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
INTRODUCTION

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; Chuhan et al., 2002), until the onset of quartz cementation at about 70–80°C (Bjørlykke & Egeberg, 1993; McBride, 1989). The transition from mechanical to chemical compaction typically corresponds to a depth of about 2–2.5 km on the Norwegian continental shelf (Bjørlykke et al., 1992; Giles et al., 1992). 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). Porosity-preserving mechanisms such as grain coats prevent quartz precipitation and can preserve porosities well above an expected porosity-depth trend (Bloch et al., 2002; Heald & Larese, 1974) as grain coats reduce the surface area of the detrital quartz grains available for nucleation and growth of quartz crystals (Ehrenberg, 1993; Walderhaug, 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 Øygarden 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 relocked 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

![Figure 1](image-url)
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.
4 | 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).
MLS is restricted to a few examples in the lower reservoir interval, whereas it is thicker in the upper reservoir interval. MCS and MLS are distinguished from one another based on textural properties and the composition and distribution of the clasts (Figure 5, core photo 7). The reservoir units within the Agat Formation are only found within MCS and MLS. The conglomeratic to pebbly sandstones (CPS) comprises pebbly sandstones with clasts ranging from granule to pebble size and cobble to boulder grade conglomerates (Figure 5, core photo 8). The composition of the clasts includes brown sideritic and phosphatic mud clasts and green chloritic clasts. The conglomeratic sandstones of CPS are separated with an erosional surface marking the boundary between several depositional events. The lowermost unit in the studied section is distinctively different from the other facies because of its siltty to a fine sandy matrix and the wide range of clast sizes, from mm to up to dm in scale, which are chaotically distributed and hence called the chaotic facies association (CFA) (Figure 5, core photo 9). The clasts are typically seen to be floating quartz grains or mudstone clasts, some of which are red/brownish blocks or clasts of what is likely to represent the shales of the surrounding Rødby Formation.

Sedimentological analyses (Figure 4a) show that a repeated stacking pattern can be recognized in the lower reservoir unit where MCSs are overlain by a conglomeratic succession (CPS) and a basal chaotic silty sandstone (CFA). 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

| Key | Name | Description | Interpretation |
|-----|------|-------------|---------------|
| MCS | Massive clast-rich sandstone facies association | 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 | Deposited by high-density turbidity currents |
| MLS | Massive-laminated facies association | 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 | Deposited by low-density turbidity currents |
| CPS | Conglomeratic-pebbly sandstone facies association | 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 | Deposited by high-density turbidity currents |
| CFA | Chaotic facies association | Matrix supported siltsone to fine-grained sandstone with large (mm to dm) clasts randomly distributed. Clasts: mudstones, floating quartz grains. Deformation structures, sandy/silty injectites | Slide complex |
| Sample depth | Felspar | K-Felspar | Plagioclase | Mica | Muscovite | Biotite | Rigid R.F. | Ductile R.F. | Chloritized Mica | Authigenic chloride | Quartz cement | Macroporosity | IGV |
|--------------|---------|-----------|-------------|------|-----------|---------|------------|-------------|----------------|------------------|---------------|--------------|-----|
| mDD          |         |           |             |      |           |         |            |              |                 |                  |               |              |     |
| 2X38.20      | 35.0    | 11.5      | 10.0        | 1.5  | 8.5       | 2.0     | 6.5        | 3.0         | 14.0            | 0.5              | 7.0           | 6.0          | 25 |
| 2X39.55      | 37.0    | 10.5      | 9.0         | 1.5  | 6.0       | 2.0     | 4.0        | 4.0         | 17.0            | 2.0              | 7.5           | 7.5          | 20 |
| 2X41.69      | 44.5    | 14.0      | 11.5        | 2.5  | 3.0       | 1.0     | 2.0        | 1.5         | 2.5             | 4.5              | 0.5           | 11.0         | 29.5 |
| 2X42.52      | 40.5    | 12.5      | 11.5        | 1.0  | 0.5       | 0.0     | 0.5        | 1.0         | 7.5             | 6.0              | 0.5           | 15.5         | 2.0 |
| 2X47.02      | 38.5    | 7.0       | 6.5         | 0.5  | 0.5       | 0.0     | 0.5        | 6.5         | 7.5             | 7.5              | 0.0           | 16.0         | 2.0 |
| 2X50.40      | 36.5    | 7.0       | 6.0         | 1.0  | 0.5       | 0.0     | 0.5        | 27.0        | 1.0             | 5.5              | 1.5           | 10.0         | 21 |
| 2X62.06      | 34.0    | 8.0       | 8.0         | 0.0  | 0.0       | 0.0     | 0.0        | 15.0        | 2.0             | 5.5              | 0.5           | 13.0         | 21 |
| 2X71.06      | 34.0    | 4.0       | 4.0         | 0.0  | 0.5       | 0.0     | 0.5        | 32.0        | 1.5             | 2.0              | 1.0           | 9.5          | 25 |
| 2X78.02      | 41.0    | 8.0       | 7.5         | 0.5  | 0.0       | 0.0     | 0.0        | 18.5        | 1.5             | 4.5              | 0.5           | 15.0         | 26 |
| 2X83.57      | 39.5    | 6.0       | 6.0         | 0.0  | 0.0       | 0.0     | 0.0        | 18.0        | 5.0             | 3.5              | 1.0           | 11.0         | 27 |
| 2X04.76      | 18.0    | 4.0       | 4.0         | 0.0  | 0.0       | 0.0     | 0.0        | 38.0        | 6.0             | 6.0              | 1.0           | 15.0         | 26.5 |
| 2X16.02      | 23.5    | 3.5       | 3.5         | 0.0  | 0.0       | 0.0     | 0.0        | 30.0        | 4.5             | 7.0              | 7.5           | 19.5         | 24.5 |
| 2X24.02      | 25.5    | 6.5       | 6.5         | 0.0  | 0.5       | 0.5     | 0.0        | 26.5        | 6.5             | 3.5              | 5.0           | 19.0         | 26 |
| 2X27.02      | 29.0    | 4.0       | 3.5         | 0.5  | 0.5       | 0.5     | 0.0        | 21.5        | 5.0             | 3.5              | 5.5           | 24.5         | 26 |
| 2X35.02      | 23.5    | 2.0       | 1.5         | 0.5  | 0.5       | 0.5     | 0.0        | 26.0        | 5.0             | 3.5              | 7.5           | 5.5          | 32 |
| 2X37.02      | 35.5    | 9.5       | 7.5         | 2.0  | 1.0       | 0.5     | 0.5        | 11.0        | 0.5             | 5.0              | 6.0           | 23.0         | 31 |
| 2X40.02      | 28.5    | 10.0      | 9.0         | 1.0  | 1.0       | 1.0     | 0.0        | 21.0        | 5.0             | 7.0              | 7.0           | 14.5         | 30 |
| 2X43.95      | 33.0    | 7.0       | 6.5         | 0.5  | 0.0       | 0.0     | 0.0        | 15.5        | 2.0             | 3.5              | 8.0           | 23.0         | 31 |
| 2X46.02      | 36.0    | 7.5       | 7.0         | 0.5  | 1.5       | 0.5     | 1.0        | 17.5        | 2.5             | 7.0              | 8.0           | 14.5         | 19 |
| 2X47.57      | 22.0    | 8.0       | 7.5         | 0.5  | 1.0       | 0.0     | 1.0        | 30.0        | 9.5             | 4.5              | 3.5           | 9.5          | 19 |
| Avg. upper   | 38.1    | 8.9       | 8.0         | 0.9  | 2.0       | 0.6     | 1.4        | 12.7        | 6.0             | 4.2              | 0.7           | 11.0         | 19.0 |
| Avg. lower   | 28.3    | 6.1       | 5.4         | 0.6  | 0.5       | 0.4     | 0.1        | 21.6        | 4.1             | 4.7              | 6.6           | 18.4         | 28 |

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 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 overall, the iron-bearing mineral content is noticeably greater in the lower reservoir unit where it averages 31.7% compared to 18.7% in upper reservoir (Figure 6b). Further, textural parameters obtained from thin section analysis (Figure 6c) show that there is a positive correlation between grain sizes and sorting, but each sample seems to vary independently of being from the upper and lower reservoir unit. In fact, the results show that there is a good correlation between the textural parameters and the defined FA, 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 (Figures 7d and 10a). The small siderite crystals can sporadically be observed to be partly embedded in the chlorite coating (Figure 7e). In addition, 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 8c), 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 8c), 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 neoformed 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
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 rift- ing (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 euchedral 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
that the formation has been exposed to quartz cementation assuming a geothermal gradient of 30–35 °C. Formation in the studied well has exceeded 3,000 m and by 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 clay 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 chlorite 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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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available on request to the corresponding author.

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