Estonian Journal of Earth Sciences, 2015, **64**, 1, 47–55 doi: 10.3176/earth.2015.09

New evidence of an early Pridoli barrier reef in the southern part of the Baltic Silurian basin based on three-dimensional seismic survey, Lithuania

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Received 30 June 2014, accepted 17 December 2014

Abstract. Reefs and a barrier reef have been newly identified and mapped by three-dimensional (3D) seismic survey in Lithuania. Seismic data analysis has allowed the size and geometry of these reefs to be determined. The largest reefs occur at Pavasaris and South Bliudziai. They have a similar shape and are about 1.5 km long and 1 km wide. A circle-shaped smaller patch reef at North Bliudziai is 1 km in diameter. The overall heights of the studied structures do not exceed 30–40 m. The reefs consist of coarse-grained bioclastic stromatoporoid limestone. A barrier reef rising structurally from SW to NE was established in the west of the mapped area. The stratigraphic position (early Minija Regional Stage) and lateral distribution of the barrier reef suggest it started to form earlier than the group of patch reefs. The development of patch reefs was related to the transgression of the Silurian Baltic basin.

Key words: Silurian, Baltic basin, Pridoli, barrier reef, three-dimensional seismics.

INTRODUCTION

Silurian (Pridoli) reef carbonates were first identified as possible reservoir rocks in Lithuania in 1964 (Lapinskas & Smilgis 1972; Lapinskas & Čekavičius 1981). In the southern part of the Baltic Silurian basin (Lithuania) the first reefs – North Bliudziai, Kudirka, Pavasaris and Šaukėnai – were discovered in 1970. A number of researchers have interpreted the Silurian Baltic basin as a platform depositional system (Laufeld & Bassett 1981; Nestor & Einasto 1997; Calner et al. 2004). The limestones in the central facies belt of the basin are dominated by stromatoporoids with a variable content of tabulate and rugose corals and crinoids. For many decades Gotland (Sweden) and Estonia were major research areas of Silurian reef limestone in Europe. Some of the reefs are very small, others are more extensive, ranging from a few metres to tens of metres. These reefs usually have a height of 1–6 m and the diameter between 4 and 50 m (Kaljo 1977). According to Kershaw (1993), some reefs in Gotland vary from 0.5 to 12 m in height and from 50 to 100 m in width. According to other authors, the same Högklint Formation reefs in Gotland are described as mere patch reefs up to 35 m thick and 100–150 m wide (Watts & Riding 2000). Reef-like build-ups have been interpreted from seismic data under the Baltic Sea. Some researchers have stated that these are not true barrier reefs but rather composed of several vertically stacked flat biostromes (Bjerkeus & Eriksson 2001; Flodén et al. 2001). In a recent article Tuuling & Flodén (2013) mention that the shallow shelf offshore Saaremaa was divided by a large barrier-reef-like structure. They also write that the width of this SW-migrating barrier (ca 8 km) and the extent of reef bodies within it (ca 4 km) are the largest known in the Baltic region, thus acknowledging the presence of a barrier-type reefs in the Baltic Silurian basin. Contrary to the mentioned authors, Bičkauskas & Molenaar (2008a) conclude that the carbonate build-ups of the Pridoli of Lithuania are not reefs since the framework-constructing fauna is absent. The latter authors suggest, however, that patch (isolated) reefs are not excluded; they do not play a dominant role in the Pridoli carbonate ramp system.

The primary objective of the recent study was to map the reef zone discovered by drilling applying the three-dimensional (3D) seismic acquisition method and understand when these reefs originated. In addition, resistivity and gamma ray logs as well as core description data were used for palaeoenvironmental interpretations.

GEOLOGICAL SETTING

The Baltic Silurian basin is located at the margin of Baltica, which was in the tropical climate belt just south of the equator during the Silurian (Cocks & Torsvik 2005). During the Caledonian Orogeny the Baltica continent collided with Avalonia in the latest Ordovician and with Laurentia in the Wenlock. The collision led to the closure of the Iapetus Ocean in the late Silurian (Cocks & Torsvik

2005, table 1). The upper part of the Silurian section in the studied area shows progressive increase in subsidence. The Minija Regional Stage forms the lower part of the Pridoli (Paškevičius 1997) (Fig. 1). Carbonates of the Minija Regional Stage serve as a good example of a carbonate ramp system with a stromatoporoid–crinoid–brachiopod-dominated carbonate factory. According to the lithofacies distribution, the ramp can be subdivided into five main facies belts (Fig. 2) (Bičkauskas & Molenaar 2008b). Although tectonic activity was minor, the shallow

System Period	Series Epoch	Stage Age	Regional stage	Beds	Biozones		
					Graptolites	Conodonts	
SILURIAN	PRIDOLI		JŪRA			*O. e. reimscheidensis*	
			MINIJA	Varniai	*N. lochkovensis*	*O. e. eosteinhornensis*	
				Silale	*N. ultimus - N. parultimus*		
	LUDLOW	LUDFORDIAN	PAGĖGIAI		*M. formosus* *M. valleculosus*	*O. crispa*	
					M. balticus	*R. dubia*	*O. tillmani*
			DUBYSA		*P. tauragensis*	*P. siluricus*	
		GORSTIAN			*L. scanicus*	*K. variabilis*	
					L. progenitor		
					N. nilssoni	*O. bohemica*	

Fig. 1. The Upper Silurian stratigraphy of Lithuania, modified according to Paškevičius (1997).

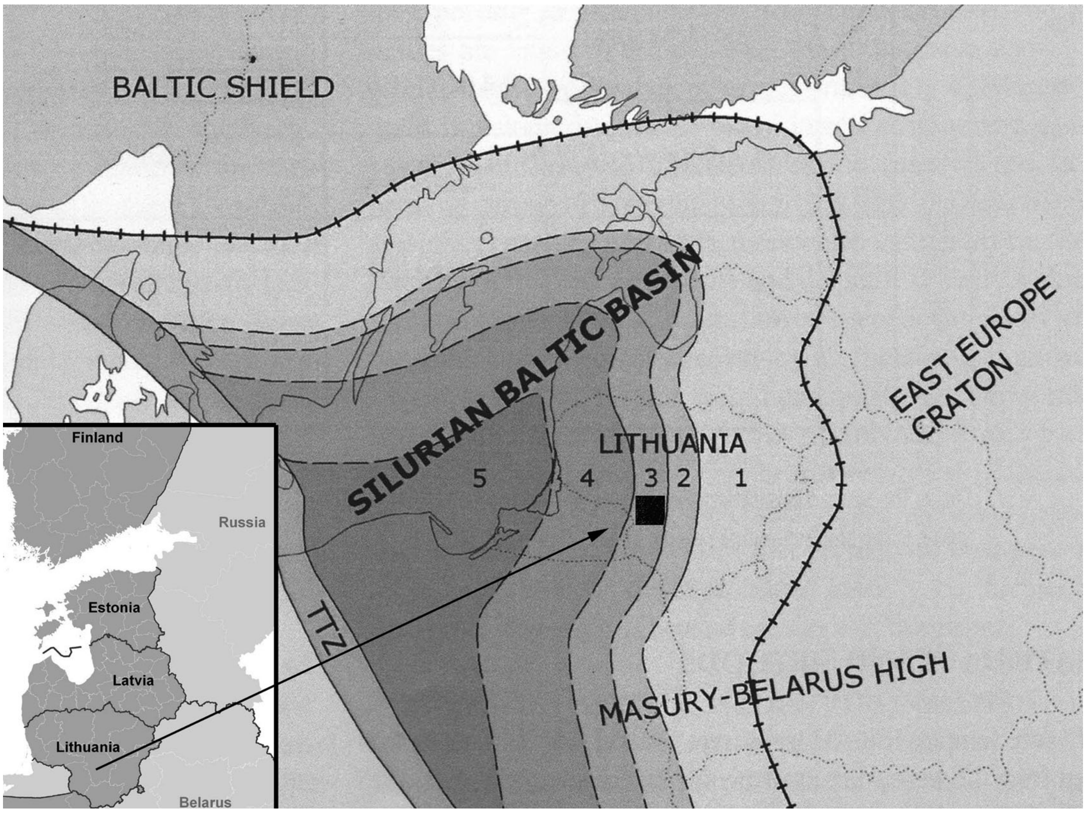

Fig. 2. The main facies belts of the Pridoli in the Baltic basin according to Bičkauskas & Molenaar (2008b) and the studied area (black square). Facies belts: 1, intertidal-subtidal (sabkha); 2, inner-shallow ramp; 3, mid-ramp; 4, outer ramp; 5, lower ramp slope – deep basin. TTZ, Teisseyre–Tornquist Zone.

coastal transitional facies of shallow subtidal and intertidal dolostones are partly lacking because of the Post-Silurian (lower Devonian) uplift of the eastern marginal area of the basin and erosion of a part of the succession (Lapinskas 2000). Carbonates of the studied wells are mainly of coarse-grained bioclastic, crinoidal, brachiopod and stromatoporoid limestones intercalated with marls (Fig. 3).

METHODS

Three-dimensional seismics

For the confident mapping of structures the following 3D seismic survey parameters were selected: orthogonal survey design (Cordsen et al. 2000, pp. 13–55), 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. Three-dimensional seismic field survey was performed by the Lithuanian geophysical company ‘Geobaltic’. One seismic channel consisted of the RAU-ex (Sercel) seismic recorder and a single high-sensitivity geophone GS-One (Geospace Technologies) per group. The AWD system AF-450 installed on crawler IC-35 (United Service Alliance) was used as a seismic source. Standard 3D Prestack Time Migration (PSTM) data processing routine was applied, with special attention to velocity analysis and residual static correction evaluation in order to achieve the highest possible definition of target objects. At the interpretation stage structural time and depth mapping of carbonate bodies were performed. Additionally, Root Mean Square (RMS) attribute maps were calculated for different time windows in order to map seismic reflection strength at different stratigraphic depths.

Compilation of the clay content cross section

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

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

where GR_{clean} is the minimal natural gamma-ray curve value reflecting pure limestone radioactivity (in our case 2–4 mcR/h), GR_{shl} is the 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 it is 1. The cross section of clay content was compiled by interpolating V_{shl} values in the plane between the wells. The clay content cross sections were prepared due to contrasting clay content within the reef bodies and surrounding carbonate rocks.

RESULTS AND DISCUSSION

Reefs in the Baltic Silurian basin formed alongshore in a high-energy environment and their growth and disintegration were of a similar magnitude. The lower Pridoli rock sequence is locally poorly preserved in its central and western parts. General trends and dynamics in reef distribution off Saaremaa (Estonia), i.e. their NE–SW repeated migration in time, reflect first of all alternating transgressive–regressive cycles (Tuuling & Flodén 2013). The culminating Caledonian Orogeny with rising land areas undoubtedly intensified erosion and boosted influx of the terrigenous component into the basin. As a result, carbonate sedimentation became 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). The RMS attribute maps revealed one barrier and three patch reefs (Figs 4, 5). The northern patch reef (North Bliudziai) has already been drilled through twice, while the southern one (Pavasaris) was discovered in one well drilled during the 1970s. The new reef of South Bliudziai (Fig. 5) was discovered by the current 3D seismic survey. The size and geometry of these reefs were unknown until now. Current seismic data analysis allowed us to determine that the two biggest, the Pavasaris and South Bliudziai reefs, have a similar shape and are about 1.5 km long and 1 km wide, while the smaller North Bliudziai reef is a round body 1 km in diameter. According to seismic data, the amplitudes of all structures are in the range of 25–33 ms TWT (two-way time). According to the existing well data, the average seismic velocity to the top of the Silurian is 2500 m/s, therefore the amplitude of the structures in the depth scale is not higher than 30–40 m. The Vadzgirys barrier reef is structurally rising from SW to NE and is about 1–1.5 km wide (Figs 4, 5). This barrier reef was discovered within the current 3D seismic project. The existence of barrier-type reefs in the southern Silurian basin was predicted by Lapinskas in the 1970s (Lapinskas 2000). According to

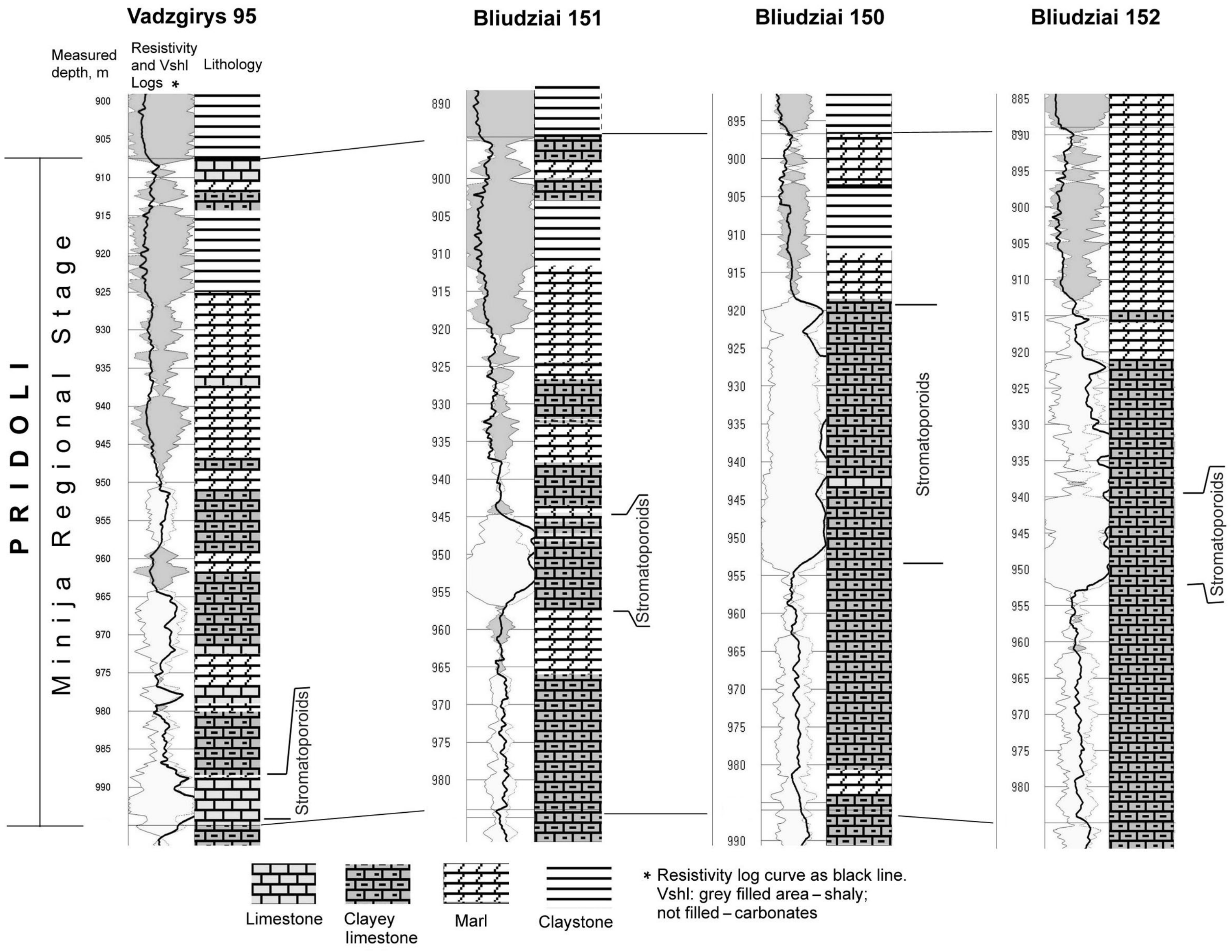

Fig. 3. The simplified lithology of the Minija Regional Stage section in wells in the studied area, resistivity and V_{shl} logs. Root-mean-square (RMS) windows from the top of the Silurian: RMS1, 90–135 m, RMS2, 135–180 m. Intervals with stromatoporoid limestone are indicated because they have the strongest relative seismic reflections.

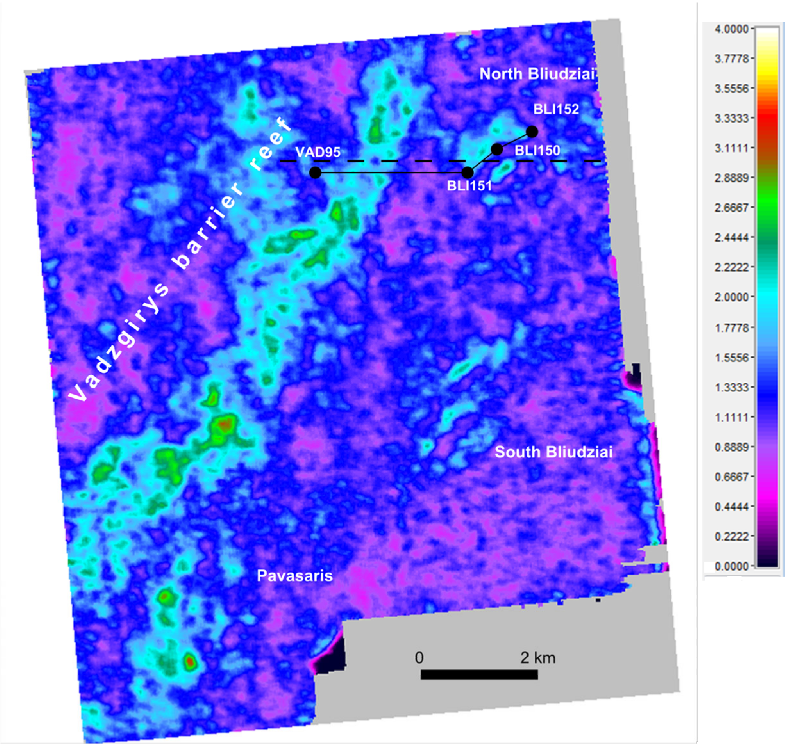

Fig. 4. Root-mean-square attribute map calculated for 135–180 m (RMS1) from the top of the Silurian. The 3D seismic cross line on the map is shown as a dashed line. The black dots connecting the solid line show the V_{shl} cross section. The colour scale denotes relative seismic reflections strength. Well abbreviations: VAD95, Vadzgirys 95; BLI150, Bliudziai 150; BLI151, Bliudziai 151; BLI152, Bliudziai 152.

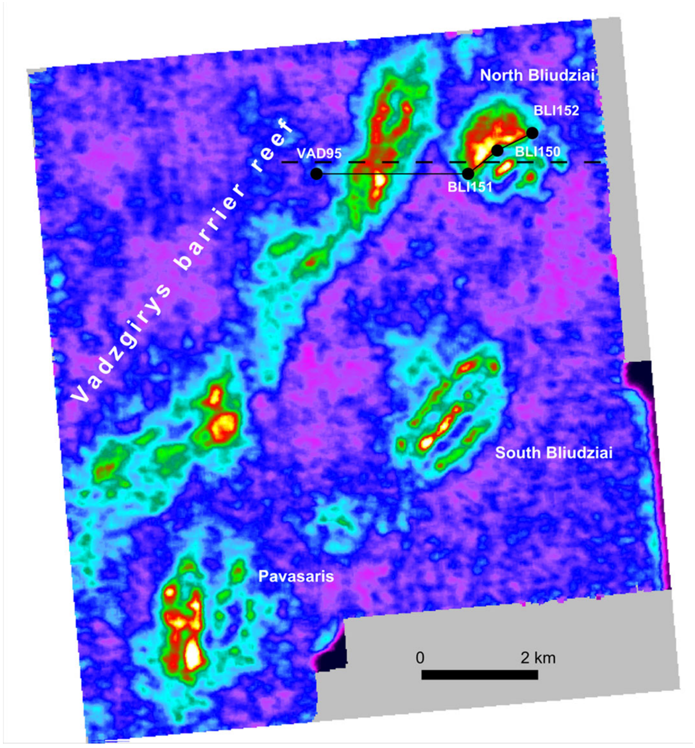

Fig. 5. Root-mean-square attribute map calculated for 90–135 m (RMS2) from the top of the Silurian. See Fig. 4 for legend.

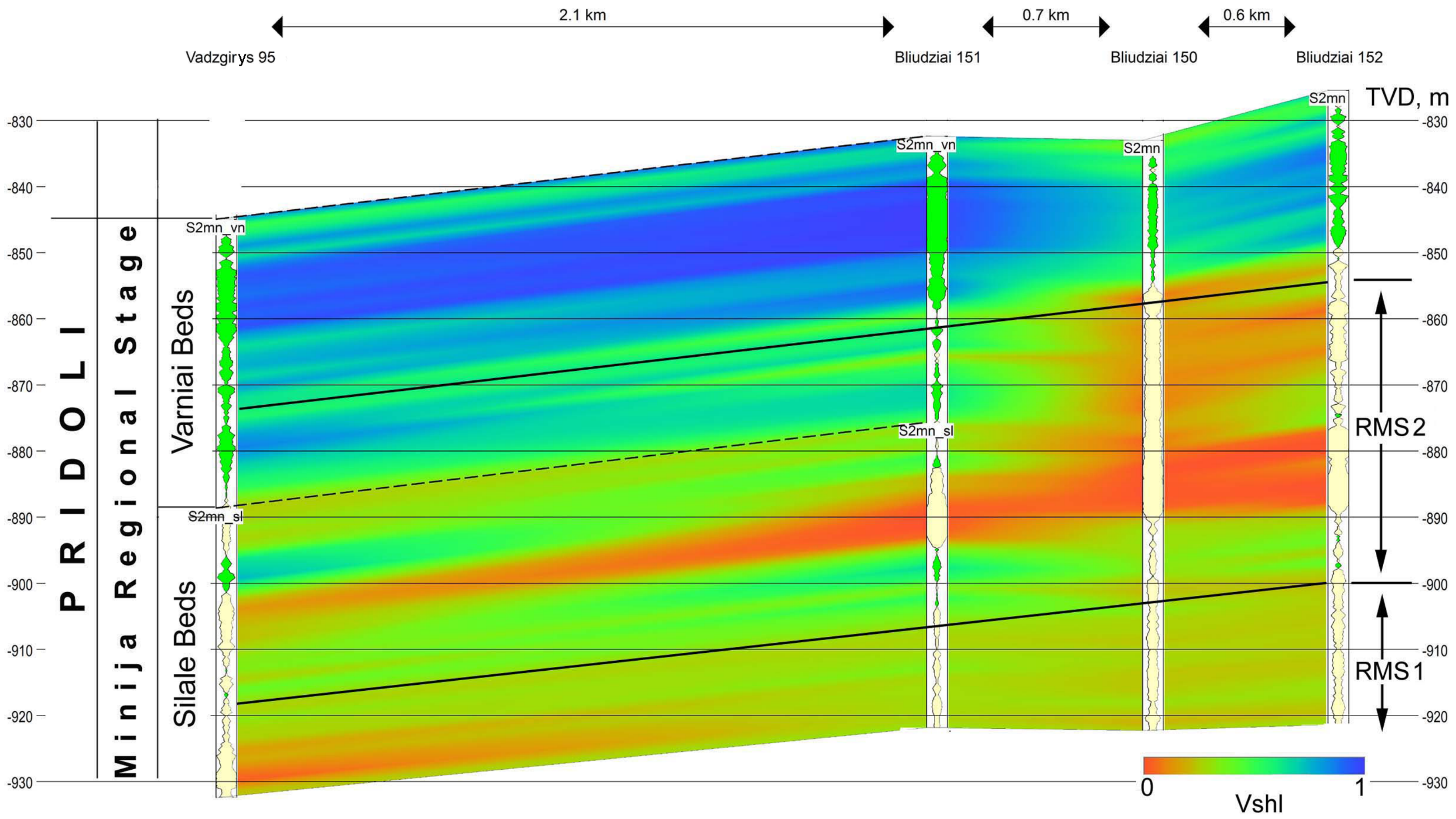

Fig. 6. The cross section of clay content interpolating V_{shl} values in the plane between the wells. For RMS1 and RMS2 refer to Fig. 3. The dashed line is the correlation line and the solid lines denote the RMS windows. TVD is true vertical depth in metres. The colour scale indicates clay content (V_{shl}): blue stands for maximum clay and red for a maximum in carbonates.

Fig. 7. Stromatoporoid coarse-grained limestone: **A**, Bliudziai 150 (sample depth 946.9 m); **B**, Bliudziai 152 (sample depth 946.1 m) wells (Bičkauskas & Molenaar 2008b).

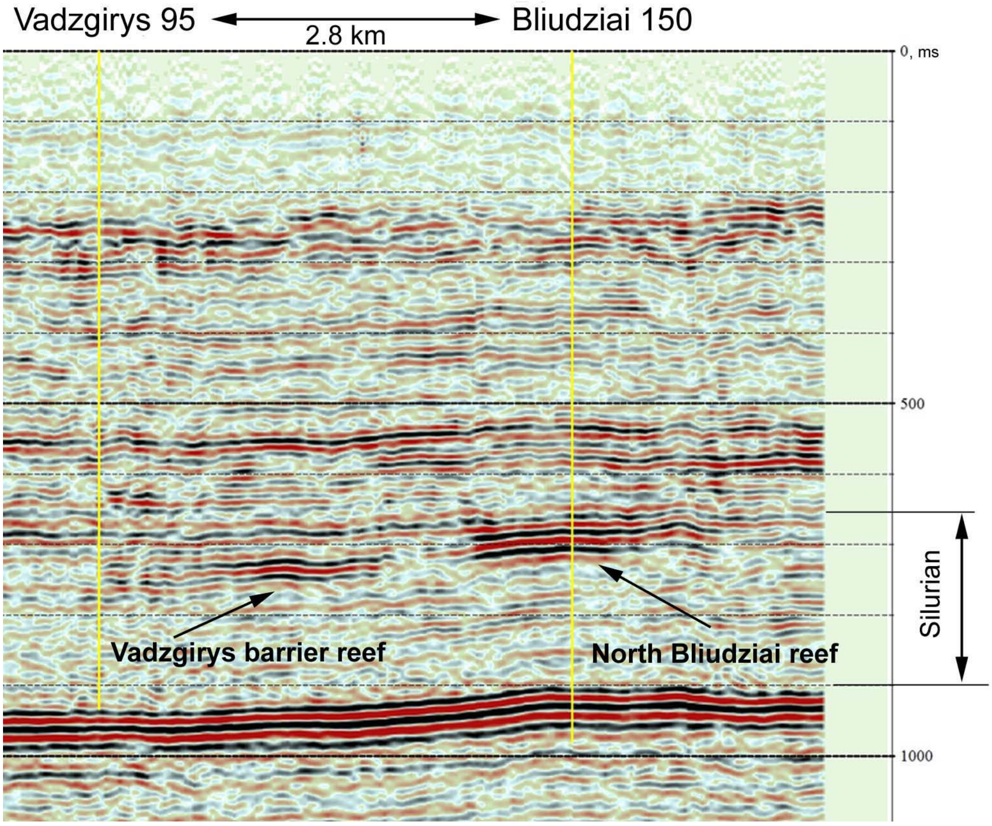

Fig. 8. Three-dimensional seismic cross line. See RMS attribute maps for its location.

him, the barrier could be 2–6 km wide and stretch for about 240 km. Interestingly, based on the well core data, he predicted that the barrier was 23–43 m thick, which is very close to our estimated 30–40 m. From literature we know that the most distinctive sedimentological and morphological feature of reef units is the narrow elongated reef barriers, consisting of biostromal limestones formed in very shallow water (Riding 1981). These reef barriers seem to have formed as more or less continuous structures along the Silurian Baltic coasts, and apart from Gotland and the present area east of Gotland, have been subdivided in the transitional area of the inner and outer shelf of the Silurian basin in Lithuania and Latvia (Lapinskas 1987a, 1987b). The carbonates of the North Bliudziai reef are mainly of coarse-grained bioclastic stromatoporoid limestone which has the lowest V_{shl} value as well as the highest resistivity (Figs 3, 6). The surrounding facies with moderate V_{shl} values are represented by marls with some coarser bioclastic packstones dominated by crinoids and brachiopods. The top of the North Bliudziai reef (Bliudziai 150 well) is sealed with laminated marls and claystone (Figs 3, 6). The core description of the wells that penetrate the North Bliudziai reef indicates that the most significant reflections are possibly related to stromatoporoid limestone: carbonates are mainly coarse-grained bioclastic stromatoporoid limestone (Figs 3, 7). From the stratigraphical and structural positions as well as from RMS maps we suggest that the Vadzgirys barrier reef appeared earlier (early Minija age) than the group of patch reefs. From the seismic cross-line and RMS map (Figs 5 and 8) we can see that the barrier and North Bliudziai reefs are separate structures.

CONCLUSIONS

1. The use of 3D seismic survey enabled a discovery of a new South Bliudziai reef and Vadzgirys barrier reef in the southern Silurian basin.
2. The geophysical and lithological data suggest that these reefs are mainly composed of stromatoporoid limestone which shows the strongest relative seismic reflections.
3. The RMS maps and stratigraphical position of the reefs indicate that the Vadzgirys barrier reef started to develop in the early Minija age. The North and South Bliudziai as well as Pavasaris patch reefs started to form later.
4. The formation of the mentioned reefs in the early Pridoli was controlled by the transgression cycle of the southern Silurian Baltic basin.

Acknowledgements. The studies were supported by the European Social Fund (Subsidy contract No. SUT-13T-93). The authors thank the Lithuanian oil company TAN Oil for access to their license area and support in preparation of the paper. Tõnu Meidla and Kathleen Histon are thanked for their reviews. Dimitri Kaljo provided many helpful comments on the manuscript. This is a contribution to the IGCP Project 591 'The Early to Middle Palaeozoic Revolution'.

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