Reservoir quality of the Upper Triassic to Lower Jurassic sediments, NW Barents Shelf: understanding porosity evolution through diagenesis and sedimentology

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Preface

This thesis entitled "Reservoir quality of the Upper Triassic to Lower Jurassic sediments, NW Barents Shelf: understanding porosity evolution through diagenesis and sedimentology" has been submitted to the Department of Geosciences at the University of Oslo in agreement with the requirements for the degree of Philosophia Doctor. This PhD study was completed as part of a three year Trias North project. A group of geologist from different Universities in collaboration with international experts from foreign Universities established Trias North project. This project was framed under the working title "Reconstructing the Triassic Northern Barents shelf, basin infill patterns controlled by gentle sags and faults". The project was funded by the research Council of Norway (RCN). Tullow Oil Norge, Lundin Norway, Statoil Petroleum, Edison Norge and RWE Dea Norge have also provided financial support. This thesis is part of the larger Trias North project in particular associated with work package two concerning assessment of sedimentary systems.

The aims of the study reported herein were: 1) to evaluate the effect of diagenesis on reservoir quality and constrain thermal history, 2) to establish characteristic depositional sedimentary facies based on outcrops and link them to diagenesis, 3) evaluate the controlling factor for the modes of occurrences and abundances of clay minerals in sedimentary sequences (grain coatings or pore-filling), 4) analyze the nature and extent of grain coatings with effects on the chemical compaction (quartz cementation), and 5) to evaluate the impact of sill-induced diagenesis on reservoir quality of the Upper Triassic to Lower Jurassic sandstones of the NW Barents Sea.

This article-based PhD thesis is organized into two parts: (I) introduction and (II) manuscripts. The introduction part of the thesis is encompassed by a brief description of the scope and objectives, the study area and methods, scientific background information on the parameters controlling diagenesis of clastic sandstones and ultimately reservoir quality followed by a summary of the manuscripts and lastly some concluding remarks and implications of the key findings of this study on the exploration activity in the Barents Sea region.

Acknowledgements

My whole-hearted thankfulness and appreciation go to my supervisor Associate Professor Helge Hellevang whose professional guidance, invaluable assistance and prompt responses to my questions and inquiries were highly valuable for the success of this PhD. His constructive criticism, thought-provoking questions, comments, corrections and suggestions have been extremely important, and without these I doubt that the realization of this work would have been possible. I would like to thank him for his diligent follow-up of my academic progress and professional development.

> *Helge, you are more than a supervisor for me, – my best friend and brother; I totally go short of words for your invaluable time and guidance in the whole process of buying the flat in Oslo. I would not have imagined buying a flat without you on the first hand. I have been extremely lucky to have a supervisor who cares so much about my work and my personal wellbeing. Above all your encouragement and motivation have been super for my involvement in numerous research topics. I really appreciate your belief in me, also when I doubted myself. You have imprinted in me the "yes I can"-dictum.*

I am also very grateful to my supervisor Professor Jens Jahren, who has been supportive since the days I began working on his project as a researcher. Ever since, Jens has supported me not only by providing a research assistantship over almost two years, but also as a wonderful supervisor of my PhD. He is such a patient and knowledgeable person who got always great ideas at hand. He has always been there to support me academically and emotionally on this rough road. This has robustly contributed for the successful completion of this work. He has given me the moral support and freedom I needed when writing the articles and this thesis.

In my work of linking depositional facies and diagenesis studies, I am particularly indebted to Tore Grane Klausen. This project greatly benefited from his experience and talent in sedimentology. I thank him for his significant contributions in the write-up process with critical and thought-provoking comments and suggestions. I appreciate and am at the same time overwhelmed by his prompt answers for all types of enquiry. Even in the very challenging Arctic weather, he was always smiling and patience to answer my questions. I have been very pleased to know Tore and work in partnership with him.

I must express my gratitude to Professor Alvar Braathen for his continued support and encouragement throughout my study. His kind care and guidance, especially during fieldwork, is highly appreciated. I thank him for supervising in selecting relevant PhD courses, and also for inviting me to join the geoscience field trip principally focusing on sedimentology and structural geology on the world-class exposed outcrops in Utah. The lessons I learned in that fieldwork gave fundamental input while performing fieldwork at Edgeøya.

I am very grateful to Gudmund Anders Dalsbø for making my life easier upon handling and simplifying administrative stuffs. Without his quick solutions I would not have participated in fieldwork and taken courses at UiB and UNIS. Especially, his extraordinary support in the hectic process of buying a flat in Oslo was super. Big thanks for that! I will never forget his unreserved support during the process of moving into my new flat.

I would like to acknowledge the Research Council of Norway for providing the funding that made my PhD study possible under the Trias North project “Reconstructing the Triassic Northern Barents shelf, basin infill patterns controlled by gentle sags and faults”. I would like also to extend my thanks to the financial support provided by Tullow Oil Norge, Lundin Norway, Statoil Petroleum, Edison Norge and Dea Norge affiliated to this project.

I do not really know how to thank enough Professor Per Aagaard: simply my immense heartfelt thanks! He was my Master thesis supervisor, and I experienced his respect for student’s thoughts, independent work and freedom. He is a wonderful person professionally and personally. He introduced me to the world of thermodynamics and kinetics of crystal growth and precipitation in a multicomponent geological system than the simplified chemical system. He also introduced me to the very best persons who have come into my life, Jens and Helge.

A very special gratitude goes out to Professor Knut Bjørlykke who has been an inspiration on how to critically evaluate articles published associated with diagenesis. I am also incredibly appreciative to him for sharing his ample knowledge, experience and wisdom so willingly. I have benefited a lot from his expertise. I consider myself an ever-lucky person taught by such a pioneer in the field.

I would like to express my appreciation to Professor Annik M. Myhre for her technical support, guidance and encouragement during my PhD study. Special mention has to go to her for being excellent social event organizer and excellent maker of cake in celebrating accepted manuscripts. A big thank you for that.

I thank Professor Dag Karlsen for giving me his invaluable time for answering my questions regarding pros and cons of the thermal maturity indicators and supplying me with relevant and timely references. My thanks go to Tesfamariam Birhane Abay for his time and candid brotherly support in performing the screening of source rock samples for Rock-Eval analysis, all the time opening his door for discussions regarding source rock geochemistry, and supplying relevant and important references in the field.

My former office-mates Kelai Xi, Javad Naseryan-Moghadam and Mohsen Kelani and my current office-mates Shaomin Zhang, Line Hedvig Lina, and Daniel Jan Morad, are thanked for their support and kindness and being nice all the time. I would like to thank you all for insightful and thoughtful discussions in both diagenesis and non-subject related issues and also nice lunchtime chats and socialization moments. I would like to thank Ingrid Anell, Daniela Röhnert, Mark Mulrooney, Kei Ogata and Luka Blazic for their assistance and kind support during Triassic North fieldwork. Furthermore, all Trias North Group members are acknowledged for their assistance and care in the wild Arctic. Special thanks go to Urszula Czarniecka for her dedication and perseverance in a teamwork environment. Many thanks also go to Valentin Zuchuat and Anna Van Yperen for the most memorable experiences we had together while taking the course sequence stratigraphy at Svalbard. Berit Løken Berg and Mufak Said Naoroz are thanked for their kind support in performing Petrographic SEM and chemical analyses, respectively. My sincere thanks also goes to Thor Axel Thorsen who provided me every support while I was working as XRD head engineer.

I would like to thank Irfan Baig and Mohammad Nooraiepour for giving me their time for the technical support in fine-tuning some plots. I also thank Noora for useful discussions on the subject of mechanical compaction of clastic sediments and for involving me in the Skade shale experimental mechanical compaction study resulting into a successful cooperative work, leading to the publication of an article in a peer-reviewed journal. I am grateful to Rohaldin Miri for the enjoyable time we had working together. It has resulted in two publications in the most respected journal. I enjoyed working with you.

I would like to express my appreciation to my forever love, cheering and always-passionate sweetheart Ale: I owe it all to you. Words cannot express how grateful I am to you for all of the sacrifices that you have made on my behalf. I am immensely grateful Ale for your unconditional love and support, without which I would never have made it to where I am today. I would never have survived and nothing would have happened to me, my dearest and little angel, gorgeous Mekiye without you coming into my life. You are the most precious gift and blessing of almighty God that I ever had. All things came into existence through him, and without him nothing was. (John 1:3). I will give praise to the almighty God who has been my guide throughout my life.

It is always impossible to personally thank everyone who has contributed directly or indirectly for the successful completion of the study. Hence, I would like to thank all who have helped me but whose name is not mentioned here.

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Beyene Girma Haile, Oslo, December 2017

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List of papers

This PhD thesis is based on four scientific manuscripts (here onwards referred as paper I-IV) that consider parameters controlling diagenesis and ultimately reservoir quality of siliciclastic sandstones.

Paper I: Haile, Beyene Girma; Hellevang, Helge; Aagaard, Per; Jahren, Jens. Experimental nucleation and growth of smectite and chlorite coatings on clean feldspar and quartz grain surfaces. *Marine and Petroleum Geology* 2015. Volume 68. (Part A) p. 664-674

Paper II: Haile, Beyene Girma; Klausen, Tore. G; Czarniecka, Urszula; Xi, Kelai; Jahren, Jens; Hellevang, Helge (2017). How are diagenesis and reservoir quality linked to depositional facies? A deltaic succession, Edgeøya, Svalbard. *Marine and Petroleum Geology*. Published on line first, https://doi.org/10.1016/j.marpetgeo.2017.11.019.

Paper III: Haile, Beyene Girma; Klausen, Tore. G; Jahren, Jens; Braathen, Alvar; Hellevang, Helge. Thermal history of a Triassic sedimentary sequence verified by a multi-method approach: Edgeøya, Svalbard, Norway (*In press in the Journal of Basin Research*)

Paper IV: Haile, Beyene Girma; Czarniecka, Urszula; Xi, Kelai; Smyrak-Sikora, Aleksandra; Jahren, Jens; Braathen, Alvar; Hellevang, Helge. Hydrothermally induced diagenesis: Evidence from shallow marine-deltaic sediments, Wilhelmøya, Svalbard. (*In press in the Journal of Geoscience Frontiers*)

Oral Presentation

Haile, Beyene Girma; Klausen, Tore Grane; Czarniecka, Urszula; Xi, Kelai; Jahren, Jens; Braathen, Alvar; Hellevang, Helge (2017). Diagenesis of Upper Triassic sandstones, Edgeøya, Svalbard. Talking Trias workshop; 2017-10-25 - 2017-10-26.UiO.

Haile, Beyene Girma; Klausen, Tore Grane; Czarniecka, Urszula; Jahren, Jens; Hellevang, Helge (2017). The impact of depositional facies and diagenesis on the reservoir quality of the Triassic De Geerdalen Formation, Edgeøya. Trias North Industry visit; 2017-06-12.Stavanger.

Haile, Beyene Girma; Jahren, Jens; Hellevang, Helge (2017). New insights about thermally driven diagenetic changes due to the emplacement of magmatic sills into reservoir sediments at Wilhelmøya (Svalbard): Implications for reservoir quality. Norwegian Geological Society Winter Meeting; 2017-01-09 - 2017-01-1.UiO.

Haile, Beyene Girma; Klausen, Tore Grane; Hellevang, Helge; Jahren, Jens; Bjørlykke, Knut (2016). Burial diagenesis of De Geerdalen Formation control by depositional facies distribution, Edgeøya, Svalbard. Trias North annual workshop; 2016-05-24 - 2016-05-25.UiB/UiO.

Haile, Beyene Girma; Xi, Kelai; Jahren, Jens; Aagaard, Per; Bjørlykke, Knut; Hellevang, Helge (2015). Burial Diagenesis in Triassic Sandstones: key to understand reservoir quality evolution. Trias North Data sharing workshop; 2015-06-01 - 2015-06-02. UiO.

Additional contributions

I have also co-authored the following articles on topics related to diagenesis but not included in this thesis (only articles where am the second author is listed):

1. Hellevang, Helge; Haile, Beyene Girma; Abednego, Tetteh (2017). Experimental study to better understand factors affecting the CO_2 mineral trapping potential of basalt. *Greenhouse Gases: Science and Technology*. ISSN 2152-3878. *7*(1), s 143- 157. doi: 10.1002/ghg.1619

2. Nooraiepour, Mohammad; Haile, Beyene G.; Hellevang, Helge (2017). Compaction and mechanical strength of Middle Miocene mudstones in the Norwegian North Sea - the major seal for the Skade CO_2 storage reservoir. *International Journal of Greenhouse Gas Control*. ISSN 1750-5836. *67*, s 49- 59. doi: 10.1016/j.ijggc.2017.10.016

3. Hellevang, Helge; Haile, Beyene Girma; Miri, Rohaldin (2016). A Statistical Approach to Explain the Solution Stoichiometry Effect on Crystal Growth Rates. *Crystal Growth & Design*. ISSN 1528-7483. *16*(3), s 1337- 1348. doi: 10.1021/acs.cgd.5b01466

Introduction

Scope and objectives

This thesis presents the main factors controlling reservoir quality of the outcropping sedimentary successions of the Upper Triassic De Geerdalen Formation and Lower Jurassic Wilhelmøya Subgroup in the Svalbard archipelago, NW Barents Shelf. The De Geerdalen Formation and Wilhelmøya Subgroup comprise fluvial, deltaic and shallow marine deposits (Mørk et al., 1982). These sediments are time equivalent to potentially hydrocarbon prone sedimentary successions in the Barents Sea area to the south. Reservoir quality of the studied rocks can be attributed to a number of factors including, but not limited to, diagenesis and depositional setting (Fig. 1). Diagenesis modifies the reservoir quality subsequent to sediment deposition. Reservoir quality is a function of the framework primary textural and mineralogical composition, thermal and burial history, provenance and depositional processes (Bjørlykke, 2014; Morad et al., 2010). These factors dictate burial diagenetic pathways. Sediment structure and texture bear the imprint of initial processes and the depositional setting which to a high degree are attributed to depositional energy and shallow burial diagenetic processes. These factors eventually constrain subsequent burial diagenesis products and hence the evolution of rock physical properties. These factors combined control reservoir quality through the distribution of reservoir geometry, porosity and permeability. An understanding of the factors that control the diagenesis and porosity evolution of reservoir rocks is thus helpful for improving the predictability in oil and gas exploration.

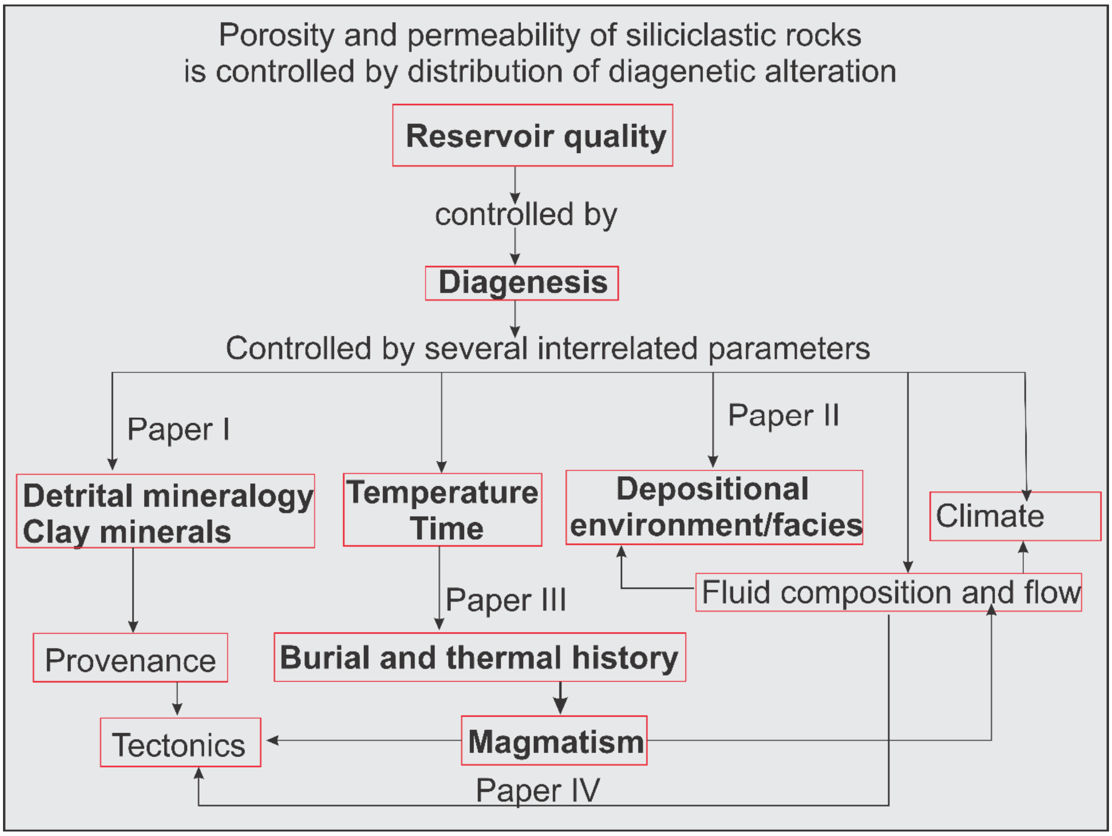

Figure 1: Diagram showing a complex array of interrelated variables controlling diagenesis and ultimately reservoir quality (modified from Morad et al. (2012) and Stonecipher et al. (1984)). Interrelated parameters lead to complicated reservoir quality distributions in sedimentary rocks. These parameters include the depositional environment and diagenesis, as well as tectonics and the burial/thermal evolution of the basin. Substantial variations in the reservoir quality distribution is challenging for the optimisation of hydrocarbon production and recovery.

As indicated above, diagenesis is affected by a complex array of parameters, and to understand how diagenesis has affected a given system demands integrating a variety of methods. This implies that diagenesis research must be a multidisciplinary effort extended beyond sedimentology and sequence stratigraphy and should include experimental diagenesis, organic geochemistry and mineralogy. Linking diagenesis with sedimentology and other disciplines is still at an immature stage. This integrated approach is however getting increased attention (Al-Ramadan et al., 2005; De Ros et al., 2012; Hiatt and Kyser, 2000; Ketzer et al., 2003; Kordi et al., 2011; Mansurbeg, 2017; McKay et al., 1995; Morad et al., 2010).

This study used an integrated approach in order to gain an improved understanding of variables controlling the spatial distribution of diagenetic features of the late Triassic rocks in the NW Barents Shelf. Factors controlling diagenesis such as temperature, primary textural and mineralogical sediment composition, depositional facies, hydrothermal convective fluid flow due to igneous sill emplacement, and grain-coating clay minerals, have been evaluated.

To accomplish this, the outcrop samples were analysed with regard to thermal history using Rock-Eval pyrolysis-related parameters, vitrinite reflectance, fluid inclusions in quartz and calcite cements, and oxygen and carbon isotopes in calcite cements. Specific depositional facies within the sedimentary sequence were described mainly based on parameters such as sedimentary structures, grain size, unit thickness, bioturbation and organic content. Texture and mineralogy of the samples were examined, identified and quantified by X-ray diffraction, X-ray elemental mapping, petrographic point counting and scanning electron microscopy. Subsequently, cathodoluminescence imaging in the scanning electron microscopy was used to distinguishing detrital quartz from authigenic quartz. Moreover, experimental diagenesis was performed in the laboratory to increase the knowledge about the mechanisms resulting in grain-coating clay minerals, since such coatings have significant effect in preserving anomalously high porosity and permeability in deeply buried sandstone reservoirs.

At a regional scale, the results provide insights into the reservoir quality development of offshore equivalent Triassic to Lower Jurassic rocks in the Barents Sea. In a broader sense, results are also applicable to sedimentary basins elsewhere with comparable geological settings, typically sandstones with similar framework mineralogical composition and depositional environment.

This work has been funded in part by the Trias North project “Reconstructing the Triassic Northern Barents shelf; basin infill patterns controlled by gentle sags and faults” (www.mn.uio.no/triasnorth/) under grant 234152 from the Research Council of Norway (RCN). Tullow Oil Norge, Lundin Norway, Statoil Petroleum, Edison Norge and RWE Dea Norge have also provided financial support.

The primary research objectives were to:

- Find out whether or not the formation of grain-coating clay minerals on clean detrital quartz and feldspar surfaces without precursor clay minerals is possible under laboratory experimental conditions (**Paper I**).
- Examine how diagenesis and reservoir quality are linked to depositional facies (**Paper II**).
- Investigate the factors controlling the abundance and occurrences of clay minerals in sediments (**Papers II and I**).
- Understand the impacts of the volume of clay fraction on the mode of occurrence of detrital grain-coating Fe-rich chlorite (**Paper II**).
- Evaluate the thermal history of the Triassic rocks by applying multi-method approaches such as chemical indices, the authigenic mineral assemblage, and fluid inclusion microthermometry (**Paper III**).
- Discriminate sill-induced diagenesis from normal diagenesis through burial-heating using carbon and oxygen isotopes, diagenetic signatures, Rock-Eval pyrolysis Tmax and other associated parameters, fluid inclusion microthermometry and vitrinite reflectance (**Papers III and IV**).
- Study the effect of sill-induced diagenesis on sandstone reservoir properties (**Paper IV**).

Study area and data

The study area is located in NW parts of the Barents Shelf, and comprises outcrop belts of De Geerdalen Formation on Edgeøya, and De Geerdalen Formation and Wilhelmøya Subgroup at Wilhelmøya (Figs. 2 and 3). Edgeøya and Wilhelmøya are located within the eastern part of Svalbard (Fig. 2), which represents a part of the Barents Sea uplifted during Cenozoic times (Faleide et al., 1993; Worsley, 2008). The exposed Triassic successions are divided into the Lower-Middle Triassic Sassendalen Group and the Upper Triassic Kapp Toscana Group (Mørk et al., 1999). The Sassendalen Group comprises Vikinghøgda and Botneheia formations while the Kapp Toscana Group includes sediments categorised into the Tschermakfjellet Formation, the De Geerdalen Formation and the Wilhelmøya Subgroup (Fig. 3). Onshore sedimentological and sequence stratigraphic investigations have been conducted on Edgeøya and Wilhelmøya because they encompass excellent outcrop analogues to potential petroleum reservoirs in the Barents Sea (Lord et al., 2017; Lord et al., 2014; Mørk et al., 1999). The De Geerdalen Formation and the Wilhelmøya Subgroup are considered useful analogues to the Barents Sea

Snadd Formation and Realgrunnen Subgroup sandstones, respectively. These sandstones are known for their potential as reservoir rocks (Klausen et al., 2015; Mørk et al., 1999).

The sedimentary successions exposed on Edgeøya and Wilhelmøya were intruded by dolerite sills in Early Cretaceous times (Nejbert et al., 2011). The exposed outcrops are therefore considered a natural laboratory for examining the impact of the Early Cretaceous magmatism and the Cenozoic uplift, and subsequent erosion, on reservoir quality and source rock maturity (Faleide et al., 1996; Henriksen et al., 2011; Maher Jr, 2001; Nejbert et al., 2011; Senger et al., 2014b). The uncertainty in source rock, reservoir rock and cap rock quality and distribution for the NW Barents shelf is high compared to the SW Barents Shelf (NPD, 2017). For that reason, there is a common consensus among academic institutions, oil companies and governmental organisations to collect more data and to increase our understanding of this petroleum exploration target region (Abay et al., 2017; Blaich et al., 2017; Gautier et al., 2009; Henriksen et al., 2011; Johansen et al., 1992; Lerch et al., 2016; NPD, 2017; Ohm et al., 2008; Worsley, 2008). Furthermore, new discoveries in recent years, such as Johan Castberg, Wisting and Alta/Gotha, bring optimism and encourage petroleum exploration activity. 50 % of the undiscovered Norwegian petroleum resources on the Norwegian Continental Shelf are still expected to be in the Barents Sea (NPD, 2016).

This study is based on two field surveys carried out in 2014 and 2015 at the outcrops of De Geerdalen Formation and Wilhelmøya Subgroup sediments in NW Barents Shelf, Svalbard. A total of 153 samples were collected from 17 localities on Edgeøya and Wilhelmøya and conventional sediment logs were recorded from nine localities. Apart from the reservoir rocks, samples also include rocks rich in organic matter from the Botneheia and Tschermakfjellet formations and coal samples from the De Geerdalen Formation.

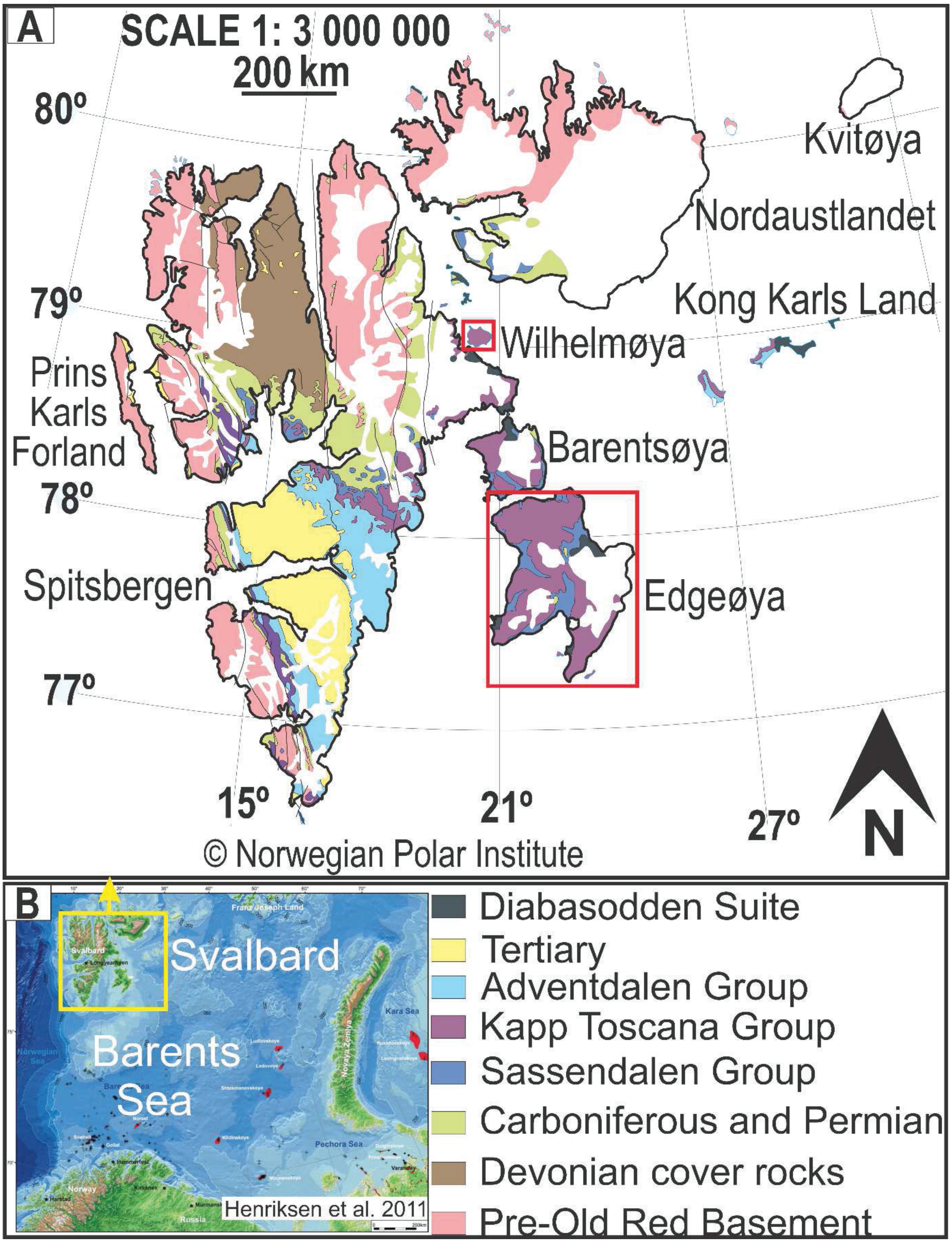

Figure 2: A) The geological map of Svalbard shows the major stratigraphic units. Edgeøya and Wilhelmøya, the focus of this study, are marked with red rectangular boxes. B) Inset map showing an overview of the position of Svalbard in relation to the Barents Sea. Svalbard is

outlined by the yellow rectangle in the inset map. The inset map is modified from Henriksen et al. (2011).

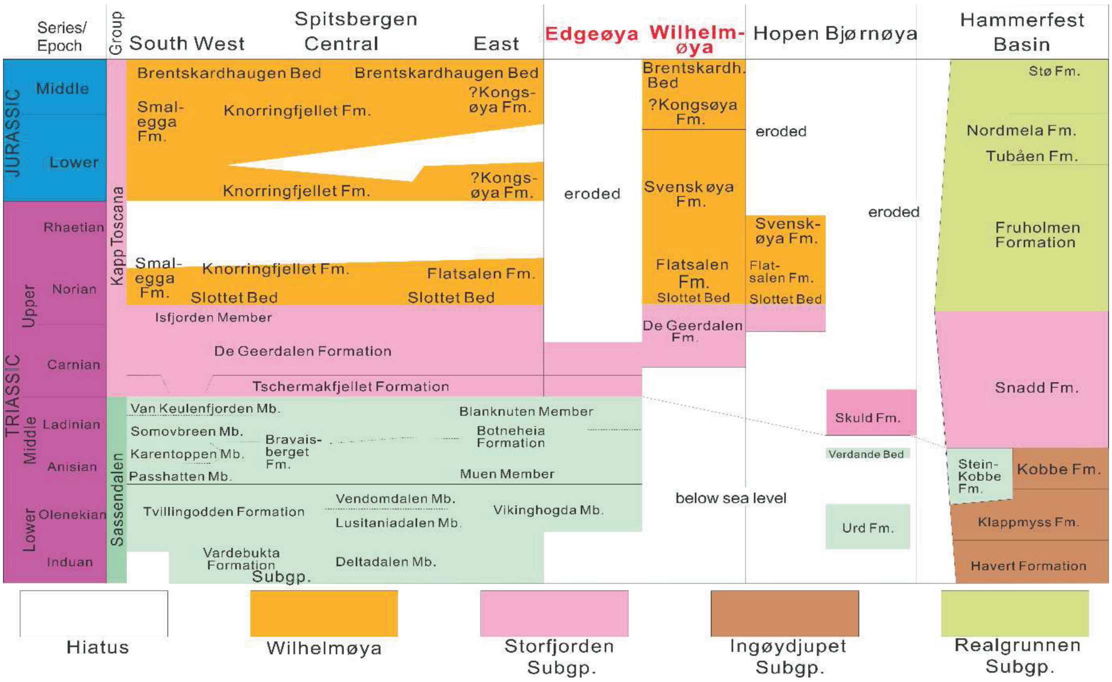

Figure 3: Generalised lithostratigraphy of the Triassic to middle Jurassic successions at various locations across Svalbard and the Barents Sea. Modified from Mørk et al. (1999).

Scientific background

The world energy market is currently in a transition from fossil-fuel based into renewable, but an increasing global population and rapid development in emerging economies will still require supply of oil and gas in the decades to come (Dorian et al., 2006). The energy demand is the key driver for studying diagenesis in coarse siliciclastic sediments within both academia and industry. Diagenetic processes and products significantly influence the reservoir quality in sandstones at shallow and deep burial depth. Depositional processes, modes of occurrences of clay minerals, thermal history of the basin, provenance, initial sediment texture, and composition, determine the initial porosity and permeability. The initial porosity and permeability of the rocks generally decrease with increasing intensity of diagenesis during progressive burial as a function of primary depositional environment. Appropriate interpretation of depositional environment of the reservoir rocks that employ various observable things including sedimentary structures is thus very important. Sedimentary structures recorded in the rock provide information about the extent and geometry of the reservoir. Moreover, the arrangement pattern of framework grains into specific sedimentary structures affects reservoir quality. These depositional structures are also modified by diagenesis, starting at the onset of deposition. Understanding this complex array of interrelationships (Fig. 1) between these attributes, reservoir quality, diagenesis and depositional environment, contributes to the characterisation of reservoirs and for the prediction of their quality before drilling. In the following section, these reservoir quality-controlling parameters will be discussed in detail.

Sedimentology and facies analysis

Sedimentology is primarily associated with the identification of sediment depositional processes and thus categorisation of depositional environments from recorded evidences in the rock record. Sedimentology and analyses of sedimentary facies are fundamental to recognising and mapping sedimentary environments. The description of sedimentary strata into facies and facies associations and characterisation of stratigraphic intervals is used to interpret depositional environments. This aids in developing the sequence stratigraphic framework to better understand reservoir quality development. Depositional environment preserved in the sedimentary record is recognized based on sedimentary structures, trace fossils, colour, lithology, composition, bedding characteristics, biogenic content and grain size. Sedimentary facies studies include identification of visually distinguishable lithological components of sedimentary deposits and sedimentary structures to examine the vertical and lateral extent of a sediment body. The relative dominant depositional processes such as fluvial, tidal and wave considerably affect the morphology and distribution of sand bodies within a given depositional environment, leading to variations in depositional facies (Figs. 4 and 5).

The various sedimentation processes, sedimentary facies characteristics and sand-body geometry are useful to depict the diagenetic processes controlling reservoir quality (Bjørlykke, 2014; Morad et al., 2000; Nyberg and Howell, 2016; Worden, 2000). First and foremost, understanding how these sedimentary facies packages or stacking patterns formed in a stratigraphic record is essential.

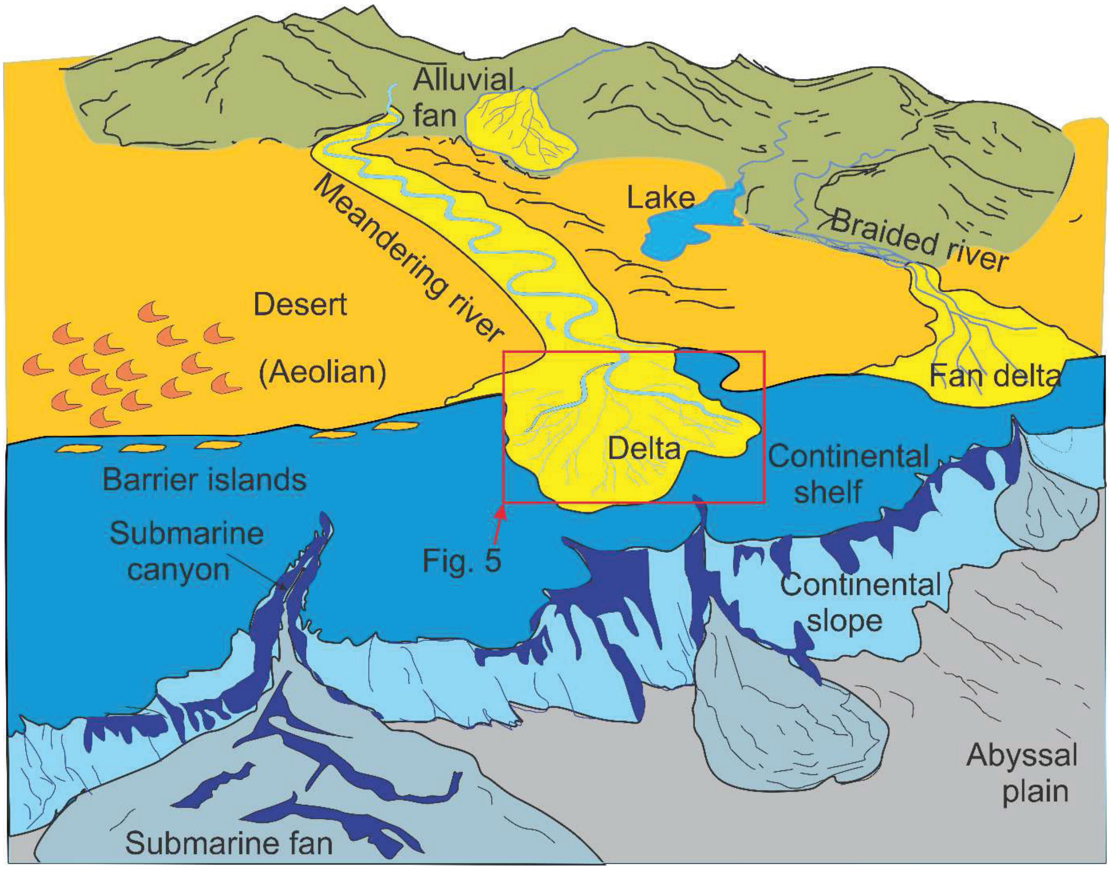

Figure 4: Schematic representations of various depositional environments. Variations in depositional facies due to the prevailing sedimentary processes and parent material can characteristically result in significant differences in the intensity of burial diagenetic reactions and ultimately reservoir quality distribution within a sandstone sequence (modified from Bjørlykke, 2014).

Figure 5 shows an example of the distribution of different types of diagenetic alteration of sedimentary rocks in a deltaic setting. The spatial distribution patterns of diagenetic alterations and reservoir quality vary as a function of discrete depositional facies. This indicates that breaking down the gross depositional environment strengthens our current capabilities to make predictions of siliciclastic rock properties in the subsurface (Bjørlykke, 2014).

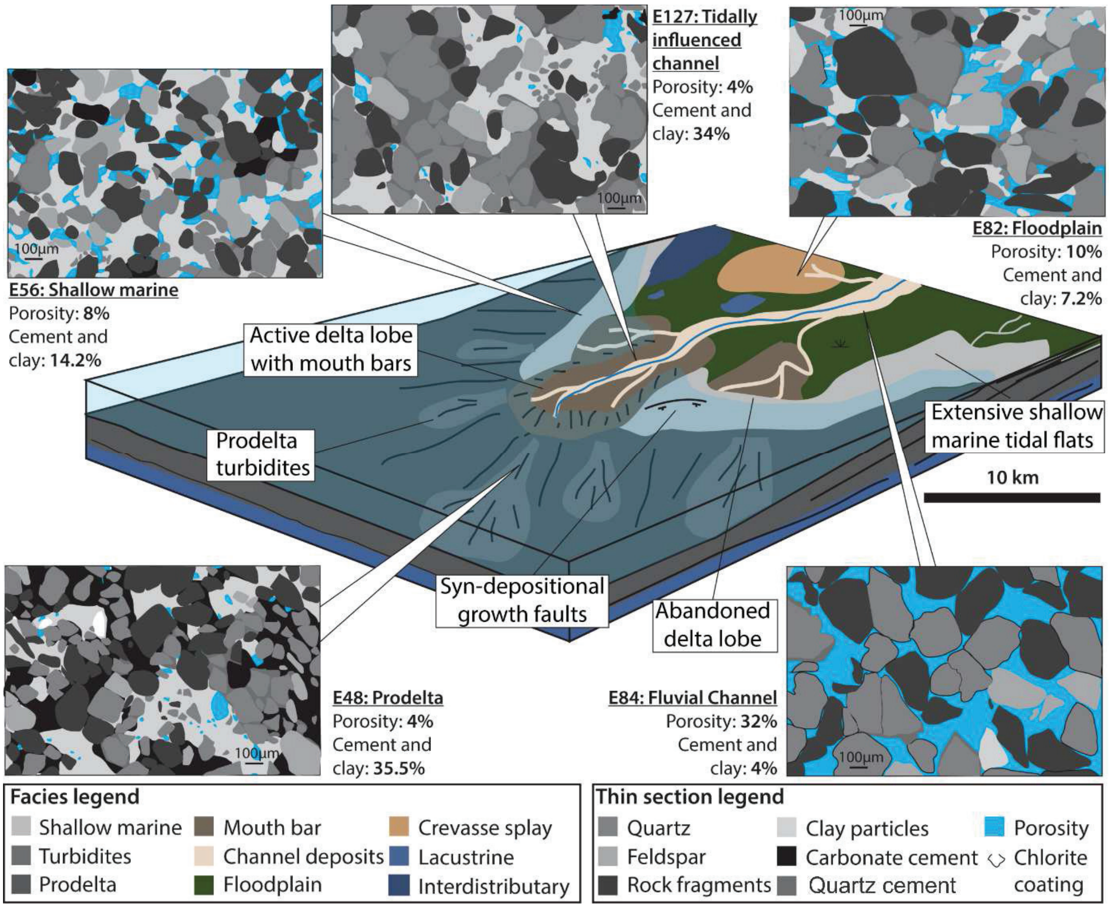

Figure 5: Representation of the distribution of diagenetic signatures, specific depositional environments and sediment composition in a deltaic setting. It shows the advantage of breaking down the gross depositional environment of a deltaic setting for predicting reservoir quality distribution (Haile et al., 2017).

Diagenesis

Diagenesis refers to mechanical, chemical and biological processes that transform sediments into consolidated rock at the onset of sediment deposition. A complex array of geological parameters controls diagenesis: parent material, sediment primary composition, climate, depositional environment, and temperature, to mention some among many (Figs. 1 and 6). The depositional setting probably exerts the most substantial control on sediment composition and therefore the diagenetic progression from early to deep burial diagenesis (Fig. 6). The sedimentation rate, depositional water chemistry, rock texture, biogenic activity and depositional facies strongly dictate burial diagenesis pathways. This implies that knowledge obtained from linking different parameters controlling diagenesis will facilitate our capability of predicting changes in reservoir rock properties during progressive burial of the sediments.

Mechanical and chemical compaction significantly influence the porosity development in reservoir sandstones. These processes result in considerable modification of reservoir quality in part or all of the sedimentary succession and thus greatly influence exploration activity. The driving force for mechanical compaction of sediments is the vertical effective stress which is imposed by overburden strata. Mechanical compaction leads to porosity decline and bulk density and velocity increases. Rock physical properties at shallow burial depth up to ~2-3 km are mainly dictated by mechanical compaction, however early carbonate cementation may cause total or partial porosity loss leading to lithification of siliciclastic sediments (Bjørlykke, 2014; Bjørlykke and Jahren, 2015). The depth could be less/greater than suggested here because it is temperature controlled and thus depends on the geothermal gradient and burial history (Bjørlykke and Høeg, 1997).

Chemical compaction becomes prevalent over mechanical compaction at burial depths of approximately 2-3 km and at temperatures of 60-80 ºC. Quartz cementation and a stiffening of the rock preventing further mechanical compaction lead to a sharp transition into a domain dominated by chemical compaction. The quartz cementation is associated with other diagenetic reactions occurring at the same time, such as illitisation or chloritisation of smectite, albitisation of K-feldspar, etc. (Walderhaug, 2000; Worden and Morad, 2000). Thermodynamics and mineral kinetics control the chemical compaction process and hence cement distribution in sedimentary basins. Burial diagenesis products are expressions of the depositional environment, primary sediment composition, parent rock (Figs. 4-6) and climate (Bjørlykke, 2014; Cox and Lowe, 1995; Johnsson, 1993). Studying the properties of sediments in the framework of the architecture of sedimentary facies is indispensable in order to understand the interrelationships between these complex arrays of parameters that influence burial diagenesis.

The relative importance of compaction versus cementation in porosity loss is evaluated by measuring the intergranular volume (IGV) (Houseknecht, 1987). IGV is the sum of intergranular porosity and cement as measured by point counting standard petrographic thin sections (Paxton et al., 2002). It is a useful method for describing the porosity evolution of sandstone reservoirs as a function of diagenetic changes. The only uncertainty linked to this method is the reference value of the original porosity. This initial porosity is largely dependent on the dynamics of the depositional process and textural characteristic such as sorting, size and shape of the grains. Even though some uncertainty is related to the standard initial porosity, the method has been proven to give reasonably reliable and reproducible results (Ehrenberg, 1995). As illustrated above, diagenesis and porosity have very complex relationships indicating that this problem demands an integrated approach (Morad et al., 2012).

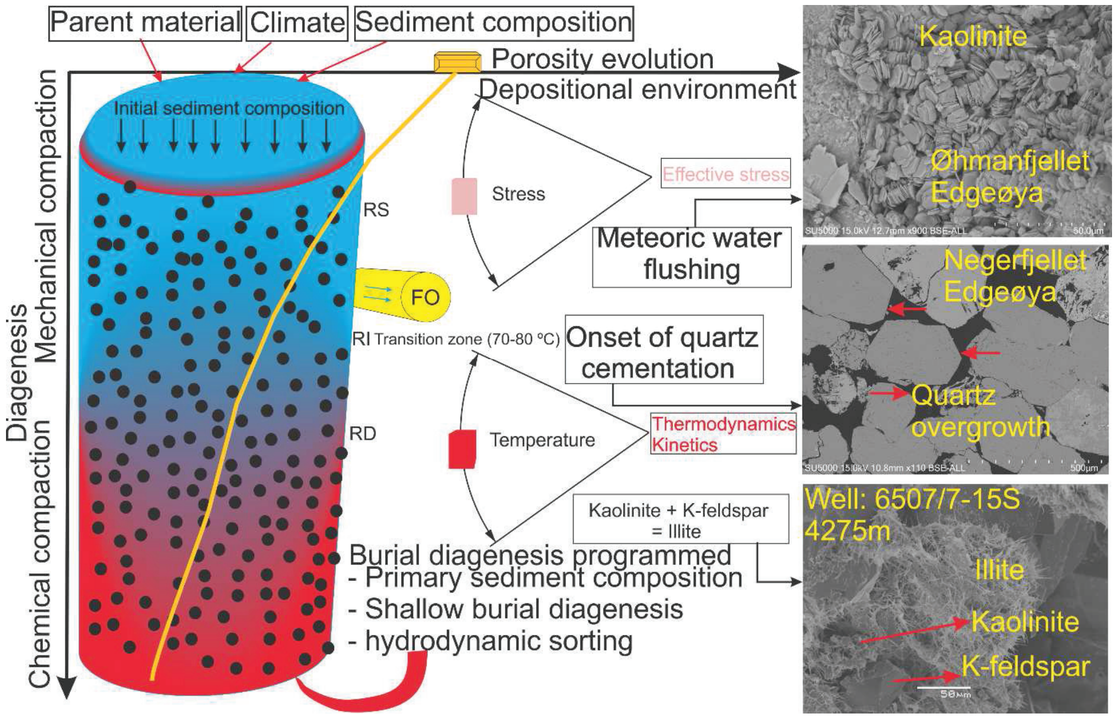

Figure 6: Burial diagenesis is typically programmed by parent material, sedimentary processes at various depositional environments, primary sediment composition and shallow burial diagenesis. (RS, RI, and RD = reaction at shallow, intermediate and deep burial environments, respectively, and FO = flux out)

Quartz cementation and grain coatings

Diagenetic processes such as mechanical compaction and quartz cementation are the most significant porosity reducing processes as function of depth through time in reservoir sandstones. Understanding porosity deterioration and factors that can preserve porosity to great burial depth is one of the major aims of diagenetic studies. Precipitation of quartz cement on detrital quartz grains is mostly considered as the most important porosity-occluding process in quartz-rich sandstones at elevated temperatures and greater burial depths.

Grain-coating materials may impede or prevent the nucleation of syntaxial quartz overgrowths on detrital sandstone grains, and hence preserve reservoir quality. The common grain coating clay minerals are chlorite, smectite and illite (Aagaard et al., 2000; Dowey et al., 2017; Ehrenberg, 1993; Haile et al., 2015; Line, 2015; Storvoll et al., 2002; Wooldridge et al., 2017). These grain-coating clay minerals play a central role for the presence of anomalously high porosity/permeability in deeply buried sandstones (Bloch et al., 2002; Warren and Pulham, 2001). Microcrystalline quartz coatings on detrital quartz grains, like clay minerals, has been known to preserve high porosity in deeply buried Upper Jurassic sandstones of the Central Graben area of the southern North Sea, Norway (Aase et al., 1996).

Grain-coating precursor berthierine or odinite and precursor clay minerals containing Fe and Mg like smectite are predominantly found in fluvio-deltaic sandstones (Dowey et al., 2012). Fe-rich precursor clay minerals are transformed into the most commonly reported grain coating chlorite at >90 ºC (Aagaard et al., 2000). This chlorite coating preserves reservoir quality by inhibiting the growth of quartz (Dowey et al., 2012; Ehrenberg, 1993). Sedimentary successions with high amount of mud intraclasts are susceptible to porosity and permeability reduction due to ductile deformation. In such type of sandstones, the clay mineral coatings do not have any significant effect on porosity preservation. It is thus crucial to understand the type, origin and abundance of these clay minerals as a function of sedimentary facies in sedimentary basins, and examine what will be the governing factors for their mode of occurrence, as either coatings or pore-filling, and hence whether they preserve or degrade reservoir quality. Coupling the presence of clay mineral coatings and other diagenetic signatures to depositional facies improves our ability to predict reservoir quality evolution and identification of the controlling parameters on reservoir quality and heterogeneity (Morad et al., 2010).

Experimental diagenesis

Knowledge about clay mineral diagenesis in sedimentary basins is key for understanding rock physical properties (Bjørlykke, 1998). Understanding the type, origin, abundance and occurrence of clay minerals in sedimentary basins is therefore crucial to predict where the good reservoir rocks can be found. Hydrocarbon exploration activity has produced huge amounts of data about the geology of sedimentary basins since the birth of sequence and seismic stratigraphy (Vail et al., 1977). Despite this vast dataset, our understanding of reservoir quality development in the light of clay mineral diagenesis in the sedimentary rocks is often very limited (Bjørlykke, 2014).

The subsurface diagenetic reactions can be simulated by performing experimental diagenesis in order to gain understanding about these multicomponent geochemical reactions. However, we need to be careful interpreting experimental results since experiments will not completely mimic natural conditions, but only provide useful realistic constraints and clues about complex and multicomponent geochemical systems. The data obtained from this type of study can be employed as input in geochemical modelling to enhance subsurface data and knowledge about the distribution and quality of potential reservoir sedimentary sequences before drilling.

Chlorite, illite, mixed layer illite/smectite and smectite coatings on detrital sediment grains are observed in natural settings (Dowey et al., 2012; Hansen et al., 2017; McKinley et al., 2003; Storvoll et al., 2002), but the reaction mechanisms and the main controlling parameters are still poorly understood. For that reason, a few experimental studies have been performed to complement natural observation and to understand the mechanism of clay mineral coatings at the surface of detrital sediment grains (Aagaard et al., 2000; Haile et al., 2015; Nadeau, 1998; Needham et al., 2005; Small et al., 1992). Furthermore, results from experimental diagenesis can be coupled with diagenetic modelling to understand more about the variables that control the mechanism of clay mineral coatings at the surface of detrital grains in the natural environment.

The morphology of experimentally formed clay coatings resemble naturally formed ones, indicating similar mechanisms responsible for their formation (Small et al., 1992). This has important implications. Firstly a cautionary signal, particularly when analyzing authigenic clay minerals forming in sedimentary basins. These authigenic clay minerals may have formed due to normal burial heating or high temperature induced heating. This may have considerable consequence in using temperature sensitive diagenetic signatures because clay mineral diagenesis is used to acquire information on the burial and thermal history of sedimentary rocks (Cathelineau and Nieva, 1985; Pollastro, 1993). Secondly, if properly performed, experimental diagenesis can be used to identify more accurately and in a definitive manner the main factors controlling the processes of formation of clay coating on the surface of detrital grains (Small et al., 1992). Such a study will help to identify the major controlling element for the formation of clay mineral coatings on the surface of grains.

Magmatic heat induced diagenesis

Intrusive sill complexes have impacts on petroleum systems both at regional and local scales (Aarnes et al., 2010; Senger et al., 2014b). Triassic sedimentary rocks in NW and East Barents shelf are intruded by varying thickness of Cretaceous igneous sills (Nejbert et al., 2011; Polteau et al., 2016; Senger et al., 2014a). This magmatic activity covers approximately 900,000 km^2 in these parts of the Shelf (Fig. 7) and hence presents an important geological risk in petroleum exploration activity (Polteau et al., 2016).

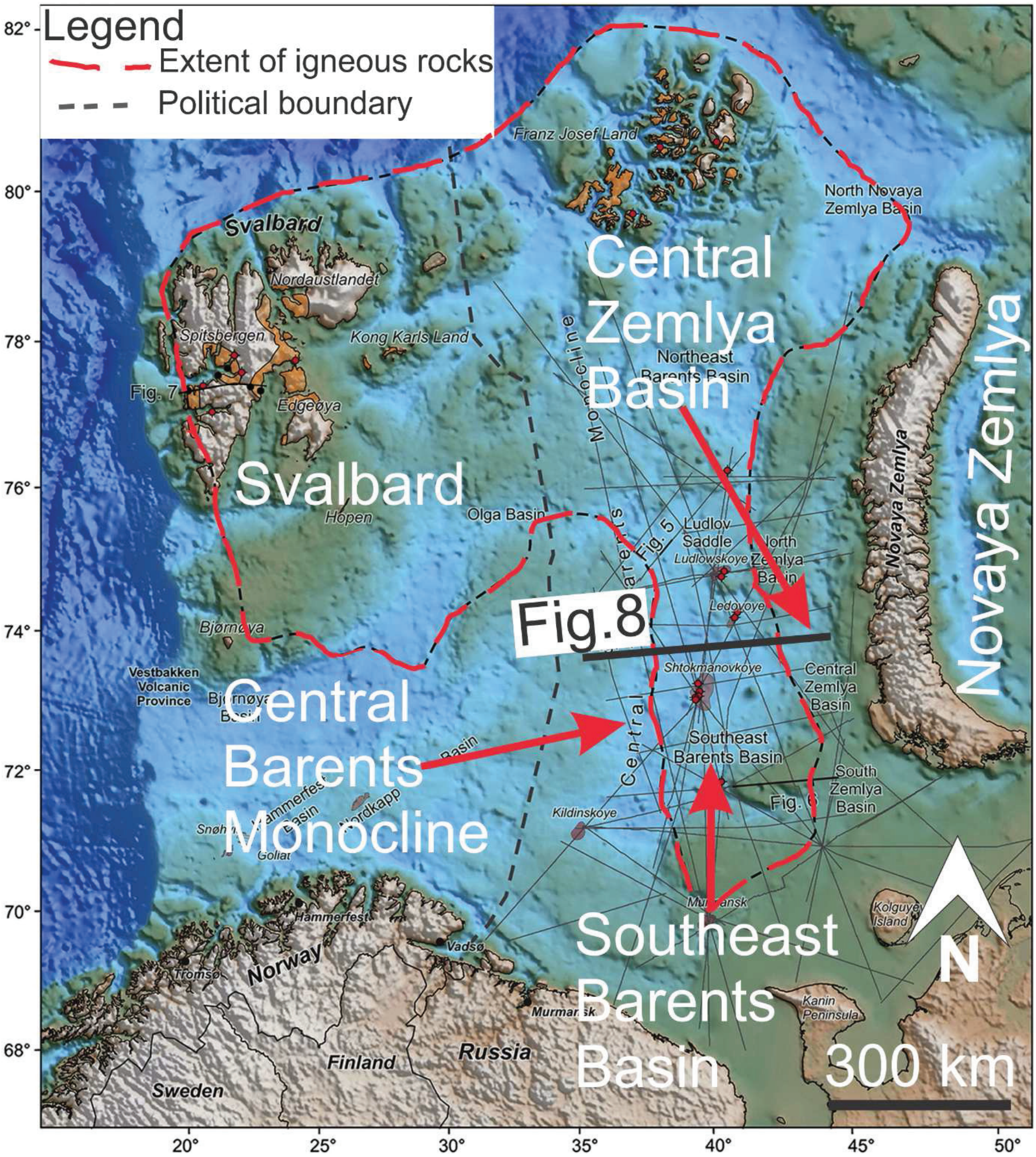

Figure 7: Map showing the distribution of the Cretaceous igneous sills both onshore and offshore in the Barents Sea Shelf. Modified from Polteau et al. (2016).

The increasing shift in the focus of hydrocarbon exploration from the southwestern Barents Shelf towards the northwestern and eastern Barents Shelf demands a better understanding of the impact of this magmatic activity on the quality and distribution of source rocks rather than reservoir rocks in this area (Abay et al., 2017; Brekke et al., 2014). Therefore, an improved understanding of whether the impacts of igneous activity on both reservoir and source rocks are beneficial or detrimental is important for reducing exploration uncertainties.

The influence of igneous intrusion in sedimentary basins on the maturity of source rocks and the quality of reservoir rocks, is associated in most of the literature with contact metamorphism (Brekke et al., 2014; Mckinley et al., 2001; Senger et al., 2014a). However, a few studies have indicated that intrusion of igneous rocks into the prospective sedimentary basins has resulted in the formation of hydrothermal convection cells that have possibly affected reservoir quality (Einsele et al., 1980; González-Acebrón et al., 2011; Holford et al., 2013). Predicting the spatial and temporal distribution of diagenetic alterations in siliciclastic successions, and separating the contributions of normal burial heating from those induced by the sill intrusions, is a challenging exercise (González-Acebrón et al., 2011). Sill intrusions can also result in compartmentalisation of significant volumes of basin stratigraphy. Examples of igneous intrusions within the Triassic and Permian section recorded in seismic data from the Barents Shelf is shown in Figure 8. Compartmentalisation can significantly influence fluid migration pathways in sedimentary basins, in addition to affecting source rock maturity and reservoir quality.

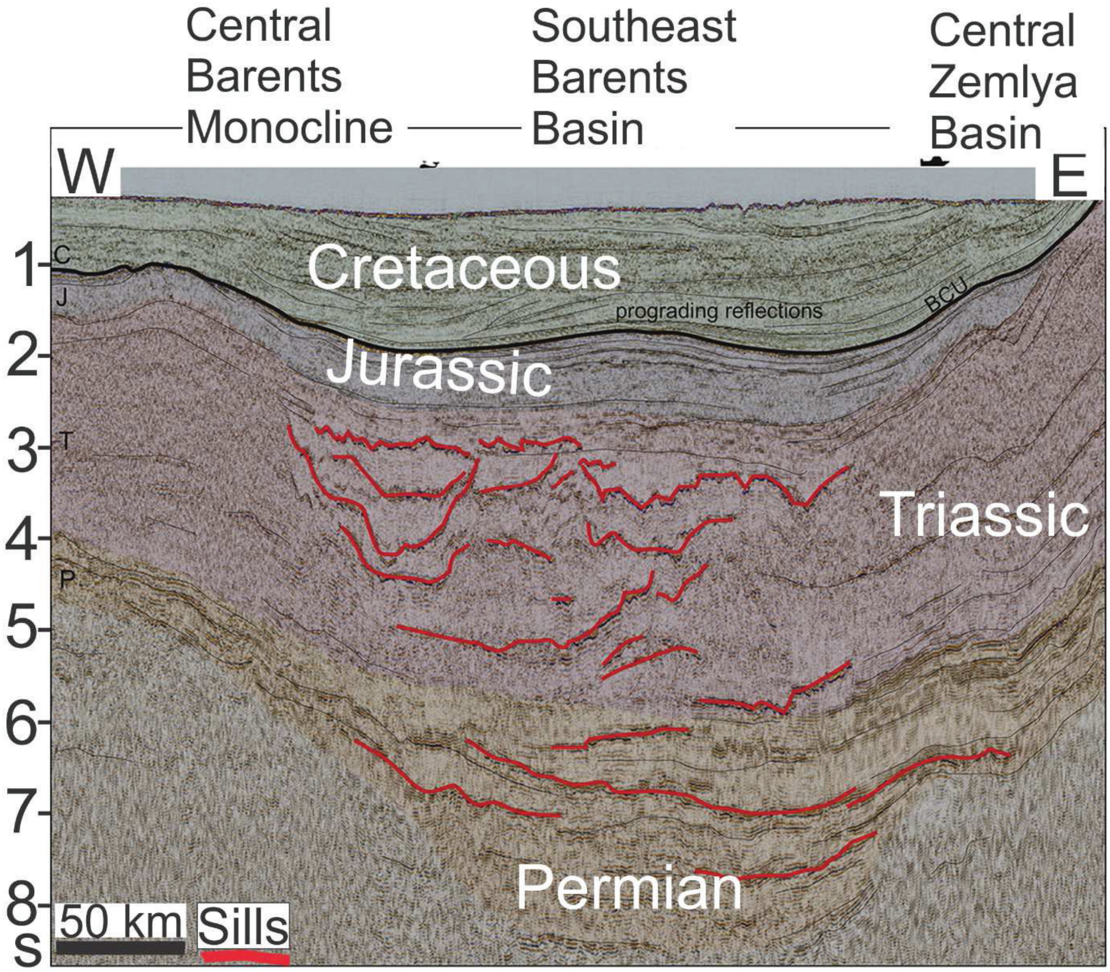

Figure 8: The seismic profile across the central Barents monocline, southeast Barents Basin and central Zemlya Basin. See Fig. 7 for location. This seismic line illustrates the spatial and temporal distribution of extensive igneous sills in the Mesozoic sedimentary strata. Modified from Polteau et al. (2016).

General descriptions of the work

This thesis contains four papers that deal with chemical diagenesis and how it links to the depositional environment. The **first paper** presents an experimental diagenesis study on the formation of clay coatings on clean surfaces of quartz and feldspar, i.e. without precursor clay phases. The **second paper** presents links between diagenesis and sedimentology to reveal reservoir quality evolution and the factors that control the formation of clay mineral coatings in a natural diagenesis setting. The **third paper** presents the importance of linking source and reservoir rock geothermometers in the stratigraphic record for unravelling the thermal history. The **last paper** investigates the implication of sill-induced diagenesis on reservoir quality.

Papers details

The following section summarises the main findings and conclusions presented in the papers. A complete version of each paper is included in enclosures 1-4.

Paper I

Experimental nucleation and growth of smectites and chlorite coatings on clean feldspar and quartz grains surfaces (*published in Marine and Petroleum Geology*)

This paper presents laboratory experimental evidence of the formation of grain-coating smectites and chlorites on clean quartz and feldspar grains. Authigenic chlorite and smectite are common authigenic minerals in sandstones. It is known that the presence of such types of clay minerals in the form of coatings inhibit quartz overgrowths in siliciclastic sandstones. They hence act to preserve anomalously high porosity at deep burial depth. Many studies have looked at the origin of authigenic clay formation, but the required conditions and mechanisms of formation are still not fully understood. Most studies have suggested that alteration of precursor clay minerals is required for the formation of the chlorites and smectites, whereas formation on clean sandstone grains has been found unlikely.

The aim of this study was to experimentally investigate if direct nucleation and growth of smectites and chlorites on clean feldspar and quartz surfaces was possible. The experiments were performed at 100 and 150 °C using artificial formation waters with Mg-concentrations in the upper range of North Sea brines and with varied pH and carbonate content. The experiments were run for 21-50 days in batch reactors. Raman spectroscopy and SEM/EDS were used to examine the clay-coats and the geochemistry software PHREEQC v3 was used to calculate *in situ* mineral saturation indices. The experiments suggest that the silica activity is the main factor determining whether grain-coating smectites or chlorite form. The clay minerals formed easily both on clean quartz and feldspar surfaces, but chlorite coatings were formed only on feldspar surfaces while smectite coatings were formed on both feldspar and quartz. The chlorite morphology varies between honeycomb, edge-to-face and rosette patterns, while all smectite formed with honeycomb-like textures. The secondary clay coatings are morphologically similar to naturally occurring diagenetic clay minerals. The study suggests that the nucleation of clay coatings in nature may be possible even on clean quartz and feldspar surfaces. There may however be a possibility that pre-existing clay minerals in natural systems prevent high aqueous supersaturations and thereby reduce or inhibit the formation of the grain-coating phases on clean reservoir minerals. This must be further examined.

Main findings and conclusions:

- The experimental results strongly indicate that clay mineral coatings can be formed on the surface of different substrates by varying the pH, temperature and supersaturation.
- In natural sediments and sedimentary rocks, it is commonly believed that the formation of clay coatings is promoted by pre-existing clay mineral drapings on the mineral grains. However, this study demonstrates that grain-coating smectites and chlorites can form on clean feldspar and quartz surfaces at 100-150 ºC, given sufficient supersaturation and time.
- K-feldspar was the source of Al and silica for clay mineral overgrowths. Excess supply of silica due to quartz dissolution in addition to feldspar facilitated the growth of smectite rather than chlorite.
- The hydrothermally formed clay coatings, smecite and chlorite, have similar morphology to naturally occurring clay coatings. This suggests similarity in the reaction mechanism for the development of clay coatings in the hydrothermal and burial heated systems. This indicates the importance of performing laboratory experiments to characterise clay coat formations in sedimentary basins. Moreover, this improves our knowledge related to the variables controlling clay overgrowths in sedimentary environments.
- The effects of the substrates were two-fold: (1) providing surface areas for nucleation of the clay particles; and (2) providing elements required for the clay growth such as Al, Si and K. The low solubility of aluminum around neutral pH conditions suggests that local supply rates of aluminum and spatial diffusive transport may control clay growth in sedimentary rocks.

Paper II

How are diagenesis and reservoir quality linked to depositional facies? A deltaic succession, Edgeøya, Svalbard (*published online November 16, 2017 in the Journal of Marine and Petroleum Geology*)

The relationship between depositional facies and diagenesis in a deltaic succession of Triassic reservoir sandstones at Edgeøya, Svalbard, was investigated. This succession consists of time-equivalent rocks to those in the Barents Sea. It has been difficult to predict the reservoir quality of these Barents Sea sandstones. Investigating the distribution of diagenetic alteration in a depositional facies context is seen as vital to improve the predictability. Our study improves the current understanding of reservoir potential within deltaic sandstones by linking depositional facies with diagenesis and their impact on reservoir quality.

Mechanical compaction was the main cause of porosity destruction in the channel, shallow marine and floodplain samples, while early carbonate cementation occludes the intergranular volume in the prodelta samples. Depositional setting within a deltaic to shallow marine system does not exert a strong control on the abundance of chlorite, but it does influence whether the chlorite is pore-filling or grain-coating and porosity-preserving. Efficient chlorite coating has aided in preserving porosities up to 32% in the well sorted medium grained sandstones deposited in fluvially dominated channels.

Main findings and conclusions:

- ❑ Diagenetic signatures that control the quality of reservoir rocks vary systematically as a function of depositional facies. This is because the sediments that belong to different depositional facies respond differently to burial diagenesis.
- ❑ Mechanical and chemical compaction is conspicuous in the floodplain, channel and shallow marine depositional facies. However, mechanical compaction was the main cause of porosity destruction in these facies.
- ❑ Carbonate cements are the prevalent porosity-occluding cements in prodelta depositional facies and occasionally also in the shallow marine facies. Quartz cements and locally carbonates principally occlude the porosity of the shallow marine depositional facies.

- In general, variation in the extent of chlorite coatings is noted as a function of depositional facies, grain size, sorting, and percentage of clay fraction. Chlorite is abundant in comparable concentrations in all of the depositional facies, but its mode of occurrence varies markedly. The well to very well sorted, medium to fine-grained channel depositional facies sediments are noticeably characterised by well-developed continuous grain-coating chlorite, whereas the floodplain sediments have only minor and patchy coatings. Grain coatings are absent in the shallow marine and prodelta sediments.
- This study shows that sorting does not exert a strong control on the abundance of chlorite but it does on the mode of occurrence. The well to very well sorted medium to fine-grained sediments of the channel depositional facies display the best reservoir quality (φ = 18 % to 32 %).
- In general, sedimentary depositional processes influence sediment grain size and sorting and consequently the modes of occurrence of chlorite in the sediments, and finally the reservoir quality.
- In general, this study illustrates that predicting reservoir quality of sediments in a deltaic setting can be better delineated by linking diagenesis with depositional facies.

Paper III

Thermal history of a Triassic sedimentary sequence verified by a multi-method approach: Edgeøya, Svalbard, Norway (in press, accepted manuscript *in the Journal of Basin Research*)

This study offered a new and improved thermal history evaluation of Triassic rocks from Edgeøya, Svalbard. Previous burial estimates of the Triassic rocks on Svalbard are based solely on source rock maturation data. The source rock maturation may have been affected by late Mesozoic magmatism, and there is therefore uncertainty in estimated burial depths and later uplift. The aim of this project was to provide more accurate temperature estimates by utilising a broader data set including source rock maturity parameters, reservoir rock diagenesis overprints, and fluid inclusion microthermometry in diagenetic quartz. Rock-Eval pyrolysis data indicates that the De Geerdalen Formation experienced burial temperatures of ≥ 92 °C.

This is further supported by the presence of a mixture of authigenic kaolinite and dickite, implying that the sediments have been subjected to temperatures > 90 ºC. The underlying strata, Tschermakfjellet and Botneheia formations, experienced burial temperatures of about >124-138 °C. Fluid inclusions in authigenic quartz indicated that De Geerdalen Formation sandstones have been subjected to a maximum burial temperature of around 124 ºC. This is consistent with the absence of illlite formation associated with kaolinite since the temperature did not exceed 130 ºC. This study illustrates that fully integrating chemical indices, mineral indices and fluid inclusion data will aid in assessing the quality of temperature proxies and thus constrain the thermal history of any basin.

Main findings and conclusions:

- The indicators of thermal maturation, HI and Tmax (430-455 ºC) and the calculated vitrinite reflectance (0.58-1.03) indicate that all the Triassic source rocks were within the oil generation window during maximum burial. This is consistent with the identification of temperature sensitive intermediate burial depth authigenic minerals in the studied succession such as dickite, ankerite, illite from smectite, and chlorite.
- Production index related to Rock-Eval Tmax are appropriate thermal elements to discriminate igneous sill induced thermal impacts from burial heating. Unlike the study area, sill induced thermal signatures were recorded in the samples obtained from the Reddikeidet and Muen sections located in the northwestern part of Edgeøya.
- Kaolinite to dickite transformation indicates that De Geerdalen Formation sandstones have been subjected to temperatures above 90 ºC but ≤ 124 ºC based on the fluid inclusion temperature in quartz. Likewise, the sedimentary rocks do not reveal any evidence of diagenetic reactions like kaolinite to illite occurring above 120-130 ºC.
- Chemical indices coupled with mineral indices showed a very good match. This implies that even though the sedimentary basin has been subjected to magmatic activity and multiple uplift and consequent erosion, it is possible to constrain its thermal history reliably. Furthermore, this multi-method approach provides the best cross-checking and testing platforms between different geothermometers regarding the trustworthiness of each method. Such type of an integrated approach is also very beneficial for analysing

the thermal history of a basin, especially when sedimentary strata with organic matter are present butt lack vitrinite for reflectance measurements.

- Results of this study suggested that magmatism could have significant effect on the maturation of organic material, while little or no effect on the diagenetic products such as quartz cementation associated with reservoir rocks. Therefore, authigenic quartz overgrowth can be used to distinguish normal burial temperatures from magmatic heat. This may be due to quartz cementation being too slow to record the effects of the relatively short magmatic heating event, compared to the organic matter.

Paper IV

Hydrothermally induced diagenesis: Evidence from shallow marine-deltaic sediments, Wilhelmøya, Svalbard (in press, a*ccepted manuscript in Geoscience Frontiers*)

This study represents new insights about hydrothermally driven diagenetic changes due to the emplacement of magmatic sills into potential reservoir sediments at Wilhelmøya (Svalbard) and its implications in reservoir quality evolution. This locality is an excellent natural laboratory to study the effect of sill intruding permeable, largely uncompacted and unconsolidated, sediments. Dolerite sill intrusions in the studied area are of limited vertical extent, ~12 metres thick, but there are indications that they created localised hydrothermal convection cells affecting sediments at considerable distance from the intrusions such as more than five times the thickness of the sill.

Based on the evidence presented in this study, the sedimentary sequence can be divided into two thermal regions: 1) burial heating with a maximum burial temperature lower than 60-70°C; and 2) sill-induced heating within and below thinner carbonate cemented intervals that have experienced hydrothermal temperatures around 140°C. Hydrothermally induced high temperature diagenetic alteration products affecting the porosity and hence reservoir quality were not detected in the burial heating region of the reservoir intervals. However, sill induced diagenesis was distinguished preferentially along calcite cemented flow baffles. These layers revealed high temperature hydrothermal induced reactions such as recrystallisation of carbonate cements, localised sericitisation of feldspars, albitisation of both K-feldspar and plagioclase, and formation of fibrous illite nucleated on kaolinite. These sill induced diagenetic signals infer hydrothermal alteration at T >120-140 °C at distances considerably further away than expected from dissipation of heat by conduction only, which commonly affect sediments up to twice the thickness of the sill intrusion.

Main findings and conclusions:

- Magmatic sill intrusions have affected the carbonate cemented sandstone intervals both close to the sill ~1 m and ~65 m away from the sill intrusion. High temperature igneous sill induced diagenesis signatures were recorded in these thin carbonate cemented sedimentary intervals considerably further away, up to more than five time the thickness of the sill, than expected by conduction only. Heat dissipation by conduction commonly affects sediments up to twice the thickness of the sill intrusion. The carbonate layers are interpreted to represent original flow baffles controlling and focusing convective hot brine mobilised by the magmatic heat.
- Hydrothermal fluids selectively influence reservoir quality. The sedimentary strata under investigation showed diagenetic signature stratification: 1) burial diagenesis lower than about 60-70 °C; and 2) sill induced diagenesis around 140 °C due to hydrothermal fluid flow. The sill induced hydrothermal fluid does not appear to affect the reservoir quality of the sedimentary sequence outside the thin calcite cemented sedimentary layers.
- The sedimentary succession on Wilhelmøya has never been deeply buried. The effects of the hydrothermal alteration were therefore easily distinguished from the background low-temperature diagenesis alteration. This study thus provides information of how hydrothermal alterations can be discriminated from burial diagenetic alterations in sandstones.

Summary and Main messages

There are many excellent published works that describe the Triassic sedimentary sequences on the Barents Shelf in terms of sedimentology, sequence stratigraphy, tectonic and depositional environments (Glørstad-Clark et al., 2011; Glørstad-Clark et al., 2010; Klausen and Mørk, 2014; Lord et al., 2017; Lord et al., 2014). However, this work presents for the first time a detailed and comprehensive study of the diagenesis and reservoir quality evolution of the De Geerdalen Formation and Wilhelmøya Subgroup from Edgeøya and Wilhelmøya. Major factors controlling diagenesis and ultimately reservoir quality evolution in a deltaic setting were investigated. These factors include depositional facies, temperature, primary sediment composition, magmatic activity, and grain-coating clay minerals. The results of this thesis demonstrate that integration of sedimentology and diagenesis can be used to better understand reservoir quality evolution in sandstones as a function of burial.

Experimental diagenesis was performed to add information in order to develop a better understanding of clay mineral formation in relation to available substrates (**Paper I**). The study clearly indicated the possibility of forming clay mineral coatings on the surface of clean detrital grains without precursor clay phases (**Paper I**). The formation of clay mineral coatings was controlled by silica activity and the pH of the solution (**Paper I**). This result illustrates the need to investigate thoroughly and cautiously the mechanism of clay coating formation in natural settings. Even though clay minerals are present only in small amounts of the total rock volume, they may have profound impact on reservoir quality evolution either positively or negatively, depending on their mode of occurrence (**Paper II**).

The distribution of diagenetic patterns and styles is constrained by breaking down the deltaic depositional setting into its component parts or sub-environments rather than considering the gross depositional environment (**Paper II**). This clearly provides a powerful tool to predict clay mineral distribution, modes of occurrences of clay minerals as pore-filling or pore-lining and distribution of diagenetic alterations controlling reservoir heterogeneity and quality across a given depositional system. In order to better understand the interlinking between depositional facies and modes of occurrences of chlorite coatings in sandstones more case studies should be performed. The integration of depositional facies and diagenesis will clearly improve our capability to predict the evolution of clay minerals during burial resulting into either deterioration or preservation of anomalously high porosity. However, such studies should be associated with well-constrained thermal history investigations (**Paper III**) and knowledge of initial rock composition and early burial diagenetic alterations (**Paper II**).

In this work systematic variation in diagenetic signatures as a function of depositional facies was observed (**Paper II**). This indicates that the best reservoir quality in a deltaic setting could be predicted with knowledge on the distribution of diagenetic signatures, specific depositional facies, and primary sediment composition (**Paper II**). The clay mineral contents and the volume percentage of clay fraction differences found within each depositional facies may have resulted in facies-dependent differences in mechanical and chemical compaction processes during burial and thus reservoir porosity variations (**Paper II**).

The effect of sill induced hydrothermal convecting fluids with respect to alteration involving the framework grains is an important factor to consider for predicting porosity evolution in sedimentary basins. Such sill induced diagenesis was observed in parts of the sedimentary sequence of Wilhelmøya (**Paper IV**). Based on all the evidence, two diagenetic stratigraphic zones were distinguished: 1) uncemented layers which had experienced burial temperatures of around 60-70 °C; and 2) thinner carbonate-cemented layers which had experienced hydrothermal temperatures of around 140 °C, based on their respective diagenetic signatures (**Paper IV**). The study presented here suggests that sill intrusions may affect the sediments by means of localised hydrothermal circulation systems at a considerably greater distance from sill intrusions than is the case with contact metamorphism or conduction. Conduction may affect sediments up to twice the thickness of the magmatic intrusion. This result is new. The bulk properties of the reservoir rocks, however, were not influenced as only pre-existing flow-baffles were affected by hydrothermal circulation (**Paper IV**).

To constrain the thermal history of a sedimentary layer with an integrated approach is important because temperature is the prime control on the quality of reservoir rocks and hydrocarbon maturation potential in source rocks. Knowledge of the thermal history of the basin is fundamental to reconstruct basin evolution. Moreover, it is required to calibrate and verify the modelled burial history trend curves in a given sedimentary basin. With regard to this matter, the maximum burial temperature (≤ 124 ºC) for the De Geerdalen Formation at Edgeøya was determined using different independent analytical methods. These methods included mineral indices, chemical indices, and fluid inclusion microthermometry in quartz overgrowth (**Paper III**). This temperature corresponds to about 2 to 2.5 km of uplift in the study area, which is in agreement with previous studies of regional uplift trends in the region.

Implications for hydrocarbon exploration in the Barents Sea

The Barents Sea Shelf represents a novel region for exploration in the Arctic. The geology of Svalbard is a window into the Barents Sea hydrocarbon province (Dallmann et al., 1993; Harland et al., 1997). This is because Svalbard has subaerially exposed Triassic successions that can serve as analogues for subsurface successions of the Barents Sea (Lundschien et al., 2014). This scenario seems likely since the De Geerdalen Formation at Hopen was a good analogue to the upper part of the Triassic Snadd Formation in the Barents Sea (Klausen and Mørk, 2014). Similarly, the sedimentary facies observed at Hopen are also similar to those observed at Edgeøya (Lord et al., 2014; Rød et al., 2014). Furthermore, the sandstone channel bodies recorded at Hopen are relatable to those observed in the Barents Sea Snadd Formation (Klausen and Mørk, 2014; Lord et al., 2014). Additionally, reconstruction of the deltaic environment during late Triassic showed the large-scale prograding deltaic system that gradually filled the present-day Barents Sea Shelf with sediments mainly sourced from the Uralian mountain chain (Bue and Andresen, 2014; Klausen et al., 2017; Klausen et al., 2015).

To sum up, the sedimentary sequences found onshore are analogues deposited in similar depositional environments and have similar sediment composition to the sequences found in the subsurface further to the south. Depositional environments and sediment composition are the most critical factors in order to use outcrops as analogues for subsurface successions (Bjørlykke, 2014). The aforementioned studies therefore suggested that the knowledge obtained from this study regarding the distribution of diagenetic alterations as a function of depositional facies in the Triassic sequences are likely comparable with the diagenesis found in the Snadd Formation located in the subsurface Barents Sea area.

In the deltaic depositional environment at Edgeøya, the main diagenetic alterations recorded were early siderite and calcite cements and late ankerite cementation, quartz cementation, pore-filling kaolinite formation due to leaching of both feldspar and mica, kaolinite dickitisation, and chloritisation. Similarly, the occurrence of burial-diagenetic quartz, chlorite, and ankerite that has been reported from the Snadd Formation has been buried to depths appropriate to lead to temperatures sufficient to form these phases (Line, 2015). Chlorite coatings preserving anomalously high porosity have been documented from the Snadd Formation (Line, 2015) although the occurrence of chlorite coatings in De Geerdalen Formation has not been highlighted previously. Late diagenetic chlorite is a phenomenon in the Snadd

Formation, related to the channel depositional facies (Line, 2015). Likewise, chlorite coating is noted in the channel depositional facies of the De Geerdalen Formation (**Paper II**).

It is thus worth speculating briefly on what the Snadd Formation would look like in terms of diagenesis and reservoir properties in sections both in shallow to deeply buried settings compared to in the DGF. Similarities observed regarding temperature sensitive diagenetic signatures lead to an inference that the Snadd Formation (~3.3 km) corresponding to well 7228/7-1A from Nordkapp Basin (Line, 2015) has been subjected to burial depth relatively similar to that of the De Geerdalen Formation (~3.1 km) from Edgeøya (**Paper III**).

Increasing the depth of the above sections by several hundred to a thousand meters may have relatively little effect on porosity and permeability in the chlorite coated channel facies sequences. This indicates that the chlorite coats would impose a significant effect in preserving anomalously high porosity in samples buried much more than the Snadd Formation's present day depth (Ehrenberg, 1993). There would be less ankerite than siderite and calcite in the less deeply buried sections, though the total quantity of carbonate likely be close to the amount found in the above-described studies. Decreasing the depth of section by several hundred to a thousand meters may have relatively little effect on average porosity and permeability since they are largely controlled by early diagenetic and depositional factors. However, the reduced volume of quartz cement would allow the cleanest sandstones perhaps to have higher permeability values than those found in the De Geerdalen Formation.

The northerwestern Barents Sea had been influenced by the extensive Cretaceous age magmatic activity of ~80-130 Ma (Nejbert et al., 2011; Senger et al., 2014b). Sill intrusions from that are common on both Svalbard and larger parts of Barents Sea North area. Therefore, a study investigating this phenomenon has significance for the exploration activity targeting the Triassic and Jurassic sedimentary sequences in the northwest Barents Sea. The results obtained regarding the effect of sill-induced diagenesis on reservoir quality from Wilhelmøya indicate that rock volumes further away than conventionally believed as due to convection may be affected by heat transfer when a sill is emplaced in a sedimentary sequence. Despite the indications of convective heat and fluid transport, the flow is only affecting a minor part of the reservoir i.e. the flow baffles and focused flow channels, and the effect on the bulk porosity/permeability is therefore likely low. However, this process requires more investigation from different localities to better constrain the vertical and lateral changes in the rock property around sill intrusions. If the hydrothermal convection cell heat dissipation mechanism as found at Wilhelmøya is also present at other localities in the area, care should be taken during exploration to quantify the effect of sills on expected reservoir properties not only in the Triassic strata at which sills are predominantly emplaced but also in the potential reservoir rocks of the overlying Jurassic strata.

Further Work

Several research questions were encountered during the course of this three-year PhD project; however, not all of them could be fully explored in this study. Therefore, some parameters controlling diagenesis and ultimately reservoir quality evolution of the clastic sediments studied should be addressed in future work:

Chlorite coating: As has been shown in this study, clay minerals certainly play an important role in sandstone diagenesis, and ultimately in reservoir quality evolution. Grain-coating clay minerals have a positive effect on porosity preservation while pore-filling clay minerals have a negative role. Understanding the mode of occurrence and abundance of these clay minerals and the controlling factors on the mode of occurrence and abundances at a given depositional environment are significant for clastic reservoir exploration. However, the major controlling factors for the modes of occurrences of these clay minerals, i.e. either pore-filling or grain-coating, are still poorly understood and hence this requires further investigation. This signals the need to perform more experimental work on the mechanism of clay coat formation using both chemical (**Paper I**) and mechanical (Matlack et al; 1989) methods.

Sill induced diagenesis: The NW Barents shelf is potentially a future hydrocarbon exploration frontier, but there is evidence for past intrusive igneous activity, likely constraining the distribution and quality of both reservoir (**Paper IV**) and source rocks (Abay et al., 2017; Brekke et al., 2014). What is the dominant heat transfer mechanism in the highly porous sedimentary sequences? How does sill intrusion affect reservoir quality? In contrast to what has been suggested earlier in the literature, diagenetic alterations in sill induced clastic sedimentary sequences are not mediated merely by conduction, but by hydrothermal convection cell formation (**Paper IV**). Hydrothermal convection cell impact is evidenced in carbonate-cemented intervals approximately up to five times the thickness of the sill away (**Paper IV**). Still the result from this case study is preliminary and it requires more isotope, vitrinite reflectance and fluid inclusion data to better constrain the thermal history and rigorous study regarding hot fluid flow pathways backed by field observation and more data collection.

Porewater chemistry: it is important to constrain the porewater chemistry and sedimentary facies since both control diagenetic reactions in sandstones. Processes in the depositional environment has significant control on the initial porewater composition and diagenetic styles in sandstones. Porewater chemistry is an essential input in chemical equilibrium models to predict fluid-rock interactions. Obtaining data regarding porewater composition will thus aid the modelling of geochemical reactions. The diagenetic reaction products obtained from the model can be compared with diagenetic reactions observed from petrographic and geochemical studies. If similar results are obtained, predicting diagenetic patterns in a similar geological setting will likely be performed before drilling. Moreover, since porewater chemistry and depositional environment are highly interrelated, it would also enhance depositional environment interpretations (Mansurbeg, 2017). Therefore, performing stable carbon, hydrogen and oxygen isotope analyses and LA-ICPMS fluid inclusion microanalysis is suggested to obtain porewater chemistry that would: (i) validate outcrops as testing platforms to allow an alternative approach to use numerical models of fluid-rock interaction to predict diagenetic alteration patterns in the subsurface before drilling and (ii) enhance reliable identification of depositional environments.

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Enclosures

Paper I

Experimental nucleation and growth of smectites and chlorite coatings on clean feldspar and quartz grain surfaces

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Paper II

How are diagenesis and reservoir quality linked to depositional facies? A deltaic succession, Edgeøya, Svalbard

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Paper III

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Paper IV

Hydrothermally induced diagenesis: Evidence from shallow marine-deltaic sediments, Wilhelmøya, Svalbard

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Research Paper

Hydrothermally induced diagenesis: Evidence from shallow marine-deltaic sediments, Wilhelmøya, Svalbard

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ABSTRACT

Sedimentary basins containing igneous intrusions within sedimentary reservoir units represent an important risk in petroleum exploration. The Upper Triassic to Lower Jurassic sediments at Wilhelmøya (Svalbard) contains reservoir heterogeneity as a result of sill emplacement and represent a unique case study to better understand the effect of magmatic intrusions on the general burial diagenesis of siliciclastic sediments. Sills develop contact metamorphic aureoles by conduction as presented in many earlier studies. However, there is significant impact of localized hydrothermal circulation systems affecting reservoir sediments at considerable distance from the sill intrusions. Dolerite sill intrusions in the studied area are of limited vertical extent (~12 m thick), but created localized hydrothermal convection cells affecting sediments at considerable distance (more than five times the thickness of the sill) from the intrusions. We present evidence that the sedimentary sequence can be divided into two units: (1) the bulk poorly lithified sediment with a maximum burial temperature much lower than 60–70 °C, and (2) thinner intervals outside the contact zone that have experienced hydrothermal temperatures (around 140 °C). The main diagenetic alteration associated with normal burial diagenesis is minor mechanical plastic deformation of ductile grains such as mica. Mineral grain contacts show no evidence of pressure dissolution and the vitrinite reflectance suggests a maximum temperature of ~40 °C. Contrary to this, part of the sediment, preferentially along calcite cemented flow baffles, show evidence of hydrothermal alteration. These hydrothermally altered sediment sections are characterized by recrystallized carbonate cemented intervals. Further, the hydrothermal solutions have resulted in localized sericitization (illitization) of feldspars, albitization of both K-feldspar and plagioclase and the formation of fibrous illite nucleated on kaolinite. These observations suggest hydrothermal alteration at T > 120–140 °C at distances considerably further away than expected from sill heat dissipation by conduction only, which commonly affect sediments about twice the thickness of the sill intrusion. We propose that carbonate-cemented sections acted as flow baffles already during the hydrothermal fluid mobility and controlled the migration pathways of the buoyant hot fluids. Significant hydrothermally induced diagenetic alterations affecting the porosity and hence reservoir quality was not noted in the noncarbonate-cemented reservoir intervals.

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1. Introduction

The quality of petroleum reservoirs depends strongly on the burial history and diagenesis, and understanding the processes that change the properties of reservoir rocks are therefore of economic importance. Diagenesis of sandstones involves physical and chemical processes that are responsible for changing the mineral composition, texture and fluid flow properties of sedimentary rocks. Diagenesis is responsible for the formation of secondary porosity, for porosity destruction through compaction and in some cases porosity preservation to great depths (Surdam et al., 1983; Bjørlykke, 1988; Ehrenberg, 1993; Salem et al., 2000; Bloch et al., 2002). Investigating the processes and products of diagenesis is thus critical for constraining rock texture, porosity and permeability during burial (Bjørlykke et al., 1979; Worden and Morad, 2000; Ajdukiewicz and Lander, 2010; Morad et al., 2010; Taylor et al., 2010; Bjørlykke and Jahren, 2012). Moreover, understanding diagenesis improves our ability to predict reservoir quality at a local scale and modeling the evolution

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of sedimentary basins at regional scales (Wilson et al., 2006; Zhu et al., 2006).

As the energy demand in the world is increasing, the exploration activity for hydrocarbons moves towards more challenging systems such as basins affected by magmatic activity (Senger et al., 2014, 2017; Schofield et al., 2015b). There are numerous challenges for petroleum exploration in such basins because igneous intrusions may impact diagenesis, thermal history, seismic imaging, reservoir compartmentalization, source rock maturation, and hydrocarbon migration pathways (Holford et al., 2012, 2013; Rateau et al., 2013; Jerram, 2015; Eide et al., 2017; Grove et al., 2017; Schofield et al., 2017; Senger et al., 2017). To date, basins influenced by magmatic intrusions have become a major focus for many exploration companies. It is therefore important to understand the influence of intrusion-induced diagenesis on reservoir quality in such type of basins (e.g. Vøring Basin, Faroe-Shetland Basin, the Northern parts of the Barents Sea, western Australian continental margin, and offshore Madagascar). This is essential to reduce exploration risk.

When sills intrude sedimentary rocks, heat can be transferred by conduction and/or by convection of fluids (Ferry and Dipple, 1991). Most published works associate the impact of sill intrusions in sedimentary strata to pyrometamorphism and/or contact metamorphism (Reeckmann et al., 1985; Karlsen et al., 1998; Mckinley et al., 2001; Grapes, 2010; Aarnes et al., 2011). It has however also been demonstrated that magmatic sills intruded into highly porous sediments have resulted in hydrothermal fluid mobility that influenced rock properties further from sill intrusions (Einsele et al., 1980), and also recent studies have shown that hydrothermally induced fluid migrations affect the temperature history and diagenesis in the host sedimentary rock (Schofield et al., 2015a; Angkasa et al., 2017; Grove et al., 2017; Senger et al., 2017).

Svalbard is suitable to examine the influence of heat-flux related to short-lived events of hydrothermal induced diagenesis in sandstones, as outcrops of highly porous Mesozoic sedimentary units that have been intruded by igneous rocks are abundant and well exposed. The Triassic (De Geerdalen Formation) and Lower Jurassic (Wilhelmøya Subgroup) sediments exposed at Wilhelmøya are time equivalent to subsurface rocks in the Barents Sea area (Mørk et al., 1982). The outcrops, in addition, provide information on the 3D spatial variability of sedimentary facies of deltaic and shallow marine strata and provide good insight into the depositional environment and the related spatial variability of diagenesis. They can also serve as an excellent natural laboratory to give insights about diagenetic alteration and ultimately reservoir quality evolution in the subsurface where sediments interact with sills. Furthermore, reservoir quality modifications as a result of diagenesis and documentation of this process is important because: (1) there are relatively few studies on hydrothermally induced diagenesis compared to normal burial diagenesis (Mckinley et al., 2001; Ahmed, 2002; Machel and Lonnee, 2002; Rossi et al., 2002; Ochoa et al., 2007; González-Acebrón et al., 2011; Grove, 2013; Holford et al., 2013; Grove et al., 2017); (2) despite several published papers on sedimentology, sequence stratigraphy, structural and tectonic evolution of the Barents Sea area (Faleide et al., 1993; Glørstad-Clark et al., 2010, 2011; Klausen and Mørk, 2014; Klausen et al., 2014, 2015; Anell et al., 2016; Lord et al., 2017), the impacts of diagenesis on reservoir quality evolution of the Triassic sequences is scarce (Mørk, 2013); and (3) Mesozoic outcrops at Svalbard are located in the uplifted parts of the Barents sea region which has a comprehensive burial history leading to different burial diagenesis compared to other basins.

On Svalbard, as a general trend, Mesozoic sandstones are well cemented and have low porosities and permeabilities. Contrary to this the Wilhelmøya Subgroup, as observed at the type location at Wilhelmøya, are composed of poorly lithified sediments with some thinner cemented intervals. These sediments have never been buried deeply (~<2 km), explaining the general lack of cementation. The diagenetic overprints occurring at the onset of the transition from mechanical to chemical compaction window makes the sequences at Wilhelmøya an excellent natural laboratory to investigate early chemical diagenesis. Moreover, by using diagenetic observations that enable placing constraints on the temperature of the sediments, the sequence offers the opportunity to shed new light on the uplift and temperature history of the area. Diagenetic processes, such as the onset of quartz cementation, pressure-dissolution at stylolites, and the transformation of smectites to illite occur in the same temperature range. Diagenetic fingerprints can therefore be used as indicators of maximum burial temperatures before uplift, and the extent of the uplift.

Temperature proxies may in addition be useful to better understand the effect of sill intrusions penetrating the sediments in this region and sediments deposited in similar settings. A larger part (~900,000 km^2) of the northern and eastern Barents Sea (it covers both Norwegian and Russian territorial waters) contains abundant igneous intrusions with a volume estimate of 100,000 to 200,000 km^3 predominantly in the Permian to Triassic sedimentary units across the Barents basin (Polteau et al., 2016). The sill intrusions in the study area have moderate vertical extent but have still influenced the heat budget of the area. Moreover, because sedimentary successions on Wilhelmøya have never been buried deeply, the effects of the hydrothermal alteration can easily be distinguished from the background low-temperature diagenesis. This paper examines the effect of sill intrusion-induced diagenesis compared to the normal diagenesis on sandstone reservoir properties.

2. Geological background

2.1. Svalbard geology

Svalbard is situated at the north-western parts of the Barents Shelf, bordered to the north by a rifted continental margin and to the south-west by a sheared margin (Johansson et al., 2005; Faleide et al., 2015). During the Late Cretaceous a regional uplift of the northern Barents Shelf resulted in subaerial exposure of the Svalbard archipelago (Johansen et al., 1992; Riis et al., 2008; Worsley, 2008; Dörr et al., 2012, 2013; Blinova et al., 2013). The magnitude of the uplift has been suggested to be strongest in the northern and western parts of Svalbard, however, the entire Barents Shelf region has been uplifted and eroded in the late Cenozoic (Nøttvedt et al., 1988, 1992; Vorren et al., 1991). The average thickness of the strata removed due to erosion was estimated up to approximately one km in SW Barents Sea; however, the uplift was more intense north of 75ºN, and with uplift close to three km on Svalbard (Nøttvedt et al., 1992; Henriksen et al., 2011; Dörr et al., 2012).

Based on coal rank data, the subaerially exposed areas of the north eastern part of Svalbard have been subjected to an overburden of 2000 m (Mørk and Bjorøy, 1984). Similarly inferring to the organic geochemical analyses data, the northern Barents Sea (the region between Svalbard and Franz Josef Lands), the thickness of the sedimentary section removed due to erosion was almost 2000 m (Gustavsen et al., 1997). Reports based on T_{max} values of 434 °C and 436 °C from the Olga basin area located south west of the northern Barents Sea, indicates uplift of 1900 m in this area (Antonsen et al., 1991). In the same area, based on a regional study vitrinite reflectance data revealed uplift of 1500–2000 m (Nyland et al., 1992).

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The magnitude of uplift increases northward up to 2000 m on Franz Josef Land compared to the center of the South Barents basin which experiences 400–500 m erosion (Sobolev, 2012). Using apatite fission track analyses, the northern Svalbard (Albert I Land, Ny Friesland and Nordaustlandet) has undergone approximately 60 °C cooling (~120–60 °C) which is equivalent to 2–3 km at a geothermal gradient of 20 to 30 °C/km (Dörr et al., 2012). The aforementioned exhumation and erosion burial paleo-history estimates of the areas around the Wilhelmøya Island and the vitrinite reflectivity data have indicated that the sediments at Wilhelmøya may never been subjected to high burial temperature assuming normal geothermal gradients. It should be noted that estimates from a single thermal maturity indicator likely is uncertain, however, combining the various methods may decrease this uncertainty (Haile et al., in review; Henriksen et al., 2011).

The basin evolution of the Svalbard archipelago began with post-orogenic subsidence of pre-Devonian basement (Caledonian orogeny and older units) during extensional collapse linked to deposition of Devonian Old Red Sandstones (Johansen et al., 1992; Blomeier et al., 2003; Braathen et al., in press). The next major tectonic event occurred late Carboniferous rifting (Gjelberg and Steel, 1981), with a transition from broad depressions to formation of fault narrow half-grabens. The Permian was a period of tectonic quiescence which is characterized by the formation of stable marine carbonate platforms (Stemmerik and Worsley, 1989). In the late Permian, a seaway connecting East Greenland and the North Sea opened, changing the marine carbonate platforms from a hot to cold-water environment. This is seen as a transition from prevalent ramp carbonates and evaporites to mainly spiculitic limestones and shales (Worsley, 2008). During the Mesozoic (Triassic), Svalbard gradually changed its position from about 45°N to approximately 60°N (Smith et al., 1994; Ditchfield, 1997). This era was characterized by sea level rise and warm climatic conditions (Hallam, 1985), with the Svalbard climate reflecting a humid temperate domain. The Mesozoic deposits on Svalbard are mostly marine, and three main successions were deposited from Triassic to Cretaceous; the Sassendalen, Kapp Toscana and Adventdalen groups. These groups are made up of terrestrial deposits that are dissected by magmatic intrusions. During the Mesozoic period, sediments were in general siliciclastic in nature and deposited in a continental shelf setting dominated by shale and sand. There was no or little tectonic activity at the eastern and north eastern parts of Svalbard (Worsley, 2008), albeit (Anell et al., 2013) argue for some late fault activity. In contrast, the western part of the Barents Sea was a tectonically active region throughout the Mesozoic and Cenozoic times, showing comprehensive tectonic evolution characterized by several orogenic events (Faleide et al., 1984). These tectonic events affected the Barents Sea region and thus controlled the basin configurations and sedimentary responses (Gabrielsen, 1984; Mørk et al., 1989; Johansen et al., 1992; Breivik et al., 1998; Klausen et al., 2015) with the establishment of a transform fault between Svalbard and Greenland at the end of the Mesozoic. The Cenozoic saw the creation of a mountain belt in the west and a related foreland basin eastward in the central part of Svalbard. Continental to marine and back to continental sediments filled this depression, prior to uplift and erosion.

2.2. Studied stratigraphy

The samples studied here are the Upper Triassic to Jurassic Kapp Toscana Group exposures on the islands of Wilhelmøya. Wilhelmøya is an island situated in the eastern part of the Svalbard archipelago, approximately 50 km east of the main island Spitsbergen covering an area of about 120 km^2 (Fig. 1A). The island is located in the north-eastern part of the eastern Svalbard platform near to the N–S oriented Lomfjorden Fault zone (LFZ) (Fig. 1A).

The Kapp Toscana Group includes sediments categorized into two main subdivisions: De Geerdalen Formation and Wilhelmøya Subgroup. Upper Triassic to Lower Jurassic sedimentary sequence comprises the Carnian to early Norian De Geerdalen Formation overlain by the Wilhelmøya Subgroup (Fig. 1B). The depositional setting for the De Geerdalen Formation and Wilhelmøya Subgroup has been interpreted to be nearshore deltaic environments. Based on detailed sedimentological studies, the De Geerdalen Formation is ascribed to a shallow marine to prograding deltaic sandstone succession (Mørk et al., 1982; Krajewski, 2008; Lord et al., 2017) while the Wilhelmøya Subgroup comprises a coastal plain and in deltaic to shallow marine platform environments (Worsley, 1973; Dypvik et al., 2002). The sandstones of De Geerdalen Formation are texturally and compositionally immature while that of Wilhelmøya Subgroup consists of mineralogically mature sand and sandstones (Mørk et al., 1982; Mørk, 2013). The Wilhelmøya Subgroup is further subdivided into the Flatsalen, Svenskøya and Kongsøya formations, with regionally defined boundaries the Slottet bed of phosphatic nodular beds occur at the base and similar phosphatic beds of Brentskardhaugen bed at the top. A major transgression in the early Norian initiated marine sedimentation of the Wilhelmøya Subgroup in Svalbard and of the correlative Realgrunnen Subgroup in the Barents Sea area (Riis et al., 2008). There is a general thickening of the Wilhelmøya Subgroup and De Geerdalen Formation towards the east (Steel and Worsley, 1984).

The sediment source areas during the late Triassic were positioned to the east, northeast, and west (Nøttvedt et al., 1992; Mørk, 1999). However, in recent studies the main source of the sediments deposited in the northeastern part of Svalbard has been suggested to be from the east, mainly sourced from the Uralian orogeny, similar to suggestions by Steel and Worsley (1984). This interpretation is based on results from detrital zircon age analyses (Bue and Andresen, 2013), clinoform geometries observed on seismic data, and seismic studies in the Barents Sea (Faleide et al., 1984, 1993, 2008; Lundschien et al., 2014), and finally sedimentological and sequence stratigraphic investigations (Riis et al., 2008; Glørstad-Clark et al., 2010, 2011; Klausen and Mørk, 2014; Lord et al., 2014, 2017; Rød et al., 2014).

The Kapp Toscana Group sandstones exposed on Wilhelmøya are intruded by magmatic sill intrusions. Large and widely spread thermal activity in the Arctic has been identified during the late Mesozoic (Maher, 2001; Nejbert et al., 2011). This activity is collectively named as the High Arctic Large Igneous Province (HALIP) (Maher, 2001). The late Mesozoic (early Cretaceous) magmatism has a widespread occurrence throughout Svalbard and is represented predominantly by sill intrusions up to 100 m thick and laterally continuous for up to 30 km. The sills studied from different parts of Svalbard contain plagioclase, clinopyroxene, alkali feldspar, Fe-Ti oxides and accessory minerals such as olivine, apatite, quartz, pyrite, chalcopyrite and bornite (Nejbert et al., 2011). Generally, similar to at other islands, the sills of Wilhelmøya are tholeiitic (Weigand and Testa, 1982). The dolerite intrusions at Wilhelmøya have an undulating morphology (Fig. 2). Unlike other islands in the archipelago, sill intrusions on this island have more abundant biotite.

3. Materials and methods

Samples of Upper Triassic to Lower Jurassic aged Kapp Toscana Group sediments were collected from well-exposed outcrops at Wil-

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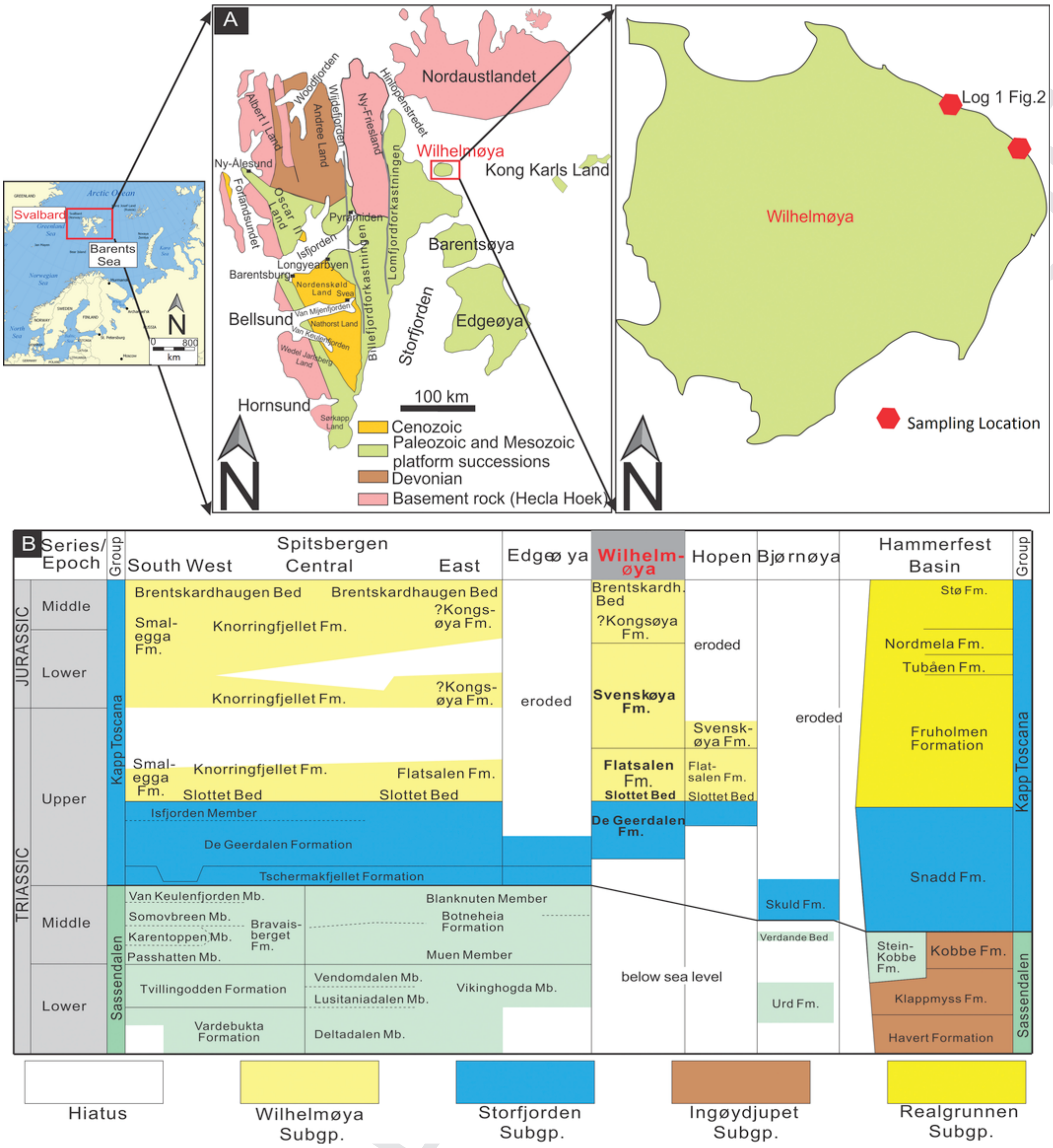

Figure 1. A) Simplified geological map of Svalbard. The location of Wilhelmøya (Wilhelm Island) is outlined. Red hexagonal shapes depict sampling locations. The sampling location in eastern Wilhelmøya has UTM coordinates (LOG 1 site 33X 619981E and 8784911N and other site 33X 621117E and 8783543N). B) The lithostartigraphy of Svalbard and the Barents Sea from the Lower Triassic through the Middle Jurassic. The figure is modified fromMørk et al., 1999.

helmøya and the lowermost sequence found below the sill intrusion was logged (Fig. 2). Sampling of the DF and WS was concentrated at two locations approximately 2–3 km apart laterally. The sampling locations based on GPS coordinates are indicated in Fig. 2. The Samples collected represent the full range of stratigraphic variation within DF and WS both from tight carbonate cemented intervals and relatively uncemented intervals. No obvious weathering effects have been observed in the sandstone strata of either DF or WS. Fresh sediment samples taken directly beneath the exposed parts of sediment surface were sampled for diagenetic, petrographic, mineralogical and geochemical analyses.

Thin sections were prepared for 16 sandstone samples; 5 from the De Geerdalen Formation and 11 from the Wilhelmøya Subgroup. Conventional petrographic analyses were made to inspect the grain size, shape and mineral composition of samples. Moreover, the crystal morphology and textural relationships between the grains and pore-filling materials at thin section scale were investigated and the diagenetic features were examined using a JEOL JSM-6460LV scanning electron microscope (SEM). The SEM coupled with an energy-dispersive spectrometer (EDS) was used to perform spot chemical analyses to obtain semi-quantitative mineral compositions. Quartz cement is often difficult to delineate clearly using optical microscope and SEM coupled with backscattered electron (BSE) images. Therefore, SEM coupled with cathodoluminescence (CL) analyses was used to differentiate quartz overgrowths from detrital quartz. Moreover, stub samples were analyzed using SEM in order to complement the thin-section study and to decipher the morphology of some clay minerals where it was not obvious in the 2D thin-section (for example illite, chlorite and kaolinite).

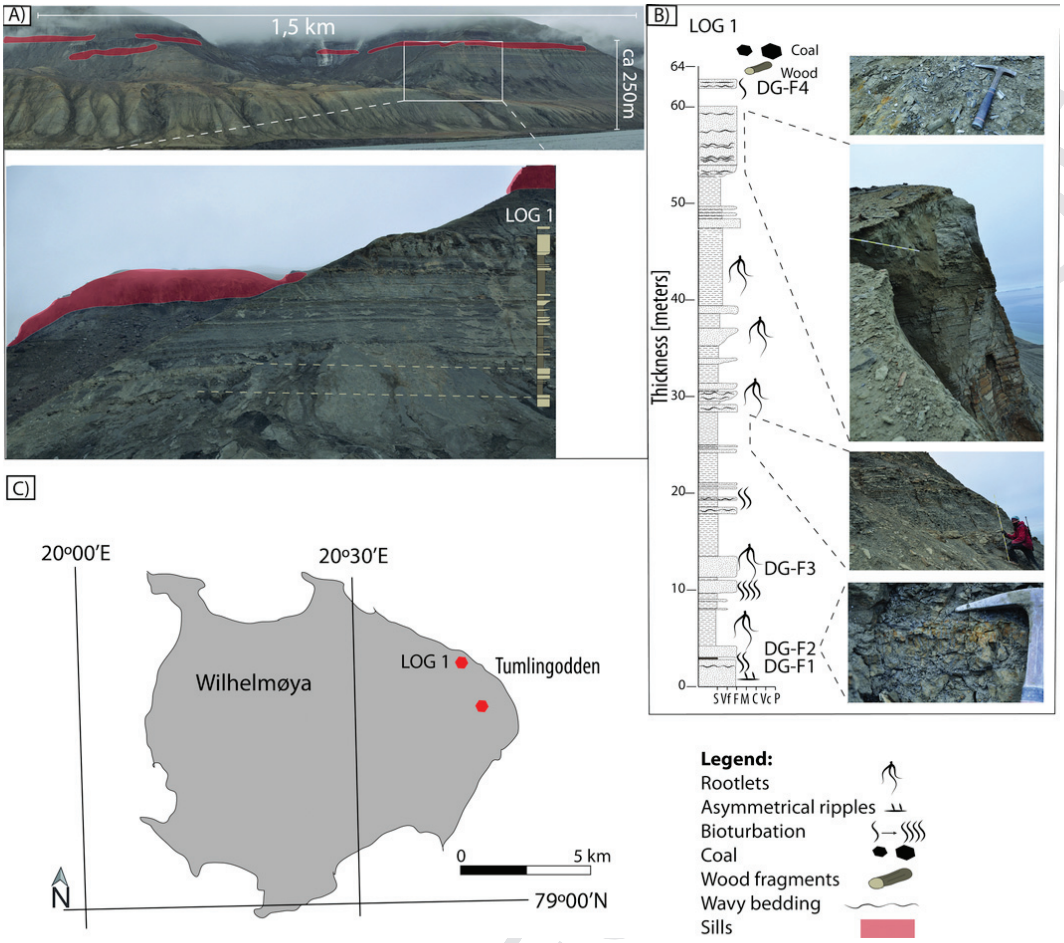

Figure 2. Sample locations and distribution of Early Cretaceous mafic sill intrusion. (A) An overview field picture showing the spatial distribution of the sill intrusion (top part) in the sedimentary strata and closer view of the lowermost sediment section where logging and sampling was done. View is westward. The sill intrusions are sub-parallel to layering. (B) Shows conventional sediment log of the lowermost succession (De Geerdalen Formation) below the sill intrusion. (C) Schematic map of Wilhelmøya showing sampling and sediment logging localities. S = silt, Vf = very fine sand, F = fine sand, M = medium sand, C = coarse sand, Vc = very coarse sand, and P = pebbles.

X-ray powder diffractometry (XRD) analyses of bulk-rock samples were performed: (1) to complement optical petrography and SEM/EDS in order to identify and quantify sandstone constituents, and (2) to guide the thin section analysis. About 3.5 g of each sample were crushed, milled in ethanol in a McCrone micronizing mill and then dried at 60 °C. Randomly oriented powders were prepared by top loading into PMMA (Polymethylmethacrylate) sample holders designed with concentric circular geometry grooved shallow wells. The powder diffraction patterns were then collected using a Bruker D8 Advanced diffractometer with Cu Kα radiation at a wavelength of 1.5406 Å. All XRD data collected were first analyzed for phase identification using the search-match module of the EVA software using the reference data bases ICDD PDF-2 and COD. After phases were identified with EVA, they were further analyzed based on the Rietveld quantitative X-ray diffraction refinement approach (RQXRD). Rietveld QXRD was performed using the Profex-BGMN-bundle software version 3.5.0 (Döbelin, 2015) and using the BGMN crystal structure files.

Vitrinite reflectance, fluid inclusion, and stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope analyses were performed on selected samples. One coal sample, from the Lower Jurassic strata, was analyzed for vitrinite reflectance at Applied Petroleum Technology (APT) at Kjeller, Norway, and all analytical procedures followed NIGOGA, 4th Edition (Weiss et al., 2000). Reflected light studies were carried out using polished bulk samples mounted in resin blocks, and polished isolated kerogen samples, mounted in resin on petrographic slides. Reflectance measurements were made with a Zeiss Epiplan-Neofluar 40X oil immersion objective and 10X eyepieces, with an inherent tube magnification of 1.6X giving a total visual magnification of 640X. R_0 (Random) reflectance measurements were made in non-polarized light setting. All the performed measurements were calibrated with regard to standards of known reflectance. The maximum burial temperature was estimated from R_o using: $T\ (°C) = [\ln (R_o) + 1.68\ ]/0.0124$ (Barker and Pawlewicz, 1994). This model was chosen because it can reproduce comparable results as that of the kinetic model developed by Sweeney and Burnham, (1990). The Sweeney and Burnham (1990) kinetic model (thermal history) predictions of maximum burial temperature can be used where the burial history of the geological systems is well known.

Eight outcrop samples were prepared as polished thick sections of approximately 60–70 μm thick for fluid inclusion petrographic analyses and microthermometry measurements. Microthermometric determinations on fluid inclusions were carried out on quartz overgrowths and pore-filling calcite cement. The fluid inclusion data were collected mainly on primary inclusions using a Zeiss Axioscope A1 APOL digital transmission microscope coupled with a calibrated Linkam. TH-600 heating and cooling stage at China University of Petroleum, Qingdao, China. The instrument enables measurement of temperatures of phase transition in the range of –180 °C to 500 °C. Homogenization temperature (T_h) measurements were determined using a heating rate of 10 °C/min when the temperature was lower than 60 °C and 5 °C/min when the temperature exceeded 60 °C. The measured temperature precision for T_h is ±1 °C. The salinity data were calculated from freezing point depression in the system NaCl-H_2O for aqueous inclusions (Bodnar, 2003).

Stable carbon and oxygen analyses were made at Institute for Energy Technology (IFE) at Kjeller, Norway. Analyses were performed on four calcite-cemented sandstone samples: two from the De Geerdalen Formation and two from the Wilhelmøya Subgroup. These data are reported in per mil (‰) relative to the Vienna Pee Dee Belemnite (V-PDB) standard. The samples were heated to 400 °C for 4 h in order to remove any organic compounds. Approximately 100 µg sample was then transferred to a 10 mL vacutainer and put in a temperature controlled aluminum (Al) block. The sample was flushed with helium (He) gas for 5 min. Each bulk sample was reacted with 0.1 ml of concentrated phosphoric acid (H_3PO_4) at 30 °C for 2 h. The produced CO_2 gas (calcite fraction) was then flushed out with helium to a Poraplot Q GC column and analyses were done directly on a Finnigan MAT DeltaXP Isotope ratio Mass Spectrometer. Based on repeated analyses in the laboratory with respect to standards (V-PDB), the precision of reported results was ±0.1‰ (2σ) for both $\delta^{18}O$ and $\delta^{13}C$. Since we do not know the composition of the formation water that calcite precipitated from, we have used the equation established by Keith and Weber, (1964) that linearly relate $\delta^{13}C$ and $\delta^{18}O$ with the Z parameter. Z-values above 120 are classified as marine while those below 120 are meteoric (fresh) water. Calcite temperatures were calculated using the calcite-water fractionation factor equation ($1000\ln\alpha_{\text{cal-water}} = 2.78 \times 10^6\ T^{-2} – 2.89$) by assuming the water isotopic composition relative to SMOW based on the Z-value computations (Friedman and O'Neil, 1977).

4. Results

Both De Geerdalen Formation (DF) and Wilhelmøya Subgroup (WS) have sediment layers (<0.5–10 m thick) that are heavily cemented by mainly carbonates. There is apparently no relation between the frequency of occurrence and stratigraphic position of these cemented units or between cement and distance to the magmatic intrusions.

4.1. Mineralogy of the DF and WS sands and sandstones

The DF and WS sediments are very fine to medium-grained and are usually moderately well sorted, but range from well to poorly sorted. Quartz, feldspars and lithic rock fragments are the most frequent framework components. Lithic rock fragments are mainly of igneous and metamorphic origin but some sedimentary fragments are also found. Micas (mostly muscovite), glauconite, chert, hornblende and bioclasts represent other detrital grains observed. The studied sandstones are mostly feldspathic litharenites to sublitharenite, but also lithic arkoses and subfeldsarenites (Fig. 3, appendix A). DF and the lower section of WS (Flatsalen Formation) sediments are mineralogically immature but samples collected from the middle section of WS (likely Svenskøya Formation?) are mineralogically mature (Fig. 3). The average framework composition of this middle section is $Q_{88}F_5L_7$.

Bulk XRD quantitative analyses suggest that quartz is the main framework mineral in all of the samples. K-feldspar, kaolinite, albite, muscovite, calcite, and Fe-rich chlorite are the remaining dominant minerals, while pyrite was found in very few of the samples and gypsum only in one sample. The XRD suggest that the amount of quartz ranges from 10% to 98%, K-feldspar from 0.6% to 7.9%, albite/plagioclase from 1.2% to 21%, kaolinite from 1% to 9.4%, chlorite from 0.7% to 11%, Muscovite/illite from 1.3 to 13%, calcite from 1.2% to 86%, siderite from 8% to 46%, pyrite from 0.2% to 0.8%, and gypsum constituted about 1.5%. The results of the quantitative XRD Rietveld refinement, SEM and optical microscope micrographs of selected samples as a function of proximity to the sill are presented in Fig. 4. The amount of calcite cement in sampled carbonate cemented intervals is 17% at 1 m, 29% at 2 m and 33% at 50 m distance from the sill intrusion (Fig. 4).

4.2. Compaction

The sediment fabric is a result of mechanical and chemical compaction processes (Einsele, 2013). The most common textures resulting from compaction are sediment grains floating in cements, and tangential-, straight-, sutured-, and concavo-convex intergranular contacts (Fig. 5A–C). The DF and WS sediments exhibit dominantly point contacts and floating grains followed by long or line contacts, but a few concavo-convex and sutured contacts are also identified (Fig. 5A–D). Both, in the very porous weekly consolidated and calcite-cemented sedimentary units, mica grains show no evidence of plastic ductile grain deformation, but minor mica deformation is noted (Fig. 5G).

4.3. Quartz overgrowth

The samples belonging to DF and WS show quartz overgrowths on detrital quartz. Quartz cement includes quartz overgrowth (Fig. 6A–H) and microquartz (Fig. 6B). Microquartz occur as coatings on detrital framework grains in the WS sediments. Thin sections under an optical microscope reveal clearly the quartz overgrowths (Qo) on detrital quartz grains (Fig. 6A–H). The quartz overgrowths, however, appear to be rounded and dissolved or parts being spalled off (Fig. 6A, C–E). Quartz overgrowths can be distinguished readily from detrital quartz grains due to the presence of dust rims on detrital quartz grains (Fig. 6A–H). However, it is difficult to distinguish quartz overgrowths from detrital quartz in SEM-BSE micrographs and such distinction may also be misleading unless supported by other analytical methods. SEM-BSE display quartz overgrowths that appear euhedral (Fig. 6D). Close-up inspections of BSE micrographs however indicate that also these surfaces have been dissolved or abraded (Fig. 6A, C, and E). This is further supported by SEM-Cl micrographs (Fig. 7A–F). Quartz overgrowths (red arrows) often have very low Cl intensity or non-luminescent (appears dark) compared to the detrital quartz grains (appears bright) (Fig. 7A,D). SEM-Cl micrographs furthermore reveal a high fracture intensity of detrital quartz grains and fractures that have been healed with quartz cement (Fig. 7A,D).

4.4. Feldspar alteration

Alteration of plagioclase and K-feldspar is only found in the calcite cemented sedimentary units within DF and WS. Most plagioclase grains have been altered to some degree and pervasively leached grains are most commonly observed (Fig. 8A–C). Plagioclase leaching leaves large (~30 µm to 150 µm) secondary pores with little

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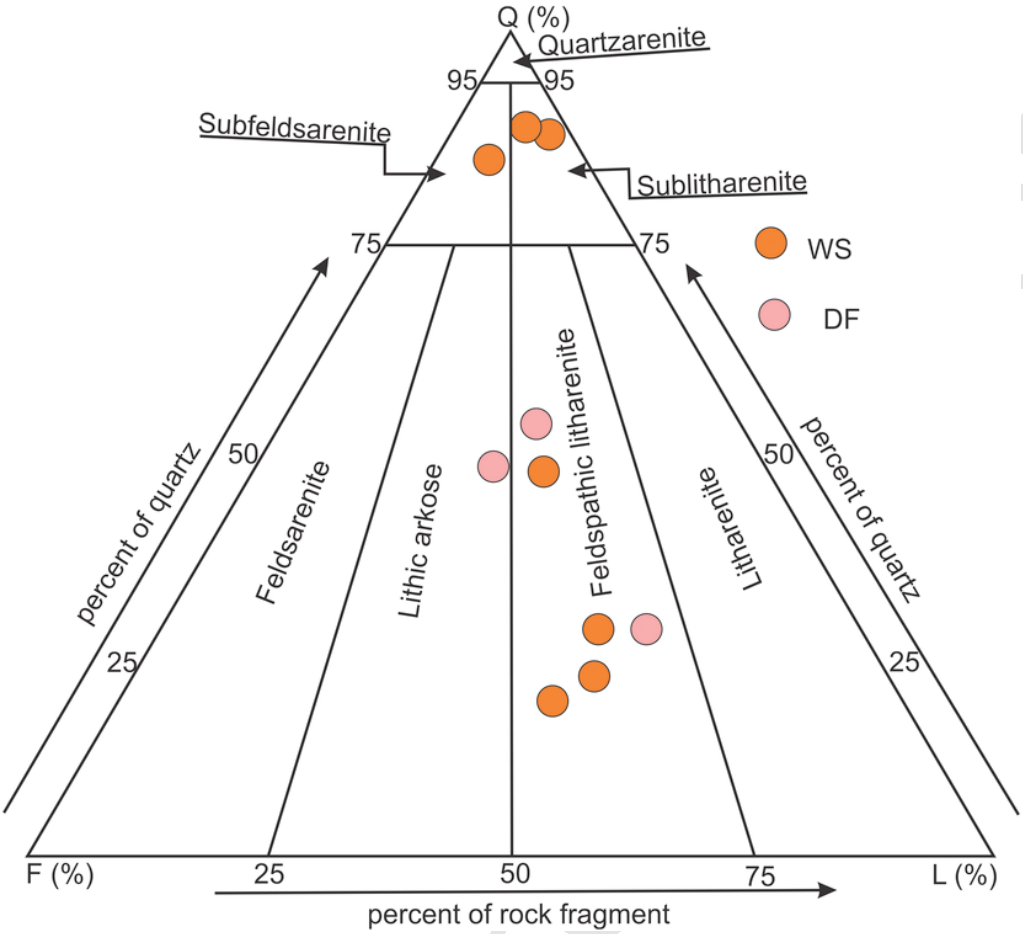

Figure 3. QFL composition of the studied thin sections; Q-quartz, F-feldspars, L-lithoclsats (the QFL triangle classification is after (McBride, 1963; Dott, 1964; Folk et al., 1970; Williams et al., 1982; Pettijohn et al., 2012). Petrographic point count data are presented in Appendix A. Table 1.

remnant grain material (Fig. 8A–C). Plagioclase leaching results in some albite formation within the voids previously occupied by detrital plagioclase grains. The replacement of the original detrital plagioclase grains by albite has resulted in the formation of aggregates of small euhedral albite crystals (Fig. 8A–C). Due to calcite cement, the secondary porosity formed from plagioclase dissolution is a stable void maintaining the shape of the dissolved plagioclase grains (Fig. 8A–C).

The potassium feldspars appear to be generally fresh and less altered compared to plagioclase (Fig. 8B and C). Crystallization of very thin albite rims (~2 μm) are predominantly observed around K-feldspar grains, and may indicate leaching of K^+ and recrystallization of the K-feldspar (Fig. 8A–C). The rims around K-feldspar grains are pure albite in composition and the albite crystals have abundant micro-intercrystalline porosity (Fig. 8D). In contrast to this, in the units lacking carbonate cement, there was no crystallization of albite rims observed around K-feldspar grains (Fig. 8E), likewise there was no plagioclase albitization (Fig. 8K).

Near K-feldspar grains with albite rims, fibrous illitic type clay phases occur mainly accompanied with microquartz crystals (Fig. 8F and G). These clay minerals are composed of interwoven fibrous illite bridging the pores between microquartz grains. Illitization is difficult to observe in thin-sections. However, SEM examination of the texture of authigenic illite using stub samples, show that fibrous illite nucleated and grew onto kaolinite around altered K-feldspar grains (Fig. 8H). SEM-EDS analyses of the illitic clay phase yields the major elements: K, Al, Si and O (Fig. 8F). Similar to the albite formation, illite formation is only observed in the carbonate-cemented intervals.

Plagioclase and K-feldspar alteration into sericite (illite) was recognized in the carbonate cemented layers (Fig. 8I and J), but sericite was not found associated with plagioclase and K-feldspar in sedimentary units lacking carbonate cement (Fig. 8K and L). Relict plagioclase grains show grain contacts with poikilotopic calcite cement and relict grains are sometimes engulfed by the cement (Fig. 8A–C).

4.5. Clay minerals

Kaolinite (Kao) is found in primary pores of both carbonate cemented and uncemented sandstone layers associated with mica and K-feldspar (Fig. 9A–E). Kaolinite crystals are observed between mica flakes and at the inter-fingering edges of mica (Fig. 9A–C) and also associated with relict K-feldspars (Fig. 9D–F). Replacement of mica by kaolinite was commonly observed in mica grains squeezed between rigid framework grains (Fig. 9A).

The most common clay mineral observed in addition to kaolinite is Fe-rich chlorite. SEM inspection and XRD analyses revealed that chlorite is present in all of the studied De Geerdalen Formation and

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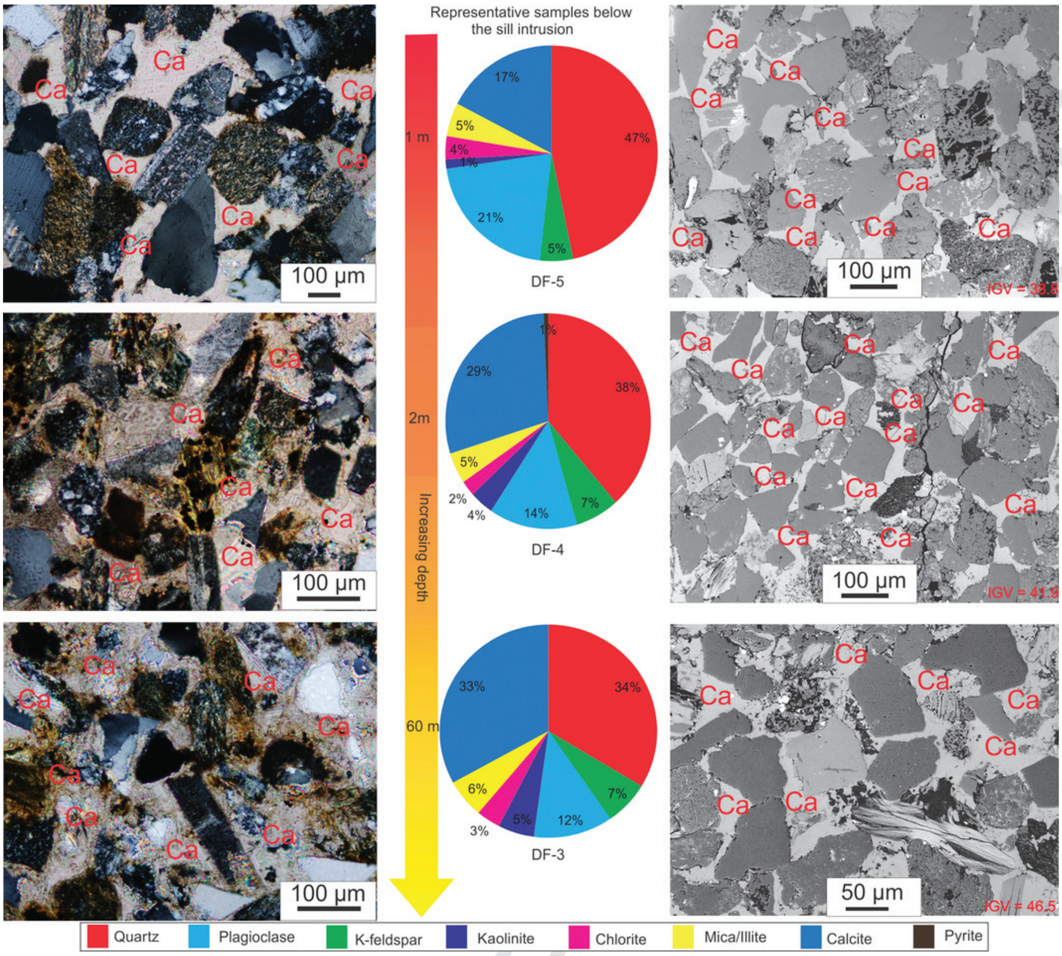

Figure 4. Thin section XPL photomicrographs, bulk XRD mineralogy and SEM photomicrographs DF samples collected from calcite-cemented intervals below the sill intrusion at Wilhelmøya. Ca = Calcite, DF = De Geerdalen Formation.

the Wilhelmøya Subgroup sandstone samples. The Fe-chlorite occur as masses of interwoven flakes of small crystals (~0.2 µm) with loose internal structure arranged in a chaotic pattern at the surface of framework grains (Fig. 9G–I), but also noted as massive aggregates (orange arrows) in the pore space (Fig. 9H). However, very close to the surface of the grains, the chlorite crystals occur with parallel or slightly oblique orientation (Fig. 9I). The chlorite coats are not continuous and display thickness variations along the surface of detrital grains (Fig. 9G and H). They predominantly occur at the embayments (yellow arrows) but are absent or scarce at rounded and flat edges of the grains (red arrows) (Fig. 9G and H). SEM stub samples display the clay coatings with an overlapping flaky aggregate and ragged outlines (Fig. 9J). SEM-EDS analyses of the clay coats and rims give similar elemental composition interpreted to be primarily a chloritic-type clay in composition (Fig. 9K). There is no clear chlorite recrystallization noted (Fig. 9L).

4.6. Carbonate cements

Carbonate cements are only found sporadically in DF and WS. Some intervals, generally less than 1–2 m thick, are however heavily cemented. A closer examination of these cemented beds shows that most of the pore space is filled with calcite and siderite, and the remaining porosity is less than 4% (Fig. 10A–F). The inter-granular volume (IGV) of the cemented intervals is generally higher (around 40%) than the non-cemented intervals (Fig. 4). The sandstones are cemented by poikilotopic calcite (Figs. 4 and 10). In some parts of the sandstones, the poikilotopic calcite cement has replaced partially to pervasively the framework grains such as plagioclase (Fig. 10A,D) which resulted in the presence of oversized calcite cement. The transformation of the original carbonate cement via the dissolution of the hot focused fluids into a new and different carbonate fabric is the recrystallization we refer to backscattered SEM images. The backscattered SEM images reveal that recrystallized calcite cement dominantly fill pore spaces (Fig. 10A). Similarly, recrystallized calcite cement interfingers into quartz grains (Fig. 10C). Pervasively etched calcite cements are visible under optical microscope (Fig. 10D). Moreover, stub samples inspected under SEM display a micro-topography with dissolution pits, smooth surfaces and sharp edges unequivocally supporting textures observed under optical microscope (Fig. 10E and F). Calcite crystals display a scalenohedral pyramidal geometry (Fig. 10E and F).

4.7. Paleo-temperature proxies

4.7.1. Sediment temperature from vitrinite reflectance

The vitrinite reflectivity (VR) for coal sample in the upper part of the section was 0.30% based on 37 measurements (Fig. 11A). Based

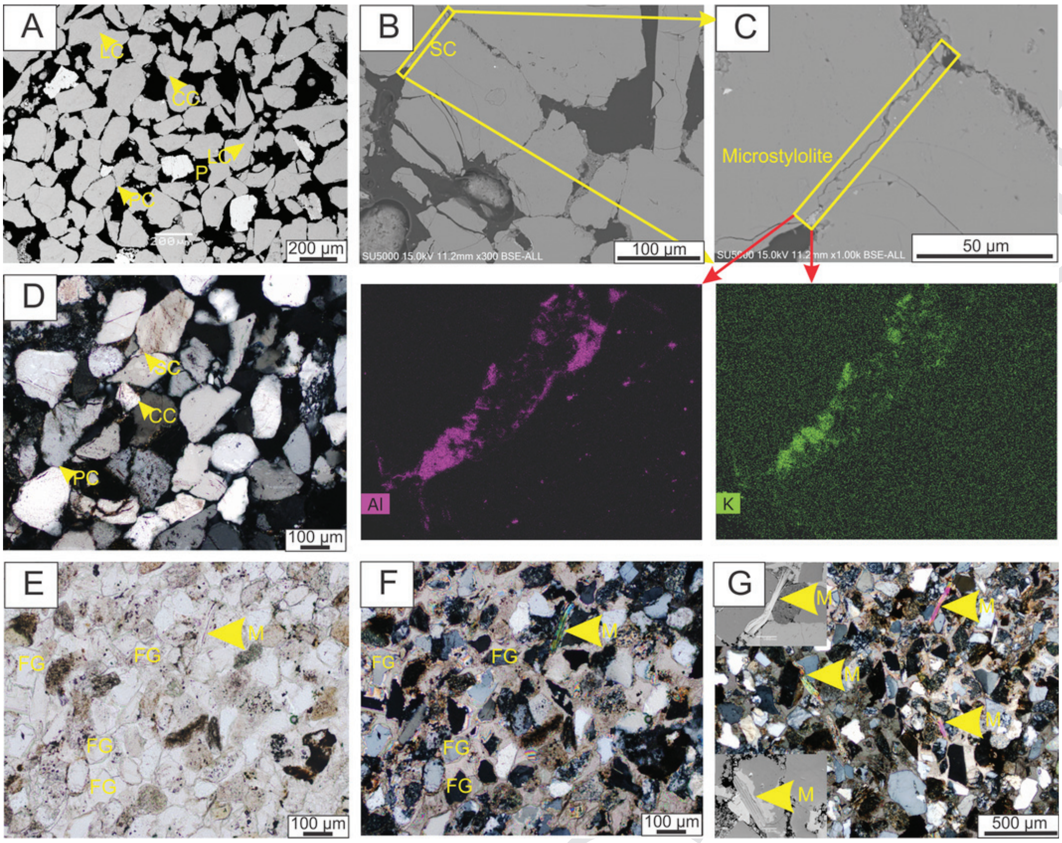

Figure 5. Some representative thin sections and SEM micrographs showing diagenetic textural features in DF and WS outcrop samples. (A) SEM micrograph of sample from intervals lacking carbonate cement displaying point, line and concavo-convex contacts between the grains. (B) SEM micrograph showing sutured contact (microstylolite). (C) Close up view of SEM micrograph of the sutured contact at "B". X-ray elemental mapping of the sutured contact shows K and Al indicating the existence of illitic material between detrital grains. (D) Photomicrograph showing sutured, concavo-convex and point contacts between the grains. (E, F) PPL and XPL photomicrograph from the same carbonate cemented units, respectively, showing floating grains engulfed with calcite cements. (G) SEM micrographs and thin section display no deformation of mica, while only minor deformation is noted. CC = concavo-convex, P = porosity, LC = line contact, SC = sutured contact, FG = floating grains, PC = point or tangential contact, M = mica, PPL = plane polarized light, XPL = cross-polarized light. Samples represented by micrographs A–D (Lower Jurassic WS), E–F (Upper Triassic DF), and G (Lower Jurassic WS).

on the model of Barker and Pawlewicz (1994), this vitrinite reflectivity value corresponds to a maximum burial temperature of 38.4 °C.

4.7.2. Temperature of formation of the diagenetic phases

Aqueous inclusions for quartz overgrowths with irregular or rounded type of faces (Fig. 6) were homogenized in the range from 89.8 °C to 128.6 °C with an average temperature value of 109 °C (Fig. 11B), but these grains were most likely recycled. It was not possible to find any quartz that is without doubt authigenic with euhedral face and containing fluid inclusions. Therefore, no temperatures were therefore recorded from the authigenic quartz actually that could have formed in-situ.

Calcite cement in the heavily cemented parts contained aqueous fluid inclusions with T_h between 100 °C and 138 °C with an average value of 123 °C (Fig. 11B). The $\delta^{13}C_{V\text{-}PDB}$ values vary from –7.5‰ to –10.2‰ and $\delta^{18}O_{V\text{-}PDB}$ values range from –13.3‰ to –20.6‰ (Table 1). The Z-values were calculated based on $\delta^{13}C$ and $\delta^{18}O$ ranged from 97 to 105. The gray shaded region illustrates the possible ranges of precipitation temperatures (65–140 °C) assuming the waters involved were of meteoric origin based on the Z-values calculation with $\delta^{18}O_{\text{V-SMOW}}$ ranging from –3.5‰ to –7.5‰ (Fig. 11C).

5. Discussion

Diagenetic signatures reveal that the DF and WS sediments have been subjected to two types of thermal conditions: (1) normal diagenesis resulting in increasing temperature as a function of increasing burial depth, and (2) hydrothermal induced diagenesis from heating and focused fluid flow generated by sill intrusions. The reservoir quality in these sediments is thus a function of both low- and high-temperature diagenesis. The following section discusses the relative influence of both normal and sill induced diagenesis on present reservoir quality of these sediments.

5.1. Normal diagenesis

Ductile grains such as mica register the effects of mechanical compaction (Chuhan et al., 2002). The detrital mica being predominantly flat or undeformed to slightly bent in DF and WS sediments indicate shallow burial of the sediments before uplift. This is consistent with the types of grain contacts identified in the studied sediments. The abundance of the grain contacts being tangential and long including floating grains indicates that the sediments have been subjected to little mechanical compaction (Wilson and McBride, 1988). Concavo-convex contacts being uncommon and the existence

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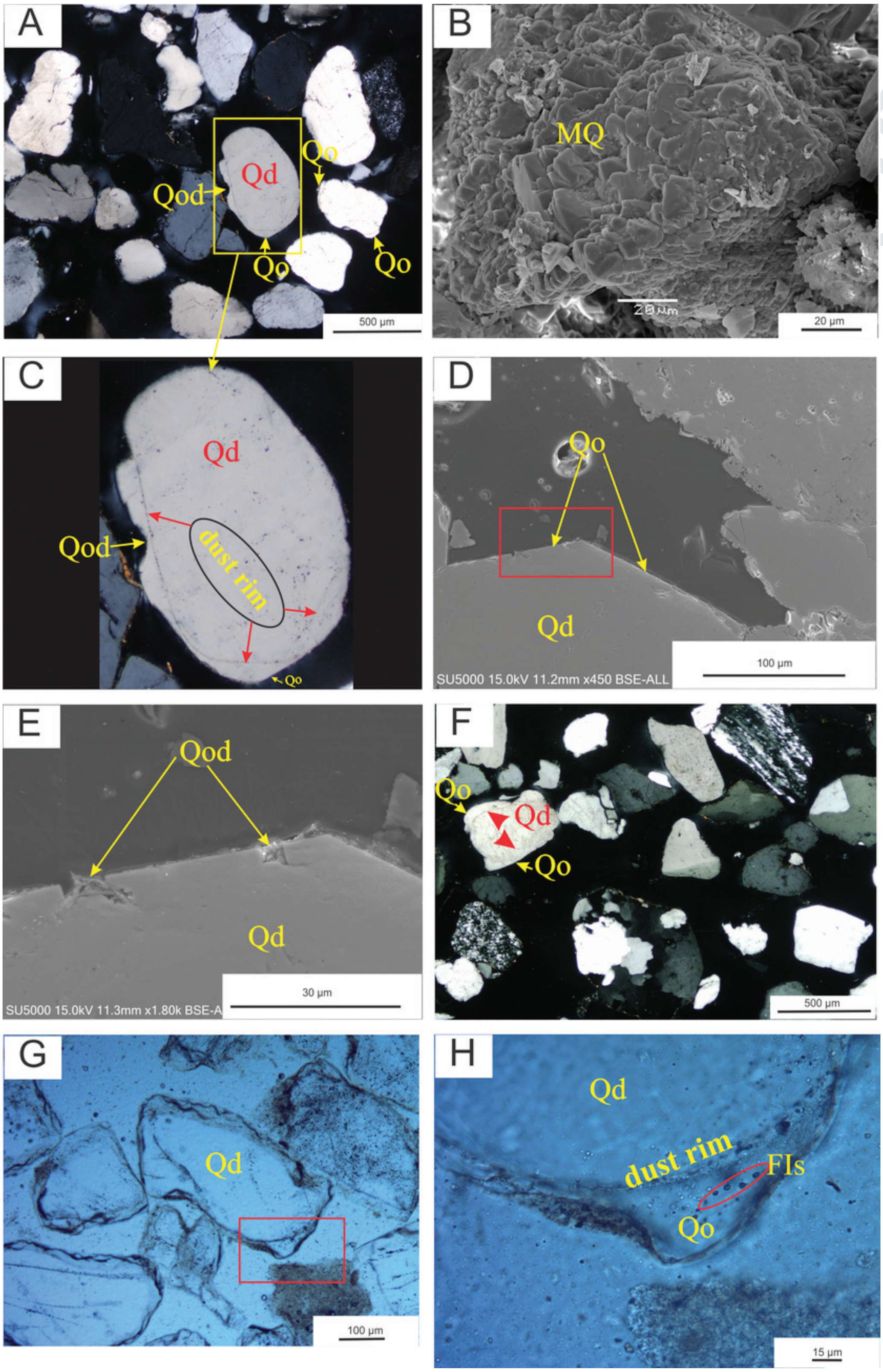
A
Qd
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C
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SU5000 15.0kV 11.2mm x450 BSE-ALL
100 μm
E
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SU5000 15.0kV 11.3mm x1.80k BSE-A
30 μm
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Figure 6. SEM and optical microscope cross-polarized thin section micrographs illustrating. (A) Optical micrographs of rounded quartz overgrowths (Qo) and dissolved quartz overgrowth (Qod) around detrital quartz (Qd). The sediments display well developed "dust" lines marking the boundary between the detrital quartz and overgrowth. The quartz overgrowth thickness varies from 2 to 5 µm. (B) Microquartz coating at the surface of a detrital quartz grain. (C) Closeup view of detrital quartz showing rounded and dissolved quartz overgrowth demarcated by dust rims (red arrows). (D) Quartz overgrowths that looks like euhedral crystal faces. (E) An enlargement of the area outlined by the red box in Fig. 6D reveals abrasions and breakage (discontinuous euhedral faces) quartz overgrowths or dissolved quartz overgrowths. (F) Photomicrographs of rounded quartz overgrowths (Qo) around detrital quartz (Qd). (G) Micrograph showing rounded quartz overgrowth (Qo) on a detrital quartz grain (Qd) where fluid inclusion analyses were performed. (H) An enlargement of the area outlined by the red box in Fig. 6G that reveals rounded quartz overgrowths and fluid inclusion associations in the quartz overgrowth. Samples represented by micrographs D–E (Upper Triassic DF) while the rest are (Lower Jurassic WS).

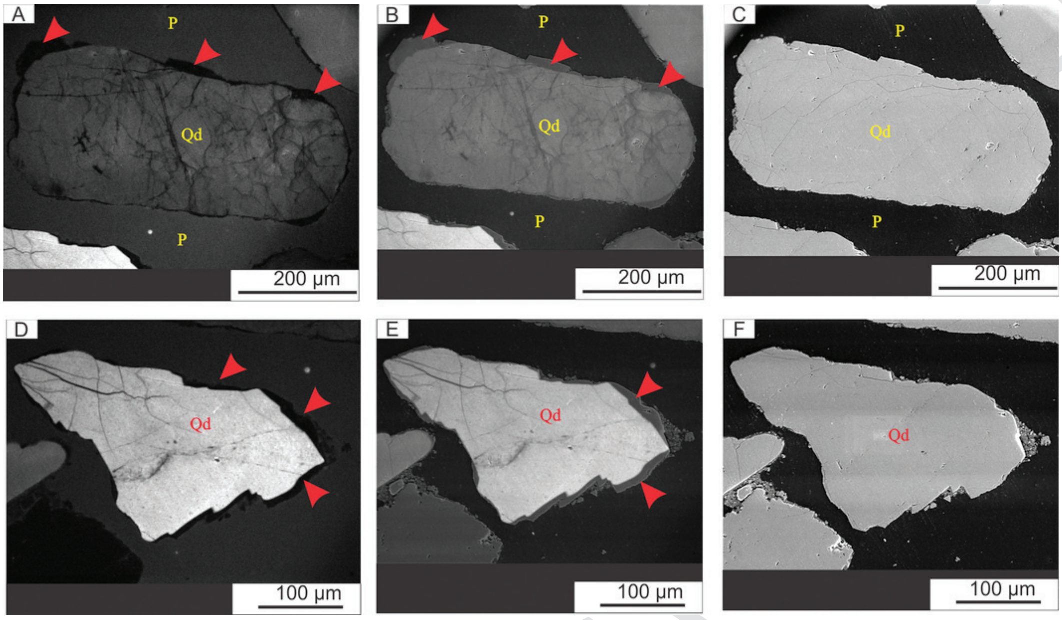

Figure 7. SEM-Cl images of detrital and authigenic quartz. A-F) SEM-Cl, Cl-SE combined, and SE micrographs, respectively showing rounded and dissolved quartz overgrowths around two different types of detrital quartz grains, marked by red arrows. The CL micrographs display authigenic quartz filling the fracture in detrital quartz grain. P = pore space. Samples represented by micrographs A-F (Lower Jurassic WS).

of only incipient sutured contacts between adjacent grains indicate that the sediments underwent no or very limited chemical compaction. This is consistent with the absence of euhedral quartz overgrowths. This indicates that the sediments have not reached temperatures in excess of 60–70 °C (Walderhaug, 1994). This is in accordance with the vitrinite reflectance (VR) data translating into a temperature of about 38.4 °C (Fig. 11A). The VR is one of a number of organic thermal maturation indicators that provides the maximum temperature exposure of sedimentary rocks. However, the empirically based or kinetic translation of VR values to paleo-temperature values is still challenging. Furthermore, all the diagenetic evidence such as microquartz coatings, feldspar dissolution and precipitation of kaolinite and early calcite cementation, indicate that these sediments have not reached quartz precipitation temperatures (>65 °C) before they have been uplifted. All the above-mentioned data indicate that the sediments at Wilhelmøya have been subjected to the shallow burial depth (~< 2 km).

The quartz overgrowths identified in this study do not display euhedral shape, but are rounded and show dissolution features (Fig. 6). The existence of these rounded and dissolved quartz cements suggest that the quartz cement overgrowths were not forming in-situ but rather are inherited overgrowths, i.e. redeposited grains (Sanderson, 1984). Quartz overgrowths possibly represent remnants of cement formed at the detrital quartz surface from a previous sedimentary cycle at deep burial. This is unequivocally supported by the homogenization temperature (T_h) measurement from these quartz overgrowths. Th ranges from 90 °C to 130 °C (Fig. 11B). The quartz overgrowth T_h values undoubtedly depart from the normal burial history of the sediments in study area.

The precipitation of microquartz crystals requires fluids with high silica supersaturation which provides a large number of small nuclei rather than few and larger crystals. Such supersaturation is most commonly provided by the dissolution of unstable biogenic silica and other small silica fossils (Williams et al., 1985; Taylor et al., 2010). The most commonly cited biogenic precursor phase for the growth of microcrystalline quartz, for instance in the Upper Jurassic reservoir rocks from North Sea, is sponge spicules (Aase et al., 1996). However, spongy spicules have not been observed in these samples during optical microscope and SEM investigations. At this stage, it is not clear what was the source of microcrystalline quartz.

As noted in this study, most of the kaolinite was pore-filling while occasional kaolinite crystals were observed between mica flakes and at the inter-fingering edges of mica. Authigenic kaolinite is in general the alteration product of feldspars and micas at shallow burial depth related to flushing by meteoric waters either during early diagenesis or after structural inversion (Bjølykke, 1980). Similarly, the authigenic kaolinite observed in DF and WS sandstones have formed as a consequence of feldspars and micas dissolution by meteoric water.

Authigenic chlorite may be formed locally as a replacement of reactive grains such as volcanic rock fragments (VRF), and transformation of the precursor clay minerals such as berthierine (Aagaard et al., 2000; Haile et al., 2015). Recrystallized authigenic chlorite

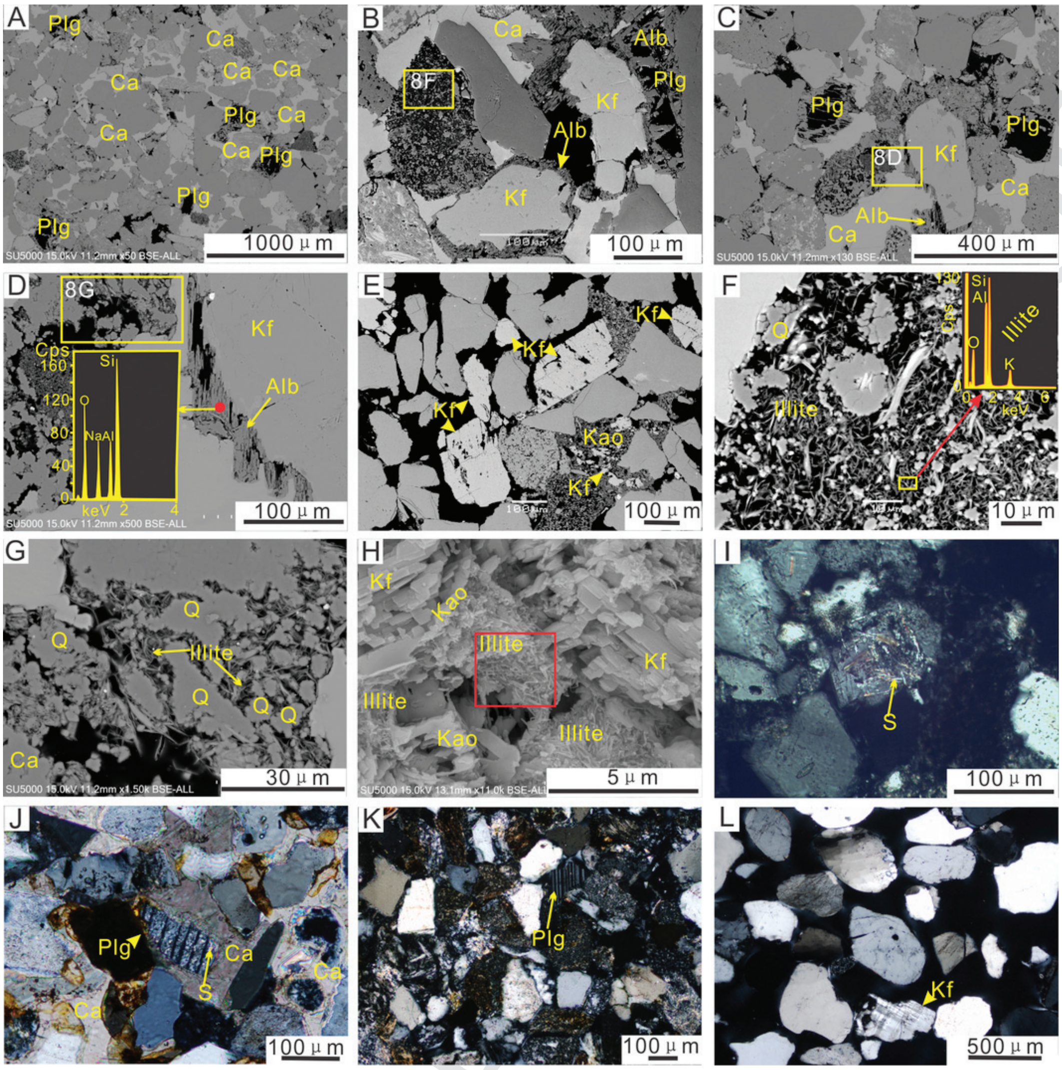

Figure 8. SEM and cross-polarized light (XPL) micrographs showing the extent of feldspar alteration. (A) Intensive leaching of plagioclase in carbonate cemented sedimentary units. (B, C) Albite rims around unaltered feldspar grains and tiny (~< 1 μm) euhedral albite crystals growing within leached plagioclase grains within a calcite cemented sedimentary unit. (D) Albite rims around K-feldspar and its texture with dissolution front noted on K-feldspar grains. Albite rims occur as crystals perpendicular to the surface displaying a palisade type texture. (E) Some K-feldspar grains show no evidence of albitization while minor and intensive dissolution of K-feldspar were noted. (F, G) An enlargement of the area outlined by the yellow box in Fig. 8B and D, reveals fibrous illitic clay in between quartz crystals in completely transformed grain at the vicinity of albite rimmed K-feldspar. The identification of original grain is virtually impossible. (H) Stub sample displaying illitic fibers grown at the edges of small crystals of kaolinite in the pore space associated with remnants of K-feldspar. (I, J) Feldspar sericitization (illitization) within calcite cemented units. (K, L) absence of feldspars sericitization (illitization) within calcite uncemented sedimentary units. Plg = plagioclase, Ca = calcite, Alb = albite, Kf = K-feldspar, Kao = kaolinite, Q = quartz, S = sericite, spectra of inset D is albite while spectra of inset C is illite. Samples represented by micrographs A–D and F–H (Upper Triassic DF) while E and I–L (Lower Jurassic WS).

coating form mainly from iron-rich precursor clay phase and will show a perpendicular orientation relative to the grain surface. Well-developed crystals having euhedral morphology will therefore commonly be arranged in an edge-to-face stacking pattern (Wilson and Pittman, 1977; Pittman et al., 1992; Grigsby, 2001; Haile et al., 2015). Moreover, such radial authigenic chlorite coats are often thick and continuous on the detrital grain surfaces. However, in this study, the chloritic clay coats are: (i) attached tangentially at the surface of detrital framework grains, (ii) patchy and discontinuous, sparsely distributed at rounded and flat surfaces but thick at the embayments in the form of loose aggregates, and (iii) the chlorite crystals are poorly-developed. These evidences indicate the detrital nature of the origin of the chloritic-type clay coats (Wilson and Pittman, 1977; Moraes and De Ros, 1990). SEM-BSE micrograph of the stub sample show overlapping flaky aggregates with ragged outlines oriented nearly tangential to the surface of the grains (Fig. 9J) is also another clear evidence suggesting the detrital origin of the clay phase covering the surface of the grains (Moraes and De Ros, 1990). Recrystallization of chlorite coats take place above about 80 °C (Aagaard et al., 2000). This will in most cases result in growth of radial chlorite crystals on top of the tangential precursor towards the pore. This will often result in a brighter BSE greyscale image towards the pore space compared to the grain side because the recrystallized chlorite contain more Fe. Fig. 9L indicates no such chlorite recrystallization indicating that the chlorite coats never reached temperatures approaching 80 °C. Usually recrystallization of chlorite coats above 80 °C result in a brighter (more Fe) BSE greyscale image towards the pore space compared to the grain side. Fig. 9L indicates no such recrystallization

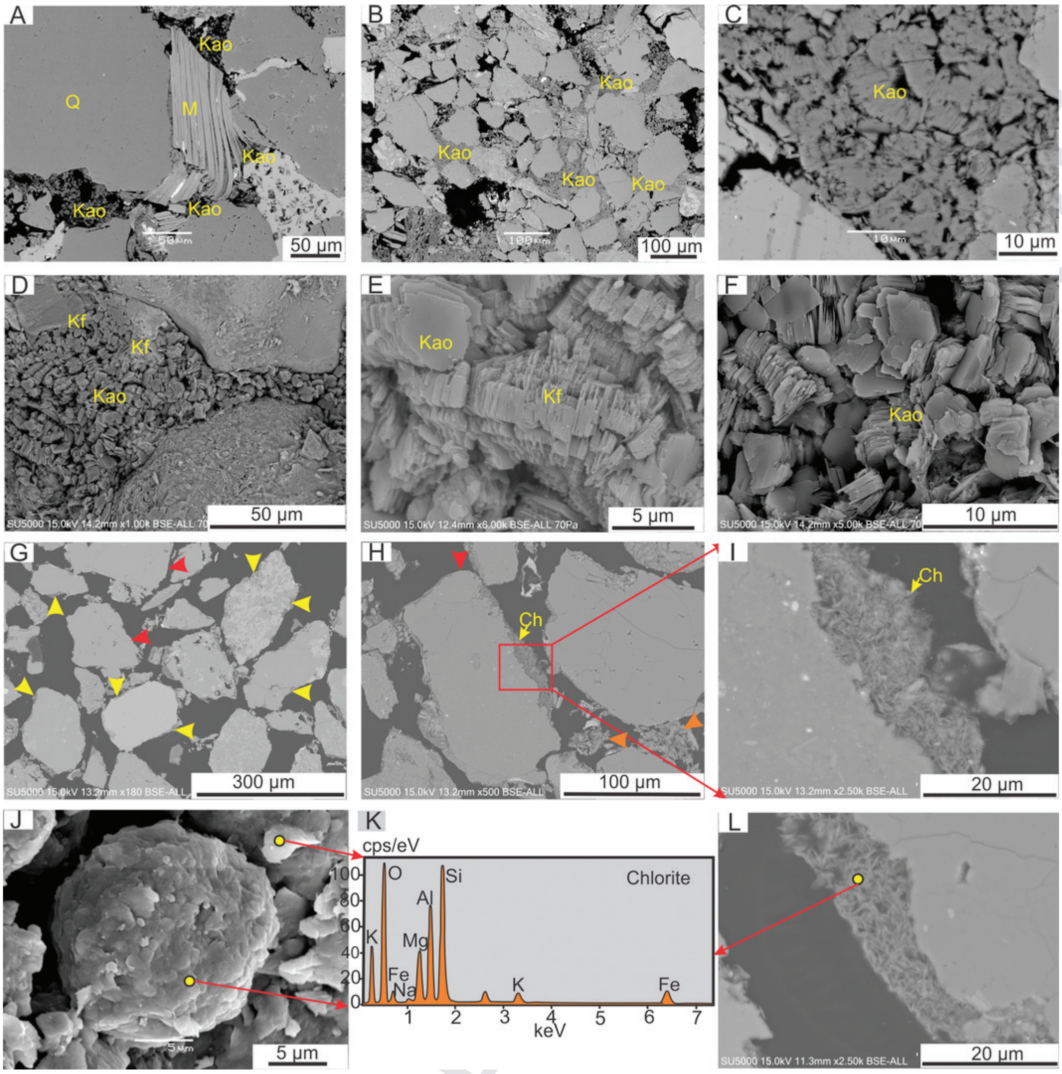

Figure 9. SEM micrographs showing pore-filling authigenic kaolinite and chlorite coats. (A) Splaying mica (M) grains with intercalated neoformed kaolinite (Kao). (B) Abundant pore-filling authigenic kaolinite. C) Closer view of pore-filling kaolinite (Kao) at "B" associated with relict of muscovite. (D, E) Pore-filling kaolinite (Kao) associated with relict of dissolved K-feldspars (kf). (F) Closer view of pore-filling kaolinite associated with K-feldspar leaching. (G, H) Immature crystals of chlorite (Ch) rims on the surface of framework grains. (I) pore filling immature crystals of chlorite with similar texture as that of chlorite rims on the surface of framework grains. (J) BSE micrograph of Stub sample showing the texture of chloritic-type clay mineral coatings. Poorly developed chloritic type coatings attached parallel to the detrital grain surface. (K) SEM-EDS of clay coat from stub sample and rims from thin section sample shows similar elemental composition that fits well with chloritic-type clay. (L) Thin section sample showing the texture of Clay rims around detrital sediments. Samples represented by micrographs A, G-L (Lower Jurassic WS) while B-F (Upper Triassic DF).

indicating lower temperature than about 80 °C (Ehrenberg, 1993; Aagaard et al., 2000; Worden and Morad, 2003).

5.2. Evidence of hydrothermal induced diagenesis

Hydrothermal fluids have an effect on porosity and permeability evolution in reservoir rocks and the thermal maturation of source rocks (Karlsen et al., 1998; Ochoa et al., 2007; Holford et al., 2013; Senger et al., 2014; Grove et al., 2017). There have been discussion in the literature regarding the criteria necessary to identify ancient hydrothermal heating events based on geochemical reaction signatures (e.g. Machel and Lonnee, 2002). In sedimentary sections with anomalously high paleotemperatures compared to burial history models, geochemical reactions may be used to identify the influence of hydrothermal systems (Ochoa et al., 2007). However, in this study, sill-induced hydrothermal diagenetic processes can unequivocally be separated from normal diagenesis, because: (i) The sediments at Wilhelmøya were only at shallow burial depths before uplift (Mørk and Bjorøy, 1984) and (ii) the diagenetic signatures studied herein and also the vitrinite reflectance data show only shallow burial processes, except for the carbonate cemented layers.

5.2.1. Diagenetic fingerprints in the carbonate cemented sedimentary units

In the carbonate cemented sedimentary units diagenetic evidence, such as sericitization (illitization) of feldspars, feldspar albitization, and fibrous illite formation, suggest more different diagenesis than the normal burial diagenesis. Sericitization (illitization) of feldspar grains in cemented intervals further strengthens the interpretation of local hydrothermal alteration (Meunier and Velde, 1982; Que and

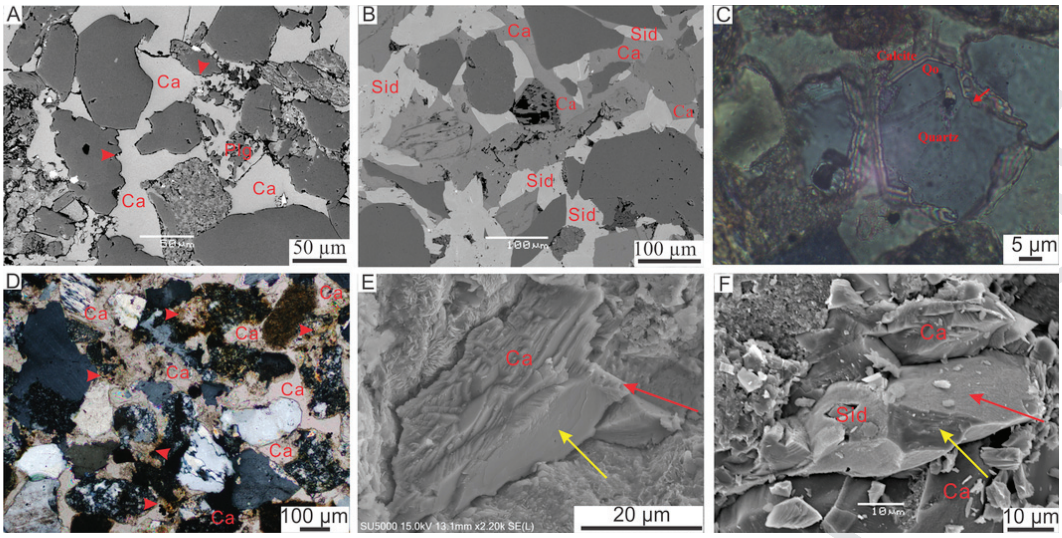

Figure 10. SEM and optical micrographs showing the nature of carbonate cements at thin-section scale. A) Backscattered electron (BSE) micrograph of recrystallized poikilotopic calcite cement (Ca) filling pore spaces displaying dissolution fronts on quartz grains. Poikilotopic calcite cement has replaced plagioclase (Plg). B) BSE micrograph showing pores completely carbonate cemented with calcite (Ca) and siderite (Sid) with no apparent quartz cement. C) Thin section micrograph under XPL showing interfingering (red arrow) of quartz and recrystallized calcite cement (Ca). D) Thin section micrograph under XPL showing recrystallized poikilotopic calcite cement. Zones where etched calcite is designated by red arrows. E) Stub sample micrographs of BSE displaying carbonate cements occluding the pore space. The carbonate crystal displays a scalenohedral pyramidal geometry. The calcite crystal show sharp edges along with smooth surfaces (yellow arrow) and rough surfaces with itch pits or dissolution front (red arrow). F) Stub sample micrographs of BSE displaying carbonate cements whereby siderite engulfed by calcite. The surface of siderite shows predominantly etch pit (dissolution features) outlines (red arrow) but also smooth surfaces (yellow arrow). Qo = quartz overgrowth, XPL = Cross-polarized light. Samples represented by micrographs A, C and E (Upper Triassic DF) while B, D and F (Lower Jurassic WS).

Allen, 1996). The replacement of feldspar by sericite (illite) occurs when hydrothermal fluid temperatures reaches above 100 °C (Verati and Jourdan, 2014).

The IGV values for the carbonate-cemented intervals are high and the presence of floating framework grains and straight flat mica grains engulfed by carbonate cement without any sign of deformation indicate an early near surface formation (before significant burial compaction) of the calcite cement. Therefore, the calcite fluid inclusion data, giving homogenization temperatures, between 100 ^{o}C and 138 ^{o}C reflect hydrothermal induced recrystallization of calcite. Calcite cements show pervasively etched micro-topography with dissolution pits and smooth surfaces with sharp edges (Fig. 10D–F). This suggests the dissolution-reprecipitation process that took place when hydrothermal fluids were focused around the carbonate-cemented units. Hellevang et al. (2017) documented calcite crystals with similar morphology grown at high temperature laboratory experimental conditions. The precipitation-dissolution processes take place as a result of competitive environment for divalent ions between clay minerals and carbonates (Hellevang et al., 2017). In the experimental study (Hellevang et al., 2017), similar to the natural setting reported herein, the newly formed calcite crystals display both etched and euhedral crystal outlines (see Fig. 2 in Hellevang et al., 2017).

The analyzed calcium carbonates are depleted in ^{13}C with $\delta^{13}C_{V\text{-}PDB}$ values ranging from –7.5‰ to –10.2‰. The carbon isotope values may suggest derivation of dissolved carbon either from oxidation of methane or microbial sulphate reduction. Moreover as documented in Grove et al. (2017), this carbon isotope value may suggest magmatic carbon. The carbon isotope values of this study are not definitely from oxidation of methane even though likely from bacterial sulphate reduction. Sulphate reduction reaction drives alkalinity and often produces pyrite. The majority of cemented beds lack however, correlation between the calcite cement and pyrite content, which precludes the importance of sulphate reduction. The carbon isotope compositions of calcite samples (δ^{13}C of –7.5‰ to –10.2‰) are not indicative of a specific source of the bicarbonate ion. These values could result from precipitation in pore waters bicarbonate ions supplied from two sources. Alternatively, the carbon isotope composition could reflect the dissolution, equilibration and re-precipitation, of in situ carbonate cements with a single CO_2 isotopic composition produced during hydrothermal invasion resulting from sill intrusions (Grove et al., 2017). The Z-values for the paleowater ranged from 97 to 100 suggests that calcite precipitated from meteoric water rather than saline water, but this may be highly uncertain. The δ^{18}O values of calcite cements (–13.3‰ to –20.6‰) indicate precipitation at temperatures of approximately 65 °C to 140 °C (Fig. 11C). The range obtained may reflect variations in diagenetic zones (normal burial diagenesis and hydrothermal induced diagenesis) or variations in δ^{18}O of the original pore waters during early diagenesis due to fluctuations in dry or wet periods or the carbonates were affected by multiple thermal pulses during the emplacement of the magmatic sills. Most likely the temperature and isotopic composition range obtained in this study is a result of water percolation resulting from a sill intrusion induced hydrothermal convection cell.

The origins of the carbonate-cemented zones in the sedimentary strata are not clear, however, they may be derived from: (1) dissolution products of unstable Ca- and Mg-bearing non-carbonate minerals and (2) reprecipitation of dissolved bioclastic particles (Fig. 12A–D). The existence of layers composed mostly of bivalves (Fig. 12D) indicate that at least some of the carbonate layers may be derived from dissolution of mineralogically unstable bioclasts which are predominantly bivalves (Fig. 12A–D). Accumulated bivalve assemblages can easily be transported and redeposited in layers (Fig. 12D, the bottom part). This part of the section as shown in Fig. 12, is the conglomeratic Slottet member of the Wilhelmøya subgroup, and it contains phosphate mineral nodules in addition to bivalves. Bivalves are not, however, restricted to this bed, rather ob-

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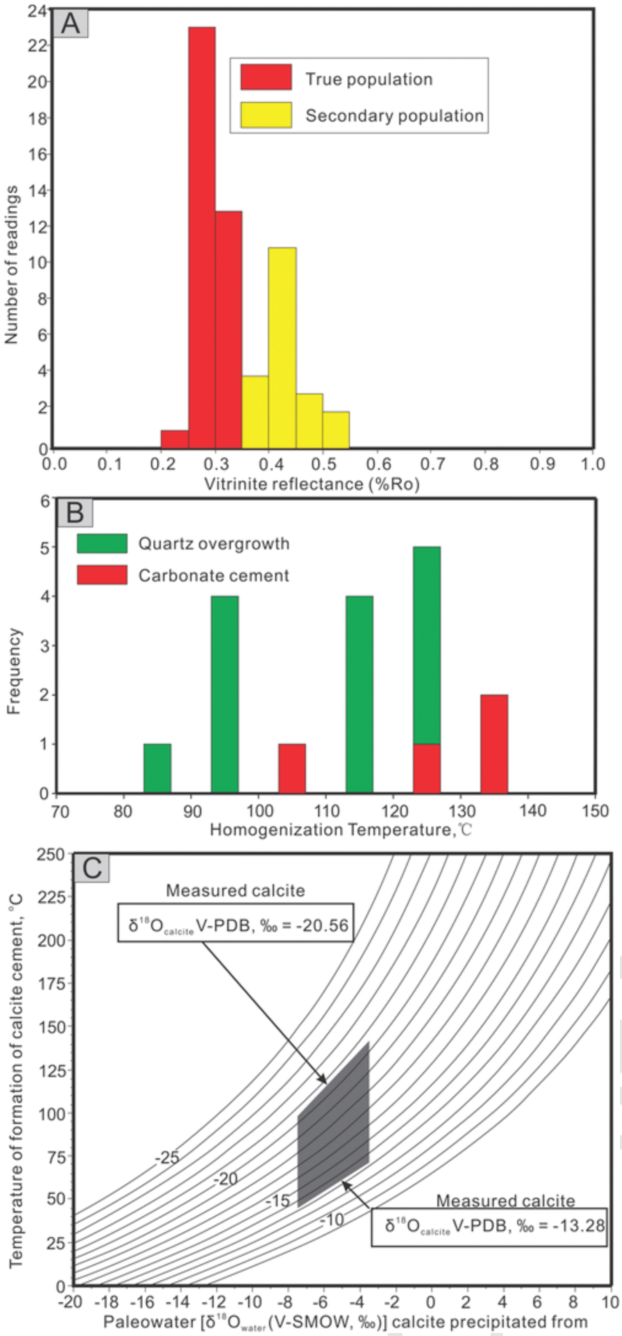

Figure 11. Plots showing paleotemperature proxies. A) Histogram showing vitrinite reflectance (% Ro) data of coal samples with two population types: a true population (indigenous population of vitrinite) and a secondary population (population of vitrinite that may represent either oxidation or effects of mineralization). As indicated in the plot, the true population has a vitrinite reflectivity of 0.30% Ro from 37 measurements while the secondary population (higher reflectivity population) comprises 20 measurements. There was little morphological difference between the particles from the two populations, but the true population material occurred as particles in isolation. B) Frequency distribution histogram of homogenization temperatures (T_h) for fluid inclusions in authigenic cements of outcrop samples. T_h for the aqueous inclusions found in quartz cement varies between 89.8 °C and 128.6 °C with a mean value of 109 °C whereas T_h for the aqueous inclusions in calcite cement varies between 100 °C and 138 °C with a mean value of 123 °C. C) Plots of the equilibrium oxygen isotope fractionation between calcite and water as a function of temperature. The Z-value calculations suggest precipitation of calcite from meteoric pore waters. The Z-value calculations were based on Keith and Weber (1964). The gray shaded region illustrates the possible ranges of precipitation temperatures if the waters involved were of meteoric origin ($\delta^{18}O_{V\text{-}SMOW}$ ranges between -3.5‰ to -7.5‰). The isotopic composition of calcite is illustrated as contours. Calcite temperatures were calculated using Friedman and O'Neil (1977) the calcite-water fractionation factors equation ($1000\ln\alpha_{cal\text{-}water} = 2.78 \times 10^6\,T^{-2}-2.89$) by assuming the water isotopic composition relative to SMOW based on the Z-value computation.

Table 1
$\delta^{13}C$ and $\delta^{18}O$ pore-filling calcite cement stable isotope analyses for samples of upper Triassic to Lower Jurassic sediments from Wilhelmøya, Svalbard.

Sample	$\delta^{13}C_{V\text{-}PDB}$, Calcite	$\delta^{18}O_{V\text{-}PDB}$, Calcite	Z-values
DF-3	-7.5	-13.3	105
DF-4	-10.2	-19.1	97
WS-3	-9.7	-20.6	97
WS-4	-8.8	-18.8	100

served associated with carbonate cemented units in the sedimentary succession.

There was no sign of albitization of plagioclase and K-feldspar in sedimentary units lacking carbonate cement, however, in the calcite-cemented intervals the K-feldspar and plagioclase grains have been albitized. The absence of feldspar albitization in the majority of the sedimentary units except in the carbonate-cemented intervals suggest that the host sediments have not reached the feldspar albitization temperature window.

Plagioclase is preferentially albitized compared to K-feldspar, (Morad et al., 1990), whereby albite crystals predominantly exist in the voids left by dissolved detrital plagioclase. Albite grains exist mainly as aggregates of euhedral albite crystals that replace the detrital plagioclase grain. Albite is formed mainly as very thin rims on K-feldspar grains. The replacement appear to be pseudomorphic within K-feldspar while mainly non-pseudomoprhic in the plagioclase. This suggests that the mechanism of plagioclase and K-feldspar albitization processes are quite different. The very thin albite rims found on K-feldspar grains may signify the low abundance of secondary potassium sinks observed. Apparently, small amounts of fibrous illite formed locally associated with kaolinite and dissolved feldspar. This chemical environment may have stabilized K-feldspar and thus restricted the albitization process.

Albite formation as a replacement of plagioclase starts when the temperature is higher than about 75 °C (Boles and Ramseyer, 1988; Morad et al., 1990), but the minimum temperature of plagioclase albitization is still poorly constrained. The albitization of K-feldspar is commonly associated with illitization of kaolinite at greater burial depths and temperatures above about 125 °C (Morad et al., 1990). The calcite-cemented intervals in the studied sandstones reveal evidence of fibrous illite formation related to kaolinite. This indicate that the sediments may have been subjected to a high temperature event transforming kaolinite to illite. However, illite may also be formed from smectite at temperatures above about 60–70 °C (Hower et al., 1976; Bjørlykke and Jahren, 2015). Morphologically diagenetic illite show a lath-shaped texture that resembles the precursor smectite (Bauer et al., 2000). Fibrous illite on the other hand, is normally only found at high temperatures (>120 °C), as the energy barrier of nucleating these crystals are high on e.g., kaolinite (Wilkinson and Haszeldine, 2002; Lander and Bonnell, 2010). Fibrous illite in this study was only found locally together with the other evidence of hydrothermal alteration, further pointing to alteration along localized features (e.g., flow baffles). This suggests that the calcite-cemented sedimentary units of DG and WS have been affected by processes deviating from the normal burial diagenesis trend in the study area.

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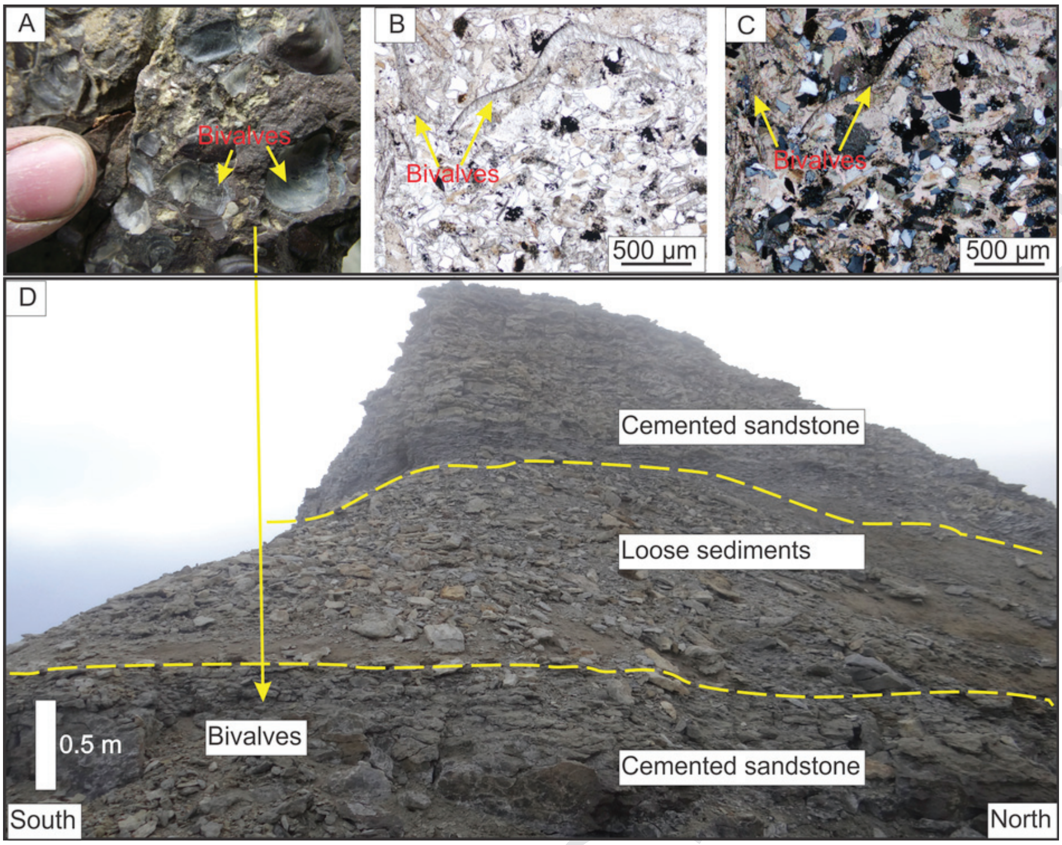

Figure 12. The sample and outcrop is from Wilhelmøya subgroup at Wilhelmøya. A) Picture of hand sample showing bivalves. B, C) Optical micrographs showing the distribution of bioclasts (bivalves) and carbonate cements at thin section scale. The calcite cement replaces bioclasts. D) A picture of an outcrop section showing thin carbonate cemented layers with bivalves at the bottom, loosely cemented layers in the middle and thick carbonate cemented layers at the top. The location of outcrop section is eastern Wilhelmøya (79.06825°N and 20.72986°E) and view is westward. B is picture taken in plane polarized light while C in cross-polarized light.

5.3. Mechanism of the hydrothermal induced diagenesis

Abnormally high temperature authigenic phases were distinguished in the calcite-cemented intervals both above and below the sill intrusion at distances up to more than five times the thickness of the sill. The conductive mechanism commonly used to explain heat transport away from sill intrusions fail to explain this observed diagenetic pattern. Instead, an explanation invoking that the formation of thermal convection hydrothermal cells can take place in a sedimentary basins consisting of interbedded highly porous-permeable sediments and semi-permeable or impermeable layers such as shale or calcite-cemented units (Genthon et al., 1990). Such cells may form focused flows along the flow baffles, limiting the high temperature alteration to these narrow zones.

Magmatic sills intruding into reservoirs rocks may change the petro-physical properties of the reservoir rocks intruded. Mobilization of hydrothermal fluids setting up convective fluid flow cells may affect strata located a considerable distance away from magmatic activity. The fluid flow will follow the most permeable sandstone strata or along permeable faults or fracture zones (Wilson et al., 2007).

There are several indications that calcite cemented intervals of the sediments have been subjected to higher temperatures. This is shown by the sericitized feldspars, albitized feldspars, carbonate fluid inclusions, and fibrous illite formation associated with kaolinite and relict feldspar, all pointing to hydrothermal alteration ($T > 120–140$ °C). The sericite (illite) could likely be detrital in origin but its nonexistence in the uncemented intervals suggests in situ formation related to hydrothermal fluids.

The source of the heat is presumably the magmatic sill intrusions penetrating the sediments at several levels. The magmatic sill intrusions are generally not sufficiently thick to thermally affect the entire sequence because the thickness of the sedimentary strata that could be affected by thermal heat generated by the sill intrusions due to conduction according to most estimates is approximately twice the width of the sill (Dow, 1977; Peters et al., 1978; Karlsen et al., 1998; Brekke et al., 2014). However, intrusion into shallow highly porous sediments can create hydrothermal convection cells, which is the most effective way of dissipating the excess energy (Einsele et al., 1980).

Fluid flow due to sill emplacement will most likely initiate close to the top of the gently dipping sill surface and also likely under the sill. This will be at either tip of the sill since sills tend to be saucer shaped structures (Jamtveit et al., 2004) and under the sill due to build-up of high fluid pressures sufficient to trigger fluid mobilization. The prevalent geometry of the igneous intrusions emplaced during the early Cretaceous has been identified as saucer-shaped in central Spitsbergen (Senger et al., 2013). This would explain why the sandstone strata has been altered only in areas where permeability differences resulting from existing carbonate cemented layers has led to channeling of the hydrothermal fluids.

The heat perturbation related to the emplacement of relatively small sill bodies is short-lived (Galland et al., 2006; Parnell, 2010). However, the reactivity of the pore water will be highly enhanced when mixed with heated hydrothermal fluids because this may lead to undersaturation with respect to carbonates. This will then induce dissolution followed by precipitation of the carbonates whose dissolution-precipitation kinetics is known to be fast. As mentioned above, the diagenetic fingerprints of most of the highly permeable sedimentary succession and the vitrinite reflectance indicate that the sandstones have not been subjected to higher temperature. Only the low permeable calcite cemented intervals that have been exposed to the hydrothermal pore water flow, contain high temperature diagenetic phases. Based on the above observation, we proposed that buoyant fluids have been partly following tight carbonate cemented flow baffles, before migrating into the sedimentary strata (Fig. 13A). On a local scale, the amount of calcite cement in each cemented intervals vary (Fig. 13B). The observations of hydrothermal induced diagenesis associated with the cemented sedimentary strata both close (~1 m) and far away (~65 m) from the sill suggest hydrothermal fluid mobility through the strata (Fig. 13).

The main effect of the hydrothermal fluids is recrystallization of already existing carbonates, and localized formation of hydrothermal albite, illite and sericite. Most likely, the carbonate containing layers lost their remaining porosity due to the hydrothermal activity but these layers must already have been flow baffles before the magmatic intrusions were emplaced. Identification of fluid pathways both vertical and lateral has not been done in the investigated area. Fluid movement resulting from sill emplacements should be studied further in the area in order to elucidate possible flow patterns generated by sills better.

5.4. Implications of sill intrusions on reservoir quality

The hydrothermal fluids injected into cooler host rocks due to sill intrusion emplacement may have impacts on porosity distribution (Einsele et al., 1980; Holford et al., 2013; Senger et al., 2014). The data presented above show that diagenetic reactions related to hydrothermal fluid flow related to sill emplacement were observed in carbonate-cemented intervals only. No apparent diagenetic effects like porosity decrease related to the sill emplacement was observed within intervals lacking carbonate cements. This is in accordance with earlier findings where the total porosity even as close as a few centimeters from the sill intrusion was unaffected by contact diagenesis (Mckinley et al., 2001; Grove, 2014; Grove et al., 2017). However, the hydrothermal fluid flow set up by the sill intrusion affected already existing flow barriers or baffles related to carbonate cemented layers. This lead to recrystallization and possibly increased cementation along already cemented intervals resulting in increased reservoir compartmentalization. Increased compartmentalization due to recrystallization should be considered since thin carbonate cemented layers and/or shale layers might exist in many siliciclastic reservoir rocks. This observation can be extended to any sedimentary basin where interbedded sandstone with thin carbonate or shale layers is common. Porosity will probably be reduced within the cemented layers after recrystallization while the reservoir quality outside the recrystallized zones will probably not be affected significantly.

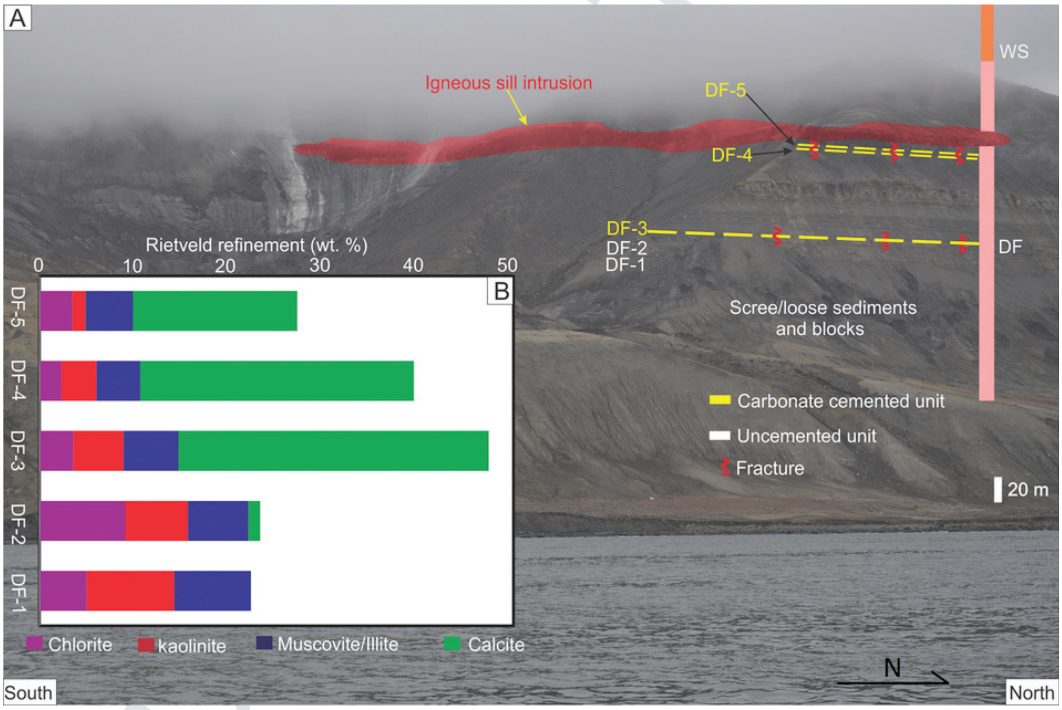

Figure 13. Shows layer superimposed with red colored transparency is a mafic Early Cretaceous intrusion (ca. 124.5 ma) that is cutting through Triassic strata (De Geerdalen Formation) along the eastern shores of Wilhelmøya (ca. 3.5 km east of Tumlingodden locality), Svalbard. The location of cliff section is eastern Wilhelmøya (79.08144°N and 20.68276°E) and view is westward. The intrusion is sub-parallel to layering for most of its length. Sampling locations of the hosting sedimentary layers are indicated with sample codes (DF-1 to DF-5). The samples were collected from both carbonate cemented and uncemented layers. B) Histogram displays results of quantitative XRD Bulk mineralogy of DF-1 to DF-5 for primarily showing the variation of weight percent of calcite in the cemented intervals.

6. Conclusion

Investigating impact of igneous intrusions on reservoir properties is important in order to evaluate their impact on the hydrocarbon potential of the northwestern Barents Sea and sedimentary basins elsewhere. In this study, the influence of sill intrusions on diagenesis and hence reservoir quality was evaluated.

Diagenetic evidences show that the upper Triassic and lower Jurassic sandstones at Wilhelmøya may be divided into intervals with different thermal histories; one being the bulk sediment, being largely unconsolidated and with a maximum burial temperature much lower than about 60-70 °C; and the second being thinner intervals that have experienced higher temperatures related to hydrothermal activity. The hydrothermally altered intervals are all tightly carbonate cemented layers. These intervals were most likely already carbonate cemented before the hydrothermal activity commenced, and would therefore have been flow baffles during the hydrothermal activity and thereby partly controlling the migration pathways of the buoyant hot fluids.

The hydrothermal fluid flow set up by the magmatic sill intrusions have affected the carbonate cemented sandstone intervals both close to the sill (~1 m) and away (~65 m) from the sill intrusion. The carbonate cemented intervals revealed high temperature hydrothermal induced reactions such as recrystallization of carbonate cements, localized sericitization of feldspars, albitization of both feldspar and plagioclase, and formation of fibrous illite nucleated on kaolinite. Within the intervals not affected by hydrothermal activity, there was no indication of hydrothermal induced diagenetic changes. This implies that the sill intrusion emplacement has not affected the porosity of these intervals.

Most of the available literature has focused on the effect of sill intrusion through conduction only. This work shows that igneous sill intrusion can also affect host rock intervals due to heat transfer through fluid flow. Possible hydrothermal fluid convection cells resulting from emplacement of sills should therefore be assessed together with conduction heat transfer when the influence of sill intrusions on reservoir quality is evaluated. The results from this study are applicable to the more general case of sedimentary basins having equivalent settings to the Wilhelmøya sediments.

Performing numerical modeling regarding the hydrothermal convection cell is beyond the scope of this study; however, the results obtained from this study could likely serve as inputs to perform such type of modeling in a future study. This will allow performing mass and energy balance calculations in order to understand the interplay between porous and permeable sediments and magmatic intrusions. This may enhance our quantitative predictive ability regarding reservoir quality evolution in such settings.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.gsf.2018.02.015.

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