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Clay-induced pressure solution as a Si source for quartz cement in sandstones of the Cambrian Deimena Group

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The Middle Cambrian Deimena Group sandstones are the main oil reservoir in Lithuania with 18 oilfields discovered so far in the western part of Lithuania. The sandstones show a great variability in reservoir quality, making the reservoir exploration and the construction of its models difficult. The porosity and permeability show a complicated variability even within a single oilfield; closely spaced wells within a single oilfield may have a different reservoir quality, whereas in the vertical sense their properties also vary greatly within the reservoir bodies. Quartz cementation is the main diagenetic process influencing and controlling the petrophysical properties of Cambrian sandstones. The amount of quartz cement, and inversely its porosity and permeability, are only weakly correlated with the burial depth and palaeotemperature within particular oilfields. Evidently, factors other than general physical conditions and overall chemical conditions related to burial depth must locally have influenced the processes involved in quartz cementation and controlled the location and amounts of quartz cement. The main factor is the reservoir architecture. The amount of quartz cement positively correlates with the amount of shale structures in sandstone bodies. Clay-induced chemical compaction and pressure solution of detrital quartz at shale–sandstone contacts and within thin shale lamina is the main process yielding silica for local quartz cement. The supply of silica for quartz cement in the sandstones is thus dependent on the number of thin clay lamina and clay intercalations within the reservoir sandstones. The sandstone/shale ratio and the thickness of sandstone bodies control the location and degree of quartz cementation and thus the reservoir quality.

Key words: sandstone, quartz cementation, Cambrian, Baltic Basin, pressure solution

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INTRODUCTION

Quartz cementation has been long recognized as a main diagenetic process in quartz-rich sandstones (*e.g.*, McBride, 1989), influencing and largely controlling the petrophysical properties. Quartz cement controls to a large degree the properties in many hydrocarbon reservoirs such as in the North Sea (Bj¸rlykke & Egeberg, 1993; Oelkers et al., 1996) and in the Palaeozoic Baltic Basin (Lashkova, 1979; Vosylius, 2000). Because of the economic interest to predict reservoir properties for enhancing exploration, a large number of studies have dealt with the processes involved in precipitation of quartz cement. Nevertheless, the source of silica for quartz cement is still a matter of debate. A number of studies concluded silica sources placed outside the reservoir bodies to implicitly involve a mechanism for a large-scale advective flow of diagenetic fluids. On the contra, other studies suggest silica sources within or at a short distance from the reservoir sandstone bodies, avoiding the difficulties of large-scale transport due to the limited silica solubility. As stated quite early (Blatt, 1979), because of the low solubility of silica, large volumes of diagenetic fluids would be needed for silica supply from the outside. This may be attainable under near-surface conditions where a hydraulic head can form the mechanism for flow, but it certainly is not a realistic scenario under deeper subsurface conditions (Bj¸rlykke & Egeberg, 1993).

Under burial conditions, a large-scale flow may be involved with faulting and ascendance of hot fluids and induced by thrusting, although in isolated cases such mechanisms may supply silica externally, the common widespread and in fact regional occurrence of quartz cement, *e.g.*, in the Jurassic Brent group sandstones in the North Sea (Bj¸rlykke et al., 1992) and in the Cambrian sandstones in the Baltic Basin, the subject of the current study. This contradicts ascending cooling fluids as a common source for quartz cement and suggests that quartz cementation is not related to specific tectonic activity.

More evidence against large-scale transport is given by the fact that formation waters are often diagenetically evolved seawater that remained in place (*e.g.*, Hogg et al., 1995). Other studies concluded, however, that meteoric water has been involved and mixed or replaced the original marine pore water (*e.g.*, Williams, 1997). The latter would point to a larger-scale flow but not necessary implies that the silica is also externally delivered during the same phase of flow. The presence of the original pore water strongly suggests that silica is supplied through diffusion from internal or short distance sources. It seems therefore likely that quartz cementation can take place regardless of the type of formation water present.

If silica was externally supplied, advective flow being involved in silica transport, then quartz cement would be expected as the most interconnected and at that time most permeable parts of the sandstone bodies. The contrary is often true, and the thicker sandstone units often have better petrophysical properties and form hydrocarbon reservoirs. Also, model calculations show that when silica is transported by advection, quartz cementation would be more pervasive in coarser-grained and more permeable sandstones, allowing for high flow rates (Canals & Meunier, 1995).

The regional as well as local distribution of quartz cement, and inversely the petrophysical properties, intrinsically contain information about the processes involved in quartz cement precipitation, including silica sources and the transport mechanism of dissolved silica towards the place of cementation. Regional distribution patterns may point to general threshold conditions and/or confining physical and/or chemical conditions for quartz cementation. Local quartz cement variability, however, is more likely to be linked to small-scale variability in sedimentary parameters possibly associated with depositional facies.

This will be tested by a case study of the Cambrian marine siliciclastic sandstones in the Lithuanian part of the Palaeozoic Baltic Basin. The Cambrian sandstones are widespread in Lithuania and are an example of quartz arenites with dominant quartz cement in the west (Lashkova, 1979; Vosylius, 2000). The petrophysical properties show a rather large variability even on a local scale. The study focuses on West Lithuania where a number of producing oilfields occur at a present day burial depth from about 1700 to 2200 metres.

METHODS AND DATA

Because of the petroleum exploration and production activities, sample petrophysical data, geophysical well logs and core material are available for research. The natural gamma ray logs are used to calculate the shale content.

Polished thin sections of about 200 samples were used to study the texture and mineralogical composition by polarized light microscopy. The components in 83 sandstone samples were quantified by image analysis using microphotographs from backscattered electron (SEM-BS) microscopy, cathode luminescence scanning electron (SEM-CL) and cold cathode (CL) luminescence microscopy using a standard point counting and the image ImagePro Plus analysis software. The mineralogical composition was confirmed by backscattered electron imaging (SEM-BS) and EDX microscopy and bulk X-ray diffractometry (XRD). XRD was also used for clay mineral determinations in 62 samples (oriented mounted fraction <2 mm, non-treated, ethylene glycolated and stepwise heated to 350 and 500 ˚C) according to standard methods.

Porosity and permeability data from existing industrial reports, listing nearly 10,000 measurements of sandstones from special core analyses, provided consistent information on the lateral changes of the reservoir properties. In addition, the porosity and permeability of the new samples were measured. Helium porosity was determined by the standard gas expansion method using a HGP100 helium porosimeter. The permeability was measured using a digital gas permeameter DGP200 corrected for the Klinkenberg effect.

BURIAL HISTORY

Lithuania is situated on the south-eastern flank of the Baltic sedimentary basin, which is the largest tectonic feature of the western margin of the Eastern European

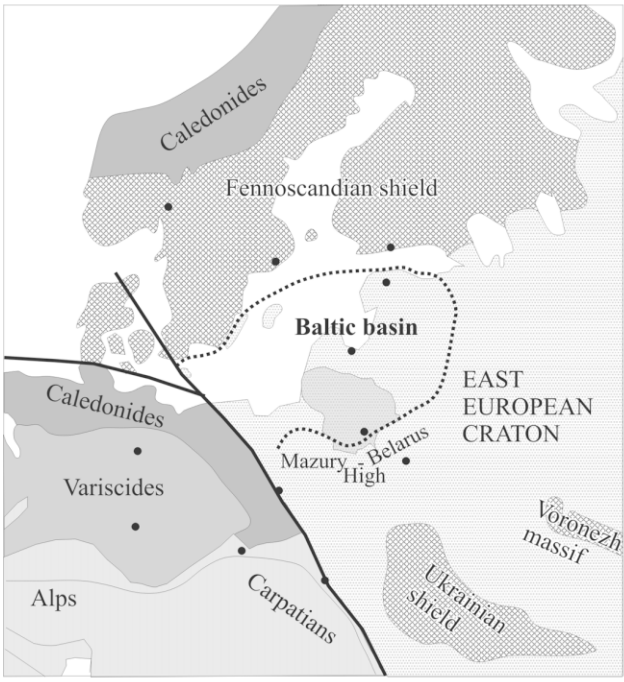

Fig. 1. Location of the Baltic Basin and Lithuania
1 pav. Baltijos baseino ir Lietuvos paplitimo schema

Craton (Fig. 1). The sedimentary succession consists of Vendian to Quaternary sedimentary rocks resting on a Early Proterozoic crystalline basement. The thickness of the sedimentary fill ranges from 0.2 km in East to 2.3 km in west Lithuania. Cambrian deposits represent the basal part of the sedimentary cover. They are overlain by a carbonaceous-shaly succession of Ordovician age. The thickness of the Cambrian ranges from a few tens of meters in the east to 170 m in the west. The succession comprises alternating beds of sandstones, siltstones and shales with different proportions across the basin, which were deposited in shallow-marine and shelf environments in Lithuania during minor sea level fluctuations (Laškova, 1987; Jankauskas, 1994). The depositional environment ranges from shallow-marine inner shelf, which is partly tidally influenced, to the outer shelf with storm-induced currents as the dominant transport and depositional mechanism. Fine-grained shale drapes and shale intercalations are common within sandstone bodies. The sandstones are interbedded and finger out distally into marine shales. Deposits on the mid shelf are alternations of sandstone, and shale becomes more dominant towards the distal, outer parts of the shelf. The sandstone/shale ratio and the thickness of sandstone-dominated successions thus systematically decrease towards the outer shelf.

The present day burial depth in the study area in West Lithuania coincides with the maximum burial depth attained in the geological history (Fig. 2). The subsidence rates and geometry of the Baltic basin have changed throughout the Phanerozoic (Poprawa et al., 1999; McCann et al., 1997). During the Cambrian and Ordovician, deposition took place in a passive margin setting with a total subsidence of 150–500 m during the Cambrian and 50–250 m during the Ordovician. The geodynamic situation changed during the Silurian into a converging continental margin setting with an intense subsidence ranging from 100–200 meters in the east up to 4–5 km in the westernmost part of the Baltic basin in Central Poland and NE Germany. The magnitude of the Silurian subsidence in West Lithuania is 700–900 m. Intense subsidence persisted during the Devonian during which period about 1 km thick terrigenous and calcareous sediments accumulated in the basin centre.

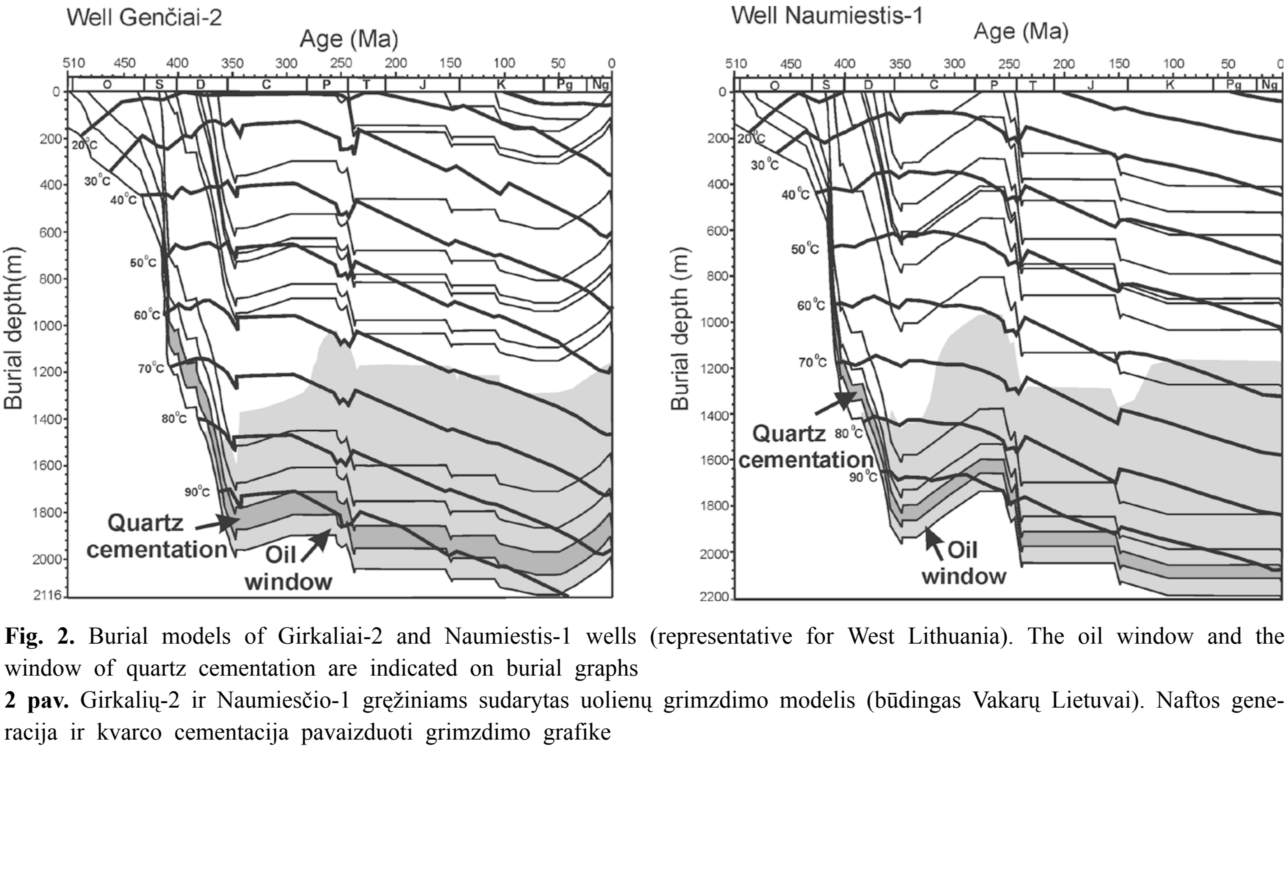

Fig. 2. Burial models of Girkaliai-2 and Naumiestis-1 wells (representative for West Lithuania). The oil window and the window of quartz cementation are indicated on burial graphs

2 pav. Girkalių-2 ir Naumiesčio-1 gręžiniams sudarytas uolienų grimzdimo modelis (būdingas Vakarų Lietuvai). Naftos generacija ir kvarco cementacija pavaizduoti grimzdimo grafike

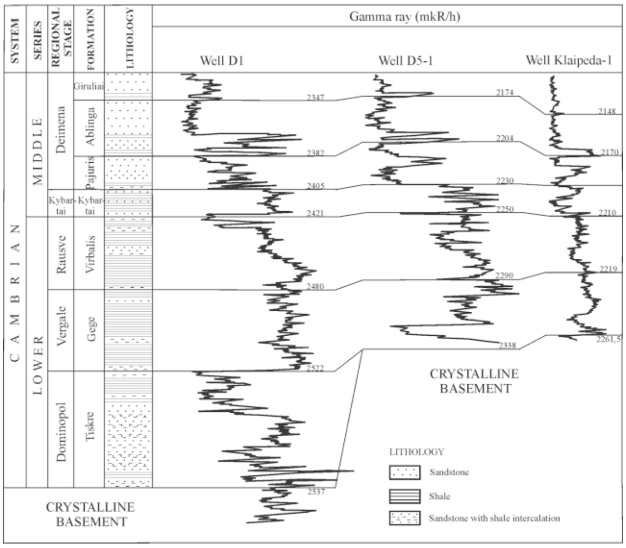

Fig. 3. The West Lithuanian Cambrian succession subdivided into groups and formations based on well logs (natural gamma radiation)

3 pav. Vakarų Lietuvos kambro pjūvio koreliacija pagal geofizinių tyrimų gręžiniuose kreives (gama metodas)

The subsidence drastically decelerated during the earliest Carboniferous giving way to uplift and erosion of the basin flanks during the Carboniferous – earliest Permian; in some places the magnitude of erosion is estimated to as much as 0.5–2 km. Numerous diabase intrusions penetrated the Cambrian–Silurian succession in the central part of the Baltic Sea. During the succeeding Permian–Cainozoic times only central, southern and western parts of the basin were involved in the subsidence in a range of 0.1 km (east) to 1.5 km (southwest).

CAMBRIAN STRATIGRAPHY

The whole Cambrian succession, Lower-Middle Cambrian, has a thickness ranging from 10.5 (uplifted and eroded Cambrian succession in East Lithuania) to 177 metres in Southwest Lithuania with an average thickness of 116 m (No = 154). Traditionally, the succession is subdivided into groups and formations based on well logs (Figs. 3 and 4). The detrital composition of the sandstones is dominated by quartz (95–99%) (Laškova, 1987; Kilda & Friis, 2002). Detrital grains are mostly very-fine to fine-grained sand-sized (on average well sorted), with rounded to well-rounded quartz grains. Besides the dominant mono- and polycrystalline quartz grains, there are also negligible amounts (less than 1%) of feldspar, lithic grains, and heavy minerals (opaque minerals, zircon, garnet and rutile). Glauconite grains occasionally are abundant and related to sequence boundaries. The sandstones can be considered as mineralogically very mature and are classified as quartzarenites (cf. Folk, 1964). Shales are dominantly composed of illite or interlayered smectite-illite with variable amounts of kaolinite, and minor chlorite. The shales are silty-sandy and contain variable amounts of detrital quartz and minor K-feldspar with very fine-grained sand and silt size. The shales have a matrix-supported framework.

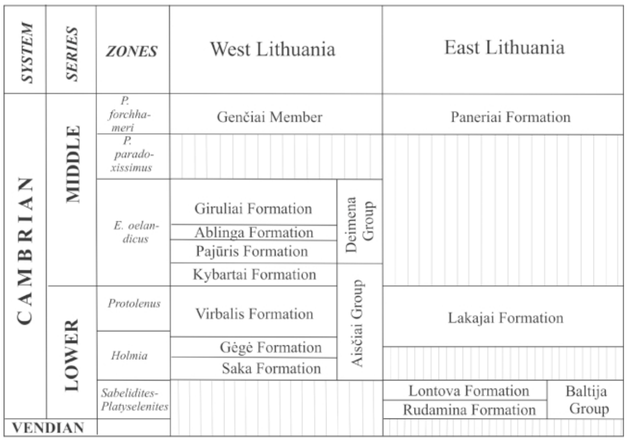

Fig. 4. Stratigraphic scheme of the Lithuanian Cambrian

4 pav. Lietuvos kambro stratigrafinė schema

The Lower Cambrian succession is up to 80 m thick and consists of fine-grained light grey, rarely brown and greenish grey sandstones, which alternate with siltstones and shales. Siltstones and shales are grey, greenish grey and brown in colour. The lowermost Cambrian "Blue Clay" formation occurs in the eastern part of Lithuania. The Middle Cambrian succession, dominated by light grey sandstones with intercalated shales and siltstones, reaches a thickness of 70–80 m in Central and West Lithuania (Fig. 3). The lower part of the Middle Cambrian succession (The Kybartai Formation, about 10 m thick) is mainly composed of siltstones and shales. The overlying, around 60 m thick, succession of quartzose sandstones with a number of shaly sandstones-siltstones and shale layers represents the main oil reservoir in Lithuania, which is defined as the Deimena Group. This is classically subdivided into Giruliai, Ablinga, Pajūris Formations from top to bottom successively (Fig. 4). The Kybartai Formation and Deimena Group are attributed to the *Paradoxides oelandicus* trilobitic zone of the Middle Cambrian. Further west in the Polish offshore area, these deposits grade into deeper-marine siltstones and shales. The overlying Paneriai Formation of the *Paradoxides paradoxissimus* zone is only locally presented in a few wells in Eastern Lithuania, constituting of small isolated residues of sandstones and siltstones several meters thick. It is widely distributed in the east on the western flank of the Moscow palaeobasin (up to 20–30 m thick) and the western periphery of the Polish Basin. Upper Cambrian deposits are absent in Lithuania; sedimentation was confined to the westernmost part of the Baltic basin during that time (Jankauskas & Lendzion, 1992).

RESULTS

Cambrian lithofacies

The shale content and the sandstone bed thickness are two main parameters in distinguishing depositional fa-

Table 1. **Summary of main characteristics of the lithofacies distinguished in West Lithuania**
1 lentelė. **Vakarø Lietuvos litofacijø apibûdinimas**

Facies	Subfacies	Lithology	Sedimentary structures	Bed thickness	Facies thickness	Sandstone percentage	Depositional environment
S	S_1	Massive sandstone (quartz arenite)	Horizontal or low angle cross-lamination	Metres	5–20 m	>95	Inner shelf; amalgamated storm and storm surge deposits
	S_2	Thick-bedded sandstone with few shale lenses or lamina at the top	Wave ripples. Small-scale hummocky cross stratification	Decimetre-metre	2–8 m	88–95	Inner shelf; storm deposits
	S_3	Thin-bedded sandstones with shale lamina	Horizontal or cross-bedded lamination. Rare bioturbation	Decimetre-centimetres, 0.10–10 mm shale	5–10 m	80–88	More distal inner shelf: intermediate distal storm deposits and super-imposed wave current activity
H		Thin inter-bedded sand-stones and shales	Lenticular-wavy bedding, horizontal lamination, wave and current ripples: up to strongly bioturbatedsome	Centimetres	5–15 m	50–80	Mid shelf: distal storm deposits and wave activity and biological activity
SH		Shales with sandstone laminas and lenses	Horizontal lamination to lenticular bedding; intense bioturbation	Millimetrs-centimetres	1.5–5 m – 20 m	<50	Outer shelf, below normal storm-wave base; low energy and intense biological activity

cies in the Cambrian succession as relevant for understanding the reservoir properties. Based on core descriptions and well logs, in particular the natural gamma ray logs, a number of lithofacies with a different sandstone–shale ratio can be distinguished in the Lower and Middle Cambrian succession: sand-dominated, intermediate heterolithic and shale-dominated lithofacies are distinguished (Table 1). The further subdivision in the sandstone subfacies was based on sandstone bed thickness. The sandstones contain variable amounts of intercalated shale, whereas bed thickness and size of cross-bedding increase with sandstone content. The shales, on the other hand, contain variable amounts of thin or lenticular-bedded sandstones and siltstones.

Reservoir bodies

The reservoir is built from two up to four sandstone-dominated bodies (individual sandstone bodies ranging from around 10 to 35 metres in thickness) separated by shales or shaly sandstones. The reservoir is heterogeneous because of the vertical and lateral variability in porosity and permeability within the sandstone bodies as a consequence of differential quartz cementation. The effective thickness of the reservoir is reduced by heavily quartz-cemented, low-porosity sandstone layers. The effective thickness shows a considerable variation, which is largely caused by drastic changes in the content of quartz cement, which is increasingly important in the west. Individual layers and bodies are sheet-like or lenticular. The thickness of the sandstone bodies partly is modified by amalgamation, and the facies are influenced by the local synsedimentary tectonic activity during the Middle Cambrian, and the sandstone is thicker and with less shale intercalations in the central domal parts of the reservoirs and uplifted structures in general (*e.g.*, the Girkaliai structure).

The detrital composition is homogeneous quartzarenite, but the grain-size distribution and thus the initial texture of the sandstones is variable. Even more important is that the lithological succession is variable both in the

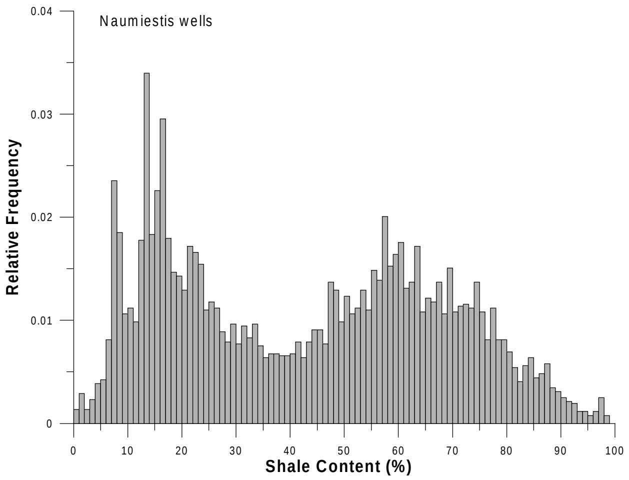

Fig. 5. Histogram showing shale content in Lower and Middle Cambrian derived from natural gamma radiation logs for Naumiestis wells (West Lithuania)
5 pav. Naumiesčio gręžinių apatinio ir vidurinio kambro uolienų molingumas, apskaičiuotas pagal gama metodo kreives

vertical and the lateral sense. Sandstone bed thickness and the content of shale show a wide range (Fig. 5).

Sandstone diagenesis

Pore reduction by mechanical compaction, as evident from the reduced IGV values (Table 2) and quartz cement are the main controls of the petrophysical properties of the Cambrian sandstones.

The intergranular volumes (IGV) defined according to Paxton et al. (2002), *i.e.* is corrected for secondary pores, point to the importance of mechanical compaction in reducing porosity and causing lithification. Compaction comprised the mechanical rearrangement of grains throughout the sandstones as well as the chemical compaction located along shale-sandstone contacts and within the shales. Grain breakage is rare, and no intergranular pressure solution in clay-free clean sandstones has been observed. In the sandstones, detrital quartz grains mainly have point contacts. The variation in IGV reflects differences in the degree of mechanical compaction. This is probably related to both maximum burial depth and variations in the depositional texture and susceptibility of the sand to mechanical compaction.

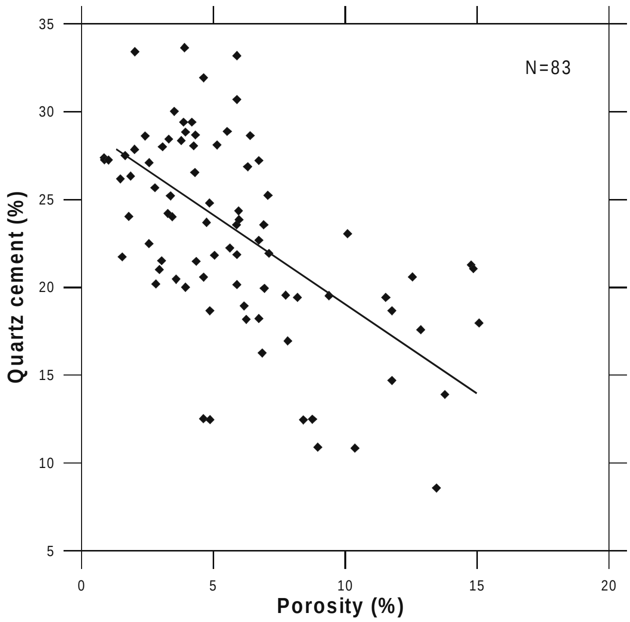

Fig. 6. Graph showing a statistically significant negative correlation between quartz cement and porosity
6 pav. Kvarcinio cemento ir poringumo reikšmių neigiama koreliacija

Quartz, in the form of authigenic overgrowths on detrital quartz grains, is the main cement mineral (Laškova, 1979; Kilda & Friis, 2002). Quartz cement is regionally widespread, but mainly confined to areas where present day temperatures in the Cambrian are over 50 to 90 degrees. The amount of quartz cement increases towards the deeper buried parts of the basin in West Lithuania, but is highly variable on a local scale and even within individual oilfields. Quartz cement contents show a negative correlation with porosity (Fig. 6). The numerical values were obtained by point-counting of 1000–2000 points on digital SEM-CL micrographs (average values from several micrographs of a single sample). The quartz cement values range from 9 to 33% (average 22%). The spread in values can be explained by variation in intergranular volume (corrected for secondary porosity) (Table 2). Since much more porosity data from special core analyses are available than quartz cement percentages from petrographic analysis, po-

Table 2. Average sandstone composition based on thin section, SEM-CL and SEM-BS image quantification
2 lentelė. Bendra smiltainio sudėtis, pagrįsta šlifų, SEM-CL ir SEM-BS nuotraukų analize

	Detrital Quartz (%)	Quartz cement (%)	Porosity (%)	IGV (%)*
Average	70.60	22.62	6.31	26.54
Standard deviation	4.35	5.81	4.53	4.10
Minimum	60.87	8.59	0.85	17.14
Maximum	82.87	33.64	26.67	39.07
N	85	85	85	85

* The IGV values are corrected for secondary porosity.
* IGV reikšmės koreguotos įvertinant antrinį poringumą.

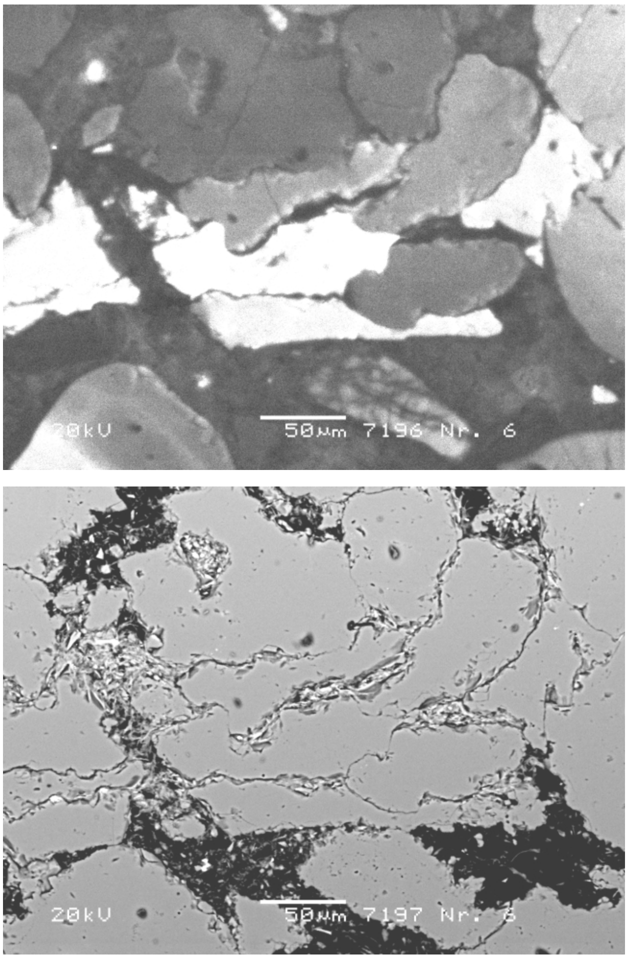

Fig. 7. SEM-CL and BSE micrographs of thin sections, showing pressure solution of quartz grains. Well location Lašai-3, depth 2092 m

7 pav. SEM-CL ir BSE šlifų nuotraukose – kvarco grūdelių tirpdinimas dėl slėgio. Lašų-3 gręžinys, gylis 2092 m

rosity will be used as an inverse proxy to quartz cement content.

Besides the prevailing quartz cement, some Fe-dolomite cement, pyrite and authigenic illite are present. Authigenic illite occurs adjacent to a shale lamina. Fe-dolomite cement occurs as dispersed patches (<1%), with no effect on porosity or permeability. In the eastern, marginal parts of the basin the sandstones are weakly lithified with Fe-dolomite or calcite and minor quartz cement.

Elongate and angular grains with sutured grain contacts are common in the shales (Fig. 7) and along shale–sandstone contacts (Fig. 8), and point to an extensive pressure solution of detrital grains. Also, at mica-rich laminas, dissolution of quartz grains took place. The micas are mainly muscovite and biotite. These phyllosilicates are aligned in preferred orientation or randomly oriented due to bioturbation. The micas appear to be unaffected by dissolution, their shape being virtually intact. Dissolution has produced sutured boundaries in the case of clay–quartz contacts (Fig. 9) and straight boundaries at mica–quartz contacts.

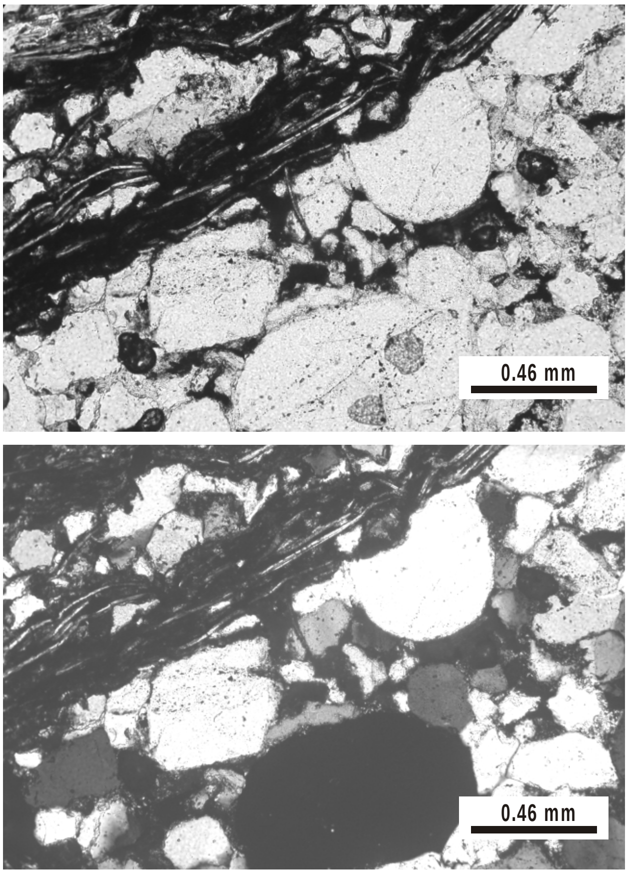

Fig. 8. Micrographs of thin section showing solution of detrital quartz grain along clay- and mica-rich lamina (top – plane polarised light; bottom – idem with crossed polarization filters). Well location Vabalai-1, depth 2105 m

8 pav. Šlifo nuotraukose – detritinio kvarco grūdelių tirpdinimas išilgai molio ir žėručiu praturtinto tarpsluoksnio (vaizdas poliarizacinėje šviesoje ir su poliarizacijos filtrais). Vabalų-1 gręžinys, gylis 2105 m

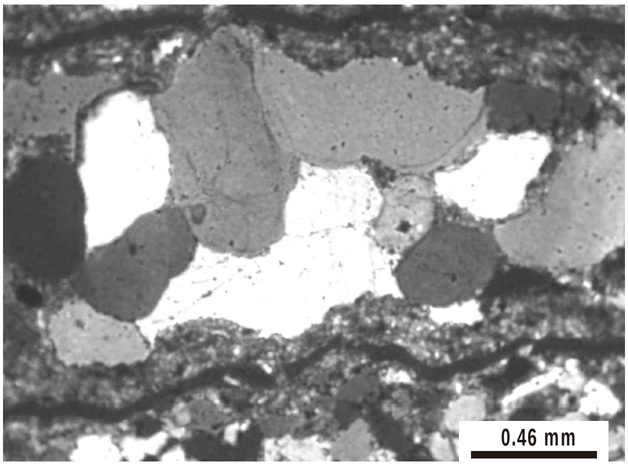

Fig. 9. Micrograph of thin section showing quartz dissolution at shale–sandstone contact surface and the formation of sutured boundaries (plane polarized light and with crossed polarization filters). Well location Šilgaliai-1, depth 2067.6 m.

9 pav. Šlifų nuotraukose – kvarco tirpdinimas argilito ir smiltainio kontakto paviršiuje bei dantytų ribų formavimasis (vaizdas poliarizacinėje šviesoje ir su poliarizacijos filtrais). Šilgalių-1 gręžinys, gylis 2067,6 m

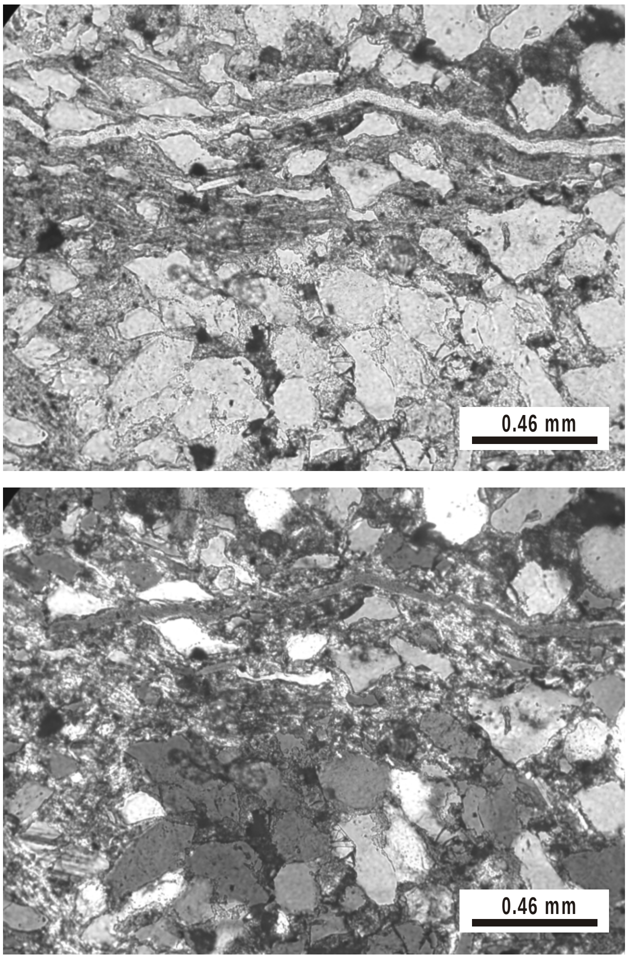

Fig. 10. Micrographs of thin section, showing dissolution of quartz in clay-enriched layers. Quartz grains are largely dissolved with only small detrital grain fragments left (top – plane polarised light; bottom – idem with crossed polarization filters). Well location Pašaltuonis-94, depth 1646 m

10 pav. Pašaltuonio-94 gręžinio šlifo nuotraukos, gylis 1646 m. Kvarco grūdelių tirpdinimas moliu praturtintuose sluoksniuose; grūdai stipriai aptirpę, likę nedideli detritinių grūdų fragmentai (vaizdas poliarizacinėje šviesoje ir su poliarizacijos filtrais)

The intensity and extent of dissolution left only fragments of detrital quartz grains (Fig. 10). The solubility of quartz at mica–quartz and clay–quartz interfaces adjoining stylolites appears to be more enhanced (Fig. 7) than at quartz–quartz grain contacts. The latter are point contacts indicating that intergranular pressure solution was absent. It appears that clay or phyllosilicate induced pressure solution of detrital quartz took place before the true penetrative stylolititization or intergranular pressure solution could start. The volume of dissolved detrital quartz in West Lithuania is estimated in the range of 20–25%, in some places even larger.

Detailed analyses of facies and petrophysical properties show that sandstone intervals containing a thin shale lamina are more intensely quartz-cemented and have a lower porosity than thick sandstone bodies without shale intercalations (Fig. 11). Lithofacies changes

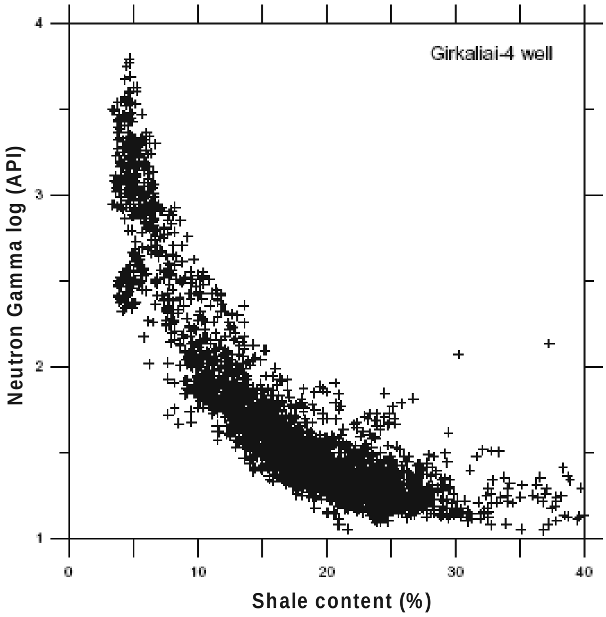

Fig. 11. Neutron gamma log *versus* shale content (from natural gamma logs). Graphs of dry well Girkaliai-4

11 pav. Neutrono gama metodo kreivės ir molingumo (iš gama metodo kreivės) priklausomybė Girkalių-4 gręžinyje

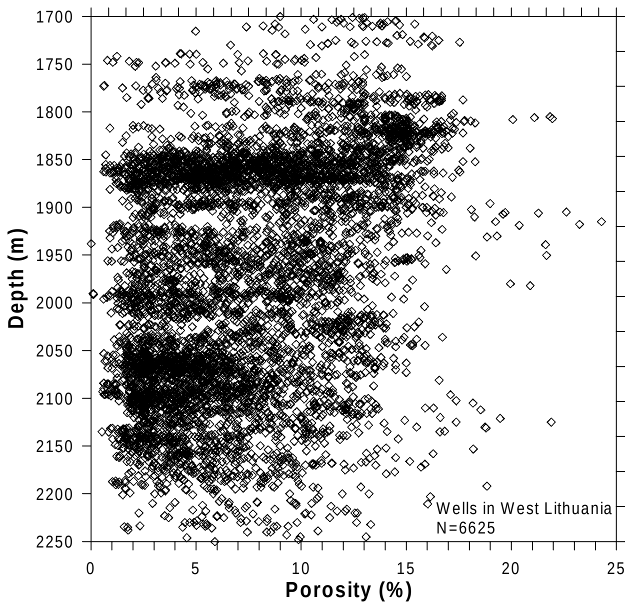

Fig. 12. Porosity *versus* depth for selected oilfields in West Lithuania

12 pav. Poringumo ir gylio priklausomybė pasirinktuose Vakarų Lietuvos naftos telkiniuose

are minor within particular structures. However, even small synsedimentary variations have a considerable impact on the rate of quartz cementation.

Petrophysical properties

In the study area, the top of the Cambrian succession occurs at a depth of 1700 up to 2230 metres. Its petrophysical properties show a rather large range in values (Table 3). The porosity of the sandstones varies

Table 3. **Average values, standard deviation and range of main petrophysical properties for all wells with the Cambrian succession below the depth of 1700 m (West Lithuania)**
3 lentelė. **Kambro uolienų, slūgsančių giliau nei 1700 m, kolektorinių savybių statistikos rodikliai (Vakarų Lietuva)**

	Porosity (%)	Horizontal permeability (mD)	Vertical permeability (mD)	Grain density (kg/m^3)
Average	7.47	51.499	40.833	2412
Standard deviation	4.15	144.581	113.434	101
Minimum	0.01	0.001	0.001	2121
Maximum	24.29	2153	1871	2702
Number	6658	5628	4936	6580

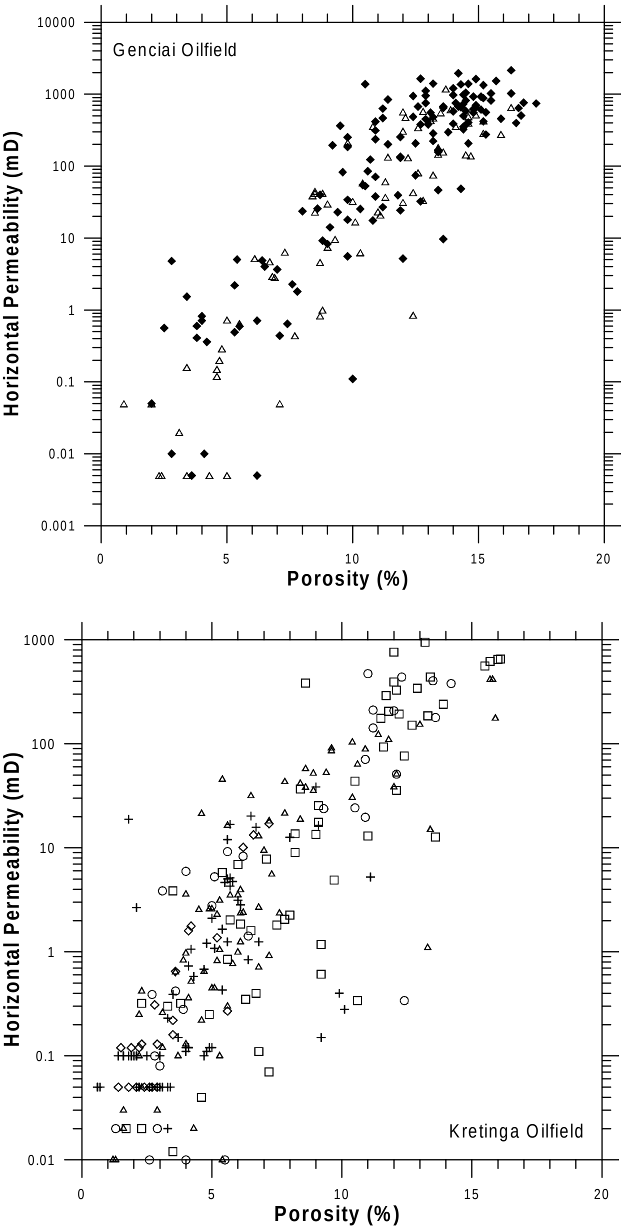

Fig. 13. Example from Kretinga and Genčiai oilfields showing that porosity values vary even among closely spaced wells within single oilfields or dry fields. Symbols show different wells within single oilfield
13 pav. Poringumo reikšmių kaita Kretingos ir Genčių naftos telkiniuose. Simboliais nurodyti skirtingi gręžinių numeriai naftos telkinyje

from 0.01 to 24.29% with an average of 7.47%. The average is close enough to the porosity of 9.2% predicted using existing models such as by Scherer (1987) (corrected for cement). The horizontal permeability ranges from 0.001 to 2152 around an average of 51 mD. The main properties show a wide scatter, and only a weak correlation with burial depth or temperature exists. The maximum porosity and permeability decrease with increasing depth or temperature (Fig. 12).

Towards the east, with decreasing burial depth, the amount of quartz cement decreases drastically, and the porosity is up to 20–25% with a permeability of 100–2300 mD in the shallow eastern part of the basin (Vosylius, 1998 and 2000). All stratigraphic levels show the same pattern (Vosylius, 2000).

Also on a local scale, the main petrophysical properties, such as porosity and permeability, have a complicated variability, even within a single oilfield, making the exploration of the reservoir and construction of its models difficult. Closely spaced wells within a single oilfield may have different reservoir quality (Fig. 13).

Although the succession is relatively simple, composed of sheet-like sandstone beds and amalgamated bodies separated by shales and shaly sandstones, and individual oilfields can be described as layer-cake reservoirs (Weber and Geuns, 1990), there is a distinct vertical and lateral variability in petrophysical properties and lithology, namely the sandstone/shale ratio. In particular, the properties vary greatly in the vertical sense within the reservoir succession in a particular field, but also within individual sandstone bodies building up the reservoir. However, the properties are clearly related to shale content and thus to depositional facies (Fig. 10, Table 4), and this must be explained in terms of the processes involved and the controls on quartz cementation. The shale content is related to porosity as shown by the increasing porosity from neutron gamma logs with increasing natural gamma ray readings. The porosity decreases with increasing shale content (derived from natural gamma ray logs) (Fig. 14).

DISCUSSION

Any model for quartz cementation must be able to explain a set of general observations: the onset of quartz

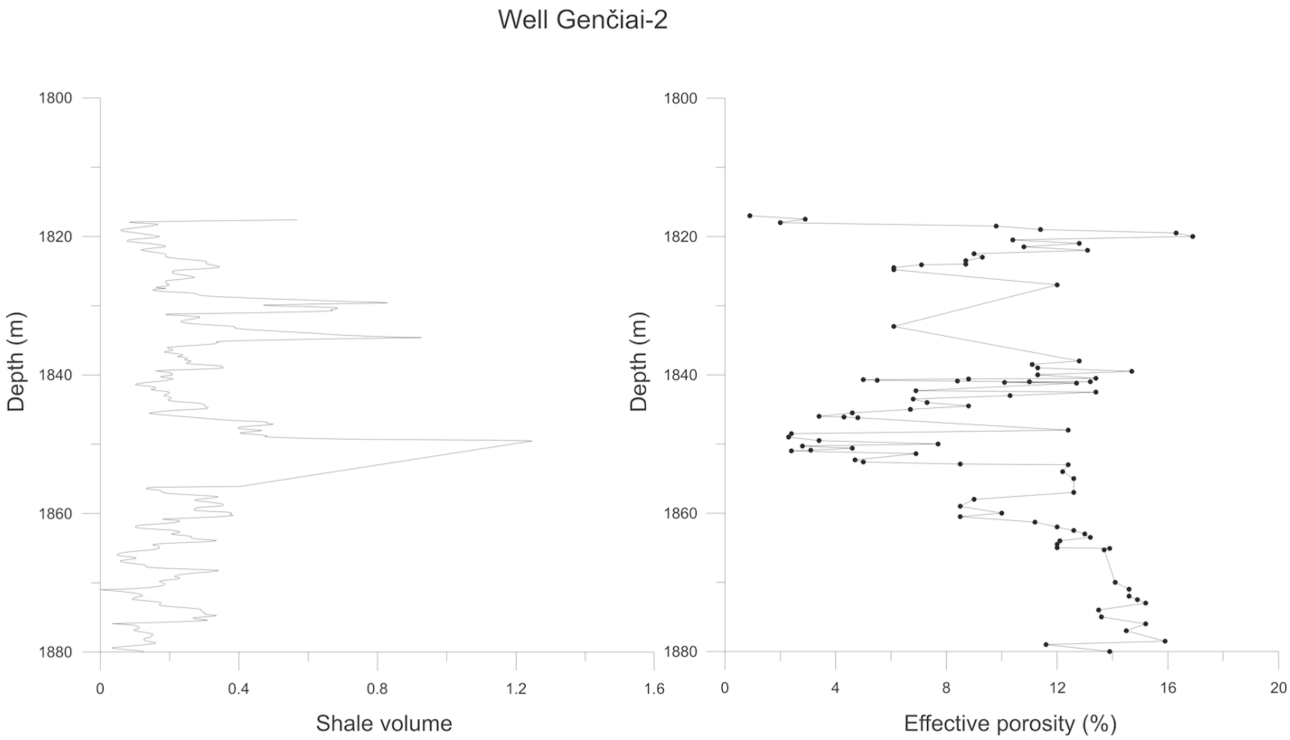

Fig. 14. Graphs of well Genčiai-2 showing porosity decrease with increasing shale volume (shale volume from natural gamma log recalculated for sandstone facies). Intervals containing thin shale laminas in the sandstones are more intensely quartz-cemented than thick sandstone bodies without shale intercalations

14 pav. Poringumo ir molingumo priklausomybė Genčių-2 gręžinyje: didėjant molingumui poringumas mažėja (smiltainio facijų molingumo reikšmės apskaičiuotos iš gama metodo kreivės). Smiltainio intervalai su plonais molio tarpsluoksniais stipriau sucementuoti kvarciniu cementu nei masyvus smiltainis be molio tarpsluoksnių

Table 4. **Property ranges and variations for the main sandstone lithofacies**
4 lentelė. **Smiltainio litofacijų kolektorinės savybės**

Sandstone lithofacies		Porosity (%)	Vertical permeability (mD)	Horizontal permeability (mD)
S1	Average	7.37	139.112	53.783
	Standard Deviation	5.61	254.682	120.987
	Minumum	0.66	0.015	0.001
	Maximum	26.69	873.046	672.932
	N	49	10	35
S2 + S3	Average	4.75	2.004	0.632
	Standard Deviation	1.98	3.720	2.048
	Minumum	2.50	0.015	0.018
	Maximum	10.24	8.630	8.000
	N	16	5	15

cementation at certain advanced temperatures, the increase in the degree of quartz cementation with T (or burial depth), the regional occurrence and the local small-scale variability in quartz cement content.

Different temperatures have been noted in various studies for the onset and main phase of quartz cementation, mainly using temperatures based on studies of fluid inclusions in quartz cement (Walderhaug, 1994). The temperature seems to vary from basin to basin and within basins. Temperature, which is merely a function of burial depth and varies according to a local geothermal gradient and tectonic setting, therefore in itself may not be that important. Instead, it implies that other variables related to burial depth such as pressure or effective pressure, a more independent variable, are more important than temperature. Effective pressure varies also with the texture of the sandstone and the general architecture of the succession and overpressured conditions. This may explain regional variations in burial depth and the onset of quartz cementation, but still cannot explain the observed local variation in the amount of quartz cement.

The general trends of increasing quartz cement content with increasing the burial depth as in the North

Sea (Ramm, 1992) and Baltic Basin (Cyziene et al., 2001; Šliaupa et al., 2004) suggests that an increase of temperature and the associated reaction rates or of (effective) pressure, *i.e.* physical conditions related to burial depth, are involved in the rate of quartz cementation. In the Cambrian sandstones, more distinct is the variation of porosity values found at any depth range. It is evident that temperature variations cannot cause such small-scale variability, indicating that factors other than general physical and chemical conditions related to burial depth, including temperature, effective pressure and pore water chemistry, are also involved in quartz cementation.

The regional and local distribution and amount of quartz cement, and inversely its porosity, point to general confining physical and/or chemical conditions or thresholds for quartz cementation. Of importance is the fact that although quartz cement is regionally widespread, it is only a dominant feature in areas where present-day temperatures in the Cambrian are over 50 to 90 degrees. This indicates that conditions defined by temperature or depth, both showing a positive and significant correlation in Lithuania, form a threshold to quartz cementation. However, this cannot explain the local variation, which is even more typical and evident than the general trend. The local quartz cement variability, however, is more likely to be linked to a small-scale variability in sedimentary parameters probably associated with depositional facies. These local factors are, however, a dominant control of the distribution and quantity of quartz cement.

Contradictory results exist about the various mechanisms involved in quartz cementation, comprising silica generating processes, transport mechanism, and precipitation. Transport mechanism and silica source are interdependent processes and need to be fully understood for predicting the amount of quartz cement in potential reservoir sandstones. At least the physical constraints need to be known for translating standard available data during exploration of production planning into reservoir models.

External sources of silica implicitly need a flow of diagenetic fluids and transport mechanisms that are difficult to explain. Silica from internal or adjacent sources may be transported to the precipitation site by mere diffusion, only needing a gradient in the chemical potential (Sheldon et al., 2003). Diffusion of silica avoids the difficulties of large-scale transport, and potentially opens a wider diagenetic window during burial history solely related to the existence of chemical gradients. In fact, only local supply of silica can explain the regional occurrence of quartz cement and the fact that thinner sandstone layers or intervals with a lower hydraulic conductivity are most intensely quartz-cemented.

Pressure solution has been recognized as a potential internal source of silica. This process usually takes place in deeply buried sandstones in the form of intergranular solution, stylolitization, and through clay-induced pressure solution but in less deep burial conditions.

Grain to grain pressure solution will be dependent not only on effective stress but also on detrital texture and detrital composition, the variability of which may cause local changes related to facies, and this process could be active within a range of burial depths. In general, IGV of sandstones do not correlate positively with quartz cement as would be expected in case of intergranular pressure solution generating silica for quartz cement (Paxton et al., 2002), suggesting other main sources for silica. IGV in fact negatively correlates with quartz cement in Cambrian sandstones, suggesting that quartz cement started at different times, which is confirmed by burial history modelling (Fig. 2), and halted the further mechanical compaction. The fact that with decreasing IGV less quartz cement is found in the Deimena sandstone points against intergranular pressure solution as a source of silica.

Stylolites have been described in sandstones including quartzose arenites and quartzarenites, but seem to be restricted to a relative deep burial. On the other hand, the possibility of clay promoting process of pressure solution has been studied by a number of researchers. Penetrative stylolites have been suggested by Bj¸rkum (1996) and Walderhaug (1996) as a silica source. True stylolites are present but only in the deepest wells. In fact, most of these stylolites concentrate along a thin shale lamina. Dissolutional features of detrital grains commonly occur along shale–sandstone contacts and within shales with detrital quartz grains show partial dissolution.

Presence of clay has been long recognized as promoting pressure solution (Heald, 1956; Thomson, 1959; Weyl, 1959; Saibley & Blatt, 1976). Heald (1956) suggested that clay simply acts as a catalyst. Weyl (1959) advanced the idea about solution favoured by a greater diffusion through clay between grains, which has been confirmed by later studies (Renard et. al., 1997; Renard & Ortoleva, 1997). The thickness of water films at grain contacts and the pressure play a crucial role in the process (Renard et al, 2000). The pH may play a role since it determines the surface charge of minerals and the thickness of water films. At low temperatures the reaction kinetics is slow and limits the process, whereas at increased burial depths and increased pressure, diffusion is a limiting factor because of thinning of water films, and finally at a burial depth of more than 3 to 4 km the process is expected to cease (Renard et al., 1997; Renard & Ortoleva, 1997; Alcantar et al., 2003).

Pressure solution could generate silica, but its occurrence, its onset and final effects are not only dependent on the effective stress but evidently are also expected to be related to the depositional facies, with clay-induced pressure solution more prominent in sandstones with interbedded or interlaminated shales. In discrete pressure solution, long penetrative stylolites appear active at a later stage during a deeper burial.

The scale at which quartz dissolution has occurred at lithological interfaces and within sandy-silty shales suggest that the clay-induced pressure solution with its characteristic sutured boundaries might have been a source of the bulk of silica cement found on quartz grains in sandstones. Thus, the silty-sandy shale layers were efficient silica exporters to the neighbouring well-sorted sandstones, the clay minerals enhancing quartz dissolution and inhibiting local quartz precipitation. The water-film diffusion (WFD) mechanism is likely the main operative in the clay-enriched portion of sandstone. Clay minerals are capable of promoting mineral dissolution through water film diffusion because of the thick water film that can be preserved at their surfaces among grain contacts (Renard & Ortoleva, 1997; Renard et al, 2000). This is coupled to the large surface area and the structural electric charges spread on the surface of clay minerals, which stabilize the water film and allow the solutes to diffuse easily to adjacent pores.

Without giving evidence, Füchtbauer (1979) suggested that cementation of sandstones adjacent to shales is more intense. Some evidence has been presented later to support this by Sullivan & McBride (1991). However, they mainly showed the distribution of chlorite cement to be related to the distance to shales. Beside grain pressure solution in shales, other processes such as illitization of smectites, organic matter maturation and associated organic acids from the shales could play a role in sandstone cementation. Export of silica to adjacent sandstones is probably a function of shale thickness (Wintsch & Kvale, 1994) and thus of the architecture of the siliciclastic succession.

Evidence from the Cambrian shows clay-induced pressure solution of detrital quartz at shale–sandstone contacts and within thin shale lamina to be the main process locally yielding silica for quartz cementation but operating on a regional scale. The supply of silica for quartz cement in the sandstones is thus dependent on the number of thin clay lamina and clay intercalations within the reservoir sandstones. The sandstone/shale ratio and the thickness of sandstone bodies control the location and degree of quartz cementation and thus the reservoir quality.

Pressure solution is determined by temperature but mainly by effective pressure and sediment texture. Variation in the latter and the occurrence of overpressured zones in many basins may explain the observed general variation in temperatures of quartz cementation shown by oxygen isotope studies and fluid inclusion studies of quartz cement (*e.g.*, Walderhaug, 1994; Haszeldine et al., 2000).

CONCLUSIONS

The Cambrian marine sandstone bodies are complex sedimentary successions composed of sandstones and shales with variable lithological architecture. Clay-induced chemical compaction and pressure solution of detrital quartz at shale–sandstone contacts and within thin shale lamina was the main process yielding silica for local quartz cement. The exact nature of the sandstone–shale alternation controls the potential amount of quartz cement generated through clay-induced pressure solution. The general physical conditions, mainly in terms of effective pressure, constrain the onset of the pressure solution. The sandstone/shale ratio and the thickness of sandstone bodies locally control the degree of quartz cementation and thus the reservoir quality.

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MOLIO ĮTAKA KAMBRO DEIMENOS SERIJOS SMILTAINIŲ KVARCO CEMENTACIJAI

S a n t r a u k a

Vakarų Lietuvos kambro uolienas sudaro kvarcinis smiltainis, molis ir aleurolitas. Vidurinio kambro Deimenos serijos smiltainiuose yra surasta 18 naftos telkinių su labai sudėtingu kolektorinių savybių pasiskirstymu, apsunkinančiu angliavandenilių paiešką ir gavybą. Regeneracinis kvarcinis cementas, pasižymintis

atvirkščia poringumo ir skvarbumo koreliacija, turi didžiausią įtaką smiltainių kolektorinėms savybėms. Autigeninio kvarco kiekis Vakarų Lietuvos Deimenos serijos smiltainiuose kinta nuo 18 iki 33%. Regioniniu mastu apkvarcėjimo procesus nulemia slėgio ir temperatūros pokyčiai, tačiau šie parametrai negali paaiškinti labai kaitaus cementacijos laipsnio atskiruose gręžiniuose ir lokaliuose plotuose, kur autigeninio kvarco kiekis kinta nuo 28–33% iki 8–12% (poringumas atitinkamai kinta nuo 3–6% iki 12–14%). Detalūs petrografiniai tyrimai rodo, kad sukvarcėjimo intensyvumas tiesiogiai priklauso nuo kolektoriaus sinsedimentacinių ypatumų. Smiltainio intervaluose, kuriuose yra daugiau molingų sluoksnelių ir būdinga smulkiai horizontaliai sluoksniuota tekstūra, sukvarcėjimo intensyvumas yra didesnis nei masyviame smiltinyje. Detritinių kvarco grūdų tirpimas (cheminis sutankėjimas) smiltainio ir molio kontaktuose yra pagrindinis silicio šaltinis. Molingų sluoksnelių ir smiltainio kontaktuose formuojasi stilolitai, kurie yra silicio šaltiniai ir turi įtakos cementacijos procesams. Petrografinių tyrimų duomenimis, būtent čia vyksta intensyvus kvarco grūdelių tirpimas. Šis sąryšis patvirtina vietinį silicio šaltinį kambro smiltainiuose, o difuzija čia yra pagrindinis procesas perskirstant ištirpusį silicį gretimuose smiltainiuose. Taigi formuojant kambro kolektorių modelius, pagrindinis dėmesys turi būti skiriamas sinsedimentacinių uolienų ypatumų analizei (smiltainio ir molio santykiui, smiltainio storiui, litofacijoms).

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ÐÀÑÒÂÎÐÅÍÈÅ, ÑÂßÇÀÍÍÎÅ Ñ ÃËÈÍÈÑÒÛÌ ÂÅÙÅÑÒÂÎÌ, ÊÀÊ ÈÑÒÎ×ÍÈÊ ÊÐÅÌÍÅÇ¨ÌÀ ÄËß ÊÂÀÐÖÅÂÎÉ ÖÅÌÅÍÒÀÖÈÈ ÊÅÌÁÐÈÉÑÊÈÕ ÏÅÑ×ÀÍÈÊÎÂ ÄÅÉÌßÍÑÊÎÉ ÑÅÐÈÈ

Ðåçþìå

Êåìáðèéñêèå îòëîæåíèÿ Çàïàäíîé Ëèòâû ñëîæåíû êâàðöåâûìè ïåñ÷àíèêàìè, àðãèëëèòàìè è àëåâðîëèòàìè. Â ïåñ÷àíèêàõ ñðåäíåãî êåìáðèÿ Äåéìÿíñêîé ñåðèè íàéäåíî 18 íåôòÿíûõ ìåñòîðîæäåíèé, êîòîðûå îòëè÷àþòñÿ êîëëåêòîðñêèìè ñâîéñòâàìè. Ðàçíîîáðàçèå ýòèõ ñâîéñòâ îñëîæíÿåò ïîèñê è äîáû÷ó íåôòè. Ðåãåíåðàöèîííûé êâàðöåâûé öåìåíò, êîòîðûé èìååò îáðàòíóþ êîððåëÿöèþ ñ ïîðèñòîñòüþ è ïðîíèöàåìîñòüþ, îêàçûâàåò áîëüøîå âëèÿíèå íà êîëëåêòîðñêèå ñâîéñòâà ïåñ÷àíèêà. Êîëè÷åñòâî êâàðöåâîãî öåìåíòà â ïåñ÷àíèêàõ Äåéìÿíñêîé ñåðèè Çàïàäíîé Ëèòâû ìåíÿåòñÿ ñ 18 äî 33%. Â ðåãèîíàëüíîì ïëàíå ïðîöåññ êâàðöåâàíèÿ çàâèñèò îò äàâëåíèÿ è òåìïåðàòóðû. Îäíàêî ýòè ïàðàìåòðû íå ìîãóò îáúÿñíèòü ðåçêóþ ñìåíó öåìåíòàöèè â îòäåëüíûõ ñêâàæèíàõ è íà ëîêàëüíûõ ïëîùàäÿõ, â êîòîðûõ ñîäåðæàíèå êâàðöåâîãî öåìåíòà ìåíÿåòñÿ ñ 28–33 äî 8–12% (ïîðèñòîñòü ñîîòâåòñòâåííî ìåíÿåòñÿ ñ 3–6 äî 12–14%). Äåòàëüíûå ïåòðîãðàôè÷åñêèå èññëåäîâàíèÿ ïîêàçûâàþò, ÷òî èíòåíñèâíîñòü êâàðöåâàíèÿ ïðÿìî çàâèñèò îò ñèíñåäèìåíòàöèîííûõ îñîáåííîñòåé êîëëåêòîðà. Â èíòåðâàëàõ ïåñ÷àíèêîâ ñ ïîâûøåííûì ñîäåðæàíèåì ãëèíèñòûõ ïðîñëîåâ, äëÿ êîòîðûõ õàðàêòåðíà ìåëêàÿ ãîðèçîíòàëüíàÿ ñëîèñòîñòü, èíòåíñèâíîñòü êâàðöåâàíèÿ çíà÷èòåëüíî áîëüøå, ÷åì â ìàññèâíûõ ïåñ÷àíèêàõ. Ðàñòâîðåíèå äåòðèòîâûõ çåðåí êâàðöà (õèìè÷åñêîå óïëîòíåíèå), ïðîèñõîäÿùåå ïðè êîíòàêòå ïåñ÷àíèê–ãëèíà, ÿâëÿåòñÿ îñíîâíûì èñòî÷íèêîì êðåìíåçåìà. Ïðè êîíòàêòàõ ãëèíèñòûõ ïðîñëîåâ è ïåñ÷àíèêîâ îáðàçóþòñÿ ñòèëîëèòû, êîòîðûå ÿâëÿþòñÿ èñòî÷íèêàìè êðåìíåçåìà è âëèÿþò íà ïðîöåññ öåìåíòàöèè. Ïî äàííûì ïåòðîãðàôè÷åñêèõ èññëåäîâàíèé èìåííî çäåñü ïðîèñõîäèò èíòåíñèâíîå ðàñòâîðåíèå êâàðöåâûõ çåðåí. Ñâÿçü ýòèõ ïðîöåññîâ ïîäòâåðæäàåò ìåñòíûé èñòî÷íèê êðåìíåçåìà â êåìáðèéñêèõ ïåñ÷àíèêàõ, à äèôôóçèÿ çäåñü ÿâëÿåòñÿ îñíîâíûì ïðîöåññîì ïåðåíîñà ðàñòâîðåííîãî êðåìíåçåìà â áëèæàéøèå ïåñ÷àíèêè. Àâòîðû ïðèøëè ê âûâîäó, ÷òî ïðè ôîðìèðîâàíèè ìîäåëè êåìáðèéñêèõ êîëëåêòîðîâ îñíîâíîå âíèìàíèå äîëæíî áûòü óäåëåíî ñèíñåäèìåíòàöèîííûì îñîáåííîñòÿì ïîðîä (ñîîòíîøåíèå ïåñ÷àíèêà–ãëèíû, ìîùíîñòü ïåñ÷àíèêîâ, ëèòîôàöèè).