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# The Leba Ridge–Riga–Pskov Fault Zone – a major East European Craton interior dislocation zone and its role in the early Palaeozoic development of the platform cover

Igor Tuuling

Institute of Ecology and Earth Sciences, University of Tartu, Ravila 14A, 50411 Tartu, Estonia; igor.tuuling@ut.ee

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**Abstract.** Analysis of data published on basement faulting in the Baltic region makes it possible to distinguish the >700 km long East European Craton (EEC) interior fault zone extending from the Leba Ridge in the southern Baltic Sea across the Latvian cities of Liepaja and Riga to Pskov in Russia (LeRPFZ). The complex geometry and pattern of its faults, with different styles and flower structures, suggests that the LeRPFZ includes a significant horizontal component. Exceptionally high fault amplitudes with signs of pulsative activities reveal that the LeRPFZ has been acting as an early Palaeozoic tectonic hinge-line, accommodating bulk of the far-field stresses and dividing thus the NW EEC interior into NW and SW halves. The LeRPFZ has been playing a vital role in the evolution of the Baltic Ordovician–Silurian Basin, as a deep-facies protrusion of this basin (Livonian Tongue) extending into the remote NW EEC interior adheres to this fault zone. The Avalonia–Baltica collision record suggests that transpression with high shear stress, forcing the SE blocks in the LeRPFZ to move obliquely to the NE, reigned in the Ordovician. In the Silurian, the LeRPFZ with surrounding areas became increasingly affected by Laurentia–Baltica interaction and compression from the NW, while the orogenic load by Avalonia–Baltica collision flexed the foreland basin along the NW margin of the EEC. As a highly mobile basement flaw liable to differentiated tectonic movements, the LeRPFZ has experienced tectonic inversion in accordance with the stress-field changes induced by Avalonia–Baltica–Laurentia interaction. Being an axial area of the Livonian Tongue in Ordovician–early Silurian time, by the Devonian, due to the progressing Caledonian Orogeny and growing compression from the NW, the LeRPFZ became the most uplifted and intensively eroded zone in the NW EEC interior.

**Key words:** East European Craton, Leba Ridge–Riga–Pskov Fault Zone, Avalonia–Baltica–Laurentia collision, palaeostress, strike slip faulting, Baltic Ordovician–Silurian Basin.

## INTRODUCTION

The current paper has been initiated from a detailed study on the Valmiera–Lokno Uplift (VLU), a striking tectonic dislocation emerging in the remote interior of the East European Craton (EEC; Tuuling & Vaher 2018; Fig. 1). This, up to 700 m uplifted, about 170–180 km long and 30–50 km wide basement block with five individually bulging uplifts (Lokno, Haanja, Mõniste, Valmiera and Smiltene) overlaid by a strongly deformed and eroded platform veneer, has been regarded as one of the largest tectonic structures in the northwestern East European Platform (NW EEP; Figs 1–3; Misans & Brangulis 1979; Suveizdis et al. 1979; Brio et al. 1981; Puura & Vaher 1997). Former debates on the nature and development of this complex structure have focused mainly on its five individual basement uplifts along with the thickness and lithology changes in the folded platform cover above them (e.g. Kajak 1962; Paasikivi 1966; Kaplan & Hasanovich 1969; Vaher et al. 1980; Brio et al. 1981; Mens 1981; Puura & Vaher 1997). However, since similar fault-related basement-cored anticlines (BCAs) occurring copiously across the Baltic Syneclise (BS) have been treated as local platform structures (Brio et al. 1981; Stripeika 1999), little attention has been paid to their broader structural setting and possible kinematic perspective.

The VLU and numerous other BCAs in Latvia converge around an extensive and tectonically highly active zone of basement faulting known as the Liepaja–Riga–Pskov Fault Zone (LRPFZ, Fig. 2; Afanasev & Volkolakov 1972; Misans & Brangulis 1979; Suveizdis et al. 1979). Yet, based on later studies offshore, this >700-km-long zone with a striking number, density and magnitude of faults extends evidently to the Leba Ridge in the southern Baltic Sea (Volkolakov 1974; Puura et al. 1991; Brangulis & Kanev 2002; Šliaupa & Hoth 2011, fig. 2.1; Sopher et al. 2016, fig. 1A) and in this paper will henceforth be treated as the Leba Ridge–Riga–Pskov Fault Zone (LeRPFZ; Figs 1, 3).

Thus, a cursory glance at the regional tectonic setting of the VLU alongside its striking magnitude and subparallel, that is, deviating from the general northeasterly course of the LeRPFZ, trend, as well as the highly complex fault pattern with varying style and kinematics, evoked strong suspicions in favour of substantial horizontal movements along this major intracratonic fault zone (Tuuling & Vaher 2018). This suggestion was furthermore strengthened by the size and magnitude of the individual BCAs, which, along the LeRPFZ, particularly around its most elevated VLU section, greatly overpower other similar structures in the NW EEP. Moreover, signs appear that horizontal movements along this zone may have played an important role in shaping a large cratonic depression, the BS, which determined the configuration, bathymetry and sediment distribution with facies zonation in the shallow-cratonic Baltic Ordovician–Silurian Basin.

In aiming to analyse the nature of the LeRPFZ and its role in the geological history of the NW EEC, the following aspects are targeted more closely in this paper: (1) the general structural position of the LeRPFZ with respect to the regional tectonic setting and major platform structural units; (2) the LeRPFZ versus the general pattern and characteristics (styles, trends and magnitudes) of the basement faulting with deformed overlying platform cover across the NW EEP interior; (3) detailed analysis of the structural pattern and possible fault kinematics with palaeo-stresses along the LeRPFZ and (4) tectonic activities along the LeRPFZ in the light of the general geological/tectonic history of the NW EEP, with general insight into the evolvement of the Baltic Ordovician–Silurian Basin.

## REGIONAL GEOLOGICAL AND TECTONIC SETTING

In the NW EEC interior, the coherent mass of the continental crust around the Baltic Sea has been largely formed during several episodes of Svecofennian orogenic accretion between ca 1.93 and 1.80 Ga (Gaál & Gorbatschev 1987; Gorbatschev & Bogdanova 1993; Nironen 1997; Bogdanova et al. 2008; Kirs et al. 2009; Vejelyte et al. 2010; Janutyte et al. 2015). Hence, assemblages of various metamorphic rocks detached by distinct shear zones divide the cratonic basement here into different tectonic units. Besides that, this Palaeoproterozoic Svecofennian Domain is pierced in places by post-orogenic (~1.67–1.46 Ga) rapakivi intrusions (Laitakari et al. 1996; Puura & Flodén 1999; Skridlaite & Motuza 2001; Kirs et al. 2009). Exposed across the Baltic Shield, which bends the northern Baltic Sea in Sweden and Finland, the southerly to southeasterly deepening Palaeoproterozoic crystalline basement gets overlaid below the central part of this sea by the sedimentary bedrock sequence of the EEP (Fig. 1). The latter bedrock sequence, constituting the platform cover formed in the course of a complex Ediacaran to Neogene depositional/erosional history, extends over the vast areas of the southern Baltic Sea with neighbouring Baltic countries, Poland, Belarus and Russia (Figs 1, 4, 5). Due to the changing regional tectonic setting and stress field, induced by drift and interaction of the EEC as a separate continent, Baltica, or as a part of a larger continent with other terrains, the NW EEP divides structurally into different regions with varying rates and magnitudes of tectonic activities as well as types and morphologies of the resulting dislocations.

Based on the depth, tilting angle and azimuth of the crystalline basement surface, the NW EEP divides into numerous large platform structural units (Fig. 1) with various thicknesses, deformation rates and attitudes of the sedimentary bedrock strata. In general, the southern Baltic Sea and the nearby mainland areas embracing the BS, that is, the largest and most subsided cratonic portion with the thickest and stratigraphically most complete platform cover, forms a structural hub of the NW EEP. At its southwestern margin, bordering with the Trans-European Suture Zone (TESZ), this early Palaeozoic depocentre is >4.5 km deep (Zdanaviciute & Lazauskiene 2004; Šliaupiene & Šliaupa 2012, fig. 3). Because of its northeasterly elongated and rising axis, from the cratonic interior side, the BS is surrounded in a horseshoe manner by numerous smaller platform structural units, which have a sloping bedrock sequence towards the centre of this basement depression (Fig. 1).

From southeastern Sweden to eastern Estonia, that is, on the slope of the Baltic Shield, the boundary of the BS is tentatively drawn along the 550-m-b.s.l. structure contour on the top of the crystalline basement (Puura & Vaher 1997; Tuuling & Flodén 2016; Tuuling 2017). Along this limit, there remains an approximately 50–300-km-wide strip of the platform cover between the BS and the erosional shield–platform boundary (Fig. 1). The wider eastern part of this strip on the southern slope of the Baltic Shield with gently (6–13′) southerly/southeasterly tilted sedimentary bedrock layers between eastern Estonia and northern Gotland is distinguished as the Baltic Homocline (BH; Fig. 1; Tuuling & Flodén 2001, 2016; Tuuling 2017). Following the attitude changes of the crystalline basement surface, the remaining sedimentary bedrock sequence, which is mostly less than 100 km wide, has a slightly higher tilt (10–20′) along the Swedish east coast compared to the BH, with a trend that turns gradually towards the southeast from northern Gotland to Öland (Flodén 1975; Tuuling 2017). Towards the EEP interior, the eastward-rising slope of


**Fig. 1.** Geological map of the NW East European Platform showing major platform structures discussed in text with structural setting of the Leba Ridge–Riga–Pskov Fault Zone, a frame of the map shown in Fig. 15 and sites of the geological cross sections A–B and C–D shown in Figs 4 and 5, respectively. VLU – Valmiera–Lokno Uplift.

the BS transfers to the Latvian Saddle, whereas its southeastern and southern slopes in Lithuania and in Poland are bordered by the Mazurian–Belorussian Anteclise (Figs 1, 3; Suveizdis et al. 1979; Stripeika 1999). The last two structures with an elevated crystalline basement slope further east to northeast to another large cratonic depression, the Moscow Syneclise, which encompasses the vast central areas of the EEP (Fig. 1; Alekseev et al. 1996; Nikishin et al. 1996; Zhuravlev et al. 2006).

Besides lateral variations, the sedimentary bedrock succession in the NW EEP interior also divides vertically into distinctive structural packages (Suveizdis et al. 1979; Grigelis 1981; Puura et al. 1991; Brangulis & Kanev 2002; Tuuling & Vaher 2018). Due to the external stresses induced by major orogenic events and margin loads, the development/distribution of the sedimentary basins across the NW EEC has been substantially influenced by extensive epeirogenetic movements, and thus the formation of the platform cover has undergone several

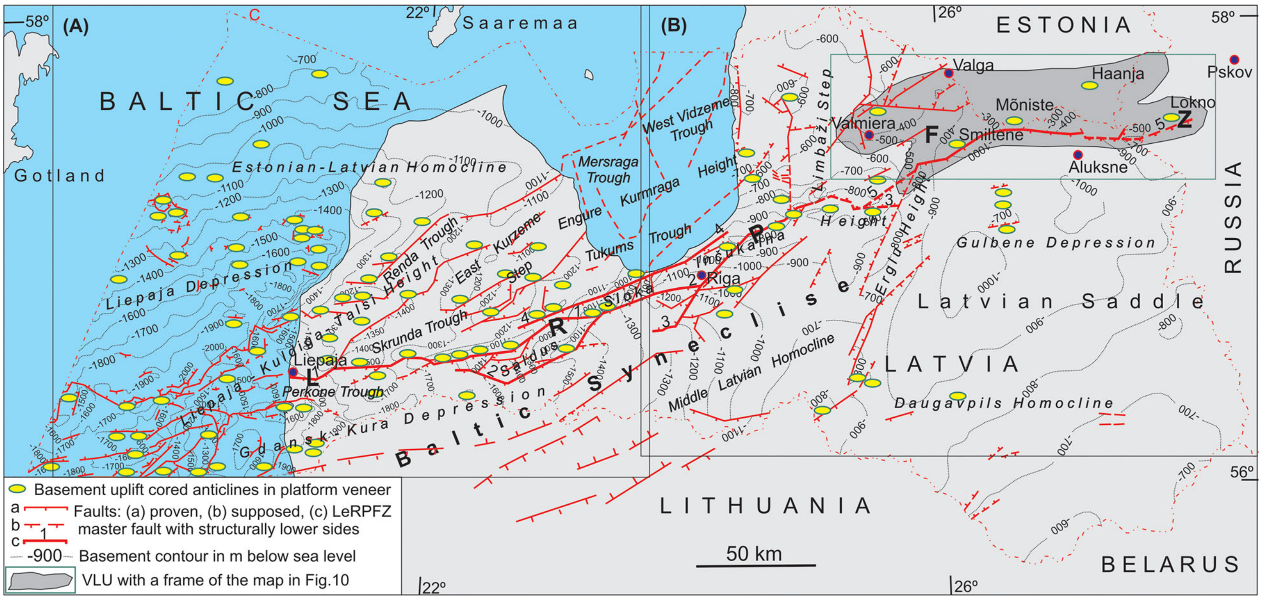


**Fig. 2.** Structure contour map on top of the crystalline basement in Latvia with the Liepaja–Riga–Pskov Fault Zone (LRPFZ) and names of structural units (heights, troughs, etc.) induced by basement faulting (modified after Brio et al. 1981; Brangulis & Kanev 2002). Frames **A** and **B** – enlargements of maps shown in Fig. 9A, B, respectively. Numbered master faults of the LeRPFZ: 1, Liepaja–Saldus; 2, Dobele–Babite; 3, Sloka–Carnikava; 4, Olaine–Inčukalna; 5, Smiltene–Ape.

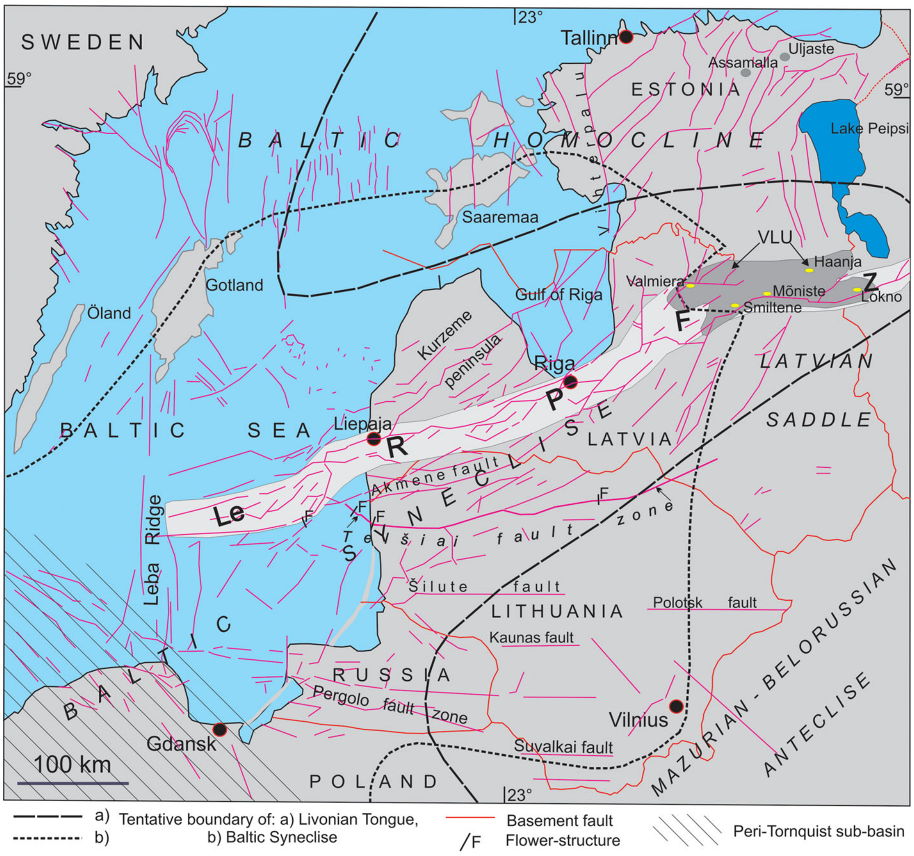


**Fig. 3.** Map of basement faults with dislocated platform cover in the NW East European Craton (after Flodén 1980; Puura & Vaher 1997; Tuuling & Flodén 2001; Brangulis & Kanev 2002; Sliaupa & Baliukevicius 2011; Šliaupa & Hoth 2011) with locations of the Leba Ridge, Leba Ridge–Riga–Pskov Fault Zone (LeRPFZ) and the Valmiera–Lokno Uplift (VLU) with five basement-cored anticlines.

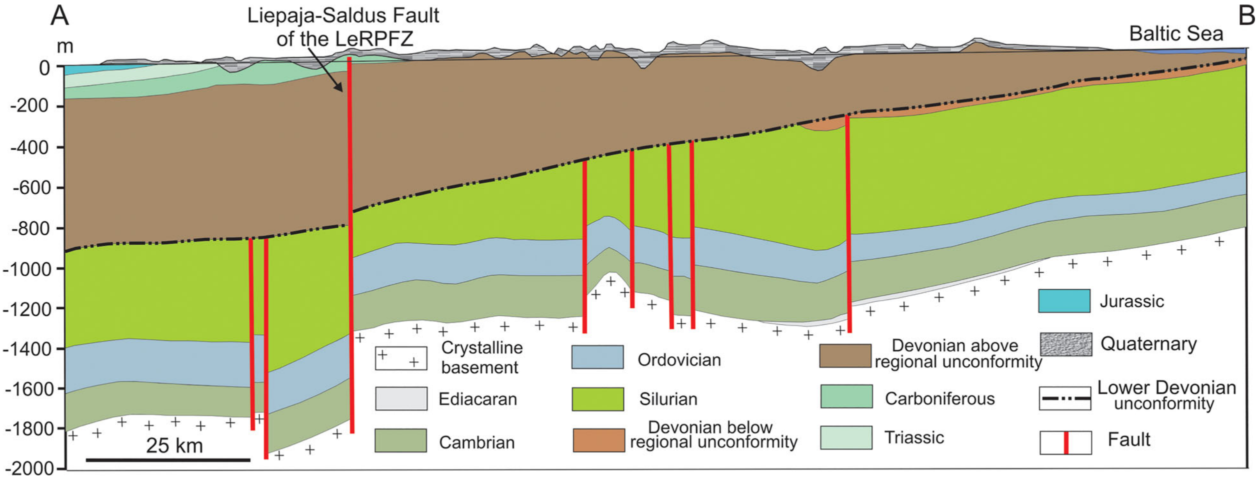


**Fig. 4.** Submeridional geological cross section of western Latvia across the Liepaja–Saldus fault of the LeRPFZ (modified after Brangulis & Kanev 2002). For location see Fig. 1.

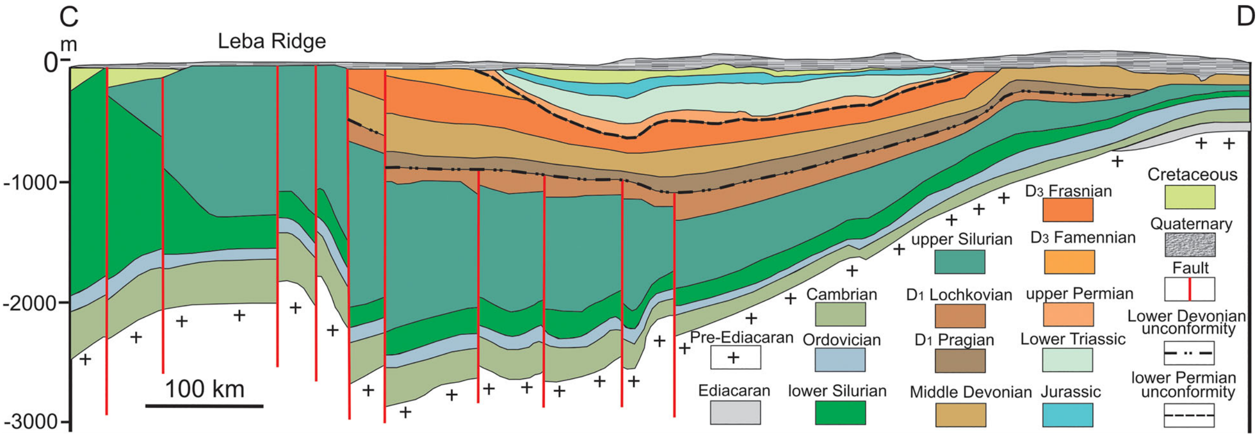


**Fig. 5.** Subparallel geological cross section from Lithuania across the Leba Ridge in the southern Baltic Sea (modified after Šliaupa & Hoth 2011). For location see Fig. 1.

phases of structural rearrangements with longer or shorter periods of erosion. Based on that, four distinctive structural complexes divided by regional-scale unconformities, namely the Timanian (Ediacaran–lower Cambrian), the Caledonian (lower Cambrian–lower Devonian), the Hercynian (lower Devonian–lower Permian) and the Alpine (upper Permian–Neogene), are distinguished in the platform cover around the Baltic Sea (Suveizdis et al. 1979; Grigelis 1981; Puura et al. 1991; Šliaupa & Hoth 2011; Figs 4, 5). Depending on the location and distance of a tectonically active EEC margin with respect to the above-listed platform structural units, the lateral extents and time spans of these regional unconformities with stratigraphic gaps across them can vary considerably.

## RESTRICTING THE STUDY AREA AND MATERIALS/DATA USED

In assessing the basement faulting and dislocations in the recumbent platform cover induced by it, we have to bear in mind that the NW margin of the EEC, sutured along the TESZ with the Phanerozoic continental block of central/western Europe (Fig. 1), represents one of the most fundamental lithospheric boundaries of Europe, extending from the North Sea to the Black Sea (Pharaoh et al. 1997; Pharaoh 1999; Winchester et al. 2002; Bergerat et al. 2007, fig. 1; Krzywiec 2009). The highly complex structure around the TESZ, which has been tectonically active during most of the Phanerozoic, has been described in many papers (e.g. Thybo 2001;

Krawczyk et al. 2002; Grad et al. 2003; Mazur et al. 2005, 2015, 2018; Guterch & Grad 2006; Graversen 2009; Janutyte et al. 2015; Jensen et al. 2017). Hence, where the EEP abuts the TESZ in Denmark, Sweden, Germany and Poland, it is normally more intensely deformed than in its interior areas around the central Baltic Sea, where the LeRPFZ with the VLU is located. In this sense, the Baltic Ordovician–Silurian Basin inundating the NW EEC can be divided into two entities (Poprawa et al. 1999, fig. 1; Lazauskiene et al. 2002, 2003): (1) the cratonic margin, NW–SE-trending narrow Peri-Tornquist sub-basin adjacent to the TESZ (Fig. 3) and (2) the cratonic interior, NE–SW-elongated Baltic Depression sub-basin that adheres clearly to the tectonically mobile LeRPFZ. Besides the general complexity, intensity and magnitude of dislocations, these sub-basins also have clearly different faulting trends that are largely following orientations of the TESZ and LeRPFZ, respectively, and thus the axial areas of these basins (Fig. 3).

Focusing on the LeRPFZ, this study embraces above all the inner cratonic Baltic Depression sub-basin, that is, the Baltic Syneclise–Baltic Homocline (BS–BH) areas around this major intracratonic fault zone. From the southwest, the latter basin is bordered by a wide set of submeridional faults extending from Poland towards Gotland, the central, about 1 km uplifted asymmetrical arch-like basement section of which is known as the Leba Ridge/Arch (Domžalski et al. 2004; Šliaupa & Hoth 2011; Motuza et al. 2015; Sopher et al. 2016; Figs 3, 5). This basement elevation, formed in the late Palaeozoic, which has led to the truncation of more than 1 km of Devonian/uppermost Silurian rocks from the southwestern BS (i.e., from the Peri-Tornquist sub-basin), also traverses the LeRPFZ and terminates its extension towards the SW (Fig. 3).

The present study does not include any original field data; that is, it is entirely based on the analysis of the earlier geological mapping and prospecting information performed in the Baltic countries for more than the last 50 years. These activities have yielded a great amount of geophysical/drilling data revealing extensive basement faulting with deformed platform cover in the BS–BH area. The bulk of the data used in this study are distributed across the following publications: Misans & Brangulis (1979), Suveizdis et al. (1979), Flodén (1980), Brio et al. (1981), Polivko (1981), Brangulis (1985), Puura & Vaher (1997), Stripeika (1999), Tuuling & Flodén (2001), Brangulis & Kanev (2002), Šliaupa & Hoth (2011), Šliaupene & Šliaupa (2012), Tuuling (2017) and Tuuling & Vaher (2018), which, besides individual fault descriptions, often include generalizing tectonic/structural maps. As many of these publications have been released in local Russian- or Latvian-based journals and monographs, they may have remained unnoticed by the wider international community and potential readers interested in the tectonics of the EEC interior. To summarize and analyse these data, different scales of maps and geological cross sections with basement faulting and platform structures induced by it along the LeRPFZ with surrounding EEP areas were used, modified (Figs 2, 4–12, 14, 15), or composed (Figs 1, 3, 13).

## INTRACRATONIC BALTIC HOMOCLINE–BALTIC SYNECLISE BASEMENT FAULTING AND THE LEBA RIDGE–RIGA–PSKOV FAULT ZONE

In general, the EEC interior platform cover around the Baltic Sea reveals two types of dislocations related to basement faulting. Overlying the basement faults monocline (drape/force) folds with varying trends, extents, styles and magnitudes are spread widely across the whole of the BS–BH area (Figs 3, 6–8). Around the LeRPFZ and further south within the BS, isolated BCAs emerge occasionally on the elevated blocks of more extensive high-magnitude faults (Figs 2, 8). To assess the possible role of the LeRPFZ in accommodating the far-field stresses and thus shaping the stress field in the NW EEP interior, the general pattern and characteristics (extent, magnitude, trend and style) of the basement faults with deformed platform cover will be treated across this fault zone below.

### General structure and structural setting of the LeRPFZ

Based on the investigations performed, the LeRPFZ can be divided into poorly studied submarine and better explored Liepaja–Riga–Pskov (LRPFZ) onshore sections. The latter >500-km-long segment converges around five extensive (100–150 km long) high-angle basement faults [Liepaja–Saldus, Dobele–Babite, Olaine–Inčukalna, Sloka–Carnikava, Smiltene–Ape (1–5 in Fig. 2; Figs 4, 9A, B; Suveizdis et al. 1979)]. Except for the 145-km-long reverse Olaine–Inčukalna fault with downthrown northwestern/northern block, which bends from Olaine southwest of Riga to the VLU, the others are interpreted as normal faults with subsided southern blocks (Brangulis & Kanev 2002). These master faults reveal locally curved traces and a highly varying offset that usually remains within a few hundreds of metres but can at the largest traces of the Liepaja–Saldus and Smiltene–Ape faults reach occasionally >600 m (Brangulis & Kanev 2002). A deep seismic profile from northern Estonia to the Kaliningrad district further south reveals that the Smiltene–Ape fault, which limits the VLU from the south, obviously reaches the mantle (Ankudinov et al. 1994;

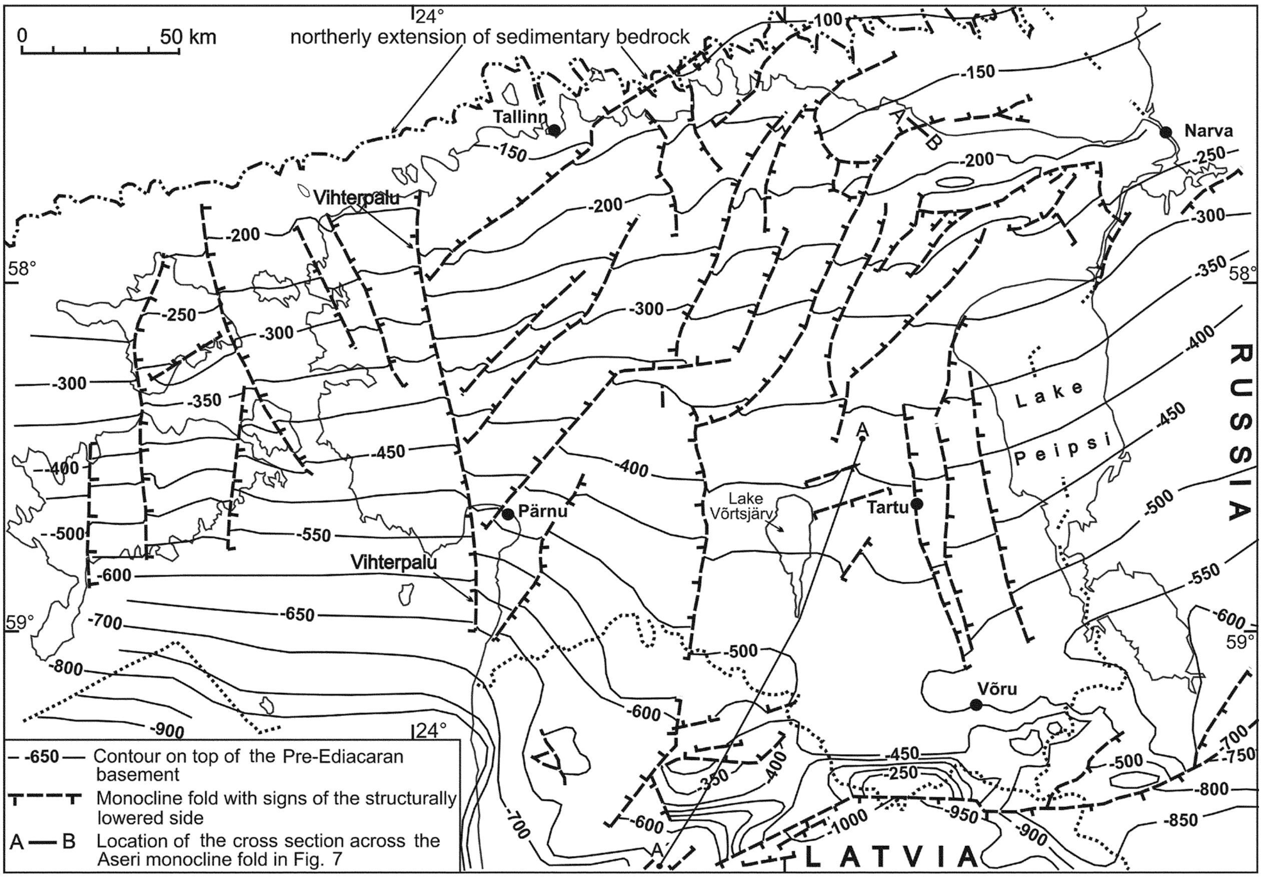


**Fig. 6.** Structure contour map on top of the cratonic basement of the Estonian Homocline with platform monocline folds (modified after Puura & Vaher 1997). A–A′ – location of the cross section in Fig. 8.

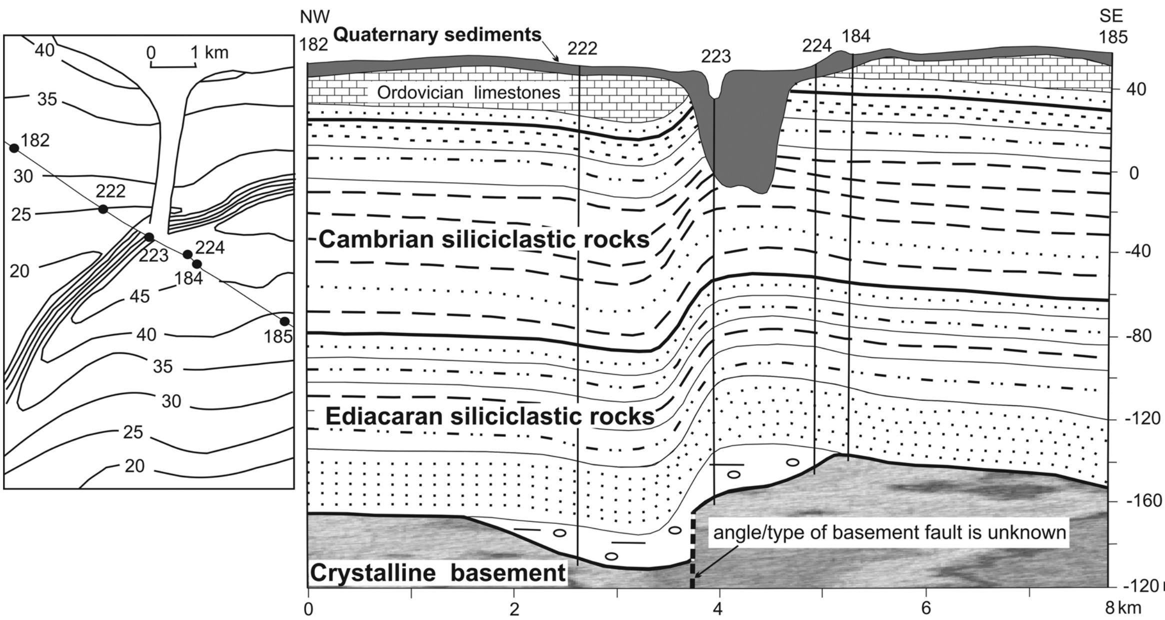


**Fig. 7.** Geological cross section across the Aseri basement fault (with a detailed excerpt of the structure contour map of the platform cover) showing the monoclinal forced fold in the overlying platform cover (modified after Puura & Vaher 1997). For location see Fig. 6.

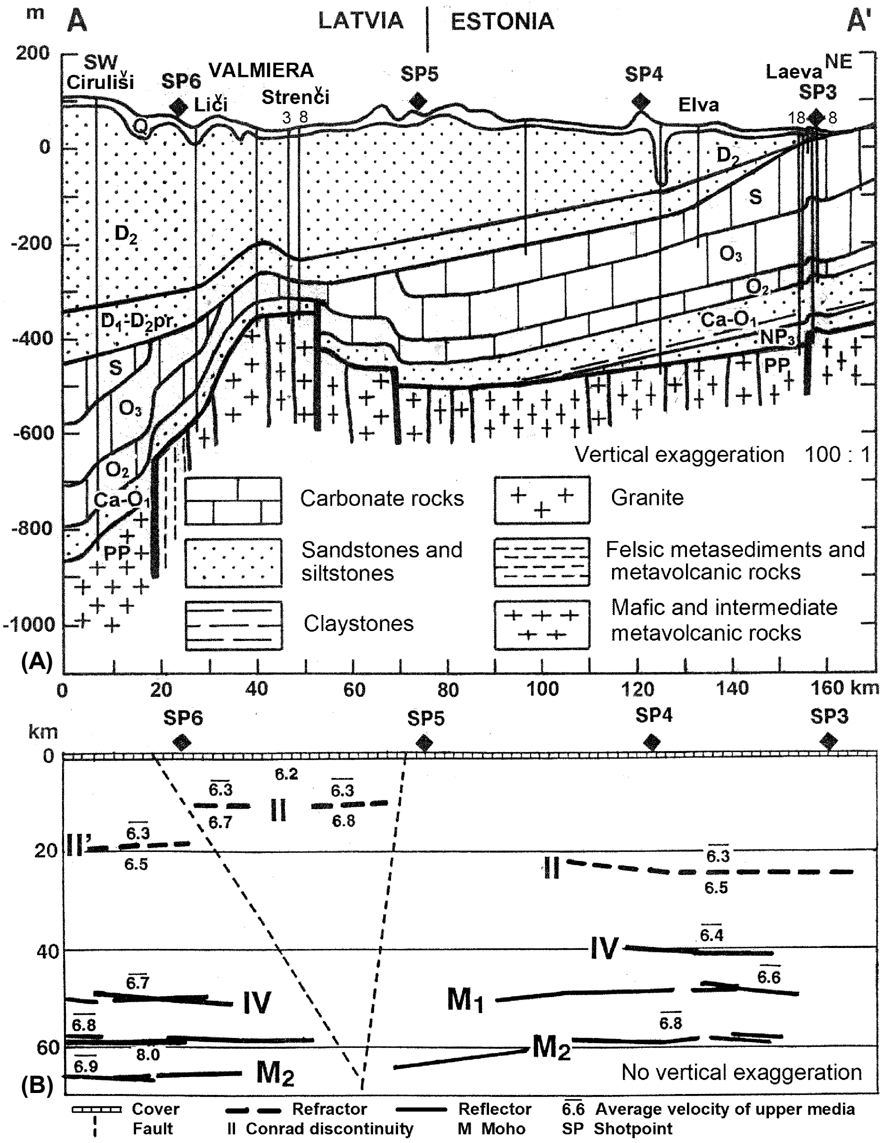


**Fig. 8.** Geological cross section (**A**) and deep seismic profile interpretation (**B**) (modified from Puura & Vaher 1997 and Ankudinov et al. 1994, respectively), across the VLU with the Valmiera Uplift. For location see Fig. 6.

Fig. 8) and brings about the thickening of the Earth crust from about 50 km (in the BH) up to 60 km (in the BS).

The structural complexity of the LeRPFZ is boosted by numerous smaller and larger subsidiary/splay faults, whose number and magnitude increase around the larger master faults with higher offsets. Thus, a striking set of northeasterly trending faults, bordering a basement elevation branching at an angle of 30–40° from the LeRPFZ (the Liepaja–Kuldiga–Talsi Height), arises just north of the Liepaja–Saldus master fault on the Kurzeme Peninsula (Figs 2, 9A). Another area with a striking set of subsidiary faults emerges around the overlapping section of the Olaine–Inčukalna and Smiltene–Ape master faults at the western margin of the VLU (Figs 2, 9B).

The >200-km-long submarine part of the LeRPFZ is, in terms of the number, exact course, offset and style of faults, poorly studied and rarely discussed. Still, the Latvian nearshore area, which is more explored (e.g. Volkolakov 1974), reveals that a dense and complex set of basement faults with heavily deformed platform cover congregates largely around the submarine segment of the Liepaja–Kuldiga–Talsi Height (Figs 2, 9A; Brangulis & Kanev 2002). The faults off Liepaja, occurring often in a sub-parallel array or limiting isolated graben or horst-like structures, occasionally reach a few hundred metres in amplitude. However, in case of a parallel fault system, the stepwise-falling basement relief along the borders of the Liepaja–Kuldiga–Talsi Height can exceed 500 m.

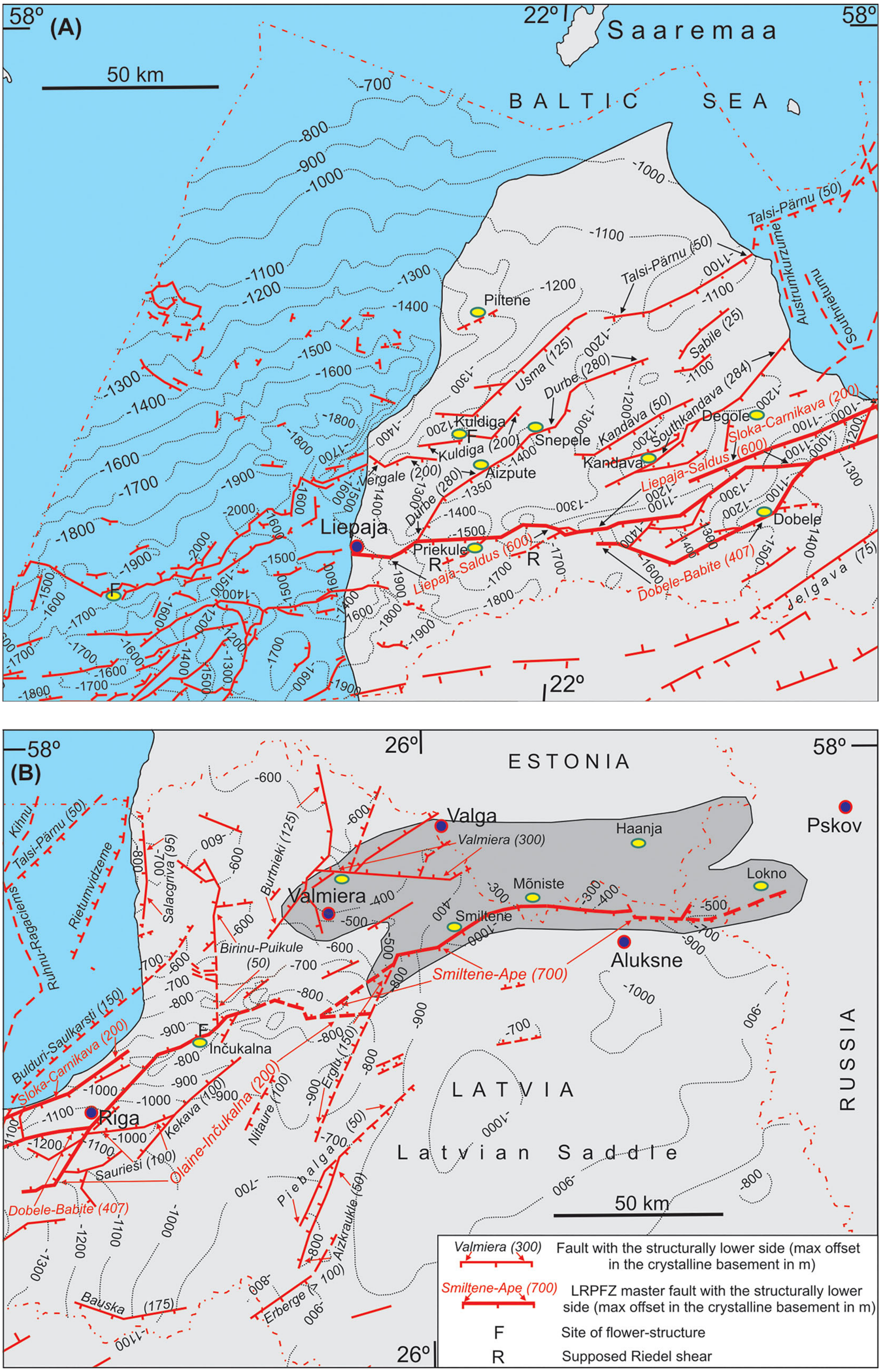


**Fig. 9.** Enlarged excerpts from the western (**A**) and eastern (**B**) halves of the Liepaja–Riga–Pskov Fault Zone shown in Fig. 2. For locations of frames A and B and for more map symbols see Fig. 2.

Although data about the style/kinematics of the faults off Liepaja are scarce, their reverse character around the elevated basement blocks has been pointed out (Kanev & Peregudov 2000; Brangulis & Kanev 2002).

Regarding the position of the LeRPFZ with respect to the large EEP structural units described above, this major fault zone can be divided into two entities. Its E–W-trending eastern section, largely following the Smiltene–Ape fault at the southern border of the VLU, runs into an intricate structural junction of the Baltic Homocline, the Baltic Syneclise, the Latvian Saddle and the Moscow Syneclise (Figs 1–3, 9B). The remaining, generally northeasterly trending (azimuth ~070°) section between the VLU and the Leba Ridge, however, coincides roughly with the axis of the BS, thus dividing this vast EEC interior depression into northwestern and southeastern halves (Fig. 3). Still, due to curving master faults, the latter section reveals a few perceptible bends. Thus, besides the remarkable arc at the western margin of the VLU, the strongly winding Olaine–Inčukalna fault also induces a minor trend turn around the Riga area (Figs 2, 9B). Another curve, comparable with the bend near to the western VLU, appears offshore of Liepaja around the area where the Liepaja–Kuldiga–Talsi Height branches from the LeRPFZ (Figs 2, 3, 9A). Hence, based on the changes in the course, the northeasterly running and BS-splitting section of the LeRPFZ divides into three slices (the Leba Ridge–offshore Liepaja, the offshore Liepaja–Riga and the Riga–VLU), as its E–W-trending VLU section separates the BH from the Latvian Saddle (Figs 1–3).

**Basement-cored platform dislocations around the LeRPFZ and in the EEC interior areas further north and south of this major fault zone**

Considering available information about the EEC interior basement faulting, the area north of the LeRPFZ divides into the relatively well studied BH and the poorly covered northern half of the BS (Fig. 3).

*The Baltic Homocline*

Across the BH, a gentle southerly tilt of the sedimentary bedrock layers varies mainly due to the frequent monocline folds above the high-angle basement faults (Puura & Vaher 1997; Tuuling & Flodén 2001; Tuuling 2017; Figs 6, 7). These folds are normally 1–4 km wide and 20–60 km long, as the offset between the monocline limbs, which is usually within a couple of tens of metres, can reach up to 50 m at the Vihterpalu fault in western Estonia (Puura & Suuroja 1984; Figs 3, 6). Regarding their trends, two areas with dominating N–S and SW–NE orientation, respectively, west and east of the submeridional Vihterpalu fault emerge within the BH (Figs 3, 6; Tuuling 2017). In fact, the N–S trend also prevails in southern Estonia, where the 550-m-b.s.l. contour on top of the crystalline basement shifts southwards remarkably, due to the elevated VLU block, and the BH reaches its largest width of about 300 km (Fig. 6).

Regarding the relative block movements, the areas with a similar design may alternate with districts where N–S-trending zones may have either eastern or western blocks at a higher or lower structural position (Tuuling 2017). As a result, elevated or lowered basement sections, resembling the graben/horst-like blocks, appear in places in southern Estonia and around the Baltic Sea–West Estonia transition. Conversely, northeast of Gotland and in northern Estonia, the basement faults have prevailingly western and southeastern blocks, respectively, in a higher position, thus resembling parallel or *en echelon* arrays of faults (Fig. 6). However, the exact style, possible kinematics and timing of these blind faults which deform the BH basement have never been meticulously studied and are still poorly known (Tuuling 2017).

Differently from the LeRPFZ and southern BS, no BCAs have been discovered in the platform cover within the BH. Yet, a group of four similar structures with an amplitude of up to 20 m have been outlined in the Uljaste and one in the Assamalla district in northern Estonia (Puura & Vaher 1997, fig. 119; Fig. 3). However, these anticlines seem to be resting on the local dome-like basement monadnocks, which vary from 1 to 6 km in diameter and 30 to 130 m in height, without any clear linkage to basement faulting. Because of morphological similarities with the intracratonic folds in the Mid-continent Great Plains of the USA (Clark 1932; Merriam 2012) or in the Volga–Ural district (Shatskiy 1967; Sanarov 1970), the Uljaste–Assamalla anticlines have been considered as plain-type supratenuous folds or placanticlines (Afanasev et al. 1973; Afanasev & Volkolakov 1981). However, lithological evidence, alongside the thickness and facies analysis (Vaher et al. 1964; Mens 1981), indicates that these structures have undergone recurrent movement pulses. Hence, beside differential compaction across basement bulges, the folding of the platform cover in the Uljaste–Assamalla area has also been boosted by uplift of the crystalline basement (Vaher et al. 1980; Puura & Vaher 1997).

*The Baltic Syneclise north of the Leba Ridge–Riga–Pskov Fault Zone*

Structurally, the southern limit of the BH, drawn roughly along the 550-m-b.s.l. isohypse on top of the crystalline basement (Puura & Vaher 1997; Tuuling 2017), divides into two distinctive segments. The eastern one, plummeting across the LeRPFZ to the Latvian Saddle

(Figs 1–3, 8), bounds the elevated VLU block. Its western section transfers smoothly to the BS, which, however, is divided into NW and SE halves by the NE-trending LeRPFZ portion (VLU–Leba Ridge section). As no noticeable modifications in deformation intensity have been ascertained in the platform cover around the BH–BS transect, the gently (20–40′) south- to southeast-falling and slightly deformed northern slope of the BS is also referred to as the Estonian–Latvian Homocline (Misans & Brangulis 1979; Brangulis & Kanev 2002; Fig. 2). However, closer to the BS dividing LeRPFZ, the intensity of basement faulting and the deformation rate induced by that, as well as the dislocation magnitudes in the platform cover, increase abruptly. This is particularly well expressed around northwestern Latvia, where the slightly deformed area (Liepaja Depression with the northern Kurzeme Peninsula) becomes a zone around the Liepaja–Kuldiga–Talsi Height, heavily dissected by faults/fault systems just north of the LeRPFZ (Suveizdis et al. 1979; Brangulis & Kanev 2002; Figs 2, 9A). Onshore these faults (Kuldiga, Kandava, Durbe and Talsi), trending at an angle of about 35–40° to the Liepaja–Saldus master fault (Figs 2, 9A), can exceed 50 km in length and in places have >200 m downthrown southeastern sides. Thus, this set of northeasterly trending normal faults just north of the LeRPFZ on the Kurzeme Peninsula has a clearly different orientation, much larger extent and magnitude compared to the BH further north to northeast.

Towards the Gulf of Riga and the VLU, the trend of the faults near to the north of the LeRPFZ turns gradually northwards, that is, it becomes more similar to that of the BH in southern Estonia (Figs 2, 9A, B). This change in the faults trend appears to be related to the orientation change(s) along the LeRPFZ. Thus, after the Riga bend and before the VLU curve where the LeRPFZ turns towards Pskov, a few submeridional faults arise along the eastern coast of the Gulf of Riga. One of them with numerous splays (Birnu–Puikule) branches directly from the major Olaine–Inčukalna reverse fault (Figs 2, 9B). A striking set of radially branching submeridional faults around the subparallel Valmiera and SW- to NW-curving Burtnieki faults, possibly reflecting a flower structure, appears around the western VLU just north of the Valmiera Uplift (Fig. 9B). Notably, these submeridional faults around the western VLU have, in contrast to most of the LeRPFZ, largely downthrown northwestern/western blocks (Figs 2, 9B). Equally exceptional is the downfaulted northern block along the Valmiera fault, which, however, resembles the nearby curvy Olaine–Inčukalna master fault. There is no solid information about the style/kinematics of these exceptional faults around the western VLU, although a reverse nature of the Valmiera fault is suggested based on the similarities of its style and trend with the Olaine–Inčukalna fault (Brio et al. 1981).

### *The Leba Ridge–Riga–Pskov Fault Zone and the Baltic Syneclise south of it*

In all, considering the rate, extent and magnitude of basement faulting and dislocations in the platform cover induced by that, the LeRPFZ represents by far the most intensely deformed zone in the NW EEC interior. The faults with varying styles, kinematics and offsets along and around its better studied onshore section (LRPFZ) have induced a complex set of alternating, larger and smaller uplifted, subsided and tilted basement blocks. Thus, based on its highly undulating and complex surface topography, the crystalline basement with overlying deformed platform cover around the LRPFZ is divided into numerous depressions, troughs, heights, steps, ramparts and homoclines (Brio & Bendrup 1973; Misans & Brangulis 1979; Polivko 1981; Brangulis & Kanev 2002; Figs 2, 9A, B).

Except for the sublinear Sloka–Carnikava fault, curvilinear master faults spaced in a relay array dominate in a map view and thus in shaping the general faulting pattern along the LeRPFZ. However, their locally curved, non-coplanar and stepover sections alongside the numerous subsidiary and splay faults occasionally create the impression of a highly complicated, even braided array of faults (Figs 2, 9A, B). As mentioned above, the throw of the dislocated basement surface along individual faults and thus the LeRPFZ can vary greatly, reaching about 700 m at the largest master faults (Liepaja–Saldus and Smiltene–Ape) and >200 m at some subsidiary faults (e.g. Kuldiga–Vergale) on the Kurzeme Peninsula (Brangulis & Kanev 2002).

A high deformation rate of the platform cover, induced largely by the basement faults/fault zones (Akmene) running nearly parallel to the LeRPFZ, also continues close to the south of this major fault zone (Figs 2, 3). Like the area to the north of the LeRPFZ, the faults near to the south of it have an increasingly northerly trend with structurally lowered northwestern sides along the Riga–VLU section of the LeRPFZ (Figs 2, 9B). Like the area to the north of the Olaine–Inčukalna master fault, it is suggested that reverse faulting also prevails to the south of it (Suveizdis et al. 1979). Highly deformed platform cover, induced largely by NE–SW- and E–W-trending basement faults, is also ascertained in offshore and onshore areas, respectively, further south of the LeRPFZ (Šliaupa & Hoth 2011, fig. 2.11; Fig. 3). Thus, in Lithuania and Kaliningrad district, the most intense faulting largely congregates along several extensive E–W-trending fault zones (e.g. Telšiai, Šilute and Suvalkai; Šliaupa & Hoth 2011, fig. 2.11; Sliaupa & Baliukevicius 2011, fig. 1; Fig. 3). Normally, these faults do not surpass 50 m in offset, although their amplitude can still exceed a few hundred metres in the largest zones (e.g. Telšiai and Suvalkai). Regarding the relative block movements, the high-angle faults/fault zones may then have structurally lowered northern (Suvalkai), as well as southern flanks (Telšiai), or this issue can change even along the same fault zone (Šilute) (Fig. 3; Suveizdis et al. 1979). Despite rare data on style/kinematics, it is suggested that reverse faulting, being ascertained at many faults (e.g. Akmene and Telšiai), prevails and is spread widely across the southern BS (Stripeika 1999; Sliaupa & Baliukevicius 2011; Šliaupa & Hoth 2011). Indeed, complex sets of faulting induced by transpressional tectonics, with excellent flower structures, have been revealed by seismic profiling at the LeRPFZ, as well as in many places south of this major fault zone (Brangulis & Kanev 2002; Šliaupiene & Šliaupa 2012, figs 15, 16; Figs 3, 9A, B).

## Basement-cored anticlines in the platform cover around the LeRPFZ and in the southern Baltic Syneclise

More than 100 fault-related BCAs are recognized in the platform cover around the LeRPFZ. The great majority of them occur within the BS in Latvia, as only the largest five (Valmiera, Smiltene, Mõniste, Haanja and Lokno) arise within a structurally complex VLU junction around the joining Latvian, Estonian and Russian territories (Figs 2, 3; Brangulis & Brio 1981; Brangulis & Kanev 2002; Tuuling & Vaher 2018). Similar structures are also abundant further south in Lithuania and Kaliningrad district (Suveizdis et al. 1979; Stripeika 1999, fig. 23) as well as off the Polish coast (Domžalski et al. 2004, fig. 1). They are best studied around the LeRPFZ, particularly at its most elevated VLU section (Brangulis & Brio 1981; Tuuling & Vaher 2018).

Along the LeRPFZ, BCAs arise mostly on the upthrown blocks of the curved fault sections, whereas the largest uplifts with more complicated structure are often associated with intersections of variously trending basement faults (Brangulis & Brio 1981). They are normally slightly elongated and occasionally isometric in shape, whereas the elongated brachyforms (e.g. Kuldiga and Haanja–Lokno) reveal a strongly undulating basement surface with several distinctive peaks (see fig. 12 in Brangulis & Kanev 2002; Tuuling & Vaher 2018, figs 3, 6; Figs 2, 9A, B). In places, similar structures outline on structure contour maps as structural noses (e.g. Piltene in Fig. 9A; Misans & Brangulis 1979; Stripeika 1999). Since the BCAs usually arise near to or directly at the verge of the uplifted basement block, their faultward wings join the monocline fold (flexure) above that fault more or less smoothly (Fig. 8). Thus, similar BCAs usually have a strongly asymmetrical shape, i.e., with faultward wings that are steeper and fall much deeper structurally (Tuuling & Vaher 2018).

The dimensions of the BCAs in the platform cover are clearly dependent on the intensity and offset of the underlying basement faulting, as their size and magnitude differ considerably at the VLU, around the NE-trending LeRPFZ section in Latvia, and in the faults/fault zones further south in the BS (Afanasev et al. 1973; Suveizdis et al. 1979; Brangulis & Brio 1981; Tuuling & Vaher 2018). Thus, their lengths, widths, areal extents and amplitudes are by far the largest within the VLU, that is, at the most elevated and intricate LeRPFZ section, varying, respectively, in the ranges of 30–50 km, 4–15 km, 140–700 km$^2$ and 80–>350 m. Around the Liepaja–VLU section in Latvia, with a few exceptions (e.g. Priekule, Inčukalna and Dobele; Fig. 9A, B; see Brangulis & Kanev 2002, figs 10–12, 14), the longer axis of basement uplifts and the areal extent rarely exceed 10 km and 100 km$^2$, respectively, as their height, being typically within the limits of 30–80 m, exceeds 100 m only at the largest structures (e.g. Inčukalna, Dobele and Kandava). The mentioned larger structures, arising around the most complicated/dislocated LeRPFZ sections, that is, around the Liepaja–Saldus fault and the western VLU, mainly cling to the bending sections of the more extensive faults. The areal extents and heights of analogous isolated BCAs further south in the BS, vary, respectively, within 5–30 km$^2$ and 30–80 m (Stripeika 1999).

## Deformation timing of the platform cover versus origin of the basement faults

Based largely on the stratigraphic span and trends of the overlying monocline folds, the BH–BS basement faults were thought to have formed mostly during the Caledonian Orogeny culminating around the Silurian–Devonian transition (Suveizdis et al. 1979; Puura & Vaher 1997; Šliaupa & Hoth 2011). Gradually accumulating data along with detailed studies of the LeRPFZ with the VLU, however, indicate that many of these faults have had long and pulsatile histories, which can be dated back to the latest Neoproterozoic (Ediacaran) (Brangulis & Brio 1981; Tuuling & Vaher 2018) and may even reach the early stages of formation of the Svecofennian Domain (Tuuling 2017). Thus, as noticed in North America (e.g. Marshak & Paulsen 1997; van der Pluijm et al. 1997; Pinet 2016), once created, faults exist as basement flaws liable to reactivation as stresses induced by the interaction of lithospheric plates are transmitted into the remote cratonic interiors.

This is best revealed in Southern Finland (Elminen et al. 2008; Mertanen et al. 2008; Wennerström et al. 2008), where exposed shear zones and basement faults with various orientations, styles and thus different stress-field conditions/kinematics cross-cut each other. Based on types and trends, Elminen et al. (2008) noted seven groups of recurrently activated faults formed at different stages of the Svecofennian Orogeny, during the post-orogenic rapakivi magmatism and at the later epochs of cooling and exhumation of the basement. The well-known post-rapakivi faulting event created a number of Mesoproterozoic graben-like structures, filled with 1.4–1.3 Ga Jotnian sandstones, around the present Baltic Shield–EEP contact and along the Gulf of Bothnia (Flodén 1980; Winterhalter et al. 1981; Wannäs 1989; Söderberg 1993; Amantov et al. 1995, 1996). Many of these structures reveal signs of the 1.27–1.25-Ga-post-Jotnian and the late Palaeozoic downfaulting; some of them were obviously reactivated even during the uplift of Scandinavia in the latest Cenozoic (Flodén 1980; Puura et al. 1996; All et al. 2004; Tuuling 2017). The Palaeozoic, in places even Mesozoic, reactivation of the faults/shear zones in Scandinavia has also been proved by the palaeomagnetic and thermochronological data, as well as by the Sm–Nd isotope age calculations in the fluorite–calcite–galena-bearing hydrothermal veins (Larsson et al. 1999; Murell 2003; Alm et al. 2005; Preeden et al. 2008, 2009).

Comparing the settings of the exposed and blind basement faults, respectively, in southern Finland and in the nearby EEP areas, there are strong indications that many monocline folds in the BH, although shaped at the prime of the Caledonian orogeny, are resting on the former Pre-Ediacaran basement faults (Tuuling 2017). Similar suggestions that many dislocations of the platform cover are probably due to reactivation of the older Proterozoic faults in the Phanerozoic have also been voiced for the BS (Misans & Brangulis 1979; Šliaupa & Hoth 2011; Šliaupiene & Šliaupa 2012). In all, based on various evidences in the platform cover (e.g. Afanasev & Volkolakov 1981; Brio et al. 1981; Puura et al. 1996; Stripeika 1999; Alm et al. 2005; Mazur et al. 2005; Šliaupa et al. 2006; Bergerat et al. 2007; Graversen 2009; Šliaupa & Hoth 2011; Jensen et al. 2017; Lidmar-Bergström et al. 2017; Tuuling 2017; Tuuling & Vaher 2018), the following epochs of tectonic activity with possible reactivation of older basement faults can be distinguished in the NW EEP: (1) Ediacaran–Cambrian; (2) progressing Ordovician–Silurian with culmination at the Silurian–Devonian transect; (3) so-called Permo-Carboniferous, culminating in late Carboniferous–early Permian time; (4) Late Cretaceous inversional reactivation around the NW section of the TESZ; (5) uplift of Scandinavia in two, that is, early and late, stages of the Cenozoic.

All epochs are more or less clearly tied to the significant tectonic/orogenic events occurring either directly at or near different margins of the EEC. In the Baltic Depression sub-basin of the EEC interior, three first epochs with their activity peak at the prime of the Caledonian Orogeny are clearly dominating. The signs of the last two phases, being widespread in the Peri-Tornquist sub-basin near to the NW border of the EEC, although faintly discernible, are largely missing in the cratonic interior areas around the LeRPFZ.

## DISCUSSION

### The LeRPFZ – the EEC interior tectonic hinge-line with a significant horizontal faulting component

Despite its recurrently treated mainland sections, the presence of an extensive unique EEC interior fault zone (LeRPFZ) and thus its regional tectonic setting, origin and kinematics, as well as its possible influence on the formation of the platform cover around the BS, have so far basically remained outside discussions. This is because of the dispersed, scarce and often confusing data, as, being buried under a thick sedimentary bedrock sequence, the LeRPFZ is inaccessible to direct studies of outcrops. Thus, concerning the description of the LeRPFZ given above, there exist many ambiguities about the exact pattern and contrasting views on the possible style and kinematics of its basement faults. It is even suggested that most of them must be, similarly to the southern BS, reverse faults (Stripeika 1999), or most likely they all denote normal faults (Popovs et al. 2015). A possible strike slip component with oblique block movements, inducing significant variations in the stress field with a wider range of kinematics and styles of the faults, although pondered (Šliaupa & Hoth 2011), has so far remained outside serious debates.

### The general Baltic Homocline–Baltic Syneclise basement faulting versus the LeRPFZ

Summarizing the intensity rate, complexity and magnitude of the basement faulting described above, it is obvious that the LeRPFZ, which includes the VLU and divides the BS, manifests tectonically by far the most mobile and intensely deformed zone in the NW EEP interior (Fig. 3). Furthermore, based on the differences in trends and magnitudes, as well as on rare data on the style/kinematics of the faults, it is evident that this zone splits the Baltic Depression sub-basin into the less deformed northern (BH with northern BS) and more intensely dislocated southern (southern BS) parts. Thus, if the extent of the faults north of the LeRPFZ rarely exceeds 60 km and the offset usually remains within 10–20 m (max. 50 m), then many basement faults/fault zones in the southern BS are >200 km long and can reach >200 m in magnitude. The dominating fault trends, which differ between the northern (N–S/NE–SW) and southern (E–W) parts (Fig. 3), clearly deviate from the prevailing NE trend (070°) of the LeRPFZ on both sides.

The fault patterns and trends in the vicinity of the LeRPFZ seem, however, to be either directly following or strongly influenced by this major fault zone. Thus, near to the south of the LeRPFZ, the fault orientation between Liepaja and Riga adjusts mostly to the main northeasterly course of the LeRPFZ. Yet, southwest of the VLU and Liepaja, that is, around the two largest LeRPFZ bends, the bulk of the basement faults attain a NE trend, clearly traversing the main course of this major fault zone (Figs 2, 3, 9A, B). The change in the course at the latter fault assemblages, both reminiscent of tentatively *en echelon* arrays, apparently reflects stress-field modifications around the significant LeRPFZ curves. Near to the north of the LeRPFZ, however, the fault trends mostly traverse the main course of this major fault zone. Thus, the set of normal faults parallel to the Liepaja–Kuldiga–Talsi Height trends at angles of about 30–40° to the LeRPFZ on the Kurzeme Peninsula. Towards the VLU, however, the faults near to the north of the LeRPFZ, similarly to the area south of it, have an increasingly northerly trend with mostly structurally lowered northwestern/northern blocks and signs of reverse kinematics. Thus, the ubiquitous changes in the fault patterns/characteristics around the Olaine–Inčukalna master fault are obviously due to the stress-field changes around the major LeRPFZ bend at the western VLU.

In all, the basement faults and their sets further north and south of the LeRPFZ with noticeably differing characteristics, being both largely untouched by tectonic activities along this major fault zone, represent basically independent fault settings. The faults adjacent to the LeRPFZ, however, seem to be more or less affected by tectonic movements along this major deformation zone. Variations and trends traced in the fault patterns/characteristics in the closest vicinity along the LeRPFZ point towards rapidly changing stress conditions. The similar distribution of the dislocation rate alongside the patterns, magnitudes and trends of the faults predicts that the LeRPFZ has played an essential role in distributing and releasing the far-field stresses in the NW EEP interior. Hence, as a major intracratonic basement flaw, the LeRPFZ separates the more intensely deformed southern BS from the less deformed platform area north of it. The stresses induced at the EEC margin(s) and spread across its interior were largely accommodated around the LeRPFZ, resulting in the formation of a complex and rapidly changing stress-field pattern, where faults with different styles, often with oblique kinematics, developed.

**Indications of strike slip movements along the LeRPFZ**

A qualitative kinematic study to obtain explicit strike slip evidence along a fault zone requires a good exposure of its faults. Only this makes it possible to outline the general fault pattern and assess the visible kinematic markers (e.g. slip lineations, offset markers, mesoscopic folds, *en echelon* veins) produced by horizontal block displacements with sufficient credibility and detail (Christie-Blick & Biddle 1985; Marshak et al. 2003).

Still, in spite of the lack of outcrops and the ambiguities in interpretations of faults, the generalizing description above reveals numerous circumstantial signs suggesting that the strike slip component has had an important role in the evolution of the LeRPFZ. This is first of all expressed in its highly varying and complex fault pattern, where numerous subvertical master faults with locally curved traces and different kinematics, intervening relay zones and rapidly changing offsets include locally parallel branches and are accompanied by numerous splay/subsidiary faults and folds. An impression of a braided fault pattern, often created by neighbouring bifurcating and merging curvy faults with a significant strike slip component (van der Pluijm & Marshak 2003), can be tentatively discerned around the overlapping sections of the strongly curving Liepaja–Saldus, Dobele–Babite and Olaine–Inčukalna master faults (Figs 2, 9A, B). Highly complex and rapidly changing relief with alternating positive and negative forms, typical for extensive fault zones with a significant horizontal component (Sylvester 1988; Cunningham & Mann 2007), emerges unambiguously on top of the crystalline basement around the LeRPFZ (Figs 2, 9A, B).

Highly complex fault patterns with varying style and kinematics usually arise due to transpressive/transtensive segments developing around curvy sections of sinuous strike slip faults (Cunningham & Mann 2007). The best proofs for similar sections with partitioned block movements are the flower structures revealed by seismic studies in the area offshore Liepaja and onshore near to the VLU (Brangulis & Kanev 2002, figs 10, 12, 14; Šliaupa et al. 2006, fig. 7; Šliaupiene & Šliaupa 2012, figs 15, 16; Figs 3, 9B). It is notable that the upwards-splaying flower structures at the LeRPFZ normally arise around bends in larger faults with a significant BCA.

The most diverse and complicated fault patterns with varying stress fields and kinematics along the LeRPFZ are visibly congregating near to its two most striking bends: (1) around the western VLU, at the stepover of the Olaine–Inčukalna and Smiltene–Ape faults and (2) around the offshore area of Liepaja (Figs 3, 9A, B). Notably, both of the mentioned areas emerge near to significant basement elevations (VLU and Liepaja–Talsi

Height) around the western sections of the two largest LeRPFZ faults with the highest known offsets (Smiltene–Ape and Liepaja–Saldus). Furthermore, both areas reveal sets of the NE- to N-trending faults with signs of reverse kinematics that traverse the main northeasterly course of the LeRPFZ.

The changes in the fault pattern/kinematics west-southwest of the VLU are likely due to the amounting transpression around the stepover of the bending Olaine–Inčukalna and Smiltene–Ape master faults (Figs 2, 9B). As a result, a set of the NE- to N-trending subsidiary/splay faults sharply traversing the main LeRPFZ course, with signs of an *en echelon* setting and reverse kinematics, settled around the western VLU. Their radially branching map view around the Valmiera Uplift (Figs 2, 9B) may exhibit an upwards-splaying flower structure. In all, at this complex stepover with signs of transpressional tectonics, the NE- to SE-curving easternmost section of the Olaine–Inčukalna reverse fault transfers to the NE- to E-trending Smiltene–Ape normal fault with the heavily uplifted northern block that makes up the VLU. A structural pattern like this predicts that a steadily rising transpression/compression, inducing reverse kinematics with oblique block movements, was developing around the remarkable bend of the Olaine–Inčukalna fault. The majority of this stress was obviously accommodated as the VLU block northeast of this bend (Fig. 9B) was pushed upwards. At the same time, tensional stress was developing south of the VLU, causing basement down-faulting along the Smiltene–Ape fault.

Evidence of stress field alteration also arises around another significant LeRPFZ bend in the area offshore Liepaja (Figs 2, 3, 9A), where a highly complex fault pattern with signs of transpression and reverse faulting congregates around the Liepaja–Kuldiga–Talsi Height. This basement elevation, which is about 20 km wide and >100 km long, branching from the LeRPFZ and bounded by major faults, protrudes deeply into the Latvian mainland (Fig. 2). A set of normal faults running parallel to this basement elevation and traversing the main course of the LeRPFZ at an angle of ~30–40° appears to show that an extension was dominating on the Kurzeme Peninsula southeast of this height. Still, further south, rare signs of possible shear stress with strike slip appear along the Liepaja–Saldus master fault.

Although distinguishing the Riedel shears and their sinistral/dextral nature would be quite speculative at the LeRPFZ, due to the poor and controversial dataset, similar branches of splay faults propagating a short distance out from larger master/subsidiary faults do occasionally arise along the LeRPFZ. The best possible example for this are a few short successive splays, trending at an angle of about 20° from the southern side of the Liepaja–Saldus fault, which may be interpreted as an *en echelon* array of Riedel shears induced by sinistral strike slip (Fig. 9A).

## Tectonic activities along the LeRPFZ, the Baltic Syneclise and the sedimentary basins in the NW EEC interior

Considering the tectonic setting argued above (Fig. 1) and the significance of the LeRPFZ in releasing the stresses induced at the EEC margins, the role of this major fault zone in the development of the platform cover in the NW EEP has so far been underestimated and insufficiently dealt with. Indeed, its central position in distributing and accommodating the far-field stresses alongside the striking intensity rate with overwhelming magnitudes of faulting suggests that the LeRPFZ must have had a significant impact on shaping the BS and the early Palaeozoic sedimentary basins around it.

The well-established stratigraphic subdivision of the Ediacaran–Devonian strata has promoted detailed thickness (with accuracy <1 m) and lithology analysis of the platform cover in numerous drillings around the mainland section of the LeRPFZ (Misans & Brangulis 1979; Brangulis & Brio 1981; Brio et al. 1981; Grigelis 1981; Polivko 1981; Ulst & Yakovleva 1981; Ulst et al. 1982; Brangulis 1985). In this sense, its most elevated and best explored VLU segment has provided highly valuable information (Tuuling & Vaher 2018). These analyses showed that basement faulting at the LeRPFZ has had a long and complex history, where tectonic activation pulses alternating with quieter or inactive periods can be distinguished since the latest Neoproterozoic (Ediacaran). Furthermore, these pulses can vary considerably even between closely spaced LeRPFZ sections.

## The Ediacaran–earliest Palaeozoic activity of the LeRPFZ

Although a sharp change in Moho depth (Ankudinov et al. 1994; Fig. 8) may predict an early cratonic origin of the LeRPFZ (Šliaupa & Hoth 2011), its Pre-Ediacaran background remains largely unclear. Based on elongated gravity and magnetic anomalies often dividing different types of basement rocks, somge larger faults or their sections around the VLU (e.g. Olaine–Inčukalna, Smiltene–Ape, Valmiera, Burtnieki, Birinu–Puikule) are supposedly formed prior to the overlying platform cover (Misans & Brangulis 1979; Brangulis 1985, fig. 1; Figs 2, 9A, B). Thus, the firm signs of the LeRPFZ activities appear first in the Ediacaran strata mapped at the eastern VLU and in western Latvia. However, already in the Cambrian layers, occasional traces of tectonic activities appear all along the LeRPFZ onshore track (Brangulis & Brio 1981; Tuuling & Vaher 2018).

On a wider scale, the LeRPFZ reveals no explicit control over the distribution of the Ediacaran–Cambrian sedimentary basins that flooded the NW EEC sporadically from various directions (see the palaeogeographic/isopach maps in Hagenfeldt 1989; Nikishin et al. 1996; Mens & Pirrus 1997; Modliński et al.1999; Šliaupa et al. 2006; Nielsen & Schovsbo 2011). This appears also on the thickness map of the Cambrian sequence in Latvia (Brangulis 1985, fig. 8), where isopachs crossing the LeRPFZ approximately orthogonally refute the presence of a regional-scale depocentre clinging to this major fault zone. Their vigorous undulation across western Latvia, however, reflects obviously locally restricted differentiated fault movements around the Liepaja–Saldus section of the LeRPFZ.

It is hard to pinpoint a specific pervasive event boosting the Ediacaran–Cambrian tectonic activity in this remote EEC interior area. Considering the plate tectonic reconstructions, we have to bear in mind that the present-day orientation of Baltica was gained only with its late Cambrian–Middle Ordovician anti-clockwise (120°) rotation (Torsvik & Cocks 2013). Thus, in the earliest Palaeozoic, the present NW EEC margin was not facing the opening Iapetus Ocean with tensions between the diverging Baltica and Laurentia continents (see fig. 2 in Cocks & Torsvik 2006). Still, the restricted patch of the early Ediacaran Zura Formation in western Latvia can reflect failed rifting with an extensional regime that seems to have reigned around the NW EEC margin in latest Neoproterozoic–earliest Palaeozoic time (Poprawa et al. 1999; Cocks & Torsvik 2005; Šliaupa & Hoth 2011). Moreover, it is difficult to assess the possible role of the Timanide Orogeny, which evolved in the Ediacaran–early Cambrian at the NE margin of the EEC (Gee & Pease 2004; Gee et al. 2008; Pease et al. 2008), in activating the LeRPFZ. Warping an extensive Ediacaran–early Cambrian basinal depression across the NE EEC, this orogeny, evidently rearranging the structural setting and shaping a widespread lower Cambrian unconformity >1000 km away in the Baltic region (Grigelis 1981), could easily also reactivate the LeRPFZ (Tuuling & Vaher 2018).

## Tectonic activities of the LeRPFZ during Ordovician–Silurian time

In general, compared to the latest Silurian to earliest Devonian climax of the Caledonian Orogeny, most of Ordovician–Silurian time in the NW EEC interior, particularly farther north of the LeRPFZ, is considered to be a tectonically relatively stable period with no significant faulting activities (Šliaupa & Hoth 2011; Tuuling 2017). A detailed thickness/lithology analysis of the platform cover at the VLU and around some BCAs (e.g. Aizpute in Fig. 9A) shows, however, that fault activities along the LeRPFZ are already evident in Early Ordovician Tremadocian–Floian time (Brio et al. 1981; Tuuling & Vaher 2018). Yet, around the VLU, this activation is followed by a post-Floian (Billingen)[1] interval of quiescence that may be due to the later erosion of the overlying Ordovician–Silurian units (Fig. 10), confined only until mid-Darriwilian (Aseri) time (Tuuling & Vaher 2018). At the same time, several BCAs with a more complete Ordovician–Silurian sequence southwest of the VLU (e.g. Inčukalna, Dobele, Aizpute and Kuldiga; Fig. 9A, B) reveal LeRPFZ sections that have been tectonically activated at times since the Middle Ordovician (Brio et al. 1981, table 1). Thus, it cannot be excluded that the VLU, as the most elevated LeRPFZ segment, may also have been active during the post mid-Darriwilian Ordovician–Silurian period prior to its major uplift at the prime of the Caledonian Orogeny. Signs of the Late Ordovician faulting with an amplitude of a few dozens of metres also appear in seismic recordings from offshore Lithuania and Latvia (Šliaupa & Hoth 2011), whereas the latter faults near to the LeRPFZ show reverse kinematics (Kanev & Peregudov 2000).

## The LeRPFZ and the Baltic Ordovician–Silurian Basin with the deep-basinal Livonian Tongue

The most solid evidence of lasting Ordovician–Silurian tectonic activities around the LeRPFZ is imprinted into the evolution of the sedimentary basin, which started to evolve across its NW margin with the inundation of the EEC by the Iapetus Ocean. Indeed, bathymetric changes with adjustments in facies zonation and thickness distribution/trends in the Baltic Ordovician–Silurian Basin (Männil 1966; Kaljo 1970, 1977; Jaanusson 1973, 1976; Grigelis 1981; Ulst et al. 1982; Bassett et al. 1989; Einasto 1995; Nestor & Einasto 1997; Paškevičius 1997; Modliński et al. 1999) confirm that the LeRPFZ has had a key role in shaping the large northeasterly elongated Baltic Depression sub-basin in the NW EEC interior. This is best expressed in a tongue-shaped protrusion of the Central Baltoscandian facies belt, clinging to the LeRPFZ and stretching from Sweden across Latvia deeply into the remote EEC interior (Figs 3, 11–13). This clay-rich, at times red-coloured deep-basinal ‘protuberance’, normally with Ordovician–Silurian units two to five times thicker than their nearshore calcareous equivalents (Einasto 1995), confined between the Estonian and Lithuanian shallow-marine facies (Fig. 13), was called the Livonian Tongue by Jaanusson (1973, 1976).

[1] Here and henceforth the corresponding Ordovician–Silurian age/stage name for the Baltic Basin is given in brackets.

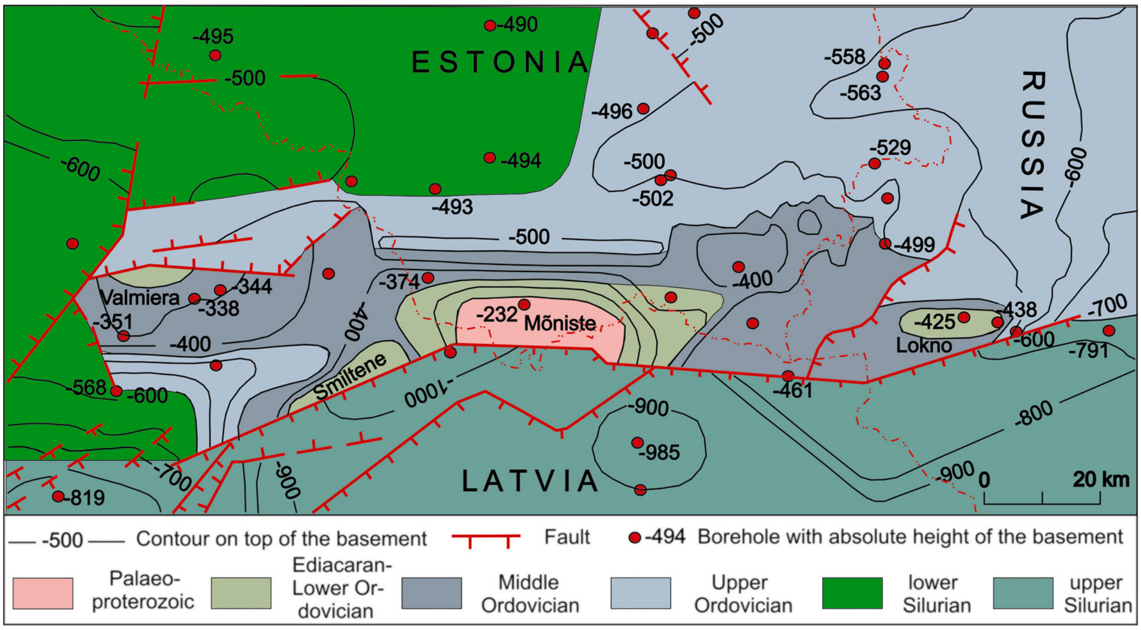


**Fig. 10.** Subcrop map revealing erosional inlier below the lowermost Devonian unconformity on the uplifted VLU area plotted against the structure contours on top of the crystalline basement (after Tuuling & Vaher 2018).

A restricted depocentre, embryo of the Livonian Tongue, emerges first around the Liepaja–Saldus and Dobele–Babite faults at about the Tremadocian–Floian transition (Hunneberg time) (Männil 1966, fig. 48; Fig. 11). This depocentre, called the Jelgava Depression, was widening along the LeRPFZ both towards the NE and SW in the following Floian (Billingen) time, as the Livonian Tongue with deep-basinal reddish limy muds elongated further EEC interior beyond the Smiltene–Ape fault by the end of Dapingian (Volkhov) time (Männil 1966, fig. 51; Ulst et al. 1982, fig. 10v; Fig. 11).

Since its outlining in the late Early Ordovician the extent and lithological contrast of the Livonian Tongue oscillates clearly along the LeRPFZ, as well as with respect to the Estonian and Lithuanian facies belts (Männil 1966; Kaljo & Jürgenson 1977; Ulst et al. 1982; Bassett et al. 1989; Nestor & Einasto 1997). These fluctuations depend largely on regional transgressive–regressive cycles and differentiated tectonic movements around the LeRPFZ, which are both controlled chiefly by the ongoing Caledonian Orogeny at the nearby NW EEC margins. Individual fault movements are imprinted into locally varying thicknesses of different Ordovician–Silurian units. Larger-scale epeirogenetic rising/subsiding tendencies with the LeRPFZ tectonics are determining the sites/relocations of evolving depressions with thickness distribution/trends and readjustments in facies zonation in the Baltic Ordovician–Silurian Basin (Fig. 12). A gradual demise of the Livonian Tongue alongside the regional uplift of the NW EEC interior with a widespread southwesterly regression of the Baltic Basin towards the closure of the Silurian reflects obviously onset of the final phase of the progressing Caledonian Orogeny. The orogenic compression generated by the mid-Silurian Baltica–Laurentia collision affected most notably the LeRPFZ, causing the fault blocks of this basement flaw move upwards. Thus, the evolvement of the Livonian Tongue largely reflects the accommodation history of the Ordovician–Silurian far-field stresses around the LeRPFZ.

## The Ordovician–Silurian plate tectonic framework around the NW EEC margins, the LeRPFZ and development of the Baltic Basin

Since the EEC interior is considered as a tectonically inactive area, due to a thick and in the Palaeoproterozoic consolidated crystalline basement, the possible role of the far-field stresses in shaping the Baltic Ordovician–Silurian Basin has so far been largely neglected. However, studies in the Midcontinent of North America (van der Pluijm et al. 1997) revealed that orogenic compression at craton margins can create sufficient differential stress (of the order of ~20 MPa) for faulting activities at distances >2000 km inside the cratons. Furthermore, the cratonic interior stress state appears to be independent from the detailed nature of the plate activity and orogenic architecture at the compressional plate margins, indicating

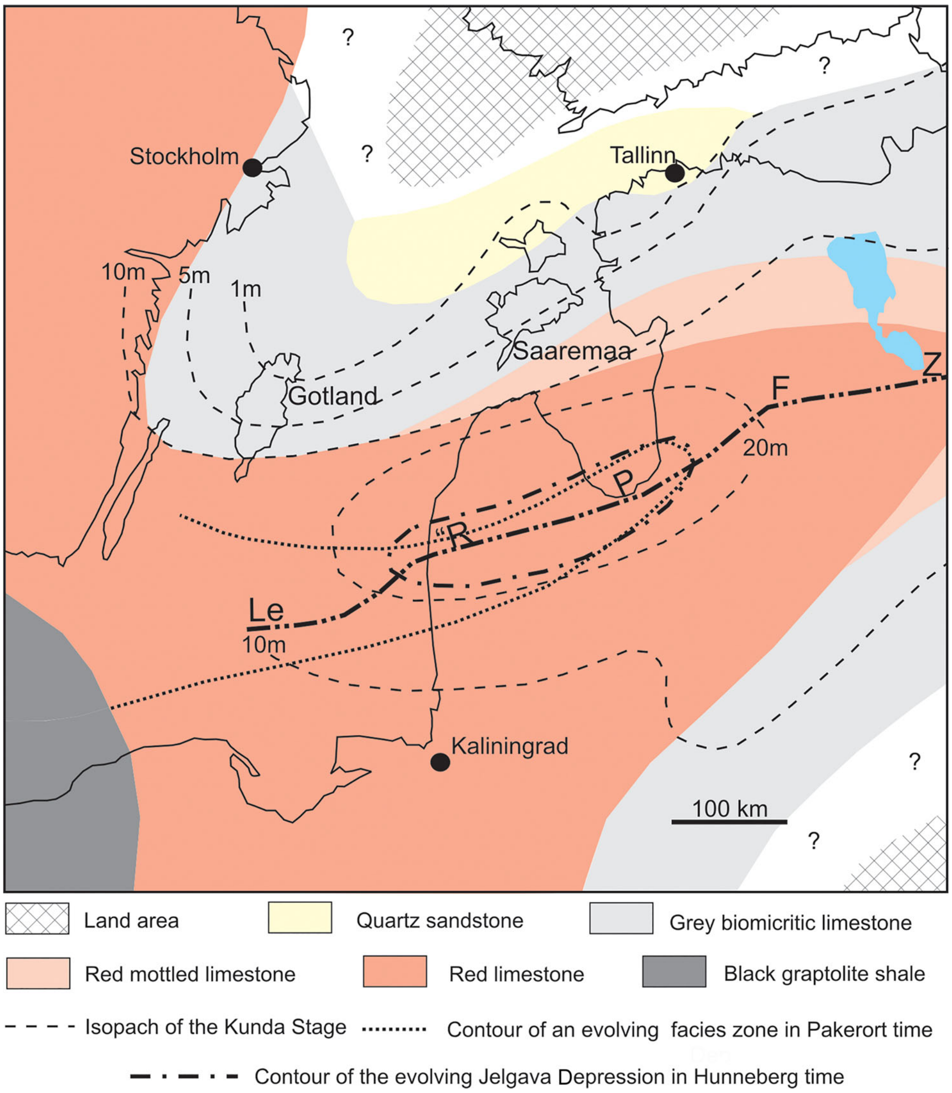


**Fig. 11.** Sketch of the Baltic Basin facies/thickness distribution with the Livonian Tongue in early Darriwilian (Kunda) time (modified after Männil 1966).

that tectonic properties like obliquity of convergence, slab dip and lateral extent of colliding elements may not be reflected in plate interior stresses. The compressive palaeostress inside the cratons is largely perpendicular to the orogenic front and reactivation of a 'weak' fault zone there depends mainly on its orientation and distance relative to the compressional plate margin.

### The Ordovician–Silurian plate tectonic framework around the NW EEC

The Baltic Ordovician–Silurian basin is sometimes, based on the Avalonia–Baltica collision, treated as a typical foreland basin bent by orogenic load on a craton margin (Poprawa et al. 1999; Lazauskiene et al. 2002, 2003; Mazur et al. 2018; Fig. 14). However, these discussions admit also that this conception, being fully valid for the SE–NW elongated Peri-Tornquist Silurian basin along the NW EEC margin, is hardly applicable to the SW–NE elongated intracratonic Baltic Depression sub-basin (Fig. 14). Indeed, besides the insufficient overthrust load and negation of the foreland basin traverse to the craton margin anatomy (Lazauskiene et al. 2002), this protrusion of the Baltic Basin elongating deeply into the EEC interior started to contour around the LeRPFZ already in the Early Ordovician, that is, long before the Baltica–Avalonia collision at about the Ordovician–Silurian boundary. Thus, regarding the origin and development of the Baltic Depression sub-basin with the Livonian Tongue clinging around the LeRPFZ,

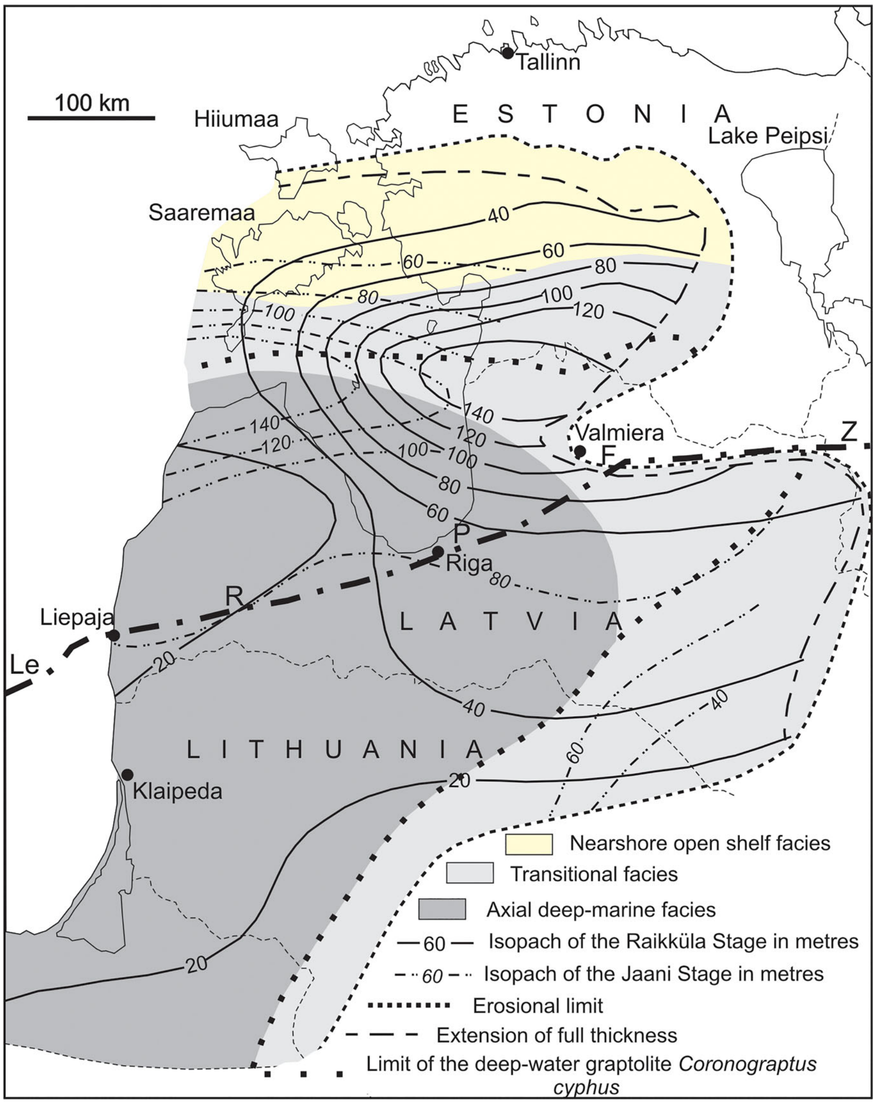


**Fig. 12.** The Baltic Basin facies/thickness distribution with the Livonian Tongue in Aeronian (Raikküla) time and locations of the early Silurian Raikküla and Jaani depressions on the Scandinavian side of the LeRPFZ (modified after Kaljo & Jürgenson 1977).

the NW EEC plate tectonic history with probable intracratonic stresses has to be analysed already since the earliest Ordovician.

Based on the palaeomagnetic and biostratigraphical data, the basics of the latest Neoproterozoic–early Palaeozoic drift of Baltica and its interaction with other large terrains are well documented (Torsvik & Rehnström 2003; Cocks & Torsvik 2005, 2006; Torsvik et al. 2012; Torsvik & Cocks 2013). The Late Neoproterozoic–early Palaeozoic reign in the extensional tectonics around the westerly margins of Baltica evidently changed in the earliest Ordovician when the widening of the Iapetus Ocean ceased and subductions began near to Laurentia in the west and Avalonia (that was then splitting from Gondwana) in the southwest (Torsvik & Cocks 2013; Fig. 13). Instead, with the shrinking of the Tornquist and Iapetus oceans, a compressional setting started to progress as Avalonia and Laurentia gradually neared Baltica, which was speedily rotating 120° anti-clockwise in Late Cambrian–Early Ordovician time. Thus, the Ordovician–Silurian stress field in the NW EEC interior was largely shaped by the interaction of Baltica with two large continents, Avalonia and Laurentia, which drifted towards the EEC and collided successively with it, respectively, towards the close of the Ordovician and mid-Silurian periods (Torsvik & Rehnström 2003; Cocks & Torsvik 2006; Torsvik & Cocks 2013; Fig. 13).

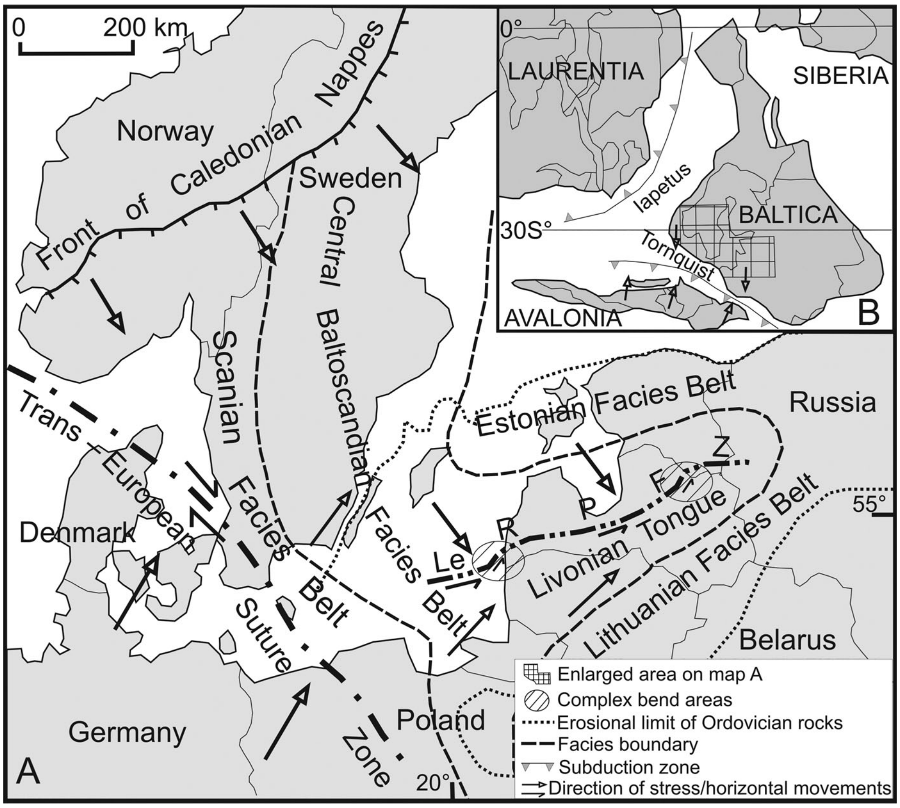


**Fig. 13.** (**A**) General facies zonation with the Livonian Tongue of the Baltoscandian (Ordovician) Basin (modified after Kaljo et al. 2007) with (**B**) Late Ordovician (Katian, at 450 Ma) plate tectonic relations of the Baltica–Avalonia–Laurentia continents (modified after Torsvik & Cocks 2013) and suggested directions of palaeostresses with horizontal fault movements.

Besides different timings, these collisions also had different styles, trends/angles and distances with respect to the LeRPFZ. Thus, before the mid-Silurian nearly frontal Laurentia–Baltica collision in the northwest, an oblique convergence with a relatively soft Avalonia–Baltica docking took place around the Ordovician–Silurian boundary in the southwest (Torsvik & Rehnström 2003; Torsvik & Cocks 2013). As a result, the present collision lines along the Scandinavian and North German–Polish Caledonides, located, respectively, about 800 and 200–250 km from the nearest LeRPFZ section, have correspondingly about the same and oblique trends relative to the course of the LeRPFZ (Fig. 13). Due to the rotation of Baltica, the positions of Avalonia and Laurentia were evidently different with respect to the present collision lines, and thus the LeRPFZ at the beginning of the Ordovician.

**Expected Ordovician–Silurian stress field(s) around the LeRPFZ and development of the Baltic Basin**

According to the convergence/collision record of Baltica, Avalonia and Laurentia, the NW EEC interior stress field, and thus the evolvement of the Baltic Basin in relation to the LeRPFZ tectonics was, until the earliest Silurian, mainly driven by Avalonia–Baltica interaction. Hence, northerly drifting Avalonia, nearing Baltica from the SW, shaped the NE stress in the EEC interior (Fig. 13), which likely already became oriented at an acute angle with respect to the LeRPFZ faults towards the end of the Early Ordovician, despite the continuing rotation of Baltica. This, however, led to a high transpressional shear stress along the LeRPFZ, forcing southeastern blocks in this fault zone to slip obliquely towards the NE at times. As the Baltica–Avalonia convergence was progressing throughout the Ordovician, the odds of the high shear stress with oblique NE faulting along the LeRPFZ continued to grow towards the Silurian.

Although the Avalonia–Baltica collision also proceeded supporting the oblique NE faulting along the LeRPFZ in the Silurian, the Ordovician stress pattern became increasingly reshaped and complicated by two concurrent tectonic events. The first was the ongoing Laurentia–Baltica convergence and collision in the mid-Silurian (Torsvik & Cocks 2013), which led to

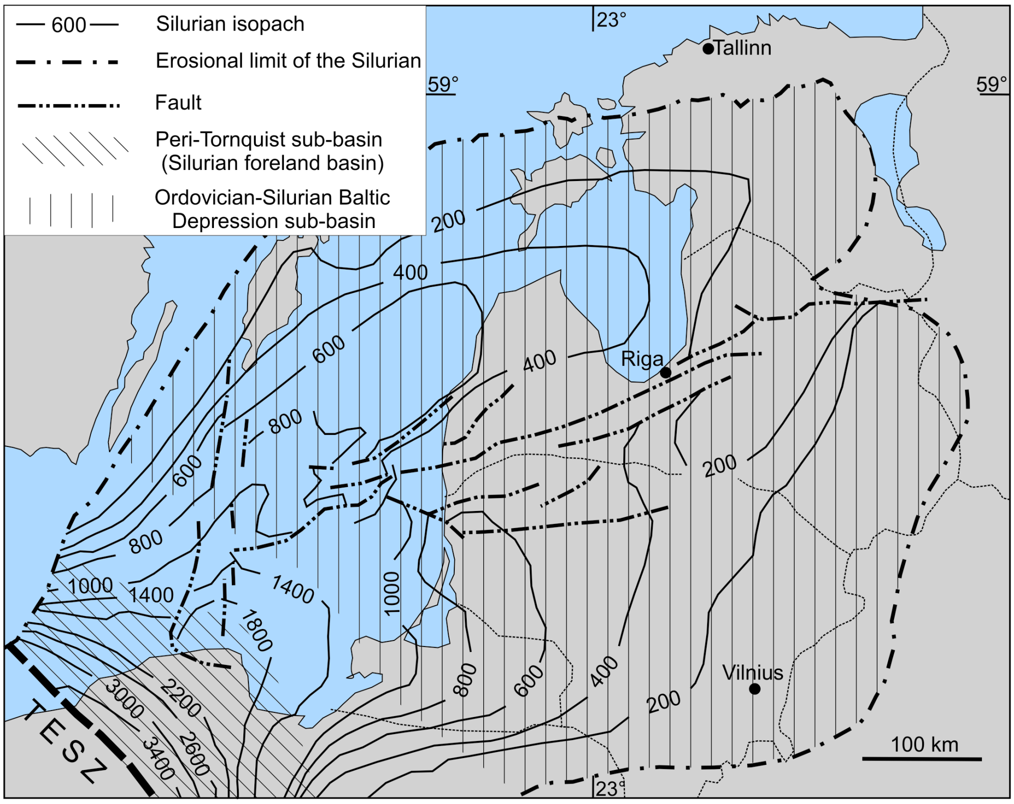


**Fig. 14.** Silurian isopach map of the Baltic Basin reflecting the formation/location of the narrow SE–NW-trending Silurian foreland basin along the Trans-European Suture Zone (TESZ) abutting the NW EEC margin (Peri-Tornquist sub-basin) and the cratonic interior Baltic Depression sub-basin that already started to evolve around the LeRPFZ in the Early Ordovician (modified after Lazauskiene et al. 2002).

the formation of the Scandinavian Caledonides by the Devonian northwest of the LeRPFZ. This collision induced evidently compressive SE stress relative to the NE-trending LeRPFZ (Fig. 13). The latter compression, being opposed to or mingled with NE stress induced by the Avalonia collision, was gradually growing in accordance with the progressing Laurentia–Baltica convergence/collision and probably reached its peak at the prime of the Caledonian Orogeny. Another process influencing the stress field with the faulting regime and general dynamics around the LeRPFZ was obviously the overthrusting of Avalonia onto Baltica, which resulted in extensive flexural bending and formation of the foreland basin along the EEC margin abutting the TESZ (Fig. 14). The impact of this flexuring was increasing through most of the Silurian in accordance with the growing orogenic burden and subsidence of the EEC margin. A clear acceleration in subsidence with the thickening of Silurian units abruptly towards the foreland basin and the regressing Baltic Basin became particularly distinctive from Wenlock–lower Ludlow time (Lazauskiene et al. 2003; Fig. 14).

## Tectonic inversion of the LeRPFZ

Based on the NW EEC interior stress field modifications, induced by the Avalonia–Baltica–Laurentia Ordovician–Silurian interaction/collision record, two major phases in the tectonic regime can be distinguished in the development of the LeRPFZ. Thus, before the amalgamated Avalonia–Baltica collided in the mid-Silurian with Laurentia, the LeRPFZ acted largely as a subsidence centre of the Baltic Syneclise, that is, was an axial area of a large NW EEC interior depocentre. Being most clearly expressed in the formation of the Livonian Tongue, this period became towards the Silurian growingly influenced by differentiated tectonic movements driven by intensifying Baltica–Laurentia interaction. That led to the formation of a row of early Silurian depressions with a gentle slope dividing the deep and shallow basinal/facies areas on the northern, that is, on the Scandinavian side of the LeRPFZ (Kaljo 1971; Kaljo & Jürgenson 1977; Nestor & Einasto 1997; Fig. 12).

The second period, driven growingly by the progressing Laurentia–Baltica collision induced compression from the NW, is characterized by a regional uplift of the EEC interior LeRPFZ area with the gradually SW regressing Baltic Silurian Basin. Hence, along with substantial rearrangements in the regional structural setting, the LeRPFZ with adjacent areas dwindled gradually acting as a cratonic interior subsidence centre and underwent inversion in the tectonic regime. Instead, the former axial area of the Livonian Tongue around the LeRPFZ emerged by the earliest Devonian as the most notably raised and intensively eroded zone of the NW EEC interior (Fig. 15). On its most elevated VLU section, where the platform cover has been entirely removed from the Mõniste Uplift, the estimated amount of missing early Palaeozoic rocks exceeds 500 m (Tuuling & Vaher 2018; Figs 10, 15).

**Possible signs of earthquakes**

The facts/knowledge listed below, achieved throughout the years in studying the Baltic Basin, point towards Ordovician–Silurian tectonic activities in the NW EEC interior: (1) an approximately metre-thick sandstone–siltstone lobe with a classical Bouma division of the turbidite sequence, occurring in the earliest Dapingian (Volkhov) argillaceous limestone facies on the slope of the Jelgava Depression (Põldsaar et al. 2019); (2) the enigmatic early Darriwilian (Kunda) sedimentary dikes in NW Estonia, formed in a polygonal set of fissures (Puura & Tuuling 1988; Põldsaar & Ainsaar 2014); (3) extensive hiatuses and sets of erosional channels, in many occasions evidently submarine (deep-basinal) origin, discovered in Estonia, on Gotland, as well as below the central Baltic Sea in the mid-Katian pre-Vormsi layers, at about the Ordovician–Silurian and the Silurian Aeronian–Telychian (Raikküla–Adavere) boundaries (Martinsson 1968; Grahn 1982, 1995; Nõlvak 1987; Ainsaar 1995; Perens 1995; Nestor & Einasto 1997; Tuuling & Flodén 2000, fig. 1, 2007, 2009a, 2009b, 2011; Grahn & Nõlvak 2010); (4) severe bedding distortions with enigmatically chaotic fold-like structures, revealed in the late Katian (Pirgu) layers in many places by seismic studies NE of Gotland (Tuuling & Flodén 2000, fig. 12).

It has been pondered in many occasions that the above-listed features might have been induced by earthquakes. The most plausible earthquake triggering event in this remote NW EEC interior area is usually thought to be meteoritic impacts rather than faulting activities. However, intense (strike-slip) faulting along the LeRPFZ evidently triggered at times strong earthquakes that likely became imprinted into the sedimentary sequence of the Baltic Ordovician–Silurian Basin.

## CONCLUSIONS

The structural/tectonic setting of the Leba Ridge–Riga–Pskov Fault Zone (LeRPFZ), the highly complex pattern

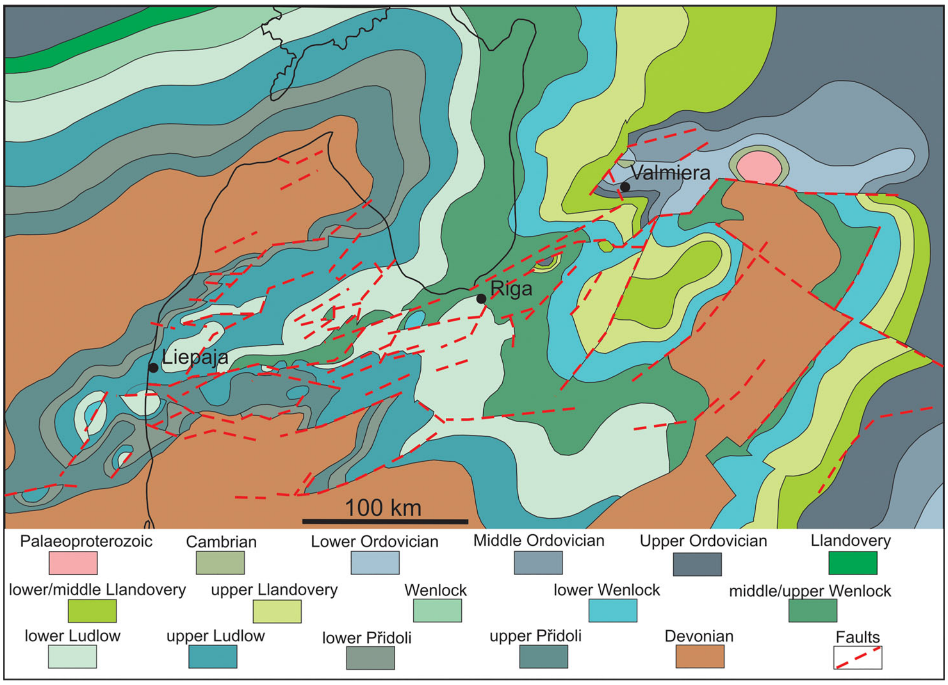


**Fig. 15.** Subcrop map revealing the extent of erosion below the lowermost Devonian unconformity around the LeRPFZ onshore section (modified after Polivko 1981).

of its faults having varying styles and magnitudes which are exceptionally high for this region, as well as tectonic activity pulses of the LeRPFZ, in the light of the general early Palaeozoic plate tectonic history of the NW EEC with the development of the Baltic Ordovician–Silurian Basin, allow the following conclusions to be drawn:

1. The LeRPFZ, as a unique, regional-scale tectonic dislocation zone in the NW EEC interior that has obviously played a vital role in the formation and deformation of the platform cover in the Baltic region, has so far remained outside any serious attention and debates in the geological literature.
2. As a major Pre-Ediacaran fault zone of the NW EEC interior, the LeRPFZ has, through early Palaeozoic convergence/collisions of the Baltica–Avalonia–Laurentia continents, recurrently acted as a primary basement flaw accommodating a large amount of the stresses induced at the EEC margin(s) by the interaction of these continents.
3. Considering the general faulting density/intensity, as well as the trends, styles and magnitudes of faults across the NW EEC, the LeRPFZ, as an accumulating/releasing centre of the cratonic interior far-field stresses with a highly complex and rapidly varying pattern (styles/trends) of faulting, acted as a tectonic hinge-line dividing the NW East European Platform into two independent halves, namely the less intensely deformed NW (Latvian–Estonian–Swedish) half and the more intensely deformed SE (Latvian–Lithuanian–Polish) half.
4. The complex geometry/pattern of the LeRPFZ faults with varying styles points towards a rapidly changing stress field evidently induced by a substantial horizontal faulting component along this major fault zone. The most complex areas with signs of reverse faulting, the highest magnitudes and heavily elevated basement blocks/heights congregate around two remarkable LeRPFZ bends around Liepaja with the Kurzeme Peninsula (at the Liepaja–Saldus fault with the Liepaja–Kuldiga–Talsi Height) and around the western VLU (at the stepover of the winding Olaine–Inčukalna and Smiltene–Ape faults).
5. Besides circumstantial strike-slip evidence, the best proof of significant transpressional tectonics with high shear stress and oblique (sinistral) faulting along the LeRPFZ is the flower structures revealed by seismic studies around this major fault zone, mostly around its two striking bend areas.
6. According to the plate tectonic record(s), transpression with NE shear stress and oblique faulting along the LeRPFZ, induced by the convergence and collision of Avalonia with Baltica, increasingly dominated in the Ordovician, causing the creation/development of the SW–NE elongated Baltic Depression sub-basin with the Livonian Tongue around this fault zone of the NW EEC interior.
7. The influence of the SE stress in the NW EEC interior and thus compression around the LeRPFZ, which was induced by the convergence and collision of Laurentia with Baltica, emerged increasingly towards the closure of the Ordovician, leading to the formation of a steeper basinal slope and depression(s) on the Scandinavian (NW) side of the LeRPFZ in the Silurian. The SE compression and NE transpression, being concurrently applied on the NW and SE sides, respectively, of differently trending LeRPFZ faults, created a highly complex and rapidly changing stress field with a varying style of faulting along this major fault zone.
8. The progressing convergence of Laurentia and Baltica and their collision in the mid-Silurian, along with the concurrent overthrust of Avalonia onto Baltica, led to a regional uplift of the NW EEC interior areas around the LeRPFZ and the formation of the foreland basin (Peri-Tornquist sub-basin) along its subsiding margin. Opposing tectonic movements, causing the Baltic Silurian Basin to regress southwestwards, exposed large areas of the NW EEC interior to erosion as the foreland basin started to fill up rapidly with sediments derived from the adjacent orogenic belts and uplifted cratonic interior areas.
9. As a result of the complex and changing stress field pattern induced by Avalonia–Baltica–Laurentia interactions, the LeRPFZ, as the most tectonically mobile zone in the NW EEC interior, underwent a clear inversion in tectonic regime during the Ordovician–Silurian period. Thus, acting largely as a subsiding depocentre during Ordovician–early Silurian time, the LeRPFZ became, due to the progressing Laurentia–Baltica convergence and final collision in the mid-Silurian, the most intensively rising and eroded area in the NW EEC interior towards the culminating Caledonian Orogeny around the Silurian–Devonian boundary.
10. As a basement block pushed fiercely upwards, with its southern flank plummeting >700 m to the Latvian Saddle along the Smiltene–Ape fault, the VLU represents the easternmost and most dislocated/uplifted segment of the LeRPFZ with an exceptional E–W trend. Thus, following the largest LeRPFZ bend at the overlapping winding sections of the major Olaine–Inčukalna (reverse) and Smiltene–Ape (normal) faults, which is surrounded by a very complex pattern of subsidiary/splay faults with varying trends, signs of reverse faulting and occasional flower structures, the VLU was forming in highly complex/varying stress conditions with a high transpression and shear stress component.

11. Intense LeRPFZ faulting in the early Palaeozoic evidently triggered earthquakes of high magnitude in the cratonic interior, many of which likely became imprinted into the sedimentary record of the Baltic Ordovician–Silurian Basin. Thus, the above-described and so far unexplained evidences, as well as unambiguous or enigmatic evidences discovered in the feature that distort, dissect or channel/erode the normal horizontal bedding structure in the Ordovician–Silurian rocks of the NW EEC interior, could also be analysed from the point of view of possible faulting activities induced earthquakes.
12. To resolve contradictory views on the nature and fault characteristics of the LeRPFZ, further investigations are needed to detail/reassess the pattern, style and kinematics of its faults taking the substantial strike-slip component of this major NW EEC interior fault zone into account.

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# Ida-Euroopa Kraatoni sisene Łeba Kerke-Liepāja-Riia-Pihkva murranguvöönd ja selle tähtsus Balti regiooni varapaleosoilise platvormse pealiskorra kujunemisel

Igor Tuuling

Ligi pool sajandit on teada ulatuslik Liepāja-Riia-Pihkva murrangute vöönd, mis hilisemate mereuuringute põhjal ulatub ilmselt Läänemere lõunaosas asuva Łeba Kerkeni (LeRPFZ). Ida-Euroopa Platvormi mõõduka tektoonilise rikutuse foonil tuleb kraatonisisene LeRPFZ esile oma väga tiheda ja keerulise pea- ja kõrval- ning harumurrangute võrgu ja murrangute erakordse suure amplituudiga. Kui üldiselt küünib murrangute amplituud kraatoni sisemuses LeRPFZ-ist põhja ja lõunasse jääval alal harva, vastavalt kuni 50 ja >200 meetrini, siis LeRPFZ-i peamurrangutes ületab see paaris kohas >600 m. Siiani puudub ühtne arusaam LeRPFZ-i moodustavate murrangute tüüpidest (normaal- või kerkemurrang) ja sellest tulenevalt valitseb ebaselgus ka murranguid tekitanud tektooniliste sündmuste ning kraatonisiseste pingete osas. LeRPFZ-i murrangutevõrgu komplitseeritus ja eri tüüpide varieeruvus viitab muutlikule pingeväljale, mis on iseloomulik murranguvöönditele, kus on oluline horisontaal- ehk nihkepinge komponent, mille tähtsust Balti regiooni murrangutüüpide hindamisel on ilmselt alahinnatud. Ulatusliku nihkepinge parimaks tõendiks on arvukad, seismilistel profiilidel tuvastatud nn lilleõielaadsed struktuurid (*flower structures*).

LeRPFZ, mis selge tektoonilise telgjoonena jaotab Balti Sünekliisi tektooniliselt vähem rikutud põhja- ja enam rikutud lõunaosaks, poolitab ka Balti Ordoviitsiumi-Siluri Basseini, õigemini selle keelelaadse süvafatsiaalse vööndi (Liivi Keele), mis ulatub Rootsis üle Läänemere keskosa ning Läti kaugele kraatoni sisemusse. Kõrvutades Liivi Keele arengutendentse Baltica paleokontinendi triivi ja selle lääne- ning edelaserval aset leidnud Kaledoonia Orogeneesi sündmustega, tuleb LeRPFZ-i tektoonikas selgelt esile kaks etappi. Ordoviitsiumis ja Siluri algul, mil Avaloonia paleokontinent lähenes lõunaedelast Balticale ning põrkus viimasega Ordoviitsiumi ja Siluri vahetusel, tekitas see piki LeRPFZ-i suure, kirdesse suunatud nihkepinge komponendi. Koos LeRPFZ-i (lõunapoolsete) murrangplokkide nihkumisega kirdesse toimus ka basseini keskosa sügavnemine ja Liivi Keele migreerumine kraatoni sisemusse. Ordoviitsiumi lõpul hakkab üha enam ilmnema lääne ja loode poolt lähtuva Laurentia paleokontinendi Baltica-suunalise triivi mõju, mis Siluri keskel päädis nende kontinentide põrkumisega. See tõi kaasa Ida-Euroopa Kraatoni loodeosa üldise kerkimise ja Balti Basseini järkjärgulise taandumise edelasse. Progresseeruva survepinge tingimustes kerkis enim kraatonisisene, murrangutest enim lõhestatud ja seega ka “nõrgim” ning mobiilseim LeRPFZ, kus kraatoni äärealadel tekitatud pinged kergitasid üksikuid kristalse aluskorra plokke sadu meetreid. Kaledoonia Orogeneesi kulmineerudes kujunes Siluri ja Devoni vahetusel Ida-Euroopa Platvormi sisemuses LeRPFZ-i ümbruses enim kerkinud vöönd, kust suur osa varapaleosoilisi setteid enne järgnevat Devoni transgressiooni ära kulutati.