The key factors controlling reservoir quality of the Middle Cambrian Deimena Group sandstone in West Lithuania

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Sandstones of the Middle Cambrian Deimena Group are commercially important as they make up the largest part of the hydrocarbon-bearing reservoir in 15 oil fields discovered in West Lithuania. However, the sandstones are characterised by a very complicated spatial distribution of reservoir quality. In order to better understand the distribution of reservoir properties and their controlling parameters, eighty-two sandstone samples from twenty-one boreholes were studied by means of thin section description, scanning electron microscopy, using backscattered and cathodoluminescence modes and clay fraction analyses. Generally, the sandstones are strongly cemented by quartz, result-ing in almost total destruction of porosity but porous domains with preserved early stage quartz cement occur in a complex pattern. The close location of the early and late stage overgrowth types indicates that some sandstone parts were preserved from intense authigenic quartz precipitation. We believe that early carbonate cement was such an inhibitor. Detrital quartz grains in carbonate ce-mented domains are mostly free of authigenic quartz and as a rule show weakly compacted fabric as compared to the quartz cemented parts. Moreover, large secondary pores are located close to the carbonate cemented domains and indicate that some carbonate cement eventually dissolved. Appar-ently, the best reservoir properties within the generally strongly quartz cemented Deimena Group sandstones are found in domains where dissolution of the early carbonate cement took place.

Key words: Deimena Group, sandstone, porosity, quartz overgrowths, authigenic quartz, early carbonate cement.

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The succession of Cambrian sandstones in the Baltic Basin contains several hydrocarbon reservoirs and is considered to be the most prospective part of the sedimentary sequence for petroleum exploration in the region. Approximately forty oil and gas accumulations have been discovered in the sandstones onshore and offshore Poland, the Russian Kaliningrad enclave and onshore Lithuania. This includes fifteen oil fields that have been located in the western part of Lithuania within Middle to Upper Cambrian sandstones.

In order to enhance oil production, the distribution of good or tight reservoir rocks should be described within an oil field. However, vital formation evaluation parameters such as porosity and permeability have an extremely complicated distribution even on a single oil field scale. Closely located wells within an oil field may have extremely different reservoir quality – one has commercial net pay thickness while another has no potential flow units and is impermeable in the pay part of the succession. This vertical and lateral heterogeneity of reservoir properties is caused by a number of diagenetic alterations, chiefly by quartz cementation. Separate parts of the Middle to Upper Cambrian succession are completely cemented by quartz leaving just a few percents of porosity and extremely low permeability while others have more than 10% porosity and permeability up to a few Darcy. Recently compiled generalised porosity maps of the Deimena Group show the average porosity to be from 4 to 12 percent in West Lithuania, located in the central part of the Baltic Basin (Vosylius & Vaznonis 2000). As a general trend, the lower prospective part of the Middle Cambrian – the Pajūris Formation – has 1.5 times higher porosity than the overlying part of the

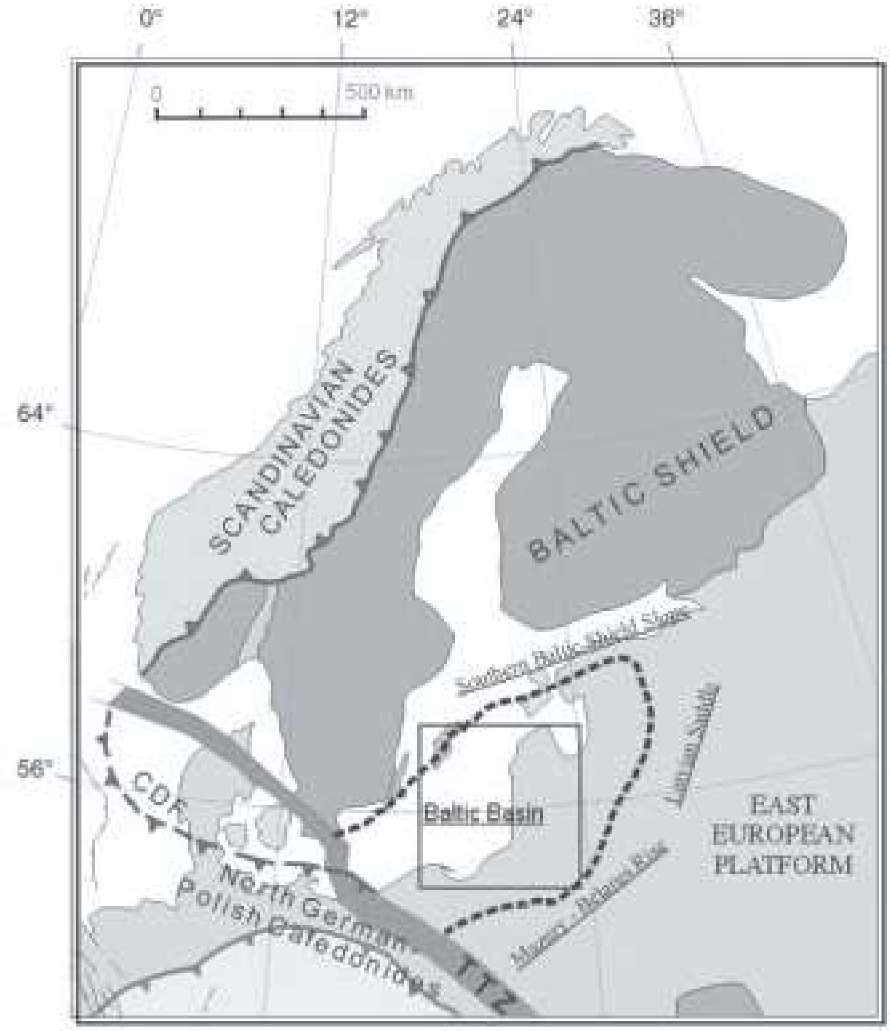


Fig. 1. Tectonic map of the Central – Northern Europe and location of the Baltic Basin (modified after Lazauskiene et al., 2001, reprinted by permission). The square on the map shows the location of the Fig. 2. CDF: Caledonian Deformation Front, TTZ: Teisseyre – Tornquist Zone.

Middle Cambrian succession (Vosylius & Vaznonis 2000). Due to the strong grade of cementation, fracture porosity prevails in the upper part whereas the Pajkris Formation consists mainly of porous reservoir rocks. The volume and importance of authigenic quartz decreases towards the basin margins with decreasing burial depth of the Cambrian succession. Laškova (1979, 1985, 1987, 1993, 1994), Vosylius (1998), Vosylius & Vaznonis (2000) and many others have investigated reservoir properties and distribution of quartz cementation in Cambrian sandstones from Lithuania over the last 30 years since the first Cambrian oil field was discovered. They suggested that potential sources of silica were pressure dissolution, clay mineral transformation, waters expelled from mudstone units and geothermal waters migrating upwards through the fault zones. They concluded that the degree of cementation was mainly controlled by the distribution of detrital clay that would enhance pressure dissolution and produce silica during clay mineral transformation. However, in our opinion there is no strong evidence that these processes alone could explain the extreme variation between completely damaged reservoir and highly porous and permeable reservoirs in closely located parts of the succession.

The application of advanced petrographic techniques such as scanning electron microscope (SEM) with secondary electron imaging (SEI), backscatter mode (BSE) and cathodoluminescence detector (CL) has enabled a much more detailed interpretation of the diagenetic history and porosity evolution of the Middle Cambrian sandstones from West Lithuania. Based on our studies, we suggest that a late dissolution of pre-compactional carbonate cement had a major influence on the present distribution of porosity within the central part of the Baltic Basin.

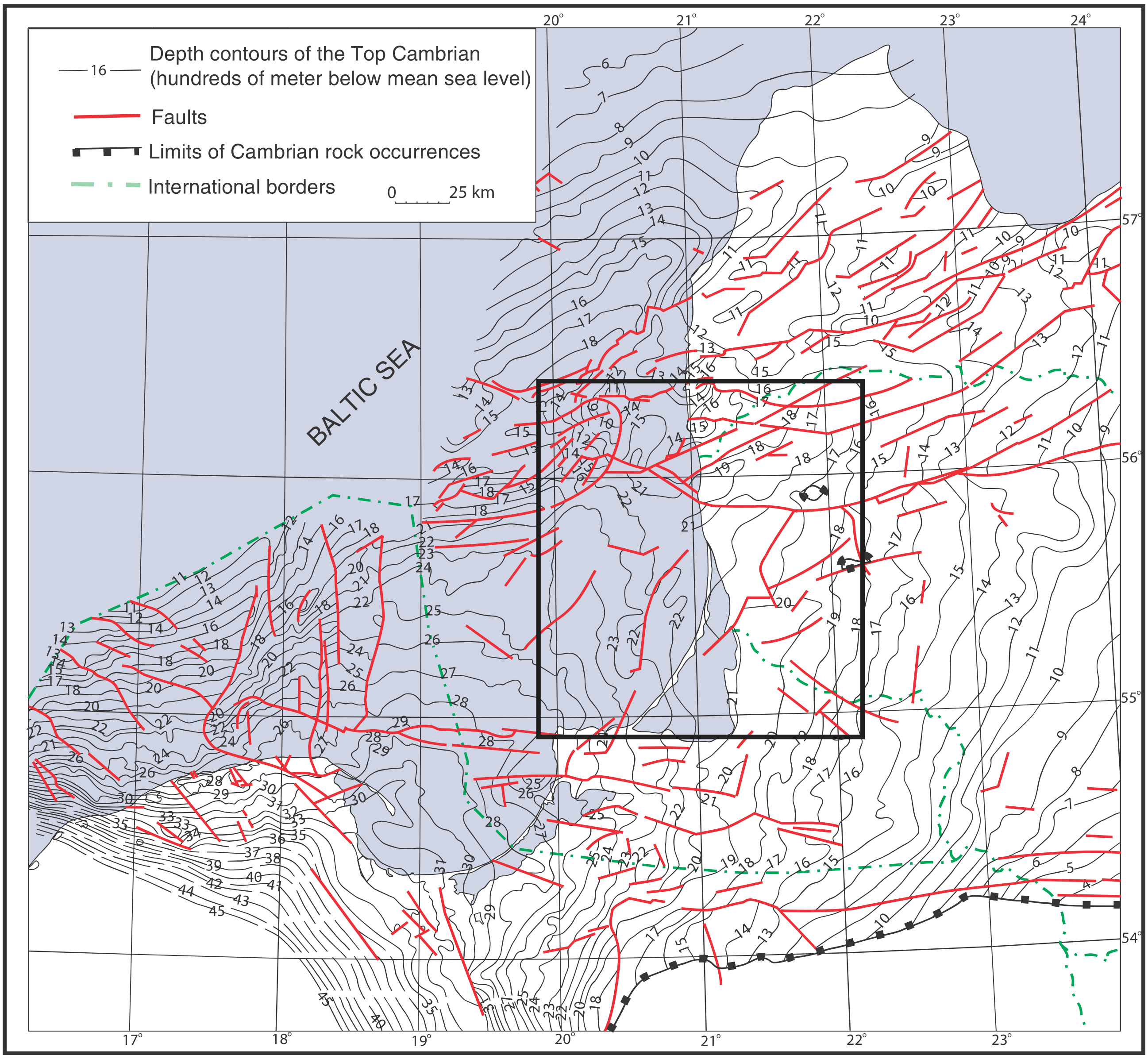


Fig. 2. Depth contour map of the Top Cambrian in the Latvian, Lithuanian and Polish parts of the Baltic Basin (from Modlinski et al. 1998, reprinted by permission). The square on the map shows the location of the Fig. 4.

Geological setting

The Baltic Basin is the largest tectonic feature of the western margin of the Eastern European Platform and is a part of the Baltic – Lvov hydrocarbon bearing province. This basin, also called the Baltic Syneclise, is bounded by the Baltic Shield, the Latvian Saddle and the Mazury – Belorussian Anteclise to the north, east and south-east respectively (Fig. 1). The sedimen-tary succession consists of Vendian to Quaternary rocks resting on the Precambrian crystalline basement. The thickness of the sedimentary cover increases from 2 km in the central part to 4–5 km at the south-western margin of the basin (Laškova 1987; Paškevičius 1994; Vejbæk, Stouge & Poulsen 1994). In Lithuania the top of the Cambrian occurs at a depth range from 300–500 m in the eastern part to 2200–2300 m in the western part of the country and Lithuanian offshore sector (Fig. 2). Lower and Middle Cambrian deposits constitute the major part of the Cambrian succession in the investigated area while the Upper Cambrian is less than 2 m or missing (Fig. 3). Lithologically the succession comprises alternating beds of sandstone and mudstone that were deposited in shallow marine environ-

System	Series	Group	Formation	Description
CAMBRIAN	UPPER CAMBRIAN		SALANTAI MEMBER	Sandstone 0.1-0.2 m, occasionally up to 2 m thick
CAMBRIAN	MIDDLE CAMBRIAN		PANERIAI FORMATION	Sandstone and dark clays up to 2.7 m thick
CAMBRIAN	MIDDLE CAMBRIAN	DEIMENA GROUP	GIRULIAI FORMATION	Sandstone with claystone and siltstone interlayers, up to 80 m thick
CAMBRIAN	MIDDLE CAMBRIAN	DEIMENA GROUP	ABLINGA FORMATION	
CAMBRIAN	MIDDLE CAMBRIAN	DEIMENA GROUP	PAJÛRIS FORMATION	
CAMBRIAN	MIDDLE CAMBRIAN	AISÈIAI GROUP	KYBARTAI FORMATION	Interlayering of claystone and glauconite rich sandstone, up to 30 m thick
CAMBRIAN	LOWER CAMBRIAN	AISÈIAI GROUP	VIRBALIS FORMATION	Alternation of sandstone, siltstone and claystone layer, up to 50 m thick
CAMBRIAN	LOWER CAMBRIAN	AISÈIAI GROUP	GEGË FORMATION	Sandstone, claystone and siltstone, at the top – brown iron rich sandstone, up to 30 m thick

Fig. 3. Cambrian stratigraphic scheme of West Lithuania (after Jankauskas 1994; Jankauskas & Laškova 2000).

Fig. 4. Location map of the Middle Cambrian oil fields and boreholes selected for the study.

Table 1. Collected core samples locations and carried out investigations

Sample ID	*Borehole ID*	*SEM specimen*	*XRD analysis*	*Clay fraction investigations*	*Polished thin sections*	*Sample depth, m*	*Formation**
A2001	ABLINGA-2	Y				2118.5	UPPER
A5001	ABLINGA-5	Y		Y		2170	UPPER
A5002	ABLINGA-5	Y		Y		2207	LOWER
D5001	D5-1	Y		Y	Y	2168.8	UPPER
D5002	D5-1	Y			Y	2150	UPPER
D5003	D5-1	Y				2194	UPPER
D5004	D5-1	Y		Y		2175	UPPER
DG1001	DIEGLIAI-1	Y		Y	Y	1976	UPPER
DG1002	DIEGLIAI-1	Y				1997	UPPER
DG2001	DIEGLIAI-2	Y		Y	Y	1952	UPPER
DG2002	DIEGLIAI-2			Y		1964	UPPER
ET1001	EITUCIAI-1	Y		Y	Y	1857	UPPER
ET1002	EITUCIAI-1	Y				1882.5	UPPER
ET1003	EITUCIAI-1	Y		Y	Y	1904.5	LOWER
G2001	GIRKALIAI-2	Y	Y			1901	UPPER
G2002	GIRKALIAI-2	Y	Y			1903	UPPER
G2003	GIRKALIAI-2	Y	Y			1907.5	UPPER
G2004	GIRKALIAI-2	Y				1910.2	UPPER
G2005	GIRKALIAI-2	Y	Y			1915.5	UPPER
G2006	GIRKALIAI-2	Y				1917.2	UPPER
G2007	GIRKALIAI-2	Y		Y		1926	UPPER
G2008	GIRKALIAI-2	Y	Y			1927.1	UPPER
G2009	GIRKALIAI-2	Y	Y			1944	LOWER
G3001	GIRKALIAI-3	Y		Y		1929	UPPER
G3002	GIRKALIAI-3	Y				1931.5	UPPER
G3003	GIRKALIAI-3	Y	Y			1932	UPPER
G3004	GIRKALIAI-3	Y	Y			1934.7	UPPER
G3005	GIRKALIAI-3	Y				1957.3	UPPER
G3006	GIRKALIAI-3	Y	Y			1968.8	LOWER
G5001	GIRKALIAI-5	Y				2043	UPPER
G5002	GIRKALIAI-5	Y		Y		2047	UPPER
G5003	GIRKALIAI-5	Y	Y			2049	UPPER
G5004	GIRKALIAI-5	Y	Y			2053	UPPER
G5005	GIRKALIAI-5	Y		Y		2059	UPPER
G5006	GIRKALIAI-5	Y				2063	UPPER
G5007	GIRKALIAI-5	Y				2068	UPPER
G5008	GIRKALIAI-5	Y	Y			2087	LOWER
G5009	GIRKALIAI-5	Y	Y			2090.5	LOWER
G5010	GIRKALIAI-5	Y				2095.8	LOWER
G7001	GENCAI-7	Y	Y			1853	UPPER
G7002	GENCAI-7	Y	Y			1857	UPPER
G7003	GENCAI-7	Y	Y			1863	UPPER
G7004	GENCAI-7	Y	Y			1873	UPPER
G7005	GENCAI-7	Y		Y		1890	LOWER
G8001	GENCAI-8	Y	Y			1840	UPPER
G8002	GENCAI-8	Y		Y		1844.5	UPPER
G8003	GENCAI-8	Y	Y			1849	UPPER
G8004	GENCAI-8	Y	Y			1861	UPPER
G8005	GENCAI-8	Y				1880	LOWER
G8006	GENCAI-8	Y	Y			1884	LOWER
M1001	MACUICIAI-1			Y	Y	2102	UPPER
M1002	MACUICIAI-1	Y		Y		2107	UPPER
M1003	MACUICIAI-1	Y		Y	Y	2126	UPPER
M1004	MACUICIAI-1	Y				2138	LOWER
M1005	MACUICIAI-1	Y			Y	2148.5	LOWER
NM1001	NAUMIESTIS-1	Y		Y	Y	2047	UPPER
NM1002	NAUMIESTIS-1	Y			Y	2087	UPPER
NM1003	NAUMIESTIS-1	Y		Y	Y	2109	UPPER
P1001	PURMALIAI-1	Y		Y		2200	UPPER
P1002	PURMALIAI-1				Y	2188	UPPER
P1003	PURMALIAI-1	Y				2147.5	LOWER
P1004	PURMALIAI-1				Y	2149	LOWER
P5001	POCIAI-5			Y	Y	1985	UPPER
P5002	POCIAI-5	Y				1992	UPPER
P5003	POCIAI-5	Y		Y		2017.5	LOWER
R1001	RUSNE-1			Y	Y	2031.5	UPPER
R1002	RUSNE-1			Y	Y	2052	UPPER
R1003	RUSNE-1	Y				2042.5	UPPER
R1004	RUSNE-1	Y			Y	2079	LOWER
R1005	RUSNE-1	Y		Y		2072	LOWER
SK1001	SAKUCIAI-1	Y		Y	Y	2029	UPPER
SK1002	SAKUCIAI-1	Y				2039	UPPER
SK1003	SAKUCIAI-1	Y		Y		2068	LOWER
SL1001	ŠILGALIAI-1			Y	Y	2044.7	UPPER
SL1002	ŠILGALIAI-1	Y		Y	Y	2049	UPPER
SL1003	ŠILGALIAI-1	Y			Y	2074	LOWER
SL3001	SALANTAI-3	Y		Y		1949.5	UPPER
SL3002	SALANTAI-3			Y		1956.5	UPPER
TR4001	TRAUBAI-4	Y		Y	Y	2065.5	UPPER
TR4002	TRAUBAI-4	Y			Y	2075.5	UPPER
TR4003	TRAUBAI-4			Y	Y	2083	UPPER
ZM2001	•EMYTE-2	Y		Y	Y	1704	UPPER

***UPPER - the upper part of the Deimena Group (Giruliai and Ablinga formations)**
***LOWER - the lower part of the Deimena Group (Pajuris Formation)**

ments during minor sea level fluctuations (Laškova 1979, 1987; Jankauskas 1994). Therefore, the sandstone and claystone layers are laterally contin-uous and in most case they can be correlated within the studied area. The Middle Cambrian Deimena Group is sandier than the underlying Aisčiai Group (Paškevičius 1994) and contains the largest com-mercial reserves of oil (Fig. 3). The Salantai Member (Upper Cambrian) and Paneriai Formation (Middle Cambrian) are rather thin and are unimportant reservoir rocks. The Deimena Group is subdivided into three formations: the Giruliai, Ablinga and Pajkris. The last one in general is most porous and permeable among Cambrian reservoirs in the central part of the Baltic basin. Regionally this formation is overlain by a 5–10 m thick shale at the base of the Ablinga Formation. This shale is a good marker for correlation throughout West Lithuania.

Approach

Twenty one boreholes located in the central part of the Baltic Basin were chosen for this study, including one offshore well D5–1 (Fig. 4). As the selected wells are distributed over the whole West Lithuanian region they are considered to be representative of this part of the basin. Eighty-two samples were taken from Upper and Middle Cambrian sandstones, mainly from the Deimena Group within a depth range from 1704 to 2207 m (Table 1). The sampling was performed to represent porous/non porous and oil bearing/water saturated lithologies. This allows us to compare samples with very different reservoir properties and to evaluate the different impact on pore structure, size and distribution from various diagenetic processes. The core sample study included scanning electron microscopy (SEM) examination of 72 specimens, petrographic description, BSE and CL-study of 26 polished thin sections, and X-ray diffraction of separated clay fractions from 36 samples.

Polished thin sections were prepared from sandstone that was saturated with a blue epoxy resin prior to the preparation. This allowed the preparation of thin sections from relatively porous and loose sandstone. The sections were investigated with a standard petrographic microscope. A number of the polished thin sections were coated with carbon and examined on the SEM using the BSE and CL modes. The clay fraction was separated from sandstones with clay laminae by decantation. Subsamples for exami-nation by XRD were air dried, glycol treated and heated to 550°C, respectively.

Investigations were performed on a "CamScan" MX2500 SEM that is controlled by MaXim 4 software and also equipped with Energy Dispersive X-ray Analyzer, Backscattered Electron Imaging, Secondary Electron Imaging and Cathodoluminescence detectors at the Aarhus University (Denmark). Besides "Adobe PhotoShop 5.0" software was employed for BSE and CL image analysis in order to estimate image porosities and authigenic quartz amount in the thin sections.

Petrography

Mineralogically the Deimena sandstone is considered to be a mature rock as detrital quartz makes up to 90–99% of framework grains and consequently falls into the quartz arenite group (Laškova 1979, 1987). Detrital quartz grains are fine to medium in size –0.15 –0.5 mm, however, occasionally coarse grains are observed. Due to deposition in the active marine environment the original grains are well rounded. Grain sorting, however, is rather poor and generally improves in the Pajkris sandstone compared to overlying part of the Middle Cambrian succession. Besides prevailing quartz the feldspars, clay minerals, carbonates, pyrite, apatite and other minerals constitute small rock volume. Many of these volumetrically unimportant minerals formed during diagenesis and are present as cement.

Compaction

The study of the SEM specimens and polished thin sections shows that detrital quartz grains are very unevenly compacted. Separate domains exhibit tight packing of the grains whereas neighbouring domains may show rather open frameworks. The compaction degree is reflected in the IGV (the intergranular volume) which is the calculated percentage of the authigenic quartz and porosity. In the studied samples the IGV ranges from 18 to 29%. Cathodoluminescence images analysis shows that most often this compaction parameter varies from 22 to 26%, but may be 29–35% in carbonate-cemented domains. A few samples are only slightly compacted and have quite large open pores and few grain contacts (Fig. 5).

Authigenic quartz

Quartz overgrowths fill initial pore space partially or completely and were observed in all samples. Sandstones that are clay free or contain only traces of clay minerals comprise two types of the quartz overgrowths

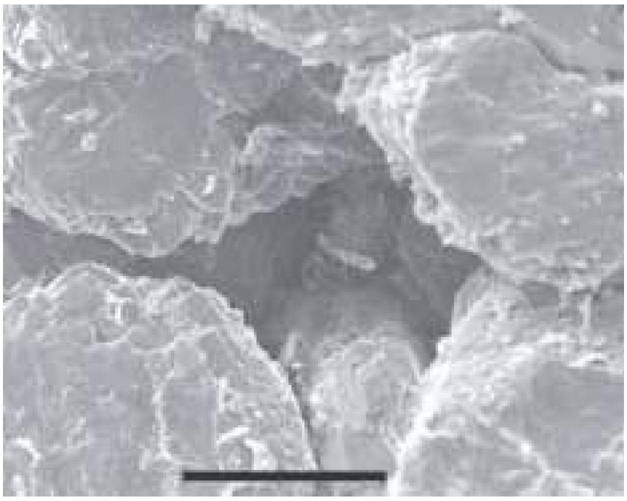


Fig. 5. Undercompacted sandstone. Quartz grains are not in contact on the left side, a large pore is present in the centre of the picture. Authigenic quartz crystals are growing separately on detrital grains. Sakučiai-1, 2068 m. Scale bar is 100 µm.

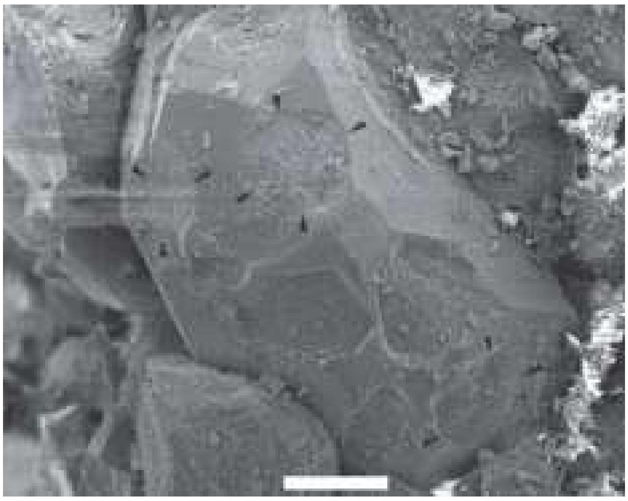


Fig. 7. Secondary quartz crystals form large regular overgrowth surfaces. Very shallow grain contact areas (arrows) on the quartz grain show that the added layer of authigenic quartz is rather thin. Advanced stage of quartz cementation. Eituiai-1, 1857 m. Scale bar is 200 µm.

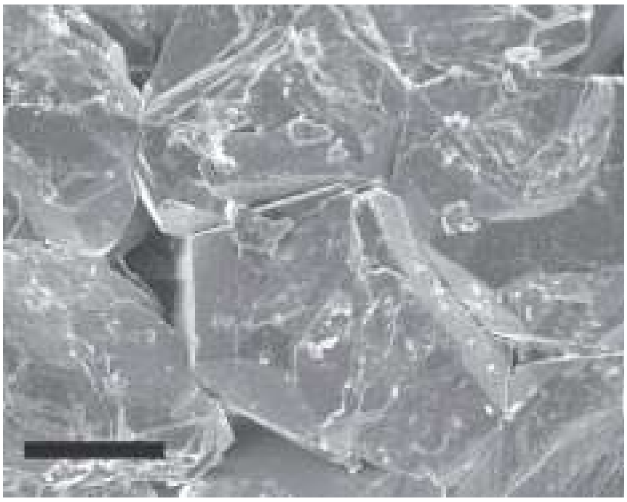


Fig. 6. Regular well-developed syntaxial morphology of quartz overgrowths. Secondary crystals form large regular overgrowth surfaces. Just a few isolated pores are present. Advanced stage of quartz cementation. Girkaliai-2, 1901 m. Scale bar is 100 µm.

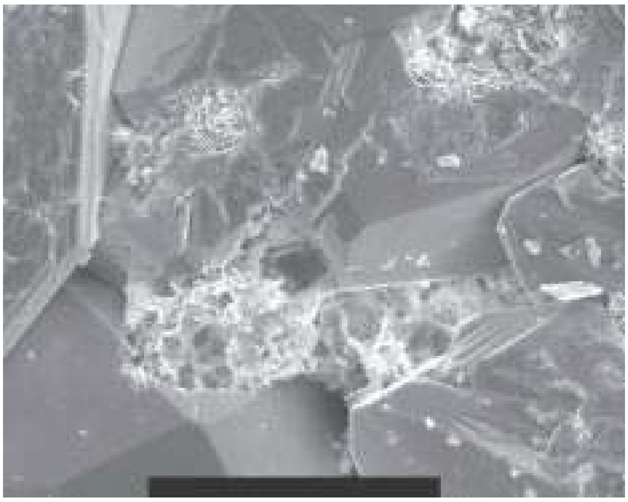


Fig. 8. Illitic clay fills in pits in the authigenic quartz crystal faces, extends into a pore space. The clay also is entrapped in the secondary quartz layer at the top of the figure. Girkaliai-5, 2096 m. Scale bar is 100 µm.

separated by their general growth pattern. The first type is characterised by a regular, well-developed syntaxial morphology of secondary crystal faces. The overgrowths form large smooth faces and almost completely cover detrital quartz grains (Fig. 6). This corresponds to an advanced stage of quartz cemen-tation (Scholle 1979). Preserved pores are small, isolated and scattered. However, the regular quartz overgrowths sometimes were identified within fairly porous sandstone. In these cases, the precipitated layer of authigenic quartz on the detrital grains is rather thin (Fig. 7). The thickness was estimated from examination of grain contact areas. The quartz grain contact areas (grain impression marks) are original grain contacts revealed by the removal of one grain during the specimen preparation. They can be distinguished by their typical oval shape and as a rule they are surrounded by quartz overgrowths. Shallow grain contact areas demonstrate a thin authigenic quartz layer while deeper contact areas indicate a larger amount of secondary quartz.

The second type of authigenic quartz appearance is

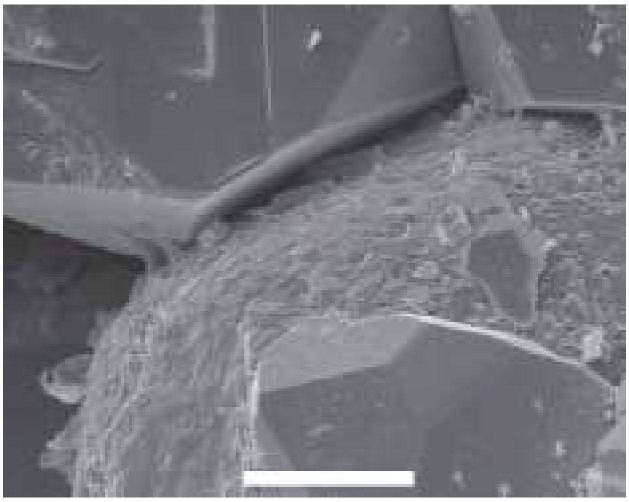


Fig. 9. Widely spaced small single crystals of authigenic quartz on the detrital quartz grain. Several of them have merged together forming small regular overgrowth surfaces. Nicely developed regular large quartz overgrowths extend from other grains. Degliai-1, 1976 m. Scale bar is 50 μm.

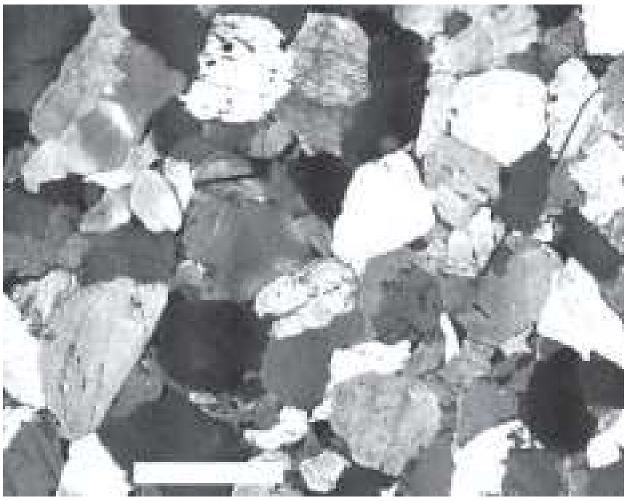


Fig. 11. BSE image. Contacts between most of quartz grains are sutured, indicating intense pressure dissolution. It can be seen that a large portion of several quartz grains was dissolved. Sakučiai-1, 2029 m. Scale bar is 400 μm.

Fig. 10. CL image. Tightly compacted detrital quartz grains. Most of the contacts between them are convexo-concave or flat. Black rims on detrital grains are quartz overgrowths. Image width is 1.5 mm. Purmaliai-1, 2195 m.

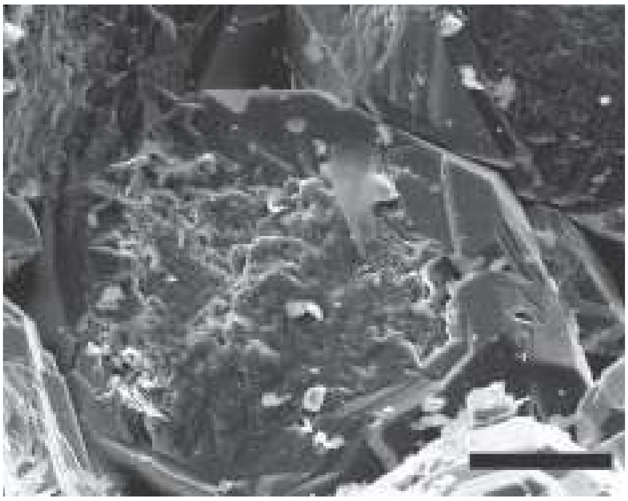


Fig. 12. Grain contact area exhibits rough surface with channel and island structures. Its surrounding authigenic quartz layer is relatively thick and well developed. Macuičiai-1, 2149 m. Scale bar is 50 μm.

represented by poorly developed overgrowths. Often, the detrital quartz grains are only partly covered by small overgrowths which may be independently growing on detrital grain surfaces without coalescing to large crystals (Fig. 5). The size of the crystals is highly variable; sometimes they are rather large and reach other crystals growing from adjacent grains. Areas of the original rounded surface of detrital quartz grains often can be seen between the small authigenic crystals. Pores within this type of sandstone generally are relatively large, closely located and well interconnected. Porosity ranges from 9 to 20% as estimated from thin section image analysis. This type of cementation, with poorly developed irregular faces and separate quartz crystal development on detrital quartz grains, is typical of an early stage of quartz cementation (Scholle 1979).

With increasing amounts of authigenic clay within the sandstones, the morphology of quartz overgrowths is significantly influenced. The clay minerals are entrapped in the precipitated quartz resulting in irregular crystal faces and microporosity. Pits in the crystal

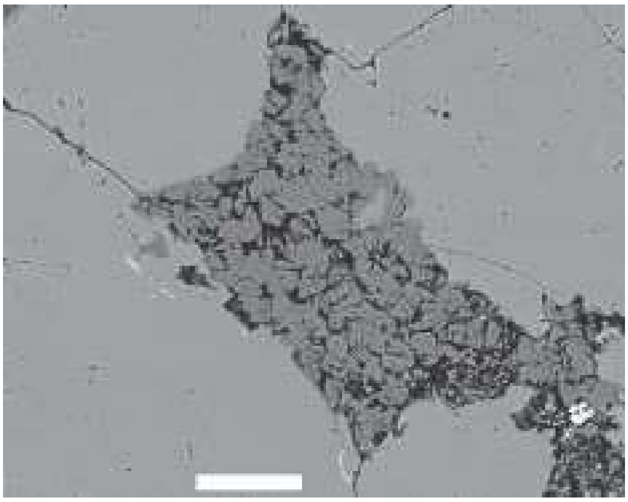


Fig. 13. BSE image. Aggregate of kaolinite booklets in pore. Some clay crystals are entrapped in the authigenic quartz layer. Traubai-4, 2066 m. Scale bar is 50 µm.

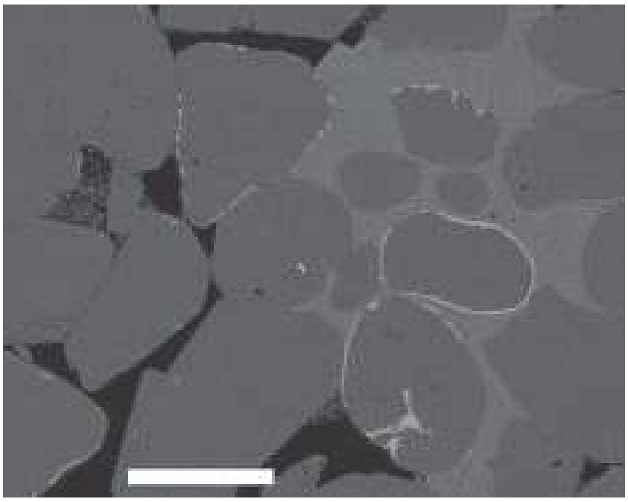


Fig. 15. BSE image. Carbonate (light grey) cemented domain. Quartz grains located within the carbonate cement are well rounded without obvious overgrowths and in general weakly compacted. In the porous domain quartz grains are angular indicating a layer of authigenic quartz on them. Pores (black) are relatively large; a few grains do not touch each other indicating limited compaction. Bright linings on the detrital grains are apatite. Image analysis porosity: 9%. Eitučiai-1, 1857 m. Scale bar is 500 µm.

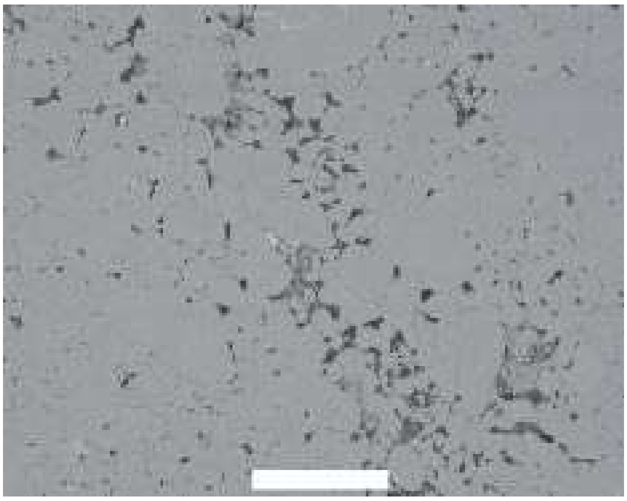


Fig. 14. BSE image. Very strongly quartz cemented domain in thin section. No open pores are observed. All pores preserved from authigenic quartz growth are completely filled with clay minerals. Most of quartz grains with clay coatings are rounded indicating detrital surfaces. Clay filled porosity is 4% as revealed by image analysis. Traubai-4, 2076 m. Scale bar is 1 mm.

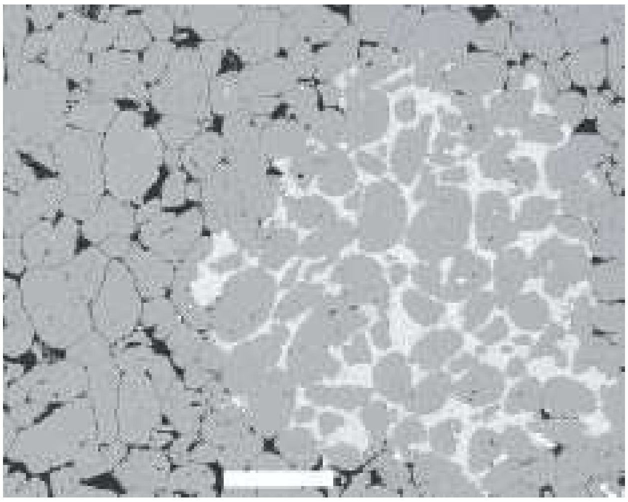


Fig. 16. BSE image. Carbonate (light gray) and quartz cemented domains. Most of quartz grains are floating in the carbonate and exhibit etched margins. Degliai-1, 1976 m. Scale bar is 500 µm.

faces of authigenic quartz may be filled with hairy and fibrous illite or with kaolinite booklets (Fig. 8). Therefore, separate detrital surface areas were preserved from SiO_2 precipitation by the presence of authigenic clay on them. Commonly, however, the coatings did not completely prevent precipitation of quartz on the detrital grains. The complete preser-vation of detrital surfaces was only seen where detrital clay occurs as a matrix in very clayey parts while detrital quartz grains are located within or close to clay laminae.

Sandstones where authigenic clay has influenced the formation of quartz overgrowths generally are more porous than other advanced cementation stage sandstones as seen on SEM specimens. This porosity is mainly present as microporosity and does not contribute much to the permeability.

A number of sandstone samples show different cementation pattern in different parts. The sandstone that generally contains large, open pores and

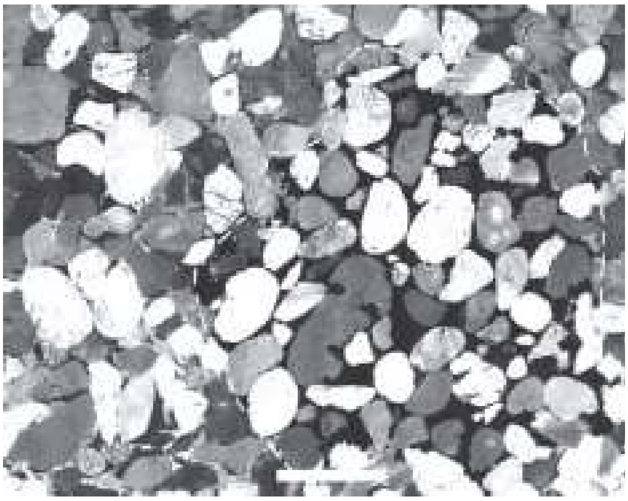


Fig. 17. The same thin section part as in Fig. 16, but in CL mode. Quartz grains are more tightly compacted within the quartz cemented domain compared to carbonate cemented (black) part of the image. Carbonate cemented domain is delimited by dashed line. Degliai-1, 1976 m. Scale bar is 500 μm.

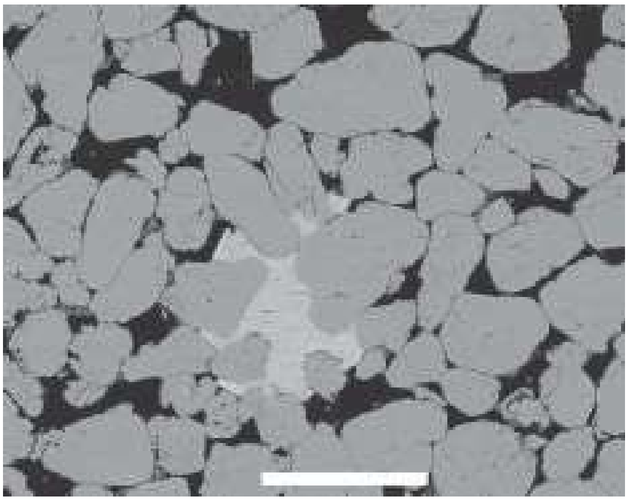


Fig. 18. BSE image. Carbonate cemented spot surrounded by very porous domain. Black is porosity. Pores are elongated, well interconnected and some of them are even oversized. Image analysis porosity: 18%. Eitučiai-1, 1905 m. Scale bar is 500 μm.

overgrowths of irregular morphology may in some domains show rather well developed overgrowth surfaces and be strongly cemented with just occasional pores visible. Taking into account the size of a SEM specimen it demonstrates a highly variable distribution of quartz cement on a scale as small as 1 cm or even 1 mm (Fig. 9). These observations are also confirmed by the thin section study.

On several thin sections CL pictures the authigenic quartz has two different colour intensities that may reflect timing of SiO_2 precipitation. A dark quartz type commonly rests directly on detrital grains whereas a brighter, pore-filling quartz type is located on the dark overgrowths. This probably indicates that the dark authigenic quartz formed first and covered detrital surfaces with a thin layer while the pore-filling quartz precipitated later in larger volumes. In most samples, however, it was impossible to reliably distinguish between these two authigenic quartz types.

Pressure dissolution

Cathodoluminescence investigations revealed that the most common shapes of detrital quartz grain contacts are convexo-concave or flat (Fig. 10). This indicates that dissolution took place, but the small amplitude of dissolution seams suggest that not more than 5–7% of the grain volume was dissolved. Also, microstylolite development and sutured grain contacts were identified, showing that intense pressure dissolution took place (Fig. 11). The removed volume of quartz along microstylolites on CL images is estimated to be 20–25%, or even larger. This very approximate estimation has been made by drawing probable initial contours of dissolved quartz grains. Sutured contacts between detrital quartz grains most commonly occur along detrital clay laminae but are also seen in clay-free parts. As a general rule, the parts of the sandstone adjoining dissolution seams are very quartz cemented, leaving just occasional small open or clay filled pores. Furthermore, pressure dissolution was observed also in fairly porous sandstone samples. In these samples, solution seams are found in domains with more quartz cement than the average sandstone, but in some cases, sandstone parts closely located to the dissolution seams are fairly porous and exhibit very little secondary quartz precipitation. In order to give a better evaluation of the extent of pressure dissolution within the Middle Cambrian succession and to support thin section observations, the quartz grain contact areas were carefully examined on SEM specimens. Most of such areas are rather smooth and relatively small, corresponding to the dominating convexo-concave or flat contact pattern observed in CL images. It indicates that significant intergranular pressure dissolution did not take place. In contrast, a number of impression marks exhibit rough, large areas with a channels-and-islands structure (Fig. 12). These grain contact areas would exhibit sutured interfaces between the grains such as we can see in thin sections. The study of grain impression marks on SEM and grain contacts on CL images show that pressure dissolution is a widespread process in Deimena Group sandstone.

Clays

Sandstone samples with clay laminae are generally rich in illite or kaolinite, occasionally with traces of chlorite. The XRD results did not show evidence of mixed layer illite/smectite. Two sandstones, however, showed traces of smectite. One of these samples was collected from the Pociai-5 well at a depth of 2017 m. This well is located close to the centre of a geothermal anomaly and has a reservoir temperature above 80°C, and we do not believe that discrete smectite may still be present under these conditions. The presence of smectite may be a result of drilling mud invasion into porous parts of the sandstone. Presence of discrete illite and absence of mixed-layer illite/smectite leads to the conclusion that most detrital smectite, if any, has been transformed to illite.

The thin section analysis and SEM-study of clay minerals usually demonstrates fibrous and hairy illite or kaolinite booklets. Kaolinite was found aggregated in pores or partially entrapped into secondary quartz, suggesting its authigenic origin (Fig. 13). Illite is the most common clay mineral. It was observed in most samples in varying quantities and a variety of locations. It lines or bridges pore space, covers some parts of detrital quartz grains that are preserved form quartz overgrowths, rests on overgrowths, and surrounds or coats grain impression marks (Fig. 8).

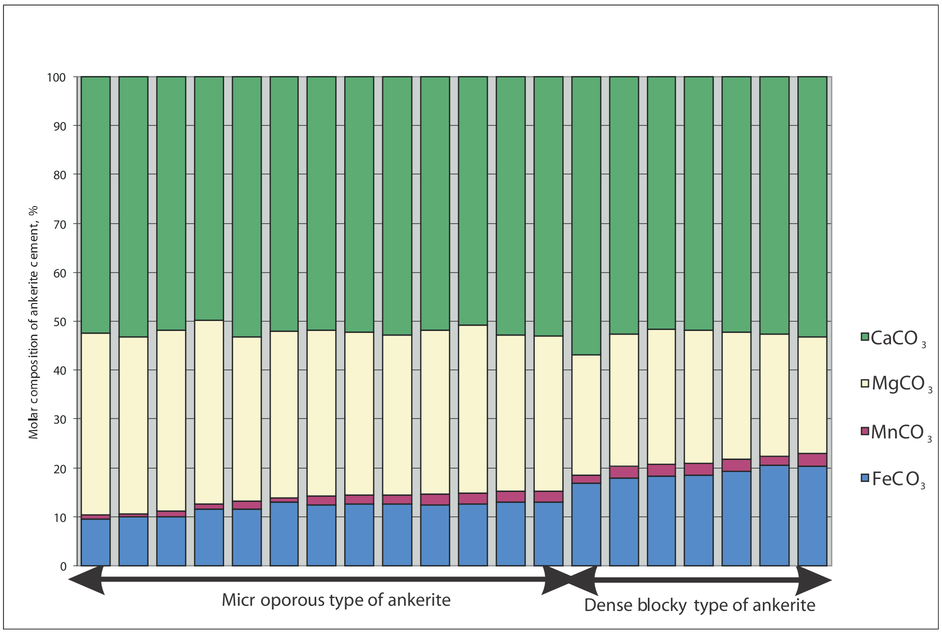
Further, in strongly cemented sandstones some pores are filled with illite or kaolinite and are almost free of authigenic quartz (Fig. 14). By visual examination the amount of pore filling authigenic clay is found to be higher in sandstones that contain laminae of detrital clay. These samples are generally very clayey and pore space is abundant in authigenic clay. A similar pattern was observed in samples closely located to the mudstone units. These observations may indicate that the presence of detrital clay was impor-tant for authigenic clay formation in the Deimena Group sandstones.

Carbonates

Carbonate cement was observed in a number of samples. The obtained energy dispersive X-ray spectra proved the cement to be ankerite. It occurs mainly as sparsely distributed poikilitic cement clustered in spots up to 2×2 mm in size. The spots are composed of two different types of carbonate as seen on BSE images. The first type is characterised by a distinct microporous texture and usually constitutes the central part of the spot. The second type located at margins of the carbonate spots has a very dense, blocky texture and does not show microporosity. EDX analyses revealed that the second type contains a larger proportion of iron compared to the first one (Table 2).

The carbonate occludes a large number of quartz grains which are mainly subrounded to well rounded (Fig. 15). In most cases, quartz overgrowths were not observed on the grains floating within ankerite. However, on the CL images a thin authigenic layer was observed on several quartz grains within the carbonate. These overgrowths cover separate parts of very few detrital quartz grains but do not occlude their

Table 2. Molar composition of two ankerite cement types.



margins completely. The estimated amount of secondary quartz within ankerite is less than 1–2%. The carbonate cemented parts are significantly less compacted than the quartz cemented parts (Figs 16–17). Sometimes the grains are completely floating in the cement and do not touch adjacent grains. In some cases, carbonate cemented intergranular pores are approximately as large as adjacent quartz grains. BSE and CL image analysis gave IGV values of 29–35% in carbonate cemented parts compared to 18–29% in the entire rock. Some of the quartz grains located within the ankerite cement have been intensively etched and in a few cases just tiny remnants of quartz are seen (Fig. 16).

Small and isolated ankerite crystals occur on detrital quartz grains or are trapped within quartz cement and clay linings. Probably they represent remnants of dissolved larger carbonate crystals.

The spots of carbonate cement were found in very porous samples with large and interconnected pores (Fig. 18) with an image porosity range from 9 to 19%. Outside carbonate spots, the pores tend to be elongate and occasionally oversized. Yet, in some large pores, remnants of dissolved quartz grains are present and in some cases it is possible to follow the original outline of such grains.

Discussion

The interpreted sequence of diagenetic events within the Middle Cambrian Deimena Group in West Lithuania is presented in Table 3. Initial sandstone porosity is generally in the range from 40–55% and is being reduced to 20–25% by grain rearrangement during burial (Atkins & McBride 1992; Wilson & Stanton 1994). Mechanical compaction and grain rearrangement is one of the most important factors responsible for damage of good reservoir quality during early burial. The sandstones of the Deimena Group, as well as many Cambrian sandstones within the Baltic Basin, exhibit a medium to high grade mechanical compaction (Møller & Friis 1999; Schleicher 1994; Sikorska 2000). The IGV in strongly quartz cemented sandstones ranges from 18–29% and the estimated compaction due to pressure solution is small (Fig. 10). In carbonate cemented parts the quartz grains are less compacted and the IGV is up to 29–35%. This shows that carbonate occluded the quartz grains at an early compaction stage. Quartz cementation occurs in all samples and generally fills the largest portion of remnant porosity. The growth pattern varies from quite regular late stage cementation with well developed large crystal faces to more irregularly growing crystals in samples rich in clay. Apparently, clay linings prevented quartz growth from separate parts of detrital grain surfaces but the overall cementation pattern was only slightly influen-ced. The presence of clay caused some preservation of porosity in pits and grooves in the quartz cement. The cementation pattern of porous sandstones can be classified as an early cementation stage (Scholle 1979), either with few and scattered small overgrowths or very thin coalesced overgrowths. This growth pattern is registered mainly in reservoir sections but is also found in minor patches in cemented sandstones.

However, an early stage cementation should not be expected in sandstones where many parts are completely cemented and almost without remnant porosity. We suggest that the under-compacted and under-cemented sandstones result from dissolution of early formed carbonate cement. The presence of carbonate cemented spots and small separate ankerite crystals in some of these sandstones are in good agreement

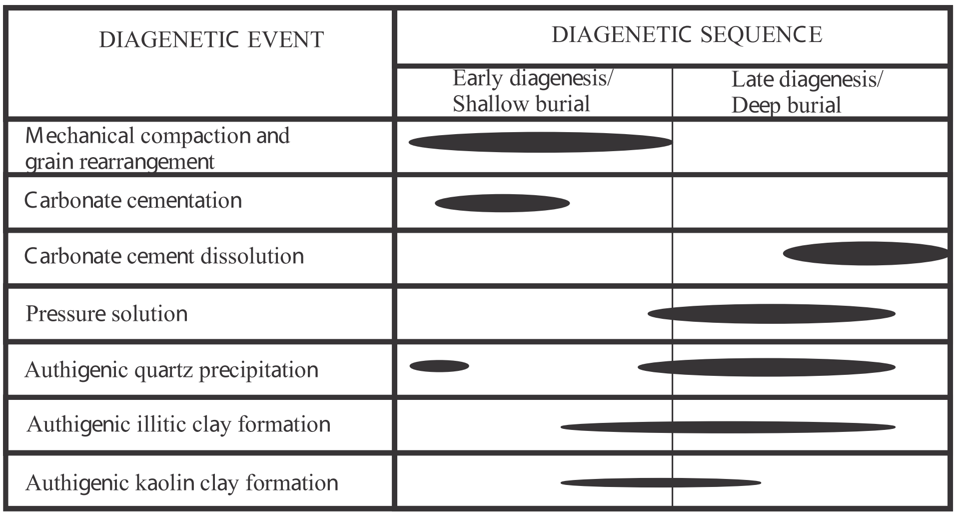


Table 3. The interpreted sequence of diagenetic events within the Middle Cambrian Deimena Group in West Lit-

with this explanation. The presence of partially dissolved, intensively etched quartz grains also indi-cates the former presence of carbonate cement. The morphology of the pores and their size and distribution indicate a secondary origin rather than a primary (Schmidt, McDonald & Platt 1977). The carbonate dissolution probably took place after the main phase of intense quartz precipitation since only a negligible amount of secondary quartz precipitated in the secondary porosity, resulting from dissolution of carbonate. The presence of very thin quartz over-growths on some detrital grains within the carbonate cemented areas demonstrates that there were at least two phases of quartz cementation. The first one took place during very early burial, prior to the carbonate cementation and prior to intense mechanical compac-tion. Although the first cementation phase in most cases can only be recognised in the carbonate cemented part, we believe that only small amounts of authigenic quartz precipitated during this phase. The second phase of quartz precipitation was significantly more important than the first one. Quartz cement is most abundant where pressure dissolution is also common. Pressure dissolution of detrital quartz probably took place contemporaneously with precipitation of quartz cement and was the main silica source. Since preci-pitation of quartz also took place in secondary porosity after dissolution of carbonate, pressure dissolution of quartz may also have continued to take place, although at a more limited rate. Strongly cemented sandstones may resist overburden stress and consequently, limited pressure dissolution takes place. Such sandstones exhibit a more open framework with a large proportion of IGV preserved. Furthermore, early carbonate cement is likely to prevent compaction. Many large pores present in such sandstones simply would not survive intense mechanical compaction and would have collapsed unless some other cement stabilised the sediment during compaction. In a number of samples with carbonate cement there are quite tightly quartz-cemented areas with evidence of pressure dissolution adjacent to the areas with elongated and oversized pores. This indicates that the carbonate cement may not have been massive.

The carbonate may originally have been a calcite which was later replaced by ankerite. The microporous fabric might relate to a loss of volume during this process. The replacement may have taken place in relation to the partial dissolution of the calcite precur-sor. The massive, iron-rich ankerite which forms a narrow rim on the microporous ankerite may represent a later phase of precipitation.

Therefore, we assume that carbonate cement was much more common but in most cases was totally dissolved.

Carbonate cement has previously been described from the Cambrian succession of the Baltic Basin (for example Laškova 1979; Marino 1980; Sikorska 2000). Laškova (1979) described authigenic dolomite that marginally replaces quartz grains. Sikorska (2000) identified an early stage calcite in the Cambrian beds within the Polish part of the Baltic Basin. According to her findings, the calcite occurs as scattered and very small crystals in pores. Also, a late stage poikilitic calcite cement was observed occasionally filling micro fractures (Sikorska 2000). Vosylius & Vaznonis (2000) suggested that early carbonate cementation was important for reservoir properties, but did not provide unambiguous evident data for this suggestion. Our observations demonstrate that an early carbonate cement is crucial for present day reservoir quality because most porosity is secondary after dissolved carbonates.

Clay minerals which are mainly illite and kaolinite are located on detrital surfaces overgrown by secondary quartz as well as entrapped within a thick authigenic quartz layer. Therefore, the authigenic clays formed prior to and contemporary with the second quartz precipitation phase. Furthermore, fibrous and hairy illite sometimes rests on quartz overgrowths indicating that growth of illite continued at later stages of burial after the intense quartz precipitation phase. The importance of clay for preservation or destruction of reservoir properties has been discussed by several authors (for example Eslinger & Pevear 1988; Dewers & Ortoleva 1991). It is generally accepted that thick continuous clay coatings on detrital quartz grains may severely inhibit formation of quartz overgrowth (Friis 1987), while thin clay coatings or laminae located between detrital quartz grains enhance pressure dissolution during burial (Heald 1959; Eslinger & Pevear 1988). Further, authigenic clays tend to line or bridge pore space, significantly reducing the perme-ability of the sandstone. Pores that contain authigenic clays often show microporosity that does not contribute to fluid flow through the sandstone. Consequently, as the authigenic clay linings did not inhibited the SiO_2 precipitation on the detrital surfaces and formed on pore walls after intense quartz cementation stage further reducing macroporosity and permeability the clay must be a reservoir quality damaging factor, not a preserving factor, in the Deimena Group sandstones.

Conclusions

Compaction and grain rearrangement significantly reduced initial high porosity and permeability during burial.

Quartz cementation is the most important factor in reservoir quality destruction and is found in all Deimena Group sandstones. Two phases of secondary quartz formation are distinguished. The early phase was volumetrically unimportant and took place before carbonate cementation.

Pressure dissolution is widespread within the sandstones and is concluded to be the most important source of silica. It is observed both in strongly cemented sandstones and in porous parts of the sandstones.

Clay minerals partially preserved pores from quartz precipitation in parts where clay completely plugs pore space, whereas clay coatings did not inhibit quartz precipitation. Authigenic illite and kaolinite often fill pores that are not completely cemented by quartz resulting in low permeability. Generally, the presence of clay results in poor reservoir quality.

Early carbonate cement partially preserved separate domains of the sandstone from tight compaction and extensive quartz cementation. Dissolution of the carbonate resulted in high porosity consisting of oversized and elongated secondary pores. These parts are considered as the best reservoir rocks among the investigated samples.

Acknowledgements

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Erratum

In the article by Kilda & Friis entitled 'The key factors controlling reservoir quality of the Middle Cambrian Deimena Group sandstone in West Lithuania', *Bulletin of the Geological Society of Denmark* 49(1), pp. 25-39, Figur 2 on p. 27 and Figur 4 on page 28 were printed incorrectly outwith the editor's control. The correct figures are reproduced below.

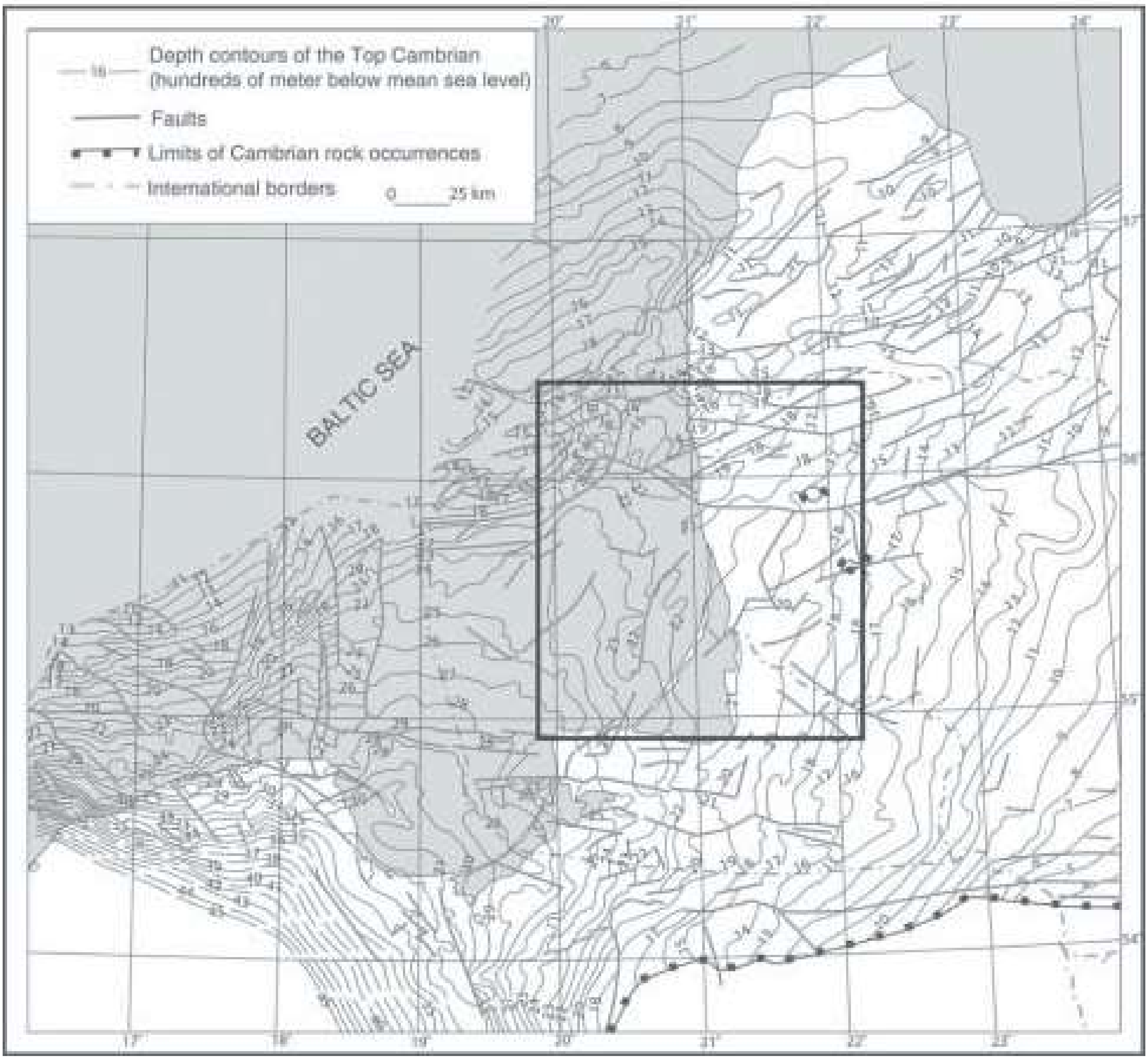

Fig. 2. Depth contour map of the Top Cambrian in the Latvian, Lithuanian and Polish parts of the Baltic Basin (from Modlinski et al. 1998, reprinted by permission). The square on the map shows the location of the Fig. 4.

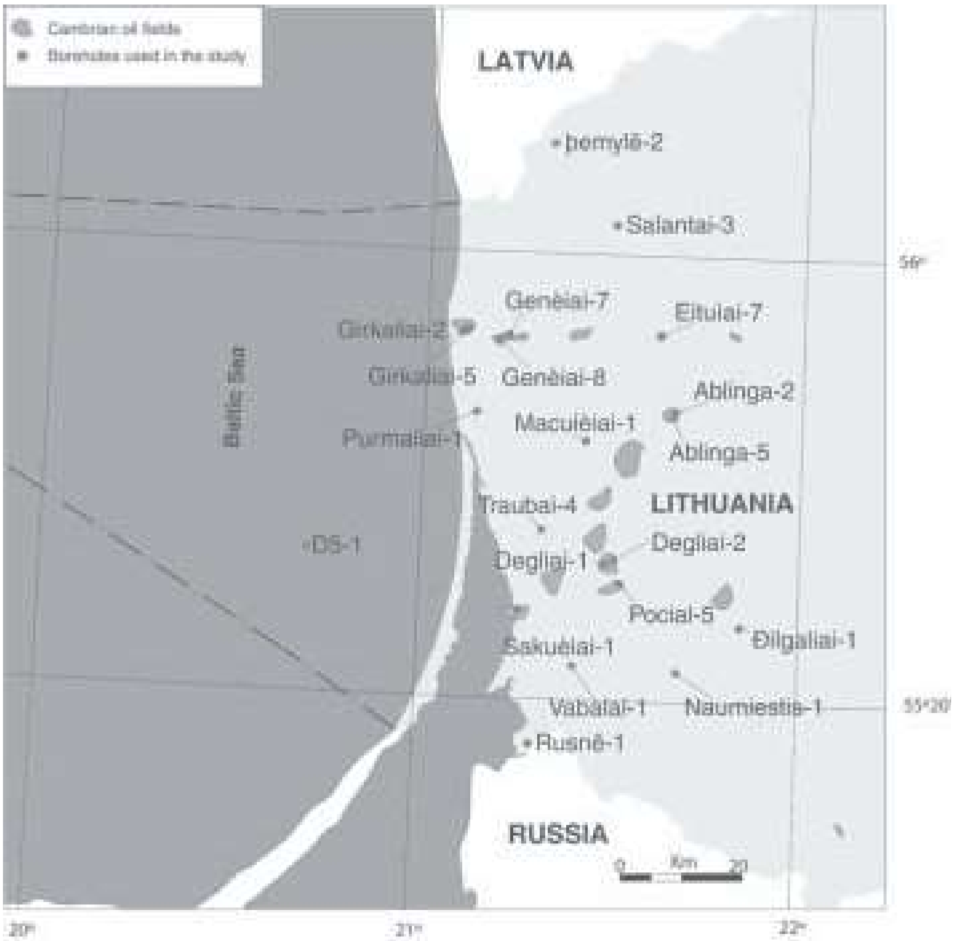

Fig. 4. Location map of the Middle Cambrian oil fields and boreholes selected for the study.