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Syn-Depositional, Diagenetic and Petrophysical Characterization of the Cambrian Reservoir of Lithuania along a Regional East-West Scale-Profile

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The Cambrian represents one of most the important geological-economic bodies in the Baltic region, providing drinking water in shallow setting (a few hundred meters depth), gas storage at depths of about 1 km. Oil deposits have been discovered in three geological complexes: Cambrian, Ordovician and Silurian. The main oil-producing layers in the Baltic basin are confined to the Cambrian of western Lithuania. Cambrian is regarded as a prospective hydrothermal and mineral water reservoir. Temperature ranges from 7-9 ºC in the east to 90-100 ºC in the western Lithuania, it associates with increasing water salinity from <1 g/l in the east to 200 g/l in the west. The temperature increase is related both to increasing depth of the Cambrian reservoir and increasing heat flow, accordingly from 38-40 mW/m^2 to 80-95 mW/m^2.

The Baltic basin (Fig. 1) represents an excellent natural laboratory to study diagenetic and reservoir quality changes from shallow (dozens of meters) to deep (>2 km) reservoir, study of which can considerably contribute to improve existing siliciclastic reservoir models.

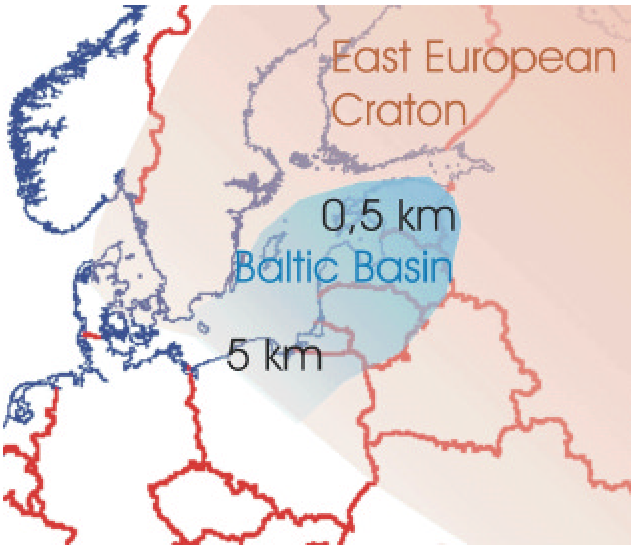

Figure 1. Location of the cambrian Baltic basin.

Porosity and permeability of siliciclastic sandstones are a function of both depositional and postdepositional or diagenetic processes. Theoretically, porosity is independent of grain size for uniformly packed and graded sand, but in practice, coarser sand sometimes have higher porosities than finer sands or conversely. This disparity may be due to separate but correlative factors such as sorting and cementation.

Permeability declines with decreasing grainsize, because pore diameter decreases and hence cappilary pressure increases. Thus a sandstone may have porosities of 10 percent or more. Whereas the former may be a permeable reservoir, the latter may be an impermeable cap rock. Porosity increases with improved sorting. As sorting decreases, the pores between the larger, framework-forming are infilled by the smaller particles. Permeability decreases with sorting for the same reason. Sorting sometimes varies with the grain size of a particular reservoir sandstone, thus indicating a possible correlation between porosity and grain size.

The texture of sediment is closely correlated with its porosity and permeability. The texture of a reservoir rock is related to the original depositional fabric of the sediment, which is modified by subsequent diagenesis. This diagenesis may be trivial in many sandstones, but in carbonates it may be sufficient to obliterate all traces of original depositional features.

However, diagenesis starts immediately and bioturbation clay infiltration and early cementation-dissolution processes start. These may depend on detrital mineralogy, and net sedimentation rates.

Depositional processes determine sedimentary structures and textures, whereas these primary textures afterwards are modified by diagenetic processes as a consequence of changes in physical and chemical conditions during burial. On a general level, based on the burial and thermal history of a basin and the stratigraphic position of the reservoir sandstone involved, its petrophysical properties are often gradually changing according to depth and age dependent trends. This allows prediction of permeability and porosity (and also density, acoustic velocity etc.) on a general level. Porosity of sandstones in the Baltic basin flanks is around 25-30 % and systematically decreases to the west to 15-18 % in the central Lithuania and 2-4 % in western Lithuania. This is mainly due to late diagenetic cementation, essentially secondary quartz as in the western Lithuania.

However, such models are case sensitive because they are based on data being specific for certain basins and stratigraphic levels. These empirical models usually correctly describe the general tendencies, such as a decrease of porosity and permeability with increasing burial depth and geological age. However, a large variation in properties is superposed on the general trends, inhibiting precise numerical prediction or interpolation.

Factors like burial depth and formation age are thus usually incorporated in the models, which tend to predict that Paleozoic sandstones and sandstones buried deeper than about 3 km do not have high reservoir potential anymore. However, Cambrian sandstones in the Baltic region are a good example of old and deeply buried sandstone with sizable reservoir quality. It is thus clear that existing models need some revision.

Cambrian deposits represent the basal portion of the Baltic sedimentary basin. The depth systematically increases from several meters in Estonia to more than 2 km in western Lithuania. This is associated with significant syn-depositional and essentially diagenetic changes across the basin. The thickness of Cambrian rocks ranges from several meters in the east and north to 150 m in the west of Lithuania. They are represented by alternation of sandstone, siltstone and claystone, which show different proportions across the basin.

The aim of study is recognition of those combined petrophysical-lithological transitions.

Lithology and cementation are factors controlling reservoir properties of the Cambrian in the Baltic basin. Cambrian sandstones are mainly composed of quartz (95-99%). Feldspar does not exceed 1-5%. Close to the high emerging drape structures of the basement, some wells show feldspar content of up to 30%. Sandstones are mostly fine-grained, quartz graines are well rounded, medium-sorted and poor-sorted. Sandstones are cemented by secondary quartz, which dominates central and western lithofacies. Three dominant types of cement – quartz, quartz-dolomite, dolomite are documented in sandstones and siltstones. Quartz is mainly related to sandstones and it is not common in siltstones where dolomite and clay are the representative cement. Quartz solution and precipitation took place at burial of Cambrian rocks. Still, in some layers the cement is dominated by early-diagenetic quartz, someplace filling up all the pores. Its origin can be related to the Late Cambrian uplift and exposure of siliciclastic and infiltration of meteoritic water.

The carbonate cement dominates in the flanks of the basin, some places constituting 20-35% of rock volume thus reducing pore space to nearly zero. With increasing depth its content in sandstones decreases, averaging 1-5% in western Lithuania. The local distribution of carbonates is highly variable relating to post-depositional redistribution which associates with variations in reservoir properties.

Samples were collected from two basin-scale profiles, one E-W and one N-S, from the shallow basin flanks to the deep basin center. Lithologies of Cambrian change considerably across the basin. The west-east cross-section of Cambrian rocks across Lithuania are represented by alternation of sandstone, siltstone and claystone, which show different proportions across the basin (Fig. 2). The diagenetic sequence of Cambrian siliciclastics in the eastern and central Baltic basin comprises early, middle and late diagenetic minerals.

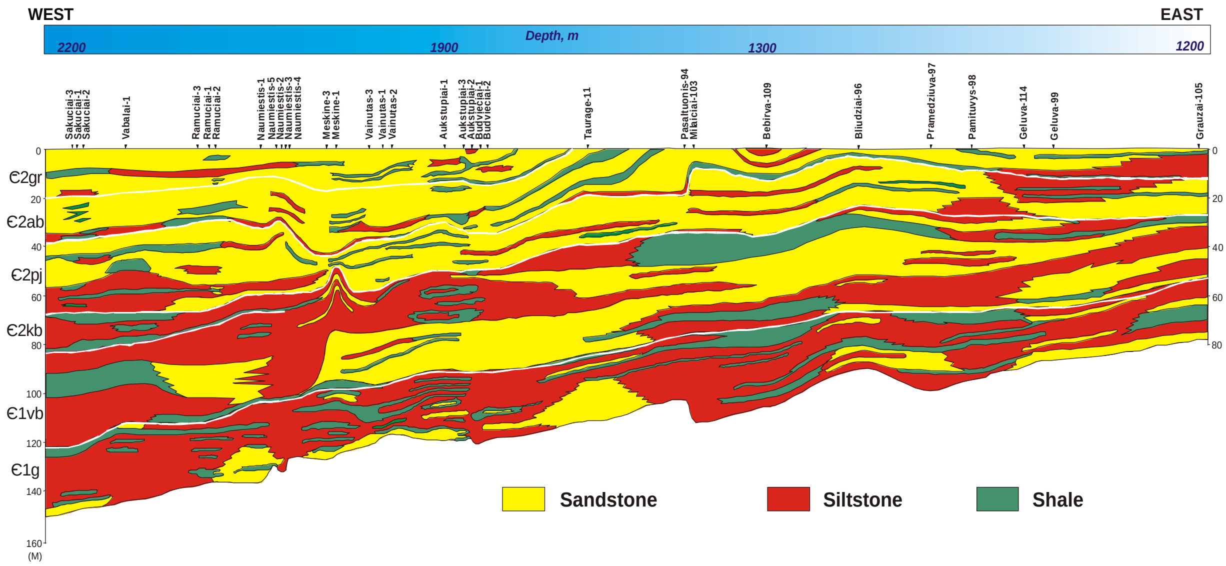

Figure 2. West-East cross-section through the Cambrian, Lithuania.

Due to complex basin history, reservoir properties of the Cambrian changes considerably. Porosity of sandstones in the basin flanks is around 25-30 % and systematically decreases to the west down to 15-18 % in the central Lithuania and 2-4 % in western Lithuania (Fig. 3). This is accounted mainly to late diagenetic cementation, essentially secondary quartz in the western Lithuania. Gas (helium) permeability shows depth – controlled changes (Fig. 4). At the depth of 1000 – 1800 m it remains rather stable clustering around 0.5-1 D. It sharply decreases from 10^{-1}D to 10^{-5}D bellow the depth of 1800m. The density of sandstones changes from shallow to deep accordingly from 1.92 g/cc to 2.7 g/cc. Four depth zones are recognized in the clay rock density variations (from few hundred meters to > 3 km) that is largely accounted to mineral composition changes of diagenetic nature. Seismic velocities increase accordingly from 1.8 to 5.9 km/s.

The other dominant factor of statistical significance was referred to as “iron minerals”, having the strongest correlation with magnetic properties of the Cambrian rocks, it also relates positively to clay and dolomite elements.

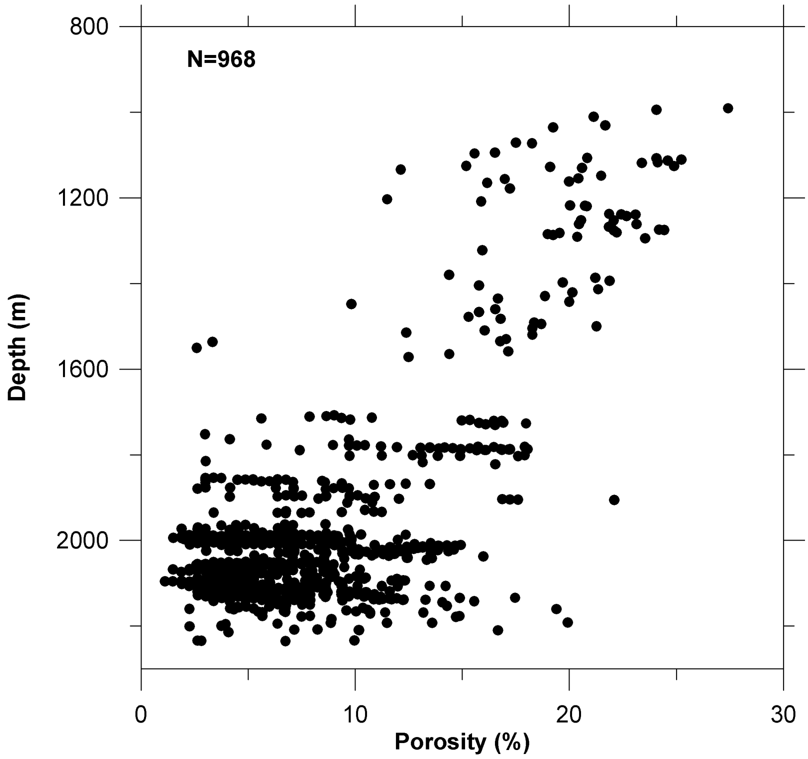

Figure 3. Porosity versus burial depth.

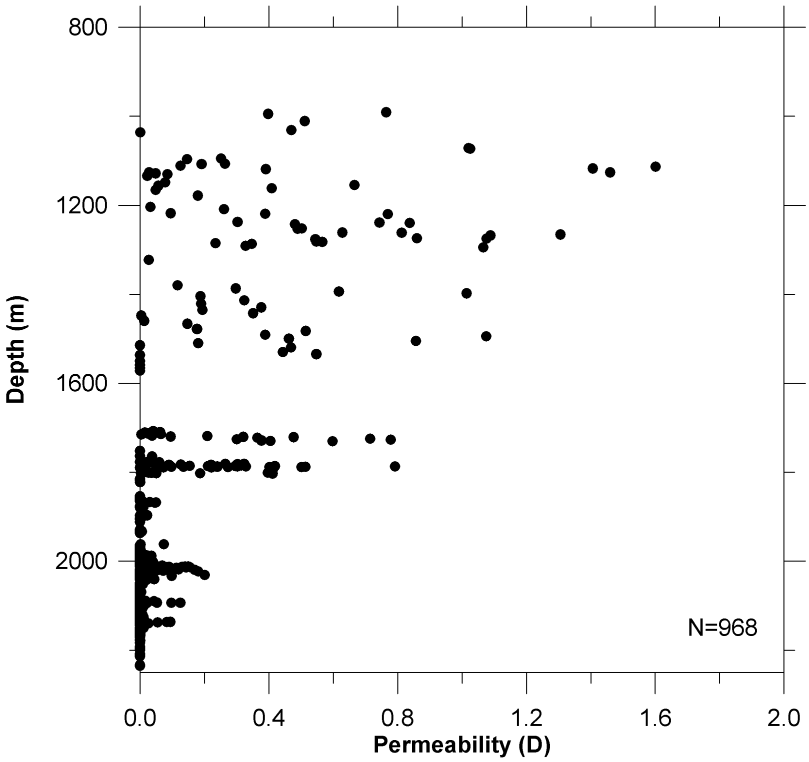

Figure 4. Permeability versus burial depth.

The closest correlation of iron content was stated for magnetic susceptibility (correlation R=0.88, Fig. 5). Claystones and siltstones show slight paramagnetic properties, ranging from 1 to $30*10^{-5}$ SI . The majority of western Lithuanian sandstones are diamagnetic (0 to $-2*10^{-5}$ SI) which is typical for quartz dominated rocks. Only sandstones containing an increased amount of clay, dolomite and ferric minerals show paramagnetic features. By contrast, the central Lithuanian sandstones are commonly paramagnetic. This associates with slight enrichment in iron content of central sandstones by comparison to western sandstones. A difference in total iron content is also of one order. This difference originally reflects syn-depositional features of the shallow to deeper parts of the basin, the syn-depositional O_2 zone confined to the basin periphery, while H_2S environment dominated further west.

The magnetic properties of Cambrian rocks are closely related to the porosity variations. Fig. 6 shows magnetic susceptibility versus porosity. The former correlation is explained in terms of higher content of diagenetic quartz in less siliciclastic sandstones. Also the eastern porosity facies has more dolomite cement in sandstones which has higher magnetic susceptibility.

It is suggested that besides the general physical and chemical conditions, acting on basin scale, also the textures, structures, internal build up and architecture of reservoir bodies play an important role in controlling-constraining diagenetic processes (cementation, compaction, dissolution). Mechanical compaction is but one of the processes acting on primary properties. Other main processes are precipitation of quartz, carbonates etc. often causing lithification by physically connecting individual grains (cement).

In order to make models less case sensitive, it would be necessary to involve the geological-diagenetic processes in the model. The sensitivity of sandstones to mechanical compaction according to their detrital composition is a well-known example. Less well understood, but certainly as important, are the effects of texture and composition on cementation processes. The compositional dependency is due to the difference in susceptibility of clastic grains to diagenetic processes. Depositional composition is generally related to grain size distribution and thus to depositional facies, resulting in differential diagenesis.

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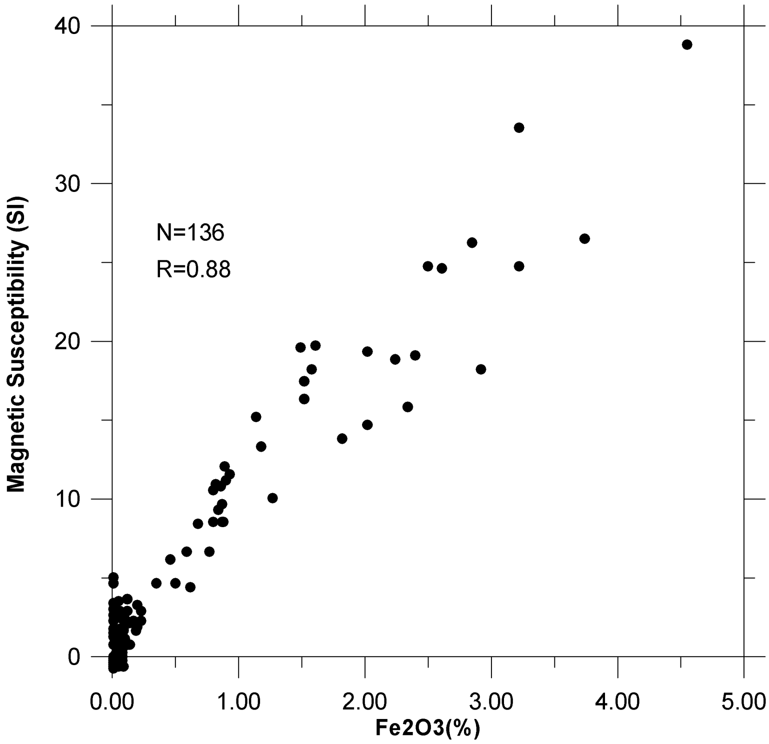

Figure 5. Magnetic susceptibility versus Fe_2O_3.

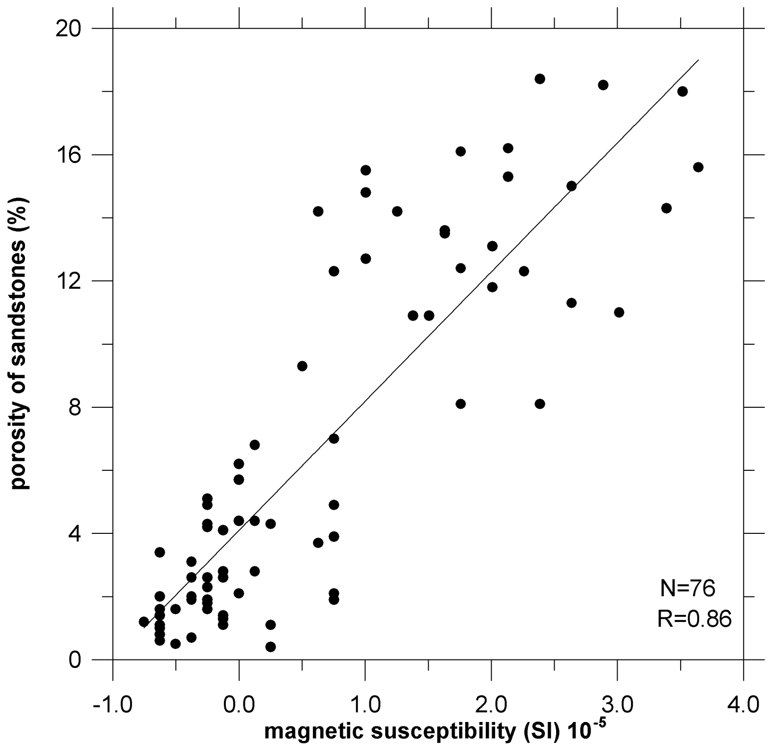

Figure 6. Magnetic susceptibility versus porosity.