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Predicting porosity through simulating quartz cementation of Middle Cambrian sandstones, West Lithuania

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Quartz cementation is a major parameter controlling the reservoir properties of the Middle Cambrian quartz arenites of the central and western parts of the Baltic Basin. Marked local variations in the porosity and permeability severely complicate oil exploration and exploitation in West Lithuania. Commonly, the porosity of the oil reservoirs is 6–8%. Therefore even minor changes in the porosity have a considerable impact on the potential of oil fields. A predictive model of the quartz cementation is proposed, based on kinetic modelling results. The precipitation rate-limiting model effectively explains sharp variations in quartz cementation controlled by grain-size changes. The model was further improved by incorporating the sorting factor. Even so, the amount of quartz cementation is overpredicted by 4–7% in some intervals, implying that the precipitation rate-limiting model is too simplified. A good correlation was obtained between stylolite spacing and quartz cementation, the overpredicted quartz amount increasing with an increase in stylolite spacing. The modelling results argue against any discernable impact of the oil on the reservoir quality of the sandstones. The successful prediction of reservoir quality mainly depends on correct reconstruction of the sedimentary environment of the Middle Cambrian deposits. The evolutionary model of the quartz cementation suggests a good reservoir quality of the Cambrian sandstones during the later part of Late Palaeozoic, when most of oil was generated in the basin.

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INTRODUCTION

Middle Cambrian siliciclastic rocks represent the most important reservoir of the Baltic sedimentary basin. Numerous oil fields have been discovered offshore from Poland, in West Lithuania and in the western Kaliningrad District, while small oil accumulations have been identified in West Latvia (Brangulis *et al*., 1993). The Cambrian strata also form one of the most prospective geothermal reservoirs (Šliaupa *et al*., 2003) and underground gas storage units. The Middle Cambrian succession is dominated by quartzose sandstones with scarce interlayers of siltstone and shale. The main factor controlling the porosity and permeability of the sandstones of the prospective central and western parts of the basin is the late diagenetic quartz cement. Within the context of a general decrease in porosity to the west, related to an increase in burial depth, marked local variations in reservoir quality have been documented, the porosity changing from 3–5 to 10–15%. Thus there has been a need to develop a predictive model of quartz cementation through understanding of the major factors involved. Reconstructing the reservoir quality at the different stages of basin evolution is also important for predicting the quality of the oil pathways and traps.

A previous evolutionary model of quartz cementation in the Cambrian sandstones of the western part of the Baltic Basin has been suggested by Sikorska and Pacześna (1997) based on qualitative subsidence analysis. Lander and Walderhaug (1999) presented a general kinetic model of the Baltic Cambrian sandstones. Quartz cementation modelling of the Middle Cambrian sandstones was recently performed for the Baltic offshore area, aimed at correlating the oil generation-migration and quartz cementation events (Šliaupa *et al*., 2004). The work reported here is focused on the development of a predictive model of the reservoir quality variations of the Cambrian sandstones of the central part of the basin, based on an integrated lithological, petrographic and kinetic modelling approach.

METHODS AND DATA

Kinetic modelling is often applied to better understand quartz cementation trends in sedimentary basins (e.g., Dewers and Ortoleva, 1990; Dove and Crerar, 1990; Oelkers *et al.*, 1992, 2000; Angevine and Turcotte, 1993; Walderhaug, 1994; Wangen, 1998). In this study, a quantitative model for quartz cementation in sandstones via silica diffusion within a closed system has been applied. In essence, the modelling is based on fitting quartz cementation rates, obtained from petrographic data, to the exponential relationship $r_w = a \times 10^{bT}$ (Walderhaug *et al.*, 2001). The rate of quartz cementation is controlled by the coupled rates of quartz dissolution, silica diffusion, and precipitation. The west Lithuanian Cambrian reservoir is affected by moderate temperatures (55–90°C); in these conditions the coupled rates tend to be limited by slow mineral reaction rates (Oelkers *et al.*, 1996). It is assumed that the precipitation is the slowest process and therefore only the precipitation step is modelled (Walderhaug, 1994). Calculation of the porosity reduction due to quartz cementation incorporates the average grain-size composition, the clay coating percentage, time and temperature:

$$Vq = \frac{M}{\rho} A_0 a \int_{t0}^{t1} 10^{b(c_1 t + d_1)}\, dt + \frac{M}{\rho} A_1 a \int_{t1}^{t2} 10^{b(c_2 t + d_2)}\, dt + \ldots \qquad [1]$$

where: Vq — volume of quartz cement, M — molar mass of quartz (60.09 g/mol), ρ — density of quartz (2.65 g/cm^3), A_o — original surface area of the quartz grains, A_1 — surface area at time $t1$, c — heating rate (°C/s), d — initial temperature (°C), a and b — kinetic constants (2x10^{-22} mol/cm^{2}s and 0.018° C^{-1}), t — time (s).

The specific surface of quartz grains is calculated for each step:

$$A=(1-C)6fV\phi/V\phi_o \qquad [2]$$

where: f — volume fraction of quartz grains prior to cementation, D — grain diameter, C — fraction of grain surface area coated by clay (3%), $V\phi_o$ — porosity when quartz cementation starts.

The pre-exponential parameter b was estimated for West Lithuanian and eastern Baltic Sea Cambrian sandstones by running a number of models with different b values until a good agreement between the modelled and measured porosity values of the reference wells was achieved. The obtained value 0.018°C^{-1} (Šliaupa *et al.*, 2004) is rather low compared to most of the basins shown to have b>0.020°C^{-1} (Walderhaug *et al.*, 2001).

The accuracy of the model depends on available data characterising the reservoir. The parameters of the Cambrian succession are well characterized due to extensive oil exploration of the western part of Lithuania.

A database of the grain-size composition of Cambrian sandstones was collected from oil exploration industrial reports listing around 1300 measurements. Nine fractions >2, 2–1, 1–0.5, 0.5–0.25, 0.25–0.1, 0.1–0.05, 0.05–0.01, 0.01–0.001, <0.005 mm were measured. The average grain-size and sorting (Trask index) were calculated for each sample.

Middle Cambrian sandstones from the reference wells were studied petrographically using standard polarized light, hot cathodoluminescence (CL) and backscatter electron (BSE) microscopy to identify the pores and to separate detrital grains from authigenic quartz overgrowths. The stylolite spacing was counted in drill cores of reference wells.

Present temperatures of the Cambrian reservoir were measured in most of the deep exploration wells of West and Central Lithuania. These data were recently revised and incorporated into the geothermal database of Lithuania (Šliaupa, 2002). Apart from present temperatures, palaeotemperatures are of primary importance for the modelling of quartz cementation. Burial graphs were calculated using a 1D modelling technique allowing calibration of the thermal regime with vitrinite reflectance and *Tmax* (*RockEval*) data as presented by Zdanaviciute and Swadowska (2002) and Lazauskiene and Marshall (2002) and some oil company exploration reports.

The porosity and permeability of the Cambrian sandstones were measured in all oil exploration wells, the available data exceeding 10 000 samples (Šliaupa *et al.*, 2001).

STATIGRAPHY, LITHOLOGY AND GRAIN-SIZE COMPOSITION OF THE MIDDLE CAMBRIAN

Cambrian rocks comprise the basal part of the Baltic sedimentary basin, the depth ranging from outcrops at the basin periphery to more than 3 km in the west (Fig. 1). Cambrian deposits cover the entire territory of Lithuania, except for the southernmost part affected by Late Palaeozoic erosion. The thickness changes from a few dozen metres to 170 m. The succession is represented by Lower Cambrian and lower Middle Cambrian sandstones, siltstones and claystones that show different proportions across the basin (Jankauskas and Lendzion, 1992). The Lower Cambrian consists of quartzose sandstones grading into siltstones and shales to the west (Fig. 2). The Middle Cambrian regressively overlies the Lower Cambrian and is up to 70–80 m thick. The basal part consists of the organic-rich shales of the Kybartai Regional Stage. The major reservoir comprises the Deimena Group composed of quartzose sandstones with rare shale and siltstone interlayers. Three distinct cycles are identified, referred to as the Pajuris, Ablinga and Giruliai formations. Lithological and palaeontological evidence suggest deposition of Cambrian sediments in the shoreface and outer shelf environments.

The Middle Cambrian sandstones are composed of 95–99% quartz. The feldspar content not exceeding 1–2%. The sandstones are mostly fine-grained, rarely medium- to coarse grained. The grain-size varies from 0.08 to 0.32 mm, the average West Lithuanian value being 0.16 mm. The sandstones are dominated by the 0.10–0.25 mm fraction, composing 40–80% of the rock. The sorting is in the range of So(trask)=1.2–3.5; the average value is 1.57. A distinct correlation of the sorting with the average grain-size is recognized (Fig. 3). The minimum So(trask) values (well sorted sandstones) cluster around 0.165 mm aver-

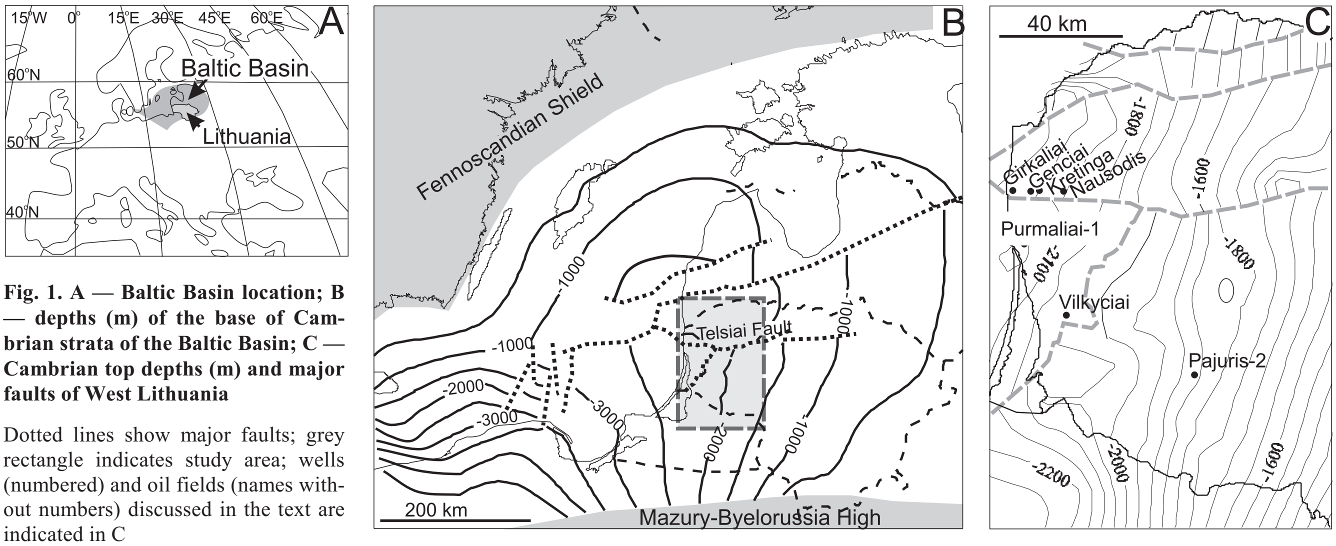

Fig. 1. A — Baltic Basin location; B — depths (m) of the base of Cambrian strata of the Baltic Basin; C — Cambrian top depths (m) and major faults of West Lithuania

Dotted lines show major faults; grey rectangle indicates study area; wells (numbered) and oil fields (names without numbers) discussed in the text are indicated in C

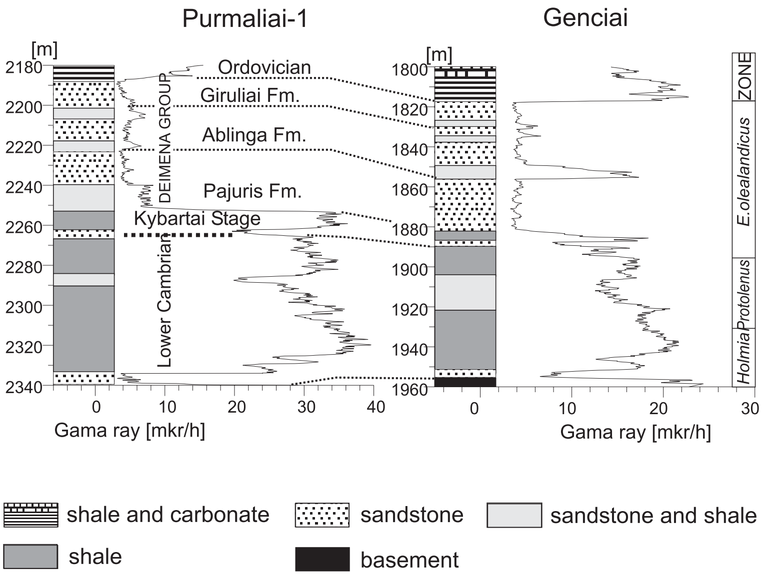

Fig. 2. Gamma-ray logs and stratigraphic correlation of Cambrian strata, West Lithuania (wells Purmaliai-1 and Genciai)

age diameter, while two sorting minima correlate with the average diameters of 0.115 and 0.24 mm respectively. The average grain-size correlates with the amount of the 0.25–0.1 mm fraction (Fig. 3).

Clay layers are also present, attaining 0.1–4 m in thickness. The clay also (predominantly illite and mica) in bedding-parallel stylolites in the sandstones occurs. The distance between stylolites varies from ~0.5–10 cm in thinly laminated sandstones to 10–30 cm in massive sandstones. The apparent thickness of clay laminae ranges from a few microns to several millimetres.

QUARTZ CEMENT

The Cambrian sandstones are cemented by authigenic quartz in the central and western parts of the basin (e.g., Rydzewska, 1975; Lashkova, 1979). The quartz cement formed during the late diageneis stage (Laskova, 1979; Sikorska and Pacześna, 1997). It composes syntaxial overgrowths on the detrital quartz grains, partly or totally filling the pore space (Fig. 4). The amount of the authigenic quartz increases from 2–4% in Central Lithuania (depths of 900–1200 m) to 15–30% in the west (depths 1.8–2.3 km). The intergranular volume (IGV) ranges from 25 to 33% (Kilda, 2002; Šliaupa *et al*., 2004).

A local sourcing of silica, mainly related to stylolite dissolution, was suggested for the Baltic Cambrian sandstones (Fig. 5) (Šliaupa *et al*., 2001, 2003), while the grain-to-grain dissolution mechanism (Fig. 5) provided negligible amounts (no more than a few per cent) of the quartz cement (Kilda, 2002). Additional sourcing from Cambrian shales is suggested by distinct 0.5–1 cm thick quartz rims punctuating some shale-sandstone contacts and by more intense quartz cementation of sandstones confined between thick shale layers.

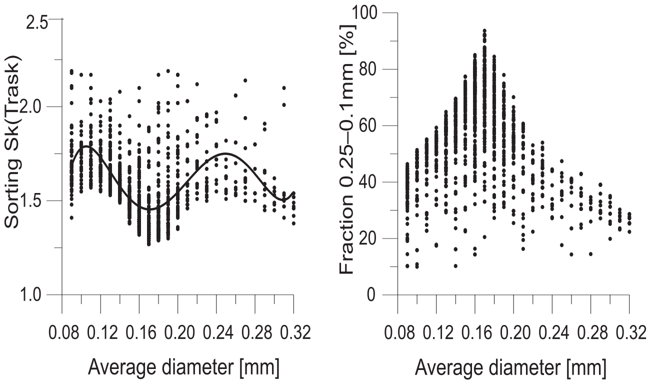

Fig. 3. Grain-size and sorting plots of Cambrian sandstones (1300 samples)

The sandstones contain little or no clay matrix. It is generally believed that clay coatings inhibit quartz cementation, and preserve porosity in deeply buried sandstones

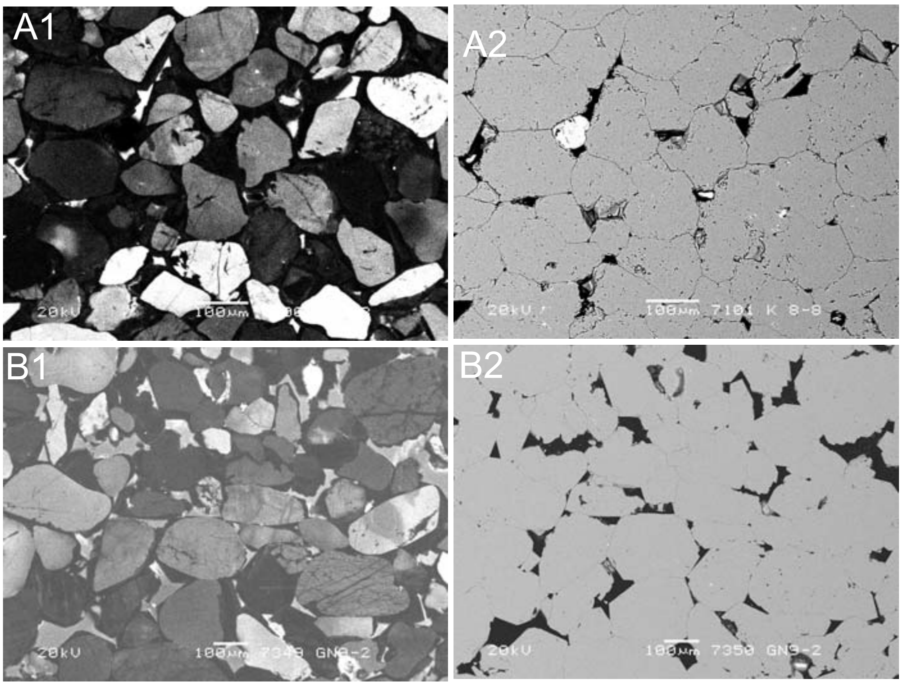

Fig. 4. CL and BSE micrographs of Cambrian sandstones

A1, A2 — well Kretinga-8, depth 1860 m, porosity 3.5%; B1, B2 — well Genciai-9, depth 1820 m, porosity 10%; quartz cementation correlates with grain-size of sandstones

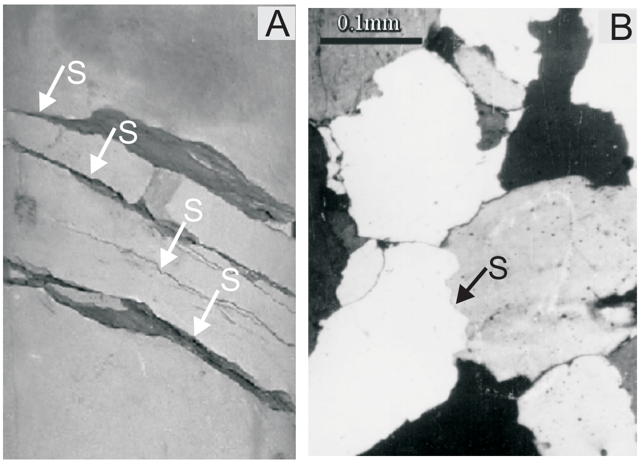

Fig. 5. A — drill core (7×13 cm) of Cambrian sandstones, Girkaliai-5 borehole; B — micrograph illustrating grain-to-grain dissolution of Cambrian sandstones, Vilkyciai-10 borehole; it should be noted that this case is rather rare in Cambrian sandstones

Abundant stylolites visible in the core provided silica for quartz cementation of the sandstones; porosity is 4–7%; the upper part of the drill core is slightly saturated with oil; the inclination of the lamination is due to inclined drilling

(Walderhaug, 1994; Aase *et al*., 1996). Petrographic observations, however, show that this factor is of little effect in these Cambrian sandstones, as the protecting role of clay seems to decrease with the age of the reservoir. The very long burial history also explains the occurrence of quartz at the rather low temperature of 40°C (Šliaupa *et al*., 2004), which is much lower than the temperature of 70–80°C commonly considered as the lower limit of the quartz cementation. The low-temperature "quartz window" identified in the Baltic Basin is similar to that reported from other ancient basins (Worden and Morad, 2000; Giles *et al*., 2000).

RESERVOIR PROPERTIES

The porosity of Cambrian sandstones decreases from 20–25% in the shallow eastern periphery of the basin to 2–4% in West Lithuania (Fig. 6). There is no correlation of the porosity with depths shallower than 1 km. A trend of decrease in the porosity is recognized below ~1 km depth, primarily related to occurrence of the authigenic quartz. The porosity of the Cambrian sandstones is 12–18% in the depth range of 1–1.8 km. The most significant reduction of the porosity to 3–15%, due to a drastic increase in quartz cementation, is recorded at depths greater than 1.8 km (>65–70°C) (Šliaupa *et al*., 2004). The average porosity of the oil fields of West Lithuania is about 6–8%. Therefore, even minor changes in the quartz cementation have a considerable impact on the potential of oil fields. The permeability is in the range of 10^2–10^3 mD in East and Central Lithuania and sharply decreases to 10^2–10^1 mD in the west. It closely correlates with the porosity. In West Lithuania a change in porosity of 2% results in an order-of-magnitude permeability change.

BURIAL HISTORY

1D modelling of the burial history was aimed at reconstruction of the thermal conditions of the Cambrian reservoir at different stages of basin development. The passive margin subsidence was slow during Cambrian and Ordovician and dramatically accelerated during the Silurian (Fig. 7), this being related to the orogenic bending of the western margin of the Baltica plate (Poprawa *et al*., 1999). The Cambrian reservoir was buried to 500–900 m by the end of Silurian. It was followed by 1 km subsidence during the Devonian and uplift during the Carboniferous–Early Permian. The total Permian to Cenozoic subsidence amounted to 100–600 m.

The geothermal conditions vary considerably across Lithuania. The heat flow changes from 40mW/m^2 in the east and north to >90W/m^2 in the South of West Lithuania (Šliaupa, 2002). The temperatures of the Cambrian succession range from 15 to 90°C (Fig. 8). Yet, the heat flow was not stable. Several geothermal events are suggested by the high thermal matu-

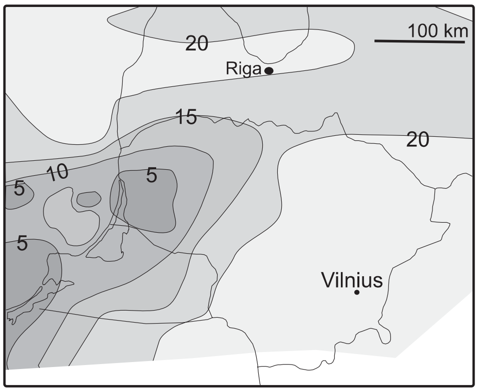

Fig. 6. Average porosity distribution of Cambrian sandstones

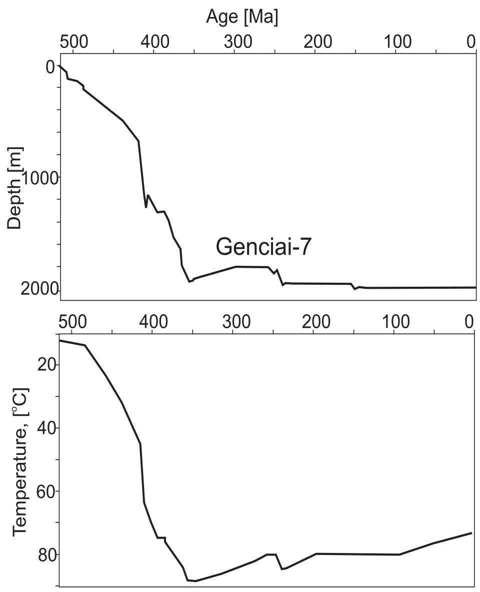

Fig. 7. Subsidence and thermal history of the Middle Cambrian sandstones, Genciai-7 borehole

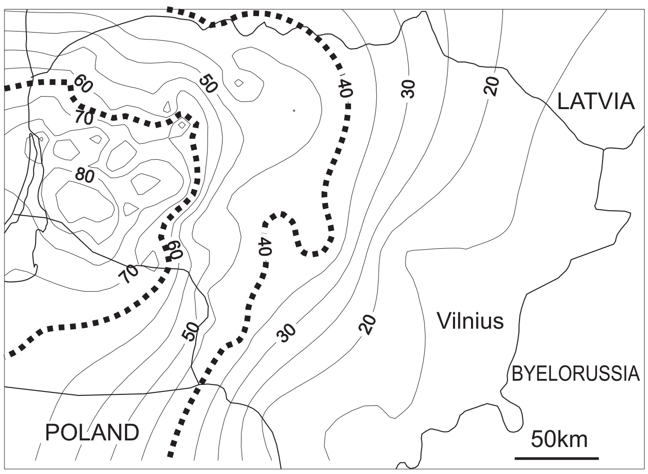

Fig. 8. Present temperatures (°C) of top of the Cambrian succession

The 40 and 65°C isotherms are shown; they coincide respectively with the occurrence and marked increase of the quartz cement content

rity of the organic matter in the Palaeozoic rocks (Zdanaviciute and Swadowska, 2002; Lazauskiene and Marshall, 2002). *Tmax* (*RockEval*) values of the Cambrian and Ordovician source rocks change from 432°C in the north to 452°C in the west and south-west. The reflectance of vitrinite-like macerals is in the range of 0.55 to 1.0, some fault-related local anomalies reaching up to 1.96. A heat flow increase of 15–20 mW/m^2 during the latter part of the Late Palaeozoic was incorporated into the model. Accordingly, the maximum palaeotemperatures of the Cambrian rocks reached 90–120°C during the Late Devonian–Early Carboniferous (Fig. 7). A Mesozoic thermal event has also been suggested (Katinas and Nawrocki, 2004).

QUARTZ CEMENTATION MODEL

Different alternatives were proposed to explain the uneven distribution of the authigenic quartz, such as protecting influence of oil, lower pressure in the local uplifts, hydrothermal water flow along the faults, a changed geochemical environment close to shale layers, and so on; these, however, were discarded after critical inspection of the available data.

The impact of syn-sedimentary features on the quartz cementation intensity seems to better explain observed variations (Šliaupa *et al*., 2004). In the model presented the quartz is assumed to dissolve at grain contacts, the dissolved silica being transported by diffusion out to the pore space, where the silica precipitates as cement (Bjørkum, 1996; Dewers and Ortoleva, 1990; Oelkers *et al*., 1992; Angevine and Turcotte, 1993). The lower limit of the initial quartz cementation is assumed to be 70°C (e.g., Worden and Morad, 2000), this being reached during the latter part of the Devonian (380–360 Ma). A porosity of 25% at the beginning of cementation is assumed according to IGV values defined by petrographic studies (Kilda, 2002).

According to the model results the most rapid quartz cementation is predicted for south-west Lithuania, much lower values in North Lithuania being mainly accounted for by differences in thermal conditions. Furthermore, the modelled quartz cementation curves show that the quality of the Cambrian reservoir was quite high during the Late Palaeozoic and most of Mesozoic (Fig. 9). The influence of the Late Palaeozoic thermal event was significant, whereas the Jurassic thermal event (+17 mW/m^2) (Šliaupa *et al*., 2004) did not significantly reduce porosity (estimated at less than 0.5%).

The temperature controls regional-scale variations in quartz cementation, while the grain-size composition is crucial for local changes (Fig. 9). The Girkaliai, Genciai, Kretinga, and Naumiestis oil fields (25 wells), located along the western Telsiai Zone, were studied in detailed (Fig. 1). This area represents the best testing-ground to study the impact of syn-sedimentary architecture on quartz cementation, as the thermal conditions vary only little (69–75°C). The Genciai oil field has the highest porosity, essentially the upper part of the Deimena Group (Fig. 10). The latter feature is sometimes explained in terms of the inhibiting role of the oil on quartz cementation (Laskova, 1979). It should be noted, however, that the oil is distributed very unevenly, the reservoir layers alternating with

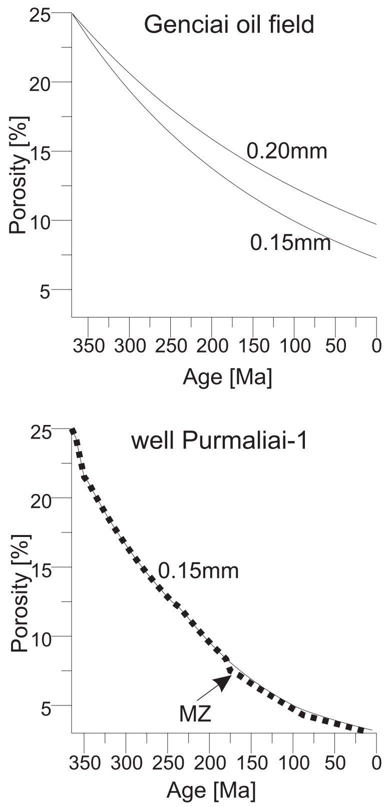

Fig. 9. Evolutionary models of quartz cementation of the Middle Cambrian sandstones of West Lithuania (Genciai and Purmaliai localities)

The grain-size (0.15 and 0.20 mm) effect is illustrated in the Genciai oil field; the impact of the Mesozoic thermal event (MZ) is evaluated in the Purmaliai borehole (average grain-size 0.15 mm); present temperatures of the Genciai and Purmaliai sites are 75 and 81°C respectively

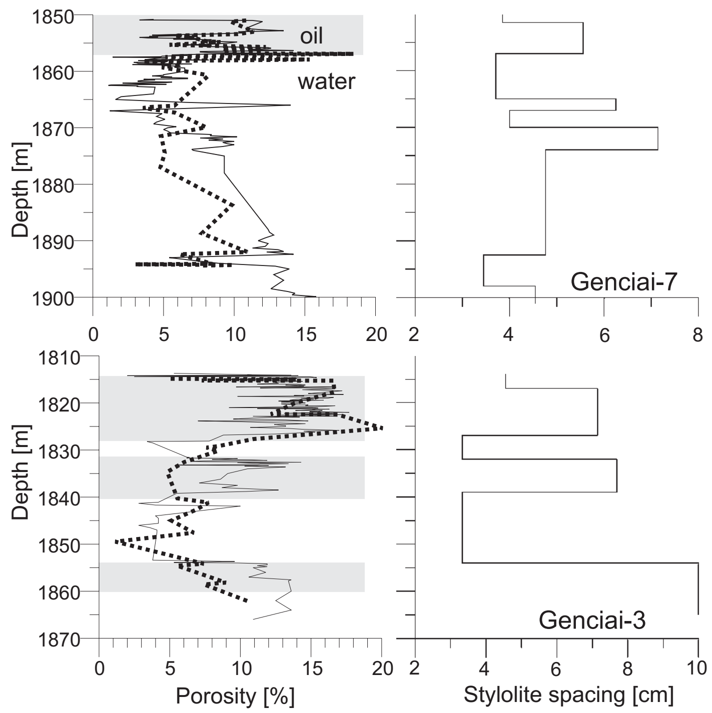

Fig. 10. Comparison of measured (solid line) and modelled (dotted line) porosities of Middle Cambrian sandstones, Genciai oil field

Oil intervals are marked in grey; stylolite spacing plots are shown on the right; temperature of reservoir is 75°C

strongly quartz-cemented sandstones. The modelling indicates that these variations have nothing to do with the presence of oil, but rather are result of the varying original grain-size composition of the sandstones. A good fit between modelled and observed porosity values was obtained without any incorporation of an extra oil effect (Fig. 10). The upper high-quality interval correlates well across the oil field, while the underlying reservoir shows considerable variations in porosity and permeability attributed to uneven quartz cementation governed by pronounced changes in sandstone lithofacies. The middle part of the section is generally characterized by the lowest quality due to intense quartz cementation that correlates with the generally smallest grain-size of the sandstones.

The Kretinga oil field, located west of the Genciai area, is of lower quality. Yet, it shows similar quartz cementation trends; in particular, the high-quality layer is present in the uppermost part of the Deimena Group. Again, the modelling results suggest that it is related to the specific grain-size composition (Fig. 11).

The misfit between the modelled and observed values is, however, unsatisfactorily large for some intervals. This misfit is less evident in the Genciai area where the syn-sedimentary lithology variations are less pronounced. Seeking to improve the predictive model, the sorting of sandstones was incorporated, as this has been shown to be an important parameter also (Waples, 2002). The sorting closely correlates with the grain-size that can be described by 5th-order polynomial (Fig. 3). This effect was included into equation [1] by calibrating observed and modelled values:

$$Vq_s=Vq-10.7x105xD^5+11.2x10^5xD^4-4.4x10^5xD^3+0.83x105xD^2-7.2x103xD+208.4+26 \quad [3]$$

where: Vq_s — modelled porosity with incorporated sorting effect, Vq — modelled porosity according to equation [1], D — average grain-size.

The incorporation of the sorting reduced the discrepancies between the model and measured values (Fig. 11). The map of the calculated porosities of the Talsiai oil fields is in good agreement with observed reservoir quality, indicating correctly the best quality in the Genciai oil field, and the lowest in the Girkaliai oil field (Fig. 12).

The model was extended to the whole of West Lithuania, incorporating 63 wells. Porosities were simulated separately for the Girkaliai and Ablinga formations that represent the most important part of the Deimena Group for oil exploration (Fig. 12). The general pattern of modelled porosities is in good agreement with the petrophysical observations. The lowest porosities are predicted in the south-west, this part of Lithuania being accordingly of the highest exploration risk were average porosities are 3–6%. In the north the modelled (and observed) porosities are in the range of 8–14%.

Discrepancies between the modelled and measured porosities are in some places still unsatisfactorily high because of ig-

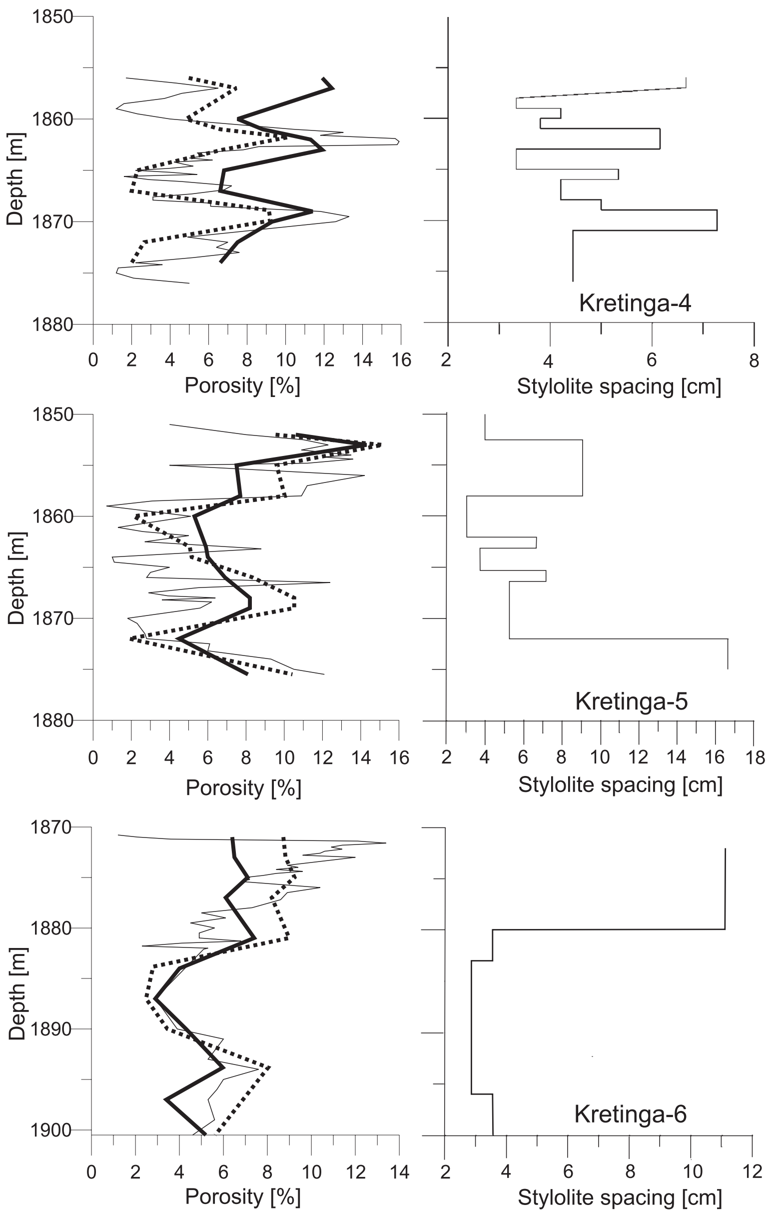

Fig. 11. Comparison of measured (solid line) and modelled (bold line with no sorting, dotted line with sorting incorporated) porosities of Middle Cambrian sandstones, Kretinga oil field

Stylolite spacing plots are shown on the right; present temperatures are 67–74°C

norance of other (than grain-size composition) factors. The role of secondary porosity, related to dissolution of the carbonate cement, has been stressed as a factor increasing reservoir quality (Kilda, 2002). This factor, as well as dissolution of some detrital grains, is however of minor importance, increasing porosity by only a few percent (Šliaupa *et al*., 2004) and cannot explain systematic discrepancies exceeding 4–5% of the porosity.

The major limitation of the precipitation-rate based model is ignorance of the spacing between stylolites which represent the main source of silica. Different spacing of stylolites should intuitively result in different oversaturation of the pore water by silica. The importance of this factor has been recognized in other basins (e.g., Oelkers *et al*., 1996; Bjørkum *et al*., 1998; Walderhaug and Bjørkum, 2003). The stylolite spacing of Middle Cambrian sandstones varies from 0.5–4 to 10–30 cm (Figs. 10–11). In general, three types can be defined:

— thinly spaced (0.5–4 cm),
— medium spaced (5–8 cm),
— widely spaced (9–30 cm) stylolite sets.

They closely correlate with porosity changes. The best fit between the modelled (precipitation-limited) and measured reservoir properties has been found for the first sandstone type, while misfit is perceptible (2–3% porosity) for the second group. The massive sandstones with scarce stylolites show the most obvious discrepancies, in the range of 4–7%, between modelled and measured porosities. This effect is acute in south-west Lithuania where massive sandstones dominate the lower half of the section (Fig. 13).

DISCUSSION AND CONCLUSIONS

Quartz cementation is the main parameter controlling the reservoir properties of the Middle Cambrian sandstones of the central and western parts of the Baltic Basin. The general trend of the porosity reduction to the west and south-west is explained by increasing burial. The highest exploration risk is accordingly related to the southern part of West Lithuania where the thermal regime is most pronounced.

Temperature controls regional porosity variations, whereas syn-sedimentary architecture is related to drastic local-scale changes of the quartz cementation. The precipitation rate-limiting model shows a reasonably good fit to observed reservoir quality variations, indicating the primary role of the grain-size in the sandstones. The differences in the grain-size composition result in local porosity changes of 2–12% that are high relative to the 6–7% average porosity of Cambrian sandstones, and therefore have a considerable effect on the potential of the reservoir. Furthermore, grain sorting is important. The incorporation of this parameter improves the model, changing the modelled porosities by 2–4% in some instances.

The precipitation rate-limiting model is too simplified. The discrepancies between the predicted and measured porosities attain 4–7% in some intervals. It is shown that the reservoir quality is intimately related to the abundance of stylolites suggesting that variations in silica oversaturation have to be considered. Moreover, this suggests local sourcing of the silica. In general, three types of stylolite sets are defined in Middle Cambrian sandstones showing different spacings, respectively of 0.5–4, 5–8 and 9–30 cm. No correction to the precipitation-limiting model is needed for the densely spaced stylolite sets, while the quartz cementation is increasingly overpredicted for the two latter types, respectively by 2–3 and 4–7%. These values

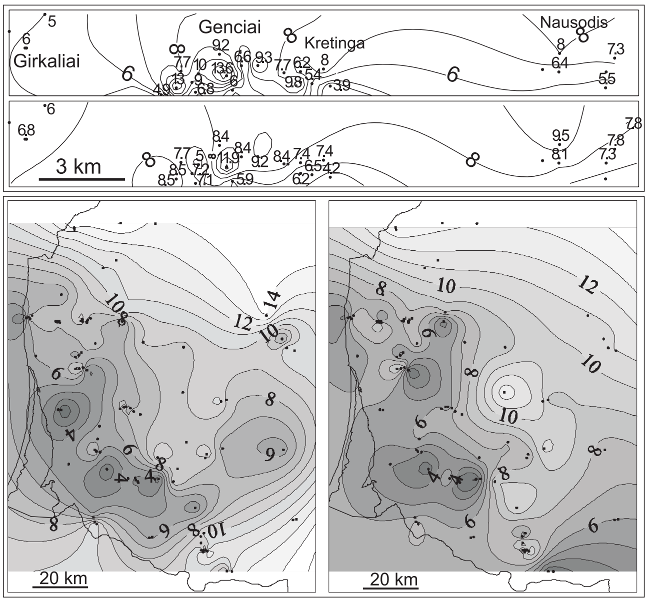

Fig. 12. Upper figure shows comparison of measured (above) and modelled (below) porosities of Middle Cambrian sandstones in oil fields of the Telsiai Zone; the lower picture shows modelled porosities of sandstones of the Giruliai (left) and Ablinga (right) formations of West Lithuania

are in close agreement to overpredicted quartz cementation rates of the Jurassic sandstones of the southern Barents Sea, showing that low abundance of stylolite precursors causes preservation of higher porosities (Oelkers *et al.*, 1992; Walderhaug and Bjørkum, 2003). Accordingly, these values have to be incorporated into any prediction model of West Lithuanian sandstones. It should be noted that the stylolite infill is different in thinly-medium laminated and massive sandstones. The former are clay (illite) rich, whereas stylolites of massive sandstones mainly comprise micaceous laminae that may cause different dissolution rates.

Both grain-size and stylolite spacing are closely related to the Middle Cambrian lithofacies, represented by laminated and massive sandstones. Therefore, the key parameter for successful prediction of the quartz cementation (and resulting porosity) is an appropriate sedimentation model. The interpretation of recent 3D industrial seismic data indicate that lithofacies changes were closely related to undulations of the sea bottom during deposition. These variations are slight, but they had a dramatic impact on quartz cementation rates. The presence of moderately laminated and especially of massive sandstones increases the potential of oil fields. These two sandstone facies typically compose the upper portion of the Middle Cambrian succession of north-west Lithuania, thus enhancing the potential of the oil fields. In the south the upper part of the section is commonly dominated by medium- and thinly laminated fine-grained sandstones that show strong quartz cementation (porosity 3–5%). These are underlain by massive sandstones that have anomalously high porosity (10–15%).

The simulation of oil fields indicates that the oil does not have any perceptible impact on the rate of the quartz cementation. This contradicts the hypothesis of an inhibiting role of the hydrocarbons (e.g., Marchand *et al.*, 2002) and supports the opposing view (e.g., Ehrenberg, 1990; Bjørkum and Nadeau, 1998). The better quality of oil-saturated intervals is related to syn-sedimentary features controlling the quartz cementation pattern. Conversely, marked variations in the reservoir properties within the oil lag do not conflict with the concept that the presence of the oil in sandstones increases the heterogeneity of quartz cementation due to lower diffusion rates and increased tortuosity (Oelkers *et al.*, 2000).

An evolutionary model of quartz cementation provides some prediction of reservoir quality during oil migration and accumulation. Petrographic studies show that two generations of authigenic quartz can be identified (Laskova, 1979; Sikorska, 1994; Jaworowski and Sikorska, 2003). Both generations are related to the late diagenesis of the Cambrian sandstones. Subsidence analysis of the western part of the basin suggests an onset of cementation during the latest Silurian (Sikorska and Pacześna, 1997) and Mid- to Late Devonian (Šliaupa *et al.*, 2004). Micrometric studies support these inferences. Authigenic quartz formed in the temperature range of 50 to 90–110°C in the western Baltic Sea (Jarmołowicz-Szulc, 1999). Similar temperatures of 60–90°C were estimated for the north-west Lithuanian sandstones of the western Telsiai Zone (P. Hoth, pers. com.). On the basis of these burial modelling results, such temperatures were reached in west Lithuania in Mid to Late Devonian (Šliaupa *et al.*, 2004). This is in good agreement with K-Ar dating of illite in Lower Cambrian strata in West Lithuania (384–372 Ma) (Zaitseva *et al.*, 2005). All these data are consistent with the onset of late diagenetic quartz cementation in the Mid to Late Devonian.

An evolutionary model of the quartz cementation in West Lithuania suggests a good reservoir quality of Cambrian sandstones during the later part of Late Palaeozoic time, representing the main stage of oil generation and migration in the basin. Accordingly, a good corridor existed between deep western sources and the West Lithuanian local uplifts of high reservoir quality. The model confirms the contemporaneity of

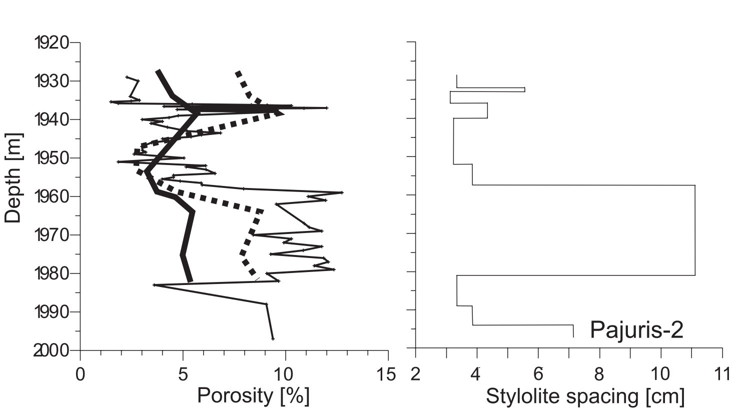

Fig. 13. Comparison of measured (solid line) and modelled (bold line with no sorting, dotted line with sorting incorporated) porosities of Middle Cambrian sandstones, Pajuris-2 borehole

Stylolite spacing plot is indicated on the right; temperature is 83°C quartz cementation and oil accumulation during the Late Palaeozoic, as suggested by petrographic observations of hydrocarbon entrapment between the detrital grains and authigenic quartz rims (Lashkova, 1979; Sikorska, 1994). In the course of basin evolution the porosity gradually decreased, resulting in reduced potential for oil fields. Hydrocarbon fillings of microcracks cutting detrital grains and quartz overgrowths relate to late phases of oil migration (Sikorska, 1994).

Besides controlling porosity and permeability, the quartz cementation has affected the fracturing pattern. Fracturing is an important factor as regards the reservoir properties of the Cambrian sandstones (Michelevicius, 2003). Analysis of borehole cores indicates that fractures are more abundant within the less well cemented intervals, thus increasing their reservoir quality.

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