differential loading by prograding sedimentary wedges on continental margins: An arch-forming mechanism. *Journal of Geophysical Research*, Vol. 108, doi:10.1029/2001JB001145.

LAMERS, E, and CARMICHAEL, S M M. 1999. The Paleocene deepwater sandstone play West of Shetland. 645–659 in *Petroleum Geology of Northwest Europe, Proceedings of the 5th Conference*. FLEET, A J, and BOLDY, S A R (editors). (London: The Geological Society).

LARSEN, M, RASMUSSEN, T, and HJELM, L. 2010. Cretaceous revisited: exploring the syn-rift play of the Faroe-Shetland Basin. 953–962 in *Petroleum Geology—From mature basins to new frontiers. Proceedings of the 7th Petroleum Geology Conference*. VINING, B and PICKERING, S. (editors). (London: The Geological Society.)

LESLIE, A B., HITCHEN, K., and STOKER, M S. 2010. *Sedimentology of the Eocene Succession in BGS Borehole 99/3*. British Geological Survey Commissioned Report, CR/10/141.

LOVELL, B. 2010. A pulse in the planet: regional control of high-frequency changes in relative sea level by mantle convection. *Journal of the Geological Society, London*, Vol. 167, 637–648.

LUNDIN, E, and DORÈ, A G. 2002. Mid-Cenozoic post-breakup deformation in the "passive" margins bordering the Norwegian-Greenland Sea. *Marine and Petroleum Geology*, Vol. 19, 79–93

LUNDIN, E, and DORÉ, A G. 2005a. NE Atlantic break-up: a re-examination of the Iceland mantle plume model and the Atlantic-Arctic linkage. 933–945 in *Petroleum Geology: North-West Europe and Global Perspectives, Proceedings of the 6th Petroleum Geology Conference*. DORÉ, A G, and VINING, B (editors). (London: The Geological Society.)

LUNDIN, E R, and DORÉ, A G. 2005b. Fixity of the Iceland 'hotspot' on the Mid-Atlantic Ridge: Observational evidence, mechanisms, and implications for Atlantic volcanic margins. 627–651 in Plates, Plumes and Paradigms. Foulger, G R, Natland, J H, Presnall, D C, and Anderson, D L (editors). *Geological Society of America Special Paper* 388.

LUNDIN, E R, and SIGMOND, E M O. 2007. Geology of the Northeast Atlantic region (Grønlandshavet and Norskehavet). 63–68 in *Geology of the land and sea areas of northern Europe*. SIGMOND, E M O, and ROBERTS, D (editors). Norges geologiske undersøkelse Special Publication 10.

LUNDIN, E R, and DORÉ, A G. 2011. Hyperextension, serpentinisation, and weakening: A new paradigm for rifted compressional deformation. *Geology*, Vol. 39, 347–350.

MACLENNAN, J, and LOVELL, B. 2002. Control of regional sea level by regional uplift and subsidence caused by magmatic underplating of Earth's crust. *Geology*, Vol. 30, 675–678.

MASSON, D G, CARTWRIGHT, J A, PINHEIRO, L M, WHITMARSH, R B, BESLIER, M –O and ROESER, H. 1994. Compressional deformation at the ocean–continent transition in the NE Atlantic. *Journal of the Geological Society, London*, Vol. 151, 607–613.

MILLER, K G, KOMINZ, M A, BROWNING, J V, WRIGHT, J D, MOUNTAIN, G S, KATZ, M E, SUGARMAN, P J, CRAMER, B S, CHRISTIE-BLICK, N, and PEKAR, S K. 2005. The Phanerozoic record of global sea-level change. *Science*, Vol. 310, 1293–1298.

MOSAR, J, TORSVIK, T H, and the BAT team. 2002a. Opening of the Norwegian and Greenland Seas: Plate tectonics in Mid Norway since the Late Permian. 48–59 in *BATLAS — Mid Norway plate reconstruction atlas with global and Atlantic perspectives*. EIDE, E A (co-ordinator). (Trondheim: Geological Survey of Norway.)

MOSAR, J, LEWIS, G, and TORSVIK, T H. 2002b. North Atlantic sea-floor spreading rates: implications for the Tertiary development of inversion structures of the Norwegian-Greenland Sea. *Journal of the Geological Society, London*, Vol. 159, 503–515.

MUDGE, D C, and BUJAK, J P. 1994. Eocene stratigraphy of the North Sea basin. *Marine and Petroleum Geology*, Vol. 11, 166–181.

MUDGE, D C, and BUJAK, J P. 1996. An integrated stratigraphy for the Paleocene and Eocene of the North Sea. 91–113 in Correlation of the Early Paleogene in Northwest Europe. KNOX, R W O'B, CORFIELD, R M, and DUNAY, R E (editors). *Geological Society, London, Special Publication*, No. 101.

MUDGE, D C, and JONES, S M. 2004. Palaeocene uplift and subsidence events in the Scotland–Shetland and North Sea region and their relationship to the Iceland Plume. *Journal of the Geological Society, London*, Vol. 161, 381–386.

NEAL, J E. 1996. A summary of Paleogene sequence stratigraphy in northwest Europe and the North Sea. 15–42 in *Correlation of the Early Paleogene in northwest Europe*. KNOX, R W O'B, CORFIELD, R M, and DUNAY, R E (editors). (London: The Geological Society.)

NILSEN, T H. 1978. Lower Tertiary laterite on the Iceland-Faeroe Ridge and the Thulean land bridge. *Nature*, Vol. 274, 786–788.

NILSEN, T H., and KERR, D R. 1978. Turbidites, redbeds, sedimentary structures and trace fossils observed in DSDP leg 38 cores and the sedimentary history of the Norwegian-Greenland Sea. 259–288 in *Supplement to Volumes XXXVIII, XXXIX, XL and XLI of the Deep Sea Drilling Project*. (Washington: US Government Printing Office.).

OGG, J G, OGG, G, and GRADSTEIN, F M. 2008. *The Concise Geologic Time Scale*. (Cambridge: Cambridge University Press.)

ÓLAVSDÓTTIR, J., BOLDREEL, L O., and ANDERSEN, M S. 2010. Development of a shelf margin delta due to uplift of the Munkagrunnur Ridge at the margin of Faroe-Shetland Basin: a seismic sequence stratigraphic study. *Petroleum Geoscience*, Vol. 16, 91–103.

PASSEY, S R, and JOLLEY, D W. 2009. A revised lithostratigraphic nomenclature for the Palaeogene Faroe Islands Basalt Group, NE Atlantic Ocean. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, Vol. 99, 127–158.

PASSEY, S R, and HITCHEN, K. 2011. Cenozoic (igneous). 209–228 in Geology of the Faroe-Shetland Basin and adjacent areas. RITCHIE, J D, ZISKA, H, JOHNSON, H, and EVANS, D (editors). *British Geological Survey Research Report*, RR/11/01, *Jarðfeingi Research Report*, RR/11/01.

PEREIRA, R, ALVES, T A, and CARTWRIGHT, J A. 2011. Post-rift compression on the SW Iberian margin (eastern North Atlantic): a case for prolonged inversion in the ocean–continent transition zone. *Journal of the Geological Society, London*, Vol. 168, 1249–1263.

PRAEG, D, STOKER, M S, SHANNON, P M, CERAMICOLA, S, HJELSTUEN, B O, LABERG, J S, and MATHIESEN, A. 2005. Episodic Cenozoic tectonism and the development of the NW European 'passive' continental margin. *Marine and Petroleum Geology*, Vol. 22, 1007–1030.

QUINN, M, VARMING, T, and ÓLAVSDÓTTIR, J. 2011. Petroleum geology. 254–280 in RITCHIE, J D, ZISKA, H, JOHNSON, H, and EVANS, D (editors). *British Geological Survey Research Report*, RR/11/01, *Jarðfeingi Research Report*, RR/11/01.

RITCHIE, J D, GATLIFF, R W, and RICHARDS, P C. 1999. Early Tertiary magmatism in the offshore NW UK margin and its surrounds. 573–584 in *Petroleum Geology of Northwest Europe, Proceedings of the 5th Conference*. FLEET, A J, and BOLDY, S A R (editors). (London: The Geological Society).

RITCHIE, J D, JOHNSON, H, and KIMBELl, G S. 2003. The nature and age of Cenozoic contractional deformation within the NE Faroe-Shetland Basin. *Marine and Petroleum Geology*, Vol. 20, 399–409.

RITCHIE, J D, JOHNSON, H, QUINN, M F, and GATLIFF, R. W. 2008. Cenozoic compressional deformation within the Faroe-Shetland Basin and adjacent areas. 121–136 in The Nature and Origin of Compression in Passive Margins. JOHNSON, H, DORÉ, A G, HOLDSWORTH, R E, GATLIFF, R W, LUNDIN, E R, and RITCHIE, J.D (editors). *The Geological Society, London, Special Publication*, No. 306.

RITCHIE, J D, ZISKA, H, KIMBELL, G, QUINN, M, and CHADWICK, A. 2011. Structure. 9–70 in *The Geology of the Faroe-Shetland Basin, and adjacent areas*. RITCHIE, J D, ZISKA, H, JOHNSON, H, and EVANS, D (compilers). British Geological Survey, Edinburgh and Jarðfeingi, Torshavn.

ROBERTS, D G, THOMPSON, M, MITCHENER, B, HOSSACK, J, CARMICHAEL, S, and BJORNSETH, H-M. 1999. Palaeozoic to Tertiary rift and basin dynamics: mid-Norway to the Bay of Biscay - a new context for hydrocarbon prospectivity in the deep water frontier. 7–40 in *Petroleum geology of NW Europe: Proceedings of the 5th conference.* FLEET, A.J. and BOLDY, S.A.R (editors). (London: The Geological Society.)

ROBINSON, A M. 2004. *Stratigraphic development and controls on the architecture of Eocene depositional systems in the Faroe-Shetland Basin*. University of Cardiff PhD thesis (unpublished).

ROBINSON, A M, CARTWRIGHT, J, BURGESS, P M, and DAVIES, R.J. 2004. Interactions between topography and channel development from 3D seismic analysis: an example from the Tertiary of the Flett Ridge, Faroe-Shetland Basin, UK. 73–82 in 3D seismic Technology: Application to the Exploration of Sedimentary Basins. DAVIES, R J, CARTWRIGHT, J A, STEWART, S A, LAPPIN, M, and UNDERHILL, J R (editors). *The Geological Society, London, Memoir* 29.

ROHRMAN, M, and VAN DER BEEK, P. 1996. Cenozoic postrift domal uplift of North Atlantic margins: an asthenospheric diapirism model. *Geology*, Vol. 24, 901–904.

RUDGE, J F, SHAW CHAMPION, M E, WHITE, N, MCKENZIE, D, and LOVELL, B. 2008. A plume model of transient diachronous uplift at the Earth's surface. *Earth and Planetary Science Letters*, Vol. 267, 146–160.

SAUNDERS, A D, FITTON, J G, KERR, A C, NORRY, M J, AND KENT, R W. 1997. The North Atlantic Igneous Province. 45–93 in *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. MAHONEY, J J, and COFFIN, M F (editors). American Geophysical Union Geophysical Monograph, No. 100.

SCHRADER, H-J., and FENNER, J. 1976. 30. Norwegian Sea Cenozoic diatom biostratigraphy and taxonomy; Part 1, Norwegian Sea Cenozoic diatom biostratigraphy. 921–962 in *Initial reports of the Deep Sea Drilling Project*, **38.** TALWANI, M., UDINTSEV, G., *ET AL*. (editors). (Washington: US Government Printing Office.)

SHAW CHAMPION, M E, WHITE, N J, JONES, S M, and LOVELL, J P B. 2008. Quantifying transient mantle convective uplift: An example from the Faroe-Shetland basin. *Tectonics*, Vol. 27, TC1002, doi:10.1029/2007TC002106.

SISSINGH, W. 2001. Tectonostratigraphy of the West Alpine Foreland: correlation of Tertiary sedimentary sequences, changes in eustatic sea-level and stress regimes. *Tectonophysics*, Vol. 333, 361–400.

SKOGSEID, J, PLANKE, S, FALEIDE, J L, PEDERSEN, T, ELDHOLM, O, and NEVERDAL, F. 2000. NE Atlantic continental rifting and volcanic margin formation. 295–326 in Dynamics of the Norwegian Margin. Nøttvedt, A (editor). *Geological Society, London, Special Publication*, No. 167.

SMALLWOOD, J R. 2004. Tertiary inversion in the Faroe-Shetland Channel and the development of major erosional scarps. 187–198 in 3D seismic Technology: Application to the Exploration of Sedimentary Basins. DAVIES, R J, CARTWRIGHT, J A, STEWART, S A, LAPPIN, M, and UNDERHILL, J R (editors). *The Geological Society, London, Memoir* 29.

SMALLWOOD, J R, and GILL, C E. 2002. The rise and fall of the Faroe-Shetland Basin; evidence from seismic mapping of the Balder Formation. *Journal of the Geological Society, London*, Vol. 159, 627–630.

SMALLWOOD, J R, and WHITE, R S. 2002. Ridge-plume interaction in the North Atlantic and its influence on continental breakup and seafloor spreading. 15–37 in The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes. JOLLEY, D W, and BELL, B R (editors). *The Geological Society, London, Special Publication*, No. 197.

SMALLWOOD, J R, and KIRK, W J. 2005. Paleocene exploration in the Faroe-Shetland Channel: disappointments and discoveries. 977–991 in *Petroleum Geology: North-West Europe and Global Perspectives, Proceedings of the 6th Petroleum Geology Conference*. DORÉ, A G, and VINING, B (editors). (London: The Geological Society.)

SØRENSEN, A B. 2003. Cenozoic basin development and stratigraphy of the Faroes area. *Petroleum Geoscience*, Vol. 9, 189–207.

STOKER, M. S. 2002 Late Neogene development of the UK Atlantic margin. 313–329 in Exhumation of the North Atlantic margin: Timing, mechanisms and implications for petroleum exploration. DORÉ, A G, CARTWRIGHT, J A, STOKER, M S, TURNER, J P, and WHITE, N. (editors). *The Geological Society, London, Special Publication* No. 196.

STOKER, M S, PRAEG, D, HJELSTUEN, B O, LABERG, J S, NIELSEN, T, and SHANNON, P M. 2005a. Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin. *Marine and Petroleum Geology*, Vol. 22, 977–1005.

STOKER, M S, PRAEG, D, SHANNON, P M, HJELSTUEN, B O, LABERG, J S, VAN WEERING, T C E, SEJRUP, H P, and EVANS, D. 2005b. Neogene evolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): anything but passive. 1057–1076 in *Petroleum Geology: North-West Europe and Global Perspectives, Proceedings of the 6th Petroleum Geology Conference*. DORÉ, A G, and VINING, B (editors). (London: The Geological Society.)

STOKER, M S, HOULT, R J, NIELSEN, T, HJELSTUEN, B O, LABERG, J S, SHANNON, P M, PRAEG, D, MATHIESEN, A, VAN WEERING, T C E, and MCDONNELL, A. 2005c. Sedimentary and oceanographic responses to early Neogene compression on the NW European margin. *Marine and Petroleum Geology*, Vol. 22, 1031–1044.

STOKER, M S, MCINROY, D B, JOHNSON, H, and RITCHIE, J D. 2010a. Cretaceous Tectonostratigraphy of the Faroe–Shetland Region. *British Geological Survey Commissioned Research Report*, CR/10/144.

STOKER, M S, HOLFORD, S P, HILLIS, R R, GREEN, P F, and DUDDY, I R. 2010b. Cenozoic post-rift sedimentation off northwest Britain: Recording the detritus of episodic uplift on a passive continental margin. *Geology*, Vol. 38, 595–598.

STOKER, M S, and VARMING, T. 2011. Cenozoic (sedimentary). 151–208 in RITCHIE, J D, ZISKA, H, JOHNSON, H, and EVANS, D (editors). *British Geological Survey Research Report*, RR/11/01, *Jarðfeingi Research Report*, RR/11/01.

STOKER, M S, KIMBELL, G S, MCINROY, D B, and MORTON, A C. 2012. Eocene post-rift tectonostratigraphy of the Rockall Plateau, Atlantic margin of NW Britain: linking early spreading tectonics and passive margin response. *Marine and Petroleum Geology*, in press: http://dx.doi.org/10.1016/j.marpetgeo.2011.09.007

TALWANI, M., and UDINTSEV, G. 1976. 24. Tectonic synthesis. 1213–1242 in *Initial reports of the Deep Sea Drilling Project*, 38. TALWANI, M., UDINTSEV, G., *ET AL*. (editors). (Washington: US Government Printing Office.)

TALWANI, M., UDINTSEV, G., *ET AL*. 1976. 2. Sites 336 and 352. 23–116 in *Initial reports of the Deep Sea Drilling Project*, 38. TALWANI, M., UDINTSEV, G., *ET AL*. (editors). (Washington: US Government Printing Office.)

TUITT, A, UNDERHILL, J R, RITCHIE, J D, JOHNSON, H, and HITCHEN, K. 2010. Timing, controls and consequences of compression in the Rockall–Faroe area of the NE Atlantic margin. 963–977 in *Petroleum Geology—From mature basins to new frontiers. Proceedings of the 7th Petroleum Geology Conference*. VINING, B and PICKERING, S. (editors). (London: The Geological Society.)

TURNER, J D, and SCRUTTON, R A. 1993. Subsidence patterns in western margin basins: evidence from the Faeroe-Shetland Basin. 975–983 in *Petroleum Geology of Northwest Europe, Proceedings of the 4th Conference*. PARKER, J.R. (editor). (London: The Geological Society.)

VÅGNES, E, GABRIELSEN, R H, and HAREMO, P. 1998. Late Cretaceous–Cenozoic intraplate contractional deformation at the Norwegian continental shelf: timing, magnitude and regional implications. *Tectonophysics*, Vol. 300, 29–46

VANNESTE, K, HENRIET, J-P, POSEWANG, J, and THIELEN, F. 1995. Seismic stratigraphy of the Bill Bailey and Lousy Bank area: implications for subsidence history. 125–139 in The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region. SCRUTTON, R A, STOKER, M S, SHIMMIELD, G B, and TUDHOPE, A.W (editors) *The Geological Society, London, Special Publication*, No. 90.

WAAGSTEIN, R. and HEILMANN-CLAUSEN, C. 1995. Petrography and biostratigraphy of Palaeogene volcaniclastic sediments dredged from the Faeroes Shelf. 179–197 in The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region. SCRUTTON, R A., STOKER, M S., SHIMMIELD, G B., and TUDHOPE, A W. (editors). *The Geological Society, London, Special Publication*, Vol. 90.

WESTERHOLD, T., ROHL, U., ,MCCARREN, H K. and ZACHOS, J C. 2009. Latest on the absolute age of the Paleocene-Eocene Thermal Maximum (PETM): New insights from exact stratigraphic position of key ash layers + 19 and -17. *Earth and Planetary Science Letters*, Vol. 287, 412–419.

WHITE, N, and LOVELL, B. 1997. Measuring the pulse of a plume with the sedimentary record. *Nature*, Vol. 387, 888–891.

WHITE, R S. 1988. A hot-spot model for early Tertiary volcanism in the N Atlantic. 3–13 in Early Tertiary Volcanism and the Opening of the NE Atlantic. MORTON, A C, and PARSON, L M. (eds). *The Geological Society , London, Special Publication*, No. 39.

WHITE, R S. 1989. Initiation of the Iceland plume and opening of the North Atlantic. 149–154 in Extensional Tectonics and Stratigraphy of the North Atlantic Margins. TANKARD, A J, and BALKWILL, H R (editors). *American Association of Petroleum Geologists Memoir,* No. 46.

WHITE, R S, and MACKENZIE, D. 1989. Magmatism at rift zones: The generation of volcanic margins and flood basalts. *Journal of Geophysical Research*, Vol. 94, 7685–7729.

ZIEGLER, P A. 1988. *Evolution of the Arctic–North Atlantic and the Western Tethys*. American Association of Petroleum Geologists Memoir 43. (Tulsa: USA).

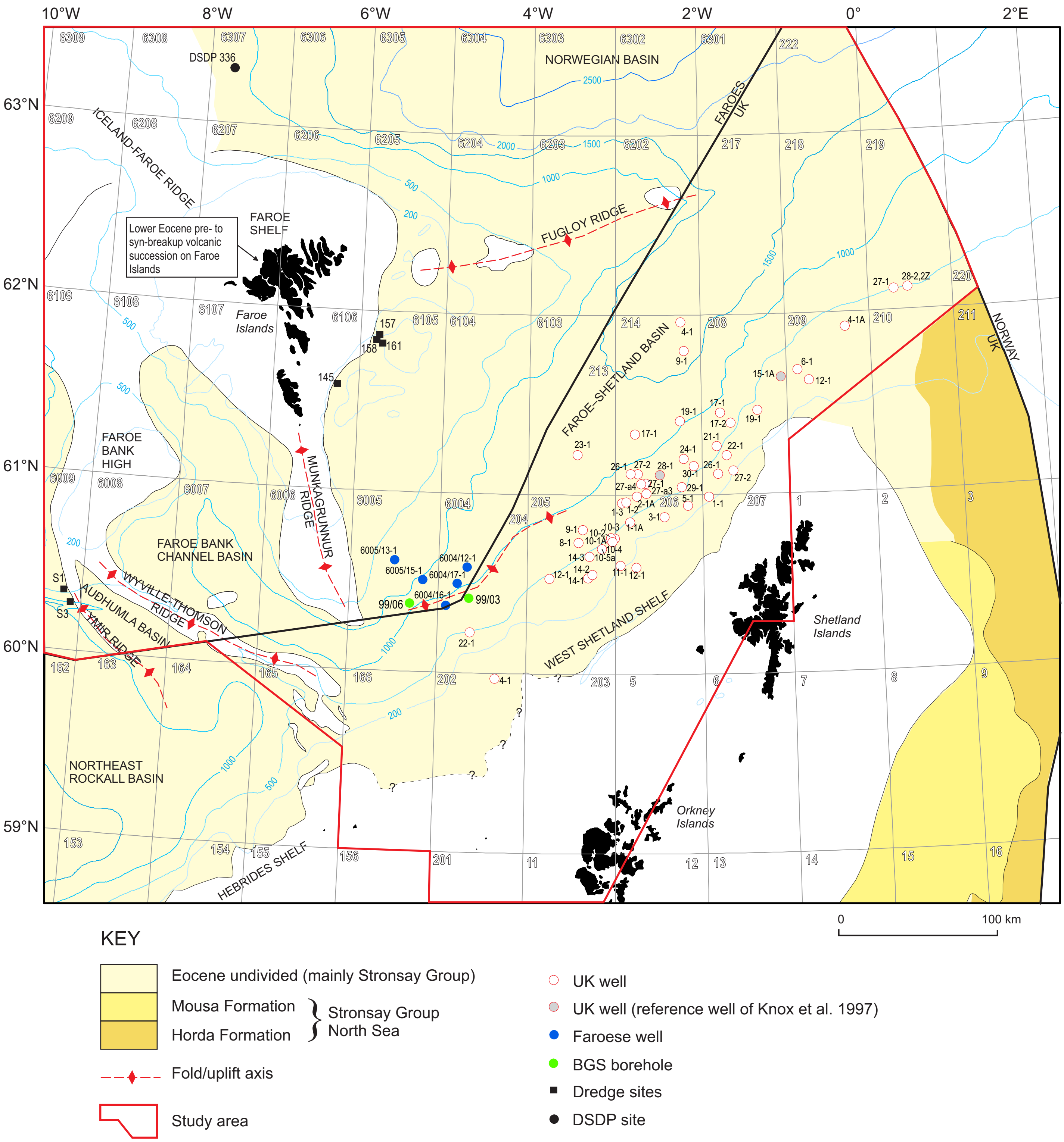
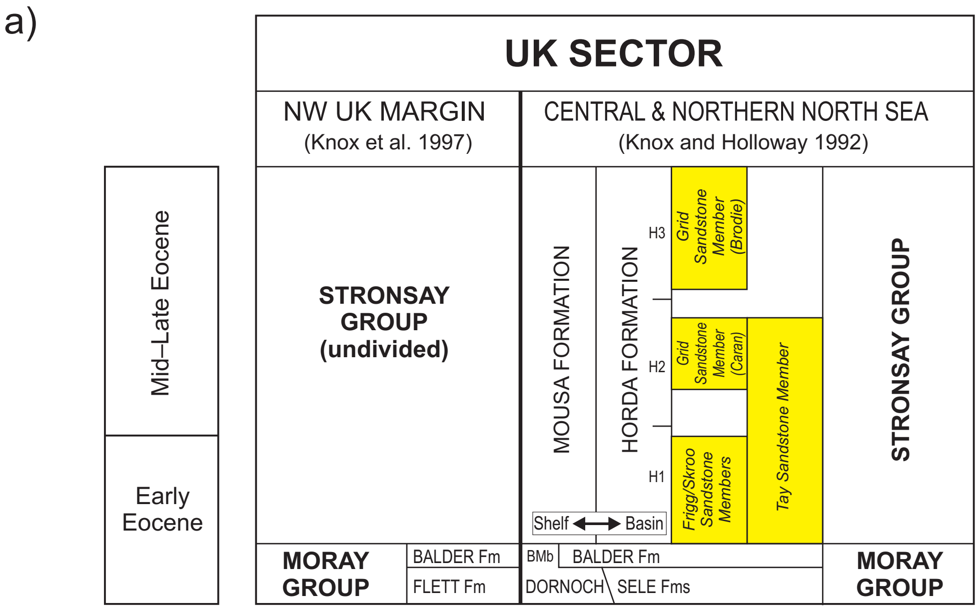


Figure 1 Location of study area, distribution of Eocene rocks, position of commercial wells, BGS and DSDP boreholes and dredge sites used in this study. North Sea information derived from Johnson et al. (1993) and Knox and Holloway (1992). Bathymetry in metres.



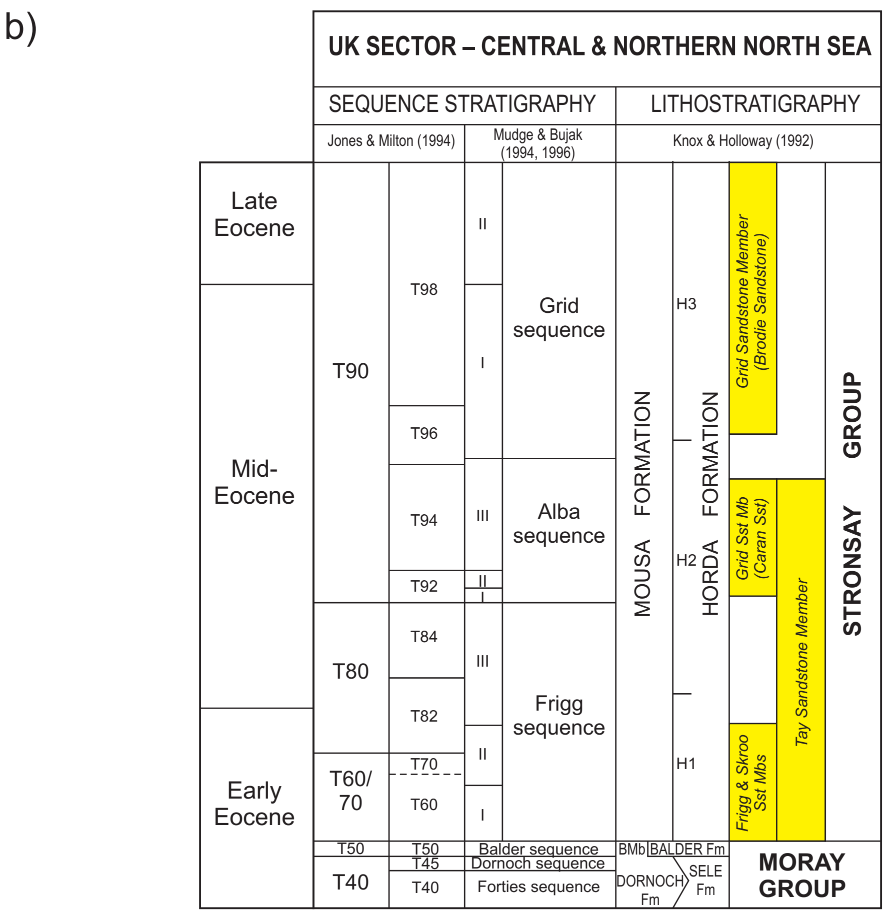


Figure 2 (a) Existing lithostratigraphic terminology for, and correlation between, the Eocene successions on the NW UK margin and the central and Northern North Sea. (b) Correlation between the sequence-stratigraphic and lithostratigraphic schemes in the central and northern North Sea. In (b), the correlation between the 'T' sequences of Jones and Milton (1994) and the sequence stratigraphy of Mudge and Bujak (1994, 1996) is taken from Jones et al. (2003); however, the correlation between Mudge and Bujak's sequences and the lithostratigraphy is taken from Mudge and Bujak (1994). This contrasts with Jones et al. (2003) who place the sandstone members as follows: base upper Grid, in T94; base lower Grid, in T84; top Frigg/Skroo at top T70. It should be noted that the basal Moray Group units and the T40 sequence extend into the Late Paleocene. Abbreviation: BMb, Beauly Member.

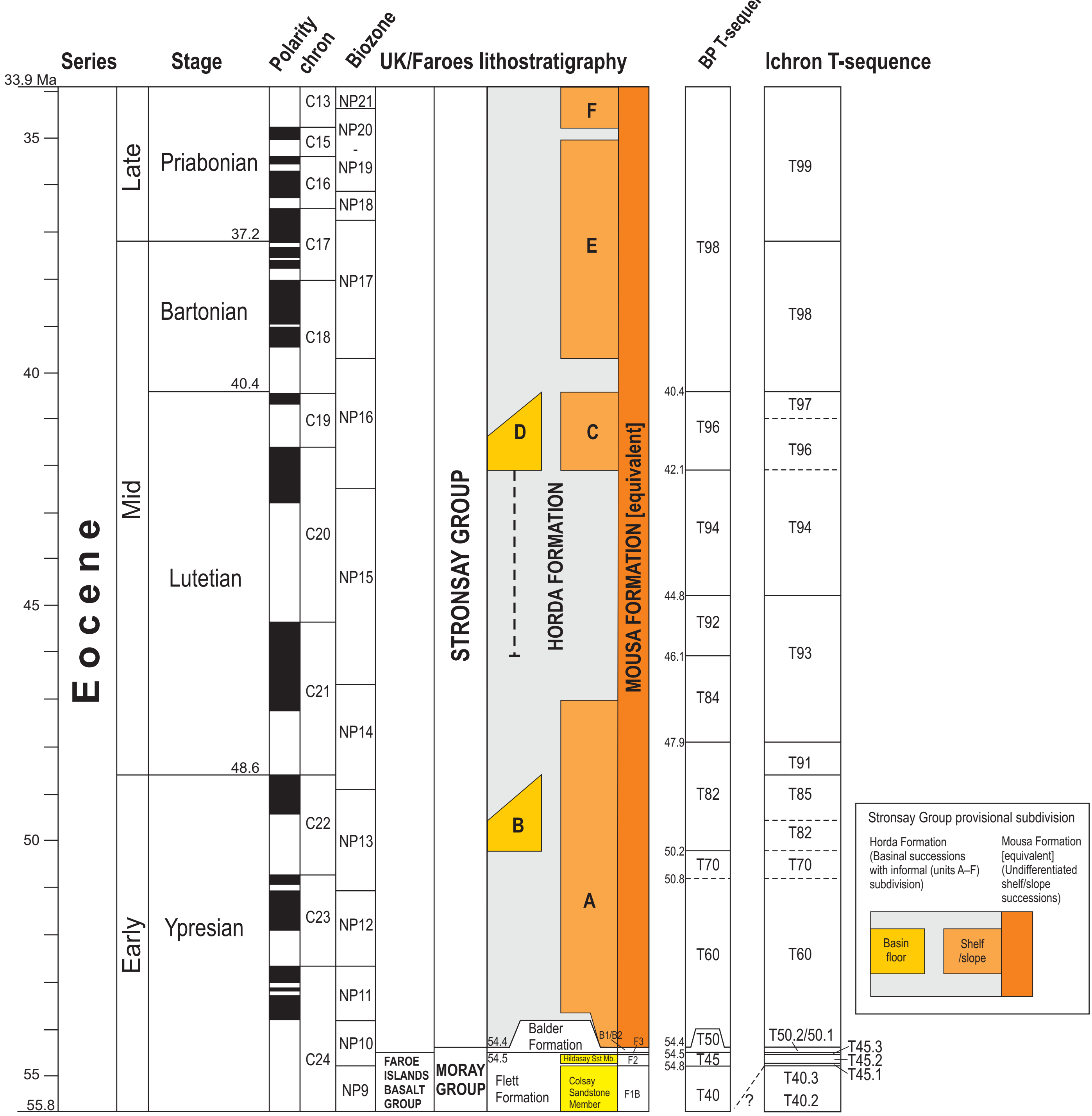


Figure 3 Eocene chronostratigraphic scale correlated with the BGS/Faroese lithostratigraphy,and the BP and Ichron T-sequence stratigraphies. The timescale is from Gradstein et al. (2004) and Ogg et al. (2008). The UK lithostratigraphy is from Knox et al. (1997), with a provisional informal subdivision of the Stronsay Group based on this study; the Faroes lithostratigraphy is from Passey and Jolley (2009) and Passey and Hitchen (2011). The BP T-sequences are from Jones and Milton (1994) and Jones et al. (2003), with Balder Fm modification from Passey and Jolley (2009). The chronostratigraphic placement of the lithostratigraphy and BP sequence stratigraphy is based on Jolley et al. (2005), Passey and Jolley (2009), and Passey and Hitchen (2011). The Ichron T-sequences are taken from the reports provided by Ichron (Ichron Limited 2010a, b) for the purpose of this project. Ichron have placed the top of their sequences T85, T97 and T98 at the stage boundaries, and it has been assumed that the T60, T70 and T94 sequences are equivalent to the BP sequences. The chronostratigraphic placement of the intervening Ichron sequences has been interpolated from the biostratigraphic zonation chart presented in the Ichron reports. However, it should be noted that the placement of the T40 and 45 sequences differs between the BP and Ichron schemes; in the BP scheme, the T40 sequence straddles the Paleocene/Eocene boundary, whereas the Ichron scheme shows T40 to lie wholly within the Late Paleocene. According to Ebdon et al. (1995) the T40/45 boundary is associated with the extinction of the dinoflagellate cyst *Apectodinium augustum,* which according to the timescale of Gradstein et al. (2004) postdates the Paleocene/Eocene boundary by about one million years (i.e. at 54.8 Ma). Thus, we have adopted the chronostratigraphic placement of the BP T-sequences as standard in this report, and have adjusted (where necessary) the Ichron T-sequences accordingly (cf. Passey and Hitchen, 2011, p. 216, for further discussion on this issue).

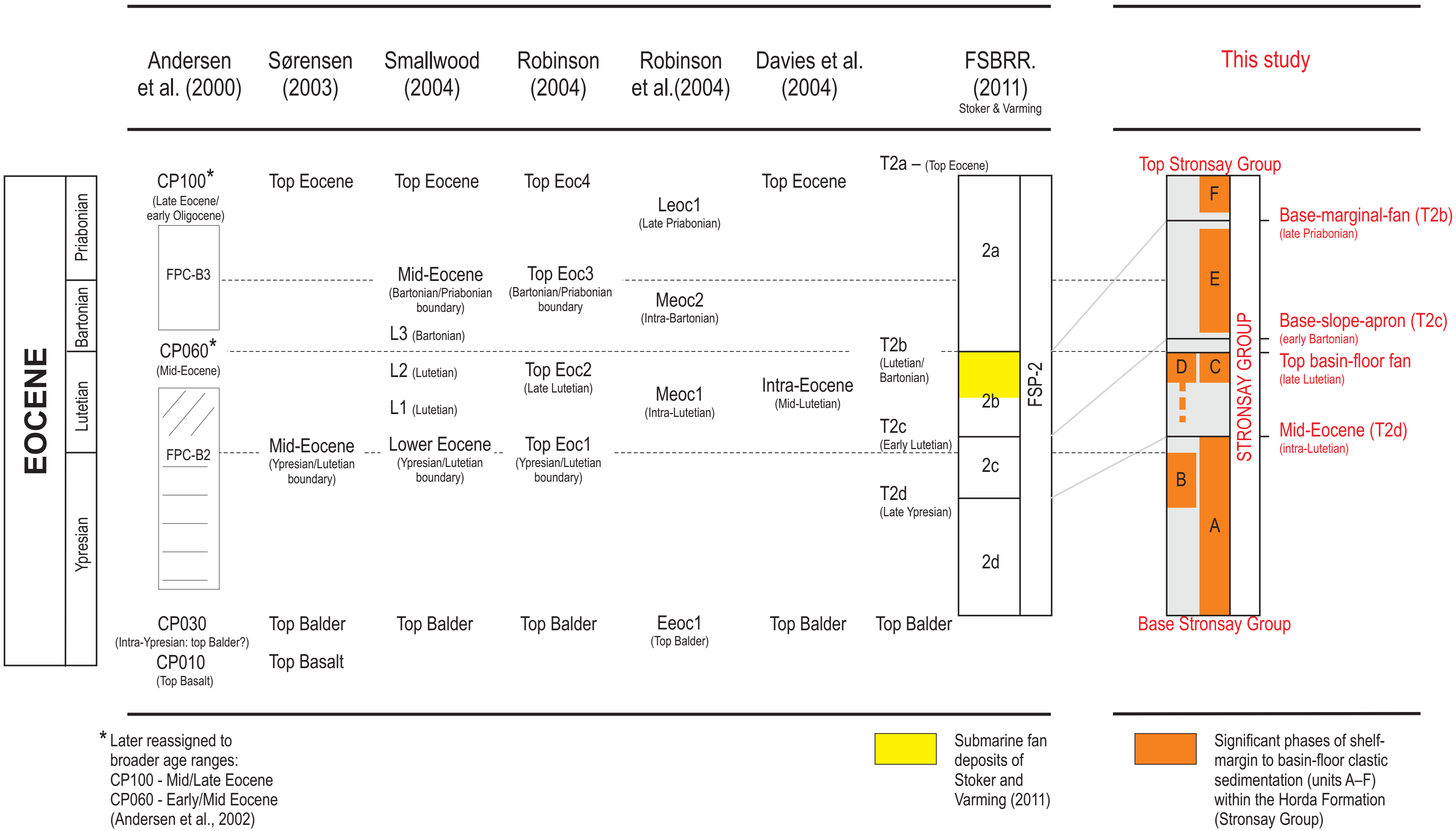
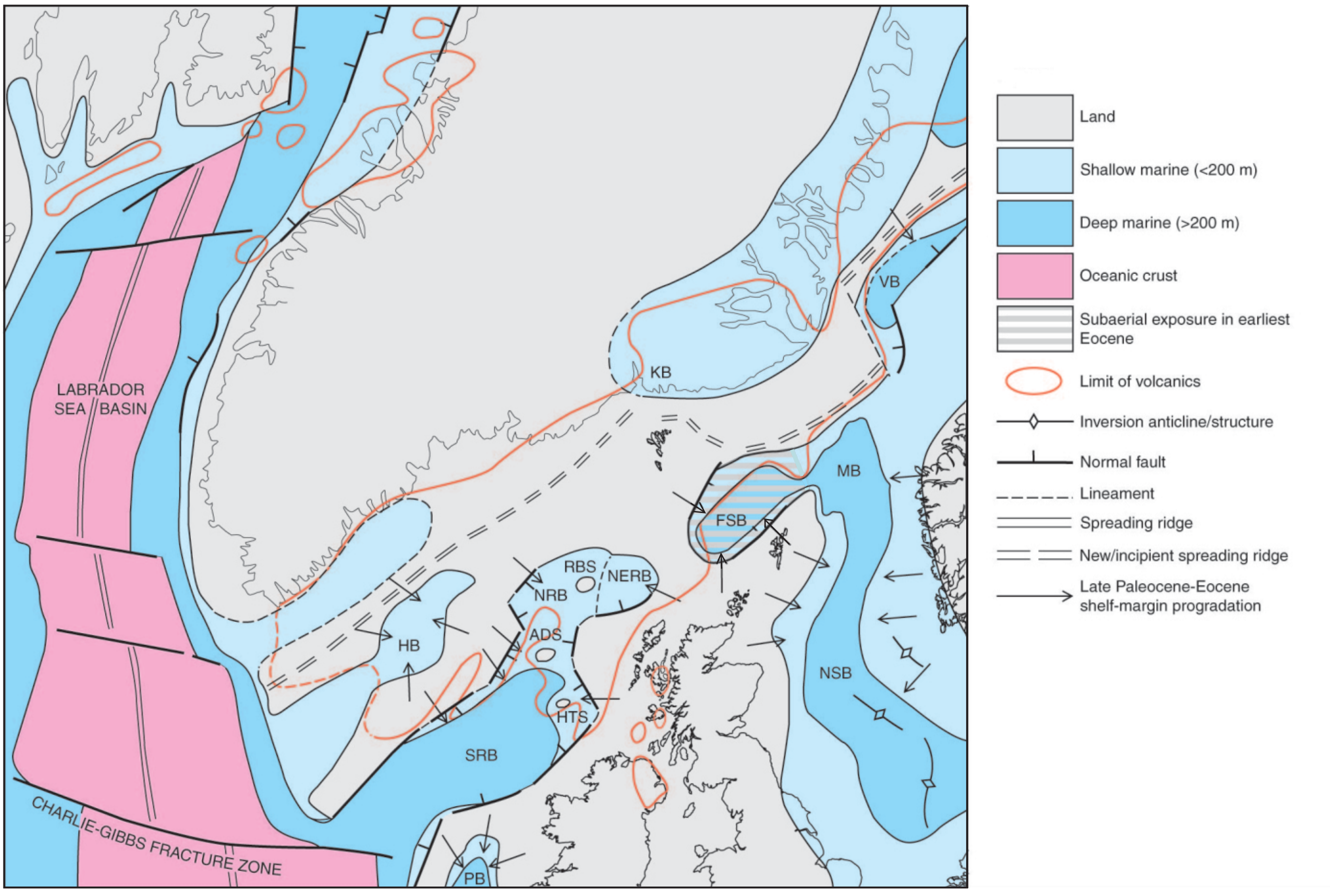


Figure 4 Correlation of previous seismic-stratigraphic schemes and key reflectors with this study. Note the revised correlation of the submarine fan deposits of Stoker and Varming (2011) with informal unit E of this study (see text for details). Abbreviation: FSBRR, Faroe-Shetland Basin Regional Report.

a)



b)

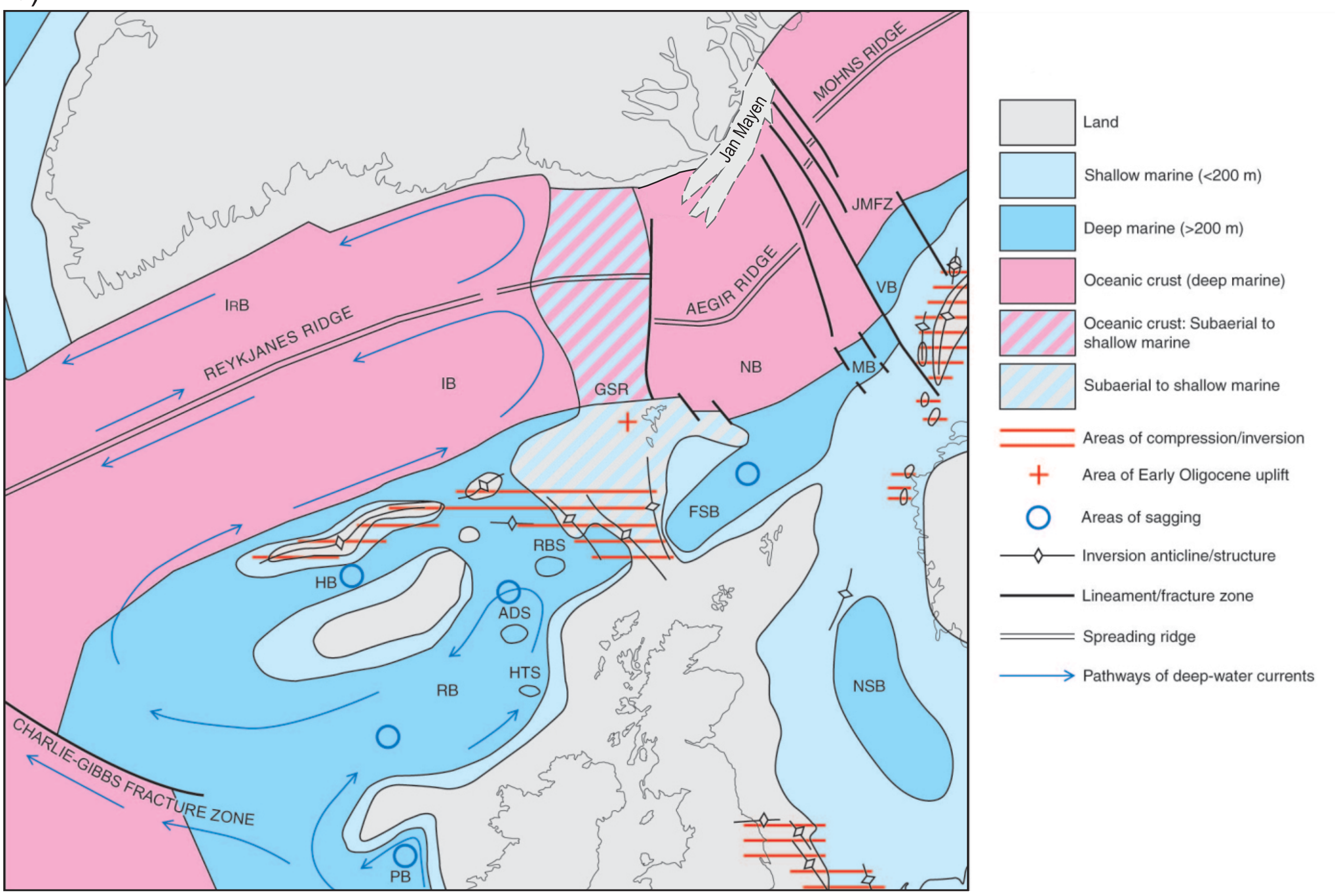


Figure 5 Palinspastic maps for a) the Late Paleocene to Early Eocene interval and b) the Late Eocene to Oligocene interval (modified from Stoker and Varming, 2011). Palaeo-position of Jan Mayen microcontinent based on Mosar et al. (2002a) and Gaina et al. (2009). Abbreviations: ADS, Anton Dohrn Seamount; FSB, Faroe-Shetland Basin; GSR, Greenland-Scotland Ridge; HB, Hatton Basin; HTS, Hebrides Terrace Seamount; IB, Iceland Basin; IRB, Irminger Basin; JMFZ, Jan Mayen Fracture Zone; KB, Kangerlussuaq Basin; MB, Møre Basin; NB, Norwegian Basin; NERB, North East Rockall Basin; NRB, North Rockall Basin; NSB, North Sea Basin; PB, Porcupine Basin; RB, Rockall Basin; RBS, Rosemary Bank Seamount; SRB, Southern Rockall Basin; VB, Vøring Basin.

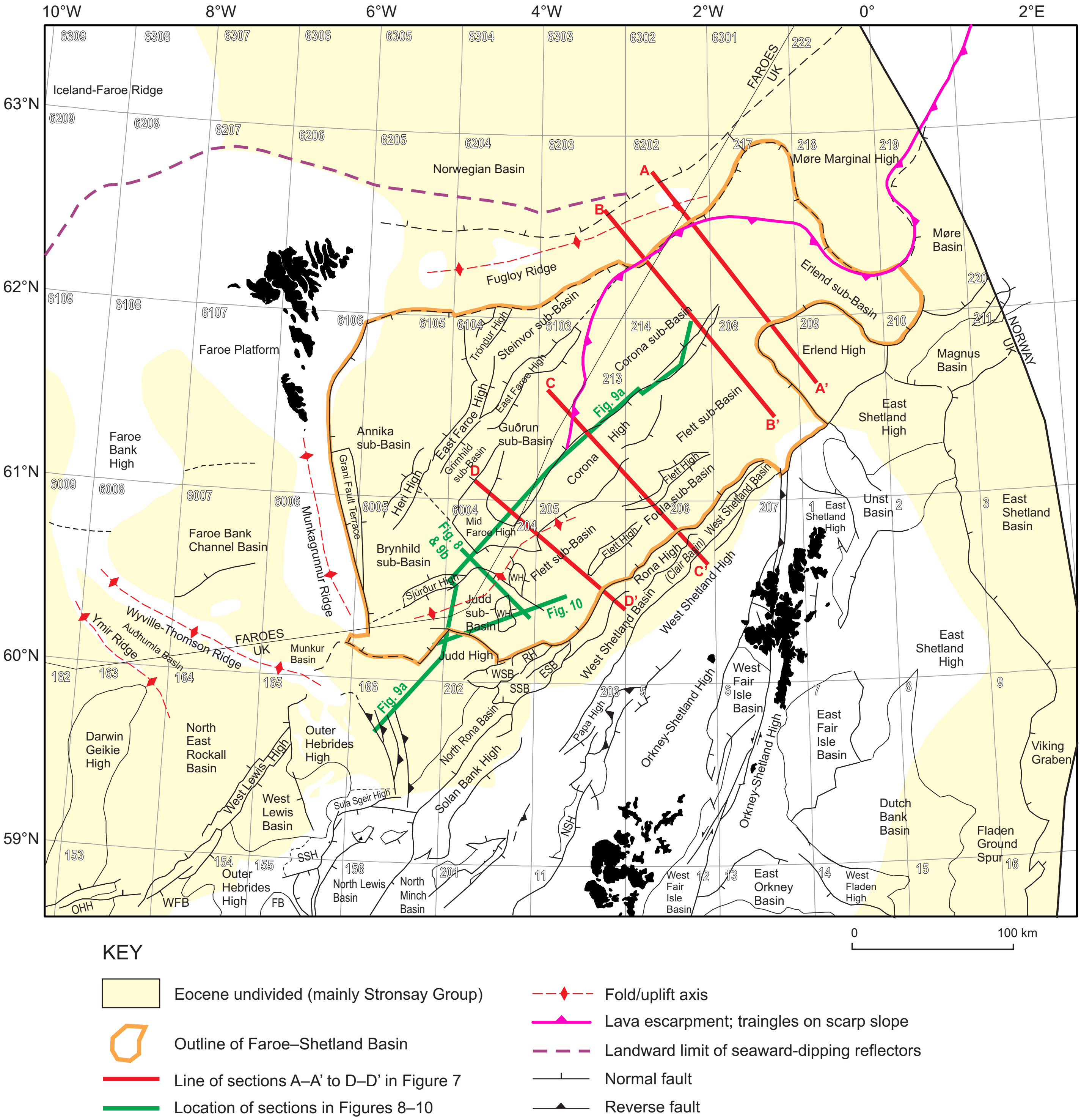


Figure 6 Structural framework of the Faroe–Shetland region, including the northern North Sea. Abbreviations: ESB, East Solan Basin; FB, Flannan Basin; NSH, North Shoal High; OHH, Outer Hebrides High; RH, Rona High; SSB, South Solan Basin; SSH, Sula Sgeir High; WFB, West Flannan Basin; WH, Westray High; WSB, West Solan Basin.

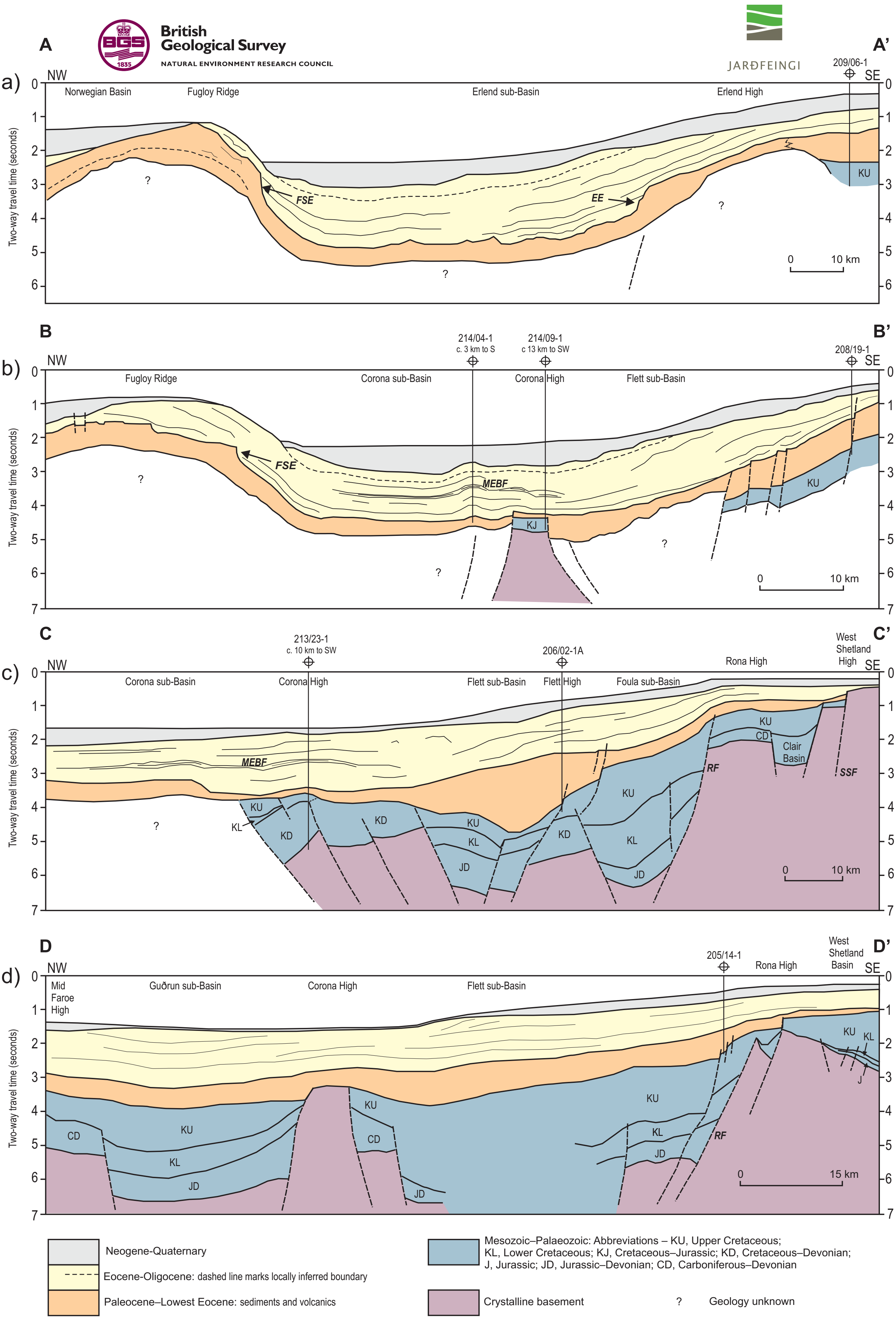


Figure 7 Geoseismic profiles showing the structural and stratigraphic framework of the Faroe–Shetland region (line drawings derived from, and modified after, Ritchie et al., 2011). Abbreviations: EE, Erlend Escarpment; FSE, Faroe-Shetland Escarpment; RF, Rona Fault; SSF, Shetland Spine Fault. Profiles located in Figure 6.

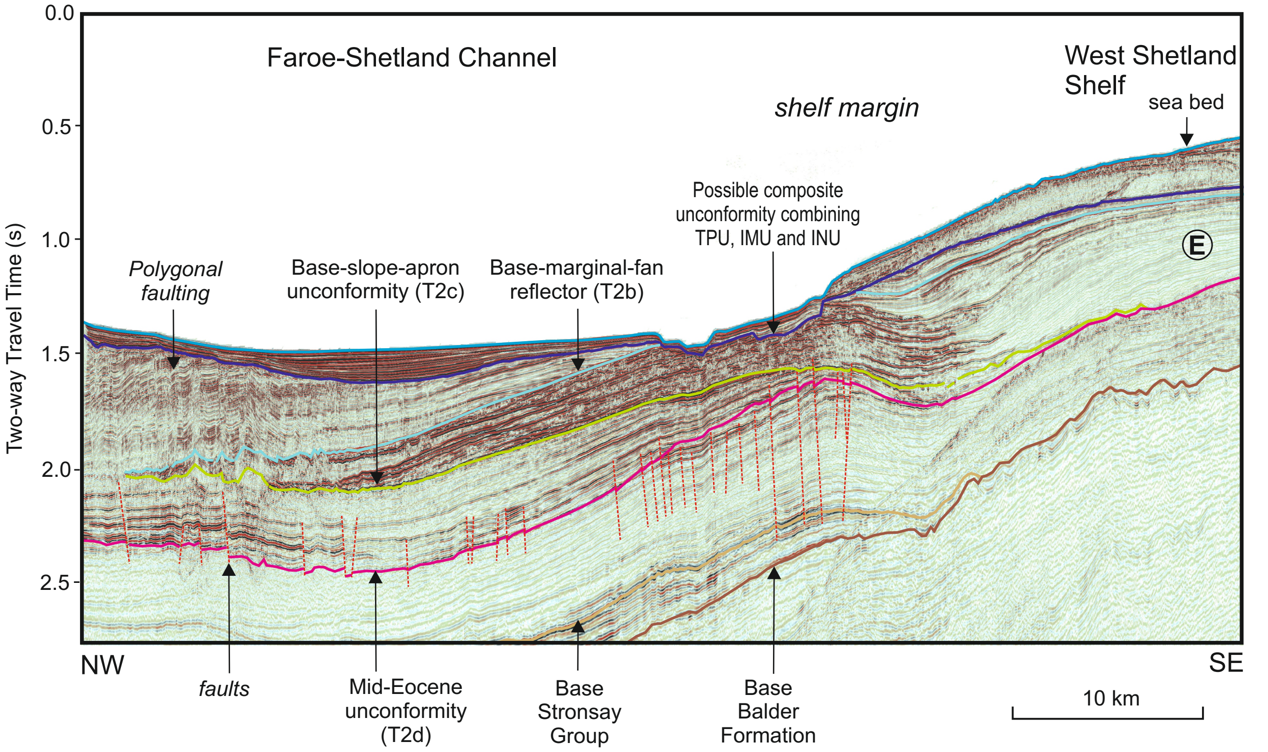
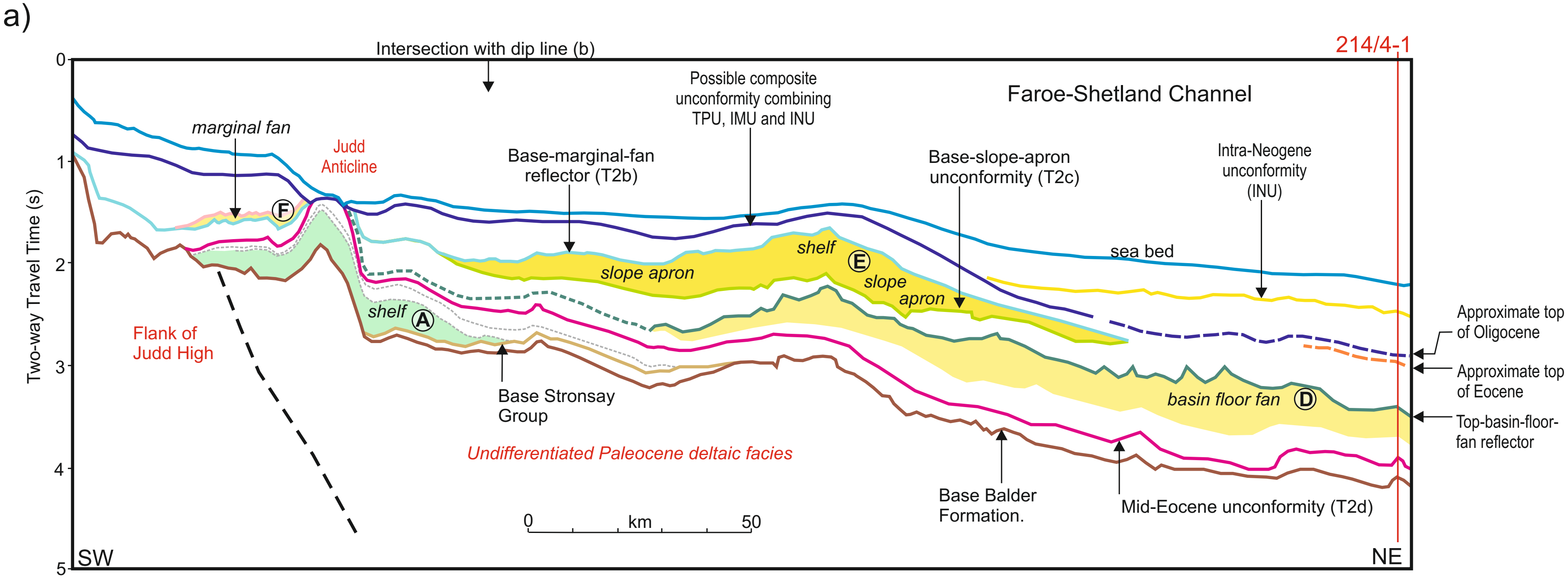


Figure 8 Seismic profile extending from the West Shetland Shelf into the Faroe-Shetland Channel showing the seismic-stratigraphic expression of the Stronsay Group, several of the key seismic reflectors, and informal unit E, which is interpreted as a northerly prograding, clastic shelf margin sequence associated with submarine fan deposition at the base of the slope apron (modified after Stoker and Varming, 2011). For location of profile see Figure 6; see text for further details. Abbreviations: IMU, Intra-Miocene unconformity; INU, Intra-Neogene unconformity; TPU, Top Palaeogene unconformity



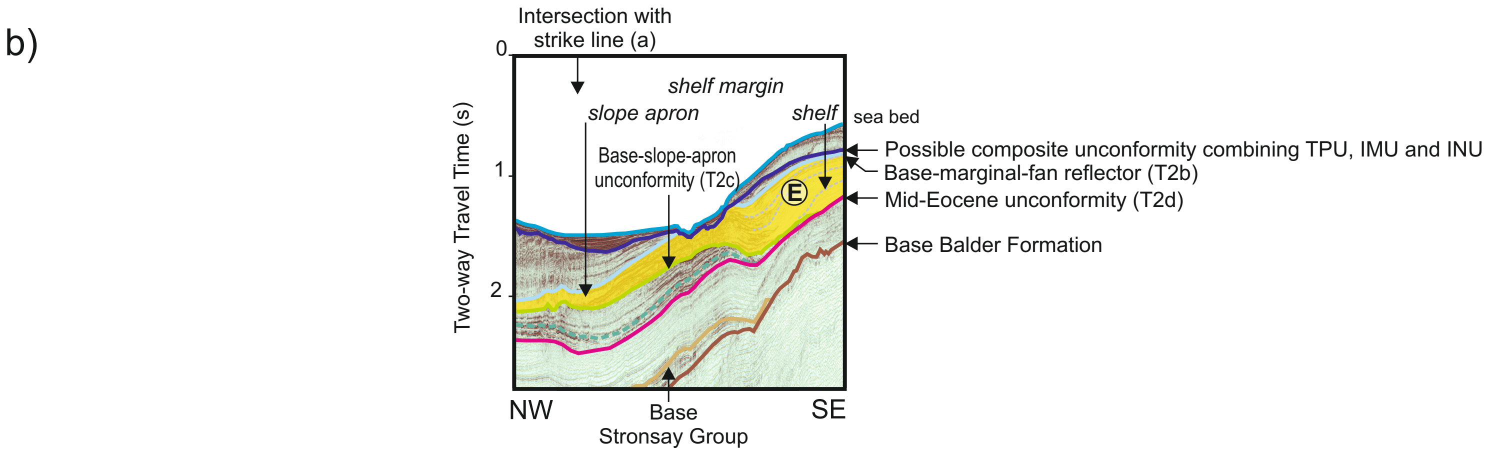


Figure 9 a) Line drawing along axis of Faroe-Shetland Channel (modified after Robinson, 2004); b) intersecting dip profile (from Figure 8) at same scale. Profiles show seismic-stratigraphic expression of the Stronsay Group, the key seismic reflectors, and the relative position of informal units A, D, E and F. Well 214/4-1 provides a key tie-point. Of particular note is the unambiguous preservation of a stacked and cyclical record of shelf margin to basinal deposits that comprises the Stronsay Group: Unit A represents the Munkagrunnur Ridge Delta of Ólavsdottir et al. (2010); Unit D incorporates the basin floor fans described by Davis et al. (2010) and DECC (2010); Unit E is the shelf margin package described by Stoker and Varming (2011; their Figure 102); Unit F is a mounded deposit, described here as a marginal fan, which postdates the Late Eocene shelf package (Unit E) (see Figure 10). It is characterised by a chaotic pattern of internal reflectivity and may have originated as a debris flow. For location of profiles see Figure 6. Abbreviations: IMU, Intra-Miocene unconformity; INU, Intra-Neogene unconformity; TPU, Top Palaeogene unconformity.

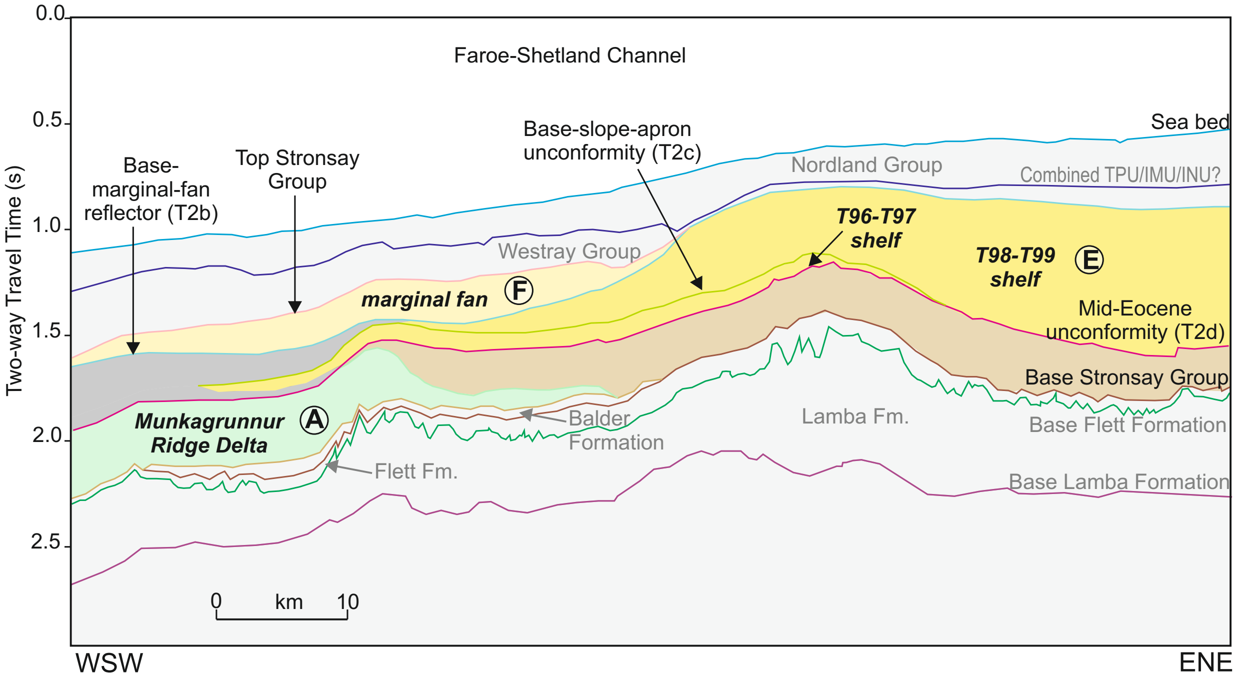
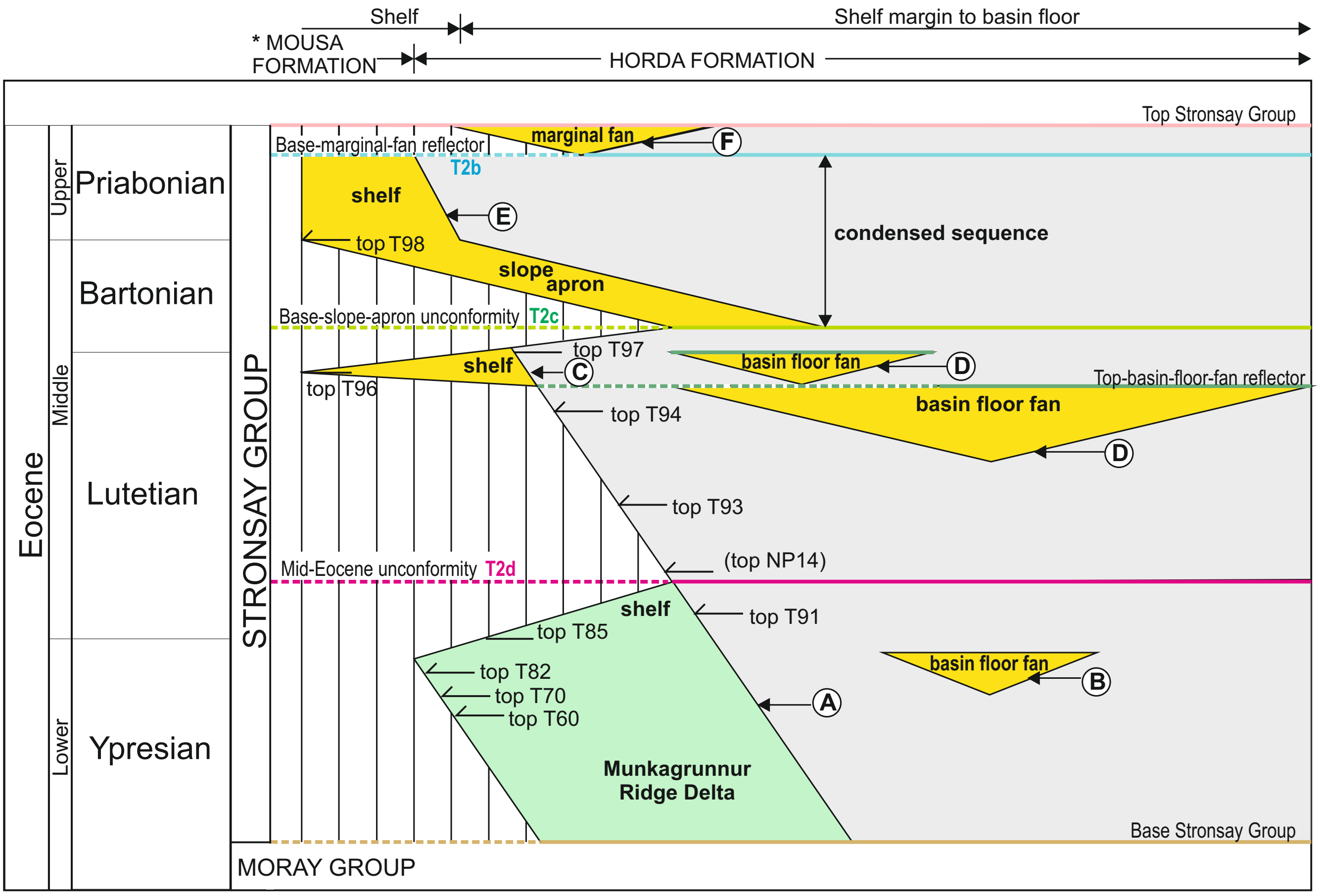


Figure 10 Line drawing showing the relationship within the Stronsay Group between the marginal fan (Unit F), the main Late Eocene shelf (Unit E), and the Early Eocene Munkagrunnur Ridge Delta (Ólavsdóttir et al. 2010) (Unit A). Profile located in Figure 6; see text for further details. Abbreviations: IMU, Intra-Miocene unconformity; INU, Intra-Neogene unconformity; TPU, Top Palaeogene unconformity.



* Undifferentiated shelf deposits assigned to Mousa Formation

Figure 11 Provisional informal subdivision of the Stronsay Group in the SE Faroe-Shetland region, based on a combination of seismic-stratigraphic and lithostratigraphic information (see text for details).

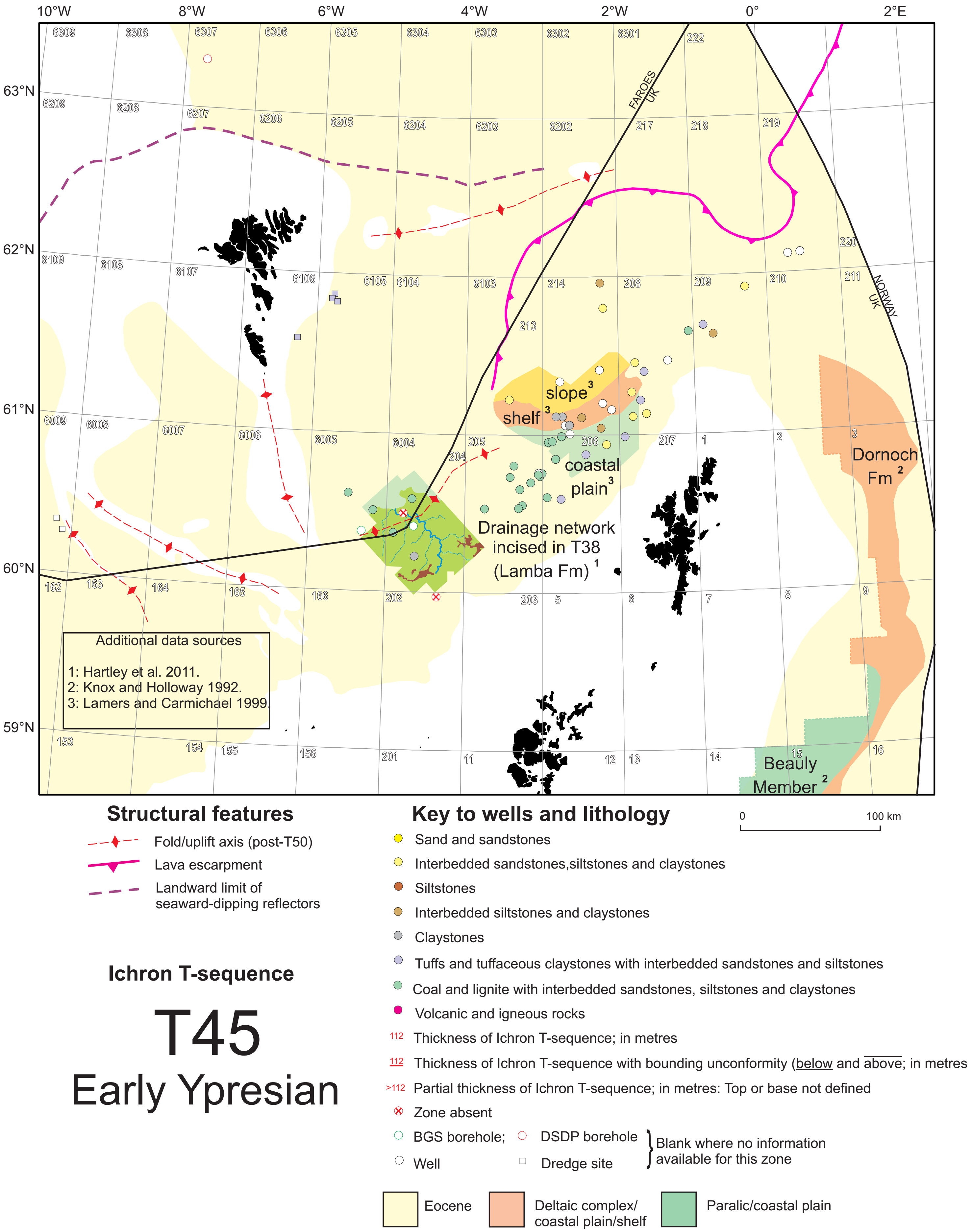
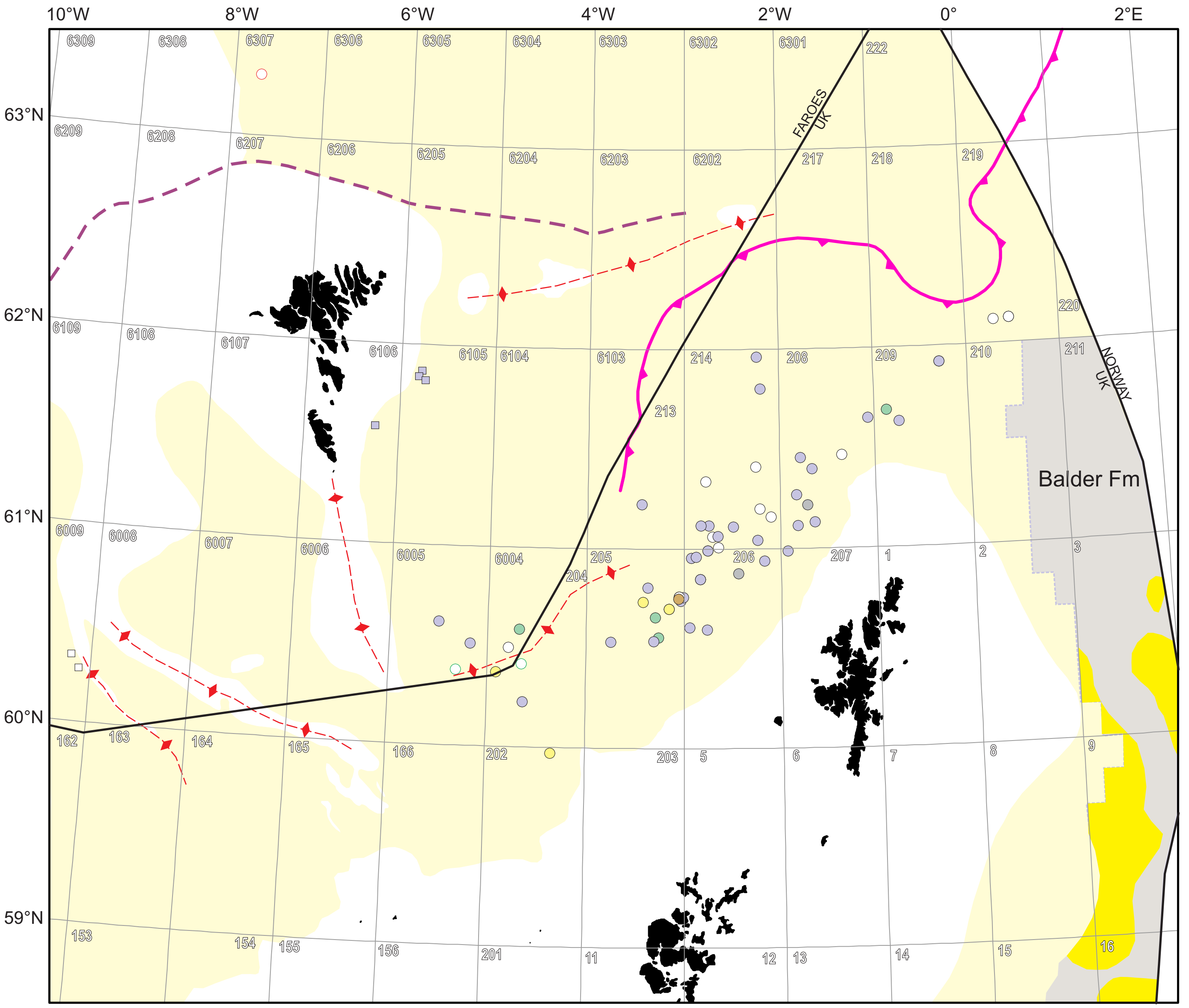


Figure 12 T45 timeslice map: Early Eocene, Moray Group (Upper Flett Formation) (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

JARÐFEINGI



Structural features

- Fold/uplift axis (post-T50)
- Lava escarpment
- Landward limit of seaward-dipping reflectors

Key to wells and lithology

- Sand and sandstones
- Interbedded sandstones,siltstones and claystones
- Siltstones
- Interbedded siltstones and claystones
- Claystones
- Tuffs and tuffaceous claystones with interbedded sandstones and siltstones
- Coal and lignite with interbedded sandstones, siltstones and claystones
- Volcanic and igneous rocks
- 112 Thickness of Ichron T-sequence; in metres
- 112 Thickness of Ichron T-sequence with bounding unconformity (below and above; in metres
- >112 Partial thickness of Ichron T-sequence; in metres: Top or base not defined
- Zone absent
- BGS borehole; DSDP borehole
- Well; Dredge site

Blank where no information available for this zone

Eocene | Balder Fm. | Sandstones in Balder Fm. (Knox and Holloway 1992)

Ichron T-sequence

T50

Early Ypresian

Figure 13 T50 timeslice map: Early Eocene, Moray Group (Balder Formation) (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

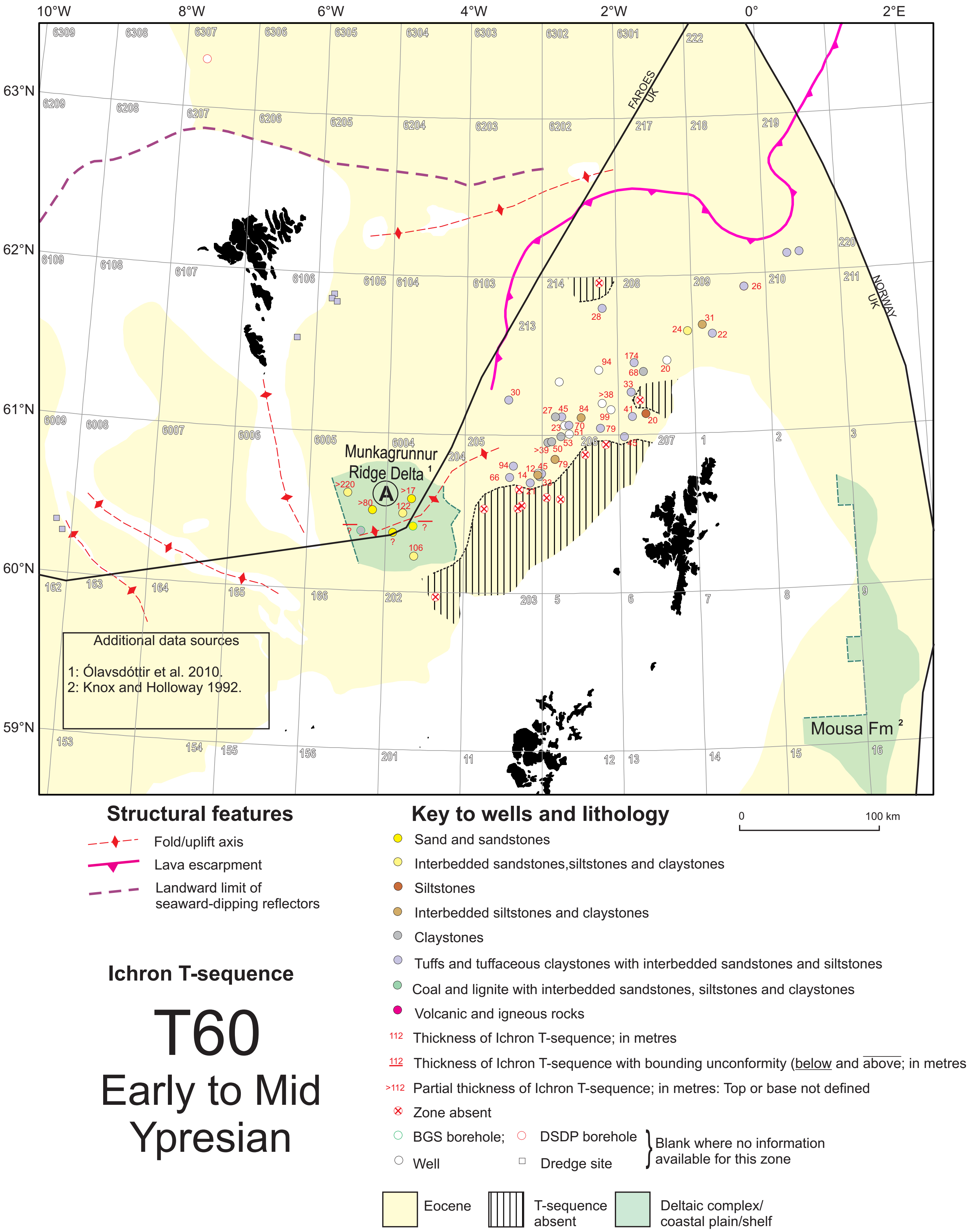
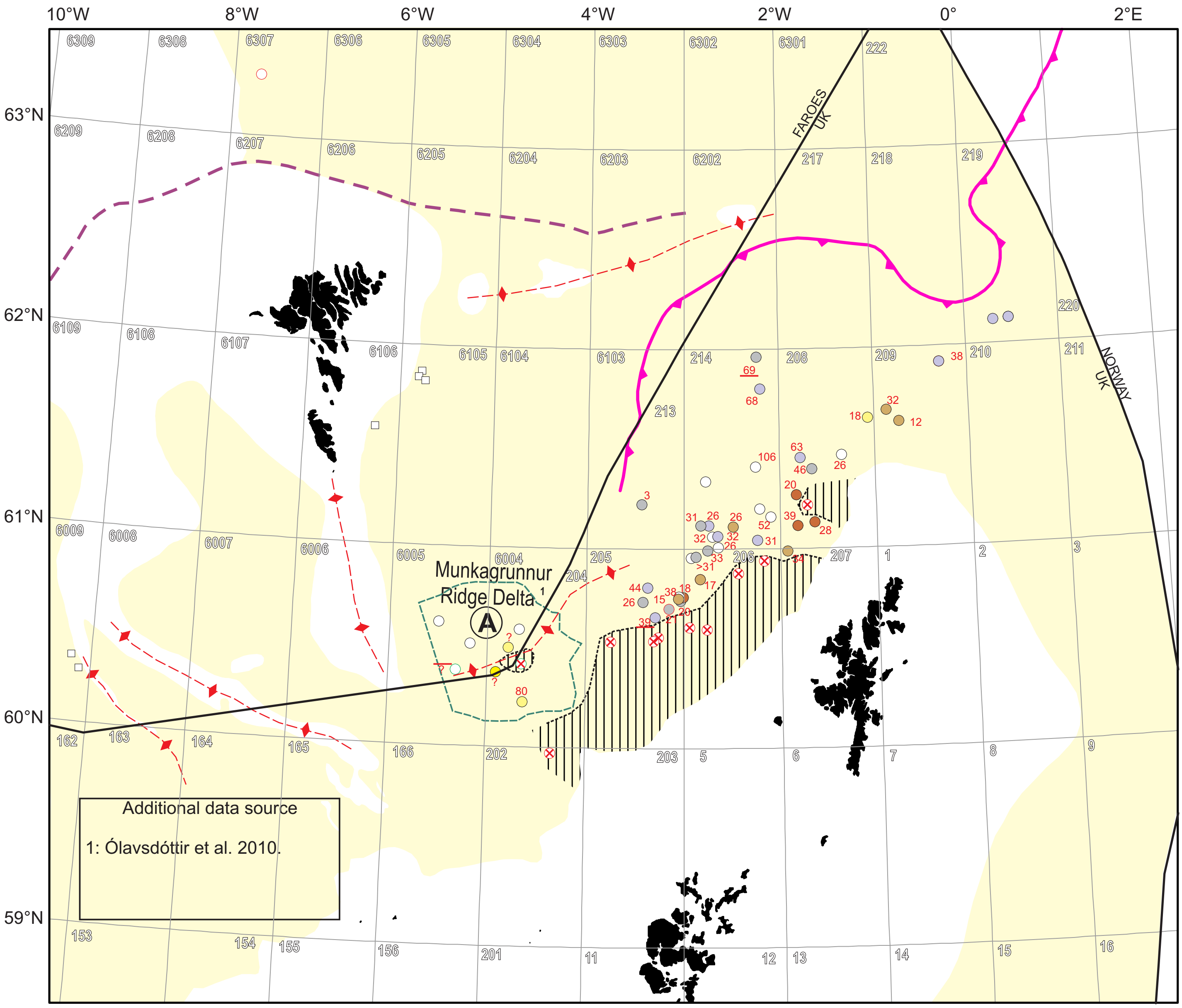


Figure 14 T60 timeslice map: Early Eocene,Stronsay Group, including location of unit A (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

JARÐFEINGI



Structural features

- Fold/uplift axis
- Lava escarpment
- Landward limit of seaward-dipping reflectors

Key to wells and lithology

0 100 km

- Sand and sandstones
- Interbedded sandstones,siltstones and claystones
- Siltstones
- Interbedded siltstones and claystones
- Claystones
- Tuffs and tuffaceous claystones with interbedded sandstones and siltstones
- Coal and lignite with interbedded sandstones, siltstones and claystones
- Volcanic and igneous rocks
- 112 Thickness of Ichron T-sequence; in metres
- 112 Thickness of Ichron T-sequence with bounding unconformity (below and above; in metres
- >112 Partial thickness of Ichron T-sequence; in metres: Top or base not defined
- Zone absent
- BGS borehole; DSDP borehole
- Well; Dredge site

} Blank where no information available for this zone

Eocene | Tsequence absent | Deltaic complex/ coastal plain/shelf

Ichron T-sequence

T70

Mid to Late Ypresian

Figure 15 T70 timeslice map: Early Eocene, Stronsay Group, including location of unit A (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

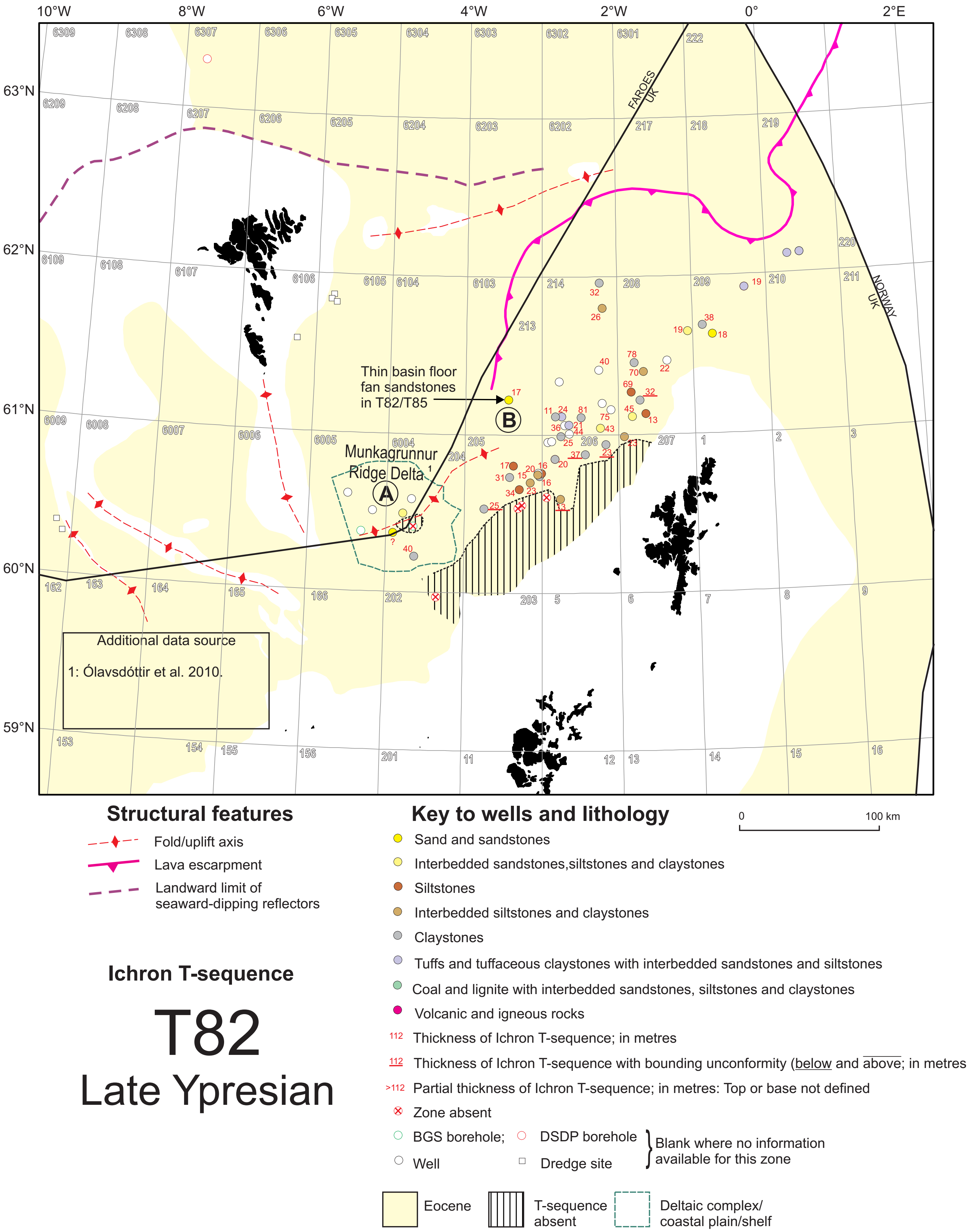


Figure 16 T82 timeslice map: Early Eocene, Stronsay Group, including locations of units A and B (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

JARÐFEINGI

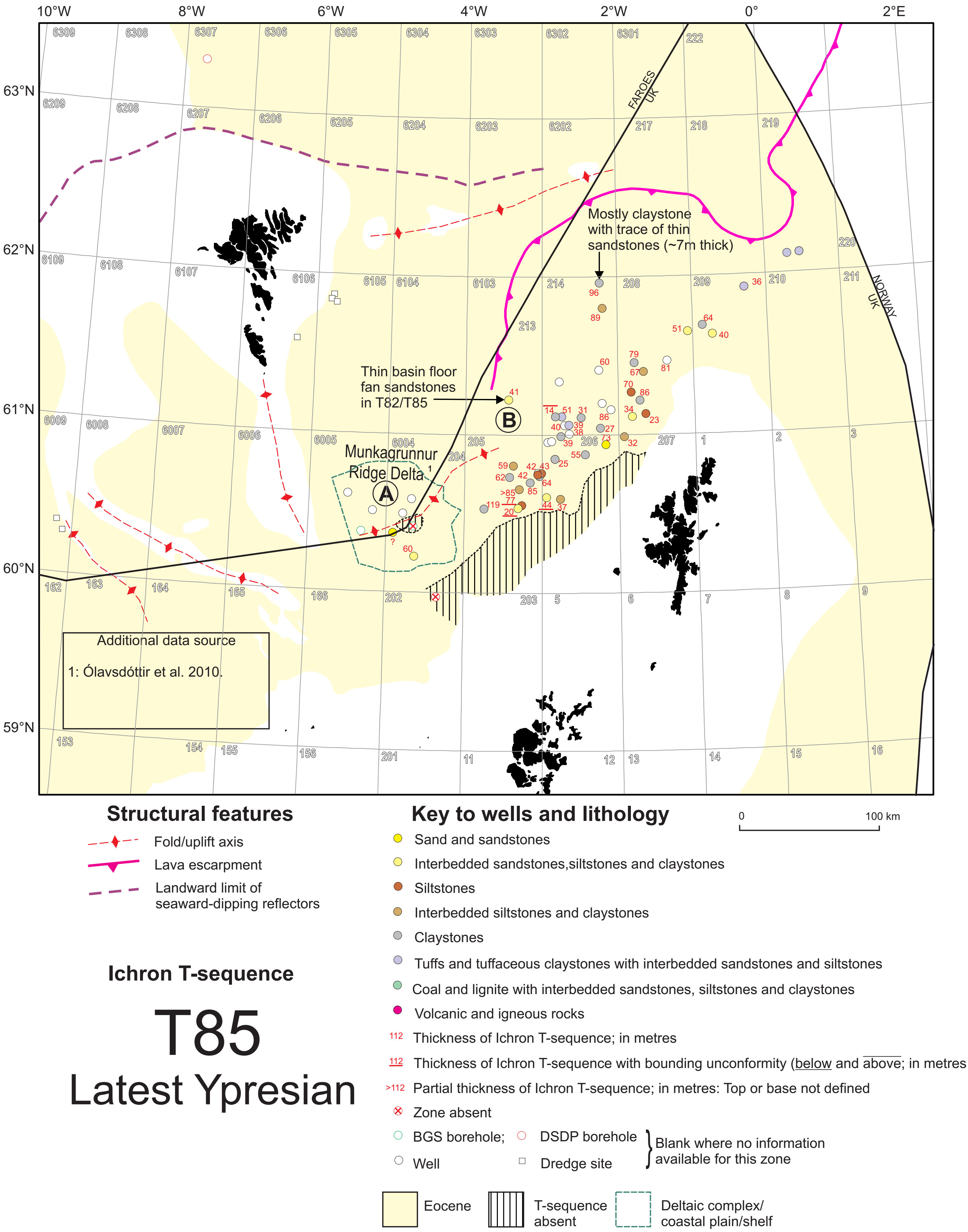
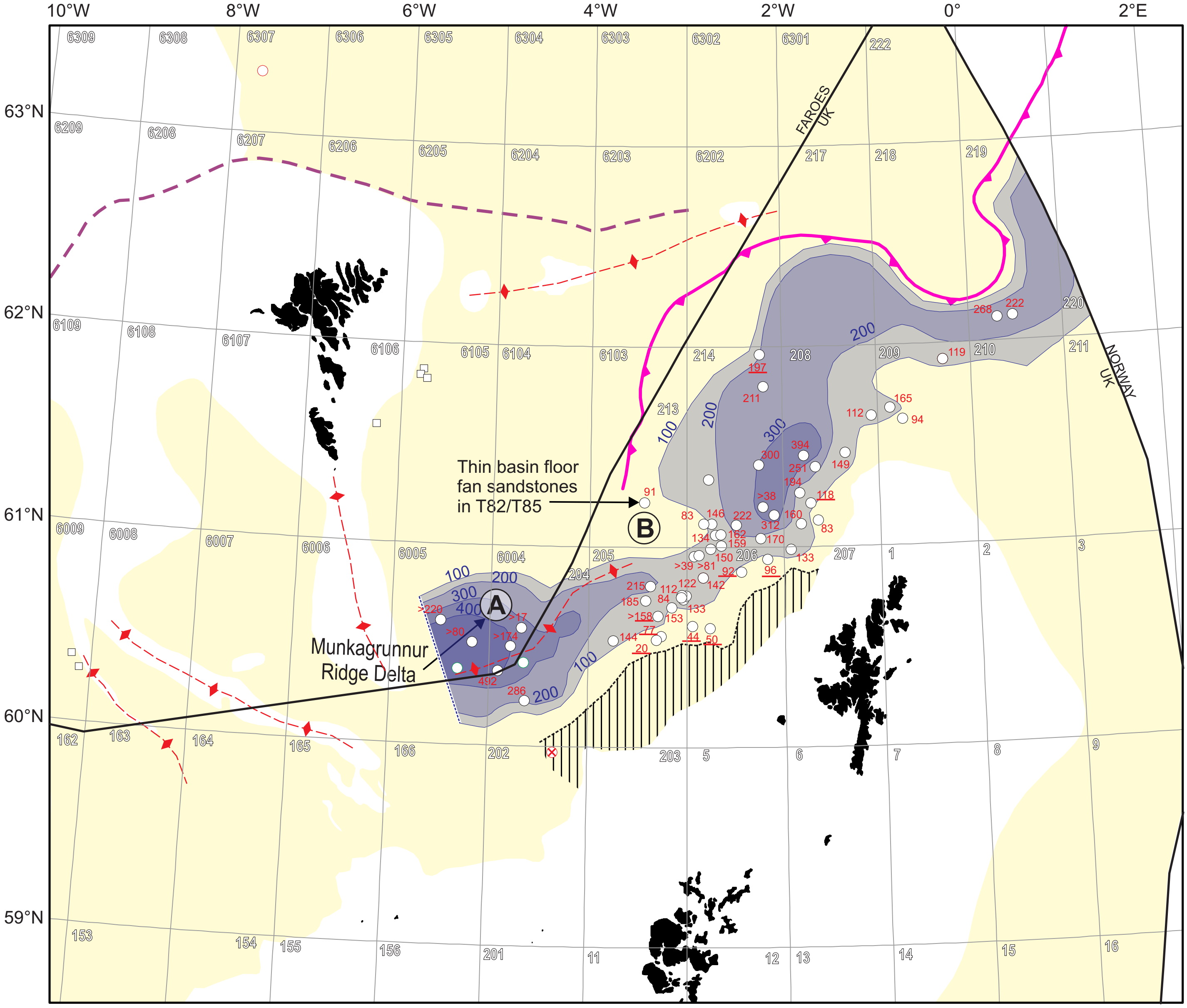


Figure 17 T85 timeslice map: Early Eocene, Stronsay Group, including locations of units A and B (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.



Structural features

- Fold/uplift axis
- Lava escarpment
- Landward limit of seaward-dipping reflectors

Key to wells and lithology

- Sand and sandstones
- Interbedded sandstones,siltstones and claystones
- Siltstones
- Interbedded siltstones and claystones
- Claystones
- Tuffs and tuffaceous claystones with interbedded sandstones and siltstones
- Coal and lignite with interbedded sandstones, siltstones and claystones
- Volcanic and igneous rocks
- 112 Thickness of Ichron T-sequence; in metres
- 112 Thickness of Ichron T-sequence with bounding unconformity (below and above; in metres
- >112 Partial thickness of Ichron T-sequence; in metres: Top or base not defined
- Zone absent
- BGS borehole; DSDP borehole
- Well Dredge site

0 100 km

Eocene | T-sequence absent | 200 Thickness (m)

Ichron T-sequence

T60-T85

Post-Balder Fm.

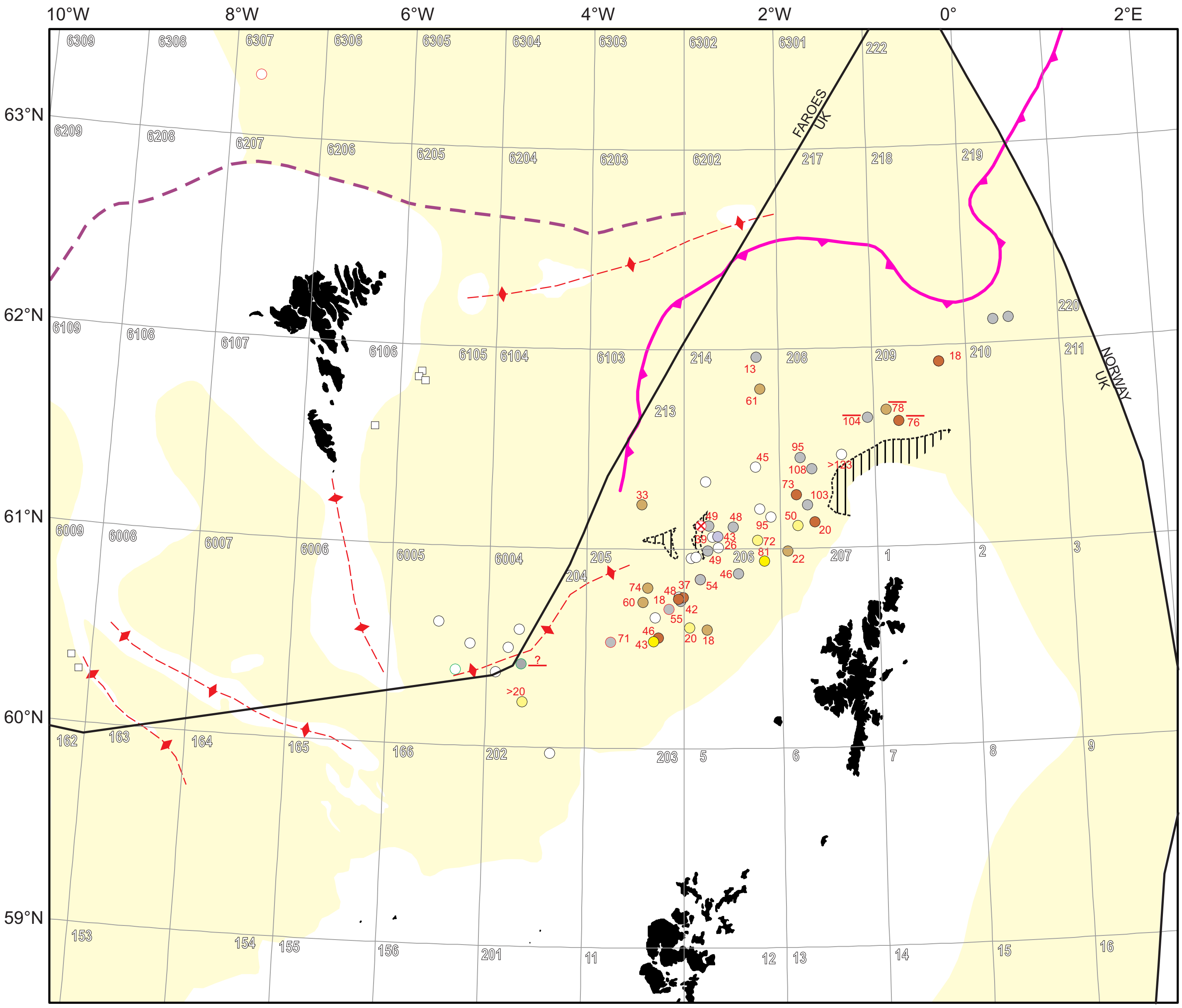
Ypresian isopach

(well lithologies not shown)

Figure 18 Composite T60-T85 isopach map of Early Eocene, Stronsay Group, based on well data, and including locations of units A and B (see text for details).

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

JARÐFEINGI



Structural features

Fold/uplift axis

Lava escarpment

Landward limit of seaward-dipping reflectors

Ichron T-sequence

T91

Early Lutetian

Key to wells and lithology

0 100 km

Sand and sandstones

Interbedded sandstones,siltstones and claystones

Siltstones

Interbedded siltstones and claystones

Claystones

Tuffs and tuffaceous claystones with interbedded sandstones and siltstones

Coal and lignite with interbedded sandstones, siltstones and claystones

Volcanic and igneous rocks

112 Thickness of Ichron T-sequence; in metres

112 Thickness of Ichron T-sequence with bounding unconformity (below and above; in metres

>112 Partial thickness of Ichron T-sequence; in metres: Top or base not defined

Zone absent

BGS borehole; DSDP borehole

Well Dredge site

} Blank where no information available for this zone

Eocene

T-sequence absent

Figure 19 T91 timeslice map: Mid-Eocene, Stronsay Group (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

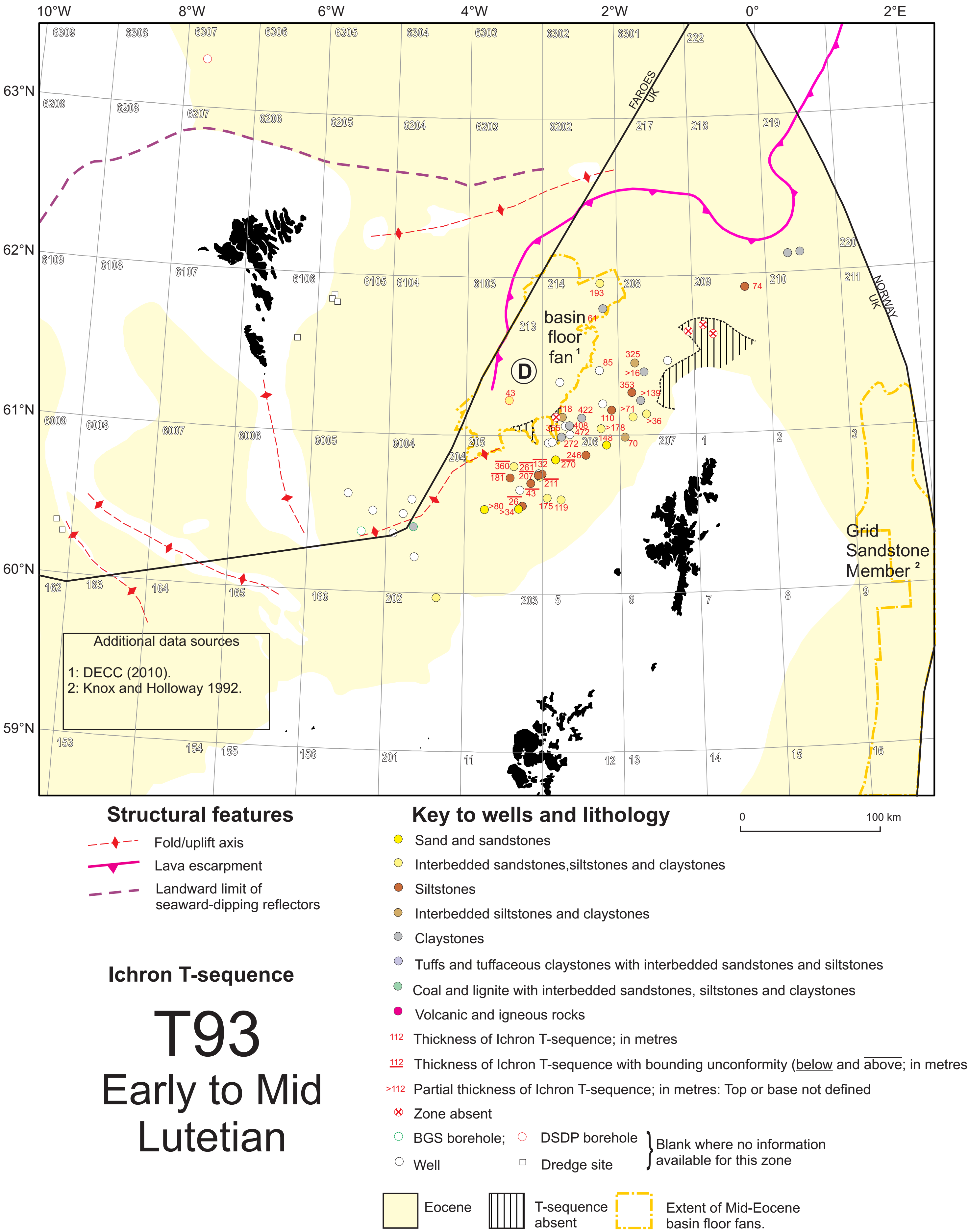
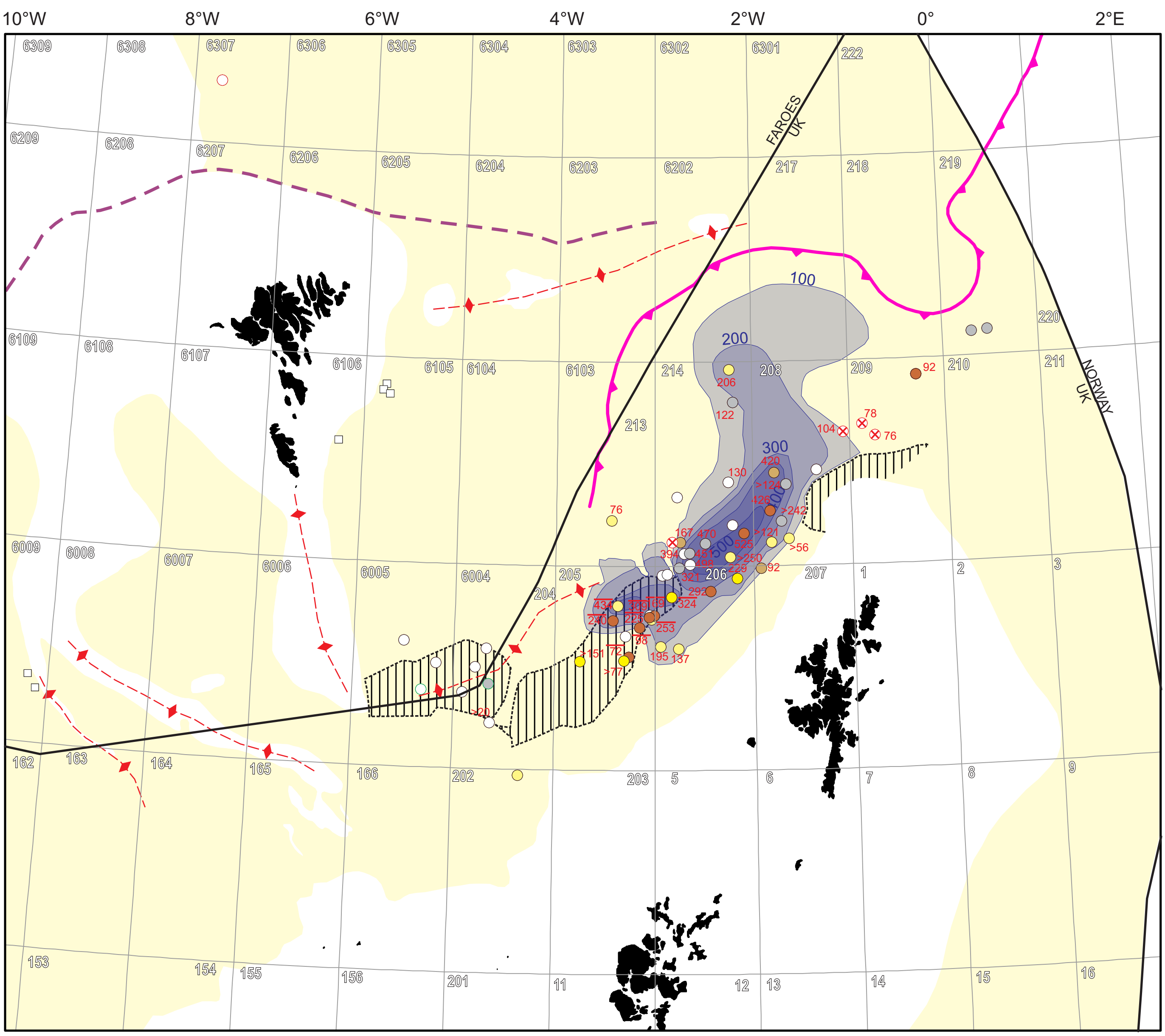


Figure 20 T93 timeslice map: Mid-Eocene, Stronsay Group, including location of unit D (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.



Structural features

- Fold/uplift axis
- Lava escarpment
- Landward limit of seaward-dipping reflectors

Key to wells and lithology

0 — 100 km

- Sand and sandstones
- Interbedded sandstones,siltstones and claystones
- Siltstones
- Interbedded siltstones and claystones
- Claystones
- Tuffs and tuffaceous claystones with interbedded sandstones and siltstones
- Coal and lignite with interbedded sandstones, siltstones and claystones
- Volcanic and igneous rocks
- 112 Thickness of Ichron T-sequence; in metres
- 112 Thickness of Ichron T-sequence with bounding unconformity (below and above; in metres
- >112 Partial thickness of Ichron T-sequence; in metres: Top or base not defined
- Zone absent
- BGS borehole; DSDP borehole
- Well; Dredge site

} Blank where no information available for this zone

Eocene | T94-sequence absent (erosion of T93) | 200 Thickness (m)

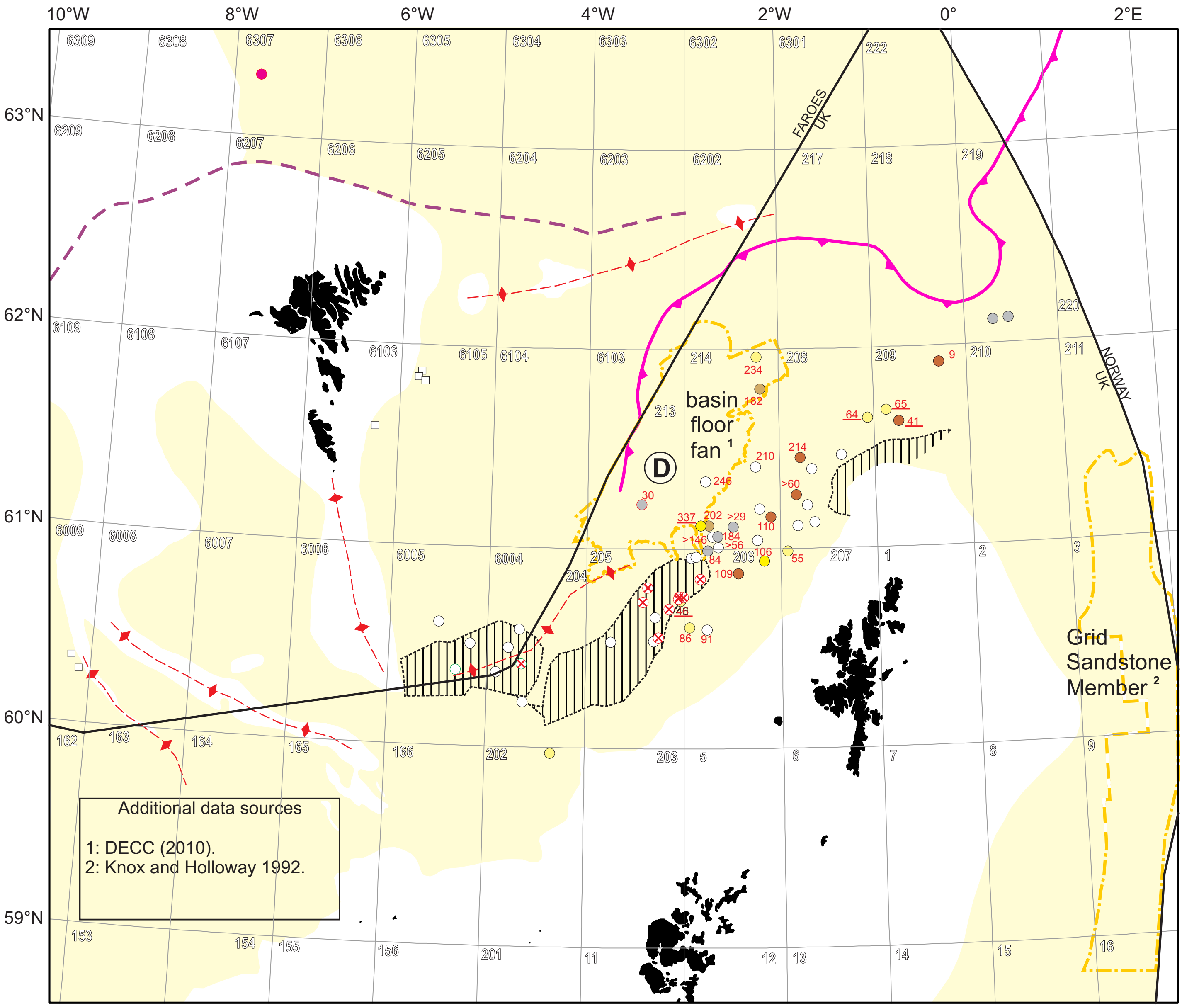
Ichron T-sequence

T91-T93

Early to Mid Lutetian isopach

(with well lithologies from T93)

Figure 21 Composite T91-T93 isopach map of early Mid-Eocene, Stronsay Group, based on well data (see text for details).



Structural features

- Fold/uplift axis
- Lava escarpment
- Landward limit of seaward-dipping reflectors

Ichron T-sequence

T94

Mid to Late Lutetian

Key to wells and lithology

0 — 100 km

- Sand and sandstones
- Interbedded sandstones,siltstones and claystones
- Siltstones
- Interbedded siltstones and claystones
- Claystones
- Tuffs and tuffaceous claystones with interbedded sandstones and siltstones
- Coal and lignite with interbedded sandstones, siltstones and claystones
- Volcanic and igneous rocks
- 112 Thickness of Ichron T-sequence; in metres
- 112 Thickness of Ichron T-sequence with bounding unconformity (below and above; in metres
- >112 Partial thickness of Ichron T-sequence; in metres: Top or base not defined
- Zone absent
- BGS borehole; DSDP borehole
- Well; Dredge site

Blank where no information available for this zone

Eocene — T-sequence absent — Extent of Mid-Eocene basin floor fans.

Figure 22 T94 timeslice map: Mid-Eocene, Stronsay Group, including location of unit D (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

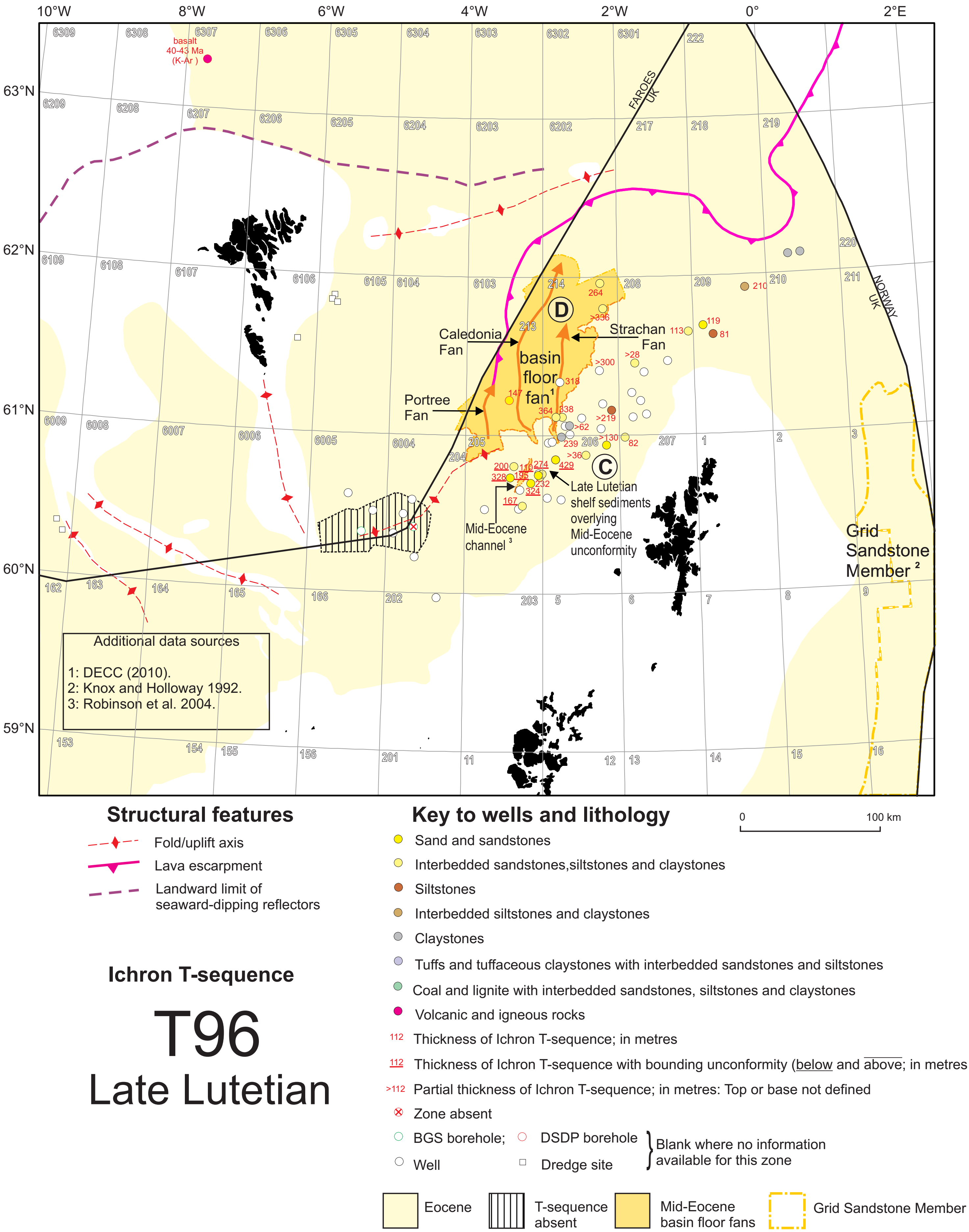


Figure 23 T96 timeslice map: Mid-Eocene, Stronsay Group, including location of units C and D (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

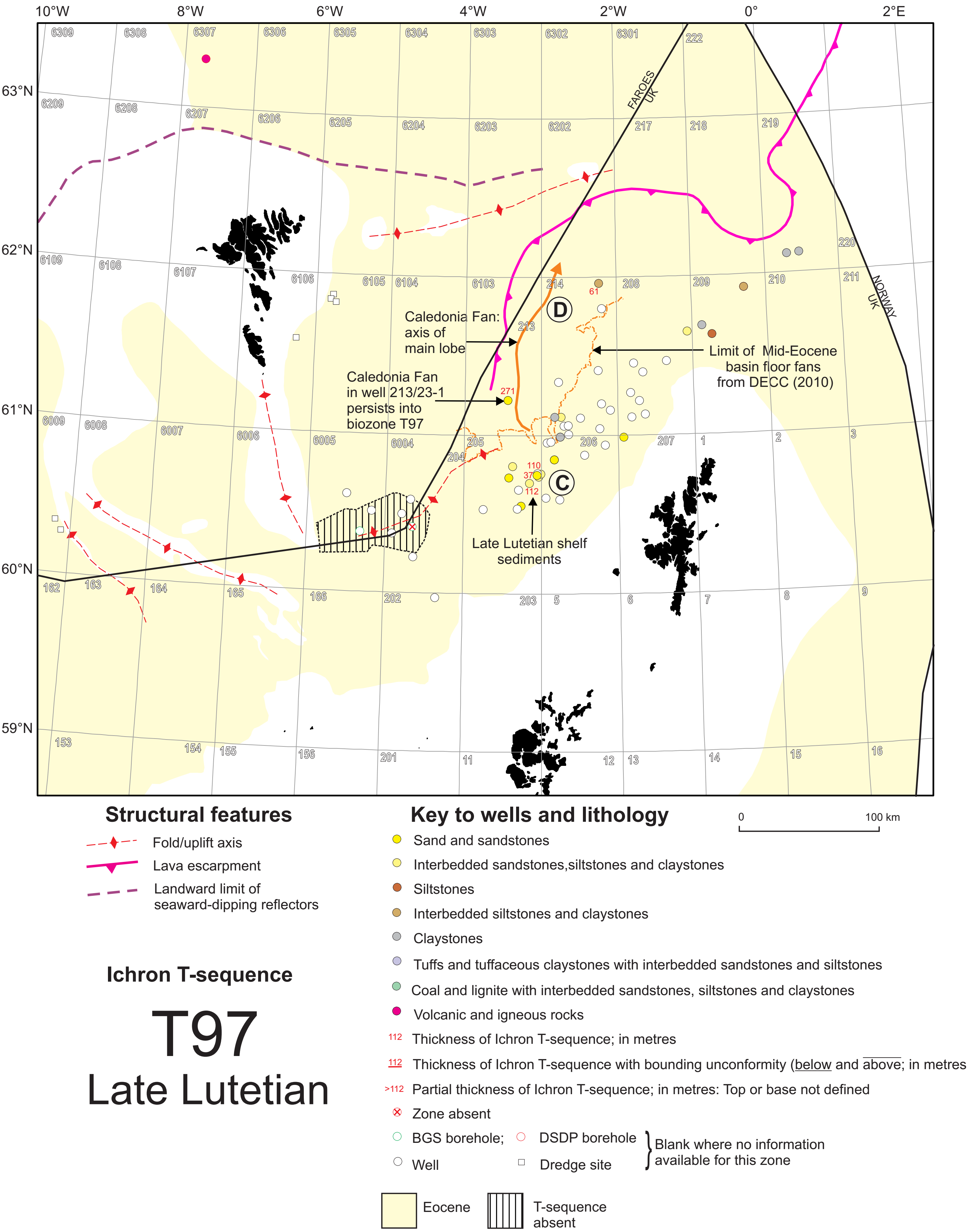
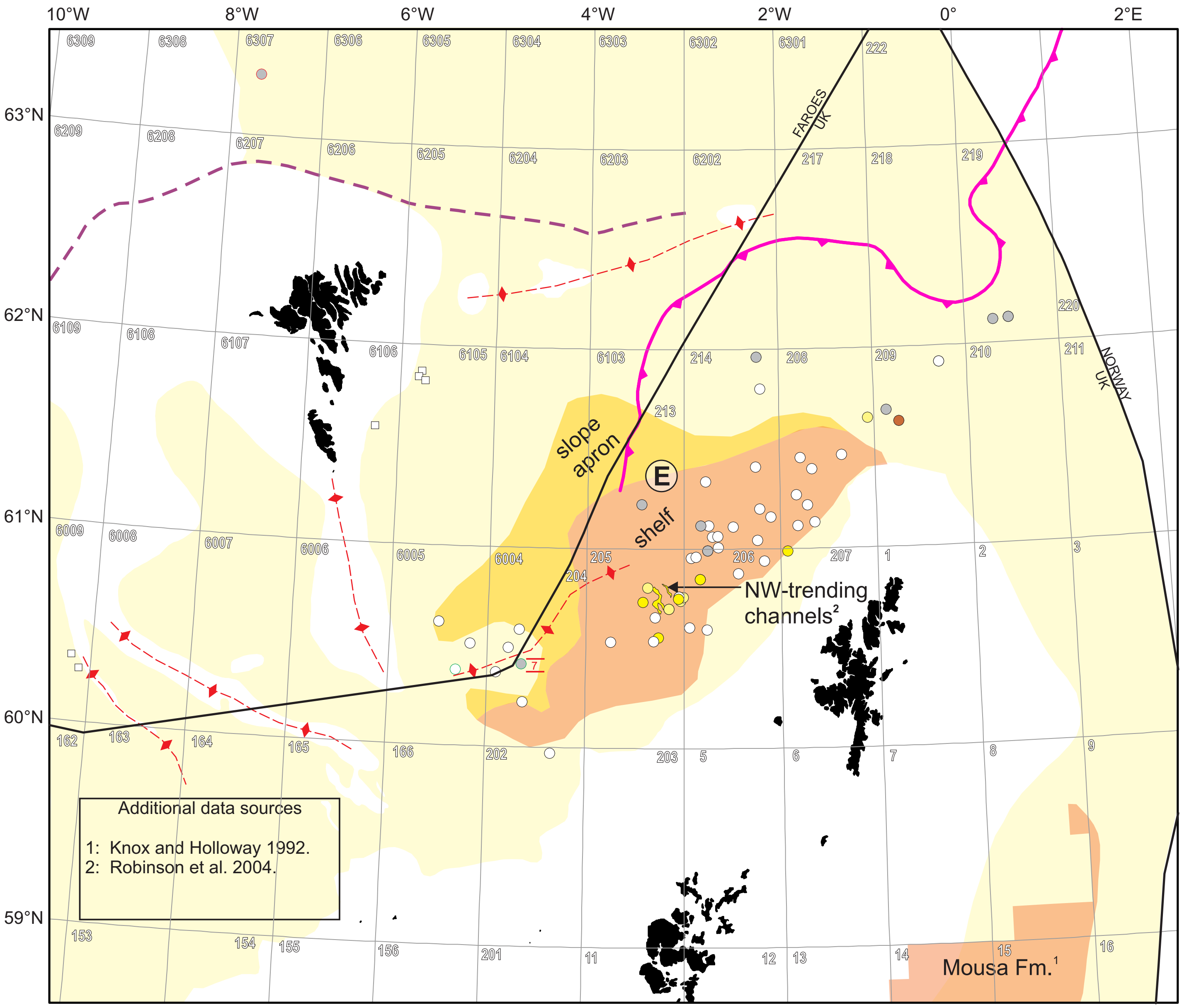


Figure 24 T97 timeslice map: Mid-Eocene, Stronsay Group, including location of units C and D (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

JARÐFEINGI



Structural features

- Fold/uplift axis
- Lava escarpment
- Landward limit of seaward-dipping reflectors

Key to wells and lithology

0 — 100 km

- Sand and sandstones
- Interbedded sandstones,siltstones and claystones
- Siltstones
- Interbedded siltstones and claystones
- Claystones
- Tuffs and tuffaceous claystones with interbedded sandstones and siltstones
- Coal and lignite with interbedded sandstones, siltstones and claystones
- Volcanic and igneous rocks
- 112 Thickness of Ichron T-sequence; in metres
- 112 Thickness of Ichron T-sequence with bounding unconformity (below and above; in metres
- >112 Partial thickness of Ichron T-sequence; in metres: Top or base not defined
- Zone absent
- BGS borehole; DSDP borehole
- Well; Dredge site

} Blank where no information available for this zone

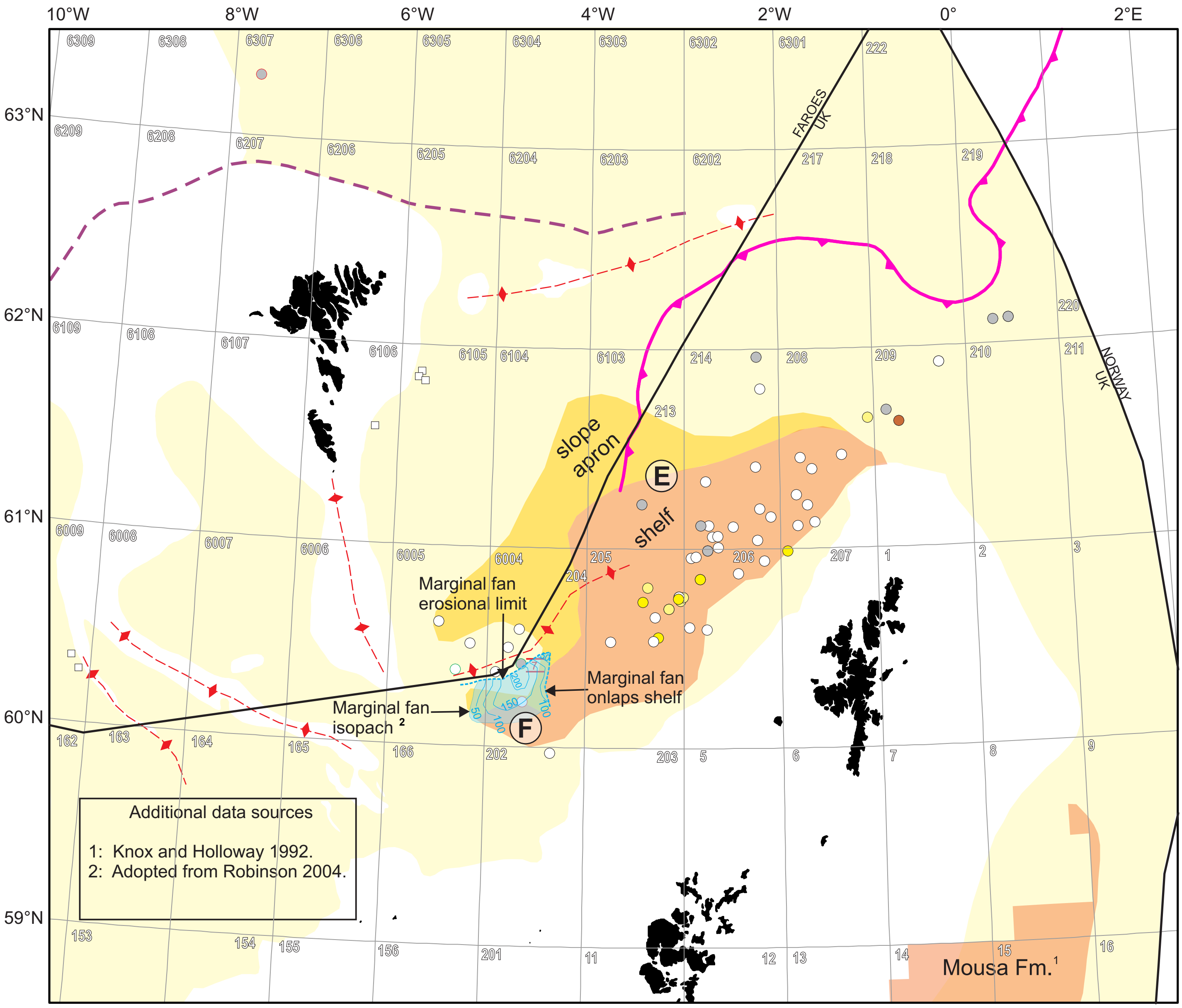
Eocene | shelf | slope apron

Ichron T-sequence

T98–T99

Bartonian–Priabonian

Figure 25 T98-T99 timeslice map: Mid- to Late Eocene, Stronsay Group, including location of unit E (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.



Structural features

- Fold/uplift axis
- Lava escarpment
- Landward limit of seaward-dipping reflectors

Key to wells and lithology

0 — 100 km

- Sand and sandstones
- Interbedded sandstones,siltstones and claystones
- Siltstones
- Interbedded siltstones and claystones
- Claystones
- Tuffs and tuffaceous claystones with interbedded sandstones and siltstones
- Coal and lignite with interbedded sandstones, siltstones and claystones
- Volcanic and igneous rocks
- 112 Thickness of Ichron T-sequence; in metres
- 112 Thickness of Ichron T-sequence with bounding unconformity (below and above; in metres
- >112 Partial thickness of Ichron T-sequence; in metres: Top or base not defined
- Zone absent
- BGS borehole; DSDP borehole
- Well; Dredge site

Blank where no information available for this zone

Eocene | shelf | slope apron | marginal fan estimated thickness (m)

Ichron T-sequence

T98–T99

Bartonian–Priabonian

(with marginal fan)

Figure 26 T98-T99 timeslice map: Mid- to Late Eocene, Stronsay Group, including location of units E and F (see text for details). The well lithology colours are calibrated with the stratigraphic-range chart (Figure A1): for greater clarity of colour registration at specific well sites please refer to the PDF version of this report. See Figure 1 for sample site identification.

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

JARÐFEINGI

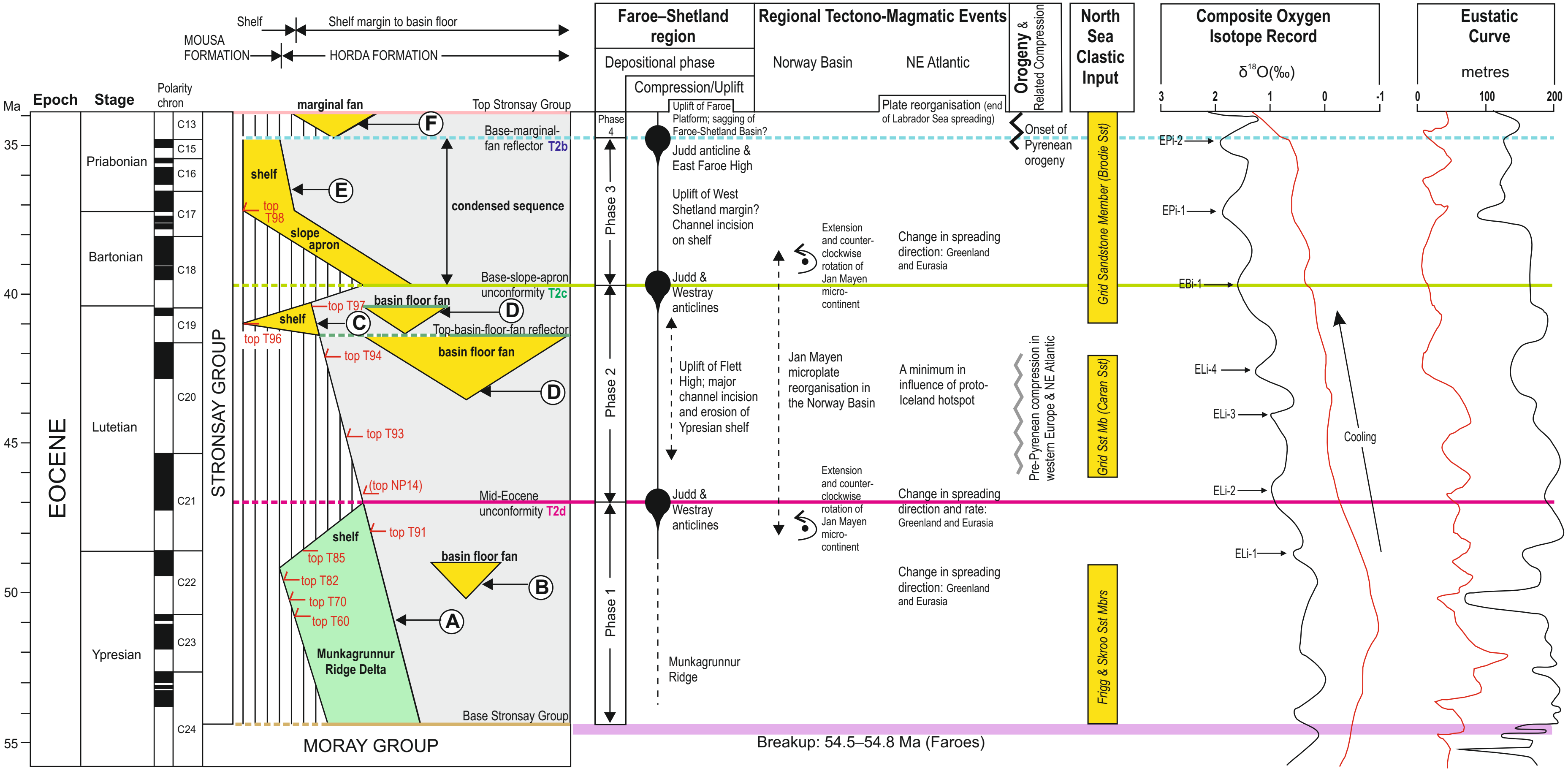


Figure 27 Preliminary Eocene tectonostratigraphy for the Faroe–Shetland region (see text for details). Information derived from the following sources: Compression/Uplift – Boldreel and Andersen (1993), Andersen et al. (2000), Robinson et al. (2004), Smallwood (2004), Ritchie et al. (2008), Ólavsdóttir et al. (2010) and Johnson et al. (2012); Regional Tectono-Magmatic Events – Mosar et al. (2002a, b), Lundin and Doré (2005), Kimbell et al. (2005), Gaina et al. (2009), and Passey and Jolley (2009); Orogeny & Related Compression – Masson et al. (1994), Hibsch et al. (1995); Sissingh (2001), Doré et al. (2008), Pereira et al. (2011); North Sea Clastic Input – Knox and Holloway (1992); Composite Oxygen Isotope Record and Eustatic Curves – Abreu and Andersen (1998) and Neal (1996) (black lines), and Miller et al. (2005) (red lines). Timescale is from Gradstein et al. (2004) and Ogg et al. (2008).

Block	Well	Block	Well
202	202/4-1[+]	209	209/4-1A
204	204/22-1[+]		209/6-1
	BGS 99/3		209/12-1
205	205/8-1	213	213/23-1
	205/9-1	214	214/4-1
	205/10-1A		214/9-1
	205/10-2		214/17-1
	205/10-3		214/19-1
	205/10-4		214/24-1
	205/10-5A		214/26-1
	205/12-1		214/27-1
	205/14-1		214/27-2
	205/14-2		214/27a-3
	205/14-3		214/27a-4
206	206/1-1A		214/28-1
	206/1-2		214/29-1
	206/1-3		214/30-1
	206/2-1A	219	219/27-1[+]
	206/3-1		219/28-2,2Z[+]
	206/5-1	6004	6004/12-1*
	206/11-1		6004/16-1Z*
	206/12-1		6004/17-1*
207	207/1-1	6005	6005/13-1A*
208	208/15-1A		6005/15-1*
	208/17-1		BGS 99/6
	208/17-2	6009	Dredges S1, S3
	208/19-1	6105	Dredges 145, 157
	208/21-1		158, 161
	208/22-1	6307	DSDP 336
	208/26-1		
	208/27-2		

Table 1 Commercial wells, BGS boreholes, dredge and DSDP sites used in this study.

Biostratigraphic data provided by Ichron for all wells, except: [+] CDA; * Jardfeingi