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The nature of the so-called 'reefs' in the Pridolian carbonate system of the Silurian Baltic basin

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There is a growing interest in different aspects of carbonate reservoirs because of the importance of a number of large and giant carbonate oilfields in the Middle East and the Caspian Sea area. A number of these reservoirs are found in Palaeozoic carbonates. Silurian carbonates in the Silurian Baltic Basin form an excellent target for research because of the availability of numerous cores and outcrops and a limited impact of tectonic deformation in this marginal cratonic basin. This research is focused on Pridolian carbonates, including shallow to deep basin facies, in the Lithuanian subsurface. In this paper, a new opinion will be presented about the sedimentological nature of the so-called reefs in this basin. The term *reef* appears often loosely applied to different types of deposits. Although the tectonic synsedimentary setting is undoubtedly important, it is however crucial to determine the exact nature of the reefal deposits because they tend to determine the nature of the carbonate system. In case of real reefs, i. e. bioconstructed deposits with a significant relief, carbonate platforms while otherwise ramps develop. The research shows that Pridolian carbonates lack reefs since the framework-constructing fauna is absent, and probably was absent during most of the Palaeozoic. Contrary to bioherms or reefs, biostromal deposits are formed on a ramp system and appear to be one of the main carbonate-producing parts of the system. The exact importance of the different facies belts in carbonate production is difficult to assess. It is crucial to distinguish between the ramp and the platform systems because these two end member systems react differently to diagenesis which ultimately determines the petrophysical properties and thus the reservoir quality.

Key words: carbonates, reef, biostrome, ramp, Silurian Baltic Basin, Pridoli

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INTRODUCTION

There is a renewed interest in carbonate depositional systems since most of the giant oilfields are in carbonate sediments such as the well-known Saudi Arabian fields (Meyer, Price 1993; Alsharhan, Magara 1995; Alsharhan, Whittle 1995; Saner, Abdulghani 1995; Cantrell et al., 1999; Saner, Sahin 1999; Ziegler, 2001; Dasgupta et al., 2001; Wani, Al-Kabli, 2005; Swart et al., 2005) and the more recently discovered fields in and around the Caspian Sea. The giant oilfields in the latter regions occur in Palaeozoic reefal carbonates (Ulmisheck, 2001; Konyuhov, Maleki, 2006; Konyukhov et al., 2006). The understanding and prediction of the petrophysical properties relevant for hydrocarbon production are crucial for our fossil energy supply. In siliciclastic sediments, terrigenous supply and hydrodynamic conditions during deposition determine grain-size distribution and mineralogy that have the dominant impact on reservoir properties. In carbonates, these properties are far more dependent on local environmental conditions that impact on the carbonate-producing flora and fauna associations. A correct determination of these conditions and the resultant depositional facies is therefore crucial for understanding diagenesis.

Palaeozoic depositional environments are far less well known than Mesozoic and Cainozoic environments where fauna and flora assemblages are more similar to recent ones. The Silurian carbonates in the Baltic Basin are an excellent target to enhance current knowledge on Palaeozoic carbonate systems. The Silurian carbonates are cropping out extensively along the northern part of the Baltic Sea and have been studied for decades. The carbonates are extensively drilled and cored in the eastern part of the basin for hydrocarbon exploration and production in oilfields in the Middle Cambrian siliciclastic sandstones in Lithuania, Kaliningrad and Poland. Silurian shales are one of the source rocks for much of that oil (Zdanavičiūtė, Lazauskienė, 2004). Research was also targeting Ordovician and Silurian carbonates because of oil shows in Gotland and in Lithuania (Paškevičius, 1997; Zdanavičiūtė, Bojesen-Koefoed, 1997; Lapinskas, 2000; Stentoft et al., 2003).

The fact is that Silurian carbonate deposits built up by essentially stromatoporoids have been called reef in the Silurian

System Period	Series Epoch	Stage Age	Index	Regional stage	Biozones: Graptolites	Biozones: Conodonts
DEVONIAN			D_1	TILŽĖ		
SILURIAN	PRIDOLI		S_4	JŪRA		O. e.remscheidensis
				MINIJA	N.lochkovensis	O. e.eosteinhornensis
					N.ultimus-N.parultimus	
	LUDLOW	LUDFORDIAN	S_3	PAGĖGIAI	M.formosus	O.crispa
					M.valleculosus	
					M.balticus	R.dubia / O.tillmani
				DUBYSA	P.tauragensis	P.siluricus
		GORSTIAN			L.scanicus	K.variabilis
					L.progenitor	
					N.nilssoni	O.bohemica
	WENLOCK	HOMERIAN	S_2	GĖLUVA	C.ludensis	
					P.virbalensis-P.deubeli	O.siluricus
					G.nassa	
				JAAGARAHU	M.testis	K.amsdeni
					C.radians	
		SHEIWOODIAN			C.perneri	
				JAANI	M.flexilis	K.ranuliformis
					S.antennularius	
					M.riccartonensis	
					C.murchisoni	
					C.centrifugus	
	LLANDOVERY	TELYCHIAN	S_1	ADAVERE	C.lapworthi	P.amorphognathoides
					O.spiralis-M.wimani	L.celloni / P.angulatus
					M.crenulata	
					M.griestoniensis	L.pennatus
					M.crispus	A.latus
					S. turriculatus	
					R.linnaei	
		AERONIAN			M.sedgwickii	D.kentuckyensis
					D.convolutus	
				RAIKKÜLA	D.millepeda	
					M.pectinatus-D.triangulatus	
		RHUDDANIAN			C.cyphus	
				JUURU	D.confertus	O.?nathani

Fig. 1. The Silurian biostratigraphic scheme after Paškevičius (1997)
1 pav. Silūro biostratigrafinė schema pagal Paškevičių (1997)

Baltic basin. Since they are observed in a certain belt across the basin, they subsequently have been interpreted as a reef belt or barrier reef. This has been followed up by the interpretation of the whole carbonate depositional system as a platform, mainly because of the shear presence of these reefs. As innocent as it may appear, it has severe consequences for the architecture of the basin fill and its economic potential, i.e. the potential presence of hydrocarbon reservoirs. Reef deposits, using its broad and often weak definition, are main reservoir rocks, at least in Mesozoic and Cainozoic deposits, because of the presence of an aragonitic interconnected framework and because modern-like reefs build up to sea level and are thus easily pray to meteoric water influx and the development of secondary porosity during sea level changes. The question may be asked if this expectation is also true for Palaeozoic reef-like carbonates in general, and more specifically, if this may be true for the carbonates in the Silurian Baltic basin.

The focus of this study is on the Pridolian (Silurian) carbonates in the Lithuanian part of the Silurian Baltic basin. The Silurian succession in Lithuania is quite complete. The stratigraphic schema and regional stages according to biozonation of Paškevičius (1997) are shown in Fig. 1. The Silurian Baltic basin

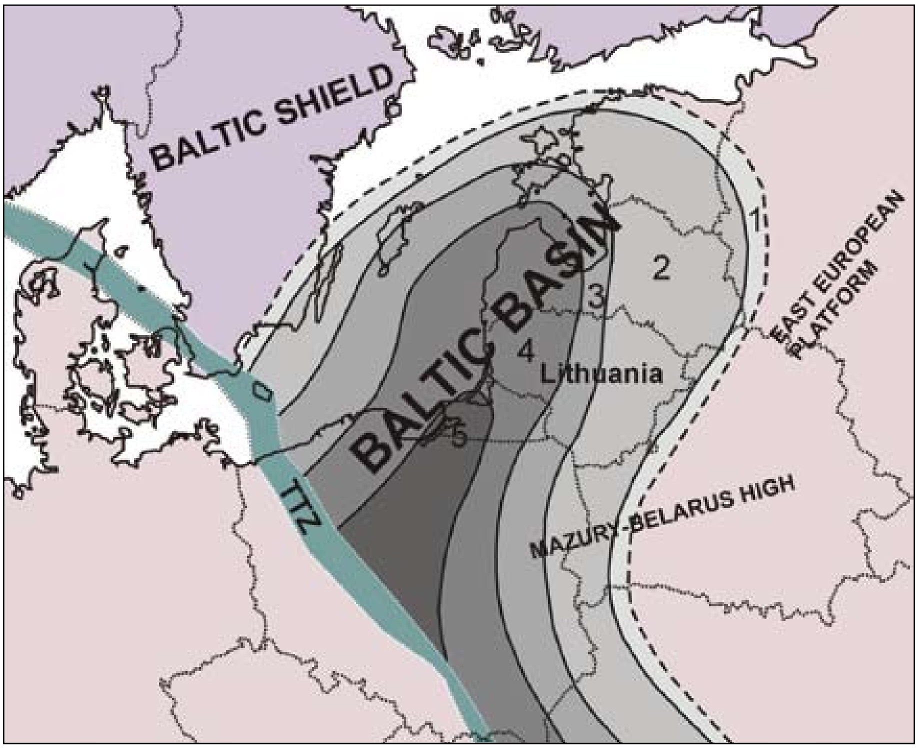

Fig. 2. The main facies belts of the Pridolian ramp in the Baltic Basin. *1* – Sabkha, *2* – inner-shallow ramp, *3* – mid ramp, *4* – outer ramp, *5* – lower ramp slope – deep basin; TTZ – Tornquist–Teisseyre Zone

2 pav. Pagrindinės pržidolio rampos uolienų facijos zonos Baltijos baseine. *1* – Sabha; *2* – vidinė sekli rampa; *3* – vidurinė rampa; *4* – išorinė rampa; *5* – apatinis rampos šlaitas – gilus baseinas; TTZ – Tornkvisto-Teizerio zona

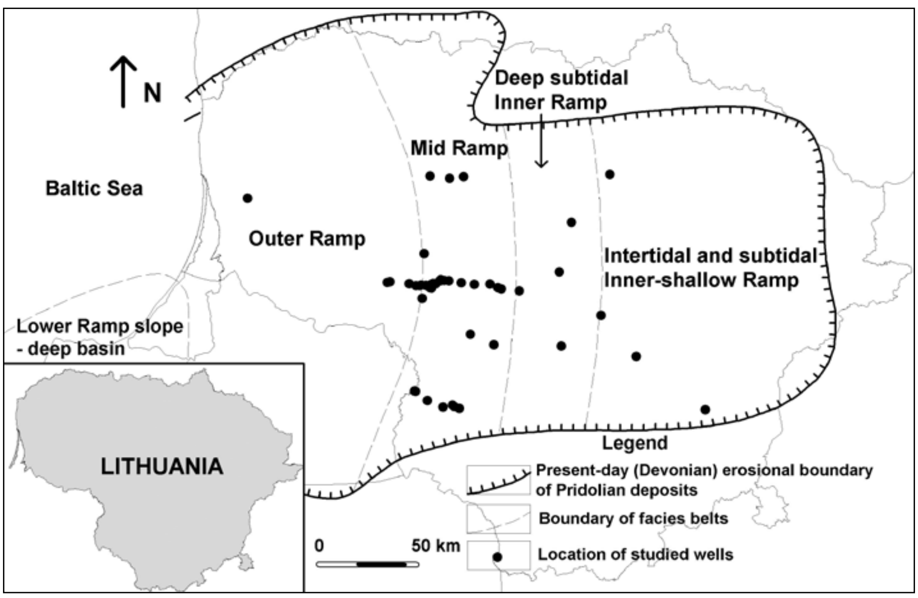

Fig. 3. Locations of wells and cores. Also shown are the main environmental subdivisions of the carbonate ramp in Lithuania and the erosional outlines of Pridoli deposits

3 pav. Gręžiniai, iš kurių paimti ėminiai kerno tyrimui. Pagrindinis karbonatinės rampos sedimentacinių aplinkų padalijimas Lietuvos teritorijoje, pržidolio uolienų dabartinis paplitimas

(Fig. 2) is located at the margin of the Baltic craton which was in the tropical climate belt just south of the equator during the Silurian (Cocks, Torsvic, 2005).

METHODS AND DATA

Core material with excellent recovery and geophysical well logs from a number of wells (N = 47) throughout Lithuania (Fig. 3) has been studied to assess various depositional carbonate facies from the shallow basin margin in the east towards the deeper parts of the basin in West Lithuania. Selected core samples, in particular from the reef-like intervals, were slabbed and polished for a detailed study of the macroscopic features. The main facies belts in Lithuania, as well as the locations of the study cores, are indicated in Fig. 3. A total of 323 thin sections (20 µm thick) were available for petrographic analyses and microfacies determination according to the classification of Dunham (1962) extended by Embry and Klovan (1971).

DEFINITIONS OF REEF-LIKE CARBONATE DEPOSITS

Many definitions of reefs have been given whereas opinions and insights in the development and significance of such deposits have changed with time, in particular, the role of microbes in micrite production and establishment of rigid structures and bioherms with relief (e. g., Wood, 2001). The term *reef* is therefore often used loosely in the literature, leading to misunderstanding about the nature of the sediments involved and the consequences for the depositional system and the distribution of petrophysical properties. The terminology needs to be more strictly used, or the pertinent sediments need to be better described, allowing more useful interpretations of the depositional systems and their economic, i. e. oil, potential.

It is often not completely clear what kind of deposits the term reef refers to, i. e. whether it implies to bioherms with a true coherent framework of calcareous skeletons from colonial organisms, lithified by early marine cement and with clearly expressed morphology on a sea floor accompanied by talus deposits, bioherms with a loose structure lacking a stable framework, or biostromes lacking both framework components and any substantial seafloor relief. It is essential to determine the nature of the deposit, bioherms / reefs versus biostromes, since the impact on the depositional system is completely different for real reefs or for biostromes, as is also their significance for the occurrence of hydrocarbon reservoirs. A reef with a rigid skeletal framework and its high carbonate productivity, early marine cements and flanking reef talus and debris has a high reservoir potential. Many large hydrocarbon reservoirs in fact occur in such deposits. It also has a major hydrodynamic influence leading to the development of a carbonate platform because of the significant hydrodynamic effects, e. g., sheltering effects behind the physical barrier formed by the reef. Such a reef thus strongly influences the local sediment distribution patterns. Also, biostromes can form the main carbonate factory, but they do not form a relief and thus do not create a set of specific environments leading to platform development. Mud mounds and bioherms-reefs can probably be considered as end members of a continuum range, but both have distinctly different sets of environmental conditions (Wood, 2001). Mud mounds, i. e. deep water bioherms, usually are associated with shaly or nodular marly deposits on the basin slope and because of their initial microporosity and early-cemented nature are unlikely to be hydrocarbon reservoirs.

"The term *reef* was originally used by navigators for a shoal or a ridge on which ships could ground. The term was later applied to algal-coral rich sediment bodies that were frequently associated with these shoals or ridges" (cf. Bjerkéus, Eriksson, 2001). Thereafter, a number of definitions have been suggested with different intentions by geologists but also by biologists referring to recent equivalents. Geologically 'the term *reef* is used for different types of carbonate bodies: carbonate build-up, carbonate mass, and an ecologic or stratigraphic reef' (Bjerkéus, Eriksson, 2001). "The term *carbonate build-up* describes a locally formed carbonate body that has a topographic relief", whereas *carbonate mass* refers to "a carbonate body showing only a slight relief and consisting of pure limestone" (Bjerkéus, Eriksson, 2001). The term *ecologic reef* and *stratigraphic reef* (cf. Dunham, 1970) would then refer to carbonate bodies that include both of the above-mentioned concepts (Bjerkéus, Eriksson, 2001).

Longman (1981) considered as a reef any biologically influenced buildup of carbonate sediments that affected deposition in adjacent areas… and stood topographically higher than surrounding sediments during deposition.

Wood (1998) described a *reef* as being formed "as the direct or indirect result of organic activity, developing due to the aggregation of sessile epibenthic marine organisms, with the resultant higher rate of in-situ carbonate production than in surrounding sediments".

A very general approach was recently suggested by Riding (2001), in which a reef is merely a calcareous deposit created by "essentially in place sessile organisms". This encompasses many carbonate deposits and therefore does not appear to be a useful approach either from a sedimentological or palaeontological-biological point of view. A more precise definition was given by Kiessling et al. (2003): "Laterally confined biogenic structures, developed by the growth or activity of sessile benthic organisms and topographic relief and (inferred) rigidity".

Flodén et al. (2001) call *reef* "…any kind of biologically influenced carbonate buildup", and addionally uses the term *reef barrier* for describing the "laterally extensional topographic coast-following buildups that have a distinct control over the facies distribution in the surrounding basin". "The term *barrier reef* is used for a curvilinear offshore belt of an organic accumulation that is separated from the coast by a lagoon" (Bjerkéus, Eriksson, 2001).

"The term *patch reef* is characteristically an isolated semi-circular area of organic framework build-ups" (Bjerkéus, Eriksson, 2001).

Bioherm is a non-genetic term for a lens-like accumulation with a significant relief consisting of the remains of mainly sedentary organisms. The term *biostrome* refers to bedded, lenticular structures without a significant relief (James, 1983).

A sedimentological approach is suggested in this study, and the definition of a reef adapted here has a true morphological expression stabilized by a framework and early marine cement that is able to withstand waves and current (Insalaco, 1997; Schlager, 2003; Dullo, 2005). The aforementioned 'real' reefs have a characteristic talus of coarse-grained debris or breccia that gives evidence for the morphology. Reefs and in particular fringing or barrier reefs lead to the development of carbonate platform systems with a large area of shallow-water facies, often with the development of lagoons with restricted connections to the open sea and therefore aberrant salinity. A platform has a steep slope from the reef belt towards the deep basin. Opposite to the platforms are ramp systems with gradual slopes towards the deep basin that lack reefs or reefs forming a belt or barrier. A biostromal belt does not lead to protected lagoons and platform development and probably is more typical of ramp systems.

BRIEF REVIEW OF SILURIAN 'REEFS' IN THE BALTIC BASIN

The limestones in the central facies belt, the so-called reef belt, in the Silurian Baltic basin are dominated by stromatoporoids with a variable content of tabulate and rugose corals and bryozoa as main carbonate producing metazoan fauna elements and crinoids. Occasionally corals are dominant. Rarely do they contain calcareous encrusting organisms such as microbialites, calcimicrobes and calcareous algae. It appears from the literature that this central facies belt is almost a priori interpreted as a reef belt with reefs (bioherms) and barrier reefs (e. g., Lapinskas, 2000;

Stentoft et al., 2003). The shear presence of stromatoporoids and corals seems to evoke this almost routinely interpretation. Probably as a consequence of the supposed presence of reefs, the entire depositional system is often referred to as a platform (e. g., Nestor and Einasto, 1997).

Often contrasting opinions exist about the same deposits, suggesting that a revision may be warranted. Thus is corroborated by the results of a more detailed study of the sediments.

For many decades, Gotland (Sweden) (Llandovery, Wenlock and Ludlow deposits) and Estonia (Llandovery-Pridoli deposits) were major research areas in Europe for Silurian reef-like carbonates, i. e. reefs in the implicit or explicit sense of biologically produced build-ups with relief. In particular, there are numerous studies on the reefs of Gotland, some of them with excellent and comprehensive descriptions (e. g., Manten, 1962). Most of these studies are based on outcrops which are common along the coastal cliffs around Gotland and the north of Estonia. Similar reef-like buildups recently have been interpreted from seismic data under the Baltic Sea (Flodén et al., 2001).

Several types of reefs have been distinguished based upon their main fossil associations and also upon the dimensions, but also various classifications and interpretations were offered. Most of the reefs described from the Silurian in the Baltic basin are of limited extension and thickness (Riding, 1981; Nestor, 1995). Some of the reefs are very small, merely a few single colonies in a single bed, others are more extensive in the range of metres to tens of metres and thicker, but seldom more than a few metres in thickness. In particular, in Estonia most of the described reefs are small, usually only decimetres thick and a few meters across (Kaljo, 1977). Kaljo (1977) described three different types of bioherms in Estonia, based on their fossil association. The first type of bioherm mostly contains bryozoans, corals and algae. The second one consists mostly of corals and algae, and the third type contains corals, stromatoporoids and algae. These bioherms are relatively small, their height varying from 1 to 6 m and the diameter between 4 and 50 m (Kaljo, 1977).

Kershaw (1993) regards the Silurian carbonates on Gotland containing mainly stromatoporoids or other autochthonous fauna like corals or algae as reefs. The size of these reefs varies from 0.5 to 12 m in hight and from 50 to 100 m in width. One reef can have both biohermal and biostromal phases such as the early Ludlow reefs in the Högklint and Kopparsvik formations in Gotland (Kershaw, 1993). On the contrary, the same Hogklint formation reefs are described by other authors as mere patch reefs up to 35 m thick and 100–150 m wide (Watts, Riding, 2000).

Stromatoporoids dominate deposits of the Ludlow Hemse group with dimensions of 0.5–5 m in thickness and from a few tens of meters to more than 1 km in lateral extension. Since some of these deposits have predominantly *in situ* fossils, they are regarded as reefs (e. g., Sandström, Kershaw 2002). A contradictory interpretation was given by Flodén et al. (2001) who investigated the Klinteberg-Hemse reef succession (Upper Wenlock-Lower Ludlow) and claimed that: "…the reef barriers are built up of biostromal limestone dominated by stromatoporoids in an argillaceous or crinoid limestone matrix with bryozoans and solitary corals". Other authors interpret the same deposits as areas with patch reefs (Watts, Riding, 2000; Calner et al., 2004)

Bjerkéus and Eriksson (2001) interpreted reef structures from seismic data. They found at least four reef barriers in Hemse sedimentary rocks in the offshore area east of Gotland, which extend from the mainland of Gotland to the Estonian and Latvian mainland. They acknowledge that these are not, in the strict sense, true barrier reefs but rather composed of several vertically stacked flat biostromes (Bjerkéus, Eriksson 2001).

From the available descriptions of reefs it can be deduced that most are in fact biostromes and, although they may be the main carbonate factory, they have nothing to do with real reefs. However, the supposed presence of reefs leads to further misleading interpretations of the whole system. A number of researchers interpreted the Silurian Baltic basin as a platform depositional system because of the presence of reefs (Laufeld, Bassett, 1981; Nestor, Einasto, 1997; Calner et al., 2004). The argumentation for platform or ramp interpretation is not always clear and some authors even suggested that during the Silurian the systems are mainly platforms, but ramps are also present (Sandström, Kershaw, 2002; Calner et al., 2004).

DEPOSITIONAL FACIES IN THE SILURIAN (PRIDOLI) BALTIC BASIN

During much of the Pridoli, carbonate deposition prevailed in the shallow parts of the Baltic basin with dolostones along the shallow margins, limestones in the central part that grade into marly and finally shaly deposits towards the deeper southwestern part of the basin. The Pridolian carbonate system can be subdivided in five major, parallel depositional facies belts, each with typical lithofacies associations. From the shallow, near coastal to the deep, central basin these are: 1 – a proximal, near coastal facies of dolomitic mudstones with intertidal and shallow subtidal features such as stromatolitic lamination, intertidal breccias and fenestral structures; 2 – a shallow, subtidal facies above the wave base with bioturbated wackestones and mudstones with some coarser bioclastic coarse-grained packstone and grainstone intercalations. The fauna consists of bivalves, ostracods, gastropods, crinoids and brachiopods; 3 – a central facies with coarse-grained bioclastic stromatoporoidal and crinoid deposits ranging from grainstones to rudstones and floatstones; 4 – a more distal and deeper muddy facies belt with bioturbated mud-wackestones and some coarser grained bioclastic packstones; 5 – a deep ramp slope or basinal facies with intercalated marls-shales and black shales. Although tectonic activity was minor, the shallow coastal transitional facies of shallow subtidal and intertidal dolostones are partly lacking because of the Post-Silurian (lower Devonian) uplift of the eastern margin of the basin and erosion of part of the succession (Lapinskas 2000). The various sedimentological properties of the different facies belts are summarized in Table.

The carbonates are invariably detrital with bioclastic grains and a micrite carbonate matrix. The coarser carbonate material is exclusively bioclastic, produced by a non-photic macrofauna association comprising flat to domal and irregular stromatoporoids, crinoids, brachiopods, and foliate bryozoans. In the central facies belts, some tabulate and rugose corals also occur. Most of the rugose corals are solitary, but some small colonies occur as well. All corals and stromatoporoids are relatively small (mainly

Table. **Description of the lithology, classification and fossil content of facies belts across the Pridolian carbonate ramp in Lithuania, based up on core descriptions, thin section petrography and fauna distribution**

Lentelė. **Litologinis aprašymas, klasifikacija ir fosilijos facinėse zonose Lietuvoje skersai pržidolio karbonatinės rampos (pagal kerno medžiagą, šlifų petrografiją ir faunos pasiskirstymo dėsningumus)**

Main ramp facies	Intertidal - subtidal shallow inner ramp	Subtidal inner ramp	Mid ramp	Outer ramp	Basin floor
Lithology	Dolostones	Limestones	Limestones	Limestones, marls and shales	Marls and shales
Dunham classification	Mudstones	Bioturbated Wackestones and mudstones with some coarser grained packstones and grainstones	Mostly rudstones and floatstones with grainstones, packstones, wackestones and mudstones	Bioturbated Mudstones and wackestones-packstones	Mudstones with wackestones (packstones)
Fossil content	Brachiopods, Bivalves?	Crinoids, brachiopods, ostracods, solitary tabulate corals, bivalves, gastropods	Stromatoporoids, crinoids, tabulate and rugose mostly solitary corals, brachiopods, bryozoans, trilobites	Crinoids, brachiopods, gastropods, ostracods, bivalves	Crinoids, brachiopods, ostracods,

cm-sized and rarely up to domal forms 5–10 cm in diameter) and often occur in sediments with a mud-supported texture or mudmatrix, i. e. indicating a generally low-energetic and muddy seafloor. The stromatoporoids and corals are not attached to a hard substrate and thus did not form a significant relief, but merely a single individual or colony above the sea floor. In addition, trilobite, gastropod, ostracod and pelecypoda shell remains occur. Bioturbation is intense in the mud-supported deposits and packstones and structures indicating tractive transport are lacking. Carbonate mud is abundant across all facies belts, much of the lithology being pack-wackestones. In packstones, the matrix was burrowed or infiltrated, the latter with geopetal accumulations. The intensive bioturbation suggests low net-sedimentation rates. Micritization and microboring of skeletal grains are present, but only to a minor degree.

THE MAIN CARBONATE FACTORY

According to the literature, the central facies belt in Lithuania contains reefs or barrier reefs. This is, however, not confirmed by the data acquired by the present study. Some oil shows have been found in deposits of this central facies belt, and the presence of reefs therefore created expectations about the potential existence of suitable hydrocarbon reservoirs in the region. The vertical succession is arranged in more or less symmetrical depositional-lithological cycles that range from marls, nodular limestones to limestones that form the main lithology in this facies belt. The limestones are mainly packstones and grainstones, some of them being coarse grained, and are better-called rudstones or floatstones, with few wackestones and mudstones. The coarse bioclastic material is mainly stromatoporoids, with bryozoans and some tabulate and rugose corals. The finer bioclastic material consists mainly of crinoids, brachiopods, bryozoans and trilobites. The limestones are all well bedded.

Most of the rudstones and floatstones (Figs. 4 and 5) consist of coarse-grained calcareous fossils such as stromatoporoids and tabulate or rugose corals that are mostly displaced and not *in situ*. The matrix is dominant in floatstones, but in rudstones it occurs as well. Flat stromatoporoids are often arranged parallel to the bedding but have random stratigraphic facing, flattening accentuated by pressure solution and stylolitization during burial. These limestones are arranged in merely cm-dm thick beds. Most of the fauna is displaced, not in life position, re-orientated and transported for some distances by storm-induced currents.

Floatstones and rudstones are generally assumed to be associated to the true reef facies forming the flanking talus deposits in front and backside of reefs. Intraclasts, i.e. cemented broken parts of a true synsedimentary lithified reef, are lacking completely in the studied area. In addition, evidence for synsedimentary marine cementation is also absent. Talus deposits are absent in most if not all of the Silurian Baltic basin (Manten, 1962). The observed floatstones and rudstones (Fig. 6) are not talus deposits, but instead form the biostromal facies proper which is characterized by a varying degree of displacement and redeposition by storm-induced currents (e. g., Sandström, Kershaw, 2002).

In general, it appears that the prevailing sedentary fauna associations were not able to build any significant relief other than a single colony because of the lack of attachment to hard substrates or skeletal material and thus do not form a rigid framework. Recent studies show that stromatoporoids and corals alone are not able to build a framework (Nose et al., 2006) which is vital for true reefs.

The presence of framework building skeletal remains may be clear in outcrops, but may be difficult to detect in cores. Similarly *in situ* and life, the position of skeletal elements is a difficult and unclear criterion since much of the skeletal organisms may be dislocated by storms, in particular in Mesozoic-Cainozoic reefs that grow in shallow water close to the sea level. However, encrusting organisms or remains of photosynthetic calcareous algae are easy to detect but have not been found.

Fig. 4. Photograph of a polished core sample showing a stromatoporoidal floatstone (limestone) with dm-sized stromatoporoids typical of the central facies belt

4 pav. Klinties (*floatstone*) antšlifio nuotrauka iš vidurinės facijos dalies su decimetro dydžio stromatoporoidėjų nuolaužomis

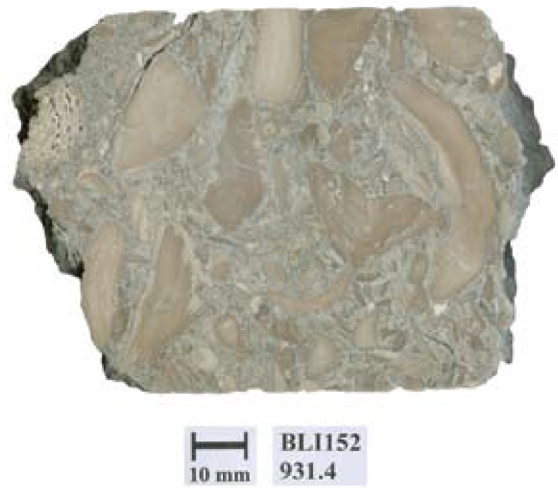

Fig. 5. Photograph of a polished core sample showing an example of a typical stromatoporoidal rudstone (limestone) with coarse, unsorted and random-oriented remains of stromatoporoids from the central facies belt

5 pav. Klinties (*rudstone*) antšlifio nuotrauka iš vidurinės facijos dalies su stambiomis, nerūšiuotomis ir atsitiktinai orientuotomis stromatoporoidėjų nuolaužomis

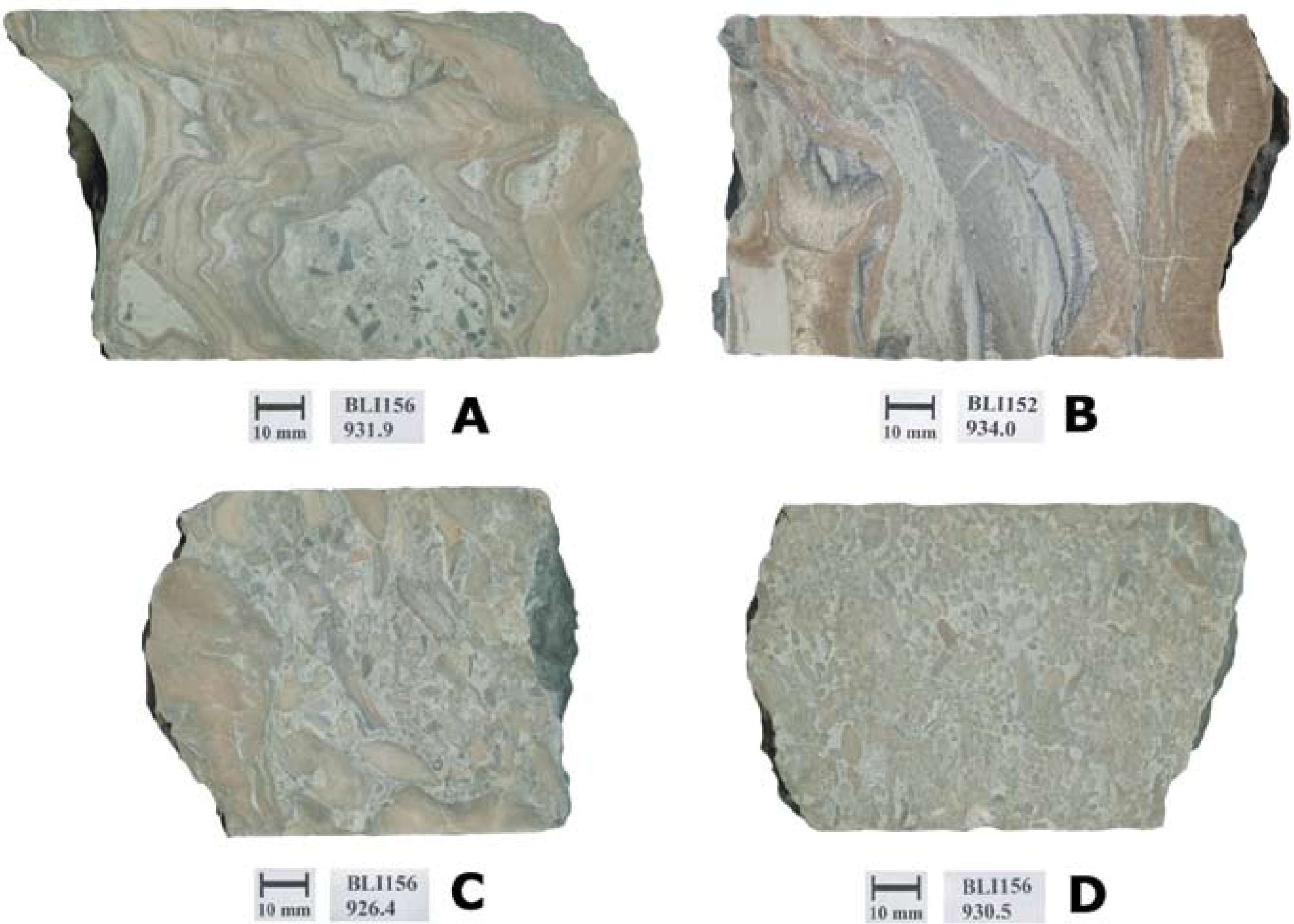

Fig. 6. Photographs of polished core samples from the central facies belt. *A* – floatstone mainly consisting of stromatoporoids with a mud-dominated matrix; *B* – floatstone consisting of coarse, laminar stromatoporoids not bound together and forming no framework; *C* – rudstone consisting mostly of unsorted stromatoporoids of random orientation; *D* – rudstone consisting of well-rounded stromatoporoids and bryozoans.

6 pav. Klinčių antšlifių nuotraukos iš vidurinės facijos dalies. *A* – klinties (*floatstone*) antšlifio nuotrauka su stromatoporoidais, paplitusiais smulkiagrūdėje (dumblingoje) matricoje; *B* – klinties (*floatstone*) antšlifio nuotrauka su stambianuolaužiniais stromatoporoidais, kurie nesurišti vienas su kitu ir neformuoja organinio karkaso; *C* – klinties (*rudstone*) antšlifio nuotrauka su blogai išrūšiuotomis ir netvarkingai orientuotomis stromatoporoidų nuolaužomis; *D* – klinties (*rudstone*) antšlifio nuotrauka su gerai apzulintomis gana smulkiomis stromatoporoidų ir briozojų nuolaužomis

DISCUSSION

Since the interpretation of carbonate systems as platforms based on the presence of reefs often seems to be almost an automatism (e. g., Nestor and Einasto, 1977, 1997), it makes sense to investigate these supposed reefs in more detail and question whether the interpretation is indeed sound. The terms used in this interpretation do not merely have a semantic meaning, but they have a profound impact on the distribution of depositional facies, the diagenesis and thus on the development of petrophysical properties such as porosity and permeability.

Adequate petrophysical models must be available for hydrocarbon exploration and production. If indeed diagenesis and the final petrophysical property distribution are linked to the depositional facies, it is important to have a good depositional-lithofacies model. In siliciclastic systems, depositional processes in terms of hydrodynamic conditions are linked directly to depositional facies and lithofacies as well as to the primary distribution of petrophysical properties. This link is not so straightforward in carbonates, but it can nevertheless be expected to be important and form the basis for reservoir models.

A carbonate platform comprising a reef belt is one end member, the opposite being a ramp, of the range of possible depositional carbonate systems (Pomar, 2001). Both platforms and ramps have a different distribution of depositional facies, and the predominance of certain facies is fundamentally different in both systems (Pomar, 2001). The platform and the ramp systems have effects not just on synsedimentary processes and the distribution of facies, but also on the postdepositional diagenetic processes. Sediments of a platform system could be open in the sense of redistribution of mass during exposure above sea level. Because of changes in sea level, subaerial exposure and influx of meteoric and mixing water can be expected to influence the carbonate sediments. Changes in water chemistry will trigger diagenesis. In the opposite case of the ramp system, far less of the system can be exposed during sea level low stands and most likely a ramp behaves like a more closed system. Diagenesis is then triggered by changes in physical conditions during burial and constrained by the lithofacies itself. No redistribution of mass takes place within the system itself.

The nature of reefs has changed through time as has the plate tectonic situation, global currents and nutrient situation, atmospheric conditions and thus terrestrial runoff with nutrient conditions, and sea-level stand through eustatic sea level changes. The evolution changed the fauna flora assemblages in the particular ecological niches and their impact on the surroundings. This is likely to have had consequences for carbonate systems and depositional and lithofacies distributions of the main carbonate factory and for susceptibility to diagenesis and development of properties as relevant for hydrocarbon occurrences and production.

Most, if not all, of the Mesozoic and Cainozoic reefs originate in the (eu)photic zone, although some bioherms (merely implying the morphological aspect) have been detected at a greater water depth such as in the Gulf of Florida (Reed, Ross, 2005; Reed et al., 2005). These, however, lack framework-building organisms and have no further major consequence for the surrounding depositional facies. The most important current photosymbionts had developed during the Triassic and there are no clear data to support the presence of photosymbiotic reef-associated faunas before the Triassic (Wood, 1989). The presence of photosymbionts is often supposed to have increased the rate of carbonate production. However, Palaeozoic reefal carbonate factories seem to have had similar carbonate production rates equal to that of moderns reefs (Kiessling et al., 2003). It merely restricted the scleractinian and red algae reefs in the Mesozoic and Cainozoic to the photic, shallow-water zone, whereas Palaeozoic reefs were independent of the photic zone and thereby of decreasing the potential exposure to meteoric water during sea-level lowstands.

Reefs and talus deposits have often a great hydrocarbon reservoir potential because of the aragonitic composition of many of the important framework builders such as the Mesozoic-Cainozoic scleractinian corals, and because of the interconnected framework texture. Moreover, the photic organisms and thus shallow-water occurrence and rapid growth of scleractinian and algal reefs give them a high potential for subaerial exposure and the consequent development of secondary porosity through aragonite leaching. Post-Palaeozoic reefs have a framework of aragonite or high-Mg calcite components and early cement of the same soluble minerals that may lead to the development of an interconnected network of secondary porosity. Most current reefs are restricted to the tropical and euphotic zones, implying aragonite and high-Mg calcite as the main components of biomineralization and early marine cementation. The potential for developing secondary porosity is far lower in ramp systems with stromatoporoidal biostromes, i. e. sheet-like bodies without framework or elevation above the surrounding seafloor other than the producing organisms and skeletal material that are partly or largely reworked (e. g., Kershaw 1994). In such carbonate factories, carbonate production may take place in deeper and therefore cooler water with lower degrees of supersaturation to calcium carbonate. In addition, ramp systems are less susceptible to sea level changes and thus meteoric water infiltration and early massive dolomitization, but also to changes in carbonate productivity.

In the Early Palaeozoic, it is assumed that sedentary colonial organisms such as tabulate and rugose corals and in particular stromatoporoids had a similar function as scleractinian corals during the Cainozoic. In the Silurian, it is only the combination with encrusting calcareous organisms such as encrusting stromatoporoids, microbialites, calcimicrobes or calcareous red algae that can lead to development of a stable framework (Meyer, Price, 1993; Nose et al., 2006). However, it is questionable whether stromatoporoids, often the dominant metazoan present in the Ordovician through Carboniferous carbonate systems (e. g., Kiessling et al., 2003), indeed occupied the same environmental niche resulting in deposits similar to modern scleractinian coral and red algae reefs. The widespread nature of stromatoporoidal carbonates and the close association with equally widespread and abundant crinoidal carbonates (pack-grainstones) suggest a different ecology of the main carbonate factory in the early Palaeozoic.

The main fauna element in the Silurian reefs is stromatoporoids. It is assumed that stromatoporoids are indeed able to build bioherms. According to Calner (2005), stromatoporoids are the common reef-builders in Silurian strata. This is, however, questionable. The shear presence of a sessile fauna (e. g., stromatoporoids) appears often a sufficient reason to classify the deposits as a reef. However, it may be difficult to determine whether the fossils are indeed in place and undisturbed, especially if the fauna does not build a framework (Sandström, Kershaw, 2002). Sandström and Kershaw (2002) presented the opinion that stromatoporoids did not fixate them at all to a substrate. Larger ones are unstable and easily turned over, smaller ones being more stable, but potentially mobile. Kershaw (1998) and Sandström and Kershaw (2002) presented experimental evidence that currents can move stromatoporoids without being overturned.

Most likely stromatoporoids and corals alone did not account for the formation of a rigid framework at all (Nose et al., 2006). "Stromatoporoids and many tabulate corals alone are not normally capable to form large and rigid framework, which result in generally low-profile reef structure" (cf. Kershaw, Keeling, 1994; May, 1997; Kershaw, 1998; Wood, 2000; Nose at al., 2006). The term *reef* should thus be avoided. They need the presence of encrusting organisms such as microbialites, calcimicrobes or calcareous red algae. According to Kershaw (1998), rigid frameworks are absent in stromatoporoid reefs in Gotland unless they are bound by microbial crusts. Moreover, the common observation is that most stromatoporoid remains are not *in situ*. This is confirmed by experimental evidence that stromatoporoids can be moved by wave or current action (Sandström, Kershaw, 2002). This indicates that stromatoporoids are not really sessile and not firmly attached to a hard substrate, inferring that they appear to be soft-bottom dwelling organisms. Therefore, most of the reefs with a fauna dominated by stromatoporoids and lacking encrusting-binding organisms cannot be classified as reefs any more and should be more correctly as biostromes.

The abundance of carbonate mud is often accounted for by the so-called baffling effect of stromatoporoid and crinoid thickets. It is more likely that stromatoporoids are able to inhabit existing soft and muddy substrates independent of depth and light since they lacked photosymbiotic organisms.

In contrast with the common occurrence of shallow-water reef belts and carbonate platforms in the post Palaeozoic, biostromes and ramp systems are more likely to dominate in the Palaeozoic. These have a lower potential for developing secondary porosity because of the absence of large areas that are easily pray to subaerial emergence and subsequent meteoric water influx, and because of the lack of an interconnected framework of aragonitic carbonate such as in Mesozoic and Cainozoic reefs.

CONCLUSIONS

Reefs in the sense of organic buildups with a stable framework through the colonial calcareous fauna and early synsedimentary marine cementation capable of resisting wave action have not been found in the Pridoli of Lithuania. Most of the macrofauna is non-photic and non-framework building, and the coarse material is forming tabular deposits with typical rudstone or floatstone fabrics. Reef talus deposits are lacking, indicating the absence of a significant relief above the seafloor. The coarse-grained material is mostly displaced, and most fossils are not in life position, probably as a result of intermittent storm-induced currents. Stromatoporoids are the main constituent of biostromes, whereas tabulate and rugose corals with crinoids and bryozoans are present, but relatively rare. The main carbonate factory is therefore building biostromal deposits. The term *biostrome* can be applied to tabular-shaped sediment bodies without a real skeletal framework or substantial relief and to skeletal material which is partly or largely reworked. Since photic organisms are absent, this suggests that the main carbonate factory was below the photic zone, but above the storm wave base.

Most of the organic reefs described from the Silurian with a framework through encrusting organisms and photosynthetic algae are of limited lateral extension and thickness and probably are mere patch reefs occurring at shallower depths than the stromatoporoidal biostromes.

The main conclusion is that, although the existence of local, isolated real (patch) reefs is not excluded, they do not play a dominant role in the Pridolian carbonate ramp system either as main sediment producers or as hydrodynamic barriers.

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BALTIJOS SILŪRO BASEINO PRŽIDOLIO KARBONATINĖS SISTEMOS „RIFŲ“ PRIGIMTIS

Santrauka

Pastaruoju metu dėl didelių naftos telkinių Artimuosiuose Rytuose ir Kaspijos jūros teritorijoje yra pastebimas padidėjęs susidomėjimas karbonatinių uolienų naftos kolektoriais. Kai kurie iš jų yra paleozojaus karbonatinės uolienos. Silūro karbonatinės uolienos Baltijos baseine yra labai palankus tyrimo objektas, kadangi daugelio gręžinių bei atodangų medžiaga yra lengvai prieinama, teritorija patyrusi nedidelį tektoninį poveikį. Šio tyrimo objektas yra pržidolio karbonatinės uolienos, kurias galima pasiekti tik gręžiant ir kurių facijos kinta nuo priekrantinių iki giliavandenių. Straipsnyje pateikta nauja idėja apie vadinamųjų „rifų“ sedimentologinę prigimtį minėtame baseine. Rifo terminas yra labai dažnai taikomas skirtingos kilmės dariniams apibūdinti. Neabejotina, kad tektoninės sinsedimentacinės sąlygos yra reikšmingos, bet iš esmės yra labai svarbu nustatyti tikslią rifogeninių darinių prigimtį, nes tai nulemia ir pačią karbonatinę sistemą. Tikrųjų rifų atveju, kai pagrindinį vaidmenį vaidina biologinės konstrukcijos statiniai su išsiskiriančiu reljefu, susiformuoja platforminio tipo sistema, kitu atveju turime rampinio tipo karbonatinę sistemą. Tyrimai rodo, kad pržidolio karbonatinėse uolienose nėra rifų, nes nėra juos konstruojančių organizmų ir tikriausiai nebuvo per visą paleozojų. Vietoje biohermų ar rifų rampinio tipo baseine formavosi biostrominio tipo dariniai, greičiausiai pasižymėję didžiausiu karbonatiniu produktyvumu. Labai sunku nustatyti tikslų karbonatų produktyvumą atskirose facinėse zonose. Svarbu atskirti platformos ir rampos sistemą, nes jos skirtingai reaguoja į diagenezę. Šiuo atveju diagenezė nulemia petrofizines uolienų savybes, o šios – uolienų kolektoriaus kokybę.

Гедрюс Бичкаускас, Николаас Моленаар

ПРИРОДА „РИФОВ“ В КАРБОНАТНОЙ СИСТЕМЕ ПРЖИДОЛИ БАЛТИЙСКОГО СИЛУРИЙСКОГО БАССЕЙНА

Резюме

В последнее время из-за больших месторождений нефти на территориях Ближнего Востока и Каспийского моря повышенную заинтересованность вызывают коллекторы карбонатных пород. У некоторых из них палеозойский возраст. Силурийские карбонатные породы Балтийского бассейна представляют собой весьма интересный во многих аспектах объект: они легко доступны в обнажениях (Эстония, Готланд) и в буровых скважинах во всей Прибалтике и претерпели незначительное тектоническое воздействие. Объектом исследования являются карбонатные породы пржидоли, которые доступны только буровыми скважинами и фации которых меняются от прибрежных до глубоководных. В данной статье выдвигается новая идея о седименталогической природе „рифов“ в Прибалтийском бассейне. Термин „риф“ часто употребляется для различных по происхождению образований. Нет сомнения, что тектонические сенседиментационные условия являются весьма важными, однако не менее важно точно определить природу рифогенных образований, чем определяется и сама карбонатная система. В случае настоящих рифов, где основную роль играют биологические конструкции с ярко выраженным рельефом, формируется система платформенного типа. В другом случае образуется рамповая карбонатная система. Исследования показали, что в карбонатных породах верхнего силура рифы отсутствуют из-за того, что отсутствуют и рифостроящие организмы. Видимо, такие организмы отсутствовали и на протяжении всего палеозоя. В месте биогермов или рифов в бассейне рампового типа формировались биостромовые образования, которые, вероятно, и определяли основную карбонатную продуктивность в системе. Определить карбонатную продуктивность в отдельных фациальных зонах достаточно трудно. Важно отделить платформенную систему от рамповой, ввиду того, что они различно реагируют на диагенез. В данном случае диагенез определяет петрофизические свойства пород, которые в свою очередь обусловливают коллекторные качества последних. Все эти обстоятельства в совокупности помогают понять и предугадать расположение месторождения нефти.