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Structure and development of the Valmiera–Lokno Uplift – a highly elevated basement block with a strongly deformed and eroded platform cover in the East European Craton interior around the Estonian–Latvian–Russian borderland

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Based on drillings, a number of geological cross-sections, and structure contour and isopach maps were composed to describe/analyse the structure and development of the Valmiera–Lokno Uplift (VLU), a basement block elevated up to 700 m with a heavily deformed and eroded platform cover in the East European Craton interior, along the regional Liepaja–Riga–Pskov Fault Zone (LRPFZ). Five isolated basement-cored anticlines (BCA), the Lokno, Haanja, Mõniste, Valmiera and Smiltene uplifts, arise in the platform cover on the VLU, whereas the downthrown LRPFZ side defines a complex monoclinal fold. The anticlines, straddling or occurring near the monocline, merge with it and thus have highly asymmetrical shapes. Thickness changes of stratigraphic units across the VLU reveal its complex history, reflecting regional tectonic activation pulses that varied noticeably even between neighbouring BCAs. In all, the latest Precambrian–earliest Ordovician initiation epoch of the VLU was followed by modest tectonic activity or a standstill period in the Middle Ordovician–Early Silurian. Intensifying tectonic movements culminated again in the prime of the Caledonian Orogeny in latest Silurian–earliest Devonian time, and faded thereafter towards the end of Early Devonian. The VLU has been reactivated occasionally since the latest Devonian and emerges as a crustal weakness in the recent movement and seismicity patterns. To decipher the origin of the VLU, hitherto factually undiscussed topics, a more detailed study of the LRPFZ, analysis of its fault pattern and kinematics alongside the regional tectonic setting/history is needed. A cursory look hints to a substantial Early Paleozoic sinistral strike-slip along the LRPFZ, allowing interpreting the VLU as a possible restraining bend structure.

Key words: East European Craton interior, Baltic Homocline–Baltic Syneclise junction, Liepaja–Riga–Pskov Fault Zone, Valmiera–Lokno Uplift, platform cover basement-cored anticlines, strike-slip movements.

INTRODUCTION

In the remote interior of the northwestern part of the East European Craton (EEC), the gently slanting (10–20’) southern slope of the Baltic Shield composed of Paleoproterozoic crystalline rocks, deformed and consolidated by the Svecofennian Orogeny (1.93–1.8 Ga), is overlain by a thin, southward-thickening Ediacaran–Early Paleozoic cover of the East European Platform (EEP; Fig. 1). The northwestern, up to 550 m thick and ~8–13’ southerly tilted sedimentary bedrock sequence of the EEP, extending from eastern Estonia across the central Baltic Sea, forms the Baltic Homocline. It transfers gradually to the Baltic Syneclise further south to south-west (Tuuling and Flodén, 2016; Tuuling, 2017; Figs. 1 and 2). However, around the Estonian–Latvian border and its junction with Russia, this gentle tilt of the platform cover is interrupted by a significant easterly trending tectonic structure, developed along the deep basement-rooted Liepaja–Riga–Pskov Fault Zone (LRPFZ). This ~160–170 km long and up to 40–50 km wide, locally >700 m raised structure, called the Valmiera–Lokno Arch (Projection) or the Valmiera–Lokno Uplift (VLU), represents one of the largest zones affected by tectonic strain that evolved in the north-west of the EEP (Figs. 1 and 2; Misans and Brangulis, 1979; Brio et al., 1981; Puura and Vaher, 1997).

First hit by drilling in the Haanja–Lokno district in 1945, this oddly high-standing block of the cratonic basement was followed by further drillings westwards, and contoured finally by a seismic survey around the Latvian city of Valmiera in 1977–1978 (Figs. 1–3; Brio et al., 1981). Besides notable undulation, the basement top of the uplifted VLU block reveals several striking bulges overlain by anticlines in the platform cover. In all, four similar individual basement-cored anticlines (BCA),

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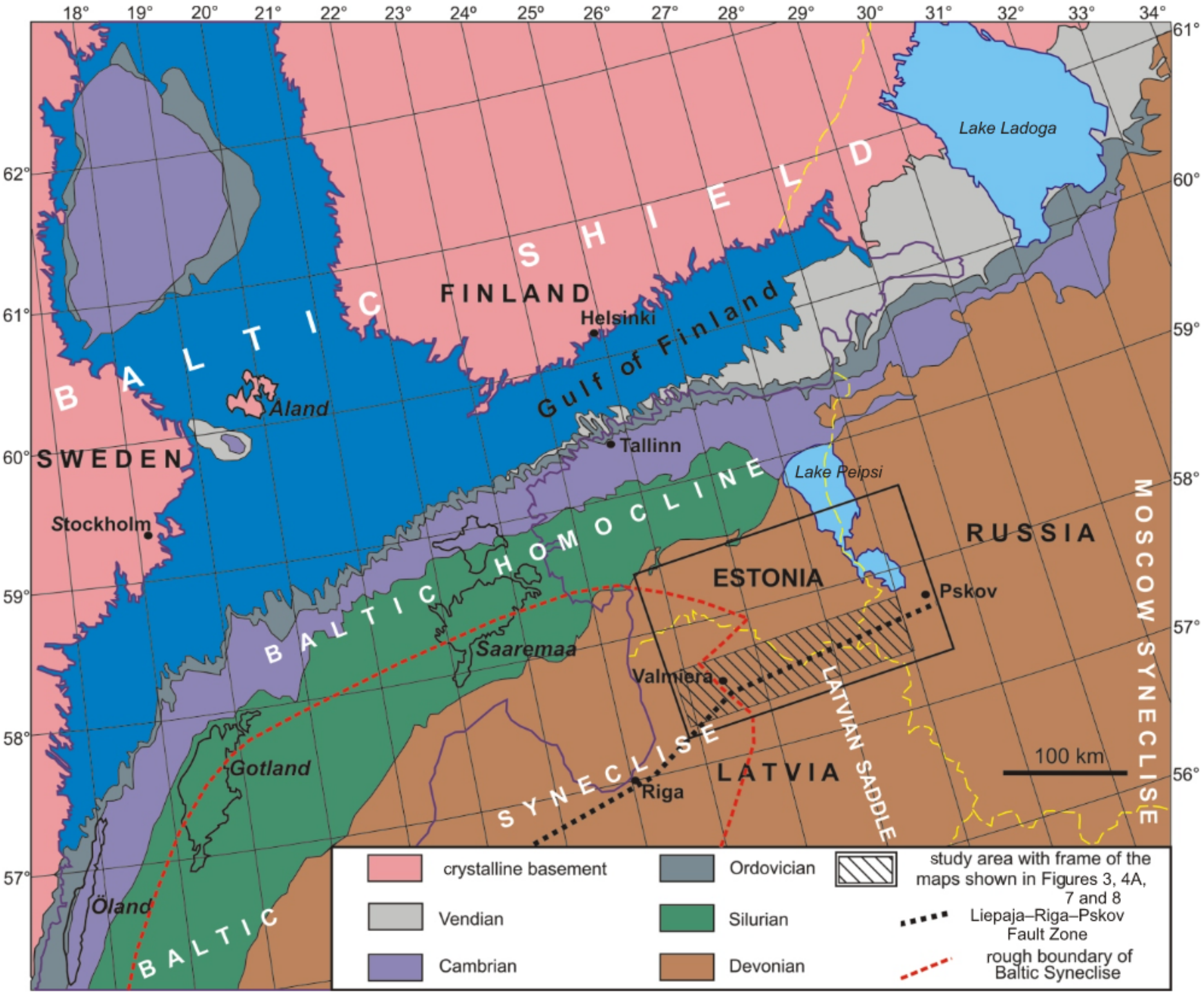

Fig. 1. Geological-structural setting with location of the study area

called the Haanja–Lokno, Mõniste, Valmiera, and Smiltene uplifts, have been outlined within the VLU based on drillings and seismic data (Figs. 2–4B).

The top of the basement has been contoured by boreholes around the Haanja–Lokno, Valmiera, and Mõniste uplifts, while the Smiltene Uplift has been outlined based only on a seismic survey. Besides that, the thickness and lithology of the overlying Paleozoic rocks have been studied across the VLU area in a number of boreholes that terminate in the platform cover. Based on this data, the general geology of the VLU, particularly the morphology, timing, and development style of its solitary basement uplift-induced anticlines in the platform cover have been discussed in several papers (e.g., Kajak, 1962; Paasikivi, 1966; Kaplan and Hasanovitch, 1969; Vaher et al., 1980; Brio et al., 1981; Mens, 1981; Puura and Vaher, 1997).

Analogous sites around the LRPFZ with the highly elevated cratonic basement and solitary BCAs have been described also further south-west of the VLU (Brangulis and Brio, 1981). However, all this information, describing different sections and solitary BCAs along the LRPFZ is scattered between several papers, and thus lacks a summarizing and generalizing approach. Furthermore, large majority of this data, being published in the local Russian-based scientific journals/monographs, has remained so far inaccessible for potential readers worldwide who might be interested in basement faulting and the resultant deformation of the overlying platform cover in the EEC interior.

Thus, our goal with this paper is for the first time to collect, combine and generalize all available data concerning the geology of the VLU with the following purposes: (1) to visualize and describe the overall structure/morphology of the VLU and its solitary basement uplifts with the overlying anticlines in the platform cover by drawing geological cross-sections and structure contour maps; (2) to perform a detailed thickness analysis of platform cover across the VLU, in particular across its solitary basement-cored anticlines, by constructing isopach maps of different stratigraphic units (with <1 m thickness accuracy based on drill cores); (3) to discuss the origin and likely tectonic scenarios for the VLU development in the light of the other analogous structures along the LRPFZ.

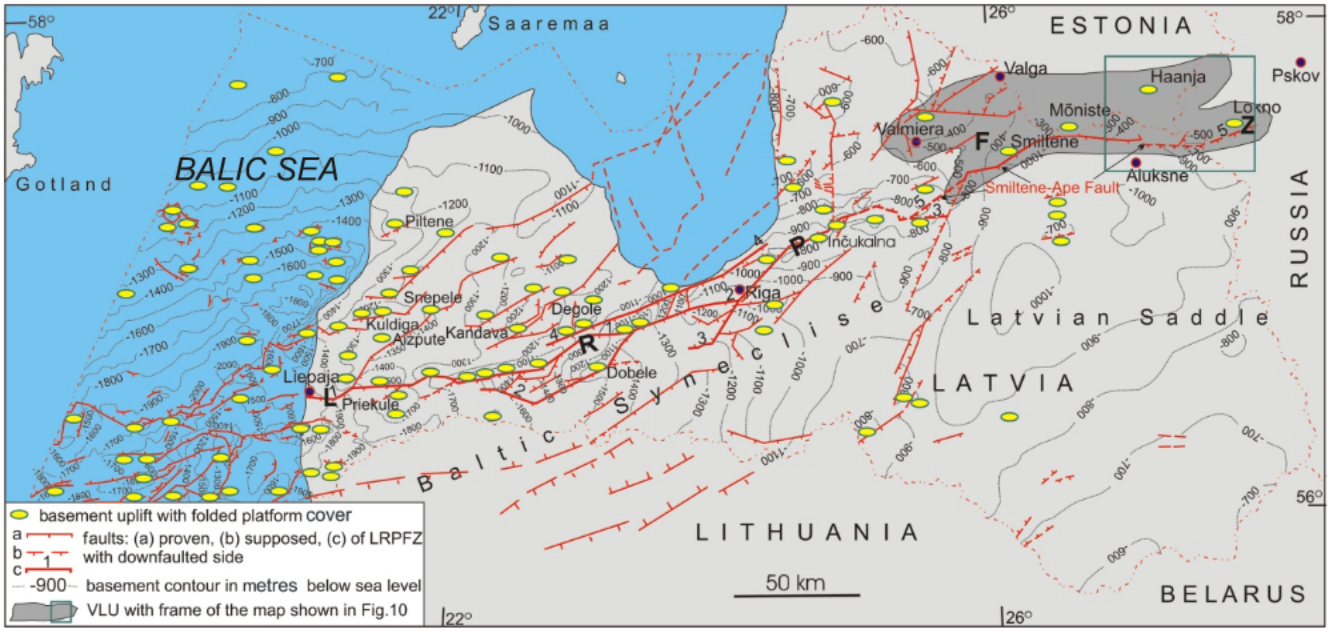

Fig. 2. Structure contour map of the crystalline basement in Latvia with the basement faults, Liepaja–Riga–Pskov Fault Zone (LRPFZ), VLU location/contour, and local basement-cored anticlines in the platform cover (modified after Brio et al., 1981; Brangulis and Kanev, 2002)

Numbered master faults of the LRPFZ: 1 – Liepaja–Saldus, 2 – Dobele–Babite, 3 – Sloka–Carnikava, 4 – Olaine–Inčukalna, 5 – Smiltene–Ape

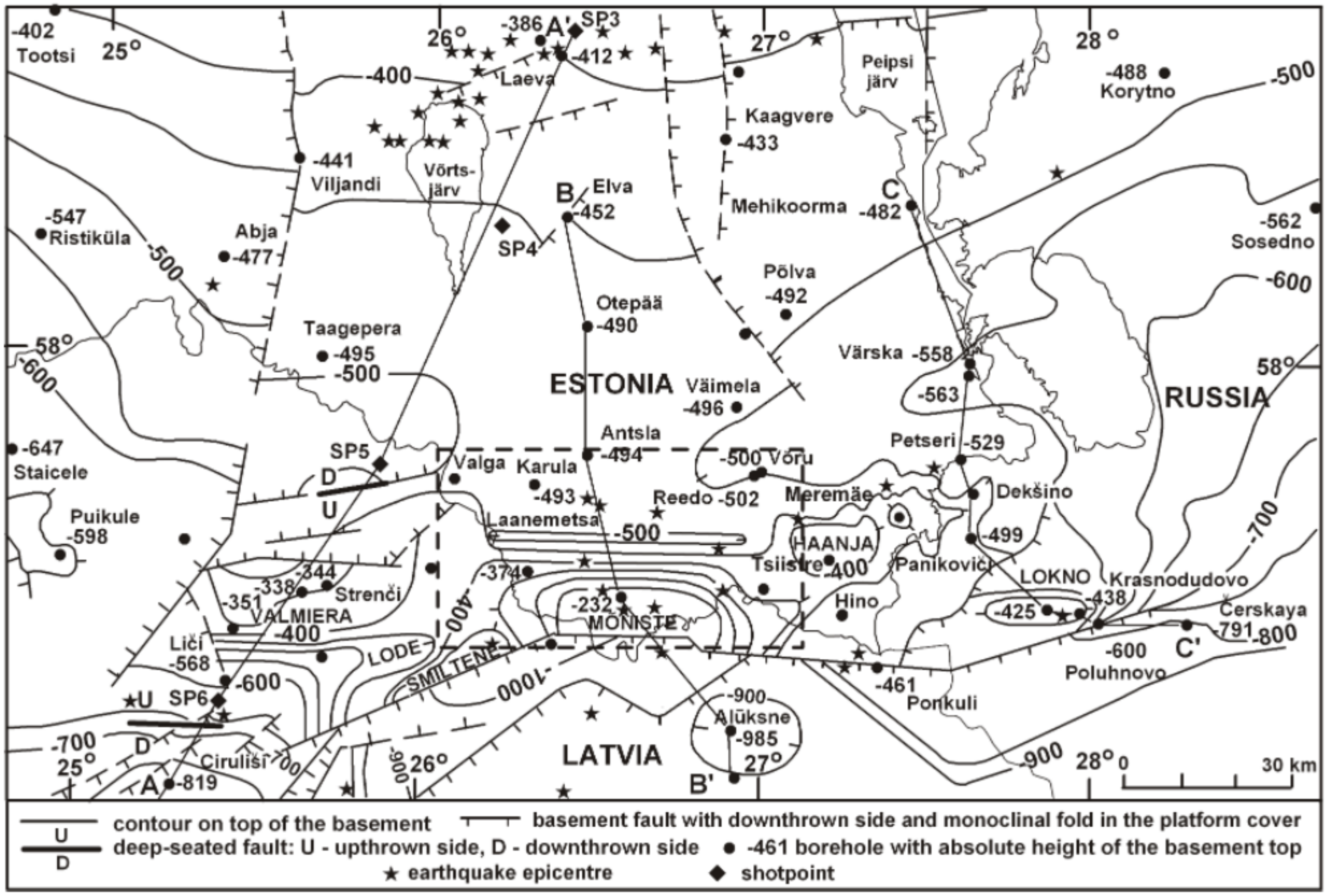

Fig. 3. Structure contour map of the top of crystalline basement around the Valmiera–Lokno Uplift with solitary basement uplifts (Valmiera, Smiltene, Mõniste, Haanja, Lokno) and major basement faults

Contour interval is 50 m; lines A–A', B–B' and C–C' show the location of cross-sections in Figures 5 and 6; dashed-line frame shows excerpt of repeated levelling area around the Mõniste Uplift given in Figure 11; for location see Figure 1

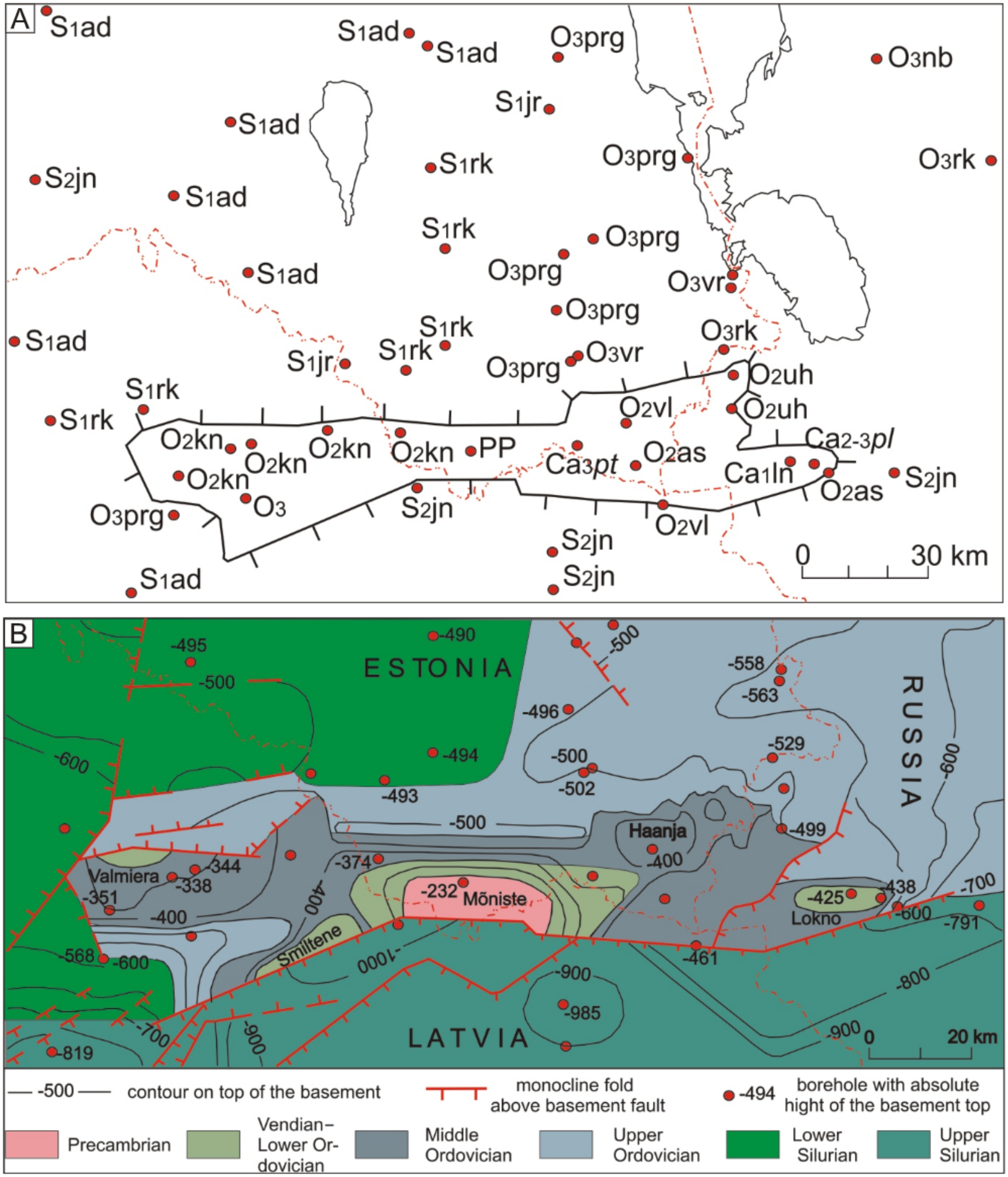

Fig. 4. Pre-Devonian erosional inlier around the Valmiera–Lokno Uplift

A – unconformity surface revealing Precambrian (PP) and different Cambrian to Silurian stages/formations (see Table 1) in boreholes, overlain by Devonian rocks with a contour/location of the elevated northern part of the VLU; **B** – the same surface plotted against the excerpt of the structure contour map (see Fig. 3) of the VLU area; for location see Figure 1

GENERAL GEOLOGY

DEEP-SEATED LIEPAJA–RIGA–PSKOV FAULT ZONE

A submeridional deep seismic profile from northern Estonia across Latvia and Lithuania (Ankudinov et al., 1994: fig. 2) reveals the ~50 km thick Earth's crust within the Baltic Homocline. Around the VLU area, dissected by deep faults extending to the mantle, the crust thickens and reaches up to ~60 km further south within the Baltic Syneclise (Figs. 2, 3 and 5).

The major faults bounding the VLU to the south define a >500 km-long fault zone that extends from the Russian city of Pskov across Riga to Liepaja in western Latvia and further offshore (Brangulis and Kanev, 2002; Šliaupa and Hoth, 2011; Šliaupiene and Šliaupa, 2012; Figs. 1 and 2). Its slightly north-east to east-trending onshore section, known as the LRPFZ, converges around five extensive (1–5 in Fig. 2), mostly normal, high-angle master faults with subsided southern blocks (Misans and Brangulis, 1979; Suveizdis et al., 1979; Brangulis and Kanev, 2002). Exceptionally, between Riga and the VLU, the Olaine–Inčukalna Fault (3 in Fig. 2) is interpreted as a reverse fault with downthrown northwestern/northern block. These major faults reveal locally curved traces and a highly varying offset that remains usually within a few hundreds of metres, however, along some faults (Liepaja–Saldus and Smiltene–Ape), can reach 700 m (Brangulis and Kanev, 2002). The structural complexity of the LRPFZ is increased by numerous smaller and larger subsidiary/splay faults along and around this major fault zone. In the overlying platform cover, these faults are usually expressed as asymmetrical flexures or monoclinal folds.

THE CRYSTALLINE BASEMENT AND ITS STRUCTURAL SETTING

The crystalline basement in the VLU area belongs to the Estonian–Latvian Granulite Belt. This complex of mafic volcanic rocks was formed in a volcanic arch of the Svecobaltic Orogeny (1.84–1.80 Ga) and underwent granulite facies metamorphism at 1.78–1.77 Ga (Soesoo et al., 2006; Kirs et al., 2009; Fig. 5A). Besides prevailing mafic to intermediate metavolcanic rocks, pyroxene gneisses subjected to charnockitic and granitic migmatization are widespread in the granulite belt (Koistinen et al., 1996).

Taking into account the basement top configuration, the VLU is located in a structural transition-knot in the northwestern part of the EEP, at the junction of the Baltic Homocline, Baltic Syneclise, Latvian Saddle and Moscow Syneclise. To the south it bounds the gently southerly dipping Baltic Homocline, and to the north-west the easterly rising slope of the Baltic Syneclise. The VLU's southern margin merges with the Latvian Saddle along the LRPFZ. Across the latter saddle-like structure in eastern Latvia, the westerly located Baltic Syneclise vaults to another large cratonic depression to the east, the Moscow Syneclise in western Russia (Misans and Brangulis, 1979; Zhuravl'ev et al., 2006; Figs. 1 and 2).

THE GEOLOGICAL AND STRUCTURAL SETTING OF THE PLATFORM COVER

The Neoproterozoic Vendian (Ediacaran) to Paleozoic (Cambrian–Devonian) platform cover in the north-western corner of the EEP (Fig. 1 and Table 1) formed largely when the EEC drifted as a separate continent (Baltica) from high southern to northern equatorial latitudes (Torsvik et al., 2012; Torsvik and Cocks, 2013). Due to drift-related environmental changes during the deposition, the sedimentary cover sequence around the VLU divides into three lithological portions (Table 1): (1) an Ediacaran, Cambrian and Lower Ordovician succession of normal marine clays, silts and sandstones; (2) a Middle Ordovician–Silurian succession of equatorial marine carbonate rocks; and (3) the Devonian Old Red Sandstone sequence with rare intercalating layers of marlstones, limestones and dolostones, formed largely in the arid interior of Laurussia (Domeier and Torsvik, 2014), i.e. after the collision of Baltica with Laurentia. Stratigraphically, this mainly shallow-marine cover succession is divided into numerous regional stages/formations (Table 1).

Besides the palaeoenvironmental imprint, the platform cover in the north-west of the EEP reveals extensive, regional-scale changes in the structural setting, triggered by interaction of Baltica with other large continental blocks. Induced by the Timanide and Caledonian orogenies, culminating during latest Precambrian–earliest Paleozoic and latest Silurian–earliest Devonian times (Roberts, 2003; Gee and Pease, 2004; Gee et al., 2008; Pease et al., 2008), respectively, two regional unconformities divide the sedimentary bedrock sequence around the VLU into three structural complexes (Table 1): (1) Timanian, including the Vendian and the Lontova Stage of the Lower Cambrian; (2) Caledonian, embracing the post-Lontova Cambrian, the Ordovician–Silurian, and the Lower Devonian Tilže/Kemeri stages; and (3) Variscan, including the post-Kemeri Devonian rocks.

However, taking into consideration that the sedimentary sequence on the southern slope of the Baltic Shield, i.e. within the Baltic Homocline, thickens gradually southwards, the platform cover in the VLU area, instead of an expected steady 500–600 m, shows an abnormally high thickness variation (300 to 1100 m; Figs. 5–8). This is because of syn- and post-sedimentary block movements triggered by the basement faulting, which have also produced not only numerous basement-cored folds of varying morphologies in the overlying platform cover but also high thickness variations with extensive erosion. Thus, wedging out or thinning due to removal by erosion, as well as thickening of particular platform units towards the uplifted and down-faulted basement blocks, respectively, reveals the complex tectonic history of the VLU.

MATERIAL AND METHODS

Detailed study of the VLU is based largely on the drilling data complemented with the results of the previously interpreted seismic studies given in the manuscript reports of the Geological Survey of Estonia and the Latvian Environment Geology and Meteorology Agency, and in a number of publications and tectonic maps (Paasikivi, 1966; Kaplan and Hasanovich, 1969; Suveizdis et al., 1979; Mens, 1981; Brio et al., 1981; Brangulis and Brio, 1981; Brangulis and Kanev, 2002). Altogether, 166 boreholes (43 piercing the basement) were used to compose auxiliary drawings and tables with thickness data to visualize and support describing/analysing the general structure and the formation history of the VLU.

Most of the boreholes reaching the crystalline basement occur north, and only two (Alūksne, Čerskaya) remain south of the LRPFZ, i.e. on its upthrown and downthrown sides, respectively (Fig. 3). Nine, five, and two deep boreholes located on the elevated side of the LRPFZ hit the bulging basement top around the Haanja–Lokno, Valmiera, and Mõniste uplifts, respectively. Five basement-reaching boreholes remain within the LRPFZ (Ciruliši, Liči, Ponkuli, Poluhnovo, Krasnodudovo) and pierce the monocline fold(s) in the platform cover.

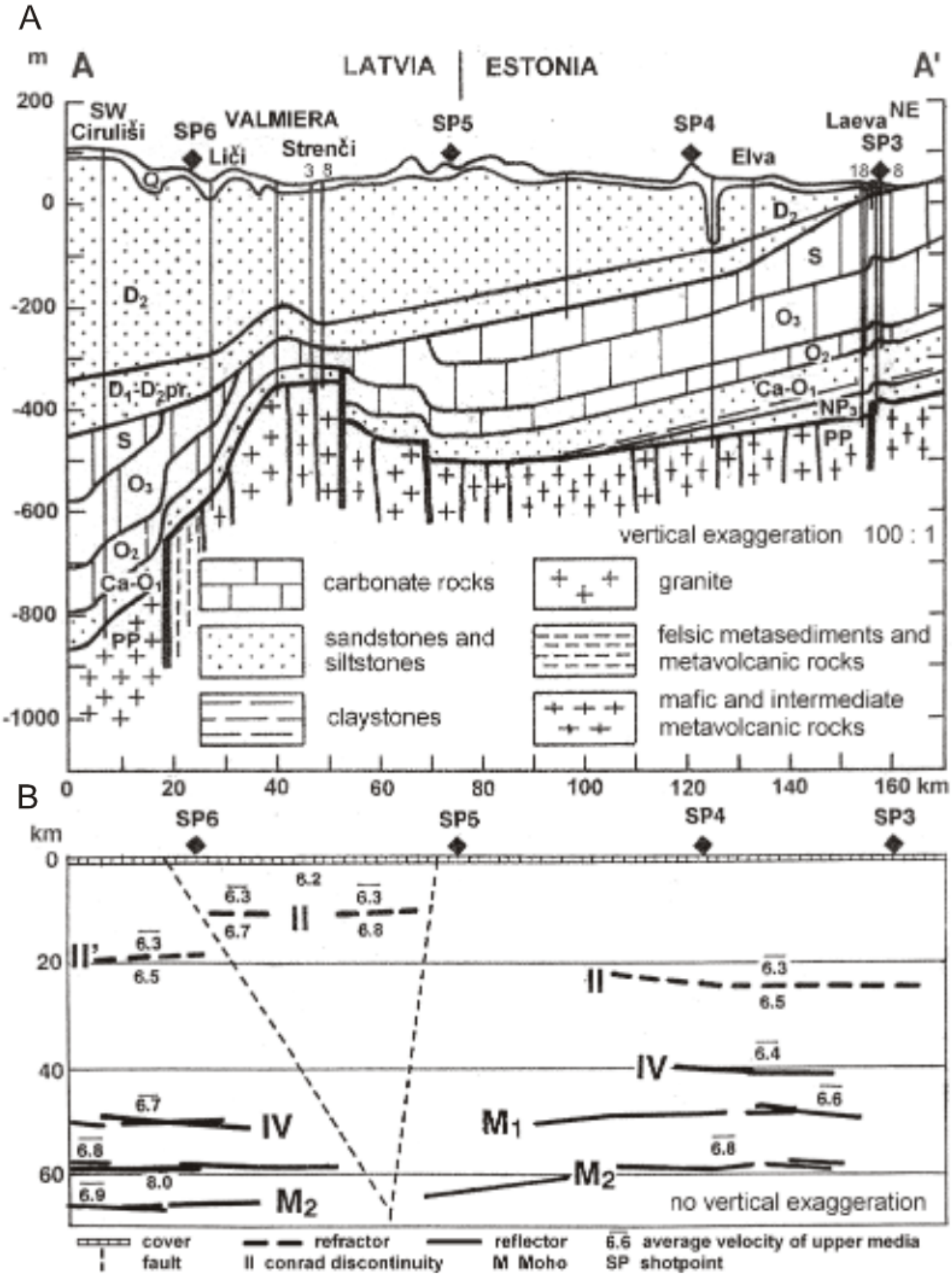

Fig. 5. Geological cross-section (A) and deep seismic profile interpretation (B) (modified from Puura and Vaher, 1997 and Ankudinov et al., 1994, respectively) across the Valmiera Uplift

See location in Figure 3

DESCRIPTION OF THE VALMIERA–LOKNO UPLIFT

Facilitating the overall structural/geological description of the VLU, a detailed structure contour map of the basement top for the VLU area (Fig. 3) and the same map plotted against a subcrop map of the pre-Devonian erosional/unconformity surface with distribution of different stratigraphic units below the Devonian rocks (Fig. 4) were drawn. To illustrate and describe the morphology of the solitary basement uplifts with overlying anticlines in the platform cover, detailed geological cross-sections of the Valmiera (Fig. 5A), Mõniste (Fig. 6A) and Haanja-Lokno uplifts (Fig. 6B) were composed.

LIMITING THE VALMIERA–LOKNO UPLIFT

The geological literature has been so far largely focused on the Valmiera, Smiltene, Mõniste, Haanja and Lokno basement uplifts and the anticlines in the platform cover above them

Table 1

Stratigraphic, lithological and tectonic subdivision of the platform cover in the Valmiera–Lokno Uplift area (based on subdivision given in Raukas and Teedumäe, 1997; Mark-Kurik and Põldvere, 2012)

System	Series	Regional Stage/Formation	Index	Lithology	Structural complex
DEVONIAN	UPPER	Daugava	D$_3$dg	Limestone	VARISCAN
		Dubniki	D$_3$db	Marlstone	
		Pļaviņas	D$_3$pl	Dolo-, lime- and marlstone	
	MIDDLE	Amata	D$_2$am	Sand-, silt- and claystone	
		Gauja	D$_2$gj	Sand- and siltstone	
		Burtnieki	D$_2$br	Sand- and siltstone	
		Aruküla	D$_2$ar	Sand- and siltstone	
		Narva	D$_2$nr	Marl-, dolo-, clay-, silt- and sandstone	
		Pärnu	D$_2$pr	Sandstone	
	LOWER	Rezekne	D$_1$rz	Sandstone	
		Kemeri	D$_1$km	Silt- and sandstone	CALEDONIAN
		Tilžė	D$_1$tl	Silt- and sandstone	
SILURIAN	WENLOCK	Jaani	S$_2$jn	Marl- and mudstone	
	LLANDOVERY	Adavere	S$_1$ad	Lime-, marl- and mudstone	
		Raikküla	S$_1$rk	Lime-, marl- and mudstone	
		Juuru	S$_1$jr	Lime-, marl- and mudstone	
ORDOVICIAN	UPPER	Porkuni	O$_3$pr	Lime- and marlstone	
		Pirgu	O$_3$prg	Lime- and mudstone	
		Vormsi	O$_3$vr	Marl-, lime- and claystone	
		Nabala	O$_3$nb	Limestone	
		Rakvere	O$_3$rk	Lime- and marlstone	
		Oandu	O$_3$on	Marlstone and black shale	
		Keila	O$_3$kl	Marl- and limestone	
		Haljala	O$_3$hl	Lime- and marlstone	
		Kukruse	O$_3$kk	Limestone	
	MIDDLE	Uhaku	O$_2$uh	Limestone	
		Lasnamägi	O$_2$ls	Limestone	
		Aseri	O$_2$as	Lime- and marlstone	
		Kunda	O$_2$kn	Limestone	
		Volkhov	O$_2$vl	Limestone	
	LOWER	Billingen	O$_1$bl	Sandstone and dolomite	
		Hunneberg	O$_1$hb	Sand- and mudstone	
CAMBRIAN	FURONGIAN	Petseri Fm.	Ca$_4$*pt*	Sand- and claystone	
	SERIES 2–3	Paala Fm.	Ca$_{2\text{-}3}$*pl*	Sandstone	
	TERRENEUVIAN	Võrgale	Ca$_1$vr	Sandstone	
		Dominopol'	Ca$_1$dm	Sand- and siltstone	
		Lontova	Ca$_1$ln	Clay- and sandstone	TIMANIAN
EDIACARAN		Kotlin (Vendian)	NP$_3$kt	Clay-, silt- and sandstone	

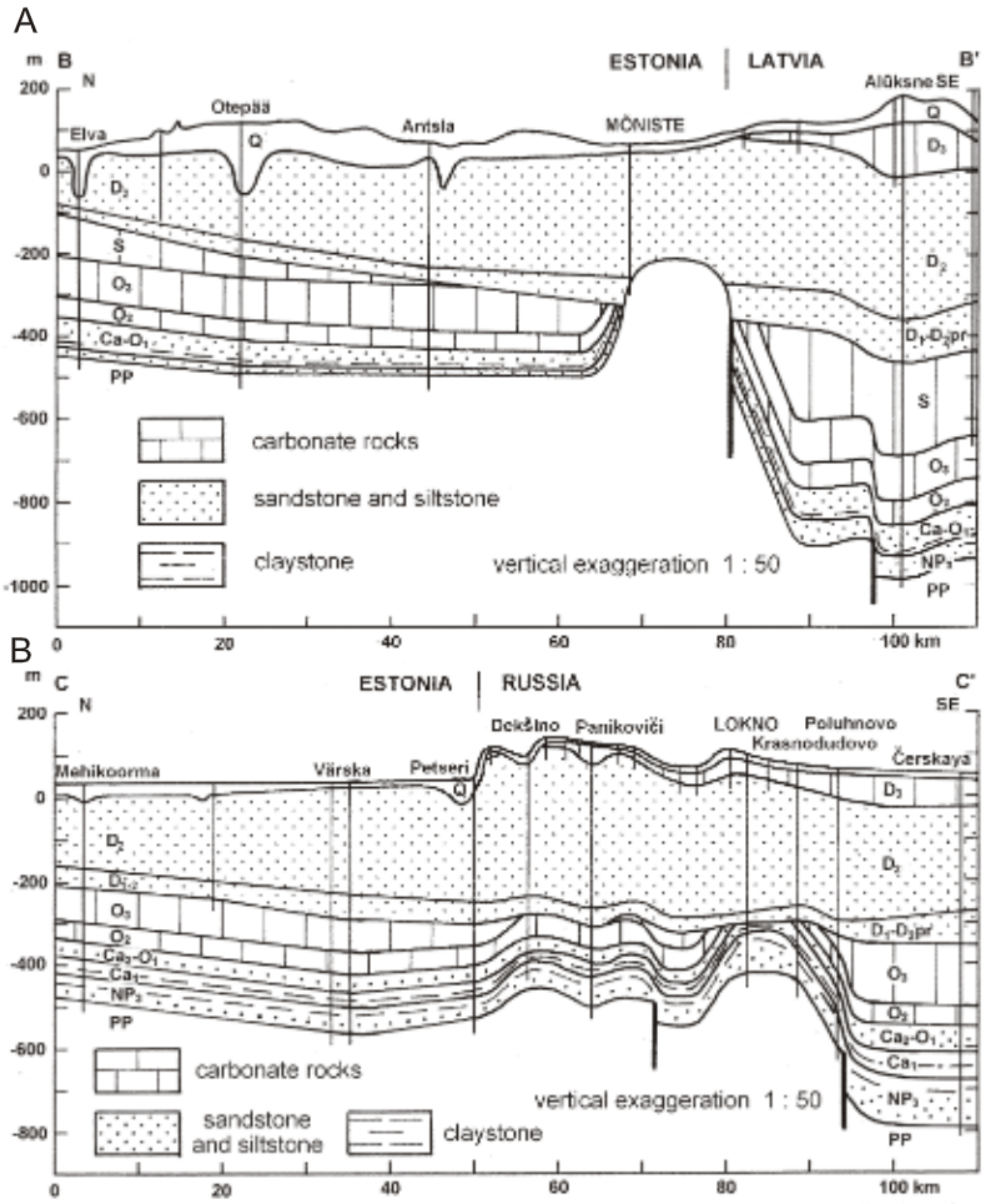

Fig. 6. Geological cross-sections across the Mõniste (A) and Haanja–Lokno (B) uplifts (see locations in Fig. 3)

(Figs. 2–4), without paying much attention to their broader structural background making up the VLU. However, it is the VLU that should be first of all regarded as a composite basement block, highly uplifted along the LRPFZ and showing an undulating top surface with some individual bulges, accompanied by a complex set of folds and faults in the platform cover (Figs. 2–6). The structural geometry of the VLU is distinctly traceable only at its southern margin where monoclonal folds in the platform cover have developed. A great part of that border coincides with an E–W-oriented eastern section of the Smiltene–Ape normal fault (Suveizdis et al., 1979; Brangulis and Kanev, 2002; Figs. 2 and 3). The southwestern corner of the VLU occurs around a complex stepover between the NE-trending section of the Smiltene–Ape and the E–W-trending section of the heavily curved Olaine–Inčukalna reverse faults. In all, in the west and, to a greater degree, in the north and east, where faults occur occasionally, the VLU can be tentatively limited by a top crystalline basement structure contour of 500 m b.s.l. (Figs. 3 and 4).

Thus, the gently southward dipping slope of the Baltic Shield rises within the VLU gradually above 500 m b.s.l. (reaching even >200 m b.s.l. on the solitary protruding basement uplifts) and drops abruptly thereafter along extensive basement faults by hundreds of metres towards the Latvian Saddle and the Baltic Syneclise (Figs. 2–6). In this sense, the VLU can be divided into the elevated northern section and the southern section down-faulted along the LRPFZ, which reveal BCAs and monoclinal fold(s), respectively, in the overlying platform cover.

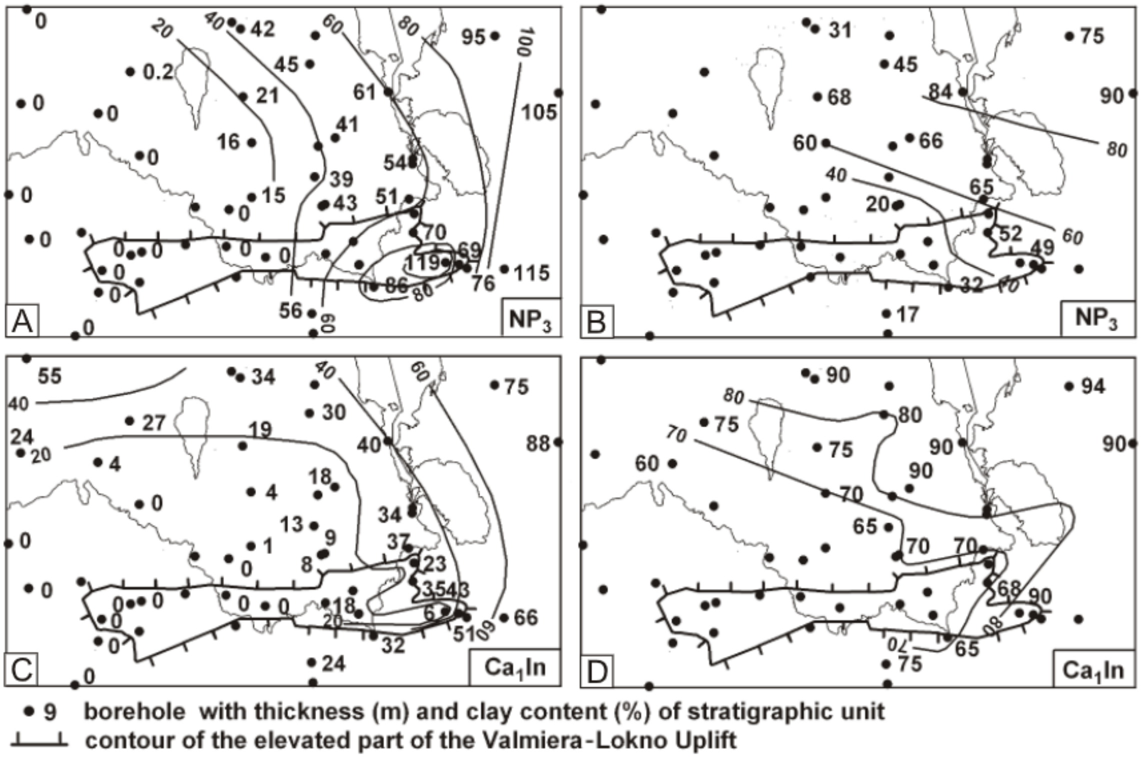

Fig. 7. Isopach and clay content maps of the Neoproterozoic (NP$_3$) Vendian (A, B) and the Lower Cambrian Lontova (C, D) rocks (modified from Mens, 1981) of the VLU area

All maps cover the same area as the maps in Figures 3, 4A and 8, whose location is shown in Figure 1; see Figures 2 and 4 for location/contours of the VLU and its elevated northern part

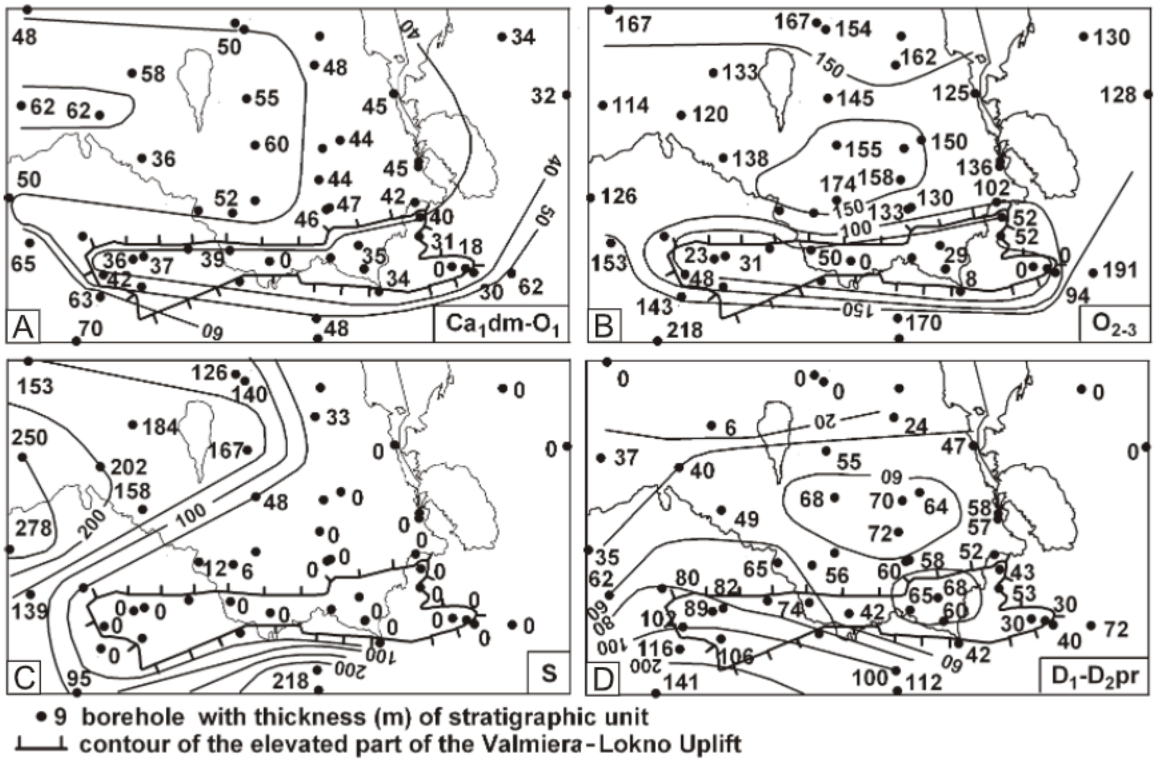

Fig. 8. Isopach maps of the post-Lower Cambrian–Lower Ordovician (A), Middle and Upper Ordovician (B), Silurian (C), and pre-Narva Devonian (D) rocks of the VLU area

All maps cover the same area as the maps in Figures 3, 4A and 7, whose location is shown in Figure 1; see Figures 2

All maps cover the same area as the maps in Figures 3, 4A and 7, whose location is shown in Figure 1; see Figures 2 and 4 for location/contours of the VLU and its elevated northern part

Since the Silurian and most of the Ordovician rocks were removed from its uplifted portion, the northern part of the VLU can be described as an erosional inlier with mostly the Middle Ordovician rocks (mainly of the Kunda Stage) subcropping below the unconformably overlying Devonian strata (Puura and Vaher, 1997; Table 1; O_{2kn} in Fig. 4A).

The high standing northern part of the VLU, with its solitary basement uplifts and intensely eroded platform cover, is disturbing the normal transition from the Baltic Homocline to the Baltic Syneclise and, as a whole, covers an area of ~4500 km^2, stretching ~160–170 km from east to west and ~20–30 km from north to south (Fig. 4). However, along the LRPFZ, the VLU varies considerably in width; ranging from a few kilometres along the high-angle Smiltene–Ape normal fault in the Haanja–Lokno area, up to several tens of kilometres around the structurally complex Smiltene–Valmiera area, where the latter fault steps over to the Olaine–Inčukalna reverse fault (Figs. 2, 3, 5A and 6).

SOLITARY BASEMENT UPLIFTS OVERLAIN BY ANTICLINES IN THE PLATFORM COVER

All afore-listed solitary basement uplifts have highly asymmetrical shapes, their crestal areas are either dissected (Smiltene, Mõniste and Lokno uplifts) or located slightly north (Valmiera and Haanja uplifts) of the Smiltene–Ape Fault, and straddle the uplifted northern and the downthrown southern section of the VLU (Figs. 2–6). Thus, the crests of the uplifts in the first group are dissected from the south by either a high-angle fault or a stepwise-falling fault system of the LRPFZ, while the uplifts in the second group have somewhat wider and steeply southward-falling slopes (Figs. 5A and 6).

In general, the pre-Devonian and Devonian portions of the sedimentary cover are distinct as regards the amount and magnitude of the faults and folds in the platform cover above the block-faulted crystalline basement. The noticeably folded and erosionally levelled Vendian-Silurian succession, i.e. the Timanide–Caledonian complex (Table 1), exhibits highly asymmetrical, largely monoclinal folds, whereas only very weak folding occurs in the Hercynian structural complex above the lowermost Devonian regional unconformity (Table 1; Figs. 5A and 6). The faint folding in the latter portion of the cover, untouched by the prime activity of the Caledonian Orogeny, is restricted to the uplift crests or to the direct neighbourhood of some basement faults. Probably for this reason, most of the basement faults in Latvia, though their exact stratigraphic span is not always ascertained (Brangulis and Brio, 1981), on tectonic maps are routinely extended up to the unconformity underlying the Lower Devonian Rezekne Stage (D_1rz in Table 1; Brangulis and Kanev, 2002).

The Valmiera Uplift. The east-west elongated basement core of the Valmiera Uplift, as contoured mostly by seismic profiling, has an areal extent of ~400 km^2, is ~35 km long and 12 km wide, and bulges ~130–150 m above the nearby basement top, >270 m b.s.l. (Brio et al., 1981; Figs. 2–5A). Induced by a highly asymmetrical basement block, the Valmiera Uplift is bounded by high-angle faults/fault systems on the north, west and south. Thus, if the northern and western flanks of the Valmiera Uplift are plummeting along the Valmiera and Lode faults, respectively, some 100–150 m, then its 20 km wide southern slope falls >400 m across a structurally very complex LRPFZ section (Figs. 3–5A).

The platform cover across the Valmiera Uplift forms a complex anticline that reveals an evident upward decrease in amplitude (Fig. 5A). It largely follows the fault-induced height difference and asymmetric shape of the underlying basement. Thus, further south in the LRPFZ (Ciruliši core), the basement top, the upper boundary of the Lower Ordovician, the base of the Devonian, and the top of the Middle Devonian Pärnu Stage are lowered compared to the Strenči core at the uplift crest by 475, 440, 245 and 205 m, respectively (Figs. 3–5A and Table 2). The corresponding values with respect to the Karula core just outside the northern flank of the VLU (Fig. 3) are, however, only 155, 130, 40 and 15 m, respectively. Deduced from the combined drilling and seismic data, the Rezekne Stage layers rest on top of the Valmiera Uplift, i.e. in the hinge area of the anticline, unconformably on the Cambrian rocks (Brio et al., 1981; Table 1) that are replaced successively by younger Ordovician and Silurian rocks towards the fold wings (Table 2; Figs. 4 and 5A).

Table 2

Thickness of the pre-Narva units around the western part of the Valmiera–Lokno Uplift along the Ciruliši–Karula profile

Index	Boreholes and stratigraphic interval thicknesses [m]					
	Ciruliši	Liči	Valmiera	Strenči	Laanemetsa	Karula
D_1-D_2pr	141	116	102	82	74	56
S_2jn	33	–	–	–	–	–
S_1rk-ad	34	–	–	–	–	–
S_1jr	28	–	–	–	–	6
O_3pr	17	–	–	–	–	10
O_3prg	59	21	–	–	–	44
O_3vr	4	4	–	–	–	4
O_3nb	15	12	–	–	–	11
O_3hl-rk	20	19	–	–	–	21
O_2ls-O_3kk	41	40	–	–	3	48
O_2as	3	2	–	–	5	6
O_2kn	31	26	26	10	15	15
O_2vl	28	20	22	21	22	21
Ca$_2$-O_1	70	63	42	37	39	52
Ca-S	383	207	90	68	84	237

Explanation of stratigraphic indexes are given in Table 1; see Figure 3 for borehole locations

The Smiltene Uplift. This basement uplift, located ~40 km SE of the Valmiera and ~30 km south-west of the Mõniste Uplift, has been distinguished and studied only on seismic profiles. The north-east elongated basement core of the Smiltene Uplift, rising ~80 m above the surrounding areas, is ~35 km long and 4 km wide and has an areal extent of ~140 km^2 (Brio et al., 1981; Figs. 2 and 3). Its southeastern flank, along the NE-trending section of the Smiltene–Ape Fault, drops some 600–700 m. Near the basement crest of the Smiltene Uplift, which supposedly rises up to ~320 m b.s.l., the Lower Devonian layers are allegedly resting unconformably on the Cambrian rocks. About 10 km wide, the northwesterly trending Lode depression separates the Smiltene and Valmiera uplifts (Fig. 3).

The Mõniste Uplift. The subparallel, ~50 km long and 15 km wide, highly asymmetrical basement core of the Mõniste Uplift has an areal extent of ~700 km^2, and makes up the highest part of the VLU, reaching, according to seismic data, >350 m above the surrounding crystalline basement to >200 m b.s.l. (Figs. 2–4 and 6A). Its southern flank along the LRPFZ plummets stepwise along two high-angle faults by nearly 800 m (Fig. 6A) and is likely dissected by a fault at its steeply falling northern side. On the crest of the Mõniste Uplift, the Middle Devonian rocks are supposedly resting directly on the crystalline basement (Figs. 4 and 6A). This is because somewhat away from the uplift top, the platform cover in the Mõniste core terminates only with the 7.2 m thick layer of the Rezekne Stage (Kleesment and Mark-Kurik, 1997; Table 1). The asymmetry of the Mõniste Uplift is best expressed by the altitude differences of various stratigraphic boundaries between its northern and southern flanks. Thus, with respect to the Mõniste core, the top surfaces of the basement and the Middle Devonian Pärnu Stage in the Alūksne core south of the LRPFZ are 750 and 180 m lower, respectively. The corresponding values regarding the Karula core NW of Mõniste Uplift (Fig. 3 and Table 2) are only 260 and 15 m. Thus, like at the Valmiera Uplift, the amplitude of the platform fold clearly decreases up the cover succession.

The Haanja–Lokno Uplift. The Haanja–Lokno Uplift has been described either as two different uplifts divided by a depression (Paasikivi, 1966) or as a unique structure (Kaplan and Hasanovitch, 1969). In fact, this is a complex structure, where two distinctive basement peaks are dissected by a minor, NE-oriented depression accompanied by a fault (Figs. 2–4 and 6B). The NE-trending basement core of the Haanja Uplift is ~40 km long and 10 to 15 km wide, has an areal extent of ~500 km^2, and is characterized by an undulating surface with culminations at Haanja (Tsiistre core), Meremäe and Dekšino (Fig. 3). Based on seismic data, the basement core of the Haanja Uplift bulges ~150 m above the nearby basement relief, reaching 350 m b.s.l. at its highest point near Haanja. Around its most elevated part, the Lower Devonian Rezekne Stage lies unconformably on the dolostones of the Middle Ordovician Volhov Stage (Põldvere, 2007; Mark-Kurik and Põldvere, 2012; Table 1 and Fig. 4).

The east-west trending basement core of the Lokno Uplift is ~30 km long and 5–10 km wide, has an areal extent of ~240 km^2, and plummets across the Smiltene–Ape Fault more than a few hundred metres towards the Latvian Saddle (Figs. 2–4 and 6B). Around the uplift crest, where ~125 m above the nearby basement top bulging area reaches ~425 m b.s.l. (Lokno core), the Devonian rocks rest on the Lower Cambrian Lontova Stage (Table 3 and Fig. 4). The altitude differences of the basement top, the pre-Devonian surface, and the upper boundary of the Pärnu Stage between the Lokno and the Alūksne core further south-west are 560, 170 and 100 m, respectively (Figs. 3, 6 and Table 3). The corresponding values between the Lokno and the Petseri boreholes further north-east of the VLU are 100, 10 and 25 m.

THICKNESS AND LITHOLOGY VARIATIONS OF DIFFERENT STRATIGRAPHIC UNITS AROUND THE VALMIERA–LOKNO UPLIFT

Various concepts of the VLU development have been put forth based largely on thickness and lithology analyses of the platform cover. In this sense, a key aspect has been how to interpret gradually decreasing thicknesses and clay content in some Paleozoic units across the crests of the basement-cored anticlines in the platform cover (e.g., Paasikivi, 1966; Kaplan and Hasanovitch, 1969; Afanasyev et al., 1973; Vaher et al., 1980; Mens, 1981).

To promote thickness analysis, the platform cover was divided into several stratigraphic portions that were illustrated with the isopach maps (Figs. 7A, C and 8). Formerly, the most heatedly discussed Vendian and Lower Cambrian Lontova se-

Table 3

Thickness of the pre-Narva units around the eastern Valmiera–Lokno Uplift along the Petseri–Poluhnovo profile

Index	Boreholes and stratigraphic interval thicknesses [m]						
	Petseri	Dekšino	Panikoviči	Lokno	Krasnodudovo	Poluhnovo	Čerskaya
D_1-D_2pr	52	43	53	30	30	40	72
S	–	–	–	–	–	–	–
O_3rk	3	–	–	–	–	–	191
O_3kl-on	11	–	–	–	–	–	
O_3kk-hl	36	–	–	–	–	40	
O_2as-uh	26	25	24	–	–	28	
O_2kn	9	9	9	–	–	9	
O_2vl	17	18	19	–	–	18	
$Ca_{2\text{-}3}$-O_1	42	40	31	–	18	30	62
Ca_1ln	37	23	35	6	43	51	66
NP_3	51	>34	70	119	69	76	118
NP_3-O	206	>159	187	125	141	269	437

See Figure 3 for borehole locations; explanation of stratigraphic indexes are given in Table 1

quences (Kaplan and Hasanovitch, 1969; Mens, 1981; Table 1) were supplemented with the clay content distribution maps (Fig. 7B, D). To maximize the number of stratigraphic units with thickness information, two tables with detailed thickness trends were composed across the western and eastern margins of the VLU across the Valmiera (Table 2) and the Haanja–Lokno (Table 3) uplifts, respectively, where the preserved platform cover is, compared to the area around the Mõniste Uplift, more complete.

THE VENDIAN (NP_3) LOWER CAMBRIAN LONTOVA STAGE (Ca_1 ln)

Due to the rareness of deep boreholes, thickness data of the Vendian and Cambrian Lontova sequences from the VLU area are scarce. However, the regional palaeogeographic data suggest that, during their deposition, the VLU remained near the western to southwestern limit of the Vendian basin (Mens and Pirrus, 1997a: fig. 11) and the earliest Cambrian Lontova basin (Mens and Pirrus, 1997b: fig. 14). Thus, both units, reaching only as far as the Haanja and Lokno uplifts at the eastern margin of the VLU, follow the regional trends with the easterly increasing thicknesses (Fig. 7A, C).

Except for its abnormally high value of 119 m around the crest of the Lokno Uplift, the Vendian within the VLU is generally ~20–30 m thicker than it normally is to the north (40–50 m) (Fig. 7A and Table 3). Thus, except for the Lokno anomaly, the eastern part of the VLU has a rather steady Vendian thickness (70–80 m) both on its uplifted northern and monoclinal southern (Krasnodudovo and Poluhnovo cores) sections (Table 3). In the Čerskaya borehole near the southeastern LRPFZ, however, this unit thickens abruptly by some 30–35 m. The clay content in the Vendian strata, the values of which are available only north-east of the VLU (Fig. 7B), reveals a northeasterly increasing trend, i.e. towards the gradually deepening part of the Vendian basin.

The Lontova Stage, however, clearly decreases some 15–20 m in thickness around the northeastern margin of the VLU, i.e. towards the Haanja Uplift (Dekšino core in Figs. 3, 7C and Table 3). Although the highly reduced thickness (6 m) of the Ca_1ln unit in the Lokno core (Table 3) is due to later erosion, its thinning trend from the down-faulted side of the VLU (66 m in Čerskaya core) across the LRPFZ (51 m in Poluhnovo and 43 m in Krasnodudovo cores) towards the crest of the Lokno Uplift is obvious. Clear diminution of the clay content in the Lontova Stage towards the Haanja–Lokno Uplift (Fig. 7D) corroborates the thickness data, pointing towards an elevated and shallower area around the eastern VLU.

THE POST-LONTOVA CAMBRIAN AND LOWER ORDOVICIAN SECTION (Ca_{1dm}-O_1)

The decrease in thickness of the Ca_{1dm}-O_1 unit above the VLU is evident on the isopach map (Fig. 8A), being particularly clearly expressed across its western margin along the Cirulīši–Karula profile (Fig. 3 and Table 2). Thus, compared to the Cirulīši and Karula cores, the Ca_2-O_1 unit is reduced in thickness on top of the Valmiera Uplift (Valmiera and Strenči cores) and on the eastern slope of the Mõniste Uplift (Laanemetsa core) by some 30 and 10–15 m, respectively. Across the eastern margin of the VLU, however, a clear decrease in thickness in this unit appears only around its south-eastern corner, where the $Ca_{2\text{-}3}$-O_1 unit thins from the Čerskaya core towards the Poluhnovo core on the Lokno Uplift in the north-west by ~30 m (Figs. 6B, 8A and Table 3). No evident thickness changes occur in this unit near the north-eastern corner of the VLU, i.e. at the Haanja Uplift.

THE MIDDLE AND UPPER ORDOVICIAN SEQUENCE ($O_{2\text{-}3}$)

As described above, the elevated part of the VLU contours best as an erosional inlier of the Middle Ordovician rocks overlain unconformably by the Devonian sequence (Fig. 4). Thus, for most of the VLU, the greater part of the Ordovician strata (Table 1) has been removed by later erosion, culminating at the Silurian/Devonian transition. Since the Ordovician sequence starts rapidly growing in thickness right outside the elevated part of the VLU, this structure is clearly outlined on the isopach map of the $O_{2\text{-}3}$ unit (Fig 8B). However, Ordovician units untouched by erosion suggest that no remarkable thickness changes occur at least up to the Upper Ordovician Pirgu and the Middle Ordovician Uhaku (Table 1) units around the western (Table 2) and eastern (Table 3) VLU, respectively.

THE SILURIAN SEQUENCE

Although placed near the eastern extent of the Silurian layers, the VLU area is outlined on its isopach map as a SW-trending indentation void of Silurian rocks (Fig. 8C; see Polivko, 1981: fig. 3). The southern and western limits of this notch with eroded Silurian rocks clearly follow down the faulted borders of the VLU. Thus, near these borders, the Silurian sequence thickens abruptly from 0 to >150 m within ~10–20 km. North of the VLU, however, the Silurian sequence thickens gradually, whereas its 150 m isopach retreats gradually from the northwestern corner of the VLU towards the north-east (Fig. 8C). Thus, being ~10–20 km away from the faults surrounding the Valmiera Uplift, the 150 m Silurian isopach occurs ~70–80 km further north of the Mõniste Uplift, i.e. from the highest central part of the VLU (Figs. 3, 4 and 8C). Due to the extensive erosion, a more detailed thickness analysis to specify possible tectonic activity pulses at the VLU in the Silurian is impossible.

THE LOWER DEVONIAN TO MIDDLE DEVONIAN PÄRNU STAGE (D_1-D_2pr)

The D_1-D_2pr unit in the VLU area consists largely of the Rezekne and Pärnu stages, since the patches of the Early Devonian Tilžė and Kemeri stages (Table 1) occur only around its western margin (Kaplan and Hasanovitsh, 1969; Kleesment and Mark-Kurik, 1997: figs. 74 and 79). In the latter area, the isopachs of the D_1-D_2pr unit cross the Valmiera and Smiltene uplifts without any remarkable deviation from their regional northerly to northeasterly thinning trend (Fig. 8D). However, in the central and eastern parts of the VLU, this unit reveals a clear local thickness reduction. Thus, on top of the Mõniste Uplift, the D_1-D_2pr unit (42 m) is ~15–25 m thinner than in the cores from adjacent boreholes, including even the Tsiistre core (68 m) from the top of the Haanja Uplift (Figs. 3 and 8D). Also along the VLU's eastern margin, this unit decreases by ~10 and 20 m in thickness around the northeastern slope of the Haanja Uplift (43 m in Dekšino core) and at the crest of the Lokno Uplift (30 m), respectively. Further south-east within the LRPFZ, i.e. on the southeastern slope of the Lokno Uplift, the D_1-D_2pr unit thickens slightly again up to 40 m in the Poluhnovo core, and abruptly reaches 72 m in the Čerskaja core outside the VLU (Figs. 3, 8D and Table 3).

DISCUSSION

Besides the VLU, there are currently >100 similar isolated basement-cored anticlines (BCA) recognized in the platform cover onshore and offshore in Latvia, most of them occurring

around the LRPFZ (Brangulis and Brio, 1981; Brangulis and Kanev, 2002; Fig. 2). Based largely on seismic studies, a large number of basement faulting-related anticlines in the platform cover have been contoured also further south in the Baltic Syneclise in Lithuania and the Kaliningrad district (Suveizdis et al., 1979; Stripeika, 1999: fig. 23), as well as offshore Poland (Domżalski et al., 2004: fig. 1).

As potential oil traps, similar BCAs in the platform cover have been a main priority in oil prospecting of the Baltic Syneclise. Besides the morphological details, one of the fiercely debated key issues has been their possible origin and development. Although the VLU is not a prospect for oil accumulation, its BCAs in the platform cover obviously belong to the best-studied ones in this region. This is because of the most detailed stratigraphic subdivision and extensive drilling of the platform cover and the fact that the crystalline basement on the crests of similar uplifts reaches the highest values within the VLU by far, being covered by the thinnest platform cover, which misses a substantial portion of Paleozoic units (Figs. 2–6). On the other hand, the incomplete platform cover with numerous gaps and a highly varying stratigraphic span considerably hampers describing details in the development of similar structures around the VLU, particularly during the Ordovician and Silurian.

ORIGIN OF THE BASEMENT-CORED ANTICLINES IN THE PLATFORM COVER

Two contrasting standpoints have been put forward as regards the nature of the basement-cored anticlines (BCAs) in the platform cover sequence around the LRPFZ. Early ideas of the tectonic origin have been disputed in the light of amassing data on the possible time scale and continuity of similar uplifts, i.e. on details when similar structures began to rise and whether this has been a single event (Kaplan and Hasanovitch, 1969), a steady progression (Kajak, 1962; Paasikivi, 1966), or a series of tectonic events (Brio et al., 1981). At the same time, their non-tectonic compactional origin across an unevenly eroded basement surface was strongly promoted by Afanasyev et al. (1973).

Indeed, BCAs in the platform cover around the LRPFZ have many features (e.g., amplitude increase with depth, thinning/wedging out of basal units above the crests of the anticlines, etc.) characteristic of supratenuous "plains-type" folds (Clark, 1932; Shatsky, 1945; Sanarov, 1970; Merriam, 2005, 2012), named this way after their common occurrence over the cratonic areas of the North American Great Plains. However, systematic geological studies in the 1970s brought forward evidence stressing the significance of a tectonic setting in which synsedimentary tectonism led to the formation of the BCAs around the LRPFZ. Geophysical data have shown that their location is strictly controlled by basement faults, whereas the consistently refined stratigraphic subdivisions, alongside the growing number of available borehole sections, revealed that the thickness in some Paleozoic units can vary significantly even over closely spaced uplifts. It became problematic to explain it merely by compaction, why the same stratigraphic units thin markedly across some particular basement uplifts while they experience no thinning or even show occasional thickening on similar uplifts nearby. These attributes, being particularly well expressed across the VLU, suggest that the BCAs in the platform cover around the LRPFZ are largely of tectonic origin.

Thus, stratigraphic units varying greatly in thickness across the BCAs revealed that similar structures around the LRPFZ must have undergone pulses of high tectonic activity, whose initiation times, as well as reactivation epochs for individual uplifts, vary considerably. Based on that, Brangulis and Brio (1981: fig. 2 and tab. 1) distinguished three groups of uplifts, all showing maximum growth during the prime of the Caledonian Orogeny around the Silurian–Devonian boundary, but differing in their histories: (1) those established in the Late Silurian (e.g., Inčukalna, Aizpute in Fig. 2); (2) those created and strongly uplifted in the Cambrian (e.g., Prekule, Piltene in Fig. 2), and (3) those formed in latest Precambrian and earliest Cambrian times (e.g., Kuldiga, Dobele in Fig. 2).

With a few exceptions (e.g., Kuldiga, Snepele in Fig. 2), most uplifts around the LRPFZ were essentially inactive or revealed only slight movements during most of the Ordovician and Early Silurian. However, after the culmination of the Caledonian Orogeny, accompanied by formation of an extensive lowermost Devonian unconformity, the growth of the basement uplifts became remarkably reduced, as most of them remained inactive in the Early Devonian (Brangulis and Brio, 1981). However, despite their faint expression and varying extent, some structures (e.g., Priekule in Fig. 2) can be traced all through the platform cover profile, terminating with the Carboniferous strata. Some of the latter structures reveal even signs of post-Carboniferous activities (Brangulis and Brio, 1981).

Two analogous groups of fault-related BCAs were also distinguished by Stripeika (1999) further south in the Baltic Syneclise, where the platform cover is more complete. One group was interpreted to have initiated in the Cambrian to earliest Ordovician, reactivated at the prime of the Caledonian Orogeny, and became thereafter intermittently active until the end of the Mesozoic. The other group, revealing no thickness changes in the Cambrian–Silurian units, was introduced at the transition of the Silurian and Devonian periods and was recurrently reactivated in the Late Paleozoic towards the culmination of the Variscan Orogeny.

Similar differential vertical movements, causing thinning of various stratigraphic units over the crests of the plains-type anticlines compared to their limbs, have been also described in the mid-continent of the USA (Merriam, 2005). Thickness reduction in certain stratigraphic units alongside the signs of tectonically unstable sedimentary environments ("seismites", including, e.g., convolute bedding and minor intraformational faults) around the anticlines reflect the mobility of basement fault blocks, which have been periodically readjusting to external regional stresses.

GEOLOGICAL HISTORY AND DEVELOPMENT OF THE VALMIERA–LOKNO UPLIFT

Assuming that the above-described thickness and lithological changes are mostly due to the differential basement movements caused by external stresses, the timing and magnitude of structural activities across the VLU, in particular around its solitary basement uplifts, can be assessed. Taking into account thickness changes, a series of structural cross-sections were composed across the Haanja–Lokno Uplift, showing possible basement relief, and thus the rise of the eastern VLU area at different stages of the Paleozoic (Fig. 9). Based on the basement relief growth, three tectonic activity epochs with varying intensities can be distinguished around the VLU.

LATEST PRECAMBRIAN–EARLY ORDOVICIAN DIFFERENTIATED MOVEMENTS AROUND THE VLU

Due to the limited distribution of the Vendian and lowermost Cambrian Lontova rocks (Fig. 7A, C), the tectonic activity of these time intervals can be assessed only around the eastern VLU. Although both units have varying thicknesses there, their variations reveal different patterns. Thus, neither the isopach map nor the submeridional Petseri–Čerskaya profile reveal any signs suggesting a basement rise in the Vendian around the Haanja and Lokno uplifts (Figs. 3, 6B, 7A and Table 3). More-

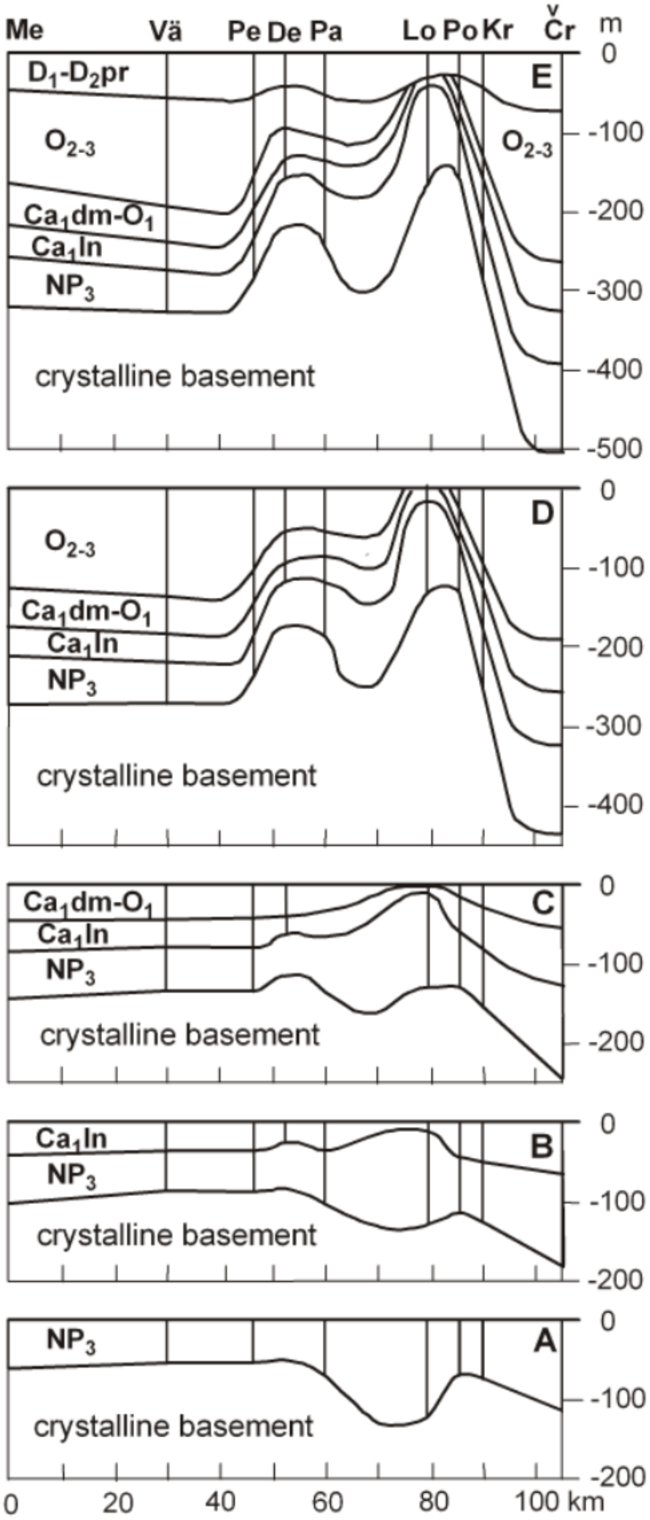

Fig. 9. Palaeotectonic cross-sections based on thickness analysis, showing the rise of the basement across the Haanja and Lokno uplifts by the end of different time intervals: Vendian (A), post-Lontova Cambrian (B), Early Ordovician (C), Silurian (D), Middle Ordovician Pärnu (E)

Boreholes: Me – Mehikoorma; Vä – Värska; Pe – Petseri; De – Dekšino; Pa – Panikoviči; Lo – Lokno; Po – Poluhnovo; Kr – Krasnodudovo; Če – Čerskaya; see locations in Figure 3

over, from Petseri towards Panikoviči, the thickening Vendian sequence with its abnormally high thickness around the centre of the Lokno Uplift implies that the eastern VLU existed at that time as a rather lowered area where some presently uplifted basement blocks existed even as minor depressions (Fig. 9A). Also, the clay content of the Vendian north-east of the VLU (Fig. 7B) reveals no shallower area around the Haanja Uplift. Nevertheless, significant thickness reductions of the Vendian from Lokno towards the Krasnodudovo and Poluhnovo cores, and its abrupt thickening in the Čerskaya, Ponkuli, and Alūksne cores (Figs. 3, 6B, 7A and Table 3), suggest that the southeastern VLU along the Smiltene–Ape Fault experienced differential tectonic movements already in the Vendian.

The thickness distribution in the earliest Cambrian Lontova sequence, however, points unambiguously towards a rising and high-standing VLU with bulging basement centres around its northeastern (Haanja Uplift) and southeastern (Lokno Uplifts) corners (Figs. 7C, 9B and Table 3). An elevated and shallower area around the eastern VLU is also clearly outlined on the clay content distribution map of the Lontova Stage (Fig. 7D).

The isopachs of the post-Lontova Cambrian to Lower Ordovician portion the oldest platform unit that allows estimating tectonic activity over the entire VLU area imply that, concurrently with the differentiated tectonic movements along the LRPFZ, all the basement uplifts, except the Haanja, were forced upwards (Fig. 8A). Based on a very rough estimation, the basement rise around the Haanja–Lokno Uplift reached ~7% of its present height by the end of this period (Fig. 9C).

TECTONIC ACTIVATION OF THE VLU AT THE SILURIAN/DEVONIAN TRANSITION

Due to extensive erosion, the thickness data concerning the Middle Ordovician–Silurian stages at the VLU are very limited, and thus it is hard to assess the tectonic activities for most of this time period around this structure. Although no signs of tectonic activity appear until the latest Ordovician around the western and eastern margins of the VLU, we have no direct clues to make any solid conclusions for the rest of the subsequent Ordovician and Silurian time. Still, based on circumstantial evidence further south-west, where thickness variations appear in some Ordovician-Early Silurian rocks at some basement uplifts (e.g., Inčukalna, Dobele, Aizpute, Kuldiga in Fig. 2), particularly in the latest Silurian strata (Brio et al., 1981: tab. 1), we cannot exclude that the VLU, as by far the most uplifted structure along the LRPFZ, may have also been active in the Late Silurian or even at some earlier time.

Thus, contouring the VLU Ordovician and Silurian isopachs, which reveal a striking contrast along its basement fault-controlled southern and western borders (Fig. 8B, C), is only due to its crucial uplift and erosion at the Silurian/Devonian transition. This timing is because distinctive folding with vigorously varying thicknesses around the VLU and across its individual basement uplifts occurs only in the Vendian–Silurian sequence, as these features are very weakly expressed in the overlying Devonian rocks, resting above a regional-scale unconformity (Figs. 5 and 6). Taking into consideration the stratigraphic span of the eroded pre-Devonian rocks (removed entirely from Mõniste and up to the lowermost Cambrian and the Ordovician on the Lokno and Haanja/Valmiera uplifts, respectively), the amount of the missing rocks from the most elevated areas exceeds 500 m. Before the Devonian deposition, the basement relief between the highest uplift and the lowest down-faulted LRPFZ sections of the VLU ranged from ~350 m at the Valmiera to ~600 m at the Mõniste uplifts. Thus, by rough estimations, the basement uplifts reached ~70–80% of their present values by that time (Fig. 9D).

THE DEVONIAN AND POST-DEVONIAN TECTONIC MOVEMENTS IN THE VLU AREA

The thickness distribution in the D_1-D_2pr unit, i.e. in the strata resting directly on the unconformity surface (Fig. 8D), suggests that differentiated tectonic movements around the Lokno and the Mõniste uplifts continued towards the end of Early Devonian times. The available thickness data on the younger Devonian stages (Kaplan and Hasanovitsh, 1969; Kleesment and Mark-Kurik, 1997: figs. 81, 82, 84, 86–88) do not indicate further Devonian tectonic activity around the latter uplifts. However, while the Valmiera Uplift and the Haanja/Lokno uplifts, along with the Smiltene–Ape Fault, are clearly outlined by structure contours along the top of the Pärnu Stage (Brio et al., 1981: fig. 3) and Middle Devonian rocks (D_2am in Table 1; Fig. 10), respectively, the VLU has obviously been reactivated either in the latest Devonian or sometime in the post-Devonian. Similar reactivation pulses have been traced at some basement-cored platform folds further southwest around the LRPFZ, as well as in the southern Baltic Syneclise (Brio et al., 1981; Stripeika, 1999).

RECENT VERTICAL MOVEMENTS IN THE VLU AREA

Short-term (1988–1991) instrumental studies on seismicity revealed two areas of microseismic activities (with a magnitude <3) in Estonia with probable focal depths at approximately 5–10 km, i.e. in the uppermost Earth's crust (Sildvee and Vaher, 1995). One of them is located at the north of Lake Võrtsjärv 70–80 km north of the VLU, the other near the Mõniste Uplift (Fig. 3). Taking into consideration the slight glacioisostatic subsidence of southeastern Estonia (Vallner et al., 1988), the axis of the present-day uplift around the Mõniste Uplift occurs, according to the repeated levelling profile Valga–Mõniste–Võru, slightly north of its crestal area (Fig. 11). Relying on the present height differences at the top of the Middle Devonian strata (61 m between Lokno and Alūksne, 144 m between Meremäe and Alūksne, and 181 m between Meremäe and Antoškina), the post-Early Devonian uplift accounts for ~10–20% of the present height of the VLU (Figs. 9A and 10).

STRUCTURAL EVOLUTION AND KINEMATICS OF THE LRPFZ AS A KEY ISSUE IN UNDERSTANDING THE NATURE OF THE VLU

Former debates on the nature and development of the VLU have been focused mainly on its individual basement uplifts along with the lithological and thickness studies of the folded platform cover across them. Thus, very little attention was paid to the wider structural background and possible LRPFZ activities-derived kinematic perspective of these individual uplifts, as they were considered local cratonic structures. This is despite the fact that even a cursory look at the regional tectonic setting and the above morphological details of thickness variations give a strong implication that the VLU and its solitary basement uplifts are to be treated alongside the fault movements in the LRPFZ.

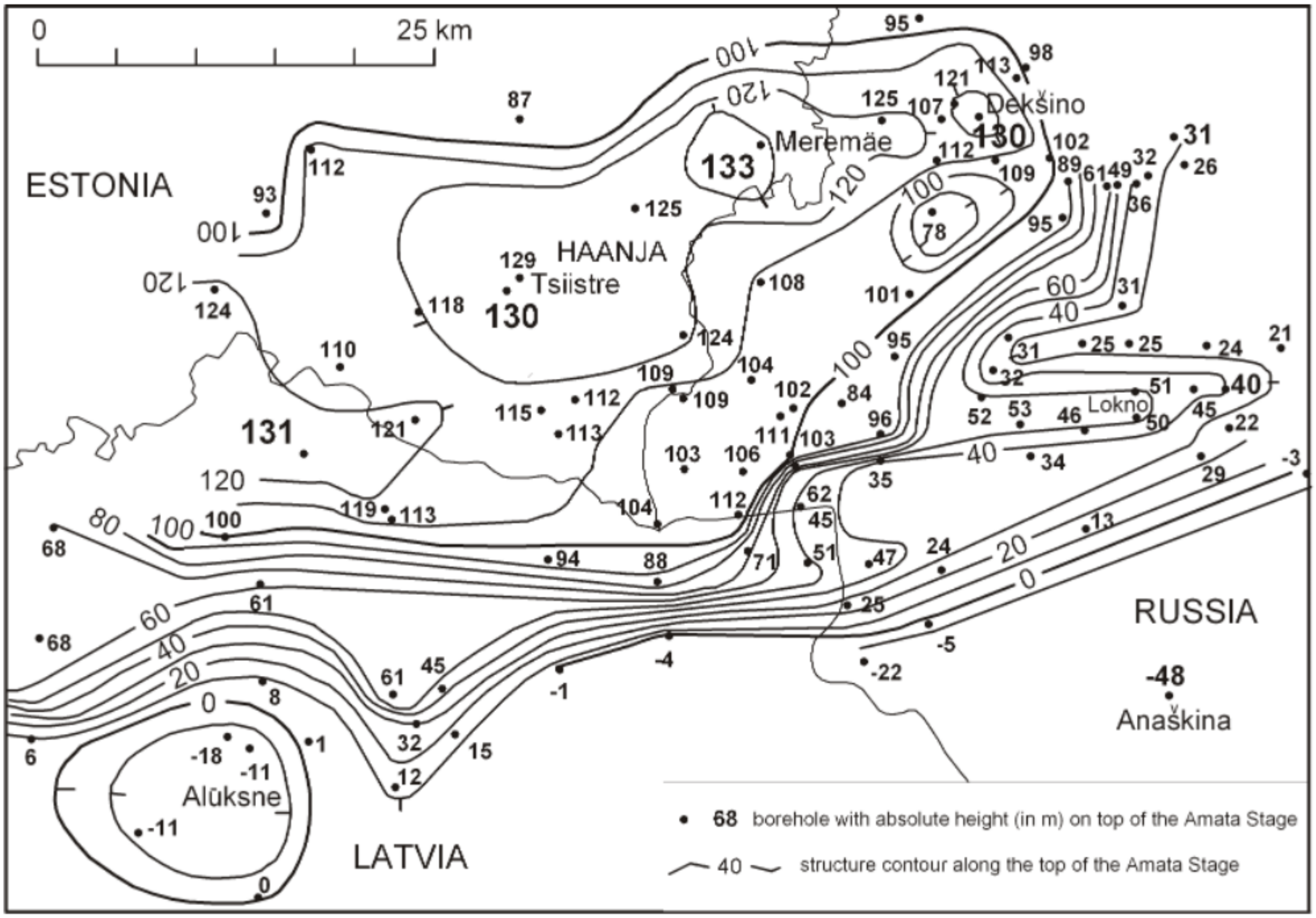

Fig. 10. Structure contour map of the top of Middle Devonian strata around the Haanja–Lokno Uplift based on borehole data

See Figure 2 for map location

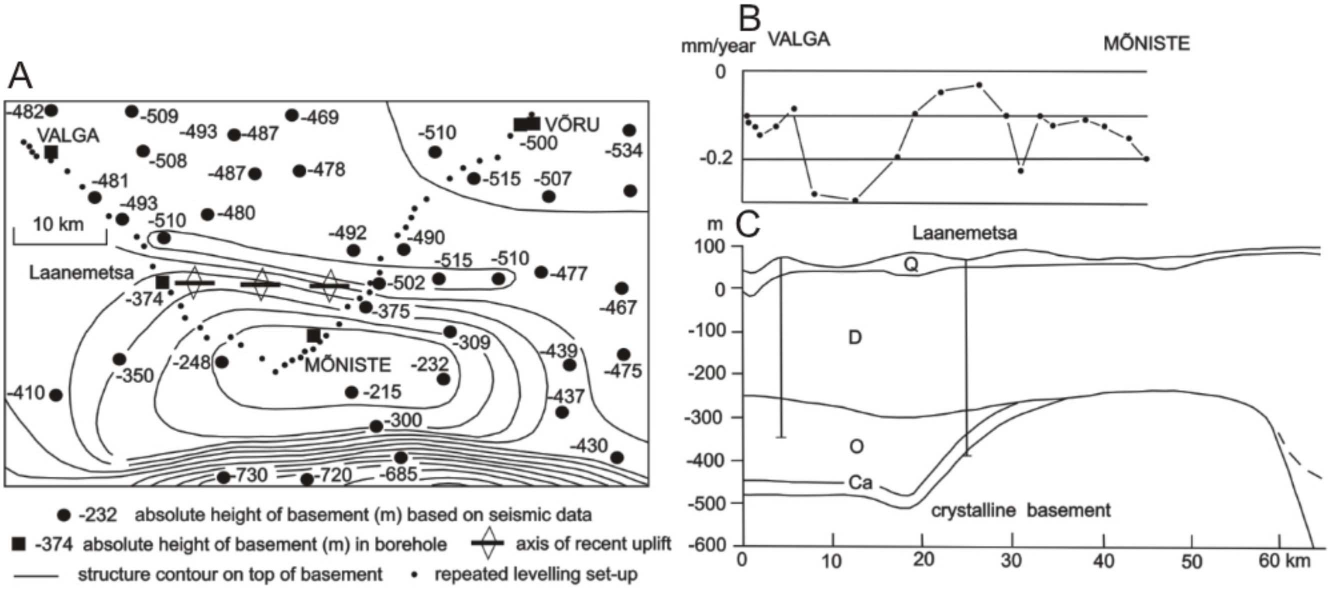

Fig. 11. Recent land rise around the Mõniste Uplift based on the Valga–Mõniste–Võru repeated levelling profile: A – excerpt from the structure contour map shown with a dashed-line frame in Figure 3; B – velocity graph of recent vertical movements; C – rough geological cross-section (modified from Sildvee and Vaher, 1995)

Stratigraphic units: Q – Quaternary; D – Devonian; O – Ordovician; Ca – Cambrian

Indeed, the general structural setting and style of the Valmiera, Smiltene, Mõniste, Haanja–Lokno uplifts fits well with other analogous structures around the remaining LRPFZ portion (Brangulis and Brio, 1981), as well as with the basement-cored anticlines described by Suveizdis et al. (1979) and Stripeika (1999) further south in the Baltic Syneclise. Thus, similar basement cored anticlines in the platform cover arise mostly on the upthrown sides of the curved fault sections and are often associated with intersections of differently trending faults (Brangulis and Brio, 1981). They are normally slightly elongated, and are occasionally isometric in shape or may be outlined on structure contour maps as structural noses (e.g., Piltene in Fig 2; Misans and Brangulis, 1979; Stripeika, 1999; Figs. 3 and 4). Elongated brachyforms are occasionally revealed (e.g., Kuldiga, Haanja; Figs. 2–4) as heavy undulations on the basement surface with several distinctive peaks (Brangulis and Kanev, 2002: fig. 12). Clinging to basement faults or placed slightly away from them, similar BCAs in the platform cover normally have a strongly asymmetrical shape due to dissection by faults, and subsided steeper slopes. Most of similar structures reveal a distinctive, upward-directed, i.e. towards the younging Paleozoic units, decrease in amplitude.

However, there appears to be a significant size and magnitude difference between BCAs at the VLU and along the remaining section of the LRPFZ (Afanasyev et al., 1973; Suveizdis et al., 1979; Brangulis and Brio, 1981). Thus, outside the VLU, with a few exceptions (e.g., Priekule, Inčukalna, Dobele, etc. in Fig. 2; see Brangulis and Kanev, 2002: figs. 10–12, 14), the longer axes of similar basement bulges rarely exceed 10 km in length, as their height, being typically within the limits of 30–80 m, can only exceed 100 m in larger structures (e.g., Inčukalna, Dobele, Kandava). The areal extent of the BCAs around the LRPFZ (20–700 km^2) is remarkably larger than that of the similar structures further south in the Baltic Syneclise (5–50 km^2; Suveizdis et al., 1979; Brangulis and Brio, 1981; Stripeika, 1999). Furthermore, the same parameter within the VLU (140–700 km^2), i.e. along the subparallel, northeasternmost section of the LRPFZ, is significantly larger than that in its remaining, NE-trending section within the Baltic Syneclise (20–70 km^2).

Faulting accompanied by growth of basement uplifts in cratonic interiors is controlled by external stresses, evoked by boundary loads on the continent (van der Plujim et al., 1997). Generally, the LRPFZ, compared to the surrounding EEP interior areas, reveals by far the highest offset on the basement faults as well as the largest size of the BCAs in the platform cover; both of which clearly reach their maximum at the VLU. Thus, the outstanding VLU magnitude, as well as by far the largest size of its BCAs in the platform cover must be explained by the regional geological history and structural evolution of this major regional fault zone.

Based on the general knowledge about the structural style and patterns/kinematics of faults induced along a strike-slip fault zone (Christie-Blick and Biddle, 1985; Marshak et al., 2003; van der Plujim and Marshak, 2003), even a cursory look at the LRPFZ hints that horizontal movements may have played a significant role in the history of this major cratonic interior fault zone. Thus, deviating from the general northeast trend of the LRPFZ, the roughly E–W elongated, heavily uplifted VLU section of this major fault zone may have arisen as a restraining bend structure. This assumption is furthermore supported by the fact that this major fault zone, evolving in the EEC interior, has probably also played an important role in the formation and development of a large cratonic depression, the Baltic Syneclise, that largely controlled also the bathymetry and facies zonation in the Palaeobaltic Ordovician–Silurian sedimentary basin. The best proof for that might be the so-called Livonian Tongue, a tongue-like northeasterly protrusion of a deep facies belt, the areal extent and configuration of which follows clearly the LRPFZ. This protrusion in the Palaeobaltic basin appeared already in Early Ordovician Floian time, and became increasingly accentuated following the gradual differentiation of a gently tilted basinal ramp (turned out to be more differentiated towards the end of the Ordovician) and the growth of a distinctive deep basinal axial depression evolved by Silurian time (Nestor and Einasto, 1997: fig. 138). Thus, combining all the

known facts about the LRPFZ (regional structural setting, geometrical pattern, style/kinematics of its faults, etc.) with the above-described facies/bathymetry changes in the Palaeobaltic basin, we may predict that sinistral strike-slip displacements, induced by the progressing Caledonian Orogeny, occurred along this major cratonic interior fault zone. However, to further debate and advance the hypothesis of strike-slip movements along the LRPFZ, a more detailed structural/kinematic analysis of the LRPFZ is needed, which should take into account also the regional tectonic history of the western/south-western borders of Baltica. That, however, remains out of scope of this paper.

CONCLUSIONS

Concerning the regional tectonic setting and the general structure of the Valmiera–Lokno Uplift (VLU), with its solitary basement-cored anticlines (BCAs) in the platform cover, the following conclusions can be made:

1. The VLU represents a complex structure formed along a major, regional-scale fault zone in the EEP interior, the Liepaja–Riga–Pskov Fault Zone (LRPFZ), where a highly elevated basement block with an undulating surface and the solitary bulging Valmiera, Smiltene, Mõniste, Haanja and Lokno uplifts have remarkably deformed the overlying platform cover along deep faults.

2. The VLU can be divided into an elevated northern part with solitary basement uplifts overlain by anticlines in the platform cover, and a southern part, subsiding largely along the Smiltene–Ape normal fault, in places >700 m, with monoclinal fold(s) in the platform cover. The structurally more complex western border of the VLU has been formed at a stepover between the NE-trending section of the Smiltene–Ape and the E–W directed section of the strongly curvy Olaine–Inčukalna reverse faults.

3. The solitary basement uplifts, straddling or located slightly north of the Smiltene–Ape Fault, with overlying anticlines in the platform cover, have strongly asymmetrical shapes with down-faulted southern sides. A great portion of the platform cover of Paleozoic rocks has been eroded from the elevated portion of the VLU, in particular from the solitary basement uplifts.

4. The changes in thickness of different Paleozoic units across the VLU and the solitary basement uplifts reveal that the VLU has existed since the latest Precambrian and has had a long tectonic history including several activation/uplift pulses alternating with quieter or inactive periods. The initiation, as well as activity stages, for different, even closely spaced basement-cored platform folds, can vary considerably.

5. The initiation and the first tectonic activity epoch of the VLU occurred in the latest Precambrian to earliest Ordovician, followed by a period of modest activity or standstill in the Middle Ordovician–Early Silurian, intensifying again towards the end of the Silurian. The main uplift phase, inducing the most severe deformation of the platform cover, associated with the most intense erosion of the uplifted portion of the VLU, culminated in the prime of the Caledonian Orogeny. This formed a regional-extent unconformity at the Silurian–Devonian boundary, with strongly and only slightly deformed Paleozoic rocks beneath and above it, respectively.

6. The slight deformation of the Devonian rocks above the regional unconformity at the VLU is partially due to the fading tectonic activities of the Caledonian Orogeny towards the end of the Early Devonian. However, the VLU, together with its basement (Haanja–Lokno) uplifts and the Smiltene–Ape Fault, have been reactivated since latest Devonian time.

7. Recent seismicity studies with repeated levelling data confirming a faint uplift with microseismic activities just north of the Mõniste Uplift reveal that the VLU area can be still considered a structural weakness in the continental crust in the EEC interior.

8. Considering the regional tectonic setting alongside the general north-east trend of the LRPFZ, the VLU represents the exceptional nearly E–W directed eastern section of this major fault zone that runs into an intricate junction of numerous regional-scale platform structures: the Baltic Homocline, the Baltic Syneclise, the Latvian Saddle, and the Moscow Syneclise.

9. The latter setting, alongside the fact that the VLU represents the most uplifted portion of the LRPFZ with the largest BCAs in the platform cover and the fact that the LRPFZ has clearly controlled the development of a tongue-shaped deep facies protrusion (the Livonian Tongue) in the Palaeobaltic Ordovician–Silurian sedimentary basin, give strong indications in favour of substantial Early Paleozoic sinistral strike slip movements along this EEC interior fault zone.

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