Reservoir quality characterization and prediction of deeply buried clay coated sandstones on the NCS, Examples from the South Western Barents Sea and Northern North Sea

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Preface

This article-based dissertation has been submitted to the Department of Geosciences, Faculty of Mathematics and Natural Sciences at the University of Oslo (UiO) in accordance with the requirements for the degree of Philosophiae Doctor (PhD). The PhD study was completed in four years and the Ministry of Education and Research funded the project. The main supervisors of this work were Prof. Jens Jahren and Dr. Beyene Girma Haile.

The main objective of this work was to characterize clay coats in reservoir sandstones in the subsurface to better understand their formation, distribution and implications for reservoir quality heterogeneity. This work is a multidisciplinary study that employs petrographic-, sedimentological-, experimental- and data science methods and it was conducted based on core- and well log data from the North Sea and Barents Sea regions on the Norwegian Continental Shelf (NCS).

This thesis consists of six chapters that provide a general background and a summary of the main messages from the Journal articles. The full-length versions of the papers can be found in Appendix A.
Acknowledgement

I want to extend my sincere gratitude to the people who have guided me over the past four years as a PhD-student at the University of Oslo. Firstly, my main supervisor, Professor Jens Jahren. Thank you for all our great conversations the past years, both professional and personal. Your door is always open, and I have always been welcomed with a warm and big smile. I am truly thankful for all your support, motivating words and professional guidance throughout my Master’s- and PhD studies. You have been essential to my professional- and personal development. You have been a father figure for me (a funny one). I am also very thankful for the guidance, discussions and support from my co-supervisor Dr. Beyene Girma Haile. You have taught me so much and your willingness to help and guide me has been essential for my professional development. I highly appreciate you as a colleague and friend. A big thank you also go to Anja Sundal, my second co-supervisor.

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Finally and most importantly, my loving- and supportive partner and our dear son, Kristine and Jakob, we share this accomplishment together. You have brightened up this journey with your smiles and love. Thanks for always being there.

Henrik N. Hansen, Oslo, August 2022.
List of articles

**Paper I – Published paper:**


**Paper II - Published paper:**


**Paper III – In press, Journal of Petroleum Science and Engineering:**


**Paper IV – Published paper:**


**Paper V – Published paper:**

Additional contributions

Conference and invited talks


Master thesis co-supervision

Ghebreiesus. (2021). *Reservoir quality and diagenesis of the Sognefjord formation, northern North Sea*. URL: https://www.duo.uio.no/handle/10852/89857
Chapter 1: Introduction

1. Introduction

The oil and gas industry is increasingly shifting its focus toward the exploration of mature provinces to exploit existing infrastructure to save time and cost, and meet the demand of lowering production related to CO₂ emissions. This strategy includes exploring new profitable hydrocarbon reserves as well as characterize potential sites for CO₂ storage in surrounding areas. Exploration in mature provinces usually means exploring deeper buried prospects, which calls for a thorough understanding of diagenetic processes that control reservoir properties (i.e., porosity and permeability) at great burial. Clay coats are widely recognized to preserve reservoir quality in deeply buried sandstone intervals, but still their formation and distribution and hence their predictability is elusive. Essentially, all major geological processes associated with the source-to-sink profile (Figure 4) have implications for the developing high quality reservoir sandstones, as well the formation of effective grain coats. Therefore, it is challenging to establish generalized models that can accurately predict the occurrence of clay coats in the subsurface. One major unresolved challenge with respect to the formation of clay coats and their occurrence ties to the depositional environment and more specifically the fundamental mechanism(s) responsible for attaching clay particles to the surface of detrital grains. This problem has to some degree been addressed from two sides of the source-to-sink profile in the literature, where: (1) the major controls on variations in sediment composition in sedimentary basins as a function of the hinterland rock suit and alteration during transport are well known and (2) detailed case studies of in-situ clay coated reservoirs, where a back-stepping approach has been commonly used to infer the formation of clay coats by linking their occurrences to provenance, depositional settings that favor co-deposition of sand- and clay-sized sediments and the formation of marine clay minerals. While case studies are essential for characterizing the distribution and morphological features of clay coats in the subsurface, the study of natural analogues integrated with experimental work can be key to unlock a better control on their formation and distribution within a specific depositional environment and thus increase predictability. This thesis focuses on three main objectives related to detrital clay coats in reservoir sandstones (Figure 1): (1) detailed characterization and comparison of two distinct types of clay coats and their implications for the reservoir quality distribution, (2) prediction and characterization of reservoir quality in clay coated reservoirs on a regional scale and (3) study the clay coating attachment process. The latter is an important knowledge gap with respect to the precursor clay formation and hence their distribution in various sedimentary systems.
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1.1 Outline

This thesis consists of six chapters which make up the thesis body and an appendix, which contains the full length version of four published scientific papers and one submitted manuscript (Figure 1). Chapter 1 introduces the main objectives and motivation in addition to a presentation of methods and data and a general introduction to the study area. Chapter 2 presents a scientific overview of geological processes important for the formation of clay coats and high grade reservoir sandstones. Chapter 3 contains a summarized version of the objectives and motivation for each paper along with a list of bullet points that highlights the main messages and conclusions. Chapter 4 presents a higher level summary where the main findings from the scientific contributions are interlinked, whereas a list of concluding remarks are given in Chapter 5. In Chapter 6, suggestions for further work are presented.

Figure 1: Overview of scientific papers included in the thesis.
1.2 Motivation and objectives

This thesis focuses on clay coats in reservoir sandstone units that have a detrital origin, meaning that the clay coats- or a precursor clay phase formed before burial. The three main objectives of this study are: (1) give a detailed characterization of two distinct types of clay coats and their implications for the reservoir quality distribution, (2) prediction and characterization of reservoir quality in clay coated reservoirs on a regional scale and (3) study the clay coating attachment process (Figure 1). This is achieved through case studies of clay coated reservoir sandstones of Cretaceous- and Jurassic age from the Norwegian Continental Shelf (NCS) and through experimental work. The Jurassic sandstone of the Stø Formation in the South-Western Barents Sea (SW Barents Sea) comprises an extremely thin illitic clay coating that shows highly varying degrees of clay coat coverage in sandstone units that predominantly have been deposited in a shallow marine setting. Alternatively, the Cretaceous sandstone of the Agat Formation in the northern North Sea comprises exceedingly thick and continuous chlorite coats in sandstones that were deposited by sediment gravity flows in a deeper marine sedimentary system. Hence, the highly contrasting morphological characteristics of the two above-mentioned types of clay coats make them suitable candidates for assessing and comparing implications for reservoir quality in two extreme scenarios. Moreover, both the Stø- and Agat formations have undergone significant post-depositional burial in their respective study areas which makes these cases studies relevant for characterizing the effect of diagenesis. Also, their origin within different depositional settings may give clues about the formation and distribution of clay coats in various sedimentary systems. A secondary aim in this thesis is to characterize and predict reservoir quality in clay coated reservoirs from well log data aided by machine learning. As core data are expensive and time consuming to acquire and the industry is increasingly focusing on deeply buried targets in mature provinces to exploit already operating installations, the need for innovative and efficient methods for assessing reservoir quality in deeply buried prospects is clear. The results from this investigation can have important implications for efficient reservoir quality delineation at a regional scale. The third area of focus in this thesis is to start the process of unrevealing the fundamental controls on clay coat attachment on the surface of detrital sand-sized grains. This is a complex problem which will be given attention in the form of simple experimental mechanical mixing of sand and clay, which may guide further research on the topic.
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1.3 Methods and data

This multidisciplinary study call for the implementation and integration of various geo- and data scientific methods including petrographic-, petrophysical-, sedimentological-, experimental- and machine learning analyses (Figure 1). Papers I, II and IV, the case studies, implement detailed petrographic analyses and petrophysical- and sedimentological characterizations. These studies are based on well log and core data from 15 wells on the NCS, 14 wells in the SW Barents Sea and 1 well in the northern North Sea, out of which cores from 5 wells have been strategically sampled and made into 58 thin sections. The thin sections were analyzed in both optical- and scanning electron microscopes. Paper III employs petrophysical- and machine learning based analysis to characterize porosity distributions and well log responses within the Stø Formation in the SW Barents Sea. This study is predominantly based on well log- and core plug data from 38 wells located in the Hammerfest Basin, Ringvassøy- and Bjørnøyrenna Fault Complex, Polheim sub-platform, Fingervåg Sub-basin and the Bjarmeland Platform (Figure 2B). In total, this study uses 5915 helium porosity data samples, obtained from core measurements within the Stø Formation, in the 38 wells. The machine learning analysis was performed using the python programming language (Van Rossum and Drake Jr, 1995) and the third-party package Scikit-learn (Pedregosa et al., 2011). Paper V is an experimental laboratory study, which investigates the effect of mechanical mixing of industrial quartz grains and natural chlorite, purchased from the Clay Minerals Society. Batch experiments were characterized using binocular stereo- and scanning electron microscopes (SEM). Semi-quantitative clay coat coverage estimations were obtained for each experiment using python and the image processing library Scikit-image.

1.4 Study areas and geological settings

The case study areas in this thesis are located on the Norwegian Continental Shelf (NCS) within the North- and Barents Sea regions (Figure 2A). More specifically, papers I, II and III are conducted in the SW Barents Sea area with paper I being based on data from one well in the Bjørnøyrenna Fault Complex and paper II on data from 14 wells within the Bjørnøyrenna Fault Complex, Hammerfest Basin and Ringvassøy Fault-Loppa Fault Complex. Paper III is based on well data from 38 wells located in the Hammerfest Basin, Ringvassøy- and Bjørnøyrenna Fault Complex, Polheim sub-platform, Fingervåg Sub-basin and the Bjarmeland Platform (Figure 2B). The Barents Sea is an epicontinental platform on the northwestern flank of the Eurasian continental plate and the Barents Sea area are bounded by the northern coasts of Norway to the south, Svalbard to the north-west and by Franz Josef Land and Novaya Zemlya to the north and north-east, respectively. The study area that formed the basis for
**Paper IV** is located in the northern part of the North Sea. The North Sea is an epeiric sea that lies between Great Britain to west, Denmark, Germany, the Netherlands, Belgium and France to the south and Norway and the Norwegian Sea to the North (Figure 2A). The well being studied is situated on the Måløy Slope in an area to the northeast of the Gjøa field (Figure 2C).

The SW Barents Sea area is characterized by numerous basins, highs and platforms that have formed in response to a complex geological evolution. This structural architecture was dominated by three major rift phases following the Caledonian Orogeny in the Late Devonian-Carboniferous, Middle Jurassic-Early Cretaceous and Early Cenozoic (Faleide et al., 1984, Faleide et al., 1993). The Hammerfest...
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Basin, where most of the data in this study originate from, is a 70 km wide and 150 km long basin with an ENE-WSW trending axis. Thick sedimentary successions ranging from late Paleozoic to Cenozoic in age are present in the SW Barents Sea region, where most of this sedimentary package consists of siliciclastic sediments, except for some carbonates and evaporites of Carboniferous to Permian age (Faleide et al., 1984). The Triassic- and Jurassic successions are the main targets in terms of petroleum exploration in the area, where particularly the Jurassic sandstones of the Stø Formation exhibit good reservoir quality at certain intervals (Olaussen et al., 1984). The Stø Formation is part of the Norian-Bajocian Realgrunnen Subgroup and was deposited between the Pliensbachian to Bajocian during the Lower-Middle Jurassic epochs (Figure 3) (Dalland et al., 1988). The Stø Formation is thickest in the western part of the SW Barents Sea and a gradual thinning is generally recognized eastwards toward the Horda Platform. The formation overlies the Fruholmen Formation and this contact can generally be determined by a sharp transition from the more chaotic gamma ray patterns of the Fruholmen, to the more blocky and smooth curve that characterizes the Stø Formation (Dalland et al., 1988). The fact that the Stø Formation is highly condensed, and that it was deposited over a significant time span and covers more than 300 by 600 km, makes it difficult to map and place this formation into a clear depositional history (Klausen et al., 2018). However, sandstone units that comprises this formation are generally texturally- and mineralogical mature (Figure 3), and were mainly deposited in a shallow marine setting that was influenced by tidal- or wave processes (Olaussen et al., 1984, Klausen et al., 2018). The mature nature of the Stø Formation has been attributed to extensive reworking, including reworked Triassic sediments in the lower part of the formation (Klausen et al., 2019), and the mature source area of the rejuvenated hinterland in the south (Bergan and Knarud, 1993, Worsley, 2008). The gross evolution of the area at the time was likely an overall prograding coastal regime that was interrupted by several transgressive events which is represented by thin siltstone- and shale layers within the formation (Olaussen et al., 1984, Gjelberg et al., 1987, Dalland et al., 1988, Klausen et al., 2018).

Similar to the SW Barents Sea, the structural framework of the North Sea is a result of major tectonic events, where the Upper Jurassic-Lower Cretaceous riftiing is considered the most important, which compartmentalized the area into a series of rotated fault blocks (Badley et al., 1988, Færseth, 1996). Following this rift event, the normal faulting ceased and the Early Cretaceous period was mainly characterized by post-rift subsidence and where the inherited basin configuration had a major influence on sediment-routing pathways and infill (Bugge et al., 2001, Gabrielsen et al., 2001). The Cretaceous sedimentary successions in the area have been interpreted to be deposited during an overall transgressive period because the rock record points toward an overall deepening throughout the Cretaceous time (Skibeli et al., 1995). The primary potential reservoir targets within this time frame
are the sandstones of Åsgard- and Agat formations, which were deposited during the Late Ryazanian to Barremian- and the Albian stage, respectively (Isaksen and Tonstad, 1989, Skibeli et al., 1995). The Agat Formation, as defined by Isaksen and Tonstad (1989), is a member of the Cromer Knoll Group and consists of sandstone units that are interbedded with the extensive Rødby shale (Figure 3). Several depositional models have been suggested for the Agat Formation, for example these sandstones have been interpreted to represent slump and mass flow deposits that were relocated from a narrow shelf and deposited in an upper slope setting (Shanmugam et al., 1994, Skibeli et al., 1995). Other studies have interpreted these sandstones as turbidities, where amalgamated thinner sandstone units form thicker massive successions at certain locations (Nystuen, 1999, Bugge et al., 2001, Martinsen et al., 2005).

Figure 3: Stratigraphy of the Jurassic and Cretaceous successions in the northern North Sea and in the SW Barents Sea. Figure modified from Gradstein et al. (2010).
2. Scientific background

2.1 Reservoir quality in the context of a source-to-sink profile

The distribution of reservoir properties (porosity and permeability) within siliciclastic sandstones in the subsurface are a function of a complex array of geological processes occurring along the source-to-sink profile; including provenance, transport, depositional- and diagenetic processes (Figure 4). These processes collectively determine the framework grain composition, textures and cements that characterize a sandstone reservoir (Ajdukiewicz and Lander, 2010, Bjørlykke and Jahren, 2012, Bjørlykke, 2014), as well as the development of clay coats (Bloch et al., 2002, Morad et al., 2010, Dowey et al., 2012). This is so because sedimentary units tend to retain an overall constant bulk chemistry during burial which is inherited from the depositional site and hence provenance (Bjørlykke, 2014). Since these geological processes are essential for understanding reservoir quality and clay coating distribution in the subsurface, this chapter will present an overview of the source-to-sink profile.

2.1.1 Provenance and transport

The rock suit of a catchment area exerts a first-order control on sediment- or rock composition at any step along the source-to-sink profile (Figure 4A). Additionally, the rate- and amount of sediment supply to sedimentary basins is a function of the tectonic setting, relief and climatic processes occurring at the earth surface (von Eynatten and Dunkl, 2012). Tectonic- and volcanic activity may expose rocks formed deep in the earth’s crust at the surface along with second order sedimentary units and these rocks are broken down into smaller fractions (i.e., soils and sediments) due to weathering. The climate controls the rate- and type of weathering, where chemical weathering is more prominent under humid conditions, typically in regions with high annual precipitation rates because the chemical reactions are governed by the interaction between rock and water (and air) (Grantham and Velbel, 1988). Additionally, rock fractures formed in response to a decrease in stress and temperature associated with large scale tectonic uplift, serve as initial pathways for meteoric water. These fractures increase the overall surface area of the exposed rock which enhances the rate of weathering (Kump et al., 2000). Goldich (1938) recognized that the rate of weathering in various mineral phases was linked to the continuous- and discontinuous reaction series of magmatic rock formations, where Olivine and Plagioclase are the first to form from a mafic- and felsic melt, respectively. These minerals are less stable at the earth surface compared to for example K-feldspar, mica and quartz and are more
susceptible to weathering (Kowalewski and Rimstidt, 2003, Wilson, 2004). Depending on the mineral assemblages of the host rock, relief and climate, various weathering products may be produced, which subsequently control the composition of the sediment. For example, in terms of clay coated reservoirs, a review study by Dowey et al. (2012) indicated that a mixed host rock composition could be a prerequisite for developing chlorite coats in coarse-grained reservoir sandstones with an overall quartzofeldspathic grain framework. Here, the felsic rock suits are crucial for supplying constituents for the formation of coarse grained sandstones (Primmer et al., 1997), whereas mafic rocks contribute instead with the formation of clay rich sediments (Velde and Meunier, 2008). Additionally, the supply of particulate iron-oxides and hydroxides through weathering of ferromagnesian minerals facilitates the formation of Fe-rich clays in coastal-marine environments e.g., (Ehrenberg, 1993).
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Figure 4: Source- to sink profile with emphasis on processes important for porosity evolution in siliciclastic sedimentary rocks and clay coat formation formed from a Fe-rich precursor clay phase. Figure not to scale.
Even though the host rock composition to a large degree determine the composition of the weathering products, the detritus is constantly altered during transport. Climate and topography exert an essential role in further alteration, because they control weathering intensity and residence time of grains under which weathering occurs (Suttner and Dutta, 1986, Grantham and Velbel, 1988, Morad et al., 2010). This can ultimately dictate the ratio of stable and more unstable mineral grain assemblages delivered to sedimentary basins (von Eynatten and Dunkl, 2012). Rivers are the major transport agents responsible for relocating numerous terrigenous sediments, both solid and dissolved materials, from the hinterlands to sedimentary basins (Milliman and Meade, 1983, Milliman and Syvitski, 1992). The transport mechanisms within fluvial systems involve bed loads, where sediments are moved along the river bed by rolling or saltation, or as suspended material due to fluid turbulence (Figure 4B) (Syvitski et al., 2000). Depending on the hydrological regime, clay, silt and sand particles can be transported in suspension whereas coarser particles tend to be transported as bed loads.

2.1.2 Depositional environment and shallow burial diagenesis

The depositional environment is a key factor in determining reservoir heterogeneity in the subsurface because it controls important aspects like the spatial and temporal distribution of sand bodies, sand-clay ratio and the modes of occurrences of clay minerals (Wilson and Pittman, 1977, Wilson, 1992, Morad et al., 2010, Bjørlykke, 2014). Additionally, the textural properties of sand sized sediments can be associated with a specific depositional setting, although grain size and sorting tend to vary considerable within a facies. This is because the grain size distribution to a large degree is determined by the sediment supply from the hinterlands and varying depositional energy (including biogenic activity) within each setting (Bloch et al., 2002). Beard and Weyl (1973) showed how initial (depositional) porosity and permeability vary systematically as a function of grain size and sorting. The above-mentioned factors control the initial porosity and permeability of the sediment which subsequently influence the diagenetic pathway, along with stress, time and temperature, which further modify the porosity and permeability distributions during burial (Morad et al., 2010). Moreover, sediments are most prone to react with meteoric water and the atmosphere in the top few meters of the sediment column. In appose to diagenetic processes at greater burial, the geochemical system at shallow burial can be regarded as an open system where meteoric water, which is initially understated with respect to minerals in the sediments, can alter the overall sediment composition (Bjørlykke and Jahren, 2012). The formation of kaolinite through leaching of K-feldspar and muscovite is a common process in settings with a high meteoric fluxes, because the reaction is governed by a high
Chapter 2: Scientific background

H+/K+ ratio (Figure 5). These favorable conditions are obtained from the constant supply of acidic meteoric water and the removal of potassium and silica (Bjørlykke and Jahren, 2012). Leaching of feldspar and muscovite can be an effective way to increase the mineralogical maturity of shallow marine sandstones in certain settings, e.g., transgressive sands (Mork, 1999), because repeated sediment reworking can remove kaolinite which will increase the overall quartz content of the sediment.

Figure 5: Leaching of feldspar and precipitation of kaolinite in neighboring macro pore. The original outline of the feldspar is preserved due to the presence of clay coating. However, these features are most often destroyed during mechanical compaction. Modified from Bjørlykke and Jahren (2012).
Clay coats with a detrital clay origin

The depositional environment is important for the co-deposition of sand- and clay material, which have important implications for developing clay coats in the subsurface that are formed diagenetically via a precursor clay phase or as clay coats that largely maintain their mineralogical- and morphological characteristics due to being non-reactive during burial. However, the link between facies and the formation of detrital clay coats are still elusive, because the exact mechanisms responsible for the clay attachment process(es) are poorly constrained. Moreover, clay coats form in various depositional settings and by various processes.

Wilson (1992) used the term inherited clay rims to describe detrital clay coats that form before their final deposition and found that they are common in sandstones that originate from eolian and marine-self environments. These detrital clay rims have certain characteristics that make them differentiable from authigenic cements, like the presences of clay at grain contacts between framework grains (Figure 6A), highly variable thickness including the tendency to exhibit thicker coats in grain indentations (Figure 6B) and they are absent on diagenetic components (Figure 6C) (Wilson, 1992). Matlack et al. (1989) also observed detrital clay coats in coastal environments, where clay coats were most abundant in fluvial, deltaic and marginal marine facies. From experimental work, this study concluded that the detrital clay coats formed by the means of infiltration, because clay bridges were commonly seen between framework grains (Figure 6D) (Matlack et al., 1989). The development of clay coats due to infiltration is a function of the grain size of sand- and clay particles, clay particle morphology and it is favorable in settings with a high concentration of suspended sediments, fluctuating water levels and minimum subsequent reworking (Matlack et al., 1989). However, Wilson (1992) suggested that clay coats can survive mild reworking and this is further supported by a recent experimental study (Verhagen et al., 2020). This experimental study shows that coating thickness and coverage is noticeably degraded during transport, but still sufficient grain coat coverages were retained in post experimental samples. They concluded that the resultant clay coat extent is governed by more complete and thicker grain coats prior to transport (Verhagen et al., 2020). Modern analogue studies of sediments from estuaries have also shown to be a suitable setting for the formation of detrital clay coats (Dowey et al., 2017, Wooldridge et al., 2017b, Virolle et al., 2019), where their development has been attributed to a combination of infiltration- and biological processes. Exopolymeric substances (EPS) secreted by organisms have also been reported as an additional contributor to binding detrital clay on sand grain surfaces in these systems (Wooldridge et al., 2017a, Duteil et al., 2020). Detrital clay coats has also been observed in deep marine sandstones where the formation of these clay coats have been linked to sediment dewatering processes (Houseknecht and Ross Jr, 1992, Porten et al., 2019).
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Chlorite coats are widely referenced in the literature and these clay coats form in a range of depositional environments and from varying precursor clay phases, e.g., (Humphreys et al., 1989, Ehrenberg, 1993, Anjos et al., 1999, Haile et al., 2018, Azzam et al., 2022) or in other cases as direct precipitates from the dissolution of unstable detrital grains (De Ros et al., 1994, Berger et al., 2009). Detrital iron rich chlorite coats form from an Fe-rich precursor clay phase during burial (Aagaard et al., 2000) where the precursor clay phase has been tied back to specific depositional settings that favor the co-deposition of high quality reservoir sands and Fe-rich clays. The review paper of Dowey et al. (2012) found that most occurrences of chlorite coats in the literature are reported from delta- and fluvial environments (Figure 7) and that these clay coats are predominantly iron-rich. Aagaard et al. (2000) described how Berthierine transformed into chlorite during burial at temperatures of about 90°C. However, the Berthierine is likely an intermediate clay phase between the diagenetic chlorite and a detrital Fe-rich clay phase (Ehrenberg, 1993), like Odinite (Phyllite V) observed in modern analogue settings, which is a 7 Å clay mineral associated with the Verdine facies as described by Odin (1988), and defined by Bailey (1988). Odinite contain considerably more ferric iron than berthierine,
which contains predominantly ferrous iron. Odinite has not yet been identified in rock records older than the Recent Quaternary, likely due to being highly susceptible to alteration (Bailey, 1988). The clays of the Verdine facies form under reducing conditions, where ferric iron is reduced to ferrous iron in the post oxic zone. Depending on the ratio of the iron states, various 7 Å and 14 Å (or a mixture) clay mineral phases may form, where they are collectively referred to as green marine clays (Figure 4C) (Velde, 2005). Berner (1981) defined a geochemical zonation that is established in response to the metabolism of various available ion complexes by organisms. The ferric iron is sourced from the catchment area in response to weathering of (oxidation of ferrous iron) iron bearing minerals in the host rock (e.g., biotite or pyroxene), but ferric iron is insoluble in water, meaning that most of the iron is delivered to sedimentary basins as particulate iron oxides/hydroxides. Rivers are the predominant transport mechanism of flocculated iron oxides and – hydroxides along with clay and organic matter and these clumps are co-deposited along with other clay and clastic sediments, typically close to a river entry point into marine waters (Figure 4C) (Ehrenberg, 1993). However, Fe-rich chlorite coats forming from a precursor clay phase have also been identified in fluvial channels, e.g. (Haile et al., 2018), which indicate that Fe mineralization (clay formation) is important in larger parts of the source to-sink-profile.

![Figure 7: A histogram illustrating the occurrences of chlorite coatings as a function of depositional environment and their effect on reservoir quality. Taken from Dowey et al. (2012).](image-url)
Ehrenberg (1993) linked the chlorite content of high porosity zones to shallow marine environments based on the observation of abundant chlorite rich ooids, pellets and expanded mica within chlorite coated sandstones on the NCS. He argued that rapid Fe-clay formation may occur in higher energy environments on the seafloor in settings with a sufficient supply of reactive iron from the hinterland. Traditionally, the formation of these clays has been reported from environments characterized by low sedimentation rates (Odin, 1988). From a sequence stratigraphic perspective, grain coating Fe-clays are most abundant in transgressive- and early high stand system tracts (Figure 4D) (Morad et al., 2010) and particularly within deltaic environments (Morad et al., 2010, Dowey et al., 2012). These settings can be important for dictating the modes of occurrence of clay, where pore-filling clays can be removed whereas clay coats can be retained- or potentially fixated on the surface of detrital grains during mild reworking e.g., (Haile et al., 2018).

3.1.3 Intermediate- and deep burial diagenesis

**Mechanical compaction**

The initial porosity immediately after deposition (depositional porosity) depends on the textural properties of the sand particles, grain size and sorting, where coarser grained and better sorted sediments will have a higher initial porosity (Beard and Weyl, 1973). Initially, as stress is applied to the rock frame due to the weight of the overburden, sediments will start to compact mechanically by rotating and rearranging individual sand particles to form a closer packing, thus reducing porosity (Chuhan et al., 2002) (Figure 4E). Mechanical compaction of a sedimentary unit is the strain associated with a certain effective stress, where the compressibility of the rock frame is a function of the textural-and mineralogical composition (Chuhan et al., 2002, Bjørlykke, 2014). Effective stress is the difference between lithostatic stress (overburden stress) and pore pressure, which can significantly reduce the effective stress if it increases well above the hydrostatic pressure (Bjørlykke, 1999). Mechanical compaction is the predominant porosity reducing mechanism in sedimentary rocks, acting from the time of deposition to the onset of quartz cementation, typically at about 2 km depth (Bjørlykke, 1999). Experimental compaction studies have shown that for well sorted quartz rich sediments, the porosity loss is more intense in coarse grained- compared to fine grained sediments (Chuhan et al., 2002) (Figure 8A). This behavior is attributed to the total number of grain contacts, which increases with a
decrease in grain size. This means that the force acting at each individual grain contact is smaller in fine- compared to coarse grained sediments because the effective stress can be divided over more grain contacts. Typically, this will in turn lead to more intense grain fracturing (Figure 8B) in coarse grained sands which enhances the porosity loss (Chuhan et al., 2002). The fracture intensity is also dependent on grain shape because angularity can control the total grain contact area (Fawad et al., 2011). However, intense grain crushing may suppress the rate of compaction because it is difficult to crush this material any further. The coarse grained lithic sand shows an even higher rate of porosity loss (Figure 8A) and more intense grain fracturing (Figure 8B) compared to the coarse grained mono-quartz sand, which illustrates the effect of compositional variations due to varying grain strength (Chuhan et al., 2002). Thus, for sandstones in natural settings the rate of porosity loss can be greatly affected by the total content of rock fragments or other ductile fragments and clay. Experimental compaction studies have shown that there are large variations in the compressibility of various clay minerals and clay mineral mixtures (Mondol et al., 2007). However, these results are most important for shale units because sandstone frameworks are usually grain supported.

Figure 8: Experimental mechanical compaction of mono-quartz and lithic sands. A) Effective stress vs. porosity, B) effective stress vs fracture intensity. Modified from (Chuan et al. 2002).
Intergranular volume (IGV)

IGV is a useful measure of the proximity of neighboring framework grains and can be used to characterize the degree of compaction in sandstones. This value can be obtained from modal point count data and is defined as the sum of intergranular porosity, pore-filling cement and depositional matrix (Paxton et al., 2002). Hence, the IGV can be viewed as the maximum potential porosity before the onset of quartz cementation. However, within the chemical compaction regime, clay induced dissolution may be significant which will bring framework grains closer together and thus reduce the IGV. For example, varying IGV in coated- and negligible coated intervals within the Stø Formation in the SW Barents Sea have been linked to pressure solution along grain contacts (Hansen et al., 2017, Løvstad et al., 2022). However, Paxton et al. (2002) showed that the IGV of well sorted rigid sands typically declines rapidly from about 42% to 28% in the depth range of 0 to 1500 m. A slow decline in IGV follows down to about 2500 m, where the IGV stabilizes at about 26% (Paxton et al., 2002). The concept of IGV is a valuable addition to standard porosity-depth curves because it can be used to characterize the contribution from mechanical- and chemical compaction processes, on the intergranular volume loss.

Chemical compaction

Chemical compaction concerns the processes of dissolution and precipitations of minerals which are controlled by kinetics and thermodynamics. At the time of deposition, many minerals are thermodynamically stable but as temperature and stress increase with burial, new mineral phases may form (Figure 4E). In the following, some common and important processes that can affect the reservoir quality of sandstones will be presented.

Grain coating micro-quartz

Another type of grain coating that can be important under special circumstances is the development of micro-quartz grain coats (Aase et al., 1996). These grain coats are most commonly seen to originate from amorphous silica sponge spicules that dissolve and precipitate as micro-quartz coatings from supersaturated silica pore-waters at temperatures of about 60°C (Vagle et al., 1994). The micro-quartz grain coats have been documented to effectively preserve porosity at great burial depths (Aase et al.,
1996), because the random orientation of these small crystals prohibits the formation of macro-quartz overgrowth (Heald and Larese, 1974).

Quartz cement

As sandstone units reach temperatures of about 70-80°C, quartz cement will start to precipitate (Walderhaug, 1994) and this process rapidly becomes the most predominant porosity reducing mechanism in well sorted quartz-rich sandstones (McBride, 1989, Bloch et al., 1990, Bjorlykke and Egeberg, 1993). The source of silica is in most cases derived from the dissolution of quartz at micro- and macro-stylolites due to illite- and mica induced dissolution (Bjorkum, 1996, Oelkers et al., 1996) and hence sediment compaction is mainly concentrated along these surfaces. The dissolution of quartz at stylolites and precipitation of quartz overgrowth can be viewed as redistribution processes or bulk volume reduction within the sediment, which transforms the friable sandstone- to solid rock by reducing porosity (Figure 9A) (Oelkers et al., 2000). Quantitative modelling by Walderhaug et al. (2001) of sandstone thinning due to dissolution at stylolites illustrates the rate at which sandstones are compacted as a function of time and varying temperature scenarios (Figure 9B). Here, the sandstone column in all modeled scenarios will asymptotically approach a thinning that corresponds to the available pore space at the onset of quartz cementation.

![Figure 9: Quartz cementation in sandstones. A) Silica is mainly sourced from clay- and mica induced dissolution at micro- and macro stylolites and quartz cement is precipitated in inter-stylolite space. Figure from Bjørlykke and Jahren, (2012). B) Modelling of rate of sandstone thinning (compaction) for various temperature scenarios. Figure from Walderhaug, (2001).](image-url)
Chapter 2: Scientific background

The rate-controlling step in the quartz cement process is considered the rate of precipitation, which is controlled by temperature and available surface area. This is supported by evidence like the tendency of quartz cement volumes to be uniformly distributed in inter-stylolite space, which indicates that silica saturation is not the limiting factor within any parts of the sandstone body (Walderhaug, 1994). Modeling results of Walderhaug (1994) show how quartz cement volumes in sandstones with varying available surface area differ as a function of the time-temperature integral (TTI). The available surface area is controlled by the presence of grain coats and varies systematically as a function of grain size. For example, the results illustrate how a fine grained sandstone will be more heavily quartz cemented per unit time compared to a coarse-grained sandstone due to the large surface area associated with a finer grain fraction (Walderhaug, 1994). This implies that, even though fine grained sandstones may be less mechanically compacted compared to coarse-grained sediments, these fine-grained units can be significantly quartz cemented in deeply buried intervals without the presence of grain coats. The quartz cement process is by far the most important porosity reducing mechanism in deeply buried clean sandstones and thus it essential to evaluate its implications in any deep prospect evaluation.

**Grain coat alteration in deeply buried sandstones and their effect on reservoir quality**

As mentioned in the previous section, Fe-rich chlorite coats form from a precursor clay phase and this precursor phase is recrystallized into chlorite in response to changes in temperature during burial. The formation of Fe-rich chlorite coats from berthierine has been shown experimentally- and by field observations by Aagaard et al. (2000) to occur at approximately 90°C. However, this study also pointed out that the exact nature of the whole chlorite formation process is uncertain, but they discovered that the precursor clay phase was thin and did not cover grains entirely, while a neoformed chlorite coating was continuous in its nature. This process implies that other solid minerals must dissolve to accompany the necessary ingredients for the neoformed chlorite, but evidence for such dissolution features was difficult to detect (Aagaard et al., 2000). Chlorite coatings formed from the dissolution of iron- and magnesium-rich detrital grains have been reported in the literature (Berger et al., 2009, Dowey et al., 2012). Thus, the process could be extremely important for forming complete grain coats in scenarios with an incomplete precursor clay coating, because patchy grain coats will allow quartz cement to be precipitated on clean quartz surfaces (Walderhaug, 1994, Ajdukiewicz and Lander, 2010, Taylor et al., 2010). Ongoing quartz cementation in deeply buried sandstones with a patchy clay coating has been under characterization in papers included in this thesis (Hansen et al., 2017, Løvstad et al., 2022) and the effect of chemical compaction as a function of varying coating coverage is illustrated by
a hypothetical modelling case example by Ajdukiewicz and Lander (2010) (Figure 10). Moreover, studies of clay coat coverage in recent sediments have shown that detrital clay coats are generally patchy with a typical maximum coverage in the excess of 30%, e.g. (Wooldridge et al., 2017b, Virolle et al., 2019). The experimental work performed in this thesis (Haile et al., 2022), regarding mixing of sand and clay to study the clay attachment processes, also reported, at best, clay coat coverage at around 30%. Thus, a dissolution-precipitation transformation and/or a recrystallization of precursor clay phases may be key to develop effective grain coats during burial in many settings that have reactive clay coats. However, in most studies of iron rich chlorite coated reservoir resulting from a precursor clay phase, the chlorite coating seems to have been recrystallized from a precursor clay phase of varying thickness that is omnipresent on most grains (Ehrenberg, 1993, Line et al., 2018, Hansen et al., 2021). Chlorite coats have in most cases a positive effect on reservoir quality (Dowey et al., 2012), because they can retard quartz cementation. However, in reservoirs with thick chlorite coats, permeability may be significantly reduced due to tight pore throats, e.g. (Hansen et al., 2021).

Figure 10: Hypothetical modelling case of porosity evolution in well-sorted fine-grained sandstones as a function of burial and varying clay coat coverage. A) depositional porosity, B) porosity loss due to mechanical compaction, C) porosity loss in a sandstone at great burial in sandstone with 50% coating coverage, D) IGV is nearly constant after the onset of quartz cementation and porosity loss is accompanied by quartz cementation rather than mechanical compaction.
3. Scientific contributions

This chapter presents a summary of the main findings from the scientific papers included in this thesis. The complete papers are included in Appendix A.

3.1 Paper I

- Clay coating preserving high porosities in deeply buried intervals of the Stø Formation

Motivation, objectives and methods

The Lower-to Middle Jurassic Stø Formation is present over larger parts of the South-Western Barents Sea and is one of the primary targets for petroleum exploration (Worsley et al., 1988) because the formation has proven to exhibit excellent reservoir quality (Olaussen et al., 1984). However, due to its extensive lateral distribution, the Stø Formation has been subjected to highly varying burial diagenesis which has resulted in reservoir quality deterioration in certain parts, because of pervasive quartz cementation. Based on helium porosity data from within the Stø Formation in well 7219/8-2, a noticeable high porosity zone was detected that differed from surrounding low porosity intervals. The main objective of this study was to investigate the cause of this abnormally high porosity region. Core analysis, including detailed petrographic investigations, was carried out using optical- and scanning electron microscopy. Strategic sampling of core material above, within and below this high porosity interval were collected and thin sections were prepared.

Key outcomes:

- An illitic clay coating was identified to cover most quartz grains in samples from within high porosity regions, whereas only remnants of this clay coat were observed in low porosity samples. The clay coating was found to be effective in retarding quartz overgrowth when present. However, the clay coating within high porosity intervals is patchy and allows for sporadic quartz overgrowth.
- Modal point count results show that porosity is inversely proportional to quartz cement volumes. This trend is interpreted to reflect the effectiveness of the clay coating which is linked to the total grain coat coverage. The results show that samples with negligible clay coating had
quartz cement volumes exceeding 20%, whereas samples with a higher degree of coating coverage had quartz cement volumes of around 10% or lower.

- The appearance and distribution of the illitic clay coating i.e., chaotic texture, more abundant on rougher grains, thicker in grain indentations, present at grain contacts and clay bridges between detrital grains, indicate that the clay coating is detrital and that clay alteration during subsequent burial was limited. The higher clay coat coverage and the presence of clay bridges in high porosity samples indicate that the clay attachment processes, at least partly, occurred after the final deposition. The presence of clay coat remnants in low porosity samples indicate that the clay attachment processes occurred prior to final deposition. The unconformity observed at the top of the most prominent high porosity interval has been interpreted to be representing a transgressive event, meaning that the overlying layer could have been subjected to more substantial reworking and hence partly removed the already emplaced coating. The slightly higher degree of sorting and finer grain size, the absence of clay bridges and poorer coating coverage of negligible coated samples support this interpretation.
Chapter 3: Scientific contributions

3.2 Paper II

- The porosity preserving effect of basin wide illitic coating in deeply buried sandstone intervals of the Lower Jurassic Stø Formation, Barents Sea

Motivation, objectives and methods

The Stø Formation in the Bjørnøyrenna Fault Complex (well 7219/8-2) has proven to exhibit a patchy illitic clay coating that is characterized by a varying degree of detrital grain coverage between certain units (Hansen et al., 2017). The clay coating is effective in limiting significant quartz overgrowth where the illitic clay coating is abundant, while intervals with poor coating coverage show degraded reservoir quality at great burial. The sandstones of the Stø Formation have been observed to show similar mineralogical and textural properties at various locations within the SW Barents Sea (Olaussen et al., 1984, Klausen et al., 2018), however the illitic clay coating have only been studied in detail in one well (Hansen et al., 2017), hence little is known about the distribution and extent of such clay coats elsewhere in the region. Therefore, the main objective of this study was to investigate the occurrence of illitic clay coats within the Stø Formation in a regional context in wells where the formation has experienced significant burial diagenesis. In this study, petrographic thin section data from 4 wells in the Hammerfest Basin and Ringvassøy Fault Complex are examined in detail to uncover the occurrence of clay coats and their control on the porosity distribution. Additionally, petrophysical and helium porosity data from 14 wells in the Hammerfest Basin, Ringvassøy Fault Complex and Bjørnøyrenna Fault Complex are investigated to characterize the porosity distribution and the response in elastic parameters with respect to coated- and uncoated intervals. Successful identification of effective grain coats at a regional scale within the Stø Formation could have important implications for petroleum exploration in the area.

Key outcomes:

- Illitic clay coating is observed in all wells with petrographic thin section data obtained from the Hammerfest Basin and Bjørnøyrenna Fault Complex. This indicates that the illitic clay coating is common on a regional scale within the Stø Formation in the SW Barents Sea.
- Helium porosity data from 14 wells in the area show that abnormally high porosity intervals are common within deeply buried parts of the Stø Formation. These bimodal porosity distributions are interpreted to reflect the degree of quartz cementation due to the presence or absence of an effective grain coating. This interpretation is further supported
by the porosity-depth trend which shows that the porosity distribution becomes increasingly wider as a function of maximum burial depth.

- The CPI generated porosity data show a good match with the available helium porosity- and modal point count porosity data. This allowed for the characterization of high- and low porosity intervals within the Stø Formation using the P-wave velocity and density. Based on a threshold porosity of 15%, the results show that high porosity intervals in deeply buried parts of the formation have distinctly different P-wave velocity- and density signatures compared to low porosity regions. This indicates that powerful predictive models could be established, without the need of expensive petrographic- and core plug data, for recognizing intervals with effective grain coats in new wells.
Chapter 3: Scientific contributions

3.3 Paper III

- New direction for regional reservoir quality prediction using Machine Learning – Example from the Stø Formation, SW Barents Sea, Norway (In press: The journal of petroleum science and engineering)

Motivation, objective and methods

Recently, the oil and gas industry has increasingly shifted its focus to exploring for deeply buried reservoir discoveries and potential CO$_2$ sites close to existing infrastructure to increase the lifespan of already operating installations and thus save time and cost. This offers the possibility of exploiting already acquired high quality data to be successful and effective in their endeavor of reservoir quality delineation at the same stratigraphic intervals within a particular area. It can therefore be essential for the petroleum industry to find innovative approaches that can effectively exploit existing data like facies analysis, porosity- and petrographic data to aid exploration in a regional context. In this study, we demonstrate how historical core data can be used by integrating petrographic- and facies analysis with a pure predictive machine learning based porosity predictor to make a formation-specific predictive framework. With the framework, lithological- and diagenetic attributes can be deduced within a formation of frontier areas based on only basic well logs, which can significantly increase the efficiency and further reduce costs. The machine learning based porosity predictor was created based on a large dataset consisting of helium porosity- and well log data from 38 wells containing the Stø Formation in the SW Barents Sea Area. The model was trained using well log- and helium porosity data as features and labels, respectively. An exhaustive grid search was carried out in conjunction with a 3-fold cross validation for hyperparameter optimization. Based on previous detailed petrographic studies (Hansen et al., 2017, Løvstad et al., 2022), the Stø Formation has proven to exhibit bimodal- and wide porosity distributions in deeply buried intervals. This trend has been interpreted to reflect the effectiveness of a patchy illitic clay coating, which ultimately controls quartz cement volumes. This particularly makes the porosity distribution of clean sand intervals within the Stø Formation interesting to study in a regional context. Therefore, the modeled continuous porosity curves were split strategically into different subsets to target the upper- and lower most parts of the porosity distribution along the depth profile. The high quality modeled continuous porosity logs allowed for the characterization of different well log parameters and their signatures.
Key outcomes

- The results show that machine learning can be an effective way of exploiting already acquired helium porosity data to generate continuous porosity logs in wells with basic well log data. Aided by petrographic knowledge, the porosity data can be strategically split into subsets to target specific intervals of interest.

- The ML-derived porosity data show a similar porosity-depth trend compared to the published trend of Løvstad et al. (2022), that is based on helium porosity data for 14 wells in the SW Barents Sea which shows that the porosity distribution becomes wider as a function of depth. The fact that the same porosity-depth trend can be seen over this large dataset, indicates that intervals with effective grain coats are likely common in certain intervals of the Stø Formation in large parts of the SW Barents Sea.

- The results show that the upper- and lower-most parts of the porosity distribution within the Stø Formation have distinct Vp and density signatures that make them separable in intervals with a deep maximum burial (> 3300m). However, intervals with an intermediate burial depth (i.e., maximum burial depth < 2700m) show a clustering behavior which makes the separation ambiguous. A similar trend is observed for facies colored data, where shoreface- and more clay and silt rich distal facies show distinct wireline log signatures in intervals with a deep maximum burial.

- The GR-porosity parameter domain has been found to be particularly useful for discriminating lithological- and diagenetic attributes within the Stø Formation irrespective of the maximum burial depth. For intermediate burial wells (~2100 – 2700 maximum burial depth) a clear elongated trend can be used to deduce the varying clay content related to various facies. At deeply buried intervals (> 3000 m maximum burial depth), the data show a characteristic L-shaped trend which both depicts the effect of varying clay content and the degree of quartz cement.

- GR-porosity data from well 7219/8-2 indicate that the lower shoreface facies may have a higher abundance of effective clay coats and thus show higher porosities. These results can be seen in the combination of previous published results (Hansen et al., 2017, Løvstad et al., 2022), where intervals with poorly developed clay coats were interpreted to result from post-depositional reworking, which could be more intense in an upper- than a lower shoreface setting.
3.4 Paper IV

- Chlorite coating patterns and reservoir quality in deep marine depositional systems – Example from the Cretaceous Agat Formation, Northern North Sea, Norway

**Motivation, objectives and methods**

Sediment gravity flows transport large volumes of sand and clay minerals from the shelf to deeper submarine sedimentary systems which can form high quality reservoirs and store important reserves of oil and gas. Similar to other clean sandstone units of a shallow marine origin, these intervals are susceptible to intense quartz cementation where they have been buried to great depths, which will drastically degrade reservoir quality unless quartz cementation is hampered by the presence of grain coats. However, knowledge about grain-coating clay mineral origin and distribution in submarine sedimentary systems is poorly documented. In this study, we document the occurrence and distribution of chlorite coats in sediment gravity flow derived sandstones of the Cretaceous Agat Formation in one well located in the northern North Sea. The objectives are to characterize the morphology, distribution, extent and the origin of the chlorite coatings in this deep marine deposit, in addition to assessing their effect on reservoir quality. We used a multimethod approach which included analyses of petrographic-, petrophysical- and sedimentological data. The findings of this study can be important for reservoir quality delineation in petroleum prospects with gravity flow derived sandstones.

**Key findings**

- The results of this study reveal the potential for commercial targets within deeply buried sandstones with a sediment gravity flow origin due to an omnipresent chlorite coating that effectively prevents pervasive quartz cementation.

- The chlorite coating formed from an iron-rich precursor clay phase that progressively recrystallized into chlorite upon burial. Petrographic- and sedimentological results indicate that the Agat Formation has fingerprints from an initial shallow marine origin and that these sediments were later remobilized into the submarine system by gravity flows. Moreover, the morphology, distribution and extent of the underlying precursor clay phase indicate that the
precursor clay coating was emplaced before sediment remobilization. This is supported by the presence of clay coating on grain contacts, the fact that the clay coating is present on all detrital components, the occurrence of clay coated green marine clay pellets and the absence of clay bridges between detrital grains. Thus, unlike other reported studies where clay coat formation in submarine sedimentary systems has been attributed to sediment-dewatering processes after deposition, this study shows that clay coated sandstones can form in such environments due to an inherited precursor clay coating.

- Although the chlorite coating has an overall positive effect on reservoir quality due to its omnipresence on detrital components, highly varying coating thickness can significantly reduce the effective porosity and permeability in intervals with exceedingly thick chlorite coats. This is illustrated by the upper reservoir section within the Agat Formation which is characterized by an average coating thickness of 4.5 µm and excellent reservoir quality, whereas the lower reservoir section shows significantly lower permeability readings and an average coating thickness of 24 µm, which leads to pore-throat blockage.

- Helium porosity data show only a small discrepancy between the upper- and lower reservoir sections, but modal point count analysis indicates that the helium porosity measurements are unrealistically high in the lower reservoir unit. This is attributed to the large volume of water-filled micro pores in the chlorite coating. Thus, this study indicates the importance of an integrated approach to assess porosity thoroughly in reservoirs with thick chlorite coatings.

- The difference in coating thickness and thus reservoir quality between the upper and lower reservoir units have been linked to small variations in the initial sediment composition prior to sediment remobilization. The lower reservoir unit is characterized by a noticeably higher content of iron bearing minerals which could imply that more pore-filling precursor clay material was available at the time of emplacement and thus increased the final chlorite coat thickness.
Chapter 3: Scientific contributions

3.5 Paper V
- How do chlorite coatings form on quartz surface?

Motivation, objectives and methods

Chlorite coats on quartz grains that formed from a precursor clay phase are common in various sedimentary environments and they have proven effective in limiting extensive quartz overgrowth where these sandstone units have been buried to great depths. However, despite their abundance in numerous sedimentary environments and their importance for retaining high reservoir quality during burial, the fundamental mechanism(s) involved in the precursor clay attachment processes is poorly understood. In this study, we investigated potential controlling factors of the precursor clay attachment process on the surface of quartz grains through various batch experiments. The experimental configuration includes batches of quartz and chlorite (ripidolite) that were investigated under various conditions of ionic strength and pH, as well as the presence of different solid phases like iron (Fe)- and aluminum (Al)- oxides and humic acid (HA). The batches were prepared in plastic tubes and fitted to a mechanical shaker to simulate current agitated conditions. The resultant distribution of the clay phase and the extent of clay coat coverage on quartz grains were characterized in optical- and scanning electron microscopes.

Key findings

- The results show that ripidolite particles on the surface of quartz grains form edge-to-edge and face-to-edge- rather than a face-to-face stacking pattern and that these ripidolite particles are oriented parallel to the quartz surfaces. These geometrical arrangements are similar to occurrences of clay particles reported from natural environments which suggest that the emplacement occurred by similar mechanisms.

- The results show that clay particles attach to the surface of quartz grains in the absence of binding agents like Fe- and Al oxides and in non-saline solutions. Additionally, clay attachments do not consistently follow the binding agent attachment patterns in samples characterized in the fluid phase, and they occur in both saline- and non-saline solutions in pure quartz-chlorite batch experiments. Clay coats were also found to be particularly infrequent in batches containing organic matter, which is a commonly proposed binding agent. These results suggest
that salinity and binding agent cannot be prerequisites for clay attachment at the surface of quartz grains.

- At pH 7, the quartz-chlorite and quartz-chlorite-Fe/Al oxide batch experiments show comparable clay coverage in saline and non-saline solutions, whereas for similar batch experiments at pH 5 and 9 the clay coverages are superior only in saline solutions. The dynamic interaction between various solid- and solution chemistry can vary the electrokinetic properties at the mineral-solution interfaces and we therefore suggest that the electrokinetic response in various heterogeneous systems serves as an important mechanism in the clay attachment process.
4. Synthesis

This thesis has focused on clay coats in reservoir sandstone units that have a detrital origin, meaning that the clay coats- or a precursor clay phase formed before burial. The three main objectives of this study are: (1) to provide a detailed characterization of two distinct types of clay coats in reservoir sandstones (illitic and chlorite) and their implications for reservoir quality distribution (2) prediction and characterization of reservoir quality in clay coated reservoirs on a regional scale and (3) study the clay coat attachment process. The following section presents an interconnected summary of the main results from the individual scientific papers which are outlined according to the defined objectives in this thesis.

4.1 Clay coat characteristics and implications for reservoir quality

The Stø- and Agat formations have both been shown to exhibit clay coats in sandstone intervals on the NCS, located in the SW Barents Sea and northern North Sea, respectively. However, the detailed petrographic case studies present in this thesis (Paper I, II and IV) show that there are several dissimilarities between the two occurrences of clay coats including mineralogy, morphology, distribution and depositional setting.

The detailed case studies of the Stø Formation (Paper I and II) have shown that the clay coats consist of a thin (typically 1-4 µm) illitic clay that does not show any signs of significant alteration during burial. The illitic clay coats are patchy, but they are present at most detrital grains in samples where they are abundant and they show clear signs of being detrital. This is supported by their tendency to be thicker in grain indentations, their tangential emplacement pattern on detrital grains, their absence on diagenetic mineral phases, their presence at grain contacts and the existence of meniscus shaped clay bridges between framework grains. The latter indicates that the illitic clay coats were emplaced, at least partly, by the means of infiltration. This implies that samples where clay bridges are preserved between detrital grains, coating was emplaced after the final deposition. In contrast, samples where clay bridges are absent could indicate that these intervals have been relocated, most likely due to post depositional reworking, and can be characterized as inherited clay coats (Wilson, 1992). The differential intensity of sediment reworking within various parts of the Stø Formation interval may explain the presence or absence of clay bridges as well as the varying clay coat coverage. This leads to an uneven distribution of clay coats within different sandstone units of the Stø Formation (Paper I and II).
In appose to the Stø Formation, the chlorite coats within the Agat Formation are evenly distributed across the entire sandstone interval (Paper IV) and they are continuous and cover all detrital constituents. However, the clay coat thicknesses are observed to vary significantly between samples from the upper- and lower part of the reservoir with an average thickness of 4.7 µm and 24.1 µm, respectively. Similar to the illitic clay coats of the Stø Formation, the chlorite coats in the Agat Formation show evidence of being detrital. These clay coats are thicker in grain indentations, absent on diagenetic products, the inner portion of the clay coating exhibits a chaotic morphology and they are present at points of contact between framework grains. However, meniscus shaped clay bridges are not observed in samples from the Agat Formation, which could mean that they were emplaced by some processes other than infiltration, or that these delicate features were broken during sediment remobilization. In any case, this study has concluded that the Agat sands exhibit an inherited precursor clay coating that was emplaced in a shallow marine setting and that they were remobilized with the host sediment and deposited in a slope setting (Paper IV). This interpretation is supported by the above-mentioned morphological features as well as the presence of green marine clay pellets, the fact that the clay coats are continuous and present across the entire Agat interval (about 100 m thick) in the studied well. This interpretation is in contrast to similar reported occurrences in the literature (Houseknecht and Ross Jr, 1992, Porten et al., 2019), where chlorite coated sandstones deposited by turbidities have been interpreted to form by sediment dewatering processes immediately after the final deposition.

The exact cause of the distinct difference in clay coat distribution, -morphology and –coverage observed between the illitic- and chlorite coats of the Stø- and Agat Formation remains unresolved, but the variability is likely due to a complex interaction between sediment source (provenance) and depositional setting, which subsequently control depositional energy, clay-sand ratios and clay mineralogy. An important notice is that the Stø Formation was deposited over several millions of years in a stable and large shallow marine area with a southern mature source area (Olaussen et al., 1984, Klausen et al., 2018). This is a setting where already relatively mature sediments are probably transported basin-ward and where repeated sediment reworking likely prevailed due to being highly sensitive to small sea-level fluctuations. Such a setting can increase sediment maturity, increase the sand-clay ratio and possibly limit the likelihood of producing thicker and continuous clay coats. In contrast, the Agat Formation was deposited on a narrow shelf setting (Martinsen et al., 2005), and the sediments were likely sourced from a more complex rock suit. This means that the sediments were possibly exposed on the shelf for a shorter period before remobilization and that the initial depositional area was directly affected by the more immature sediment supply from the hinterland. Such a setting can be prone to deposit more clay and silt material, which may lead to the development
of continuous and thicker clay coats. It should be underlined that the chlorite coats of the Agat Formation are a result of a recrystallized precursor clay phase, whereas the illitic clay coats of the Stø Formation seem to have been largely non-reactive during burial. This makes it difficult to determine the appearance of the initial detrital clay coats of the Agat Formation. However, they were likely formed in a depositional setting that promoted the formation of iron containing precursor clays and were subsequent moderate sediment reworking facilitated the clay attachment processes. Although the exact processes that are involved in the formation of detrital clay coats are still uncertain, these results indicate that the sediment source and depositional environment play a key role in the resultant clay coat type, distribution and morphology. More detailed sedimentological- and facies analysis in clay coated sandstone intervals should be conducted to increase our understanding of the link between clay coat formation and physical processes that are associated with specific depositional settings.

In terms of the potential of reservoir quality (porosity and permeability) preservation during deep burial diagenesis, the case studies presented in the thesis have shown that both the illitic- and chlorite coating mostly have a positive effect on reservoir quality because they effectively retard quartz cement overgrowths (Paper I). The results have shown that both the illitic- and chlorite coatings can retain intervals of abnormally high porosities at great burial compared to regional porosity-depth trends. However, the chlorite coats of the Agat Formation show a unimodal porosity distribution (Paper IV) whereas the porosity distribution of the Stø Formation typically demonstrates a clear bimodal distribution (Paper II) (Figure 11). Additionally, the illitic clay coats of the Stø Formation are not as effective in preserving high porosity as the chlorite coats of the Agat Formation, where the patchy nature of the illitic coating allows for some quartz cementation to precipitate, even in intervals with relatively high coat coverage. The patchy and highly varying degrees of clay coat coverage in the Stø Formation cause the porosity distribution within the Stø Formation to capture this distinct bimodal distribution pattern (Paper II). This dissimilarity in porosity distribution patterns between the two clay coat types can be illustrated by helium porosity data from two wells where the Stø- and Agat Formation show comparable maximum burial depths (Figure 11). However, with respect to the chlorite coats of the Agat Formation, this study has signaled the importance of assessing porosity thoroughly in intervals with exceedingly thick chlorite coats (> 15- 20 µm). Helium porosity measurements may give an unrealistically high effective porosity estimate because these data will represent both macro- and micro-pore volumes of the chlorite coating.
Similarly, intervals with exceedingly thick chlorite coats may show a significant reduction in permeability because thick clay coats will reduce the pore throat size (Paper IV). The thin and patchy illitic clay coats will not directly affect permeability, but intervals with less effective clay coats will generally see a reduction in permeability due to higher volumes of quartz cement.

4.2 Prediction and characterization of clay coated reservoir on a regional scale

Papers I, II and III collectively illustrate how relatively small amounts of core data within a specific formation can be exploited to aid effective reservoir quality prediction and characterization at a regional scale. A prerequisite for such a workflow is to first obtain a good understanding of the mechanisms that control reservoir quality in the system. Therefore, this study conducted a detailed petrographic characterization of mineralogical- and textural properties in relation to the total pore volume of the Stø Formation in well 7219/8-2, located in Bjørnøysenrenna Fault Complex (Paper I) (Figure 2B). Helium porosity data from this well confirmed the presence of a distinct abnormally high porosity interval, which contrasted with surrounding low porosity regions. Paper I established a qualitative relationship between the degree of clay coat coverage and quartz cement volume, thus indicating that the thin illitic clay coating controls the porosity distribution within deeply buried parts of the Stø Formation. Guided by the results from Paper I, Paper II explored for similar trends in a more regional
Chapter 4: Synthesis

context within the Stø Formation. A detailed study of thin sections and helium porosity data from 13 additional wells located in the Hammerfest Basin and Rinvassøy-Loppa Fault Complex was conducted (Figure 2B). The results from Paper II indicated that these high porosity intervals are common within the Stø Formation on a regional scale within the SW Barents Sea (Figure 2). This conclusion was partly based on the characterization of helium porosity data in wells without petrographic thin section samples, which showed that the parts of the Stø Formation that do have effective clay coats tend to exhibit a distinct bimodal and- wide porosity distribution pattern (Paper II) (Figure 11). Additionally, the study showed how the rate of porosity loss is slower in coated intervals compared to negligible coated intervals as a function of increase in burial, i.e., the TTI (time-temperature integral) (Walderhaug, 1994). The need for efficient and innovative workflows that do not rely on expensive and time consuming data material, like cores, for assessing reservoir quality at a regional scale is crucial for reducing costs- and lower CO₂ emissions related to petroleum exploration. In addition, data from the core material offers only sporadic data points (e.g., helium porosity, thin sections) and cover typically limited parts of the target formation. Such a workflow is particularly welcomed for reservoir units like the Stø Formation because of the highly varying degrees of clay coat coverage, which directly controls the reservoir quality heterogeneity. Therefore, the characterization of reservoir quality heterogeneity is potentially more efficiently and accurately conducted by relying on continuous data sources. In Paper III a machine learning based porosity model was established from available well log and helium porosity data, in which the model was used to derive continuous porosity profiles within the Stø Formation in 38 wells in the SW Barents Sea (Figure 2). The results from this study show that machine learning can be an effective way of generating continuous porosity profiles from well log data and that small amounts of petrographic data can aid the interpretation of these profiles (Paper I and II). For instance, in this study, the petrographic knowledge was essential for strategically splitting the porosity data into different subsets to target presumably coated- and uncoated regions within the Stø Formation (Paper III). The ML-based framework was used to deduce distinct well log responses related to lithological- and diagenetic attributes and the results show that distinct bed types can be recognized particularly in intervals of the Stø Formation that show a significant maximum burial depth (> 3000 m).
4.3 The clay coat attachment process

In appose to the regional reservoir quality prediction study of Paper III, which relied on the occurrence of clay coats to be known in advance (Paper I and II), a better understanding of clay particle attachment mechanisms, i.e. processes responsible for fixating and holding clay particles on detrital sand grains, could seriously aid the prediction of new clay coat occurrences in frontier regions. This knowledge can be essential for deep burial exploration and prediction of reservoir quality distribution within sedimentary successions because clay coat formation may be linked to distinct sedimentary environments. The lack of this knowledge is also a limitation in the case studies presented in this thesis (Paper I, II and IV) and a better understanding of the clay coat attachment process would increase our understanding- and our ability to predict their distributions in such sedimentary systems. This is because it is challenging to infer results solely from detailed petrographic- and facies analysis to the formation of detrital clay coats without knowing the controls on clay particle attachment. Moreover, both the illitic- and chlorite coats characterized in this study originated in high energy environments, i.e. environments influenced by repeated sediment reworking in- and sand remobilization from a shallow marine setting, respectively. This could indicate that the clay particles may attach and that they can be durable to abrasion in such high energy environments (Paper I, II and IV). Therefore, the objective of paper V was to investigate potential mechanisms that control the clay particle attachment process. The results from this study indicate that the electrokinetic response in various heterogeneous systems may serve as an important mechanism in the clay attachment process. However, the need for several systematic and detailed experiments is required to fully understand the clay attachment process. This is because the electrokinetic properties of such heterogeneous systems are a function of a complex interaction between parameters like mineralogy, grain size of clay particles and solution chemistry.
5. Concluding remarks

This article-based thesis has investigated the occurrence of clay coated reservoirs that have a detrital origin. Based on this topic, three main objectives have been addressed: 1) a detailed characterization of two distinct types of clay coats in reservoir sandstones (illitic and chlorite) and their implications for the reservoir quality distribution, (2) prediction and characterization of reservoir quality in clay coated reservoirs on a regional scale and (3) study of the clay coating attachment process. The following conclusions can be drawn from the conducted investigations:

- The illitic- and chlorite coats observed within the Stø- and Agat formations, respectively, exhibit distinctly different morphological characteristics. The illitic clay coats are thin (typically 1-4 µm) and show a patchy morphology on detrital grains, whereas the chlorite coats are thick (in some samples thicker than 25 µm) and omnipresent on all detrital grains. Moreover, the chlorite coats are evenly distributed throughout the sandstone reservoir, although the coating thickness varies noticeably, whereas the illitic clay coats show a more heterogeneous distribution with only certain intervals showing a higher degree of clay coat coverage. The observed differences in clay coat characteristics can be related to a complex interaction between provenance and depositional settings. Both types of clay coats show clear indications of having a detrital origin. The following observations support that interpretation: the clay coats are present at grain contacts and tend to be thicker in grain indentations, they are present on detrital components but absent on diagenetic mineral phases and clay particles close to the detrital grain surfaces are attached tangentially. The clay coats have commonly a positive effect on reservoir quality in deeply buried reservoir units because they can effectively prevent extensive quartz overgrowth. However, the illitic clay coats allow some quartz cement to precipitate and their effectiveness is related to the degree of clay coat coverage. The chlorite coats completely retard quartz cementation, but in intervals with exceedingly thick chlorite coats (> 15-20 µm), effective porosity and permeability can be significantly reduced.

- This study has shown that machine learning derived workflows can be effectively used to predict- and characterize reservoir quality in clay coated sandstone reservoirs by exploiting historical core- and well log data. In this way, formation-specific models can be generated, which can aid reservoir quality delineation on a regional scale without the need of additional core material. This study has emphasized how detailed petrographic knowledge can be effectively integrated with such workflows to aid the interpretation of modeled data. The results from this study show that distinct well log signatures related to lithological- and
diagenetic attributes within the Stø Formation can be differentiated in parts of the formation that have experienced deep post-depositional burial (> 3000m).

- A better understanding of clay coat attachment processes can be essential for linking their formation to distinct sedimentary environments, which can aid the exploration of high reservoir quality sandstone prone bodies in frontier regions. This study has performed simple sand-clay batch experiments to study the controls of the clay attachment process. The results indicate that the electrokinetic response that arises in heterogeneous systems can be an important mechanism in the clay coat attachment process.
6. Further work

This study has investigated the occurrences of detrital clay coats in reservoir sandstones on the NCS in the Stø- and Agat Formation, located in the northern North Sea and SW Barents Sea, respectively. However, even though this study has addressed various important aspects related to detrital clay coats in sandstones, their formation and link to specific depositional settings are still uncertain. Successful documentation of the following research objectives may further increase our understanding of clay coat formation and distribution in the subsurface:

- Although it is difficult to quantify the degree of clay coat coverage during modal point count analysis with use of optical microscopy, a successful delimitation of this metric can have important implications for a better understanding of the relationship between clay coat coverage and quartz cement volumes. SEM analysis offers the possibility to conduct this investigation, though the work will be more time consuming. A combination of the above-mentioned points and a more comprehensive facies analysis in relation to the occurrence of clay coats within the Stø Formation could likely aid reservoir quality delineation at a regional scale. Moreover, this study has identified a higher abundance of pore-filling kaolinite in certain intervals within the Stø Formation, which can be related to the degree of post-depositional reworking along with the observed delicate meniscus shaped clay bridges. A detailed study of their abundance and distribution in relation to the degree of clay coat coverage and facies may better constrain specific intervals within the Stø Formation that are prone to exhibit effective clay coats.

- Perform several experimental batch studies to better constrain the influence of electrokinetic responses in various heterogeneous systems. A systematic set-up with a particular focus on varying clay mineralogy and clay particle sizes may better constrain conditions that control clay coat coverage. Additionally, a detailed study of quartz surfaces using advanced analytical techniques may add knowledge to the clay coat attachment process.
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Appendix A
Paper I
Clay coating preserving high porosities in deeply buried intervals of the Stø Formation

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Grain coating  
Illite  
Porosity preservation

**A B S T R A C T**

The Stø Formation is the most important reservoir interval in the Norwegian Barents Sea, however the reservoir quality can be highly affected by the detrimental effects of quartz cement where there have been extensive post depositional burial. Core plug data from well 7219/8-2 in the Southwestern Barents Sea shows abnormally high porosity and permeability values in certain units of the deeply buried and otherwise highly quartz cemented Stø Formation. The amount of quartz cement in the samples is inversely proportional to the porosity. Samples with high and low porosities are similar texturally and mineralogically, but the high porosity samples have a layer of illitic clay coating the majority of the detrital quartz grains. Illitic clay coating present at grain contacts can result in a lowered IGV given they aid in the dissolution of quartz at interfaces, also creating a source of dissolved silica. Clay induced dissolution means that silica saturation is not a limiting factor in quartz cementation in these samples. The results show that the illitic clay coating is capable of limiting the amount of authigenic quartz overgrowth from 20 to 23% in samples with negligible grain coating to 5–11% in the intervals with high coating coverage. The illitic clay coating inhibits quartz overgrowth by limiting the surface area available for nucleation on detrital grains. The Stø Formation comprises mainly shallow marine deposits of highly reworked clean sandstone. Abnormally high porosities appear to be linked to settings where sediments of a more proximal location are preserved without extensive reworking. The grain coating clay is illitic and most likely originates from clay in filtration processes prior to final deposition. The difference in extent of clay coating in similar facies can mostly be correlated with varying amount of post depositional reworking. This study suggests that there is a potential for considerable porosity and permeability to be preserved in deeply buried sandstones in the Barents Sea. This study could be important in the future exploration activity of deeply buried structures in the area.

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1. Introduction

In this study samples from the Stø Formation in well 7219/8-2 are investigated with respect to porosity preserving processes during deep burial. The Stø formation is present across most of the Norwegian Barents Sea and is an important target for petroleum exploration (Worsley et al., 1988). The formation is mainly composed of clean mature sandstone (Olausen et al., 1984) that has been subjected to large maximum burial depths in areas (formation depths from wells available at the Norwegian Petroleum Directorate, uplift corrected using data from Baig et al. (2016)), and can thus be subjected to extensive quartz cement growth, causing low porosities. From core plug measurements provided to the authors by Tullow oil (data released 2015), an interval of the Stø Formation in well 7219/8-2 is identified as having porosity values above other intervals of the Stø Formation in the same well with a similar mineralogical composition.

Reduction of porosity in sandstones with increasing burial is a function of mechanical compaction causing reorganization and crushing of grains with increasing pressure, with the sediments’ response to increasing pressure being determined by the textural and mineralogical parameters e.g. (Bjørlykke et al., 1989; Lundegard, 1992; Chuhan et al., 2002; Paxton et al., 2002; Marcusen et al., 2010). At temperatures exceeding 70–80 °C, rates of authigenic quartz cementation become significant (Mcbride, 1989; Bjørlykke and Egeberg, 1993). Quartz cementation is commonly considered the main controlling factor of the porosity distribution in deeply buried clean sandstone reservoirs (Bjørlykke...
The amount of quartz cement can be reduced if grain coats cover a large part of the surface of detrital quartz grains (Heald and Larese, 1974). Grain coats hampering the precipitation of quartz cement by reducing the surface area available for nucleation of authigenic quartz on detrital grains have been observed and discussed in several papers from the Norwegian continental shelf, mainly from the North Sea and Norwegian Sea (Ehrenberg, 1993; Aase et al., 1996). Primarily microquartz and authigenic chlorite coating have been found to preserve porosities well above the porosity depth trend in deeply buried sandstones. Storvoll et al. (2002) also found that illite or illite/chlorite coating could reduce quartz cement. Other important factors to consider is stylolitization (Ehrenberg, 1990), clay mineralogy (Walderhaug et al., 2006) and textural properties (Chuhan et al., 2002; Fawad et al., 2011). In the Barents Sea, Walderhaug and Bjørkum (2003) related differences in quartz cement volume to stylolite spacing within the Stø Formation from well 7120/6-1 situated in the Hammerfest Basin. Exceedingly clean sediments can lack sufficient clay to form significant stylolites resulting in a high stylolite spacing (>20 cm), limiting the supply of silica in solution to the sediments due to the limited ability of the pore fluids to diffuse over large distances (>20–30 cm) (Walderhaug and Bjørkum, 2003).

The aim of this study was to investigate any higher than expected porosities in deeply buried intervals of the Stø Formation and its causes. The Stø Formation in well 7219/8-2 were well suited for this study since it has had a significant maximum burial depth and also clearly defined intervals of varying porosity with a similar lithological composition.

2. Geological setting

The Barents Sea is an epicontinental platform situated on the Northwestern flank of the Eurasian continental plate. Well 7219/8-2 is located in the Bjørnøyrenna Fault Complex just west of the Polhems sub-platform (Fig. 1).

The Stø Formation is a part of the Realgrunnen Subgroup and is late Pliensbachian to Bajocian in age. The original sediments of the Stø Formation is interpreted to have been deposited in a prograding coastal regime interrupted by several transgressive events marked by thin siltstone and shale layers, and generally consists of very mature sandstones that are moderately to well sorted (Olaussen et al., 1984; Gjelberg et al., 1987; Worsley et al., 1988; Klausen et al., 2017). The sandstones of the Stø Formation usually have a quartz content of 91–100% (Bergan and Knarud, 1993). The mature sandstones probably reflect extensive reworking owing to the shallow marine/coastal depositional environment (Worsley, 2008),
and also partly the mature source area (Bergan and Knarud, 1993; Ryseth, 2014). The Stø Formation was deposited in a low accommodation setting over a period of 14 million years, with several transgressive and regressive events caused by relative sea level change and with three major transgressive events forming a basis for an overall division of the formation into three stratigraphic units (Olaussen et al., 1984; Gjelberg et al., 1987).

The Stø Formation is overlain by the Fuglen Formation, characterized by pyritic mudstones and interbedded limestones (Worsley et al., 1988). Underlying the Stø Formation is the Nordmela Formation characterized by interbedded sandstones, siltstone, mudstone and claystone (Worsley et al., 1988). The present day depth of the Stø Formation in the well is shown in Table 1. The formation most likely reached maximum burial in the Eocene or Oligocene (Baig et al., 2016). Subsequent uplift of the Barents Sea area means that the present day burial depth does not represent maximum burial.

The amount of uplift varies across the Southwestern Barents Sea, generally increasing towards the North-East. The Bjørnøyrenna Fault Complex and Ringvassøy-Loppa Fault complex are assumed to have experienced an uplift of ~1000 m (Baig et al., 2016).

3. Methods and data

Eleven thin sections were prepared from core samples from the Stø Formation in well 7219/8-2 at the Norwegian Petroleum Directorate. The samples were selected based on core plug measurements of porosity and permeability provided to the authors by Tullow Oil. Each thin section was point-counted once with 300 measurements of porosity and permeability provided to the authors by the Norwegian Petroleum Directorate. The samples were selected based on core Plug measurements (Baig et al., 2016). Temperature estimates are based on current geothermal gradient. All values are calculated at the top of formation.

<table>
<thead>
<tr>
<th>Well name</th>
<th>7219/8-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>72° 19’ 17.55” N</td>
</tr>
<tr>
<td></td>
<td>19° 35’ 21.28” E</td>
</tr>
<tr>
<td>Vertical depth [mRKB]</td>
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</tr>
<tr>
<td>Bottom hole temperature [°C]</td>
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<tr>
<td>Geothermal gradient [°C]</td>
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</tr>
<tr>
<td>Formation [mRKB]</td>
<td>2898-2985 (Stø Fm.)</td>
</tr>
<tr>
<td>Thin sections</td>
<td>11</td>
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<tr>
<td>Estimated uplift*</td>
<td>1100</td>
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<tr>
<td>Maximum burial depth [MD from surface]</td>
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</tr>
<tr>
<td>Present day temperature [°C]</td>
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Table 1
General well information is summarized in the table below. *Maximum burial are based on (Baig et al., 2016). Temperature estimates are based on current geothermal gradient. All values are calculated at the top of formation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz grains (%)</th>
<th>Feldspar grains (%)</th>
<th>Rock fragments (%)</th>
<th>Muscovite (%)</th>
<th>Clay (%)</th>
<th>Mica cement (%)</th>
<th>Kaolinite (%)</th>
<th>Carbonate cement (%)</th>
<th>Observed porosity (%)</th>
<th>Mean grain size (µm)</th>
<th>Sorting (σ)</th>
<th>Core plug porosity (%)</th>
<th>Rock porosity (%)</th>
<th>Stylolite spacing [cm]</th>
<th>SEM</th>
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<td>0.3</td>
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<td>3.3</td>
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<td>-</td>
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<td>12.0</td>
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<td>-</td>
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<td>14.0</td>
<td>27.7</td>
<td>10</td>
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</tr>
</tbody>
</table>

3.1 Petrographic composition and petrophysical data

Table 2
Point count results from all studied thin sections. Also marked are which samples that were analyzed in SEM. Samples with coated grains — red, underlined samples — white.

4. Results

The Stø Formation can be classified as a quartz arenite in all the samples as the quartz grain content compared to feldspar grains and rock fragments are close to 100% (Table 2). The muscovite content do not exceed 1% in any of the samples, but were sporadically observed to penetrate detrital quartz grains showing clearly the potential of mica to facilitate quartz dissolution at the interfaces of quartz-mica grains (Bjerkum, 1996). Quartz cement is by far the dominant authigenic mineral and varies from about 5 to 23% in the studied samples. The primary porosity is also highly variable and ranging from 3 to 17%. Secondary porosity is negligible in all samples. The pore filling clay content is approximately 1—5% in the studied samples and the clay consists mainly of illite, but small crushed fragments of quartz- and muscovite grains are commonly incorporated in the clay mixture. In addition, small amounts of pyrite, apatite and ankerite occur in association with the pore filling.
clay. Pore-filling aggregates of kaolinite is present in nearly all the samples, but commonly makes up less than 1%. Illite was also observed as grain coating in 6 of the studied samples. The illite was partly to completely covering the majority of the detrital quartz grains in these samples. Contacts between coated detrital quartz grains typically are sutured suggesting that dissolution has occurred.

Core plug porosity data from the deeply buried Stø Formation in well 7219/8-2 shows significant higher porosity- and permeability values within certain intervals compared to the overall trend (Fig. 2A). A consistently high porosity interval is observed between 2957 and 2963 mRKB. The porosity distribution, displayed in Fig. 2B, has a subpopulation of markedly higher porosities. Based on an uplift estimation by Baig et al. (2016), the maximum burial temperature at the top of the Stø Formation was approximately 141.7 °C (Table 1), assuming a geothermal gradient similar to today. The present day formation temperature is approximately 99 °C leaving it within the temperature range where quartz cementation can still take place.

4.2. Sedimentological differences between high and low porosity interval

The Stø Formation is characterized by a condensed interval of

![Graph A](image1)

**Graph A**: Gamma ray log, core plug measurements, and observed porosity and quartz cement volume from the Stø Formation in well 7219/8-2. Core plug porosity (black points), core plug permeability (red points), observed porosity (blue points), observed quartz cement (green points). Observed porosity and quartz cement volume data are obtained from point counting in the optical microscope (Table 2).

![Graph B](image2)

**Graph B**: Core plug porosity distribution from the Stø Formation in well 7219/8-2 showing a subpopulation of abnormally high porosities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Fig. 3. Left: a log covering an interval from 2948 to 2972 m from well 7219/8-2. Center: a more detailed log of the interval 2957–2958 m and the associated core photo with core plug porosity and permeability values. Note the conglomerate separating the interval with high porosity and permeability below and the interval above with poorer porosity and permeability. Right: two examples of core photos and core plug data above and below the conglomerate. (Red) Core photo from 2955 to 2956 m, above the conglomerate, showing reduced porosity and permeability. (Blue) core photo of the interval 2963–2964 m showing similar composition and core plug measurements compared to what is observed just below the conglomerate (see Fig. 2 for complete core plug database). All depths are given in mRKB. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
stacked sandstone deposited within a shoreface environment (Olaussen et al., 1984). In well 7219/8-2 the Stø Formation is 88 m thick and consists of repeated successions of shoreface deposits, with certain intervals of tidal deposits in the lower parts of the formation and offshore transition to shelf deposits in the uppermost parts of the formation (Klausen et al., 2017).

The alternating sequence of shoreface deposits with varying energy of deposition exists also in the main studied interval (Fig. 3). Transgressive pulses are common in this interval of the Stø Formation (Olaussen et al., 1984; Klausen et al., 2017) and the conglomerate observed (Fig. 3) can then possibly be caused by one of these events as a transgressive ravinement surface.

The sandstone above the conglomerate has a grain size population that is slightly finer grained and better sorted than the sandstones below (Table 2). In the interval above the conglomerate vertical burrows are common. The mineralogical composition is the same in both intervals. The better sorting and presence of vertical burrows indicate more reworking in the interval above the conglomerate compared to interval below.

Sandstones in well 7219/8-2 at depths of 2969 to 2957.2 m in the interval with higher porosities and permeability appear to have been deposited in a lower energy environment given their poorer sorting and higher degree of preservation of grain coats (Fig. 4).

4.3. Properties of grain coating clay

From core plug data three samples with low porosities (5–11%) and six samples with high porosities (11–18%) were selected for SEM analysis (Table 2).

Quartz cement abundances range from 5 to 10% for the high porosity samples and 20–23% for the lower porosity samples (Table 2). In samples with well-developed grain coating the coating tend to cover the entire grain or be largely absent (Fig. 5C) these coatings generally have thicknesses in the order of 4 microns where the detrital grain surfaces are smooth but thin to ~1 micron in places (Fig. 5D). Where the detrital grains have significant indentations or rougher surfaces the coating are thicker, up to 20 microns (Figs. 4 and 5E). The grain coating clay was chaotic in appearance with the clay particulates often too small to define even in the electron microscope. The outer rim of the grain coating clay generally has an undulating appearance.

As expected the low porosity samples have large, well developed quartz overgrowths on the detrital quartz grains (Fig. 5A and B). Only sporadic grain coating clay were observed in these samples with an average of 1 in 20 grains showing traces of coating. Those coatings that are present are generally limited to significant indentations in detrital grains. The areas do not have associated overgrowth cements. EDS spectra of the grain coating clay show peaks for potassium, aluminum, silica and oxygen but no significant traces of magnesium or iron. The composition and appearance of the clay indicate that the grain coating clay is mainly illitic (Matlack et al., 1989; Dutton and Diggs, 1992).

4.4. Diagenetic effects of grain coating

Samples with well preserved coatings tend to be slightly coarser grained and better sorted compared to samples with negligible grain coating (Fig. 6A and Table 2).

The results also show that coated samples have a lower intergranular volume (IGV) and significantly lower amounts of quartz cement (Fig. 6B). Sutured grain contacts between quartz grains were commonly observed in samples with significant grain coating (Fig. 7) and indicate that dissolution of detrital quartz grains has occurred along the quartz-clay interfaces. This observation is consistent with the lower IGV values observed in coated samples.

Fig. 4. 7219/8-2, 2959.50 m varying thickness of illitic clay covering the detrital quartz grains. Micrographs on the right show the elemental mapping of aluminum clearly showing the clays surrounding the grains. The elemental mapping on the bottom right image shows more noise as it was acquired over a shorter period of time and with a lower resolution.
The distance to the nearest stylolite above or below each sample was measured, and the results in relation to the observed quartz cement volume can be seen in Fig. 6D. The results show that sample 2957.50 and 2959.50 have exceptionally large stylolite spacing and are characterized by a quartz cement volume around 5%. Most of the remaining samples have a stylolite spacing in the range of 10–20 cm, but still a noticeable difference can be observed in the quartz cement volume in these samples. Fractured grains were sporadically recognized in samples examined in the SEM utilizing CL. Comparing the CL- and BSE micrograph obtained from sample 2959.50 m show that these fractures are partly-to completely filled with quartz cement (Fig. 8).

Observed porosity plotted against the observed quartz cement volume demonstrates a correlation between less quartz cement and better preserved porosity (Fig. 6C). Samples observed to contain coated grains have a quartz cement volume in the range of 5–11%, whereas samples with uncoated grains have a cement volume between 20 and 23%. This results in a bimodal distribution of coated and uncoated samples where quartz cement volumes either were below 11% or above 20% (marked by black arrow in Fig. 6C).

5. Discussion

5.1. Intervals with high prevalence of coating in relation to facies

Within the high porosity intervals of the Stø Formation the majority of grains show at least a partial degree of coating. Coatings are best developed on the rougher grains, with the thickest layer of clay coating observed where there were significant indentations in the detrital grains (Fig. 5E). As mentioned in Wilson (1992) in filtration clay will be found in larger extent where the geometry of the detrital grains will allow a more substantial retention of the clay introduced to the sediments. Rough geometry of the grains will aid the preservation of grain coating clay should the sediments be exposed to any subsequent reworking after the emplacement of grain coats. The amount of reworking would therefore have a strong impact on the subsequent reservoir quality of the sediments. The interface between the clay coats and the pore space were most often undulating and smooth. The amount of coats both in thickness and areal extent were larger on rougher grains. Remnants of grain bridging clay were also observed (Fig. 5C). These observations indicate that the grain coats originally formed by means of
infiltration processes (Dutton and Diggs, 1992; Wilson, 1992), and were later subjected to a varying degree of reworking. A typical scenario for the clay emplacement would be infiltration by muddy waters on flood plains where the sediments situated in the vadose zone later retained the coating. Infiltrated clays are most easily emplaced in sediments where there exist a high amount of clay in suspension, fluctuating water levels, allowing for intermittent periods of clay retention on grains, and minimal sediment reworking (Matlack et al., 1989). In situ sands in the vadose zone after clay infiltration have both grain coatings and meniscus shaped bridges of clay at grain contacts (Matlack et al., 1989). The grain bridging clays will easily be removed by transport and reworking, but some grain coats would persist in certain units.

The differences between the high porosity interval underlying the conglomerate and the overlying interval with lower porosity (Fig. 2) were studied in detail. Both intervals consist of predominantly clean sandstone and the mineralogical composition is the same. The most significant difference between the two intervals is the textural parameters. The sandstone above the unconformity (Fig. 3) shows significantly less porosity and permeability and consists on average of marginally finer grains. The sorting is also better than within the underlying interval. The interval above also shows vertical burrows. This difference may be caused mostly by variation in energy of the depositional environment, with the interval above the unconformity being subjected to higher energy and more substantial reworking.

The unconformity is believed to be caused by a transgressive event, since a pulse of incoming sediments is needed to explain the transition observed. The variation in textural parameters as well as the retention of coating in the sediments below can be explained by an increase in base level, facilitating the preservation of more proximal sediments.

The low relief of the area at time of deposition (Olaussen et al., 1984) means that any eustatic sea level change would impose a significant alteration of the relative location of the coast line. The long period of deposition means that these kinds of events could be quite common in the Ste Formation and would cause a varied distribution of high porosity intervals both laterally and temporally by alternating energy of the depositional setting.

Since traces or remnants of coating where seen also in samples with low porosity it is reasonable to assume that formation of temporarily coated grains was quite common in the Ste Formation. Subsequent variation in degree of clay coating was then determined mostly by the energy of the depositional setting and the preexisting textural and mineralogical properties.

5.2. Textural and mineralogical properties and diagenetic effects of grain coats

The IGV (Fig. 6B/Table 2) shows a trend where samples with coated grains have a reduced IGV compared to samples where grain coats are infrequent. The textural properties (grain size/sorting) of samples with negligible grain coating are not considerably different to samples where grain coats are common (Fig. 6A) and

Fig. 6. Textural- and diagenetic parameters regarding grain coating and stylolite spacing. Undefined data points represent unexamined samples with respect to the degree of grain coats. A) Sorting and mean grain size (phi scale) categorized with respect to grain coating. B) Displaying the relation between the calculated intergranular volume (IGV), observed quartz cement and grain coating. C) Observed porosity- and quartz cement volume color coded with respect to grain coating. D) The relation between the observed quartz cement volume and the distance to the nearest stylolite above or below each sample. All data from Table 2.
are not the cause of the observed difference in IGV. Sutured grain contacts are frequently observed in samples with coated grains indicating that detrital quartz grains are dissolved along grain contacts, due to the presence of the illitic clay coating (Fig. 7). Bjørkum (1996) observed interpenetration of detrital quartz grains in samples where a thin layer of illitic clay was present at the point of contact and suggested that dissolution of silica occurred due to a clay induced dissolution process. A lowering of the IGV would be an expected response if quartz grains are dissolved along grain contacts.

Since macro-stylolites are thought to be the main source of dissolved silica (Heald, 1955), the distance to the nearest stylolite above or below each sample is shown in Fig. 6D. The results demonstrate that all samples typically have a stylolite spacing of 5–20 cm and a quartz cement volume between 7 and 11%. Sample 2957.50 m and 2959.50 m had exceptionally large stylolite spacing (80–120 cm) and a quartz cement volume of 5.3% and 6.3%, respectively. Walderhaug and Bjørkum (2003) found that exceedingly clean intervals with great stylolite spacing (>20 cm), within the Stø Formation, were characterized by a low quartz cement volume. Based on the SEM BSE- and CL micrograph from sample 2957.50 m in Fig. 8, the sample with a stylolite spacing of 120 cm and extensive grain coating, fractured quartz grains were observed to be filled with quartz cement. Quartz overgrowths were also commonly detected on grains where the grain coating was discontinuous (Fig. 5C). These overgrowth cements indicate that the silica concentration is sufficient for extensive quartz precipitation even within the low quartz cement interval due to the clay induced dissolution process along coated grain contacts, i.e. micro-stylolites. As a consequence, intervals with a low quartz cement volume are believed to be governed by more effective grain coats and not a lack of silica in solution. The effect of high stylolite spacing would probably be more dominant if the illitic clay coating was absent.

Fig. 6C demonstrate the link between high quartz cement volume and poorly preserved grain coating. The difference in quartz cement volume in the most heavily cemented sample (2953.50 m) and least cemented sample (2957.50) is 17.4% (Table 2). The intergranular volume in the two samples are 30.3 and 24.7%, respectively, meaning that sample 2953.50 had the highest potential...
6. Conclusions

Porosity preserving effects are present in certain intervals of the Stø Formation in the Southwestern Barents Sea. High porosity intervals contain grains coated with illitic clay causing quartz cement volume to be significantly reduced.

- Six samples from intervals comprising coated grains have a quartz cement volume in the range of 5–11%, whereas the three samples where grain coats were observed to be negligible have quartz cement volume of 20–23%.

- The high porosity interval in well 7219/8-2 (2957–2969 m) had in general a large stylolite spacing ranging from 35 to 120 cm. However, there is two strong evidence indicating that the reduced amount of quartz cement do not reflect a lack of dissolved silica but instead reflect decreased area of overgrowth nucleation: (1) Sutured contacts and lower IGV in coated intervals are consistent with a local silica source and (2) Internal fractures within grains are observed to be quartz cemented.

- The appearance and distribution of grain coats indicate they were mainly formed during the final depositional phase for the well coated samples and prior to final deposition in the poorly coated sediments. The variation in the amount of reworking after the main coating phase is therefore controlling the extent and distribution of the coating.

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Paper II
The porosity preserving effect of basin wide illitic coating in deeply buried sandstone intervals of the lower Jurassic Stø Formation, Barents Sea

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ABSTRACT

The Stø Formation contains the main target reservoirs for petroleum exploration in the Norwegian Barents Sea Area. However, the clean sandstones of the Stø Formation can be heavily quartz cemented in areas that have undergone extensive post depositional burial. The Stø Formation in well 7219/8-2 has previously been identified as having porosities well above the expected porosity depth trend due to the porosity preserving effects of illitic grain coating. In this study the Stø Formation in 14 wells with maximum burial depths at top of formation ranging from 2672 to 3623 m have been investigated and several new intervals of the formation show abnormally high porosities relative to the expected burial trend. Thin sections from 4 wells were available and in all of these remnants of grain coating illitic clay was observed in varying amounts, with the effectiveness in reducing quartz cement overgrowth being determined by the continuity of grain coats. This indicates that the degree of grain coating coverage exerts the main control on the porosity of the clean deeply buried parts of the Stø Formation. With increasing burial depths, the porosity difference between intervals with continuous grain coats and intervals with less continuous grain coats becomes ever larger. Intervals observed to have extensive grain coating coverage compact with a significantly reduced rate with increasing burial compared to poorer coated intervals in the chemical compaction domain. The noticeable and consistent difference in the chemical compaction trend between coated- and negligible coated intervals within the Stø Formation could allow for establishment of powerful predictive models without the need for expensive petrographic- or core plug data.

1. Introduction

The oil and gas industry is to an increasing degree shifting their focus towards deeply buried reservoir prospects, and the predictability of reservoir quality in these prospects is therefore becoming ever more important.

The Stø Formation is present across most of the Norwegian Barents Sea and the formation is an important target for petroleum exploration (Worsley et al., 1988). The Stø Formation has in places been subjected to considerable maximum burial depths, up to 3623 m in the studied wells e.g. Baig et al. (2016). The mainly clean homogenous sandstones of the Stø Formation (Olaussen et al., 1984), may thus have been subjected to extensive quartz overgrowth causing significantly lowered porosities. Previously grain coating clay minerals, from hereon called grain coats, of sufficient extent to limit quartz cementation have been seen to preserve porosities well above the porosity depth trend in the Stø Formation. This was mainly seen in intervals interpreted to be of an upper shoreface facies that was deposited in periods of relative quiescence compared to other sections of the Stø Formation (Hansen et al., 2017).

During mechanical compaction the amount of porosity lost with increasing burial is governed by the sediments textural and mineralogical composition e.g., (Bjørlykke et al., 1989; Lundegard, 1992; Chuhan et al., 2002; Paxton et al., 2002; Marcussen et al., 2010), but if the sediments are subjected to temperatures above 70–80 °C, precipitation of silica becomes a significant factor (McBride, 1989; Bjørlykke and Egeberg, 1993). The amount of chemical compaction (quartz cementation) is a function of the time temperature integral (TTI) (Walderhaug, 1994). TTI reflect the burial curve/temperature history, including uplift within the chemical compaction domain. Quartz cement is considered to be the most important factor controlling porosity distribution in deep clean sandstone reservoirs (Bjørlykke and Egeberg, 1993). Grain coats if present on a large part of the detrital grain surface have the ability to reduce the amount of quartz cement precipitated by reducing the surface area available for nucleation of authigenic quartz (Heald and Larese, 1974). Variations in the degree of grain coating coverage will result in different responses to increasing burial in regard to the amount of...
porosity lost due to quartz cement in otherwise similar sands (Ajdukiewicz and Lander, 2010) (Fig. 1). Grain coats preserving porosity well above expected levels from average porosity depth trends have been discussed in several papers from the Norwegian continental shelf, mainly from the North Sea and the Norwegian Sea (Ehrenberg, 1993; Aase et al., 1996; Ramm et al., 1997; Bjerlykke, 1998; Jahren and Ramm, 2000; Maast et al., 2011), but recently also from the Barents Sea and Svalbard areas (Haile et al., 2018; Line et al., 2018). Microquartz and authigenic chlorite coating have primarily been found to preserve porosity. Albeit less often seen, Storvoll et al. (2002) also found illite or illite/chlorite coating to reduce precipitation of quartz cement.

Matlack et al. (1989) showed experimentally that infiltration of muddy waters can be an effective way of emplacing clay particles as coating on detrital sand grains. With high volumes of suspended clay along with fluctuating water levels yielding the most significant amount of grain coating clay minerals. Other studies have reported bioturbation as a factor in the emplacement of detrital clay on sand grains either by sand grains passing through the digestive systems of organisms or facilitated by the burrowing action of organisms (Wilson, 1992; Needham et al., 2005). Some studies have also shown estuaries to be a suitable for the formation of precursor grain coats (Wooldridge et al., 2017a, 2017b; Griffiths et al., 2018; Virolle et al., 2019) where the emplacement of clay coatings could be due to extracellular polymeric substances that are secreted by microorganisms and forming a biofilm that causes clay particles to attach to sand sized grains (Wooldridge et al., 2017a).

Remnants of inherited grain coats where seen in all our samples from the Stø Formation indicating that previous emplacement of grain coats is common, but only extensively preserved in certain intervals (Klausen et al., 2017). Previously the research on the Stø Formation has mostly been focused on provenance and the depositional processes, the regional structural and general sedimentological makeup of the formation, e.g., (Olaussen et al., 1984; Gjelberg et al., 1987; Worsley et al., 1988; Bergan and Knarud, 1993b; Klausen et al., 2018, 2019). In this study our prime objective is therefore to investigate the regional occurrence of grain coating illitic clay and its control on the porosity distribution in deeply buried parts of the Stø Formation.

2. Geological setting

The Stø Formation was deposited during late Pliensbachian to Bajocian times. The formation is a part of the Realgrunnen subgroup (Norian – Bajocian) where it overlies the Nordmela Formation consisting of interbedded sandstone, siltstone, mudstone and claystone, overlying the Stø Formation is the Fuglen Formation consisting of pyritic mudstones with interbedded limestone (Fig. 2). The Stø Formation generally consists of medium to very fine-grained mature sandstones that are moderately to well sorted. The Stø Formation is highly condensed and consists mainly of shallow marine sandstone deposited in an overall prograding coastal regime with several transgressive events interrupting the overall trend marked by thin siltstone and shale layers (Olaussen et al., 1984; Gjelberg et al., 1987; Worsley et al., 1988; Klausen et al., 2018).

The quartz content of the Stø Formation is generally around 91–100% of the detrital grains (Bergan and Knarud, 1993a). The mature nature of the formation is due to both the shallow marine depositional environment yielding a high amount of sediment reworking (Worsley, 2008), and the mature source area of the rejuvenated hinterland in the south (Bergan and Knarud, 1993a; Ryseth, 2014; Line et al., 2020). Furthermore Klausen et al. (2019) found a tectonically induced change in provenance within the Stø Formation, from reworked Triassic sediments in the lower part of the formation to mature sediments coming from the Caledonides in the upper part, with this altered tectonic setting causing not only a shift in provenance area but also a concurrent shift in the depositional setting. From more tidally influenced transgressive lags in the lower part of the formation to more fluvial influenced deposits in the upper part (Klausen et al., 2018). Table 1 shows the present depth to top Stø Formation as well as the estimated maximum burial depth of the formation, most likely reached in Eocene or Oligocene (Baig et al., 2010).

Fig. 1. Porosity evolution with burial for a well-sorted, fine-grained, rigid-grained quartz-feldspathic eolian sandstone with variable grain coat coverage. A sand deposited with an initial porosity of 42% (A) undergoes subsidence to a depth of 6200 m over a period of 155 m.y. with no uplift or overpressure development. In this example porosity decrease by means of mechanical compaction to a depth of 2 km, at this point (B) the porosity is 26%. From this point further mechanical compaction in rigid-grained sandstones continues at an exceptionally low rate (red curve). When temperatures increase to above 70–80 °C quartz cement can precipitate, with the rate of precipitation mainly determined by the time temperature integral and quartz grain surface area available for nucleation of quartz cement. Grain coats limit this surface area and with increasing burial depth the variation in porosity between differently coated sands becomes ever increasing (e.g., C to D). Figure from Ajdukiewicz and Lander (2010). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
The amount of uplift varies across the Southwestern Barents Sea and ranges from 850 m to 1100 m in the studied wells. The Stø Formation in all studied wells have reached burial depths corresponding to temperatures well above what is required for the precipitation of quartz cement (Table 1).

The locations of the studied wells are shown on the map in Fig. 3. The wells are situated in the Bjørnøyrenna Fault complex, west of the Polhem subplatform, in the Ringvassøy-Loppa fault complex, west of the Hammerfest Basin and in addition, 10 of the wells are situated in the Hammerfest Basin. In the Hammerfest Basin one well is in the Northwestern

Table 1
General well information. *Maximum burial are based on Baig et al. (2016). Temperature estimates are based on the current geothermal gradient. All values are calculated at the top of formation. Temperatures in brackets for well 7120/5-1 and 7120/12-2 are the authors’ estimate of a more realistic temperature gradient.

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corner of the basin on the boundary towards the Loppa high, two are in the Southwestern corner on the boundary to the Finnmark Platform and the remainder of the wells are in the middle of the basin, mainly in the western parts.

3. Methods and data

Coreplug- and petrophysical data from 14 wells formed the basis for this study (Table 1). In addition point count data from 4 wells were available, well 7219/8-2 from Hansen et al. (2017), and 3 additional new wells point counted for this study (Table 2). The petrographic database consists of 38 thin section samples where the mineralogical distribution was determined by analogue point counting of each sample using a Nikon Eclipse 50/pol optical microscope. Textural parameters were obtained by measuring grain sizes in the Infinity Analyze software using an optical microscope fitted with a camera.

The thin sections available were point counted with 300 points counted per sample. The longest axis was measured on >100 randomly picked detrital grains. Sorting calculations were performed using the method defined by Folk and Ward (1957). Thin sections were inspected in a Hitachi SU5000 scanning electron microscope (SEM) using back-scattered electrons (BSE) and energy dispersive spectroscopy (EDS). SEM analysis was used to detect and analyze the composition and appearance of grain coatings. The grain coats was not recognizable in the optical microscope. This was due to the grain coats being both exceedingly thin and because of its morphology. The grain coating minerals were situated tangentially on the grain surfaces. Had the clay coating minerals been situated radially on the grain surfaces it may still have been possible to differentiate the coating in the optical microscope using cross polarized light and looking for the interference color of the illite. Thus, it was not possible to obtain a quantitative measure of the degree of grain coating coverage. Instead, a qualitative classification was made on all samples studied in SEM, determining the visual extent of the grain coats. All depths mentioned are in meters below rotary table (mRKB) unless otherwise stated. Maximum burial depth estimates are based on the uplift map in Baig et al. (2016). Maximum temperatures at the top of the Stø Formation are based on the present-day geothermal gradient as calculated from the recorded bottom hole temperature (BHT). Note that temperatures shown for the Stø Formation in the wells 7120/12-2 and 7120/5-1 are too low, this is most likely the result of erroneous BHT measurements. The geothermal gradients in the 7120/12-2 and 7120/5-1 wells are much more likely similar to those recorded in nearby wells. The amounts of quartz cement observed in parts of the formation in these two wells are also a strong indication that the temperature estimates are much too low. Porosity estimations were done in Interactive Petrophysics (IP) and consisted of neutron-density measurements corrected for shale volume, shale density, shale porosity, pore fluids and resistivity. The porosity estimation was quality checked against core plug measurements of horizontal helium porosity. For all the wells included in this study, core-plug measurements of porosity and permeability were available with a sample spacing of approximately 30 cm. Similar intervals of the Stø Formation in different wells were identified by characteristic petrophysical parameters facilitating an easy comparison and the ability to easily discriminate based on fixed values. Different intervals were defined primarily by the amount of shale (Vshale), porosity, P-wave sonic velocity (Vp) and density. The Vshale estimates were averaged from gamma ray and neutron-density calculation and performed uniquely for each well.

Fig. 3. Position of the studied wells in the Southwestern Barents Sea on a structural map (Norwegian Petroleum Directorate FactMap, retrieved August 27, 2018 from http://gis.npd.no/factmap).
4. Results

4.1. Petrographic results

The Stø Formation can be classified as a quartz arenite in all physical samples investigated in this study (Table 2). Percentages listed are in relation to total bulk volume. The quartz content ranges from 62 to 79% of the bulk volume and the feldspar and rock fragment content accounts for less than 2% each. Muscovite grains were also observed in all samples, but the amount is typically less than 1%. The pore-filling detrital clay content is highly variable ranging from approximately 1-12%. SEM analyses indicate that the pore-filling clay consists of illitic clay, occasionally with deformed lithic grains consisting of illite and microquartz incorporated in the matrix. Illitic clay was also observed in the SEM as grain coats on detrital quartz grains in several samples (Fig. 4 A–F), and each sample selected for SEM analysis was characterized. The exceedingly thin grain coats means that any volumetric percentage is impossible to determine, but as the degree of coating coverage is the governing factor on the ability of grain coats to limit quartz cement a qualitative approach were used to characterize the samples (red = negligible coating, if grain coats are present, it is only seen as remnants. green = coated sample, a large portion of the detrital grain surface is coated) (See Table 2). The results indicate that samples with a higher porosity tend to be more significantly coated compared to samples with low porosity (Table 2). Furthermore, in samples characterized as negligible grain coated, the clay fraction was predominantly observed as being pore-filling (Fig. 4G–I)). The authigenic cements observed in the studied samples are kaolinite-, carbonate- and quartz cement. The kaolinite- and carbonate cement are far less volumetrically significant compared to the quartz cement, ranging between approximately 0-4% and 0–9% respectively. The carbonate-cemented intervals are easily recognized in the sonic log with significantly higher Vp values. The quartz cement content is highly variable between individual samples and reaches approximately 23% in the most heavily cemented samples and as low as 3% in samples where quartz cement is limited (e.g., comparing Figs. 5C and 4D). The intergranular porosity observed in these samples is highly variable and ranges from approximately 3 to 17% (Fig. 4 and Table 2).

4.2. Grain coating illitic clay

Grain coats are present to some degree in all samples investigated, but with varying extent and thickness (Fig. 4). EDS spectra shows that the grain coats in all the samples contain potassium, aluminum, silica and oxygen, which along with the textural appearance indicate a mainly illitic composition (Matlack et al., 1989; Dutton and Diggs, 1992). In each sample selected for SEM analysis was characterized. The exceedingly thin grain coats means that any volumetric percentage is impossible to determine, but as the degree of coating coverage is the governing factor on the ability of grain coats to limit quartz cement a qualitative approach were used to characterize the samples (red = negligible coating, if grain coats are present, it is only seen as remnants. green = coated sample, a large portion of the detrital grain surface is coated) (See Table 2). The results indicate that samples with a higher porosity tend to be more significantly coated compared to samples with low porosity (Table 2). Furthermore, in samples characterized as negligible grain coated, the clay fraction was predominantly observed as being pore-filling (Fig. 4G–I)). The authigenic cements observed in the studied samples are kaolinite-, carbonate- and quartz cement. The kaolinite- and carbonate cement are far less volumetrically significant compared to the quartz cement, ranging between approximately 0-4% and 0–9% respectively. The carbonate-cemented intervals are easily recognized in the sonic log with significantly higher Vp values. The quartz cement content is highly variable between individual samples and reaches approximately 23% in the most heavily cemented samples and as low as 3% in samples where quartz cement is limited (e.g., comparing Figs. 5C and 4D). The intergranular porosity observed in these samples is highly variable and ranges from approximately 3 to 17% (Fig. 4 and Table 2).
Fig. 4. Backscatter SEM micrographs from three different thin section samples with accompanying elemental maps showing the aluminum (Al)- and potassium (K) response of the area shown in the backscatter micrographs on the left. The thin clay coating is best seen in the Al-map. The potassium map indicate that the clay coating has an illitic composition. A-C) from well 7120/6-1, sample 2446.50. D-F) from well 7120/6-1, sample 2446.26. G-I) from well 7120/6-1, sample 2391.22. Note that remnants of clay coatings are present on some grains.
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had a high degree of grain coat coverage (Fig. 4 A-C and D-F). Other samples showed only remnants of grain coats and they were mainly characterized by abundant quartz cement (Fig. 4G-I). The grain coats exhibit a chaotic appearance (Fig. 5C) with an undulating outer rim and with a tendency to be patchy in some samples (Fig. 4 A-C and Fig. 5 A and B), while the grain coats are more continuous in other places (Fig. 4D-F). Another observation is that clay bridges are typically also seen in samples defined as coated (Fig. 5 D). When present, the grain coats are in most cases 1–4 μm thick (Fig. 5 C), but where indentations in the detrital grains exists, the thickness of grain coats can be significantly thicker (Fig. 5 E). Grain coats are also present at most detrital grain contacts in samples with a significant amount of grain coats (Fig. 4 A-F and Fig. 5 F). The contacts between detrital quartz grains in coated samples are often sutured (e.g., Fig. 4 A), indicating that the presence of grain coats facilitates quartz dissolution at the detrital quartz-clay interface at points of grain contact.

Based on the petrographic results, the quartz cement content was plotted against the IGV and porosity in order to investigate factors related to the grain coating illitic clay (Fig. 6 A and B). The intergranular volume (IGV) varies from as low as 20%–35% in the point counted samples. The results indicate that the IGV is generally lower in samples where significant grain coats have been observed (Fig. 6 A, Table 2). The results also show that samples with grain coats have lower quartz cement volumes (Fig. 4 A and D compared to G, Fig. 6 B) -.
porosities (Fig. 6B) – a slightly poorer sediment sorting and a coarser grain size (Fig. 6C and D) compared to samples with negligible grain coating. Especially, there seems to be a strong relation between the observed quartz cement volume and IGV, where a gradual increase in quartz cement volumes favors a higher IGV. These observations agree with results from the reference well 7219/8–2 (Fig. 6A and B).

4.3. Porosity, sonic velocity (Vp) and density

It is important to determine the relationship between core plug porosity, calculated porosity and the petrophysical characteristics of the sediments with abnormally high porosities. This will aid the possibility of detecting intervals with abnormally high porosities in wells or parts of the formation without petrographic control. A porosity line was calculated within the Stø Formation in all wells in order to obtain an accurate and continuous porosity estimate throughout the entire formation. Based on wells with petrographic control a cutoff value of 15% porosity was chosen (shaded area in Fig. 7A) for the calculated porosity curve in order to evaluate intervals without petrographic data that are likely to have effective grain coats within the Stø Formation. Fig. 7B shows a cross plot of core-plug porosity and the calculated neutron-density porosity and shows a strong correlation between the two. In the reference well 7219/8–2, a porosity cutoff value of 15% coincides with the interval proven to be significantly coated (Hansen et al., 2017). Although a threshold porosity of 15% in the wells from the Hammerfest basin (7121/5–1, 7120/6–1 and 7120/2–3 S) allow intervals with less petrographic certainty to be defined as possibly coated intervals, it successfully includes regions where grain coats have been proven and reject intervals where grain coating was observed to be negligible (Fig. 7A). Where the Stø Formation have undergone less – or more
burial, the cutoff value should be changed according to the porosity-depth trend in order to more accurately identify abnormally high porosity intervals in each individual well.

The data points are then filtered into two groups based on the cutoff porosity. The high porosity interval in well 7219/8-2 (Fig. 8A), shown to be significantly grain coated, have a whole rock density in the range of 2.25–2.38 g/cm³ and a P-wave velocity ranging from approximately 3750 m/s to 4400 m/s. The density and P-wave velocity in the sub-population of porosities less than 15% gradually increases towards a density of approximately 2.62 g/cm³ and a velocity exceeding 5000 m/s.

The wells with petrographic data from the Hammerfest Basin (Fig. 8B), shows a similar trend, separating between high and low porosity intervals in the Vp-density domain. However, some of the data points of the higher porosities show elevated density readings (exceeding 2.4 g/cm³). This is most likely reflecting intervals with a slightly higher amount of pore filling clays. Finally, a cross plot of all available density and P-wave velocity data in this study (reference well 7219/8-2 not included) shows the acoustic response from the Stø Formation in the study area (Fig. 8C). The results show that there is a significant spread in velocities both for intervals with porosity greater than 15% and intervals with porosity less than 15%. In terms of density, the intervals show an expected trend where intervals with higher porosity have a lowered density and vice versa.

### 4.4. Porosity distribution

All helium porosity data from within the Stø Formation in all wells included in the study can be seen in Fig. 9. The core plug porosity distribution often shows abnormal subpopulations of both higher and lower porosities deviating from a normal distribution of porosites. The sub-populations of abnormally low porosites almost exclusively correlates to high density calcite cemented layers. The sub-populations of abnormally high porosities coincide with intervals of grain coats in all four wells where petrographic data were available.

### 4.5. Porosity depth trend

Excluding the parts of the Stø Formation with a Vshale content above 20%, the Stø Formation still show a large spread in porosity values in each of the studied wells (Fig. 10A). The spread in the porosity distribution for a given depth level is observed to increase with increasing burial depths. The parts of the Stø Formation in the different wells assumed to consist of clean, i.e., less than 10% clay by volume, well cemented non coated sands shows a high degree of compaction with depth in the chemical compaction domain and is likely to plot closer to the red line (Fig. 10A). The cleaner parts of the formation assumed to consist of clean, well-coated sands with less quartz cement compact less with increasing depth and will plot closer to the green line (Fig. 10A). This is also supported by the core plug porosity depth trend colored with P-sonic data (Fig. 10B) that indicates that sonic velocity fluctuations vary systematically with change in porosity.
5. Discussion

The petrographic (Fig. 4) and textural parameters (Fig. 5) of the Stø Formation in wells 7121/5–1, 7120/6–1 and 7120/2–3 in the Hammerfest Basin are similar to those recognized in the reference well 7219/8–2, located in the Bjørnøyrenna Fault Complex (Hansen et al., 2017). This uniform composition of the sediments and the widespread occurrence of grain coats of an illitic composition found regionally within the Stø Formation in all the studied wells (Table 2) indicates that similar depositional conditions and grain coat emplacing processes have taken place over large areas. The process(es) resulting in the original emplacement of precursor clay on detrital grains in the Stø Formation is not possible to conclude from the data presented in this paper. Hence, detailed sedimentological- and experimental studies should be conducted to investigate this further. However, the study has shown that delicate features like clay bridges between detrital grains and a slightly better sediment sorting can be observed in coated intervals, while remnants of grain coats can be observed in intervals with negligible coating. This could indicate that whatever process responsible for the emplacement of the coating was common throughout the development of this very condensed section, but where the balance between this process and the amount of sediment reworking subsequently controlled the extent of precursor grain coats.

The results show that there is an overall strong positive correlation between IGV and quartz cement content (Fig. 6A) and a strong negative correlation between quartz cement and porosity (Fig. 6B). The coated
samples are characterized by a lower IGV and a lower amount of quartz cement compared to samples with negligible grain coats. Grain coating illitic clay will to some extent reduce the IGV, and porosity, of the sediments due to a clay induced dissolution process (CID) acting at points of contact between the detrital quartz grains (Bjørkum, 1996). This means that too extensive illitic clay coating could have a negative effect on the reservoir quality and should be taken into consideration. However, the total amount of illitic clay in the Stø Formation is generally not enough to cause this to be a major factor in the resultant porosity. The grain coats limits the amount of chemical compaction in these well-coated intervals (Fig. 4A–F) as the illitic clay decreases the available nucleation area for quartz cement (Walderhaug, 1994). The strong correlation between IGV and amount of quartz cement (Fig. 6A) in samples with grain coats are therefore likely to represent the combined effect of quartz cement retardation and the effect of microstylolitization with quartz cementation being the major factor. In addition, continued mechanical compaction due to low initial quartz cement volumes during early chemical compaction may also be responsible for reducing the IGV to a certain degree in well coated intervals. However, substantial mechanical compaction within the chemical compaction domain would likely only take place in intervals with an exceedingly continuous grain coating coverage. In intervals where grain coating illite is negligible (Fig. 4G–I) the IGV is likely to be kept constant, i.e., representing the IGV as it was just after onset of quartz cementation and further mechanical compaction is prevented. In such cases detrital quartz grains is mainly dissolved along macroscopic stylolites acting as a silica source for quartz cement growth within the volume between the stylolites (Walderhaug, 1996). It is also important to underline that the low quartz cement volume in intervals with abundant grain coats are not likely to be a result of insufficient silica concentrations. All points of contact between a quartz grain and the illitic clay or mica grain, whether emplaced as coating or pore-filling clays, can be a source of silica (Bjørkum, 1996; Walderhaug, 1996). Hansen et al. (2017) also observed that intra-granular cracks in detrital quartz grains were filled with quartz cement within intervals with grain coats. This indicate that sufficient silica supersaturation for quartz cement growth was present also in sections of the Stø Formation with grain coats and little quartz cement overgrowth. Moreover, samples with extensive coating coverage have higher porosities but a lower IGV (Fig. 6A, C and D). In terms of textural properties, the samples with extensive coating coverage have slightly coarser grain sizes and poorer sorting (Fig. 6C and D). Coarser grained and poorer sorted sediments are prone to compact more mechanically (Chuhan et al., 2002), and this could to some extent explain the lower IGV values in these samples. However, the higher porosities in these samples indicates that the differences in textural parameters are not the main controlling factor on porosity distribution in deeply buried parts of the Stø Formation, but rather the amount of quartz cement which is controlled by coating coverage. The porosity distribution plots seen in Fig. 9 shows that the normally distributed population of porosities is centered around a mean value consistent with the porosity depth trend of clean uncoated shallow marine sands (Marcussen et al., 2010). However there are several subpopulations of porosities in the Stø Formation that are abnormally high. The porosity depth trend for the Stø Formation in the 14 studied wells is shown in Fig. 10. The depths have
been corrected for exhumation and since porosity reduction is largely a non-reversible process the data closely represents the real depth trend of the formation. Any differences in textural and mineralogical composition (size, sorting, clay content etc.) will cause variations in porosity due to varying response to increased mechanical compaction, but due to the homogenous nature of the Stø Formation (Table 2) the depth trend within the mechanical compaction domain will likely be similar across the formation (e.g., Fawad et al., 2011), exemplified here by the Paxton et al. (2002) compaction line in Fig. 10A. The amount of quartz cement will be by far the most important factor controlling porosity within each depth interval in the chemical compaction domain. Since the TTI can be assumed to be relatively uniform for all the wells studied, higher porosities would reflect lower quartz cement volumes within some sections of the Stø Formation due to coating. The spread in porosity i.e., the range of porosity values in the clean intervals of the Stø Formation is clearly seen to increase with depth (Fig. 10). This is in accordance with what is expected from the rate of silica precipitation, governed by the TTI, with a significant increase in the rate of silica precipitation with higher temperatures (Walderhaug, 1996). The uncoated parts of the Stø formation will therefore lose porosity at an ever-increasing rate compared to the coated sands in the chemical compaction domain (Fig. 10). Even the intervals with the highest degree of grain coating coverage compact more than what would be the case if compaction were a function of mechanical compaction only, showing that some precipitation of quartz cement takes place even in the sediments with the highest degree of grain coating coverage (Fig. 10B). The most extreme difference in rate of compaction in coated- and negligible coated intervals within the Stø Formation can be represented by hypothetical compaction lines following the upper – and lower porosity limit as a function of depth (Fig. 10). This result agrees with the model of Ajdukiewicz and Lander (2010) (Fig. 1) and fits well with SEM observations showing that in most cases the coating does not completely cover the detrital grains, allowing some quartz cement formation (e.g., Fig. 5 A and B).

The Stø Formation in all the studied wells have been subjected to burial depths well within the temperature range required for quartz cementation prior to uplift, but there is a large variation in the amount of
quartz cement in what is otherwise similar sediments both in respect to composition and burial history. The homogenous nature of the sediment composition of the Sto Formation makes it especially interesting to understand the relationship between the varying amount of quartz cement and the corresponding variations in sonic velocity and bulk density in order to see if possibly coated intervals at various depths are easily detectable by petrophysical data alone. The strong correlation between the computer processed interpretation (CPI) porosity curves and core plug data (Fig. 7) allowed for the well log data to be included in the characterization of the elastic parameters with higher confidence (Fig. 8). For the wells with petrographic control studied here, a cutoff porosity of 15% coincide well with coated intervals having porosities higher than this, and less coated intervals having lower porosities (Fig. 7 A). The widespread distribution of data points in the Vp-density domain (Fig. 8) is likely a result of several different factors that are difficult to accurately account for and includes the type of fluid saturating the rock, porosity, mineralogical composition and calibration and type of tools used to acquire the elastic parameters. However, the results indicate that coated and negligible coated intervals should be distinguishable in the Vp-density domain (Fig. 8). The link between the petrophysical- and petrographical data established herein also indicate that these two types of intervals are common on a regional scale in this formation. This means that it may be possible to infer reservoir quality within deeply buried parts of the Sto Formation on a regional scale using only basic well logs due to the different rate of compaction in intervals with effective grain coats vs-negligible coated intervals. Hence, powerful predictive models could likely be established without the need for expensive petrographic- or core plug data within the Sto Formation.

6. Conclusion

14 wells containing the Sto Formation from the Hammerfest basin and Bjoernsryonna Fault Complex were studied to investigate the regional occurrence of grain coating illitic clay and its control on the porosity distribution in deeply buried parts of the formation. Grain coating clay is observed in the potentially good reservoir sands of the Sto Formation in all the studied wells, indicating that the emplacement of grain coating illitic clay is common on a large regional scale. The extent of the grain coating coverage on the detrital grains however is highly varying and only some intervals are seen to have extensive grain coats sufficient to significantly inhibit quartz cementation and preserve abnormally high porosities. The Sto Formation is largely homogenous and although variations in mineralogical and textural parameters are present, the extent of grain coating coverage is the main factor in controlling porosities in deeply buried parts of the formation. With increasing burial depths, an ever-wider porosity distribution will be caused by the massively different rate of quartz cementation between intervals with significant coating coverage and those with negligible coating coverage. The large difference in the compaction trend between intervals with significant grain coat coverage and those with less consistent grain coats could allow for easy generation of predictive models without the need for expensive petrographic- or core plug data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References


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Paper III
New direction for regional reservoir quality prediction using machine learning - Example from the Stø Formation, SW Barents Sea, Norway

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ABSTRACT

Recently, the petroleum industry has focused on deeply buried reservoir discoveries and exploring potential CO₂ storage sites close to existing infrastructure to increase the life span of already operating installations to save time and cost. It is therefore essential for the petroleum industry to find an innovative approach that exploits the existing core- and well log data to be successful in their endeavor of effectively characterizing and predicting reservoir quality. Continuous data sources (e.g. wireline logs) have a huge potential compared with expensive, time inefficient and sporadic data from cores in determining reservoir quality for use in a regional context. However, whereas core analysis offers in-depth knowledge about rock properties and diagenetic processes, continuous data sources can be difficult to interpret without a formation-specific framework. Here, we demonstrated how the pre-existing core data could be effectively used by integrating petrographic- and facies data with a pure predictive machine learning (ML) based porosity predictor. The inclusion of detailed core analysis is important for determining which reservoir parameter(s) that should be modeled and for the interpretation of model outputs. By applying this methodology, a framework for deducing lithological and diagenetic attributes can be established to aid reservoir quality delineation from wireline logs that can be used in frontier areas. With the ML porosity model, a Random Forest Regressor, the square of the correlation was 0.84 between predicted- and helium porosity test data over a large dataset consisting of 38 wells within the Stø Formation across the SW Barents Sea. By integrating the continuous ML porosity logs and core data, it was possible to differentiate three distinct bed types on wireline log responses within the Stø Formation. Particularly, the relationship between Gamma ray (GR) and porosity was effective in separating high porosity clean sand-, low porosity cemented clean sand and more clay and silt rich intervals. Additionally, in the P-wave velocity (VP) - density domain, separation of high porosity clean sand- and heavily cemented low porosity clean sand intervals were possible. The results also show that the ML derived porosity curves coincide with previously published and independent facies data from a selection of the wells included in the study. This demonstrates the applicability of the model in the region, because the Stø Formation has been described to exhibit similar lithological- and mineralogical properties over large parts of the Western Barents Sea area. Even though, continuous porosity data could be estimated from other sources like VP, neutron or density logs, this would generally require matrix and fluid information. This study demonstrated the effectiveness of the ML model in generating continuous porosity logs that are useful for characterizing and predicting reservoir properties in new wells. This methodology offers a workflow for exploiting already acquired core and well log data for frontier exploration that can be adapted to other formations and exploration scenarios worldwide.

1. Introduction

Reservoir quality characterization and prediction outside cored intervals remains a key challenge in offshore subsurface exploration because reservoir properties cannot be accurately determined from any remote sensing tools. This makes in particular reservoir property assessments on a regional scale demanding because core data are expensive and time consuming to acquire and these data are sporadic rather than continuous measurements along the well track. Hence, various predictive models and workflows are constantly being established and refined to increase the success rate of accurate reservoir quality delineation e.g., (Ajdukiewicz and Lander, 2010). More recently,
machine learning, a pure predictive workflow, has been employed for this purpose e.g. (Ahmadi and Chen, 2019; Urang et al., 2020). ML can effectively generate continuous porosity profiles that can be used for reservoir quality assessment in a regional context, but the lack of geological understanding can make predictions ambiguous, particularly moving away from wells or intervals without core material.

Detailed core analysis is crucial for characterizing the depositional- and diagenetic history of a sedimentary unit, however, such a workflow is cumbersome and expensive for reservoir quality discrimination in a regional context. This approach can make it difficult to constrain the spatial and temporal distributions of intervals with varying reservoir quality. To address this problem, several studies have focused on the interpretation of lithological- and diagenetic facies—e.g. (Ozkan et al., 2011; Cui et al., 2017), and electrofacies analysis e.g. (Klael et al., 2015), from wireline log data, while other studies have focused on pure predictive workflows for estimating key reservoir parameters e.g., (Helle et al., 2001; Liao, 2005; Urang et al., 2020; Agbadze et al., 2022). Here we present a hybrid methodology, which integrates detailed core analysis with a pure predictive workflow to aid effective reservoir quality discrimination. This study demonstrate the potential of using historical core data to estimate reservoir properties using ML and how these results can be integrated with detailed petrographic- and lithological knowledge to collectively aid regional reservoir quality delineation in intervals without cores. The integration of detailed petrographic knowledge aid the interpretation of model results and forms the basis for generating formation-specific templates that can deduce lithological- and diagenetic characteristics from well log responses. This approach differs from conventional electrofacies analysis in that it uses predetermined diagenetic- and lithological information and a predicted reservoir parameter, in this case porosity, to aid the discrimination of diagenetic and lithological attributes from well log data. It also differs from pure predictive workflows because detailed core analysis from a selection of wells are integrated and fundamental to several key steps in the methodology (Fig. 2). The availability of well log data and routine core analysis within the most important reservoir sandstone units from the Norwegian Continental Shelf (NCS), and likely for equivalent settings elsewhere in the world, makes this hybrid methodology adaptable to several exploration scenarios. Exploiting the existing infrastructure with nearby field development can for example significantly increase the life span of an installation and reduce operating costs.

The Ste Formation was chosen to test this integrated methodology in predicting nonlinear heterogeneous reservoir properties because the sedimentary succession has proven to exhibit large porosity variations in otherwise similar sandstone intervals consisting of texturally- and mineralogical mature sedimentary units (Olaussen et al., 1984; Klausen et al., 2018) across larger parts of the SW Barents Sea. Moreover, a patchy illitic clay coating has been identified to be the most important factor controlling reservoir quality. The patchy nature of this clay coating ultimately dictates quartz cement volumes and thus porosity (Hansen et al., 2017; Lavstad et al., 2022). In the context of petroleum exploration, clay coated sandstone reservoirs have gained much attention because for their ability to retain excellent reservoir properties even at great burial (Heald and Larese, 1974; Ehrenberg, 1993; Storvoll et al., 2002; Berger et al., 2009; Taylor et al., 2010; Ajdukiwicz and Larese, 2012; Dowey et al., 2012; Haie et al., 2018; Liao et al., 2018; Porten et al., 2019; Worden et al., 2020). However, despite their huge potential in preserving reservoir quality at depth, no attempts have been made to characterize these units using wireline log data, to increase their predictability. Up until now, reservoir quality assessment of the Ste Formation has relied on core data, like helium porosity measurements and thin section analysis, and where the extent of the patchy illite coating has proven difficult to quantify (Lavstad et al., 2022). Therefore, it is of particular interest in this study to establish a framework for separating these units based on simpler means of data, which are continuous in its nature and applicable on a regional scale. Successful identification of clay-coated sandstone intervals may have huge implications for identifying hydrocarbon- and CO2 storage reservoir sites in frontier areas, without the need of additional core material.

This study intends to demonstrate the potential in using historical core data to aid effective reservoir quality delineation at a regional scale without the need of additional core data. This methodology will be exemplified with the use of Ste Formation in the SW Barents Sea as a case study. The research objectives are to: (1) establish a ML based porosity predictor that can serve the purpose of effectively generating continuous porosity profiles outside cored intervals, (2) demonstrate how the integration of detailed core analysis can be used to strategically sub group data and aid the interpretation of the modelling results and (3) exemplify how this integrated methodology can be applicable to construct formation-specific templates from well log responses and facies data to aid reservoir quality determination in intervals without core data.

2. Geological setting

The study area lies within the SW Barents Sea, which is part of an epicontinental sea situated at the northern western corner of the Eurasian continental plate. The study includes wells situated in the Hammerfest Basin, Bjarmeland Platform, Fjordjeput sub-basin, Bjørnøyrenna Fault Complex, Polheim sub-platform and Ringvassøy Fault Complex (Fig. 1), all of which comprise the Ste Formation. The Ste Formation is part of the Realgrunnen Subgroup and is a Jurassic sandstone that was deposited between the Pliensbachian and Bajocian times (Dalland et al., 1988). The sandstones of the Ste Formation comprises shallow marine to offshore deposits. The most reservoir prone clean sandstone intervals were deposited in a shallow water coastal environment with fluctuating energy levels (Olaussen et al., 1984) and with relative influence of tidal- and wave action at certain locations depending on sea-level fluctuations and local basin topography (Klausen et al., 2018). The Ste Formation have been interpreted to be deposited in low-accommodation basins over large parts of the SW Barents Sea region in an overall transgressive regime (Olaussen et al., 1984; Klausen et al., 2018) that was interrupted by several regressive cycles. The highly condensed nature of this succession testifies the co-acting of deposition, erosion and reworking over several million years, which resulted in the texturally- and mineralogical mature sandstones that is typical for this formation. The Ste Formation is currently not buried to its maximum burial depth because of extensive uplift that influenced the entire southwestern Barents Sea region sometime during the Oligocene and Eocene (Baig et al., 2016). For example, within the Hammerfest Basin, where most of the wells in this study are located, results of Baig et al. (2016) show that this area is uplifted from 800 – 1400 m and where there is an increase in the magnitude from west towards the east. The burial history of the Ste Formation is of particular importance in areas where the formation has been subjected to large maximum burial depths (>2.5 km). Several studies (Olaussen et al., 1984; Bergan and Knarud, 1993) have shown that the Ste Formation is fieldspar poor and consist predominantly of mature quartz arenites which have important implications for diagenetic processes that occur upon burial. Quartz cementation has been identified as the key controlling factor on reservoir quality heterogeneity in settings where the formation has been deeply buried (Olaussen et al., 1984). More detailed petrographic studies (Hansen et al., 2017; Lavstad et al., 2022) have revealed that a thin illitic clay coating is present in varying amounts within the Ste Formation, and those intervals with effective clay coats can limit the amount quartz cementation and thus preserve abnormally high porosities in certain units.

3. Methods and data

3.1. Detailed petrographic study – a prerequisite for a successful modelling process

This methodology (Fig. 2) require an in-depth geological
understanding of processes (e.g., diagenetic processes and lithological characteristics) that affect reservoir quality heterogeneity within the formation under consideration. This is important for a couple of reasons: (1) detailed core analysis will aid the interpreter deciding which reservoir quality parameters to model (e.g., porosity, permeability, water saturation, clay content) and (2) a comprehensive understanding of reservoir quality controlling factors is crucial for the interpretation of the model output and separating the modeled data into strategic subsets. The latter can aid the interpreter to successfully cluster data representing key lithological and/or diagenetic attributes.

In this study, porosity was chosen as the parameter to be modeled. This selection is based on detailed petrographic studies (Hansen et al., 2017; Levstad et al., 2022) that concluded that quartz cementation is the predominant factor controlling reservoir quality heterogeneity. As a consequence, porosity and permeability tend to exhibit a linear relationship within these sandstones, which is further indicated by the study of Ogebule et al. (2020). Therefore, permeability was excluded from the modelling process to keep the model as simple as possible. However, permeability can be a crucial parameter to model in other scenarios and the parameter selection should be based on a solid understanding of reservoir quality controls.

3.2. Data preprocessing

The dataset consists of a collection of helium porosity- and wireline log data from 38 wells within the Stø Formation in the SW Barents Sea Area (Fig. 1 and Table 1). The included wireline logs were limited to the most basic well logs commonly available for all wells on the NCS, namely depth, GR, density, VP, neutron, medium- and deep resistivity (Table 2). This to ensure that the model can be relevant to most wells with basic well log data. The initial dataset consisted of 20899 data points and included all selected wireline log- and helium porosity data from within the Stø Formation in the 38 wells. Several preprocessing steps were carried out before training the ML algorithms on the dataset. The first step was to remove all feature instances that did not contain an accompanied helium porosity value, meaning that the initial data set was reduced to 5915 data instances (Table 2). Next, the dataset was split into training- and test sets where 80% of the data was used in training and 20% was used for testing. This subdivision was performed using a random split of data instances, but with a seed that ensures reproducible results. Following the train-test split, the training set was standardized by removing the mean and scaling to unit variance.

3.3. The modelling process

In this study, we compared the performance of two machine-learning algorithms over a compiled dataset that has shown the ability to solve complex non-linear problems; a fully connected feed forward Neural Network (NN) and a Random Forest Regressor (RFG). The modelling process was defined as a supervised regression problem, using the wireline log- and helium porosity data as features and labels, respectively. The RFG and NN hyperparameter optimization was carried out using an exhaustive grid search in conjunction with 3-fold cross validation over the training set, where the exhaustive grid search was defined after some trial and error exploration. The chosen hyperparameter settings for the two models were the parameter combination showing the highest mean test score after cross validation. After searching for the optimal parameter settings, the models were trained using the training set and tested on the test set. A final evaluation and comparison of the two models was performed by assessing the coeffi-

Fig. 1. Map showing the location of wells included in the study. Each well have a unique well id: 1: 7324/8-1, 2: 7324/7-2, 3: 7224/7-1, 4: 7220/8-1, 5: 72220/5-1, 6: 7119/12-2, 7: 7125/1-1, 8: 7321/8-1, 9: 7220/10-1, 10: 7120/10-1, 11: 7220/7-1, 12: 7120/9-1, 13: 7121/7-1, 14: 7121/5-3, 15: 7121/7-2, 16: 7120/12-2, 17: 7219/9-1, 18: 7321/7-1, 19: 7122/6-1, 20: 7120/12-1, 21: 7120/8-2, 22: 7120/8-1, 23: 7120/7-2, 24: 7120/12-3, 25: 7120/8-3, 26: 7120/5-1, 27: 7121/4-1, 28: 7121/5-2, 29: 7122/4-1, 30: 7121/5-1, 31: 7120/6-1, 32: 7120/7-1, 33: 7019/1-1, 34: 7121/4-2, 35: 7119/9-1, 36: 7120/7-3, 37: 7219/8-2, 38: 7119/12-3.
Detailed core analysis
Determine factors controlling reservoir quality heterogeneity.

Parameter selection
Select reservoir quality parameter(s) to model (labels) based on core analysis.

Data preprocessing
Compile data, feature selection, data cleaning, scale data, define training and test set.

ML modelling
Model shortlisting, hyperparameter optimization, define final model, testing.

Generate data
Predict reservoir quality parameter(s) to obtain continuous curves of predefined property(ies).

Interpret modeled data
E.g., interpretation of data distributions, define data subsets related to diagenesis/lithology.

Generation of templates
Generate formation-specific templates, relate well log responses to lithological/diagenetic attributes, include other data (e.g. facies information), complement with additional analysis (e.g. electrofacies clustering). Fig. 2. Workflow diagram highlighting key steps of the methodology.

\[
R^2 = 1 - \frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}
\]

\[
MAE = \frac{1}{n} \sum_{i=1}^{n} |Y_i - \hat{Y}_i|
\]

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{n}}
\]

where \( Y \) is the label, \( \hat{Y} \) is the predicted value, \( \bar{Y} \) is the mean value of all labels and \( n \) is the number of data points.

Based on the RFG model’s hyperparameter settings, two specific porosity modelling approaches were tested and compared, (1) test the model’s ability to predict porosity in wells where a subset of the core plug data was involved in the training set (random split - RS) and (2) test model performance in wells excluded from training (Blind test split - BS). The only difference between the generations of the models resulting from the two approaches is the train-test split. The former approach randomly splits data instances from the entire dataset into a train- and a test set, whereas the latter approach picks 33 random wells for training and uses the remaining 5 wells for testing. For both approaches, 25 unique iterations with varying random train-test splits were performed to assess the result, meaning that 25 models were generated in each case, all trained on a slightly different subset of the data. Additionally, the performances of the RS- and BS approaches were tested and compared for a fixed case based on data from three wells with good helium porosity coverage, namely 7121/5–1, 7120/6–1 and 7219/8–2. For the RS case, this meant simply using the RFG model to predict porosity in these wells, while a new model was established for the BS approach by excluding these three wells from the training process and only fitting the model based on the remaining 35 wells. The entire workflow from combining wireline log- and core plug data to cleaning- and plotting data and training the ML models was carried out using Python (Van Rossum and Drake Jr, 1995) and the third party libraries Pandas (McKinney, 2010), Matplotlib (Hunter, 2007) and Scikit-learn (Pedregosa et al., 2011), respectively. Specific details on how the NN and RFG models are trained and make predictions can be found in the literature (Gardner and Dorling, 1998; Breiman, 2001; Pedregosa et al., 2011).

3.4. Linking ML model results with key geological information

Continuous porosity logs were generated for all 38 wells within the Sto Formation based on the initial RFG model that was constructed based on the training set used to search for the optimal hyperparameters. This enabled the inclusion of the entire dataset (20899 data points) with all wireline log measurements for further analysis. Shale volume (V-shale) was also estimated in all wells based on the GR log (Asquith and Krygowski, 2004) using the non-linear Larionov for older rocks correction (Larionov, 1969), where all data points with a V-shale > 20% were subsequently filtered out. Additionally, a secondary depth curve representing the maximum burial depth was generated on the basis of uplift estimates for the area presented by Baig et al. (2016). Based on previous detailed petrographic studies (Hansen et al., 2017; Lavstad et al., 2022), the Sto Formation exhibits highly varying- and wide porosity distributions in deeply buried intervals depending on the effectiveness of a patchy illitic clay coating, which ultimately controls quartz cement volumes. This makes the porosity distribution of clean sand intervals within the Sto Formation interesting to study in a regional context and, in particular, the high-and low porosity range. To target the upper- and lowermost part of the porosity distribution, the entire dataset was divided into three subsets from here on referred to as the Q1-, IQR- and Q3 data. For every 100-m depth interval, all data instances associated with that depth interval were labeled Q1 if the accompanying predicted porosity value was lower than the 25th percentile, IQR if the porosity value was within the interquartile range or Q3 if the predicted porosity value was above the 75th percentile (e.g., Fig. 6A). Finally, Q1, IQR and Q3 labeled data points were merged with other similarly labeled data points from all other 100-m depth intervals, forming the full Q1, IQR and Q3 datasets along the entire porosity-depth profile (e.g., Fig. 6B–D). These datasets are fundamental for the
Klausen et al. (2018) offered the possibility to study four wells in more detail by relating the ML generated porosity and various wireline log parameters to facies and diagenetic fingerprints (Fig. 1, wells: 7219/8–2 (37), 7219/9–1 (17), 7220/7–1 (11) and 7220/5–1 (5)). These wells are particularly suited for this purpose because their spatial distribution is limited and facies interpretations have been correlated between them. In addition, well 7219/8–2 (37) have been buried about 1000 m deeper compared to the other three wells, which is ideal for comparing the diagenetic effect with respect to the wireline log responses and across the various facies. Analysis where facies data are included were not filtered based on V-shale, rather all data points along the well track were presented study. Additionally, facies data in four wells obtained from Klausen et al. (2018) offered the possibility to study four wells in more detail by relating the ML generated porosity and various wireline log parameters to facies and diagenetic fingerprints (Fig. 1, wells: 7219/8–2 (37), 7219/9–1 (17), 7220/7–1 (11) and 7220/5–1 (5)). These wells are particularly suited for this purpose because their spatial distribution is limited and facies interpretations have been correlated between them. In addition, well 7219/8–2 (37) have been buried about 1000 m deeper compared to the other three wells, which is ideal for comparing the diagenetic effect with respect to the wireline log responses and across the various facies. Analysis where facies data are included were not filtered based on V-shale, rather all data points along the well track were

Table 1
Well data summary. Data retrieved from the Norwegian Petroleum Directorate.

<table>
<thead>
<tr>
<th>Well</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Sta FM top [MD]</th>
<th>Sta FM base [MD]</th>
<th>Uplift [m]</th>
<th>Masb. depth (Sta FM top) [°]</th>
<th>WD [m]</th>
<th>KB [m]</th>
<th>No. core plugs</th>
<th>Publication date</th>
</tr>
</thead>
<tbody>
<tr>
<td>7231/7-1</td>
<td>77.28906</td>
<td>25.14900</td>
<td>1755.09</td>
<td>1762.87</td>
<td>345.01</td>
<td>2744.01</td>
<td>750</td>
<td>251</td>
<td>345</td>
<td>February 11, 2005</td>
</tr>
<tr>
<td>7220/6-1</td>
<td>72.48619</td>
<td>24.39200</td>
<td>2015.09</td>
<td>2021.87</td>
<td>120.01</td>
<td>2764.01</td>
<td>700</td>
<td>231</td>
<td>120</td>
<td>February 11, 2005</td>
</tr>
<tr>
<td>7219/5-1</td>
<td>71.83911</td>
<td>20.42100</td>
<td>2090.09</td>
<td>2096.87</td>
<td>200.01</td>
<td>2784.01</td>
<td>800</td>
<td>261</td>
<td>200</td>
<td>February 11, 2005</td>
</tr>
<tr>
<td>7219/4-1</td>
<td>71.03811</td>
<td>19.74600</td>
<td>2150.09</td>
<td>2156.87</td>
<td>260.01</td>
<td>2844.01</td>
<td>850</td>
<td>261</td>
<td>260</td>
<td>February 11, 2005</td>
</tr>
<tr>
<td>7218/3-1</td>
<td>70.23811</td>
<td>19.04100</td>
<td>2200.09</td>
<td>2206.87</td>
<td>310.01</td>
<td>2904.01</td>
<td>900</td>
<td>231</td>
<td>310</td>
<td>February 11, 2005</td>
</tr>
</tbody>
</table>

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Aided by the ML-derived porosity data, the study will focus on identifying distinct log responses related to lithological- and diagenetic character using the GR, VP, density and the P-impedance, which is a product of VP and density.

4. Results

4.1. Machine learning – an effective method for generating porosity data

The data presented here show the efficiency of ML in generating accurate continuous porosity logs. The NN and RFG models show very similar performances in predicting porosity over the presented dataset (Table 3) and the porosity distributions obtained from both models seem consistent with the distribution of the helium porosity data (Fig. 3).

However, the RFG model showed overall slightly better results for all reported metrics compared to the NN model (Table 3). However, the difference between the root mean squared error (RMSE) and mean absolute error (MAE), which can be used to diagnose the variance in individual errors, are shown to be similar. Based on the superior performance, the RFG model was used to estimate continuous porosity logs in all wells included in the study.

The results after 25 unique runs for the random split (RS)- and blind test (BT) approach indicate that the RFG model is capable of accurately predict porosity in the former approach (Fig. 4 A), while the RMSE- and MAE scores for the latter approach indicate that it is less accurately predicting porosity in blind wells (Fig. 4 B). Moreover, the results show that there is a noticeably higher variance in predictions from the BT-approach compared to the RS-approach. This can be exemplified by the e.g., the calculated 95% confidence intervals of RMSE, showing 2.66 ± 0.06 and 2.87 ± 0.11 for the RS and BT approach, respectively. For this study, additional wells without core plug data were not included in the study because of the need for accurate porosity data is crucial to describe the porosity distribution in detail and link this property to wireline log responses. The results from the two different train-test split approaches in the fixed case (Table 3 and Fig. 5) shows that the random split approach outperforms the blind well test approach. Moreover, the two porosity curves deviate more from each other at certain intervals, while other intervals are similar. Both approaches show higher deviations in intervals where the helium porosity data fluctuate considerably over short depth intervals (Fig. 5).

The generation of continuous porosity logs within the Stø Formation in all 38 wells allow for detailed characterization of the porosity distribution as a function of depth (Fig. 6). Firstly, even though there are few data points above 2270 m, there seems to be a marked change in the porosity - maximum burial depth trend at this interval, where the rate of porosity loss is increasing abruptly as a function of depth (Fig. 6 A and D). Further, this porosity-depth trend can be viewed in two different ways; (1) characterization of various parts of the porosity distribution for all depths (Fig. 6A-D) and (2) characterization of the entire porosity distribution within a specific depth interval (Fig. 6E-H). In the first case, the cross plots of porosity vs maximum burial depths colored coded with Q1, IQR and Q3 distributions show that the Q1 (Fig. 6 B) and IQR data (Fig. 6 C) contain the whole range of porosity values, whereas the Q3 data (Fig. 6 D) are skewed toward higher porosities. Additionally, the Q3 data have a minimum porosity around 10%, while the Q1 and IQR data show porosities close to 0%. In the latter case, the shallowest porosity data (Fig. 6 F) (<2500 m) are normally distributed with a mean porosity of about 25%. The intermediate depth (2500 m–2800 m) porosity data (Fig. 6 G) show a similar pattern, but where the entire distribution is shifted toward lower porosities (mean porosity around 20%). In contrast, the porosity data that lie below 2800 m show a clear bimodal distribution with a noticeable subpopulation of higher porosities (Fig. 6 H).

To characterize the maximum and minimum rates of porosity loss within the Stø Formation, data points shallower than 2270 m and the IQR data were excluded, the Q1 and Q3 porosity data were plotted as a function of maximum burial depth (Fig. 7). The results also show a tendency for the Q1 distribution to become narrower with an increase in the burial depth, while the Q3 distribution show an opposite trend and

---

**Table 2**

Summary of data used in porosity modelling.

<table>
<thead>
<tr>
<th>FEATURES</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>5915</td>
</tr>
<tr>
<td>Mean</td>
<td>2073.1</td>
</tr>
<tr>
<td>Std.</td>
<td>500.0</td>
</tr>
<tr>
<td>Min</td>
<td>663.2</td>
</tr>
<tr>
<td>25%</td>
<td>1829.6</td>
</tr>
<tr>
<td>50%</td>
<td>2168.7</td>
</tr>
<tr>
<td>75%</td>
<td>2387.2</td>
</tr>
<tr>
<td>Max</td>
<td>3270.6</td>
</tr>
</tbody>
</table>

**Table 3**

Summary of the metrics of the Neural Network (NN)- and Random Forest Regressor (RFG). * RS = random split, BT = blind test. Reported metrics for the fixed test case. Reference to Fig. 5. See method section for more details.

<table>
<thead>
<tr>
<th>Metrics – Performance test set</th>
<th>R²</th>
<th>MSE</th>
<th>RMSE</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neural Network (NN)</td>
<td>0.826</td>
<td>6.478</td>
<td>2.545</td>
<td>1.584</td>
</tr>
<tr>
<td>Random Forest Regressor (RFG)</td>
<td>0.838</td>
<td>6.019</td>
<td>2.457</td>
<td>1.488</td>
</tr>
<tr>
<td>RFG – RS*</td>
<td>0.829</td>
<td>4.416</td>
<td>2.101</td>
<td>1.421</td>
</tr>
<tr>
<td>RFG – BT*</td>
<td>0.732</td>
<td>6.905</td>
<td>2.628</td>
<td>1.951</td>
</tr>
</tbody>
</table>
becomes wider as a function of depth (Fig. 7 A). There is a noticeable difference in the rate of porosity loss between the two distributions, where the fitted lines demonstrate a porosity loss of 8.1% and 6.4% per 500 m for the Q1 and Q3 distributions, respectively (Fig. 7 A). However, data below 3300 m in the Q1 distribution deviate slightly from the linear trend line and shows somewhat lower rates of porosity loss compared to the shallower data. Fig. 7B illustrates a new case representing a modified version of the Q3 distribution that is filtered based on porosity greater or equal to 12%. This result indicates that the average rate of porosity loss is 5.6% per 500 m for the modified Q3 distribution.
4.2. Generating formation-specific templates

4.2.1. VP, density, P-impedance and ML porosity

Fig. 8 shows cross plots of VP vs density (A and B) and P-impedance and porosity (C and D) where each parameter combination is shown for the Q1 and Q3 distribution in each plot but with a depth constrain. Fig. 8 A and C demonstrate the responses from VP - density and P-impedance-porosity in shallow buried intervals (<2700 m), respectively, whereas Fig. 8 B and C show the same parameter combinations for deeply buried units (>3300 m). The results show that the Q1 and Q3 distributions are
difficult to separate from the VP-density responses and with respect to P-impedance-porosity in shallow buried intervals. Even though it is possible to distinguish certain parts of the two distributions from each other, this is especially true for the P-impedance-porosity case, large part of the two distributions is clustered (Fig. 8 A and C). In contrast, data points from deeply buried intervals (>3300 m) indicate that the Q1 and Q3 distributions are easily distinguished (Fig. 8 B and D).

A more detailed characterization which include facies data show a similar pattern in four wells (Fig. 1, well id: 37, 17, 11, 5) as demonstrated in Fig. 9. The results show that the P-impedance-porosity- and Vp-density signatures from the three wells with maximum burial between about 2100 m and 2600 m have an unordered structure where most data points are clustered (Fig. 9 A, E, B, F, C and G). However, all these wells have a tail of data points deviating from the overall cluster, which mainly concerns the offshore-embayment facies that consist of finer grained- and silty material, and likely parts of the cleaner sandstone intervals with abundant carbonate cement (see Table 1 in Klausen et al. (2018) for complete facies description). These deviating lithologies

Fig. 7. Maximum burial depth vs porosity trends for the Q1 and Q3 distributions for data points with maximum burial greater than 2270 m and shale volume <0.2. The fitted lines illustrate the differences in rate of porosity loss for the Q1-and Q3 data for two cases: A) all data included. B) Porosity less than 12% excluded from the Q3 distribution.

Fig. 8. Comparison of Vp, density and P-Impedance of the Q1 and Q3 distributions at shallow (<2700 m) and deep (>3300 m) maximum burial. A-B) Vp-density plot with shallow data (A) and deep data (B). C-D) P-impedance – porosity plots with shallow data (C) and deep data (D).
are characterized by an elevated Vp and density (and P-impedance) and corresponding decrease in porosity. For well 7219/8-2, the deeply buried well (Fig. 9 D and H), the results show that recorded facies are more easily separated both with respect to the P-impedance-porosity and Vp – density parameter combinations. The clean sand of the upper- and lower shoreface facies are clustered and exhibit a wide range of values with respect to the various parameters. This elongated distribution has been interpreted to represent the cement trend. The offshore transition/inner shelf facies follow a similar pattern but are characterized by slightly elevated density readings compared to the shoreface facies in the Vp-density domain and slightly lower porosities in the porosity-P-impedance parameter space.

4.2.2. GR log vs. ML porosity

The four wells with available facies data were also characterized with the use of GR and porosity (Fig. 10A-D). The results show that this parameter combination can be useful for discriminating lithological characteristics in wells with shallow maximum burial (Fig. 10A-C), where the more clay rich inner shelf deposits are separated from shoreface facies associated with an increase in GR. Moreover, a clear negative correlation exists between the GR log and porosity where higher gamma coincides with a decrease in porosity (Fig. 10A-C). This trend is particularly dominant in well 7220/7-1 and 7220/8-1, where even a separation of the upper- and lower shoreface facies is evident based on the GR and porosity response. In the deeply buried well, 7219/8-2 (Fig. 10 D), the shoreface facies span predominantly over a large range of porosities but with consistently low GR readings. However, some data points within the lower shoreface facies show elevated gamma readings, which contribute to an overall “L-shaped” trend within lower shoreface facies in deeply buried intervals. It should be mentioned that the elevated gamma signals are likely not caused by any variation in K-feldspars content because the sediment is feldspar depleted (Bergan and Knarud, 1993), which could be a cause for slightly elevated GR readings. On the contrary, the upper shoreface facies shows in general lower GR readings (Fig. 10D). The facies associated with lower depositional energy, like the more distal inner shelf facies, show even higher gamma readings, consistent with the trend observed in wells with shallow burial. Based on this plot, three distinct endmember bed types can be differentiated: 1: clean sandstone with high porosity, 2: clean sandstone with low porosity, 3: low porosity fine-grained sandstone with silty- and clay rich material. The same parameter combination is plotted in two other deeply buried wells from the study area, well 7120/5-1 from the Hammerfest Basin and well 7119/9-1 from the Ringvassøya Fault Complex (Figs. 1 and 10 E). The results demonstrate a similar trend where the three distinct bed types can be distinguished from one another. Fig. 10 F, show four more examples from wells with different maximum burial depths but without facies data. The results show that the three bed types could be recognized and it demonstrates that the Stø Formation not necessarily contain all the endmember lithologies in each well.

5. Discussion

5.1. Machine learning – an effective porosity prediction method

Being able to accurately predict reservoir quality from continuous data sources, like wireline logs, has a huge potential compared to expensive and sporadic data obtained from cores. Several studies have focused on the interpretation of diagenetic-and lithological characteristics (Avseth et al., 2001; Ozkan et al., 2011; Cui et al., 2017) from wireline log data to determine reservoir quality, while other studies have focused on using a pure predictive workflows for estimating reservoir parameters e.g., (Helle et al., 2001; Urang et al., 2020). A pure predictive workflow can effectively generate large amounts of porosity data for use in a regional exploration context, but the lack of a geological understanding, can make predictions away from wells or intervals without core material ambiguous. This study has employed an integrated methodology that combines core analysis with a ML based porosity predictor, to establish a framework that can deduce diagenetic and lithological characteristics from distinct well log responses to aid reservoir quality determination. In this way, historical data can be effectively used to aid detailed interpretations in blind wells. The consistent and good performance of the RFG-RS porosity model provide reliability in the model’s capability for generating accurate continuous porosity logs in wells where some of the helium porosity data were involved in training (Table 3, Fig. 4). The RFG-BT model (Table 3) is slightly less robust for making accurate porosity estimates, compared to the RFG-RS model (Fig. 4), but the results are still adequate to make porosity predictions in blind wells (Fig. 5). Consequently, the RFG-BT modelling approach can still be useful in the exploration of frontier areas. The findings in this study exemplify that once a predictive framework for determining lithological- and diagenetic characteristics from wireline log responses has been established; the inclusion of RFG-BT porosity estimator can complement these interpretations in new wells that lack core information (Fig. 5). However, in the process of establishing a formation-specific framework we propose using the RFG-RS modelling approach, where continuous porosity logs are predicted in wells where helium porosity data were involved in training.

5.2. Machine learning derived porosity profile is consistent with petrographic analysis

It is essential to have a good understanding of diagenetic- and depositional processes that control reservoir quality variations when trying to deduce lithological characteristics from well log data within a specific formation. In the Stø Formation, the main reservoir intervals are found within shallow marine shoreface facies consisting mainly of texturally- and mineralogically mature sedimentary units (Gaussen et al., 1984; Klausen et al., 2018; Ogebule et al., 2020). In deeply buried parts of the Stø Formation (about >3000 m), quartz cement is the main factor controlling porosity, which has subsequently been interpreted to be controlled by the presence or absence of an illicy clay coating (Hansen et al., 2017; Lavstedt et al., 2022). With the use of helium porosity data from 14 wells, mainly within the Hammerfest Basin, Lavstedt et al. (2022) also found that the rate of porosity loss between coated- and negligible coated intervals becomes increasingly larger as a function of burial depth.

In the Stø Formation case, it is therefore essential to evaluate the ML generated porosity profile’s ability to capture this trend, if present, in a regional context. The Q1 and Q3 datasets, which are meant to represent negligible coated and coated intervals, respectively, exhibit expected porosity distributions as a function of maximum burial depth (Fig. 6B and D). When all porosity data are included, the porosity distributions as a function of varying depth also exhibited expected patterns that reflect the gradual increase of diagenesis (Fig. 6F–H). Here, shallow and intermediate buried intervals are normally distributed (Fig. 6F and G), whereas the deeply buried intervals show a bimodal distribution with a clear subpopulation of abnormally high porosity (Fig. 6H). This subpopulation of higher porosities can be a clear sign of a porosity preserving mechanism (Bloch et al., 2002), in this case the clay-coated intervals of the Stø Formation. When examining the Q1 and Q3 data separately, it is evident that the Q1 porosity distribution becomes narrower- and the Q3 distribution becomes wider as a function of increasing burial depth (Fig. 7). This observation explains the tendency of negligible coated intervals to become increasingly more quartz cement with an increase in the time-temperature integral (TTI) (Walderhaug, 1994, 1996), whereas the quartz cement volumes in the coated intervals are dictated by the clay coating coverage and thus exhibit a wider range of porosity (Ajdukiewicz and Larsen, 2012). The presented results imply that the ML model is capable of representing the petrographic observations and interpretations made from core data by Lavstedt et al. (2022), which shows a greater difference in porosity loss as a function of burial depth between negligible coated- and coated intervals (Fig. 7).
Fig. 9. Characterization of elastic parameters in four wells colored with facies data from Klausen et al. (2018). A-D) P-impedance vs porosity and E-F) Vp-density plots. D and H plots are from the more deeply buried well 721978–2, while the other plots are from wells with maximum burial of 1000 m shallower or more.
However, the porosity data from the deepest part of the Q1 data deviate slightly from the fitted line. A similar trend was observed by Marcussen et al. (2010) in the Etive formation in the northern North Sea, where the porosity-depth gradient is steeper than for shallower buried intervals. The reason for this is that the surface area available for quartz nucleation is reduced as the pore volumes are filled with significant amounts of quartz cement (Walderhaug, 1996). The above results indicate that the petrographic observations of Løvstad et al. (2022) are applicable in a regional context within the Stø Formation. More importantly, the separation of the Q1 and Q3 data exemplifies the potential for scaling up petrographic analysis and integrating with a pure predictive workflow to assess reservoir quality in frontier areas within the same formation.

The successful characterization of these distinct diagenetic features within the Stø Formation via the ML based porosity data makes it possible to link these diagenetic attributes to typical well log responses.

5.3. Machine learning porosity data can distinctly identify well log responses of lithological- and diagenetic characters

As discussed above, petrographic results concerning reservoir quality controls were crucial for scaling up the diagenetic variation observed within the Stø Formation to the ML generated porosity data, which in this case resulted in the Q1 and Q3 data subdivision. These distinct diagenetic attributes can be characterized from well log responses aided by the ML porosity profile that are color coded by this diagenetic property, i.e. clay coated high porosity sand (Q3) and negligible coated heavily cemented sand (Q1). For other formations, diagenetic alterations that control reservoir quality may differ and should be adapted accordingly. For intermediate and shallow buried intervals, facies data could also be effective, if available, because clay and silt content tends to control reservoir quality more frequently than quartz cementation. In this way, formation-specific frameworks that can deduce lithological-
and diagenetic characteristics related to primary reservoir controls can be established for use in frontier regions. VP and density are interesting parameters to investigate for several reasons. Firstly, they are usually recorded along most boreholes in their entirety, which makes them applicable to use for interpretations in wells on a regional scale. Secondly, they have seismic properties, which mean that they can be linked to seismic amplitude information e.g., (Avseth et al., 2001). Thirdly, VP and density are particularly sensitive to diagenetic alterations because of their strong correlation with the amount of quartz cement volume and hence porosity (Marcussen et al., 2010). The clustering behavior of the Q1 and Q3 data for VP and density (Fig. 8A) indicates that intervals with intermediate maximum burial (>2700 m) have very similar acoustic impedances (Fig. 8C). This means that the reasoning for the Q1 and Q3 data labeling may not hold for intermittently buried intervals. According to Levin et al. (2022), the significant porosity variation across negligible- and coated intervals within the Stø Formation was solely investigated in deeply buried intervals. As mentioned in the previous section, the ML based porosity data show only a bimodal distribution with a subpopulation of higher porosity in deeply buried intervals, meaning that the differentiation between intervals affected by the presence or absence of clay coats seems only applicable to units with larger TTI’s. The successful separation of the Q1 and Q3 data with the use of VP and density at intervals with significant burial depths (>3300 m) agrees with this interpretation (Fig. 8B). However, the boundary between Q1 and Q3 labeled data could be challenging to depict from raw well log data, which emphasizes the potential in the scaling up interpretations of core analysis to the ML generated porosity profile. Additionally, note that Q1 and Q3 data are filtered on shale volume, which could be necessary to avoid overlap from more silt and clay rich intervals that are common in certain parts of the Stø Formation (Olausen et al., 1984; Klausen et al., 2018). This can be particularly important for multi-well analysis because there will be a higher risk of masking small but important variations in VP and density response compared to single well analysis. The results from unfiltered data in single well analysis, that includes facies information, show the potential for separating distinct lithological characteristics, both in terms of cement- and matrix content variations, from the P-impedance-ML porosity and VP - density signatures (Fig. 9 D and H, respectively). Still, the separation seems ambiguous for intervals with intermediate burial depths (Fig. 9 A-C and 9 E-G). Consequently, the need for a parameter combination that can handle variations in cement- and matrix content irrespective of burial depth is needed for truly being able to delineate reservoir quality variations in blind wells on a regional scale.

This study have shown that the GR - ML porosity combination can be well suited for this purpose (Fig. 10). This is also where the integration of a ML based porosity predictor will truly shows its potential. This is because, (A) the ML model enables porosity to be used directly, which means that we do not need to infer this key property via some other parameter. (B) It does not require any known fluid- or rock properties to predict porosity from well logs in blind wells (Helle et al., 2001) in appose to density- or the sonic derived porosity. (C) It is computationally time efficient to make continuous porosity profiles in new wells once a pipeline has been established. Alternatively, in contrast to P-wave- and density parameters discussed earlier, the GR nor porosity can be directly tied to seismic amplitude information, which could be a limiting factor if results are to be integrated with seismic data. The GR – porosity relationship had earlier been investigated in one well from the Stø Formation (Ramm, 1991). Ramm (1991) discovered an interesting relationship between these parameters, but the relationship was not studied in detail with the inclusion of facies data nor the applicability on a regional scale. This study have shown that the GR – ML porosity plots enable the separation of three distinct bed types irrespective of burial depth; (1) high porosity clean shoreface sands with a varying degree of clay coating, (2) heavily cemented clean shoreface sands with negligible clay coating and (3) silt- and clay rich intervals (Fig. 10A–D). Furthermore, adding Q1 and Q3 data labels to the cleaner shoreface facies in this parameter domain could further facilitate a simple way of mapping out these units in deeply buried intervals. This could for example be useful for linking clay-coated intervals between wells in regional studies within the Stø Formation. The test of the GR – porosity combination in wells without facies information at various locations in the SW Barents Sea (e.g., Hammerfest Basin and Bjønnyrenna Fault Complex, see Fig. 10E and F and map in Fig. 1) shows the potential of this parameter domain for use in reservoir quality delineation on a regional scale within the Stø Formation.

Additionally, we could speculate that the elongated and “L-shaped” trends observed within the upper- and lower shoreface facies for intermediate and deeply buried wells respectively, could reflect varying amount- and different modes of clay within the Stø Formation. From this, we could interpret the lower shoreface facies to have a higher total clay content compared to the upper shoreface facies. Moreover, the occurrences of clay in the lower shoreface facies is dominated as either clay coats or pore-filling, i.e. the low GR-high porosity- and slightly higher GR-lower porosity responses, respectively. The GR-ML porosity response for the upper shoreface facies reflect in general a cleaner sandstone, where also the extent of effective clay coats is lower, leading to more heavily quartz cemented units. Based on this result we can speculate that effective clay coats are most prone to develop in the lower shoreface facies. This interpretation is comparable with the findings of Hansen et al. (2017) and Levin et al. (2022), which linked the amount of post depositional reworking to clay coat coverage. The amount and modes of occurrences of clay have also been shown to vary significantly within juxtaposed coastal sub-environments in other studies, that ultimately can be a key factor controlling diagenetic signatures (Halle et al., 2018). Moreover, as indicated by Woldridge et al. (2017) there seems to be an optimum range of total clay content within the sediment that can aid the development of effective clay coats at depth.

5.4. General implications

The Stø Formation and time-equivalent formations have been studied in the context of depositional environment and mineralogical composition from several locations in the greater Western Barents Sea area and include, but not limited to, rock and core data from the Hammerfest Basin, Ringvassøy-Loppa Fault Complex, Bjørnøyrenna Fault Complex, Williamnaya at Svalbard and the Bjarmeland Platform (Olausen et al., 1984; Hansen et al., 2017; Klausen et al., 2018, 2019; Halle et al., 2019; Levin et al., 2022). These studies show that the Stø Formation is predominantly consisting of mineralogically- and textural mature quartz arenitic sandstone beds representing wave dominated shallow marine deposits that originated in an overall transgressive development. The results show the potential in effective use of historical core data and how the presented integrated methodology can be used to construct formation specific templates that can display lithological- and diagenetic attributes from distinct well log responses. Due to the widespread and consistent composition of the Stø Formation and its time-equivalents in the greater Barents Sea area, the presented results can have important implications for effective reservoir quality delineation in intervals or wells without core data in this region or in other similar settings worldwide.

6. Conclusion

The petroleum industry is increasingly seeking new reservoir discoveries and potential CO2 storage sites close to existing infrastructure to increase the life span of already operating installations to save time and cost. After several tens of years of exploration on the NCS, an extensive database consisting of wireline log and core data is available. This valuable dataset has a huge potential for being exploited to establish formation-specific predictive frameworks for use in already mature provinces. ML has enabled an effective (both and time and cost) and
accurate method for estimating reservoir properties from existing core data. This study demonstrate that effective use of historical core data in conjunction with a pure predictive ML-based workflow can be used to establish formation-specific frameworks for deducing distinct lithological- and diagenetic attributes from well log data. The study also emphasize the importance of conducting detailed core analysis prior to utilizing data-driven methods for predicting reservoir quality parameter, because: (1) detailed geological information can aid the geologist to decide on which reservoir quality parameters to model and (2) lithological and diagenetic information will assist the interpretation of data derived from the model. The latter can be crucial for making strategic data subsets that can be used to link key lithological and diagenetic attributes to well log responses. The results show that high porosity clean sand-, cemented clean sand- and clay/silt rich intervals can be distinguished within St Fomation. These distinct bed types can be recognized from basic well log data in new wells without core material and thus serve as a framework for effectively delineate reservoir quality variations on a regional scale. Particularly, the relationship between GR and ML porosity shows promising results for reservoir quality delinea
don the work reported in this paper.

Declarion of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

Data availability

Data will be made available on request.

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References

Paper IV
Chlorite coating patterns and reservoir quality in deep marine depositional systems – Example from the Cretaceous Agat Formation, Northern North Sea, Norway

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Abstract
Sediment gravity flows transport large volumes of sand and clay minerals into submarine systems, which store some of the world's major reserves of oil and gas. However, knowledge about grain-coating clay mineral formation and its role in preserving reservoir quality in deep marine settings is poorly documented. Here we present a case study on the Agat Formation, a deep marine deposit interpreted as a series of turbidites, using a multimethod approach including petrographical, petrophysical and sedimentological data. This study investigates the occurrence and origin of chlorite coating and demonstrates how extensive chlorite coating substantially affects reservoir quality. The presence of green marine clay pellets suggests an initial shallow marine origin and sedimentological evidence reveals that the sediments were later remobilized by gravity flows and deposited at their present location. We suggest that the precursor clay coating was emplaced prior to sediment remobilization because of the presence of clay coating on grain contacts and all detrital components, the continuous nature of coating and the lack of clay bridges between the grains. Therefore, the origin of chlorite coating in deep marine environments may be recognized using the characteristic properties of inherited precursor clay coating. Chlorite coating thickness varies between an upper and lower sand unit, with an average of ca. 4.5 µm and ca. 24 µm, respectively. Permeability is significantly reduced in the interval with exceedingly thick chlorite coating but shows only a subtle decrease in helium porosity. This study enlightens the importance of crucially evaluating porosity in sandstones with thick chlorite coating using a multimethod approach. The results from this study can be useful in future exploration endeavours in the area and in other deep marine systems with a similar setting worldwide.

Keywords
Agat Formation, chlorite coating, gravity flows, inherited clay coating, North Sea, porosity preservation, reservoir quality
The oil and gas industry is continuously seeking new ways to improve the predictability of reservoir quality in the subsurface. As many of the more easily accessible hydrocarbon reservoirs have been discovered, companies are now increasingly shifting their focus towards exploring for high reservoir quality in deeply buried prospects.

Sandstones subjected to increasing burial depth will compact mechanically by reorganization and crushing of grains due to increased overburden stress (Bjørlykke et al., 1989; Chuhun et al., 2002). Beyond this point, continued reduction in porosity is mainly a function of the amount of precipitated quartz cement. The rate of quartz cementation within a given sandstone unit is highly dependent on the burial history, where the time-temperature integral is key in determining quartz cement volumes and hence reservoir quality (Walderhaug, 1994, 1996). Therefore, the prediction and evaluation of grain-coated sand intervals can be important when examining reservoir potential of deeply buried prospects.

Clay coats that hamper quartz overgrowth and preserve porosity have been recognized in numerous studies on the Norwegian Continental shelf (Aase et al., 1996; Ehrenberg, 1993; Jahren & Ramm, 2000; Haile et al., 2018; Hansen et al., 2017; Line et al., 2018; Skarpeid et al., 2018; Storvoll et al., 2002). Other types of grain coats such as micro-quartz have also been shown to preserve reservoir quality (Aase et al., 1996; Jahren & Ramm, 2000), but clay coats are by far the most common and widespread coating type. Chlorite coats form as a result of the recrystallization of a detrital precursor clay phase and laboratory experiments have indicated that well-crystallized chlorite coats may be formed at temperatures of about 80–90°C if sufficient precursor clay material is available (Aagaard et al., 2000).

A review article, gathering information on chlorite-coated sandstones in the literature, suggests that the rock composition of the hinterland and proximity to river systems are important factors that control the supply of the precursor clay material (Dowey et al., 2012). Shallow marine early diagenetic iron-rich clay minerals often form granules and pellets modifying original faecal pellets in the post-oxic geochemical zone (Berner, 1981). This environment, called the verdine facies (Odin, 1985), contains a series of minerals like Fe–Al smectites, odinite, berthierine, chamositic and glauconitic phases. The type of mineral formed depends on several factors including chemistry, organic matter, diffusion conditions and biological activity (Meunier & El Albani, 2007). In addition, in such environments precursor grain coatings can form. However, exact mechanisms responsible for emplacing the precursor clay coats on sand grains prior to burial are uncertain.

An experimental study by Matlack et al. (1989) showed that infiltration of muddy waters can be an effective way of emplacing clay particles as coats on sand grains. The clay coats are most effectively developed in settings with high volumes of suspended clay and fluctuating water levels. Other studies have reported that emplacement of detrital clay on sand grains occurs due to bioturbation, either in response to the sand grains passing through the digestive system of the organism or in response to the burrowing action of organisms (Needham et al., 2005; Wilson, 1992). Numerous studies (Griffiths et al., 2018; Virolle et al., 2019; Wooldridge, Worden, Griffiths, Thompson, et al., 2017; Wooldridge, Worden, Griffiths, & Utley, 2017) have also shown that estuaries are suitable precursor clay factories where the emplacement of clay coatings are facilitated by extracellular polymeric substances secreted by microorganisms, forming biofilms (Wooldridge, Worden, Griffiths, Thompson, et al., 2017), which causes clay particles to be attached to the sand-sized sediment fraction.

Examples of clay-coated sandstone units with a coastal origin are well documented in the literature and with deltaic environments being particularly common (Dowey et al., 2012). However, studies of clay-coated sandstone units deposited by sediment gravity flows into deeper marine settings are rare and the origin of clay coats in such systems has been attributed to sediment dewatering processes at the time of deposition (Houseknecht & Ross, 1992; Porten et al., 2019).

In this study, we documented extensive chlorite coating with an inherited detrital texture in gravity flow deposits of the...
Agat Formation in one well located in the northern North Sea of the west coast of Norway. The main questions that this study aims to answer are: What is the morphology, distribution and extent of the chlorite coating in the Agat Formation, What evidence exists with regards to the origin of this coating in this deep marine deposit? and How do the chlorite coats influence the reservoir quality of the Agat Formation?

2 | GEOLOGICAL SETTING

The studied well is situated in the northern North Sea, northeast of the Gjøa field, on the Måløy Slope in the area between the Sogn Graben and Øyggaard Fault Complex (Figure 1a,b). The structural framework of the North Sea is a result of several rifting events, with the Upper Jurassic–Lower Cretaceous rifting considered the most important. This rift event compartmentalized the study area into a series of rotated fault blocks (Badley et al., 1988; Færseth, 1996). Following the Upper Jurassic–Lower Cretaceous syn-rift phase, the normal faulting ceased during the Early Cretaceous post-rift stage and this period was mainly characterized by subsidence and the inherited basin configuration had a great influence on the sediment distribution (Bugge et al., 2001; Gabrielsen et al., 2001). The various Cretaceous stratigraphic units are interpreted as being deposited in an overall transgressive setting due to an overall deepening trend throughout the Cretaceous time (Skibeli et al., 1995). The main potential reservoir sands are found in the Agat and Åsgard Formations of Albian and Hauterivian to Barremian age, respectively (Skibeli et al., 1995).

The Agat Formation is a member of the Cromer Knoll Group (Isaksen & Tonstad, 1989) and represents a series of stacked sandstone units interbedded with the extensive Rødby shale (Figure 1c). The Agat Formation has been suggested to represent slump and mass flows deposits, which were relocated from a narrow shelf and redeposited on an upper slope environment (Shanmugam et al., 1994; Skibeli et al., 1995). Other workers have interpreted the sandstones of the Agat Formation as turbidities, where massive sandstone units

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**FIGURE 1** (a) Overview of the study area, which is located in the North Sea offshore Norway. (b) Map showing the study area. The studied well is located on the Måløy Slope within the northern North Sea. (c) Chronostratigraphic chart of Cretaceous sediments in the Northern North Sea. Figure modified from Skibeli et al. (1995)
within the Agat Formation represent amalgamated thinner turbidite units (Bugge et al., 2001; Martinsen et al., 2005; Nystuen, 1999). A depositional model of the Agat Formation in the studied well is presented in Figure 2 based on the Agat model from Martinsen et al. (2005), showing the sands being remobilized from a narrow shelf and deposited in a slope environment by turbidity currents.

3 | METHODS AND DATA

Neptune Energy A/S provided the authors with petrographical and petrophysical data from the studied well. Petrographical data included mineralogical point count results from 20 thin section samples, textural properties, core plug data and optical thin section images. The core plug data comprise helium porosity and horizontal gas permeability measurements throughout most of the studied section (Figure 3). Helium porosity and gas permeability will be referred to onwards as core plug porosity and permeability. Thin section samples were selected from core plugs/pieces and prepared with a coloured resin for aiding pore space identification. Each thin section was point-counted with 200 counts per sample and the longest axis was measured on 100 randomly picked detrital grains in order to obtain an estimate on mean grain size and sorting. Additional samples were collected at Weatherford Laboratories (Sandnes, Norway) by the authors and stub samples, a small rock chip from each sample, and thin sections were prepared specifically for analysis by scanning electron microscope (SEM) (these samples were not point counted). Hence, the SEM micrographs presented in this article may deviate from the depths where the quantitative mineralogical data were acquired (Figure 4a). Petrophysical data comprise well logs and computer-processed interpretations. Due to sensitivity in some of the presented data, any reference to depth will be anonymized. The upper and lower reservoir units were determined based on well logs, core plug and petrographical data. Especially, a distinct difference between the units is observed in terms of permeability and the petrographical results (Figure 3 and Table 2). The upper interval ranges from ca. 2X36 to 2X92MD and the lower interval is limited to the depth between ca. 2X05 and 2X44MD. The uppermost part of the Agat Formation has no core plug measurements and is excluded from the reservoir subdivision. The intervals between ca. 2X92–2X95MD and ca. 2X95–2X05MD are also excluded from being defined as reservoir intervals because they are rather different in texture and composition and include a highly calcite-cemented interval and a conglomeratic layer, respectively. One coating thickness measurement was obtained in each sample from optical microscope images and can be considered as a qualitative result that can be used for comparison purposes between samples. Coating thicknesses were also measured in the samples investigated in SEM, where exact thickness measurements are easily performed, which indicated that coating thickness measurements performed on optical microscope images were accurate.

FIGURE 2 Conceptual representation of the depositional model for the Agat Formation in the studied well. The model of Agat Formation is based on Martinsen et al. (2005)
RESULTS

4.1 Well logs and core plug data

Figure 3 shows the gamma, caliper, neutron and density log along with the core plug horizontal and vertical permeability within the Agat Formation in the studied well. The top of the Agat Formation is recognized by a decreased response in the gamma log compared to the overlying Rødby shale (Figure 3). This boundary is also easily seen in the neutron-density logs, where there is a positive separation in the overlying shale compared to a strong negative separation in the gas-filled upper part of the Agat Formation. The results show that the Agat Formation can be separated into two distinctly different units based on the measured core plug permeability (Figure 3). These distinct differences in permeability made it convenient to separate the reservoir into an upper and a lower reservoir unit (Figure 3). The upper reservoir unit is characterized by consistently high permeability readings, whereas the lower reservoir unit is characterized by a low permeability interval in comparison, even though the permeability readings are seen to fluctuate throughout this unit (Figure 3). A scatter plot is included showing the correlation between the core plug porosity and permeability measurements from these two intervals (Figure 3). The results show that there is only a small difference in terms of core plug porosity between the two intervals where the upper and lower reservoirs exhibit an average porosity of 27.8% and 25.4%, respectively (Figure 3). The histogram of the core plug porosity distribution also illustrates this with readings from the
lower reservoir shifted slightly towards lower porosities. In terms of permeability, the histogram on the y-axis shows that the permeability in the upper reservoir interval frequently shows readings above 1,000 mD, whereas the lower reservoir interval tends to have a permeability <10 mD.

4.2 | Sedimentological description and interpretation

A sedimentary log (Figure 4a) was constructed based on core descriptions and coloured with four different facies associations (FA), each representing a set of related facies. Summary of the different FAs and interpretations are presented in Table 1. The Agat Formation in the studied well is mainly composed of medium- to coarse-grained massive and clast-rich sandstones (MCSs). However, MCSs also consist of dewater structured- and faint horizontal bedded sandstones at certain intervals. The clasts are observed to be of granules to pebbles in size and randomly distributed with a varying composition including quartz and lithic fragments. Some larger pebble size mud clasts, green chloritic clasts and a few examples of armored mud clasts coated with coarse sand and gravel (Figure 5, core photo 1) can also be observed sporadically. These armoured mud clasts are poorly to moderately rounded, indicating some traction where the mud clasts could pick up coarser particles (Li et al., 2017). The MCSs are present in both the upper and lower reservoir units (Figure 5, Core photos 1, 2, 3 and 4). The second major FA consists of moderate to well sorted, medium to fine-grained predominantly massive or laminated sandstone units (MLS). These units tend to show an upward fining trend, with abundant mud clasts at certain intervals towards the top of these successions, which are concentrated along with subhorizontal bedding (Figure 5, core photo 5 and 6). The mud clasts are elongated and poorly rounded, that is they have a low textural maturity, which indicate a short transport distance and were likely eroded by the flow on the slope (Li et al., 2017). The
MCS is in turn capped with the thinner sandstone units of MLS. The stacking of MLS and MCS is repeated three times in the lower reservoir unit although MLS is not observed in the uppermost part of the lower reservoir. The results show that the upper reservoir has the same stacking pattern, although on a larger scale and the sequences are only repeated once. The four different FA were also plotted along with core plug data to investigate potential relations (Figure 4b). The results show that there is no clear correlation between reservoir quality and facies that comprises the upper and lower reservoir units (i.e. MCS and MLS). In comparison, CPS and especially the authigenic calcite-cemented layer show consistently poor reservoir quality throughout. Core plug data are not available for CFA, but reservoir quality is likely to be low within this unit.

The sandstones of the Agat Formation in the present well have been interpreted to be deposited by various turbidity currents. The MCS which consists of massive clast-rich medium to coarse-grained sandstones, with locally faint horizontal bedding and fluid pipes have been interpreted to be deposited by high-density turbidity currents. The internal variations, that is clast-rich intervals, faint horizontal lamination and sand–sand amalgamation, can be explained by variations in the original source material and/or turbidite evolution regarding the dilution and/or the turbidity of the flow. MLS consists of medium to fine-grained, moderate to fine-grained mostly clean structureless sandstone. Enriched with dark grey mudstone clasts of various types (including armored clasts) towards the top of the succession. Subhorizontal bedding is highlighted by abundant elongated mud clasts

**Table 1** Description of recognized facies associations and their interpretation within the Agat Formation in the studied well

<table>
<thead>
<tr>
<th>Key</th>
<th>Name</th>
<th>Description</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>MCS</td>
<td>Massive clast-rich sandstone facies association</td>
<td>Medium to coarse-grained, moderately sorted primarily massive sandstones, with intervals enriched with coarser clasts. Clasts include mud (some of which is armored mud balls), quartz and lithic clasts (granules to pebbles). Faint-horizontal lamination, fluid escape pipes and sand–sand amalgamation can be observed</td>
<td>Deposited by high-density turbidity currents</td>
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<tr>
<td>MLS</td>
<td>Massive-laminated facies association</td>
<td>Moderate to well sorted, medium to fine-grained mostly clean structureless sandstone. Enriched with dark grey mudstone clasts of various types (including armored clasts) towards the top of the succession. Subhorizontal bedding is highlighted by abundant elongated mud clasts</td>
<td>Deposited by low-density turbidity currents</td>
</tr>
<tr>
<td>CPS</td>
<td>Conglomeratic-pebbly sandstone facies association</td>
<td>Moderately to poorly sorted, medium to fine-grained pebbly (granule to pebble) sandstone. The conglomerate consists of a variety of different clasts including large dark grey mud, brown sideritic/phosphatic and green chloritic mud clasts</td>
<td>Deposited by high-density turbidity currents</td>
</tr>
<tr>
<td>CFA</td>
<td>Chaotic facies association Matrix supported siltstone to fine-grained sandstone with large (mm to dm) clasts randomly distributed. Clasts: mudstones, floating quartz grains. Deformation structures, sandy/silty injectites</td>
<td>Slide complex</td>
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</table>
### Table 2

Point count results from available thin section samples from the upper reservoir unit (green) and the lower reservoir zone (red) (Figure 3)

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<th>Plagioclase</th>
<th>Mica (total)</th>
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<th>Ductile R.F.</th>
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<th>Authigenic chlorite</th>
<th>Optically non-resolvable clay</th>
<th>Quartz cement</th>
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<th>IGV</th>
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<th>Horizontal permeability [µD]</th>
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</table>

Note: The petrographic database consists of 10, 7 and 3 samples from the upper reservoir, lower reservoir and conglomeratic interval, respectively. Please note that the micrographs shown in the article originate from slightly different depths relative to the exact depth that mineralogical data represent (see section 3 for more details).

Abbreviations: Avg., average; Const., constituents; R.F., rock fragments.
well-sorted sandstones with intact mud clasts and is interpreted to have been deposited by low-density turbidity currents. The variations in mud clast intensity could be linked to the amount of suspended clay particles either due to source variations or due to clay entrapment during flow propagation (Haughton et al., 2003, 2009). Nystuen (1999) determined a similar sandstone facies of the Agat Formation to be deposited by turbidity currents, with the massive ungraded and parallel laminated parts corresponding to Ta and Tb intervals of the Bouma sequence, respectively. The conglomeratic and pebbly sandstones of CPS are separated by erosional contacts and are interpreted to represent energetic high-density tractional currents, consisting of shelf- and locally derived components. The basal CFA, containing chaotically distributed large clay clasts in a silty to the muddy matrix, is believed to represent a slide complex, possibly reflecting a submarine canyon or channel incision that later acted as the pathway for the shelf-derived Agat sands. The lack of finer-grained sediments between and within the various events of the MCS and MLS could indicate deposition in a confined environment and/or on a significant slope.

4.3 | Petrographic results

4.3.1 | Mineralogy

The mineralogical results presented below (Figure 6a) are based on the average mineralogical composition from all available thin section samples taken from the upper and lower reservoir units, respectively. A complete list of all samples included in the averaged units can be seen in Table 2. The average mineralogical composition of the two intervals is almost identical, but the relative amount of some of the constituents shows noticeable variations between the upper and lower reservoirs. The most prominent difference is the varying quartz content, which is observed to be 38% in the upper reservoir and 28.3% in the lower reservoir. Other noticeable differences are the number...
of rigid rock fragments, authigenic chlorite and green marine clay pellets, which all are more volumetrically significant in the lower reservoir interval (see Table 2 for details). Moreover, the green marine clay pellets make up only 0.7% of the upper reservoir unit, whereas these clay pellets make up 6.6% in the lower reservoir zone. The green marine clay pellets include both glauconitic and clay pellets (Figure 7a–c), with the latter likely being of a chamositic composition. The two types of clay pellets can be hard to separate using optical microscopy, but SEM-EDS analysis suggests that the clay pellets of a chamositic composition are much more abundant. The results also indicate that large phosphatic clasts and chloritized mica grains are present (Figure 7d,f). The porosity obtained from point count is also shown to be noticeably higher in the upper reservoir unit, averaging 10.6% in the studied samples as opposed to the lower reservoir unit where the average point count porosity is observed to be 4.1%. The quantified feldspar content is on average slightly higher for the upper reservoir unit and with K-feldspar being the dominant feldspar phase throughout (Table 2). The rigid rock fragments constitute predominantly metamorphic fragments not only consisting of schistose polycrystalline quartz and mica composites but also igneous fragments consisting of quartz, feldspar and mica occur along with sedimentary fragments like chert and phosphatized claystone. Ductile rock fragments include sedimentary and degraded igneous rock fragments, where the sedimentary fragments

![FIGURE 6](image_url)

(a) The averaged mineralogical composition of samples from the upper reservoir and lower reservoir interval. The averaged result is based on the data presented in Table 2, comprising 10 and 7 samples from the upper and lower reservoirs, respectively. (b) The average content of iron-bearing constituents from thin section samples in upper and lower reservoirs. Some of these minerals are included in the ‘other constituents’ category in A and B due to being volumetrically minor. (c) Textural results from all samples in Table 2 showing a positive correlation between sorting and grain size. Notice that the MCS is subdivided into two groups, whether the sample originates from a more clast-rich or structureless interval.
FIGURE 7 Various mineralogical constituents observed within the Agat Formation in the studied well. The green/red squares with poro-perm data included in each image and micrograph indicate whether the sample is from within the upper/lower reservoir. All samples are also marked in Figure 4a. (a) Glauconitic pellet (green marine clay pellets) from sample 2X14.72 MD. See Figure 7g for EDS for spectra (lower reservoir). (b) Green marine clay pellet form sample 2X15.90 MD. The EDS spectra indicate a chamositic composition (see Figure 7g) (Lower reservoir). (c) Optical thin section photo form sample 2X04.76 MD, showing green marine clay pellets. These are probably of chamositic composition shown in (b). The detached clay coating (white arrow) is likely due to sample preparation (lower reservoir). (d) Elemental mapping (coloured with P and Ca) in the SEM from sample 2X47.50 MD indicates the presence of phosphatic rich clast. Also note uncoated siderite crystals (yellow arrows) (upper reservoir). (e) Optical thin section photo from sample 2X71.06 showing chlorite coating and primary pore space. Siderite crystals are observed to sit partly within the chlorite coating (red box) (upper reservoir). (f) Chloritized mica. 2X40.69 MD (upper reservoir). (g) List of EDS for the points shown in figure (a) and (b)
include claystone and siltstone fragments, and the degraded igneous rocks consist of distorted and compacted grains with quartz and remnant feldspar. Other minor constituents include optically nonresolvable clay and quartz cement, where the optically nonresolvable clay comprises detrital pore-filling clay and pseudo-matrix. Quartz cement volume is almost negligible in most samples, but some overgrowth can be observed on clean quartz grains in a few samples (Table 2). The intergranular volume (IGV) is similar for samples from the upper and lower reservoir unit, 27% and 28%, respectively (Table 2). The mineralogical results also show that the outermost chlorite coating phase has a dense and chaotic texture which further can be separated into two distinct phases based on the relative iron content (Figure 8e), whereas the outermost chlorite coating phase is characterized by more radial crystals (Figures 8e and 10b). The results show that there are large variations in the chlorite-coating thickness between samples investigated from the upper and lower reservoir units within the Agat Formation (Table 2, Figures 9 and 10). The variations seem to be governed by the thickness of the inner denser and more chaotic portion of the chlorite coating which is seen to be much thicker in samples from the lower reservoir unit (Figure 9d) compared to samples from the upper reservoir unit (Figure 9c).

Concerning reservoir quality, there are some clear trends between the measured core plug permeability and porosity, and the grain coating thickness (Figure 9). Permeability varies systematically with observed grain coating thickness (Figure 9a), where a decreased coating thickness corresponds to a higher permeability. Furthermore, the primary porosity is to a lesser extent influenced by coating thickness variations (Figure 9b), even though a slight increase in porosity can be observed on average in the upper reservoir compared to the lower reservoir interval when all core plug porosity data from the two intervals are included (Figure 3). Based on thin section measurements, the coating thickness varies from about 2 to 10 µm (average 4.6 µm) in the upper reservoir interval and from 18 to about 29 µm (average 24.1 µm) in the lower reservoir (Table 2). Figure 9c,d shows examples of micrographs (with measured coating thickness) from the upper and lower intervals, respectively, showing that the grain coating is significantly thicker in the sample obtained from the lower reservoir. The influence on reservoir quality due to varying coating thickness can also simply be anticipated by a visual inspection and comparison of micrographs from the two intervals (Figures 8g,h and 10a,b), where it is possible to recognize that exceedingly thick chlorite coats block pore throats.

4.4 Coating characterization

The chlorite coating observed in the studied samples is continuous (Figure 8f,g,h), that is coats are present at all detrital grains and cover the entire grain surfaces. Diagenetic minerals like small siderite crystals and rare quartz overgrowths are observed without clay coating (Figures 7d and 10a). The small siderite crystals can sporadically be observed to be partly embedded in the chlorite coating, likely sitting on the initial precursor clay coating (Figure 7e). The chlorite coats are also present at grain contacts and they tend to be slightly thicker in grain indentations (Figure 8a,b,c,f). However, the remnant clay coating present at grain contacts is in some cases extremely thin and is nearly invisible even at high magnification (Figure 8b). All these observations point to the clay coating having a detrital origin. Two types of clay coating can be recognized based on energy-dispersive X-ray spectroscopy (EDS) analysis of stub samples in the SEM. The trough-shaped features (Figure 8c), which represent the underside of the coating (coating that is closest to the grain surface), were observed to contain less iron compared to outer coating (Figure 8d, points 1 and 2), indicating a slightly different clay composition. EDS spectra from a thin section sample (Figure 8e, points 3–6) show a similar trend where the relative iron content increases from the inner portion of the coating towards the pore space. The EDS results suggest that the coating could possibly be of a chamositic composition. In the lower reservoir, the inner portion of the chlorite coatings has a dense and chaotic texture which further can be separated into two distinct phases based on the relative iron content (Figure 8e), whereas the outermost chlorite coating phase is characterized by more radial crystals (Figures 8e and 10b). The results show that there are large variations in the chlorite-coating thickness between samples investigated from the upper and lower reservoir units within the Agat Formation (Table 2, Figures 9 and 10). The variations seem to be governed by the thickness of the inner denser and more chaotic portion of the chlorite coating which is seen to be much thicker in samples from the lower reservoir unit (Figure 9d) compared to samples from the upper reservoir unit (Figure 9c).

Concerning reservoir quality, there are some clear trends between the measured core plug permeability and porosity, and the grain coating thickness (Figure 9). Permeability varies systematically with observed grain coating thickness (Figure 9a), where a decreased coating thickness corresponds to a higher permeability. Furthermore, the primary porosity is to a lesser extent influenced by coating thickness variations (Figure 9b), even though a slight increase in porosity can be observed on average in the upper reservoir compared to the lower reservoir interval when all core plug porosity data from the two intervals are included (Figure 3). Based on thin section measurements, the coating thickness varies from about 2 to 10 µm (average 4.6 µm) in the upper reservoir interval and from 18 to about 29 µm (average 24.1 µm) in the lower reservoir (Table 2). Figure 9c,d shows examples of micrographs (with measured coating thickness) from the upper and lower intervals, respectively, showing that the grain coating is significantly thicker in the sample obtained from the lower reservoir. The influence on reservoir quality due to varying coating thickness can also simply be anticipated by a visual inspection and comparison of micrographs from the two intervals (Figures 8g,h and 10a,b), where it is possible to recognize that exceedingly thick chlorite coats block pore throats.

5 DISCUSSION

5.1 What is the morphology, distribution and extent of the chlorite coating in the Agat Formation and what evidence exists with regards to the origin of this coating in this deep marine deposit?

The results show that all detrital components in all thin section samples are extensively covered with chlorite coating, whereas small siderite crystals can be observed to be clay free (Table 2, Figures 8g,h and 10a). These early formed diagenetic siderite crystals can form if reduced iron is still available in the post-oxic nonsulfidic zone (Berner, 1981). Therefore, they are likely to post-date the initial precursor clay coating (Figure 7d), though later recrystallized and ne-ofomed chlorite coating causes these crystals to be partly embedded in the chlorite coating (Figure 7e). In addition, the inner portion of the chlorite coating has a chaotic texture,
compared to an outer chlorite coating that is characterized by a more euhedral rosette-like texture (Figures 8c,d and 9d). These observations suggest that the chlorite coating, at least partly, results from a precursor clay coating. Chlorite coating forming from a precursor clay coating phase is widely accepted (Aagaard et al., 2000; Ehrenberg, 1993; Worden et al., 2020) and the present coating morphology is a result of progressive recrystallization of the detrital clay phase during burial.

A few studies have documented detrital clay-coated sandstones deposited by sediment gravity flow in deep marine environments (Houseknecht & Ross, 1992, Porten et al., 2019). Houseknecht and Ross (1992) found clay coats in channelized turbidite facies and suggested that clay coats were effectively
FIGURE 8 The green/red squares with poro-perm data included in each image and micrograph indicates whether the sample is from within the upper/lower reservoir. All samples are also marked in Figure 4a. (a) Sample 2X40.69 MD. The coating appears to be slightly thicker in grain indentations compared to coating fixated on more smooth grain surfaces. Note that grain contact seems to be free of clay material (upper reservoir). (b) Sample 2X40.69MD (yellow square in Figure 7a). High magnification shows clay remnants at grain contacts. (c) Stub sample 2X35.60 MD. Trough-shaped features are believed to represent the inner portion of the coating that was left behind after detrital grains were removed (probably during sample preparation). This also illustrates that clay grain contacts are a common feature. The authigenic chlorite is seen in the darker grey areas (lower reservoir). (d) Stub sample from 2X35.60MD, showing a cross-section of the chlorite coating. EDS spectra indicate that the clay phase situated closer to the detrital grain surface has a lower iron content compared to the clay phase adjacent to the pore space (Lower reservoir). (e) Micrograph from thin section sample 2X41.47 MD. EDS spectra show the same result as in 8D with the iron content increases from the inner to outer portion of the chlorite coating. Four spectra were acquired, from the quartz grain (spectrum 3) to the outer chlorite coating (spectrum 6) (lower reservoir). (f) Elemental mapping of an area in a thin section sample from 2X41.47 MD. The micrograph is coloured with the mapping of iron, which outlines the continuous chlorite coating. Also note the presence of coating on grain contacts (lower reservoir). (g) Optical thin section photo from sample 2X40.02 MD showing thick and omnipresent chlorite coating. (h) Thin section photo from sample 2X62.06 MD showing thin continuous chlorite coating is present on grain surfaces (upper reservoir).

emplaced in these sands due to sediment dewatering. Porten et al. (2019) also observed well-developed detrital clay coating in certain intervals interpreted to have experienced intense sediment dewatering. Even though the sedimentological results in this study indicate that the Agat Formation was deposited by similar processes in a deep marine environment (Figures 4a and 5), the petrographic characterization suggests that the precursor clay is an inherited clay coating, meaning that it was emplaced prior to final deposition (Wilson, 1992). This interpretation is based on observed features like the presence of clay at grain contacts, the tendency of thicker coating in grain indentations and the lack of clay bridging between detrital grains (Figures 7, 8 and 10) (Wilson, 1992). Furthermore, the mineralogical data show that the sandstones of the Agat Formation comprises abundant green marine clay pellets in certain intervals (Table 2 and Figure 7c), some of which show a glauconitic composition (Figure 7a,b,g), which can be associated with a shallow marine origin (Velde, 2003). The phosphatic clasts are also likely to represent shelfal material and could indicate that they originated from an environment near a site of ocean upwelling (Velde, 2003). The depositional environment of the Agat Formation have been debated in the literature, for example from slumps and debris flow-dominated (Shanmugam et al., 1994; Skibeli et al., 1995) to turbidity current-dominated environments (Nystuen, 1999) but with a general agreement that the Agat sands were deposited in a slope setting. Thicker sandstone intervals have been attributed to the amalgamation of individual units (Bugge et al., 2001; Nystuen, 1999), which was likely deposited within a channel system (Nystuen, 1999). The sands were likely sourced from the east through one or several E-W-oriented paleovalleys connected to the Norwegian margin (Bugge et al., 2001), where deposition was controlled by local topography inherited from Late Jurassic rifting (Bugge et al., 2001; Martinsen et al., 2005) (Figure 2). Additionally, the Agat sands have been described to be a result of reworked shallow marine sands due to the high glauconite content, which also indicates that the sands were stored on the shelf for some time prior to remobilization (Martinsen et al., 2005). Trigger mechanisms responsible of initiating the remobilization of the Agat sands are uncertain but could be linked to tectonic events, for example Austrian tectonic phase (Brekke et al., 2001), to the several regressive cycles during this overall transgressive period (Bugge et al., 2001) and/or collapse of delta head and other shelfal sands that were fed through one or several canyons. The observed paleovalleys (Bugge et al., 2001) and the narrow shelf (Martinsen et al., 2005) could facilitate the latter situation (Figure 2). The resemblance between the mineralogical and sedimentological results presented in this study and the published literature from wells in the Agat area indicate that similar processes have formed the Agat Formation in the presented well. Based on the petrographic and mineralogical results which indicate the Agat Formation have a shallow marine origin and that the precursor chlorite coating have a detrital origin, we propose that inherited precursor clay coating could be an additional way of forming chlorite-coated sandstones in deep marine environments. A similar possibility have been briefly discussed by Lien et al. (2006).

An advantage with an inherited precursor clay model is that the detrital clay coating emplacement is usually linked to processes in marginal to shallow marine environments. These settings seem to be the most frequently reported environment where detrital clay coats are likely to form (Dowey et al., 2012). In addition, these studies show that chlorite-coated sands are especially favoured in environments closely related to settings with a river discharge. The river is responsible for transporting the ingredients needed to form good reservoir sands in addition to the precursor clay material, all of which are dictated by the composition of the drainage area (Dowey et al., 2012; Ehrenberg, 1993). On the other hand, an inherited precursor clay model implies that the continuous precursor clay coating has survived remobilization. The fact that the same defined FA (MCS and MLS) are present in both the upper and lower reservoir sands (Figure 4a), while a noticeable coating thickness variation can be observed between the two units (Table 2, Figures 9 and 10) could imply that the transportation processes had a negligible abrasive effect
**FIGURE 9** The green/red squares with poro-perm data included in the micrographs indicate whether the sample is from within the upper/lower reservoir. Both samples are also marked in Figure 4a. (a) The link between measured coating thickness and permeability. (b) Plot showing the relation between core plug porosity and measured coating thickness. (c) Micrograph from the sample located at 2X67.12 MD, representing the interval with excellent permeability. Coating thickness = 4.05 µm (Upper reservoir). (d) Micrograph from the sample located at 2X41.47 MD, obtained from within the lower reservoir unit. Coating thickness = 24.1 µm (Lower reservoir).

**FIGURE 10** The green/red squares with poro-perm data included in the micrographs indicate whether the sample is from within the upper/lower reservoir. Both samples are also marked in Figure 4a. (a) Sample 2X40.69 MD. The micrograph shows a typical scenario in the upper reservoir unit where the detrital grains tend to be completely chlorite coated but the coating is not detrimental for permeability as pore throats are not completely blocked (yellow arrows). Please also note that the precursor clay coating is recrystallized where the coating is extremely thin (red arrow), whereas the precursor clay is not fully recrystallized in places where the coating is thicker (white arrows). The green arrows show examples of quartz cement on a grain that is partially coated which is very rare to see in the studied samples since chlorite coating tends to be continuous. (b) Sample 2X41.47 MD. Micrograph showing extensive chlorite coating in the low-permeability interval due to blocking of pore throats (yellow arrows). Measured coating thickness 21.7 µm (blue arrows).
on the precursor clay coating. This is further supported by the fact that the defined FA (Table 1) correlate better with the textural parameters, where differences in textural characteristics could record deposition from various parts of the gravity flow (Figure 6c and Table 1) but with no sign of coating thickness variations across the FA (Figure 4b). Since the precursor coating thickness is likely being determined at the sediments’ initial depositional site, the coating thickness would likely correlate better with facies occurring prior to remobilization. Wilson (1992) suggested that inherited clay rims can survive gentle reworking and flume experiments carried out by Verhagen et al. (2020) show that clay coats can persist sediment transport by certain types of turbulent flows. This could imply that detrital clay coats are durable under certain types of current-agitated conditions.

The reason for the significant difference in coating thickness between samples from the upper and lower reservoir unit is not trivial (Table 2 and Figure 9c,d). The varying coating thickness is ultimately a result of the thickness of the inner chaotic- and the outer chlorite coating with more radial crystals, where the former is observed to be significantly thicker in lower reservoir samples, thus seem to be the governing factor on differences in coating thickness. The inner portion of the chlorite coating is likely to represent a diagenetic analogue to the detrital precursor clay phase, whereas it is not clear whether the outer euhedral chlorite coating is a recrystallized or neoformed clay phase or a combination of the two (Figures 8c–e and 9c,d). The ratio between the thickness of the inner portion of the chlorite coating and the initial precursor clay thickness is also uncertain due to the recrystallization process, but it is likely that the initial thickness will influence the thickness of the diagenetic chlorite coating. Since the upper and lower reservoir units are not directly connected in the studied well but separated by a conglomeratic layer (Figure 4a), the observed chlorite thickness variations could potentially be linked to some compositional variations between the two units. Petrographic point count results show that the overall composition of samples from the upper and lower reservoir is similar (Table 2 and Figure 6a), but with some volumetrically important differences like the varying content of iron-bearing constituents (Figure 6b). Especially, the more abundant green marine clay pellets and the higher chlorite content in the lower reservoir could indicate that this unit results from a more iron-bearing rock suit, compared to the upper reservoir. In addition to the higher green marine clay pellets content, the higher rock fragment and lower quartz content of the lower reservoir unit could further indicate that the upper and lower reservoir units have a slightly different source. In addition, the chaotic portion of the chlorite coating, which can be associated with the detrital precursor clay coating, is exceedingly thicker in the lower reservoir unit compared to the upper reservoir unit (Figure 9c,d and Table 2). These results imply that the controlling factor on the coating thickness is linked to the availability of precursor clay material at the time of emplacement, which subsequently controls the resultant chlorite coating thickness. Availability of precursor clay material at the time of emplacement and an explanation for the other compositional difference observed between the upper- and lower reservoir could have been facilitated if sediments were sourced from slightly different subenvironments through one or several canyons on a narrow shelf (Figure 2).

5.2 | How do the chlorite coats influence the reservoir quality of the Agat Formation?

The upper and lower reservoir units of the Agat Formation in the studied well are separated into two distinctly different units in terms of reservoir quality due to large variations in measured core plug permeability (Figure 3). Sedimentological results show that reservoir quality correlates with facies when considering intervals outside the main target reservoir units, that is CPS and calcite-cemented layer (MCS) (Figure 4 and Table 1), which in general exhibit poor reservoir properties throughout. The same is likely to be true for CFA, because it predominantly comprises silty to clayey sediments, even though core plug data are not available from this interval. Within the massive and clean sandstone intervals of MCS and MLS, no obvious correlation between reservoir quality and facies is observed (Figure 4b) indicating that the varying reservoir quality within the target sands is controlled by other factors. The most intriguing petrographic result, with respect to reservoir quality, is the varying chlorite-coating thickness, where the measured coating thickness in each sample shows a clear negative correlation with the core plug permeability (Figure 9a). The micrographs also show that the clay coating is extremely extensive in pore throats in samples from the lower reservoir (Figures 8f and 10) and it is likely to be blocking pore throat regions. As noted by (Bloch et al., 2002; Worden et al., 2020) thick chlorite coating can be severely detrimental to fluid flow and is likely to explain the observed differences in permeability. As discussed in the previous section, the sedimentological analysis is related to the final transport and deposition and thus it is likely that reservoir quality could correlate better with the facies occurring prior to sediment remobilization. For example, Haile et al. (2018) found that the occurrence and quality of grain-coating chlorite varied systematically with depositional facies in a Triassic deltaic succession on Svalbard. Likewise, the initial depositional setting of Agat sands prior to remobilization would likely have some control on the precursor clay coating thickness, thus exert control on subsequent reservoir quality.

In terms of porosity, the core plug data also show that there is only a minor difference between the two units, with an average porosity value of 27.8% and 25.4% in the upper and lower
reservoir units, respectively (Figure 3). The small difference in porosities within these units can be explained by variations in grain size and sorting between the MCS and MLS, where better sorted- and finer-grained sediments are likely to retain more porosity upon compaction (Chuham et al., 2002). Thin section samples from MLS are characterized by having a finer grain size and better sediment sorting (Figure 6c) and tend to have slightly elevated porosities compared to intervals within the MCS FA (Figure 4b). Porosity obtained from point count, that is macroporosity, indicates that the difference between the upper and lower reservoir is more prominent (Figure 6A and Table 2). The IGV results indicate that porosity loss due to mechanical compaction have been similar for the upper and lower reservoir, with an average IGV of 27% and 28%, respectively, consistent with the compaction curve of Bloch et al. (2002), and can therefore not explain the difference in porosity obtained from point count. The core plug porosity data show a much weaker correlation with measured coating thickness compared with the correlation between coating thickness and the permeability data (Figure 9). This could be because the core plug porosity data are likely to accurately represent the total porosity, micro- and macroporosity, whereas the chlorite coating thickness will influence the effective porosity. The small difference in core plug porosity between the intervals is likely to represent the nonmicroporous volume of the thicker clay coatings and the more abundant green marine clay pellets in the lower reservoir. Hurst and Nadeau (1995) showed that diagenetic chlorite can have a microporosity of about 50% and can thus be responsible for the higher porosity seen in the core plug data. This effect will be more prominent in intervals with thicker grain coating chlorite resulting in an even greater difference between core plug and macroporosity. The thick chlorite coating resulting in large discrepancy between true and effective porosity is also likely to complicate estimations of water saturation and a thorough analysis of the microporosity distribution of the chlorite should be conducted (Hurst & Nadeau, 1995). Moreover, with regards to reservoir fluid analysis, the wettability of the outer chlorite rim could also have implications on permeability where an oil-wet outer chlorite coating could facilitate oil movement in regions with tighter pore necks (Xi et al., 2019).

Besides the changing reservoir quality due to the variable coating thickness, the petrographic results show that the chlorite coating is effectively preventing authigenic quartz cement from precipitating, thus having an overall positive effect on reservoir quality. Clay-free detrital grain surfaces, even though rarely seen in the studied samples due to the continuous clay coating, are observed to have quartz overgrowth (Figure 10a). Following the exhumation estimation of Baig et al. (2019), the maximum burial depth of the Agat Formation in the studied well has exceeded 3,000 m and by assuming a geothermal gradient of 30–35°C/km it is likely that the formation has been exposed to quartz cementation window. In addition, recrystallization of precursor clays has been observed throughout the studied interval, implying that temperatures have exceeded 90°C (Aagaard et al., 2000). This observation could also imply that the Agat Formation was within the quartz cement window for some time because precipitation of silica becomes significant when temperatures reach 70–80°C (Bjorlykke & Egeberg, 1993; McBride, 1989). In published literature, grain coating chlorite is in most cases regarded as having a positive effect on reservoir quality (Dowey et al., 2012). Much effort can often be put into describing and predicting abnormally high porosity zones in deeply buried sandstones without necessarily evaluating permeability. In many cases, a strong positive correlation between porosity and permeability can be expected for relatively coarse-grained and well-sorted sandstone reservoirs. However, this study emphasizes the importance of assessing both porosity and permeability in chlorite-coated sandstone reservoirs as permeability can be significantly reduced even though the core plug porosity is seemingly high.

6 | CONCLUSION

This study has documented extensive chlorite coatings found in gravity flow-derived sediments of the Agat Formation from the northern North Sea of the west coast of Norway. The studied sandstone units revealed the potential for commercial targets within deeply buried sandstones of a deep marine origin due to an inherited precursor clay coating. This study attempts to understand the origin of precursor clay coatings in deep marine deposits and their effect on reservoir quality.

Firstly, the petrographic and sedimentological results from the studied section indicate that the Agat Formation has fingerprints of an initial shallow marine origin and was later remobilized by gravity flows into the present location. The absence of clay bridges between detrital grains, the presence of clay coating at grain contacts and the fact that the chloride coating is continuous and present on all detrital components strongly suggest that the precursor clay coating was emplaced prior to final deposition. Hence, we suggest an alternative mechanism for the occurrence of chlorite-coated sandstones units in deep marine environments, that is due to an inherited precursor clay coating. Secondly, the chlorite coating has an overall positive effect on the reservoir quality within the studied section, as it is effective in preventing quartz cement formation. Particularly, the upper reservoir unit exhibits excellent reservoir quality due to a thin omnipresent chlorite coating with an average thickness of ca. 4.5 µm. However, the exceptionally thick chlorite coating, with an average coating thickness exceeding ca. 24 µm, observed in the lower reservoir unit significantly reduced permeability due to the blocking of pore throats. Large discrepancies between core plug- and point count porosity have also shown that the core
plug porosity data can be unrealistically high, an effect that will likely become more pronounced with an increase in chlorite coating thickness. This study has signaled the importance of an integrated approach to assess porosity and permeability thoroughly in chlorite-coated sandstones. Lastly, the results indicate that the chlorite coating thickness variation observed between the upper and lower reservoir is likely controlled by small variations in initial sediment composition. The more abundant iron-bearing mineral content in the lower reservoir unit could imply that enough precursor clay material was available at the time of emplacement to form a thick precursor clay coating in the lower reservoir. This study offers new insight into precursor clay coating origin in deep marine deposits and can be useful in future exploration activity in the area and in other similar settings worldwide. Based on these data, we propose that deep marine sediments deposited because of remobilization of precursor clay-coated shallow marine sands could be potential targets for petroleum prospects.

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The data that support the findings of this study are available on request to the corresponding author.

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REFERENCES


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Paper V
How do chlorite coatings form on quartz surface?

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A B S T R A C T
Chlorite-coats on quartz surfaces are ubiquitous in various sedimentary environments. Chlorite-coats shield the surface of quartz from quartz cement overgrowths, thus preserving anomalously high porosity in deeply buried sandstone reservoirs. The inhibition of the quartz cement implies that the chlorite-coats on the surface of quartz grains can significantly influence the physicochemical behavior of the quartz grains. Therefore, failure to notice the initial thin microscale coatings forming during deposition can have serious consequences for modeling several geochemical reactions occurring at liquid-solid interfaces. Despite this huge implication, the fundamental mechanisms involved in chlorite-coat formation is not well understood. Here we present an experimental study to determine the parameters that control chlorite-coat formation on the surface of quartz grains. The batch experiments were conducted in a concoction of quartz and chlorite under different conditions of ionic strength, pH, and presence of humic acid (HA), iron- (Fe) and aluminum (Al) oxides). HA, Fe- and Al oxides are suggested to aid the emplacement of chlorite-coat precursors. At pH 7, the quartz-chlorite and quartz-chlorite-Fe/Al-oxides mixing experiments performed in saline and non-saline solution result in equal chlorite-coat coverages, suggesting neither salinity nor Fe and Al-oxides explain the mechanisms of chlorite-coat formation. At pH 5 and 9, however the chlorite-coat coverage was superior only in saline solution, indicating differences in coat coverage may be caused by variable electrokinetic charge distribution due to the distribution and transport of dissolved salt. The chlorite-coat rarely formed in experiments that contain HA in quartz-chlorite mixtures regardless of ionic strength and pH. Against a long-standing notion, the presence of organic matter cannot necessarily be prerequisites for binding chlorite on the surface of quartz grains. The dynamic interactions between solution chemistry and surface chemistry of solid phases (quartz, chlorite, HA, Fe and Al oxides) can result in changing the electrokinetic properties in a region near the solid phases and at mineral-solution interfaces. We therefore propose that the electrokinetic response that arises in heterogeneous systems may explain the mechanisms of chlorite-coat formation.

1. Introduction

Chlorite is an Fe-containing phyllosilicate with a 14 Å unit, which is ubiquitous in deltic and fluvial depositional settings as grain-coatings on the surface of sedimentary grains (Dowey et al., 2012; Moore and Reynolds, 1997). The chlorite-coats are believed to originate due to the alteration of precursor clay minerals such as berthierine – a 7 Å chlorite (Aagaard et al., 2000), kaolinite (Boles and Franks, 1979) and smectite (Chang et al., 1986). The iron-rich precursor clay minerals form in near-shore settings associated with major riverine input. In modern settings, these coatings comprise several clays (odinite, odinite-rich mixed-layer clay, different detrital minerals and ferric chloritic minerals) whereby iron is dominantly ferric (Odin and Gupta, 1988). These modern precursor coating mineral forms in sediments buried to a few cm beneath the sediment-water interface (Odin and Gupta, 1988).

Detrital clay-coat formation in various sedimentary environments i.e. continental, coastal and marine has been explained in terms of (i) infiltration and bioturbation (Bloch et al., 2002; Dowey et al., 2017; Matlack et al., 1989; Moraes and De Ros, 1992; Wilson, 1992), (ii) surface-based hydrological processes (Wooldridge et al., 2018), (iii) benthic diatoms produced biofilms of exopolymers (Duteil et al., 2020; Virolle et al., 2019; Wooldridge et al., 2017), (iv) a reduction of flow velocity at sand-grain contacts (Cao et al., 2018), and (v) sediment dewatering in deep-marine turbiditic systems (Houseknecht and Ross, 1992; Porten et al., 2019). On the contrary to this dewatering process, a recent study has shown that the origin of chlorite coats in deep-marine sediments are inherited precursor chlorite coatings remobilized from shallow marine environments (Hansen et al., 2021). This remobilization

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hypothesis for the origin of chlorite-coats is reasonable as the clay-coats can resist abrasion (Verhagen et al., 2020).

Most studies on chlorite-coats on the surface of sedimentary particles have been carried out from the perspective of preservation of open pore networks in deeply buried sediment (Dowey et al., 2012; Haile et al., 2018; Lîne et al., 2018). Chlorite-coats inhibit quartz cement by isolating the quartz grain surfaces from silica-saturated pore fluids so anomalously high reservoir quality can be preserved at deeper burial depths. This scenario shows that the chlorite-coats can also have considerable potential to mask other reactions at sediment grain surfaces. For example, clay-coated quartz control methane gas (CH$_4$) wettability and thus methane recovery in shales (Pan et al., 2019). Understanding how chlorite-coats form on the surface of sediment is therefore central to understand various geochemical processes, including biogeochemical cycles of many elements, underground storage of nuclear waste, subsurface CO$_2$ storage and fate and transport of contaminants.

Despite its ubiquity and implications for numerous environmental surface and interface reactions, chlorite-coat formation in the context of other geosystems than petroleum prospect sedimentary rocks has not been given much attention. Even though numerous case studies have been conducted in the context of reservoir quality, to date, much remains unknown regarding how chlorite precursor particles attach on the surface of the sedimentary grains and the factors that control the attachment pathways. The evidence for where these clays form and what controls this process is not clear-cut, and mostly conjectural.

It is therefore essential to explore the mechanisms and variables that control chlorite-coat formation to predict various processes that occur at the interface between water and solid phases, especially in fluvial and deltaic settings. Because 1) clay-coats on the surface of sediment grains are abundant in fluvial and deltaic settings (Dowey et al., 2012) and 2) the fluvial and deltaic settings are the most environmentally and economically important geosystems whereby the human population within 100 km of these systems is growing (Arto et al., 2019; Cazcarro et al., 2018; Lauraia et al., 2018). The population within such systems was 2.1 billion in 1990 and is expected to grow to 3.2 billion in 2030 (Kummu et al., 2016). This population increase will result in massive human activities that have enormous potential to modify the affected drainage basins through marked anthropogenic induced changes. Human activities can increase the influx of terrestrial driven contaminants such as toxic heavy metals and emerging contaminants (e.g., microplastics, fertilizers and pharmaceuticals) into the rivers and deltas and ultimately the oceans. It is therefore indispensable to understand how clay-coats form on the surface of sediment grains, as it is fundamental in several natural and human induced phenomena, not only in the fields of petroleum geology, but also aquatic chemistry, soil chemistry, environmental chemistry and hydrogeology. The main objective of this study is therefore to unravel how clay-coats form on the surface of quartz grains.

2. Materials and methods

Laboratory batch experiments were conducted to unravel under which conditions clay-coating occurs, when iron/aluminium-oxides and humic acid were added to quartz – clay suspensions. All mixing experiments were conducted at room temperature (~20 °C) and all chemicals used were of analytical-grade quality while aqueous solutions were prepared using ultrapure water i.e. Milli-Q water (resistivity 18 MΩ/cm). Metal oxides (Al$_2$O$_3$ and Fe$_2$O$_3$) and salt (CaCl$_2$, 2H$_2$O) with purity (≥99.0%) were purchased from MERCK. Aluminium (Al) - and iron (Fe) oxide were chosen as they represent a ubiquitous and highly reactive component of the inorganic particles in fluvial and estuary systems. We also used a Ca$^{2+}$ solution, as it is the dominant cation in freshwater and important in the fluvial-marine transition. Humic acid (HA) in the form of crystalline powder purchased from Alfa Aesar was used without further purification. We used HA as it represents the fraction of naturally occurring terrestrial derived organic matter commonly found in sediments and soils (Hayase and Tsubota, 1983). The natural chlorite (ripidolite CCA-2) rock chip from Flagstaff Hill, California, USA, was purchased from the Clay Minerals Society. This natural Fe-bearing trioctahedral chlorite was chosen because it represents the commonly found Fe-rich clay mineral in a spectrum of depositional environments including deltaic and fluvial settings as coatings on the surface of sediments (Dowey et al., 2012; Worden et al., 2020). The clay rock chip was first smashed and crushed into smaller fractions. Subsequently, the crushed clay fraction was wet micronized using ethanol for 12 min using the micronizing mill.

We used clean industry standard quartz as a sediment model as it is one of the most abundant components of sediment and soil. To remove any residual contaminants, if any, from the surface of quartz, the quartz grains were soaked overnight in 2 M HCl and washed thoroughly using Milli-Q water. The grain size distribution was determined using the Beckman coulter LS 13 320 Laser Diffraction Particle Size Analyzer. The quartz grains used in all experiments have a grain size distribution ranging from 63 to 500 μm representing very fine to medium sand.

All experiments were conducted in two type solution media, one saline water (saline solution of 0.01 M CaCl$_2$) of ionic strength slightly higher than river water (estuary conditions) and other Milli-Q water (non-saline solution) representing low ionic strength conditions. The mixing experiment was performed to study how detrital clay coatings form on the surface of quartz. Varying solution chemistry, inorganic- and organic materials under conditions relevant in natural settings are considered (Table S1). The procedure employs a heterogeneous mixture of quartz-ripidolite, including Fe- and Al oxides, and HA. The aqueous solutions were prepared at various initial pH values (5, 7 and 9). The pH of all experimental solutions was adjusted by the dropwise addition of a solution of 1 M NaOH and 1 M HCl and concurrently measured using a Metrohrom 702 SM Titriino coupled pH meter. The batch experiments were conducted grounded on the presence and absence of supposedly binding agent/s into quartz-clay mixtures: Fe oxide, Al oxide, a mixture of Fe/Al oxide, HA, a mixture of HA and Fe/Al oxide and without the presence of the binding agents at the two aequous conditions selected. Experiments from each category were conducted in duplicate to make certain that the results are repeatable.

First, quartz, ripidolite, HA, Fe- and Al oxide were weighed and added in 25 mL experimental tubes according to experimental categories. Second, 15 mL of the mixing solution prepared at a desired pH and salinity was added to the batch mixing tubes consisting of solid materials. The mixing tubes were quickly stopped, and the mixtures were positioned on a horizontal axis on a mechanical shaker. The mixtures were shaken continuously at 250 rpm in the back-and-forth mode to simulate current agitated condition of coastal settings over a period of 48 h. Later, the mixtures were left for a week without any disturbances because in a natural setting, aggregates or flocs of clay particles are expected to be settled for example on sand bars during high and low tides slack water conditions. Therefore, our experimental configuration attempts to mimic environmental processes associated with sedimentary environments at the continental-marine transition. After a week, the quartz grains were sampled from each experimental mixing tube. Afterward, the samples were rinsed with Milli-Q water and the fluid was evaporated by placing the wet samples in an oven for 12 h at 60 °C. After drying, samples were loaded on individual stubs (sample holders) for analysis using Hitachi SU5000 field emission gun scanning electron microscope (PEG-SEM) at the Department of Geosciences, University of Oslo. Furthermore, wet quartz grains (without drying) were examined for the clay-coat formation using the Nikon SMZ18 binocular stereomicroscope. This investigation was done to show that the emplacement of the clay particles was not due to the drying process.

The extent of clay-coat coverages was quantified, using SEM micrographs of quartz grains. A semiquantitative coat coverage estimation was obtained for each sample by randomly selecting three representative grain surfaces from each SEM micrograph of each experiment. In
total, 108 quartz grains were analyzed. Based on the analysis of SEM micrographs using Python and the image processing library scikit-image, the extent of average clay-coat coverage was calculated (Van der Walt et al., 2014; VanRossum, 1995). Gray scale segmentation was performed on representative quartz surfaces in order to separate clean quartz surfaces from ripidolite particles using their differences in the shades of gray. As we used stub samples, the quantification results cannot be considered a perfect representation of the extent of clay-coating coverage. Because the gray scale, which is used to separate quartz grains from ripidolite particles, to some degree depends on the orientation of the selected grain surfaces. It is however, a more reliable way of estimating coating coverage compared to the commonly used visual qualitative classification method.

3. Results and discussion

The batch clay-coat experiments were conducted using a mixture of quartz-chlorite (Fe-bearing clay) in the absence and presence of initially solid phases (HA, Al- and Fe oxide), which are ubiquitous in soil and sediment deposited in fluvial and deltaic systems. These systems have been reported as common places for the Fe-rich clay-coat formation (Dowey et al., 2012). The results of the batch mixing experiments are presented and discussed below.

3.1. Solid phase control on clay-coat formation

Figure S1 shows representative SEM micrographs of quartz-ripidolite mixtures from batch mixing experiments conducted in saline and Milli-Q water at various pH values (5, 7, and 9) without the presence of HA, Fe and Al oxides (solid phases). Figures S2–S6 show representative SEM micrographs of quartz-ripidolite mixtures with the presence of HA, Fe- and Al oxides. Chlorite particle attachments were formed on the surface of quartz grains as coatings, irrespective of the absence or presence of the HA, Fe and Al oxides, though the extent of clay-coat coverage varies (Fig. 1). Fig. 1 represents the estimated clay-coat coverage on quartz grains for six categorical batch experiments, for saline- and Milli-Q water respectively. The clay-coat coverage range from ~6% to 27% in the absence of solid phases, whereas ~1% to 32% in the presence of solid phases (Fe and Al oxide). The image processing method used for quantification of clay-coat coverage revealed a strong variation in clay-coat coverage on the surface of quartz grains. All the HA mediated experiments had very low clay-coat coverage (Figs. S2–S3), ranging from ~2% to 7% (Fig. 1).

The interparticle associations between ripidolite particles on the surface of quartz grains were largely seen to form edge-to-edge- and face-to-edge patterns rather than face-to-face stacking patterns (Fig. 2 and Figs. S1–S6). Similar types of geometrical arrangement of the clay particles have been reported in both natural environments and in laboratory formed chlorite-coats (Charlaftis et al., 2021; Haile et al., 2015). Underpinning what controls the clay staking patterns is however a difficult question as complex variables, such as the particle size distribution, mechanical forces of the physical mixing process, and different types of charges on the faces and at the edges and the heterogeneity of layer charges can regulate the clay particle stacking patterns. Generally, the interaction of clay surfaces with surrounding fluid in terms of the differences in charge characteristics of the clay basal surface and edge surface of clay minerals may explain the geometric arrangement of clay particles (Bennett and Hulbert, 1986).

The ripidolite particles in coatings are oriented parallel to quartz surfaces, which is analogous to the pattern of clay-coats on sediment surfaces that has been reported in natural environments (Haile et al., 2018; Wilson and Pittman, 1977; Worden et al., 2020; Aagaard et al., 2000). This pattern suggests that the clay-coat formation occurs by similar mechanisms in a natural setting. Also, the clay-coat attachment patterns appear similar in the presence of various types of solid substrates, suggesting that the solid substrates cannot control the mechanisms of attachment.

In all experiments (Figs. S1–S6), the attachment of clay particles on
the surface of quartz grains was irregular, suggesting the surface chemistry of quartz in aqueous environments is uneven along the entire quartz surface. This observation agrees with the presence of two distinct surface groups (silanol and siloxane) that have been previously reported for the surface of quartz based on density functional theory computations (Bandura et al., 2011). These different quartz surface terminations can thus exhibit unique properties, which regulate the interactions with clay particles and attachment mechanisms.

Fig. 3A shows optical microscope micrographs of clean quartz grains before batch clay-coat experiments for comparison, whereas Fig. 3B–D shows quartz grains after batch mixing experiments. The emplaced clay and iron oxide particles on the surface of quartz grains were examined under the microscope as it was in the wet phase, i.e. before drying. Most of the quartz grains were coated with clay particles in the quartz–clay mixture (Fig. 3B) and Fe oxide particles in the quartz–Fe oxide mixture (Fig. 3C). The optical micrograph revealed that Fe oxide particles were uniformly coated on the entire surface of quartz, whereas clay particles were not in the quartz–clay–Fe oxide mixture (Fig. 3D). This result suggests that binding agent (here Fe oxide) mechanisms cannot explain clay particle attachment on the surface of quartz grains. If the metal oxide was serving as a binding agent, the clay attachment on the surface of quartz should have followed the Fe oxide attachment patterns and as a result, the entire surface of quartz should have been coated uniformly. This result is thus another supporting evidence that the presence of binding agent mechanisms cannot explain clay coatings on the surface of quartz particles.

Nevertheless, it does not mean that the presence of so-called binding agents plays no role even though their absence does not inhibit the formation of clay-coats (Fig. 3B). For example, in a mixture of Fe and Al oxide, the surface charging behavior of Al- and Fe oxide can change in the mixture because the point of zero charge of the mixed oxides is the linear combination of the corresponding quantities of the components (Kosmulski, 2002). Such a scenario can produce a conducive environment for negatively charged clay minerals to come together to form aggregates that consequently led to settlement and ultimately attachment on the surface of quartz grains.

In the presence of HA (Fig. 4A), after the batch mixing experiments, we expected that the aggregates and/or coalescence cluster complexes of clay particles to settle on quartz grains but settling of the HA-complex did not happen (Fig. 4B). It appeared that the mixtures formed aggregates that consist of a relatively low-density, soft, jelly-like, crenulated, and spiraled, hallow loose network of grains (Fig. 4C and D). Therefore, HA remained predominantly in the aqueous phase by complexing with ripidolite particles (Fig. 4B).

The formation of the complexes in the aqueous phase inhibited sedimentation and hence the attachment of ripidolite aggregates on the surface of quartz grains. Reduction of the clay-coat coverage can be related to the potential of the HA to affect the electrokinetic properties.
(e.g., zeta potential) of the solid substrates, including clay particles. HA has high affinity to form complexes with Fe and Al oxide as well as clay minerals. For example, adding 50 mg/l of humic acid caused the entire zeta potential vs pH curve of hematite to become largely negative and nonresponsive to a wide pH range (3–10), resulting in the absence of a measurable isoelectronic point (Carlson and Kawatra, 2013).

The HA scavenging property for solid phases and clay particles can modify the ion distribution and association in the bulk solution and in the electric double layer. HA complexed with charged ions can thus modify physicochemical properties of the system. This modification can limit the availability of charged ions easing flocculation of ripidolite particles. As indicated in previous studies, low ionic strength solution will result in the formation of large flocs, whereas high ionic strength into small flocs (Konduri and Fatehi, 2017; Metaxas et al., 2021; Wilkinson et al., 2017). Similarly, the modification of the electrokinetic property of the coating process has resulted in the formation of large organo-clay flocs with open structures (low-density values) maximizing the possibility of the flocs to remain in the suspension. It has been shown that organic matter-mineral associations can lower the density of pure Fe and Al mineral phases (Kaiser and Guggenberger, 2007). Therefore, the scarcely observed clay-coats for quartz-clay mixtures in the presence of HA suggests that the clays, Fe- and Al oxide in the suspension have formed an interacting network with HA. This interaction can retard settling and/or attachment process. Although the fact that the interaction of organic matter with abundant hydrous metal oxides (e.g., Al and Fe oxides) dictates many important geochemical processes in aquatic systems, including rivers and deltaic settings, it has not been given the attention it deserves. This can be the reason why the interaction mechanisms of natural organic matter with mineral surfaces are not well understood (Gu et al., 1994; Kleber et al., 2021).

Unlike the results presented here, published studies suggested organic matter-related mechanisms to explain the origin of clay-coated sand grains in modern marginal marine sediments (Wooldridge et al., 2017). According to such studies, a biofilm (expomeromic substance) that contains molecular bands fully consistent with organic-rich complex mixtures mediate clay particle attachment. Expomeromic substances (EPS) are polyamionic large organic molecules mainly containing abundant carboxyl and hydroxyl functional groups. Complex polysaccharides interact with mineral surfaces through their hydroxyl and carboxylate functional groups (Hakim et al., 2017). HA used in this study is not the same as EPS but from a functional group standpoint, we speculate that the basis for HA sorptive and adhesive properties can work also for EPS. This inference is reasonable as functional groups play a significant role in controlling physicochemical properties of the organic compounds.

This study unequivocally revealed that the attachment of clay minerals on sediment grain surfaces cannot necessarily be related to the presence of supposedly binding agents, such as metal oxides and organic matter. Therefore, our study signals the inevitability of scrutinizing the existing prevailing hypothesis about clay-coat formation i.e., the binding agent mechanisms are pivotal to form detrital clay-coats on sediment surfaces at or near the Earth’s surface (Duteil et al., 2020; Virolle et al., 2021; Wooldridge et al., 2017). The prevailing hypothesis whereby the presence of binding agents explain the mechanisms of clay-coat formation in a spectrum of sedimentary environments is therefore overly simplistic.

3.2. Solution chemistry controls on clay-coat formation

Here, the potential-controlling role of changing medium salinity and pH on clay-coat formation as a function of the response of solid surfaces is presented and discussed. Detrital ripidolite particles attach on the surface of quartz grains as coats at various pH values in saline and Milli-Q water-mediated experiments (Figs. S1–S6). These results demonstrate that the clay-coats can form across different solution chemistries with a strong variation in clay-coat coverage on the surface of quartz grains (Fig. 1).

3.2.1. Ionic strength dependence of clay-coat formation

Across the pH values, the extent of the clay-coat coverage range from ~15% to 32% and ~1% to 28% related to saline- and Milli-Q water-mediated experiments (excluding HA-mixtures), respectively (Fig. 1). At ~ pH 5, the average clay-coat coverage is two to three orders of magnitude higher in saline water compared to Milli-Q water-mediated experiments (Fig. 1, S1A-B, S4, S5–S6A-B). At ~ pH 9, the average clay-coat coverage is significantly higher (> four times) in saline than Milli-Q
water-mediated experiments (Fig. 1, S1E-F, S4, and S5E-F) except for the experiments that were conducted in the presence of a mixture of Fe and Al oxides (Fig. 1, and S6E-F).

The substantial variability in the average clay-coat coverage at fixed pH (pH 5 and pH 9) levels as a function of changing the ionic strength of the solution suggests that the quartz surface chemistry in an aquatic environment responds to changes in electrokinetic charges. Therefore, the observed variation in clay-coverage in these experiments can be linked to the behavior of minerals in solution, e.g. changes in solubility and chemical speciation, which depend on the ionic strength of the solution. The formation of the observed clay-coat formation can be related to the surface configuration of the solid-solution interface of clay minerals, quartz, Fe and Al oxide sensitivity to ionic strength in aqueous environments (Tombácz et al., 2001). This observation suggests that at these pH values the zeta potential (electrokinetic property) on quartz is basically dependent on the ionic strength.

In contrast to pH 5 and 9 systems, the average clay-coat coverage is similar in both saline and Milli-Q water-mediated experiments at pH 7 environment (Figs. S1C-D, and S4–S6C-D). The pH level and solution chemistry can dictate charged species adsorption at the solid phases (e.g., quartz and ripidolite surface), surface charge and electric double layer that can regulate the chemistry and physics of charged interfaces (Chang et al., 1993; Marchuk and Rengasamy, 2011). Results observed at pH 7 indicate that the clay-coats formed irrespective of ionic strength and the presence of the types of solid substrates. The fact that the extent of clay-coat coverage is similar irrespective of salinity at pH 7, suggests that ripidolite aggregation in saline medium due to ion-bridging mechanisms cannot explain the ripidolite attachment on the surface of quartz. Salt-induced flocculation is however proposed as a major controlling mechanism for depositing suspended matter where the river meets the seawater (Manning et al., 2011; Miotta et al., 2009). However, it has also been suggested that salt mediation of flocculation is a minor factor in controlling flocculation of suspended solid particles (Eisma et al., 1991b; Thill et al., 2001). Our observation is similar to the latter studies. Similar clay-coat coverage imply that the zeta potential on quartz in contact with aqueous saline and non-saline solutions at pH 7 was independent from ionic strength. It appears that the clay-coat process at pH 7 is complex from a theoretical perspective and thus challenging to pinpoint precisely the dominant controlling parameter. Various parameters may have acted concurrently to modify the solution chemistry and thus dictate surface charges, including charged ion associations at the interfaces and in the bulk solution.

3.2.2. pH-dependence of clay-coat formation

The pH of the solution can strongly modify the surface chemistry of quartz. The presence of silanol groups on the surface of quartz is capable of adsorbing and releasing protons. The silanol group becomes deprotonated above the pzc corresponding to the point of zero charge (pzc) of quartz that occurs at ~ pH 2.0–4.5 (Davis and Kent, 2018; Fuerstenau, 2005; Kosmůški, 2020). This means as the pH of the solution increases above the pzc, the number of deprotonated silanol groups and the negative charge of the surface increase. Therefore, the quartz–ripidolite or quartz-metal oxide interactions in the aqueous medium are expected to vary as a function of pH at a fixed ionic strength. Keeping salinity identical (Milli-Q water), the extent of clay-coat coverage varies a lot as function of pH values (Figs. S1 and S4–S6). For all experiments conducted with an increase in pH values (5 ≤ pH ≤ 9) resulted in at first by an increase and then a decrease (e.g., ~12%, 19%, 6%) in the extent of clay-coat coverage on the surface of quartz grains (Figs. S1, S4–S6 B, D, and F). This pattern suggests that altering the pH of the solution can significantly dictate the clay-coat formation mechanisms in non-saline media. Unlike the predominantly suggested environments where clay-coats form, results of this study indicate that the formation of clay-coats is feasible in non-saline media (similar to freshwater natural environments).

In the saline water-mediated experiments, the clay-coat coverage variations remain minor across the whole range of pH levels (Fig. 1). Since the clay-coat variations are minor as a function of pH, it can be concluded that the variations in the zeta potential of quartz as a function of pH in the saline solution were smaller. Therefore, in this case the pH level cannot be the key parameter controlling the extent of clay-coat coverage. This study underpins how the attachment of precursor clay particles happen, which will transform into authigenic chloride coatings during burial. A direct precipitation reaction due to the dissolution of unstable rock materials, such as volcanic rock fragments, has also been proposed to form chloride coatings in an alkaline environment (Chen et al., 2011). The direct precipitation mechanism describes only how authigenic chloride is formed rather than the emplacement mechanism of a precursory clay phase. Still, unlike the alkaline environment proposition, hydrothermal chloride synthesis experiments that simulated burial diagenesis have shown that authigenic grain-coating chlorites can be obtained at different pH values (Halle et al., 2015). This study indicates that previous suggestions about the emplacement of clay particles and their controls are probably too simplistic for chloride-coat formation in a sandstone reservoir. It appears that the electrochemical environment and the physical mixing process regulate the emplacement of clay particles on the surface of sedimentary grains than only pH values.

3.3. How do clay-coats form?

Chlorite (Ripidolite) structure shows a regular alteration of negatively charged triotahedral micaeous layers and of positively charged octahedral interlayer hydroxide sheet interacting when in contact with aqueous media. The solution chemistry and the types of solid phases in aqueous media can control ripidolite particle rearrangement via attachment, detachment and migration in sedimentary environments. Aggregates of ripidolite particles appear as irregular masses or clumps of numerous individual grains (Figs. S1–S6). The ripidolite aggregates consist of particles ranging from small (~2 μm) to large (~10 μm) and it appears that these aggregates and larger size individual ripidolite particles were attached on the surface of quartz grains.

The aggregates are mainly arranged in a chain-like structure rather than stacking in a regular pattern resembling the staircase structure. This pattern indicates that processes leading to the aggregation and settling of ripidolite particles are crucial for the coating process on the surface of quartz grains. As the aggregates get closer to the quartz surface, the strength of intermolecular binding forces that facilitate the coating process will increase. Therefore, the electrokinetic interactions that dictate the aggregation of clay particles can be regarded as possible mechanisms for sedimentation and attachment of clay particles on the surface of quartz grains. In contrast to saline water, Milli-Q water-mediated systems (pH 5 and 9) can have individual particles homogeneously dispersed forming a stable suspension. Such a process can remain virtually unchanged for long periods and will inhibit settling and thus the coating process. Although at a low rate, changes can occur in such a system, suggesting that the system is unstable in a thermodynamic sense.

A complex array of parameters that either enhance or inhibit the aggregation process can thus control the clay-coat formation. At fixed pH 5 and 9, changing the ionic strength of the solution demonstrates variations in clay-coat coverage, suggesting increasing ionic strength favors the mechanism of the clay-coat formation. In the Milli-Q water-mediated experiments (non-saline solution), aggregation can be hindered due to limited interactions between the constituent phases due to limited availability of charged ions. In contrast to the Milli-Q solution, the charged ions in the saline solution will affect the aggregate size and aggregate-settling velocity, due to the increase in the cohesive force between clay particles and other phases. These mechanisms favor the formation of aggregates of clay particles that sink many times faster than their component grains. These phenomena look like the non-equilibrium aggregation of cohesive sediments that occur in nature in turbulent type
flows through random collisions of sedimentary particles. The reason for this process is related to an increase in the mobility of the salt ions in an aqueous system affecting the electrokinetic properties, including the structure of the electric double layer and zeta potential, of quartz grains, clay particles and metallic oxides. Therefore, charged ion interactions can explain the attachment process on the surface of quartz grains.

It is obvious that clay-coats were scarcely formed under the Milli-Q water system. The exceptions tend to be experiments conducted at pH 7 (Fig. 1). This scarcity of clay-coats can be linked to a shortage of charged ions in the freshwater suspensions as the abundance of charged ions favors sticking leading into strong electrokinetic interactions. Particle attraction and association are more effective in a saline solution rather than dilute solutions (freshwater) (Dao et al., 2020; Wu and Adachi, 2018).

van der Waals attractive forces that operate between the atoms of particles can also cause particle association in saline medium. The summation of all attractive forces between all phases can result in total attractive forces between the particles. In a freshwater medium, repulsive forces between the particles can prevent particle association. The presence of such change is evident from the well-known movement of particles in an electric field system. The effectiveness of the repulsive forces can be shown to decrease with increasing ion concentration of the liquid phase in the system. Therefore, repulsive forces will prevent particle association in freshwater solution by counteracting the van der Waals attraction, but in salt solutions, they are no longer powerful enough to prevent aggregation. Salt is expected to screen the electrostatic repulsive forces between the charged particles in solution and thus via short-range van der Waals interaction to promote the rate of particle flocculation.

There was no visible clay-coat trend observed in HA/quartz–clay mixtures as a function of pH and salinity (Figs. S2–S3). An increase in pH for both saline and non-saline solutions show a minor increase in the extent of clay-coat coverage in all HA-containing experiments (Figs. S2–S3). Even though the solution chemistry varied, in general it appeared that any small variations in the extent of clay-coat coverage are to be considered negligible (Figs. S2–S3). But the clay-coat coverage appeared slightly higher in the alkaline pH range compared with acidic and neutral pH values. Increasing the pH of the solution increases the concentration of hydroxide ions in aqueous phase facilitating the adsorption of these ions on solid phases such as HA. This interaction results in a large diffuse electrical double layer, resulting in an elevated zeta potential. This interaction can to some extent have increased instability of a suspension of clay particles resulting in settling and then attachment.

The ripidolite-HA interactions give an excellent insight into the factors influencing the clay-coat formation on the surface of quartz grains. HA substantially alters clay minerals dispersion-aggregation behavior. This interaction clearly indicates that the mechanism of clay-coat formation can be constrained by processes that can change the interfacial electrochemistry of clay minerals. In natural settings, it has been proposed that the flocs form in highly turbulent areas, such as tidal inlets and narrow straits, and near the bottom in the regions of muddy sediment. Such complexes were suggested to settle on sand bars during high tides and low tide slack water conditions. The presence of organic matter and clay-organic matter complexes in the water column was suggested to enhance the flocculation of suspended particles and thus settling (Eisma et al., 1991a). However, results of this study reveal that we need to be cautious when inferring organic matter-mineral or sediment interactions in the natural setting, resulting in the flocculation of clay particles and thus settling.

Understanding HA-clay minerals interactions in the soil and sediment is significantly important. Because such a process can shape the fate and mobility of contaminants in the natural environment. Ripidolite was adsorbed on the surface of HA irrespective of ionic strength and pH variations of the aqueous media, indicating HA was acting dynamically over a range of different solution chemistries and thus modify local electrokinetic behavior of the media. HA-mineral interactions can be electrostatic between hydrophilic organic moieties and molecular between its hydrophobic portions. The aqueous complexation of HA due to its functional groups including carboxyl and hydroxyl can result in the dissolution of ripidolite to form colloidal particles hindering the formation of flocculated material. Yet, the mechanism(s) of interactions between most organic matter and most minerals in sediment and soil is incompletely understood (Mayer, 1994).

3.4. Implications

This study demonstrates that solid phases and solution chemistry can constrain chlorite-coat formation on the surface of quartz grains. The formation of chlorite-coats in simple quartz-chlorite batch experiments could indicate that chlorite-coats have the potential to form in many natural subaqueous settings where quartz grains and clay minerals (particles?) coexist. Quartz is a unique archive of chemical-mechanical processes that have affected sedimentary environments at and below the Earth’s surface. Therefore, the use of quartz as a model represents interesting environmental applications, but there will be a potential to overlook clay-coats on the surface of sediment and soil particles in numerous environmental systems. This overlooking of clay-coats is highly possible, as it has been mainly studied only from the context of petroleum reservoir quality.

Therefore, the presence of thin clay-coats (~2–3 μm) on sediment surfaces should be carefully checked in various environments. The presence of clay-coats on the surface of sediment can significantly influence the physicochemical behavior of the sediment. Understanding how and where clay-coats form on quartz and other mineral particles can therefore be crucial during modeling a spectrum of biogeochemical processes in sediment and soil. Some examples include predicting the pore network distribution in deeply buried sediments, sediment wettability (e.g., crucial for predicting CO₂ storage capacity) and determining the fate and transport of contaminants in aquifer and soil column matrix. According to their sorption affinities, clay-coats can serve as either permanent or temporary sink for contaminants. These realities signify the importance of paying attention to the factors controlling the clay-coat formation in sediment and soil systems.

Based on our investigation of the effect of binding agents on the formation of chlorite-coats, we propose that the presence of binding agents do not necessarily enhance clay-coat formation on the surface of quartz grains in opposition to the prevalent consensus. This implies that the interactions between Fe-bearing clay minerals and the binding agents as a model explanation of how clay-coats form on the surface of quartz grains were overly simplistic. Rather the solution chemistry influences the process of the clay-coat formation, which is exclusively overlooked in previous studies. This study suggests the importance of investigating the solution chemistry of diverse natural environments that host clay-coat formation. Solution chemistry is indispensable to understand various interfacial reactions and their combined impacts on the fate and transport of contaminants, cycling of nutrients and trace elements in abiotic and biotic systems.

HA remained in suspension complexed with the clay particles and metal oxides and charged ions, which suggests that HA does not necessarily result in clay-coat formation on the surface of quartz grains. Similar properties apply to other types of continentally derived organic matter carried by rivers that are entering the oceans. This result implies that complexed organic matter particles cannot settle in a relatively small area close to the mouth of the river. Therefore, such particles can travel far into the ocean. This result has implications resulting in refining our thinking regarding biogeochemical cycling of Fe in the ocean, the fate of emerging pollutants such as microplastics and heavy toxic metal distribution in the ocean.

In addition to essential nutrients (e.g., N, P, Si), rivers delivering 300–380 Tg of organic matter per year to the coastal zone (Seitzinger et al., 2010). Therefore, the observed property of HA can also have
implications for the transfer of essential nutrients from the coastal sea to the open ocean i.e., obscuring what proportion of riverine nutrients reaches the open ocean. Therefore, the behavior of HA in aqueous medium should be scrutinized to be incorporated into ocean biogeochemistry models. Considering this property allows a realistic picture of the effects of riverine nutrients and organic carbon on ocean biogeochemical cycling of nutrients.

4. Conclusion

Chlorite-quartz batch mixing experiments were conducted to study detrital clay-coat formation on the surface of quartz grains. In contrast to the prevailing hypothesis that considers binding agents and salinity as a crucial part of clay-coat formation, we show for the first time detrital clay-coats can form in the absence of the common binding agents such as Al- and Fe oxide and non-saline solution. Also, clay-coats scarcely formed in the presence of organic matter, which is the commonly proposed binding agent. Therefore, salinity and binding agents cannot be prerequisites to dictate clay-coat formation under conditions relevant in natural environments. Rather the experimental results reveal that the clay-coat formation is controlled by electrokinetic properties of the multicomponent mixtures. This indicates that the precursor chlorite coating formed at the redox boundary attach to quartz grains when dispersion of such rich clay minerals takes place during sediment reworking.

Clay-coats on the surface of quartz grains, one of the most abundant primary rock-forming minerals on the surface of the earth, can predominantly influence several geochemical processes at liquid-solid interfaces including contaminant mobilization, mineral dissolution kinetics, wettability and subsurface CO₂ storage. Failure to understand how clay-coats form on the surface of quartz grains can have serious consequences for deciphering various geochemical reactions, where reservoir quality prediction, contaminant mobilization in sediments, sediment and groundwater remediation methods can be compromised. These results add to our knowledge and understanding of the clay-coat formation in complex sediment surface-aquatic geosystems.

Data statement

The data that support the findings of this study are available in the article and supplementary Information files.

Author contributions

Beyene G. Haile: conceptualization; methodology; validation; investigation; data curation; writing original draft; writing review and editing; visualization. Henrik N. Hansen: conceptualization; methodology; validation; investigation; data curation; writing review and editing; formal analysis; visualization. Per Aagaard: conceptualization; writing review and editing; supervision. Jens Jahren: conceptualization; supervision; funding acquisition; project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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