Impact of Palaeogene sill emplacement on reservoir lithologies in East Greenland and the Faroe-Shetland Basin

Susanne Schmid



GEOLOGICAL SURVEY OF DENMARK AND GREENLAND MINISTRY OF THE ENVIRONMENT

Impact of Palaeogene sill emplacement on reservoir lithologies in East Greenland and the Faroe-Shetland Basin

Susanne Schmid

Released 31.08.2011



GEOLOGICAL SURVEY OF DENMARK AND GREENLAND MINISTRY OF THE ENVIRONMENT

Contents

Introduction	6
	7
Project Aims	'
Data sets used	7
Literature review on sill emplacement	7
Skye	9
Introduction	9
Geological background	10
Methods	11
Location description	12
Results	14
Petrographic description	14
Detrital mineralogy	14
Authigenic mineralogy	16
Modal analysis	20
Trends with contact to sill	20
Porosity-Permeability	21
Image analysis	23
Whole rock analysis – major elements	24
Major element analysis	24
Correlation to petrographic analysis data	25
Vitrinite reflectance	27
General usage of vitrinite reflectance	27
Measurements in the sandstones	27
Interpretation	28
Conclusion	29
Traill Ø	30
Introduction	30
Geological background	
Methods	
Location description (derived from Preuss. 2005)	
Results	
Petrographic description (data partly derived from Preuss. 2005)	
Detrital mineralogy	34
Authigenic mineralogy	35

Modal analysis	41
Porosity-Permeability	41
Image analysis	
Vitrinite reflectance	45
General usage of vitrinite reflectance	
Measurements in the sandstones	45
Interpretation	
Conclusion	
Geochemical modeling	49
Introduction	49
Methods	49
Results	50
Interpretation	51
Conclusion	51
Implications for the Faroe-Shetland Basin General conclusions	52 53
Acknowledgments	54
References	55
Appendix 1: Tables	63
Appendix 2: Thin section description of individual specimens	71
103 – Fine to medium-grained quartz arenite	71
106 – Calcite-cemented quartz arenite	72
108 – Calcite-cemented quartz arenite	73
109 – Calcite-cemented quartz arenite	74
110 – Very fine to fine-grained subfeldspathic arenite	75
202 – Fine to medium-grained quartz arenite	76
205 – Fine to medium-grained quartz arenite	77
207 – Fine to medium-grained quartz arenite	78
209 – Medium-grained quartz arenite	79
210 – Fine to medium-grained quartz arenite	80

Executive summary

This report represents the results of the study of the impact of Palaeogene sill emplacement on potential reservoir lithologies in East Greenland and Scotland and applies them to reservoir lithologies of the Faroe-Shetland Basin.

The overall aim of this project is to develop a model for predicting effects of sill emplacement on reservoir properties of sandstones, with particular relevance to understand the influence of diagenetic processes on permeability and thermal evolution.

The contact diagenetic changes and interpretations derived from using vitrinite reflectance data, petrographical analysis (including thin section photographs, BSE micrographs, CL micrographs and point-counting data), whole rock analysis (XRF – major elements), core analysis (Helium porosity and gas permeability) and digital image analysis.

The effect of sill emplacement on shallow-buried sandstones varies significantly depending on (1) the detrital composition of the sandstones and (2) the temperature of the intrusion.

The detrital composition of the sandstone has an effect on (1) the compaction curve during burial and subsequently porosity changes and (2) the feasibility of cementation (e.g. clay coating prevents quartz cementation).

The temperature of the intrusion has an effect on (1) the solubility of quartz (quartz becomes more likely to dissolve with increasing temperatures) and subsequently quartz cementation, (2) the degree of clay mineral replacement resulting permeability loss and (3) the extent of mineral alterations (e.g. metasomatism, albitization and chloritisation).

The extent of the contact aureole depends on the thickness and temperature of the intrusion and probably on the detrital composition of the host rock.

Sill emplacement can seal sandstones by intense quartz cementation and compaction but it can also act as flow paths for fluids along fractures associated with the intrusion. It is believed that fracturing might be related to the temperature impact of the intrusion and the spatial distribution of the sill during the emplacement.

A relationship between the upper or lower contact of sill to host rock and fracturing could not be established.

Permeability and porosity are highly reduced due to the intrusion in the contact aureole due to mechanical and chemical compaction and associated authigenic mineral precipitation and alteration.

The implications of sill emplacement studies during the course of the project for the Faroe-Shetland Basin are:

- (1) intense compaction in the contact zone of the intrusion,
- (2) temperatures of 260°C and higher in the contact sandstones,
- (3) porosity loss to about 8% regardless of differences in the diagenetic history of a sediment and
- (4) permeability loss to less than 1 mD.

The discussion of seal capability of sills and basalts becomes partly irrelevant if the contact zone is not considered as well. The study here indicates that contact zones or aureoles of sills and accompanying host rock act as seal with very low permeability and low connectivity.

Introduction

The Faroe-Shetland Basin potential reservoir rocks are intruded by sills and overlain by thick basaltic extrusive rocks. The impact of these intrusions on reservoir maturation, heat flow and reservoir properties are widely unknown.

The SINDRI group has initiated the project on the impact of Palaeogene sill emplacement on reservoir lithologies in East Greenland and the Faroe-Shetland Basin. The studies on two onshore, outcrop analogues were undertaken on the Isle of Skye (Scotland) and Traill \emptyset (East Greenland) with the goal to petrographical describe the contact rock, define the contact diagenetic changes, simulate the intrusive event in a geochemical computer model and predict the impact of sill emplacement in the Faroe-Shetland Basin.

This report presents the description of effected and non-effected sandstones and interpretation of thermal effects of sill emplacement on these sandstones. The contact diagenetic changes and interpretations derived from using vitrinite reflectance data, petrographical analysis (including thin section photographs, BSE micrographs, CL micrographs and pointcounting data), whole rock analysis (XRF – major elements), core analysis (Helium porosity and gas permeability) and digital image analysis.

Project Aims

This report presents the results of the study of the impact of Palaeogene sill emplacement on potential reservoir lithologies in East Greenland and Scotland and applies them to reservoir lithologies of the Faroe-Shetland Basin.

The overall aim of this project is to develop a model for the predicting effects of sill emplacement on reservoir properties of sandstones, with particular relevance to understand the influence of diagenetic processes on permeability and thermal evolution in the Faroe-Shetland Basin.

The specific aims of this project are:

- 1. Constraining mineralogical effects of sill emplacement on adjacent sandstones.
- 2. Constraining the relationship between sill proximity and sandstone porosity and permeability.
- 3. Quantitative modeling of coupled thermally driven fluid flow and fluid-rock geochemical interactions in reservoir lithologies relating to sill emplacement and correlation with regional models.

Data sets used

The present report integrates data from several sources (additional to GEUS):

- Point counting data from the Traill Ø area, East Greenland conducted by Thomas Preuss (PhD), Copenhagen University, DK
- Sample collection from Skye, Scotland conducted by Brian Bell, Glasgow University, UK
- Petrographic analysis of the Traill Ø samples, conducted by Thomas Preuss (PhD), Copenhagen University, DK.
- Point counting data and petrographic description of the Skye samples, conducted by RDR Leeds, UK

Literature review on sill emplacement

The focus of mafic sill or dyke emplacement in recent literature can be distinguished between:

- Intrusions of igneous material into coals and their affect on thermal maturation (Frederick et al., 1985; Gilbert et al., 1985; Stewart et al., 2005; Thrasher, 1992)

- Theoretical modeling of igneous intrusions and their affect on sediments (Wang et al., 1989; Brown et al., 1994; Galushkin, 1997)
- Thermal alteration and hydrocarbon generation in contact aureoles (Bishop & Abbott, 1995; Othman et al., 2001; Araújo et al., 2005)
- Diagenetic alterations in contact zones of igneous intrusions (Summer & Ayalon, 1995; McKinley et al., 2001; Krynauw et al., 1994; Kemp et al., 2004; Lewis et al., 1992)
- Heat flux and element mobility during igneous intrusions (Dutrow et al., 2001; Krynauw et al., 1994; Dickin & Jones, 1983)
- Sill emplacement into metamorphic rocks (Holness and Watt, 2002)

Skye

Introduction

The Isle of Skye (**Fig. 1**) provides good accessible outcrops where thick, mainly Jurassic, sediments are intruded by Tertiary sills. That setting is believed to present an onshore analogue to offshore Jurassic and Cretaceous sandstone reservoirs (Harris, 1992). The sill complex covering that area is part of the Tertiary Iceland plume that covers an area of several thousand kilometres across the Northern Atlantic (**Fig. 2**). Further, the sandstones have a very well known stratigraphy, burial history and depositional environment, which make them an excellent study object on the effect of sill emplacement. Sampling and regional reconnaissance were carried out on the Trotternish Peninsula (**Fig. 1**) in NE Skye along the coast between Portree and Staffin. Brian Bell, University of Glasgow, UK, sampled two contact sections and provided the data for GEUS. Susanne Schmid, Dirk Frei and Julie A. Hollis (GEUS) undertook a reconnaissance study and further sampling in order to understand the stratigraphic and tectonic relationship between igneous intrusions and sediments.



Figure 1. Location map of the sampling area on Skye, NW Scotland.

Geological background



Figure 2. North Atlantic reconstruction during the Early Eocene times. The area affected by the Iceland Plume is represented by a circle. Dark grey shading represents Seaward Dipping Reflector Sequences whereas the lighter grey represents areas covered by flood basalts, sediment-sill complexes, central complexes (Ritchie et al., 1999).

The Isle of Skye as part of the islands of the Inner Hebrides exposes up to 1000 m of Jurassic sediments (Thrasher, 1992) that are unconformably overlain by thinly developed Cretaceous sediments and thick deposits of Tertiary basaltic lavas and cut by Tertiary intrusions (Fig. 3). The Tertiary magmatism on Skye has been postulated to be associated with the Iceland Plume (Ritchie et al., 1999; White, 1989; Fig. 2). The Hebrides Basin is a NNE-SSW oriented half-graben delimited in the WNW by the Minch Fault (Stein, 1988; Hesselbo & Coe, 2000). The Jurassic succession is mainly deposited under marine conditions but has a paralic episode during the middle Jurassic with deposition of deltaic and fluvial sediments (Harris, 1992). Middle Jurassic deposits of the Skye area are described into two distinctive lithostratigraphic groups: the Bearreraig Sandstone of late Aalenian to late Bajocian age, and the Great Estuarine Group of late Bajocian to

Bathonian age (Hesselbo & Coe, 2000; **Fig. 4**). The Bearreraig Sandstone is largely of marine origin and well-dated by ammonites, while the Great Estuarine Group represents a complex of lagoonal, deltaic and fluvial environments (Morten & Hudson, 1995). The Bearreraig Sandstone sequence is dominated by the deposits of migrating sandsheets on a storm- and tide-swept shelf (Morten, 1983) and comprises six members (Dun Caan Shales, Ollach Sandstone, Udairn Shale, Holm Sandstone, Rigg Sandstone and Garantiana Clay). The Great Estuarine Group comprises the deposits of tidally influenced shore lagoon com-

plex (Wilkinson, 1993) within seven formations (Cullaidh Shale Fm., Elgol Sandstone Fm., Lealt Shale Fm., Valtos Sandstone Fm., Duntulm Fm., Kilmaluag Fm. and Skudiburgh Fm.). The sedimentary succession was buried up to 500 m before it was intruded and overlain by basaltic sills and lavas (Hudson & Andrews, 1987; Wilkinson, 1993). The lava cover of around 900 m thickness buried the sediments up to 1400 m with an abnormally high



Figure 3. Tertiary sill covering and intruding a Jurassic sedimentary package, Trotternish Peninsula, Skye, UK





Figure 4. Summary graphic log for the Jurassic of the Trotternish Peninsula (Hesselbo & Coe, 2000).

Figure 5. Burial history for the Great Estuarine Group on north Skye (Hudson & Andrews, 1987).

Methods

Image analysis

Thin sections were photographed in high resolution (picture width 2 mm with a dimension of 1600x1200 pixels) using a Zeiss Jenapol microscope equipped with a Nikon Coolpix 4500 digital camera. The main components – clay/heavy mineral fraction, quartz/feldspar fraction and pore space (blue epoxy) – were measured by area using the FoveaPro software package. A validation of the data was achieved by manually colour coding parts of the thin section (in that case a consecutive line of photos across the thin section) and measuring for clay content and porosity.

<u>XRF</u>

Major elements were determined by X-ray fluorescence spectrometry (XRF) on fused glass discs. The X-ray fluorescence spectrometer is a Philips P\f1605 multichannel instrument for simultaneous determination of a number of specific elements, equipped with an Rh-anode X-ray tube operated at 50 kV and 50 mA. Calibration and correction for background and line overlaps were calculated from measurements on synthetic mono-element glass discs, and corrections for matrix effects were calculated either from measurements on synthetic glass discs or from Heinrich's (1966) absorption coefficients (e.g. Sørensen, 1981).

Vitrinite reflectance

The samples were embedded in epoxy, ground, and polished to obtain a smooth analysis surface. Vitrinite reflectance (VR; $%R_o$) measurements were conducted by a Leitz reflected light microscope with a 50x objective and oil immersion at 546 nm (monochromatic light). The VR measurements are "random", i.e. the samples were not oriented before measure-

ments as is the case for maximum VR measurements ($\[max]R_{max}$). Due to the high maturity of the organic matter in the samples the microscope was calibrated against a standard with a reflectance of 7.4%R_o. As many measurements as possible were carried out in each sample.

Modal analysis

A total of ten carbonated stained thin sections were point-counted (300 points per slide) for modal analysis by RDR Leeds. Of them, eight polished thin sections were examined with a CAMSCAN CS44 high performance scanning electron microscope equipped with a secondary electron (SE) detector, a high resolution solid stage four quadrant backscattered electron (BSE) detector, a cathodoluminescence (CL) detector and an EDAX energy dispersive X-ray spectrometer (EDS) for detailed petrographic and diagenesis analysis. Further, six polished thin sections were examined with a PHILIPS XL 40 scanning electron microscope equipped with a secondary electron (SE) detector, a backscattered electron, a cathodoluminescence (CL) detector, a backscattered electron (BSE) detector, a cathodoluminescence (CL) detector, a backscattered electron (BSE) detector, a cathodoluminescence (CL) detector and a ThermoNoran energy dispersive X-ray detection system (EDX) for detailed petrographic and diagenesis analysis by GEUS.

Gas permeability (GEUS steady state instrument)

The plug is mounted in a Hassler core holder, and a confining pressure of 400 psi applied to the sleeve. The specific permeability to gas is measured by flowing nitrogen gas through a plug of known dimensions at differential pressures between 0 and 1 bar. No back pressure is applied. The readings of the digital gas permeameter are checked regularly by routine measurement of permeable steel reference plugs (Core Laboratories[™] gas permeability reference plug set). Precision for permeability is 0.001-0.01mD - 25%, 0.01-0.1mD - 15%, > 0.1mD - 4%.

Helium porosity (precision 0.1% porosity) and grain density (precision 0.003 g/cc)

The porosity is measured on cleaned and dried samples. The porosity is determined by subtraction of the measured grain volume and the measured bulk volume. The Helium technique, employing Boyle's Law, is used for grain volume determination, applying a double chambered Helium porosimeter with digital readout, whereas bulk volume is measured by submersion of the plug in a mercury bath using Archimedes principle. Grain density is calculated from the grain volume measurement and the weight of the cleaned and dried sample. The Helium porosimeter is calibrated using a set of steel plugs (Core Laboratories volume reference plug set) before the measurement of plug samples is initiated.

Location description

The two sample locations were located along a cliff section on the Trotternish Peninsula, NE Skye (**Fig. 1**). *Set 1* was sampled on the small hill of Dun Dearg at Valtos. Beneath this, by the roadside, the uppermost part of the Valtos Formation (Concretionary Sandstones) is exposed and capped by sill (**Fig. 6**). These rocks (**Fig. 7**) consist of trough and planar cross-stratified, friable, yellow sands with well developed calcareous concretions (doggers). A hundred meters northward along the coast, the yellow sandstones are overlain by interbedded limestones and sandstones. The sampled contact between sediments and sill contains such an interbedded limestone, limy sandstone and sandstone succession (**Fig. 8**). *Set 2* was sampled at the north end of the Bearreraig Bay. Access to the section at Bearreraig (**Fig. 9**) is from a small car park at Storr Lochs hydroelectric power plant. The lithostratigraphic unit of the sampled set could not be determined but limited to an interval

between the upper parts of the Bearreraig Sandstone Formation – Rigg Sandstone or the Great Estuarine Group – Elgol Formation. The sandstones of the Bearreraig Sandstone Formation and Great Estuarine Group have experienced similar early diagenetic alterations. Both contain characteristic carbonate concretions (**Fig. 10 & 11**) that were formed under the same fluid composition (Wilkinson, 1991; Wilkinson, 1993). Both sample sets were taken from the lower contact of the sill to the sandstone.



Figure 6. (*left*) Dun Dearg, Valtos – Jurassic sandstones (lower half of the photo) are capped by a sill (upper left part of the photo).

Figure 7. (right) Valtos Sandstone Formation, yellow, cross-stratified and laminar sandstones cemented by large carbonate concretions.



Figure 8. (*left*) Jurassic sandstones of the Great Estuarine Group in contact to intruded basaltic sills. **Figure 9.** (right) Bearreraig Bay, Jurassic sandstones along the lower part of the cliff is capped by thick sills that build the cliff edge.



Figure 10. (left) Bearreraig Bay waterfall behind the hydroelectric power plant, Bearreraig sandstone and mudstone sequence with the Holm sandstone member characterised as a light coloured layer. **Figure 11.** (right) Bearreraig Bay waterfall, Holm sandstone containing well rounded and bed specific carbonate concretions; note that the underlying mudstones also contain units with concretions.

Results

Petrographic description

The petrographic data generated from combined point-counting analysis (300 points) and BSE & CL image analysis is presented in **Table 1** (see Appendix) and a detailed petrographic description of selected specimen in the Appendix.

The sandstones have fairly simple mineralogies. The detrital mineralogy of the sandstones is dominated by detrital quartz with a very small amount of feldspar, rock fragments and detrital clay. For a total ten point-counted samples, six samples are quartz arenites, three are calcite cemented quartz arenites and only one is a subfeldspathic arenite.

The grain size modes of these ten sandstones examined range from very fine sand to medium sand and sorting ranges from moderately well to well sorted. Grain roundness within the sandstones ranges from subangular to subrounded, while grain sphericity ranges from elliptical to subspherical.

Detrital mineralogy

The detrital mineralogy of the sandstone samples consists of the following:

Quartz grains (54-83%) are dominated by monocrystalline quartz (53.67-82.33%) which are generally subangular to subrounded and are commonly unstrained (**Fig. 12**). Although polycrystalline quartz is observed in all of the ten samples it is often very limited in abundance (0.33-0.67%) and occurrs as grains with both equant and subequant crystals.

Feldspar grains (trace-7%) comprise K-feldspar (trace-3.67%) and plagioclase (trace-3.33%). Both thin-section and SEM studies show the presence of almost completely dissolved feldspars (**Fig. 13**) which



Figure 12. Thin section photograph showing well sorted and weak-compacted, very fine to fine-grained sandstone (sample 110), scale: image width = 2mm.

now retain only a 'skeletal' structure. Feldspar dissolution created some secondary porosity, which is indicated by oversized pores and honeycombed feldspar grains (**Fig. 14**). Plagioclase grains do not exhibit the same level of dissolution as the K-feldspar grains with only minor dissolution.

Rock fragments (0.33-2%) are present in all of samples examined and are all shale clasts.

Micas (0.33-3.67%) are dominated by scattered flakes of muscovite (0.33-3.67%; **Fig. 15 & 16**) with a trace amount of chloritised biotite (trace-0.33%).



Figure 13. (*left*) *Thin section photograph showing dominantly quartz grains, lower middle photo showing dissolved K-feldspar grain, scale: image width = 2mm.* **Figure 14.** (*right*) BSE micrograph showing partially dissolved K-feldspar grains (sample 110).



Figure 15. (*left*) BSE micrograph showing muscovite flakes in a calcite matrix and surrounded by quartz grains (sample 108).

Figure 16. (*right*) *Thin section photograph showing a muscovite flake in weak-compacted sandstone* (*sample 110*), *scale: image width = 2mm*.

Heavy mineral grains (0.33-0.67%) are present in all of samples examined and comprise small grains of zircon, rutile, sphene and apatite.

Detrital clay – illite - (matrix) occurs in all samples examined and ranges in abundance from 0.33-14%. Matrix clay is detrital in origin, and occurs as bioturbated clay, clay clasts, rip-ups, and deformed clasts (pseudomatrix). The distribution of matrix clay is heterogeneous on all scales. The most abundant detrital clay (matrix) is found in *sample 207* (14% of bulk rock volume; **Fig. 17**), whereas the least abundant detrital clay (matrix) is found in three calcite-cemented sandstones (0.33 of bulk rock volume).



Figure 17. Thin section photograph showing high content of detrital clay minerals filling pores between detrital quartz grains (sample 207).

Authigenic mineralogy

The most abundant authigenic phases are calcite (including ferroan calcite) and quartz



Figure 18. Paragenetic sequence of the diagenetic minerals in the Skye sandstones. Length of the solid bars indicates relative time of diagenetic events.

overgrowth which make up to 31.50-40.75% and 1-8.67% of the rock volume respectively. Other diagenetic phases present in small amounts include pyrite, kaolin, chlorite and illite. The sandstones have experienced diagenetic alteration involving mechanical and chemical compaction, mineral precipitation and feldspar grain dissolution. For quantitative data for each of the sandstone samples please refer to the modal analysis **Table 1** (see Appendix). The diagenetic history that has been inferred is summarised schematically in **Figure 18** and each diagenetic process is discussed separately below.

Mechanical and chemical compaction

Mechanical compaction of sediments, involving grain re-arrangement and the crushing of soft lithoclasts, has been discussed by a number of authors (e.g. Houseknecht, 1987; Pittman & Larese, 1991; Giles et al., 2000). Operating alone it can reduce the porosity of clay-free, well-sorted sandstones to values of around 30% (Houseknecht, 1987); in clay-rich sandstones it can be more effective. Porosity-depth trends (e.g. Ramm, 1992; Ramm & Bjørlykke, 1994) suggest that mechanical compaction occurs in a linear manner until a temperature threshold which chemical compaction dominates (~90°C in Jurassic sandstones of the North Sea). Overpressuring may decrease the rate of mechanical compaction by reducing the effective stresses at grain contacts. Early cementation can also retard mechanical compaction (Fisher et al., 1999).

Chemical compaction (pressure solution) refers to the process of mineral dissolution at stressed grain-contacts. In quartzose sandstones, the time-temperature history is probably the most important variable affecting the diffusive mass transfer (DMT) processes involved, quartz dissolution being very slow at temperatures below 90°C but significantly at higher temperatures. The rate of pressure solution can be enhanced by small concentrations of phyllosilicates at grain-contacts.

The sandstones in the studied samples are well compacted with textural evidence for both mechanical and chemical compaction present. Detrital muscovite grains commonly are bent and distorted around quartz grains. Concavo-convex, linear and sutured contacts between quartz grains provide evidence for intergranular pressure solution and compaction (**Fig. 19 & 20**). The process of compaction clearly degraded the porosity-permeability properties. In general, sandstones with higher concentrations of ductile grains (rock fragments and feldspar grains) and matrix (detrital clay) experienced stronger compaction than those with low concentrations of ductile grains and matrix.

Calcite and ferroan calcite cement

Calcite and ferroan calcite cement are only present in three out of ten samples (106, 108 and 109) with their abundance up to 40.75% of rock volume. The massive calcite (including

minor ferroan calcite) occludes all intergranular porosity (**Fig. 21 & 22**) and dramatically reduces the porosity and permeability of these three sandstones. The high minus-cement porosity and floating-grain texture suggest that calcite precipitated in the very early stage at shallow burial.



Figure 19. (*left*) Thin section photograph showing concavo-convex, linear and sutured contacts between grains indicating that significant chemical compaction has occurred (sample 103), scale: image width = 2mm.

Figure 20. (left) Cross-polarised, thin section photograph showing concavo-convex, linear and sutured contacts between grains indicating that significant chemical compaction has occurred (sample 209).



Figure 21. (*left*) BSE micrograph showing the massive calcite cement (sample 108); note that the high minus-cement porosity and the floating-grain texture indicates the very early cementation at shallow burial.

Figure 22. (right) Thin section photograph showing the calcite-cemented, fine to medium-grained quartz arenite (sample 109), note that the high minus-cement porosity and the floating-grain texture indicates the very early cementation at shallow burial, scale: image width = 2mm.

Quartz precipitation

Except three calcite-cemented sandstones and *sample 110*, authigenic quartz is a ubiquitous and volumetrically important component of the sandstones examined. It occurs in mesocrystalline form, as up to 100 µm thick syntaxial overgrowths on detrital quartz grains. Image analysis on CL photomicrographs suggests that it can make up to 8.67% of the rock volume (**Fig. 23 & 24**). The well-developed nature of the quartz overgrowth demonstrates that the sandstones have spent significant amounts of time under temperatures beyond ~90°C. Silica for quartz cementation could have been sourced locally through chemical compaction (pressure solution) and the dissolution/alteration of unstable detrital silicates.

Sample 207 and sample 110 have least quartz overgrowth (<2%) due to the common presence of grain-coating clays in these two sandstones.



Figure 23. (left) Thin section photograph showing well developed quartz overgrowth on detrital quartz grains (see red box) entirely occluding pore space (sample 202), scale: image width = 2mm. **Figure 24.** (right) Combined BSE and CL micrograph showing the detrital quartz grains (orange light colour) by CL and quartz overgrowth (non-luminescent), note that the quartz cement is not visible using BSE alone (sample 202).

Key factors controlling the abundance on mesocrystalline quartz cement in reservoir sandstones are now quite well understood and include: (1) clay content, (2) grain size, (3) mineralogy, (4) hydrocarbon emplacement and (5) temperature-time history (e.g. Bjørlykke & Egeberg, 1993; Bjørkum, 1996; Oelkers et al., 1996; Walderhaug, 1996; Worden et al., 1998; Fisher et al., 2000). These factors are reviewed briefly below:

Clay content: The presence of clay influences both silica generation and quartz precipitation processes. Low concentrations of clay at grain-grain contacts may increase the rate of quartz dissolution because: (1) they enhance the rate of solute diffusion away from stressed dissolution sites due to the presence of enlarged absorbed water films and/or (2) they locally increase pH and hence quartz solubility. In contrast, high concentrations of grain-coating clays may suppress quartz cementation by (1) retarding solute diffusion to grain surfaces, and/or (2) blocking nucleation sites.

Grain size: The rate of quartz cementation is often controlled by quartz surface area, which decreases with increasing grain size in clean sandstones. Fine-grained sandstones are commonly observed to have experienced more quartz cementation than their coarsergrained equivalents.

Sandstone mineralogy: Since quartz surface area often controls the rate of quartz cementation, sandstones with lower concentrations of quartz grains tend to experience less cementation than quartz arenites.

Hydrocarbon emplacement: Whilst quartz cementation may continue subsequent to hydrocarbon emplacement due to solute diffusion through thin adsorbed water films, the rate of solute supply may be reduced leading to a decrease in the rate of quartz cementation. Temperature-time history: The rate governing step in quartz cementation is usually quartz precipitation, which is temperature dependant and not significant until sediments have been buried beyond 90°C. Quartz cementation should thus be of reduced importance in reservoirs that have not been buried beyond 90°C. In reservoirs buried beyond this temperature the extent of quartz cementation should be controlled by the time-temperature history.

K-feldspar dissolution

Both thin section and SEM studies show the presence of almost completely dissolved K-feldspars which now retain only a 'skeletal' structure and are partly replaced by illite (**Fig. 25**). Feldspar dissolution created well developed secondary porosity, which is indicated by oversized pores and honeycombed feldspar grains (**Fig. 14**). Plagioclase grains do not exhibit the same level of dissolution as the K-feldspar grains with only minor dissolution.



Figure 25. BSE micrograph showing intense *K*-feldspar dissolution, creating of secondary porosity and replacement by illite, pore cement is calcite (sample 108).

Kaolin precipitation

Only very small amounts of authigenic kaolin (~0.33%) are present in some samples examined as pore-filling aggregates of delicate crystals.

Chlorite precipitation

Chlorite is the most abundant authigenic clay in the samples. It occurs both as grain coatings and pore-filling aggregates at concentrations up to 9% of the rock volume (**Fig. 26 & 27**).



Figure 26. (*left*) Thin section photograph showing authigenic chlorite (yellow, green, light brown colour) filling primary pore space (sample 202), scale: image width = 2mm. **Figure 27.** (right) BSE micrograph showing massive, pore filling chlorite cement (sample 202).

Illite precipitation

Authigenic illite was observed in the samples studied, although at abundances rarely exceeding ~0.33% of rock volume. The authigenic illite that is present tends to have a hairy morphology, which is known to be particularly effective at lowering permeability because of its high surface area to volume ratio. The illite appears to have precipitated at a relatively

late stage of the burial history. It is likely that it formed as pore-fluids became increasingly K-rich via K-feldspar dissolution (**Fig. 28 & 29**).



Figure 28. (*left*) Thin section photograph showing illite and chlorite replacing detrital K-feldspar (sample 205), scale: image width = 2mm.

Figure 29. (right) BSE micrograph showing hairy illite infilling pores, replacing K-feldspars and coating detrital quartz grains (sample 205).

Modal analysis

Trends with contact to sill



Figure 30. Plot of petrographically defined (a) quantity of detrital quartz content vs. distance from sill and (b) quantity of quartz overgrowth vs. distance from sill.

Quartz - the most abundant component in the sandstones is guartz and concomitantly quartz overgrowth as the dominating authigenic phase. The plots of detrital quartz versus distance from sill and authigenic quartz versus distance from sill show that quartz overgrowth directly correlates to the amount of detrital quartz present (Fig. 30). There is no clear trend that the volume of quartz overgrowth is related to the distance from sill. However, a plot of detrital quartz versus authigenic quartz shows a very good correlation $(R^2 = 0.7)$ implicating that the amount of quartz overgrowth is partly controlled by the total volume of quartz available during diagenesis (Fig. 31).

Clay – the abundance of authigenic clay is below 1% or absent in most of the samples whereas detrital (matrix) clay takes up to 14% of the rock volume. The plot of the total clay content versus distance from sill reflects the compositional changes of the sediment in both sampled sections (**Fig. 32**). The suppression of quartz cementation by grain coating clay minerals has been noted in several reservoir studies. A plot of matrix clay versus quartz overgrowth shows a very good negative correlation ($R^2 = 0.96$; **Fig. 33**).



Figure 31. Plot of petrographically defined quantity of quartz overgrowth vs. quantity of detrital quartz content. Quartz overgrowth must be a function of quantity of detrital quartz since they show a good correlation.



Figure 32. Plot of petrographically defined quantity of total clay content vs. distance from sill.



Figure 33. Plot of petrographically defined quantity of quartz overgrowth vs. quantity of matrix clay content.

Porosity-Permeability

The porosity ranges from 1.4 to 23.87% of the rock volume, where the lowest porosity occurs in the calcite cemented sandstones. The average porosity in sample *set 2* is 8.6%, while porosities in sample *set 1* vary widely (10.4% near contact and 23.9% furthest away).

PoroPerm (**Fig. 34**) - The correlation analysis shows a strong and moderate correlation between porosity and permeability of the samples from Skye. The correlation coefficient derived from regression analysis is $R^2 = 0.86$ for sample set 1 – strong correlation and $R^2 = 0.36$ for sample set 2 – a moderate correlation.

He-Porosity – point-counting derived porosity relationship (**Fig. 35**) – In testing the accuracy of point-counting derived porosity the data were plotted versus helium porosity. The plot shows a strong correlation with a correlation coefficient of R^2 = 0.93. However, He-porosity values are slightly higher than modal data.

He-Porosity – distance from sill relationship (**Fig. 36**) – There is no correlation between porosity or permeability and distance from sill as shown in the plots.

Permeability – total clay relationship (**Fig. 37**) – Permeability is often controlled by the detrital clay content during burial diagenesis. The plot of total clay versus permeability however shows no simple correlation.

Porosity – quartz, clay relationship (**Fig. 38**) – The relationship between quartz overgrowth and total clay content versus porosity does not show a simple correlation either.

The lacking correlation between cements and porosity might indicate that cementation was not the responsible factor in porosity reduction in the sandstones. Therefore, a second variable has to be taken into account – compaction. At surface conditions, a direct relationship exits between the degree of cementation and sandstone porosity, because the presence of a certain volume of cement reduces the porosity by the same volume (Beard &



Figure 34. (left) Core analysis porosity vs. core analysis permeability for both data sets. Data set 1 shows better correlation than set 2.

Figure 35. (right) Plot of petrographically defined porosity vs. core analysis porosity.



Figure 36. (left) Core analysis and petrographically defined porosity for sample set1 and set2 vs. distance from sill.

Figure 37. (right) Plot of petrographically defined total clay content vs. core analysis permeability.



Figure 38. (left) Plot of petrographically (modal), core analysis (helium) and digital image analysis (img) defined porosity vs. petrographically defined quartz/clay ratio.

Figure 39. (right) Diagram illustrating contrasting styles of porosity loss in sandstones (after Houseknecht, 1984). Petrographically defined total cement content vs. intergranular volume defines the intergranular porosity and compaction or cementation dominated porosity loss.

Weyl, 1973; Worden et al., 1997). In the subsurface, porosity reduction will be caused by both cementation and compaction. However, the extent of porosity reduction may not be simple subtraction of cement and compaction from the surface porosity as the cement may act to stabilize the sandstone framework and thus restrain compaction. The relative effects of compaction and cementation on sandstone porosity can be illustrated by a plot of intergranular volume (IGV) versus total cement (Ehrenberg, 1989, 1990; Houseknecht, 1987, 1989). Mechanical compaction by packing and re-orientation of grains reduces IGV from an initial depositional value of approximately 45% to a theoretical minimum of 26% (Taylor & Soule, 1993). Further reduction in IGV would require grain volume-loss through intergranular pressure solution or porosity loss due to ductile grain deformation. The plot here (**Fig. 39**) shows clearly that the sandstones are divided in two groups. Three samples fall into the cementation dominated porosity loss field and represent the samples that contain very early calcite cements preserving the primary porosity under surface conditions of about 45%, while the non-calcite cemented samples plot in the compaction dominated porosity loss field. Compaction had the dominant effect on porosity in those sandstone.

Image analysis

Digital image analysis has been conducted in order to identify the spatial distribution of permeability and porosity reducing minerals such as clays. The imaging tool has also been used to see general pattern within the sandstone in increasing distance from the sill contact.

Nine sandstone samples have been photographed in high resolution (picture width 2 mm with a dimension of 1600x1200 pixels). The main components – clay/heavy mineral frac-



Figure 40. Assembled thin section photograph generated by individual thin section photographs showing the general porosity distribution (blue colour) and degree of homogeneity in the sediment.

tion, quartz/feldspar fraction and pore space (blue epoxy) - were measured by area using the FoveaPro software package (Fig. 40 & 41). A validation of the data was achieved by manually colour coding parts of the thin section (in that case a consecutive line of photos across the thin section) and measuring for clay content and porosity. The derived porosity was plotted versus quartz/clay ratios and compared to helium porosity and modal porosity data (Fig. 38). All three methods show the same trends in porosity but vary in magnitude. The image analysis data record lowest porosities in comparison, with accuracy decreasing with decreasing porosity. The main advantage of the digital imaging is that clay fraction distribution can easily be identified for a thin section and special areas can then be targeted using SEM, CL or other techniques. The colour coding of selected areas shows that clays and subsequently quartz cements (see modal analysis chapter) are not equally distributed throughout the thin section. As a result, the porosity - especially in sample 202 and 205 is concentrated to specific areas in the sandstone and permeability due to low connectivity is diminished. In samples 106 and 109 porosity is virtually invisible due to the pervasive calcite cementation (Fig. 42). Image analysis revealed that calcite cements evolved from what appears to be like remains of shell fragments and so helps to visually understand early calcite cementation in these sandstones.

There is no obvious trend in sample set 2 with distance from sill. Sample set 1 had been strongly calcite cemented before compaction; therefore only two samples (closest and furthest away) can be compared. The sample closest to the sill – 202 - shows less porosity than the sample furthest away - 210.



Figure 41. (*left*) Digital image analysis – colour coding - of a sandstone sample showing distribution of clays, porosity and permeability. Blue colour represents visible pore space; green colour represents visible clay minerals.

Figure 42. (right) Digital image analysis – colour coding – of a sample showing distribution of calcite cement, biogenic clasts and porosity. Light blue colour represents visible biogenic clasts; green colour represents visible calcite cement.

Whole rock analysis - major elements

Major element analysis

Whole rock analysis of sill and sandstone samples was determined (**Table 2**). The sills of both locations have been classified as basalt after the SiO_2 vs. Na_2O+K_2O total alkali-silica plot (Middlemost, 1994; **Fig. 43**). The calculation of the CIPW-norm shows a mineral com-

position of (in order or volume) albite, anorthite, diopside, hematite, hypersthene, sphene, orthoclase, quartz, apatite and ilmenite (**Table 3**, see Appendix). The composition of the

sandstones is dominated by SiO₂ with up to 97% of the rock volume (56-97%), followed by CaO (0-23%), Al₂O₃ (0.4-4.5%) and Fe₂O₃ (0.1-3.7%). Major elements (oxides) that have between 0.1 and 1% of the rock volume are TiO₂, MgO and K₂O. It is notable that Na₂O only reaches up to 0.19% and is generally below than 0.1% of the rock volume. The plot of CaO versus LOI (lost on ignition) shows for all samples with CaO that Ca content plots along the fractionation line indicating that all calcium is taken up by calcite in sample set. All major elements were plotted versus distance from sill. In sample set 2 (Fig. 44) SiO₂ has an inverse correlation to Al₂O₃ and K₂O, probably indicating an increased



Figure 43. Plot of SiO₂ vs. Na_2O+K_2O after TAS Middlemost (1994) showing the basaltic composition of sill sample from set 1 and set 2 (identical).

abundance of K-feldspar in some samples. Sample set 1 (**Fig. 45**) shows no distinctive changes in chemical composition or mineral abundance with distance from sill. Sample set 2 has a notable increase in the abundance of MgO, Fe_2O_3 , Al_2O_3 and decrease in SiO₂ close to the sill contact.

Correlation to petrographic analysis data

The whole rock analysis oxides have been converted and correlated to mineral abundance derived from modal analysis measurements in order to validate the accuracy of point-counting data and optical non-resolvable element distribution as found in matrix clay. The results confirm the modal analysis data findings within an error of less than 2%. However, three distinctive observations could be made. One, the point-counted calcite content was decidedly smaller than the available CaO in the three samples (note that CaO against LOI falls on the calcite fractionation line). Therefore, the point-counted data have been recalculated for the calcite and quartz content. Second, *sample 202* shows significant variations in the abundance of SiO₂, Al₂O₃, MgO, Fe₂O₃ and CaO. SiO₂ does not account for the modal analysis derived quartz content and the others are not used by other mineral phases according to the point-counting data. Additional petrographic and SEM studies reveal that the quartz content has to be smaller (reduced by 9.5%) than point-counted values and the chlorite content has to go up significantly (8.3%). The oxide proportions in chlorite have been determined using EDX values collected during SE imaging. All "available" oxides from XRF data could be used in proportion in order to calculate the additional chlorite.



Figure 44. Plot of whole rock analysis derived major element oxides vs. distance from sill of sample set 2.



Figure 45. Plot of whole rock analysis derived major element oxides vs. distance from sill of sample set 1.

Vitrinite reflectance

General usage of vitrinite reflectance

The vitrinite reflectance, expressed as R_0 %, is used as a maturity parameter in basin modeling and hydrocarbon exploration (Zattin et al., 2006; Mukhopadhyay, 1994). Vitrinite is derived from the thermal degradation of lignin and cellulose, and can be found in kerogens rich in higher plants fragments (Teichmueller, 1987; Zattin et al., 2006). As the maturity increases, a progressive ordering takes place in the vitrinite molecular structure; this causes an increase of the reflection of the incident light. Vitrinite reflectance has also been used to estimate maximum temperatures attained by sedimentary rocks in geothermal areas (Barker, 1983; Sweeney & Burnham, 1990) and near igneous intru-



Figure 46. Calculated values of %*R*_o vs. distance from dike contact of known thermal histories and the indicated intrusion temperature. Values were computed at the same distances as the measured data; the curves represent the trend of the calculations, and the points represent measured data of Bostick & Pawlewicz (after Sweeney & Burnham, 1990).

sions (Wang et al., 1989; Galushkin, 1997). The maximum temperature attained by the host rock and the size of the maturity aureole near the intrusion depends on: (1) the initial temperature of the intrusion, (2) the duration of magma body formation within the host rock, (3) the consolidation stage of the host rock and (4) the composition of the intrusion. Therefore, the maturity reached during magmatic intrusions can only reflect the maximum temperature of the host rock experienced but not be used as a general prediction tool (**Fig. 46**).

Measurements in the sandstones

Results from vitrinite reflectance in ten sandstones from Skye are poor. Only one sample – 202 – had sufficient coal macerals for measuring mean random reflectance R_o. A total of 9 particles have minimum R_o=2.11%, maximum R_o=2.79% and mean values of R_o=2.45%. Implications for sandstone temperature – The mean R_o of 2.45% corresponds to a sill temperature of 500-600°C and a host rock (at the contact in that case) temperature of 268°C. Temperatures attained by the host rock were estimated using Barker and Pawlewicz's (1994) relationship of R_o to T_{peak}: T_{peak}=(*In*R_o+1.19)/0.00782. The temperature of the intrusion correlates with the R_o value presented in various publications (Galushkin, 1997; Sweeney & Burnham, 1990; Stewart et al., 2005). The maximum temperature (268°C) reached in the sandstones corresponds under a normal geothermal gradient to a burial depth of about 4000 to 4500 m.

Interpretation

The petrographic observations, vitrinite reflectance and porosity results lead to a consistent interpretation. The first event that took place during early diagenesis under subsurface conditions was the precipitation of pervasive calcite cement. The calcite precipitated from dissolving shell fragments and plugged all available pore space, preventing any later diagenetic alteration but preserving the sandstones primary porosity signature of 45%. Minus cement porosity varies significantly (without the calcite cemented sandstones) from 10.00 to 26.88%. The degree of compaction and the successive porosity loss is largely dependent on the ratio of brittle to ductile sand grains (Worden et al., 2000). In sandstones



Figure 47. Compaction curves for sandstones and mudstones of different primary lithologies (Worden & Burley, 2003).

composed predominantly of competent grains (e.g. quartz, feldspar) the potential for grain reorganization is much less than for mudstones (Worden & Burley, 2003; Fig. 47). The sandstones with an abundance of less ductile sand grains such as clay-rich fragments, mud intraclasts tend to undergo intense plastic deformation, resulting in enhanced porosity loss (Worden & Burley, 2003). The sandstones on Skye have been buried to approximately 1400 m prior to the intrusion (Wilkinson, 1993). The clean quartz arenites are expected to have around 33% porosity with a 1400 m overburden, while any

sandstone with a higher abundance of clay-rich lithics can reduce primary porosity to approximately 25% according to Worden & Burley (2003). The variations occurring in the Skye samples are interpreted as being the result of the degree of compaction in each sandstone bed due to varying detrital composition. The intergranular volume (minus cement porosity) is on average 15% which corresponds to a theoretical burial depth of a nonclean guartz arenite of more than 4000 m. One sample from set 1 (7 m from contact) has a higher porosity (26.88%) and represents the porosity expected under 1400 m overburden. Chemical compaction continues to reduce porosity in these sandstones to 7% adjacent to the sill contact. Quartz precipitation is the most common cement with up to 8.67% of the rock volume. Quartz cementation of ~9% is equivalent to a theoretical burial depth (normal geothermal gradient) of approximately 4000 to 4500 m and a temperature regime between 120°C and 160°C (McBride, 1989). The amount of quartz precipitated depends on saturated silica in the fluid and the amount of detrital guartz dissolved. Variations can occur e.g. if clay minerals coat quartz grains and thus prevent quartz dissolution. However, the burial signature in the sandstones was induced by the sill emplacement and not increased burial depth. It is known that non-intrusion affected sandstones in the area did not exceed more than 1400 m of burial depth (Wilkinson, 1991, 1993). Vitrinite reflectance data suggests that the maximum temperature that has been reached in the sandstones due to the intrusion was about 268°C. This temperature would be under a normal geothermal gradient the equivalent to a burial depth of 4000 to 4500 m. Porosity, quartz cement volume and vitrinite reflectance data correspondingly suggest that the sill emplacement lead to enhanced compaction and guartz cementation and consequently reduced porosity and permeability significantly. The extent of the contact aureole can not be accurately predicted because sample set 1 showed less contact influence in a sample 7 m away from the contact (27% porosity corresponding to a burial depth of ~1400 m without the effect of heating from intrusions and only minor quartz cementation (1.67%)); while a sample 9.7 m away from the contact in set 2 shows clear contact influences. Sandstones more than 25 m away from the contact were not affected by the sill emplacement.

Conclusion

The diagenetic sequence in the samples from Skye is influenced by sill emplacement through:

- (1) enhanced compaction,
- (2) elevated quartz cementation at a burial depth of 1400 m,
- (3) reduced porosity and permeability, and
- (4) a "false" diagenetic signature suggesting a burial depth of 4000 m.

The extent of the contact aureole can not be determined and varies widely between different locations mostly depending on the detrital composition of the host rock, thickness of the intrusion and temperature of the intrusion. The reduced porosity and permeability and the absence of macro- or micro fractures suggest that these sandstones below an igneous intrusion can hypothetically act as a seal. However, the variation in extent of the contact aureole and the diagenetic assemblage suggest that the prediction of influence on potential reservoir rocks is limited.

Traill Ø

Introduction

The Traill Ø area (**Fig. 48**) in East Greenland is believed to be a representative outcrop analogue for Cretaceous and Palaeocene sedimentary successions in the offshore areas of the Northern Atlantic. Particularly relevant are sandstone lenses/beds in mudstone-dominated intervals. The shallowly buried Cretaceous sandstones of Traill Ø were the focus of this study. They are intensely intruded by Tertiary basaltic sills and dykes. Sampling was carried out by Thomas Preuss and Michael Larsen on a sandstone–mudstone interval intruded by a circa 20 m thick doleritic sill. The upper contact between the sill and sediments was sampled. The field campaign was part of a PhD thesis by Thomas Preuss (University of Copenhagen) with the purpose of investigating the thermal maturity in volcanic-influenced sedimentary basins in East Greenland.



Figure 48. Simplified geological map of the Traill Ø area, East Greenland. Asterisk shows the sampling location at the mouth of the Månedal River (Preuss, 2005).

Geological background

The Jurassic-Cretaceous succession in the Traill Ø area was deposited along the western margin of the Northern Atlantic rift (Surlyk, 1977). Cretaceous sedimentation is characterised by post-rift deposition (Surlyk & Noe-Nygaard, 2001). The earliest known Cretaceous deposits are deep-water mudstones and red marls carrying rich ammonite fauna (Surlyk, 1978). During the Barremian-Albian transgression cycle, shelf mudstones were deposited (Donovan, 1957). From the Upper Albian to Campanian a relative sea level fall occurred (Whitham et al., 1999) and marine mudstones with subordinate sandy turbidites were deposited (Surlyk & Noe-Nygaard, 2001; Stemmerik et al., 1997). The sampled section on Traill Ø comprises mature turbidites of the Vega Sund Formation, Coniacian (Surlyk & Noe-Nygaard, 2001; Fig. 49). Palaeogene rifting and the onset of sea-floor spreading in the Northern Atlantic region led to intense faulting of the sedimentary succession in NE Greenland (Preuss, 2005). This tectonic phase was associated with several episodes of magmatic activity and numerous sill and dyke emplacement into the Cretaceous succession (Price et al., 1997; Hald, 1996; Stemmerik et al., 1993). Upper Eocene and Lower Oligocene syenitic plutons intruded the sediments in the easternmost part of Traill Ø (Hald & Tegner, 2000; Price et al., 1997). Lower Eocene plateau basalts are thickly developed to the north and south of Traill Ø but are not believed to have covered Traill Ø (Koch & Haller, 1971).



Figure 49. Stratigraphic scheme of the Permian-Cretaceous succession in the Traill Ø are, East Greenland (Surlyk & Noe-Nygaard, 2001).

The sedimentological section of the Vega Sund Formation derived from Michael Larsen (Preuss, 2005).

Methods

Sample collection

Samples for petrographic study were collected from three different stratigraphic levels in a westward dipping sandstone succession. The location is characterised by a vertical contact between the intrusion and the host rock. A reference sample was taken 30 m away from the sill.

Image analysis

Thin sections have been photographed in high resolution (picture width 2 mm with a dimension of 1600x1200 pixels) using a Zeiss Jenapol microscope equipped with a Nikon Coolpix 4500 digital camera. The main components – clay/heavy mineral fraction, quartz/feldspar fraction and pore space (blue epoxy) – were measured by area using the FoveaPro software package.

Vitrinite reflectance

The samples were embedded in epoxy, ground, and polished to obtain a smooth analysis surface. Vitrinite reflectance (VR; $%R_o$) measurements were conducted by a Leitz reflected light microscope with a 50x objective and oil immersion at 546 nm (monochromatic light). The VR measurements are "random", i.e. the samples were not oriented before measurements as is the case for maximum VR measurements ($%R_{max}$). Due to the high maturity of the organic matter in the samples the microscope was calibrated against a standard with a reflectance of 7.4%R_o. As many measurements as possible were carried out in each sample.

Modal analysis

A total of 39 thin sections were prepared and impregnated with blue-dyed epoxy resin. A total of 300 points were counted by a Swift automatic point counter model F in each thin section. Polished thin sections were carbon coated and examined by scanning electron microscopy (SEM) using a Philips XL40 SEM to obtain secondary electron (SE-) and back-scattered electron (BSE) images. Semi-quantitative mineral analysis was performed on the SEM with a Noran Vantage Energy Dispersive Spectral (EDS) system.

Gas permeability (GEUS steady state instrument)

The plug is mounted in a Hassler core holder, and a confining pressure of 400 psi (or specified by the client) applied to the sleeve. The specific permeability to gas is measured by flowing nitrogen gas through a plug of known dimensions at differential pressures between 0 and 1 bar. No back pressure is applied. The readings of the digital gas permeameter are checked regularly by routine measurement of permeable steel reference plugs (Core LaboratoriesTM gas permeability reference plug set). Precision for permeability is 0.001-0.01mD - 25%, 0.01-0.1mD - 15%, > 0.1mD - 4%.

Helium porosity (precision 0.1% porosity) and grain density (precision 0.003 g/cc)

The porosity is measured on cleaned and dried samples. The porosity is determined by subtraction of the measured grain volume and the measured bulk volume. The Helium technique, employing Boyle's Law, is used for grain volume determination, applying a double chambered Helium porosimeter with digital readout, whereas bulk volume is measured by submersion of the plug in a mercury bath using Archimedes principle. Grain density is calculated from the grain volume measurement and the weight of the cleaned and dried sample. The Helium porosimeter is calibrated using a set of steel plugs (Core Laboratories volume reference plug set) before the measurement of plug samples is initiated.

Location description (derived from Preuss, 2005)

The studied section is located at the mouth of the Månedal River, northern Traill \emptyset (Fig. 50) and is part of the Vega Sund Formation. The succession is faulted and approximately 130 m of sheet-like, 10-25 cm thick, normally graded sandstone turbidites are separated by thin shales. In the sample location (Fig. 51 & 52), the sediment is intruded by one or several sills of up to 20 m thickness, which are exposed at higher levels up though the succession in a westward direction. It is suggested that the intrusion represents a single sill, which jumps stepwise up through the host rock towards the west (Fig. 53). The upper contact of

the Vega Sund Formation is not known, and a precise estimate of the sedimentary overburden in the area is therefore not possible. However, based on the scattered occurrence of post-Coniacian sediments, the maximum overburden at the time of intrusion is estimated to have been no more than 600 m (Donovan, 1957; Surlyk et al., 1981; Stemmerik et al., 1993).



Figure 50. Lower and middle section of the Vega Sund Formation along the Månedal River. Height of riverbank = 20 m (photograph by Michael Larsen).



Figure 51. (left)The lower section of the Vega Sund Formation at the mouth of the Månedal River. Sampling was carried out in three stratigraphic beds (photograph by Michael Larsen). Figure 52. (right)The lower section of the Vega Sund Formation at the mouth of the Månedal River. Sampling was carried out in three stratigraphic beds (photograph by Michael Larsen).





The present exposure at Månedal after Miocene tilting. uplift and erosion.

Figure 53. Sketch of the suggested progress of the sill in the Vega Sund Formation along the Månedal River. Sample locations are marked by an arrow (Preuss, 2005).

Results

Petrographic description (data partly derived from Preuss, 2005)

Detrital mineralogy



Figure 54. Photograph of finely laminated sandstones and siltstones of the sampling area (photograph by Michael Larsen).



Figure 55. Thin section photograph showing highly dissolved K-feldspars, which are altered into clay minerals (sample 445001), scale: image width = 2 mm.

The sandstones (Fig. 54) consist of 29.3-57.3% quartz, 0-9.7% rock fragments, 0-3% feldspar and trace amounts of heavy minerals, dominated by zircon. Approximately 36.7-67.7%, averaging 55% by volume, of the sandstones comprise authigenic minerals replacing detrital minerals and filling pores. This composition classifies the majority of the sandstones as metaguartzites and sublitharenites. The sandstones are well- to very well-sorted in fine- to very finegrained beds, and dominantly moderately sorted in the medium- and coarse-grained beds. Detrital grains are subangular and occasionally angular or rounded.

Quartz – is the main detrital component (29.3-57.3%, average 40.9%), and grains are mostly monocrystalline. Most quartz grains show slight undulatory extinction. The texture of the rarer polycrystalline quartz is indicative of a metamorphic origin.

Rock fragments – (0-9.7%, average 1.8%) are dominated by plutonic grains and minor metamorphic grains. The coarse grained sandstones contain up to 6.3% sedimentary mudstone clasts.

Feldspar grains – (0-3%, averaging 0.3%) are very rare, but when present plagioclase is more abundant than K-feldspars. SEM and optical microscope studies show that K-feldspar is mostly completely dissolved (**Fig. 55**) and replaced by authigenic minerals. Therefore, it is not possible to estimate the original amount of feldspar in the sandstones.

Mica – in form of muscovite and biotite is found in all samples from trace amounts up to 10.7%, averaging 1.5%. Both muscovite and biotite suffered considerable chloritisation during diagenesis, and Ti-oxides are concentrated around and within the degraded biotite grains.

Heavy minerals, detrital clay and bioclasts occur only in trace amounts.

Authigenic mineralogy

The most abundant authigenic phases are albite, clay (phengitic, glauconitic, chloritic) and quartz overgrowth, which make up to 22.7-60% of the rock volume respectively. Other diagenetic phases present are pseudomorphs after and alusite and cordierite, epidote, Tioxides, pyrite, apatite, sphene,

zeolite (laumontite, K-zeolite, analcime), calcite and goethite. The sandstones have experienced extensive diagenetic alteration involving mechanical and chemical compaction, mineral precipitation, feldspar grain dissolution and albitization. Further, the sandstones underwent low-grade contact metamorphism. The diagenetic history that has been inferred is summarised schematically in Figure 56 and each diagenetic process is discussed separately below. For quantitative data for each of the sandstone samples please refer to the modal analysis Table 4 (see Appendix).



Figure 56. Paragenetic sequence of the diagenetic minerals in the Traill Ø sandstones. Length of the solid bars indicates relative time of diagenetic events (after Preuss, 2005).

Mechanical and chemical compaction

Mechanical compaction comprises grain crushing, stress-related extinction due to high direct stress. Fractures up to several centimetres wide occur throughout the sampled interval (**Fig. 57 & 58**) and are related to the adjacent sill intrusion. Intense chemical compaction resulted in e.g. quartz and albite overgrowth due to pressure solution.

Pseudomorphs after andalusite and cordierite

Characteristic euhedral orthorhombic or hexagonal grains are observed in several



Figure 57. Thin section photograph showing microfractures in quartz dominated sandstone (sample 445019), scale: image width = 2 mm.

samples (**Fig. 59**), in volume up to 6%. The pseudomorphs now consist of illite and chlorite. Several grains have small subhedral apatite crystals (**Fig. 60**). The inner core commonly

displays lineations and extinction patterns described as hourglass- and cross-like structures. Later diagenetic mineral growth has physically disturbed some of the grains, but widespread destruction by mechanical compaction has not occurred. Thus the main phase of compaction predates the formation of the fragile grains. Later overgrowth by chlorite, albite, apatite, quartz, sphene, pyrite, laumontite and calcite indicates that the grains were formed during one of the earliest diagenetic phases in the sandstones. Orthorhombic andalusite (Al₂SiO₅) and hexagonal cordierite ((Mg,Fe)₂[Si₅Al₄O₁₈]*nH₂O) are commonly associated with rocks formed at lower-pressure and higher-temperature conditions and in contact metamorphic fine-grained sediments. Andalusite appears to precipitate in a temperature range between 200-700°C at low pressure from kaolinite (Roy, 1954) and muscovite (Haselton Jr. et al., 1995). Cordierite has been experimentally synthesised at temperatures as low as 450°C and can be formed from biotite. Retrograde metamorphism of andalusite occurs below the equilibrium at 398°C (1 kbar). Andalusite may alter to micaceous clay, while cordierite is more frequently altered into muscovite, chlorite or serpentine minerals and iron oxides.

Epidote

Epidote occurs only in trace amount and is known to form in contact metamorphic rocks by the dissolution of feldspars, biogenic and ferromagnesian grains. Epidote is unstable in low temperatures and commonly dissolves.

Authigenic clay

Authigenic clay (**Fig. 61 & 62**), excluding the pseudomorphs, constitutes 3-27% (averaging 13.6%) of the sandstones. Chloritic clay dominates, while phengitic clay and glauconitic clay is found in trace amounts.

The phengitic clay is precipitated in secondary pores and is also overgrown by quartz, albite, sphene, zeolite and calcite. EDS-analyses reveal that the phengitic clay is found in the core of the pseudomorphs. The geochemical data thus indicate that this clay type was precipitated at the same time that the retrograde metamorphism of andalusite and cordierite occurred.

Glauconitic clay occurs as flakes in primary and secondary pores with a content ranging from trace amounts up to 6% (averaging 1.5%). Geochemically, the clay compares to an iron-rich variation of the outer, glauconitic rim on andalusite and cordierite pseudomorphs and therefore is interpreted as being precipitated in pore space at the end of the formation of the outer rim of pseudomorphs, but before the precipitation of chlorite.

Chlorite is the dominant authigenic clay mineral (3-23%, averaging 12%) and abundant in all samples. Chlorite has a yellow to greenish colour and can occur as thin grain linings, spheroids, chloritised mica, clay flakes, clay whiskers and thick, zoned clay rims on ferro-magnesian grains (**Fig. 63**). Chlorite overgrows the first, minor phase of quartz cement and the phengitic and glauconitic clays and is overgrown by albite, pyrite, apatite, Ti-oxides, quartz, sphene, zeolite, calcite and goethite.

<u>Ti-oxides</u>

Ti-oxides (trace amounts to 4%, averaging 1.3%) occur as small euhedral, prismatic crystals and elongated to needle-like crystals and are overgrown by chlorite, quartz, albite, zeo-lite and calcite.


Figure 58. Thin section composite overview showing calcite filled fracture across the entire thin section (sample 445003).



Figure 59. (left) Thin section photograph showing pseudomorphs after andalusite and cordierite in a clay, laumonite, albite matrix (sample 445019), scale: image width = 2 mm. **Figure 60.** (right) BSE micrograph showing subhedral apatite crystals in a pseudomorh after andalusite or cordierite (sample 445019).



Figure 61. (*left*) BSE micrograph showing authigenic clay minerals filling pore space and engulfing pseudomorphs (sample 445019).

Figure 62. (right) Thin section photograph showing detrital and authigenic clay filling all visible pore space (sample 445019), scale: image width = 2 mm.

<u>Pyrite</u>

Pyrite (trace amounts to 7.3%, averaging 1.4%) occurs as small framboids, large crystals and cement. It engulfs albite, euhedral quartz overgrowths and chlorite and is overgrown by zeolite and calcite.

<u>Quartz</u>

Authigenic guartz is the second-most common cement in the sandstones with a content ranging from 8.7 to 22% (average 13.8%) and occurs dominantly as overgrowths (Fig. 64) and more rarely as small, euhedral crystals. The quartz overgrowth can be up to 450 µm thick, whereas euhedral crystals are 20-25 µm in size and are commonly seen to close intergranular pore space, and triple-point contacts between quartz grains. Minor quartz overgrowth post-dates chlorite formation, but is volumetrically insignificant. Authigenic quartz has overgrown pseudomorphs, epidote, phengitic clay, Ti-oxides, chlorite, albite, pyrite, apatite and sphene. Compensation contacts between clear albite overgrowths and quartz indicate partly simultaneous growth of the two phases. Quartz cement is overgrown by sphene, pyrite cement,



Figure 63. BSE micrograph showing chlorite flakes filling pores and partly overgrowing albite (sample 445001).



Figure 64. Thin section photograph showing yellow, brownish chlorite in the sample (sample 445019), scale: image width = 2 mm.

zeolite and calcite cement. Quartz overgrowths, which enclose laumontite (zeolite), are themselves cemented by laumontite, indicating contemporaneous growth of the two phases. The silica for quartz cementation was mainly sourced by dissolution of detrital silicates due to elevated temperatures and mainly by albitization and dissolution of detrital feldspar grains.

<u>Albite</u>

Concentrations of authigenic albite in the sandstones range from 8.7 to 26% (average 16.2%). Three different types of albite occur in the sandstone: (1) dusty albite, (2) small crystals and (3) albite overgrowths. Albite crystals physically distort and cement pseudo-morphs, and overgrow phengitic and glauconitic clay, chlorite, apatite and pyrite. The crystals (**Fig. 65**) are cemented by quartz, pyrite cement, sphene, zeolite, calcite and goethite. Albite overgrowths cement sphene. Dusty albite represents albitization (**Fig. 66**) of detrital feldspar grains. It is the first and volumetrically the most important authigenic albite phase to occur, averaging 9.1% in the sandstone. Formation of dusty albite overgrowths (average 0.9%). The high content of marine pore water in the shallowly-buried sandstones, and the dissolution of detrital sodic feldspars were the most important contributors of so-

dium, silica and aluminium for albitization and albite precipitation. The process of albitization can start in an early diagenetic stage and continue throughout burial until all the detrital feldspars are albitized (e.g. Saigal et al., 1988).



Figure 65. (left) BSE micrograph showing albite crystals growing into pore space (sample 445001). **Figure 66.** (right) BSE micrograph showing partly albitized K-feldspar engulfed by calcite cement (sample 445001).

<u>Apatite</u>

Apatite is present in all samples with a content ranging from trace amounts to 2.3% (average 0.5%) and occurs as small subhedral crystals and as cement (**Fig. 67**).

<u>Sphene</u>

Secondary sphene (trace amount to 7.3%, average 1.5%) occurs as small, prismatic crystals, spheroid clusters and dense cement. Sphene overgrows pseudomorphs, chlorite, quartz and albite and is overgrown by zeolite and calcite.



Figure 67. BSE micrograph showing apatite crystals in a former pellet (sample 445001).

<u>Zeolite</u>

Three types of zeolite (**Fig. 68 & 69**) are identified in the samples, K-zeolite, analcime and laumontite. The most common type is laumontite that ranges from zero to 11% (average 1.3%).

K-zeolite is rare and occurs in veins as closing cement or as euhedral crystals and is overgrown by later diagenetic zeolite and calcite.

Analcime (trace amounts) occurs in small veins as tight, interlocking crystals and as euhedral crystals in larger veins and as scattered cement in primary and secondary pore space.

Laumontite is a calcium zeolite and the most voluminous zeolite phase in the sandstones. It occurs as patchy, inter- and intra-granular cement and forms up to 0.65 mm long, equant to lath-shaped crystals. Up to 200 μ m sized euhedral laumontite crystals were found in veins. Laumontite tightly cements pseudomorphs (**Fig. 70**) and fills secondary pores from earlier authigenic phases such as chlorite, euhedral albite, euhedral quartz, sphene, apatite and

pyrite and fills fractures (**Fig. 71**). Fracture filling calcite post-dates laumontite. Laumontite can precipitate from solution when albitization in sandstones is completed and sodium and silica is supplied in large amounts by the conversion of smectite to illite (Boles & Coombs, 1977; Helmold & van de Kamp, 1984) or as a replacement of plagioclase. The temperature needed for laumontite precipitation varies from 110°C (Helmold & van de Kamp, 1984) to 170-260°C. The precipitation of laumontite appears to be controlled by pore-fluid chemistry and post-compaction permeability variations, which are responsible for creating differences in fluid pressure between petrologically similar sandstones (Helmold & van de Kamp, 1984). Helmold and van de Kamp (1984) describe a similar diagenetic parasequence as following – "a dynamic overpressuring may have occurred in turbiditic sandstones whereby pore waters enriched in ions from shale dewatering were continuously supplied for albitization and zeolitization".



Figure 68. (left) BSE micrograph showing different types of zeolite in filled pore space engulfing and replacing pseudomorphs (sample 445001). Note: box represents figure 69. **Figure 69.** (right) BSE micrograph showing a close-up of figure 68 with K-zeolite and clay intergrowth and laumontite cement overgrowing chlorite (sample 445001).



Figure 70. (left) BSE micrograph showing laumonite cement engulfing pseudomorphs (sample 445019). **Figure 71.** (right) BSE micrograph showing laumonite cement (coloured orange) filling micro-fractures and destroying any detrital framework (sample 445019).

Calcite

Calcite cement ranges from zero to 27.7% (average 1.4%) occurring as coarse blocky and poikilotopic cement in pores and fractures, engulfing quartz, albite, sphene, K-zeolite, analcime and laumontite. Calcite commonly closes veins partly filled by zeolite (**Fig. 72 & 73**). Laumontite is the only authigenic mineral that shows dissolution to calcite contacts indicating that laumontite might have sourced calcite. Calcite occurring as vein filling cement could have also been sourced by hydrothermal fluids. Calcite can form due to (1) introduction of calcium from interstitial pore water along fractures; (2) can be a replacement of laumontite and (3) Ca^{2+} ions released during albitization and laumontitization could remain in solution until an increase in CO_2 initiates calcite precipitation.

Goethite

Goethite (traces to 3.7%) occurs as rounded, small crystals and form mainly in fractures due to weathering of iron-bearing minerals.



Figure 72. (*left*) Thin section photograph showing calcite cement filling fractures (sample 445003), scale: image width = 2 mm.

Figure 73. (right) BSE micrograph showing calcite cement next to laumontite cement that both fill secondary pore space (sample 445019).

Modal analysis

The most abundant minerals quartz, clay and albite have been plotted versus the contact of the sill (**Fig. 74**). Albite and clay show no trend while authigenic quartz decreases slightly with increasing distance to the sill. Detrital quartz content increases with increasing distance to the sill. However, the trends reflected here are not believed to reflect an influence by the sill emplacement. The sandstones were sampled from different stratigraphic beds and therefore might have varying detrital quartz contents. The decreasing trend of quartz overgrowth (**Fig. 75**) from the contact weakens when dividing the trend by sampled beds and might only be a function of the primary detrital composition in the specific samples.

Porosity-Permeability

Helium porosity ranges from 3.25 to 13.33% of the rock volume, whereas the petrographical defined porosity ranges from 0 to 1.3%. The highest porosity occurs in highly fractured samples.

PoroPerm (**Fig. 76**) - The correlation analysis shows only good correlation between porosity and permeability of the samples from Traill \emptyset sample set 3 (R²=0.76) that are 6-15 m away from the contact in the stratigraphically lowest sampled unit.



Figure 74. Plot of petrographically defined quantity of detrital quartz, authigenic quartz, authigenic clay and authigenic albite vs. distance from sill.



Figure 75. Plot of petrographically defined quantity of authigenic and detrital quartz vs. distance from sill, divided into the three sampled stratigraphic units.

He-Porosity – petrographically defined porosity relationship – In testing the accuracy of point-counting derived porosity the data were plotted versus Helium porosity. The plot shows no correlation and a huge difference in values by almost a magnitude that can only be explained by microporosity not visible by counting (**Fig. 77**).

He-Porosity – distance from sill relationship – There is no correlation between porosity or permeability and distance from sill as shown in the plots (**Fig. 78**).



Figure 76. Core analysis porosity vs. permeability plot, divided into the three sampled stratigraphic units.

He-Porosity – quartz, clay and albite cement – There is no correlation between porosity and quartz cement, authigenic clay and albite cement (**Fig. 79**).

Permeability – total clay relationship – Permeability is often controlled by the detrital clay content during burial diagenesis. The plot of total clay versus permeability however shows no correlation (**Fig. 80**).



Figure 77. Plot of petrographically defined porosity vs. core analysis porosity.

The lacking correlation between cements and porosity might indicate that cementation was not the responsible factor in porosity reduction in the sandstones. Therefore, a second variable has to be taken into account – compaction. At surface conditions, a direct relationship exits between the degree of cementation and sandstone porosity, because the presence of a certain volume of cement reduces the porosity by the same volume (Beard & Weyl, 1973; Worden et al., 1997). In the subsurface,

porosity reduction will be caused by both cementation and compaction. However, the extent of porosity reduction may not be a simple subtraction of cement and compaction from the surface porosity as the cement may act to stabilize the sandstone framework and thus restrain compaction. The relative effects of compaction and cementation on sandstone porosity can be illustrated by a plot of intergranular volume (IGV) versus total cement (Ehrenberg, 1989, 1990; Houseknecht, 1987, 1989). Mechanical compaction by packing and reorientation of grains reduces IGV from an initial depositional value of approximately (here) 50% to a theoretical minimum of 26% (Taylor & Soule, 1993). Further reduction in IGV would require grain volume-loss through intergranular pressure solution or porosity loss due to ductile grain deformation. The plot here (**Fig. 81**) shows clearly that the sandstones fall into the cementation dominated porosity loss field. However, the result is intriguing



Figure 78. Core analysis porosity vs. distance from sill, divided into the three sampled stratigraphic units.



Figure 79. Plot of (a) petrographically defined quantity of quartz vs. core analysis porosity, (b) petrographically defined quantity of authigenic clay vs. core analysis porosity, (c) petrographically defined quantity of authigenic albite vs. core analysis porosity; divided into the three sampled stratigraphic units.

since most of the cement occurs as detrital grain replacing cement and not as pore filling cement. In this case – the use of IGV plots for attaining the timing of cementation can not and should not be used. These sandstones are contact metamorphosed and metasomatically altered and unrepresentative for the primary detrital composition and texture of the sandstones.

Image analysis

Digital image analysis has been conducted in order to identify the spatial distribution of permeability and porosity reducing minerals such as clays. The imaging tool has also been used to see general patterns within the sandstone in increasing distance from the sill contact.

Eleven sandstone samples have been photographed in high resolution (picture width 2 mm with a dimension of 1600x1200 pixels). The main components - clay/heavy mineral fraction, quartz/feldspar fraction and pore space (blue epoxy) - were measured by area using the FoveaPro software package. The main result of the digital imaging is that clay fraction distribution can easily be identified for a thin section and special areas have been targeted using SEM, CL or other techniques. The following features could be identified during image analysis, (1) small fractures occur throughout the sediment (19, 27), (2) quartz and feldspar grains sit within a clay matrix (all), (3) the highest porosity occurs along partly calcite filled fractures (2, 3, 4, 7, 8) and (4) the sandstones are very homogeneous and intensely compacted (5, 9, 10) reducing the porosity visually to almost zero. Pore space measurements derived from digital analysis range from 0.9 to 2.3%.



Figure 80. (left) Plot of petrographically defined clay content vs. core analysis permeability. **Figure 81.** (right) Diagram illustrating contrasting styles of porosity loss in sandstones (after Houseknecht, 1984). Petrographically defined total cement content vs. intergranular volume defines the intergranular porosity and compaction or cementation dominated porosity loss.

Vitrinite reflectance

General usage of vitrinite reflectance

The vitrinite reflectance, expressed as R_o%, is used as maturity parameter in basin modeling and hydrocarbon exploration (Zattin et al., 2006; Mukhopadhyay, 1994). Vitrinite is derived from the thermal degradation of lignin and cellulose, and can be found in kerogens rich in higher plants fragments (Teichmueller, 1987; Zattin et al., 2006). As the maturity increases, a progressive ordering takes place in the vitrinite molecular structure; this causes an increase of the reflection capacity of the incident light. Vitrinite reflectance has also been used to estimate maximum temperatures attained by sedimentary rocks in geothermal areas (Barker, 1983; Sweeney & Burnham, 1990) and near igneous intrusions (Wang et al., 1989; Galushkin, 1997). The maximum temperature attained by the host rock and the size of the maturity aureole near the intrusion depends on: (1) the initial temperature of the intrusion, (2) the duration of magma body formation within the host rock, (3) the consolidation stage of the host rock and (4) the composition of the intrusion. Therefore, the maturity reached during magmatic intrusions can only reflect the maximum temperature of the host rock experienced but not be predicted generally (**Fig. 46**).

Measurements in the sandstones

Results from vitrinite reflectance in nine sandstones from the Traill Ø area are good. The sandstones are very mature and show mean values of 5.5%R_o throughout the sample set and a reference sample 30 m away from the outcropped sample section (Figure 82). That means that the reference sample experienced the same temperature as samples from the contact zone.

Implications for sandstone temperature – The mean R_o of 5.5% corresponds to a sill temperature of ca. 1000°C and a host rock temperature of 370°C. Temperatures attained by the host rock was estimated using Barker and Pawlewicz's (1994) relationship of R_o to T_{peak} : T_{peak} =(*In* R_o +1.19)/0.00782. The temperature of the intrusion correlates with the R_o value presented in various publications (Galushkin, 1997; Sweeney & Burnham, 1990;





Figure 82. Plot of vitrinite reflectance of several samples vs. the particle count.

Interpretation

The petrographic observations, vitrinite reflectance and porosity results lead to the same interpretation. The sediments did not experience any significant diagenetic alteration before the sill emplacement. The primary porosity of these rock that have been buried to ~600 m before the intrusion can be estimated to have been 30% (Worden & Burley, 2003; Fig. 47) for argillaceous sandstones with abundant clay-rich lithics and mudstones. Mechanical compaction driven porosity loss (intergranular volume) in the Traill Ø samples can not be determined because of the intense diagenetic alteration and the destruction of any primary composition. Chemical compaction and resulting diagenetic mineral precipitation reduced the porosity to ~7% in samples adjacent to the sill contact. However, the highest porosities (13%) were found in intensely fractured samples. Non-fractured samples have commonly a porosity of ~4%. Porosity preserved in these samples is interpreted to be largely secondary porosity. Almost total primary loss corresponds to a burial depth of more than 5000 m under a normal geothermal gradient. Authigenic albite is the most prominent feature in the sediments taking up an average of 16% of the rock volume. The total replacement of detrital K-feldspar by albite during the process of albitization is known from depths of more than 2500 m (Harris, 1989). The "remaining" detrital composition of the sediment leads to a "diagenetic guartz arenite" (Harris, 1989). Quartz cement can reach 22% of the rock volume (average 14%) and is equivalent to a theoretical burial depth (normal geothermal gradient) of more than 5000 m. The amount of quartz precipitated depends on silica saturation in the fluid and the guartz surface area available for guartz overgrowth. Variations can occur e.g. if clay minerals coat quartz grains thus preventing quartz dissolution. Pseudomorphs after and alusite and cordierite are uncommon in sediments but have been described in context with retrograde contact metamorphism. Retrograde metamorphism of andalusite occurs below the equilibrium at 398°C (1 kbar). Laumontite (zeolite) can reach up to 11% of the rock volume and can form in temperature regimes as low as 110°C but more commonly occurs in a temperature range between 170°C and 260°C or a corresponding burial depth of more than 5000 m. Laumontite precipitation is interpreted to be initiated after complete albitization of K-feldspar. Calcite found in the Traill Ø sandstone is very late and might be associated with the dissolution of laumontite. Calcite is mostly found filling fractures and producing secondary porosity during dissolution. The burial signature in the sandstone was induced by the sill emplacement and not due to increased burial depth. There are no patterns between modal analysis data and porosity/permeability and distance from sill. Vitrinite reflectance data suggest that the maximum temperature reached in the sediments was about 370°C as an effect of the intrusion, while the intrusion temperature must have been ~1000°C. This temperature would be under a normal geothermal gradient the equivalent to a burial depth of circa 7000 m. Porosity, albitization, quartz cement, laumontitization, vitrinite reflectance and pseudomorphs correspondingly suggest that the sill emplacement lead to enhanced compaction and authigenic mineral precipitation and consequently reduced porosity and permeability dramatically. The sediments in the current state can be described as being affected by low-grade metamorphism and metasomatism. The extent of the contact aureole can not be determined because all samples (including reference samples 30 m away from the contact) show high kerogen maturation implicating maximum heating temperatures of 370°C and the same diagenetic parasequence in these sandstones.

Conclusion

The diagenetic sequence in the samples from Traill \emptyset is influenced by sill emplacement through:

- (1) enhanced compaction,
- (2) total albitization of detrital K-feldspar leading to a "diagenetic lithic arenite",
- (3) elevated quartz cementation,
- (4) contact metamorphic minerals such as pseudomorphs after andalusite,
- (5) laumontitization that commonly occurs in low metamorphic temperatures and deep burial depth,
- (6) diminished porosity and permeability and
- (7) a "false" diagenetic signature suggesting a burial depth of 5000 to 7000 m.

The extent of the contact aureole can not be determined. The reduced porosity and permeability and the occurrence of macro- or micro fractures suggest that these sandstones above an igneous intrusion can hypothetically act as a fluid migration zone. However, in this case the absence of information about the extent of the contact aureole and the diagenetic assemblage allow limited prediction of influence on potential reservoir rocks.

Geochemical modeling

Introduction

Geochemical modeling must cover two aspects in order to achieve a quantitative prediction of mineral reactions - geochemical and hydrodynamic processes. Geochemical processes include aqueous speciation and redox reactions, interface reactions, precipitation and dissolution of minerals and colloids. Hydrodynamic transport processes include diffusion and migration due to advective forces, leading to dispersion of the chemical species in space and time (Kuehn, 2004). Geological processes such as diagenesis, hydrothermal ore deposit formation and metamorphism are the result of reactive transport in the subsurface. Chemical changes are driven by the interaction between migrating fluids and solid phases while fluid flow, heat transfer, solute transport and time influence the evolution of these systems. Hydrogeochemical or non-reactive fluid flow models have been the centre of much controversy concerning the validity and uncertainties of the model input (Konikow & Bredehoeft, 1992). Diagenetic or hydrothermal systems are inherently heterogeneous on a variety of scales rendering it highly challenging to know precisely the many details of the flow system and chemical composition of the fluids and the host rock. Other properties such as permeability, porosity and mineral surface area in a heterogeneous rock have to be approximated. Nevertheless, a computational quantitative model could be achieved if geochemical, hydrodynamic and physical rock properties are known and if it can be tested against a natural occurring system. However, a predictive quantitative geochemical model for a geological system with no information on e.g. rock properties, formation water and temperatures certainly challenges the limits of geochemical modeling.

Computational modeling of heat and fluid flow in geochemical processes, including quantitative description of time-dependent evolution of porosity, permeability, mineralogy and fluid flow regimes driven by heat associated with emplacement of mafic intrusion into sediments was approached using the NUFT-code developed by the Lawrence Livermore National Laboratory.

Methods

NUFT is a multiphase, multicomponent computer code for modeling fluid flow and transport in porous media under isothermal and non-isothermal conditions, with application to subsurface contaminant transport problems (Nitao, 1998). The NUFT code capabilities are: (1) aqueous speciation reactions, (2) mineral dissolution and precipitation reactions, (3) explicit representation of fracture and matrix mineralogy, (4) chemically and mineralogically heterogeneous initial conditions and source terms, (5) time-varying rock and fracture permeability and (6) run-time monitoring and post-processing capabilities. The main focus for a successful quantitative model was on mineral dissolution and precipitation reactions. The code is implementing: (1) dissolution of existing minerals, or precipitation of saturated and supersaturated mineral species that are represented by kinetic equations of the form used in transition state theory, (2) thermodynamic data needed for these calculations is derived from similar data used for aqueous species, (3) description of mineral abundance, and the effective reactive surface areas of each mineral phase in each rock unit, (4) volume of each mineral phase dissolved or precipitated at each time step, and its consequences for the porosity of the rock at each cell of the computational mesh is computed and (5) time vary-ing permeability deriving from changes in porosity (Glassley et al., 2001).

The NUFT code version 3.1 is running on LINUX RedHat Operating System PC. The following models were planned tests: (1) sandstone (quartz arenite) with porosity of 40% and temperature of 30°C, (2) sandstone (quartz arenite) with porosity of 25% and temperature of 90°C, (3) sandstone (quartz arenite) with porosity of 25% and temperature of 160°C, (4) sandstone (quartz arenite) heated to 270°C from a specific direction, (5) sandstone (quartz arenite) heated (270°C) from a specific direction and subsequent cooling, (6) sandstone (quartz arenite) heated to 200°C from a specific direction and subsequent cooling, (7) various changes in detrital composition with adding other mineral phases such as albite and plagioclase.

Results

(1) Sandstone (quartz arenite) with porosity of 40% and temperature of 30°C

The modeling of an unconsolidated quartz arenite with a porosity of 40% under a temperature of 30°C shows that no mineral dissolution occurs and no porosity loss or temperature changes take place within a modelled time of 100 years, 1000 years and 100.000 years. The aqueous phase was simulated to represent marine waters.

(2) Sandstone (quartz arenite) with porosity of 25% and temperature of 90°C

The parameters of the modeling of a quartz arenite are: a porosity of 25% under a temperature of 90°C and an aqueous composition of those of marine water and saturated with 600 ppm SiO₂. The silica was introduced in the fluid by dissolution of feldspars. The first simulation was without the SiO₂ aqueous component and the result showed no quartz precipitation or dissolution. In the second simulation silica was added to the aqueous phase and forcing a supersaturating fluid. All quartz that precipitated (0.053%) from the aqueous phase happened within the first time step of 1 year. All oversaturated silica precipitated in the first time step and the aqueous phase reached equilibrium quickly.

(3) Sandstone (quartz arenite) with porosity of 25% and temperature of 160°C

The parameters of the modeling of a quartz arenite are: a porosity of 25% under a temperature of 160°C and a simple neutral aqueous composition and saturated with 600 ppm SiO₂. The simulation result is the precipitation of 0.049% silica. Silica precipitates quickly and stops dissolving and re-precipitating after a geologically short time (1 year). The running time of the simulation was 100 years and 1000 years.

(4) Sandstone (quartz arenite) heated to 270°C from a specific direction The simulation of heating from a specific direction that should have simulated a sill emplacement into the sandstones was not performed. (5) Sandstone (quartz arenite) heated (270°C) from a specific direction and subsequent cooling

The simulation of heating from a specific direction that should have simulated a sill emplacement into the sandstones was not performed.

(6) Sandstone (quartz arenite) heated to 200°C from a specific direction and subsequent cooling

The simulation of heating from a specific direction that should have simulated a sill emplacement into the sandstones was not performed.

(7) Various changes in detrital composition with adding other mineral phases such as albite and plagioclase

The simulation of heating from a specific direction that should have simulated a sill emplacement into the sandstones was not performed.

Interpretation

The geochemical modeling of goals 4-7 was unsuccessful because, the initial conditions of a buried sedimentary unit could not be replicated by the modeling software. Subsequently, any specific changes in the model, such as heating from a specific direction, would not have been reliable. The reason for the failure of reproducing known diagenetic reactions (e.g. quartz dissolution) under known parameters (e.g. silica mobility window between 90°C and ~160°C) might be that the code tries to maintain thermodynamic equilibrium in the aqueous phase. However, diagenetic reactions are believed to be maintained due to a non-equilibrium reached from continuously varying parameters in the geological system.

Another aspect of the unsuccessful modeling is that compaction and consequently grain rearrangement play a significant role in porosity and permeability changes in contact sandstones. The NUFT code is not capable of simulating grain re-arrangement and compaction triggered by sill emplacements.

Conclusion

Calculating a geochemical or reactive transport model provides not only results but also uncertainty about the accuracy of the results (Kuehn, 2004). Several nuisance effects might occur (Nitzsche et al., 2000):

- (1) numerical problems of the code itself,
- (2) incomplete understanding of the physical and chemical phenomena,
- (3) lack of precision of the geological and hydrogeological input data,
- (4) missing data for a complete set up of a conceptual model and
- (5) experimental uncertainties in the thermodynamic data.

Therefore, one has to consider if geochemical modeling is appropriate for certain tasks such as sill emplacement, where non-reactive transport/ fluid related processes play the most significant role.

Implications for the Faroe-Shetland Basin

The impact of sill emplacement on potential reservoir rocks has been widely discussed previously. The basaltic formations have at times been suggested as a seal (Ziska & Andersen, 2005) and also to act as reservoirs (Magara, 2003). One of the most important reservoir rocks in the Faroe-Shetland Basin are Palaeocene submarine fan sandstones that have porosities of ~25% and permeability greater than 100 mD (in excess of 700 mD) (Ebdon et al., 1995). The extensive coverage of basaltic lavas across the Faroe-Shetland Basin buried sediments several kilometres in a very short time under an almost doubled geothermal gradient of 60 km⁻¹. However, according to Carr & Scotchman (2003) source rocks at 8 km depth are able to generate oil.

The implications of sill emplacement studies during the course of the project for the Faroe-Shetland Basin are:

- (5) intense compaction in the contact zone of the intrusion,
- (6) temperatures of 260°C and higher in the contact sandstones,
- (7) porosity loss to about 8% regardless of differences in the diagenetic history of a sediment and
- (8) permeability loss to less than 1 mD.

The discussion of seal capability of sills and basalts becomes partly irrelevant if the contact zone is not considered as well. The study here indicates that contact zones or aureoles of sills and accompanying host rock act as seal with very low permeability and low connectivity.

The extent of the contact aureole could not be predicted. However, the extent of the contact aureole should be possible to determine using wireline log data.

General conclusions

The effect of sill emplacement on shallow-buried sandstones varies significantly depending on (1) the detrital composition of the sandstones and (2) the temperature of the intrusion. The detrital composition of the sandstone has an effect on (1) the compaction curve during burial and subsequently porosity changes and (2) the feasibility of cementation (e.g. clay coating prevents quartz cementation).

The temperature of the intrusion has an effect on (1) the solubility of quartz (quartz becomes more likely to dissolve with increasing temperatures) and subsequently quartz cementation, (2) the degree of clay mineral replacement resulting permeability loss and (3) the extent of mineral alterations (e.g. metasomatism, albitization and chloritisation).

The extent of the contact aureole depends on the thickness and temperature of the intrusion and probably on the detrital composition of the host rock.

Sill emplacement can seal sandstones by intense quartz cementation and compaction but it can also act as flow paths for fluids along fractures associated with the intrusion. It is believed that fracturing might be related to the temperature impact of the intrusion and the spatial distribution of the sill during the emplacement.

A relationship between the upper or lower contact of sill to host rock and fracturing could not be established.

Permeability and porosity are highly reduced due to the intrusion in the contact aureole due to mechanical and chemical compaction and associated authigenic mineral precipitation and alteration.

Acknowledgments

The work on Skye samples, geochemical modeling and interpretation presented in this volume was performed during the project "Impact of Palaeogene sill emplacement on reservoir lithologies in East Greenland and the Faroe-Shetland Basin" funded by the SINDRI group. 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:

Agip Denmark BV Amerada Hess (Faroes) Ltd. Anadarko Faroes Company P/F Atlantic Petroleum BP Amoco Exploration Faroes Ltd. British Gas International BV DONG Føroyar P/F Enterprise Oil Exploration Ltd. Føroya Kolvetni P/F Petro-Canada Faroes GmbH Phillips Petroleum Europe Exploration Ltd. Shell (UK) Ltd. Statoil Færøyene AS

The following individuals are acknowledged for their support in various aspects of this project:

Foremost – Thomas Preuss for providing his PhD data on the Greenland samples (University of Copenhagen) and Brian Bell for providing samples from Skye (University of Glasgow). Further: Julie Hollis, Michael Larsen, John Boserup, William Glassley, Christian Knudsen, Dirk Frei, Quentin Fisher, Carsten Guvad, Karen Henriksen, Hanne Lamberts, Jørgen Kystol, Marga Jørgensen, Lisbeth Nielsen, Niels Springer, Hans Lorentzen, Jørgen Bojesen-Koefoed and Erik Nielsen.

References

Araújo de, C.C., Yamamoto, J.K., Rostirolla, S.P., Madrucci, V. & Tankard, A. 2005. Tar sandstones in the Paraná Basin of Brazil: structural and magmatic controls of hydrocarbon charge. Marine and Petroleum Geology 22, 671-685.

Barker, C.E. 1983. The influence of time on metamorphism of sedimentary organic matter in selected geothermal systems, western North America. Geology 11, 384-388.

Barker, C.E. & Pawlewicz, M.J. 1994. Calculation of vitrinite reflectance from thermal history and peak temperatures: a comparison of methods. In Mukhopadhyay, P.K. & Dow, W.G. (eds.) Vitrinite Reflectance as a Maturity Parameter: Applications and Limitations, American Chemical Society Symposium Series 570, 216-229.

McBride, E.F. 1989. Quartz Cement in Sandstones: A Review. Earth Science Reviews 26, 69-112.

Beard, D.C. & Weyl, P.K. 1973. Influence of texture on porosity and permeability of unconsolidated sand. American Association of Petroleum Geologists Bulletin 57, 348-369.

Bishop, A.N. & Abbott, G.D. 1995. Vitrinite reflectance and molecular geochemistry of the Jurassic sediments: the influence of heating by Tertiary dykes (northwest Scotland). Organic Geochemistry 22, 165-177.

Bjørlykke, K. & Egeberg, P.K. 1993. Quartz cementation in sedimentary basins. American Association of Petroleum Geologists Bulletin 77, 1538-1548.

Bjørkum, P.A. 1996. How important is pressure causing dissolution of quartz in sandstones? Journal of Sedimentary Research 66, 605-618.

Boles, J.R. & Coombs, D.S. 1977. Zeolite facies alterations of sandstones in the Southland syncline, New Zealand. American Journal of Science 277, 982-1012.

Bostick, N.H. & Pawlewicz, M.J. 1984. Paleotemperatures based on vitrinite reflectance of shales and limestones in igneous dike aureoles in the Upper Cretaceous Pierre Shale, Walsenburg, Colorado. In Woodward, J., Meissner, F.F. & Clayton, J.L. (eds.) Hydrocarbon source rocks of the Greater Rocky Mountain region: Denver, Rocky Mountain Association of Geologists, 387-392.

Brown, R., Gallagher, K. & Duane, M. 1994. A quantitative assessment of the effects of magmatism on the thermal history of the Karoo sedimentary sequence. Journal of African Earth Science 18, 227-243.

Carr, A.D. & Scotchman, I.C. 2003. Thermal history modelling in the southern Faroe-Shetland Basin. Petroleum Geoscience 9, 333-345.

Dickin, A.P. & Jones, N.W. 1983. Relative Elemental Mobility during Hydrothermal Alteration of a Basic Sill, Isle of Skye, N.W. Scotland. Contributions to Mineralogy and Petrology 82, 147-153.

Donovan, D.T. 1957. The Jurassic and Cretaceous systems in East Greenland: Meddelelser om Grønland 155, 214p.

Dutrow, B.L., Travis, B.J., Gable, C.W. & Henry, D.J. 2001. Coupled heat and silica transport associated with dike intrusion into sedimentary rock: Effects on isotherm location and permeability evolution. Geochimica et Cosmochimica Acta 65, 3749-3767.

Ebdon, C.C., Granger, P.J., Johnson, H.D. & Evans, A.M. 1995. Early Tertiary evolution and sequence stratigraphy of the Faeroe-Shetland Basin: implications for hydrocarbon prospectivity. In Scrutton, R.A., Stoker, M.S. Shimmield, G.B. & Tudhope, A.W. (eds.) The Tectonicsm Sedimentation and Palaeoceanography of the North Atlantic Region. Geological Society Special Publication 90, 51-69.

Ehrenberg, S.N. 1990. Relationship between diagenesis and reservoir quality in sandstones of the Garn formation, Haltenbanken, mid-Norway continental shelf. American Association of Petroleum Geologists Bulletin 74, 1538-1558.

Ehrenberg, S.N. 1989. Compaction and porosity evolution of Pliocene sandstones, Ventura Basin, California: discussion. American Association of Petroleum Geologists Bulletin 73, 1274-1276.

Fisher, Q.J., Casey, M., Chennell, M.B. & Knipe, R.J. 1999. Mechanical compaction of deeply buried sandstones. Marine and Petroleum Geology 16, 605-618.

Fisher, Q.J., Knipe, R.J. & Worden, R.H. 2000. The microstructure of deformed and undeformed sandstones from the North Sea: its implications for the origin of quartz cement. In Morad, S. & Worden, R.H. (eds.) Quartz cement: origin and effects on hydrocarbon reservoirs. International Association of Sedimentology, Special Publication.

Frederick, P.M., Warbrooke, P. & Wilson, M.A. 1985: A study of the effect of igneous intrusions on the structure of an Australian high volatile bituminous coal. Organic Geochemistry 8, 329-340.

Galushkin, Y.I. 1997. Thermal effects of igneous intrusions on maturity of organic matter: A possible mechanism of intrusion. Organic Geochemistry 26, 645-658.

Gilbert, T.D., Stephenson, L.C. & Philip, R.P. 1985. Effect of a dolerite intrusion on triterpane stereochemistry and kerogen in Rundle Oil Shale, Australia. Organic Geochemistry 8, 163-169.

Giles, M.R., Indrelid, S.L., Beyon, G.V. & Amthor, J. 2000. The origin of large scale quartz cementation: Evidence from large datasets and coupled heat-fluid-mass transport model-

ing. In Morad, S. & Worden, R.H. (eds.) Quartz cementation in oil field sandstones, Special Publications of the International Association of Sedimentologists.

Glassley, W.E., Nitao, J.J., Grant, C.W., Boulos, T.N., Gokoffski, M.O., Johnson, J.W., Kercher, J.R., Levatin, J.A. & Steefel, C.I. 2001. Performance Prediction for Large-Scale Nuclear Waste Repositories: Final Report. Lawrence Livermore National Laboratory, UCRL-ID-142866, 41p.

Hald, N. 1996. Early Tertiary lavas and sill on Traill Ø and Geographical Society Ø, northern East Greenland: petrography and geochemistry. Grønlands Geologiske Undersøgelse Bulletin 171, 29-43.

Hald, N. & Tegner, C. 2000. Composition and age of Tertiary sills and dykes, Jameson Land Basin, East Greenland: relation to regional flood volcanism. Lithos 54, 207-233.

Harris, N.B. 1989. Diagenetic quartz arenite and destruction of secondary porosity: an example from the Middle Jurassic Brent Sandstone of northwest Europe. Geology 17, 361-364.

Harris, J.P. 1992. Mid-Jurassic lagoonal delta systems in the Hebridean basins: thickness and facies distribution patterns of potential reservoir sandbodies. In Parnell, J. (ed.) Basin on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution. Geological Society Special Publication 62, 111-144.

Haselton Jr., H.T., Cygan, G.L. & Jenkins, D.M. 1995. Experimental study of muscovite stability in pure H2O and 1 molal KCI-HCI solutions. Geochimica et Cosmochimica Acta 59, 429-442.

Houseknecht, D.W. 1989. Assessing the relative importance of compaction processes and cementation to the reduction of porosity in sandstones: reply. American Association of Petroleum Geologists Bulletin 73, 1277-1279.

Houseknecht, D.W. Assessing the relative importance of compaction processes and cementation to the reduction of porosity in sandstones. American Association of Petroleum Geologists Bulletin 71, 633-642.

Heinrich, K.F.J. 1966. X-ray absorption uncertainty. In McKinley, T.D., Heinrich, K.F.J. & Wittry, D.B. (eds.) The electron microprobe. 296-377.

Helmold, K.P. & van de Kamp, P.C. 1984. Diagenetic Mineralogy and Controls on Albitization and Laumontite Formation in Paleogene Arkoses, Santa Ynez Mountains, California. In McDonald, D.A. & Surdam, R.C. (eds.) Clastic Diagenesis. American Association of Petroleum Geologists Memoir 37, 239-276.

Hesselbo, S.P. & Coe, A.L. 2000. Jurassic sequence of the Hebrides Basin, Isle of Skye, Scotland. In Graham, J.R. & Ryan, A. (eds.) Field Trip Guidebook, International Sedimentologists Association Meeting, Dublin 2000, 41-58.

Houseknecht, D.W. 1987. Assessing the relative importance of compactional processes and cementation to the reduction of porosity in sandstones. American Association of Petroleum Geologists Bulletin 71, 633-642.

Hudson, J.D. & Andrews, J.E. 1987. The diagenesis of the Great Estuarine Group, Middle Jurassic, Inner Hebrides, Scotland. In Marshall, J.D. (ed.) Diagenesis of Sedimentary Sequences. Geological Society Special Publication 36, 259-276.

Kemp, S.J., Rochelle, C.A. & Merriman, R.J. 2005. Back-reacted saponite in Jurassic mudstones and limestones intruded by a Tertiary sill, Isle of Skye. Clay Minerals 40, 263-282.

Koch, L. & Haller, J. 1971. Geological map of East Greenland 72-76 N Lat. (1:250.000), Meddelelser om Grønland 183, 1-26.

Konikow, L.F. & Bredehoeft, J.D. 1992. Groundwater models can not be validated. Advances in Water Resources 15, 75-83.

Krynauw, J.R., Behr, H.-J. & van den Kerkhof, A.M. 1994. Sill emplacement in wet sediments: fluid inclusion and cathodoluminescence studies at Grunehogna, western Dronning Maud Land, Antarctica. Journal of the Geological Society London 151, 777-794.

Kühn, M. 2004. Reactive Flow Modeling of Hydrothermal Systems. Springer Verlag, 261p.

Lewis, C.L.E., Carter, A. & Hurford, A.J. 1992. Low-temperature effects of the Skye Tertiary intrusions on Mesozoic sediments in the Sea of Hebrides Basin. In Parnell, J. (ed.) Basin on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution. Geological Society Special Publication 62, 175-188.

Magara, K. 2003. Volcanic reservoir rocks of northwestern Honshu Island, Japan. In Petford, N. & McCaffrey, K.J.W. (eds.) Hydrocarbons in Crystalline Rocks. Geological Society Special Publication 214, 69-81.

McKinley, J.M., Worden, R.H. & Ruffell, A.H. 2001. Contact diagenesis: The effect of an intrusion on reservoir quality in the Triassic Sherwood Sandstone Group, Northern Ireland. Journal of Sedimentary Research 71, 484-495.

Middlemost, E.A.K. 1994. Naming materials in the magma/igneous rock system. Earth Science Reviews 37, 215-224.

Morton, N. 1983. Palaeocurrents and palaeo-environment of part of the Bearreraig Sandstone (Middle Jurassic) of Skye and Raasay, Inner Hebrides. Scottish Journal of Geology 19, 87-95.

Morton, N. & Hudson, J.D. 1995. Field guide to the Jurassic of the Isles of Raasay, Inner Hebrides, NW Scotland. In Taylor, P.D. (ed.) Field Guide of the British Jurassic, Geological Society London, 209-280.

Mukhopadhyay, P.K. 1994. Vitrinite reflectance as a maturity parameter: petrographic and molecular characterization and its applications to basin modeling. In Mukhopadhyay, P.K. & Dow, W.G. (eds.) Vitrinite Reflectance as a Maturity Parameter: Applications and Limitations, American Chemical Society Symposium Series 570, 1-24.

Nitao, J.J. 1998. User's Manual for the USNT Module of the NUFT Code, Version 2.0 (NP-Phase, NC-Component, Thermal). Lawrence Livermore National Laboratory, UCRL-MA-130653, 76p.

Nitzsche, O., Meinrath, G. & Merkel, B. 2000. Database uncertainty as a limiting factor in reactive transport prognosis. Journal of Contaminant Hydrology 44, 223-237.

Oelkers, E.H., Bjørkum, P.A. & Murphy, W.M. 1996. A petrographic and computational investigation of quartz cementation and porosity reduction in North Sea sandstones. American Journal of Science 296, 420-452.

Othman, R., Arouri, K.R., Ward, C.R. & McKirdy, D.M. 2001. Oil generation by igneous intrusions in the northern Gunnedah Basin, Australia. Organic Geochemistry 32, 1219-1232.

Pittman, E.D. & Larese, R.E. 1991. Compaction of Lithic Sands: Experimental Results and Applications. American Association of Petroleum Geologists Bulletin 75, 1279-1299.

Preuss, T. 2005. Diagenesis in sill-intruded Upper Cretaceous sandstones from Traill \emptyset , East Greenland – a short-lived dramatic diagenetic history of sediments buried at shallow depth. In Preuss, T., Thermal maturity in volcanic-influenced sedimentary basins, East Greenland. Ph.D. thesis (paper 3), University of Copenhagen, DK. 108p.

Price, S., Brodie, J., Whitham, A. & Kent, R. 1997. Mid-Tertiary rifting and magmatism in the Traill Ø region, East Greenland. Journal of the Geological Society London 154, 419-434.

Ramm, M. 1992. Porosity-depth trends in reservoir sandstones: offshore Norway. Marine and Petroleum Geology 9, 553-567.

Ramm, M. & Bjørlykke, K. 1994. Porosity-depth trends in reservoir sandstones – assessing the quantitative effects of varying pore-pressure, temperature history and mineralogy, Norwegian Shelf data. Clay minerals 29, 4, 475-490.

Ritchie, J.D., Gatliff, R.W. & Richards, P.C. 1999. Early Tertiary magmatism in the offshore NW UK margin and surrounds. In Fleet, A.J. & Boldy, S.A.R. (eds.) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, 573-584.

Roy, D.M. 1954. Hydrothermal synthesis of andalusite. American Mineralogist 39, 140-143.

Saigal, G.C., Morad, S., Bjørlykke, K., Egeberg, P.K. & Aagaard, P. 1988. Diagenetic albitization of detrital K-feldspar in Jurassic, Lower Cretaceous, and Tertiary clastic reservoir rocks from offshore Norway: Textures and origin, Journal of Sedimentary Research 58, 1003-1013.

Stemmerik, L., Christiansen, F.G., Piasecki, S., Jordt, B., Marcussen, C. & Nøhr-Hansen, H. 1993. Depositional history and petroleum geology of the Carboniferous to Cretaceous sediments in the northern part of East Greenland. In Vorren, T.O., Bergsager, E., Dahl, S.O.A., Holter, E., Johansen, B., Lie, E. & Lund, T.B. (eds.) Artic geology and petroleum potential. Norwegian Petroleum Society Special Publication 2, 67-87.

Stemmerik, L., Clausen, O.R., Korstgård, J., Larsen, M., Piasecki, S., Seidler, L., Surlyk, F. & Therkelsen, J. 1997. Petroleum geological investigations in East Greenland: project " Resources of the sedimentary basin of North and East Greenland". Geology of Greenland - Survey Bulletin 176, 29-38.

Stewart, A.K., Massey, M., Padgett, P.L., Rimmer, S.M. & Hower, J.C. 2005. Influence of a basic intrusion on the vitrinite reflectance and chemistry of the Springfield (No. 5) coal, Harrisburg, Illinois. International Journal of Coal Geology 63, 58-67.

Stein, A.M. 1988. Basement controls upon basin development in the Caledonian foreland, NW Scotland. Basin Research 1, 107-119.

Summer, N.S. & Ayalon, A. 1995. Dike intrusion into unconsolidated sandstone and the development of quartzite contact zones. Journal of Structural Geology 17, 997-1010.

Surlyk, F. 1977. Stratigraphy, tectonics and palaeogeography of the Jurassic sediments of the areas north of Kong Oscars Fjord, East Greenland: Grønlands Geologiske Undersøgelse Bulletin 123, 56p.

Surlyk, F. 1978. Submarine fan sedimentation along fault scarps on tilted fault blocks (Jurassic-Cretaceous boundary, East Greenland). Grønlands Geologiske Undersøgelse Bulletin 128, 108p.

Surlyk, F., Clemmensen, L.B. & Larsen, H.C. 1981. Post-Palaeozoic evolution of the East Greenland continental margin. In Kerr, J.W., Fergusson, A.J. & Machan, L.C. (eds.) Geology of the North Atlantic borderlands. Canadian Society of Petroleum Geologists Memoir 7, 611-645.

Surlyk, F. & Noe-Nygaard, N. 2001. Cretaceous faulting and associated coarse-grained marine gravity flow sedimentation, Traill Ø, East Greenland. In Martinsen, O.J. & Dreyer, T. (eds.) Sedimentary environments offshore Norway – Palaeozoic to Recent. Norwegian Petroleum Society Special Publication 10, 293-319.

Sweeney, J.J. & Burnham, A.K. 1990. Evaluation of a Simple Model of Vitrinite Reflectance Based on Chemical Kinetics. America Association of Petroleum Geologists Bulletin 74, 1559-1570.

Sørensen, K. 1981. A calculated background correction method for XRF. Spectrochimica Acta 36, 243-249.

Taylor, T.R. & Soule, C.H. 1993. Reservoir characterization and diagenesis of the Oligocene 64-zone sandstone, North Belridge field, Kern County, California, American Association of Petroleum Geologists Bulletin 77, 1549-1566.

Teichmueller, M. 1987. Recent advances in coalification studies and their application to geology. In Scott, A.C. (ed.) Coal and Coal Bearing Strata: Recent Advances, Geological Society Special Publication 32, 127-169.

Thrasher, J. 1992. Thermal effect of the Tertiary Cuillins Intrusive Complex in the Jurassic of the Hebrides: an organic geochemical study. In Parnell, J. (ed.) Basin on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution. Geological Society Special Publication 62, 35-49.

Walderhaug, O. 1996. Kinetic modeling of quartz cementation and porosity loss in deeply buried sandstone reservoirs. American Association of Petroleum Geologists Bulletin 80, 731-745.

Wang, X., Lerche, I. & Walters, C. 1989. The effect of igneous intrusive bodies on sedimentary thermal maturity. Organic Geochemistry 14, 571-584.

White, R.S. 1989. Initiation of the Iceland Plume and the opening of the North Atlantic Margins. In Tankard, A.J. & Balkwill, H.R. (eds.) Extensional Tectonics and Stratigraphy of the North Atlantic Margins. American Association of Petroleum Geologists Memoir 46, 149-154.

Whitham, A.G., Price, S.P., Koraini, A.M. & Kelly, S.R.A. 1999. Cretaceous (post Valanginian) sedimentation and rift events in NE Greenland (71-77N). In Fleet, A.J. & Boldy, S.A.R. (eds.) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, 325-356.

Wilkinson, M. 1993. Concretions of the Valtos Sandstone Formation of Skye: geochemical indicators of palaeo-hydrology. Journal of the Geological Society London 150, 57-66.

Wilkinson, M. 1991. The concretions of the Bearreraig Sandstone Formation: geometry and geochemistry. Sedimentology 38, 899-912.

Worden, R.H. & Burley, S.D. 2003. Sandstone diagenesis: the evolution of sand to stone. In Burley, S.D. & Worden, R.H. (eds.) Sandstone Diagenesis: Recent and Ancient. Reprint Series 4 of the International Association of Sedimentologists, 3-44.

Worden, R.H., Mayall, M.J. & Evans, I.J. 2000. The effect of ductile-lithic sand grains and quartz cement on porosity and permeability in Oligocene and Lower Miocene clastics, South China Sea: prediction of reservoir quality. American Association of Petroleum Geologists Bulletin 84, 345-359.

Worden, R.H., Mayall, M.J. & Evans, I.J. 1997. Predicting reservoir quality during exploration: lithic grains, porosity and permeability in Tertiary clastics of the south China Sea basin. In Fraser, A.J., Matthews, S.J. & Murphey, R.W. (eds.) Petroleum Geology of South East Asia. Geological Society Special Publication 124, 107-115.

Worden, R.H., Oxtoby, N.H. & Smalley, P.C. 1998. Can oil emplacement prevent quartz cementation in sandstone? Petroleum Geoscience 4, 129-137.

Zattin, M., Cuman, A., Fantoni, R., Martin, S., Scotti, P. & Stefani, C. 2006. From the Middle Jurassic heating to Neogene cooling: The thermochronological evolution of the Southern Alps. Tectonophysics 414, 191-202.

Ziska, H. & Andersen, C. 2005. Exploration Opportunities in the Faroe Islands. In Ziska, H, Varming, T. & Bloch, D. (eds.) Faroe Islands Exploration Conference: Proceedings of the 1st Conference, Annales Societatis Færoensis, Supplementum 43, 146-162.

Sample	Depth	Grain size	Lithology	Detrital Min	eralogy								
ID	cm	mm		Total Qtz	Qtz-mono	Qtz-poly	Total Fsp	K-fsp	Plag	Total Mica	Musc.	Biotite	Frag. Sed.
103	10	0,21	Qtz-arenite	80,00	79,67	0,33	0,33	0,05	0,33	3,67	3,67	0,05	1,67
106	45	0,33	Qtz-arenite	54,00	53,67	0,33	2,33	2,00	0,33	0,33	0,33	0,05	0,67
108	120	0,30	Qtz-arenite	56,00	55,33	0,67	3,33	3,00	0,33	0,33	0,33	0,05	0,33
109	200	0,21	Qtz-arenite	59,50	59,17	0,33	4,67	3,67	1,00	0,33	0,33	0,05	0,33
110	700	0,12	Subfsparenite	63,00	62,33	0,67	7,00	3,67	3,33	0,67	0,33	0,33	0,33
202	1	0,27	Qtz-arenite	69,50	68,83	0,67	0,05	0,05	0,05	0,33	0,33	0,05	2,00
205	20	0,29	Qtz-arenite	83,00	82,33	0,67	0,33	0,05	0,33	2,00	2,00	0,05	0,33
207	95	0,29	Qtz-arenite	70,67	70,00	0,67	2,00	1,00	1,00	2,00	1,67	0,33	0,67
209	250	0,31	Qtz-arenite	81,33	80,67	0,67	0,33	0,33	0,05	0,67	0,67	0,05	0,33
210	970	0,25	Qtz-arenite	78,33	78,00	0,33	0,33	0,33	0,05	0,33	0,33	0,05	0,33

Sample	Depth			Authigenic	Mineralogy						Porosity		
ID	cm	Heavy min.	Matrix clay	Kaolinite	Chlorite	Illite	Qtz overg	Calcite	Fe-calcite	Pyrite	Total	Primary	Secondary
103	10	0,33	6,33				3,33			0,67	3,67	2,67	0,67
106	45	0,33	0,33				0,00	40,75	2,33	0,05	0,66	0,00	0,66
108	120	0,33	0,33				0,00	37,50	3,67	0,33	1,33	0,33	1,00
109	200	0,33	0,33	0,33			0,00	31,50	1,00	0,33	1,67	0,33	1,00
110	700	0,33	1,67		0,67		1,67			0,67	24,00	22,00	1,33
202	1	0,33	1,67		9,00		8,00			0,67	6,33	6,33	0,05
205	20	0,33	2,00	0,33			5,00			0,00	6,33	5,00	1,00
207	95	0,67	14,00				1,00			0,33	8,67	4,67	3,67
209	250	0,33	1,00	0,33		0,33	8,67			0,33	6,33	4,33	1,67
210	970	0,33	2,00		0,67		8,00			0,67	9,00	7,00	1,67

Sample	Depth _		Gas Perm	He-Por	Img-Por
ID	cm	Micropo	mD	%	%
103	10	0,33	0,726	9,72	2,46
106	45	0,00	0,067	2,31	4,50
108	120	0,00	0,078	3,83	
109	200	0,33	1,062	3,95	3,01
110	700	0,67	194,164	23,87	
202	1	0,05	0,236	7,87	3,49
205	20	0,33	1,106	7,47	4,68
207	95	0,33	0,153	8,70	
209	250	0,67	3,456	7,00	6,37
210	970	0,33	11,377	9,81	7,51

Appendix 1: Tables

Sample_ID	Depth	SiO2	TiO2	AI2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	Volat	Sum,maj.
	cm	%	%	%	%	%	%	%	%	%	%	%	%
101		48,651	1,786	15,598	11,677	0,158	6,490	10,533	3,230	0,510	0,178	0,670	99,481
102	1	95,500	0,123	0,924	0,188	0,001	0,208	0,158	0,030	0,043	0,022	0,590	97,787
103	10	94,791	0,333	2,443	0,274	0,002	0,051	0,016	0,120	0,354	0,026	0,590	99,000
105	25	56,297	0,079	0,624	0,173	0,008	0,259	22,652	0,080	0,310	0,022	18,510	99,014
106	45	56,126	0,059	0,627	0,189	0,016	0,184	22,973	0,050	0,312	0,029	18,580	99,145
107	80	57,314	0,160	0,850	0,175	0,016	0,238	21,730	0,110	0,380	0,035	17,870	98,878
108	120	59,166	0,130	0,536	0,311	0,011	0,117	21,293	0,060	0,250	0,028	17,310	99,212
109	200	64,263	0,237	0,673	0,236	0,011	0,114	17,959	0,100	0,349	0,035	14,700	98,677
110	700	94,356	0,495	1,812	0,403	0,003	0,130	0,047	0,190	0,769	0,021	0,420	98,646
201		48,801	1,773	15,630	11,780	0,163	6,468	10,544	3,270	0,504	0,175	0,640	99,748
202	1	86,805	0,082	2,354	3,701	0,042	1,013	2,175	0,030	0,025	0,018	2,710	98,955
203	5	95,003	0,133	1,429	0,556	0,006	0,520	0,053	0,020	0,192	0,022	0,680	98,614
204	12	96,304	0,133	1,223	0,350	0,002	0,199	0,000	0,010	0,227	0,022	0,350	98,820
205	20	97,646	0,097	1,044	0,197	0,003	0,050	0,006	0,040	0,145	0,018	0,300	99,546
206	60	96,735	0,171	1,083	0,266	0,002	0,115	0,003	0,050	0,101	0,019	0,420	98,965
207	95	93,285	0,325	3,487	0,225	0,001	0,080	0,011	0,170	0,568	0,026	0,730	98,908
208	130	91,629	0,381	4,486	0,228	0,000	0,101	0,018	0,160	0,805	0,024	1,040	98,872
209	250	97,895	0,083	0,484	0,182	0,000	0,000	0,017	0,020	0,076	0,019	0,250	99,026
210	970	97,749	0,170	0,593	0,179	0,000	0,017	0,003	0,010	0,106	0,019	0,260	99,106

Sample_ID	Depth	V	Cr	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Мо	Sn
	cm	ppm											
101		361	265	103	181	89	32	390	20	149	40	0	0
102	1	10	19	5	9	1	0	49	0	84	0	0	0
103	10	22	55	2	6	4	0	63	0	752	4	0	0
105	25	30	30	2	8	9	4	296	0	129	3	0	0
106	45	38	52	12	7	8	8	272	0	85	3	0	0
107	80	48	33	0	8	9	2	231	0	290	0	0	0
108	120	48	66	2	7	7	6	240	0	265	5	0	0
109	200	30	63	1	8	8	2	180	0	809	0	0	0
110	700	36	186	16	44	2	9	82	0	590	8	0	0
201		361	266	102	180	91	34	437	25	158	44	0	0
202	1	40	40	17	7	36	0	50	0	40	6	0	0
203	5	11	19	0	6	3	0	52	0	107	0	0	0
204	12	19	29	4	3	4	0	55	0	85	0	0	0
205	20	19	19	5	4	4	0	53	0	27	0	0	0
206	60	21	77	15	8	7	0	54	0	270	0	0	0
207	95	30	50	1	4	4	3	64	0	485	2	0	0
208	130	26	71	0	8	6	13	71	0	460	1	0	0
209	250	12	8	3	1	2	0	50	0	67	0	0	0
210	970	15	22	2	1	2	0	51	0	232	0	0	0

Table
2 contin
nued

Sample ID	Depth	Ва	La	Ce	Sum min	Total
	cm	ppm	ppm	ppm	ppm	%
101		205	6	12	1853	99,666
102	1	0	2	126	305	97,818
103	10	0	0	67	975	99,097
105	25	0	0	66	577	99,072
106	45	0	0	2	487	99,194
107	80	0	0	0	621	98,940
108	120	0	0	60	706	99,283
109	200	0	0	223	1324	98,809
110	700	0	0	0	973	98,743
201		101	0	17	1816	99,930
202	1	0	0	0	236	98,979
203	5	0	3	120	321	98,646
204	12	0	0	217	416	98,862
205	20	0	0	38	169	99,563
206	60	0	2	122	576	99,023
207	95	0	0	121	764	98,984
208	130	0	0	78	734	98,945
209	250	0	0	193	336	99,060
210	970	0	0	56	381	99,144

Table 3. Calculated CIPW-Norm for the Skye basalt

CIPW-norm

201	101	e-ID
1,44	1,47	quartz
2,98	3,01	orthoclase
27,67	27,33	albite
26,48	26,56	anorthite
14,91	14,74	diopside
9,20	9,33	hypersthene
0,35	0,34	ilmenite
11,78	11,68	hematite
3,90	3,95	sphene
0,41	0,42	apatite
99,12	98,82	Sum

Sample-ID	sill dist.	grain size	sorting	detr. Qtz	mono qtz	poly qtz	detr. Fsp	plag	k-fsp	rock frags	plutonic	metam	chert
445002	0,9	f	vw	41	37	4	0	0	0	0	0	0	0
445003	1,6	f	vw	34,3	30,7	3,7	0	0	0	5,7	3,7	1,3	0
445004	1,8	f	vw	35,7	34	1,7	0	0	0	1,7	1,7	0	0
445005	2,2	f	vw	38,3	33,7	4,7	0	0	0	2,3	1	1	0
445006	2,6	f	vw	41	35	6	0	0	0	4,7	3	1,3	0
445007	3	f	vw	32	26,7	5,3	0	0	0	2,7	1,3	0	0,3
445008	3,4	vf	vw	34,3	30,7	3,7	0	0	0	3,7	1,3	0,7	0
445009	3,8	f	vw	37	33	4	0	0	0	2	1	0,3	0
445010	4,4	f	w	38,3	33	5,3	0	0	0	5,3	2	0,3	0
445011	5	vf-f	w	42,3	36,7	5,7	0	0	0	2	1,3	0	0,3
445014	5	f	w	32,3	25,7	6,7	0	0	0	2,7	1	0.3	0
445015	6	f	w	40,3	35,3	5	0	0	0	0,7	0,7	Ó	0
445016	7	f	w	41,3	36	5,3	0	0	0	3	1,7	0	0
445017	8	f	w	36,3	30,7	5,7	0	0	0	0,7	0,7	0	0
445018	9	f	w	43,7	36,3	7,3	0	0	0	0,7	0	0	0
445019	10	m	m	45	39,3	5,7	0	0	0	4,3	2	2	0
445020	5,7	m	m	31,7	26	5,7	0	0	0	0,7	0,3	0	0
445021	6,7	m	m	29,3	25,7	3,7	3	2,3	1	1	1	0	0
445022	7,7	m	m	33	26,3	6,7	0	Ó	0	0,7	0,7	0	0
445023	8,7	m	w	31,3	27,3	4	2,7	1,7	1	1	0,3	0	0
445024	9,7	m-c	m	36,7	31,3	5,3	0,3	0,3	0	2	1	0	0
445025	10,7	m	m	42,7	34,3	8,3	0	0	0	4,3	2,3	1,3	0
445026	11,7	m	m	47,7	35,3	12,3	0	0	0	1,3	0,3	0,3	0
445027	12,7	с	р	47,3	30	17,3	0	0	0	10	3,3	0	0
445028	13,7	с	w	57,3	32	25,3	0	0	0	1,7	1,3	0	0
445029	14,7	С	m	56,7	40,3	16,3	0	0	0	6,7	1,7	0,7	0
445001	30	m-c	р	50,3	39,7	10,7	0	0	0	3,3	2,3	0,3	0

 Table 4. Traill Ø samples – point counting data (Preuss, 2005)

Sample-ID	sill dist.	clay clast	Fe-Ti min	mica	biotite	zircon	pseudomorphs	auth. Clay	phengitic clay	glauconitic clay	chlorite
445002	0,9	0	0	0	0,3	0	0	12,3	0	0,3	12
445003	1,6	0	0,3	0,7	0	0	0	10,7	0	6	4,7
445004	1,8	0	0,3	0	0	0	0	15,7	0	3,7	12
445005	2,2	0	0,7	0,3	0	0	0	12	0	4,3	7,7
445006	2,6	0	2	0,3	0	0	0	17	0	1,7	15,3
445007	3	0	3	1	0	0,3	0	15,7	0	2	13,7
445008	3,4	0	0	1,7	0	0	0	12,3	0	2,3	10
445009	3,8	0	1	0	0,7	0	0	20	0	4	16
445010	4,4	0,3	0,7	1	1,3	0,3	0	18,7	0	4	14,7
445011	5	0	2	0,3	0	0	0,3	15	0	3,3	11,7
445014	5	0	0.7	1	0.3	0	0	23	0	5	18
445015	6	0	0	0	0	0	0	15.7	0	3	12.7
445016	7	0	07	03	1	03	4	10,7	0	07	10
445017	8	0	2	0	0	0	3	17.3	0	2.3	15
445018	9	0	0.7	0.7	0 0	õ	3.7	13.3	0 0	1	12.3
445019	10	0	0	0	0,3	0	4,3	8,7	0	0	8,7
445020	E 7	0	0	0	0.2	0	0	17 7	0	0	17 7
445020	5,7	0	0	0	0,3	0	0	17,7	0	0	17,7
445021	ю, <i>1</i> дд	0	2	0	0	0,3	0	22,3	0	0	22,3
445022	1,1	0	0	0	0	0	0	17	0	0	17
445023	8,7	0	0	0,7	0	0	0	16	0	0	16
445024	9,7	0	0,3	0,7	0	0	0	3	0	0	3
445025	10,7	0	1,3	0	0	0	6	8,3	0	0	8,3
445026	11,7	0	0	0	0,7	0	4,7	6,3	0	0,3	6
445027	12,7	6,3	0,3	0	0,3	0	0	5,3	0	0	5,3
445028	13,7	0,3	0	0	0	0	2,7	6	0	0	6
445029	14,7	4	0	0	0	0	0	7,7	0	0	7,7
445001	30	0,3	3	0,3	0	0	0	11	0	0,7	10,3

Sample-ID	sill dist.	Ti-oxides	pyrite	auth. Qtz	apatite	albite	albite dusty	albite cry	albite over	sphene	K-zeolite?	analcime	laumontite
445002	0,9	0	0	19	0,7	23,7	10	10,7	1	1,3	0	0	0
445003	1,6	1,3	0	19	1,3	26	12,7	7	1,3	0,7	0	0	0
445004	1,8	1	0	20,7	0	20,3	11,7	7	0,7	0,3	0	0	0
445005	2,2	2,3	0	22	1	18	10	4,3	0,3	1,7	0	0	0
445006	2,6	2	0	14,7	0,3	16,7	7,7	6,7	0	1,3	0	0	0
445007	3	4	0	16	0,3	17,7	5,7	6,3	0	2	0	0	0
445008	3,4	3	0	20	0,3	18,7	12,3	6	0,3	0,7	0	0	0
445009	3,8	1	0,3	17,3	0	18	9,3	7,7	1	2,3	0	0	0
445010	4,4	2,3	0	17	0,3	11,3	8	3,3	0	4	0	0	0
445011	5	3,3	0	18,3	0,3	9,7	5,3	2,7	1,7	7,3	0	0	0
445014	5	1.3	0	15.7	0	21.3	13	6	2.3	0.7	0	0	0
445015	6	0	0	15	0	21	13	7	1	3.7	0	0	0
445016	7	0.7	0	17.3	0.3	17.7	10	7	0.7	1	0	0	0
445017	8	2.3	0	16	0	22	14.7	6	1.3	1	0	0	0
445018	9	0.7	2.3	15.3	0	14,7	10	4	0,7	4	0	0	0.7
445019	10	0	0	15	0,7	9,7	8,3	0,7	0,7	0	0	0	11
445020	5.7	0	1.7	8	0	22.3	10.7	11.7	0	0	0	0	0
445021	6.7	2	1.7	8.7	0	12.3	5.3	6.3	0.7	0.3	0	0	0
445022	7.7	0	1.7	8.7	1	15.3	6	8.3	1.3	0	0	0	0
445023	8.7	0	2.7	8.7	0	8.7	3.7	5	0	0.7	0	0	0
445024	9,7	0.7	7	7.3	0.3	22.3	11	6.7	4,7	1	0	0	0.3
445025	10,7	2	1.3	13,7	0,7	12	0.3	11	0,7	2,7	0	0	5.3
445026	11,7	0	2,7	12,3	Ó	18,7	10,3	6,3	2	2	0	0	3,3
445027	12,7	0.3	7,3	6.7	1	10,7	3,3	7	0,3	1,3	0	0	7,3
445028	13,7	Ó	6	10,7	2,3	11,3	4,7	6,7	0	Ó	0	0	1,3
445029	14,7	0,3	2	7,7	1,3	13,3	4,3	8,7	0,3	0	0	0	3,3
445001	30	3,3	0	9	2	13,7	6,3	6	1,3	0	0	0	3,7

Sample-ID	sill dist.	calcite	goethite	porosity	primary	secondary	He-porosity	gas perm	vitr. %Ro
445002	0,9	0,7	0,3	0	0	0	4,32	0,334	5,49
445003	1,6	0	0,3	0,7	0	0,7	5,21	0,020	
445004	1,8	0,7	3,3	0,7	0	0,7	7,03	0,014	
445005	2,2	0	1,3	1	0	1	7,17	0,015	
445006	2,6	0	1,7	0,7	0	0,7	6,52	0,012	6,20
445007	3	5,3	2,7	1,3	0	1,3	10,96	0,049	
445008	3,4	0	2,7	0,7	0,7	0	13,33	0,001	
445009	3,8	0	1,3	0,7	0,3	0,3	9,92	0,089	
445010	4,4	0	2	0,3	0,3	0	8,73	0,014	5,55
445011	5	0,3	1	0	0	0	7,52	0,024	
445014	5	0	2,7	0,3	0	0,3	11,71	0,016	
445015	6	0	3,7	0	0	0	8,89	0,012	5,44
445016	7	0	3,3	0,3	0,3	0	6,75	0,017	
445017	8	0	1,3	0	0	0	7,74	0,012	
445018	9	0	0,7	0,3	0	0,3	8,15	0,015	5,48
445019	10	0	1,3	0	0	0	5,59	0,101	
445020	5,7	16,7	1,3	0	0	0			
445021	6,7	18,3	0,3	0	0	0	7,69	0,017	
445022	7,7	21	1,3	0	0	0	9,21	0,285	7,40
445023	8,7	27,7	0,7	0	0	0	3,01	0,008	
445024	9,7	17	0,7	1,3	0	1,3	5,16	0,022	
445025	10,7	0	0,7	0,3	0	0,3	3,87	0,004	
445026	11,7	1	0	0	0	0	6,68	0,108	
445027	12,7	0	2,3	0,3	0	0,3	9,21	0,131	5,35
445028	13,7	0,7	0	0	0	0	6,50	0,052	
445029	14,7	0,7	0,3	0	0	0	3,25	0,005	
445001	30	1,7	1,7	0	0	0	6,97	0,082	5,55

Appendix 2: Thin section description of individual specimens

103 – Fine to medium-grained quartz arenite

Sample type:	Blue epoxy impregnated thin section
Lithology:	Quartz arenite
Modal porosity:	3.7%
Grain size:	Max: 0.45 mm; Min: 0.10 mm; Mode: 0.13-0.28 mm (fine-medium sand)
Sorting:	Moderately well sorted
Roundness:	Subrounded
Sphericity:	Subspherical
Detrital mineralogy:	:Dominated by monocrystalline quartz (79.7%) with a small amount of
	polycrystalline quartz (0.3%), plagioclase (0.3%) and rock fragments
	(1.7%). Rock fragments are all shale clasts. Scattered muscovite flakes
	(3.7%) and heavy mineral grains (0.3%) comprising zircon, apatite and
	rutile are also present. About 6.3% detrital clay (matrix, illite) is present
	in this sample and it occurs as interstitial and grain rimming clay. No K-
	feldspar grain is observed in this sample.

Authigenic mineralogy: Dominated by quartz overgrowth (3.3%) with a very small amount of scattered pyrite (0.7%).



App. 1. Digital image analysis derived thin section overview.

106 - Calcite-cemented quartz arenite

Sample type:	Carbonate stained, blue epoxy impregnated thin section
Lithology:	Calcite-cemented quartz arenite
Modal porosity:	0.7%
Grain size:	Max: 0.9 mm; Min: 0.12 mm; Mode: 0.23-0.42 mm (fine-medium sand)
Sorting:	Moderately well sorted
Roundness:	Subangular to subrounded
Sphericity:	Elliptical to subrounded
Detrital mineralogy	y:Dominated by monocrystalline quartz (54.7%) with a small amount of
-	polycrystalline quartz (0.3%), K-feldspar (2.0%), plagioclase (0.3%) and
	rock fragments (0.7%). Rock fragments are all shale clasts. Scattered
	muscovite flakes (0.3%) and heavy mineral grains (0.3%) comprising
	zircon and rutile are also present. Only a very small amount of detrital
	clay (matrix) (0.3%) is present in this sample as interstitial and grain
	rimming clay.

Authigenic mineralogy: Dominated by calcite cement (38.0%) with a small amount of scattered ferroan calcite (2.3%).



App. 2. Digital image analysis derived thin section overview.
108 – Calcite-cemented quartz arenite

Sample type:	Carbonate stained, blue epoxy impregnated thin section
Lithology:	Calcite-cemented quartz arenite
Modal porosity:	1.3%
Grain size:	Max: 1.0 mm; Min: 0.1 mm; Mode: 0.2-0.4 mm (fine to medium sand)
Sorting:	Moderately well sorted
Roundness:	Subangular to subrounded
Sphericity:	Elliptical to subspherical
Detrital mineralogy: Dominated by monocrystalline quartz (58.3%) with a small amount of	
polycrystalline quartz (0.7%), K-feldspar (3.0%), plagioclase (0.3%) and rock fragments	
(0.3%). Rock fragments are all shale clasts. Scattered muscovite flakes (0.3%) and heavy	
mineral grains (0.3	%) comprising zircon are also present. Only a very small amount of de-
trital clay (matrix) (0.3%) is present in this sample as interstitial and grain rimming clay.
Authiancia minoralague. Dominated by calcite compart (21,0%) with a small amount of cast	

Authigenic mineralogy: Dominated by calcite cement (31.0%) with a small amount of scattered ferroan calcite (3.7%) and pyrite (0.3%)

109 - Calcite-cemented quartz arenite

Sample type:	Carbonate stained, blue epoxy impregnated thin section
Lithology:	Calcite-cemented quartz arenite
Modal porosity:	1.7%
Grain size:	Max: 0.30 mm; Min: 0.10 mm; Mode: 0.18-0.25 mm (fine sand)
Sorting:	Moderately well sorted
Roundness:	Subangular to subrounded
Sphericity:	Elliptical to subspherical
Detrital mineralogy	:Dominated by monocrystalline quartz (62.3%) with a small amount of polycrystalline quartz (0.3%), K-feldspar (3.7%), plagioclase (1.0%) and rock fragments (0.3%). Rock fragments are all shale clasts. Scattered
	muscovite flakes (0.3%) and heavy mineral grains (0.3%) comprising zircon are also present. Only a very small amount of detrital clay (matrix) (0.3%) is present in this sample as interstitial and grain rimming clay.

Authigenic mineralogy: Dominated by calcite cement (28%) with a small amount of scattered ferroan calcite (1.0%), kaolin (0.3%) and pyrite (0.3%).



App. 3. Digital image analysis derived thin section overview.

110 – Very fine to fine-grained subfeldspathic arenite

Sample type:	Blue epoxy impregnated thin section
Lithology:	Subfeldspathic arenite
Modal porosity:	24.0%
Grain size:	Max: 0.23 mm; Min: 0.09 mm; Mode: 0.10-0.13 mm (very fine to fine sand)
Sorting:	Well sorted
Roundness:	Subangular to subrounded
Sphericity:	Elliptical to subspherical
Detrital mineralogy	Dominated by monocrystalline quartz (62.3%) with a very small amount of polycrystalline quartz (0.7%), K-feldspar (3.7%), plagioclase (3.3%) and rock fragments (0.3%). Rock fragments are all shale clasts. Scat- tered muscovite flakes (0.3%), biotite flakes (0.3%) and heavy mineral grains (0.3%) comprising zircon and rutile are also present. Only a very small amount of detrital clay (matrix) (1.7%) is present in this sample as interstitial and grain rimming clay.

Authigenic mineralogy: Only small amount of quartz overgrowth (1.7%), chlorite (0.7%) and pyrite (0.7%).



App. 4. Digital image analysis derived thin section overview.

202 – Fine to medium-grained quartz arenite

Sample type:	Blue epoxy impregnated thin section
Lithology:	Quartz arenite
Modal porosity:	6.3%
Grain size:	Max: 0.5 mm; Min: 0.12 mm; Mode: 0.2-0.35 mm (fine to medium sand)
Sorting:	Moderately well sorted
Roundness:	Subangular to subrounded
Sphericity:	Elliptical to subspherical
Detrital mineralogy	:Dominated by monocrystalline quartz (79.3%) with a small amount of
	polycrystalline quartz (0.7%) and rock fragments (2%). Rock fragments
	are all shale clasts. Scattered muscovite flakes (0.3%) and heavy min-
	eral grains (0.3%) comprising zircon, apatite and rutile are also present.
	Only small amount of detrital clay (matrix) (1.7%) is present in this sam-
	ple as interstitial and grain rimming clay. Only trace amount of K-
	feldspar and plagioclase observed in this sample.

Authigenic mineralogy: Dominated by quartz overgrowth (8%) followed by chlorite (5%) and patchily distributed pyrite (0.7%).



App. 5. Digital image analysis derived thin section overview.

205 – Fine to medium-grained quartz arenite

Sample type:	Blue epoxy impregnated thin section
Lithology:	Quartz arenite
Modal porosity:	6.3%
Grain size:	Max: 0.6 mm; Min: 0.12 mm; Mode: 0.22-0.35 mm (fine to medium
	sand)
Sorting:	Moderately well to well sorted
Roundness:	Subrounded
Sphericity:	Subspherical
Detrital mineralogy: Dominated by monocrystalline quartz (82.3%) with a small amount of	
	polycrystalline quartz (0.7%), plagioclase (0.3%) and rock fragments
	(0.3%). Rock fragments are all shale clasts. Scattered muscovite flakes
	(2.0%) and heavy mineral grains (0.3%) comprising zircon and rutile are
	also present. Only a small amount of detrital clay (matrix) (2.0%) is pre-
	sent in this sample as interstitial and grain rimming clay.
Authigenic mineralogy: Dominated by quartz overgrowth (5.0%) with a very small amount	
	of scattered kaolin (0.3%).



App. 6. Digital image analysis derived thin section overview.

207 - Fine to medium-grained quartz arenite

Sample type:	Blue epoxy impregnated thin section
Lithology:	Quartz arenite
Modal porosity:	8.7%
Grain size:	Max: 0.5 mm; Min: 0.1 mm; Mode: 0.20-0.38 mm (fine to medium sand)
Sorting:	Moderately well to well sorted
Roundness:	Subrounded
Sphericity:	Subspherical
Detrital mineralogy: Dominated by monocrystalline quartz (70.0%) with a small amount of	
	polycrystalline quartz (0.7%), K-feldspar (1.0%), plagioclase (1.0%) and
	rock fragments (0.7%). Rock fragments are all shale clasts. Scattered

muscovite flakes (1.7%), biotite flakes (0.3%) and heavy mineral grains (0.3%) comprising zircon and rutile are also present. 14.0% detrital clay (matrix) is present in this sample and it occurs as interstitial and grain rimming clay.

Authigenic mineralogy: Only small amount of quartz overgrowth (1.0%) with trace amount of scattered pyrite (0.3%).



App. 7. Digital image analysis derived thin section overview.

209 – Medium-grained quartz arenite

Sample type:	Blue epoxy impregnated thin section
Lithology:	Quartz arenite
Modal porosity:	6.3%
Grain size:	Max: 0.60 mm; Min: 0.15 mm; Mode: 0.28-0.35 mm (medium sand)
Sorting:	Moderately well to well sorted
Roundness:	Subangular to subrounded
Sphericity:	Elliptical to subspherical
Detrital mineralogy: Dominate by monocrystalline quartz (80.7%) with a very small amount	
	of polycrystalline quartz (0.7%), K-feldspar (0.3%) and rock fragments
	(0.3%). Rock fragments are all shale clasts. Scattered muscovite flakes
	(0.7%) and heavy mineral grains (0.3%) comprising zircon and rutile are
	also present. Only a very small amount of detrital clay (matrix) (1.0%) is
	present in this sample as interstitial and grain rimming clay.
Authigenic mineralogy: Dominated by quartz overgrowth (8.7%) with a small amount of	
	scattered illite (0.3%), kaolin (0.3%) and pyrite (0.3%).



App. 8. Digital image analysis derived thin section overview.

210 - Fine to medium-grained quartz arenite

Sample type:	Blue epoxy impregnated thin section
Lithology:	Quartz arenite
Modal porosity:	9.0%
Grain size:	Max: 0.70 mm; Min: 0.15 mm; Mode: 0.20-0.32 mm (fine to medium sand)
Sorting:	moderately well to well sorted
Roundness:	Subrounded
Sphericity:	Elliptical to subspherical
Detrital mineralogy	Dominated by monocrystalline quartz (78.0%) with a very small amount of polycrystalline quartz (0.3%), K-feldspar (0.3%) and rock fragments (0.3%). Rock fragments are all shale clasts. Scattered muscovite flakes (0.3%), biotite flakes (0.3%) and heavy mineral grains (0.3%) compris- ing zircon and rutile are also present. Only a very small amount of detri- tal clay (matrix) (2.0%) is present in this sample as interstitial and grain rimming clay.

Authigenic mineralogy: Dominated by quartz overgrowth (8.0%) with a small amount of scattered chlorite (0.7%) and pyrite (0.7%).



App. 9. Digital image analysis derived thin section overview.