THE SILURIAN BARRIER REEF STRUCTURES OF THE BALTIC PETROLEUM BASIN (LITHUANIA) ACCORDING TO RECENT 3D SEISMIC RESULTS

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RESUMEN

Las estructuras de la barrera de arrecifes Silúricos de la Cuenca Petrolífera Báltica (Lituania) conforme a los recientes resultados sísmicos 3D

El objetivo principal del presente estudio fue mapear la zona de arrecifes descubiertas previamente por perforación, y entender el origen de los mencionados arrecifes usando un método de adquisición sísmica 3D. El segundo objetivo fue la implementación de una técnica de adquisición sísmica respetuosa con el medio ambiente. El estudio sísmico 3D cubrió un área de 70 km^2. Un grabador sísmico inalámbrico, y caída acelerada de peso, se utilizaron para la adquisición del terreno en 3D. La interpretación de los nuevos datos 3D junto con la distribución del contenido de arcilla, permite trazar la ubicación precisa del cinturón de arrecifes, que consta de dos zonas. La zona al Este contiene 3 ó 4 parcelas de arrecife separadas (Arrecifes de N. Bliūdžiai, S. Bliūdžiai y Pavasaris), la zona Oeste (cinturón de arrecife Vadzgirys) forma una faja que crece estructuralmente de SO a NE. El análisis de los datos sugiere que el cinturón de arrecife Vadzgirys comenzó a formarse a principios del Pridoli, mientras que la zona del arrecife del Este se desarrolló más tarde durante la transgresión de la cuenca Siluriana. Teniendo en cuenta la distribución de facies de la Cuenca del Báltico Siluriano, es de esperar, que la barrera de arrecifes al igual que las parcelas, se prolonguen por cientos de kilómetros, y que formen un depósito de petróleo viable en la región del Báltico con potencial para futuras exploraciones petrolíferas.

INTRODUCTION

In the Upper Silurian (Ludlow) in the south-western Lithuania, the first small organogenous bodies were found in 1967. In 1969 the largest reef was found (Lapinskas, 2000). The first reefs – North Bliūdžiai, Kudirka, Pavasaris and Šaukėnai - were distinguished in 1970 after a summarized facies model based on well-bores. When extensive (more than 70 wells) drilling works were performed it was confirmed that the Silurian reefs contain oil. 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 limestones in the central facies belt, the so – called reef belt, in the Silurian Baltic basin are dominated by stromotoporoids with a variable content of tabulate and rugose corals and bryozoa as main carbonate producing metazoan fauna elements and crinoids. For many decades, Gotland (Sweden) and Estonia were major research areas in Europe for Silurian reef-like carbonates. Most of these studies are based on outcrops. Some of the reefs are very small; others are more extensive in the range of meters to tens of meters. These reefs usually have height from 1 to 6 m and the diameter between 4 to 50 m (Kaljo, 1977). According Kershaw (1993) the size of some reefs in Gotland varies from 0.5 to 12 m in height and from 50 to 100 m in width. By other authors, the same Hogklint formation reefs in Gotland are described as mere patch reefs up to 35 m thick and 100-150 m wide (Watts, Riding, 2000). Similar reef-like build-ups have been interpreted from seismic data under the Baltic Sea (Floden *et al.*, 2001; Bjerkeus, Eriksson, 2001). They acknowledge that these are not true barrier reefs but rather composed of several vertically stacked flat biostromes. 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 (Lapinskas, 2000; Stentoft *et al.*, 2003). An interesting opinion about the Pridolian carbonates in the Baltic Silurian basin is expressed by Bičkauskas and Molenaar (2008a). According their research Pridolian carbonates lack reefs since the framework-constructing fauna is absent. They conclude that patch (isolated) reefs are not excluded; they do not play a dominant role in the Pridolian carbonate ramp system (Bickauskas, Molenaar, 2008a). The primary objective of the current study was to map reef zone discovered by drilling and understand the origin of reefs applying 3D seismic acquisition method. The secondary target was to implement environmentally friendly technique consisting of wireless seismic recorders and accelerated weight drop (AWD) for 3D field acquisition.

GEOLOGICAL SETTING

The Baltic Silurian Basin is located at the margin of the Baltic Craton, which was in the tropical climate belt just south from the equator during the Silurian (Cocks, Torsvic, 2005). During the Caledonian Orogeny, the Baltica continent collided with Laurentia in the west and with Avalonia in the south. The collision led to the closure of the Iapetus Ocean in the early Devonian. The Baltic Petroleum Basin is mainly Early Paleozoic basin formed on the western margin of the East European Platform. The stratigraphic column showing main source rock and reservoirs are presented in Figure 1. Within the preserved section of the basin, three outstanding source rock levels are identified: the Middle and Late Cambrian and Tremadocian alum shales, the Ordovician (Caradoc) shales, and the Silurian (Llandovery) graptolitic shales. Other source rocks exist, yet are less significant. The majority of the oilfields in the Baltic Basin (Lithuania and Kaliningrad district) are located in Middle Cambrian Deimena (Faludden) and Lower Ordovician Pakerort sandstones. As for Ordovician carbonates, those of Ashgillian age are probably the most promising ones in terms of reservoir characteristics. On the island of Gotland, Ashgillian reefal build-ups are oil productive. Other Ashgill carbonate reservoirs are the oolitic – bioclastic limestones which were found oil-stained in several Latvian onshore wells. Within the Silurian succession, evidence for reservoirs is scarce. However, in Lithuania several wells drilled during soviet times proved evidence of oil productive reservoirs, related to the Pridolian-Ludlow reefal build-ups. The mentioned reef structures are the main subject of current paper. The best reservoirs in the basin are located in Devonian, however they are water-bearing over all Bašin and are not interesting for oil exploration purposes (Kanev *et al.*, 2001). The upper part of Silurian section of the studied area represents the progressive increase in subsidence. The Minija Regional Stage forms the lower sequence of the Pridoli (Paškevicius, 1997). The Minija Regional Stage carbonates are a good example of a carbonate ramp system with a stromotoporoid-crinoid-brachiopod dominated carbonate factory.

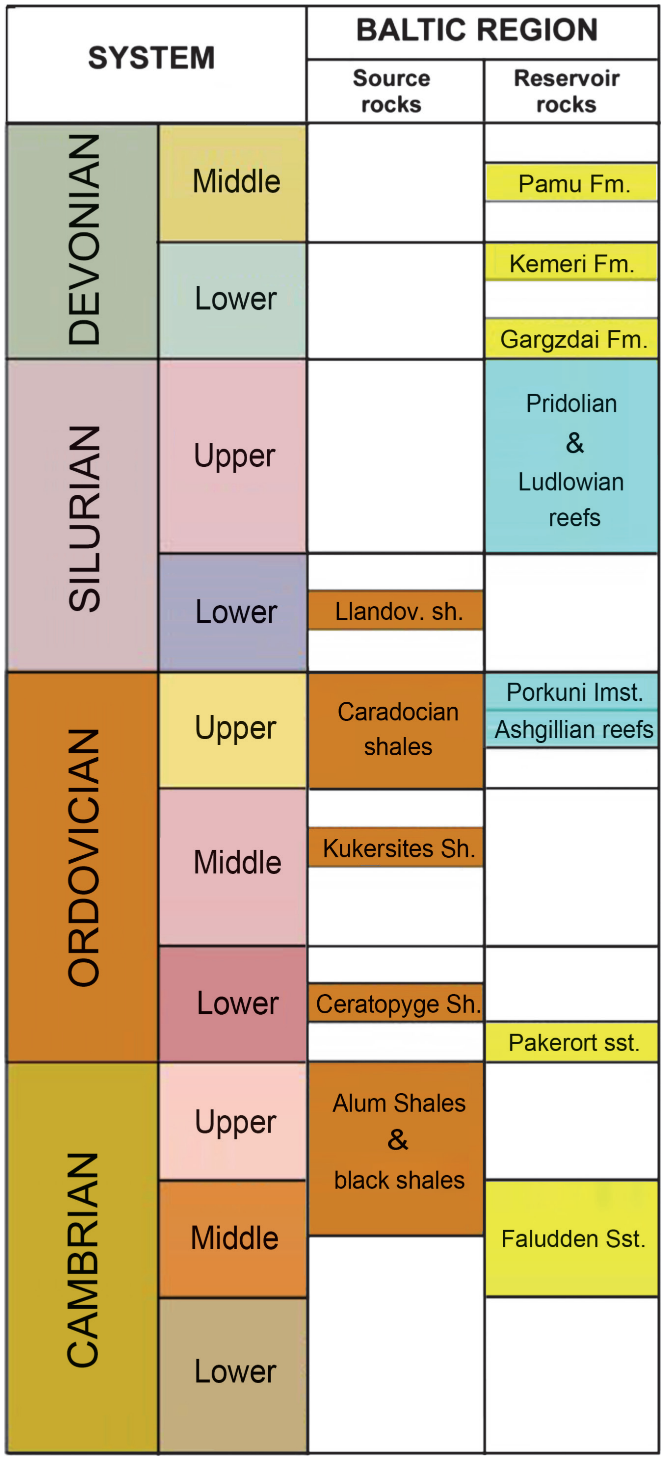

Figure 1. Source and reservoir rocks in the Baltic Petroleum Basin. brown colours indicate source rocks, yellow - reservoirs spread over all Baltic Basin, blue - scarce (mainly lithological type) reservoirs.

According to the lithofacies distribution, the ramp can be subdivided into five major parts: intertidal-subtidal inner-shallow ramp (1); inner-shallow ramp (2); mid-ramp (3); outer ramp (4); lower ramp slope – deep basin (5) (Bičkauskas, Molenaar, 2008b) (Figure 2, left). 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).

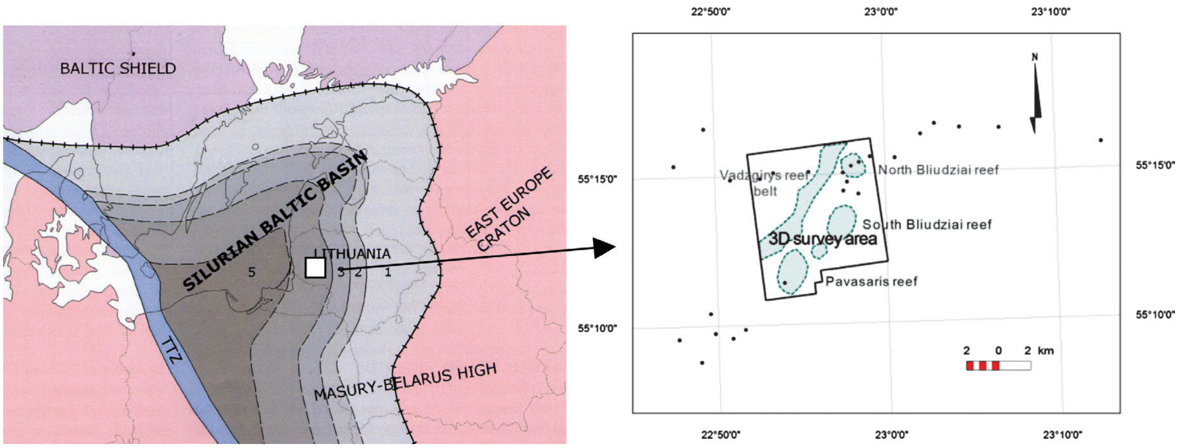

Figure 2. Left) The main facies belts of the Pridolian in the Baltic Basin according Bičkauskas&Molenaar (2008b) (see text for explanation); Right) studied area. Black dots indicate locations of wells.

METHODS

3-D seismic

According to interpretation results of old 2D seismic and well data in the area of investigations Silurian reefs are located at the depths of 900-1000 meters, their size does not exceed 1-2 kilometer. For the confident mapping of above structures following survey parameters were selected: orthogonal survey design, 14 active receiver lines, 200 m receiver line spacing, 40 receiver stations within a line, 50 m receiver station spacing, 560 active channels, 250 m source line spacing and 25 m source station spacing. 3D seismic field survey was performed by Lithuanian geophysical company "Geobaltic". One seismic channel consisted of RAU-ex (Sercel) seismic recorder and single high sensitivity geophone GS-One (Geospace Technologies) per group (Figure 3 (left)). AWD system AF-450 installed on crawler IC-35 (United Service Alliance) was used as seismic source (Figure 3 (right)). The total weight of the system reached around 5 tons; the maximum output energy not exceeded 13 kJ. Latter design of the system enabled to enter various environment (forest, wet soil, cultivated lands) located in the area of investigations.

Figure 3. Equipment utilized for 3D survey. Left) Wireless seismic recorders. Right) AWD.

Cross-sections of clay content compilation and interpretation.

A number of wells were drilled in the 3D survey area, some of them drilled into reef bodies. Almost all wells were logged using standard set of methods: natural gamma ray, resistivity and self-potential, therefore additional clay content distribution analysis in cross sections was added into current study. Clay content (V_{shl}) of the upper Silurian was calculated using the standard equation:

$$V_{shl} = \frac{GR - GR_{clean}}{GR_{shl} - GR_{clean}}$$

where – GR_{clean} - minimal natural gamma-ray curve value reflecting pure limestone radioactivity (in our case it was 2-4 mcR/h); GR_{shl} – radioactivity value of shale (15-20 mcR/h).

After recalculation to V_{shl} in case of "pure" limestone the value is 0 and in case of shale is 1. The cross-sections of clay content were compiled interpolating V_{shl} values in plane between the wells. Maximal clay content values in the cross-sections are as blue tones, minimal – as red tones. The shale content cross-sections were prepared due to shale content contrast within reef bodies and surrounding carbonate rocks. The reef carbonates (North Bliudziai reef) are mainly of coarse-grained bioclastic stromotoporoid limestone which has the lowest V_{shl} value (Figure 4). The surrounding facies with moderate V_{shl} values are wackestones and mudstones with some coarser bioclastic packstones dominated by crinoids and brachiopods. The wackestones and mudstones are dominant rocks intercalated with marl laminae. The top of Norh Bliudziai reef is sealed with bedded-laminated marls and shales having the highest V_{shl} value (Figure 4 and 5, bottom).

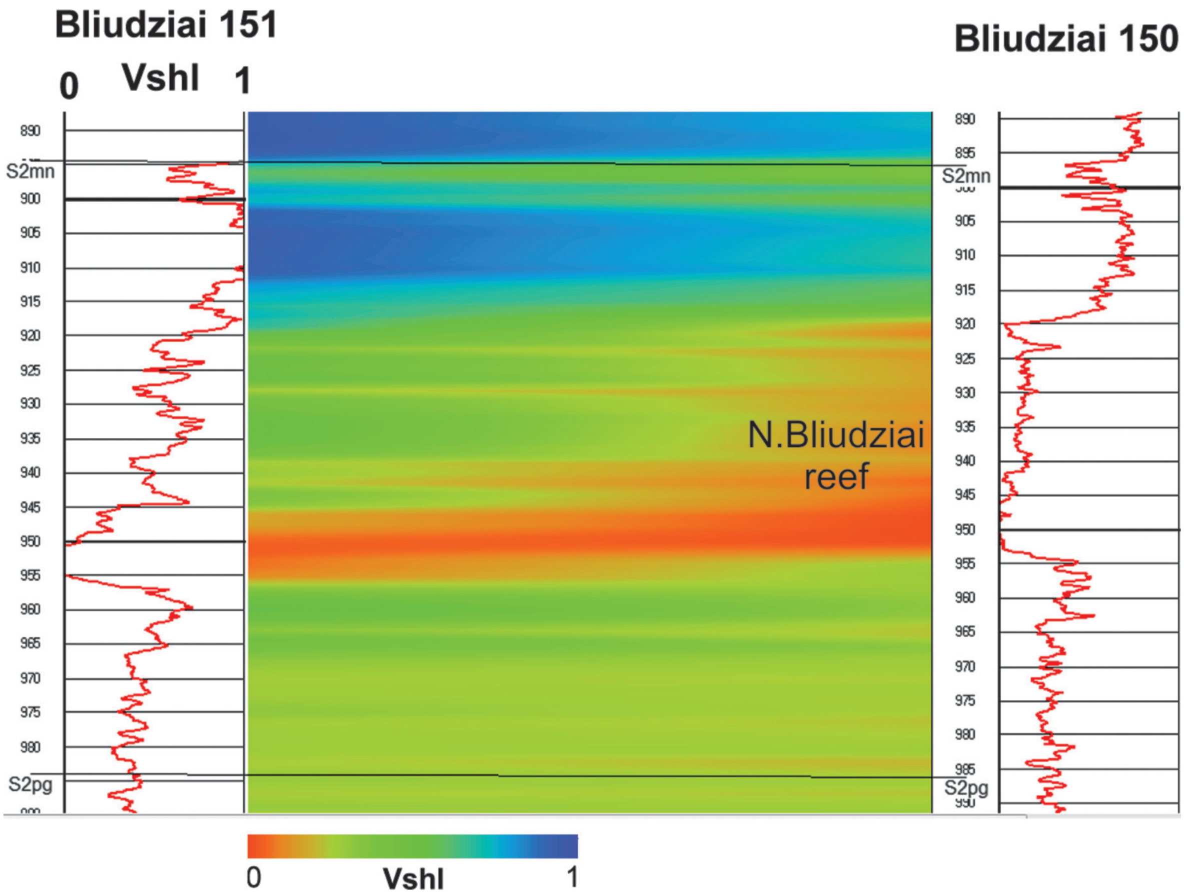

Figure 4. The Vshl section showing well Bliūdziai 151 located in reef surrounding shaly carbonate environment versus well Bliudziai-150 drilled into "clean" limestone reef body.

RESULTS

Standard PSTM processing routine was applied with the special attitude to velocity analysis and residual static correction evaluation in order to achieve highest possible definition of target objects. At the interpretation stage structural time and depth mapping of the reef bodies were performed. Analysis of processed 3D dataset showed very strong reflection from reef top surface (Figure 5 top). Intensive reflections were obtained just below continuous Top Silurian horizon at two levels: at about 700 and 730 ms seismic time. Seismic horizons were confidently correlated and mapped. Structural map of all visible reef bodies was prepared (Figure 6). RMS seismic attributes were calculated and mapped trying to understand the nature of reflection of top reef surface. RMS Amplitude attribute was calculated for series of 30 ms windows from Top Silurian as reference horizon. Figure 5 (middle left and right) shows two RMS attribute maps calculated in 30-60 ms and 60-90 ms windows from top Silurian horizon. Exact position of RMS analysis windows is shown on the 3D seismic crossline (Figure 5 top). The depth windows corresponding to RMS

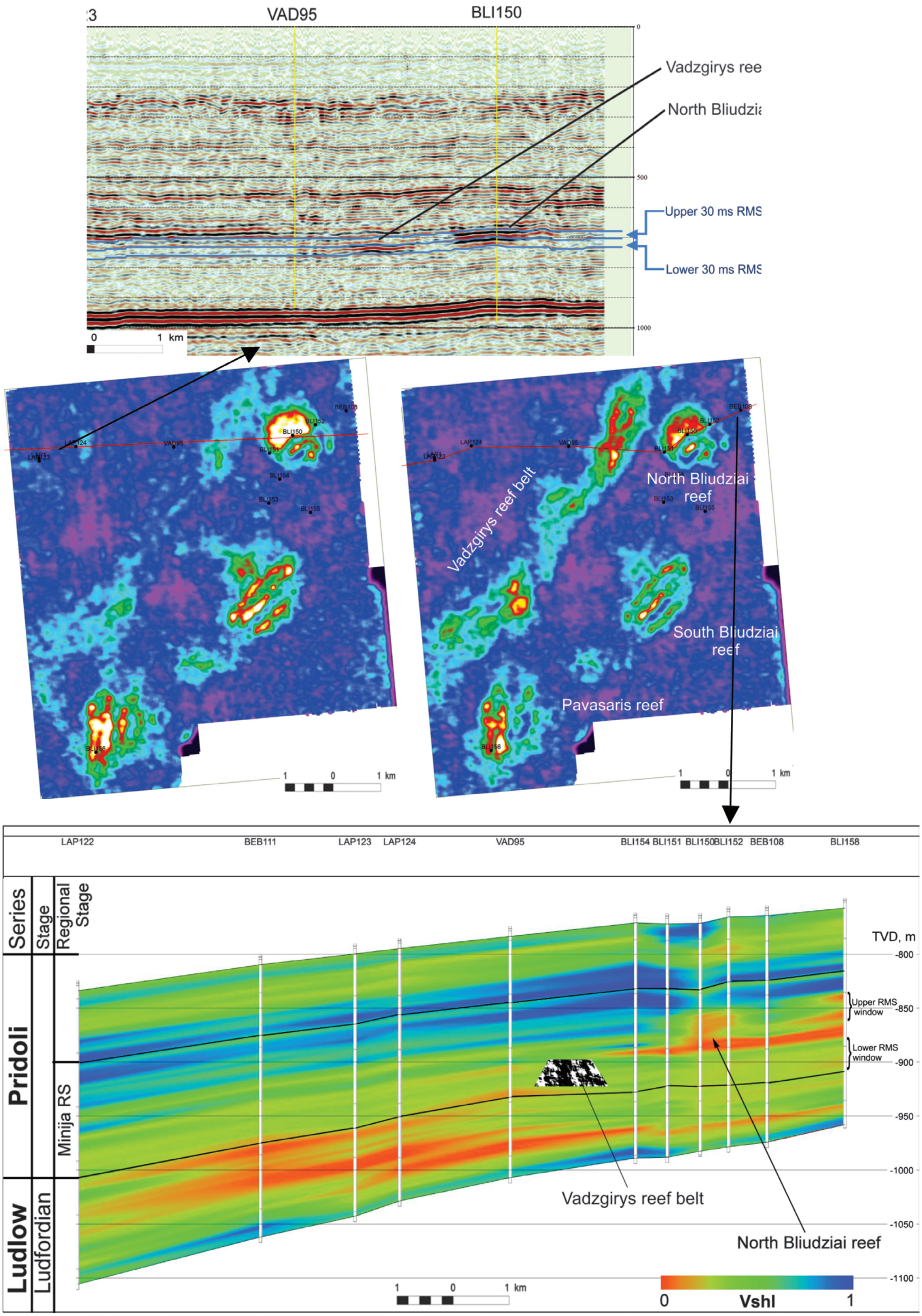

Figure 5. RMS analysis windows on the 3D seismic cross line (top). RMS attribute maps calculated in 30-60 ms (middle left) and 60-90 ms (middle right) windows from top Silurian horizon. The cross-section of clay content interpolating Vshl values in plane between the wells (bottom): drilled N. Bliūdziai reef is clearly seen as “minimum shale” anomaly, while non-drilled Vadzgirys reef belt interpretation based on seismic data.

analysis windows are shown on the shale content cross-section attached in Figure 5 (bottom). Two reef zones are clearly visible on seismic section as well as on both RMS attribute maps. According to RMS map analysis eastern reef zone appears in 30-60 ms (36-72 m) zone from top Silurian seismic horizon which stratigraphically corresponds to the upper part of Minija Regional Stage of lower Pridoli (Figure 5 middle left). The exact eastern reef zone age was proved according North Bliudziai and Pavasaris reefs well data, showing stromotoporoid-crinoid limestone at the upper part of the Minija Regional Stage. Lower RMS map characterizing 60-90 ms (72-108 m) window from the top Silurian horizon still shows patch reefs from the eastern reef zone, however more intensive reflection from the western reef zone appears in the map (Figure 5 middle right). It means that western reef zone corresponds to lower part of Minija Regional Stage of the Lower Pridoli. Both RMS maps show that reflection strength intensity from the reef top surface is not uniform. Yellow and red colours indicate highest reflection energy, blue and violet - weakest reflection. From Figure 5 (bottom) some regularities of clay content distribution in the upper Silurian cross-sections could be pinpointed. The high clay content intervals composed of marls and shales reflecting deeper sedimentation environment could serve as particular "markers". It was also noted that the cross-sections of the eastern part of the studied area are less "clayey" when compared to the western ones. It is supposed that the eastern part of the studied area was more favorable for the carbonate sedimentation during Silurian. Obtained results do not contradict the results of previous studies (Paškevičius, 1997 ir Lapinskas, 2000). The North Bliudziai reef drilled by wells BLI150 and BLI152 is clearly visible in the cross section as red colour "clean" limestone body. The Vadzgirys (lower Minija RS) belt was not discovered by wells until now, therefore its interpretation according seismic data is shown in the cross section (Figure 5, bottom).

Similarly to RMS, the structural map also clearly shows two separate reef zones. The eastern zone contains 3-4 separated patch reefs, each of them form structural trap. The northern reef (North Bliudziai) has already been drilled through by two wells BLI150 and BLI152, the southern reef structure (Pavasaris) was discovered by well BLI156 during 70's. The western reef zone (Vadzgirys reef belt) has different geometry: it forms a belt structurally rising from SW to NE. Mentioned reef belt was discovered with current 3D seismic project and was not known before. In order to analyze the nature of reflection of the top reef structural 3D view was overlaid with RMS amplitude map (Figure 6 right). The latter image shows that the highest reflection strength was obtained on the western (Pavasaris reef) or the north-western (North Bliūdžiai reef) slope of the reef structures. Most likely that following reflection strength distribution is caused by non-homogenous lithological composition of the reef. These considerations must be taken into account selecting the position for oil exploration wells. Current analysis show that the Baltic Basin Silurian reef belt development process continued minimum during two stages (lower and upper Minija RS) in lower Pridoli. Moreover, reef zones cross 3D area from S to N and most likely stretches to both sides forming a long few kilometer width zone along Silurian basin edge.

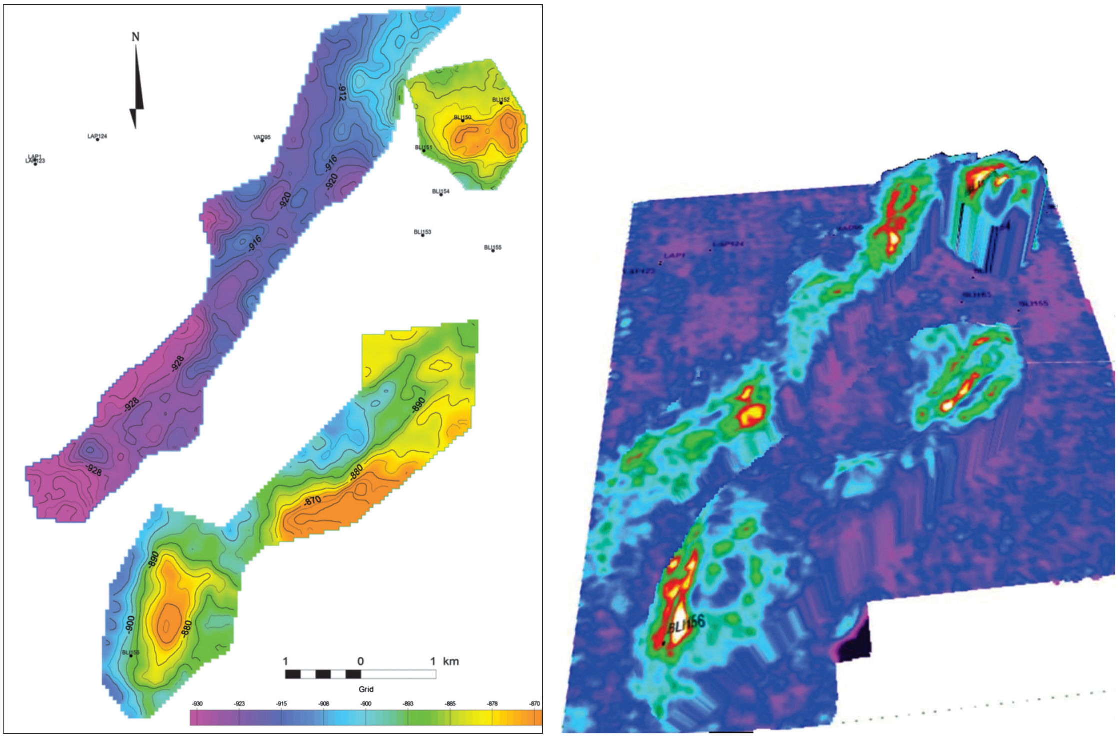

Figure 6. Structural maps of reef belt and patch reefs (left). Perspective 3-D view overlaid with RMS attribute map (right).

DISCUSSION

In the Baltic Silurian basin, the biostromes formed alongshore in a high-energy environment and their growth and disintegration were of a similar magnitude. In the Gotland area, the regressive development of the Silurian Baltic basin was locally halted at the Ludlow–Pridoli boundary, and the Burgsvik Reef is the final reef unit of an almost uninterrupted succession of reef barriers dating back at least to the Wenlock–Llandovery boundary. The locally transgressive lower Pridoli stratal sequence is poorly preserved in the central and western parts of the Baltic. A Pridoli transgressional reefal succession has been found in Lithuania. The carbonate buildup and facies zonality of the successive reefal units are very similar, and comparisons both with other submerged Silurian units in the Baltic Sea and on land on Gotland suggest that their build up is typical for the Silurian of the Baltic area in general (Flodén *et al.,* 2001). The most distinctive sedimentological and morphological feature of the reefal units is the narrow elongated reef barriers, consisting of biostromal limestones formed in very shallow waters (Riding 1981). These reef barriers seem to have formed as more or less continuous structures along the Silurian Baltic coasts, and apart from on Gotland and in the present area east of Gotland, reef barriers have been subdivided in the transitional area of the inner and outer shelf of the Silurian basin in Lithuania and Latvia (Lapinskas 1987a, 1987b). General trends and dynamics in reef distribution of Saaremaa (Estonia), *i.e.* their

NE–SW repeated migration in time, reflects first of all alternating transgressive–regressive cycles in the Baltic Silurian basin (Tuuling, Floden, 2013). The culminating Caledonian Orogeny with rising land areas undoubtedly intensified erosion and boosted influx of the terrigenous component into the Baltic Silurian basin. As a result, carbonate sedimentation has become heavily diluted since late Ludlow Kuressaare time, both in the open shelf and even in the shoal areas of the NE Baltic Silurian basin (Nestor & Einasto, 1997). As mentioned above the first reefs in Lithuania were found decades ago, however, the location of these reefs was based mostly on the well core data. Even some 2-D seismic data was available at the time; the only general location of the reefs was established.

The new 3-D seismic data interpretation along with shale content distribution study enable to draw a precise reef belt location consisting of two reef zones. Eastern zone contains 3-4 separated reefs (N. Bliūdžiai, S. Bliūdžiai and Pavasaris reefs) (Figure 5 middle), the western reef zone (Vadzgirys reef belt) forms a belt structurally rising from SW to NE (Figure 6). Seismic data shows that mentioned reef zones form two different generations: upper eastern zone is located within 30-60 ms time (36-72 m depth) window, while lower western zone appears at 60-90 ms time (72-108 m depth) below top Silurian (Figure 5 top). Lithological and shale content analysis prove that eastern reef zone corresponds to the upper Minija RS strata (N. Bliūdziai reef), accordingly, seismic interpretation of non-drilled western zone suggest that it started to form earlier, most likely during

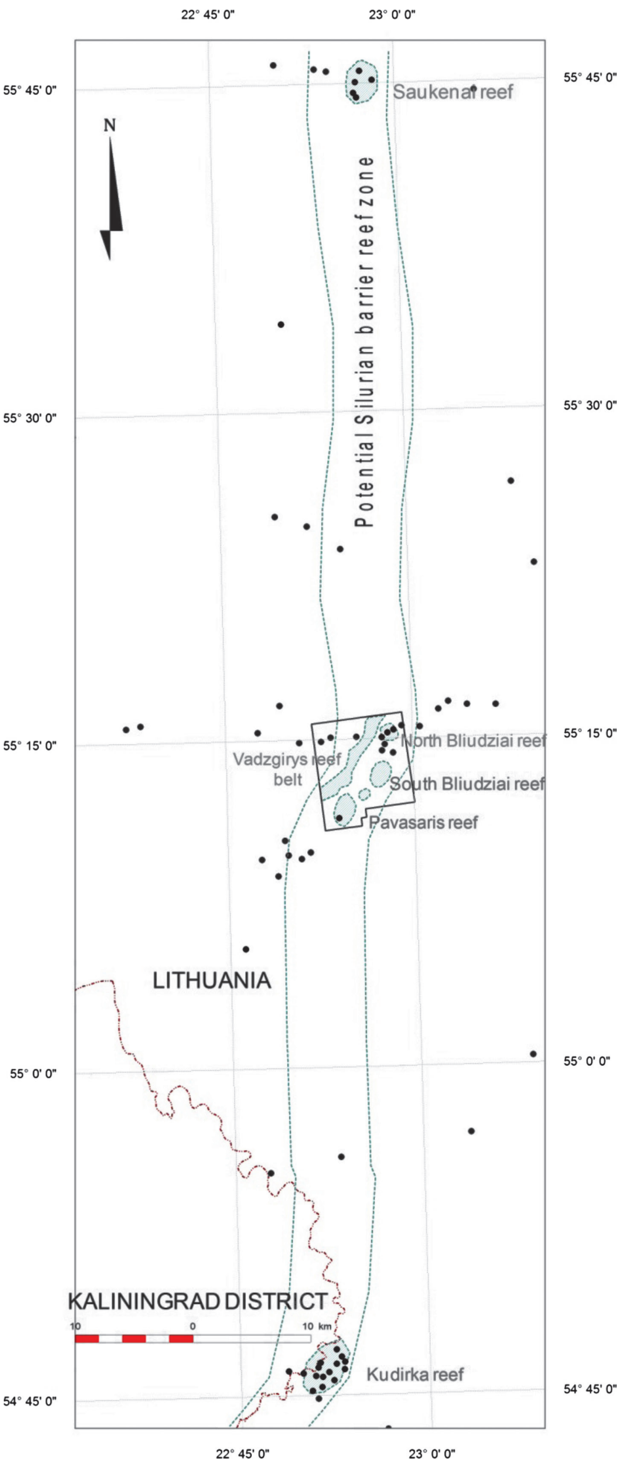

Figure 7. The potential Silurian barrier reef zone in Lithuania. Black dots indicate locations of wells.

early Minija RS (early Pridoli) stage (Figure 5 bottom). The transgression of the basin perhaps is responsible that the mentioned barrier reef migrated eastwards. As it is seen both from the cross-section and the seismic profile the North Bliūdžiai Reef as well as two other – South Bliūdžiai and Pavasaris reefs do follow the general configuration of the barrier and possibly started to develop later (Figure 5) The latter three reefs are more likely to be called as patch reefs. Available lithological data from the wells located between Southern and Northern Bliūdžiai and Pavasaris reefs as well as seismic profile support this presumption. Having in mind the facies distribution of the Baltic Silurian basin (Figure 2 left) and Kudirka and Šaukėnai reefs located southwards and northwards, respectively, one could expect that the barrier reefs as well as patch reefs prolong for hundreds of kilometers and form a viable oil play in the Baltic region potential for further oil exploration (Figure 7).

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