DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/139

Timing of the interaction between Paleocene basalts and sediments across the Faroe - Shetland region

Progress report prepared for SINDRI C46-50-01

Kristine Thrane

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/139

Timing of the interaction between Paleocene basalts and sediments across the Faroe - Shetland region

Progress report prepared for SINDRI
C46-50-01

Kristine Thrane

Released 01.01.2014

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE END ENERGY

GEUS

Contents

Summary

Project outline

The project aims to broaden our understanding of the timing of pulsing observed between sedimentary and volcanic Palaeogene deposition across the Faroe-Shetland region in order to better understand the sub-, syn- and early post-basaltic sedimentary succession offshore the Faroe Islands. The project is based on A. a detailed study of the provenance sensitive features of the possible source areas for sediment supply to the Faroe-Shetland basin in Southeast Greenland; and B. exploring the possibilities offered by baddeleyite and zircon for high precision U-Pb dating of the Paleocene basalts and mafic igneous rocks exposed in the Faroe-Shetland basin.

Project status

The project was originally set up to start by June 1., 2010, but because the original project leader Senior researcher Dirk Frei was in the process of leaving GEUS during the summer/fall of 2010, the project was not started. The project was handed over to Senior researcher Kristine Thrane by October 2010, when the contract for the project was officially signed by ATLANTICON and GEUS.
Despite the delayed start of the project, we are still aiming to have the final report ready for the SINDRI group by the end of December 2011. So fare all the samples for project A and part of the samples for project B have been located and are currently in the process of being prepared and analysed by GEUS. The remaining samples for project B will be located and processed shortly.

Background and rationale of the project

Part A: Provenance of sediments in the Faroe-Shetland basin: Characterisation of source components in Southeast Greenland

Plate reconstructions of the North Atlantic region indicate the former proximity of East Greenland to the Faroe Island region. 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. Studies by GEUS and CASP on the Cretaceous–Early Palaeogene sedimentary succession in Kangerlussuaq, East Greenland, have indicated that a major sediment input point may have existed in the Kangerlussuaq Basin in the earliest Paleocene (Larsen et al. 2005, Nøhr-Hansen et al. 2006).

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, East Greenland) marginal areas have distinctive provenance sensitive signatures with respect to detrital U-Pb zircon age distributions and heavy mineral characteristics (Frei and Knudsen 2009, Morton et al. 2009, Frei et al. 2008, Frei et al. 2005,) that can be employed to distinguish between a western (East Greenland) and eastern (UK margin) source. The detrital zircon age distributions and the bulk rock geochemistry of the sedimentary successions drilled in the Faroese sector have been investigated in the SINDRI project No. 46-32-01 “Provenance of sediments in the Faroe-Shetland basin” (Frei and Knudsen 2009, Frei et al. 2008). However, the full potential of this extensive database for the reconstruction of the sediment supply history to the Faroe-Shetland basin is only realised if the provenance sensitive signatures (especially on detrital zircon U-Pb age distributions and heavy mineral signatures) in possible source areas are sufficiently well constrained.

Determination of the provenance sensitive signatures is especially difficult for the East Greenlandic source, where the major part of the potential source area is covered by the Inland Ice and is not amenable to sampling. In this project we constrain the provenance signatures of the potential sediment source areas S of Kangerlussuaq by analysing 20 stream sediment samples. These data will significantly contribute to our understanding of the provenance characteristics of the East Greenland source and may give new information on provenance changes across major structural lineaments identified in the area (Karson and Brooks 1999). It will therefore make a significant contribution to a more sophisticated and coherent framework for the interpretation of the sediment supply history to the Faroe-Shetland basin and the correlation of sediment units across the basin based on sedimentary provenance characteristics. Furthermore, the intention is to incorporate all of the detrital zircon U-Pb age distribution data obtained in this study into a database together with data from previous SINDRI funded work. This database will cover much of the North Atlantic realm and will provide a comprehensive and coherent framework for the interpretation of the provenance of sands in the Faroe-Shetland basin based on detrital zircon U-Pb age distributions. This database will allow a more precise description, both qualitatively and quantitatively, of the sources of the sedimentary successions in the deep, central parts of the Faroe-Shetland Basin.

Part B: Testing baddeleyite and zircon U-Pb age dating as a tool for the establishment of a robust geochronological framework for Paleocene volcanic rocks in the Palaeocene interval T36 to T50

A detailed understanding of the timing of the interaction between volcanic extrusive and intrusive sills and sediments in the Paleocene interval T36 to T50 in the Faroe-Shetland basin is critically hinging on a sound geochronological framework for the extrusion and intrusion ages of the volcanic rocks in this interval. The geochronological data available for extrusive volcanics in the North Atlantic region are isolated age dates for basalts and tuffs exposed in East Greenland, the Faroe Islands and the UK margin (e.g. Hamilton et al. 1998; Tegner et al. 1998; Tegner and Duncan 1999; Chambers and Pringle 2001; Waagstein et al. 2002; Chambers et al. 2005; Storey et al. 2007) and recovered from the Lopra-1 (Waagstein et al. 2002; Storey et al. 2007) and ODP (leg 152; Sinton and Duncan 1998; holes 917 and 918; Werner et al. 1998) as well as DSDP (leg 81; Sinton and Duncan 1998) wells. For the Faroe-Shetland basin, the only existing data is that from Waagstein et al. (2002) and Storey et al. (2007). No radiometric data currently exists for the extrusive volcanics and intrusive sills present in wells in the Faroe and UK sector of the Faroe-Shetland basin. This predicament is compounded by the fact that the basalts examined in the Faroe-Shetland basin are characterised by low potassium contents (e.g. Hald and Waagstein 1984; Hald and Waagstein 1991) and are pervasively metamorphosed at zeolite to prehnite-pumpellyite facies (Waagstein et al. 2002; Glassley 2006). As a result, the $^{40}Ar/^{39}Ar$ data are difficult to interpret and have been controversially discussed (Jolley et al. 2002; Aubry et al. 2003; Srivastava 2003, Thomas 2003; Wei 2003; Jolley et al. 2003a; Jolley et al. 2003b). The difficulties related to any interpretation of $^{40}Ar/^{39}Ar$ data for basalts from the North Atlantic Igneous Province was recently demonstrated by Sherlock et al. (2009). Therefore, there is an obvious need for more robust geochronological data for the extrusive volcanic rocks present in the Faroe-Shetland basin. A possible remedy for the dilemma of obtaining high-precision geochronological data from metamorphosed and/or hydrothermally altered mafic extrusive rocks with low potassium contents is U-Pb age dating of baddeleyite and zircon. Conventional wisdom excludes baddeleyite and zircon as primary magmatic phases in mafic and ultramafic extrusive rocks. However, there is an increasing body of evidence that baddeleyite indeed occurs as a late stage, primary magmatic phase even in extrusive volcanic rocks with low Zr-contents and that it can be successfully used to date the extrusive crystallisation ages (e.g. Heaman and LeCheminant 1993; Söderlund et al. 2005; Upton et al. 2005, Holm et al. 2006). Zircon is indeed an ubiquitous phase in acidic volcanic tuff layers (e.g. Schmitz and Bowring 2001) and is frequently observed in mafic to intermediate tuffs.

This study is a pilot study that explores the possibilities for the utilisation of baddeleyite and zircon as a highly robust and precise geochronological tool for dating mafic extrusive volcanics and intrusive sills in the Faroe-Shetland basin. The results have the potential to make a major contribution towards the establishment of a solid geochronological framework for the crystallisation of volcanic rocks in the Faroe-Shetland basin.

Project aims

The project aims to contribute to an enhanced understanding of the timing of the interaction between Paleocene basalts and sediments across the Faroe-Shetland region. The project comprises two individual parts, which have the following aims:

A. the provenance of the sediments in the Faroe-Shetland basin

- To identify the provenance signatures (detrital zircon age distributions and heavy mineral signatures) of East Greenland S of Kangerlussuaq by analysing stream sediments.
- to better discriminate potential sediment source areas in Greenland
- to integrate all age data in a zircon U-Pb age database for the North Atlantic realm
- to elucidate the effect of large-scale structural grains (tectonic lineaments) and their influence on sediment provenance
- to use the database to qualitatively and quantitatively constrain the source areas for sedimentary input into the Faroe-Shetland basin.

B. dating of Paleocene basalts and tuffs using the U-Pb isotopic systematics recorded in baddeleyite and zircons.

- to test if baddeleyite and zircon are late stage magmatic phases in Paleogene mafic basaltic rocks and tuffs from the lower lava sequence exposed on Sudoroy as well as cutting samples from interval T36 to T50 in the Faroe-Shetland basin.
- if baddeleyite and zircon are found, to date them by ID-TIMS and LA-SF-ICP-MS using the U-Pb method to obtain highly precise and accurate crystallisation ages.

Sample preparation and analytical techniques

LA-SF-ICPMS

The U-Pb age determinations of zircons in this study are carried out at GEUS in Copenhagen, Denmark. The zircons are normally separated using the Wilfley table. However, the cutting samples were too small for this procedure. Instead, the samples were sieved and passed through heavy liquids as for the CCSEM analyses described below. The zircons were handpicked and mounted in epoxy and polished to expose a central cross section of each grain. Pictures were taken of the different samples such that the individual grains can be located and identified. Prior to loading the mount into the instrument, it is cleaned with ethanol to remove surface Pb contamination.
The analyses are done in situ using a ThermoScientific Element2 Sector Field Inductively Coupled Plasma Mass Spectrometer (SF-ICP-MS) coupled to a New Wave Research®/Merchantek® UP213 laser ablation unit that is equipped with a frequency quintupled ND-YAG laser (wavelength of 213 nm). All data are acquired using a 30 μm diameter single spot and an ablation time of 30 s. The result is ablation crater depths of approximately 15-20 μm, and ablated masses of approximately 65 ng.

TIMS

The U-Pb age determinations of baddeleyite in this study will be carried out at the University of Toronto in collaboration with Mike Hamilton. The baddeleyites are analysed using Isotope-Dilution Thermal Ionisation Mass Spectrometry (ID-TIMS). This is necessary as the typical grain sizes are smaller than 30 μm and they are also extremely thin. ID-TIMS analyses also offer an order of magnitude better precision, which is important when the ages are expected to be Paleocene. If large baddeleyite grains are found, attempts will be made to analyse them at GEUS using the laser ablation in-situ method described above.
The baddeleyites will be separated at Lund University under supervision of Ulf Söderlund, who has specialised in this.

Heavy mineral CCSEM

Computer Controlled Scanning Electron Microscopy (CCSEM) is a fully automated particle analysis technique developed at GEUS for the determination of chemical and physical properties of a large number of individual particles. CCSEM enables determination of the modal abundances of individual mineral fractions (e.g. ilmenite, rutile, zircon, or garnet) and their average chemical composition (as well as their compositional variation).

All sediment samples were processed as follows: 30 to 90g of sediment was split from the bulk, dried and washed on a 45 micrometer sieve. The fraction larger than 45 micrometer was then sieved through a 710-micrometer screen and the fraction between 45 and 710 micrometer was passed through a centrifuge with bromoform with a density of 2.8 g/cm^3. The heavy mineral fraction was mounted in epoxy and subsequently cut to obtain a representative section and polished. The polished sections were analysed using a Philips XL 40 SEM equipped with a ThermoNoran System Six energy dispersive X-ray analytical system. The machine automatically records the location, grain-size and shape parameters of ca 1200 grains and directs the electron beam to the grains and conducts a chemical analysis. The chemical data for each grain is compared with a mineral chemical library, classified as mineral species, and stored in a database together with the grain-size and shape parameters. Data reduction is performed using in-house developed software packages. The analyses are performed by Senior Researcher Nynke Keulen, GEUS, who will also carry out the data reduction and the final interpretation.

Sample description and progress of the project

Project A

All samples for Project A are in house. They consist of 23 stream sediment samples from South East Greenland (Fig. 1, Table 1). In the original contract 20 samples were agreed upon, but 23 were selected in case some turned out to contain none or very few zircons. The sample set consists of a) 4 samples collected by Michael Larsen in the very northern part of the area by North Parallel gletscher (north of the map boundary) and Skrækkens Bugt, b) 14 samples collected in the Tasiilaq area during the field season of 2010, c) 5 samples collected in the Skjoldungen region during the field season of 2009. The samples are currently in the process of being prepared and analysed by GEUS.

Sample nr.	Lat	Long	collected
483291	67.769833	-32.717000	2004
483292	67.769833	-32.717000	2004
483297	66.989167	-34.001183	2004
483298	66.989167	-34.001183	2004
552661	66.935053	-34.000370	2010
552670	66.665937	-34.232697	2010
550895	66.505988	-38.057202	2010
552653	66.329738	-35.456932	2010
550686	66.187322	-37.900370	2010
550886	66.083008	-36.381790	2010
550903	66.036950	-37.363685	2010
552564	65.696940	-38.684168	2010
552530	65.663343	-37.424083	2010
552620	65.630417	-39.578830	2010
552708	65.584027	-36.931407	2010
550662	65.095228	-40.001152	2010
552607	64.893163	-41.084417	2010
550645	64.335113	-40.924122	2010
550120	63.754092	-41.274758	2009
550052	63.396600	-41.545730	2009
550148	63.080387	-41.774455	2009
550272	62.863888	-42.484642	2009
550512	62.417403	-42.346882	2009

Table 1. *Stream sediment samples from Southeast Greenland*

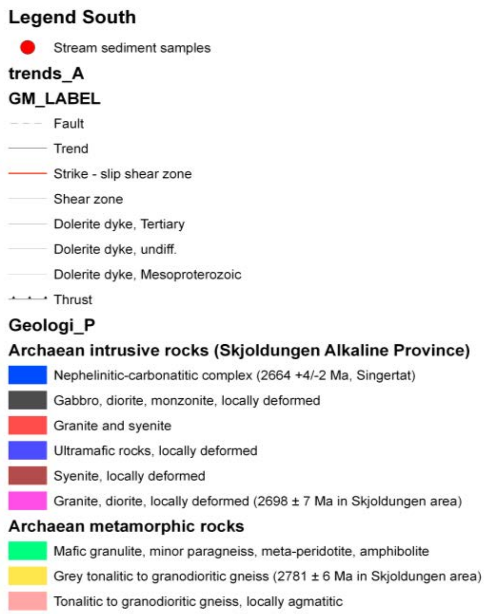
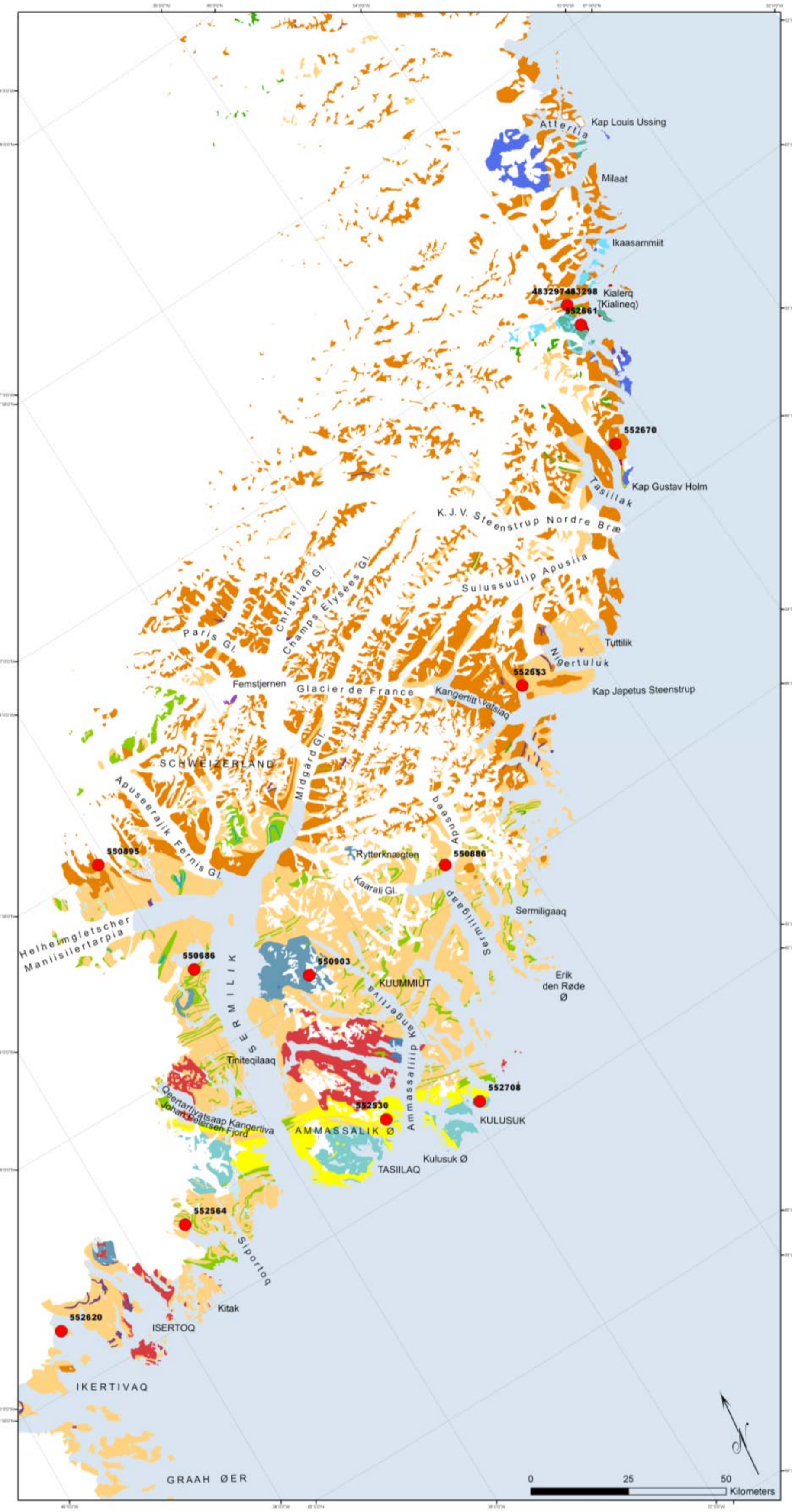


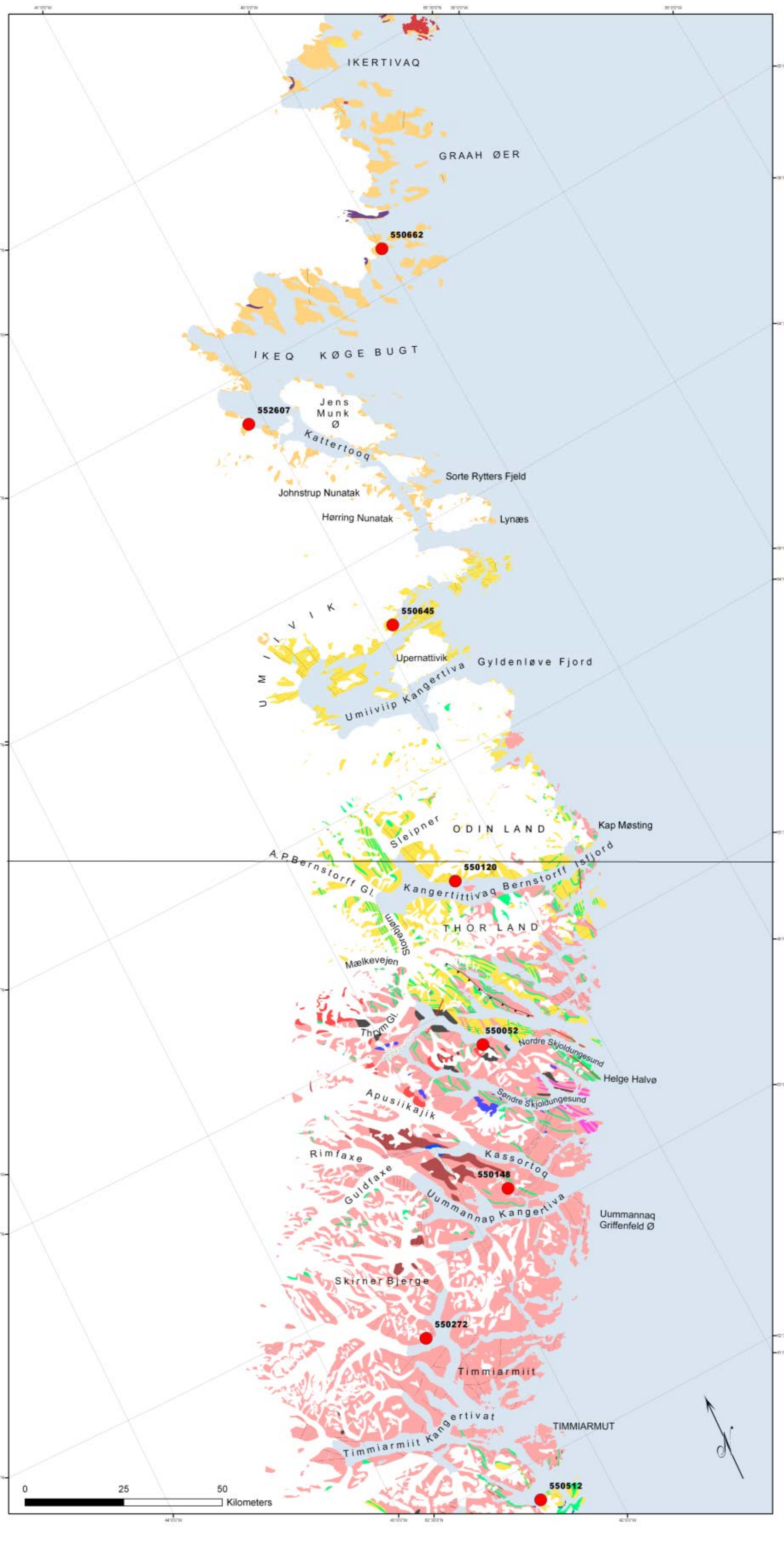
Figure 1. *On page 11 and 12 are maps of Southeast Greenland with the sample location of the stream sediment samples. The two most northern sample sites are just north of the map boundary.*

North part



Kap Louis Ussing
Attertia
Milaat
Ikaasammiit
483297
483298
Kialerq (Kialineq)
552661
552670
Kap Gustav Holm
Tasiilak
K. J. V. Steenstrup Nordre Bræ
Sulussuutip Apusiia
Christian Gl.
Champs Elysées Gl.
Paris Gl.
Tuttilik
Nigertuluk
552653
Kap Japetus Steenstrup
Femstjernen
Glacier de France
Kangertitivatsiaq
SCHWEIZERLAND
Midgård Gl.
Apuseeq
Apuseeraajik
Fernis Gl.
550895
Rytterknægten
550886
Kaarali Gl.
Sermiligaaq
Helheimgletscher
Maniisilertarpia
550686
550903
SERMILIK
KUUMMIUT
Erik den Røde Ø
Kangertivatsiaq
Tiniteqilaaq
Ammassalik Ø
552708
KULUSUK
552930
AMMASSALIK Ø
Qeertartivatsaap Kangertiva
Johan Petersen Fjord
Kulusuk Ø
TASIILAQ
552564
Siportoq
552620
Kitak
ISERTOQ
IKERTIVAQ
GRAAH ØER
0
25
50
Kilometers

South part



IKERTIVAQ
GRAAH ØER
550662
IKEQ
KØGE BUGT
Jens Munk Ø
552607
Kattertooq
Sorte Rytters Fjeld
Johnstrup Nunatak
Hørring Nunatak
Lynæs
UMIIVIK
550645
Upernattivik
Gyldenløve Fjord
Umiiviip Kangertiva
Sleipner
ODIN LAND
Kap Møsting
A.P.Bernstorff Gl.
550120
Kangertittivaq Bernstorff Isfjord
THOR LAND
Storebjørn
Mælkevejen
Thrym Gl.
550052
Nordre Skjoldungesund
Helge Halvø
Apusiikajik
Søndre Skjoldungesund
Rimfaxe
Kassortoq
550148
Guldfaxe
Uummannap Kangertiva
Uummannaq
Griffenfeld Ø
Skirner Bjerge
550272
Timmiarmiit
TIMMIARMUT
Timmiarmiit Kangertivat
550512
0
25
50
Kilometers

Project B

The majority of the samples for project B are in house. The samples are from GEUS' archives and were collected by Regin Waagstein, who is a senior researcher at GEUS and has worked many years on the Faroe Islands. He has collected many samples of both the basalts and the tuff layers from the lower lava sequence exposed at Sudoroy.

Four of the five basalt samples to be analysed have been chosen (Table 2). In the next couple of weeks we will try to extract baddeleyite from these rocks. Unfortunately, all the samples are very fine grained and this will make the task very difficult.

We have also chosen two samples from the exposed tuff layers collected by Regin Waagstein (Table 2). Another five tuff samples from cutting material from the Faroese sector are in house. The cutting samples are from the interval T36 to T50 from wells 6001/12-1, 6004/16-1, 6004/17-1 and 6005/15-1 (Table 3). These samples are currently in the process of being prepared and analysed by GEUS.

The additional basalt sample and three tuff samples will be identified shortly.

Sample nr.	Location	Rock type
RW2006.09.08-08	Hov-Túgvan, central Suduroy	Massive basalt
1981.02.27-1	Oyrnavik,Lopra	Massive basalt
1981.02.24-2	Sumba	Massive basalt
1981.03.01-5	Siglifelli	Massive basalt
RW2006.09.08-09	Hov-Túgvan, central Suduroy	Tuf
RW2006.09.08-07	Hov-Túgvan, central Suduroy	Tuf

Table 2. *Four basalt and two tuff samples from the lower lava sequence exposed on Sudoroy, collected by Regin Waagstein.*

Sample nr.	Well	Depth (m)	Geology
230507-25	6004/16-1	2224	Lamba Fm.
230507-26	6004/16-1	2221	Lamba Fm.
240507-12	6004/17-1	2650	Lamba Fm.
240507-61	6005/15-1	2760	Lamba Fm.
240507-82	6004/12-1	3117	Lamba Fm.

Table 3. *Cutting samples of tuff layers from wells in the Faroese sector. The samples are from interval T36 to T50.*

Publications

Results originating directly from the SINDRI project will be made available to the SINDRI group in the final project report that we anticipate to deliver by the end of December 2011. However it is the intention that the results should be made available to the public by publications after the project has been finalised and permission has been granted by the SINDRI group.

References

Aubry, M-P., Swisher, C.C. and Berggren, W.A. 2003: Comment on “Paleogene time scale miscalibration: Evidence from the dating of the North Atlantic igneous province”. Geology 31, 468.

Chambers, L.M. and Pringle, M.S. 2001: Age and duration at the Isle of Mull Tertiary igneous centre, Scotland, and confirmation of the existence of subchrons during Anomaly 26r. Earth and Planetary Science Letters 193, 333-345.

Chambers, L.M., Pringle, M.S. and Parrish, R.R. 2005: Rapid formation of the Small Isles Tertiary centre constrained by precise $^{40}Ar/^{39}Ar$ and U-Pb ages. Lithos 79, 367-384.

Frei, D. and Knudsen, C. 2009: Understanding sedimentary provenance in the Faroe-Shetland basin: constraints from detrital zircon geochronology. Faroe Islands Exploration Conference 2009, Abstract Volume.

Frei D., Weibel R. & Knudsen C. 2008: Provenance of sediments in the Faroese-Shetland basin: Integration of wells in the Faroese sector. Final report. Denmarks and Greenlands Geological Survey Report 2008/21(confidential report prepared for SINDRI).

Frei, D., Frei, M., Knudsen, C. (eds) 2005a: Linking the Faroese area and Greenland: an innovative, integrated provenance study. Final report for the Sindri Group, October 2005, Danmarks og Grønlands Geologiske Undersøgelse Rapport 2005/54 (confidential report prepared for SINDRI).

Glassley, W.E. 2006: Mineralogical and thermodynamic constraints on Paleogene paleotemperature conditions during low-grade metamorphism of basaltic lavas recovered from the Lopra-1/1a deep hole, Faroe Islands. Geological Survey of Denmark and Greenland Bulletin 9, 109-118.

Hamilton, M.A., Pearson, D.G., Thompson, R.N., Kelley, S.P. and Emeleus, C.H. 1998: Rapid eruption of Skye lavas inferred from precise U-Pb and Ar-Ar dating of the Rum and Cuillin plutonic complexes. Nature 394, 260-263.

Hald, N. and Waagstein, R. 1984: Lithology and chemistry of a 2-km sequence of Lower Tertiary tholeiitic lavas drilled on Sudoroy, Faroe Islands (Lopra-1). *In* Berthelsen, O., Noe-Nygaard, A. and Rasmussen, J. (eds) *The Deep Drilling Project 1980-1981 in the Faeroe Islands*, 15-38. Tórshavn: Føroya Frodskaparfelag.

Hald, N. and Waagstein, R. 1991: The dykes and sills of the Early Tertiary Faeroe Island basalt plateau. Transactions of the Royal Society of Edinburgh 82, 373-388.

Heaman, L. and LeCheminat A.N. 1993: Paragenesis and U-Pb systematics of baddeleyite (ZrO2). Chemical Geology 110, 95-126.

Holm, P.M., Heaman, L. and Pedersen, L.E. 2006: Baddeleyite and zircon U-Pb ages from the Kærven area, Kangerlussuaq. Implications for the timing of Paleogene continental breakup in the North Atlantic. Lithos 92, 238-250.

Jolley, D.W., Clarke, B. and Kelley, S.P. 2002: Paleogene time scale miscalibration: Evidence from the dating of the North Atlantic igneous province. Geology 30, 7-10.

Jolley, D.W., Clarke, B. and Kelley, S.P. 2003a: Reply to comment on “Paleogene time scale miscalibration: Evidence from the dating of the North Atlantic igneous province” by Aubry et al. and Wei. Geology 31, 469.

Jolley, D.W., Clarke, B. and Kelley, S.P. 2003b: Reply to comment on “Paleogene time scale miscalibration: Evidence from the dating of the North Atlantic igneous province” by Thomas and Srivastava. Geology 31, 471.

Karson, J.A. and Brooks, C.K. 1999: Structural and magmatic segmentation of the Tertiary East Greenland volcanic rifted margin. In. Mac Niocaill, C & Ryan, P.D. (eds) Continental Tectonics. Geological Society, London, Special Publications 164, 313-338.

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

Morton, A.C., Ellis, D., Fanning, M., Jolley, D.W. and Whitham, A. G. 2009: Heavy mineral constraints on Paleocene sand transport in the Faroe-Shetland basin. Faroe Islands Exploration Conference 2009.

Nøhr-Hansen, H., Larsen, M., Kelly, S.R.A and Whitham, A.G. 2006: Biostratigraphy zonation (palynology and
macrofossil) for the Upper Cretaceous – Lower Palaeogene based on the sedimentary succession in the Kangerlussuaq, southern East Greenland. Phase 1 report for the Sindri Group, March 2006, Danmarks og Grønlands Geologiske Undersøgelse Rapport 2006/23 (Confidential).

Schmitz, M.D. and Bowring, S.A. 2001: U-Pb zircon and titanite systematics of the Fish Canyon Tuff: an assessment of high-precision U-Pb geochronology and its application to young volcanic rocks. Geochimica et Cosmochimica Acta 65, 2571-2587.

Sherlock, S.C., Halton, A.M., Kelly, S.P. and Jolly, D.M. 2009: Why is basalt dating so difficult? A brief overview of ^{40}Ar-^{39}Ar dating system focussed on the North Atlantic Igneous Province. Faroe Islands Exploration Conference 2009, Abstract Volume.

Sinton, C.W. and Duncan, R.A. 1998: ^{40}Ar-^{39}Ar ages of lavas from the Southeast Greenland Margin, ODP Leg 152 and the Rockall Plateau, DSDP Leg 81. *In* Saunders, A.D., Larsen, H.C., Wise, W. (eds) *Proceedings of the Ocean Drilling Programme, Scientific Results* 152, 387-402.

Srivastava, S.K. 2003:Comment on "Paleogene time scale miscalibration: Evidence from the dating of the North Atlantic igneous province". Geology 31, 470.

Söderlund, U., Isachsen, C.E., Bylund, G., Heaman, L., Patchett, P.J., Vervoort, J.D. and Andersen, U.B. 2005: U-Pb baddeleyite ages and Hf, Nd isotope chemistry constraining repeated mafic magmatism in the Fennoscandian shield from 1.6 to 0.9 Ga. Contributions to Mineralogy and Petrology 150, 174-194.

Storey, M., Duncan, R.A. and Tegner, C. 2007: Timing and duration of volcanism in the North Atlantic Igneous Province: Implications for geodynamics and links to the Iceland hotspot. Chemical Geology 241, 264-281.

Thomas, E. 2003: Comment on "Paleogene time scale miscalibration: Evidence from the dating of the North Atlantic igneous province". Geology 31, 470.

Tegner, C., Duncan, R.A., Bernstein, S., Brooks, C., Bird, D.K. and Storey, M. 1998: Ar_{40}-Ar_{39} geochronology of Tertiary mafic intrusions along the East Greenland rifted margin: relation to flood basalts and the Iceland hotspot track. Earth and Planetary Science Letters 156, 75-88.

Tegner, C. and Duncan, R.A. 1999: Ar40-Ar39 chronology for the volcanic history of the Southeast Greenland rifted margin. *In* Larsen, H.C., Duncan, R.A., Allan, J.F. and Brooks, K. (eds) *Proceedings of the Ocean Drilling Programme, Scientific Results* 163, 53-62.

Upton, B.G.J., Rämö, O.T., Heaman, L., Blichert-Toft, J., Kalsbeek, F., Barry, T.L. and Jepsen, H.F. 2005: The Mesoproterozoic Zig-Zag Dal basalts and associated intrusions of eastern North Greenland: mantle plume-lithosphere interaction. Contributions to Mineralogy and Petrology 149, 40-56.

Waagstein, R., Guise, P. and Rex, D. 2002: K/Ar and 39Ar/40Ar whole-rock dating of zeolite facies metamorphosed flood basalts: the upper Paleocene basalts of the Faroe Islands, NE Atlantic. *In* Jolley, D.W. & Bell, B.R. (eds) The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic processes. Geological Society, London, Special Publications 197, 219–252.

Wei, W. 2003: Comment on “Paleogene time scale miscalibration: Evidence from the dating of the North Atlantic igneous province”. Geology 31, 467.

Werner, R., van den Boogard, P., Lacasse, C. and Schmicke, H.U. 1998: Chemical composition, age, and sources of volcanoclastic sediments from sites 917 and 918. *In* Saunders, A.D., Larsen, H.C., Wise, W. (eds) *Proceedings of the Ocean Drilling Programme, Scientific Results* 152, 93-113.