Diagenetic impact on reservoir sandstones of the Heno Formation in the Ravn-3 well, Danish Central Graben

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Oil and gas production from siliciclastic reservoirs has hitherto been in the Danish Central Graben mostly from Palaeogene and Middle Jurassic sandstone. The Ravn field was the first Upper Jurassic field to start operation. The reservoir is composed of sandstone of the Heno Formation. Production takes place at a depth of 4000 m, which makes Ravn the deepest producing field in the Danish North Sea. The Heno Formation mainly consists of marine shoreface deposits, where foreshore, middle and lower shoreface sandstones constitute the primary reservoir. The results of this study of the diagenetic impact on the mineralogical composition, porosity and permeability are presented here. Microcrystalline quartz has preserved porosity in the sandstone, whereas illite, quartz overgrowth and carbonate cement have reduced both porosity and permeability.

Geological background

The Ravn Member of the Heno Formation is located on the Heno Plateau in the Danish Central Graben (Fig. 1; Johannessen 2010). The Ravn field was discovered in the Ravn-1 well in 1986 and subsequently evaluated in the Ravn-2 well in 1987. In 2010, the Ravn-3 well was drilled to test the location of the oil–water contact and to evaluate the reservoir quality of the south-western flank of the field. Oil was found at several intervals and the oil–water contact was located at a depth of 4572 m.

The Ravn Member was deposited during an overall transgression of the Heno Plateau during the Kimmeridgian. The member consists of up to 100 m thick marine shoreface deposits (Johannessen 2010) where foreshore, middle and lower shoreface sandstones constitute the primary reservoirs (Fig. 2). The sediments are strongly bioturbated and are dominated by very fine- to fine-grained or muddy sandstones with occasional white, grey and light brown siltstones.

Methods

Sedimentological description of the Ravn-3 core was made and 18 thin sections were prepared from samples from middle, lower and foreshore sandstones (Fig. 2). Petrographical investigations of the thin sections were undertaken with transmitted light microscopy. Mineral abundances were quantified by point counting of minimum 500 grains. Additional information was obtained from scanning electron microscopy (SEM) of gold-coated rock chips and carbon-coated thin sections using a Phillips XL 40 SEM with a tungsten filament operating at 17 kV and 50–60 μA. Porosity and permeability were measured on core plugs according to the API RP-40 standard (American Petroleum Institute 1998) at the Geological Survey of Denmark and Greenland.

Results

The porosity and permeability of sandstone reservoirs reflect, among other things, depositional environmental, mineralogical composition and post-depositional diagenetic changes. In order to understand what affected porosity and permeability, these factors were investigated.

Detrital components – Quartz is the dominant component in all sandstones. The feldspar group consists of K-feldspar and minor albite. K-feldspar is typically partially dissolved and

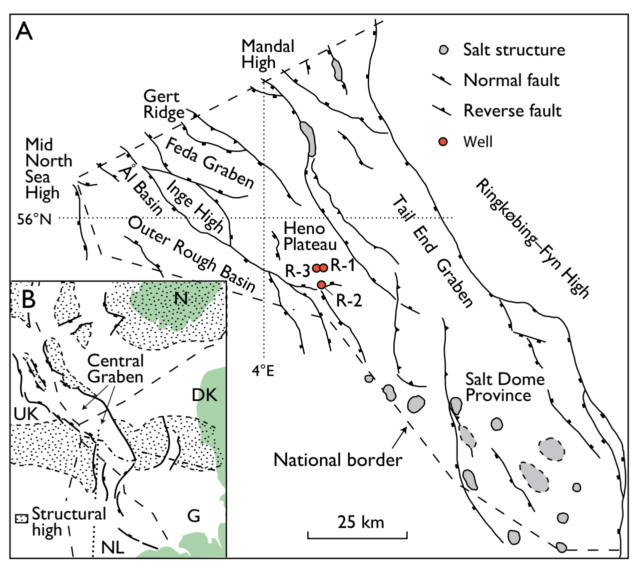

Fig. 1. **A**: Present structural framework of the Danish sector of the Central Graben. **R-1**, **R-2**, **R-3**: Ravn-1, -2 and -3 wells. **B**: Overview of the North Sea area. Green: Land. Modified from Johannessen (2010).

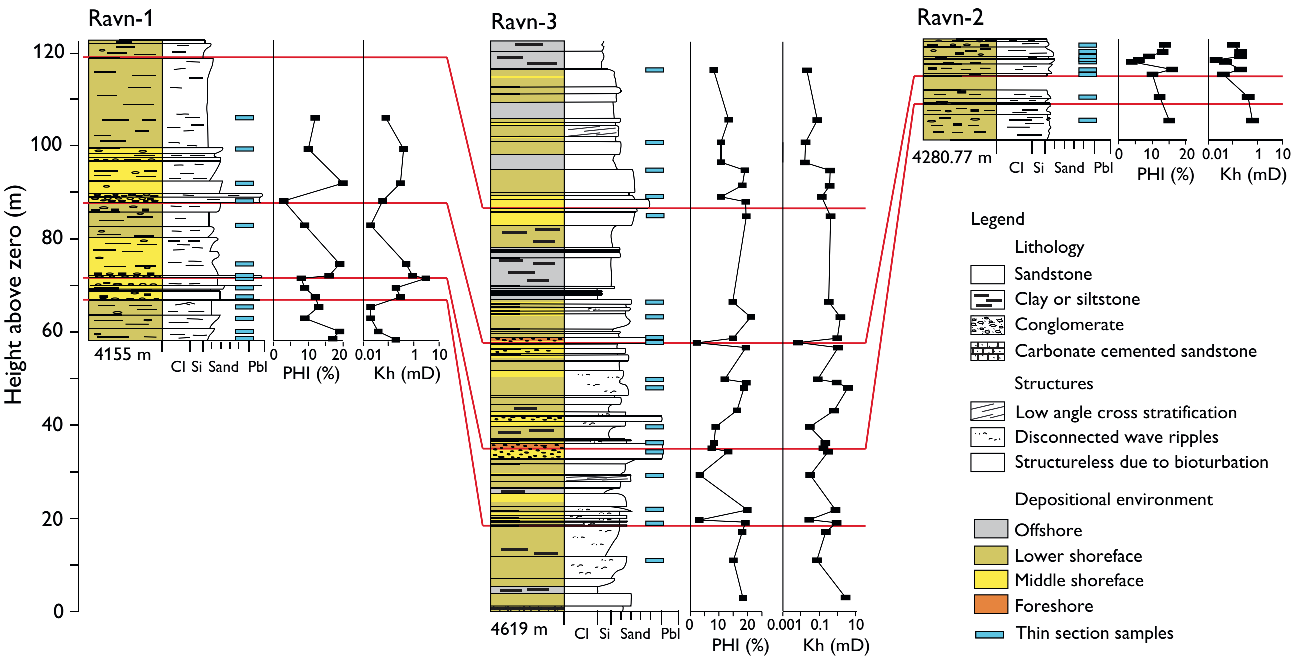

Fig. 2. Correlation panel of the cored parts of the Ravn-1, -2, and -3 wells. The Ravn-1 and Ravn-2 logs are modified from Johannessen (2010), whereas the Ravn-3 core was logged for this study. The depositional environment described in the Ravn-3 well (Panterra 2011) is based on ichnofacies. **PHI**: He-porosity. **Kh**: horizontal permeability. **Cl**: clay. **Si**: silt. **Pbl**: pebble.

minor mica, rock fragments and chlorite grains are present. Accessory minerals are tourmaline, zircon and Fe-Ti oxides. Detrital clay occurs as tangential coatings on detrital grains and as deformed clay clasts.

Diagenetic phases – Sandstones are occasionally dominated by abundant sparry Fe-dolomite and ankerite cement (Fig. 3A; Pedersen 2017). Sporadic calcite inclusions occur enclosed in the Fe-dolomite-ankerite cement. Calcite from shell fragments was recognised in one sample. Small amounts of Fe-dolomite-ankerite rhombs are present in samples where cement is not abundant. Microcrystalline quartz coatings are common in several samples independent of depositional environment (Fig. 3B). Occasionally, excessive microcrystalline quartz also occurs in the intergranular pore space (Fig. 3C). In a few sandstones, the detrital grain surfaces of quartz are only partly covered by microcrystalline quartz giving rise to growth of larger quartz overgrowths (Fig. 3C). The amount of quartz overgrowths varies from 0.2 to 10.8 vol%. Illite is present in all samples and depositional environments and occurs as fibrous and honeycomb-structured coatings (Fig. 3D). Authigenic illite occurs as protruding fibres growing from honeycomb-structured illitic-smectitic clay. Illite fibres alternate with quartz overgrowths, and are at times enclosed in quartz overgrowth (Fig. 3D).

Porosity versus permeability – The sandstones with highest porosity and permeability are dominated by microcrystalline quartz coatings and only little diagenetic illite is present together with a small amount of detrital clay (Fig. 4; Pedersen 2017). These sandstones are from the upper, middle and lower shoreface. Two groups of sandstones are defined based on intermediate porosity and low to intermediate permeability. Of these two groups, sandstones with quartz overgrowths and minor illite have slightly higher permeability than sandstones with microcrystalline quartz coatings and high illite and high detrital clay contents (Fig. 4). These latter samples are from lower and middle shoreface. Also the Fe-carbonate-cemented sandstones, which have the lowest porosity and permeability in the Heno Formation (Fig. 4), represent lower and middle shoreface samples.

Comparison between the Ravn-1, Ravn-2 and Ravn-3 wells – The Ravn-3 well was correlated with the Ravn-1 and Ravn-2 wells based on available core and well log data (Fig. 2). The various diagenetic phases in the Ravn-3 well can be recognised in the other Ravn wells. Variations occur, such as quartz overgrowth and illitisation of detrital clay being more common in the Ravn-1 well, compared to authigenic illite in the Ravn-3 well, but the reservoir units can still be recognised. The variations seen in the Ravn-1 cores are also present in the Ravn-2 cores together with additional fractures filled with barite and ankerite. The porosity and permeability in the Ravn-1 and Ravn-2 wells lie within the same range as the sandstones in the Ravn-3 well (Fig. 4).

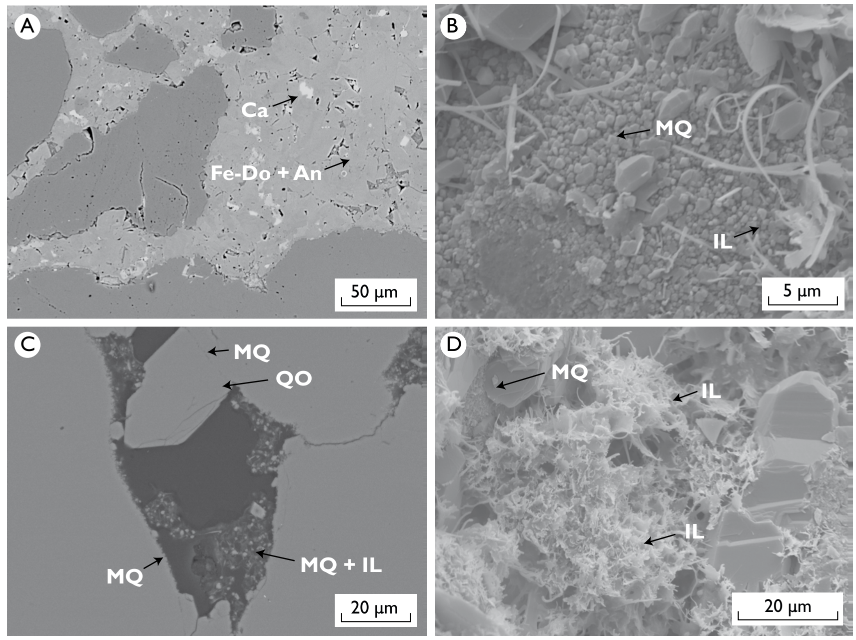

Fig. 3. **A**: Abundant Fe-dolomite (Fe-Do) and ankerite (An) occluding porosity and permeability. Remnants of the original early calcite (Ca) cement are present. **B**: Random and abundant microcrystalline quartz (MQ) coating detrital quartz grain, preventing quartz overgrowth (QO). Note the fibrous illite (IL). **C**: Microcrystalline quartz on detrital quartz and in pore space together with authigenic illite. Quartz overgrowth is partly enclosing microcrystalline quartz indicating that the quartz overgrowth precipitated later. **D**: Abundant fibrous illite growing from honeycomb- structured illite succeeding microcrystalline quartz and alternating with quartz overgrowth (QO).

Discussion

Early carbonate cement – Intergrown sparry Fe-dolomite and ankerite cement (Fig. 3A) is interpreted to be sourced from dissolved calcite from shell fragments. Calcite inclusions still occur between Fe-dolomite and ankerite. This is supported by quartz grains appearing to be 'floating' in the carbonate cement, which indicates the previous presence of an early carbonate cement or fossils. Fe-carbonates are considered more stable than calcite during late diagenesis and often replace earlier phases of carbonates (Worden & Burley 2003).

Early microcrystalline quartz – When early diagenetic microcrystalline quartz is present in the sandstones only minor quartz overgrowth has precipitated (Fig. 3B). A biogenic opal CT phase, which has been dissolved without trace, may have resulted in supersaturated pore waters that sustained nucleation of microcrystalline quartz. Grain-coating microcrystalline quartz has previously been proposed to preserve reservoir quality by impeding quartz overgrowth, which otherwise may occlude intergranular porosity and reduce permeability (Aase *et al.* 1996; Jahren & Ramm 2000; Weibel *et al.* 2010). The random growth of microcrystalline quartz may retard further development of both new microcrystalline quartz and quartz overgrowth (Jahren & Ramm 2000; Weibel *et al.* 2010). When microcrystalline quartz does not fully cover detrital quartz, it cannot inhibit precipitation of quartz overgrowth (Aase *et al.* 1996; Weibel *et al.* 2010).

Quartz overgrowths – Late diagenetic quartz overgrowths formed where the quartz grains were only partly covered by microcrystalline quartz. The quartz overgrowths probably formed under low silica oversaturation, which favoured less nucleation and promoted the growth of larger crystals (Fig. 3C; Jahren & Ramm 2000). More intensive quartz ce-

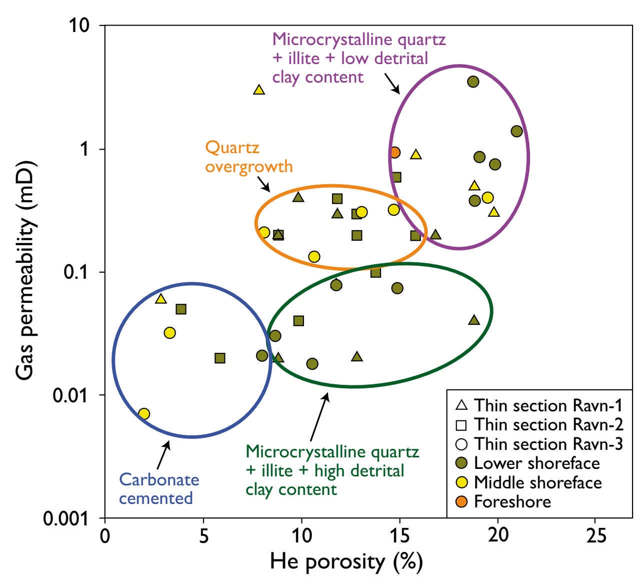

Fig. 4. He porosity versus air permeability for all thin section samples from the Ravn-3 well, together with data from the Ravn-1 and Ravn-2 wells. The thin section samples follow the trends from the Ravn-3 well marked by the four ellipses, which depict the four characteristics of the diagenesis. The purple ellipse comprises samples dominated by microcrystalline quartz, illite and low detrital clay content. The green ellipse includes samples dominated by microcrystalline quartz, illite and high detrital clay content. The orange ellipse comprises samples dominated by quartz overgrowth and the blue ellipse by extensive sparry carbonate cement.

mentation would have been expected in these quartz-rich sandstones (Bjørlykke *et al.* 1989) as they have been buried to a depth of > 4 km and hence exposed to temperatures of 112–117°C as documented by vitrinite reflectance.
As no stylolites were observed and as quartz overgrowth precipitated before and alternating with illite growth, another source for silica must have been present prior to transformation of smectite to illite. The continued precipitation of quartz overgrowth was probably from a silica source from the transformation of smectite to illite and dissolution of K-feldspar (Hower *et al.* 1976; Boles & Franks 1979). This is supported by the honeycomb-structured smectite-illite coatings and partially dissolved detrital K-feldspar.

Illite – Illite occurring as honeycomb structured coatings (Fig. 3D) is a strong indicator of a smectite precursor (e.g. Pollastro 1985). During burial, the percentage of illite in mixed-layer illite/smectite compared to smectite increases since smectite becomes more unstable with increasing temperature and pressure (Pollastro 1985), which may be the reason why only illite is present in the Ravn-3 well.

The honeycomb-structured illite commonly forms nucleation or growth points for fibrous illite. K-feldspar is typically dissolved concomitantly with smectite dissolution, and K-feldspar can be an additional source for K^+ and Al^{3+} for further illite precipitation (Hower *et al.* 1976; Boles & Franks 1979). The additional K^+ and Al^{3+} from the dissolution of K-feldspar might have led to further precipitation of the fibrous illite on illite honeycomb structures and singular precipitation in pore space. Fe-dolomite-ankerite rhombs are considered a by-product of the transition from smectite to illite, which may liberate Ca^{2+} and Fe^{2+}.

Conclusions

The porosity and permeability of the reservoir sandstones in the Ravn-3 well are controlled by the diagenetic phases formed during early and late diagenesis.

The reservoir sandstones with the highest porosity and permeability are dominated by low to moderate amounts of microcrystalline quartz, illite and detrital clay. However, the more distal lower shoreface sandstones with the same dominating diagenetic phases, but with higher detrital clay content, are considered a poor reservoir due to low porosity and permeability. Sandstones with dominance of quartz overgrowth and low detrital clay content have moderate to high porosity and low permeability. Carbonate-cemented sandstones are considered non-reservoir due to insignificant porosity and low permeability.

References

Aase, N.E., Bjørkum, P.A. & Nadeau, P.H. 1996: The effect of grain-coating microquartz on preservation of reservoir porosity. AAPG Bulletin **80**, 1654–1673.

American Petroleum Institute 1998: API Recommended Practice 40. Recommended practices for core analysis, 240 pp. Second edition. Washington DC: API Publishing Services.

Bjørlykke, K., Ramm, M. & Saigal, G.C. 1989: Sandstone diagenesis and porosity modification during basin evolution. Geologische Rundschau **78**, 243–268.

Boles, J.R. & Franks, S.G. 1979: Clay diagenesis in Wilcox sandstones of southwest Texas: implications of smectite diagenesis on sandstone cementation. Journal of Sedimentary Research **49**, 55–70.

Hower, J., Eslinger, E.V., Hower, M.E. & Perry, E.A. 1976: Mechanism of burial metamorphism of argillaceous sediment: 1. Mineralogical and chemical evidence. Geological Society of America Bulletin **87**, 725–737.

Jahren, J. & Ramm, M. 2000: The porosity-preserving effects of microcrystalline quartz coatings in arenitic sandstones: examples from the Norwegian continental shelf. In: Worden, R.H. & Morad, S. (eds): Quartz cementation in sandstones. International Association of Sedimentologists Special Publication **29**, 271–280.

Johannessen, P.N., Dybkjær, K., Andersen, C., Kristensen, L., Hovikoski, J. & Vosgerau, H. 2010: Upper Jurassic reservoir sandstones in the Danish Central Graben: new insights on distribution and depositional environments, 12–34. In: Vining, B.A. (ed.): Petroleum Geology: From Mature Basins to New Frontiers. Proceedings of the 7th Petroleum Geology Conference. Geological Society, London.

Panterra Geoconsultants 2011: Sedimentology, petrography and reservoir quality of cores from the Ravn-3 well, North Sea, Denmark. GEUS Archive Report File No **28698**.

Pedersen, S.S. 2017: The diagenetic impact on reservoir sandstones of the Heno Formation in the Ravn-3 well, Danish Central Graben, Denmark. Unpublished Master thesis, University of Copenhagen.

Pollastro, R.M. 1985: Mineralogical and morphological evidence for the formation of illite at the expense of illite/smectite. Clays and Clay Minerals **33**, 265–274.

Taylor, T.R., Giles, M.R., Hathon, L.A., Diggs, T.N., Braunsdorf, N.R., Birbiglia, G.V., Kittridge, M.G., Macaulay, C.I. & Espejo, I.S. 2010: Sandstone diagenesis and reservoir quality prediction: Models, myths, and reality. AAPG Bulletin **94**, 1093–1132.

Weibel, R., Friis, H., Kazerouni, A.M., Svendsen, J.B., Stokkendal, J. & Poulsen, M.L.K. 2010: Development of early diagenetic silica and quartz morphologies – examples from the Siri Canyon, Danish North Sea. Sedimentary Geology **228**, 151–170.

Worden, R. & Burley, S. 2003: Sandstone diagenesis: the evolution of sand to stone. In: Burley, S.D. & Worde, R.H. (eds): Sandstone diagenesis: recent and ancient. International Association of Sedimentologists Special Publication **4**, 3–44.

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