Early Palaeogene stratigraphy, volcanism and tectonics of the Faroe–Shetland region

Marine Geoscience Programme

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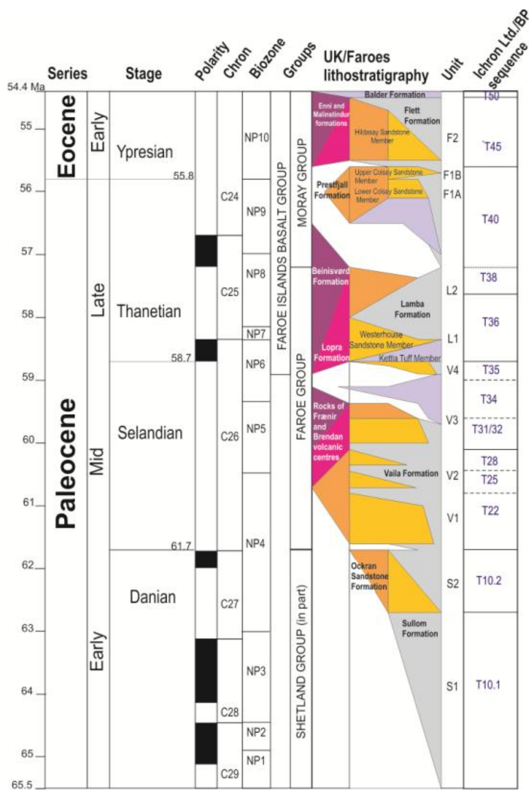

BRITISH GEOLOGICAL SURVEY

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Early Palaeogene stratigraphy, volcanism and tectonics of the Faroe–Shetland region

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Foreword

This report is the result of a study by the British Geological Survey (BGS) and Jarðfeingi into the early Palaeogene stratigraphy, volcanism and tectonics of the Faroe–Shetland region. It is based primarily on a biostratigraphical analysis of Palaeogene sediments in a set of released UK commercial wells carried out 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, BGS shallow boreholes and other published biostratigraphic information to compile a stratigraphic-range chart for the Paleocene–earliest Eocene succession.

The range chart re-emphasises the stratigraphic significance of a series of key unconformities and maximum flooding surfaces within the Faroe-Shetland Basin that have been used to sub-divide the succession in previous sequence stratigraphic interpretations. In the second part of the study, well ties to these key horizons were used to interpret a series of seismic profiles from the basin selected from a regional grid of 2D lines and a mosaic of 3D surveys within the Faroe–Shetland region.

The results of the seismic interpretation, combined with the data compiled on the stratigraphic range chart, show how the early Palaeogene sediments of the Faroe and Moray groups and the uppermost part of the Shetland Group are related to the contemporaneous volcanic rocks of the basin, which are currently incorporated in the Faroe Islands Basalt Group.

These observations form the basis of a new synthesis of the tectonic and stratigraphic development of Faroe-Shetland Basin during the early Palaeogene, beginning at 65.5 Ma and culminating in the opening of the NE Atlantic Ocean at 54.5 Ma (Gradstein et al. 2004; Ogg et al. 2008).

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

K Smith	Seismic interpretation and basin analysis; report writing.
M S Stoker	Task management; report writing and editing.
H Johnson	General contribution to the understanding and development of Cenozoic seismic stratigraphy, and project management.
Ó Eidesgaard	General contribution to the understanding of the early Palaeogene of Faroese sector and provision of Faroese well data.
M F Quinn	General contribution to the understanding of the structural elements of the Faroe-Shetland Basin.
G S Kimbell	General contribution to the understanding of early Palaeogene volcanic stratigraphy based on interpretation of gravity and magnetic data.
H. Ziska	General contribution to the understanding and development of Cenozoic seismic stratigraphy, and project management.

J Ólavsdóttir General contribution to the understanding of early Palaeogene of Faroese sector.

The authors acknowledge the assistance of other BGS colleagues, including Sandy Henderson for his work on the database, Craig Woodward for draughting the seismic panels and Derek Ritchie for his scientific review of this report. Uni Árting of Jarðfeingi added to our understanding of the stratigraphy of the Faroe Islands Basalt Group. We thank Andrew Alderson of Ichron Limited for biostratigraphic discussions and for supplying us with two non-proprietary Ichron reports. CDA are acknowledged for allowing access to further released well data. We are also grateful to the commissioning companies, who provided seismic data and gave permission to use selected seismic profiles as illustrations. The GSHHS /World Vector Shoreline used in this report is courtesy of National Geophysical Data Center (NGDC)/US Geological Survey (Wessel/Smith).

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APPENDICES

A.1. Stratigraphic-range chart

A.2. Biostratigraphic notes

Summary

This report combines well and seismic data to present a synthesis of the stratigraphic and tectonic development of the Faroe–Shetland region during the early Palaeogene, beginning at 65.5 Ma and culminating in the opening of the NE Atlantic Ocean at 54.5 Ma.

A stratigraphic-range chart, based largely on biostratigraphic data provided by Ichron Limited, details the chronological range, lithology and thickness of the early Palaeogene succession in more than fifty UK hydrocarbon exploration wells. Additional data obtained from Faroese wells and other published sources supplement the Ichron Ltd. database. Well ties to key horizons link the regional sequence stratigraphy to a grid of 2D and 3D seismic surveys. Selected seismic profiles are used, together with depth and thickness isochron maps of key areas, to assess the relationship between stratigraphy and structure.

1: Three major sequence boundaries in the early Palaeogene succession can be related to episodes of deformation in the Faroe-Shetland Basin.

2: The Sullom unconformity is related to uplift on the margins of the Faroe-Shetland Basin following localised extension during the Danian and precedes an influx of basinal sandstones, which form the main Palaeogene hydrocarbon reservoirs in the Vaila Formation. Subsequent extension in the basin mobilises Lower Paleocene shales into mud diapirs with thickened Vaila Formation sandstones ponded in adjoining withdrawal synclines. Well evidence for the onset of volcanism during the Selandian is provided by coarse volcaniclastic sandstones and tuffs derived from local central volcanoes, including Brendan and Frænir.

3: The intra-Vaila unconformity marks a period of uplift near the end of the Selandian, with overlying turbidites of the uppermost Vaila Formation forming the reservoir of the Laggan field. The sandstones are onlapped by shales and a widespread volcaniclastic unit, the Kettla Tuff, which forms the basal member of the Lamba Formation, a prograding shelf succession of Thanetian age. Throughout this time, a volcanic shield, composed of Lopra Formation hyaloclastites and Beinisvørđ Formation basalts, prograded across the Faroese sector.

4: The Flett unconformity incised the Lamba Formation to form a terrestrial landscape characterised by dendritic drainage during the late Thanetian. Related uplift in the Faroese sector truncated the Beinisvørđ Formation, which is onlapped by fluvial sandstones and coals of the Prestfjall Formation. As the lower part of the Flett Formation shelf advanced northwards, evidence of minor extrusive volcanism extending into the Eocene may be linked to an episode of basic sill intrusion during the deposition of the Colsay Sandstone Member.

5: Renewed volcanism generated the terrestrial lavas of the Enni and Malinstindur formations of the Faroes Islands Basalt Group during the Ypresian. The Enni basalts entered the marine depocentre in the north of the region as a hyaloclastite delta forming the Faroe-Shetland Escarpment. As the period of relative sea level rise continued, the marine basin encroached upon the dissected coastal plain and a transgressive coal facies was deposited in the Hildasay Sandstone Member in the upper part of the Flett Formation.

6: Oceanic opening occurred during the deposition of the Balder Formation. This succession of Ypesian tuffs and tuffaceous claystones oversteps the Flett Formation and is preserved as a conspicuous marker horizon across much of the Faroe-Shetland Basin and North Sea. Erosion of the Balder Formation with the development of erosive channels at the base of the overlying Stronsay Group is possibly linked to localised uplift near the basin margins.

7: The inferred structural history of the area adds to existing interpretations, which show that uplift and intraplate deformation of the Faroe–Shetland region continued before, during and after the formation of the NE Atlantic passive margin. A final section reviews the possible implications of these observations for different models of regional tectonics.

1 Introduction

The sediments and volcanic rocks of the early Palaeogene form a major focus of research in NE Atlantic area for two main reasons: Firstly, since the discovery of the Foinaven and Schiehallion fields boosted the known reserves of the Faroe-Shetland Basin in the 1990s, the presence of thick oil-rich turbidite reservoirs has made the early Palaeogene deep-water play the main regional focus of the hydrocarbon industry (Quinn et al. 2011); secondly, academic interest in the geology of the Faroe–Shetland region has been stimulated by the potential link it provides between the Iceland plume, intra-plate volcanism and the Cenozoic uplift of the British Isles, with many authors attributing an increase in early Palaeogene clastic sedimentation in both the Faroe-Shetland and the North Sea basins to the initial impact of a mantle plume at the base of the lithosphere (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 Faroe–Shetland region forms a key testing ground for this idea.

It was during the Early Eocene that the final segment of the NE Atlantic Ocean opened between East Greenland and the Faroe Islands (Gaina et al. 2009; Fig. 1). The presence of associated volcanic rocks of early Palaeogene age on the adjoining passive margin presents a major obstacle to effective hydrocarbon exploration of the Faroe-Shetland Basin, especially in the Faroese sector, where the cumulative thickness of the volcanic succession is known to exceed 6 km onshore (Waagstein 1988; Hald and Waagstein 1991; Waagstein et al. 2002). Shallow rocks of such high velocity have a significant detrimental effect on seismic acquisition offshore (Richardson et al. 1999) and considerable efforts continue to be made to improve imaging in the pre-volcanic section of the region (Kiørboe and Petersen 1995; White et al. 2003; Raum et al. 2005; Spitzer et al. 2005). The local lack of seismic resolution has added to the existing problems of stratigraphic correlation and structural interpretation in the Palaeogene.

The recent recognition of potentially significant intra-lava hydrocarbon reservoirs in the Rosebank discovery (Helland-Hansen 2009) has increased the importance of clarifying the stratigraphic relationship between the volcanic successions of the Faroe Platform and the predominantly sedimentary fill of the Faroe-Shetland Basin in the UK sector.

The area of study extends northwestwards from the West Shetland Shelf to the Iceland-Faroe Ridge, with a north-eastern boundary marked by the UK/Norwegian median line and a south-western boundary effectively marked by the subcrop of Palaeogene volcanic rocks along the Faroe Bank and Wyville Thomson Ridge between Quadrants 6009 and 165 (Keser Neish 2003; Sørensen 2003) (Fig. 2).

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. Following basin subsidence in the Devonian, Carboniferous sediments were preserved locally before further phases of rifting took place during the Permo-Triassic and Jurassic (Doré et al.1999; Roberts et al. 1999, and references therein). However, the main episode of basin formation offshore occurred during the Cretaceous, with instigation of the Faroe-Shetland Basin depocentre in Aptian–Albian times (Dean et al. 1999; Larsen et al. 2010). Seismic and well evidence for the development of differential uplift, subsidence and compressional deformation during the remainder of the Cretaceous has been linked to a period of regional oblique-slip tectonics associated with the incipient North Atlantic rift system (Stoker et al. 2010a).

1.1 DATA SOURCES

There are 5 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 biostratigraphy reports supplied by Ichron Limited (2010a, b) in confidence to the BGS as part of this project; the reports present the results of a palynological and micropalaeontological review of the Paleocene–Eocene interval in exploration and appraisal wells from across the Faroe-Shetland Basin. Data from wells in parts of Quadrant 204 licenced by BP, which were analysed in a separate study by Ichron Ltd., were not made available.
5. Released seismic reflection data contributed by the Faroe-Shetland Consortium members (Fig. 3).

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 METHODOLOGY

Well-log and core information taken from released commercial wells form the main rock-record component of this regional study (Fig. 2). Most of the wells are keyed into the Ichron T-sequence scheme, which is based on the original BP T-sequence framework for the Faroe-Shetland Basin first published by Ebdon et al. (1995) and subsequently modified by Lamers and Carmichael (1999). Biostratigraphic data for the remaining wells and boreholes were obtained from other published sources (including Morton et al. 1988; Stoker et al. 1988; Jolley and Bell 2002a; Jolley 2009), from CDA (in the UK sector) and from Jarđfeingi (in the Faroese sector).

Wells in the UK sector are widespread along the West Shetland margin, but the Faroese wells are clustered at the south-west end of the Faroe-Shetland Basin, with the newly released Brugdan well (6104/21-1) being the most significant offshore data point from elsewhere in the Faroese sector. Data obtained from stratigraphic boreholes drilled onshore in the Faroe Islands (Glyvurnes-1, Lopra1/1A and Vestmanna-1) provide additional constraints on the development of the early Palaeogene volcanic succession, and these are incorporated on the appropriate regional maps. Four BGS shallow boreholes provide some information from the Paleocene subcrop at the margins of the basin and other sample material has been recovered from the base of the Eocene succession around the Faroe Platform by dredging (Waagstein and Heilman-Clausen 1995). Further to the north-west, DSDP site 336 proved post-earliest Eocene sediments overlying oceanic crust on the northern slope of the Iceland-Faroe Ridge (Stoker et al. 2012b).

The range of the early Palaeogene sequence at each sample site has been captured on a stratigraphic-range chart (Appendix 1, Fig. A1). The chart includes the thickness of each sequence, a generalised indication of the predominant lithologies derived from the composite logs and additional stratigraphical notes, where necessary. Cumulative thicknesses of selected major units bound by unconformities identified on seismic data, and incorporating two or more of Ichron Ltd.'s sequences, are also included on the chart.

The format of the range chart is a modified version of the previous chart showing the overlying Eocene succession (Stoker et al. 2012b), with sample sites displayed in the same Quadrant/ Block order, so that the two charts can be superimposed. Some wells with a Paleocene succession, which were omitted from the original chart because they lack an Eocene section analysed by Ichron Ltd., have been added in separate columns to the right hand side of the chart.

Although the same timescale has been retained, the vertical chronological scale of the Paleocene–earliest Eocene chart (Appendix 1, Figure A1) has been expanded for greater clarity. Also, the base of sequence T45 has been amended from Stoker et al. (2012b), to correlate correctly with the age range of nanoplankton biozone NP10 proposed by Ogg et al. (2008).

As in Stoker et al. (2012b), a series of timeslice maps, linked to the Ichron T-sequences has been constructed for the Faroe–Shetland region. The maps show the spatial distribution of the data compiled on the Paleocene–earliest Eocene range chart. Those that display a single sequence (or T-zone) show the thickness and generalised facies of the interval at each well, with symbols identifying where the interval is absent, as well as the presence and position of associated unconformities where the succession is truncated. The report includes A4-sized hard copy versions of each of these figures, but for the best resolution and clarity of the detailed information recorded on 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.

Reflectors associated with some of the regional unconformities recognised by Ichron Ltd. within the early Palaeogene were used to interpret a selection of seismic profiles from the regional coverage of 2D and 3D data available to the current project (Fig. 3), and additional maps were compiled of the cumulative thickness of the two or more sequences that make up the larger unconformity-bound units.

In accompanying figures, the point data presented on both sets of sequence thickness maps have been summarised by hand-contoured isopachs, with the contours partly constrained by the distribution of regional structural elements obtained from Ritchie et al. (2011). Some of these regional maps show contemporaneous thickness variation in sedimentary basins (from well data) and volcanic-dominated areas (from depth-converted seismic data) and form the potential basis of a regional palaeogeographic interpretation.

2 Stratigraphic framework

The stratigraphic framework used in this report for the early Palaeogene of the Faroe–Shetland region is summarised on Fig. 4. This section briefly reviews the various elements of the stratigraphic scheme.

2.1 CHRONOSTRATIGRAPHY

During the current project, the timescales of Gradstein et al. (2004) and Ogg et al. (2008), which were used formerly to compile the range charts of Stoker et al. (2010a; 2012b), were superseded by the timescale of Gradstein et al. (2012), which modifies the age of some stage boundaries within the Palaeogene (generally by less than 0.5 Ma). To retain a comparison with previous reports in this series, these latest revisions are not incorporated in the range chart prepared for the current report (Appendix 1, Figure A1).

2.2 MAGNETOSTRATIGRAPHY

Magnetochrons depicted on the range chart are derived from the work of Cande and Kent (1995), as modified subsequently by Gradstein et al. (2004) and Ogg et al. (2008) to correspond to their revised radiometric timescales.

2.3 LITHOSTRATIGRAPHY

Lithostratigraphic interpretation of the Palaeogene succession in the Faroe–Shetland region initially made use of the stratigraphic units identified in the North Sea by Deegan and Scull (1977) and much of the subsequent formal nomenclature of the area has developed in relation to the changing interpretation of the North Sea succession (Mudge and Copestake 1992a; b; Knox and Holloway 1992).

In their standard lithostratigraphic nomenclature for the Palaeogene of the Faroe-Shetland Basin, Knox et al. (1997) retained some units, such as the Moray Group and the Balder Formation, that were originally identified by Deegan and Scull (1977) and Knox and Holloway (1992) as part of the North Sea lithostratigraphy. For the remainder of the succession however, they were required to create a number of new local names at group and formation level in the absence of a direct stratigraphic link with the North Sea Basin. The newly-defined units include the Flett Formation (broadly equivalent to the Sele Formation), the Faroe Group with its constituent units the Vaila and Lamba formations (equivalent in large part to the Montrose Group) and the Sullom and Ockran Sandstone formations (local units of Danian age included in the Shetland Goup). Knox et al.'s (1997) scheme forms the lithostratigraphic basis of this report (Fig. 4 and Appendix 1, Fig. A1).

A formal lithostratigraphic nomenclature for the preodominantly volcanic stratigraphy of the Faroe Islands was produced independently by Passey and Jolley (2009) to replace the previous informally adopted nomenclature, which divided the lavas into Lower, Middle and Upper Basalt series or formations (Ramussen and Noe-Nygaard 1970; Waagstein 1988).

The separate lithostratigraphic schemes for sedimentary and volcanic successions are used in the summary accounts of the Cenozoic of the Faroe-Shetland Basin by Stoker and Varming (2011) and Passey and Hitchen (2011). Well and seismic data presented in this report contribute to a reassessment of the relationship between the volcanic and sedimentary lithostratigraphic units and the resulting revised interpretation is summarised on Fig. 4 and Appendix 1, Fig. A1.

2.4 SEQUENCE STRATIGRAPHY

The large number of wells, extensive seismic coverage and long history of Palaeogene oil discoveries in the North Sea made it one of the key testing grounds for the principles of sequence stratigraphy during its development (Van Wagoner et al. 1988; Galloway et al. 1993) and since the work of Mudge and Copestake (1992a; 1992b), lithostratgraphic schemes for the Palaeogene of the basin have usually incorporated some elements of a sequence stratigraphic interpretation; for example, by defining locally developed sandstone units as members of more widespread mudstone-dominated formations (Knox and Holloway 1992; Schiøler et al. 2007).

Most of the Palaeogene sequence stratigraphic intervals originally recognised in the North Sea have since been identified in the Faroe–Shetland region, with links between the two basins established through a common biostratigraphy, base-level history and regional stratigraphic markers (e.g. Ebdon et al. 1995; Lamers and Carmichael 1999; Mudge and Bujak 2001).

The recognition of comparable biomarkers in the two basins enabled Ebdon et al. (1995) to subdivide the succession in the Faroe-Shetland Basin into the same broad sequence stratigraphic units recognised by BP in the North Sea (T10, T20, T30 T45 and T50, where T stands for Tertiary), while adding extra units (T32, T34, T36) within the most prospective interval (Fig. 5).

Early in the exploration of the Faroe-Shetland Basin, various stratigraphic schemes were proposed by different operators, and in the case of BP and Mobil these were based on slightly different approaches to sequence stratigraphy, with Mobil favouring an Exxon or Vail-type model based on unconformity-bound sequences (Van Wagoner et al. 1988; Mitchell et al. 1993), whereas BP, for at least a part of the succession, used the type of genetic analysis employed by Galloway et al. (1993) based on the recognition of maximum flooding surfaces as sequence boundaries (Ebdon et al. 1995; Lamers and Carmichael 1999). On a summary log of well 214/28-1, Knox et al. (1997, their Enclosure 3) show their own interpretation of the sequence stratigraphy alongside five other different interpretations proposed by various oil companies.

As exploration of the basin proceeded, finer sub-divisions of these original units were incorporated into the sequence stratigraphic analysis (Fig. 6), but the rationale behind the extra sub-divisions is not always described in the literature; for example, the significance of the sequences T22, T25, T28, T31, T35 and T38 and their relationship to the units previously proposed by Ebdon et al. (1995), is not explained when they are introduced by Lamers and Carmichael (1999). This lack of clarity is a potential source of confusion, which becomes important when the BP scheme is subsequently adopted as an informal industry standard by other operators and service companies.

Geological developments have caused other modifications to the original sequence nomenclature over time. In the North Sea, the T20 sequence was created to encompass the Maureen Formation, which commonly rests directly upon the Danian Ekofisk Formation (T10) in basinal settings. Subsequent recognition that the lower (M1) part of the Maureen Formation is of Danian age changes the significance of the stratigraphic boundary between T10 and T20 by removing the correlation between the top Ekofisk seismic event and the top of the Danian in North Sea (Knox and Holloway 1992).

In the Faroe-Shetland Basin, the T-zone intervals T22, T25, T28 are sub-divisions of the T20 sequence elsewhere. However, inspection of their biomarkers shows that none of these intervals is equivalent to the lower part of T20 in the North Sea (Maureen Formation, unit M1 of Knox and Holloway 1992), since they are solely of early Selandian age and correspond only to the upper (M2) part of the sequence. Sediments in the Faroe-Shetland Basin equivalent to the lower part of the Maureen Formation are included by Knox et al (1997) in the upper part of the Danian Sullom Formation, which corresponds to sequence T10.2 of Ichron Ltd. (2010a, b).

Although Knox et al. (1997) do not use the sequence stratigraphic T-zones proposed by BP, their interpretation of the lithostratigraphy of the basin is clearly influenced by a similar sequence stratigraphic approach to basin analysis. While Knox et al.'s (1997) record of key biomarkers allows some direct comparisons to be made between the two different schemes, there are insufficient identified biostratigraphic boundaries to correlate their lithostratigraphic units with all the currently recognised intervals in the BP T-zone scheme.

In the current report, where a sequence stratigraphic unit forms part of a defined lithostratigraphic interval, its stratigraphic position is sometimes identified in equivalent lithostratigraphic terms; for example, sequence T45 may be described colloquially as upper Flett Formation, T40 as lower Flett Formation and T35 as uppermost Vaila Formation. Although some of these units correspond broadly to lithostratigraphic intervals (such as F2, F1 and V4), which are recognised in the numbering scheme used by Knox et al. (1997), the terminology adopted here is only intended for informal use.

2.5 BIOSTRATIGRAPHY

A series of regional syntheses (Mitchell et al. 1993; Ebdon et al. 1995; Knox et al. 1997; Mudge and Bujak 2001; Mudge and Jones 2004; Gordon et al. 2010; Stoker and Varming 2011) describe the various biostratigraphic schemes adopted for the Palaeogene succession of the Faroe-Shetland Basin. Many of these were initially developed for the Palaeogene of the North Sea, with its more extensive exploration history (Mudge and Copestake 1992a, b; Knox and Holloway 1992; Neal et al. 1994; Neal 1996; Stein et al. 1995; Mudge and Bujak 1996; Ahmadi et al. 2003, Schiøler et al. 2007). The two regional assessments of Mudge and Bujak (1996, 2001) summarise the comparative biostratigraphy of these two areas.

The short account of Paleocene biomarkers provided by Harland et al. (in Appendix A of Knox and Holloway 1992) emphasises many of the drawbacks associated with regional biostratigraphic syntheses. Historically, a number of different service companies have been responsible for the biostratigraphic analyses that accompany final well reports. In some cases, sub-division of the succession in a well can be based on a particular biomarker or combination of bio-events only identified or assigned significance by a single service company.

Comparisons of different biostratigraphic schemes are difficult and often reveal discrepancies of interpretation (see discussion of Paleocene bio-events in Mangerud et al. 1999). To provide a specific example: Mudge and Bujak (2001; their Fig. 4) apply their regional biostratigraphic scheme to wells 204/24-1A, 206/1-1A, 208/19-1 and 214/27-1 and the same wells are also interpreted by Knox et al. (1997) and Ichron Ltd. (though the latter's interpretation of 204/24-1A is not available to this project). Between these different interpretations, the proposed picks for selected stratigraphic boundaries in well 206/1-1A differ by 13m at top T40 level and 58m at top T38 level; while the ranges of equivalent discrepancies for well 208/19-1 are even larger (43m at T40 and 118m at top T38).

Some of the variation between between biostratigraphic schemes is a natural consequence of the recognition of new species and fossil associations during the exploration of a basin. In addition, progressive refinements of classification, or redefinitions of species caused by naming priorities, can result in changes to fossil nomenclature, which add to the complexity of appraising biostratigraphic data for a non-specialist. Significant biomarkers in the Paleocene of the Faroe-Shetland Basin provide three examples of this: *Eoglobigerina trivialis* is a planktonic microfossil described by some authors as *Globigerina trivialis*; the radiolarian *Cenosphaera lenticularis* is often alternately known as *Cenodiscus lenticularis*, and a key palynomorph, formerly described on well reports as *Aeroligera cf senonenis*, is now assigned a new species name, *Aeroligera gippingensis* (Jolley 1992; Knox and Holloway 1992).

Other variations between biostratigraphic schemes are caused by the use of abundance data, which are used to define 'acme' bio-events based on the peak number of specimens present in a sample. Acme occurrences are more liable to be affected by lithological variation, forming locally correlatable events that may only apply within a single oilfield (Mangerud et al. 1999, p171). The chronological significance of such events may vary between basins or depocentres. In addition, the application of various abundance criteria is not standardised between service companies. Ichron Ltd., for example, apply their own statistical analysis before describing the occurrence of a particular species as single, rare, frequent, common, abundant or super-abundant and it is uncertain how any of these quantitative abundances relate to the terms ‘acme occurrence’ and ‘first consistent downhole occurrence’ widely used by other authors (e.g. Mudge and Copestake 1992a, b; Mangerud et al. 1999, p171-172).

In a biostratigraphic interpretation of a single well, the greatest significance is given to chronological events linked to the first downhole occurrence (FDO) of a biomarker since, in the absence of reworking, these are likely to correspond to synchronous extinctions. Last downhole occurrences (LDO) are equivalent to first evolutionary appearances and should be equally significant but, in analyses obtained largely from well cuttings, samples affected by contamination from the overlying part of the drilled section can obscure identification of the deepest occurrence. Since one of the main criteria for recognising the base of the Eocene in the Faroe-Shetland Basin is the last downhole appearance of the dinocyst *Apectodinium augustum*, it follows that this boundary cannot be precisely located in wells using cuttings alone.

The biostratigraphic interpretations that form the basis of this study were carried out by Ichron Ltd. as part of a regional reassessment of the basin. Ichron Ltd’s reports (2010a, b) provide a potential link between the different types of stratigraphic analysis. Each of their well log interpretations makes a direct correlation with the lithostratigraphic subdivisions of Knox et al. (1997) (V1-V4, L1, L2, etc.) and with the sequence stratigraphy by using and expanding the T-zone numbering convention of BP, with the addition of a number of new sub-zones (T35.3, T10.1, T10.2, etc.).

3 Early Palaeogene stratigraphy in the Faroe-Shetland region (Shetland, Moray and Faroe groups)

This section describes the thickness, distribution and generalised lithology of the early Palaeogene succession in ascending stratigraphic order, basing the discussion on previous published accounts, the stratigraphic-range chart compiled for this report (Appendix 1, Fig. A1) and the associated thickness summary maps. The map data are supplemented by a series of interpreted seismic profiles, the locations of which are summarised on Fig. 7.

3.1 SHETLAND GROUP

The Shetland Group is largely of Late Cretaceous age, but extends into the Early Paleocene (and possibly the earliest Late Paleocene) in the Faroe-Shetland Basin, where two formations are recognised by Knox et al. (1997).

3.1.1 **Sullom and Ockran Sandstone formations, T10 (Danian)**

The Sullom Formation consists largely of calcareous mudstones and forms the bulk of the Paleocene part of the Shetland Group, while the Ockran Sandstone Formation is a local, sandstone-dominated shelfal succession, which is laterally equivalent to part of the Sullom Formation in the south-western part of the basin. An upward change from the calcareous mudstones of the Late Cretaceous Jorsalfare Formation to the more silty, slightly less calcareous, argillaceous sediments of the Sullom Formation is described by Knox et al (1997), who interpret the base of the Sullom and Ockran Sandstone formations as the base of their sequence set ‘A’.

Inspection of seismic data shows that the intrusion of basic sills within the predominantly argillaceous succession at basal Paleocene level has obscured the junction with the underlying Jorsalfare Formation in many parts of the basin. This, combined with the lack of base Cenozoic well penetrations and the effects of subsequent shale mobilisation, means that regional thickness variation of the Early Paleocene is poor constrained.

The Ockran Sandstone, which reaches 260 m in thickness in well 205/26a-2, is a medium to coarse-grained sandstone that contains abundant bioclastic debris and thin calcite-cemented beds. A potential oil reservoir up to 215 m thick was drilled and tested at this level by well 204/22-2Z. The Ockran Sandstone Formation provides an initial indication that the corner of the basin between the Judd and Rona highs is a long-lived entry point for coarse-grained sediments (Ebdon et al. 1995). In marginal locations, some thin sandstones also occur within the grey mudstones of the Sullom Formation. In the Faroese sector, T10 mudstones provide the seal to the Marjun discovery (6004/16-1Z), which occurs in equivalent basal Paleocene sandstones within the Judd inversion anticline to the north of the Judd High (Smallwood 2004; Smallwood and Kirk 2005; Loizou et al. 2006).

The top of the Shetland Group in the Faroe-Shetland Basin defines the top of the T10 sequence and the top of the Danian, and is associated with the first downhole occurrence of the planktonic microfossil *Eoglobigerina trivialis* (Knox et al. 1997, p113). This boundary coincides with an upward change from the virtually sand-free calcareous mudstones of the Sullom Formation to the sand-rich non-calcareous mudstones of the Vaila Formation.

Lamers and Carmichael (1999, their Fig. 6) have a different sequence stratigraphic interpretation. They show that the Sullom Formation is largely equivalent to T10, but also incorporates the lower part of their T22 sequence. In their view, the top of T22 marks the top of the Early

Paleocene. This is an unexplained modification of Ebdon et al. (1995, their Fig. 6), where the top of the Danian corresponds to the top of T10. In the stratigraphic scheme adopted for this report, the T22 biozone is taken to post-date the key biomarker for the top of the Danian.

Well data in the UK sector (Appendix 1, Fig. A1; Figs. 8, 9) show that the Sullom and Ockran Sandstone formations are absent or partly eroded beneath intra-Palaeogene unconformities on the margin of the basin along the Rona Ridge, while wells within the basin indicate a broad northerly thickness increase from a few hundred metres in the southern part of the area to more than 1000 m (including basic intrusives) in Quadrant 208, where Knox et al. (1997) record a thickness of about 1040 m in well 208/17-1. The limited well evidence may indicate a local resurgence of extension during the upper part of the Danian (equivalent to sequence T10.2 of Ichron Ltd. 2010a; b) in the north of the study area, with a thinner claystone succession and the more shelfal Ockran Formation deposited contemporaneously alongside the rising West Shetland margin in the south.

In this report, the unconformity marking the top of the Sullom Formation and the Shetland Group, in wells such as 205/14-3, 208/26-1 and 214/24-1, is described as the Sullom unconformity (Appendix 1, Fig. A1). In places, the base Cenozoic unconformity at the margin of the basin may represent a combination of top Sullom Formation and intra-Sullom Formation events, with the latter equivalent to the base of sequence T10.2 (Ichron Ltd. 2010a; b). A seismic panel (Section A; Fig. 10) shows the contrast between the centre of the basin and its margins in the vicinity of the Flett High. In the basin at the NE end of the profile, a series of high-amplitude reflectors between 3.5 and 4.0 s TWTT indicate that the thick Early Palaeocene section is pervasively intruded by transgressive basic sills, which disrupt the continuity of reflections from the sedimentary succession at base Cenozoic level. In the centre of the section, the sills die out at a Paleocene intra-basinal fault. On the flanks of the basin to the SW, the base of the Paleocene is well defined by an unconformity that truncates a largely sill-free Late Cretaceous succession above the Flett High, where a series of deeper high-amplitude events may indicate the presence of a separate tectonically-deformed sill complex rising from more than 7.0 s TWTT to approximately 4.7 s TWTT. A similarly oriented seismic section further to the SE (Section C; Fig. 11) shows the absence by erosion of the early Paleocene interval at a planar top Shetland Group unconformity above the flanks of the Rona High, with evidence of two NW-trending channels backfilled by younger Paleocene sediments.

Evidence from well and seismic data in the UK sector suggests that the Sullom unconformity separates an episode of localised extension during the deposition of the Sullom Formation in the Danian from a period of more widespread extension associated with volcanic and sedimentary units in the Selandian (Appendix 1, Fig. A1).

3.2 FAROE GROUP

In the nomenclature of Knox et al. (1997), the Lamba and Vaila formations constitute the Faroe Group, which includes all the sediments between the Shetland and Moray groups (Fig. 4). The Faroe Group includes the most prospective reservoir sandstones in the Faroe-Shetland Basin.

3.2.1 **Lithostratigraphic background**

Deegan and Scull (1977) originally assigned the Paleocene sandstones deposited between the Maureen Formation and Forties Formation to the Heimdal Formation (in the northern North Sea) and the Andrew Formation (in the central North Sea). Subsequently, the biostratigraphic work of Mudge and Copestake (1992a; b) and the burgeoning application of sequence stratigraphy prompted Knox and Holloway (1992) to reduce these North Sea sandstones to member or unit status within the claystone-dominated Lista Formation and introduce a new local name, the Mey Sandstone Member, for Lista Formation sandstones in the central North Sea.

Knox and Holloway (1992) also recognised that various separate sandstone bodies could be distinguished within the Mey Sandstone interval, in particular by tracing a tuffaceous stratigraphic marker, which they termed the Balmoral Tuffite. They suggested incorporating sandstones between the Balmoral Tuffite and the overlying Forties Sandstone in an informal local unit, named the Balmoral Sandstone. Knox and Holloway (1992) proposed retaining the term Andrew Sandstone as an informal name for sandstones within the Lista Formation below the Balmoral Tuffite, despite the potential risk of confusion with the more inclusive Andrew Formation previously defined by Deegan and Scull (1977).

In the absence of a direct stratigraphic connection with the North Sea succession, Knox et al. (1997) were not prepared to extend the use of the term Lista Formation into the Faroe-Shetland Basin. Instead, they used a locally developed tuffaceous unit equivalent to the Balmoral Tuffite to split the corresponding succession into two parts. They named the tuffaceous unit the Kettla Tuff Member and used it to define the base of the Lamba Formation (thus including all the strata that would be informally described as Balmoral Sandstone in the central North Sea), while the underlying pre-Kettla sandstones of Selandian age were assigned to the Vaila Formation and are equivalent to the informal Andrew Sandstone unit and the upper part of the Maureen Formation elsewhere. The Kettla Tuff Member is thickest in Quadrants 205 and 6004; well data show that it consists predominantly of coarse and poorly-sorted volcaniclastic sandstones in the Faroese sector (Eidesgaard 2012).

3.2.2 **Vaila Formation; T22, T25, T28, T31 T32, T34 (Selandian)**

The Vaila Formation is defined by Knox et al. (1997) as a unit of sandstones and interbedded mudstones overlying the Shetland Group and forming the lower part of the Faroe Group. It incorporates strata that are age equivalent to the upper part of the Maureen Formation and the lower part of the Lista Formation in the North Sea (Knox and Holloway 1992).

Knox et al. (1997) divided the Vaila Formation informally into 4 units (V1-V4) (Fig. 4). Here we follow Ichron Ltd.'s (2010a; b) interpretation based on regional biomarkers that BP T-zone T22 probably corresponds to the Vaila Formation lithostratigraphic unit V1. The top of V1 is commonly defined at the FDO of <u>common</u> to <u>abundant</u> *Cenosphaera lenticularis*, making this biomarker a type of acme occurrence. Other typical biomarkers include the presence of <u>common</u> *Palaeocystodinium bulliforme*, which usually implies a Selandian age (Jolley and Bell 2002a; Stoker and Varming 2011, p171; See discussion in Appendix 2). Some wells in Quadrant 214, including 214/27-2 and 214/28-1, show an unconformity at top T22 level that may represent a local precursor of the subsequent intra-Vaila event (Appendix 1, Fig. A1). Sandstones in unit V1 generally consist of thinly-bedded turbidites (Knox et al. 1997).

The most significant stratigraphic boundary within the lower part of the Vaila Formation is the contact between the T20 and T30 groups of sequences, which often forms a flooding surface (Ebdon et al. 1995), corresponding to the top of sequence T28. Tuffaceous claystones within the T28 interval provide one of the first indications of early Palaeogene volcanism in the region and act as a bottom seal for the Schiehallion field (Leach et al. 1999). In lithostratigraphic terms, the top of the T28 sequence is equivalent to the top of the V2 unit of the Vaila Formation as defined by Knox et al. (1997). The V2 lithostratigraphic unit also includes the claystones and basinal sandstones of the T25 sequence (Ichron Ltd. 2010a; b).

Vaila units V1 and V2 are contemporaneous with the Selandian, M2 unit of the Maureen Formation (Knox et al. 1997) and represent a similar influx of coarser sediment from the basin margins. In the North Sea, Maureen unit M2 overlies calcareous mudstones of Danian age and consists of redeposited chalks, silty sediments of distal fan origin and widespread submarine fan sandstones derived from the East Shetland Platform (Knox and Holloway 1992). The basinal sandstones widely developed in the V1 and V2 units in the Faroe-Shetland Basin are of comparable fan origin, with thick-bedded mass-flow sandstones more characteristic of the younger V2 unit (Knox et al. 1997).

Knox et al. (1997) link the top of V2 (T28 and T25) with an influx of disc-shaped radiolarians. This biomarker, which corresponds to the first downhole (non-reworked) occurrence of the radiolarian *Cenosphaera lenticularis,* is equivalent to bioevent M3 of Mudge and Copestake (1992a; b) in the North Sea.

Late Selandian sandstones within the overlying T31, T32 and T34 sequences form some of the most prospective hydrocarbon reservoirs in the Faroe-Shetland Basin and have produced oil from NW to WNW-trending slope channel complexes in major fields in the UK sector including Foinaven (Cooper et al. 1999) and Schiehallion (Leach et al. 1999). These sandstones are largely equivalent to the V3 lithostratigraphic unit of the Vaila Formation as defined by Knox et al. (1997) and are sealed by onlapping mudstones of the overlying V4 unit, which were deposited on a flooding surface within the T35 sequence.

Well thickness data for the combined T22 to T34 sequence intervals of Ichron Ltd (2010a; b; Appendix 1, Fig. A1) are plotted on Fig. 12, together with the distribution of the partly equivalent Lista Formation in adjoining parts of the UK North Sea (Knox and Holloway 1992). These thicknesses represent all the Vaila Formation, excluding the stratigraphic sequence T35. A hand-contoured map of the well data (Fig. 13), constructed with the aid of regional structural elements obtained from Ritchie et al. (2011), indicates a NE-thinning succession along the axis of the Faroe-Shetland Basin in the UK sector, decreasing from more than 1000 m thick in Quadrant 204 west of the Westray High to less than 400 m in parts of Quadrants 214 and 208.

Seismic interpretation in Quadrant 204 (Fig. 14; Ebdon et al. 1995; Smallwood et al. 2004) suggests that the thick Vaila Formation succession west of the Westray High is controlled by an intra-Paleocene basin-bounding fault that dips gently to the south-east. This fault lies to the west of the previous basin-controlling structure of Late Cretaceous age that marks the eastern edge of the Westray High. Such changes can be interpreted as part of the process described in some regional interpretations of the NE Atlantic margin (Doré et al. 1999; Roberts et al. 1999), of the progressive movement of depocentres towards the incipent ocean margin from the late Mesozoic to the early Palaeogene.

Transverse and longitudinal seismic sections from the Flett Sub-basin in Quadrant 214 (Section B, Fig. 15; Section D, Fig. 16) show the effect of contemporaneous extension on the Vaila Formation alongside the Rona High. Here the basin margin is defined by a series of NW-dipping normal faults (Fig. 15), which acted as growth faults during the deposition of the lower part of the Faroe Group. Within the basin, however, the pattern of local thickness variation of the Vaila Formation is complicated by the mobilisation of the underlying shale-dominated Shetland Goup. Diverging seismic reflections show the Vaila Formation thickening against the flanks of contemporaneous shale diapirs. The disposition of high-amplitude reflections associated with basic sills within the sedimentary succession (Fig. 15) is also affected by the diapirs, but it is difficult to determine if this occurred during or after emplacement of the igneous intrusions. Lamers and Carmichael (1999; Fig. 17) show how facies distribution in the Vaila Formation is influenced by shale mobilisation, with the deposition of basinal fan sandstones focused in Selandian shale withdrawal synclines (or 'minibasins'). Fault activity and shale mobilisation both diminished, but did not die out entirely, towards the end of the Selandian in the UK sector, with the ENE-trending Flett Fault of Lamers and Carmichael (1999) being a good example of a younger or more persistent fault (Fig. 17).

In the Faroese sector, the Longan well (6005/15-1) terminated in a thick succession equivalent to the Vaila Formation near the margins of the Faroe Platform (Appendix 1, Fig A1; Figs. 12, 13). Here, the unbottomed Vaila Formation is more than 372 m thick (excluding sequence T35). The succession is sandstone-rich, with thin- and thick-bedded turbidites laid down in a slope or bathyal environment. Volcaniclastic siltstones, sandstones and conglomerates are extensively developed and the sequences are intruded in places by dolerite sills up to 30 m thick. A thin tuff provides an indication of contemporaneous extrusive volcanism. An interpreted seismic section presented at the 2nd Faroe Islands Exploration Conference in 2007 (Goodwin et al. 2009; their

Fig. 4) correlated the Longan well with the proposed site of the BP's William well, which was subsequently drilled as 6005/13-1A. The prognosis of the William well suggested the presence of a prograding wedge of shelf sediments below a thin cover of volcanic rocks, with possible sandstone reservoirs developed at the top and base of the shelf succession, which was provisionally assigned to BP sequences T10-T35. However, when the 6005/13-1A well was drilled, it proved the prograding sequence to consist of an unbottomed succession of hyaloclastic rocks with little reservoir potential (Fig. 18). Provisional biostratigraphic interpretation assigned the entire volcaniclastic succession to the T40 sequence of the Moray Group, conficting with the existing seismic interpretation that ties the 6005/13-1A succession to the well-defined Vaila Formation sequences in the Longan well. The post-drill discrepancy in the interpretation is noted by Varming et al. (2012).

Potential field data have been used to define a gravity anomaly on the flanks of the Munkagrunnur Ridge to the NW of the William well (Kimbell et al. 2005; Ritchie et al. 2011). It is proposed here that this anomaly, which is identified as the Frænir Volcanic Centre by Keser Neish (2004) (Fig. 13), is the source of the hyaloclasite sequence drilled by 6005/13-1A. It is also suggested that the age of the buried Frænir centre is better constrained by the seismic tie to biostratigraphic data from the T34 succession of tuffs, volcaniclastic sediments and basic sills in the nearby Longan well (6005/15-1) (BP's original prognosis; Goodwin et al. 2009), than the speculative biostratigraphic attribution to the T40 sequence in the composite log of the William well (6005/13-1A). The postulated eruption and erosion of the Frænir Volcanic Centre during T34 is pene-contemporaneous with some of the oldest Palaeogene basaltic lavas in the British part of the North Atlantic Province, such as the Canna Lava Formation (60.0± 0.23 Ma, Chambers et al. 2005).

This interpretation of the Frænir Volcanic Centre, as a locally developed lava shield of Selandian age, contributes to a fuller understanding of seismic and well data from a structurally distinct area in Quadrant 219, which is currently included in the Møre Marginal High (Ritchie et al. 2011), but was formerly interpreted as a segment of the Faroe-Shetland Escarpment, known variously as the Brendan High, Seamount or Volcanic Centre (Smythe 1983; Smythe et al. 1983).

The Brendan Volcanic Centre is correlated with large gravity and magnetic anomalies of presumed igneous origin (Kimbell et al. 2005), but a possibly related domal structure on its SE flank was identified as a potential hydrocarbon prospect by Shell (Hodges et al. 1999; Rohrman 2007) (Section K, Fig. 19). Well 219/21-1, which was drilled to test this structure, proved it to consist of a mudstone-dominated Cretaceous succession pervasively intruded by sills, buried beneath a thin succession of Palaeogene basalts.

A biostratigraphic interpretation by Jolley (2009) of the section between 1731 m MD and 1889 m MD in well 219/21-1 dates the volcanic interval as part of BP sequence T36 (Appendix 1, Fig. A1). The lavas rest with significant unconformity on Late Cretaceous mudstones. A seismic section (Fig. 19) shows that away from well 219/21-1, the analysed volcanic succession forms only a thin carapace upon a much thicker interval of discontinuous reflectors in the NW part of the profile. In the interpretation presented here, this deeper package of gently-dipping high-amplitude reflectors is assigned to a westerly-thickening interval of older Paleogene volcanic rocks, underlying the basalts penetrated by well 219/21-1. The base of the volcanic package is interpreted as the top of the Shetland Group, while underlying, more steeply-dipping reflectors within the Shetland Group at the NW margin of the seismic section are interpreted as another set of transgressive basic intrusions, some of which may post-date those encountered in the well.

A SW-NE seismic profile (Section L, Fig. 20) shows that the inferred volcanic succession has a shield-like form, with the underlying top Shetland Group reflector defining a saucer-like depression. An ischron map derived from a 3D seismic survey of the entire high-amplitude, gently-dipping reflector package, shows a pattern of contours concentric with the potential field anomalies in the area, with near-centre thicknesses in excess of 1000 ms TTWT, corresponding to approximately 2250 m of volcanic rocks on the eastern flank of the structure (depth converted using an assumed representative interval velocity of 4.5 km/s for the volcanic succession). This thickness of basalt is similar to those inferred to have formerly covered eroded shield volcanoes elsewhere in the North Atlantic Igneous Province, including >2200 m at Ben More, Mull (Emeleus and Bell 2005, p71).

The base of the thin overlying volcanic succession in well 219/21-1 is interpreted as a significant basin-wide unconformity of pre-T36 age, which is termed the intra-Vaila unconformity (Fig. 4; Appendix 1, Fig. A1). The contemporaneous erosion of Selandian shield volcanoes, such as Frænir and Brendan, which culminated at this unconformity, probably formed extensive aprons of volcaniclastic debris in the the Faroe–Shetland region, similar to the sediments rich in volcanic clasts and intruded by basic sills encountered by the Longan well (6005/15-1). Evidence of such volcaniclastic aprons may be provided by intervals characterised by high-amplitude, chaotic reflectivity underlying the prograding hyaloclastite successions that fringe the Faroe Platform. The rapid denudation of Palaeogene volcanic centres and the widespread development of such debris aprons are being increasingly recognised in the British part of North Atlantic Igneous Province onshore (Brown and Bell 2007; Brown et al. 2009).

3.2.3 **The intra-Vaila unconformity**

The intra-Vaila unconformity is identified by Ichron Ltd. (2010a; b) as a significant hiatus within the T35 sequence of the Vaila Formation in a number of wells from the Faroe-Shetland Basin, including 204/22-1, 206/5-1, 214/24-1 and 214/27-1 to -4 (Appendix 1, Fig. A1). In places, including parts of Quadrant 204 and well 219/21-1 in the Brendan area, the unconformity is marked by the onlap of the overlying T36 sequence (Fig. 19; Jolley 2009). The intra-Vaila unconformity corresponds to the erosive event that truncates the T34 shelf sequence in the stratigraphic interpretation of Ebdon et al. (1995), with its correlative conformity in the basin equivalent to the base of their Cuillin fan.

On seismic data, the unconformity commonly forms a planar event that truncates more steeply-dipping reflections in the underlying Vaila Formation, especially where they have been affected by shale diapirism (Figs. 15; 16). In the area of the Laggan oil discovery (Loizou et al. 2006; Gordon et al. 2010), the unconformity marks the base of the deepest sandstone body in the main T35 hydrocarbon reservoir. From there, it can be traced westwards onto the opposite flank of the Faroe-Shetland Basin, where contemporaneous intra-Paleocene erosion has considerably reduced the thickness of the Paleocene succession in the vicinity of well 214/21-1.

The intra-Vaila unconformity appears to mark an important change in the structural configuration of the Faroe-Shetland Basin. In the North Sea, it corresponds to the top of the Andrew Sandstone unit (Unit L1 of Knox and Holloway 1992) and is commonly overlain by a thin mudstone succession, which includes the dinocyst *Paleoperidinium pyrophorum*. In the Faroe-Shetland Basin, the associated episode of regional uplift and erosion was rapidly followed by onlap and a resumption of shelf progradation and this was accompanied in the UK sector by a marked reduction in the intensity of the extensional faulting and shale diapirism that had characterised the older Vaila Formation.

Ebdon et al. (1995) describe the base of their T36 interval as a true sequence boundary and it is this event that is probably a correlative of the T35 age intra-Vaila unconformity described here.

3.2.4 **Vaila Formation; T35 (Late Selandian)**

Well thickness data for sequence T35 are summarised on Appendix 1, Fig. A1 and Fig. 21. The maximum drilled thickness of this mixed sandstone, siltstone and claystone sequence is the 585 m proved in the Longan well (6005/15-1) in the Faroese sector. Sequences of similar thickness occur in adjoining parts of the UK sector and overlie the intra-Vaila unconformity in Quadrant 214, but elsewhere the interval generally ranges between 50 and 200 m thick. There is a significant thinning of the T35 sequence above the SW segment of the Flett High, which straddles the boundary between Quadrants 205 and 206 (Ritchie et al. 2011). This thinning may relate to contemporaneous uplift of the underlying high, though the biostratigaphic interpretations of Ichron Ltd. (2010a; b) do not recognise an unconformity at this level in the local wells.

Sequence T35 is not included in the sequence stratigraphic interpretation of Ebdon et al. (1995), but probably corresponds to the interval described as the Cuillin fan. Shales onlapping the top of the Cuillin fan are included in Vaila Formation unit V4 and are generally darker grey and more carbonaceous than mudstones of the overlying Lamba Formation (Knox et al. 1997).

In places, the shales at the top of the Vaila Formation are overlain and overstepped by a tuffaceous interval that was subsequently assigned to the basal Kettla Tuff Member of the Lamba Formation by Knox et al. (1997). Although the episode of onlap during and after the deposition of the T35 sequence was a major factor in the formation of a regional seal for the underlying turbiditic sandstones of the Vaila Formation, there are variations across the basin, with Smallwood et al. (2004) noting that the failure of the initial target in well 6004/16-1Z was caused by the lack of an integral top seal between T28 and T36.

In the North Sea, a thin mudstone succession generally occurs between the Andrew Sandstone unit and the Balmoral Tuffite, but some sandstones are occasionally preserved as part of a potential equivalent of the T35 sequence (as in well 21/7-2, Knox and Holloway 1992, p 113).

3.2.5 Lamba, Beinisvørđ and Lopra formations; T36 and T38 (Early to Mid Thanetian)

Knox et al. (1997) introduced the term Lamba Formation to describe the interval of prograding shelf sediments of Thanetian age overlying the Vaila Formation and forming the upper part of the Faroe Group. They divided the Lamba Formation into two lithostratigraphic units, L1 and L2. As well as the basal Kettla Tuff Member, Knox et al. (1997) recognise the Westerhouse Sandstone Member as a locally developed sandstone-rich succession in the L1 unit of the Lamba Formation around the southern part of Quadrant 214. Sandstones also occur in the L2 unit in the UK sector, but are not yet assigned member status. Ichron Ltd.'s (2010a; b) stratigraphic interpretation introduces an additional unit, L3, which probably corresponds to the upper, post-sandstone interval of unit L2.

All the sediments equivalent to Knox et al.'s (1997) Lamba Formation in Quadrant 204 were formerly included in the T36 sequence of Ebdon et al. (1995), but since the work of Lamers and Carmichael (1999), some of this succession has been assigned to a younger T38 sequence.

A review of stratigraphic and structural data from the Faroe–Shetland region, supported by stratigraphic thickness information derived from well and seismic data, is used here to propose that the Lamba Formation is partly age equivalent to the predominantly volcanic Beinisvørđ and Lopra formations of the Faroe Platform (Passey and Jolley 2009).

3.2.6 Lamba Formation T36 (Early Thanetian)

Some of the historical complications in the definition of T35 and T36 appear to arise from modifications to BP's original sequence interpretation, which mixed flooding surfaces and unconformities as sequence boundaries. The ad hoc nature of this scheme is liable to cause problems with the sequence designation of some transgressive successions. In this respect, it would simplify the stratigraphy of the interval post-dating the intra-Vaila unconformity, if some of Ichron Ltd.'s (2010a; b) T36 interval were to be included as a transgressive component of the underlying T35 sequence. In the UK sector, the re-assigned interval would generally consist of the upper shales of the Vaila Formation V4 unit, identified by Knox et al. (1997). The revised base of T36 would then correspond to the base of the Kettla Tuff, a regional onlap surface that marks the lithostratigraphic base of the Lamba Formation and forms a well-defined chronostratigraphic and seismic datum.

For current purposes, the original well thickness data for the T36 sequence interval as defined by Ichron Ltd (2010a; b) are retained (Appendix 1, Fig. A1; Figs. 22, 23). However, the relevant thickness of the transitional interval between the top of their T35 sequence and the base of the Kettla Tuff is also depicted on Appendix 1, Fig. A1. This shows that the sub-Kettla Tuff part of Ichron Ltd.'s T36 is generally thin in the UK sector (commonly <100 m), but is more than 200 m thick in some Faroese wells, where the increased thickness may represent an influx of coarse-grained sediment at the top of the Vaila Formation. This unit may be equivalent to, or post-date, the Cuillin fan originally mapped on seismic data by Ebdon et al. (1995) (Fig.14). Extending the distal limit of uppermost Vaila Formation turbidites into the Judd Sub-basin alongside the Sjúrður Ridge (Figs. 14, 23) provides a further indication of the westerly displacement of depocentres towards the incipient oceanic margin.

T36 sediments (as defined by Ichron Ltd. 2010a; b) form an interval of fairly uniform thickness in the UK sector, commonly ranging from 200–300 m in the main part of the basin and gradually thinning to the NE (Figs. 22, 23). As with sequence T35, the thickness of T36 in wells diminishes above the SW segment of the Flett High (Ritchie et al. 2011). The Flett High appears to consist of a stacked series of high-ampltiude reflectors at depth (Section A; Fig.10), which suggests a common structural origin with the south-eastern part of the Brendan Volcanic Centre tested by well 219/21-1 (Section K; Fig. 19). Both areas were uplifted at the time of the development of the intra-Vaila unconformity and are underlain by high-amplitude reflectors, which well 219/21-1 proves to consist of a domal series of stacked basic intrusions in Upper Cretaceous mudstones. Seismic interpretation in the Quadrant 219 area (Fig. 19) suggests that one episode of sill intrusion possibly post-dated the formation of the main Brendan lava shield and preceded the episode of volcanism associated with the basalt lavas of T36 age (Jolley 2009).

A timeslice obtained from a 3D seismic survey in the area of the Flett High (Robinson et al. 2004; their Fig. 4) indicates that some of the deep reflectors in Block 205/9 have a domal form similar to that of the deeper Brendan basic sills. Well 205/10-2 proves intrusive igneous rocks within the Upper and Lower Cretaceous succession of the Flett High, which are analogous to those in well 219/21-1 (Smallwood and Maresh 2002; Smallwood et al. 2004; Stoker et al. 2010; their Fig A1.6).

Hydrocarbon exploration well 164/7-1 in the North Rockall Basin tested a deep domal structure that proved to consist of an Upper Cretaceous mudstone succession intruded by more than 70 basic sills, ranging from 1.5 to 152 m in thickness (Archer et al. 2005; Rohrman 2007). Doré et al. (2008) describe a similar category of Late Cretaceous to Paleocene domes of tectonomagmatic origin from the Norwegian sector. Such structures clearly form a widespread part of the volcanic and tectonic inheritance of the North Atlantic margin.

3.2.7 **Lamba Formation T38 (Mid Thanetian)**

Sequence T38 is not included in the sequence stratigraphic analysis of Ebdon et al. (1995), and was introduced, without definition, in the stratigraphic scheme of Lamers and Carmichael (1999). Since it overlies sequence T36, sequence T38 is most likely to correlate with the upper part of the Lamba Formation (lithostratigraphic unit L2 of Knox et al.1997), post-dating the L1 unit which includes the Waterhouse Sandstone Member.

The Waterhouse Sandstone forms a locally-developed base-of-slope sandstone body in Quadrant 214, so that sequence T38 is best interpreted as comprising the deposits of the overlying prograding Lamba Formation shelf. However, the full seismic and biostratigraphic definition of this unit remain in doubt, with its seismic boundary potentially coinciding with any one of a series of prograding events. The biostratgraphic picks are similarly unclear and are possibly dependent upon local assemblages or acme occurrences. The Tornado oil and gas discovery in well 204/13-1 in 2009, in a prospect identified as a seismic amplitude anomaly at the toe of clinoforms within the prograding T38 sequence (Rodriguez et al. 2010), has recently enhanced the prospectivity of the Paleocene by extending the presence of hydrocarbon accumulations above the main regional seal at basal Lamba Formation level. Well data suggest that similar toe-of-slope sandstone bodies may be widely developed within the mud-prone T38 shelf succession, but prospectivity at that level may be constrained by the lack of faults penetrating the underlying regional seal, permitting fluid access to the shallower reservoirs (Rodriguez et al. 2010).

Ichron Ltd.'s (2010a; b) biostratigraphic analysis suggests that the T38 sequence ranges up to 600 m thick in wells (Fig. 24) and its pattern of thickness variation (Fig. 25) broadly defines a north-east trending synclinal axis in the Faroe-Shetland Basin of the UK sector between Quadrants 204 and 208. Wells from Quadrants 204 and 6004 show that sequence T38 is thickly developed, but everywhere truncated by an overlying unconformity (Fig. 24).

Shaw Champion et al. (2008; their Fig. 10) used 3D seismic data to map the distribution of prograding reflectors within the Lamba Formation shelf in Quadrant 204 and adjoining areas (Figs. 26, 27). They showed two main sedimentary thicks with different progradation directions. The eastern lobe progrades to the north, while the younger western lobe advances in a more westerly direction (Fig. 28). The area between the lobes is deeply dissected by a major channel in the overlying Flett Formation (confirming that the SE corner of the Judd Sub-basin is a long-lived entry point for coarse-grained sediments), so it is possible that the whole sedimentary process is controlled by channel switching; however the younger western lobe could be an indication of the onset of tilting and uplift associated with the development of an unconformity at top Lamba Formation level (see section 3.3.2). The distribution of the sparse thickness data for the T36 and T38 sequences in wells from this part of the area does not show an obvious distinction between the eastern and western lobes, and this adds to the remaining uncertainty about the correct biostratigraphic and seismic stratigraphic definition of these two sequences, which is apparent in the published literature and available reports.

3.2.8 **Beinisvørđ and Lopra formations; T36 and T38 (Early to Mid Thanetian)**

The Beinisvørđ and Lopra formations are formally defined onshore as units within the Faroe Islands Basalt Group (Passey and Jolley 2009). The Beinisvørđ Formation is known from outcrop and well data, while the Lopra Formation was originally only identified in the deepened stratigraphic well Lopra 1/1A, as the predominantly hyaloclastite succession in which the well terminated (Chalmers and Waagstein 2006). In sequence-stratigraphic terms, these lithostratigraphic units form part of the same sequence, with the marine Lopra Formation passing landward into the Beinisvørđ Formation, which consists of a contemporaneous succession of terrestrial lavas.

The Beinisvørđ Formation has a proven thickness of 3250 m on Suđuroy and largely consists of basalt lava flows averaging 20 m in thickness. Interbedded palaeosols are widely developed, especially towards the top of the formation, providing evidence of sub-aerial exposure (Passey and Jolley 2009).

Correlation of the Beinisvørđ Formation with the volcanic sequences encountered in offshore wells is hindered by poor seismic and biostratigraphic resolution and a number of different proposals have been put forward to account for the age relationship between these, the oldest known basalts on the Faroe Islands, and the other volcanic structures in the region, including the Faroe-Shetland Escarpment (Smythe 1983; Smythe et al. 1983) and basalt lavas from the UK sector of the Faroe-Shetland Basin (Ritchie et al. 1999; Naylor et al. 1999; Jolley and Bell 2002b, Jolley et al. 2002; Ellis et al. 2002; Passey and Jolley 2009; Passey and Hitchen 2011).

Geochemical correlations of the Faroese basalts with the Palaeogene volcanic rocks of onshore East Greenland have proved to be more robust (Larsen et al. 1999), and suggest that the Beinisvørđ Formation is equivalent to the Nansen Fjord Formation, not least because of distinctive similarities in the geochemistry of the overlying formations in the two areas (Malinstindur Formation in the Faroe Islands and Milne Land Formation in Greenland).

The close geochemical affinities of the basalts have been used previously to support trans-Atlantic extrapolation of biostratigraphic evidence between the Greenland and Faroe Island successions (Jolley and Whitham 2004; Jolley et al. 2005), but recent biostratigraphic work in Greenland (Nøhr-Hansen 2012) is more equivocal, broadening the palaeontological age ranges and leaving potential scope for pre-basaltic floras of different ages being preserved in contrasting structural settings on the Greenland margin. In particular, Nøhr-Hansen (2012) points out that Jolley and Whitham (2004) infer a late onset of volcanism in East Greenland (and by extrapolation the Faroe Islands) by assigning a T40 age to the observed terrestrial flora, only because of its <u>inferred</u> regional association with the characteristic T40 palynomorph *Apectodinium augustum*. This key zonal palynomorph has not itself been recognised in the East Greenland succession, it is only identified in NE Greenland north of 73ºN (Jolley and Whitham 2004). In East Greenland, only the broader range *Apectodinium homomorpha* is present, being recorded by Soper et al. (1976), under its previous name *Wetzeliella homomorpha*, although Nøhr-Hansen (2012) lacked suitable material to confirm Soper et al.'s original identification.

Nøhr-Hansen (2012) does record strong biostratigraphic evidence, in the form of the palynomorph *Palaeoperidium pyromorphum*, that much of the East Greenland pre-basaltic sedimentary succession cannot be younger than Late Selandian in age (i.e. in sequence stratigraphic terms, cannot be younger than sequence T35). Sediments of possible Thanetian age at some critical localities may be overlain, not by basalts from the oldest units, as previously described, but by younger lava formations.

In summary, this means that Jolley and Whitham's (2004) evidence from East Greenland can no longer be used, without qualification, to support an entirely young (T40) age for the Nansen Fjord Formation or, by extrapolation, for its geochemical correlative on the Faroe Islands, the Beinisvørđ Formation (Larsen et al. 1999). There is, however, additional biostratigraphic evidence from East Greenland to support a Late Selandian or later age for the onset of the main episode of volcanism (Nøhr-Hansen 2012). Extrapolation of this potentially older age would place the Beinisvørđ and Lopra formations stratigraphically above the intra-Vaila unconformity, and make them contemporaneous in part with the uppermost Vaila Formation and the Lamba Formation (T35, T36 and T38).

In the deepened Lopra 1/1A well (Chalmers and Waagstein 2006), the Beinisvørđ Formation passes downhole into a predominantly hyaloclastite succession now formally assigned to the Lopra Formation (Passey and Jolley 2009). On seismic profiles from the Faroe Platform, SE of the Faroe Islands, there is a deep interval with a trace of sigmoidal reflections that may relate to this prograding unit (Section I, Fig. 29; Section G, Fig. 30). The top of the prograding succession is characterised by a poorly-defined regional seismic marker (intra-basalt 05), which separates the inferred hyaloclastites from a more gently-dipping succession of overlying reflections, the deeper of which may correspond to the terrestrial basalts of the Beinisvørđ Formation onshore. Part of the hyaloclastite succession is penetrated by the Brugdan well (6104/21-1; Appendix 1, Fig. A1) on the East Faroe High, which terminated within a fine-grained pre-basaltic lava succession rich in volcanic detritus, with biostratigraphic indications of biozones NP8/NP7, broadly equivalent to the Lamba Formation (sequences T36 to T38). This well evidence is consistent with biostratigraphic data from East Greenland that places the base of the correlative Nansen Fjord Formation during or after the Late Selandian (Nøhr-Hansen 2012).

If the eruption of the Beinisvørđ Formation occurred during the deposition of the Lamba Formation, it is also contemporaneous with the minor episode of sequence T36 basaltic volcanism, which post-dates the intra-Vaila unconformity in well 219/21-1 in the Brendan area (Jolley 2009).

In this report, the seismically defined top of the Beinisvørđ Formation offshore is taken to coincide with a conspicuous, high-amplitude planar reflector (here termed intra-basalt 10) that divides the volcanic succession preserved on and around the Faroe Platform into two main units (Section I, Fig. 29; Section G, Fig. 30).

3.2.9 **Summary; T35, T36 and T38 (Late Selandian to Mid Thanetian)**

The cumulative thickness in wells of the unconformity-bound unit consisting of sequences T35, T36 and T38 is shown on Fig. 31 and Appendix 1, Fig. A1. In the UK sector of the Faroe-Shetland Basin, the unit is dominated by the deposits of the Lamba Formation shelf and its related basal facies, together more than 1200 m thick in places, which prograded across the older basinal successions of the Vaila Formation.

The thickness of the partly equivalent, volcanic-dominated Beinisvørđ and Lopra formations around the Faroe Platform was estimated from regional seismic data by depth converting the interval between the intra-basalt 10 reflector and the base of underlying prograding interval, which is inferred from well evidence to correspond approximately with the lithostratigraphic base of the Lamba Formation. Applying a unit interval velocity of 4.5 km/s to the seismic interval, gave a succession ranging up to 4000 m in thickness in Quadrant 6105 to the east of Tórshavn, which is similar in thickness to the equivalent unbottomed volcanic succession proven along strike at Lopra, onshore in Suđuroy (Passey and Jolley 2009) (Fig. 32).

3.3 MORAY GROUP

3.3.1 **Lithostratigraphic background**

The Moray Group as originally defined by Deegan and Scull (1977) in the North Sea consisted of the shallow marine Dornoch Formation and the paralic Beauly Formation of Late Paleocene to Early Eocene age. Mudge and Copestake (1992a; b) included the more basinal sediments of the Sele and Balder Formations within the group and this interpretation was sustained by Knox and Holloway (1992), who also expanded the Sele Formation to incorporate various basinal sandstone units, including the Forties Sandstone Member.

The Moray Group is capped by the Balder Formation, a thin extensive tuffaceous unit, which is also widely recognised in the Faroe-Shetland Basin. However, Knox et al. (1997) assigned the older sediments in the Moray Group on the Atlantic margin to a new unit, the Flett Formation, to avoid presuming a direct link to the contemporaneous deposits of the Sele Formation in the North Sea.

The Moray Group encompasses the equivalent BP sequences T40, T45 and T50 (Ebdon et al. 1995). The Flett Formation includes the Colsay Sandstone Member (T40) and the Hildasay Sandstone Member (T45), while the Balder Formation is equivalent to T50 (Knox et al. 1997; Lamers and Carmichael 1999).

A prolonged debate about the exact definition and chronostratigraphic position of the Paleocene-Eocene boundary has complicated the stratigraphic framework of the Moray Group.

The current definition of the base of the Eocene is linked to the Paleocene-Eocene Thermal Maximum (PETM) (Gradstein et al. 2004; Ogg et al. 2008). Global warming produces a systematic variation in carbon isotope ratios in contemporaneous carbonates and the onset of the largest carbon isotope ‘excursion’ at this time is now used to define the base of the Eocene (Gradstein et al. 2004; Ogg et al. 2008; Westerhold et al. 2009).

The base of the Eocene in the North Sea is probably marked stratigraphically by an impersistent high gamma spike within the Forties Sandstone Member (equivalent to the top of Sele Formation S1a), a pick which is slightly below the position tentatively proposed by Knox and Holloway (1992). The underlying boundary between the Lista (T30) and Sele (T40) formations coincides with the last (uphole) occurrence of Paleocene agglutinated foraminifera (Knox and Holloway

1992; Mudge and Bujak 1996), and this probably marks the initial rise in global temperatures towards the end of the Paleocene, which caused a major extinction event in deep sea benthic fauna. Stratigraphic correlatives of both these events can be identified in the Faroe-Shetland Basin (Mudge and Bujak 2001).

3.3.2 The Flett unconformity in the Faroe-Shetland Basin

Ebdon et al. (1995) recognised an important unconformity at the top of their T36 sequence (Fig. 5). From seismic data in Quadrant 204, they showed the overlying T40 sequence pinching out southwards against the front of an older shelf consisting of muddy shelf and slope deposits subsequently incorporated in the Lamba Formation by Knox et al. (1997) (Fig. 33). This period of relative uplift or fall in base level created a sequence boundary between the Lamba and Flett formations, which in this report is described as the Flett unconformity (Fig. 4, Appendix 1, Fig. A1).

It was not until the acquisition and interpretation of 3D seismic data across Quadrant 204 (Fig. 26) that the true nature and extent of the Flett unconformity was revealed (Smallwood and Gill 2002; Rudge et al. 2008; Shaw Champion et al. 2008). A geoseimic section from a 3D survey acrosss Quadrant 204 (Fig. 27; Shaw Champion et al. 2008, their Fig.4) shows that the top Lamba Formation is defined by a serrated reflector, which displays in map-form as a topographic surface deeply dissected by a regional pattern of dendritic drainage (Fig. 34). The eroded topopography defined by this event is partly onlapped by the unconformable base of the T40 sequence, which extends along the axis of the main channel downcut into the Lamba Formation, to the south of its former limit mapped by Ebdon et al. (1995) (Fig. 34).

3.3.3 Lower Flett Formation; T40 (Late Thanetian to Early Ypresian)

Knox et al. (1997) divide the shallow marine sandstones and mudstones of the Flett Formation into four lithostratigraphic units (F1a, F1b, F2 and F3). Sandstone-rich successions in units F1a and F1b constitute the Lower and Upper Colsay Sandstone members and correspond to BP’s T40 sequence, which is broadly age equivalent to the Forties Sandstone Member of the North Sea (**Fig. 4**). In this report, following Shaw Champion et al. (2008), the Colsay Sandstone Member and sequence T40 are informally described as the lower Flett Formation.

Unlike the Forties Sandstone, which is predominantly of basin-floor-fan origin, the Colsay Sandstone Member was laid down in a range of depositional environments in a ramp setting, with facies varying from delta-top sandstones to pro-delta mudstones (Knox et al. 1997). In some wells, the Upper and Lower Colsay Sandstone Members are separated by a more argillaceous succession around 50 m thick. A high gamma spike at the base of this interval forms the top of the lower unit (F1a) and may correspond to the Paleocene-Eocene boundary, by analogy with the North Sea succession.

The biostratigraphy of sequence T40 is characterised by an increase in dinocysts belonging to the genus *Apectodinium*. If the top of the Paleocene coincides with the top of the Lower Colsay Sandstone Member, then this horizon should mark the last downhole occurrence of the basal Eocene zonal dinocyst *Apectodinium augustum*, whose appearance and range are interpreted to define the Paleocene-Eocene Thermal Maximum. The actual base of sequence T40 lies deeper, within the Upper Paleocene, and correlates with the base of Flett Formation unit F1a, which commonly rests unconformably on the top of the Lamba Formation.

The thickness, lithology and distribution of sequence T40 sediments in wells, largely based on the biostratigraphic interpretations of Ichron Ltd. (2101a; b), are summarised on Figs. 35 and 36. These maps show that the interval is absent where the Flett Formation onlaps its basal unconformity over large parts of the older Paleocene basin and its flanks, including most of the area dissected by fluvial channels in Quadrant 204. Ichron Ltd.’s (2010a; b) biostratigraphic scheme defines three sub-zones within the T40 interval, but these have not been differentiated in wells from the Faroe–Shetland region. Since the gradual onlap by different sub-zones within the T40 succession cannot be mapped using available biostratigraphic data, it follows that areas affected by the Flett unconformity may be more extensive than shown on Figs. 35 and 36. The occurrence of conglomerates at the base of the T40 sequence in some wells may indicate the presence of an unconformity that has not been recognised biostratigraphically (Appendix 1, Fig. A1).

The relative uplift of the area around the Judd High after the deposition of the Lamba Formation caused the Flett Formation shelf to advance northwards along the axis of the Faroe-Shetland Basin. Generalised isopachs of sequence T40 obtained from well data range up to approximately 600 m and define a sedimentary thick near the front of a prograding shelf at the boundary of Quadrants 206 and 214 (Fig. 36). The prograding wedge above the Flett unconformity is shown in longitudinal section on seismic Section A (Fig. 10) and in transverse section on Section B (Fig. 15).

An isochron map derived from 3D seismic data (not figured) reveals the NW-trend of coalescing feeder channels in Blocks 206/5 and 207/1 (Section C, Fig. 11). These channels are minor features contributing to sedimentation on the shelf from the flanks of the basin, but have the same trend as the main channel in the lower Flett Formation in Quadrant 204 (Fig. 34). The isochron map also shows two small circular sedimentary thicks within the shelf front in Blocks 214/22 and 214/28. Seismic profiles indicate that local thicks at this level may be caused by the injection of shale remobilised from diapirs in the Vaila Formation at depth into the toe of the Flett Formation slope. A recent alternative interpretation of these structures has proposed an origin by the extrusion of fluidised sediment from a hydrothermal vent onto the contemporary sea floor, related to the underlying emplacement of basic sills (Grove 2013). In the same area of the shelf front, Lamers and Carmichael (1999, their Fig. 15) performed an amplitude extraction in a window based on a seismic pick at Balder Formation level, on which it is possible to distinguish different sedimentary environments controlled by the morphology of the underlying Flett Formation shelf.

Two wells in the UK sector, 205/8-1 and 205/9-1, drilled through basalt lavas interbedded with sediments at the top of the Colsay Sandstone Member in the area of the Flett High (Appendix 1, Fig. A1). The lavas, which were originally placed at the base of the F2 unit (upper Flett Formation) by Knox et al. (1997), were incorporated in the F1b unit (lower Flett Formation) by Jolley et al. (2002). Their occurrence within the Flett Formation has been used in a variety of correlations (Naylor et al. 1999; Ritchie et al. 1999; Ellis et al. 2002), but most significantly as evidence to support the proposal that all the basalts of the Faroe Platform must be of Thanetian (T40) and younger age (Jolley et al. 2002; Jolley et al. 2005). Since this biostratigraphic interpretation was in conflict with the available radiometric evidence, Jolley et al. (2002) argued that there was a possibility that the whole Palaeogene time scale was incorrectly calibrated. However, their alternative chronology was firmly refuted by Aubry et al. (2003), who argued in part that the proposed shortened duration of the Paleocene would imply a global increase in contemporary sea-floor spreading rates.

Interpretation of 3D seismic data from Quadrant 205 (Smallwood et al. 2004; Smallwood and Kirk 2005) has supported earlier suggestions (Ellis et al. 2002) that the basalt lavas in wells 205/8-1 and 205/9-1 were locally sourced in the UK sector and did not flow eastwards from the lava shield of the Faroe Platform. It would be consistent with the tectonic and volcanic development of the Faroe-Shetland Basin proposed in this report, if the lavas within the T40 sequence in the UK sector represented a minor late effusion of the Beinisvørđ Formation magma through distal sill-fed vents above the Flett High. The location of possible vent structures has been suggested from 3D seismic interpretation (Smallwood et al. 2004; Smallwood and Kirk 2005). A change in the style of eruption from the dykes to sills, could be linked to the onset of a new tectonic regime, which ended the Beinisvørđ eruptive cycle in an episode of uplift that generated the Flett unconformity. This sequence of events is a repetition of the tectonic development previously inferred for the intra-Vaila unconformity, which has been associated with the uplift and erosion of older lava shields and the presence of folded stacks of deep basic sills in the area of the Flett High and elsewhere (Figs. 10, 19). However, it should be noted that most of the dykes on the Faroe Islands are correlated geochemically with lavas post-dating the Beinisvørđ Formation, and there are no known onshore examples of dykes feeding lavas of any age, so that any link between the lava shields and dykes remains conjectural (Waagstein 1988; Hald and Waagstein 1991).

3.3.4 The Flett unconformity on the Faroe Platform and adjoining areas and the origin of the Faroe-Shetland Escarpment

On the Faroe Islands, the top of the Beinisvørđ Formation is marked by an unconformity (the Beinisvørđ-Prestfjall Unconformity or BPU of Passey and Jolley 2009; Rasmussen and Noe-Nygaard 1970), which truncates the top of the basalt shield and is overlain by a coal-bearing sedimentary unit (3–15 m thick on Suđuroy), composed of sandstones and conglomerates containing volcanic detritus, interbedded with clay and ironstone palaeosols, which Passey and Jolley (2009) assign to the Prestfjall Formation.

Offshore, the top of the Beinisvørđ Formation is probably marked by intra-basalt 10, a conspicuous, high-amplitude planar seismic reflector that divides the volcanic succession into two main units (Section I, Fig. 29; Section G, Fig. 30). In the vicinity of the Faroe Platform, east of the Faroe Islands, intra-basalt 10 occurs at the base of a thick succession of basaltic lavas characterised by parallel reflectors that pass eastwards into a series of prograding clinoforms to form the Faroe-Shetland Escarpment. This major topographic feature has long been interpreted as a submarine slope composed of hyaloclastite debris, generated when an aggrading pile of terrestrial basalts entered the marine Faroe-Shetland Basin (Smythe 1983; Smythe et al. 1983) (Section E, Fig. 37).

On a series of seismic sections, it is possible to define the changing location, close behind the Faroe-Shetland Escarpment, where the aggrading upper pile of basalts first entered the sea. This point only advances a short distance basinward during the later eruptive episode, and its rise up-section indicates that the progradation occurred during a prolonged period of basinal subsidence or relative sea level rise (Section E, Fig. 37). These relationships contrast with the structure of the basal intra-basalt 10 reflector, which extends as a planar event over a large area around the Faroe Platform, without passing basinwards into a hyaloclastite succession. There are widespread traces of clinoforms beneath intra-basalt 10 (Section H, Fig. 38), but the reflector appears to truncate all of these, before forming a minor buried escarpment feature, as mapped by Kiørboe (1999), immediately west of the younger Faroe-Shetland Escarpment. Other traces of discontinuous reflectivity beneath intra-basalt 10 may indicate the effects of local erosion, forming downcut channels in the lower volcanic pile, analogous to those observed at top Lamba Formation level on 3D seismic data elsewhere (Shaw Champion et al. 2008). Taken together, these observations support the interpretation of the intra-basalt 10 reflector as a regionally extensive unconformity equivalent to the base of the Flett and Prestfjall formations and overlying the top of an eroded lower volcanic pile composed of terrestrial Beinisvørđ Formation basalts and Lopra Formation hyaloclastites.

The episode of uplift that was responsible for the deeply dissected topography at top Lamba Formation level in Quadrant 204 can be linked to the uplift and erosion of the Beinisvørđ Formation at the intra-basalt 10 reflector. The truncation of normally magnetised basalts near the top of the Beinisvørđ Formation, following basin inversion and uplift along the western flanks of the East Faroe High, may have contributed to the formation of the Annika magnetic anomaly, a well-defined linear magnetic feature on the Faroe Platform (Smallwood et al. 2001; Kimbell et al. 2005). This possibility is currently being investigated by BGS as part of the magnetic signatures project (Kimbell, *in preparation*). If this interpretation can be sustained, it would suggest that Heri High (Keser Neish 2004; Ritchie et al. 2011) is not a buried horst analogous to the East Faroe High, but forms the southern inverted part of the Annika Basin, with some potential for the development of deeper untested sedimentary successions of Paleocene or older age.

Volcanic detritus derived from the Beinisvørđ Formation lava shield on the Faroe Platform during its construction in T36 and T38 times and its subsequent erosion during T40 is expected to have accumulated in the northern part of the Faroe-Shetland Basin. A seismic sequence characterised by high-amplitude, chaotic reflectivity, extensively developed in the northern part of Quadrants 213 and 214 (Section E, Fig. 37), was drilled by well 214/4-1 and shown to consist largely of volcaniclastic debris (Davies et al. 2004). Ichron Ltd. (2010a) interprets the drilled volcanic succession in this well as an undifferentiated volcanic complex of Late Paleocene age, in which the well terminated. The upper part of the volcanic interval does contain characteristic T40 dinocysts, but the deeper section also includes dinocysts more commonly associated with the Upper Lamba Formation (T38). These biostratigraphic data indicate that sedimentation in this area was probably dominated by erosion from a volcanic-rich hinterland during the deposition of sequences T38 and T40, which is consistent with the age of the Beinisvørđ Formation lava shield and the Flett unconformity proposed here.

Another interval characterised by high-amplitude chaotic reflectivity is widely developed across the Faroe Platform and adjoining areas and occurs, for example, about 300 ms TWTT below the intra-basalt 10 reflector on a seismic profile from the Fugloy High (Section H, Fig. 38). This interval is interpreted to consist of volcaniclastic rocks analogous to those intersected by the 214/4-1 well, but derived from the erosion of the older, pre-Beinisvørđ Formation lava shields, such as Brendan and Frænir. The interval may be intruded by basic sills, as in equivalent successions of Vaila Formation age in the Longan well (6005/15-1; See section 3.2.2).

3.3.5 **Upper Flett Formation and Balder Formation; T45 and T50 (Early Ypresian)**

Above the Colsay Sandstone Member, the remainder of the Moray Group includes sequences, T45 and T50. Sequence T45 consists of Flett Formation units, F2 and F3 (Knox et al. 1997) and in this report is described informally as the upper Flett Formation. Sequence T50 is equivalent to the Balder Formation. In the study area, these sequences were commonly laid down as part of the earliest Eocene transgression of the Flett unconformity.

The upper Flett Formation, which consists of varied shallow marine lithologies, is generally dominated by mudstone and siltstones, but includes sandstones, largely to the south-west of Quadrant 214, which Knox et al. (1997) incorporate in the Hildasay Sandstone Member. Farther to the south, the sandstones pass into a delta top facies that includes lignites, reflecting the process of coastal onlap, which continued throughout the Early Ypresian and laid down the lithologically similar Beauly Member of the Moray Group on the margins of the North Sea (Knox and Holloway 1992).

In marine successions, the absence of dinocysts of the *Apectodinium* genus distinguishes sequence T45 sediments from those of the underlying T40 sequence, but the distinction is more difficult in terrestrial successions, where it depends upon analysis of a long-lived flora, variously controlled by climate, habitat and sedimentary facies (Jolley 2009; Jolley et al. 2012).

The Balder Formation (T50) is also dominated by mudstones, but includes thin interbeds of greenish-grey tuff, which form a stratigraphic datum across a large part of the UK continenental shelf. 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). The top of unit B1 is correlated with the main London Clay transgression of southern England by Knox (1996). 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.

As in the T45 sequence, sandstones and mudstones with lignite characterise the Balder Formation succession, where it is deposited on top of the Flett Formation shelf in the south of the area (Knox et al. 1997). 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).

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., 1997b), though Knox and Holloway (1992) note that *Coscinodiscus* is known to persist into the basal part of the overlying Stronsay Group.

Variation in the combined thickness of T45 and T50 in wells is summarised on Fig. 39. Thicknesses range from just less than 100 m in onlapping areas on the south-eastern flanks of the basin, to almost 450 m in the Judd Basin and adjoining areas, reflecting a period of relative sea level rise, with Moray Group sediments retained on the shelf near their long-lived entry point at the SW margin of the basin.

In Quadrant 204, Ebdon et al.'s (1995) initial mapping, based on 2D seismic data, showed the T45 succession onlapping the front of the shelf of the T36 sequence and being overstepped by sediments assigned to the T50 sequence (Fig. 40). Re-interpretation of the Quadrant 204 area using 3D seimic data showed that the dissected Lamba Formation shelf, away from the main channel filled with lower Flett Formation (T40), was mostly onlapped by sediments of the upper Flett Formation (T45) (Shaw Champion et al. 2008). This may indicate that an additional intra-Flett unconformity separates the upper and lower parts of the Flett Formation in this area and is equivalent to the base upper Flett Formation onlap surface in the rest of the basin. In Quadrant 204, the two unconformities coalesce outside the axis of the main erosive channel (Figs. 27, 34).

Hartley et al. (2011) have digitally manipulated the 3D seismic data around Quadrant 204 to analyse the nature of the Flett unconformity. First of all the data were flattened using a reconstructed seismic datum to represent the uneroded land surface (the 'summit envelope' of Fig. 27). Then, the original topographic relief of the surface was calculated by depth converting the seismic data and decompacting the sedimentary succession, to give a regional map (Fig. 41), where some of the interfluves are calculated to have been formerly more than 1000 m above contemporary sea level.

3.3.6 **Malinstindur and Enni formations; T45 (Early Ypresian)**

Regional bathymetry during the deposition of sequence T45 is revealed by the distribution of the Faroe-Shetland Escarpment (Ritchie et al. 2011) (Fig. 39), which was formed as the basalts of the Malinstindur and Enni formations on the Faroe Islands (Passey and Jolley 2009) crossed the uplifted and eroded Faroe Platform and adjoining areas and entered the marine Faroe-Shetland Basin as a prograding slope of hyaloclastite debris (Section E, Fig. 37). The relief of the Faroe-Shetland Escarpment diminishes southwards. It dies out as a significant feature near the southern margin of Quadrant 213, in an area that is contiguous with the front of the Flett Formation shelf in the UK sector, as defined by thickness data obtained from wells and 3D seismic coverage (Figs. 36, 39).

The boundary between the Enni and Malinstindur formations was not identified on seismic data offshore, so for the purposes of this report they are considered to form a single sequence. The combined thickness of the Malinstindur and Enni formations was calculated by depth conversion (using an interval velocity of 4.5 km/s) of an isochron of the interval between the top of the Beinisvørđ Formation (intra-basalt 10 reflector) and the high-amplitude event that marks the top of the lava pile (Fig. 42). Offshore, the two younger lava formations reach a combined thickness of 2200 m in the area of the Fugloy High in Quadrant 6203, where the the dip of the basalts steepens and the succession passes north-westwards into an interval of seaward-dipping reflectors. This thickness is equal to the combined thickness of the formations estimated onshore, where the Malinstindur Formation reaches 1250–1350 m in places, and the Enni Formation exceeds 900 m (Rasmussen and Noe-Nygaard 1970; Waagstein 1988; Passey and Jolley 2009). Seismic data suggest that the lava pile thins to about 600 m south-eastwards across the Faroe Platform, and passes into the aggrading sediments of the T45 sequence in the area of the Judd Sub-basin.

A longitudinal seismic profile through the northern part of the Faroe-Shetland Basin (Section J, Fig. 43) summarises the structure and stratigraphy of the Moray Group basinward of the Faroe-Shetland Escarpment. It shows the poorly reflective basinal seismic facies of sequences T45 and T50 overlying a high-amplitude package of chaotic reflectors, which well 214/4-1 proves to consist of volcaniclastic facies of lower Flett Formation and older (Lamba Formation) age. These sequences rest upon an undrilled set of high-amplitude reflectors, which may be associated with a previous influx of volcanic debris into the basin, derived from the erosion of older lava shields, like Brendan and Frænir.

Early Eocene tuffs recovered in dredge hauls from the top of of the Enni Formation lava shield on 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), related to Early Ypresian transgressions (Waagstein and Heilmann-Clausen, 1995) (Appendix 1, Fig. A1).

On the margins of the Faroe Platform near the Fugloy High, a thin post-Enni Formation sedimentary succession is truncated by an unconformity that defines a series of broad incised channels at base Stronsay Group level (Section F, Fig. 44). The area is only covered by 2D seismic data within the current project, but there are indications that the NW-SE-trending channels may form part of a drainage system flowing away from the Fugloy High in a dissected topography similar to the older area of dendritic drainage in Quadrant 204.

The subsequent development of an Eocene depocentre south of the Brendan High may indicate a return to extensional tectonics associated with the Fugloy-Brendan Fault during the Ypresian (Section J, Fig. 43). Interpretation of the Stronsay Group shows that the Eocene basin was partly filled by Mid-Eocene basin floor fans (Stoker et al. 2012), before dextral strike-slip movement on the same fault offset some of the northerly-trending anticlinal structures in the younger Cenozoic section (Ritchie et al. 2008; Johnson et al. 2012).

The potential tectonic relationship between these diverse volcanic and structural elements is discussed in the following section.

4 Discussion: Early Palaeogene volcanism and tectonics of the Faroe-Shetland region

In the foregoing section, the lithological and stratigraphic relationships established by the well data compiled in Appendix 1, Fig. 1A were used in the interpretation of selected seismic profiles and incorporated in a series of regional maps, to produce a summary of the chronostratigraphic development of the Faroe-Shetland Basin during the Paleocene–Early Eocene (Fig. 4).

This section reviews some of the previous tectonic models of area. It goes on to consider how the links between volcanism, structure and stratigraphy in the Faroe-Shetland Basin and surrounding areas revealed by current work could form the basis of a new tectonic synthesis.

4.1 PREVIOUS WORK

In their interpretation of Atlantic opening during the Palaeogene, White and Lovell (1997) argued that pulses of volcanic (Iceland plume)-related uplift in the British part of the North Atlantic Igneous Province could be linked to episodes of increased sediment influx in the North Sea. The volcanic pulses attributed to the plume were defined by the occurrence of widespread tuffs on the continental shelf and by clusters of radiometric age dates from elsewhere in the Province, while the corresponding sediment pulses were indicated by the calculated volume of Paleocene-Early Eocene fans in the North Sea Basin (Fig. 45). The occurrence of different tuffaceous phases in the Palaeogene sedimentary record is well established (Knox and Holloway 1992; Knox 1996), but Chambers et al. (2005) have raised doubts about White and Lovell's (1997) compilation of radiometric data, which included many age determinations that no longer meet accepted analytical criteria.

The 'pulse' of a mantle plume - in effect, the cyclical variation in its magmatic productivity - is possibly caused by thermo-mechanical instabilities in the plume conduit, which may be characteristic of all plume systems (Schubert et al. 1989).

In White and Lovell's (1997) interpretation, uplift of the UK landmass, before the opening of the Atlantic, is caused by underplating, a process in which the crust is thickened by the addition of igneous material. Intrusion is commonly inferred at lower crustal depths, although extrusion or emplacement elsewhere in the crust will generate the same isostatic effect. The epeirogenic response of the crust to the addition of igneous material is the subject of geophysical calculations that must take into account the amplification of the uplift caused by the erosion of overburden during exhumation (Brodie and White 1994).

As well as noting the correlation with sedimentary flux in the North Sea, White and Lovell (1997, their Fig. 4) observe that the Cenozoic compressional episodes on the Norwegian shelf described by Doré and Lundin (1996) also occurred '*when pulsing of the plume was important*'. White and Lovell (1997, p891) go on to attribute the formation of the Norwegian contractional structures to an increase in maximum compressive stress caused by temperature-related fluctuations in the pressure head at the centre of the Iceland plume, but calculate that the amount of crustal shortening required would be insufficient to account for the Palaeogene uplift and denudation of the British Isles. This claim is supported by Brodie and White's (1994) estimation that up to 15 km of Cenozoic contraction would be necessary in the Permo-Triassic basins north of Scotland to remove the 3 km thick succession of post-rift thermal subsidence sediments inferred to have been present according to McKenzie's (1978) lithospheric models of sedimentary basin formation. A series of geological assumptions clearly underpins Brodie and White's (1994) original calculation, including the attribution of all the uplift to the Cenozoic.

Subsequent investigations have focused on the link between the Iceland plume and unequivocal contemporaneous regional uplift, as defined by intra-Cenozoic unconformities in the Faroe-Shetland Basin and adjoining areas (Clift et al. 1998; Mudge and Jones 2004; Arrowsmith et al. 2005; Rudge et al. 2008; Shaw Champion et al. 2008; Hartley et al. 2011; Davis et al. 2012).

Rudge et al. (2008) and Shaw Champion et al. (2008) worked out the amount of plume-related uplift required to generate the buried dissected topography at base T40 level in Quadrant 204 of the Faroe-Shetland Basin. After flattening on an interpolated 'summit envelope' surface (Fig. 27) to remove the effect of post-Balder Formation deformation, they estimated the total relief on the base T40 or Flett unconformity as 550 m (Shaw Champion et al. 2008, p10).

It is notable, in this case, that the amount of post-Balder Formation uplift required to be removed from the seismic profile (Fig. 27), in order to flatten it (approximately 450 ms TWTT, equivalent to about 500 m of Cenozoic section), is similar to the amount calculated to have been removed from the same area at the Flett unconformity. However, the top Balder Formation event is folded and has clearly undergone some form of contractional uplift associated with the inversion of the underlying Judd Sub-basin against the Judd High, while the Flett unconformity is attributed by Rudge et al. (2008) and Shaw Champion et al. (2008) to uplift caused by the passage of a transient thermal anomaly related to the Iceland plume. Erosion linked to the younger, post-Balder Formation uplift occurs at a shallower unconformity in the Cenozoic section (Johnson et al. 2012).

A follow-up study (Hartley et al. 2011) increased the amount of uplift and erosion at the Flett unconformity in Quadrant 204, largely by decompacting the underlying sedimentary sequence (Fig. 41). The effect of applying decompaction is almost to double the estimated amount of uplift in Shaw Champion et al. (2008). By plotting a series of river valley profiles, which revealed a consistent development of nick points, Hartley et al. (2011) showed that the uplift had occurred in a series of stages, but was essentially a short-lived, transient phenomenon, with the eroded landscape reaching more than 1000 m above contemporary sea-level, before subsiding rapidly to be buried by coastal onlap during the Early Eocene. The transience of the uplift event was used to link it to a thermal pulse emanating from the Iceland plume, which temporarily uplifted the Faroe-Shetland region, before passing eastwards across Scotland to uplift the flanks of the northern North Sea.

Evidence of the North Sea uplift was obtained from the interpretation of 3D seismic data from the margin of the East Shetland Platform carried out by Underhill (2001) in the area of the Bressay and Bentley oil discoveries. The interpreted difference in the timing of the peak uplift in both areas was used to calculate the speed of the thermal pulse, which is inferred to have traversed Scotland at mantle level, like a ripple in a pond, around the start of the Eocene. From the Faroe-Shetland Basin (where peak uplift occurred at about 55.5 Ma), the pulse of plume-related uplift spread 240 km across Scotland to uplift Block 9/3 of the East Shetland Platform at approximately 54.4 Ma. This indicates a radial flow velocity for the thermal anomaly of ~35 cm/yr (Hartley et al. 2011).

The stratigraphic interpretations of Shaw Champion et a. (2008) and Hartley et al. (2011) are undermined by geological data from the Bentley field, where well 9/3-4 shows that the eroded top of the Dornoch Delta is underlain by another older unconformity that was responsible for erosion during T40 times (Fig. 46). The deeper unconformity is onlapped by sediments that contain the characteristic T40 dinocyst *Apectodinium augustum* (Ahmadi et al. 2003). It follows that the older erosive episode was contemporaneous with the uplift that caused the Flett unconformity in the Faroe-Shetland Basin. Whatever the cause of the related uplifts, if both the Faroe-Shetland Basin and the East Shetland Platform areas were uplifted simultaneously during T40 and T45, then the stratigraphic evidence from the Moray Group used to support the ripple-like movement of an expanding transient thermal pulse between the Atlantic and the North Sea margins of Scotland is no longer valid.

Alternative tectonic schemes explaining the early Palaeogene structural development of the Atlantic margin usually attempt to link deformation to distant plate boundary forces (Holford et al. 2009; 2010; Stoker et al. 2010b). Doré and Lundin (1996, p301) represent this view by claiming that '*compressive deformation of the young sedimentary piles on the* [Norwegian] *margin was an inevitable outcome in a plate bounded by a collisional margin on one side and a spreading ridge on the other*'. Evidence of Alpine tectonics is widespread in the British Isles and distant orogenic effects are commonly invoked to explain episodes of Cenozoic basin inversion in areas such as Dorset and the southern North Sea. It is noticeable that similar inverted basins further north, such as the Cleveland Basin and the Inner Moray Firth Basin, where the Cenozoic cover is almost entirely removed, are less commonly linked to the Alpine deformation, as if a critical distance from the orogenic front had been exceeded, requiring an additional explanation of uplift.

The essential point of the alternative proposals is that tectonic correlation of uplift events the North Atlantic area with established deformation phases in the Alpine and Pyrennean orogenies, does not necessarily require the involvement of a mantle plume and this, together with other issues relating to the nature and location of the Iceland Plume, has led some authors to question the application and validity of the plume hypothesis (Lundin and Doré 2005).

The attempts of these different investigations to explain uplift and contractional deformation on the Atlantic margin have overshadowed accounts that describe the predominantly extensional origin of oceanic basins. In particular, recent work has shown that that extreme continental extension (or 'hyperextension'), accompanied by the formation of major low-angle detachments, within the crust, can take place without generating excess volcanism at an incipent oceanic margin (Reston, 2009a; b). This critical observation must be accommodated in any alternative model that proposes to explain the origin of volcanic-rich margins in the absence of a plume.

4.2 SYNTHESIS

In this section, it is argued that explanations of the relationship between Cenozoic volcanism and stratigraphy in the Faroe-Shetland Basin and the North Sea that involve the process of underplating are consistent with observations, but do not take *full* account of the possible origins of Cenozoic uplift and erosion. In an area where evidence of extensional, contractional and strike-slip deformation is widespread, it is proposed that external tectonic events may potentially control the magmatic pulses that are currently attributed to the internal dynamics of a mantle plume.

The stratigraphic summary of the early Palaeogene of the Faroe-Shetland Basin (Appendix 1, Fig. A1; Fig. 4) provides additional support for the connection between volcanism and sedimentary influxes previously established in the North Sea (White and Lovell 1997). It defines alternating periods of extension-related subsidence and relative uplift interspersed with three volcanic episodes of increasing magnitude and followed by the opening of the Atlantic Ocean during Early Ypresian times. The gross thickness of the volcanic succession overlying the continental margin is very large (~ 6.6 km onshore in the Faroe Islands according to Passey and Jolley 2009) and is almost equivalent to the average global thickness of oceanic crust (estimated as 7 km by McKenzie and Bickle 1988).

The early Palaeogene structural history of the area is divided into 6 episodes (phases 0–5):

0: Localised extension in the northern part of the Flett Basin may have controlled the thickness of the Sullom and Ockran formations during the Danian. The initial episode of uplift the base of the Cenozoic in the British Isles is generally linked to the regional onset of magmatic underplating (Brodie and White 1994; White and Lovell 1997) and may correspond in part to the Sullom unconformity at the top of the Shetland Group in the Faroe-Shetland Basin.

1: The first major extrusive volcanic episode in the Palaeogene of the area is identified in wells, on seismic profiles and from potential field data (Kimbell et al. 2005) and consists of isolated lava shields of Selandian age, including the Brendan and Frænir volcanic centres. These centres are comparable in scale to contemporaneous structures in the Hebridean part of the igneous province such as Mull and Skye (England 1994; Emeleus and Bell 2005). The offshore volcanoes developed as part of an extending sedimentary basin, alongside the uplifted Shetland Platform, which provided a high proportion of reservoir sandstones to the basin in the form of turbidite fans. Evidence from the Brendan Volcanic Centre suggests that extrusive volcanism ceased and was followed by the intrusion of basic sills at depth. The possibly coeval development of a regional unconformity (the intra-Vaila unconformity) truncated the tilted lava shields. There is some seismic and well evidence to suggest that aprons of vocaniclastic debris were deposited in basinal areas at this time.

2: The second volcanic episode is of Late Selandian to Mid Thanetian age and consists of the eruption of the Beinisvørđ Formation and its associated hyaloclastite apron, which makes up the Lopra Formation (Passey and Jolley 2009). This outpouring of lavas is centred on the Faroe Platform and is considerably larger than the Palaeogene lava shield in Northern Ireland (Walker 1995). Coeval sediments in the Faroe-Shetland Basin largely consist of the Lamba Formation, which forms a mudstone-dominated prograding shelf that commonly acts as a hydrocarbon seal in the UK sector. Major volcanism ceased and the lava shield was tilted and eroded at the Flett unconformity, while the southern part of the Faroe-Shetland Basin was deeply dissected by a regional system of fluvial channels. The Munkagrunnur and Heri highs probably form related uplifts in the Faroese sector. Seismic and well data confirm that contemporaneous volcaniclastic debris is widespread in the northern part of the Faroe-Shetland Basin. The subsequent local eruption of basalt lavas, interbedded in the Flett Formation (Smallwood and Kirk 2005) and possibly fed by sills, may provide minor extrusive evidence that Beinisvørđ Formation volcanism ended with another episode of basic intrusion at depth, while related uplift caused the lower Flett Formation shelf to advance northwards in the basin.

3: The third volcanic episode consists of the Malinstindur and Enni formations of the Faroe Platform. The local development and different chemistry of the Malinstindur Formation lavas may be an indication of differentiation and crustal assimilation, and suggest a more prolonged residence time in the crust, possibly related to lateral, as opposed to vertical, injection of magma. The overlying Enni Formation lavas formed the Faroe-Shetland Escarpment as a prograding pile of hyaloclastite debris on entering the Faroe-Shetland Basin, and pass northward into the seaward-dipping reflectors at the incipient ocean margin. Tilting of the seaward-dipping lavas may be matched by a contemporaneous uplift of the Fugloy High at edge of the adjoining continent.

4: The fourth volcanic episode consists of the Balder Formation, which includes widespread thin-bedded tuffs. These pyroclastic rocks reflect the marine inundation of volcanoes and resurgence of explosive eruptions at the continental margin during the opening of the Atlantic Ocean, but otherwise represent a continuation of the previous volcanic episode.

5: By analogy with the tectonic history of Brendan Volcanic Centre during the Selandian, it is speculated that continued Early Eocene uplift of the Fugloy High may be related to the lateral emplacement of sills at depth into the continental margin post-dating the Enni Formation lava shield and the volcanic sources of the Balder Formation. A locally-developed unconformity at the base of the Stronsay Group in the adjoining part of the basin is linked to contemporaneous deformation and uplift.

New structural data from the Hebridean igneous province revealed by multibeam survey (Smith 2012) contribute to the tectonic interpretation of Palaeogene volcanism around the Atlantic margin and add to the widespread evidence linking uplift with contemporaneous strike-slip related deformation. Elsewhere in the UK sector, NE-trending Cenozoic sinistral faults have been described from SW England, NW Wales (Bevins et al. 1996) and Northern Ireland, where at least some of the faults are demonstrably intra-Paleocene in age (Cooper et al. 2012). NW-trending Cenozoic dextral faults have been described from SW England, Cardigan Bay (Turner 1997; Ruffell and Carey 2001) and Northern Ireland (Quinn 2006). Later Cenozoic compressional anticlines are widely developed on the Atlantic margin (Doré and Lundin 1996; Johnson et al. 2012, and references therein) and other evidence of uplift caused by contraction includes the Cenozoic inversion of structures such as the Cleveland and Inner Moray Firth basins and the reverse fault mapped by Underhill (2001), updip from the unconformity-bound Dornoch Delta on the East Shetland Platform (Fig. 46).

This summary suggests that the transition between extensional and contractional magmatism varies in time and space during the structural evolution of the NE Atlantic margin. Episodes of sill intrusion and uplift linked to the formation of folds and regional unconformities, can be interpreted as a way of accommodating the horizontal stress accumulated during periods of extension, dyke intrusion and volcanism in a strike-slip regime (De Paola et al. 2005). Since the contractional deformation acts against gravity, it requires a greater accumulation of stress and will tend to post-date the associated, gravity-assisted, extensional deformation. Contractional structures are expected to develop at right angles to the maximum horizontal stress, but commonly reactivate pre-existing, favourably-oriented, shallow-dipping structures as thrusts and reverse faults. It is possible to envisage a model of contintental extension, in which the local application of contractional plate boundary forces inhibits the process of oceanic opening by deforming and uplifting the continental margin, while the component of enhanced extension acting in a perpendicular direction contributes to the origin of excess magmatism.

In conclusion, it is suggested that the scale and timing of cyclical variations in the deformation of the Cenozoic succession of the Faroe–Shetland region and their correlation with changes in plate boundary tectonics (Doré and Lundin 1996; Johnson et al. 2012; Stoker et al. 2012a; b) raise the possibility that additional forces, including those postulated to be related specifically to the internal dynamics of a mantle plume, may not be required.

5 Conclusions

- Well and seismic data are combined to present a synthesis of the stratigraphic and tectonic development of the Faroe–Shetland region during the early Palaeogene, beginning at 65.5 Ma and culminating in the opening of the NE Atlantic Ocean at 54.5 Ma.
- A stratigraphic-range chart details the chronological range, lithology and thickness of the early Palaeogene succession in hydrocarbon exploration wells from the UK and Faroese sectors, with additional data from other published sources. Well ties to key horizons link the regional sequence stratigraphy to a grid of 2D and 3D seismic surveys. Stratigraphic and structural data are summarised in map form in a series of regional timeslices.
- Three major sequence boundaries in the early Palaeogene succession can be related to episodes of deformation.
- The Sullom unconformity is related to uplift on the margins of the Faroe-Shetland Basin following localised extension during the Danian and precedes an influx of basinal sandstones in the Vaila Formation. Subsequent extension in the basin mobilises Lower Paleocene shales into mud diapirs. The onset of volcanism during the Selandian is associated with local central volcanoes, including Brendan and Frænir.
- The intra-Vaila unconformity marks a period of uplift, which tilts and erodes the central volcanoes, forming extensive fans of volcaniclastic debris that are intruded by basic sills near the end of the Selandian and capped by the Kettla Tuff Member of the Lamba Formation. A larger volcanic shield, composed of Lopra Formation hyaloclastites and Beinisvørđ Formation basalts, mantles much of the Faroese sector, while the Lamba Formation forms a slope apron and prograding shelf succession of Thanetian age on the UK side of the basin.
- The Flett unconformity truncates the uplifted Beinisvørđ Formation and incises the Lamba Formation to form a terrestrial landscape characterised by dendritic drainage during the late Thanetian. Minor local extrusive volcanism at the start of the Eocene is possibly linked to an episode of basic sill intrusion during the deposition of the lower Flett Formation (Colsay Sandstone Member).
- Renewed major volcanism generates the terrestrial lavas of the Enni and Malinstindur formations during the Ypresian. The Enni basalts form the Faroe-Shetland Escarpment as a hyaloclastite delta in the marine Faroe-Shetland Basin and pass into the seaward-dipping reflectors at the continental margin. Lignites are deposited in the transgressive upper Flett Formation (Hildasay Sandstone Member). Oceanic opening occurs during the deposition of the Balder Formation, with the inundation of volcanic centres at the continental margin generating widespread tuffs. A local unconformity at the base of the overlying Stronsay Group is followed by further subsidence during the Ypresian.
- Intraplate deformation of the Faroe–Shetland region continued before, during and after the formation of the NE Atlantic passive margin. The style of deformation has similarities with basins elsewhere that have originated by transtension in a strike-slip regime. Further interpretation of deep seismic and structural data should aim to test the possible application of this tectonic model.
- Cyclical variations in the pattern of deformation and their correlation with changes in plate boundary tectonics raise the possibility that additional forces, including those postulated to be related specifically to the internal dynamics of a mantle plume, may not be required.

Appendix 1 Stratigraphic-range chart

Note: Figure A.1 is located in the back-pocket of this report

This appendix presents a stratigraphic-range chart for the Paleocene-earliest Eocene successions of the Faroe-Shetland region that places the commercial well data, BGS 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. 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 and dredge site data are linked into the standard Palaeogene calcareous nannofossil (NP) biozones.

Additional information includes: 1) a schematic column showing the geological relationship of the lithostratigraphic units; 2) the stratigraphic position of the key regional seismic reflectors; 3) generalised lithology and thickness of sequences; 4) the thickness of other selected units, which are generally bound by regionally important unconformities and consist of two or more sequences combined; 5) the age and lithostratigraphy of the pre-Palaeogene succession in each well (where known); 6) occasional explanatory notes addressing site-specific issues.

Appendix 2 Biostratigraphic notes

5.1 SUMMARY OF BIO-EVENTS

Biostratigraphic correlations are generally linked to an absolute timescale with the aid of globally-recognised calcareous nannopankton (NP) zones, but frequent revision of the magnetostratigraphic and radiometric timescales, because of new age data, changing radiometric constants or re-defined stratotypes, hinders comparisons between different vintages of stratigraphic interpretation. The correlation of NP zones with the zones of planktonic foraminifera and dinocysts that are more widely used in the Faroe-Shetland Basin is another potential source of discrepancy between different stratigraphic schemes.

While some bio-events are widely recognised by different service companies, others vary in significance between biostratigraphic reports. The following summary, in descending stratigraphic order, highlights some of these similarities and differences.

5.1.1 **Top Balder Formation (top T50)**

This horizon is widely recognised as the first downhole occurrence (FDO) of *Deflandrea oebisfeldensis* (e.g. Mudge and Bujak 2001).

5.1.2 **Top upper Flett/Dornoch formations (top T45)**

This horizon is widely recognised as the FDO of <u>common</u> *Cerodinium wardense* (e.g. Mudge and Bujak 2001).

5.1.3 **Top lower Flett Formation (top T40)**

In sections with a marine influence, this top (equivalent to the base of the upper Flett Formation) is commonly picked at the FDO of the dinocyst *Apectodinium augustum* (e.g. Mudge and Bujak 2001). An increase in the extent of *Apectodinium spp*. and the occurrence of *A. augustum* in particular have been linked to the Paleocene-Eocene Thermal Maximum (PETM), an episode of global warming that began at the end of the Paleocene (Gradstein et al, 2004; Westerhold et al., 2009 and references therein). According to Mudge and Bujak (2001), the LDO (last downhole occurrence) of *A. augustum* occurs slightly above the base of the Flett Formation. This datum is currently considered to define the Paleocene-Eocene boundary and is linked to the onset of the global carbon isotope excursion event. The slightly older base of the Flett Formation is defined by the downhole influx of impoverished agglutinate foraminifera that marks the top of the Lamba Formation (see below). In contemporaneous non-marine successions, including sections dominated by volcanic rocks, the presence of sediments equivalent to the lower Flett Formation has been inferred from the development of an associated flora with thermophyllic affinities (Jolley 2009; Jolley et al. 2002b; 2005; 2012). Correlations between the marine and non-marine parts of the basin on this basis have generated a number of stratigraphic problems that remain unresolved.

5.1.4 **Top Lamba Formation (top T38; T36; Flett unconformity)**

Different published interpretations of T-zones and biomarkers within the Lamba Formation complicate the sequence stratigraphy of the unit and hinder the comparison of different biostratigraphic schemes.

Strata included in the Lamba Formation by Knox et al. (1997) form part of the T36 interval as originally described by Ebdon et al. (1995). In accompanying palaeogeographic maps, Ebdon et al. (1995, their figs. 10a and 10b) divided the stratigraphy of T36 into early and late intervals that were not formally defined. A tuffaceous horizon that occurs within the T36 sequence (and which may have been used by Ebdon et al. to sub-divide the T-zone) was later assigned to the Kettla Tuff Member by Knox et al. (1997).

In their subsequent sequence stratigraphic analysis, Lamers and Carmichael (1999) introduced T38 and T35 as additional T-zones above and below T36. Since their accompanying sections show that the top of T38 corresponds to the top of T36 illustrated by Ebdon et al. (1995), it appears that Lamers and Carmichael (1999) have changed the definition of T36 without providing seismic picks or biomarkers for its revised top.

Mudge and Bujak (2001, their Fig. 4) equate the Lamba Formation of Knox et al. (1997) with contemporaneous stratigraphic units in the North Sea (Lista 3b, 3a and 2). They pick the top of the Lamba Formation (corresponding to the top of Lista 3b) at the FDO of a microfauna of impoverished agglutinated foraminifera, commonly consisting of a sparse, low diversity assemblage of *Bathysiphon* and *Reticulophragmium* (Knox et al. 1997; Mudge and Jones 2004). The same microfauna is described from the central North Sea by Mudge and Bujak (1996).

Mudge and Bujak (2001) define the top of a mid-Lamba Formation unit (equivalent to Lista 3a) by the FDO of a microfauna consisting of diverse (as opposed to impoverished) agglutinated foraminifera, including *Spiroplectammina spectabilis,* and by the associated FDOs of dinocysts *Alisocysta margarita* and *Areoligera gippingensis*. They link these bio-events to the top of nannoplankton zone NP8. A deeper acme event, the top of abundant *Areoligera gippingensis* (Mudge and Bujak 1996a, b), which lies close to the base of NP8, is used by Mudge and Bujak (2001) to define a basal part of the Lamba Formation equivalent to Lista 2.

Knox et al. (1997) only recognise two units (L1 and L2) within the Lamba Formation. A third unit (L3) recognised by Ichron Ltd. (2010a, b) may be equivalent to the upper, predominantly mudstone, part of Knox et al.'s L2 unit or the mid-Lamba Formation interval (Lista 3a) of Mudge and Bujak (2001).

Mudge and Bujak (2001) also extend the top of the Lamba Formation up into nannoplankton zone NP9, which differs from the interpretation of Ichron Ltd. (2010a, b), but minor discrepancies of this sort between stratigraphic schemes may be caused by different interpretations of the acme occurrences of key biomarkers.

5.1.5 **Top Vaila Formation (top T35)**

According to Knox et al. (1997, p114), the base of the Lamba Formation and top of the Vaila Formation are identified by the first downhole occurrence (FDO) of the dinocysts, *Palaeoperidinium pyromorphum* and *Palaeocystodinium bulliforme*, though *P. pyrophorum* was noted to occur sporadically in younger sediments. Near the top of the Vaila Formation, Mudge and Bujak (2001) observe three different events related to *P. pyrophorum*; top of consistent *P. pyrophorum* (marking the top of the Vaila Formation or top DP4b/Lista 1b in their scheme), top common *P. pyrophorum* (intra DP4b) and top abundant *P.pyrophorum* (equivalent to top DP4a/Lista 1a). In their interpretation, *P. pyrophorum* is not found in situ in Lamba Formation and younger sediments (Mudge and Bujak 2001).

In the stratigraphy of the North Sea Paleocene, the FDO of *P. bulliforme* is shown near the top of the Andrew Sandstone of Ahmadi et al. (2003; their Fig. 14.12). The Andrew Sandstone underlies the Balmoral Tuffite (Knox et al. 1992), a tuffaceous sediment laid down widely in the Outer Moray Firth at the same time as the Kettla Tuff Member was deposited upon the uppermost unit of the Vaila Formation (V4) in the Faroe-Shetland Basin (Knox et al. 1997). Although the base of the Kettla Tuff forms a conspicuous regional marker horizon on seismic data, different authors have proposed various interpretations of its sequence stratigraphic significance.

Ebdon et al. (1995), in their sequence stratigraphic interpretation, describe the base of T36 as a true sequence boundary that truncates the underlying T34 zone and is linked to a basinward shift in facies belts. It is thus equivalent to a type 1 unconformity in the Exxon/Vail sequence stratigraphic model (Van Wagoner et al. 1988). In the basin, they show that the correlative of this unconformity coincides with the base of the Cuillin fan (Ebdon et al. 1995, their fig.6). Since the Kettla Tuff overlies the Cuillin fan, it follows that the base of T36 as originally defined by Ebdon et al. (1995) lies <u>within</u> the Vaila Formation of Knox et al. (1997) and not at the base of the Lamba Formation.

This complex argument is necessary because BP T-zone T35 does not form part of the sequence stratigraphic analysis of Ebdon et al. (1995). It first appears in the account of Lamers and Carmichael (1999), where its relationship with the previously described T-zones T34 and T36 (Ebdon et al. 1995) is not firmly established. It is possible that the T35 interval was first introduced to describe the sandstones that form the main reservoir for the Loyal oilfield, which was discovered by BP well 204/20-3 in late 1994 (Leach et al. 1999).

On some of Lamers and Carmichael's (1999) figures, the base of T36 is shown to correspond with the base of the Kettla Tuff. This conflicts with Ebdon et al. (1995), but suggests that Lamers and Carmichael (1999) may have redefined T36 by incorporating sediments equivalent to the Cuillin fan into a newly created T35 interval. In Lamer and Carmichael's (1999) interpretation, the type 1 unconformity used by Ebdon et al. (1995) to define the base of T36 would then become equivalent to a sequence boundary below T35.

This interpretation of changes to Ebdon et al.'s originally defined zones is supported by partial graphic logs of wells 205/9-1 and 206/1-3 presented by Loizou et al. (2006), which depict T35 sandstones, including the main reservoir of the Laggan gas field, beneath the Kettla Tuff. In this report, a seismic pick at the base of these sandstones is taken to correspond with the base of T35. It forms a major sequence boundary within the Vaila Formation and is equivalent to the base of T36 as originally defined by Ebdon et al (1995).

Ichron Ltd. (2010a, b) have accommodated these differences in sequence interpretation in a different way. In their scheme, a pre-Kettla Tuff component to T36 is retained, where it consists of only the upper part of Knox et al.'s (1997) V4 unit. However, the base of this interval is not depicted as an unconformity, as it should be, if it were equivalent to the base of T36 as defined by Ebdon et al. (1995).

In well logs illustrated by Mudge and Bujak (2001), including 208/19-1 and 214/27-1, the top of the Vaila Formation is shown as a major mid-Paleocene uplift surface overlain by the Kettla Tuff. There is no unconformity at this level in any of the wells interpreted by Ichron Ltd. (2010a, b). Mudge and Bujak (2001) do not relate their uplift surface to the sequence boundaries previously proposed by Ebdon et al. (1995) or Lamers and Carmichael (1999). However, in both their interpreted wells, the inferred base Kettla Tuff unconformity is developed slightly above the first consistent downhole occurrence of the dinocyst *Palaeoperidinium pyrophorum*, which is one of the key biomarkers for the top of the Vaila Formation cited by Knox et al. (1997).

These observations demonstrate that the biostratigraphical limits and stratigraphic relationships between BP T-zones T36 and T35 are not fixed in the published literature and that the various proposed stratigraphic schemes are difficult to reconcile in detail.

5.1.6 **Intra-Vaila Formation (Top T34; intra-Vaila unconformity)**

In wells such as 206/5-1, 214-27-1 and 214/27-2, Ichron Ltd. (2010a, b) have interpreted an unconformity at the base of T35 (Appendix 1, Fig. A1). In well 214/27-1, the unconformity is close to the base of Vaila Formation unit V4, as interpreted by Knox et al. (1997, p79). In well 214/28-1, evidence of early Paleocene reworking within T35 could be an indication of a basal T35 unconformity. Lithological interpretation of other nearby wells (including 205/9-1, 205/12-1, 205/14-1, 206-1-2, 206-2-1A and 208/17-2; Appendix 1, Fig. A1) show that the T34/T35 boundary interpreted by Ichron Ltd. (2010a, b) commonly marks the base of a coarser-grained sedimentary interval in the upper Vaila Formation. The base T35 boundary in all these wells appears to have much in common with the type 1 unconformity marking the base of T36 described by Ebdon et al. (1995). Underlying channelised slope sandstones of T34 age form part of the reservoir succession in the Foinaven and Schiehallion fields (Cooper et al. 1999; Leach et al. 1999).

5.1.7 Synthesis: Vaila Formation (T34, T35) and Lamba Formation (T36, T38)

The synthesis of these correlations adopted in the current report proposes that the main sequence boundary in the mid-Paleocene is taken to correspond to the base of T35 as identified by Ichron Ltd. (2010a, b). This horizon sometimes marks the base of the V4 unit of Knox et al. (1997) and is postulated to be equivalent to the base of T36 as originally mapped by Ebdon et al. (1995). In the basin, where the succession is conformable, the sequence boundary is overlain by a succession of coarser-grained basin floor fans, but these are transgressed and overstepped by more argillaceous sediments before the end of Vaila Formation deposition. The fine-grained succession, which makes up the upper section of Knox et al.'s (1997) V4 unit, forms part of a regional seal for the turbiditic hydrocarbon reservoirs of the underlying Vaila Formation. Onlap of the basin margin continued up to the base of the Kettla Tuff, before the basin fill became dominated by the aggrading and prograding shelf sediments of the Lamba Formation (T36 and T38). In Lamers and Carmichael (1999), the base of the Kettla Tuff is widely used to define the base of T36, but it is not clear from their text if it is for the reasons outlined here.

It is possible that parts of this succession lack sufficient well-defined biomarkers to support detailed sequence analysis. Biostratigraphic picks of speculative sequence boundaries in this area need to be confirmed by ties between wells and supported by seismic interpretation.

5.1.8 Intra-Vaila Formation (Top T32-T31)

Sandstones in BP sequences T32 and T31 form important hydrocarbon reservoirs. T31 is the main reservoir in the Schiehallion Field, where it consists of a series of laterally amalgamated NW to WNW oriented, submarine slope channel complexes up to 70 m thick and ranging from 100–1000 m wide. The overlying T34 sandstones are also oil-bearing (Leach et al. 1999). Jolley and Bell (2002a) note that the taxon *Isabelladinium viborgense* becomes extinct during sequence T31 times, so that the FDO of this taxon indicates T31 and older sediments.

5.1.9 Intra-Vaila Formation (Top T28)

The top of the Maureen Formation (T20) in the North Sea is defined by the 'Cenodiscus Claystone' a widespread mudstone unit that commonly contains abundant pyritised specimens of the eponymous radiolarian, now known as *Cenosphaera lenticularis* (Knox and Holloway 1992). This fossil occurs commonly throughout sequences T22, T25 and T28 in the Faroe-Shetland Basin. From the interpretations of Mudge and Bujak (2001) and the statistical biostratigraphic data recorded by Ichron Ltd. (2010a; b), it would appear that the position of the acme occurrence of *C. lenticularis* varies locally between wells. The interpretation of the significance of the acme occurrences also differs between the various biostratigraphic schemes. Regionally however, the first downhole occurrence of *C. lenticularis*, in wells such as 205/10-4, 205/10-5, 206/1-2 and 208/17-1, is usually interpreted as the top of the T28 sequence, and is equivalent to bio-event M3 of Mudge and Copestake (1992) in the North Sea.

5.1.10 Intra-Vaila Formation (Top T25)

Jolley and Bell (2002a) note that the first evolutionary appearance or last downhole occurrence of *Alisocysta margarita* occurs in T25 in the Faroe-Shetland Basin.

5.1.11 **Intra-Vaila Formation (Top T22)**

Knox et al. (1997, p114) use an acme event, the first downhole occurrence (FDO) of common to abundant *Cenosphaera lenticularis,* to define the top of Vaila Formation unit 1 (V1), which is probably equivalent to T22. The presence in this unit of common *Palaeocystodinium bulliforme* could support a Selandian age (Stoker and Varming (2011, p171; Jolley and Bell 2002a). However, there are different stratigraphic interpretations of this dinocyst. In Nussuaq, west Greenland, Nøhr-Hansen et al. (2002) describe *P. bulliforme* as ranging from Mid-Upper Danian to Lower Selandian and correlate their *P.bulliforme* zone with the lower to middle part of nannoplankton zone NP4 in the Mid-Upper Danian. In contrast, in the North Sea, Ahmadi et al. (2003, Fig. 14.12) show the first downhole occurrence of *P.bulliforme* at the top of NP6 (top Andrew), based on Aubry et al. (1988), and define a deeper acme event at the top of NP5, just above top Maureen level.

5.1.12 **Top Shetland Group (Top T10.2; Sullom unconformity)**

The top of the Shetland Group is widely interpreted to coincide with the FDOs of *Eoglobigerina trivialis* and *Alisocysta reticulata* (Mudge and Bujak 1996; Mangerud et al. 1999), although the distribution of *Alisocysta reticulata* indicates a possible facies control, with a preference of the species for deep water areas (Mudge and Bujak 1996). This boundary occurs within the Maureen Formation in the North Sea (Knox and Holloway 1992), but lies at the top of the Sullom Formation, the topmost unit of the Shetland Group in the Faroe-Shetland Basin (Knox et al. 1997).

5.1.13 **Intra-Shetland Group (Top T10.1)**

Within the Shetland Group, the FDO of *Senoniasphaera inornata* forms a widely recognised intra-Danian biomarker that is equivalent to the base of the Maureen Formation in the North Sea (Mudge and Bujak 1996).

5.1.14 **Intra-Shetland Group (Base T10.1 / Top Cretaceous)**

The top of the Maastrichtian corresponds to the top of the Jorsalfare Formation within the Shetland Group (Ritchie et al. 1996) and is marked by an influx of the dinocyst *Palynodinium grallator* (Mudge and Bujak 1996).

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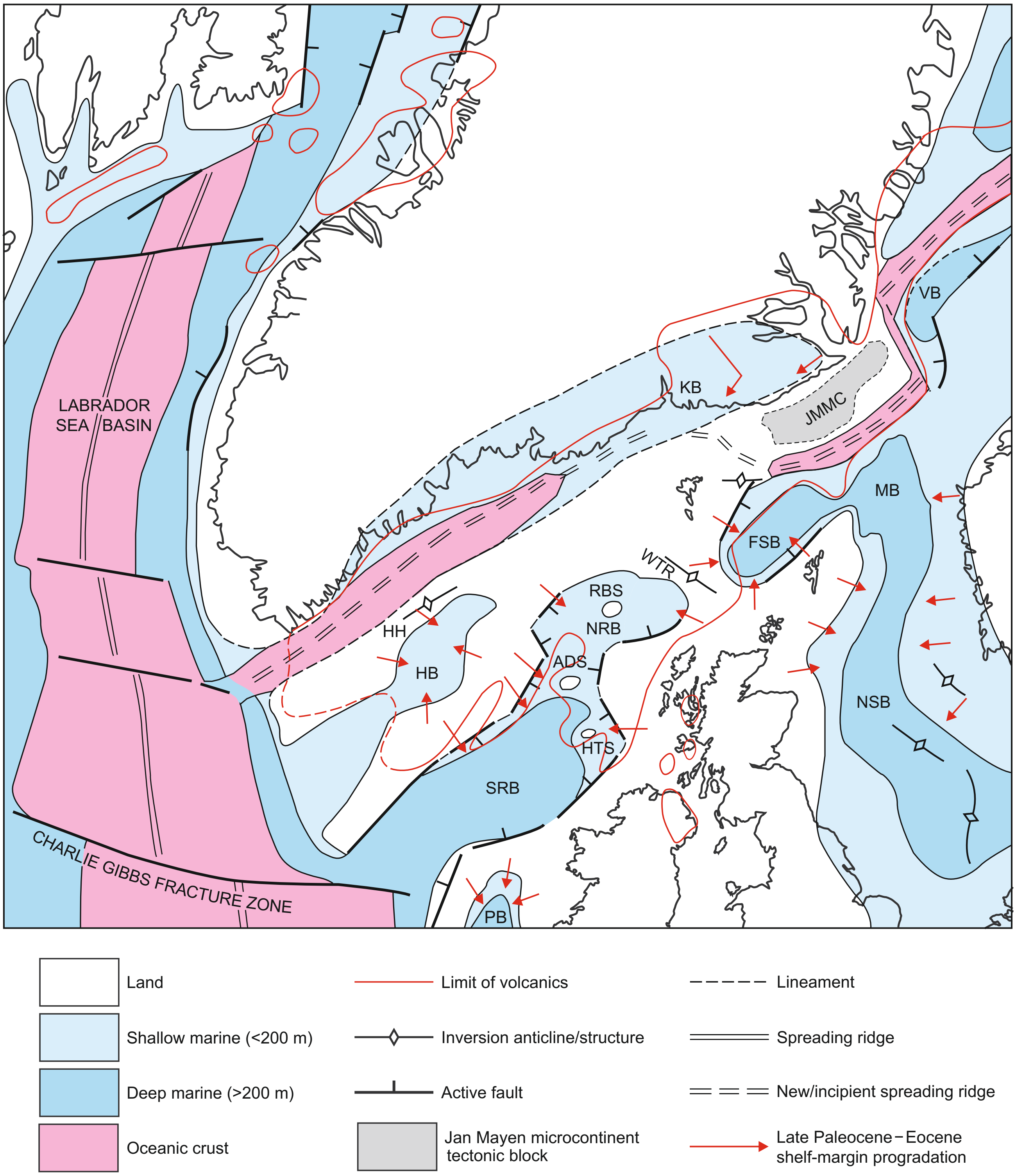


Figure 1 Generalised palinspastic map for the Late Paleocene to Early Eocene interval (from Ellis and Stoker *in press*). Abbreviations: ADS, Anton Dohrn Seamount; FSB, Faroe-Shetland Basin; HB, Hatton Basin; HH, Hatton High; HTS, Hebrides Terrace Seamount; JMMC, Jan Mayen microcontinent; KB, Kangerlussuaq Basin; MB, Møre Basin; NRB, North Rockall Basin; NSB, North Sea Basin; PB, Porcupine Basin; RBS, Rosemary Bank Seamount; SRB, South Rockall Basin; WTR, Wyville Thomson Ridge; VB, Vøring Basin.

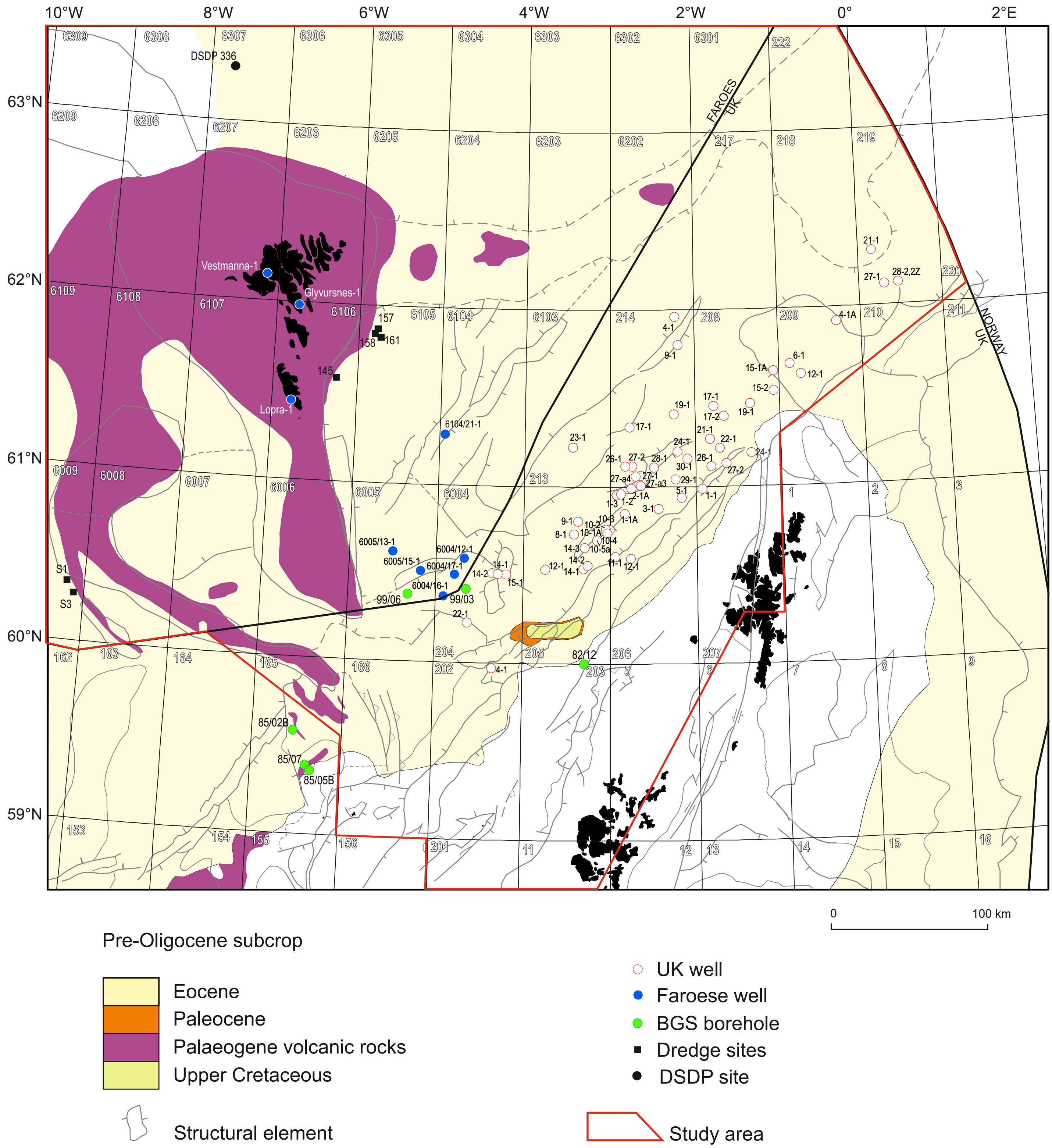


Figure 2 Pre-Oligocene subcrop map of the study area showing the location of the wells in the biostratigraphic database, with structural elements from Ritchie et al. (2011).

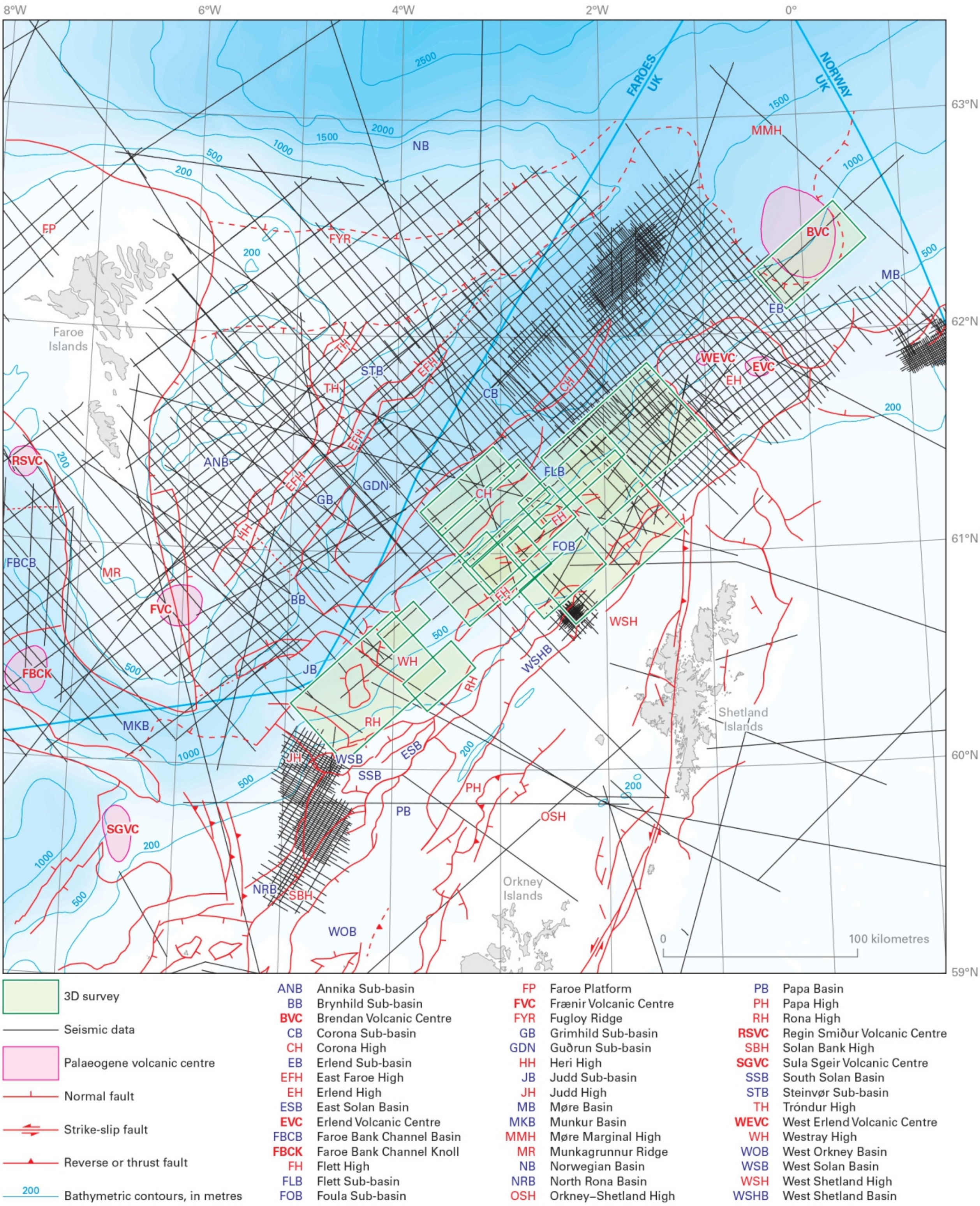


Figure 3 Seismic data location map; bathymetry, structural elements and Palaeogene volcanic centres from Ritchie et al. (2011).

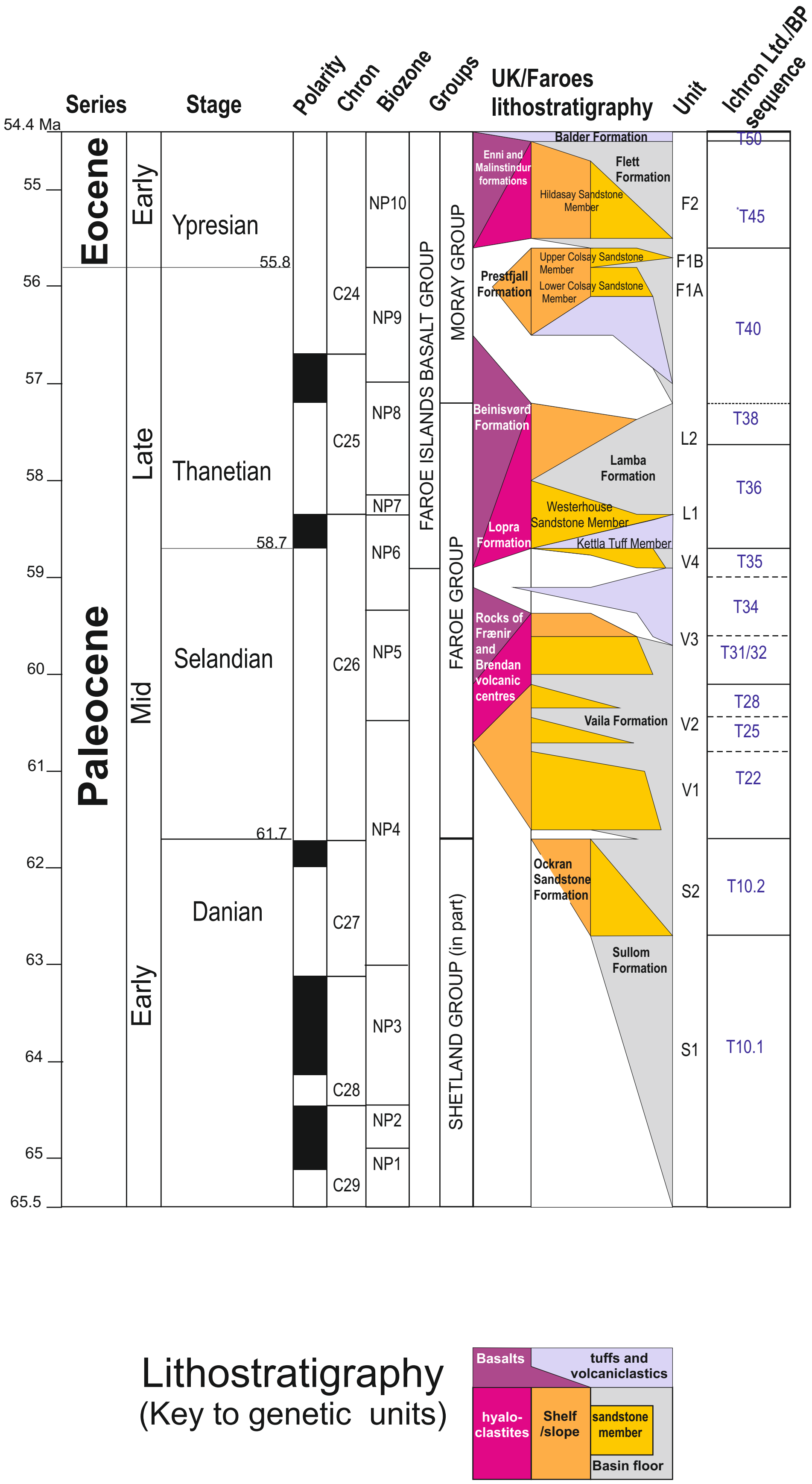


Figure 4 Paleocene-earliest Eocene chronostratigraphic scale (Gradstein et al. 2004; Ogg et al. 2008) correlated with the UK/Faroe Islands lithostratigraphy (Knox et al. 1997; Passey and Jolley 2009) and the Ichron/BP sequence stratigraphic scheme (Ichron Ltd. 2010a; b; Lamers and Carmichael 1999). Note that the base of biozone NP10 has been placed at 55.8 Ma (from Ogg et al. 2008). This is a change from Stoker et al. (2012b), where the same boundary is placed at 54.8 Ma (as in Gradstein and Ogg 2004). This change affects the position of the base of sequence T45, which in this report is now placed at 55.6 Ma, corresponding to the top of the Paleocene-Eocene Thermal Maximum (PETM), an episode of global warming which may have persisted for 200,000 years after the start of the Eocene (Storey et al. 2007).

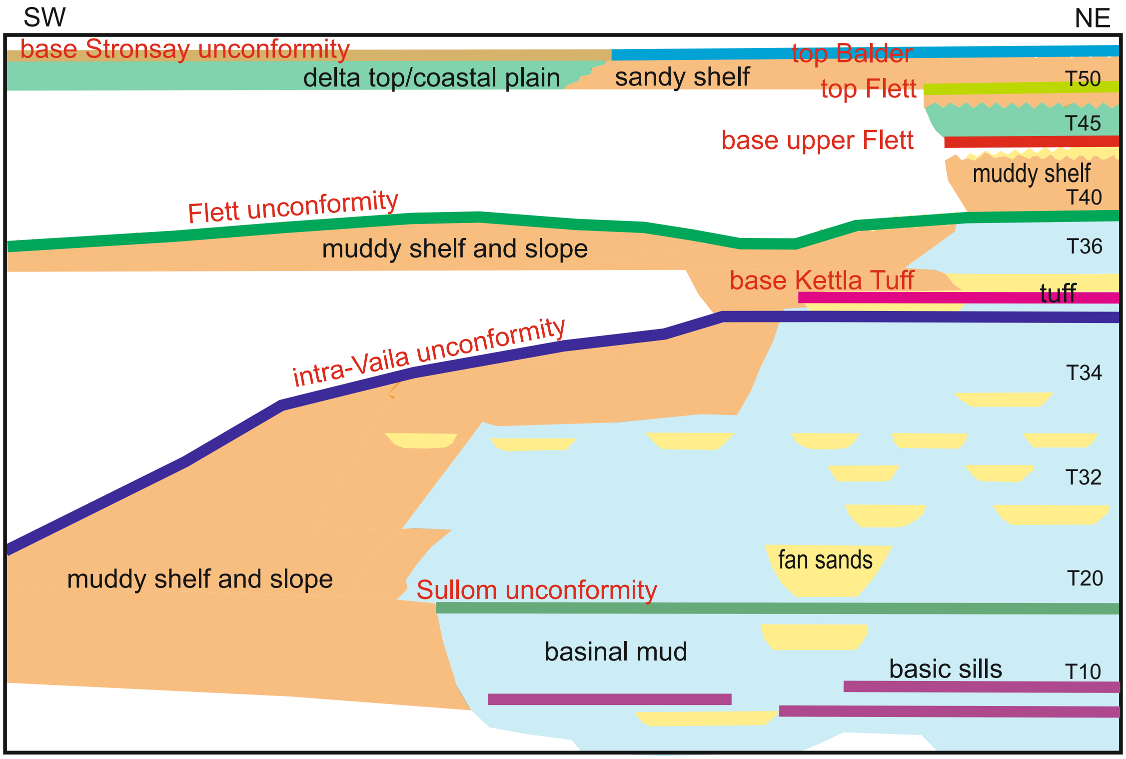


Figure 5 Simplified chronostratigraphic chart of the Paleocene and Early Eocene of the Faroe-Shetland Basin showing the main lithologies and sequences slightly modified from Ebdon et al. (1995, their Fig. 6) and including the approximate position of key unconformities and seismic reflectors from Figure 4 (see text for details).

Deegan and Scull (1977)	BP North Sea	Ebdon et al. (1995)	Lamers and Carmichael. (1999)	Ichron Ltd. (2010a; b)	Knox et al. (1997)
Balder	T50	T50	T50	T50.2	Balder
				T50.1	
Sele	T45	T45	T45	T45.3	Flett (upper)
				T45.2	
				T45.1	
Forties	T40	T40	T40	T40.3	Flett (lower)
				T40.2	
				T40.1	
Lista	T30		T38	T38	Lamba
		T36	T36	T36	
			T35	T35.3	Vaila
				T35.2	
				T35.1	
Andrew		T34	T34	T34.4	
				T34.3	
				T34.2	
				T34.1	
		T32	T32	T32	
			T31	T31.3	
				T31.2	
				T31.1	
Maureen	T20	T20	T28	T28.2	
				T28.1	
			T25	T25.2	
				T25.1	
			T22	T22.2	
				T22.1	
		T10	T10	T10.2	Sullom
Ekofisk	T10			T10.1	

Figure 6 Table showing how lithostatigraphic and sequence stratigraphic schemes, first developed in the Paleocene and Early Eocene successions of the North Sea and applied with modifications in the Faroe-Shetland Basin, have become increasingly complex.

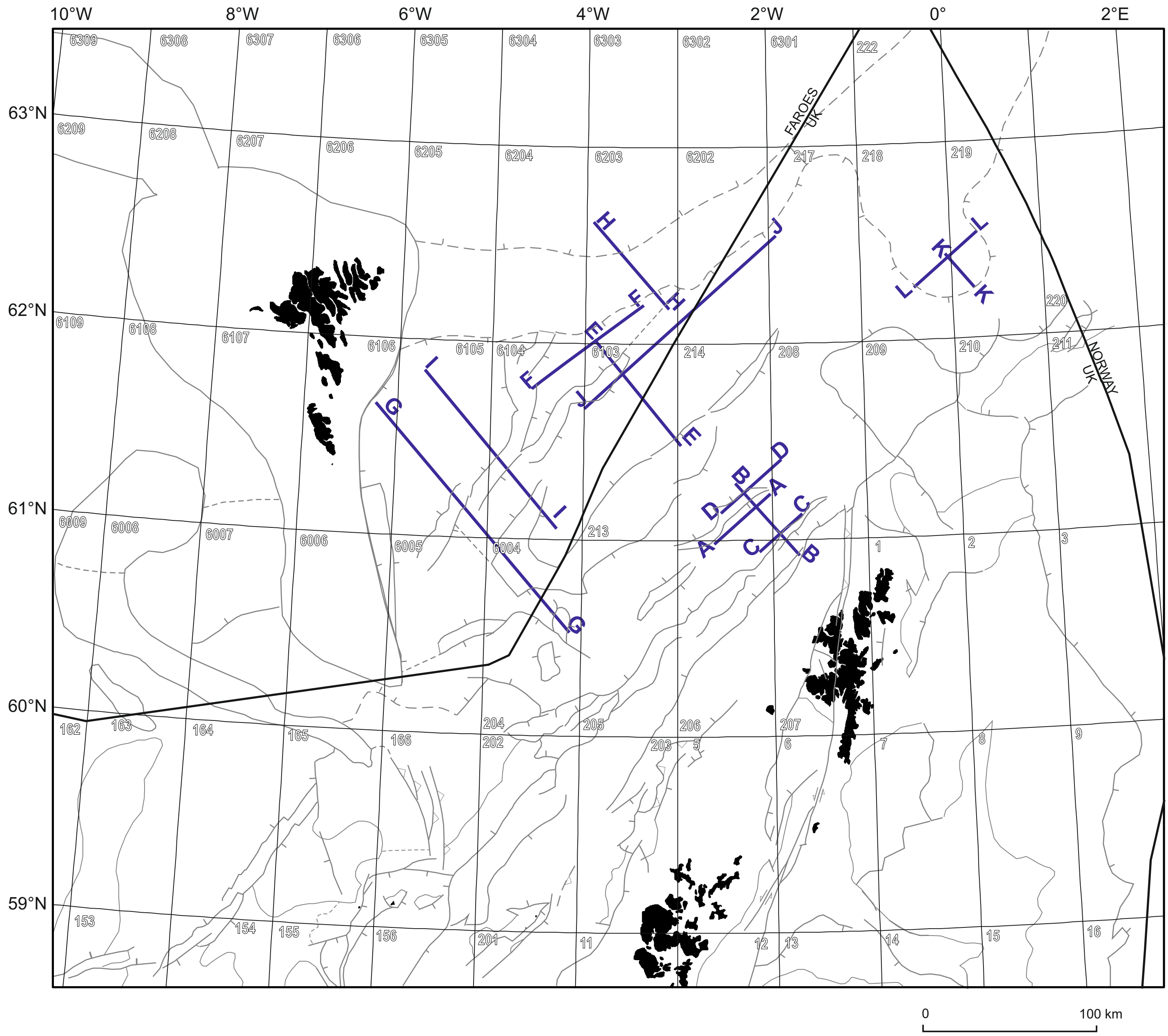


Figure 7 Map of the structural elements of the Faroe–Shetland region (Ritchie et al. 2011), showing the location of interpreted seismic reflection profiles (A-L) figured in this report.

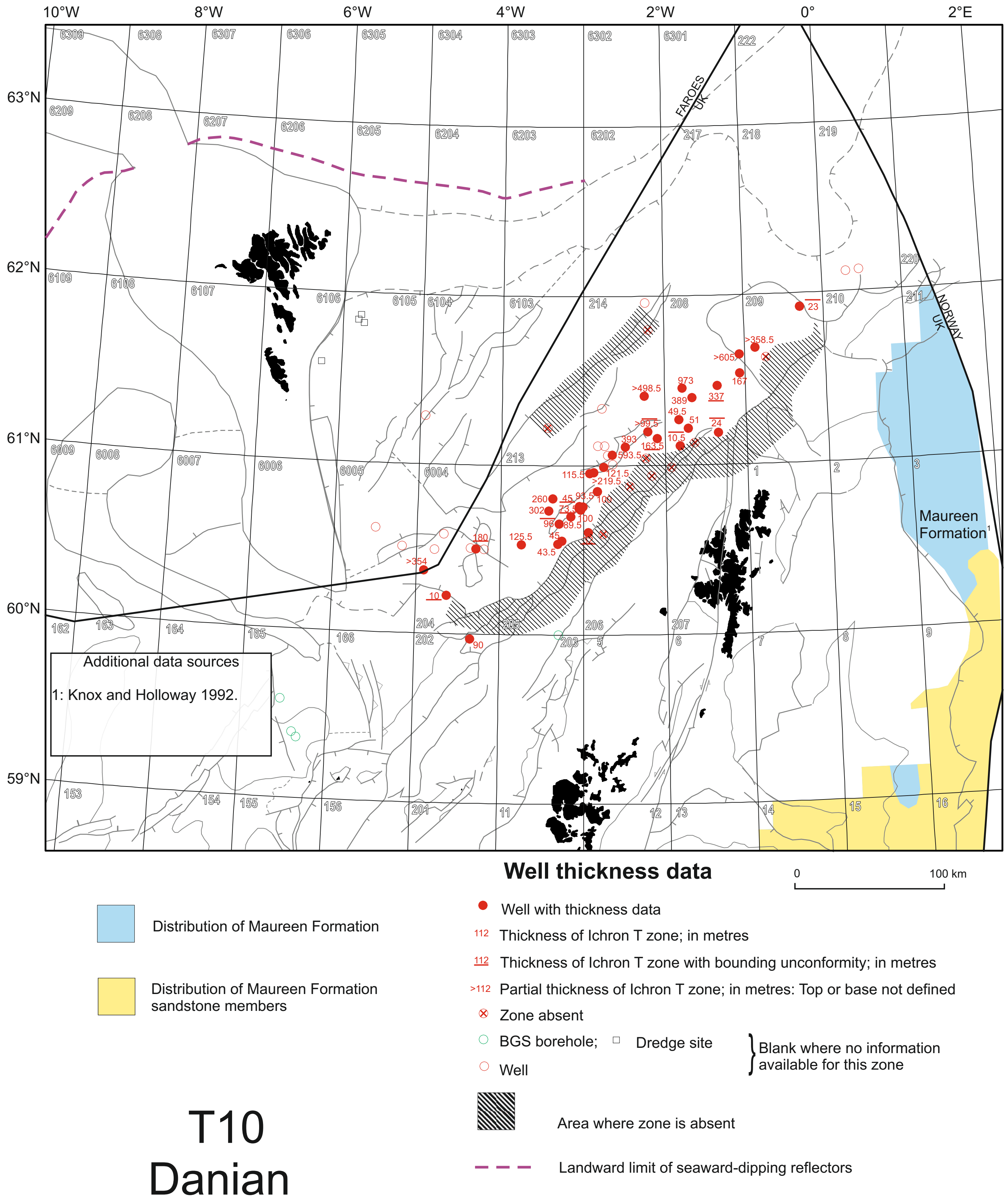


Figure 8 Thickness of the T10 (Danian) interval in wells; includes the Sullom and Ockran formations (Shetland Group) in the Faroe-Shetland Basin, which are partly equivalent to the Ekofisk and lower Maureen formations in the North Sea. See text for details.

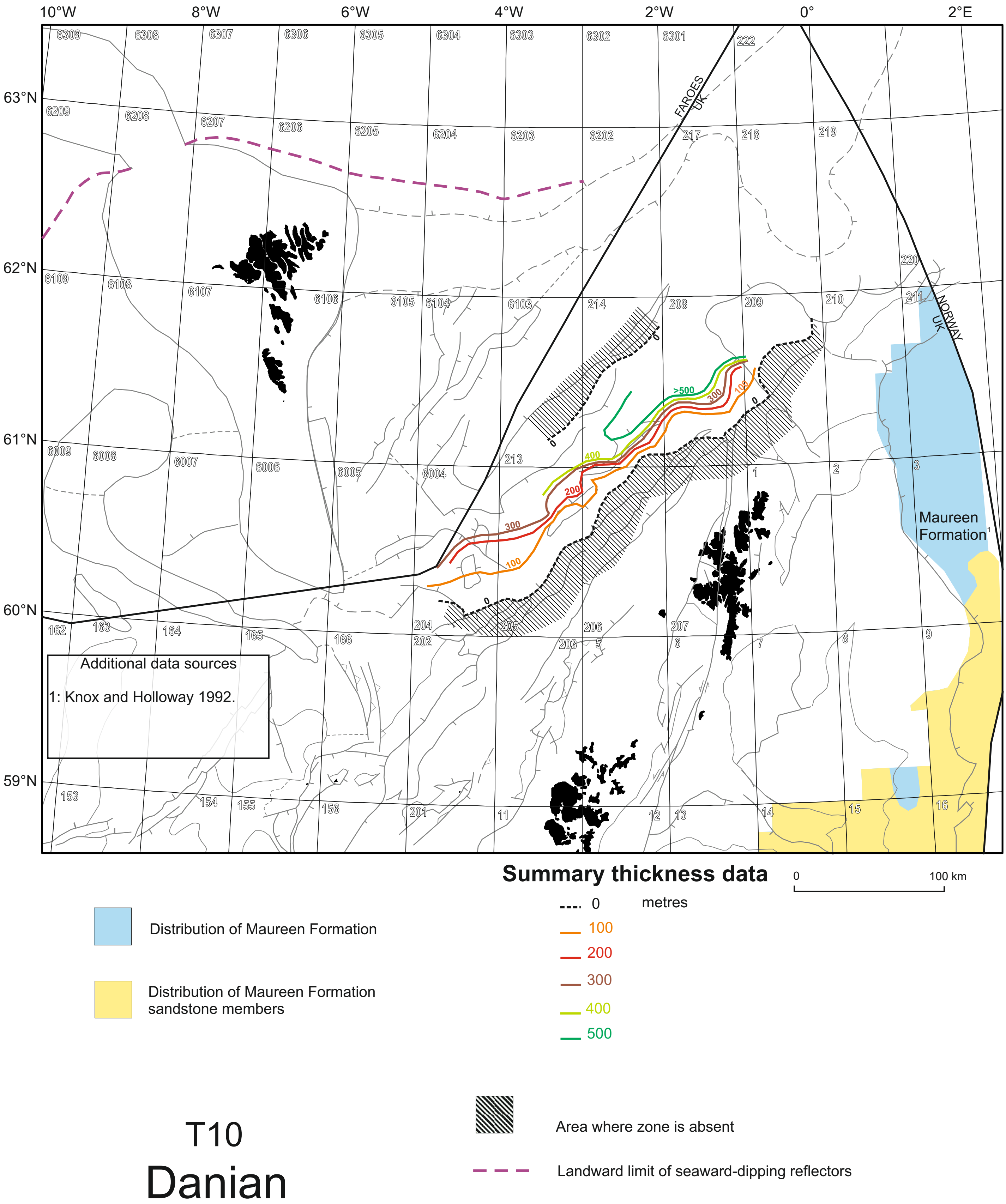


Figure 9 Contoured thickness of the T10 (Danian) interval in wells; includes the Sullom and Ockran formations (Shetland Group) in the Faroe-Shetland Basin, which are partly equivalent to the Ekofisk and lower Maureen formations in the North Sea. See text for details.

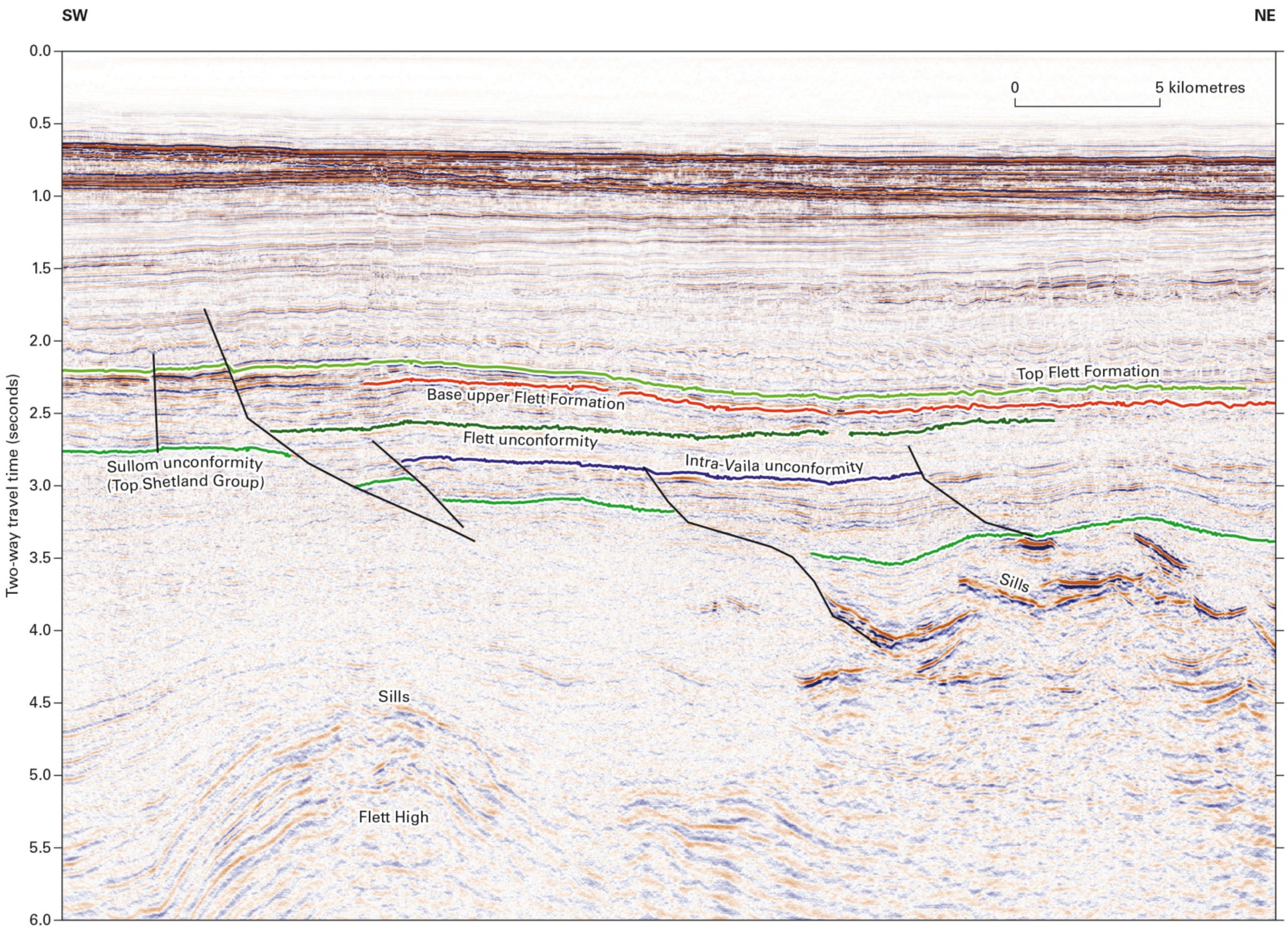


Figure 10 Section A: SW–NE seismic profile across the margin of the Faroe-Shetland Basin showing the main Early Palaeogene unconformities in the vicinity of the Flett High. At the NE end of the profile, a series of high-amplitude reflectors between 3.5 and 4.0 s TWTT indicates that the thick Early Paleocene section is pervasively intruded by transgressive basic sills. In the SW, the Flett High is marked by a deeper pile of sills between 6.0 and 4.7 s TWTT, with an overlying unconformity at top Shetland Group level. Above the Flett unconformity, the lower Flett Formation shelf thins from SW–NE. For location see Fig. 7. Seismic data by courtesy of Shell U. K. Limited.

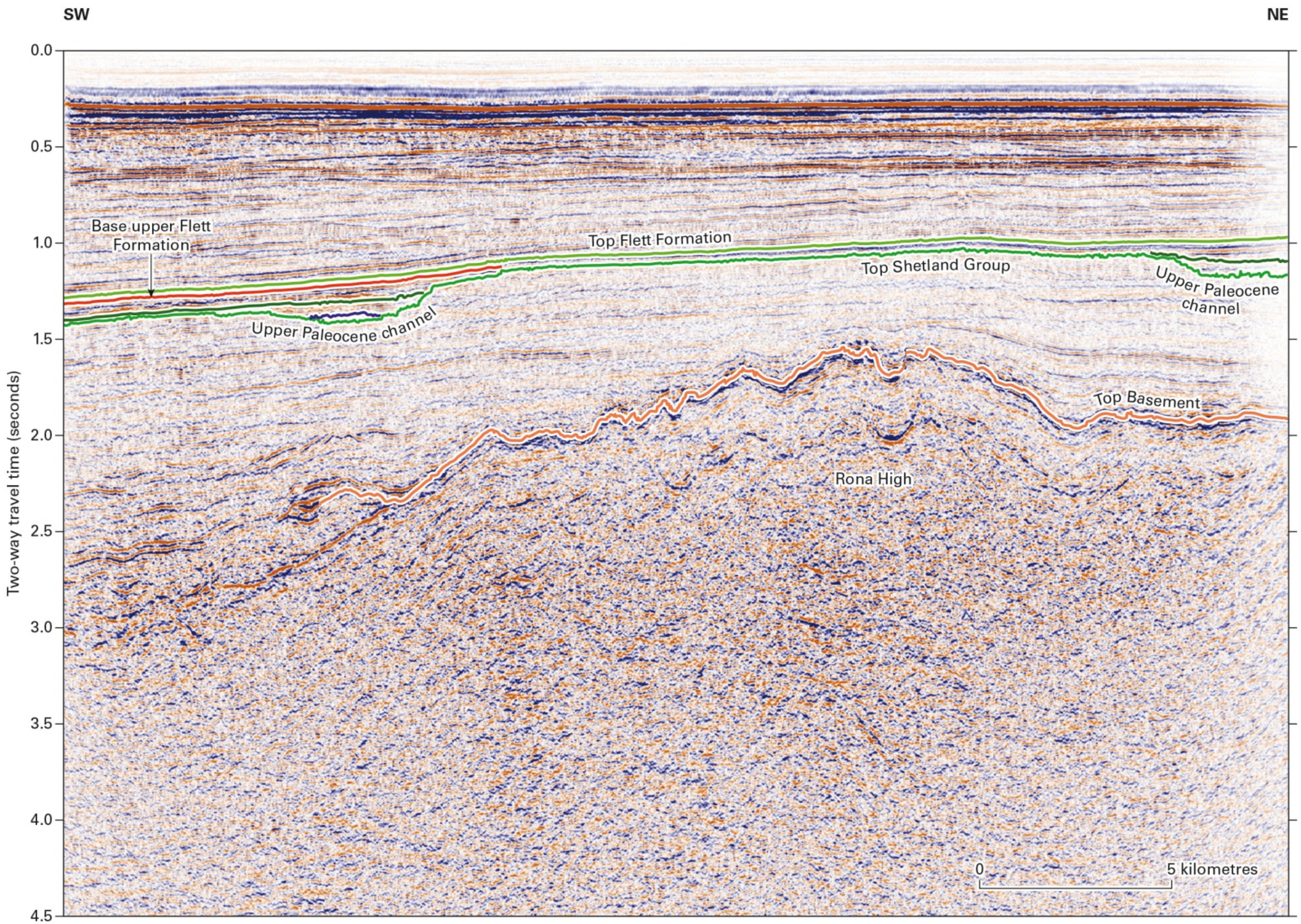
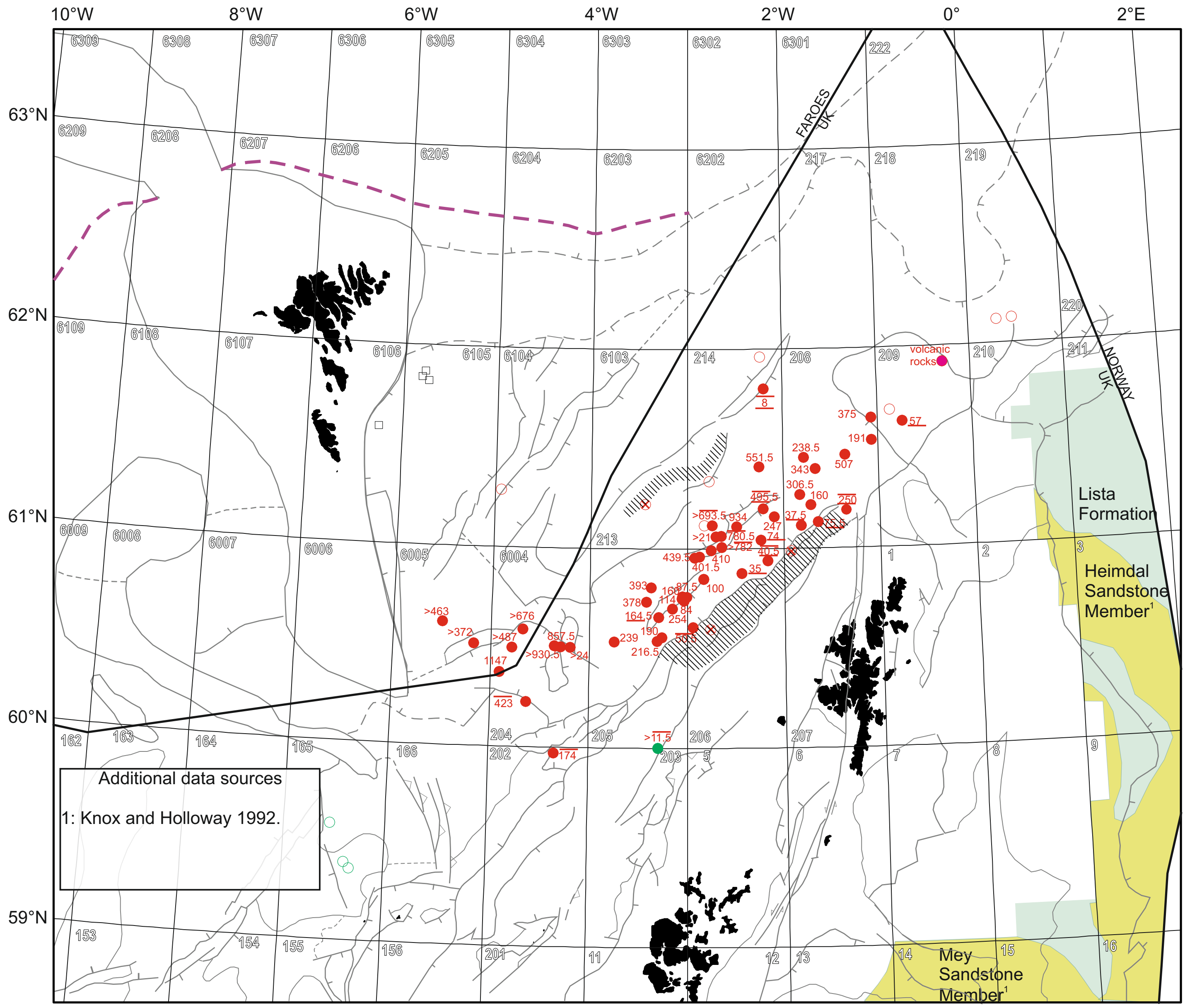


Figure 11 Section C: SW–NE seismic profile showing the the absence of the early Paleocene interval by erosion at a planar top Shetland Group unconformity above the flanks of the Rona High, with evidence of two NW-trending channels backfilled by younger Paleocene sediments. For location see Fig. 7. Seismic data by courtesy of Shell U. K. Limited.



Well thickness data

0 100 km

Distribution of Lista Formation

Distribution of Lista Formation sandstone members

Well with thickness data

112 Thickness of Ichron T zone; in metres

112 Thickness of Ichron T zone with bounding unconformity; in metres

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

Zone absent

BGS borehole; Dredge site

Well

} Blank where no information available for this zone

Area where zone is absent

Landward limit of seaward-dipping reflectors

T22 to T34

Selandian

(except T35)

Figure 12 Thickness of the T22-T34 (Selandian) interval in wells; includes all the Vaila Formation (except T35) in the Faroe-Shetland Basin; equivalent to the upper part of the Maureen Formation and the lower part of the Lista Formation in the North Sea. See text for details.

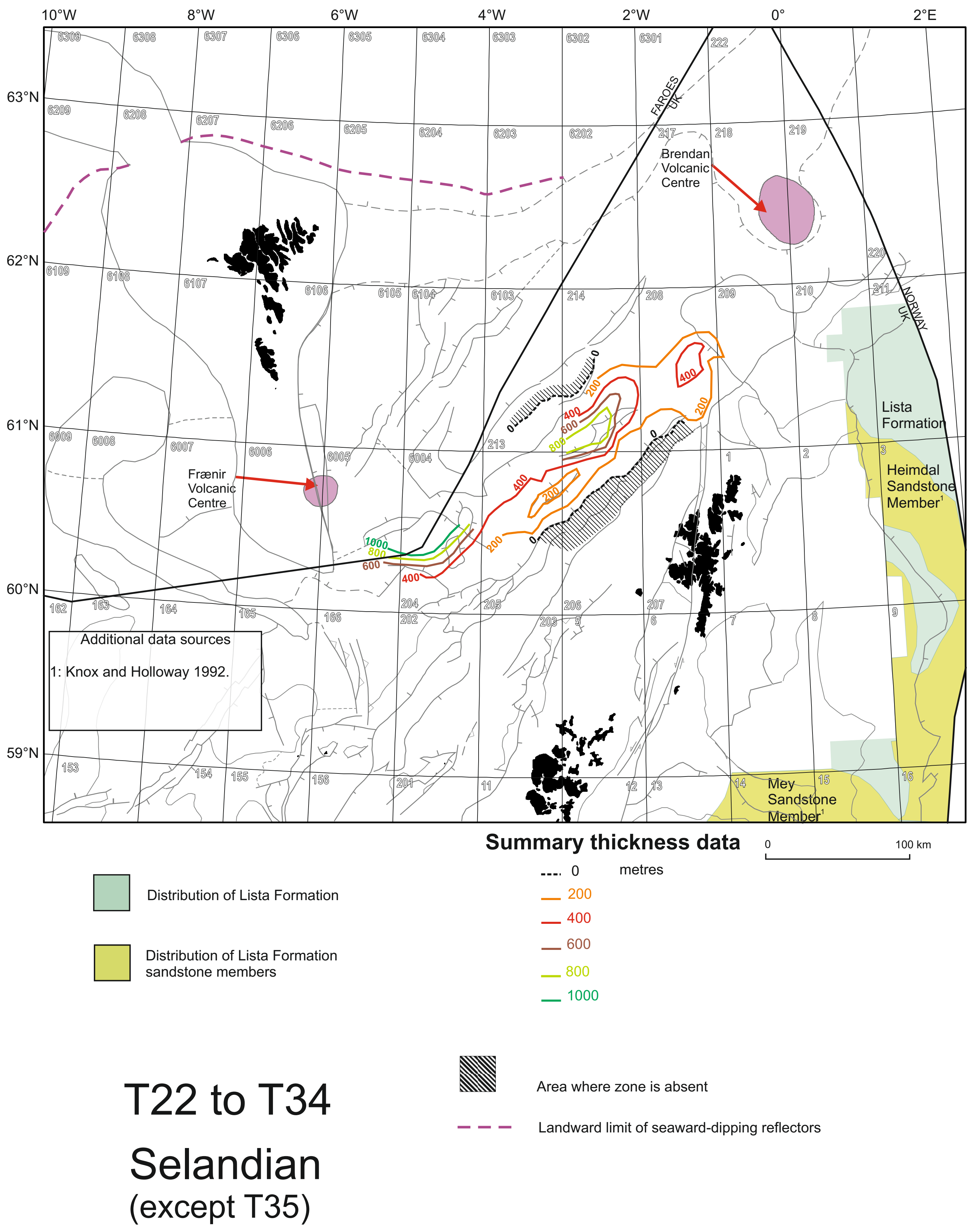


Figure 13 Contoured thickness of the T22-T34 (Selandian) interval in wells, includes all the Vaila Formation (except T35) in the Faroe-Shetland Basin; equivalent to the upper part of the Maureen Formation and the lower part of the Lista Formation in the North Sea. The locations of the possibly contemporaneous volcanic centres of Brendan and Frænir are also shown (from Ritchie et al. 2011). See text for details.

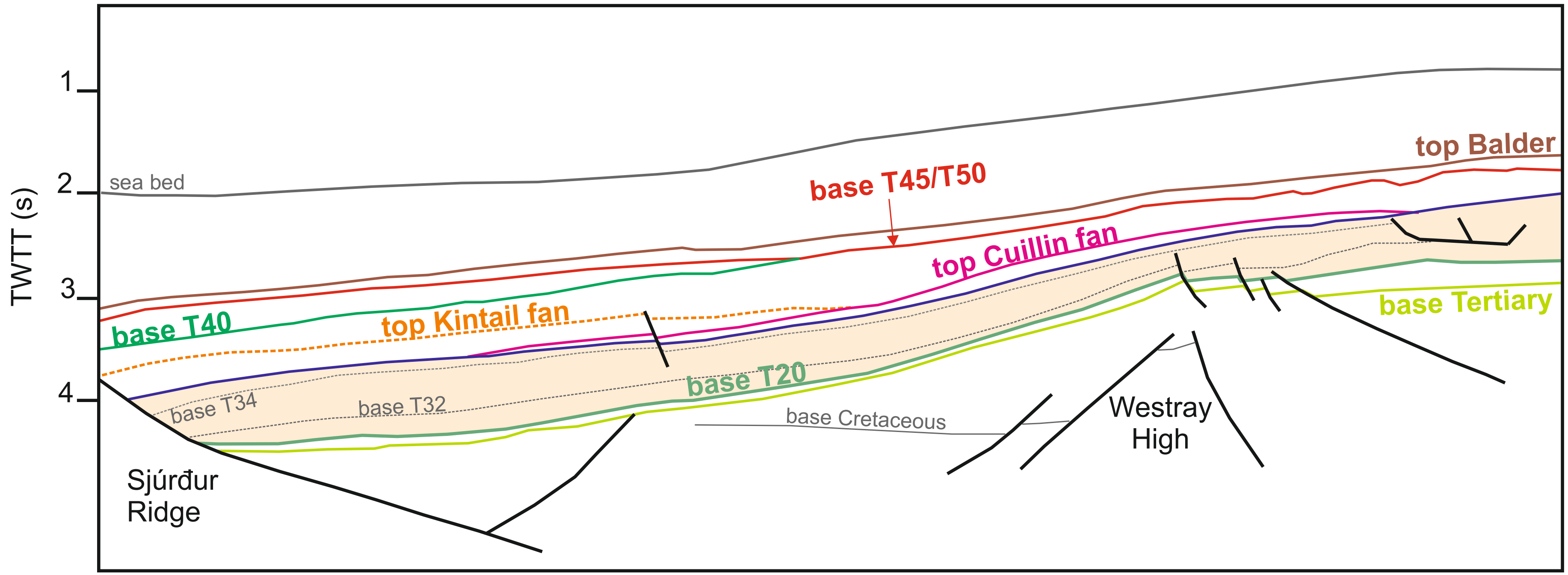


Figure 14 Generalised NW-SE geoseismic section across the Judd Sub-basin between the Westray High and the Sjúrđur Ridge (unlocated section, modified from Ebdon et al. 1995, their Fig. 7). The interval highlighted by the beige tone corresponds broadly to Vaila Formation sequences T22-T34.

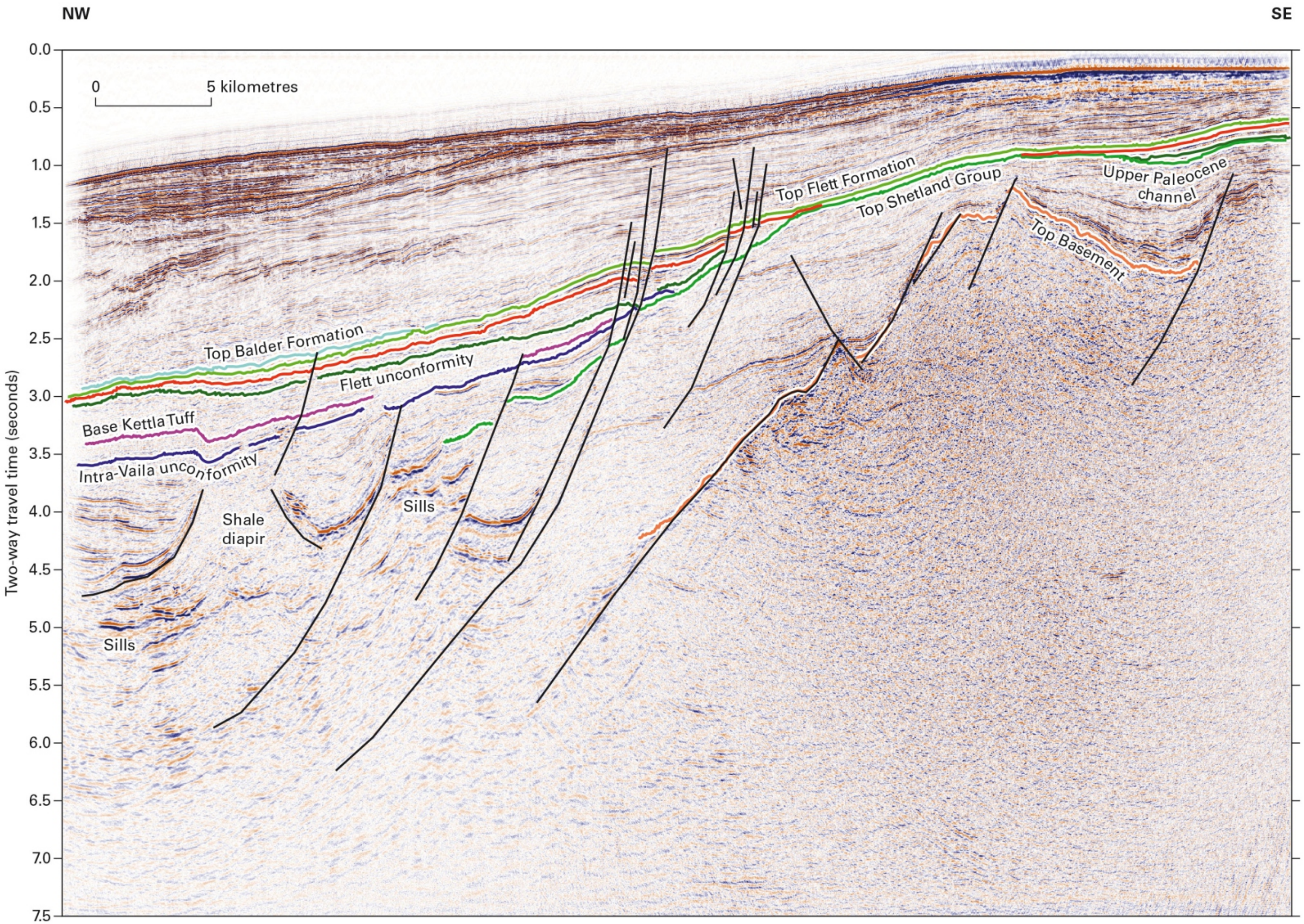


Figure 15 Section B: NW–SE seismic profile showing the effect of contemporaneous extension on the Vaila Formation alongside the Rona High, with a series of NW-dipping normal faults acting as growth faults during the deposition of the lower part of the Faroe Group. Thickness variation of the Vaila Formation within the basin is complicated by the mobilisation of the underlying shale-dominated Shetland Goup into shale diapirs, with the deposition of basinal fan sandstones focused in Selandian shale withdrawal synclines (or 'minibasins'). The lower Flett Formation shelf is shown in transverse section above the Flett unconformity at the margin of the basin. For location see Fig. 7. Seismic data by courtesy of Shell U. K. Limited.

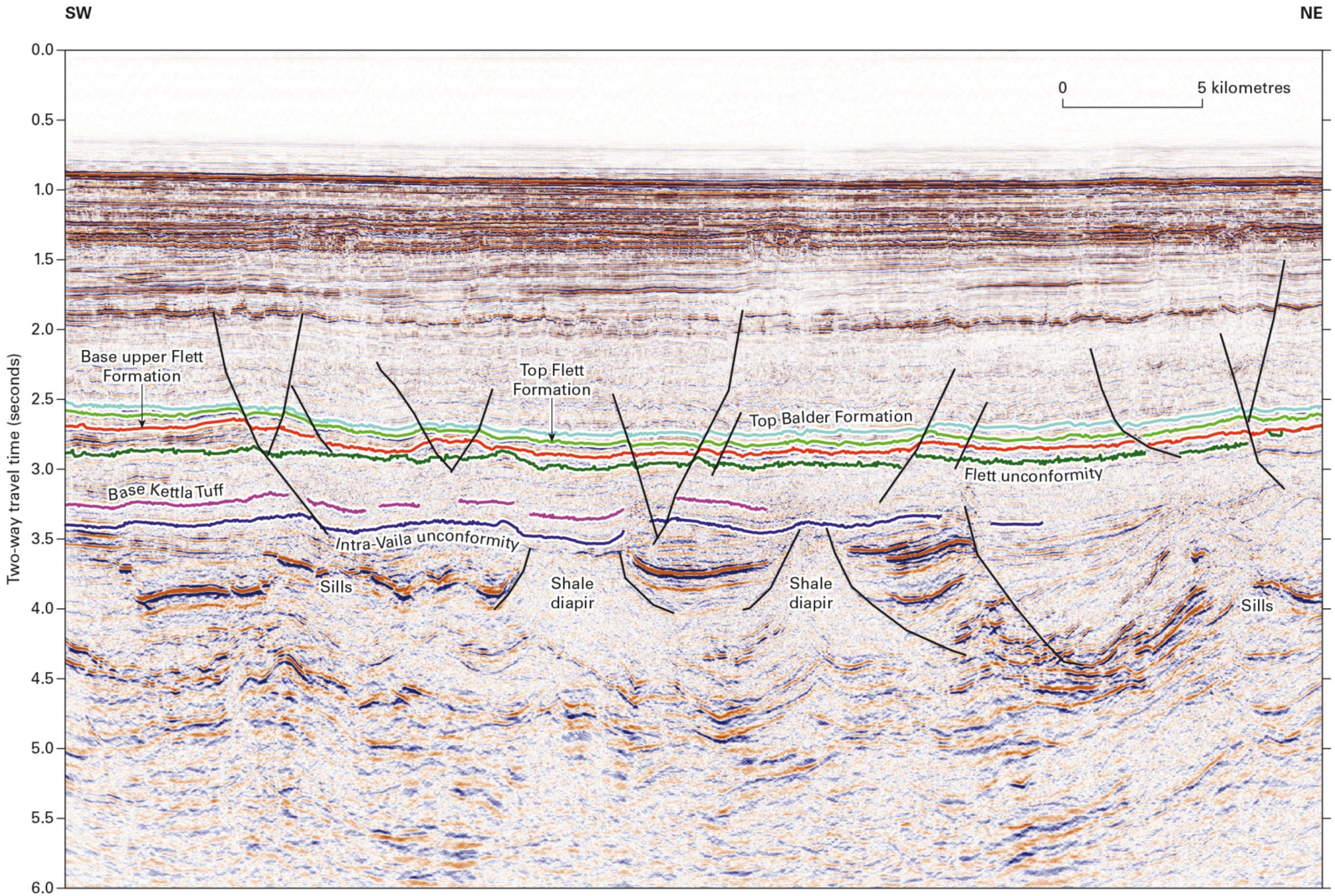


Figure 16 Section D: SW–NE seismic profile showing the effect of contemporaneous extension on the Vaila Formation in the Faroe-Shetland Basin. Mobilisation of the underlying shale-dominated Shetland Goup into shale diapirs focused the deposition of basinal fan sandstones in Selandian shale withdrawal synclines (or 'minibasins'). Fault activity and shale mobilisation both diminished, but did not die out entirely, towards the end of the Selandian in the UK sector. Above the Flett unconformity, the lower Flett Formation shelf thins from SW–NE. For location see Fig. 7. Seismic data by courtesy of Shell U. K. Limited.

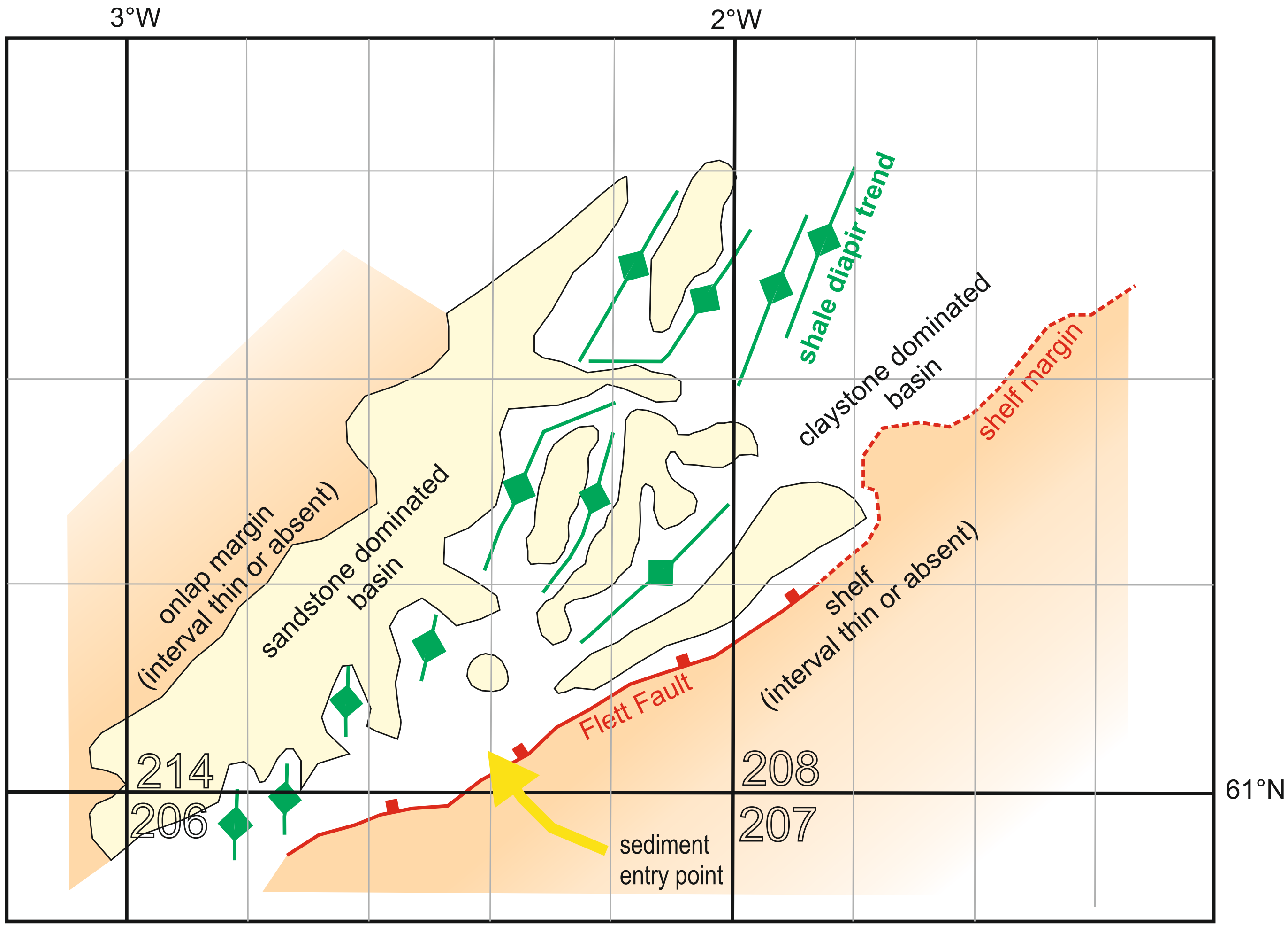


Figure 17 Summary geological map of the Flett Sub-basin, showing the distribution of T22-T25 sandstones and shale diapirs in the Vaila Formation (modified from Lamers and Carmichael 1999, their Fig. 13a).

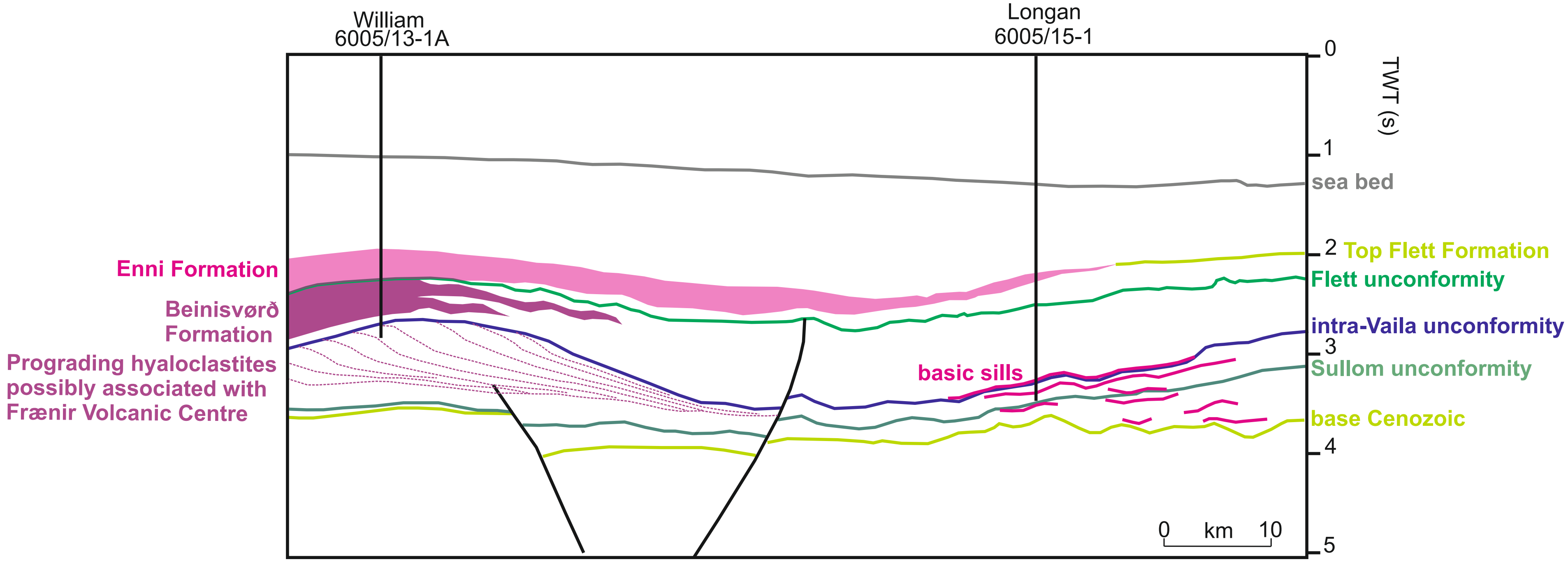


Figure 18 Geoseismic section between the William (6005/13-1A) and Longan (6005/15-1) wells (modified from Goodwin et al. 2009, their Fig. 4a), showing the key unconformities and their possible relationship with the volcanic successions in the Faroese sector. See text for details.

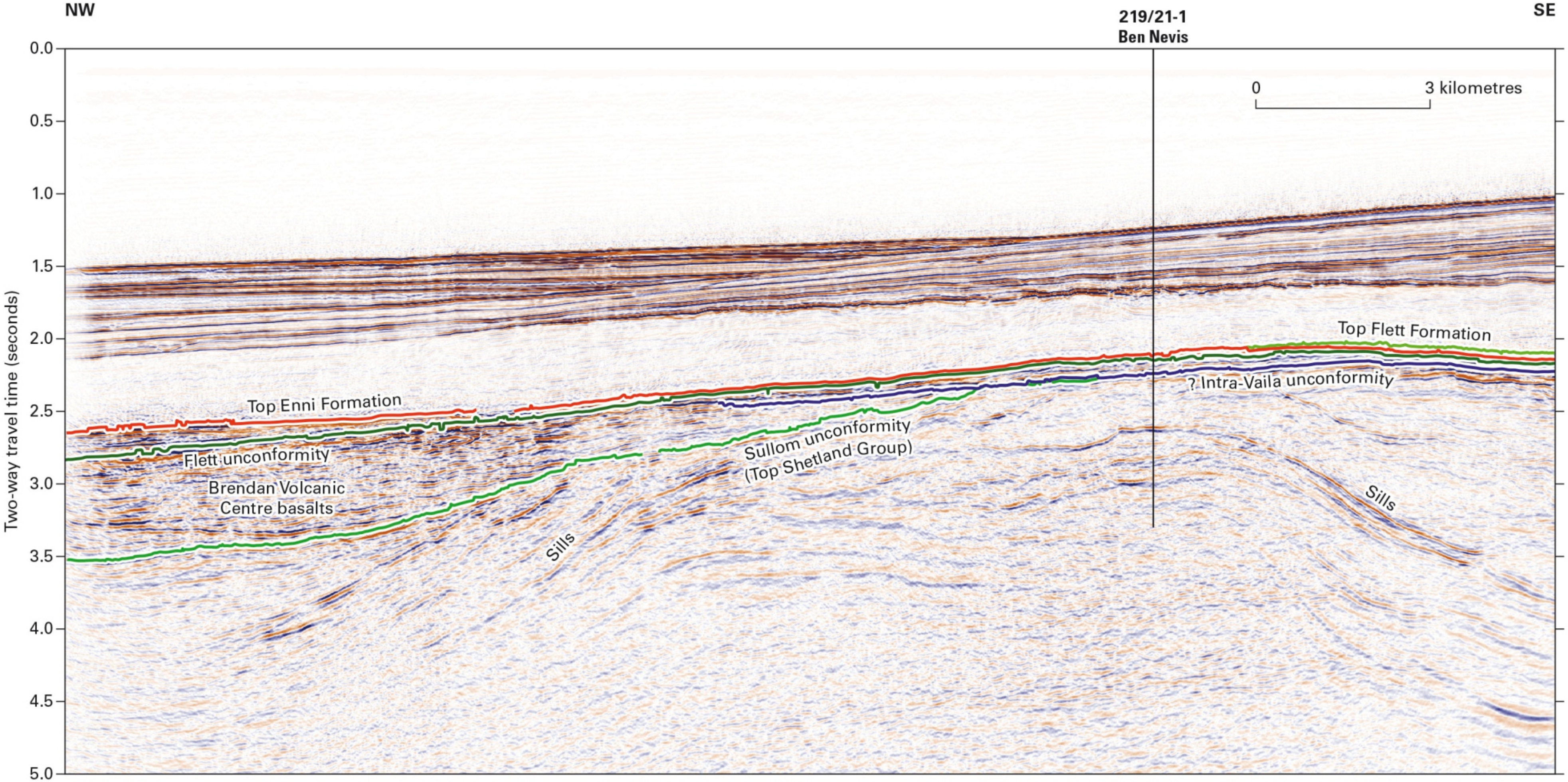


Figure 19 Section K: NW–SE seismic profile showing the lava shield associated with the Brendan Volcanic Centre. The basalts are preserved on the flanks of the Ben Nevis domal structure, which well 219/21-1 proved to consist of basic sills within the Shetland Group. Basalt lavas in the well are associated with a younger volcanic episode of T36 age (Jolley 2009), which rests unconformably on the Shetland Group in the SE and overlies the older lava shield to the NW. A thin carapace of Enni Formation basalts onlaps the volcanic centre from the NW. For location see Fig. 7. Seismic data by courtesy of Shell U. K. Limited.

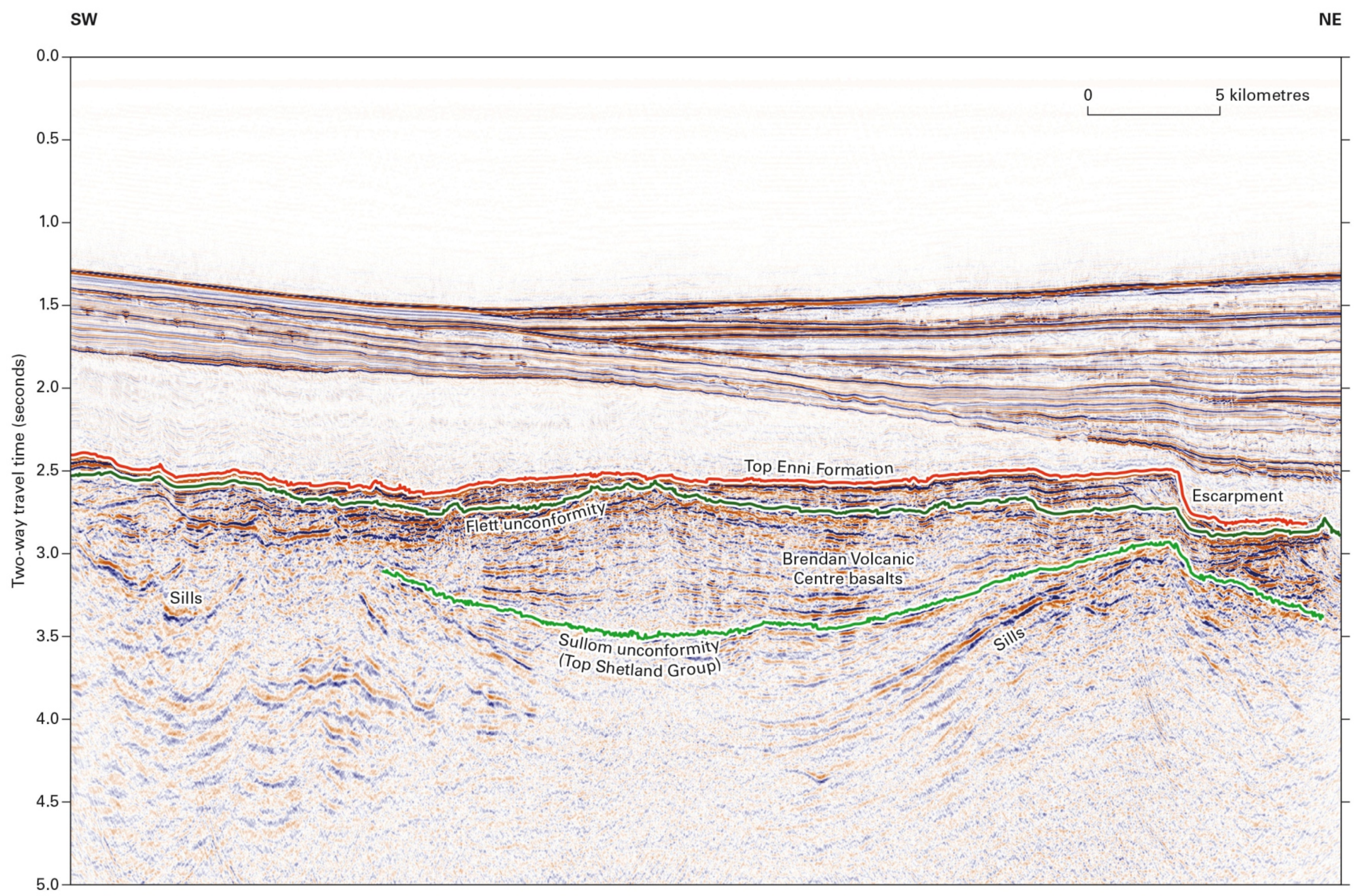
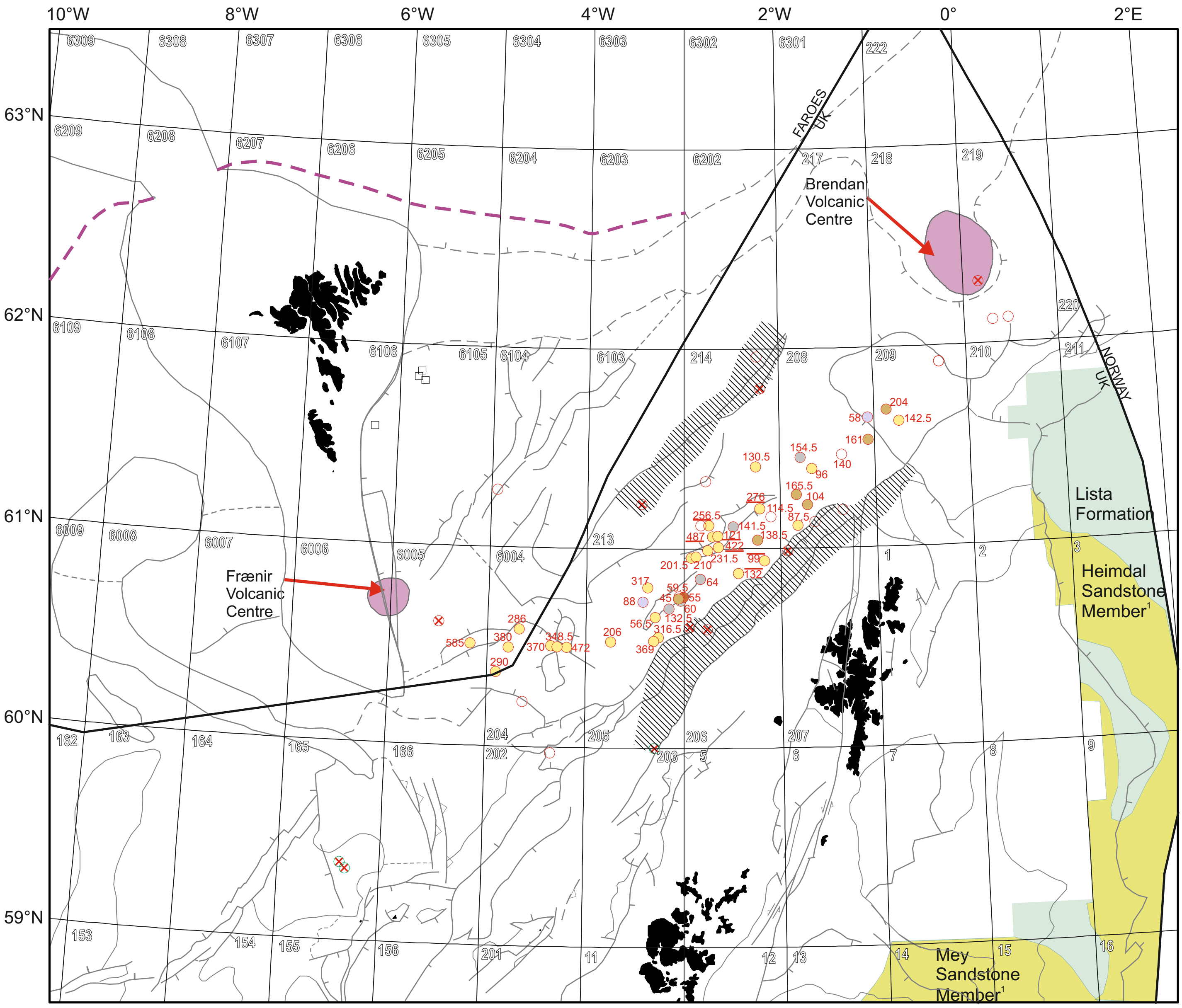


Figure 20 Section L: A SW-NE seismic profile on the flank of the Brendan Volcanic Centre showing that the inferred volcanic succession has a shield-like form, with the underlying top Shetland Group reflector defining a saucer-like depression. Basic sills show the effect of intra-Paleocene deformation, possibly associated with shale mobilisation. For location see Fig. 7. Seismic data by courtesy of Shell U. K. Limited.



0 100 km

Well 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 zone; in metres

112 Thickness of Ichron T zone with bounding unconformity; in metres

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

Zone absent

BGS borehole; Dredge site

Well

} Blank where no information available for this zone

Area where zone is absent

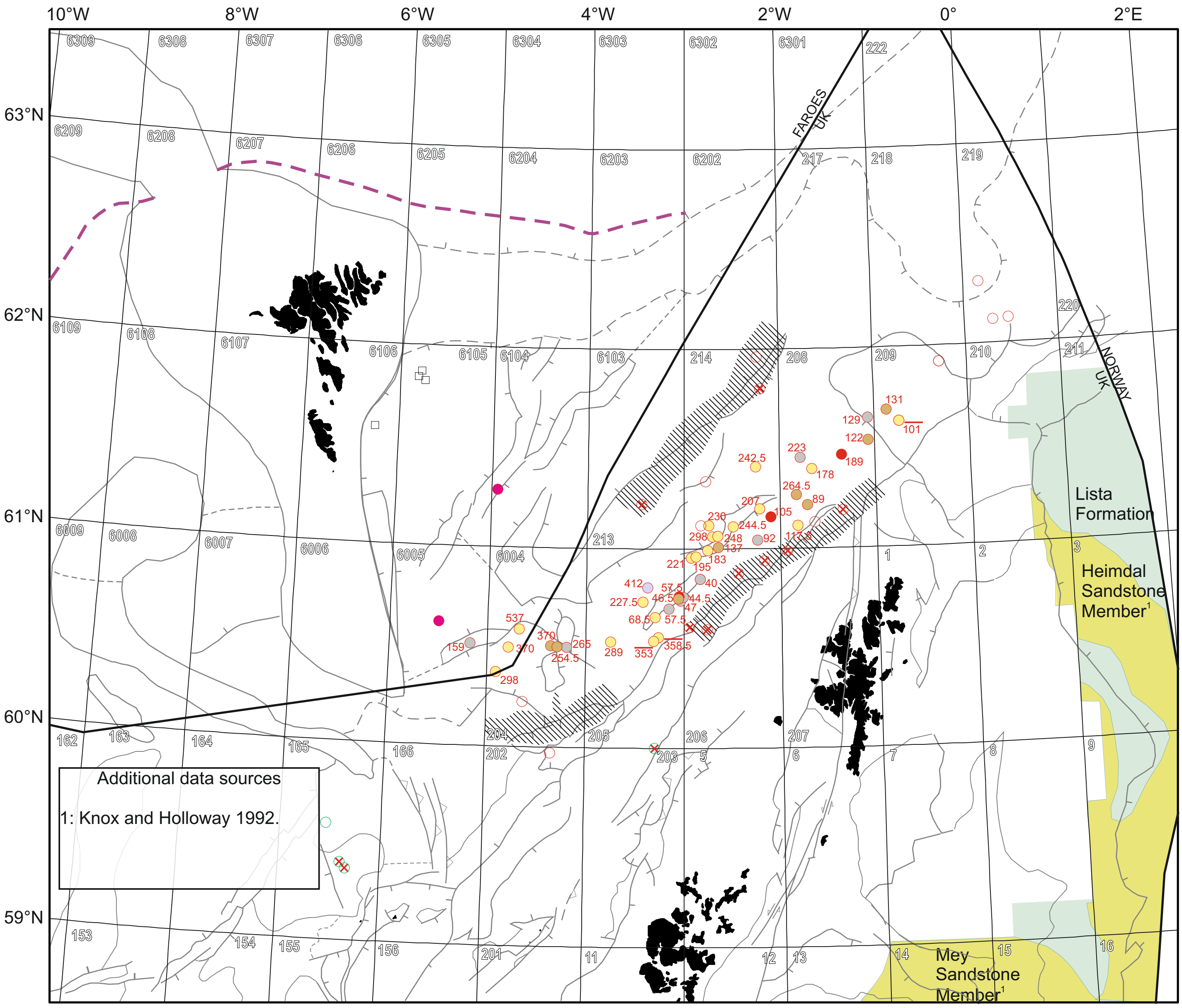
Landward limit of seaward-dipping reflectors

Distribution of Lista Formation

Distribution of Lista Formation sandstone members

T35
Late Selandian

Figure 21 Thickness of the T35 (Late Selandian) interval in wells; includes the uppermost Vaila Formation in the Faroe-Shetland Basin; equivalent to part of the Lista Formation in the North Sea. See text for details.



Well Lithology

0 — 100 km

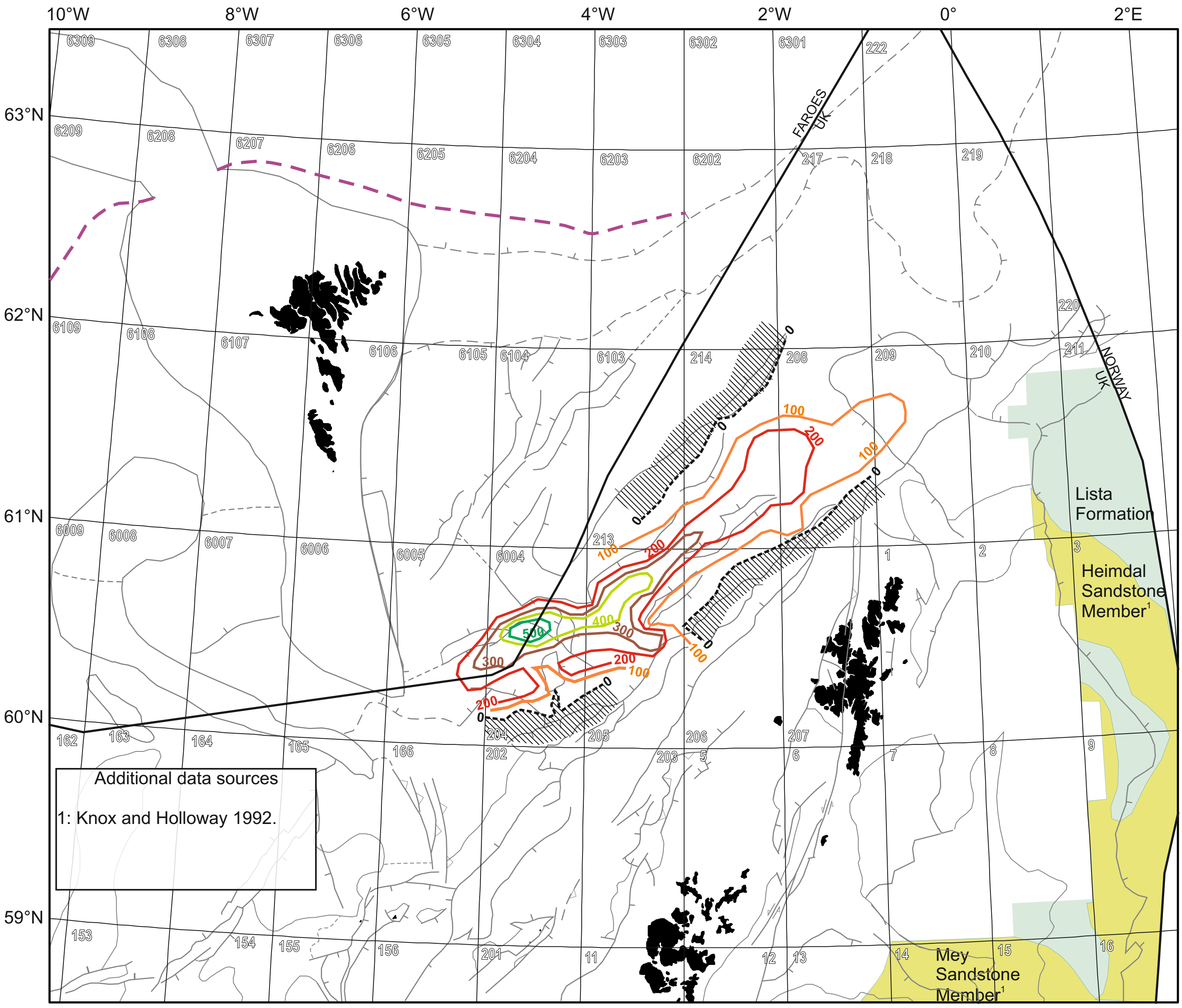
- Distribution of Lista Formation
- Distribution of Lista Formation sandstone members
- Sand and sandstones
- Interbedded sandstones,siltstones and claystones
- Siltstones
- Interbedded siltstones and claystones
- Claystones
- Tuffs and tuffaceous claystones with interbedded sandstones and siltstones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

Blank where no information available for this zone

- Area where zone is absent
- Landward limit of seaward-dipping reflectors

T36
Early Thanetian

Figure 22 Thickness of the T36 (Early Thanetian) interval in wells; includes the lower part of the Lamba Formation in the Faroe-Shetland Basin; equivalent to part of the Lista Formation in the North Sea. See text for details.



Summary thickness data

0 100 km

0 metres
100
200
300
400
500

Distribution of Lista Formation

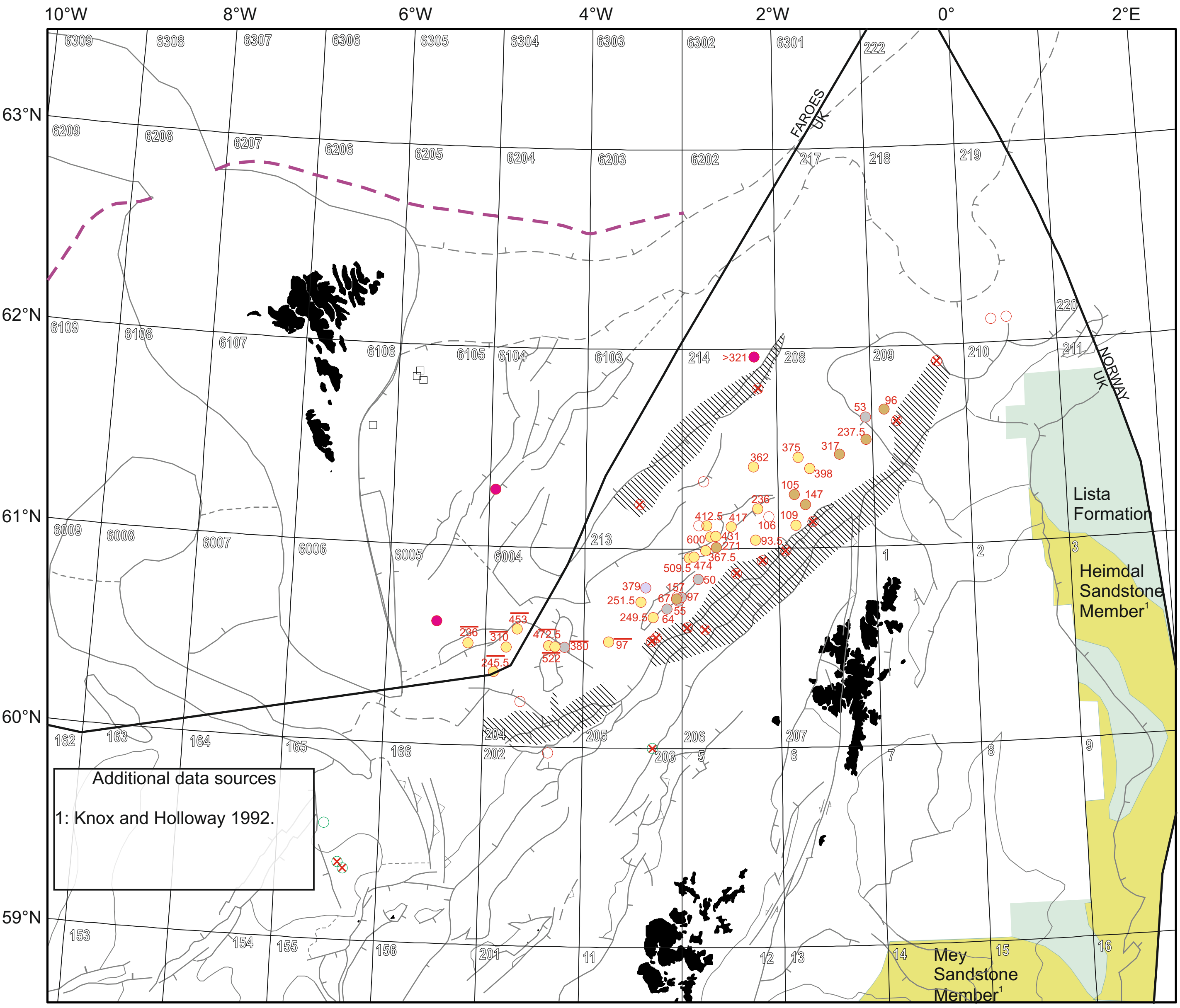
Distribution of Lista Formation sandstone members

Area where zone is absent

Landward limit of seaward-dipping reflectors

T36
Early Thanetian

Figure 23 Contoured thickness in wells of the T36 (Early Thanetian) interval; includes the lower part of the Lamba Formation in the Faroe-Shetland Basin; equivalent to part of the Lista Formation in the North Sea. See text for details.



Well 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 zone; in metres

112 Thickness of Ichron T zone with bounding unconformity; in metres

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

Zone absent

BGS borehole; Dredge site

Well

} Blank where no information available for this zone

Area where zone is absent

Landward limit of seaward-dipping reflectors

Distribution of Lista Formation

Distribution of Lista Formation sandstone members

T38
Mid Thanetian

Figure 24 Thickness of the T38 (Mid Thanetian) interval in wells; includes the upper part of the Lamba Formation in the Faroe-Shetland Basin; equivalent to the upper part of the Lista Formation in the North Sea. See text for details.

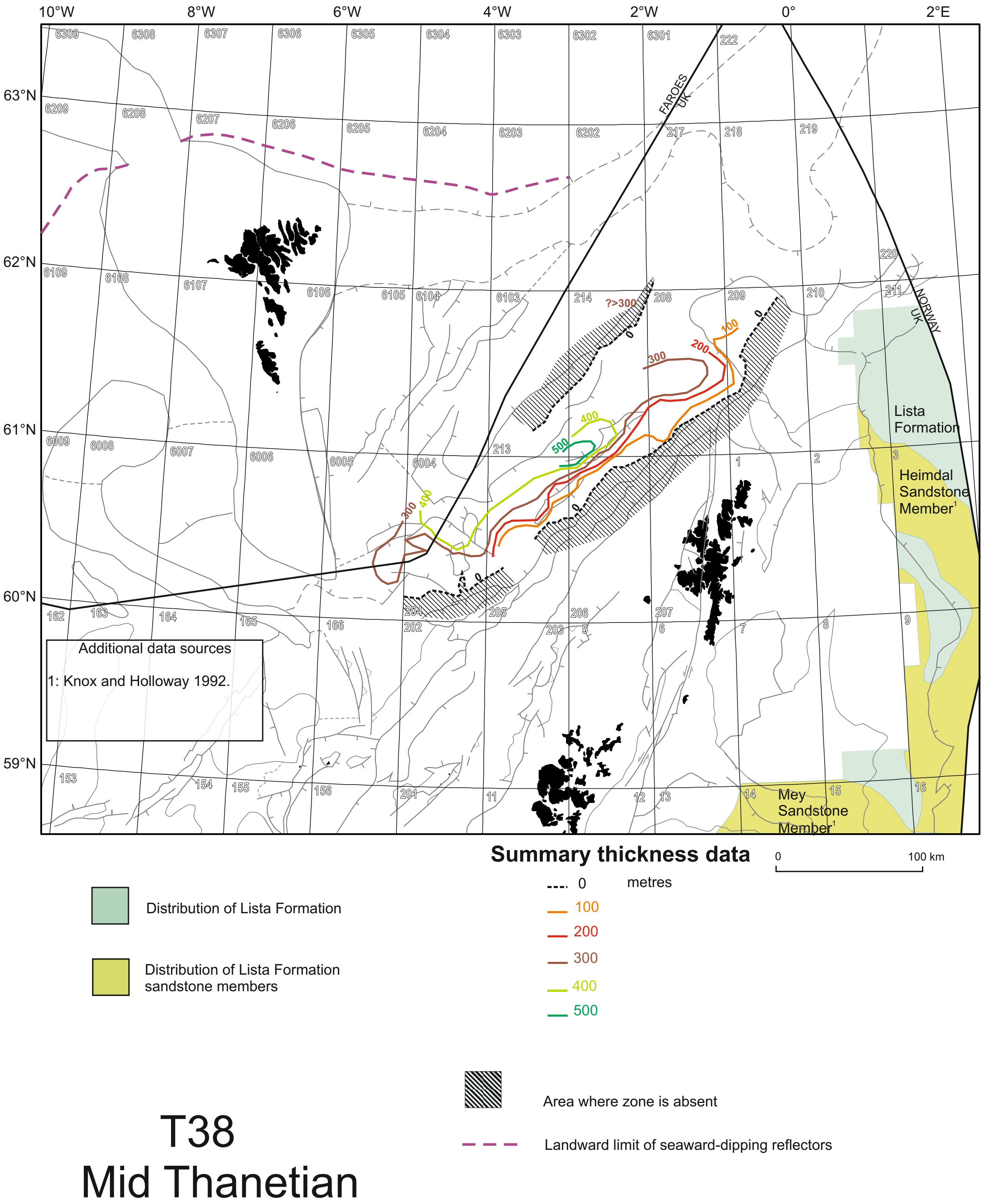


Figure 25 Contoured thickness of the T38 (Mid Thanetian) interval in wells; includes the upper part of the Lamba Formation in the Faroe-Shetland Basin; equivalent to the upper part of the Lista Formation in the North Sea. See text for details.

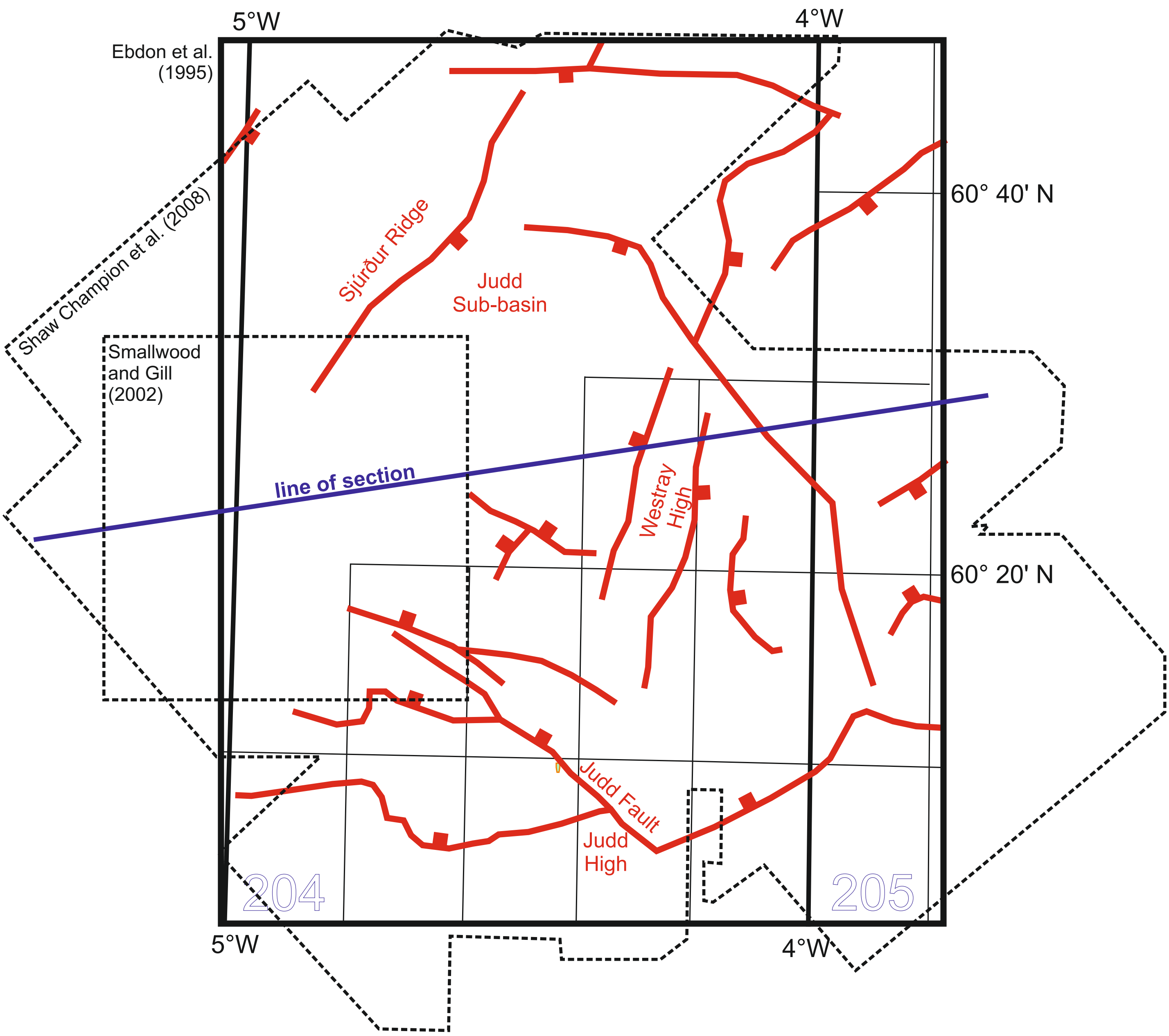


Figure 26 Structure of the Judd Sub-basin, showing the extent of Ebdon et al.'s (1995) study area (solid black rectangle), and the limits of 3D seismic coverage in Smallwood and Gill (2002) (dashed square) and Shaw Champion et al. (2008) (dashed polygon). The faults are modified from Ebdon et al. (1995, their Fig. 10) and the structural nomenclature is from Ritchie et al. (2011). The blue line shows the location of the geoseismic section in Shaw Champion et al. (2008) (see Fig. 27).

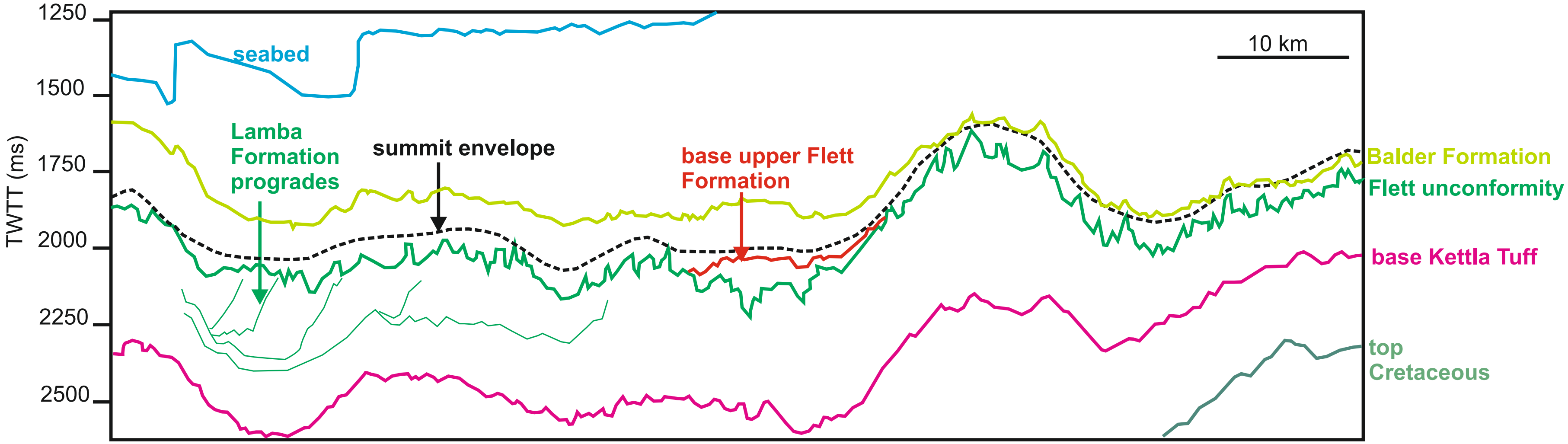


Figure 27 Geoseismic section across the Judd Sub-basin (modified from Shaw Champion et al. 2008, their Fig. 4). For location see Fig. 26. The section shows the western set of prograding reflectors in the upper part of the Lamba Formation, which are displayed in map view in Fig. 28. The Flett unconformity marks the top of the Lamba Formation and the base of the Kettla Tuff is equivalent to the top of the Vaila Formation. The Balder Formation reflector shows the effect of significant post- Early Eocene deformation, which is modelled by Shaw Champion et al. (2008) using a smoothed regional surface (the summit envelope). See text for discussion.

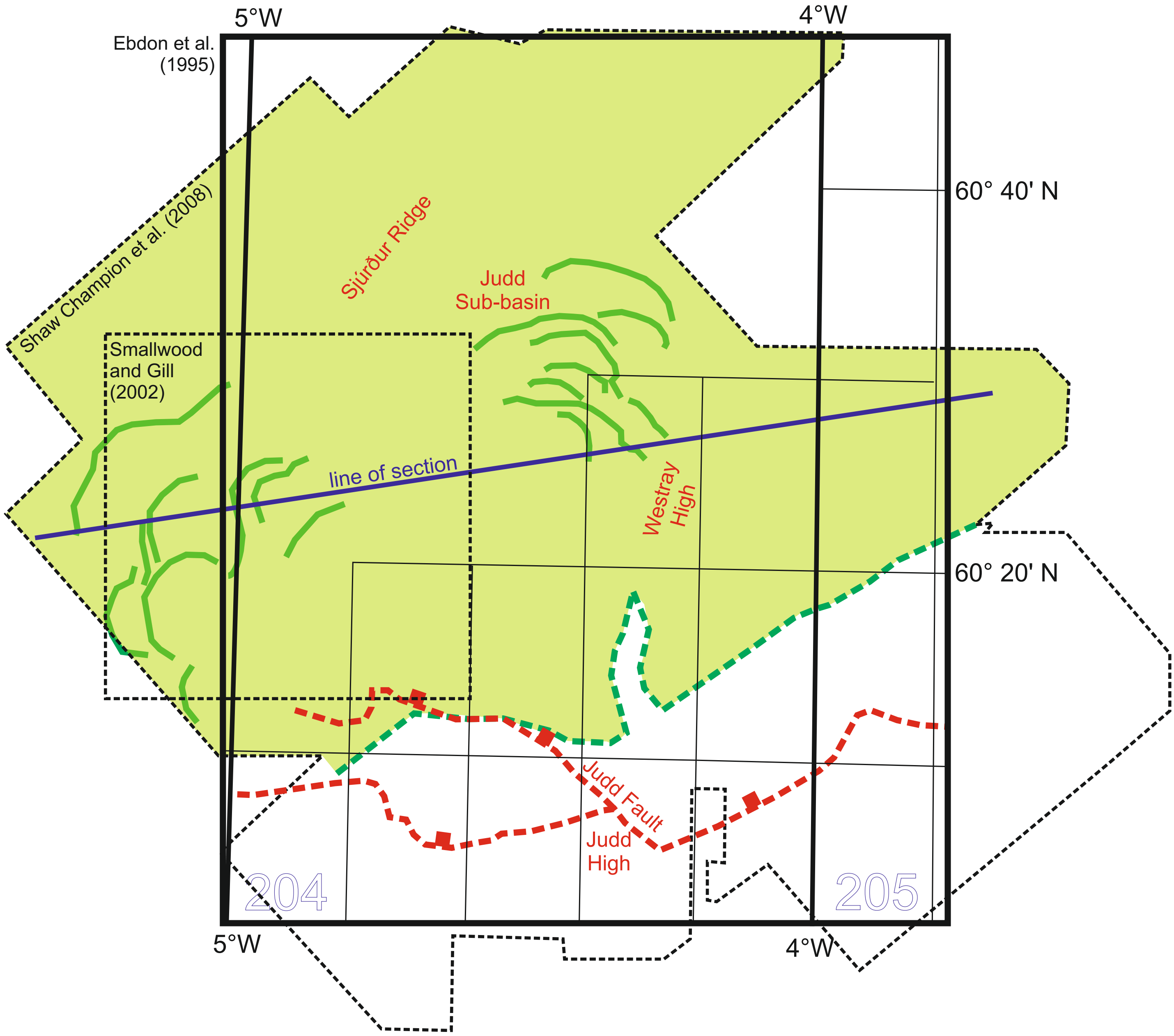


Figure 28 Distribution of the Lamba Formation (pale green tone) in the Judd Sub-basin, showing the orientation of clinoforms (green lines) in distinct northerly and westerly prograding lobes (modified from Shaw Champion et al. 2008, their Fig. 5a and Ebdon et al. 1995, their Fig. 10). Selected structural elements are taken from Ritchie et al. (2011). The labelled polygons show the extent of the data used by different authors. The line of section marks the location of Fig. 27.

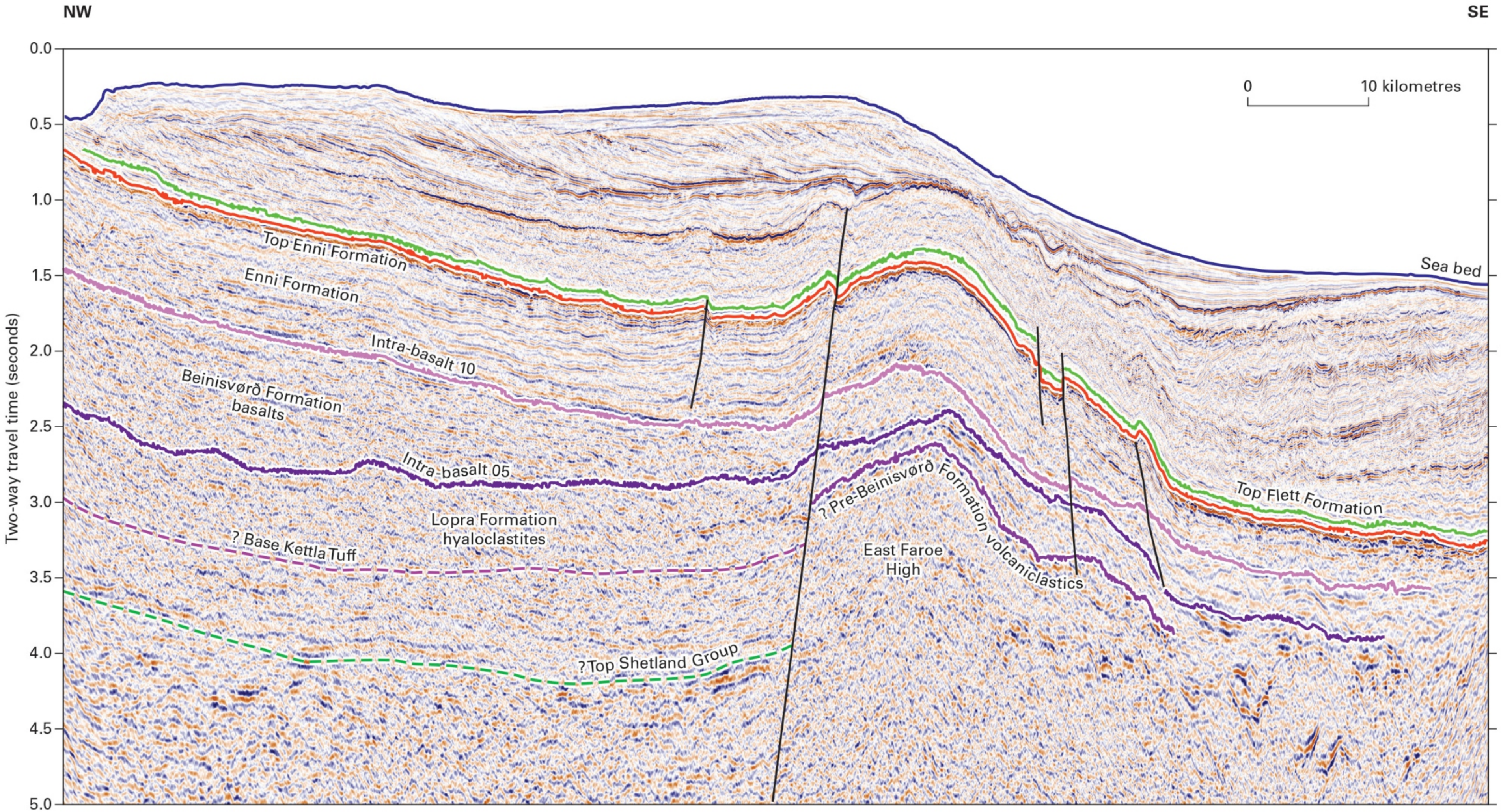


Figure 29 Section I: NW–SE seismic profile across the East Faroe High showing a complete section through the Faroe Islands Basalt Group. In the NW of the profile, a deep interval with a trace of sigmoidal reflections between 2.5 and 3.0 s TWTT is interpreted as prograding Lopra Formation hyaloclastites. The top of the prograding succession is characterised by a poorly-defined regional seismic marker (intra-basalt 05), which separates the inferred hyaloclastites from a more gently-dipping succession of overlying reflections, the deeper of which may correspond to the terrestrial basalts of the Beinisvørđ Formation onshore. The top of the Beinisvørđ Formation is defined by a regional seismic marker (Intra-basalt 10), which is correlated with the Flett unconformity in the UK sector and is overlain widely by the Enni Formation basalts, and locally by volcanic rocks of the Malinstindur Formation. Subsequent deformation of the basalt pile and the younger Cenozoic section is partly contolled by reactivation of faults bounding the East Faroe High. For location see Fig. 7. Seismic data by courtesy of WesternGeco.

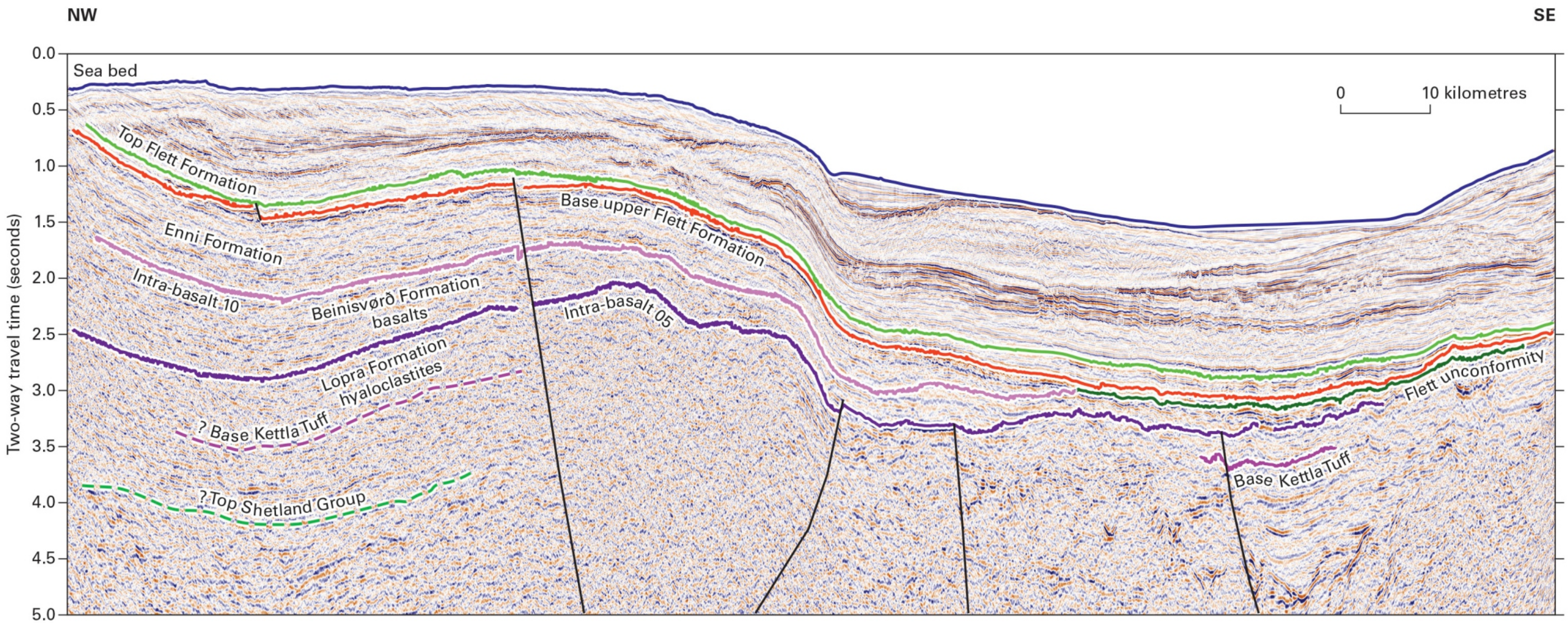


Figure 30 Section G: NW–SE seismic profile showing the Faroe Islands Basalt Group alongside the Faroe Platform. The succession is comparable to Section I (Fig. 29), but the shows the greater effect of uplift and deformation of the volcanic succession in the SW part of Quadrant 6105. Towards the SE, the intra-basalt 10 sesimic reflector is shown to pass into the Flett unconformity in the UK sector. For location see Fig. 7. Seismic data by courtesy of WesternGeco.

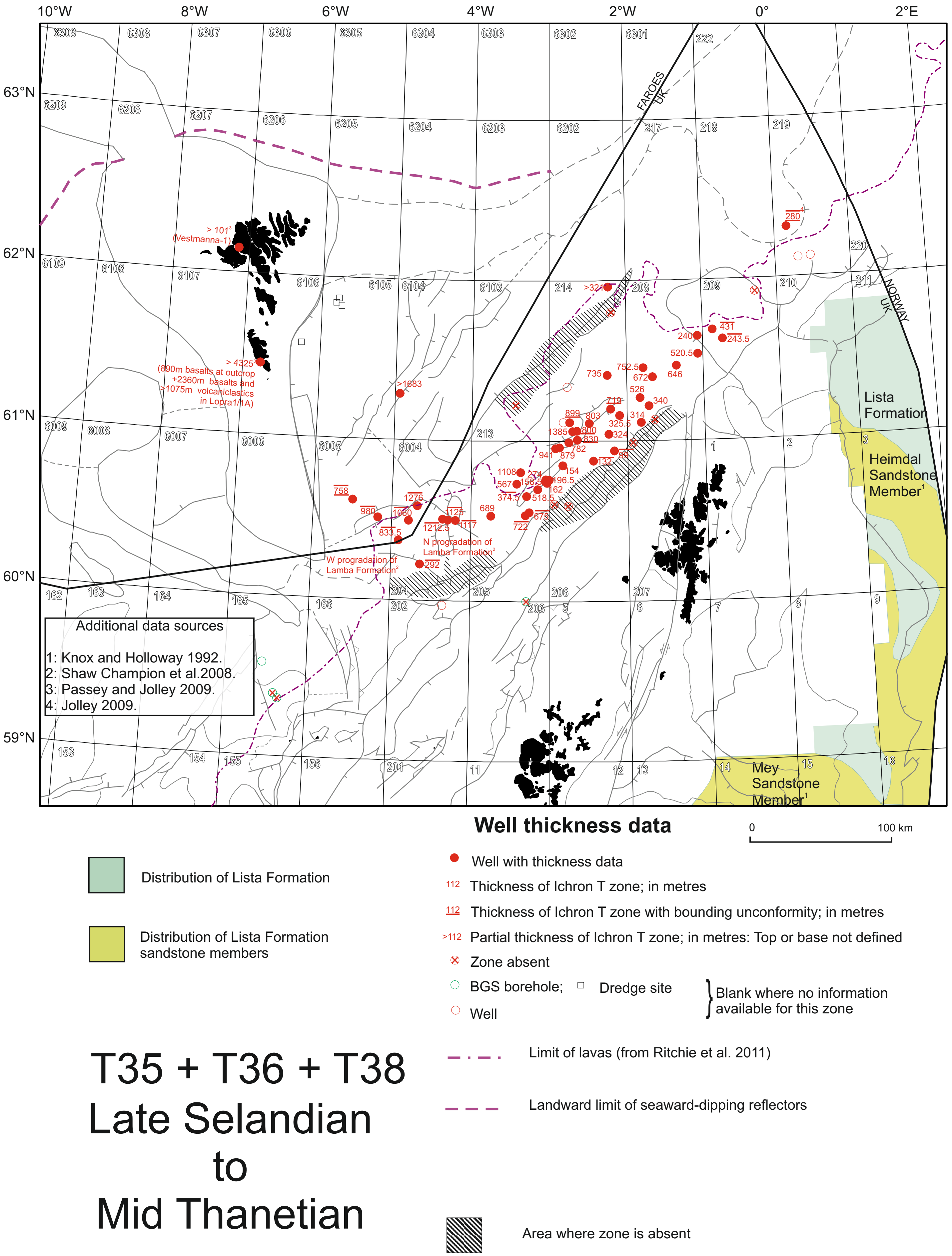


Figure 31 Combined thickness of the T35,T36 and T38 (Late Selandian to Mid Thanetian) intervals in wells; includes the Lamba Formation and upper part of the Vaila Formation in the Faroe-Shetland Basin and the Beinisvørð and Lopra formations on the Faroe Platform. See text for details.

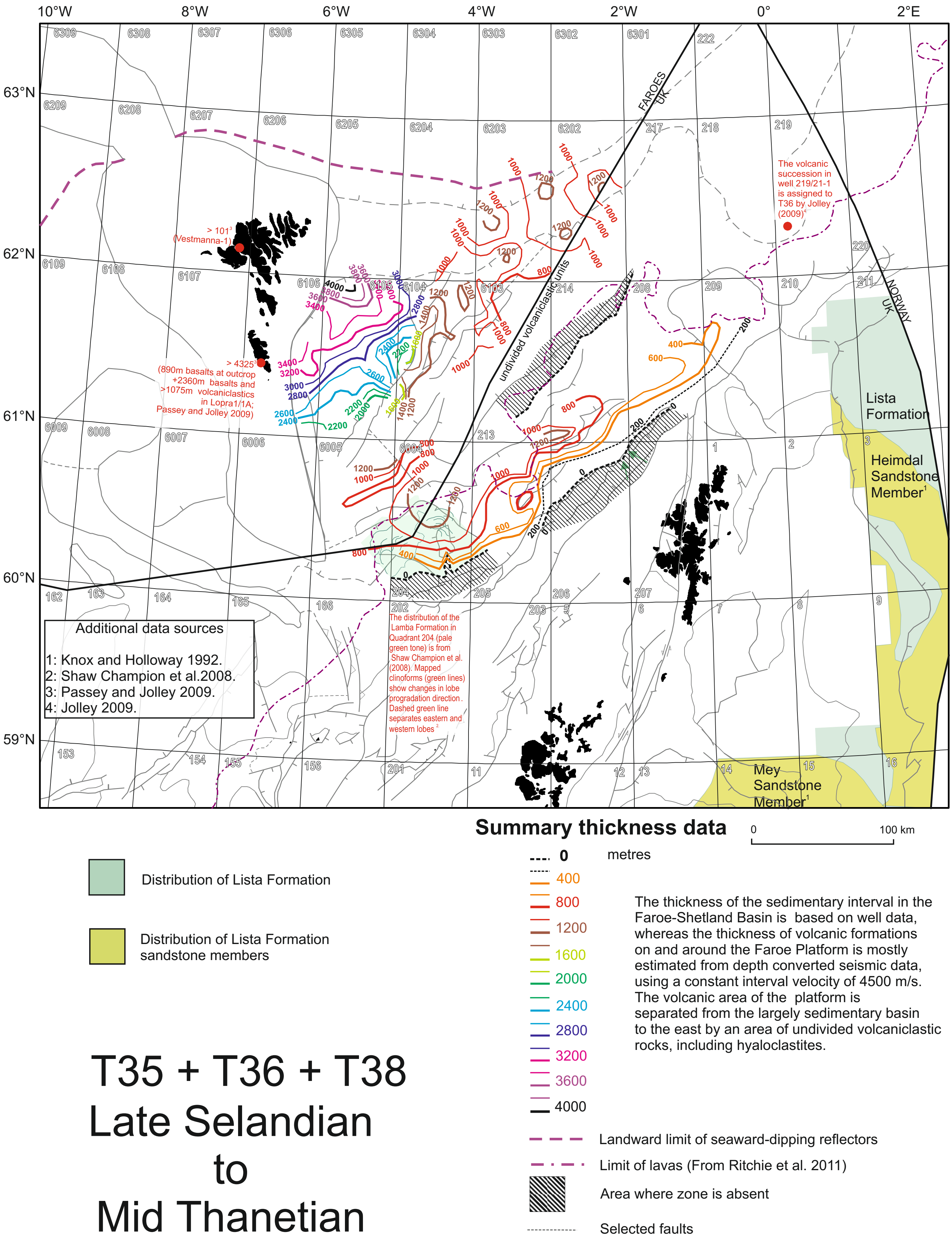


Figure 32 Contoured combined thickness of the T35, T36 and T38 (Late Selandian to Mid Thanetian) intervals; includes the Lamba Formation and upper part of the Vaila Formation in the Faroe-Shetland Basin and the Beinisvørð and Lopra formations on the Faroe Platform. See text for details.

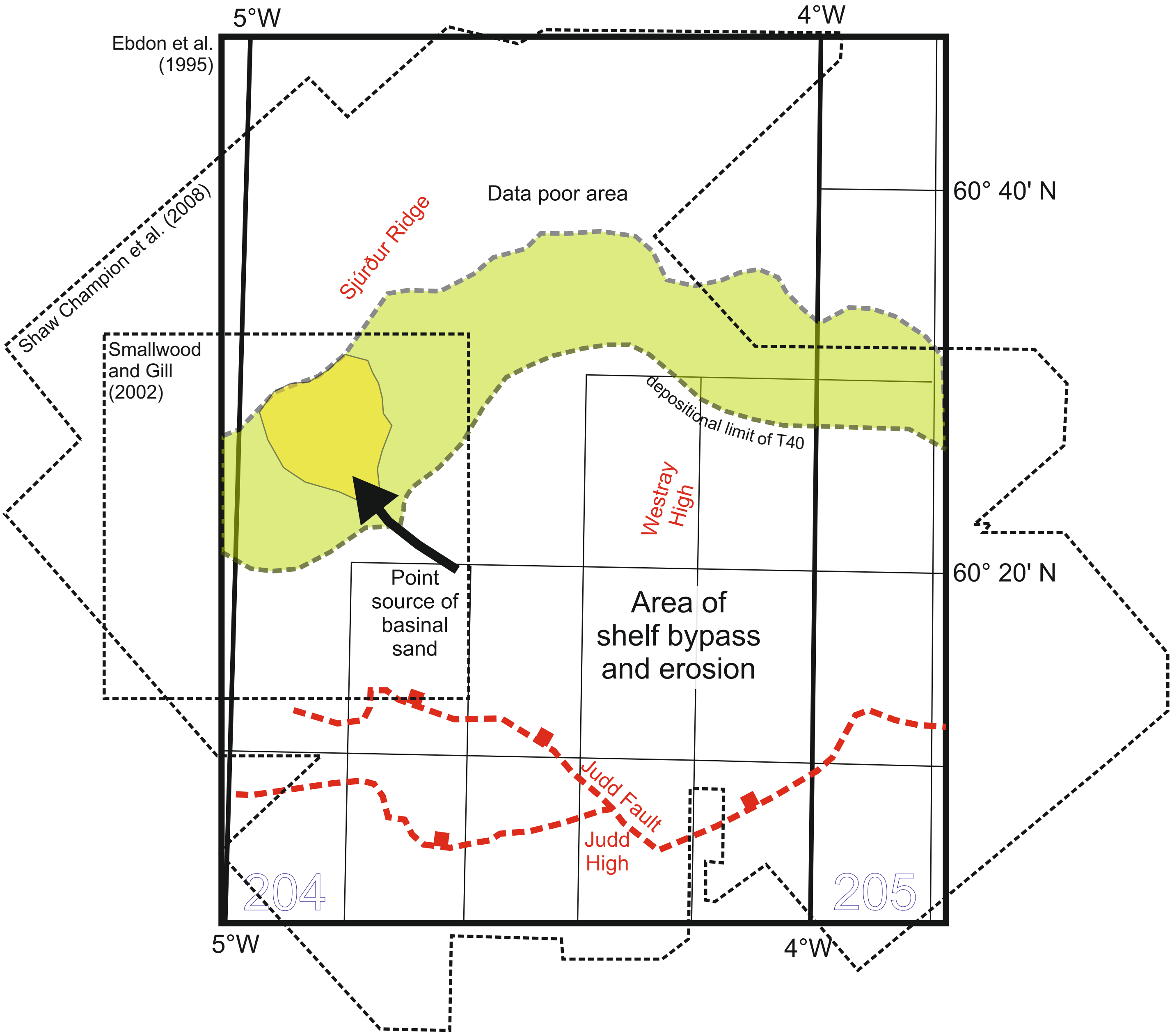


Figure 33 The Judd Sub-basin, according to the 2D seismic interpretation of Ebdon et al. (1995), showing the distribution of their T40 sequence (green tone) and a point sourced basinal sandstone (yellow tone). The southern part of Quadrant 204 is mapped as an area of shelf bypass and erosion. The dashed square and polygon show the extent of later 3D seismic coverage.

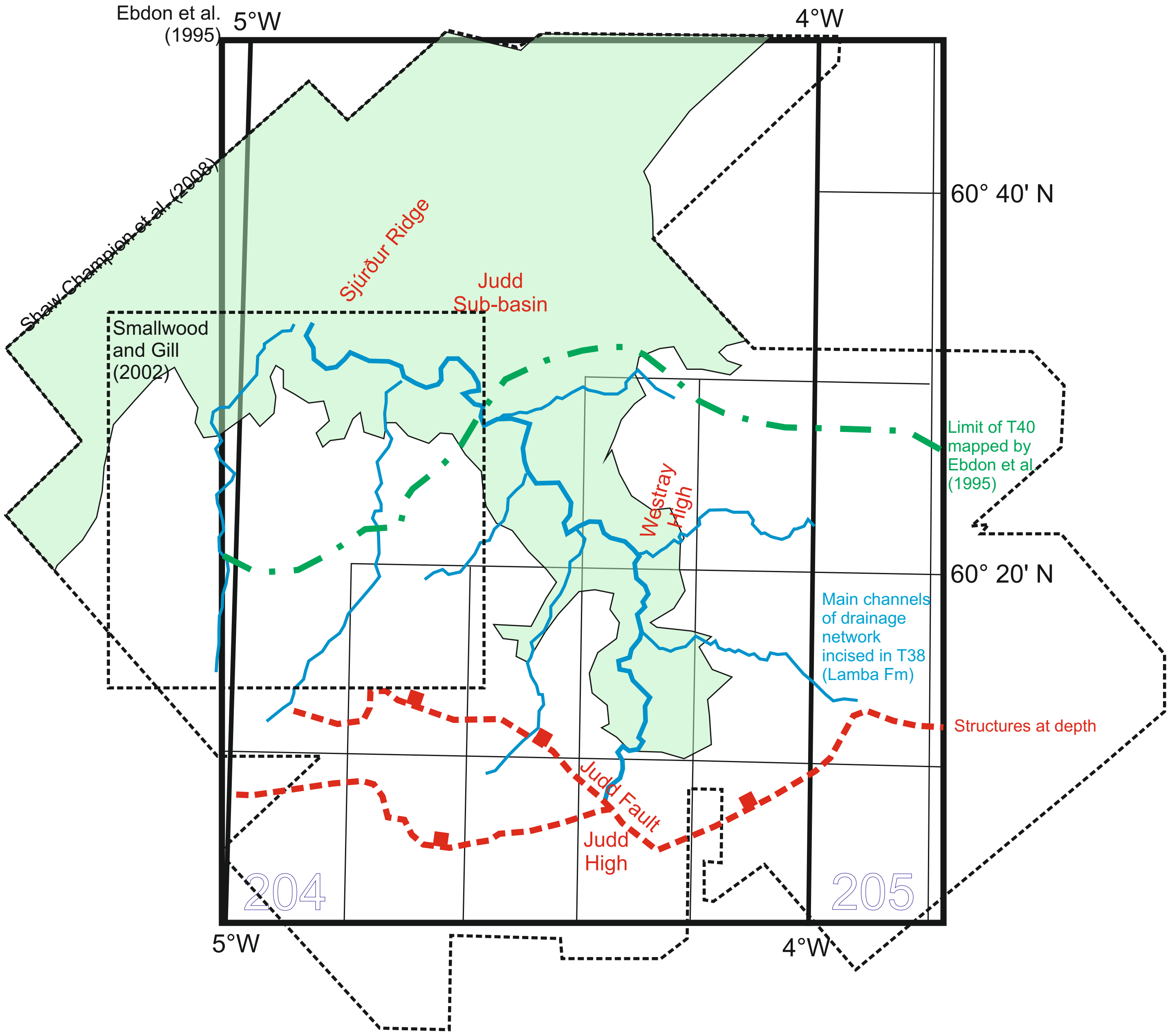


Figure 34 Comparison of the distribution of sequence T40 in the Judd Sub-basin, obtained using 3D seismic data (pale green tone; modified from Shaw Champion et al. 2008, their Fig. 5b), with the previous limit of the sequence interpreted on 2D seismic data (green dots and dashes; from Ebdon et al. 1995, their Fig. 10). The map of dendritic drainage (blue lines) at base Flett Formation level is simplified from Hartley et al. (2011).

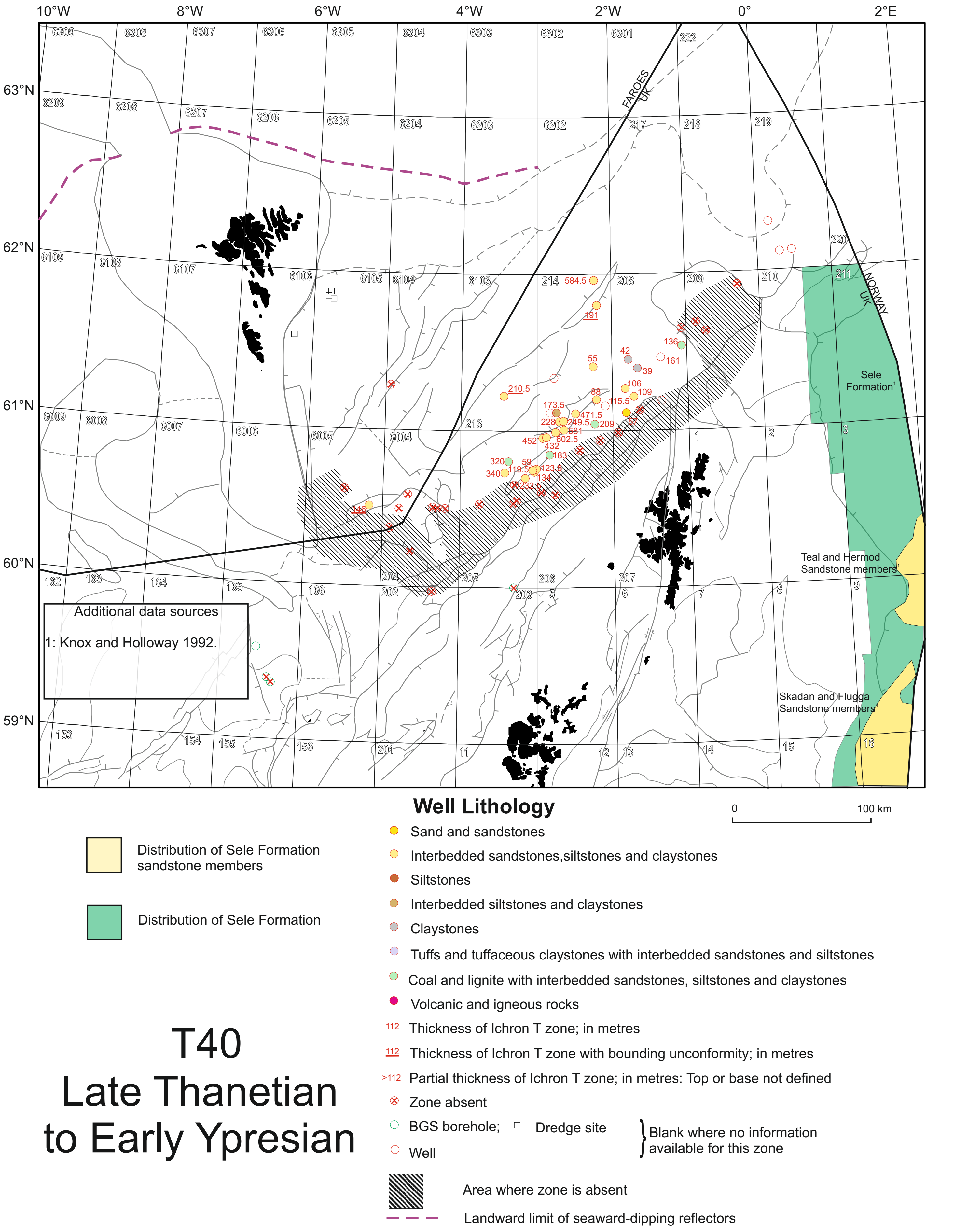


Figure 35 Thickness of the T40 (Late Thanetian-Early Ypresian) interval in wells; includes the lower Flett Formation in the Faroe-Shetland Basin; equivalent to part of the Sele Formation in the North Sea. Distribution and thickness in Quadrants 204 and 6004 are provisionally adjusted to comply with the 3D seismic interpretation of Shaw Champion et al. (2008).

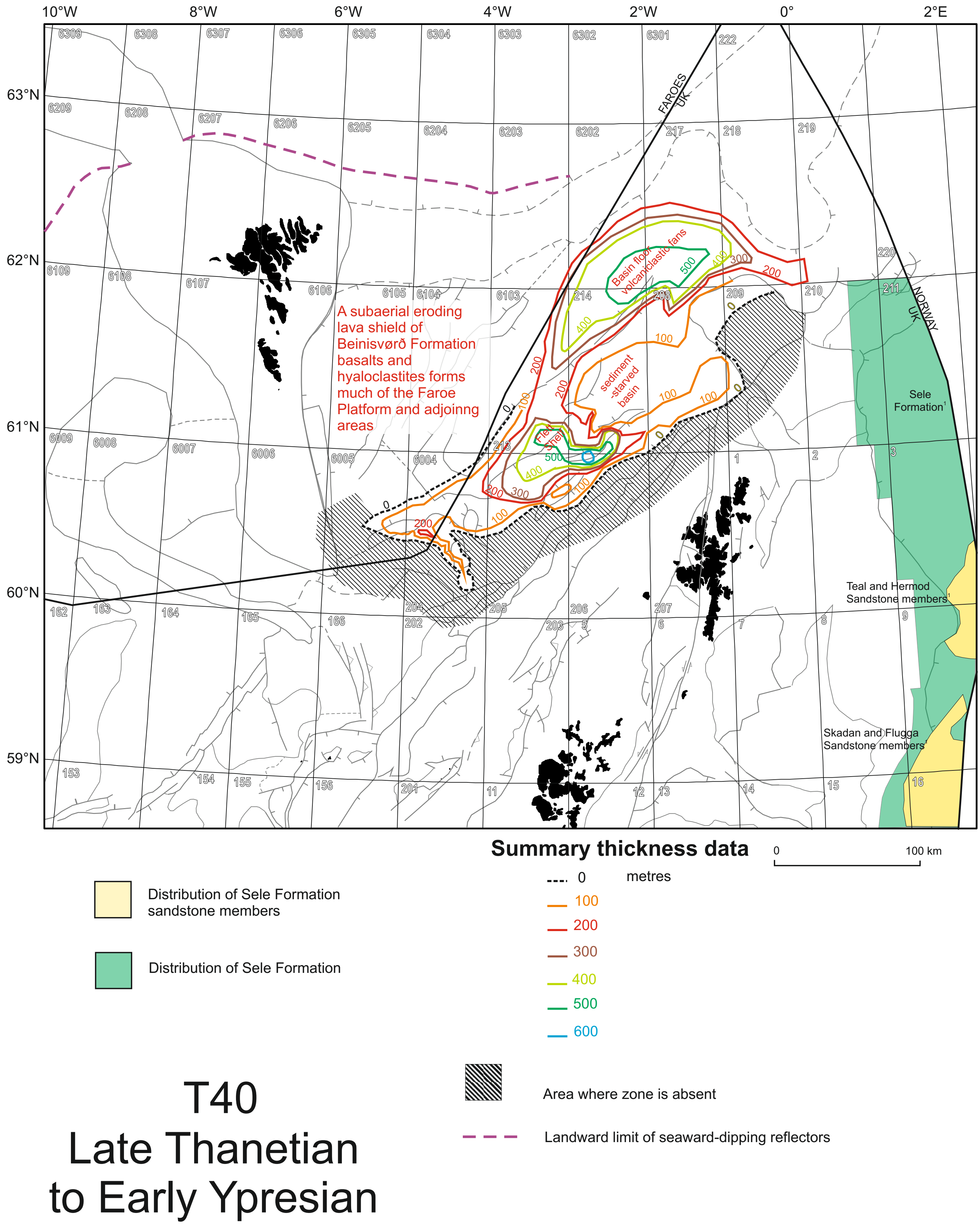


Figure 36 Contoured thickness of the T40 (Late Thanetian-Early Ypresian) interval in wells; includes the lower Flett Formation in the Faroe-Shetland Basin; equivalent to part of the Sele Formation in the North Sea. Distribution and thickness in Quadrants 204 and 6004 are provisionally adjusted to comply with the 3D seismic interpretation of Shaw Champion et al. (2008).

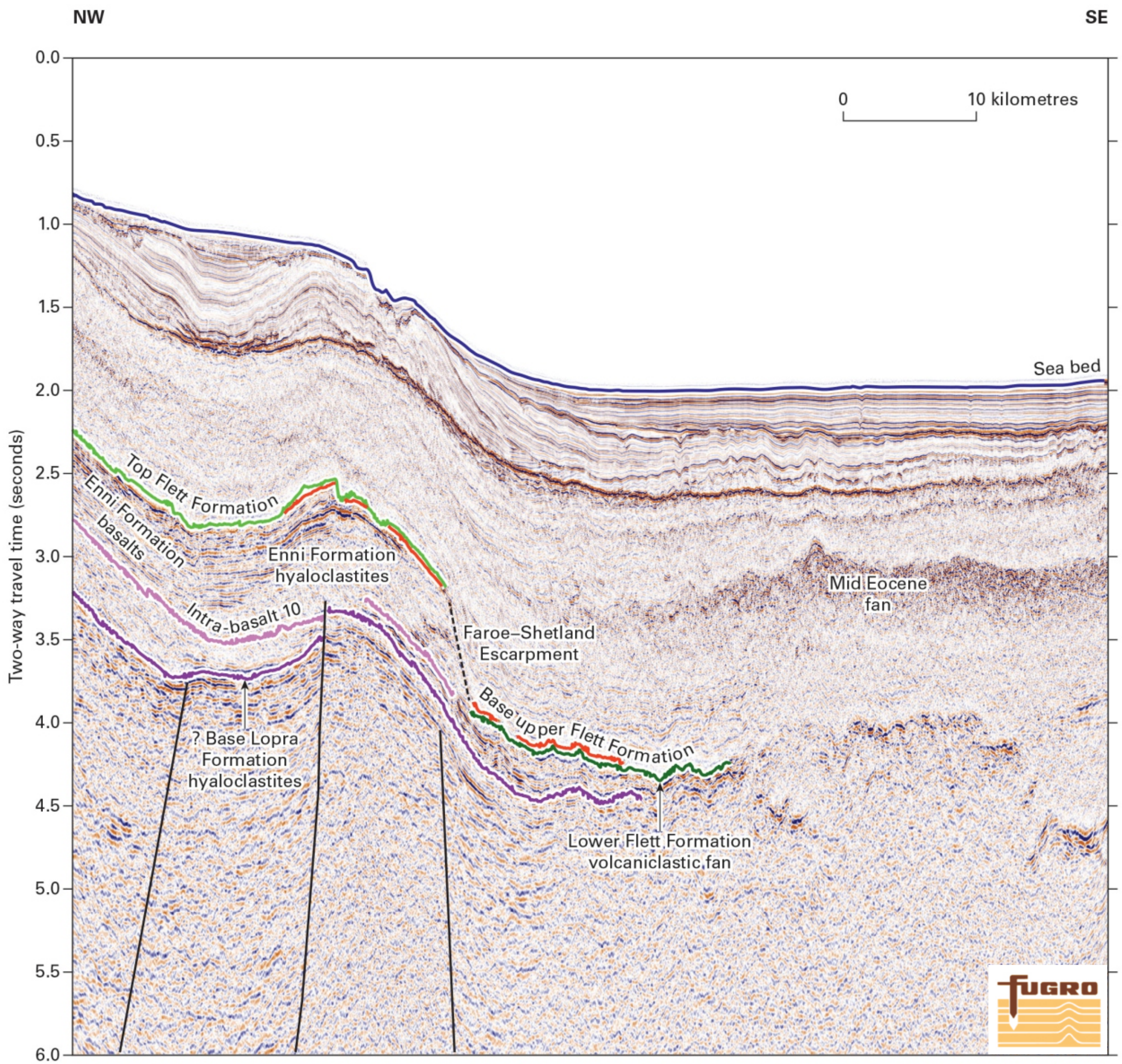


Figure 37 Section E: NW–SE seismic profile across the Faroe-Shetland Escarpment, a buried submarine slope composed of hyaloclastite debris, which formed when an aggrading pile of terrestrial Enni Formation basalts entered the marine Faroe-Shetland Basin and partly overlapped volcaniclastic deposits derived from the older lava shields. See text for discussion. For location see Fig. 7. Seismic data by courtesy of Fugro Multi Client Surveys.

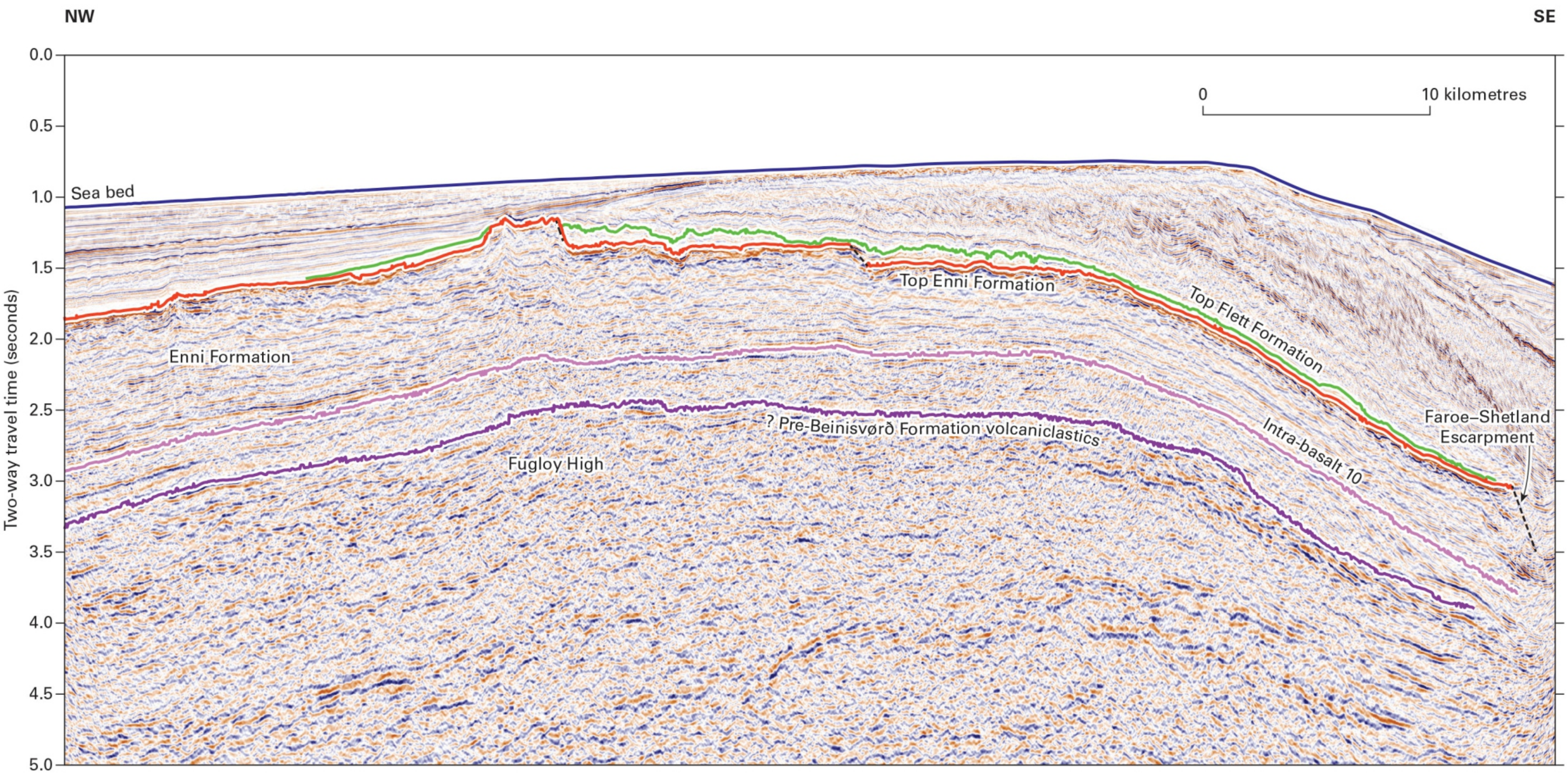


Figure 38 Section H: NW–SE seismic profile showing the Faroe Islands Basalt Group in the vicinity of the Fugloy High. The volcanic succession overlying the intra-basalt 10 reflector is thicker in this area, which adjoins the continent-ocean boundary. For location see Fig. 7. Seismic data by courtesy of WesternGeco.

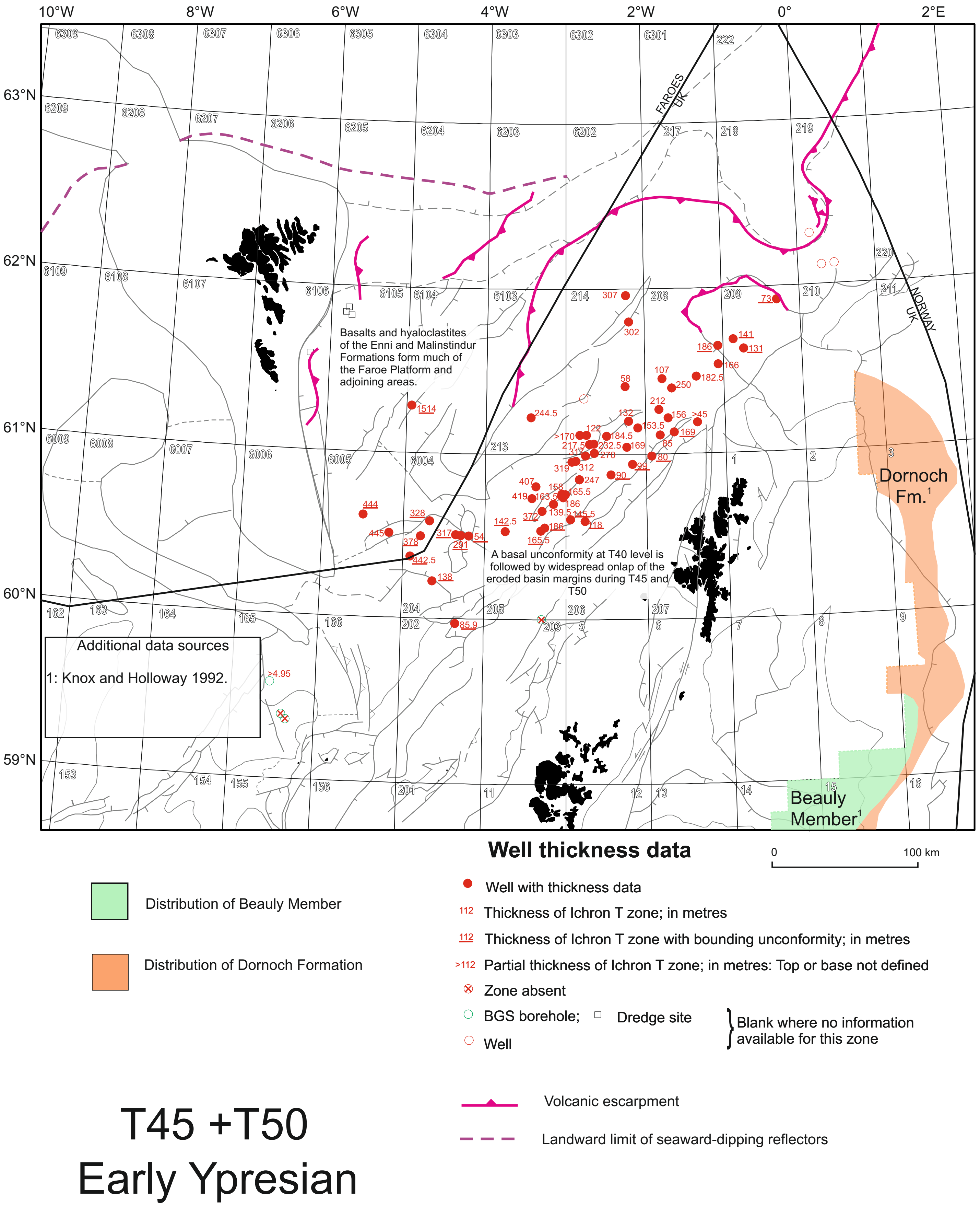


Figure 39 Combined thickness of the T45 and T50 (Early Ypresian) intervals in wells; includes the upper Flett and Balder formations in the Faroe-Shetland Basin and the Enni and Malinstindur formations on the Faroe Platform and adjoining areas. See text for details

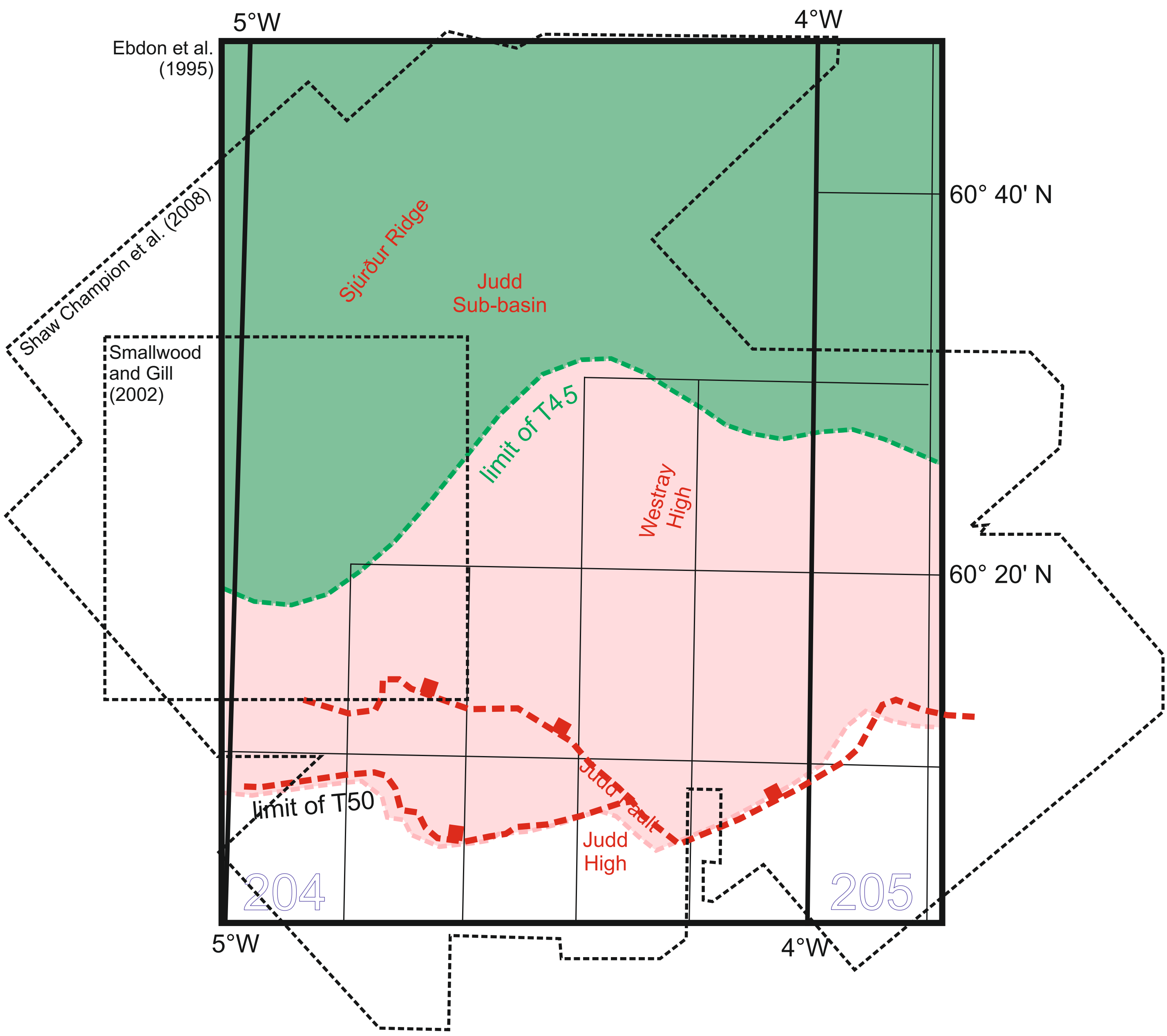


Figure 40 The Judd Sub-basin, showing the distribution of sequence T45 (green tone) and the overstepping part of sequence T50 (pink tone), based on 2D seismic interpretation (modified from Ebdon et al. 1995, their Fig 10d). The dashed square and polygon show the extent of later 3D seismic coverage (see Fig. 41).

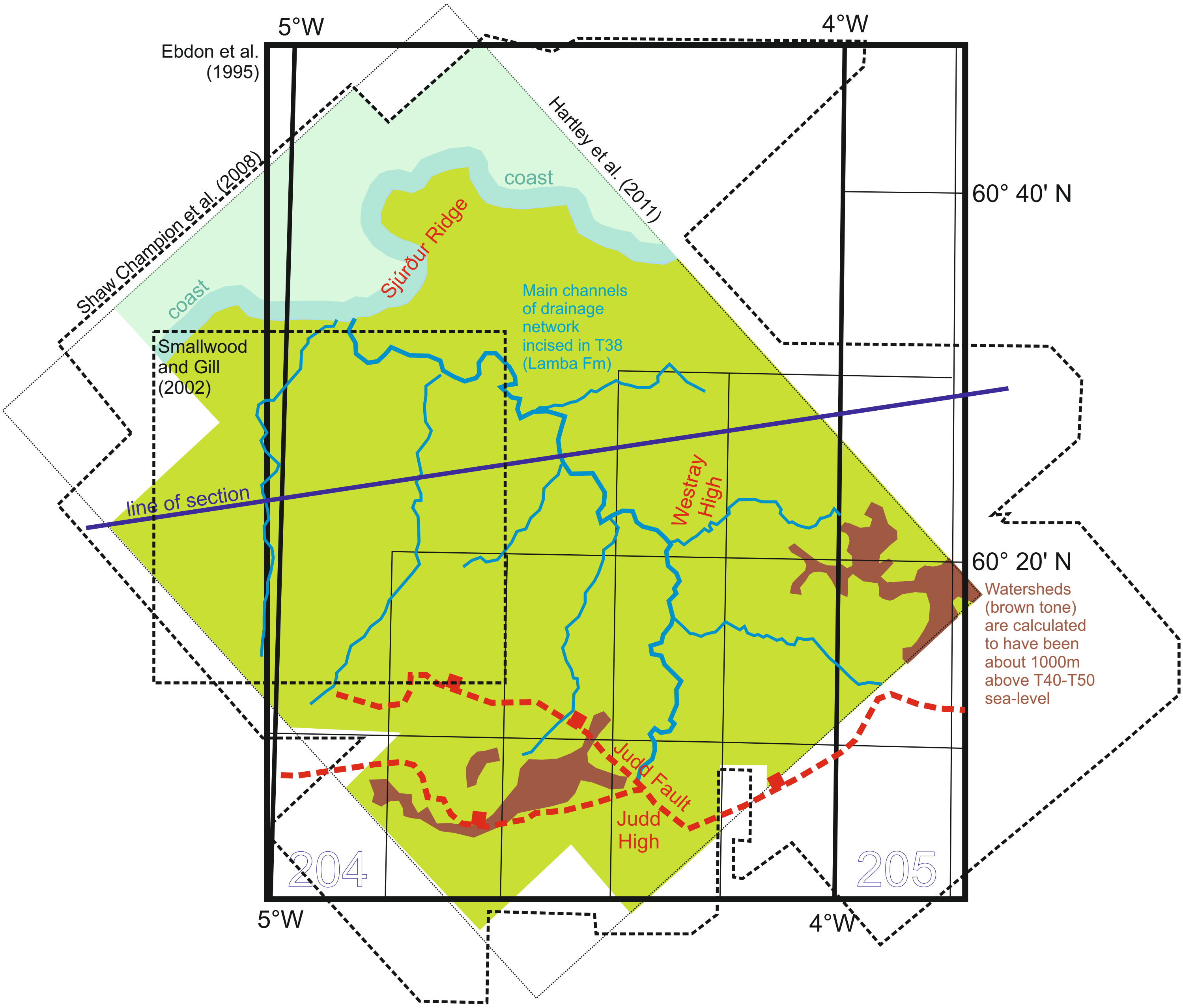


Figure 41 Topographic map derived from 3D seimic data of the eroded landscape at Flett unconformity (top Lamba Formation) level in the Judd Sub-basin (modified from Hartley et al. 2011, with selected underlying structures (in red) from Ebdon et al. 1995), showing a marine basin (pale green tone) and coast line (pale blue tone) in the north, with the extent of the dendritic drainage system (green tone) and the main fluvial channels (blue lines) indicated in the south. The interfluve areas calculated by Hartley et al. (2011) to have been more than 1000 m above contemporary sea level are highlighted in brown. The dark blue line shows the location of a geoseismic profile from Shaw Champion et al. (2008) (see Fig. 27). The dashed square and polygon show the extent of 3D seismic coverage used by different authors.

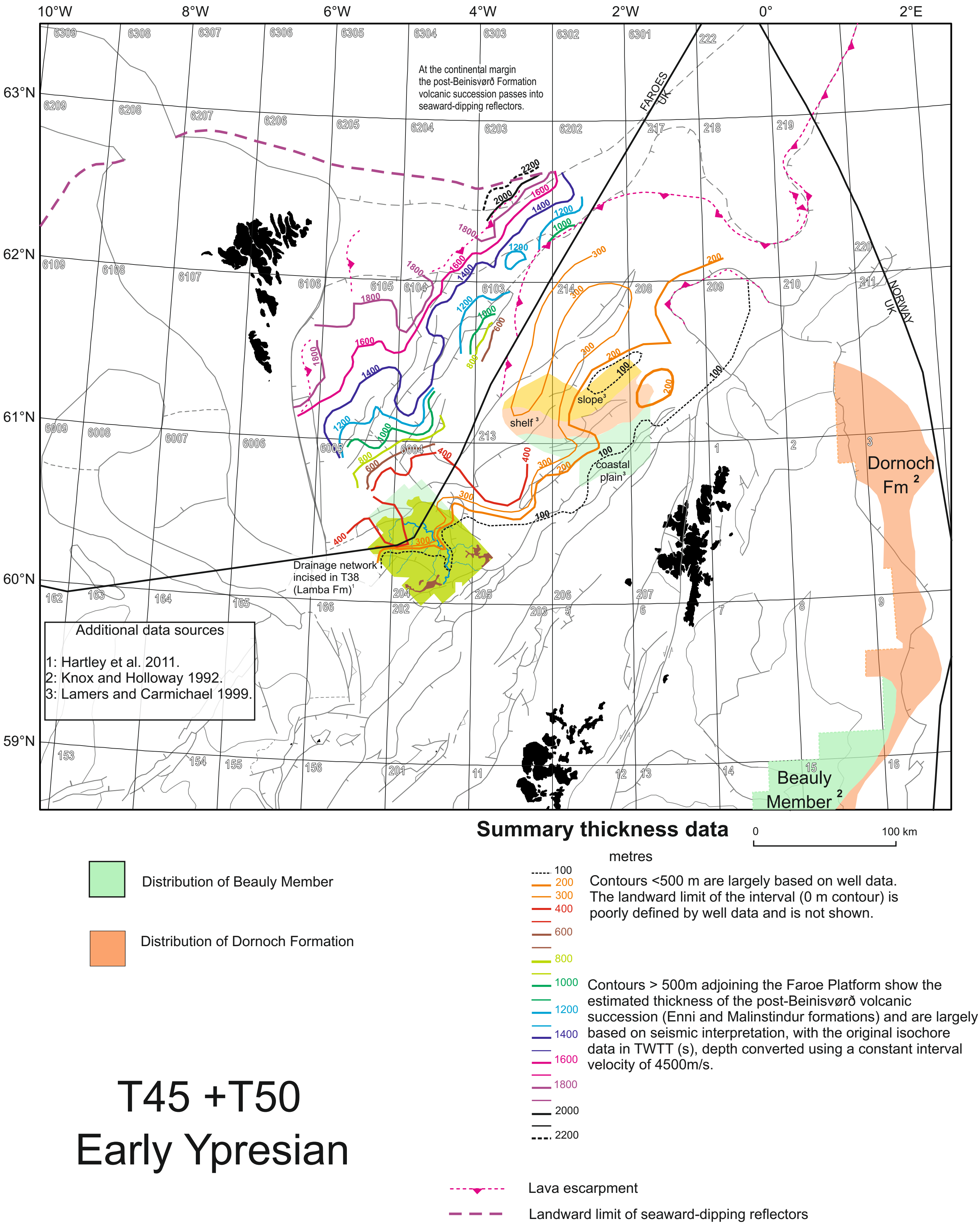


Figure 42 Contoured combined thickness of the T45 and T50 (Early Ypresian) intervals, includes the upper Flett and Balder formations in the Faroe-Shetland Basin and the Enni and Malinstindur formations alongside the Faroe Platform. See text for details.

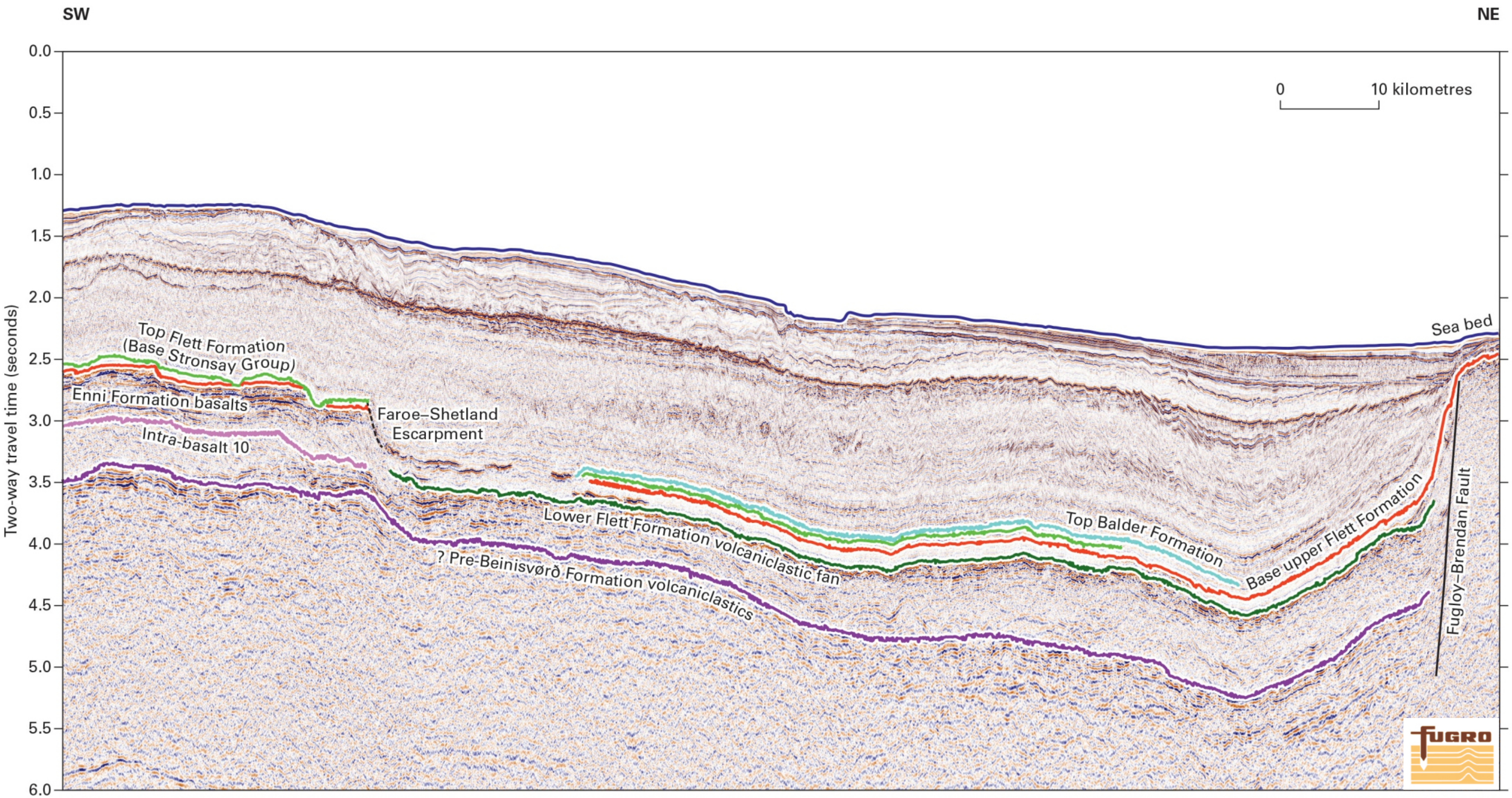


Figure 43 Section J: SW–NE seismic profile showing the Eocene depocentre of the Faroe-Shetland Basin between the Faroe-Shetland Escarpment and the Fugloy-Brendan Fault. The two deepest interpreted seismic reflectors define the top of the lower Flett Formation volcaniclastic fan (green) and the possible top of a pre-Beinisvørđ Formation volcaniclastic succession (purple). For location see Fig. 7. Seismic data by courtesy of Fugro Multi Client Surveys..

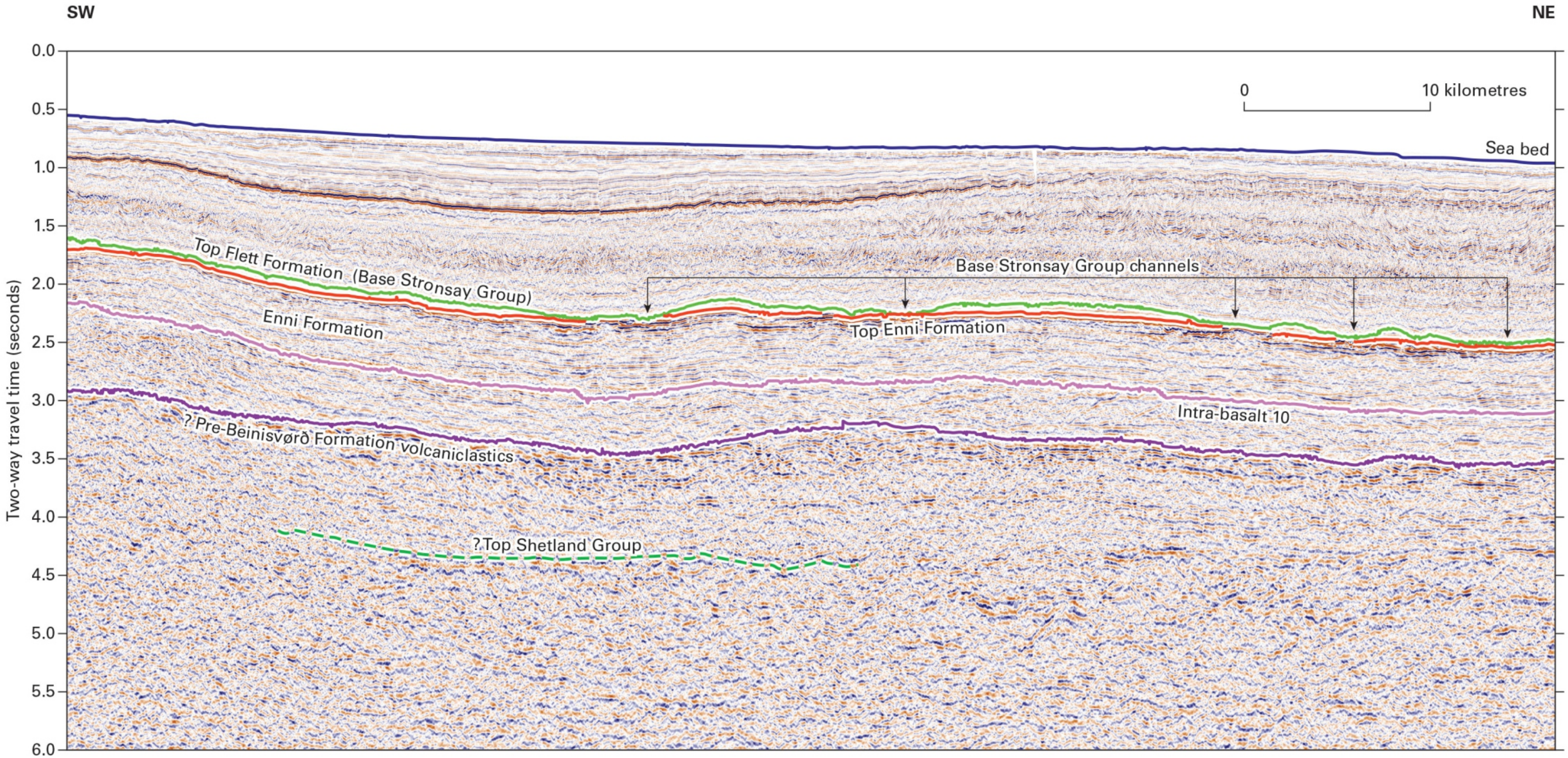


Figure 44 Section F: SW–NE seismic profile alongside the Fugloy High, showing an Early Eocene unconformity truncating the thin post-Enni Formation sedimentary succession and defining a series of broad incised channels at base Stronsay Group level. For location see Fig. 7. Seismic data by courtesy of WesternGeco.

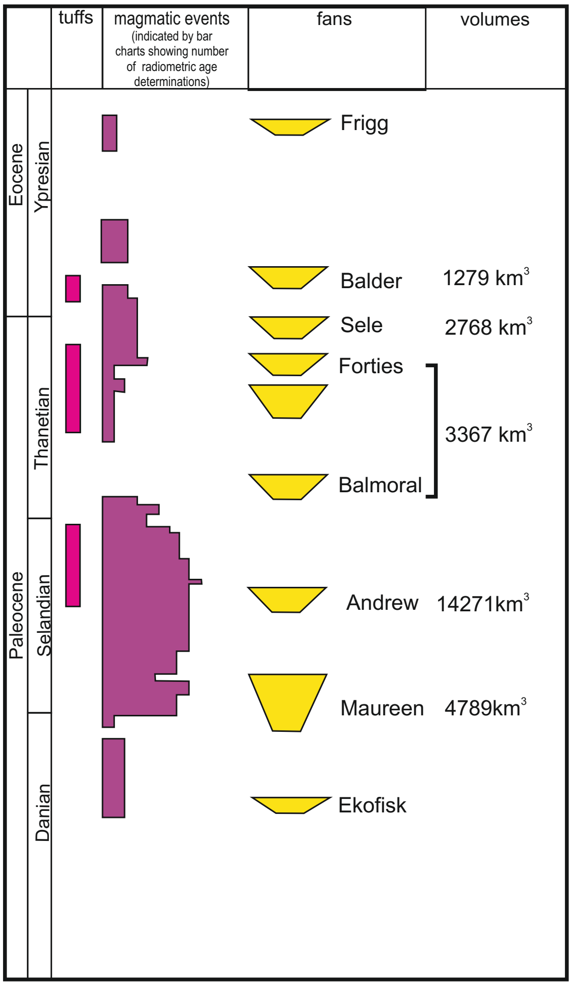


Figure 45 Stratigraphic chart (modified from White and Lovell 1997 and Chambers et al. 2005) showing a proposed relationship between volcanic and magmatic activity in the British part of the North Atlantic Igneous Province and fan deposition in the North Sea.

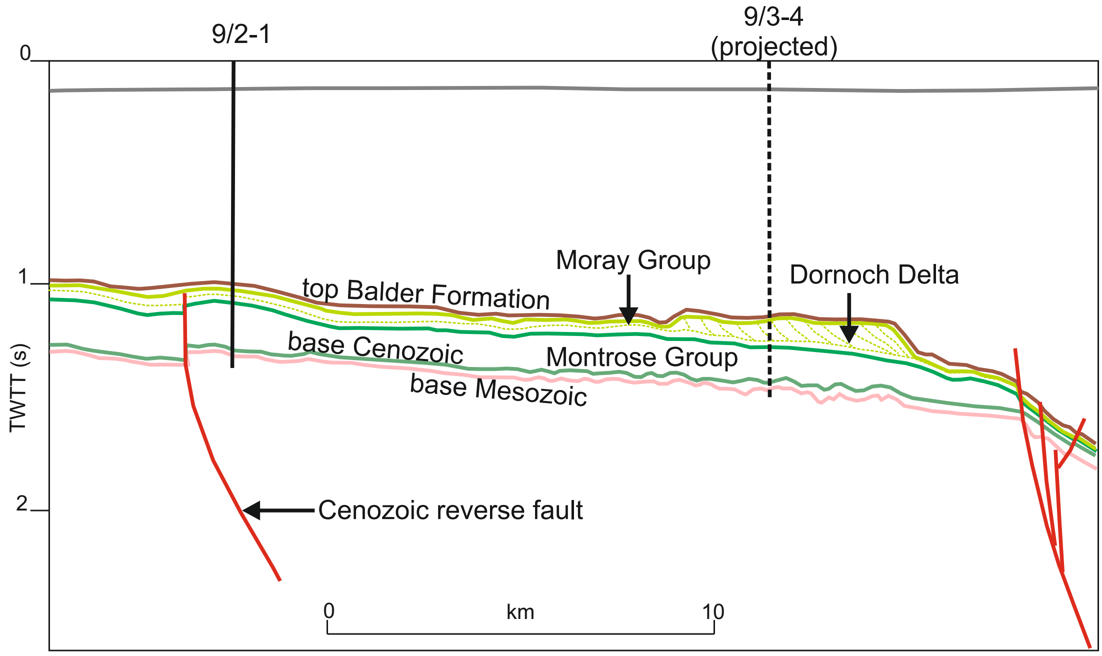


Figure 46 Geoseismic section across the eastern margin of the East Shetland Platform (modified from Underhill 2001, his Fig. 7) showing a Cenozoic reverse fault updip from the Dornoch Delta, in an area where Hartley et al. (2011) have inferred a pulse of transient uplift at top Dornoch Formation level related to the Iceland Plume.

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Figure A1. Stratigraphical-range chart showing the generalised lithology and thickness in metres of the Paleocene-earliest Eocene sequences in the Faroe–Shetland region. Timescale after Gradstein et al. (2004) and Ogg et al. (2008).