Diagenesis and porosity evolution of Cretaceous turbidite sandstones: Vøring Basin, mid-Norway passive margin

Diagénesis y evolución de la porosidad de las areniscas turbidíticas del Cretácico de la Cuenca de Vøring en el margen pasivo de Noruega

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Abstract: The Vøring Basin forms an integrated part of the passive margin off central Norway. Cretaceous sandstones are among the most important hydrocarbon exploration targets in the basin. One of the most significant features of the sandstone reservoirs is the excellent reservoir quality. The lack of early pervasive diagenetic cements and the high compositional maturity have contributed to the preservation of primary porosity. Reservoir quality evolution of the sandstones was equally controlled by cementation and compaction. Primary porosity was subjected to overall successive deterioration with increase in burial depth until the precipitation of post-compaction (mesogenetic) cements (quartz overgrowths, rhombic dolomite/ankerite, saddle dolomite and calcite). However, reservoir quality was improved through the partial to total dissolution of framework grains (mainly feldspars). The sources of acidic fluid to accomplish this dissolution are uncertain, but could be organic acids derived form thermal maturation of organic matter.

Key words: carbonate cementation, diagenesis, porosity, reservoir-quality evolution, turbidite systems.

Resumen: *La Cuenca de Vøring forma parte del margen pasivo de la costa Noruega. En esta cuenca, las areniscas Cretácicas constituyen uno de los más importantes objetivos en la exploración petrolífera de la zona. Estas areniscas destacan por su excelente calidad como reservorio. La ausencia de cementos eodiagenéticos y la elevada madurez composicional han contribuido a la preservación de la porosidad primaria. La evolución de la calidad del almacén estuvo controlada en la misma magnitud por la cementación y la compactación. La porosidad primaria disminuyó progresivamente con el enterramiento hasta la precipitación de cementos mesodiagenéticos (sobrecrecimientos de cuarzo, dolomita/ankerita rómbica, dolomita saddle y calcita). Sin embargo, la calidad como reservorio de las areniscas estudiadas mejoró debido a la disolución parcial a total de los granos del esqueleto (principalmente feldespatos). La fuente de los fluidos ácidos implicados en el proceso de disolución se desconoce, pero podría estar relacionada con la maduración térmica de la materia orgánica.*

Palabras clave: *cementos carbonáticos, diagénesis, porosidad, evolución calidad almacén, turbiditas.*

INTRODUCTION

In the past decades, hydrocarbon exploration is increasingly concentrated in deep-water turbidite sandstone reservoirs deposited in basins situated along passive continental margins. The Vøring Basin forms an integrated part of the passive margin off central Norway. The Vøring margin consists of three geological provinces, which include the Vøring marginal high, the Vøring Basin and the Trøndelag platform (Fig. 1). The Vøring Basin was developed by regional subsidence from several episodes of lithospheric extension and crustal thinning, since the end of the Caledonian orogeny. The timing and nature of the different rift phases have been debated (Smelror *et al.*, 2007; Wangen *et al.*, 2007). Cretaceous-Paleocene sandstones are important hydrocarbon exploration targets in the Vøring Basin. For this reason, large amounts of seismic data have been collected for the Vøring margin and several studies have modelled the tectonic evolution of the margin (Wangen *et al.*, 2007 and references herein). However, the sediment composition and porosity evolution of the Cretaceous fill of the basin are still poorly understood. Morton *et al.* (2005) contributed to unravel composition and provenance of late Cretaceous to Paleocene submarine fan sandstones in the Norwegian Sea using heavy minerals, mineral chemical and zircon age data. The aims of this paper are to elucidate and discuss diagenetic processes that affected turbiditic sandstone porosity and reservoir quality evolution in the Vøring Basin. Emphasis is made on determining the effect of compaction versus cementation on porosity loss in theses mineralogically mature quartz sandstones.

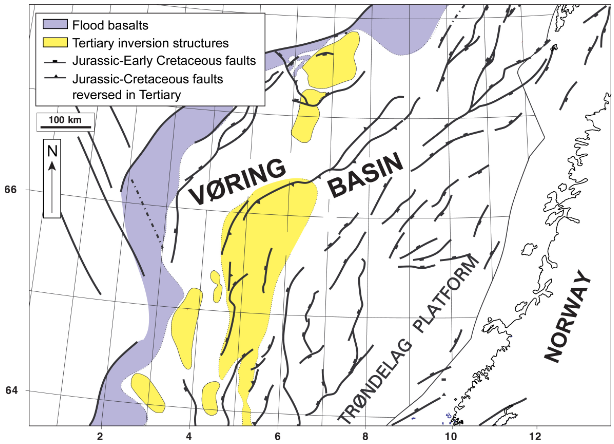

FIGURE 1. *Location map showing the general structural elements of the Norwegian continental shelf and the location of the Vøring Basin (modified from Blystad et al., 1995).*

SAMPLES AND ANALYTICAL METHODS

Hundred fifty core pieces and cuttings samples from one offshore borehole have been obtained from upper Cretaceous of the Vøring Basin in the Norwegian continental shelf. The cores comprise the interval Turonian to Campanian, the Lange and Lysing lithostratigraphic intervals. Doubled-polished thin sections were prepared from each sandstone sample after impregnating with blue-dyed epoxy resin under vacuum. Thin sections were stained for K-feldspar using sodium cobaltnitrite and for carbonates using alizarin red-s and potassium ferricyanide. Modal analyses were performed in 18 selected samples with medium to fine grain-size in order to minimize compositional differences due to grain size variations. Quantification of framework grains, porosity and authigenic minerals was achieved by counting 300 points per thin section using the Gazzi-Dickinson method (Gazzi, 1966; Dickinson, 1970). The chemical composition of carbonate cements was determined by electron microprobe analysis. Operation conditions were 15 kV accelerating voltage, 20 nA beam current and 10 µm bean size. The results were normalized to 100 mol% $CaCO_3$, $MgCO_3$, $FeCO_3$, $MnCO_3$, and $SrCO_3$. Clay mineralogy was determined by X-ray diffraction.

RESULTS

Detrital composition of sandstones

The Vøring sandstones are medium- to fine-grained, moderately- to well-sorted, occasionally displaying lamination defined by variation in grain size. In a ternary compositional plot, the Vøring sandstones are classified as subarkoses, Q86F14L0 (Fig. 2A). Monocrystalline, well rounded, non-ondulous quartz grains dominate the framework grains (average 32%). Monocrystalline quartz grains with undulous extinction, polycrystalline grains, and chert occur in smaller amounts. K-feldspar is more abundant than plagioclase

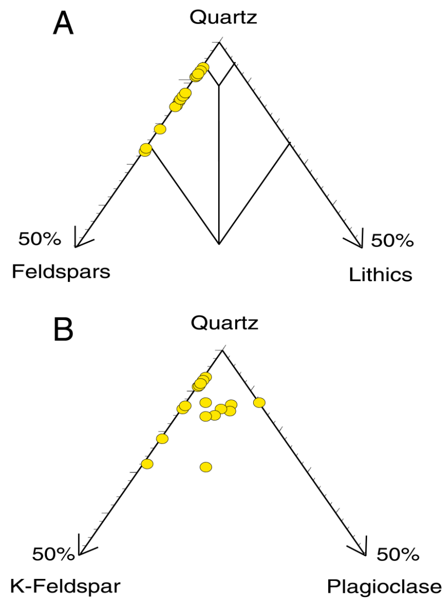

FIGURE 2. *(A) Compositional ternary plot (Pettijohn et al., 1973) of Vøring Basin turbidite arenites. Note the absence of Lithic grains. (B) Compositional ternary plot showing the relative abundance of K-feldspar and plagioclase.*

(average 5% and 2%, respectively; Fig. 2B) except in the upper part of the study well (from 2555.15 to 2559.73 m). Other detrital grains occur in relatively small amounts and include muscovite (average 2%), glauconite (average 2%) and biotite. Lithic grains are absent in the studied sandstones (Fig. 2A). Occasionally, mud intraclasts occur in very low abundances.

Petrography and geochemistry of diagenetic minerals

Quartz cement

One of the most abundant diagenetic minerals in the Vøring sandstones is quartz cement (from 17-32%; average 23%). Quartz cement occurs as syntaxial overgrowths on detrital quartz grains. Occasionally, sub-rounded quartz grains show remnants of inherited quartz overgrowths (Fig. 3A), indicating recycling of quartz sandstones in the source area.

Carbonate cement

Carbonate cement in the Vøring sandstones range from 1 to 13% (average 4%). Dolomite and ankerite cement is the most abundant diagenetic carbonate cement forming up to 13% modal abundance. Dolomite-ankerite cement has poikilotopic texture or occurs as rhombic crystals forming scattered patches (Fig. 3B). Dolomite and ankerite have replaced the detrital argillaceous grains (presumably mud intraclasts) and the feldspar grains. The average chemical composition of Fe-dolomite is $(Ca_{0.516}Mg_{0.325}Fe_{0.157}Mn_{0.001}Sr_{0.001})(CO_3)_2$ (n=33). Saddle dolomite ranges from 1 to 7% in modal abundance (average 2%) and displays the characteristic curved crystals showing wavy extinction. Saddle dolomite replaces to various extents feldspars, glauconite, mud intraclasts and pseudomatrix (Fig. 3C).

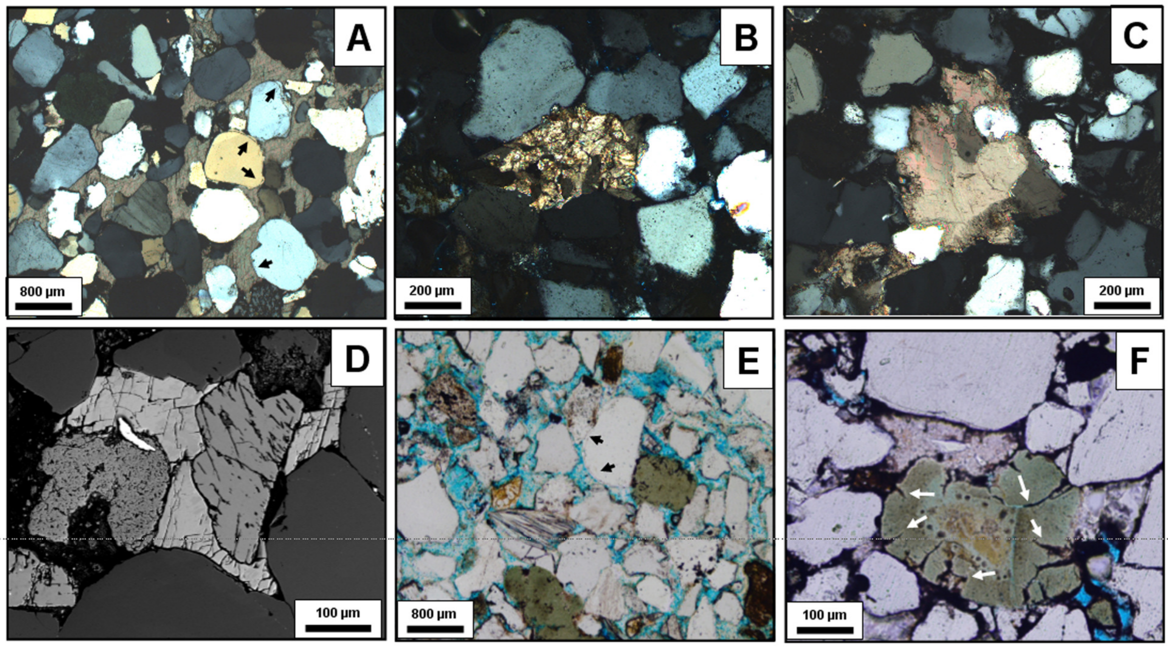

FIGURE 3. *(A) Optical photomicrograph (crossed nicols) showing quartz grains with rounded truncated overgrowths (arrows); (B) Optical photomicrograph (crossed nicols) showing grain-replacive, rhombic dolomite-ankerite cement occurring as isolated patches; (C) Optical photomicrograph (crossed nicols) of saddle dolomite with the typical sweeping extinction; (D) Backscattered electron image of poikilotopic calcite cement. Note the point contacts between framework grains; (E) Optical photomicrograph (transmitted light) showing abundant primary porosity. Note the presence of quartz grains with truncated rounded overgrowths (arrows); (F) Optical photomicrograph (transmitted light) showing the internal microcracks generated during shrinkage of glauconite grains (arrows).*

The average chemical composition is $(Ca_{0.518}Mg_{0.358}Fe_{0.122}Mn_{0.001}Sr_{0.001})(CO_3)_2$ (n=6). Calcite cement occurs in some of the sandstones as scattered patches of pore-filling, pokilotopic crystals (up to 4%; Fig. 3D). The average chemical composition of calcite cement is $(Ca_{0.933}Mg_{0.055}Fe_{0.009}Mn_0Sr_{0.003})(CO_3)_2$ (n=8). Cryptocrystalline siderite is scarce and replaces mud intraclasts and glauconitic grains. Siderite occurs also as millimetre laminae of cryptocrystalline crystals in the organic matter rich, fine-grained sandstones. In some case, siderite cements occurs as discrete distorted rhomb or lenticular crystals.

Other diagenetic minerals

Other diagenetic minerals, which occur in trace modal abundances, include: (i) anhydrite and barite occurring as small patches that are frequently engulfed by pore-filling and grain- replacive carbonate cement; (ii) the feldspar grains display textural properties similar to albitized feldspars. Albite has replaced detrital plagioclase and, less commonly, K-feldspar; and (iii) kaolin replacing K-feldspars.

Porosity and reservoir-quality evolution

Primary well connected intergranular pores (Fig. 3E) are important in the Vøring sandstones, ranging from 13 to 29% in modal abundance. The intergranular contacts between the framework grains range from point to straight (Fig. 3). Secondary porosity occurs too, ranging from trace to 5% in modal abundance. Secondary porosity occurs as moldic and oversized pores, which are interpreted to result from the partial to total dissolution of framework grains (primarily feldspars). Secondary intragranular porosity occurs within glauconite that contains abundant internal microcracks generated during shrinkage (Fig. 3F). The plot of total intergranular volume (intergranular cement + pseudomatrix + intergranular pores) versus intergranular cement (Fig. 4; Houseknecht, 1987) reveals parameters controlling the porosity loss (i.e. reservoir-quality evolution) of the sandstone. Three boundary scenarios (Figure 4) are envisaged because of the difficulty encountered in determining the recycled versus diagenetic origin of the observed quartz overgrowths in the sandstones. In scenario (i) all quartz cement quantified by modal analysis in the Vøring sandstones is considered as diagenetic in origin (i.e. precipitated in the intergranular volume); in scenario (ii) all quartz cement is considered as inherited, and are thus detrital in origin and not affecting sandstone porosity loss; and in scenario (iii) 50% of the quartz cement modal abundance is considered to be diagenetic in origin and 50% is considered to be inherited. Petrographic observations reveal that case (iii) is most realistic.

DISCUSSION AND CONCLUSIONS

One of the most significant features of the Vøring sandstones is the relatively high porosity values and the excellent reservoir quality owing to the lack of pervasive diagenetic cements and to mature mineralogical composition. The presence of small amounts of kaolinite in the studied sandstones suggests limited meteoric waters percolation into these marine turbidites. The absence of mechanically unstable ductile

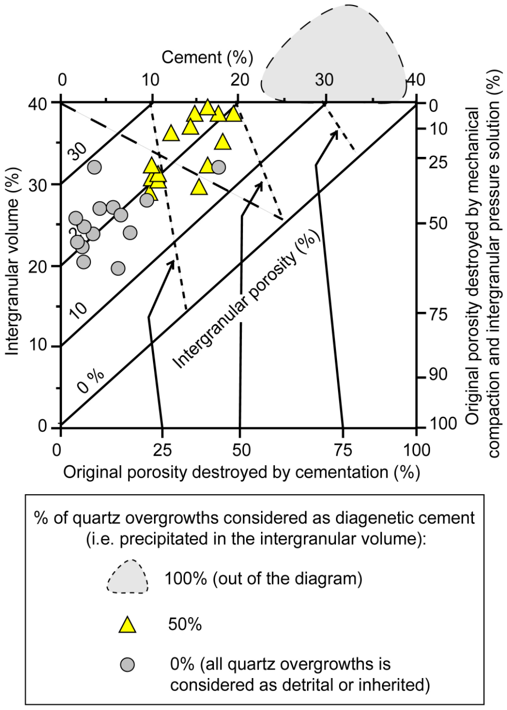

FIGURE 4. *Plot of intergranular volume (IGV) versus intergranular cements (Houseknecht, 1988; modified by Ehrenberg, 1989). Intergranular cements include quartz overgrowths, dolomite-ankerite, saddle dolomite and calcite cement. Three possible scenarios have been taken into account because of the difficulty to attribute detrital or diagenetic origin to the observed quartz overgrowths.*

grains such as the lithic rock fragments has precluded substantial porosity destruction by mechanical compaction. The main diagenetic cements (quartz overgrowths, dolomite/ankerite, saddle dolomite and calcite) are post-compactional in origin as suggested by the point to straight contact between the engulfed framework grains. The loss of intergranular porosity is attributed to equal impacts of compaction and cementation (Fig. 4).

Cementation by post-compaction (mesogenetic) carbonate and quartz had considerable impact on reservoir quality evolution pathways. The presence of saddle dolomite and quartz overgrowths witnesses the impact of relatively elevated diagenetic temperatures. However, difficulties encountered in determining the origin of the quartz overgrowths lead to uncertainties in the modal abundances of this cement, and hence of its impact on reservoir quality evolution of the Vøring sandstones. The sources of silica needed for the formation of quartz overgrowths are suggested to be mainly from illitization of interbedded mudrocks, intergranular pressure dissolution of the quartz grains, and replacement of framework silicates by carbonate cements. Reservoir quality improvement occurred due to the development of secondary porosity owing to dissolution of silicate grains, primarily feldspars. The origin of acids that could cause framework grain dissolution is uncertain. However, owing to difficulties in anticipated in circulation of considerable volumes of meteoric waters in deep-water, marine turbdites, the creation of secondary porosity is attributed to organic acids derived form thermal maturation of organic matter, which are capable of complexing and transporting the immobile Al from dissolving silicate detrital grains (Wilkinson and Haszeldine, 1996).

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