DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2008/21

Provenance of sediments in the Faroese-Shetland basin: Integration of wells in the Faroese sector

Final report prepared for SINDRI

Dirk Frei, Rikke Weibel & Christian Knudsen (eds)

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2008/21

Provenance of sediments in the Faroese-Shetland basin: Integration of wells in the Faroese sector

Final report prepared for SINDRI

Dirk Frei, Rikke Weibel & Christian Knudsen (eds)

Released 01.06.2013

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE END ENERGY

G E U S

Contents

Executive summary

Results from detrital zircon U-Pb geochronology

In this study, U-Pb ages have been determined for 2030 individual detrital zircons separated from representative sediment samples from the wells 6004/12-1 Svinoy, 6004/16-1z Marjun, 6004/17-1 Marimas, and 6005/15-1 Longan. The obtained detrital zircon age signatures allow to place tight constraints on sediment dispersal pattern in the Faroe-Shetland basin:

- The detrital zircon U-Pb age signatures in all samples from all four wells in the Faroese sector investigated are very similar. The most prominent differences are changes in the relative modal abundances of Archean to Proterozoic/Paleozoic zircons as a function of stratigraphic position in the well.
- The detrital zircon U-Pb age pattern in the wells in the Faroese sector are similar to those observed in wells in the UK sector of the Faroese-Shetland basin.
- The unique Archean age pattern observed for all samples from wells in the Faroese and the UK sector of the Faroe-Shetland basin suggest that the overwhelming majority of the sediments are sourced from the UK margin, i.e., the Hebridian Foreland and the Scottish Mainland.
- No evidence could be found for a major role of southern East Greenland as a source of sediment for the Faroe-Shetland basin.

The observed general changes in relative modal abundance of Proterozoic/Paleozoic versus Archean zircon populations in all wells in the Faroe-Shetland basin suggest pronounced changes in sediment supply from a more distal source (i.e., the Scottish Mainland) to a more proximal source (i.e., the Hebridian Foreland) during the Paleocene. This would imply that either erosion of the Scottish Mainland ceased during the Paleocene or that the direction of sediment transport changed drastically, possibly due to different uplift histories in the Hebridian Foreland and the Scottish Mainland.

The findings of this study verify the conclusion of Frei et al. (2005) that detrital zircon U-Pb geochronology provides a robust framework for the interpretation of sedimentary provenance in the Faroe-Shetland basin and hence constitutes a powerful tool for future hydrocarbon exploration.

Results from whole rock geochemistry

Geochemical investigations have been performed on Paleogene sediments from the wells Marjun (6004/16-1), Svinoy (6004/12-1), Marimas (6004/17-1) and Longan (6005/15-1) in order to achieve additional information on the provenance of the sediments in the Faroe-

Shetland Basin. Generally, the major elements were measured by XRF (X-ray fluorescence spectrometry) and the trace elements by ICP-MS (inductively coupled plasma - mass spectrometry). Because the geochemical analyses were performed on cuttings samples there is a risk of contamination from drillmud leading to artefacts, most likely from baryte. Therefore, all analysis were corrected for baryte contamination.

The Early Late Paleocene Vaila Formation is geochemical similar to the Late Paleocene Lamba Formation, though there are subtle differences. The most distinctive variations are a lower MgO/TiO_2 ratio and a higher P_2O_5/Al_2O_3 ratio for the Vaila Formation compared to the Lamba Formation. These geochemical changes may indicate a minor contribution from a western source (igneous basaltic source) mixed into the dominating easterly source (e.g., the Lewisian or the Orkney-Shetland Platform on the UK margin). Major changes in geochemistry occur at the transition from the Late Paleocene Lamba Formation to the Early Eocene Flett and Balder formations. All samples from the Flett Formation (represented in only one well) and Balder Formation have lower MgO/Al_2O_3 and MgO/TiO_2 ratios. Some samples from the Balder and Flett formations are distinguished from other sediments by higher TiO_2/Al_2O_3 and Yb/La ratios and lower Zr/TiO_2, Nb/TiO_2 and REE/TiO_2 ratios. These differences are most likely related to an influence of volcanic material.

Geochemical variations are also identified which are related to the position in the Faroe-Shetland Basin rather than the time of deposition. A high K_2O/Al_2O_3 ratio can be found in all formations in one of the Faroese wells (6005/15), whereas other wells have lower ratios. The well characterized by the lowest K_2O/Al_2O_3 ratio has the highest Zr/TiO_2 ratio. This could suggest that depending on the position in the basin one source or another might dominate. The high potassium source may be local, as this seems to be unique for the Faroese sector. The zirconium source could be Greenlandic, as East Greenlandic sediments have high abundance of Zr, but it could also origin from for example the Orkney-Shetland Platform.

In conclusion, the findings from both the U-Pb age spectra of detrital zircons as well as major- and trace element geochemistry of the successions drilled in the Faroese sector of the Faroe-Shetland basin suggest that the detritus is dominantly derived from westerly sources, i.e., the UK margin.

Editorial and introduction

Dirk Frei, Rikke Weibel, Christian Knudsen

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark

The sedimentary successions in southern East Greenland and the UK margin, the two principal source areas for sediment input into the Faroese-Shetland basin, are characterised by distinctive, provenance specific signatures with respect to detrital U-Pb zircon age distributions, detrital garnet compositions, and whole rock geochemistry (Jolley and Morton 2007; Morton et al. 2007; Frei et al. 2005a & b; Knudsen 2005; Morton et al. 2005a). This provides a robust framework for the identification of the source areas of sands in the deeper, central parts of the Faroe-Shetland Basin. Therefore, analysis of the zircon U-Pb age distributions and whole rock geochemistry of representative samples from the wells drilled in the Faroese sector of the basin are expected to allow qualitative and quantitative constraints on the source areas of the sedimentary successions in the deeper, central parts of the Faroese-Shetland Basin.

In this contribution, we report the results of the SINDRI project "Provenance of sediments in the Faroese-Shetland basin: Integration of wells in the Faroese sector" that investigated (a) the U-Pb age signature of 2030 detrital zircons recovered from 46 sandstone samples, and (b) the major, minor and trace element composition of 200 whole rock samples from all major stratigraphic units in the four so far released wells (6004/12-1 Svinoy, 6004/16-1z Marjun, 6004/17-1 Marimas and 6005/15-1 Longan; operated by British Petroleum, Amerada Hess, ENI and Statoil, respectively) drilled in the Faroese sector of the Faroe-Shetland basin. This study is a continuation of the SINDRI project "Linking the Faroese area and Greenland: An Innovative, integrated provenance study", the results of which have been reported in the Geological Survey of Denmark and Greenland Report 2005/54.

We will first give a brief introduction into the geological framework of the Faroese-Shetland area, summarise the results of previous investigations, and describe the aims of this project. Thereafter, the results of the investigations carried out in this project and their implications for qualitatively and quantitatively constraining the source areas of sediments deposited in the Faroese sector of the Faroe-Shetland basin are presented separately in two chapters describing the detrital zircon geochronology (Frei and Knudsen) and the whole-rock geochemical characteristics (Weibel and Knudsen) of the drilled successions. The methods and techniques applied in this study are described in Appendix A and the samples investigated are listed in Appendix B. All data obtained in the course of this study are reported in the accompanying CD-ROM.

Geological background

A key issue for hydrocarbon exploration in the Faroer region is the understanding of sediment dispersal patterns and depositional systems in the Faroe-Shetland Basin prior to continental breakup in the Late Paleocene to Early Eocene. Identification of sediment provenance is crucial for this goal. Location of the source areas places important constraints on sediment transport pathways and intrabasinal sand body distribution. Furthermore, the nature of the sediment source has important implications for the porosity and permeability characteristics of the deposited sediments. Identified source variations might also be used to establish correlation frameworks (at both local and regional scales) and can provide a basis for discrimination of individual sand bodies.

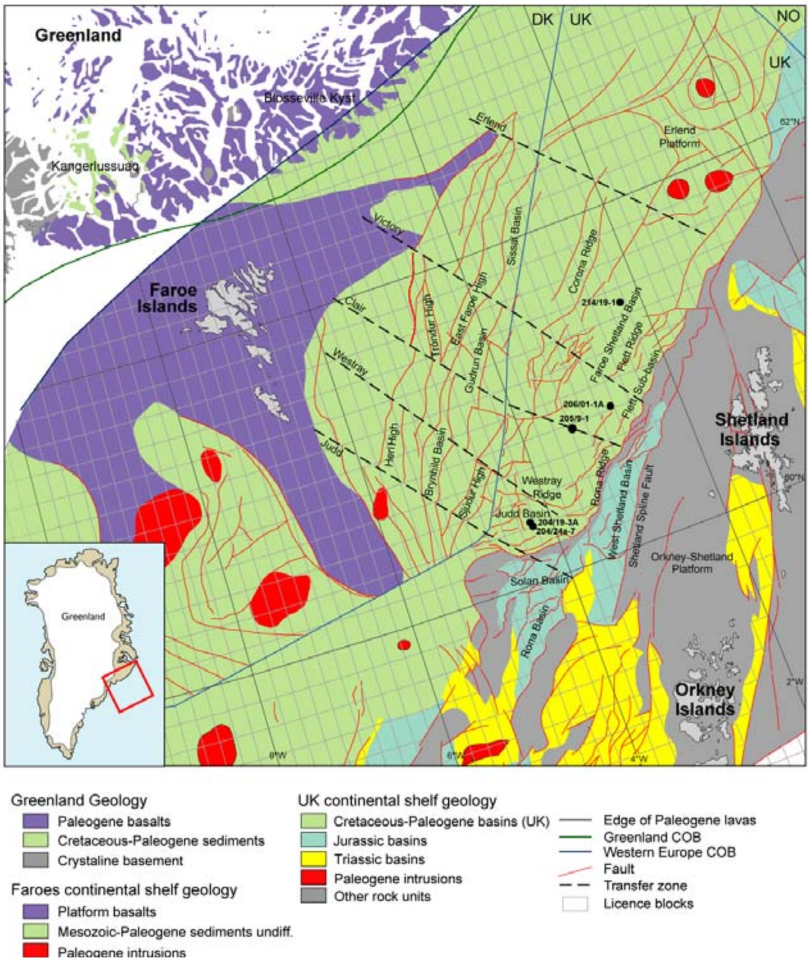


Figure 1. *Location map of southern East Greenland and the Faroe-Shetland region depicting the geographical position of the areas investigated in this study. Also shown are on- and offshore geology, main structural elements, transfer zones and position of the wells in the UK sector of the Faroe-Shetland basin. The position of the wells investigated in this study is shown in Fig. 2. Note that the position of Greenland is shown prior to Paleogene sea-floor spreading (modified from Larsen et al. 2005).*

The focus of the first exploration round in the Faroes area was the Paleocene deep-water play. The Paleocene succession is characterised by a series of sandpulses related to uplift episodes of the eastern and western marginal areas, e.g., UK mainland and southern East Greenland, respectively. The Paleocene play is the most recently described play in the area west of the Shetland Islands and Paleocene sandstones form the main reservoirs of the Foinaven and Schiehallion fields.

Plate reconstructions of the North Atlantic region indicate the former proximity of southern East Greenland to the Faroe Island region (Fig. 1). Consequently, as hydrocarbon exploration pushes further westward in the Faroe-Shetland Basin, there are increasing questions as to the role that Greenland has played as a source of sediment to the basin. Field work by GEUS and CASP on the Cretaceous–Early Palaeogene sedimentary succession in Kangerlussuaq, southern East Greenland, has indicated the presence of sequence boundaries in the Upper Cretaceous succession and also between the Cretaceous and Palaeogene successions, promoting a long distance transport of sediment to the west (Jolley and Whitham 2004; Whitham et al. 2004). A study of tectonic lineaments that may have had fundamental control on sediment disperal patterns concluded that a major sediment input point may have existed in the Kangerlussuaq Basin in the earliest Paleocene. The assumed cross rift supply of sands is believed to have come to and end with the period of rifting, which preceded continental separation and flood basalt extrusion some time between the mid-Maastrichtian and earliest Eocene.

The SINDRI project ”Linking the Faroese area and Greenland: an innovative, integrated provenance study” conclusively demonstrated that the sedimentary sources from the eastern (i.e., UK margin) and western (i.e., Kangerlussuaq basin, southern East Greenland) marginal areas have distinctive provenance sensitive signatures with respect to detrital zircon geochronology and bulk rock geochemistry. Most strikingly, the assumed western source (Kangerlussuaq basin, southern East Greenland) is generally characterised by the presence of a Middle Archean age component in detrital zircon age spectra. In contrast, in the assumed eastern source (UK margin) this Middle Archean age component in detrital zircon age distributions is absent.

The influence from the assumed western source (Kangerlussuaq basin, southern East Greenland) has not been proven in the stratigraphic intervals of the wells from the UK sector of the Faroe-Shetland Basin examined in the SINDRI project ”Linking the Faroese area and Greenland: an innovative, integrated provenance study”. However, these wells are all located on the shallower and more distal eastern margin of the basin, close to the UK margin, and it therefore might be expected that the western, greenlandic source has more importance for the more deeper and proximal central parts of the basin towards the Faroese area.

The results obtained during the SINDRI project ”Linking the Faroese area and Greenland: an innovative, integrated provenance study” are believed to have established a robust framework for the identification of the assumed western, greenlandic signature in the deeper and more proximal parts of the Faroe-Shetland basin. The new techniques available for provenance studies and the distinctive signature of the greenlandic source might therefore provide a promising and reliable way to distinguish the eastern and western provenance areas. In this project, we therefore apply these techniques to the new wells drilled in the deeper parts of the Faroe-Shetland basin in the Faroes sector, e.g. the wells 6004/12-1 Svinoy (BP), 6004/16-1z Marjun (Amerada Hess), 6004/17-1 Marimas (Eni), and 6005/15-1 Longan (Statoil). The position of the wells is indicated in Fig. 2.

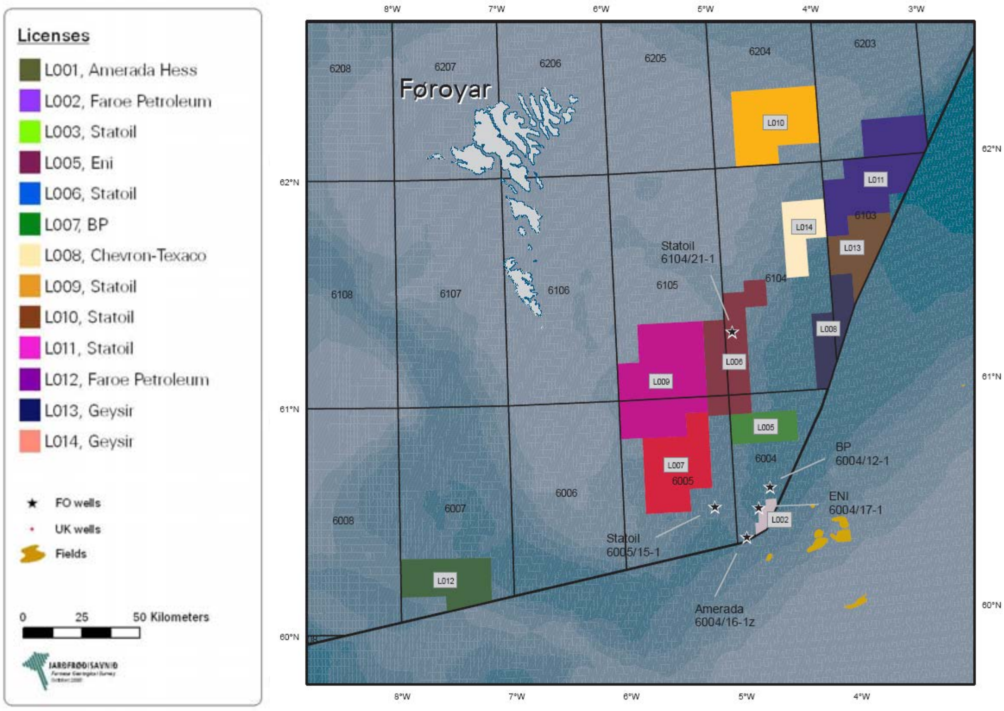


Figure 2. *Map depicting the geographical position of the wells investigated in this study (modified from JARDFEINGI).*

Project aims

The ultimate goal of this (and previous) provenance projects carried out under the umbrella of the SINDRI programme is to identify the provenance sensitive signatures of the stratigraphic successions in the Faroese-Shetland basin and to use these signatures for qualitatively and quantitatively constraining their source areas in order to establish whether there is a link between the Faroese-Shetland Basin and southern East Greenland or not. This question is highly relevant to Objective 2 of SINDRI, namely, regional geology and evolution of the entire Faroese area. Within this respect, the specific aims of the proposed project were:

- Identification of the provenance sensitive signatures (detrital zircon age distributions and detailed chemostratigraphy based on bulk rock geochemistry) in sands in the deeper, central parts of the Faroese-Shetland basin.
- Application of the identified provenance sensitive signatures in order to qualitatively and quantitatively constrain the source areas (western, greenlandic versus eastern, UK margin signature) for sedimentary input into these parts of the Faroese-Shetland basin.

- Constraining possible changes in sediment supply during the evolution of the Faroese-Shetland basin.

Some of the most important questions relevant to hydrocarbon exploration in the Faroese area that have been tackled in this project are:

- Is there a link between the sedimentary successions exposed in southern East Greenland and the Faroese-Shetland basin?
- If yes, what are the volumes of sedimentary material derived from this western, greenlandic source compared to the volumes derived from the eastern, UK margin source?
- What is the timing of the sedimentary input from these sources?

We believe that the results of this project, presented and discussed in detail in the following, allow to place tight constrains on provenance of sediments in the Faroe-Shetland basin. Hence, they represent a significant contribution in order to resolve these important questions relevant to hydrocarbon exploration in the Faroese area and can be considered as a further important step towards a coherent interpretative framework for the identification of the provenance of sands in the Faroese-Shetland Basin.

Publications

This contribution makes available the results originating directly from this SINDRI project to the SINDRI Group. However, it is our intention that the results should be made available to the interested public by publications in peer-reviewed international journals after the project has been finalised and permission has been granted by the SINDRI group.

References

Frei, D., Frei, M., Knudsen, C. (eds) 2005: Linking the Faroese area and Greenland: an innovative, integrated provenance study. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/54**.

Jolley, D.W., Whitham, A.G. 2004: A stratigraphical and paleoenvironmental analysis of the sub-basaltic Paleogene sediments of east Greenland. Petroleum Geoscience **9**: 53-60.

Larsen, M., Nøhr-Hansen, H., Whitham, A.G., Kelly, S.R.A. 2005: Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin. Volcanic basins of the North Atlantic. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/62**.

Whitham, A.G., Morton, A.C., Fanning, C.M. 2004: Insights into Cretaceous-Paleogene sediment transport paths and basin evolution in the North Atlantic from a heavy mineral study of sandstones from southern East Greenland. Petroleum Geoscience **9**: 61-72.

Understanding sedimentary provenance in the Faroe-Shetland basin: constraints from detrital zircon geochronology.

Dirk Frei, Christian Knudsen

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark

Summary

We have investigated the detrital zircon U-Pb age pattern of representative samples from wells 6004/12-1 Svinoy (BP), 6004/16-1z Marjun (Amerada Hess), 6004/17-1 Marimas (Eni), and 6005/15-1 Longan (Statoil) in the Faroese sector of the Faroe-Shetland basin. In total, 2030 individual zircons have been dated with high precision, accuracy and spatial resolution by means of laser ablation – magnetic sectorfield – inductively coupled plasma – mass spectrometry (LA-SF-ICP-MS). The resulting U-Pb age signatures in all samples investigated from all four wells are remarkably similar and are almost identical to those pattern previously reported for wells in the UK sector of the Faroe-Shetland basin. The Archean age pattern are similar in all samples so far investigated from the Faroe-Shetland basin and are in excellent agreement with the Archean age pattern of the Hebridian Foreland. In contrast, the observed Archean age pattern are strikingly different from Archean age pattern observed in the sediments exposed in the Kangerlussuaq basin in southern East Greenland, which represent the proposed Greenlandic source of sediment for the Faroe-Shetland basin. These findings suggest that the majority of the detritus drilled in the wells in the Faroe-Shetland basin is sourced from the UK margin and excludes southern East Greenland as a prominent source of sediment.

A general decrease in the modal abundance of Proterozoic/Paleozoic zircons relative to Archean zircons with increasing height in the stratigraphic column can be observed in all wells investigated in the Faroe-Shetland basin. This observation most likely reflects a change in sediment supply from a more distal source (i.e., the Scottish Mainland) to a more proximal source (i.e., the Hebridian Foreland) during the Paleocene. This would imply that either erosion of the Scottish Mainland ceased during the Paleocene or that the direction of sediment transport changed drastically, possibly due to different uplift histories in the Hebridian Foreland and the Scottish Mainland.

The results obtained in this study verify the conclusion of Frei et al. (2005) that detrital zircon U-Pb geochronology provides a robust framework for the interpretation of sedimentary provenance in the Faroe-Shetland basin and hence constitutes a powerful tool for future hydrocarbon exploration.

Introduction

Detrital zircon U-Pb geochronology is a powerful tool for constraining sedimentary provenance. Detrital zircon U-Pb geochronology uses the interpreted provenance of zircon (usually derived from the age information recorded in zircon) to unravel the geological history of sedimentary basins and their surrounding areas. The age distribution of detrital zircons are especially helpful to indentify the different provenance components present in a sedimentary unit (e.g., Hass et al. 1999) and to correlate between stratigraphic sequences on both a local and regional scale (e.g., Bingen et al. 2001). The SINDRI project ”Linking the Faroese area and Greenland: an innovative, integrated provenance study” (Frei et al. 2005) provided strong evidence that the sedimentary sources from the eastern (i.e., UK margin) and western (i.e., Kangerlussuaq basin, southern East Greenland) marginal areas have distinctive provenance sensitive signatures with respect to detrital zircon age distributions and bulk rock geochemistry.

Most strikingly, the western source (southern East Greenland) is generally characterised by the presence of a Middle Archean age component in detrital zircon age. In contrast, in the eastern source (UK margin) the Middle Archean age component in detrital zircon age distributions is absent (Fig. 1).

The influence from the western source (southern East Greenland) has not been proven in the stratigraphic intervals of the wells from the UK sector of the Faroe-Shetland Basin examined in the SINDRI project ”Linking the Faroese area and Greenland: an innovative, integrated provenance study”. However, these wells are all located on the shallower, eastern margin of the basin more proximal to the proposed source rocks in the Kangerlussuaq basin and it can be expected that the western, greenlandic source has more importance for the deeper, central parts of the basin towards the Faroese area.

Here, we present the results of a study that investigated the systematics of detrital zircon age distributions in sandstones from the wells 6004/12-1 Svinoy (BP), 6004/16-1z Marjun (Amerada Hess), 6004/17-1 Marimas (Eni), and 6005/15-1 Longan (Statoil) in the Faroese sector of the Faroe-Shetland basin. The methods and techniques applied in this study are described in Appendix A and the samples investigated are listed in Appendix B. All data obtained in the course of this study are reported in the accompanying CD-ROM.

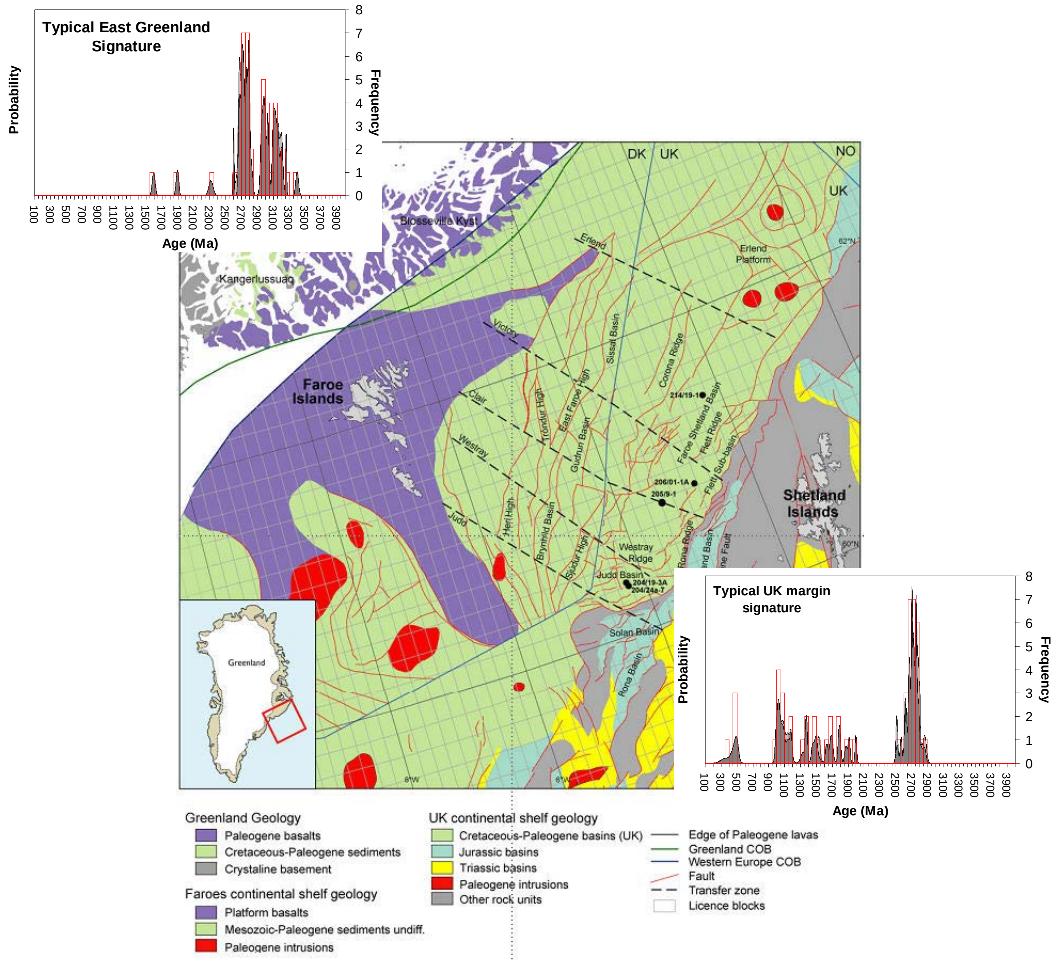


Figure 1. *Map of southern East Greenland and the Faroe-Shetland region depicting the geographical position of the areas investigated by Frei et al. (2005) and their characteristic zircon age spectra according to the findings of Frei et al. (2005). Also shown are on- and offshore geology, main structural elements, transfer zones and position of the wells investigated by Frei et al. (2005). Note that the position of Greenland is shown prior to Paleogene sea-floor spreading (modified from Larsen et al. 2005).*

Results

In total, the U-Pb ages of 2030 detrital zircons from 46 samples have been successfully determined by means of LA-SF-ICP-MS (Frei et al. 2006; Frei and Gerdes 2008). Originally, it was intended to analyse zircons from a total of 25 samples for both U-Pb ages and selected trace elements. However, during the first sample campaign it became obvious that the very limited amount of sample material available (approximately 50 g per sample) does not allow successful separation of the required amounts of zircons. We decided therefore to focus on U-Pb age dating and to discard trace element analysis of zircons. In order to recover the amount of zircons necessary for U-Pb age dating, we separated and blended zircons from two adjacent samples of the same stratigraphic formation (e.g., the two samples 240507-06/2070m and sample 240507-07/2100m from the Balder Fm. in well 6004/17-1 Marimas). Consequently, the obtained zircons were subsequently treated as one sample representative for the given depth interval (e.g., 6004/17-1 Marimas 2070 & 2100 m Balder Fm. in Fig. 5a). In total, 24 blended samples were established using this procedure (samples used for blending are indicated in Tables 1 to 4 in Appendix A).

For the overwhelming majority of the samples treated in this fashion sufficient amounts of zircons could be recovered (i.e., > 100 zircon grains per sample). Notable exceptions are one sample (6005/15-1 Longan 3209 & 3219 m Vaila Fm.) for which no zircons could be recovered and two samples (6005/15-1 Longan 1880 & 1890 m Balder Fm. and 6005/15-1 Longan 2070 & 2080 m Balder Fm.) for which only a minute number of zircons (9 and 12 zircons, respectively) could be recovered. Furthermore, in a number of samples the fraction of zircons with grains sizes < 30 µm (i.e., below the employed spatial resolution of the laser ablation system) was significant, resulting in poor ^{238}U, ^{206}Pb and ^{207}Pb signals during ablation. Consequently, these analysis gave no meaningful results and were discarded during data treatment, resulting in a total of 2030 individual zircon analyses for subsequent data interpretation.

For all samples probability density diagrams (PDDs) combined with binned frequency diagrams (Sircombe 2004) have been calculated based on the $^{207}Pb/^{206}Pb$ ages for zircons > 1200 Ma and $^{206}Pb/^{238}U$ ages for zircons < 1200 Ma. A 2 sigma error and 90 – 110% concordance criteria has been applied and of all 2030 individual zircons analysed 76% yielded ages that are concordant with respect to the applied concordance criteria. In all probability density diagrams, zircon age spectra based on concordant analyses are displayed in dark grey in the foreground whereas zircon age spectra based on all analyses are displayed in light grey in the background. All subsequent data interpretation is based on concordant zircon analyses only. However, it should be pointed out that the zircon age spectra based on all analyses (i.e., inclusive discordant grains) are almost identical to the zircon age spectra based on only concordant analyses. The major difference between the two spectra are slightly wider peaks in the spectra based on the entire zircon population; these are interpreted due to the larger error inherent with discordant analyses.

Throughout this study the Plešovice zircon reference material (Slama et al. 2008; Frei and Gerdes 2008) was analysed at least 10 times within each analytical session. In total, 130 stand-alone U-Pb age determinations of the Plešovice zircon reference material have been performed. The mean of the 130 analyses (Fig. 2) yielded a $^{206}Pb/^{238}U$ age of 334 ± 3 Ma, which is in excellent agreement with the ID-TIMS value of 337.13 ± 0.37 Ma reported by Slama et al. (2008).

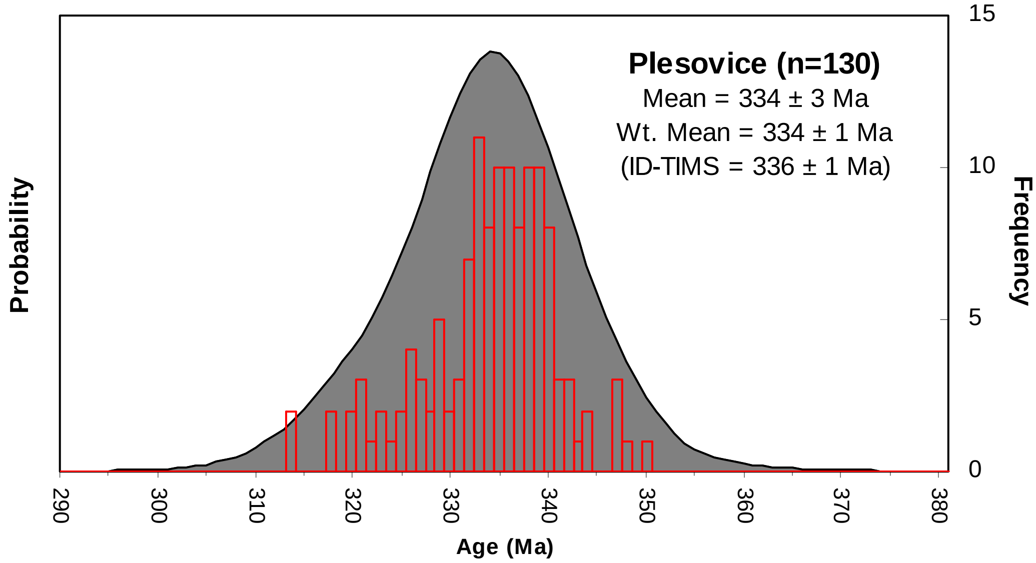


Figure 2. *Cumulative probability plot for 130 individual* $^{206}Pb/^{238}U$ *ages obtained for the Plešovice zircon reference material during the course of this study. Note that 2 sigma errors have been used for construction of the PDD.*

Detrital zircon U-Pb age spectra

The results for all investigated samples are presented in vertically stacked probability density diagrams (PDDs) combined with binned frequency diagrams (Sircombe 2004) in stratigraphic order through the Paleocene to the Eocene for well 6004/12-1 Svinoy (Fig. 4 a - e), well 6004/17-1 Marimas (Fig. 5 a - e), well 6004/16-1z Marjun (Fig. 6 a - g) and well 6005/15-1 Longan (Fig. 7 a - e). The samples cover the sedimentary succession from the Early Paleocene (Vaila Fm.) to the Early Eocene (Balder Fm.) and have been assigned to the stratigraphic subdivisions used in the well logs provided by Jardfeingi. These subdivisions are consistent with the stratigraphical framework presented by Jolley and Morton (2007). All analytical results are reported in Excel based spreadsheets in the attached data CD-ROM.

The most striking observation is that the detrital zircon age pattern for all samples from all stratigraphic subdivisions in all four wells investigated are remarkably similar. They are generally characterised by three well defined age components: (a) a Late Archean to Early Paleoproterozoic (3000 to 2400 Ma) group; (b) a Mid Paleoproterozoic to Early Neoproterozoic group (1900 to 950 Ma); and (c) a comparably young, Paleozoic group that contains mainly Ordovician to Silurian ages. In general, a discontinuous decrease of the modal abundance of the Mid Paleoproterozoic to Early Neoproterozoic group and an increase of the modal abundance of the Late Archean to Early Paleoproterozoic age group with decreasing stratigraphic age can be observed. Because of the similarities between the zircon age pattern for all analysed samples, average probability density distribution plots containing the entire zircon population have been calculated for each of the investigated wells (Fig. 3 a- d).

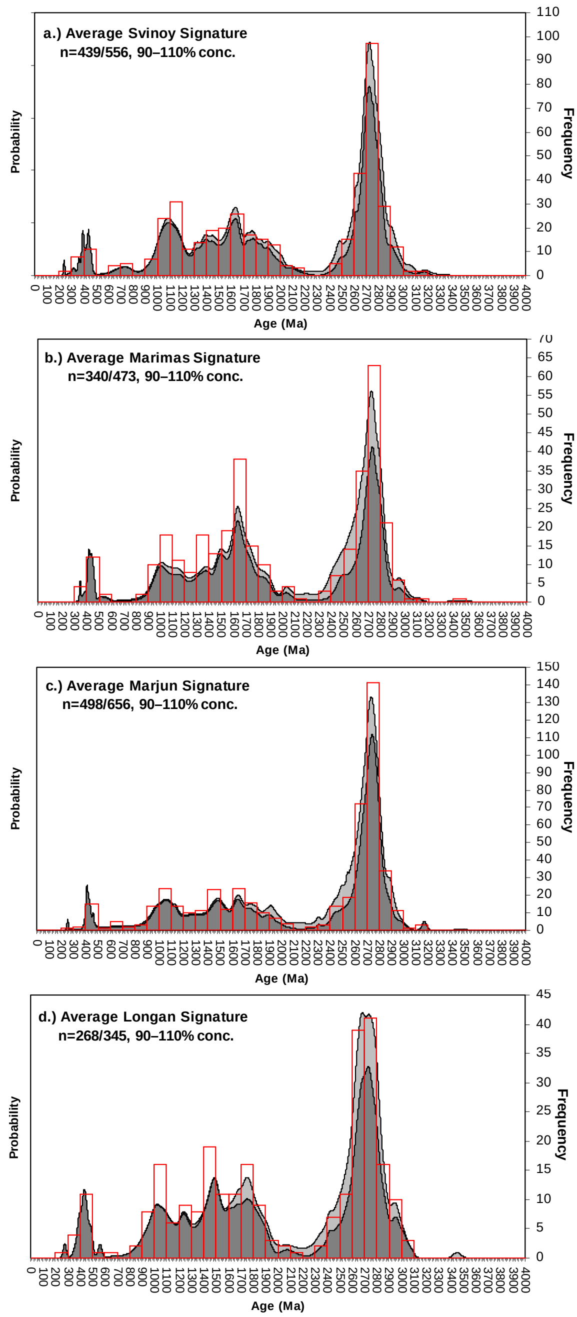


Figure 3. *Average detrital zircon age pattern based on the entire zircon populations of well well 6004/12-1 Svinoy (a), well 6004/17-1 Marimas (b), well 6004/16-1z Marjun (c) and well 6005/15-1 Longan (d) displayed in probability density diagramms combined with histogram plots. Note that 2 sigma errors have been used for construction of the PDDs.*

The Late Archean to Early Paleoproterozoic group forms on average 50 to 55% of the zircon populations and is the most characteristic feature in the zircon age pattern for all analysed samples (Fig. 6). The zircon age spectrum of this group generally shows a narrow unimodal distribution ranging from 2800 to 2700 Ma and a peak at ~2770 to 2720 Ma. This unimodal age spectrum is characteristically skewed towards the left hand side of the spectrum with a prominent shoulder at ~2600 to 2450 Ma (with a sub-peak at 2500 to 2450 Ma). To the right hand side of the spectrum minor peaks occur at ~3000 to 2900 Ma. Of the entire population of 2030 zircons analyses, only 9 concordant zircons with ages exceeding 3000 Ma have been detected, and of these only 1 zircon is of Paleoarchean age.

The Mid Paleoproterozoic to Early Neoproterozoic group (1900 to 950 Ma) forms on average 40 to 45% of the zircon populations. Although the zircon age pattern within this group show a pronounced variability in all analysed samples, they have some general features: (a) a zircon population with a relatively narrow age range from 1900 to 1800 Ma with a peak at about 1880 Ma that can be related to the Ketilidian and Svecofennian orogenic events; (b) a zircon population with ages ranging from 1850 to 1450 Ma and pronounced peaks at ~1750, 1650 and 1500 to 1450 Ma that can be related to Gothian and Labradorian orogenic events; and (c.) a zircon population ranging from 1300 to 950 Ma with a peak 1100 to 1000 Ma that can be related to the Grenvillian and Sveconorwegian orogenic events during the assembly of Rodinia.

The Paleozoic group is less pronounced and forms on average only ≤ 5% of the zircon populations, although in some marked exceptions (see below) it can comprise up to 10% of the zircon populations. The overwhelming majority of zircons in this group are of Ordovician, Silurian and Devonian age and only singular occurrences of younger, Carboniferous and Permian zircons being observed. The occurrence of Paleozoic zircons is usually more pronounced in the deeper parts of the stratigraphic coloumn (i.e., the Paleocene Vaila and Lambda Fms.; see Figs. 4 to 7).

In the following, we will describe the specific features of the zircon age spectra from the individual wells and their differences from the above described general observations.

Well 6004/12-1 Svinoy

The zircon age pattern in well 6004/12-1 Svinoy show the marked change in relative abundance of the Late Archean to Early Proterozoic and Mid Paleoproterozoic to Early Neoproterozoic groups with increasing stratigraphic level from the Paleocene to the Eocene described above (Fig. 4): From the Fugloy Sand (Fig. 4 e) to the Lambda and Balder Fms. (Fig. 4 a and b) the mode of the Late Archean to Early Proterozoic group discontinuously increases from 20 % to approx. 50%, whereas the mode of the Mid Paleoproterozoic to Early Neoproterozoic group discontinuously decreases from modes as high as 57% in the Fugloy Sand (Fig. 4 e) to 25% in the Balder Fm. (Fig. 4 a). The zircon age pattern of the Fugloy Sand is characterised by a the occurrence of a prominent Middle Paleozoic (~450 Ma) peak that forms 10% of the entire population and a singular Early Triassic zircon (241 Ma).

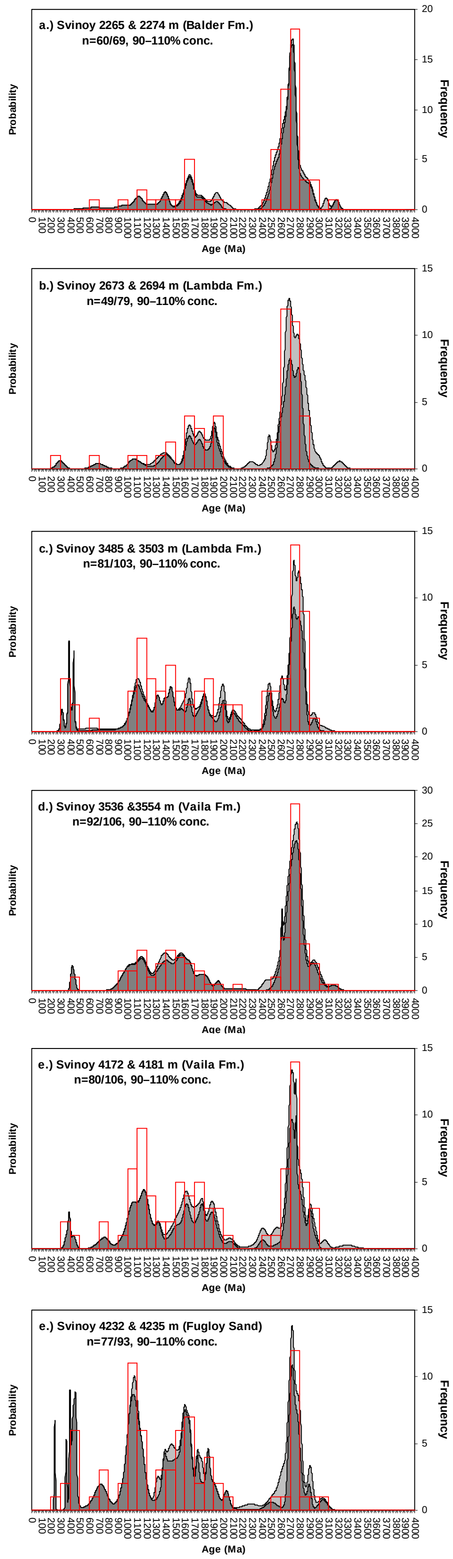


Figure 4. *Detrital zircon age pattern of samples from well 6004/12-1 Svinoy displayed in vertically stacked probability density diagramms combined with histogram plots in stratigraphic order through the Paleocene to the Eocene. Note that 2 sigma errors have been used for construction of the PDDs.*

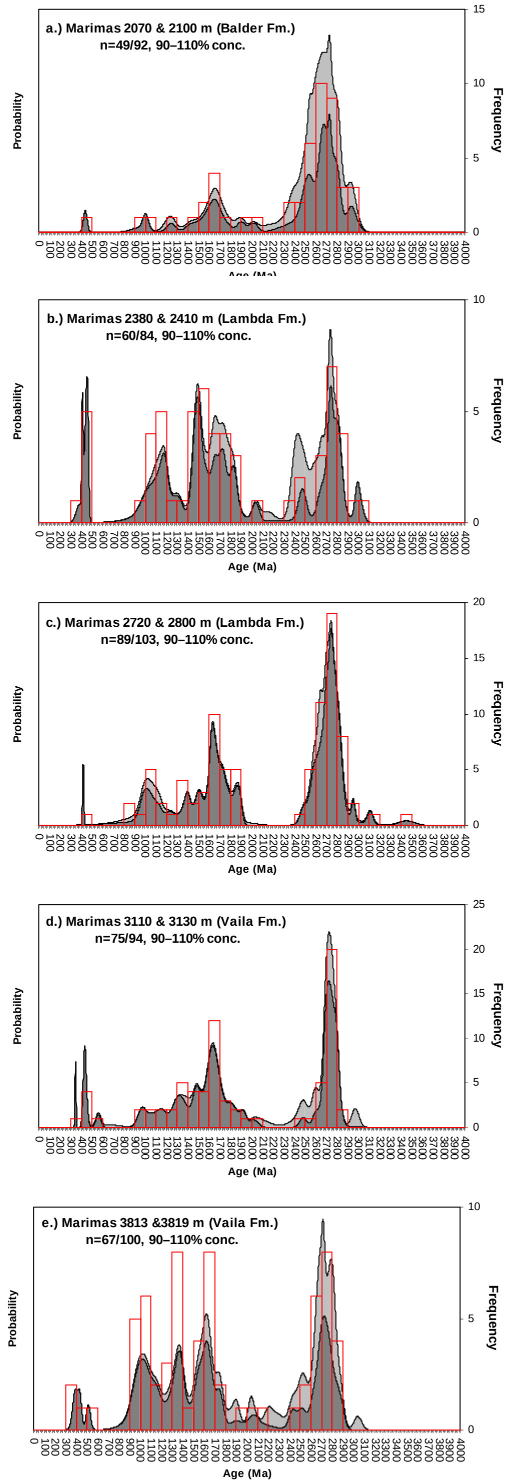


Figure 5. *Detrital zircon age pattern of samples from well 6004/17-1 Marimas displayed in vertically stacked probability density diagramms combined with histogram plots in stratigraphic order through the Paleocene to the Eocene. Note that 2 sigma errors have been used for construction of the PDDs.*

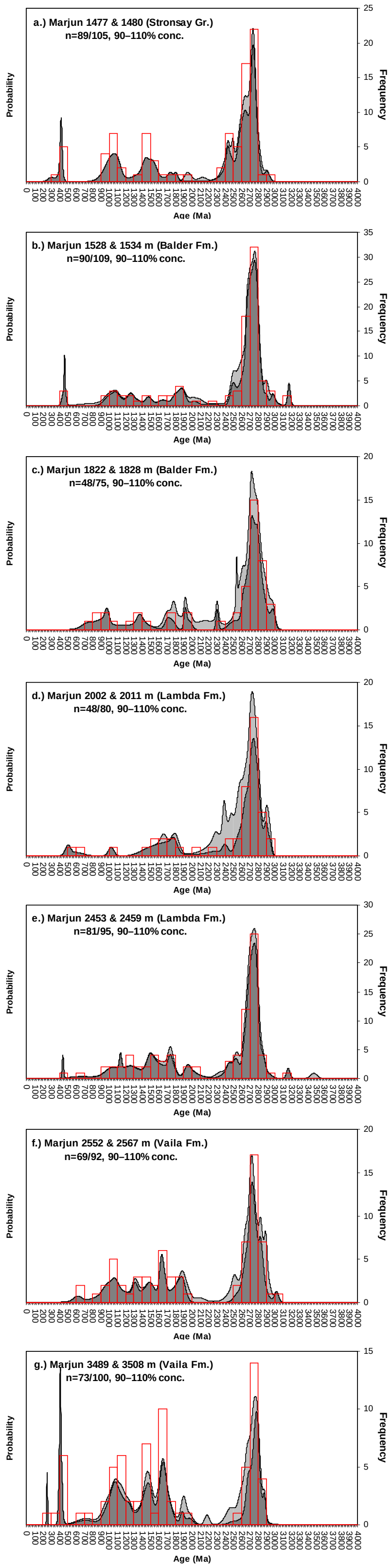


Figure 6. *Detrital zircon age pattern of samples from well 6004/16-1z Marjun displayed in vertically stacked probability density diagramms combined with histogram plots in stratigraphic order through the Paleocene to the Eocene. Note that 2 sigma errors have been used for construction of the PDDs.*

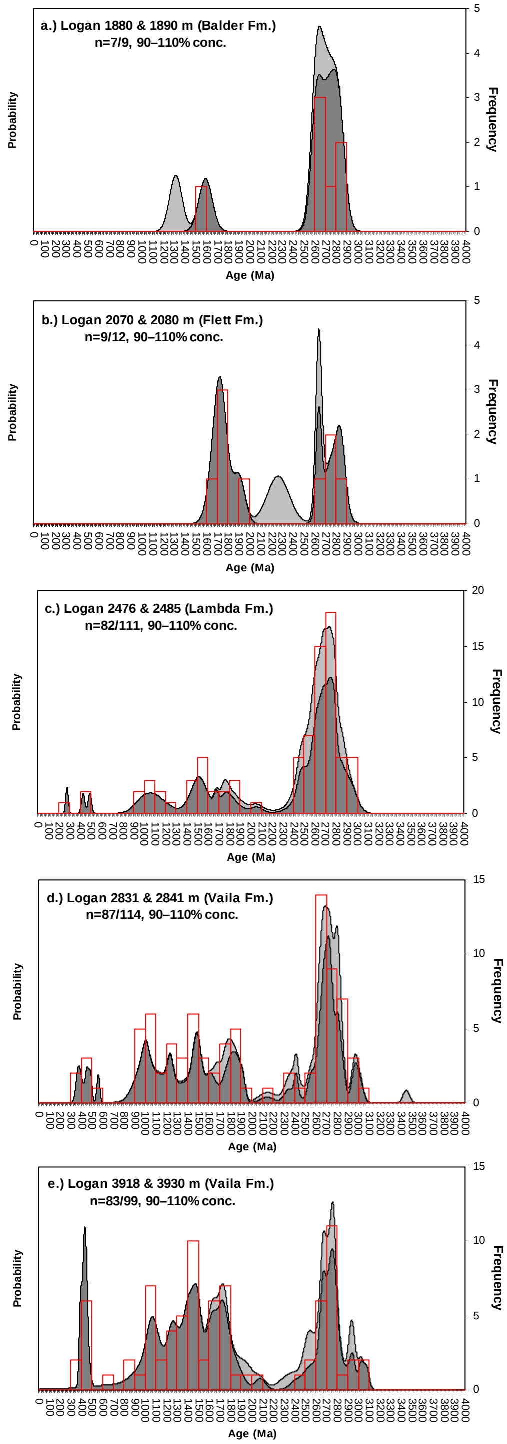


Figure 7. *Detrital zircon age pattern of samples from well 6005/15-1 Longan displayed in vertically stacked probability density diagramms combined with histogram plots in stratigraphic order through the Paleocene to the Eocene. Note that 2 sigma errors have been used for construction of the PDDs.*

Well 6004/17-1 Marimas

With the exception of the uppermost Balder Fm., the modes of the Late Archean to Early Proterozoic group (30 to 50%) and the Mid Paleoproterozoic to Early Neoproterozoic group (40 to 60 %) are relatively constant throughout the stratigraphic profile (Figs. 5 a – e). In the Balder Fm., the Late Archean to Early Proterozoic group is dominant and forms 67% of the zircon population (Fig. 5 a), whereas only 26% belongs to the Mid Paleoproterozoic to Early Neoproterozoic group. The zircon age pattern of the upper part of the Lambda Fm. (Figs. 5 b) is characterised by a the occurrence of a prominent Paleocene (~450 Ma) peak that forms 10% of the entire population.

Well 6004/16-1z Marjun

The zircon age pattern show the discontinuous change in relative abundance of the Late Archean to Early Proterozoic and Mid Paleoproterozoic to Early Neoproterozoic groups with increasing stratigraphic level from the Paleocene to the Eocene described above (Fig. 4). However, the abundance of the Mid Paleoproterozoic to Early Neoproterozoic group is much lower compared to the other wells: From the Vaila Fm. (Fig. 6 g) to the Balder Fm. (Fig. 6 b) the mode of the Late Archean to Early Proterozoic group discontinuously increases from 30 % to approx. 60%, whereas the mode of the Mid Paleoproterozoic to Early Neoproterozoic group discontinuously decreases from modes as high as 53% in the Vaila Fm. (Fig. 6 g) to 23% in the Balder Fm. (Fig. 6 b). The zircon age pattern of the Vaila Fm. (Fig. 6 g) is characterised by a the occurrence of a prominent Ordovician (~410 Ma) peak that forms 8% of the entire population and a singular Permian zircon (250 Ma).

Well 6005/15-1 Longan

Unfortunately, the samples collected from the Balder and Flett Fms. of the Longan well yielded only 9 and 12 zircons, respectively (Fig. 7 a and b). Hence, the zircon age pattern are insufficient for interpretation and are only provided for information. However, the general trend of an increasing relative abundance of the Late Archean to Early Proterozoic and a decreasing relative abundance of Mid Paleoproterozoic to Early Neoproterozoic groups with increasing stratigraphic level from the Paleocene to the Eocene described for the Svinoy, Marimas and Marjun wells is also evident in the Longan well. From the Vaila Fm. (Fig. 7 e) to the Lambda Fm. (Fig. 7 c) the mode of the Late Archean to Early Proterozoic group discontinuously increases from 28 % to approx. 67%, whereas the mode of the Mid Paleoproterozoic to Early Neoproterozoic group discontinuously decreases from modes as high as 59% in the Vaila Fm. (Fig. 7 e) to 29% in the Lambda Fm. (Fig. 7 c). Similar to the Svinoy and Marjun wells, the zircon age pattern of the Vaila Fm. (Fig. 7 e) is characterised by a the occurrence of a prominent Ordovician (~430 Ma) peak that forms 10% of the entire population.

Discussion

Source terranes

From the paleogeographic position of the Faroer Islands prior to Paleogene sea-floor spreading it is apparent that the southern East Greenland basement and the UK margin, i.e., the Hebridian foreland and the Scottish mainland (Torridonian, Moine, Dalradian) are the primary source areas which might have supplied the majority of detritus to the Faroe-Shetland basin. The geochronological structure of the basement blocks that are considered to be the primary source of the age components present southern East Greenland and the UK margin are illustrated in Figure 8.

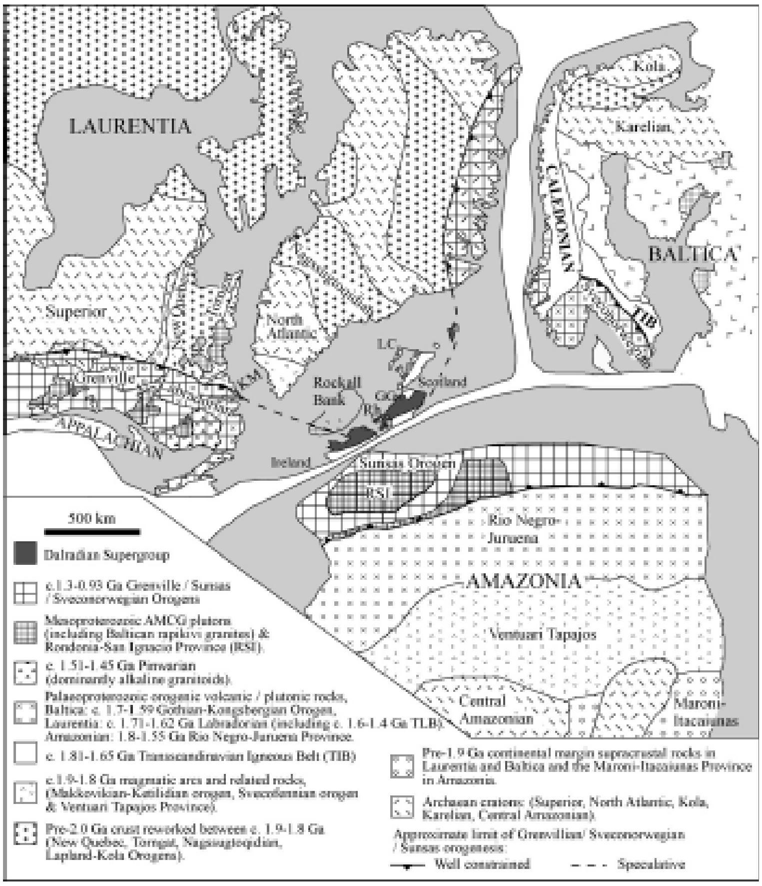


Figure 8. *Paleogeographic reconstruction of Rodinia during the Neoproterozoic (c. 700 Ma) depicting the geochronological structure of the basement blocks that are considered to be the primary source of the age components present in southern East Greenland and the UK margin (KM: Ketilidian-Makkovikian orogenic belt; LC: Lewisian Gneiss Complex; Rh: Rhinnian Complex; RSI: Rhodonian-San Ignacio Province; TIB: Transcandinavian Igneous Belt). Adapted from Banks et al. 2007 and Cawood et al. 2003.*

Southern East Greenland source

As illustrated in Figure 8, East Greenland is primarily composed of 4 main crustal elements (e.g., Kalsbeek et al., 2008; Henriksen et al. 2000):

(1) the Archean North Atlantic craton (~3600 to 2600 Ma);

(2) Archean crust reworked during the Nagssugtoqidian orogeny (between c. 2000 to 1800 Ma);

(3) the Paleoproterozoic magmatic arcs and related rocks of the Ketilidian orogen (c. 1900 to 1800 Ma); and

(4) Archean crust reworked during late Grenvillian times (ca. 950 Ma) and reworked and intruded by magmatic rocks during the Caledonian orogeny (c. 450 to 390 Ma).

Additionally, the Krummedal metasedimentary sequence exposed in northern East Greenland contains a range of Late Paleo- to Mesoproterozoic detrital zircons (Kalsbeek et al., 2008; and references therein). Because of the similarity in the detrital zircon age spectra, the Krummedal sequence is correlated with the Moine Supergroup of NW Scotland and metasedimentary sequences present in the Caledonian thrust units of Scandinavia and in Svalbard. The detritus for these sediments are most likely derived from the Grenvillian-Sveconorwegian orogen, where granitoid rocks with ages between 1700 and 1000 Ma are prominent (Kalsbeek et al., 2008; and references therein).

Because of the proximity of the Kangerlussuaq basin to the Faroe-Shetland area prior to continental break-up in the Paleogene and subsequent sea-floor spreading (Fig. 1), the approximately 900 m thick sucession of Cretaceous-Early Eocene sediments exposed in the Kangerlussuaq basin are considered to be a valuable analogue for the Faroe-Shetland basin (e.g., Whitham et al., 2004). The detrital zircon U-Pb geochronology of the sedimentary succesions have been studied in great detail by Whitham et al. (2004) and Frei et al. (2005). Both studies demonstrated that the succession can be subdivided into three units separated by major unconformities and that major changes occurred in the sediment supply to the Kangerlussuaq basin related to these unconformities:

(1) During the Early- to Late Cretaceous, sediments were derived from local Archean sources.

(2) Thermal subsidence during Late Cretaceous to Late Paleocene promoted sourcing of Proterozoic detritus from the north and south.

(3) Rifting associated with rift flank uplifting during the Late Paleocene-Early Eocene resulted in a return to sediment sourcing from local Archean sources.

The age signatures of the sediments can therefore be regarded as an approximation for the general detrital zircon U-Pb age signature of the southern East Greenland source. For comparison purposes, we have therefore calculated an average detrital zircon age signature for the sediments in the Kangerlussuaq basin (Fig. 9). This average Kangerlussuaq signature is based on 519 individual SHRIMP and LA-SF-ICP-MS (Whitham et al., 2004, and Frei et al., 2005, respectively) zircon U-Pb age determinations.

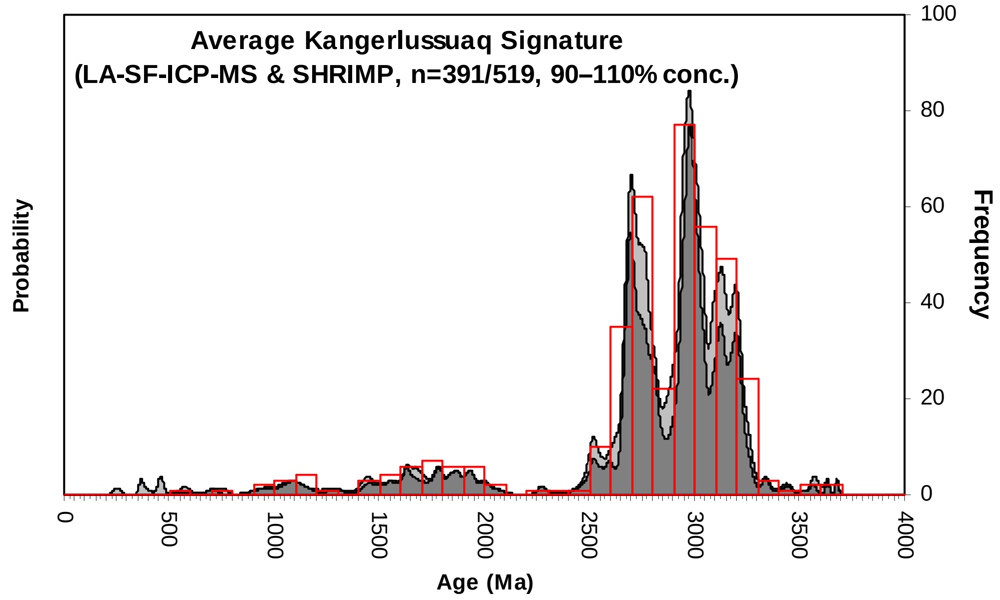


Figure 9. *Average detrital zircon age pattern of the Kangerlussuaq basin, southern East Greenland, displayed in a combined relative probability/histogram plot. The age pattern have been calculated using only samples for which LA-SF-ICP-MS (Frei et al., 2005; samples 406736, 412784, 455112, and 413245) or SHRIMP (Whitham et al., 2004; samples W4629, W4627, and P5219) age determinations have been available. No LA-SF-ICP-MS analysis are available for samples from the Late Cretaceous to Late Paleocene stratigraphic groups 4, 5, and 6. Because these groups contain abundant Paleo- to Mesoproterozoic zircons, the modal proportion of the Paleo- to Mesoproterozoic zircon populations is underestimated in the average Kangerlussuaq age signature calculated. Note that 2 sigma errors have been used for construction of the PDD.*

The average detrital zircon age pattern of the Kangerlussuaq basin contains a wide range of ages from the Eoarchean (~3700 Ma) to the Permian (~250 Ma). The most striking feature is the modally dominant group of Eoarchean to Neoarchean zircons with four distinct peaks at approximately ~3200, ~3130, ~2980, and 2740 Ma that reflect a > 1000 Ma period of crustal evolution during the Archean. Furthermore, the pattern contains modally significant Mid Paleoproterozoic to Late Mesoproterozoic age groups that are consistent with reworking of Archean crustal domains during the Nagssugtoqidian, Ketilidian, and Grenvillian orogenic events or derived from metasediments (e.g., Krummedal) that contain detritus derived from the Grenvillian-Sveconorwegian orogen. Additionally, the age pattern contain modally minor Paleozoic age groups, the most significant which of can be related to the Caledonian orogen of northern East Greenland.

UK margin source characteristics

A large body of zircon U-Pb age data exists for the main sources of detritus from the UK margin (e.g., Banks et al., 2007; Cawood et al., 2007; Cawood et al., 2004; Cawood et al., 2003; Kirkland et al., 2008; Kinnaird et al, 2007; Mason et al., 2004; Rainbird et al., 2001; Whitehouse and Bridgewater, 2001; Whitehouse et al, 1997):

(1) the Archean Lewisian Gneiss Complex (c 3000 to 2500 Ma); and

(2) the thick, siliciclastic sedimentary successions of the Torridonian, Moine and Dalradian Supergroups exposed on the Scottish mainland that represent intracratonic basins filled during the break-up of Rodinia.

Because the UK margin occupied a unique position within the Neoproterozoic supercontinent Rodinia, lying close to the junction of Laurentian, Amazonian and Baltican continental blocks, the detrital zircon age pattern of the Torridonian, Moine and Dalradian Supergroups cover a wide range of age components including Archean, Paleo-, Meso-, and Neoarchean ages. All three units have been metamorphosed and intruded by granites during the Caledonian orogeny. Additionally all three units have been affected by Carboniferous and Permian igneous and extrusive magmatism (e.g., Heeremans et al., 2004; Monaghan and Pringle, 2004) that is supposed to persisted as late as 250 Ma in the Orkneys (Upton et al., 2004).

Southern East Greenland – A source of detritus for the Faroe-Shetland basin?

As outlined above, the detrital zircon U-Pb age pattern for all samples analysed from the four wells studied in the Faroese sector of the Faroese-Shetland basin (i.e., 6004/12-1 Svinoy, 6004/16-1z Marjun, 6004/17-1 Marimas, and 6005/15-1 Longan) are generally remarkably similar. The main differences observed are within-well changes in the modal proportion of Archean to Proterozoic zircons, with a general decrease in the modal abundance of Proterozoic zircons with decreasing stratigraphic age being observed. These changes appear to be consistent in-between all four wells.

In order to compare the detrital zircon U-Pb age pattern of the sedimentary successions drilled in the wells in the Faroese (this study) and the UK (Frei et al., 2005) sector of the Faroe-Shetland basin with the age pattern of the proposed southern East Greenland and UK margin source terranes, we have calculated average detrital zircon age signatures in a similar fashion as for the sediments exposed in the Kangerlussuaq basin (see above). For the wells in the Faroese sector, a wealth of high quality LA-SF-ICP-MS age dates exist. The average detrital zircon age signature has therefore been calculated using only fully concordant analysis (i.e., applying a concordance criteria of 97 – 103%). In contrast, only 139 zircon U-Pb age dates obtained by LA-SF-ICP-MS are available from wells 204-19-3a and 205-9-1 in the UK sector. Therefore, a less strict concordance criteria (90 – 110 %) has been applied. However, it should be pointed out that application of a more conservative concordance criteria (e.g., 97 – 103 %) does not change the resulting age pattern.

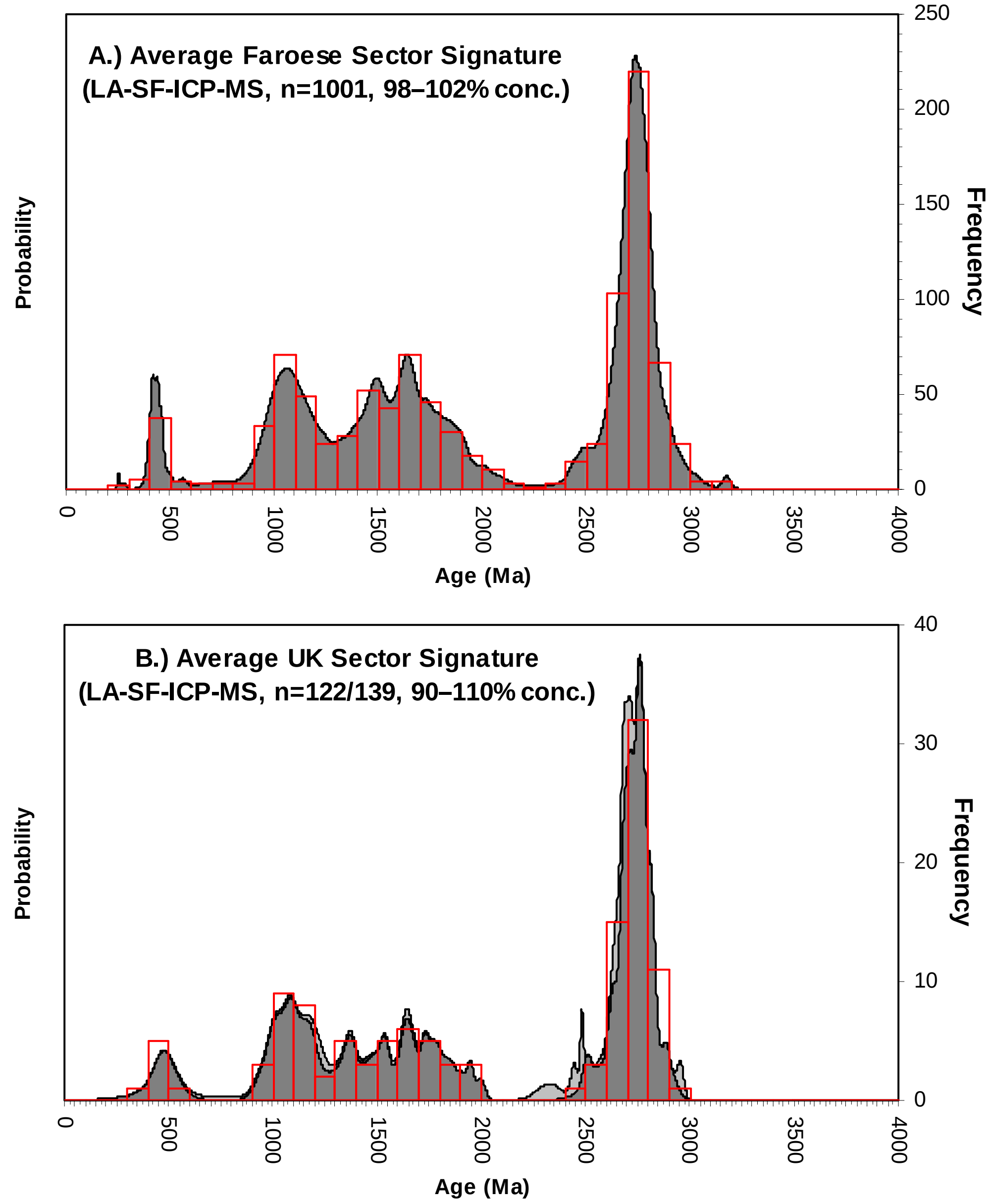


Figure 10. *Average detrital zircon age pattern of (A) wells in the Faroese sector (this study) of the Faroe-Shetland basin (b) and wells in the UK sector (Frei et al. 2005) of the Faroer-Shetland basin. Note that only age determinations carried out by LA-SF-ICP-MS have been used for calculating the PDD diagrams. Note that 2 sigma errors have been used for construction of the PDDs.*

The most striking observation is that the resulting detrital zircon age signatures for wells from the Faroese (Fig. 10a) and the UK (Fig. 10b) sector are remarkably similar. The average detrital zircon age pattern in both sectors are dominated by an almost unimodal distribution of Meso- to Neoarchean zircons ranging from ~3000 Ma to ~2450 Ma with a pronounced peak at approximately 2750 - 2850 Ma. In total, only 8 grains with ages > 3000 Ma have been detected, and none of these grains is older than 3200 Ma. Furthermore, the age distribution shows a very characteristic tail on the left hand side at ages around ~2500 Ma. Additionally, the pattern contains modally significant Mid Paleoproterozoic to Late Mesoproterozoic age peaks around 1900-1800 Ma, 1700 Ma, 1500 Ma and 1100 Ma as well as an age group ranging from 470 to 440 Ma.

Clearly, the Archean age pattern observed in sediments in both the Faroese and the UK sector of the Faroe-Shetland basin are in marked disagreement with those observed for the proposed southern East Greenland source (Fig. 9), namely (1) the almost unimodal distribution with an age peak at ~2750 (in contrast to a multi-stage crustal evolution with at least four age peaks in the southern East Greenland source); and (2) the almost complete absence of zircons with ages > 3000 Ma (in contrast to a modally dominant occurrence of this age group in southern East Greenland source).

However, these characteristic Archean age pattern are in almost perfect agreement with the zircon age pattern observed for the Hebridian foreland. The Hebridian foreland is dominated by an intensive period of magmatism with major pulses at ca. 2850 Ma and 2750 Ma (Whitehouse et al., 1997; and references therein) and a later high temperature metamorphic overprint at 2500 to 2450 Ma. This high temperature metamorphic event lead to extensive lead loss from zircons, causing a shift along a narrow cord along the concordia and resulted in a pronounced occurrence of zircons with apparently “concordant” ages between 2450 and 2850 Ma (Friend and Kinny, 1995; Kinny and Friend, 1997). We therefore argue that the observed Archean zircon age pattern of the sediments drilled in Faroe-Shetland basin can be unequivocally related to the zircon age pattern observed in the Hebridian foreland. Hence, the overwhelming majority of Archean detritus present in the wells drilled in the Faroe-Shetland basin must therefore be derived from the west, i.e., the UK margin, as already proposed for the wells in the UK sector of the Faroe-Shetland basin.

The interpretation of the Proterozoic and Paleozoic zircon age groups is less straightforward. As already pointed out above, these age groups are present in both the southern East Greenland and the UK margin source terranes. Hence, in the absence of Hf-isotopic data that would allow further constraints on potential source areas, their relation to the proposed sources is equivocal. However, in southern East Greenland, Proterozoic and Paleozoic zircons are mainly derived by reworking of older, Archean crust during Nagssugtoqidian, Ketilidian, Grenvillian and Caledonian tectonothermal events and it is yet unclear to what extent these reworked Archean crustal domains are fertile for zircons formed during these Proterozoic and Paleozoic orogenic events. The relative modest modal occurrence of Proterozoic and Paleozoic zircons in the southern East Greenland source argues for a relative infertility of the reworked Archean domains for these age groups. Moreover, a sourcing of the Proterozoic to Paleozoic zircon detritus observed in the Faroe-Shetland basin from southern East Greenland would require a mechanism that decouples the transport of Proterozoic and Paleozoic zircon detritus from Archean zircon detritus. Such a decoupling to occur in an Archean terrane that has been reworked during the Proterozoic and Paleozoic is implausible.

In contrast, all Proterozoic to Paleozoic zircon age groups observed in the Faroe-Shetland basin are, as outlined above, present in the thick, siliciclastic Dalradian, Moine, and Torridonian Supergroups exposed on the Scottish Mainland that have been deposited in intracratonic rifts during the attempted break-up of Rodinia (Cawood et al., 2007). Furthermore, the Scottish Mainland has been affected by Caledonian magmatism and metamorphism as well as Permian magmatism. It is therefore the most likely and straightforward scenario that the overwhelming majority of the Proterozoic and Paleozoic zircon detritus present in the Faroe-Shetland basin has been derived from the west, i.e., the UK margin.

If this scenario is correct, the general decrease in the modal abundance of the Proterozoic zircons relative to the Archean zircons with decreasing stratigraphic age that is observed in all wells in the Faroe-Shetland basin suggests that the more distal source (i.e., the Scottish Mainland) has subsequently become less important during the Paleocene whereas the more proximal source (i.e., the Hebridian Foreland) has become more important. This would imply that either erosion of the Scottish Mainland ceased during the Paleocene or that the direction of sediment transport changed, possibly due to different uplift histories in the Hebridian Foreland and the Scottish Mainland.

Conclusions

The detrital zircon U-Pb age pattern obtained for sediments drilled in the wells 6004/12-1 Svinoy, 6004/16-1z Marjun, 6004/17-1 Marimas, and 6005/15-1 Longan obtained in this study allows to draw some general conclusions and to place tight constraints on sediment dispersal pattern in the Faroe-Shetland basin:

- The detrital zircon U-Pb age signatures in all samples from all four wells in the Faroese sector investigated are very similar. The most prominent differences are changes in the relative modal abundances of Archean to Proterozoic/Paleozoic zircons as a function of stratigraphic position in the well.
- The detrital zircon U-Pb age pattern in the wells in the Faroese sector are similar to those observed in wells in the UK sector of the Faroese-Shetland basin.
- The unique Archean age pattern observed for all samples from wells in the Faroese and the UK sector of the Faroe-Shetland basin suggest that the overwhelming majority of the sediments are sourced from the UK margin, i.e., the Hebridian Foreland and the Scottish Mainland.
- No evidence could be found for a major role of southern East Greenland as a source of sediment for the Faroe-Shetland basin.

The findings of this study verify the conclusion of Frei et al. (2005) that detrital zircon U-Pb geochronology provides a robust framework for the interpretation of sedimentary provenance in the Faroe-Shetland basin and hence constitutes a powerful tool for future hydrocarbon exploration.

Recommendations for future work

The results obtained in this study as well as those presented by Whitham et al. (2004) and Frei et al. (2005) clearly demonstrate the usefulness of detrital zircon U-Pb age dating for qualitatively and quantitatively constraining the sources of sediments present in the Faroe-Shetland basin. The information obtained in these studies represent a solid database for a number of recommended studies that will allow further elucidation of the main pathways for sediment transport in the Northeast Atlantic:

- The detrital zircon U-Pb age signatures of the sediments drilled in wells in the UK (Frei et al., 2005) and the Faroe sector (this study) so far provide little evidence for large-scale sediment transport from the West (i.e., southern East Greenland) into the Faroe-Shetland basin. However, the proposed Greenlandic source is expected to be more important for sediments more proximal to the Faroer Islands (and hence more proximal to the Greenlandic source). We therefore suggest to carry out a detrital zircon U-Pb age dating study on the sediments drilled in the new well 6104/21-1 (Brugdan, operated by Statoil) which is located closer to the Greenlandic source. This data would also complement the now existing substantial database for detrital zircon U-Pb age signatures in the Faroe-Shetland basin and its potential source areas.
- In order to make full use of the already substantial amount of U-Pb zircon age data (for detrital, magmatic and metamorphic zircons) available for the Faroe-Shetland basin and adjacent areas, we suggest to incorporate the data produced in this and previous studies (e.g., Whitham et al., 2004; Frei et al., 2005) into the internet-based GIS database that is currently under development at GEUS.
- As outlined above and in several other studies (e.g., Whitham et al., 2004; Jolly and Morton, 2007) the sediments exposed in the Kangerlussuaq basin in southern East Greenland are considered as one of the main sources for sediment input into the Faroe-Shetland basin. The majority of the available detrital zircon age data for the sediments exposed in the Kangerlussuaq basin are based on Pb-Pb analysis by LA-Q-ICP-MS (Frei et al., 2005). Unfortunately, Pb-Pb analysis does not allow to check for concordance of the individual zircon age determinations and their interpretation is hampered by a comparably large errors, leading to broad age peaks in PDD plots not amenable for more sophisticated interpretation. We therefore suggest to re-analyse the detrital zircon samples analysed by Frei et al. (2005) with the new LA-SF-ICP-MS facility at GEUS, which allows U-Pb age dating and thereby offers the possibility for checking concordance of individaul zircon age dates and drastically improves the precision of the individual age determinations (Frei and Gerdes, 2008).
- The currently biggest impediment for the interpretation of the detrital zircon U-Pb age signatures of sediments present in the Faroe-Shetland basin (and the entire Northeast Atlantic) is the currently limited knowledge of the age structure of the sources areas in question (UK margin, Rockall plateau and East Greenland). This is especially true for East Greenland, where only a very limited number of geochronological studies exist that address the age structure of the basement. This is exacerbated by the fact that many of the available studies are based on only few U-Pb age data. We therefore suggest to rectify this state of ignorance by studying the detritial zircon U-Pb signatures of

stream sediments and tillites in order to characterise the age structure of the currently exposed and subglacial basement terrains in East Greenland, similar to the succesful approaches to characterise the provenance characteristics of the Scandinavian basement terrains (Morton et al., 2008) and subglacial basement terrains in Antarctica (Veevers et al., 2008).

- Sediment sources to the east and the west of the North Atlantic are all characterised by an high proportion of Proterozoic and Paleozoic zircon age groups that can not be unequivocally related to one source. The application of Hf-isotope analysis to these zircon age groups might allow distinction of zircon sources with similar age and is therefore expected to provide valueable new information about sediment sources.
- The apparent temporal change in relative sediment supply from the Scottish Mainland and the Hebridian Foreland during the Paleocene underscores the importance for relating the provenance sensitive features of sediments to the uplift history of the proposed source areas.

References

Bingen, B., Birkeland, A., Nordgulen, Ø., Sigmond, E.M.O. 2001: Correlation of supracrustal terranes in the Sveconorwegian orogen of SW Scandinavia: SIMS data on zircon in clastic metasediments. Precambrian Research **108**, 293-318.

Banks, C.J., Smith, M., Winchester, J.A., Horstwood, M.S.A., Noble, S.R., Ottley, C.J. 2007: Provenance of intra-Rodinian basin-fills: the lower Dalradian Supergroup, Scotland. Precambrian Research **153**, 46-64.

Cawood, P.A., Nemchin, A.A., Smith, M., Loewy, S. 2003: Source of the Dalradian Supergroup constrained by U-Pb dating of detrital zircon and implications for the East Laurentian margin. Journal of the Geological Society **160**, 231-246.

Cawood, P.A., Nemchin, A.A., Starchan, R.A., Kinny, P.D., Loewy, S. 2004: Laurentian provenance and an intrcratonic tectonic setting for the Moine Supergroup, Scotland, constrained by detrital zircons from the Loch Eil and Glen Urquhart successions. Journal of the Geological Society **161**, 861-874.

Cawood, P.A., Nemchin, A.A., Starchan, R.A., Prave, T., Krabbendam, M. 2007: Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and breakup of Rodinia. Journal of the Geological Society **164**, 257-275.

Frei, D., Rasmussen, T., Frei, M., Knudsen, C., Larsen, M. 2005: Detrital zircon age constraints on provenance of Paleocene-Eocene sandstones in the Faroe-Shetland Basin. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/54**, 93-105.

Frei, D., Gerdes, A. (2008) Precise and accurate in-situ U-Pb dating of zircon with high sample throughput by automated LA-SF-ICP-MS. Chemical Geology (in press).

Hass, G.J.M.L., de, Andersen, T., Vestin., J. 1999: Detrital zircon geochronology: new evidence for an old model for accretion of the Southwest Baltic Shield. Journal of Geology **107**, 569-586.

Heeremans, M., Timmermann, M.J., Kirstein, L.A., Faleide, J.I. 2004: New constraints on the timing of late Carboniferous – early Permian volcanism in the central North Sea. Geological Society of London, Special Publications **223**, 177-193.

Henriksen, N., Higgins, A.K., Kalsbeek, F., Pulvertaft, C.R. 2000: Greenland from Archean to Quaternary. Geology of Greenland Survey Bulletin **185**, 93 pp.

Jolley, D.W., Whitham, A.G. 2004: A stratigraphical and paleoenvironmental analysis of the sub-basaltic Paleogene sediments of east Greenland. Petroleum Geoscience **9**: 53-60.

Jolley, D.W., Morton, A.C. 2007: Understanding basin sedimentary provenance: evidence from allied phytogeographic and heavy mineral analysis of the Paleocene of the NE Atlantic. Journal of the Geological Society **164**, 553-563.

Kalsbeek, F., Thrane, K., Higgins, A.K., Jepsen, H.F., Leslie, A.G., Nutman, A.P., Frei, R. 2008: Polyorogenic history of the East Greenland Caledonides. *In* Higgins, A.K., Gilotti, J.A., Smith, M.P., eds. 2008: The Greenland Caledonides: Evolution of the Northeast margin of Laurentia. Geological Society of America Memoir **202**, 55-72.

Kinnaird, T.C., Prave, A.R., Kirkland, C.L., Horstwood, M., Parrish, R., Batchelor, R.A. 2007: The late Mesoproterozoic – early Neoproterozoic tectonostratigraphic evolution of NW Scotland: the Torridonian revisited. Journal of the Geological Society **164**, 541-551.

Kirkland, C.L., Strachan, R.A., Prave, A.R. 2008: Detrital zircon signature of the Moine Supergroup, Scotland: contrasts and comparison with other Neoproterozoic successions within the circum-North Atlantic region. Precambrian Research **163**, 332-350.

Larsen, M., Nøhr-Hansen, H., Whitham, A.G., Kelly, S.R.A. 2005: Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin. Volcanic basins of the North Atlantic. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/62**.

Mason, A.J., Parrish, R.R., Brewer, T.S. 2004: U-Pb geochronology of Lewisian orthogneisses in the Outer Hebrides, Scotland: implications for the tectonic setting and correlation of the South Harris Group. Journal of the Geological Society **161**, 45-54.

Monaghan, A.A., Pringle, M.S. 2004: 40Ar/39Ar geochronology of Carboniferous-Permian volcanism in the Midland Valley, Scotland. Geological Society of London, Special Publications **223**, 219-241.

Morton, A.C., Fanning, M., Milner, P. 2008: Provenance characteristics of Scandinavian basement terrains: Constraints from detrital zircon ages in modern river sediments. Sedimentary Geology **210**, 61-85.

Rainbird, R.H., Hamilton, M.A., Young, G.M. 2001: Detrital zircon geochronology and provenance of the Torridonian, NW Scotland. Journal of the Geological Society **158**, 15-27.

Upton, B.G.J., Stephenson, D., Smedley, D.M., Wallins, S.M., Fitton, J.G. 2004: Carboniferous and Permian magmatism in Scotland. Geological Society of London, Special Publications **223**, 195-218.

Veevers, J.J., Saeed, A., O´Brien, P.E., 2008: Provenance of the Gamburtsev subglacial mountains from U-Pb and Hf analysis of detrital zircons in Cretaceous to Quarternary sediments in Prydz Bay and beneath the Amery Ice Shelf. Sedimentary Geology **211**, 12-32.

Whitham, A.G., Morton, A.C., Fanning, C.M. 2004: Insights into Cretaceous-Paleogene sediment transport paths and basin evolution in the North Atlantic from a heavy mineral study of sandstones from southern East Greenland. Petroleum Geoscience **9**: 61-72.

Whitehouse, M.J., Bridgwater, D. 2001: Geochronological constraints on Paleoproterozoic crustal evolution and regional correlations of the northern Outer Hebridean Lewisian Gneiss Complex. Precambrian Research **105**, 227-245.

Whitehouse, M.J., Claesson, S., Sunde, T., Vestin, J. 1997: Ion microprobe U-Pb zircon geochronology and correlation of Archean gneisses from the Lewisian Complex of Gruinard Bay, northwestern Scotland. Geochimica and Cosmochemica Acta **61**, 4429-4438.

Provenance of sediments in the Faroe-Shetland Basin: constraints from whole-rock geochemistry.

Rikke Weibel, Christian Knudsen

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark

Summary

The present investigation of the provenance of the sediments in the Faroese wells: Marjun (6004/16-1), Svinoy (6004/12-1), Marimas (6004/17-1) and Longan (6005/15-1) was initiated in order to attain improved understanding of the regional geology in the Faroe-Shetland Basin. Previous works, as heavy mineral analyses and investigations of terrigenous palynoflora from the UK sector, have shown that an East Greenlandic source dominated over a source from the Orkney-Shetland Platform during Early Late Paleocene (Vaila Formation) and even continued during Late Paleocene (Lamba Formation) (Jolley & Morton 2007). In contrast, previous bulk geochemical investigations and zircon age determination of UK wells and East Greenlandic outcrops could not consolidate these findings (Knudsen 2005; Frei et al. 2005).

In all 126 cuttings samples from the Faroese wells were analysed by XRF (X-ray fluorescence spectrometry) for the major elements and ICP-MS (inductively coupled plasma - mass spectrometry) for the trace elements. The geochemical results are corrected for the baryte content, but caution must be applied with regard to other artefacts, for example steel chips.

Some geochemical variations occur between the Faroese wells, which may be related to the position in the basin rather than the time of deposition. These geochemical variations (for example the K_2O / Al_2O_3 and the Zr /TiO_2 ratios) may be related to differences in the provenance of the sediments. The wells that are characterized by the lowest K_2O / Al_2O_3 ratios generally have the highest Zr /TiO_2 ratio. This relationship can also be found in the UK wells nearest the investigated Faroese wells. A local source is most likely responsible for supplying sediment of high K_2O / Al_2O_3 ratios. On the contrary zirconium is abundant in the Greenlandic sediments, and a Greenlandic source could be responsible for the high Zr /TiO_2 ratio in some of the wells.

A minor change in the MgO / TiO_2 and P_2O_5 / Al_2O_3 ratios marks the transition from the Vaila Formation to the Lamba Formation. The MgO content has strong relations to the amounts of calcic amphiboles and clinopyroxene found in heavy mineral analyses performed by Morton and Hallsworth (2002a, 2002b); and titanium is typically related to Ti-rich heavy minerals. Variations in phosphorus contents could originate from different sources or possibly different depositional environments. Combined, though, the changed MgO / TiO_2 and P_2O_5 / Al_2O_3 ratios may indicate a minor change in the dominating source from an

eastern influence (for example from the Orkney-Shetland Platform) to a more western source (igneous basaltic).

The Balder and Flett formations are characterized by lower MgO / Al_2O_3 and MgO / TiO_2 ratios than the other sediments. Single samples form these formations are also distinguished from the other sediments in almost all geochemical parameters, showing that a major change in sediment source occurred at the boundary between the Lamba Formation and the Flett Formation, which most likely is related to increased input of volcanic material.

Introduction

The general aim of the SINDRI project is to achieve more information about the regional geology and the evolution of the entire Faroese area. The more specific aims are to identify provenance sensitive signatures (detrital zircon age distribution, zircon trace elements and bulk rock geochemistry) in the deeper and central parts of the Faroe-Shetland Basin. The provenance sensitive signatures should be applied in order to, if possible, qualitatively and quantitatively constrain the source areas: western, i.e., from East Greenland, or eastern, i.e., from the UK margin.

An important question relevant to hydrocarbon exploration in the Faroe-Shetland Basin is whether there is a link between the sedimentary successions exposed in East Greenland and the Faroe-Shetland Basin (Frei & Knudsen 2007). The aim of this work is to gain more knowledge of the volumes of sedimentary material derived from the western, Greenlandic source and the timing of the sedimentary input.

Here, we present the results of a study that investigated the geochemistry of the sedimentary successions drilled in the wells 6004/12-1 Svinoy (BP), 6004/16-1z Marjun (Amerada Hess), 6004/17-1 Marimas (Eni), and 6005/15-1 Longan (Statoil) in the Faroese sector of the Faroe-Shetland basin. In total, 158 samples (sandstones and mudstones) have been analysed. However, because only sandstones can be analysed for their detrital zircon U-Pb age spectra, we will confine our discussion to the results obtained for the 129 sandstones analysed for comparison purposes.

Geological setting

The Cretaceous basins of the North Atlantic rift formed during the major period of rifting in the Late Jurassic-Early Cretaceous (Larsen et al. 2005a). Larsen et al. (2005a) assumed that a single Cretaceous basin covered the area between Greenland and the North-West European margins. A cross rift supply of sediments from the Kangerlussuaq area (East Greenland, Fig. 1) to the Faroe-Shetland Basin in the Early Paleocene was suggested by Larsen & Whitham (2005) on the basis of studies of tectonic lineaments.

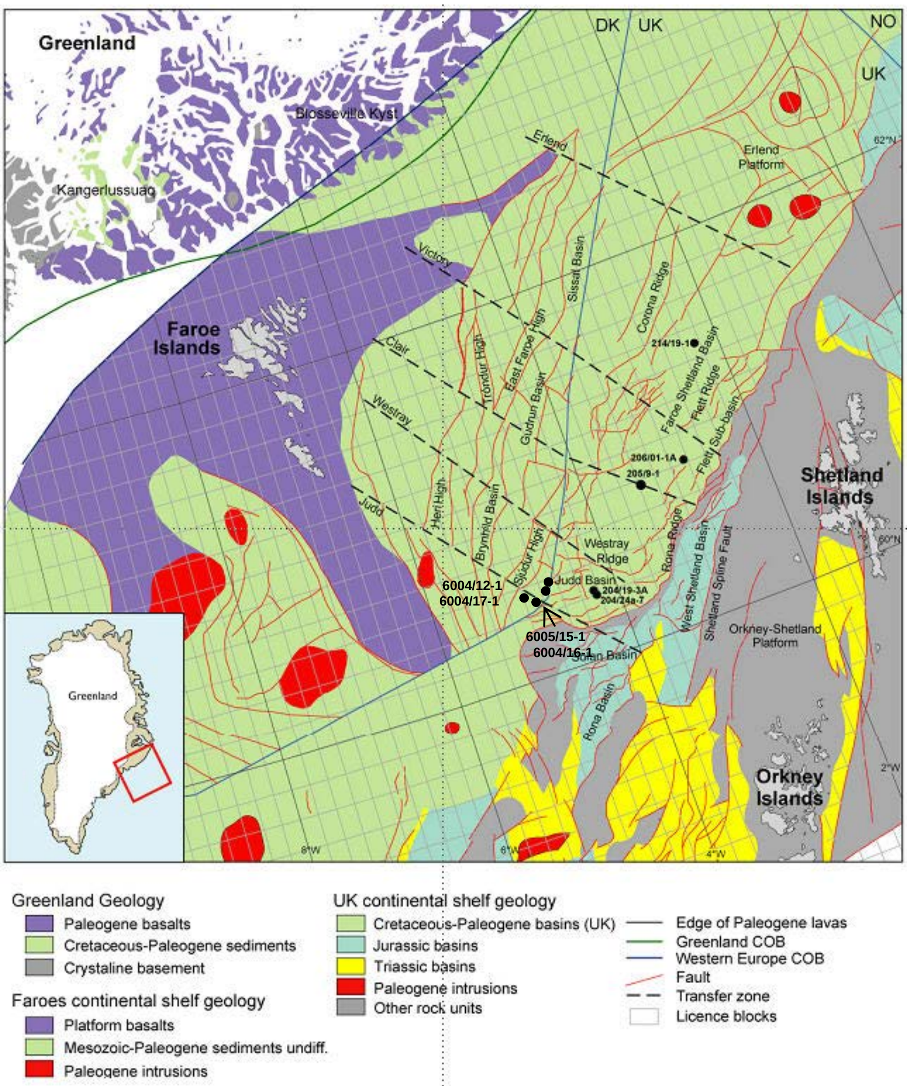


Figure 1. *Location map of East Greenland and the Faroe-Shetland region depicting the geographical position of the areas prior to the onset of seafloor spreading in the Late Paleocene-Early Eocene. Modified after Larsen et al. (2005b).*

The presence of a major unconformity is documented by palynology in the East Greenland succession (Fig. 2) spanning from the late Maastrichtian to the early Paleocene (Jolley &

Whitham 2004). The lack of sedimentation throughout the Early Paleocene and much of the late Paleocene (Fig. 2) is taken as an indication that Paleocene sedimentary systems by-passed the East Greenland Shelf, concomitantly with clastic deposition in the Faroe-Shetland Basin (Jolley & Whitham 2004).

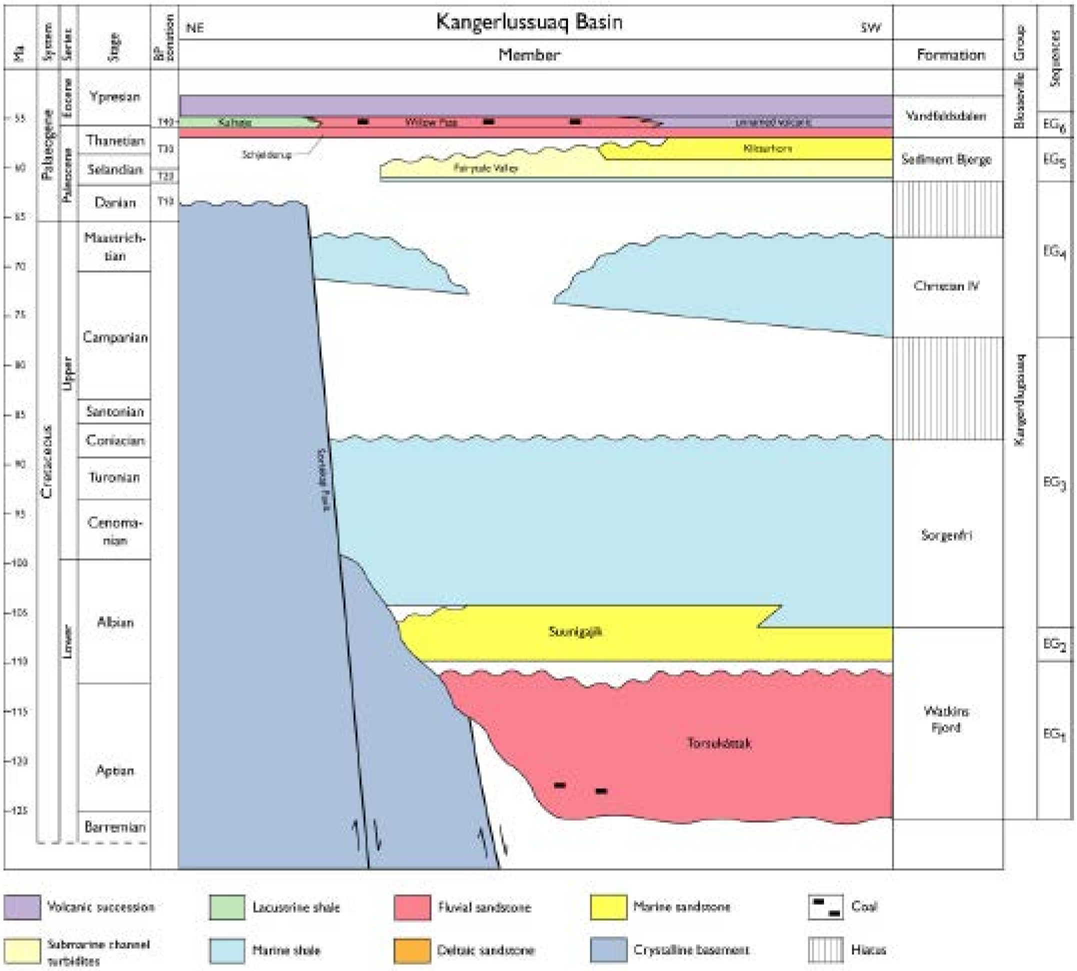


Figure 2. *Stratigraphic scheme for the Kangerlussuaq Basin, East Greeland. After Larsen et al. (2005a).*

Owing to its large size Greenland has always had the potential for supplying larger portions of sediment to the basin than the Orkney-Shetland area and the Scottish mainland (Larsen et al. 2005a). Latest, Jolley & Morton (2007) supported the sediment supply from the Kangerlussuaq area by a combination of heavy mineral analyses and investigations of terrigenous palynoflora distribution. They showed that the East Greenland source had its maximum during the deposition of the Vaila Formation (Early Late Paleocene) and even continued during the deposition of the Lamba Formation (Late Paleocene). Bulk geochemical analyses of cuttings samples from similar UK wells could not support these observations (Knudsen 2005).

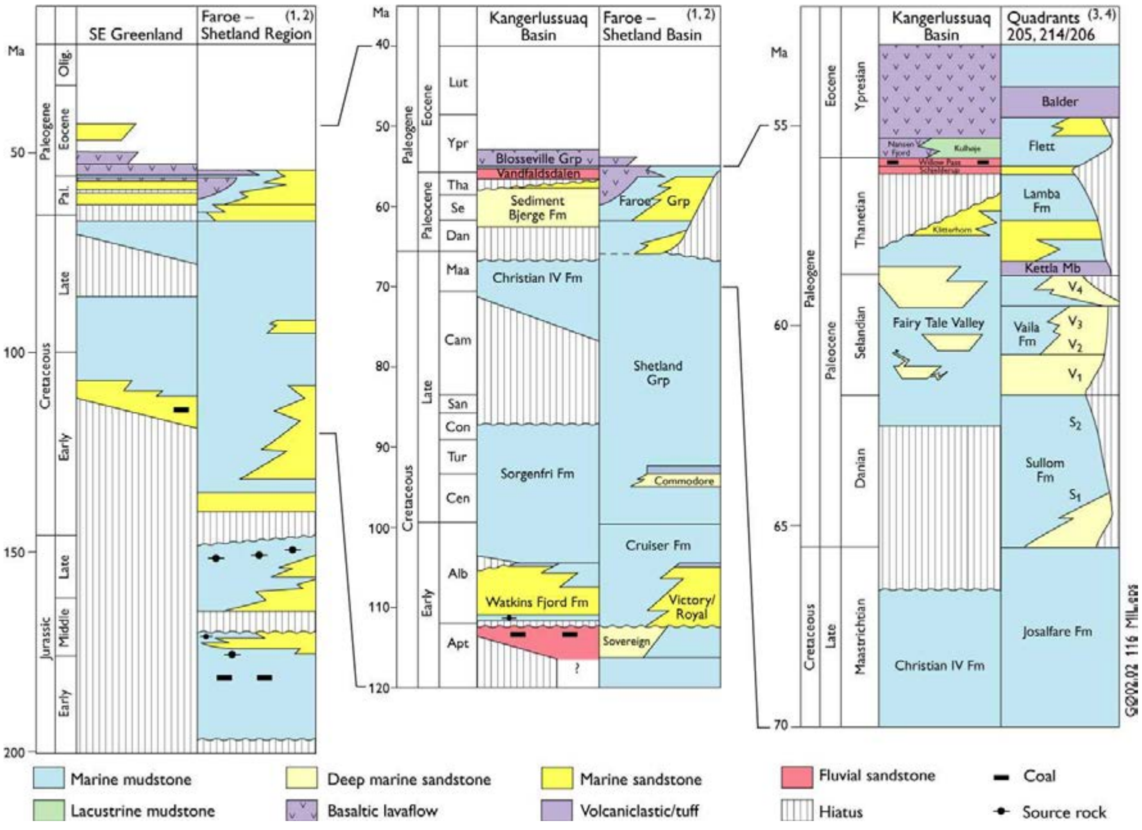


Figure 3. *Sketch of the stratigraphy in the Kangerlussuaq area and the Faroe-Shetland Basin. After Larsen et al. (2005a).*

Series	Stage	North Sea	Faroe-Shetland Basin		
		Lithostratigraphy	Lithostratigraphy		Sequence
Lower Eocene	Ypresian				
		Balder Fm	Balder Fm		T50
		Sele Fm	Flett Fm		T45
Upper Paleocene	Thanetian				T40
		Lista Fm	Lamba Fm	L2	T38
				L1	T36
				Kettla Mb	
	Selandian		Vaila Fm	V4	T35
				V3	
					T34
					T32
					T31
				V2	T28 – T25
				V1	T22
		Maureen Fm			T20
Lower Paleocene	Danian		Sullom Fm	S2	T10
		Ekofisk Fm		S1	

Figure 4. *Stratigraphic scheme for the North Sea area and Faroe-Shetland Basin. Compiled and simplified from Mudge & Bujak (2001) and Jolley & Morton (2007).*

The sediment evolution in of the Cretaceous–Paleocene succession in the Kangerlussuaq Basin finds strong parallels with successions of equivalent age in the Faroe-Shetland Basin (M. Larsen et al. 1999; Larsen et al. 2005a). Mid-Cretaceous shallow marine sandstones are overlain by Late Cretaceous mudstones in both the Kangerlussuaq Basin and the Faroe-Shetland Basin (Fig. 3; Larsen et al. 2005a). The Paleocene in both areas begins with an influx of deep marine sandstone, which is overlain by a prograding succession of pro-deltaic, fluvio-deltaic and finally fluvial sediments (Fig. 3; Larsen et al. 2005a). This succession is capped by basaltic lava flows in both areas. Lava geochemistry shows correlation of Late Paleocene-Eocene lava sequences in East Greenland and the Faroe Islands (L. M. Larsen et al. 1999). The East Greenlandic sediment supply came to an end with the incipient rifting phase (between mid-Maastrichtian and earliest Eocene) which preceded the continental separation and extrusion of flood basalt that created a barrier between Greenland and the Faroe-Shetland Basin (Jolley & Whitham 2004).

Another important similarity between the Kangerlussuaq area and the Faroe-Shetland Basin is the major sequence boundary at the base of the fluvial sediments in the Kangerlussuaq area which is suggested by Larsen et al. (2005b) to correlate with the major sequence boundary at the boundary between Paleocene and Eocene (at T40 in Fig. 4) in the Faroe-Shetland area.

Samples and Methods

For this project cuttings samples were taken from the following wells in the Faroe-Shetland Basin from the Faroese sector at the storage facility at Jardfeingi/Torshavn:

6004/12-1	Svinoy (BP)	abbreviated 4/12
6004/16-1	Marjun (Amerada Hess)	abbreviated 4/16
6004/17-1	Marimas (Eni)	abbreviated 4/17
6005/15-1	Longan (Statoil)	abbreviated 5/15

The location of the wells can be found on Fig. 1, where also the location of previously investigated wells are indicated. The previous investigations, during the 1st part of the SINDRI project, included wells from the Faroe-Shetland Basin in the UK sector (204/19-3A, 204/24A-7, 205/9-1, 206/1-1A, 214/19-1) and outcrops from the Kangerlussuaq area with contemporaneous East Greenlandic sediments (Fig. 1).

The cuttings samples were taken directly from the washed and dried cuttings. Magnetic or electrostatic removal of foreign material was avoided as it leads to preferential removal of certain minerals (i.e., rock fragments and mica).

The major elements were measured by X-ray fluorescence spectrometry (XRF) or atomic absorption spectrometry (AAS) whereas most trace elements including rare earth elements (REE) were measured by inductively coupled plasma - mass spectrometry (ICP-MS). See Frei & Knudsen (2007) for more details.

For trace elements the ICP-MS method is generally more accurate than XRF, and therefore ICP results are generally chosen instead of XRF results. However, Eu is excluded in the samples due to difficulties with correction for high barium contents. Similar problems with the ICP-MS measurements of Zn and Cu have resulted in application of respectively XRF and AAS values for these elements. XRF of Ba and Sr at extremely high concentrations are better than ICP-MS data because of difficulties in bringing and keeping them in solution; consequently XRF data for these elements have been applied for correction for baryte in the drilling mud.

The methods and techniques applied in this study are described in detail in Appendix A and the samples investigated are listed in Appendix B. The results for all 158 analysed samples are reported in electronic form as Excel-spreadsheets in the accompanying data CD.

Results and discussion

Geochemical variation between wells – local source?

Some geochemical variations show stronger affinity to the site of the well (i.e., location in the basin during deposition of the sediments) than to its appropriate member or formation. Such geochemical variations are typically related to local source areas.

One of the most distinctive features in the results is the variation in K_2O / Al_2O_3 ratios between wells, and this is independent of member and formation (Fig. 5). This relationship can be recognized in the UK sector as well, though it is less distinctive there. The ratio between K_2O and Al_2O_3 indicates whether clays or feldspars are the main contributing material. The wells from the Faroes sector generally have high K_2O / Al_2O_3 ratios compared to the UK wells. The exception is the Marjun well 6004/16-1, where most samples lie on a trend with much lower K_2O / Al_2O_3 ratios – below the illite line (Fig. 5). During deposition of the main part of the Vaila Formation in the Marjun 6004/16-1 well the K_2O / Al_2O_3 ratio was high and similar to the other wells. But at the transition from the Vaila Formation to the Lamba Formation the K_2O / Al_2O_3 ratio decreases and remains at a much lower level in the following formations in the Marjun 6004/16-1 well area. Pollution by KCl from the drilling mud could be a risk in the deepest parts of the well, but the cuttings from the Lamba Formation have their maximum K_2O content above the level of KCl introduction (2225- 4274 m). Unfortunately, information on the drilling mud composition is not available for the other wells. There does not seem to be a distinct increase in K_2O content with burial depth, so it is assumed that the washing of the cuttings samples was sufficient to remove any KCl present. The fine correlation between K_2O and Al_2O_3 for all wells, and the significant higher K_2O / Al_2O_3 ratio in the well 6005/15-, indicate that mineralogical differences must be the explanation.

In the UK sector the K_2O / Al_2O_3 ratios are generally much lower than in the Faroes sector. However, the two UK wells (204/24a-7 and 204/19-3a) closest to the investigated Faroese wells are characterized by relatively higher K_2O / Al_2O_3 ratios than the wells farther away to the North-East. Few samples (from Vaila Fm in the wells 204/24a-7 and 204/19-3a) even have K_2O / Al_2O_3 ratios above the illite line (Fig. 5).

The very low K_2O / Al_2O_3 ratio in the Faroese well 6004/16-1 close to the well 6005/15-1 which has relatively high K_2O / Al_2O_3 ratio can only be explained by extremely large local variations in deposition or by local uplift of this particular area, which may have led to diagenesis and possible leaching of K-feldspar. Rb / K_2O ratios in the Faroese and UK sector supplement the observations from the K_2O / Al_2O_3 ratios (Fig. 6), as the wells with the lowest K_2O / Al_2O_3 ratio generally have the highest Rb / K_2O ratio. The most likely explanations on the differences between wells in the K_2O / Al_2O_3 and Rb / K_2O ratios are:

1. A local source of potassium situated close to the well 6005/15-1 in the Faroes sector. Such a source should have a limited spatial extent, supplying rapidly decreasing amounts of potassium (possibly situated in K-feldspars) away from the area of the 6005/15-1 well.

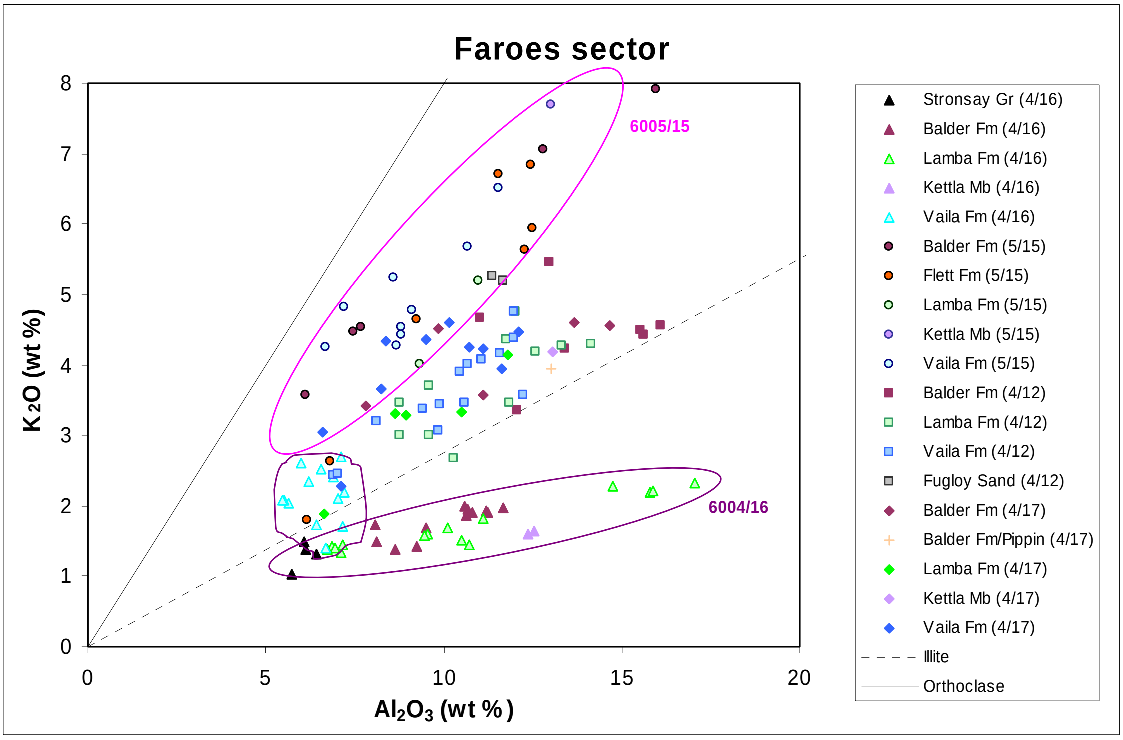
2. A Greenlandic source could have supplied to both the Faroese and UK wells. This requires, though, that the potassium-bearing minerals abruptly were deposited in the area of well 6005/15-1 in order to explain the observed variation between the Faroese and UK wells. The sediments from the Kangerlussuaq area in East Greenland show no examples of high K_2O / Al_2O_3 ratios (Fig. 5; cf. Knudsen 2005). In the Mid-Paleocene fluvial and deltaic sandstones from the Kangerlussuaq area abundant feldspar ghosts are observed, formed by preferential dissolution of K-feldspar rather than plagioclase – this atypical feldspar dissolution has been related to intense intrusive activity in the area around the Sorgenfrei Gletscher (M. Larsen et al. 1999; Preuss 2005). Consequently, the Greenlandic source may originally have been more K-feldspar-rich than the present day geochemical investigations of Greenlandic sediments suggest. However, whether the Greenlandic source was rich enough in K-feldspar that it could have served as source for the Faroese sediments is more uncertain.

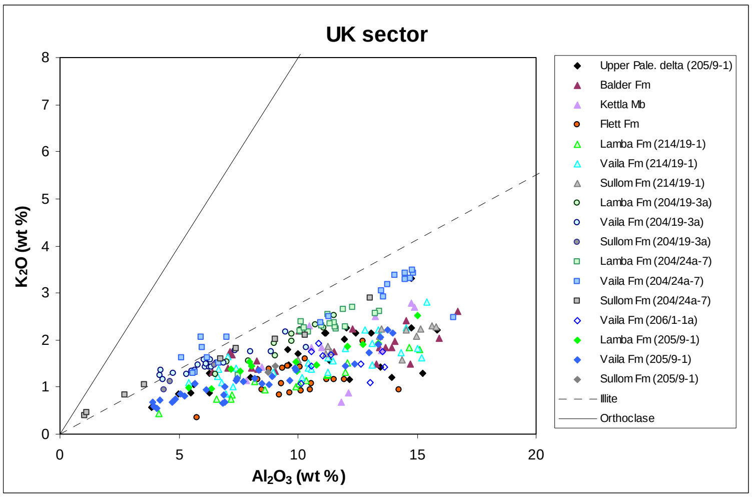
3. A source from the Orkney-Shetland Platform seems less likely as the UK wells are characterized by considerably lower K_2O / Al_2O_3 ratio and higher Rb / K_2O ratio than most of the Faroese wells.

The samples from the UK sector with relatively high K_2O / Al_2O_3 ratios (Lamba Formation in the well 205/9-1 and Vaila Formation in the well 206/1-1) also have higher Na_2O / Al_2O_3 ratios than other formations (Fig. 7). Na_2O may reflect the presence of plagioclase, smectitic clays or halite. The presence of halite from dried pore fluids or drilling mud could be a risk, but the washing of cuttings samples is assumed to have removed most salt present. The general increase in Na_2O content with increasing Al_2O_3 content up to approximately 10 wt% Al_2O_3 followed by decreasing Na_2O content at higher amount of Al_2O_3 could be an indication of a change in mineralogy from plagioclase to clays at higher Al_2O_3 contents. In the Faroese wells the relation is less simple, as the wells are characterized by different levels of sodium (Fig. 7). The well 6005/15-1 with the highest K_2O / Al_2O_3 ratio has the lowest Na_2O content, and samples from the well 6004/12-1 with medium K_2O / Al_2O_3 ratios have some of the highest Na_2O contents (Fig. 7). Whether the sodium content still reflects the presence of plagioclase is less obvious in this case.

Some of the samples from the Vaila Formation, Lamba Formation, Balder Formation and the Upper Paleocene Sands from the Faroese Marjun 6004/16-1 well are also distinguished from the similar formations in other wells by having a higher Zr /TiO_2 ratio (Fig. 8). In the UK sector there is also an overall variation in the Zr /TiO_2 ratio between some of the wells. The well 204/19-3a, closest to the investigated Faroese wells, has the highest Zr / TiO_2 ratio, whereas the well 214/19-1 has the lowest Zr / TiO_2 ratio (Fig. 8). Zirconium typically resides in the mineral zircon and high amounts of Zr most likely reflect the presence of detrital zircon grains. TiO_2 resides in rutile, anatase and other Ti-bearing minerals such as ilmenite and sphene, but may also be present in minor amounts in mafic silicates and clay minerals. Titanium can be mobilised, but tends to do so only on a local scale (Weibel & Friis 2004). A high Zr / Ti ratio (based on geochemistry) could theoretically correspond with a low RuZi, which is the ratio between rutile and the total amount of rutile and zircon grains (based on heavy mineral analyses). In the well 6005/15-1 the relationship between the heavy mineral index RuZi and the Ti / Zr ratio is reasonable, but not in the well 6004/16-1 (Fig. 9). Discrepancies between the two methods could originate from the presence of titanium in other minerals besides rutile. Sphene and anatase are of negligible importance in the investigated heavy mineral assemblage (cf. Morton & Halsworth 2002a, 2002b). But other Ti sources could be clays and especially opaque minerals, because ilmenite and titanomagnetite are not included in a conventional heavy mineral analysis. Furthermore, zircon grains smaller than 63 µm or larger than 125 µm will not be part of the heavy minerals analysis. In heavy minerals analyses low rutile content relative to high zircon content (i.e., a low RuZi) is taken as indication of a metamorphic basement source (Morton et al. 2005). It is assumed that a low Ti / Zr ratio (and a high Zr / Ti ratio) in a similar way would indicate a metamorphic basement source.

The wells characterised by the lowest K_2O / Al_2O_3 ratios generally have the highest Zr /TiO_2 ratio. But the relationship between TiO_2 and Zr is not nearly as evident as for the K_2O / Al_2O_3 ratios. Combined it could indicate that wells with high K_2O / Al_2O_3 ratios are dominated by a local source. On the other hand, wells with a high Zr /TiO_2 ratio could be more dominated by a metamorphic basement component, which could have been Greenlandic as the Greenlandic sediments can have extremely high contents of zirconium (Fig. 8). Variation and cyclicity in the zirconium content has documented local transport from the South-East to the North-West in the Judd Subbasin (Hutchison et al. 2001). This could be an indication that zirconium may be possibly be sourced also from the South-East (the Orkney-Shetland Platform).





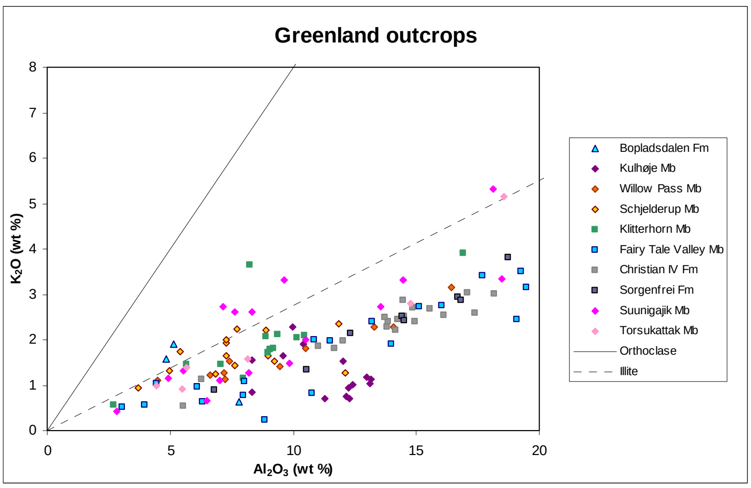
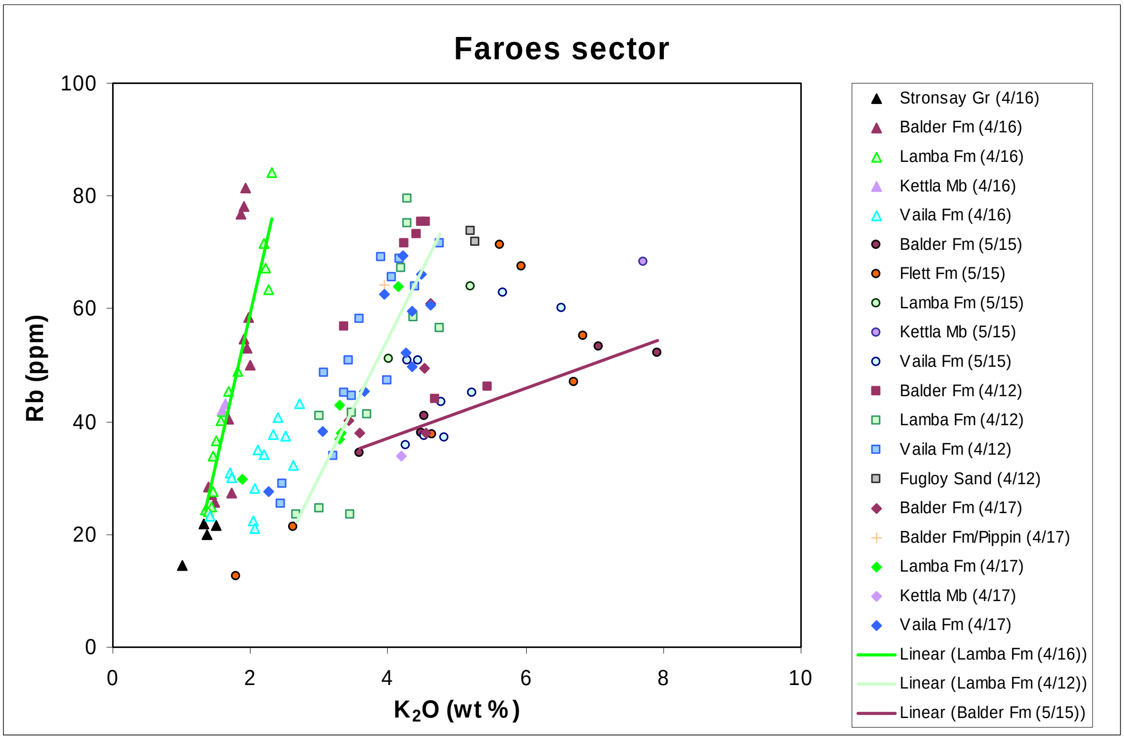
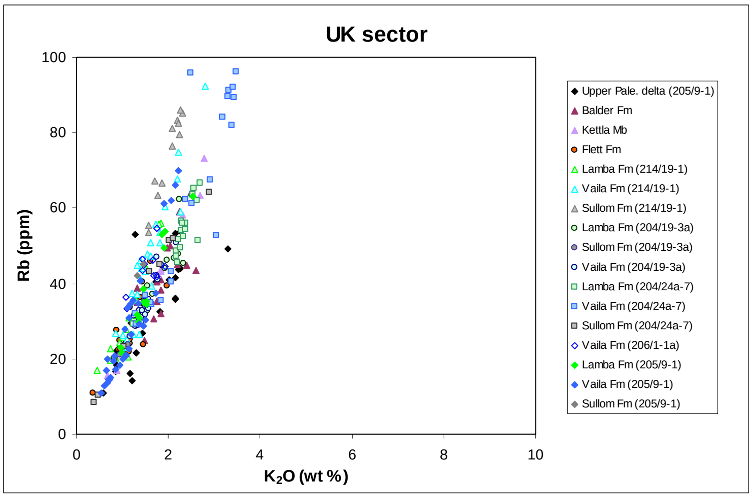


Figure 5. *In the Faroes sector (uppermost graph) the K_2O / Al_2O_3 ratio is very high for almost all investigated wells. The exception is the well 6004/16-1 which has a K_2O / Al_2O_3 ratio beneath the illite line similar to the samples from the UK sector (middle graph) and the Greenlandic outcrops (lowermost graph). Lines for orthoclase and illite have been added to the diagram for easier evaluation of the data. An imagined sediment consisting of different mixtures of quartz and K-feldspar (or illite) would lie on the K-feldspar line (or the illite line).*



12



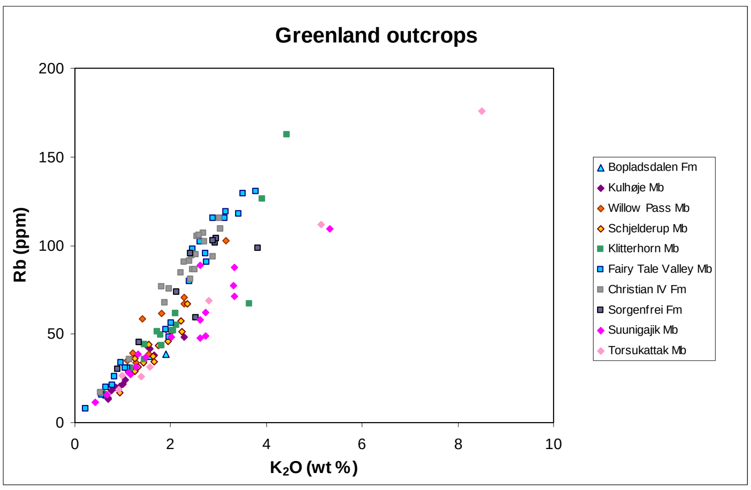
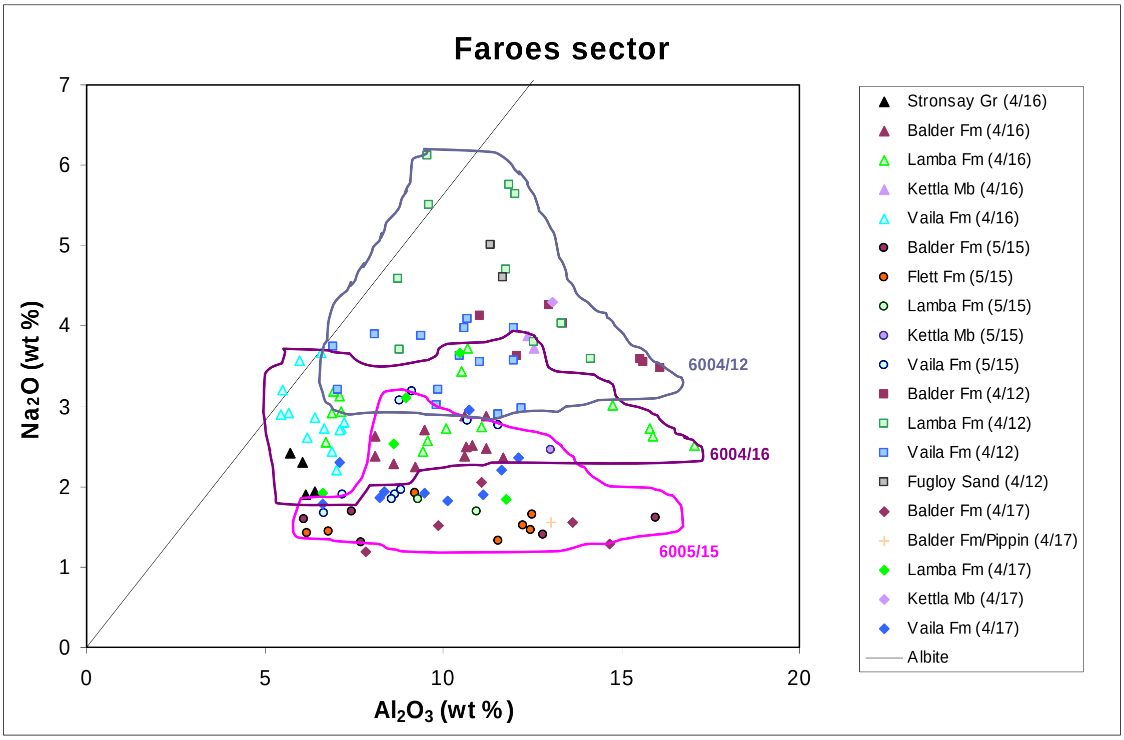


Figure 6. *A low Rb / K_2O ratio is associated with a high K_2O / Al_2O_3 ratio in both the Faroes sector (uppermost graph) and in the UK sector (middle graph). The Faroese well 6004/16-1 has high Rb / K_2O ratio similar to some of the wells in the UK sector, whereas the well 6005/15-1 has a relatively low Rb / K_2O ratio. The East Greenlandic sediments (lower graph,* ***note different scale****) have a lower Rb / K_2O ratio, but never as low as for some of the wells in the Faroes sector.*



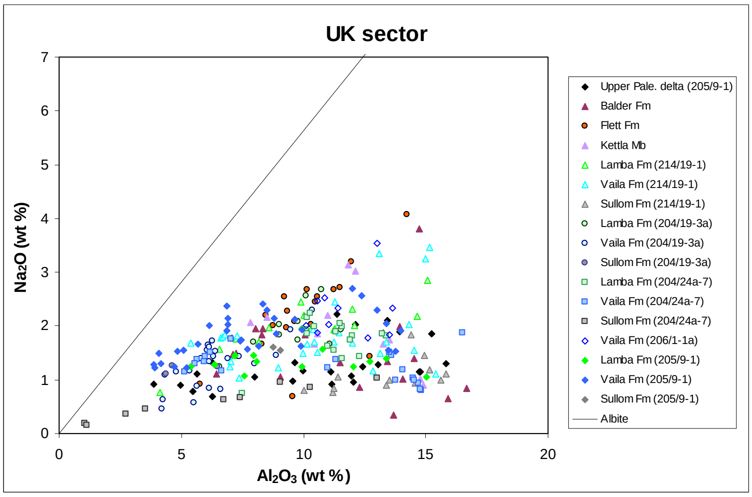
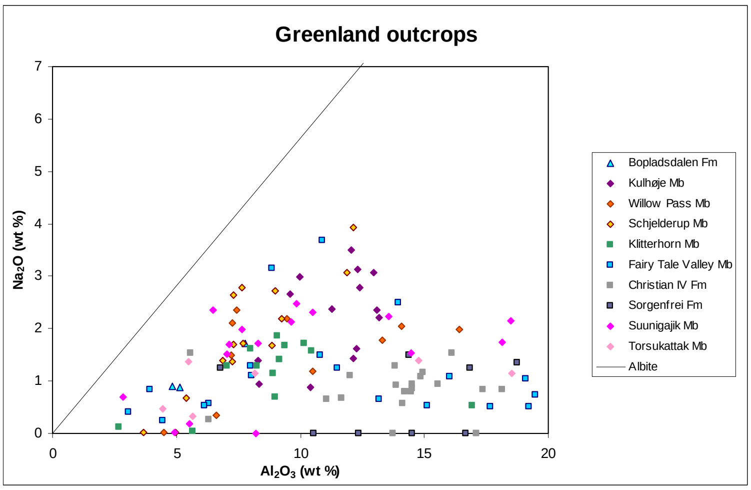
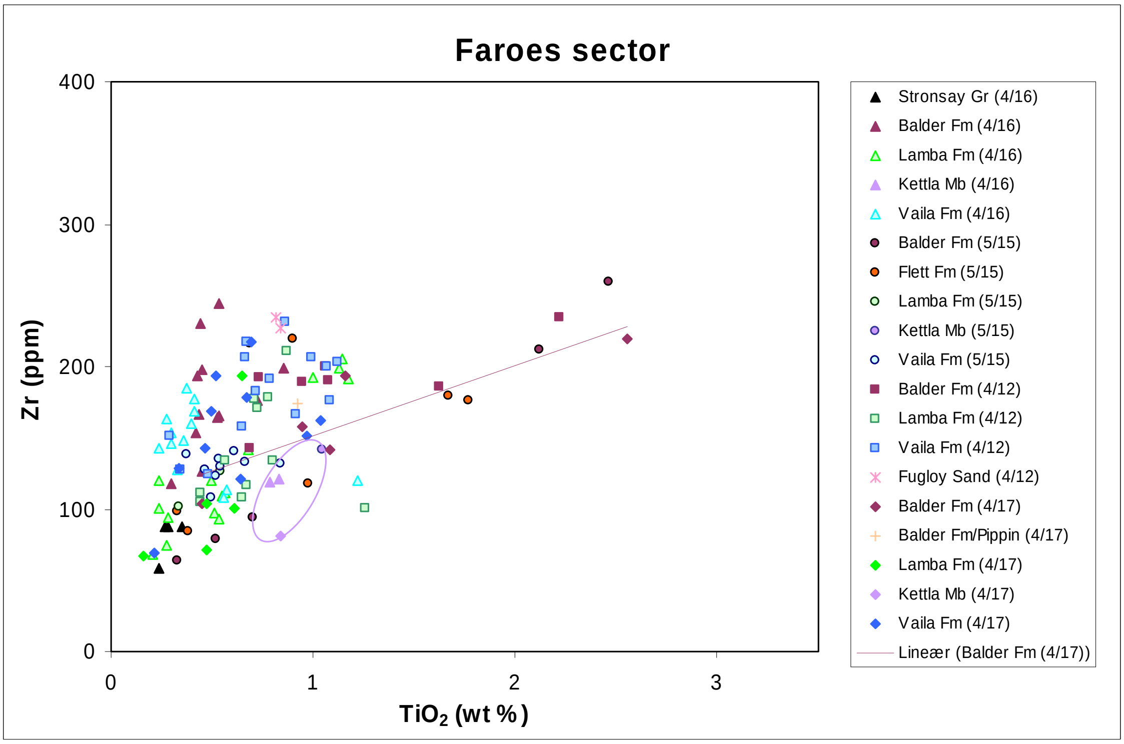
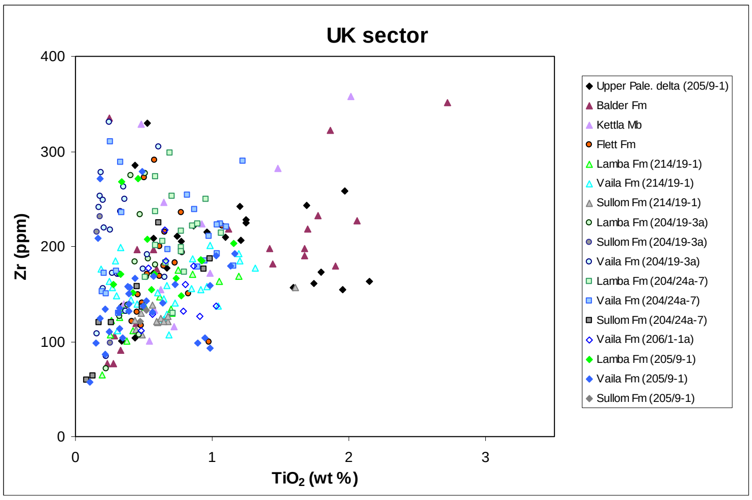


Figure 7. *In the Faroes sector (uppermost graph) the Na_2O / Al_2O_3 ratio is somewhat higher for the well 6004/12-1 and the Vaila Fm in the well 6004/16-1 than in the UK sector (middle graph) and most of the east Greenlandic outcrops (lowermost graph). A line for albite has been added to the diagram for easier evaluation of the data.*







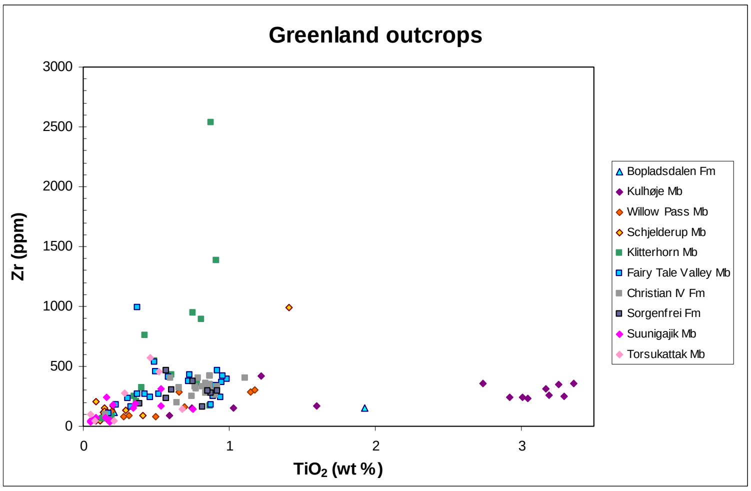


Figure 8. *In the Faroes sector (uppermost graph) the Zr / TiO_2 ratio shows some variation with well location, as the well 6004/16-1 has the highest ratio. Some samples from the Balder and Flett formations are distinguished by a rather low Zr / TiO_2 ratio and high TiO_2 content. The Kettla Member samples from the Faroes sector group together, though from different wells. In the UK sector (middle graph) the well 204/19-3a is characterised by the highest Zr / TiO_2 ratio. The Greenlandic sediments (lowermost graph,* ***note the scale is different****) typically have similar Zr / TiO_2 ratios, though some samples have extremely high Zr content and the Kulhøje Member has very high TiO_2 content.*

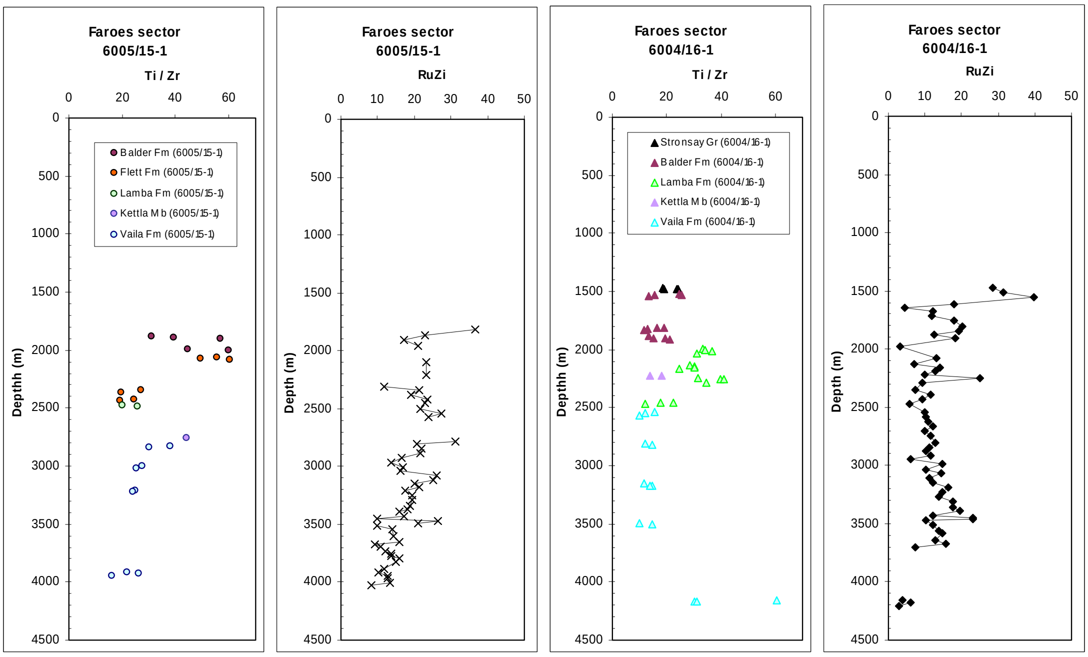


Figure 9. *Fairly good relation between RuZi index (data after Morton & Hallsworth, 2002a, 2002b) and the Zr / Ti ratio for the well 6005/15-1, but not for the well 6004/16-1.*

Geochemical characteristics of the formations

Vaila Fm and Lamba Fm

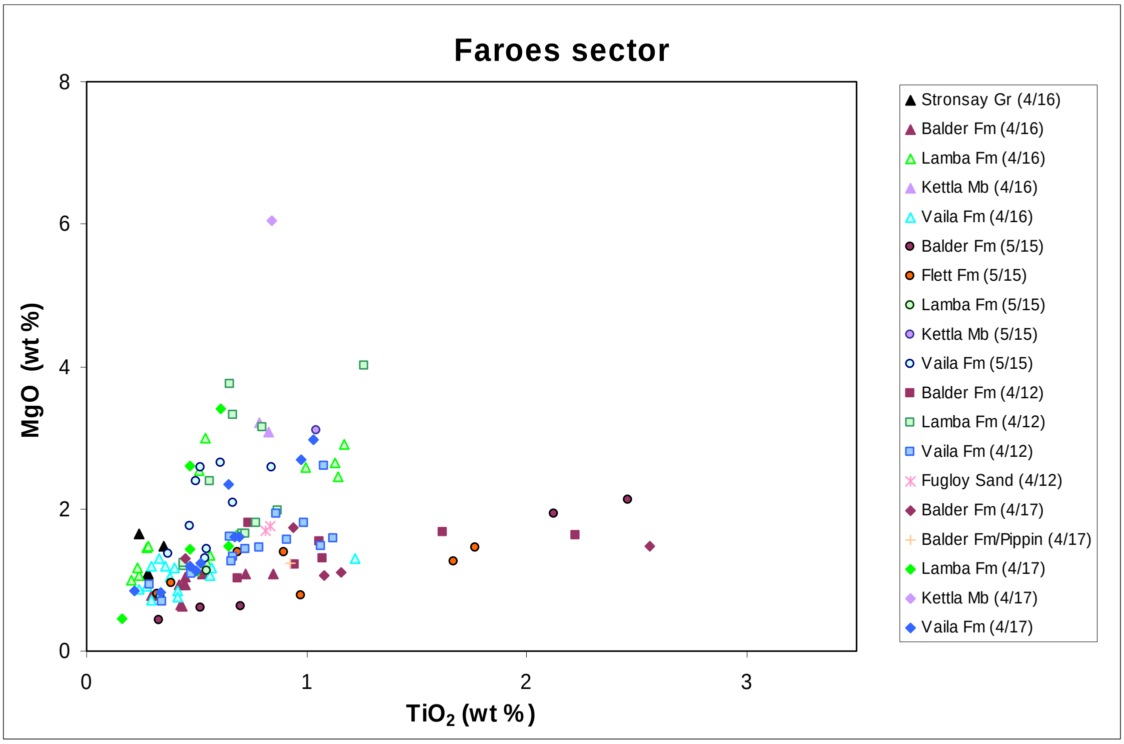
The Vaila Formation and the Lamba Formation from the investigated Faroese wells are in many ways geochemically alike, but have small variations. The MgO / TiO_2 ratio is one of the best parameters for distinguishing between the Vaila Formation and the Lamba Formation (Fig. 10). The Vaila Formation in the Faroese wells generally has a higher TiO_2 / Al_2O_3 and P_2O_5 / Al_2O_3 ratios and lower MgO / TiO_2 ratio than the Lamba Formation (Figs. 10, 11, 12. In the Judd Basin in the UK sector (in the wells 204/19-3a, 204/24a-7) similar trends can be observed, but for the wells in the Flett Subbasin (wells 205/9-1, 214/19-1) it is more difficult geochemically to distinguish between the Lamba Formation and the Vaila Formation (Figs. 10, 11, 12).

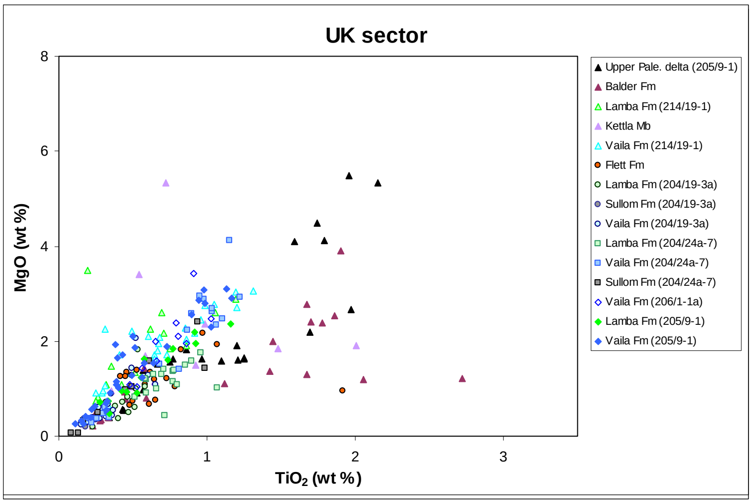
In well 6004/16-1 there seems to be some correlation between the highest amounts of MgO and the maximum abundance of calcic amphiboles and clinopyroxene in the Vaila and Lamba formations (Fig. 13; Morton & Hallsworth 2002b). The MnO content follows the MgO content. The relationship between the MgO content and the abundance of amphiboles and clinopyroxene also applies for the well 6005/15-1 in the Vaila and Lamba formations (Fig. 13). In well 6004/12-1 the maximum abundance of calcic amphiboles is also accompanied by maximum in MgO content (Morton & Hallsworth 2006). Consequently, it is assumed that for the investigated Faroese wells the MgO content mainly reflects the amount of heavy minerals, in particular amphiboles and clinopyroxes. Other minerals that could have contributed to the MgO content are for example garnet and clays. The MgO / TiO_2 ratio of the previously investigated East Greenlandic sediments have ratios similar to the Vaila Formation, but lower MgO / TiO_2 ratios than the Lamba Formation.

Phosphorus can be present in heavy minerals (in particular apatite) but may also be associated with authigenic marine phosphate or organic matter. Apatite is a relatively common heavy mineral in both the Faroese wells and the UK wells (Morton & Hallsworth 2002a, Morton & Hallsworth 2002b; Morton et al. 2005; Jolley & Morton 2007). However, there does not seem to be a simple relation between the phosphorus content and the apatite content. Phosphorus may be associated with other heavy minerals besides apatite or related to the depositional environment. The Sediment Bjerge and Vandfaldsdalen formations (Kangerlussuaq, East Greenland) have similar P_2O_5 / Al_2O_3 ratios to the Vaila Formation, but much lower P_2O_5 / Al_2O_3 ratio than the Lamba Formation (Fig. 11).

The change in the TiO_2 / Al_2O_3 and MgO / TiO_2 ratios and partly the P_2O_5 / Al_2O_3 ratio in the Faroese wells from the Vaila Formation to the Lamba Formation may thus indicate either variation in the dominating source or variation in the stability of the heavy mineral assemblage that reached the site of deposition. The previously investigated East Greenlandic sediments have both MgO / TiO_2 and P_2O_5 / Al_2O_3 ratios similar to the Vaila Formation, and they could have had common sources. The Lamba Formation in the Faroes sector on the contrary has generally a higher MgO / TiO_2 ratio, even higher than the one characterising the UK sector, which might indicate the proximity of the Faroese wells to a high-magnesium (and manganese) source.

Combined, this could be an indication of dominance of an East Greenlandic source during deposition of the Vaila Formation, and with more influence from a local high-magnesium source during deposition of the Lamba Formation in the Faroese wells (6004/16-1, 6004/12-1, 6004/17-1, 6005/15-1) and in the nearest located UK wells (204/19-3a, 204/24a-3). Another source for the other investigated UK wells is indicated by the much higher P_2O_5 / Al_2O_3 ratio in these. This source could for example be the Orkney-Shetland Platform, as sediments from the Orkney Islands are characterised by high amounts of apatite in the heavy mineral assemblage (cf. Morton et al. 2005). Alternatively, it could be soured by the Devonian-Carboniferous Upper Clair Group on the Rona Ridge, which is also characterised by high ATi (apatite content in relation to total apatite and tourmaline content (cf. Jolley & Morton 2007). The decrease in P_2O_5 / Al_2O_3 ratio from the Vaila Formation to the Lamba Formation in the Faroes sector could indicate that while this high-P_2O_5 source delivered minor amounts of material during deposition of the Vaila Formation, this source was diminished during the deposition of the Lamba Formation. The completely opposite trend can be observed in the UK wells (214/19-1) with the longest distance to the Faroese wells (Fig. 12). Here the influence from such a high-P_2O_5 source seems to increase during deposition of both the Vaila Formation and the Lamba Formation.





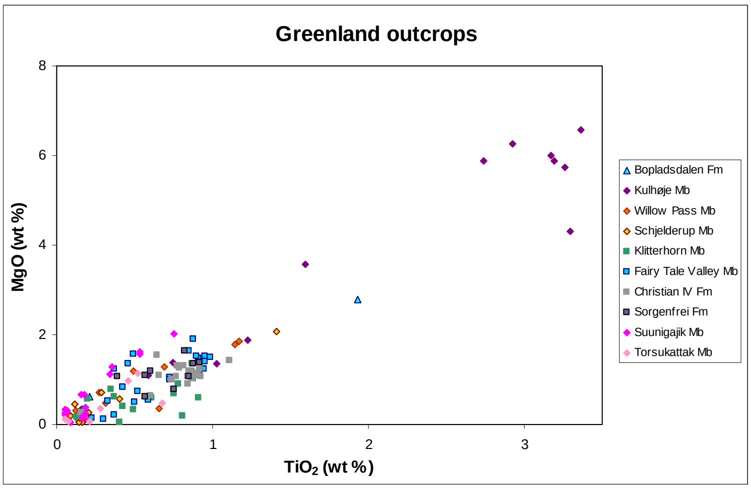
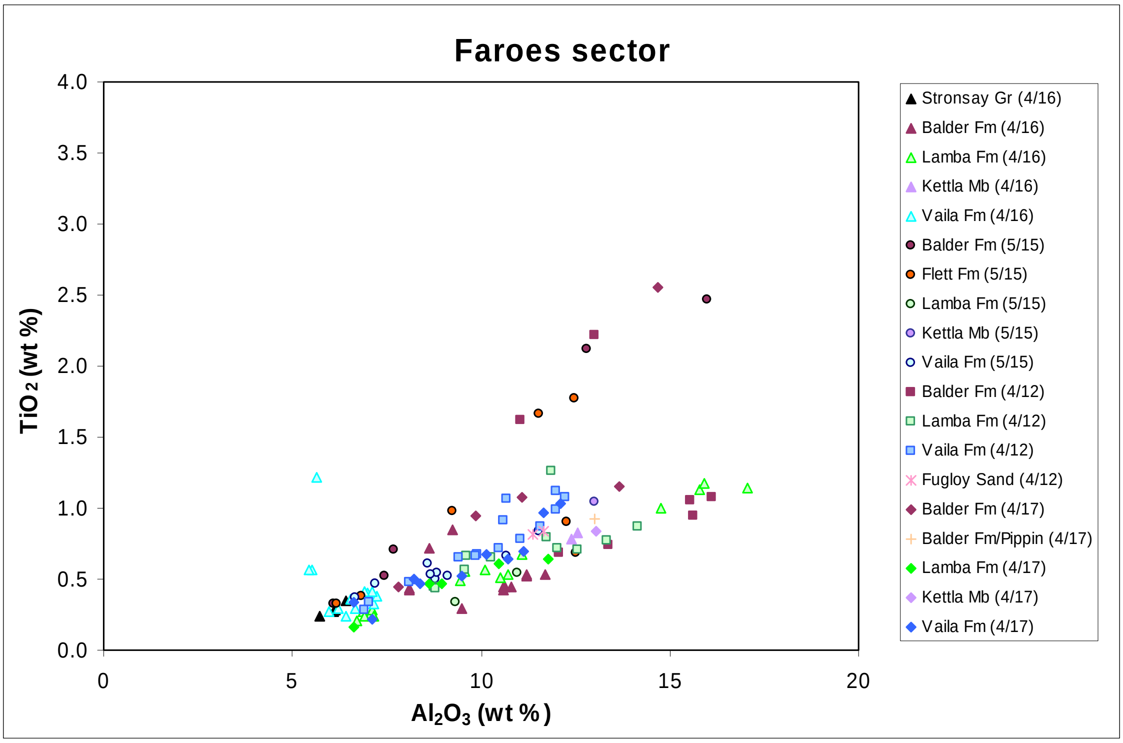
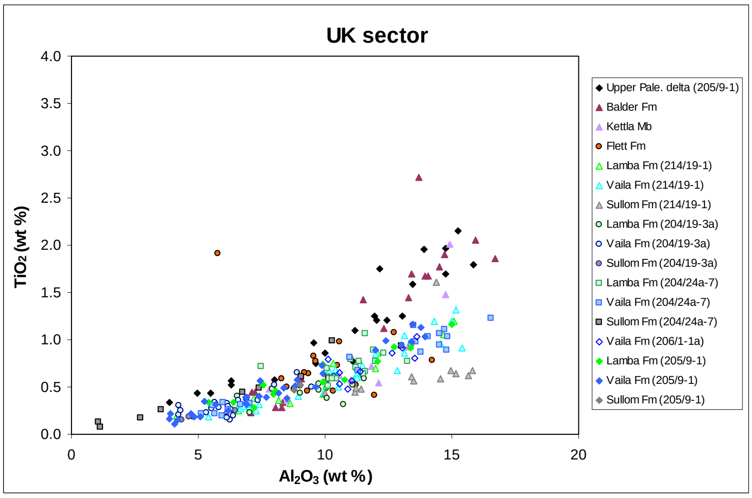


Figure 10. *In the Faroes sector (uppermost graph) the highest MgO / TiO_2 ratio is characteristic for the Lamba Fm, a medium MgO / TiO_2 ratio for the Vaila Fm and the lowest ratio for the Balder Fm. For comparison the Balder Fm in the UK sector (middle graph) also differs from the other formations by having the lowest MgO / TiO_2 ratio. The Vaila and Lamba formations in the UK sector appear with similar characteristics as in the Faroes sector for the wells 204/24a-7 and 204/19-3a, whereas the Vaila and Lamba formations cannot be separated in the well 214/19-1.*





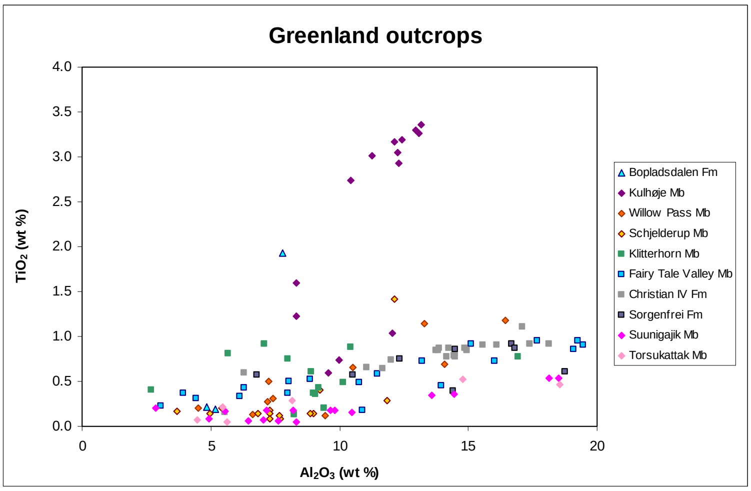
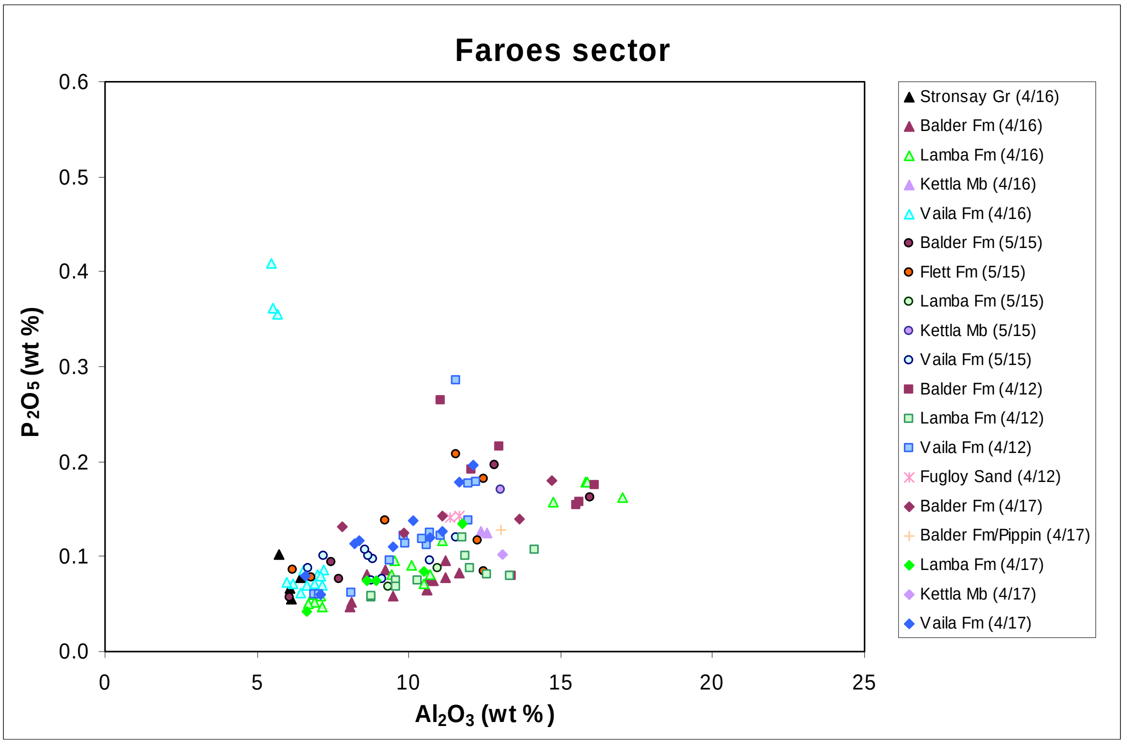
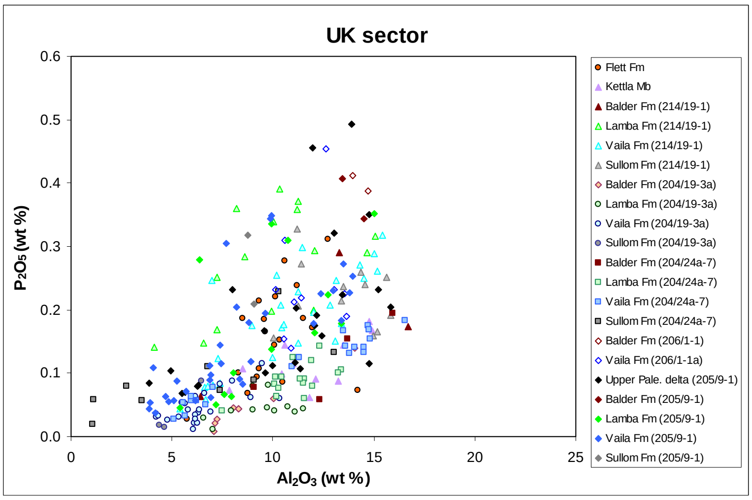


Figure 11. *In the Faroes sector (uppermost graph) the Vaila Fm generally has a higher TiO_2 / Al_2O_3 ratio than the Lamba Fm. A similar separation cannot be observed in the UK sector (middle graph). The Greenlandic outcrops (lowermost graph) generally have a very low TiO_2 / Al_2O_3 ratio. The exception is the volcanic influenced Kulhøje Mb with a very high TiO_2 / Al_2O_3 ratio on a level similar to some of the samples from Balder Fm in the Faroes sector, and the Balder Fm and Upper Paleocene deltaic sediment in the UK sector.*





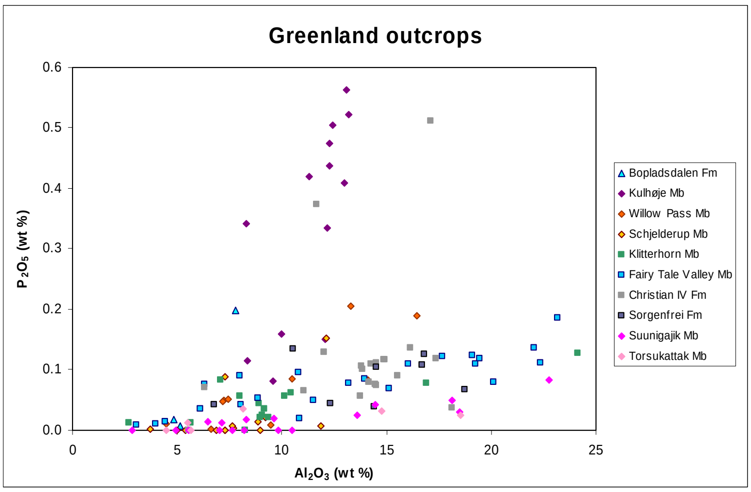


Figure 12. *In the Faroes sector (uppermost graph) the lowest P_2O_5 / Al_2O_3 ratio is characteristic for the Lamba Fm, whereas the Vaila Fm generally has a slightly higher ratio. A similar separation possibly occurs in the UK wells closest to the Faroese wells, but the UK wells farther away show almost opposite trends (middle graph). The Greenlandic outcrop samples (lowermost graph) generally have very low P_2O_5 / Al_2O_3 ratio. Again the Kulhøje Mb differs form the other formations by having relatively high P_2O_5 / Al_2O_3 ratios similar to the UK sector.*

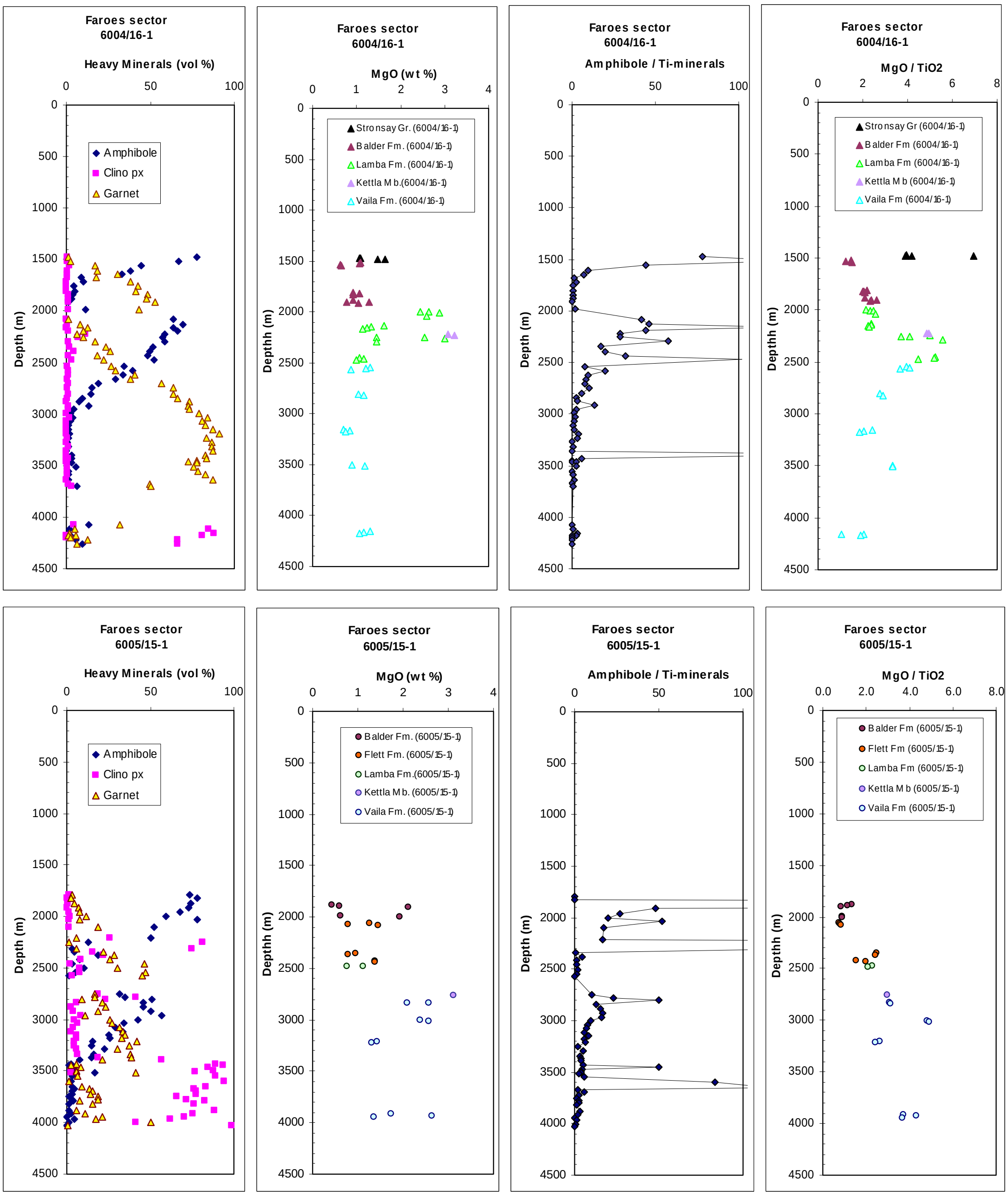


Figure 13. *Variation with depth of the MgO content in the Faroese wells 6005/15-1 and 6004/16-1 generally follows the amount of calcic amphiboles and clinopyroxes from the heavy mineral analyses by Morton and Hallsworth (2002a, 2002b). In well 6004/16-1 the depth variation in the MgO / TiO_2 ratio generally follows the amphibole / Ti minerals ratio calculated from the results by Morton & Hallsworth (2002a, 2002b). Ti minerals include, in this case, rutile, anatase and sphene. For the well 6005/15-1 this relationship is not clear, possibly because the clinopyroxes are more abundant and because the bulk TiO_2 content shows a poor correlation with the total amount of Ti-minerals, and may be more dependent on Fe-Ti oxides or clays..*

Kettla Mb

Only four samples from three different wells were taken from the Kettla Member, which limits the possible interpretations. Though, the samples are taken from three different wells they geochemically group together and plot fairly close to each other in most of the cross plots (Figs. 5, 6, 7, 8, 10, 11, 12). The largest differences between the samples are in the K_2O contents from 1.5 to 7.7 wt% (Fig. 5) and MgO contents from 3.1 to 6.1 wt % (Fig. 10). In the K_2O / Al_2O_3 plot the Kettla Member samples group together with other samples from the same well. Samples from the Kettla Member in the UK sector show larger variation in the titanium, magnesium and zirconium contents, especially within the well 205/9-1 with the thickest Kettla Member interval (Figs. 8, 10). A Greenlandic source is assumed for the Kettla Member in the well 205/9-1 due to a combination of distinctively low RuZi ratio (amount of rutile in relation to both rutile and zircons), besides high abundances of clinopyroxene, (Morton et al. 2005; Jolley et al. 2005). Abundant clinopyroxene is taken as an indication for a basaltic igneous source west of the Faroe-Shetland Basin (Morton et al. 2005). Clinopyroxene occur or are even abundant in the Faroese wells (well 6004/16-1, 6005/15-1 and 6004/12-1) in which the heavy mineral distributions have been analysed, though they do not have their maximum abundance in the Kettla Member (Fig. 13; Morton & Hallsworth 2002a, Morton & Hallsworth 2002b, Morton & Hallsworth 2006). The four Kettla Member samples from the Faroes sector have lower Zr /TiO_2 ratio than the Kettla Member in the well 205/9-1 (Fig. 9). This indicates that the metamorphic basement source or sources (i.e., Greenlandic or Orkney-Shetland Platform) may have had less influence on the Faroes Kettla Member and that this was more dominated by the basaltic igneous source than the UK Kettla Member.

The MgO (and MnO) contents in all investigated wells in the Faroes sector have their peaks in Kettla Member or in the first part of the Lamba Formation in the well 6004/12-1, where there are no samples from the Kettla Member (Fig. 13). In the UK sector there is also a relatively high MgO content in the Kettla Member, but not necessarily the maximum, which may also be located in the Vaila Fm. The MgO content is correlated with the amount of calcic amphiboles and clinopyroxenes in the investigated Faroese wells. A possible source of these relatively unstable heavy minerals could be basic igneous materials from the western side of the basin, as amphiboles and clinopyroxenes do not occur associated with basement unit on the Orkney-Shetland Platform (Morton et al. 2005). Therefore the high MgO content may be an indication of a source of abundant unstable heavy minerals, for example basic igneous material.

Flett Formation (= Sele Formation)

Flett Formation is only represented from one well 6005/15-1 in the Faroes sector. The Flett Formation from this well follows geochemically the Balder Formation. However, in the UK sector the Balder Formation and the Flett Formation seem to have larger differences.

Balder Formation

The Balder Formation in the Faroese wells is distinguished from the other formations by very low MgO / Al_2O_3 and MgO / TiO_2 ratios (Figs. 10, 14). This could be an indication of change in dominating source. This supports the previous suggestion that magnesium could be related to the content of amphiboles and clinopyroxenes for the Vaila and Lamba formations but not for the Balder Formation. In the Balder Formation in the wells 6005/15-1 and 6004/16-1 the maximum abundance of calcic amphiboles (Morton & Hallsworth 2002a, Morton & Hallsworth 2002b) is not accompanied by a similar maximum in MgO content. The composition of the calcic amphiboles may be slightly different for the Balder Formation compared to the Vaila and Lamba formations. The Balder Formation from previously investigated wells in the UK sector also has relatively low MgO / TiO_2 ratio (Fig. 10; Knudsen 2005). The Kulhøje Member, contemporaneous with the Flett Formation, contains airfall tuff (Larsen et al. 2005a), but is not distinguished from the other East Greenlandic sediments by another MgO / TiO_2 ratio, though this member has generally much higher TiO_2 and MgO contents than the other sediments.

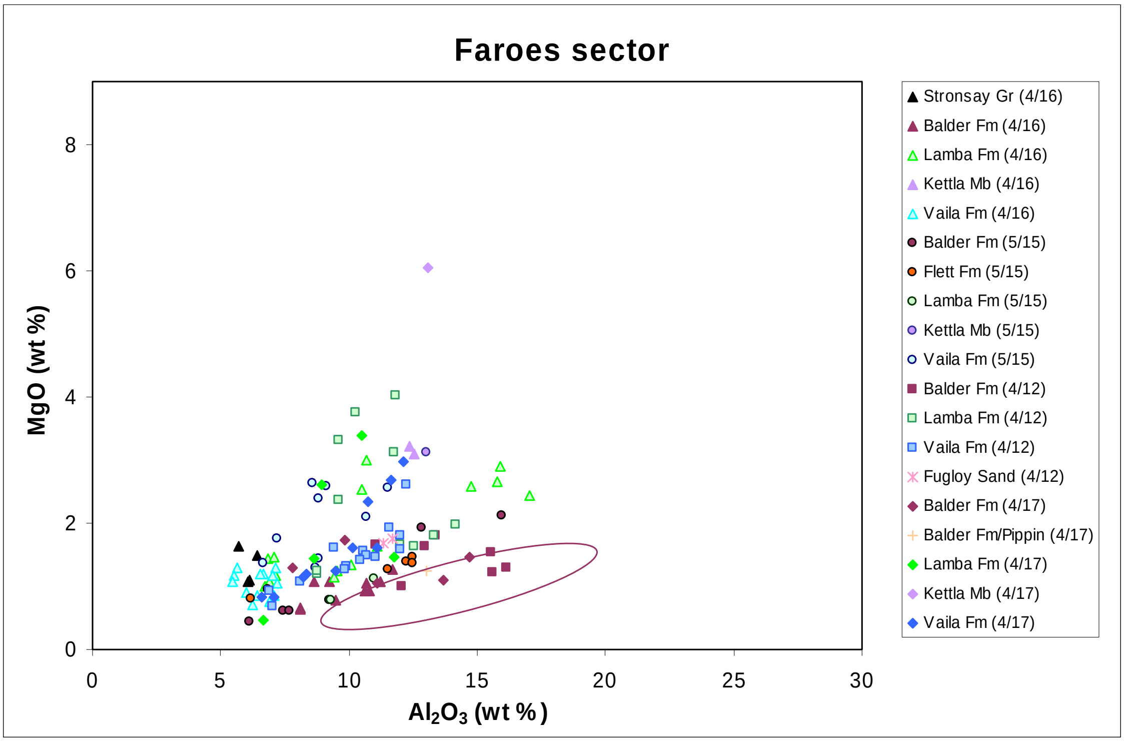
Other notable differences are the much higher P_2O_5 / Al_2O_3 ratio in the Kulhøje Member (Fig. 12); and the much higher Cr and Ti contents and higher Cr / TiO_2 ratio in the Greenlandic sediments containing volcanic material (in particular the Kulhøje Member) compared to the Balder Formation from the Faroes sector (Fig. 15). The Kulhøje Member is older than the Balder Formation (Fig. 3) and may reside components of Lower Basalt from Kangerlussuaq, which contains Cr-rich and Mg-rich primitive lavas (Fram & Lesher 1997; Ukstins Peate et al.2003). As the Faroese samples are taken from cuttings samples they could be expected to contain impurities, amongst others Cr-rich steel fragments. Some high Cr values in the Faroese samples could be caused by impurities, but the overall relatively low Cr contents of the Balder Formation are a fact.

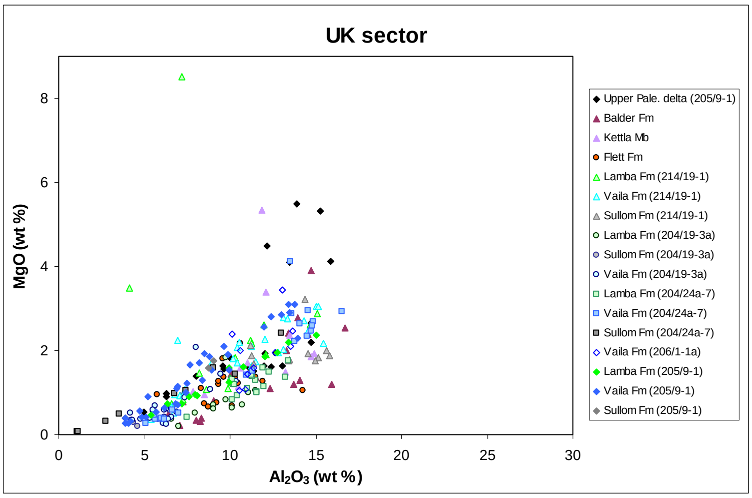
Few but distinctive samples from the Balder Formation in the Faroes sector are characterised by higher TiO_2 / Al_2O_3 and Yb / La ratios and lower Zr / TiO_2, Nb / TiO_2 and REE / TiO_2 ratios (Figs. 8, 11, 16, 17, 18). Sediments from East Greenland with a component of reworked volcanic material can be recognised geochemically by high TiO_2 / Al_2O_3, Nb / Zr and Yb / La ratios (Knudsen 2005). The Faroese samples with similar geochemical signature are probably also the result of the presence of volcanic material.

Based on geochemistry of lavas, correlations can be made between the volcanic successions in the East Greenlandic Nansen Fjord area (between the Kangerlussuaq area and the Blosseville Kyst) and the Faroe Islands (L. M. Larsen et al. 1999). Therefore, the differences between the composition of the volcanic influenced sediments in East Greenland and the Faroe-Shetland Basin could be due to local differences in the volcanic material and in the input from local sources.

In the North Atlantic region, there are marked geographical variations in the source-specific element ratio La/Ta between the different volcanic provinces (Jolley & Morton 1992). Ta, though, is a trace element in wolfram carbide – the material of the vessel used for crushing the samples. Therefore the Ta results of the present investigated samples must be applied carefully.

Balder Formation in the Maimas 6004/17-1 well has extremely high Cs values compared to the Balder Formation in other wells. This could be an interesting feature, but it is necessary to verify that Cs is not an artefact which could have been introduced to the cuttings samples during drilling.





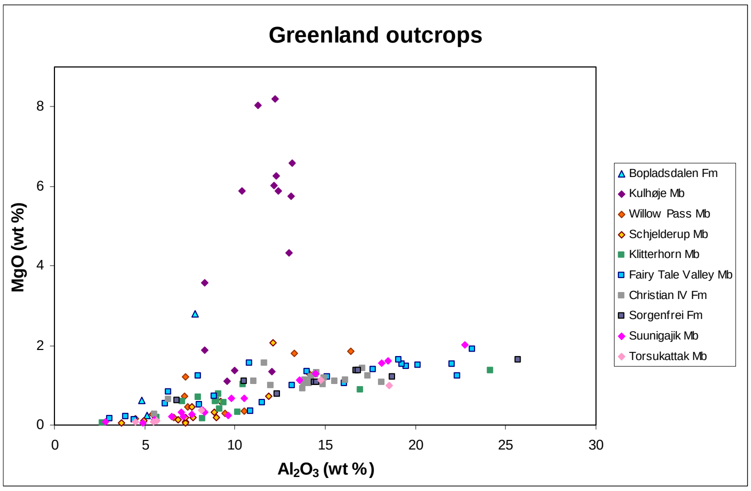
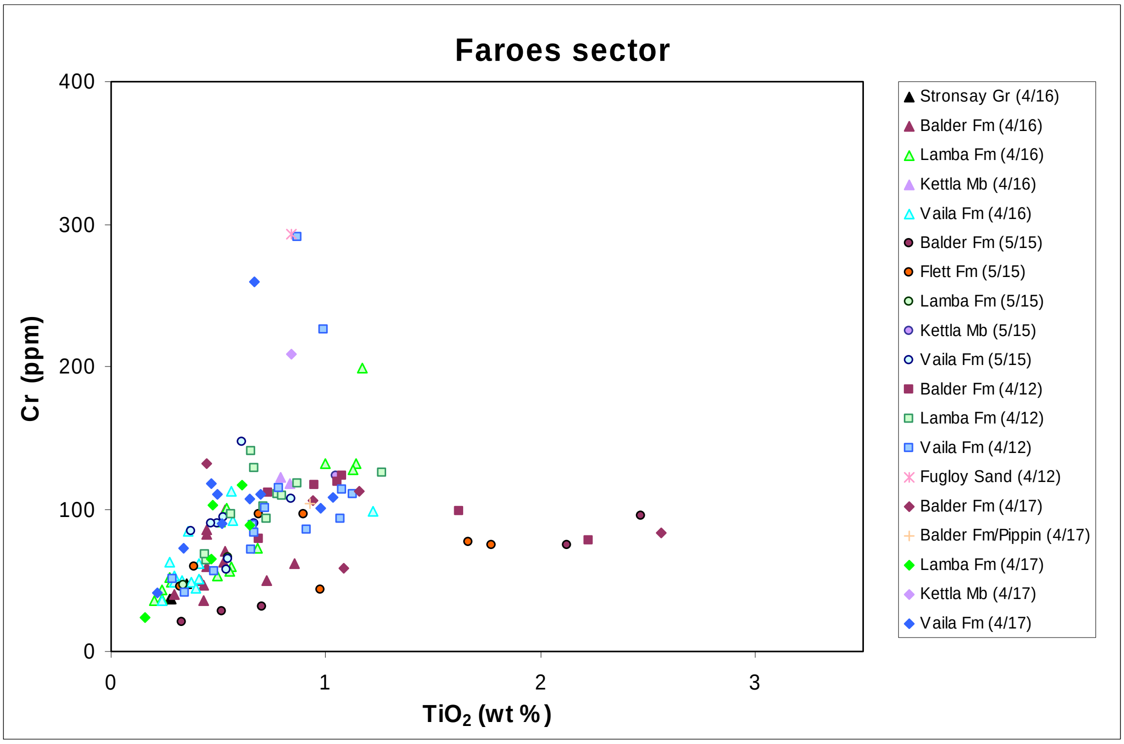
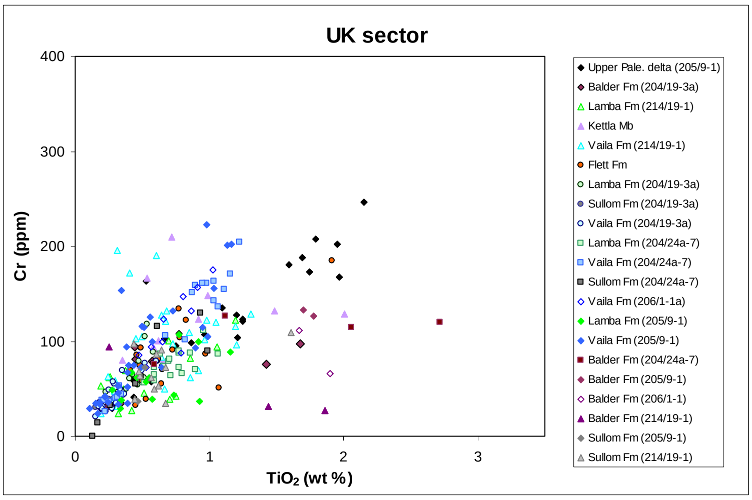


Figure 14. *In the Faroes sector (uppermost graph) the lowest MgO / Al_2O_3 ratio is characteristic for the Balder Fm, a medium MgO / Al_2O_3 ratio for the Vaila Fm and the highst ratio for the Lamba Fm. For comparison the Balder Fm in the UK sector (middle graph) also differs from the other formations by having the lowest MgO / Al_2O_3 ratio, whereas the Vaila and Lamba formations cannot be separated. The East Greenlandic sediments generally have a very low MgO / Al_2O_3 ratio, whereas the Kulhøje Mb has an extremely high MgO content.*





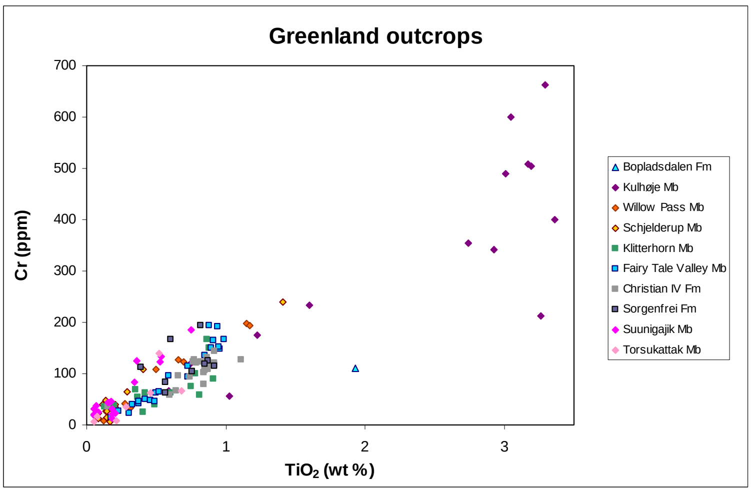
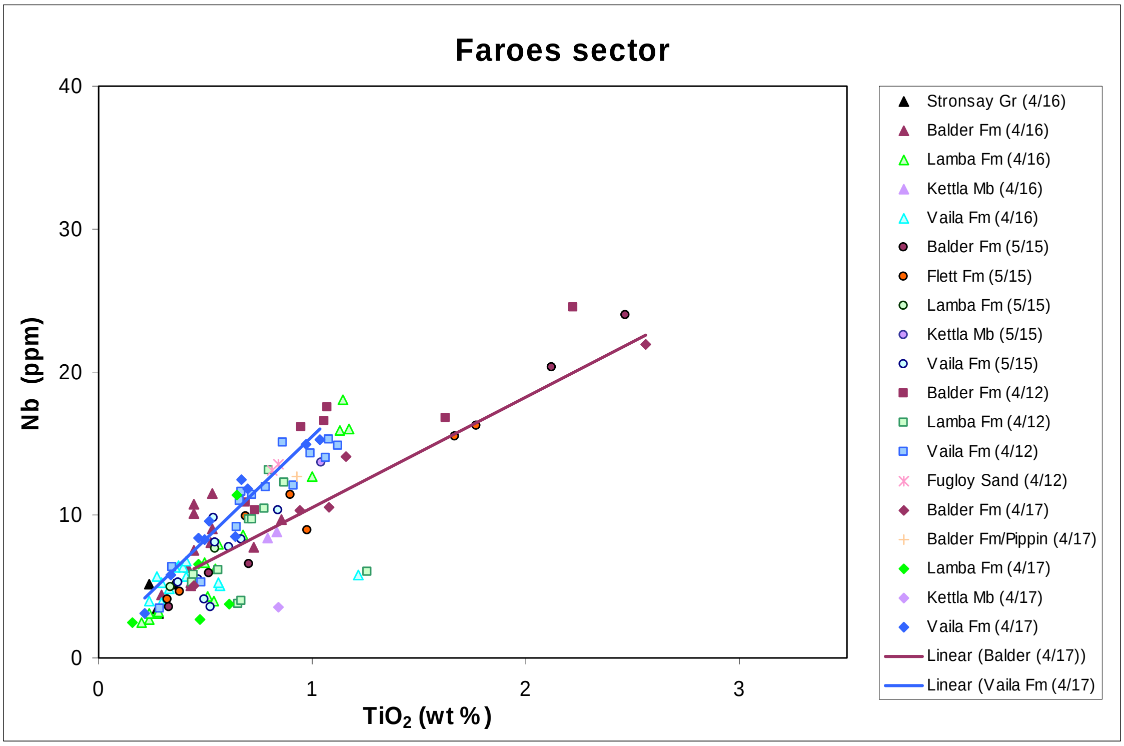
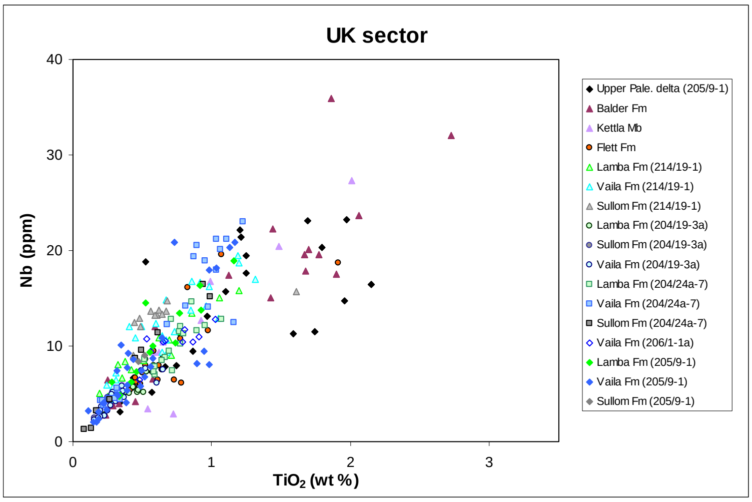


Figure 15. *The Balder Fm is characterised by the lowest Cr / TiO_2 ratio in both the Faroes sector (uppermost graph) and the UK sector (middle graph). The Vaila Fm and Lamba Fm in both the Faroese and UK sectors have generally higher Cr / TiO_2 ratios. Chromium is a potential artefact in cuttings samples, therefore the results from the UK and Faroes sectors must evaluated carefully. It is remarkable, though, that they do not differ that much from the Greenlandic sediments. The East Greenlandic sediments (lowermost graph,* ***note the different scale****) generally have Cr / TiO_2 ratios similar to the Vaila and Lamba formations in both the Faroese and UK sectors. However, the Kulhøje Mb has much higher Cr and TiO_2 contents than the other sediments.*





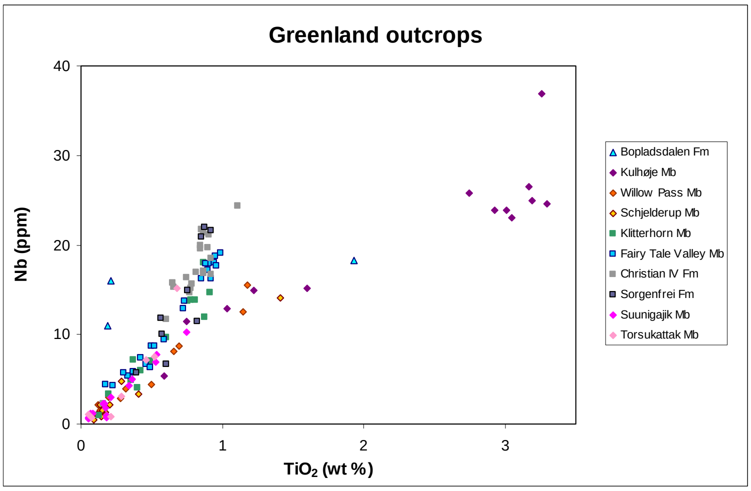
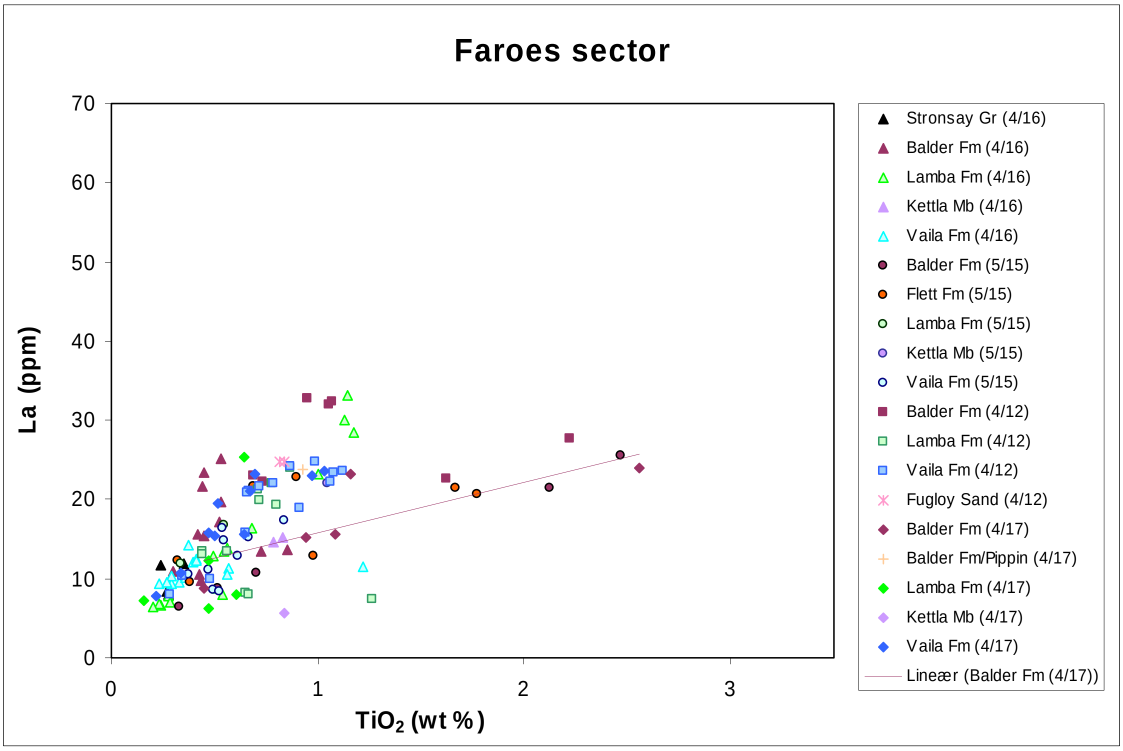
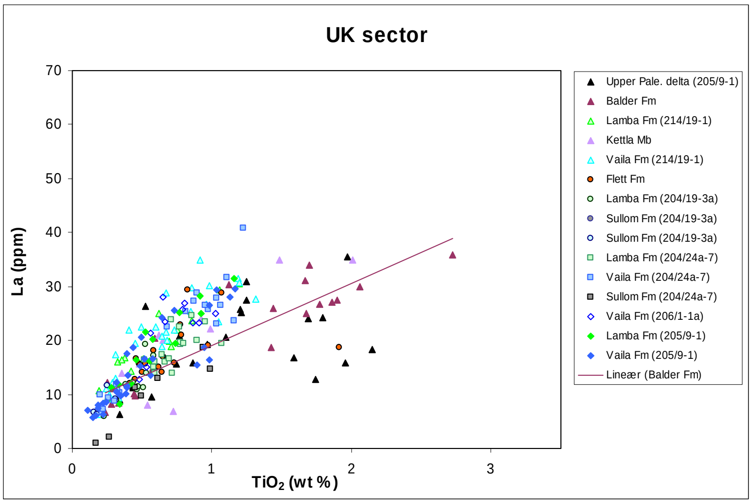


Figure 16. *The Flett and Balder formations are distinguished by a lower Nb / TiO_2 ratio than the other sediments from the Faroes sector (uppermost graph). The Balder Formation and the Upper Paleocene delta sediments from the UK area also have lower Nb / TiO_2 ratios (middle graph). The volcanic influenced Kulhøje Member from East Greenland (lowermost graph) has similar Nb / TiO_2 ratio to the Balder Formation in the UK and Faroes sectors.*





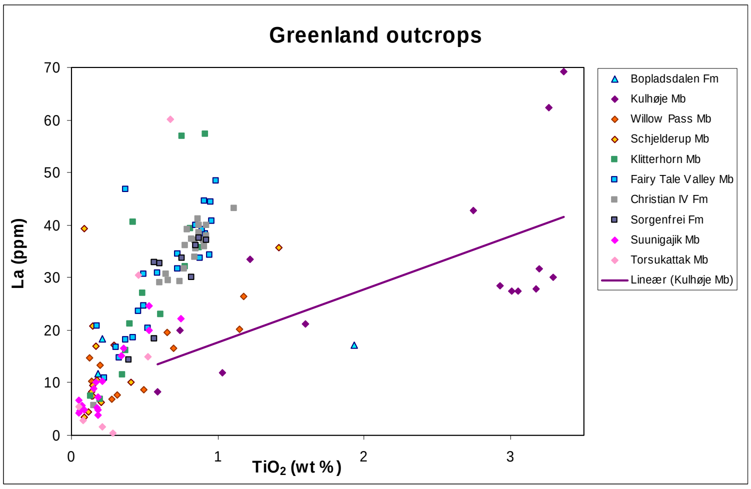
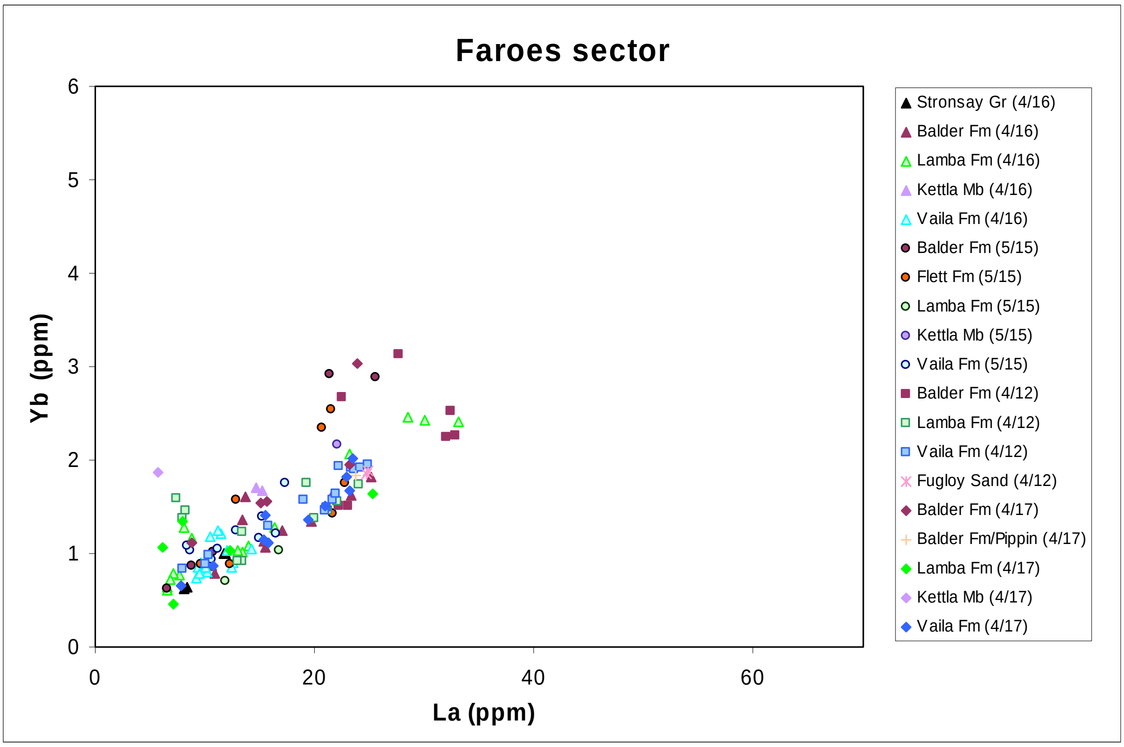
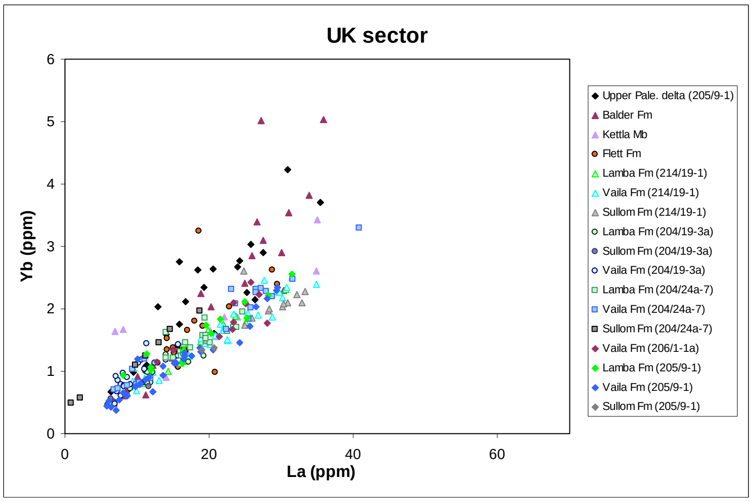


Figure 17. *The Flett and Balder formations are distinguished by a lower La / TiO_2 ratio than the other sediments from the Faroes sector (uppermost graph). The Balder Formation and the Upper Paleocene delta sediments from the UK area also have lower La / TiO_2 ratios (middle graph). The volcanic influenced Kulhøje Member from East Greenland (lowermost graph) has similar or higher La / TiO_2 ratios compared to the Balder Formation in the UK and Faroes sectors.*





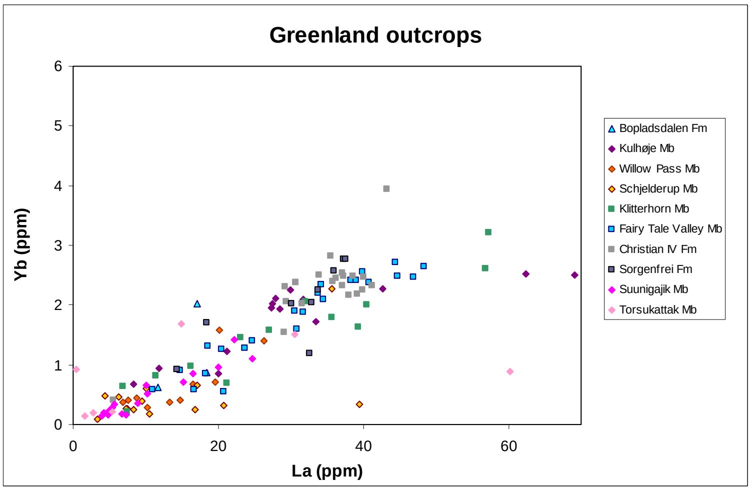


Figure 18. *Some samples from the Flett and Balder formations are characterised by a higher Yb / La ratio than the other sediments from the Faroes sector (uppermost graph). The Balder Formation and the Upper Paleocene delta sediments from the UK area also have higher Yb / La ratios (middle graph). The East Greenlandic sediments generally have lower Yb / La ratios than the Faroese and UK sediments. The volcanic influenced Kulhøje Member from East Greenland (lowermost graph) has samples with higher Yb / La ratios, but not as high as the sediments from the UK and Faroes sectors.*

Conclusion

The geochemical data presented here are based on cuttings samples, which may be influenced by artefacts. This should be considered when evaluating the results and the conclusion. Some of the most evident results are:

1. The K_2O / Al_2O_3 ratios and partly the Zr / TiO_2 ratios are dependent on the location of the wells in the Faroe-Shetland Basin. A limited local K-feldspar-rich source may be responsible for the high K_2O / Al_2O_3 ratio, which is particularly high in the well 6005/15-1. The wells (6004/16-1 in the Faroes sector and 204/19-3a in the UK sector) are characterized by low K_2O / Al_2O_3 ratios and have high Zr /TiO_2 ratios. This could indicate that a metamorphic basement source had greater influence on these particular wells (6004/16-1 and 204/19-3a), and that this source had less influence on the other investigated wells. The metamorphic basement source could be Greenlandic or from the Orkney-Shetland Platform.

2. The change from the Vaila Formation to the Lamba Formation in the Faroes sector is marked by a small increase in the MgO / TiO_2 ratio, and a decrease in the P_2O_5 / Al_2O_3 ratio. The high P_2O_5 / Al_2O_3 ratios, which are particularly common in the UK wells from the Flett Subbasin, may indicate an eastern source (for example from the Orkney-Shetland Platform). The high MgO / TiO_2 ratio may on the other hand indicate influx from an igneous basaltic source, which is unknown in the eastern part of the Faroe-Shetland Basin. During the deposition of the Vaila Formation the high-P_2O_5 source, possibly from the Orkney–Shetland Platform had some influence. But this influence diminished during the deposition of the Lamba Formation in the Faroes sector, where instead an igneous basaltic source gained influence.

3. The Flett Formation and the Balder Formation are characterised by very low MgO / TiO_2, MgO / Al_2O_3 and Cr / TiO_2 ratios. On these particular parameters the sediments seem different to the also volcanic influenced East Greenlandic sediments. Single samples form the Flett Formation and the Balder Formation in the both the Faroese and UK sectors are characterized by higher TiO_2 / Al_2O_3 and Yb / La ratios and lower Zr / TiO_2, Nb / TiO_2 and REE / TiO_2 ratios. The geochemical variation of several parameters indicates that completely new material input occurred during the deposition of the Flett and Balder formations, possibly volcanic material. The volcanic material associated with the Flett and Balder formations was different from the volcanic material incorporated in East Greenlandic Kulhøje Member, which is contemporaneous with the Flett Formation.

Recommendations

- Detailed geochemical analyses of core samples from the Vaila and Lamba formations rather than cuttings samples may reveal even more subtle geochemical variations.

- In the future combined geochemical, mineralogical, petrographical and heavy mineral investigations ought to be performed on identical core samples. Geochemical variations could then be related directly to mineralogical variations, which could have been inherited from different source rocks that might even be traced back to specific source areas. If a direct link is obtained between the geochemistry and the mineralogy it can lead to more significant provenance interpretations.

- Improve the geochemical coverage of wells in the Faroe-Shetland Basin. This will enhance the possibilities for evaluating possible transport directions.

- Mineralogical investigations of samples characterised by high potassium content. K-Ar dating of this potassium source (most likely K-feldspar) could give more information of the origin – could it be a local volcanic source?

References

Fram, M. S. & Lesher, C. E. 1997: Generation and polybaric differentiation of East Greenland Early Tertiary Flood basalts. Journal of Petrology **38**, 231–275.

Frei, D. & Knudsen, C. 2007: Provenance of sediments in the Faroese-Shetland basin: Integration of wells in the Faroese sector. Progress report for the period 1st of December – 31st of October 2007. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2007/59**, 3–22.

Frei, D., Rasmussen, T., Frei, M., Knudsen, C. , Larsen, M. & Whitham, A. G. 2005. Detrital zircon age constraints on provenance of Paleocene-Eocene sandstones in the Faroe-Shetland Basin. In: Frei, D., Frei, M. and Knudsen, C. (Eds.) Linking the Faroes Area and Greenland – An innovative integrated provenance study. Final Report for Sindri. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/54**, 93–115.

Hutchinson, A., Hartley, A., Hole, M., Whear, E. & Preston, J. 2001: High Resolution geochemical and petrographical correlation of deep marine Palaeocene sandstones from the Foinaven Field, West of Shetland. Petroleum Geoscience **7**, 123–129.

Jolley, D. W. & Morton, A. C. 1992: Palynological and petrological characterization of a North Sea Palaeocene volcaniclastic sequence. Proceedings Geological Associations **103**, 119–127.

Jolley, D. W. & Morton, A. C. 2007: Understanding basin sedimentary provenance: evidence from allied phytogeographic and heavy mineral analysis of the Palaeocene of the NE Atlantic. Journal of Geological Society, London **164**, 553–563.

Jolley, D. W., Morton, A. C. & Prince, I: 2005: Volcanogenic impact on phytogeography and sediment dispersal patterns in the NE Atlantic. In: Doré, A. G. & Vining, B. A. (eds.) Petroleum Geology: North-West Europe and Global Perspectives–Proceedings of the 6th Petroleum Geology Conference, 969–975. London: Geological Society.

Jolley, D. W. & Whitham, A. G. 2004: A stratigraphical and palaeoenvironmental analysis of the sub-basaltic Palaeogene sediments of East Greenland. Petroleum Geoscience **10**, 53–60.

Knudsen, C. 2005: Chemostratigraphy and chemical characteristics of Cretaceous-Paleocene-Eocene sandstones and mudstones in the Kangerlussuaq area, East Greenland, and in the Faroe-Shetland Basin. In: Frei, D., Frei, M. and Knudsen, C. (Eds.) Linking the Faroes Area and Greenland – An innovative integrated provenance study. Final Report for Sindri. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/54**, 117– 149.

Larsen, L. M., Waagstein, R., Pedersen, A. K. & Storey, M. 1999: Trans-Atlantic correlation of Palaeogene volcanic successions in the Faeroe Islands and East Greenland. Journal of the Geological Society, London **156**, 1081–1095.

Larsen, M. & Whitham, A. G. 2005: Evidence for a major sediment input point into the Faroe-Shetland Basin from the Kangerlussuaq region of southern East Greenland. In: Doré, A. & Vining, B. (Eds.) Petroleum Geology: North-West Europe and global perspective. Proceedings of the 6th petroleum geologiy conference. Geological Society, London **2**,913-922.

Larsen, M., Hamberg, L., Olaussen, S., Nørgaard-Pedersen, N. & Stemmerik, L. 1999: Basin evolution in sourthern East Greenland: an outcrop analog for the Cretaceous–Paleogene basins on the North Atlantic volcanic margin. American Association of Petroleum Geologists, Bulletin **83**, 1236–1261.

Larsen, M., Nøhr-Hansen, H., Whitham, A. G. & Kelly, S. R. A. 2005a: Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin. Volcanic basins of the North Atlantic. Summary report for the SIndri Group, September 2005. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/61**, 24p.

Larsen, M., Nøhr-Hansen, H., Whitham, A. G. & Kelly, S. R. A. 2005b: Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin. Volcanic basins of the North Atlantic. Final report for the Sindri Group, September 2005. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/62**, 141p.

Larsen, M., Hamberg, L., Olaussen, S., Preuss, T. & Stemmerik, L. 1999: Sandstone wedges of Cretaceous–Lower Tertiary Kangerlussuaq Basin, East Greenland – outcrop analogues to the offshore North Atlantic.In: Fleet, A. J. & Boldy, S. A. R. (Eds.) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, 337–348.

Morton, A. & Hallsworth, C. 2002a: Heavy mineral data from Well 6005/15-1, Faroes sector, Faroe-Shetland Basin. HM Research Associates Report HMRA/02/07, April 2002 for Statoil (UK) Ltd, 7p.

Morton, A. & Hallsworth, C. 2002b: Heavy mineral data from Well 6004/16-1 and -1Z, Faroes sector, Faroe-Shetland Basin. HM Research Associates Report HMRA/02/19, June 2002 for Amerada Hess Ltd, 7p.

Morton, A. & Hallsworth, C. 2006: Main points from the HM study of sidewall cores from 6004/12-1, 4p. Internal report for BP.

Morton, A., Hallsworth, C. & Whitham, A. G. 2005: Heavy mineral provenance of Paleocene-Eocene sandstones in the Faroe-Shetland Basin – results from conventional petrographic and minerals-chemical techniques. In: Frei, D., Frei, M. and Knudsen, C. (Eds.) Linking the Faroes Area and Greenland – An innovative integrated provenance study. Final Report for Sindri. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/54**, 17– 49.

Mudge, D. C. & Bujak, J. P. 2001. Biostratigraphic evidence for evolving palaeoenvironments in the Lower Paleogene of the Faeroe–Shetland Basin. Marine and Petroleum Geology **18**, 577–590.

Preuss, T. 2005: Thermal maturity in volcanic-influenced sedimentary basins, East Greenland. Unpublished Ph.D. Thesis, University of Copenhagen, Denmark, 28 p & 4 papers.

Ukstins Peate, I., Larsen, M. & Lesher, C. E. 2003: The transition from sedimentation to flood volcanism in the Kangerlussuaq Basin, East Greenland: basaltic pyroclastic volcanism during initial Palaeogene continental break-up. Journal of Geological Society, London **160**, 759–772.

Weibel, R. & Friis, H. 2004: Opaque minerals as keys for distinguishing oxidising and reducing diagenetic conditions in the Lower Triassic Bunter Sandstone, North German Basin. Sedimentary Geology, **169**, 129–149.

Acknowledgements

The work presented in this volume was performed within the SINDRI programme and was made possible through generous funding by ENI SpA. The SINDRI group was established by the Minister of Petroleum for the Faroe Islands (August 2001). It was formed as a result of the requirement for licensees within the Faroese area to fund and carry out projects of relevance to the future investigation of the Faroese continental shelf. The current licensees are: Amerada Hess (Faroes) Ltd., Anadarko Faroes Company, Atlantic Petroleum P/F, BP Amoco Exploration Faroes Ltd., BG Group, Chevron, DONG Føroyar P/F, ENI Aps, Føroya Kolvetni P/F, Geysir Petroleum, OMV, Shell (UK) Ltd. and Statoil Færøyene AS.

The following individuals are acknowledged for their support in various aspects of this project: Karen Merete Henriksen, Jørgen Kystol, Hanne Lamberts, Lotte Melchior Larsen, Afet Neimi, Karen Løvig Nielsen, Matilde Rink and Anders Scherstén. Last but not the least, we would like to thank all staff at JARÐFEINGI for their professionalism and warm hospitality during sampling in their core storage facility in Tórshavn.

Appendix A: Sample preparation and analytical techniques

The SINDRI project ”Linking the Faroese area and Greenland: an innovative, integrated provenance study” conclusively demonstrated that laser ablation – magnetic secorfield – inductively coupled plasma – mass spectrometry (LA-SF-ICP-MS) and bulk rock geochmistry are reliable, fast and inexpensive methods for advanced provenance studies (Frei et al. 2005). Accordingly, the samples obtained from the new wells in the Faroese area are analysed using these techniques. Samples from the wells have already been analysed using conventional techniques by Morton and co-workers. Accordingly, only the above highlighted techniques will be used, namely:

(1) $^{206}Pb/^{238}U$ - $^{207}Pb/^{235}U$ age dating of detrital zircons by LA-SF-ICP-MS in order to identify the source components and quantify the relative importance of the respective source components. This will also yield $^{206}Pb/^{207}Pb$ model ages for all zircons and these ages can be compared to the $^{206}Pb/^{238}U$ - $^{207}Pb/^{235}U$ age data in order to evaluate to what extent the $^{206}Pb/^{207}Pb$ ages can be used without the information concerning effects of possible leadloss.

(2) Major- and trace element analysis of bulk rock samples by XRF and solution ICP-MS, respectively, for detailed chemostratigraphy.

Sampling and sample description

For this study we have employed cutting samples from the wells 6004/12-1 Svinoy (BP), 6004/16-1z Marjun (Amerada Hess), 6004/17-1 Marimas (Eni), and 6005/15-1(Statoil). After access to well logs and well reports was granted by JARDFEINGI and the involved companies gave permission to sample the wells, cuttings from all 4 wells have been sampled from the storage facility at JARDFEINGI, the Faroese Earth and Energy Directorate, in two sampling campaigns in May and December 2007. About 50 g from 169 sandstone and tuff samples and about 10 g from 50 mudstone samples (see sample description in Appendix B) have been collected directly from the cutting boxes stored at JARDFEINGI.

Whole rock major and trace element analysis

The degree of sediment maturity is very variable in the sediments in the studied area. Apart from classical optical microscopy, major- and trace element analysis provides a rapid insight into the bulk rock composition and the changes it may have suffered during diagenesis and/or transport. Accordingly, a large number of whole rock samples (> 200) been analysed for their major and trace element compositions.

All samples have been analysed for major-, minor-, and trace elements by XRF and solution ICP-MS. Two grams of each sample were ground to fineness (i.e., particle sizes of 63 µm and below) using a tungsten carbide ball mill and are subsequently dried at 110°C for 2 hours. Aliquots of about 1 to 1.5 grams of the resulting powder are subsequently used for bulk chemical analysis.

Fusion XRF

Dried sample powders are ignited in an electric furnace at 1000ºC for 1 hour. Homogeneous glass discs are produced by fusing 1 gram of ignited powder together with a borate flux in the proportion 1:7. The glass discs are analysed with a Phillips PW1606 multichannel X-ray fluorescence (XRF) spectrometer at GEUS for all major elements excluding Na, which is determined by atomic absorption spectrometry (AAS). Ba and Sr are determined by XRF because of the better precision compared with ICP-MS analyses due to the very high contents of these elements in most of the samples. The combined content of organic material and volatiles are obtained as the loss in ignition of the samples. Analytical details, including precision, accuracy, and detection limits are reported by Kystol and Larsen (1999).

AAS

For the determination of Na by AAS, about 0.25 to 0.5 g of the dried samples are treated with hydrofluoric acid in a PTFE beaker on a hot plate. After evaporation to dryness the residue is dissolved in a hydrochloric acid - potassium chloride solution and Na is determined using a Perkin Elmer PE2280 instrument at GEUS (Kystol and Larsen 1999).

ICP-MS

For solution ICP-MS a piece of the glass disc previously used for XRF (see above) is dissolved in a HF-HNO_3 mixture, evaporated to dryness and subsequently redissolved with HNO_3 and evaporated to dryness twice. The dry residue is then dissolved in HNO_3, and diluted; the resulting solution is analysed for trace elements using a Perkin Elmer 6100 DRC quadrupole ICP-MS at GEUS. This method is a modified version of the method described by Turner et al. (1999). The use of glass discs ensures that refractory minerals such as zircon and chromite are brought completely into solution. Routine analysis of international and in-house geo-standards demonstrated that the precision and accuracy are usually better than 5 % relative for the majority of the elements analysed.

U-Pb zircon geochronology using LA-SF-ICP-MS

In this study, high precision U-Pb ages have been determined for a total of 2030 individual zircon grains from 23 samples employing laser ablation – high resolution – magnetic sectorfield - inductively coupled plasma– mass spectrometry (LA-SF-ICP-MS) facility at GEUS.

The LA-SF-ICP-MS facility for U-Pb zircon age determinations at GEUS consists of a NewWave Research/Merchantek UP213 laser ablation system equipped with a frequency quintupled Nd-YAG laser emitting at a wavelength of 213 nm coupled to an Element2 (ThermoFinnigan, Bremen) single-collector double focusing magnetic sectorfield ICP-MS equipped with a fast fieldregulator for increased scanning speed. Analytical details are reported by Frei et al. (2006) and Frei and Gerdes (2007).

Sample preparation for zircon geochronology and trace element analysis

For all age determinations and trace element analysis, zircons were separated from the bulk samples using conventional heavy liquid and magnetic separation methods. The final separation step was made by hand-picking individual zircon grains from the heavy and non-magnetic fraction using an binocular microscope. The individual zircon grains were mounted on double-sided, transparent adhesive tape and subsequently embedded in 1-inch diameter circular epoxy mounts for grinding, polishing and subsequent analysis.

References

Frei, D., Frei, M., Knudsen, C. (eds) 2005: Linking the Faroese area and Greenland: an innovative, integrated provenance study. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/54**.

Frei, D., Gerdes A. 2008: Precise and accurate in-situ U-Pb dating of zircon with high sample throughput by automated LA-SF-ICP-MS. Chemical Geology (in press).

Kystol, J., Larsen, L.M. 1999: Analytical procedures in the rock geochemical laboratory of the Geological Survey of Denmark and Greenland. Geology of Greenland Survey

Turner, S.P., Platt, J.P., George, R.M.M., Kelly, S.P., Pearson, D.G., Nowell, G.M. 1999: Magmatism associated with orogenic collapse of the Beltic-Alboran domain, SE Spain. Journal of Petrology **40**, 1011-1036.

APPENDIX B: List of samples investigated

Table 1: Samples employed in this study from well 6004/16 Marjun (Amerada Hess)

Sample Nr.	Depth [m]	Rock type	Stratigraphic unit	XRF (major elements)	ICP-MS (trace elements)	U-Pb zircon geochronology
230507-1	1483	Sandstone	Stronsay Group	X	X	
230507-2	1480	Sandstone	Stronsay Group	X	X	X
230507-3	1477	Sandstone	Stronsay Group	X	X	X
230507-4	1474	Sandstone	Stronsay Group	X	X	
230507-5	1516	Sandstone	Balder Fm.	X	X	
230507-6	1528	Sandstone	Balder Fm.	X	X	X
230507-7	1534	Sandstone	Balder Fm.	X	X	X
230507-8	1543	Sandstone	Balder Fm.	X	X	
041207-17	1600	Mudstone	Balder Fm.	X	X	
041207-18	1732	Mudstone	Balder Fm.	X	X	
041207-19	1798	Mudstone	Balder Fm.	X	X	
230507-9	1810	Sandstone	Balder Fm.	X	X	
230507-10	1816	Sandstone	Balder Fm.	X	X	
230507-11	1822	Sandstone	Balder Fm.	X	X	X
230507-12	1828	Sandstone	Balder Fm.	X	X	X
230507-13	1885	Sandstone	Balder Fm.	X	X	
230507-14	1900	Sandstone	Balder Fm.	X	X	
230507-15	1906	Sandstone	Balder Fm.	X	X	
230507-16	1912	Sandstone	Balder Fm.	X	X	
041207-20	1957	Mudstone	Lambda Fm.	X	X	
230507-17	1993	Sandstone	Lambda Fm.	X	X	
230507-18	2002	Sandstone	Lambda Fm.	X	X	X
230507-19	2011	Sandstone	Lambda Fm.	X	X	x
230507-20	2038	Sandstone	Lambda Fm.	X	X	
230507-21	2134	Sandstone	Lambda Fm.	X	X	
230507-22	2140	Sandstone	Lambda Fm.	X	X	
230507-23	2155	Sandstone	Lambda Fm.	X	X	
230507-24	2161	Sandstone	Lambda Fm.	X	X	
041207-21	2167	Mudstone	Lambda Fm.	X	X	
230507-25	2224	Kettla Tuff Mbr.	Lambda Fm.	X	X	
230507-26	2221	Kettla Tuff Mbr.	Lambda Fm.	X	X	
230507-27	2251	Sandstone	Lambda Fm.	X	X	
230507-28	2259	Sandstone	Lambda Fm.	X	X	
230507-29	2246	Sandstone	Lambda Fm.	X	X	
230507-30	2288	Sandstone	Lambda Fm.	X	X	
230507-31	2453	Sandstone	Lambda Fm.	X	X	X
230507-32	2459	Sandstone	Lambda Fm.	X	X	X
230507-33	2471	Sandstone	Lambda Fm.	X	X	
041207-22	2489	Mudstone	Vaila Fm.	X	X	
230507-34	2540	Sandstone	Vaila Fm.	X	X	
230507-35	2552	Sandstone	Vaila Fm.	X	X	X
230507-36	2567	Sandstone	Vaila Fm.	X	X	X
041207-23	2717	Mudstone	Vaila Fm.	X	X	
230507-37	2807	Sandstone	Vaila Fm.	X	X	
230507-38	2822	Sandstone	Vaila Fm.	X	X	
230507-39	3152	Sandstone	Vaila Fm.	X	X	
230507-40	3167	Sandstone	Vaila Fm.	X	X	
230507-41	3176	Sandstone	Vaila Fm.	X	X	
230507-42	3498	Sandstone	Vaila Fm.	X	X	X
230507-43	3508	Sandstone	Vaila Fm.	X	X	X
041207-24	3926	Mudstone	Vaila Fm.	X	X	
041207-25	4010	Mudstone	Vaila Fm.	X	X	
230507-44	4157	Sandstone	Vaila Fm.	X	X	
230507-45	4163	Sandstone	Vaila Fm.	X	X	
230507-46	4172	Sandstone	Vaila Fm.	X	X	

Table 2: Samples employed in this study from well 6005/15-1 (Statoil)

Sample Nr	Depth [m]	Rock type	Stratigraphic unit	XRF (major elements)	ICP-MS (trace elements)	U-Pb zircon geochronology
0412-07-1	1870	Mudstone	Balder Fm.	X	X	
230507-47	1880	Sandstone	Balder Fm.	X	X	X
230507-48	1890	Sandstone	Balder Fm.	X	X	X
230507-49	1900	Sandstone	Balder Fm.	X	X	
0412-07-2	1980	Mudstone	Balder Fm.	X	X	
230507-50	1990	Sandstone	Balder Fm.	X	X	
230507-51	2000	Sandstone	Balder Fm.	X	X	
0412-07-3	2020	Mudstone	Flett Fm.	X	X	
230507-52	2060	Sandstone	Flett Fm.	X	X	
230507-53	2070	Sandstone	Flett Fm.	X	X	X
230507-54	2080	Sandstone	Flett Fm.	X	X	X
0412-07-4	2248	Mudstone	Flett Fm.	X	X	
240507-55	2350	Sandstone	Flett Fm.	X	X	
240507-56	2370	Sandstone	Flett Fm.	X	X	
0412-07-5	2420	Mudstone	Flett Fm.	X	X	
240507-57	2427	Sandstone	Flett Fm.	X	X	
240507-58	2436	Sandstone	Flett Fm.	X	X	
240507-59	2476	Sandstone	Lambda Fm.	X	X	X
240507-60	2485	Sandstone	Lambda Fm.	X	X	X
0412-07-6	2603	Mudstone	Lambda Fm.	X	X	
0412-07-7	2723	Mudstone	Lambda Fm.	X	X	
240507-61	2760	Kettla Tuff Mbr.	Lambda Fm.	X	X	
240507-62	2831	Sandstone	Vaila Fm.	X	X	X
240507-63	2841	Sandstone	Vaila Fm.	X	X	X
240507-64	3005	Sandstone	Vaila Fm.	X	X	
240507-65	3016	Sandstone	Vaila Fm.	X	X	
0412-07-8	3047	Mudstone	Vaila Fm.	X	X	
240507-66	3209	Sandstone	Vaila Fm.	X	X	
240507-67	3219	Sandstone	Vaila Fm.	X	X	
0412-07-9	3250	Mudstone	Vaila Fm.	X	X	
240507-68	3918	Sandstone	Vaila Fm.	X	X	X
240507-69	3930	Sandstone	Vaila Fm.	X	X	X
240507-70	3945	Sandstone	Vaila Fm.	X	X	

Table 3: Samples employed in this study from well 6004/12-1 Svinoy (BP)

Sample Nr	Depth [m]	Rock type	Stratigraphic unit	XRF (major elements)	ICP-MS (trace elements)	U-Pb zircon geochronology
240507-71	2265	Sandstone	Balder Fm.	X	X	X
240507-72	2274	Sandstone	Balder Fm.	X	X	X
041207-10	2450	Mudstone	Balder Fm.	X	X	
240507-73	2472	Sandstone	Balder Fm.	X	X	
240507-73	2481	Sandstone	Balder Fm.	X	X	
041207-11	2499	Mudstone	Balder Fm.	X	X	
240507-73	2517	Sandstone	Balder Fm.	X	X	
240507-74	2526	Sandstone	Balder Fm.	X	X	
041207-12	2547	Mudstone	Lambda Fm.	X	X	
240507-75	2643	Sandstone	Lambda Fm.	X	X	
240507-76	2673	Sandstone	Lambda Fm.	X	X	X
240507-77	2694	Sandstone	Lambda Fm.	X	X	X
041207-13	2748	Mudstone	Lambda Fm.	X	X	
240507-78	2793	Sandstone	Lambda Fm.	X	X	
240507-79	2814	Sandstone	Lambda Fm.	X	X	
240507-80	2871	Sandstone	Lambda Fm.	X	X	
240507-81	2886	Sandstone	Lambda Fm.	X	X	
041207-14	2949	Mudstone	Lambda Fm.	X	X	
240507-82	3117	Sandstone	Lambda Fm.	X	X	
240507-83	3192	Sandstone	Lambda Fm.	X	X	
240507-84	3212	Sandstone	Lambda Fm.	X	X	
240507-85	3485	Sandstone	Lambda Fm.	X	X	X
240507-86	3503	Sandstone	Lambda Fm.	X	X	X
240507-87	3536	Sandstone	Vaila Fm.	X	X	X
240507-88	3554	Sandstone	Vaila Fm.	X	X	X
240507-89	3656	Sandstone	Vaila Fm.	X	X	
240507-90	3665	Sandstone	Vaila Fm.	X	X	
041207-15	3710	Mudstone	Vaila Fm.	X	X	
240507-91	3737	Sandstone	Vaila Fm.	X	X	
240507-92	3755	Sandstone	Vaila Fm.	X	X	
240507-93	3833	Sandstone	Vaila Fm.	X	X	
240507-94	3851	Sandstone	Vaila Fm.	X	X	
240507-95	3997	Sandstone	Vaila Fm.	X	X	
240507-96	3926	Sandstone	Vaila Fm.	X	X	
240507-97	3965	Sandstone	Vaila Fm.	X	X	
240507-98	3992	Sandstone	Vaila Fm.	X	X	
041207-16	4130	Mudstone	Vaila Fm.	X	X	
240507-99	4172	Sandstone	Vaila Fm.	X	X	X
240507-01	4181	Sandstone	Vaila Fm.	X	X	X
240507-02	4232	Sandstone	Fugloy Sand	X	X	X
240507-03	4235	Sandstone	Fugloy Sand	X	X	X

Table 4: Samples employed in this study from well 6004/17-1 Marimas (Eni)

Sample Nr	Depth [m]	Rock type	Stratigraphic unit	XRF (major elements)	ICP-MS (trace elements)	U-Pb zircon geo-chronology
041207-26	1850	Mudstone	Balder Fm.	X	X	
240507-04	1870	Sandstone	Balder Fm.	X	X	
240507-05	1930	Sandstone	Balder Fm.	X	X	
041207-27	1950	Mudstone	Balder Fm.	X	X	
240507-06	2070	Sandstone	Balder Fm.	X	X	X
240507-07	2100	Sandstone	Balder Fm.	X	X	X
240507-08	2223	Sandstone	Balder Fm.	X	X	
240507-09	2280	Sandstone	Balder Fm./Pippin	X	X	
240507-10	2380	Sandstone	Lambda Fm.	X	X	X
240507-11	2410	Sandstone	Lambda Fm.	X	X	X
041207-28	2480	Mudstone	Lambda Fm.	X	X	
041207-29	2600	Mudstone	Lambda Fm.	X	X	
240507-12	2650	Kettla Tuff Mbr.	Lambda Fm.	X	X	
240507-13	2720	Sandstone	Lambda Fm.	X	X	X
240507-14	2800	Sandstone	Lambda Fm.	X	X	X
240507-15	2970	Sandstone	Lambda Fm.	X	X	
240507-16	2990	Sandstone	Vaila Fm.	X	X	
240507-17	3050	Sandstone	Vaila Fm.	X	X	
041207-30	3080	Mudstone	Vaila Fm.	X	X	
250507-18	3110	Sandstone	Vaila Fm.	X	X	X
250507-19	3130	Sandstone	Vaila Fm.	X	X	X
250507-20	3300	Sandstone	Vaila Fm.	X	X	
250507-21	3340	Sandstone	Vaila Fm.	X	X	
041207-31	3370	Mudstone	Vaila Fm.	X	X	
250507-22	3501	Sandstone	Vaila Fm.	X	X	
250507-23	3516	Sandstone	Vaila Fm.	X	X	
041207-32	3675	Mudstone	Vaila Fm.	X	X	
250507-24	3813	Sandstone	Vaila Fm.	X	X	X
250507-25	3819	Sandstone	Vaila Fm.	X	X	X