The role of the Leba Ridge–Riga–Pskov Fault Zone in the tectonic evolution of the deep-facies Livonian Tongue within the Baltic Ordovician–Silurian sedimentary basin: a review

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Abstract. Located in the interior of the East European Craton (EEC), the Baltic Ordovician–Silurian Basin hosts an elongated tongue-like deep-marine depression, the Livonian Tongue (LT), which extends from Sweden across Latvia and separates the Estonian and Lithuanian shallow-marine shelves. The tectonic origin of the LT has been suggested already since its discovery in the early 1960s. However, the nature of tectonic forces and mechanisms behind the evolution of this narrow intracratonic subsidence zone in the Ordovician–Silurian of the Baltic Basin has remained poorly understood. The origin of the LT can be related to an extensive intracratonic dislocation zone known as the Leba Ridge–Riga–Pskov Fault Zone (LeRPFZ) that coincides largely with the axis of the LT. The LeRPFZ reveals some heavily uplifted basement blocks and has, therefore, been considered as an up-warped anticline-type structure. Recent studies show that the LT has developed in highly complex and changing stress field conditions during the Caledonian orogeny. The subsidence and widening phase of the LT in the Ordovician and early Silurian coincides with, and was possibly governed by, the Avalonia collision with Baltica from the SW when high shear stress forced LeRPFZ blocks to move obliquely towards the NE. As Laurentia was approaching Baltica and finally collided with it in the mid-Silurian, the shear stress became progressively mingled with compression from the NW and the subsidence of the LeRPFZ became reversed, triggering LT withdrawal to the SW. Thus, being once the deep-water centre of the Baltic Ordovician–Silurian Basin, the LT became the most uplifted and intensely eroded EEC interior zone by the Devonian.

Key words: Baltic Ordovician–Silurian Basin, Livonian Tongue, Caledonian orogeny, Leba Ridge–Riga–Pskov Fault Zone.

INTRODUCTION

A map with stratigraphically equivalent early Palaeozoic units extending from Estonia to Sweden was sketched already in the late 19th century (Schmidt 1891). However, the outlines of a unique Ordovician–Silurian sedimentary basin started to emerge only with the onset of extensive drillings in the 1950s (see Tuuling & Flodén 2009a, 2009b, 2011). These studies revealed an embayment reaching deeply into the East European Craton (EEC) interior, filled with deep- and shallow-marine facies deposits of Ordovician–Silurian age in the pericratonic Scandinavian–Poland and the intracratonic East Baltic area, respectively (Männil 1966; Kaljo 1970, 1977; Figs 1, 2).

Deep drill cores in Latvia and southeastern Estonia, made by the early 1960s, revealed that the reddish Scandinavian-type deep-water Ordovician limestone units described on the Swedish island of Öland bulge in a tongue-shaped manner into the NW EEC interior (Figs 1, 2). This deep-facies 'protuberance' divides the Estonian and Lithuanian shallow-marine shelves. Männil (1966) first described this zone as 'the Swedish–Latvian facies zone'. After the publications by Jaanusson (1973, 1976), the area became widely known as 'the Livonian Tongue' (LT). Further studies showed that the clay-rich carbonate sedimentation in the LT area extended across Latvia for most of Ordovician–Silurian time (Kaljo 1970, 1977; Kaljo & Jürgenson 1977; Bassett et al. 1989; Harris et al. 2004). Facies zones successively deepening towards the LT, with two to five times thicker (litho)stratigraphic units compared with the Estonian and Lithuanian shallow shelf equivalents, were established (Nestor & Einasto 1977; Einasto 1986, 1995). Based on that, basin dynamics with different development stages of the

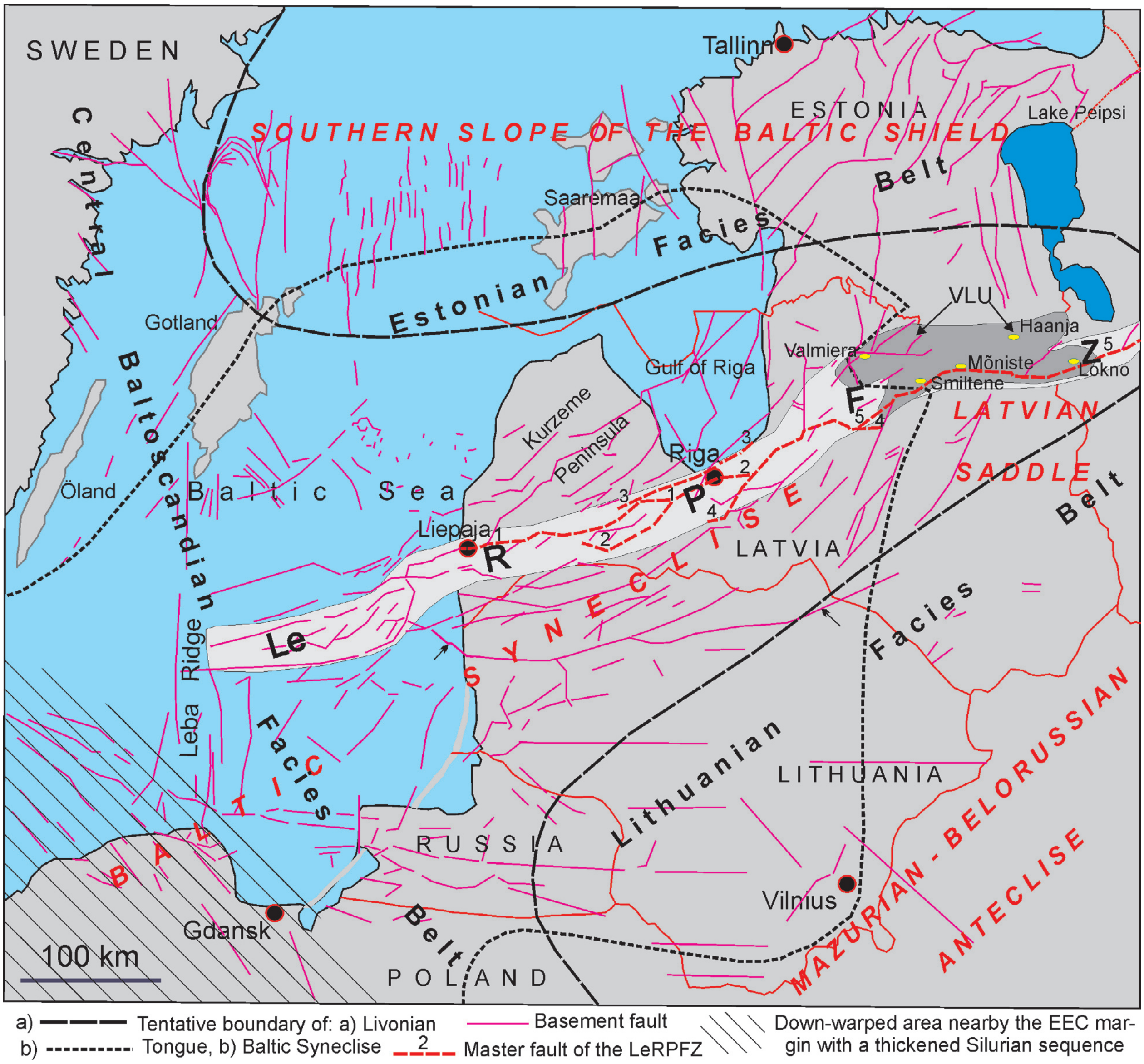

Fig. 1. Northwestern East European Craton with basement faults reflected in the overlying platform cover, major cratonic structures (red text), and facies zones with the northeasterly extending Livonian Tongue of the Baltic Ordovician Basin (modified after Kaljo et al. 2007). Numbered master faults of the Leba Ridge–Riga–Pskov Fault Zone (LeRPFZ): 1, Liepaja–Saldus; 2, Dobele–Babite; 3, Olaine–Inčukalna; 4, Sloka–Carnikava; 5, Smiltene–Ape. VLU, Valmiera–Lokno Uplift with basement cored anticlines (yellow ellipses).

Ordovician–Silurian Baltic Basin were described by Nestor & Einasto (1997).

The origin or possible tectonic context of the LT has not been discussed since Männil (1966). On the basis of the depth-derived facies and thickness changes in drill cores, Männil (1966) considered the LT as a central deep-sea zone of the Baltic Ordovician Basin, supposedly restricted by active fault zones. Although the presence of such fault zone(s) surrounding the LT has not been proven, the opinion that the deep-facies Livonian Tongue might be resting on a unique tectonically subsided basement block is still discussed (e.g. Einasto 1995). Meanwhile, a complex dislocation zone with high frequency, striking offsets and varying kinematics of faults was discovered, extending from the Latvian coastal city of Liepaja across Riga to the vicinity of Pskov in Russia (Afanasev & Volkolakov 1972; Afanasev et al. 1973). Later studies showed that this SW–NE-trending fault zone extends to offshore Liepaja (Volkolakov 1974) and probably reaches the Leba Ridge below the southern Baltic Sea (Puura et al.

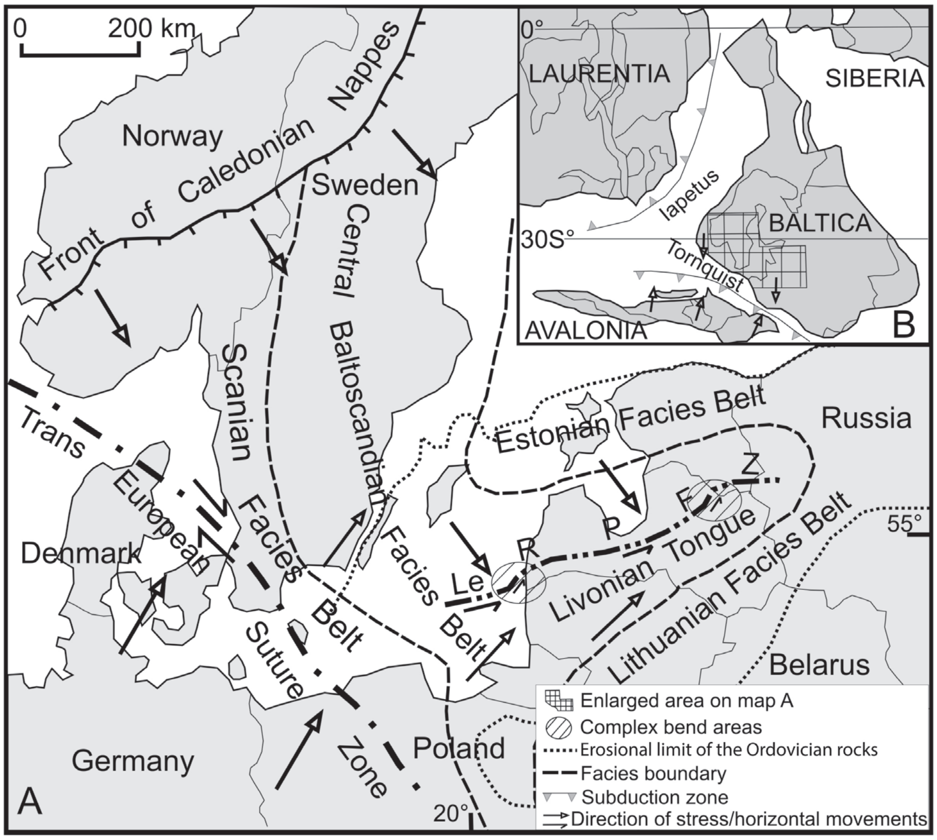

Fig. 2. A, general facies zonation indicating also the Livonian Tongue in the Ordovician Baltic Basin (modified after Kaljo et al. 2007); **B**, Late Ordovician (Katian, ~450 Ma) plate tectonic relations of the Baltica–Avalonia–Laurentia continents (modified after Torsvik & Cocks 2013) and suggested directions of palaeostresses with horizontal fault movements.

1991; Fig. 1). Also, series of heavily uplifted basement blocks (Paasikivi 1966; Volkolakov 1974), overlaid by the extensively eroded early Palaeozoic sequence (Polivko 1981; Tuuling & Vaher 2018), have been described in the onshore section of this fault zone. For the latter reason, this zone was for a long time regarded as an up-warped anticline-type of structure (Garetski et al. 1978). A possibility that there is a unique >700 km long fault zone extending from the Leba Ridge across Riga to Pskov, the Leba Ridge–Riga–Pskov Fault Zone (LeRPFZ), in the EEC interior that may have been acting as an early Palaeozoic subsidence centre in the axial area of the LT has not been discussed until recently (Tuuling 2019).

The general pattern, as well as the style and kinematics of the faults, suggests that the LeRPFZ has experienced greatly varying stress fields (Tuuling 2019). Furthermore, the LeRPFZ, which has been tectonically active throughout the early Palaeozoic, underwent inversion in the tectonic regime during the Ordovician–Silurian period due to the progression of the Caledonian orogeny (Tuuling 2019). Tuuling (2019) suggested that during the early stage of this orogeny (from the Ordovician to the mid-Silurian), governed by the progressing Avalonia convergence/collision with Baltica from the SW (Fig. 2), the LeRPFZ presumably experienced a high shear stress component that forced basement blocks to move along its NE–SW-trending faults horizontally/obliquely towards the NE. As a result, a subsidence centre, with the extending LT, started to develop along the LeRPFZ. This led to the formation of a large depression in the NW EEC, the Baltic Syneclise, which forms the hub of the Baltic Ordovician–Silurian Basin (Fig. 1; Tuuling 2019). During the late phases of the Caledonian orogeny (since the mid-Silurian), the tectonic regime of this region was governed by the Laurentia–Baltica collision and the LeRPFZ got progressively affected by compression from the NW (Fig. 2). Under the gradually modifying stress field, the LeRPFZ became the most uplifted and subsequently the most deeply eroded zone in the NW EEC interior towards the end of the Silurian.

This paper summarizes the evolution and demise of the LT as influenced by the development of the LeRPFZ. It is based on the analysis of the distribution of sedimentary facies during the Ordovician and Silurian.

THE OUTLINE OF THE CRATON BASEMENT IN THE BALTIC REGION

The basement of the EEC underlying the Baltic Ordovician–Silurian Basin is primarily composed of various assemblages of metamorphic rocks that formed during 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). Before the platform cover started to form in late Neoproterozoic Ediacaran time, the NW EEC was, along with several tectonic activation epochs, subject to intensive erosion and peneplanation (Puura et al. 1996). During these periods of tectonic activation, the cratonic basement was dissected by complex sets of faults which were complemented, in places, with the formation of new rock assemblages. Due to the post-orogenic thinning and rifting of the continental crust (Elo & Korja 1993; Puura & Flodén 1999), the Palaeoproterozoic metamorphic rocks were pierced by the ~1.67–1.46 Ga rapakivi intrusions (Laitakari et al. 1996; Puura & Flodén 1999; Kirs et al. 2009). Also, the Mesoproterozoic graben-like structures are filled by patches of 1.4–1.3 Ga post-rapakivi Jotnian sandstones and are cut by occasional post-Jotnian diabase-dikes. These are found near the rapakivi intrusions along the Gulf of Bothnia and at the present contact of the Baltic Shield and East European Platform (Flodén 1980; Winterhalter et al. 1981; Wannäs 1989; Söderberg 1993; Amantov et al. 1995). Towards the end of the peneplanation period, about 1140–900 Ma ago, the Baltoscandian region was tectonically affected by the multiphase Sveconorwegian orogeny when the EEC became incorporated into the Rodinia supercontinent (Bogdanova et al. 2008; Viola et al. 2011).

THE AGE OF THE LERPFZ AND ITS SIGNATURES IN THE EDIACARAN–CAMBRIAN SEQUENCE

In the Baltic region, the age estimates of the deeply buried basement faults, as well as reconstructions of their activity epochs, are largely based on the thickness analysis of the overlying platform cover. Therefore, because the sedimentary bedrock sequence in the area of the LeRPFZ starts with the late Ediacaran deposits, the pre-platform Proterozoic development of this major EEC interior fault zone remains largely unclear. However, there is some circumstantial evidence pointing towards the earlier Proterozoic origin of the LeRPFZ. A sharp change in Moho depth across its easternmost section with the Valmiera–Lokno Uplift (VLU) and the Smiltene–Ape master fault (Ankudinov et al. 1994; Fig. 1) hints at the early cratonic origin of the LeRPFZ (Šliaupa & Hoth 2011). The presence of the elongated gravity and magnetic anomalies which often divide different types of basement rocks shows that some larger faults, or their sections around the Valmiera–Lokno uplifted basement blocks (e.g. Olaine–Inčukalna, Smiltene–Ape, Valmiera, Burtnieki, Birinu–Puikule) were probably formed before the overlying platform cover (Misans & Brangulis 1979; Brangulis 1985). Also, the restricted occurrence of the late Ediacaran volcanoclastic/clastic Zūra strata (conglomerates, gravelstone, sandstones, siltstones and clays) near the LeRPFZ onshore and offshore western Latvia suggests that this fault zone may have been tectonically active already during the earliest stages of late Ediacaran time (Šliaupa & Hoth 2011; Lukševičs et al. 2012).

Thus, the first direct signs of faulting activity within the LeRPFZ can be tied to the late Ediacaran sequence that is distributed across this fault zone in the eastern part of the VLU and western Latvia. Already in the Cambrian layers, occasional traces of tectonic activity can be found all along the onshore section of the LeRPFZ (Brangulis & Brio 1981; Tuuling & Vaher 2018). However, these sporadic fault movements occurred in only restricted areas around the individual faults, whereas the activity pattern of even closely spaced faults can vary considerably. On a regional scale, however, the LeRPFZ reveals no explicit control over the distribution of the Ediacaran–Cambrian sediments in the NW EEC (see the palaeogeographic/isopach maps of Hagenfeldt 1989; Nikishin et al. 1996; Mens & Pirrus 1997; Paškevičius 1997; Modliński et al. 1999; Šliaupa et al. 2006; Nielsen & Schovsbo 2011). Also, the isopachs of the Cambrian strata in Latvia are crossing the LeRPFZ approximately orthogonally, refuting thus the presence of a regional-scale depocentre related to this major fault zone (Brangulis 1985). As there was no significant tectonic/orogenic activity at that time near the NW EEC margins, the Ediacaran–Cambrian structural rearrangement with early Cambrian regional unconformity and sporadically activated faults in the Baltic region were most likely induced by the far-field stresses of the Timanide orogeny occurring at the NE margin of the EEC (Gee & Pease 2004; Gee et al. 2008; Pease et al. 2008; Tuuling 2019).

THE ORDOVICIAN–SILURIAN TECTONIC ACTIVITY OF THE LERPFZ AND THE DEVELOPMENT OF THE LIVONIAN TONGUE

The Caledonian orogeny with intensive faulting activity reached its peak in the latest Silurian to the earliest Devonian period, while the NW EEC interior has been considered as a tectonically relatively stable basinal area with only rare fault movements for most of Ordovician–Silurian time (Šliaupa & Hoth 2011; Tuuling 2017).

A detailed thickness and lithology analysis of the platform cover shows, however, that the first block movements within the LeRPFZ appeared already in early Ordovician Tremadocian–Floian time, and signs of the locally restricted fault activity along this fault zone can be traced throughout the Ordovician–Silurian period (Brio et al. 1981; Tuuling & Vaher 2018; Tuuling 2019).

Concomitantly with the locally restricted fault movements, a larger regional-scale subsidence started to emerge around the LeRPFZ already in the earliest Ordovician. The subsiding area gradually widened and grew in length during the Ordovician, finally evolving into an elongated deep-marine facies zone, the LT. It protruded into the EEC interior and split the shallow-marine NE corner of the Baltic Basin into Estonian and Lithuanian shallow facies zones that existed throughout the following Ordovician–Silurian period (Figs 1, 2). The extent of the LT along the LeRPFZ, as well as its lithological contrast to the Estonian and Lithuanian facies belts, oscillated through most of the Ordovician–Silurian period (Männil 1966; Kaljo & Jürgenson 1977; Ulst et al. 1982; Bassett et al. 1989; Nestor & Einasto 1997). Fluctuations in sedimentation rates, reflected in changing lithologies and thicknesses, were largely dependent on regional transgressive–regressive cycles and differentiated tectonic movements within the LeRPFZ that were controlled by the progressing Baltica–Avalonia–Laurentia convergence/collision process at the nearby EEC margins.

Numerous earlier maps summarize the lithology, facies and thickness distribution of different Ordovician–Silurian units in the Baltic Basin (Männil 1966; Kaljo & Jürgenson 1977; Misans & Brangulis 1979; Ulst et al. 1982; Bassett et al. 1989; Nestor & Einasto 1997; Paškevičius 1997). The general structural setting of the Baltic Ordovician–Silurian basin with its facies distribution and thickness changes at different time intervals was largely outlined already in the first series of the palaeogeographic maps published for the Ordovician strata by Männil (1966) and the Silurian strata by Kaljo & Jürgenson (1977). Later studies (e.g. Nestor & Einasto 1997; Paškevičius 1997), although complementing the original dataset, enhanced only the details in different parts of the basin.

THE LIVONIAN TONGUE IN THE ORDOVICIAN

A series of lithofacies maps by Männil (1966) shows that the first signs of a faintly evolving depocentre around the LeRPFZ emerged SW of the Riga area already in the earliest Ordovician, in Tremadocian (Pakerort)[1] time (Fig. 3). At about the Tremadocian–Floian transition (Hunneberg time), a nucleus of the Jelgava Depression infilled with the reddish calcareous–argillaceous muds started to outline in western Latvia (Männil 1966; Ulst et al. 1982; Modliński et al. 1999; Fig. 3). The emergence of the latter depression around the major LeRPFZ faults (Liepaja–Saldus and Dobele–Babite in Fig. 1) can be considered as an embryonal stage of the LT. This depression was widening along the LeRPFZ towards both the NE and the SW in the following Floian (Billingen) time when the LT, marked with the deposition of deep-basinal reddish limy muds, shifted further towards the EEC interior beyond the Smiltene–Ape fault by the end of Dapingian (Volkhov) time (Männil 1966; Ulst et al. 1982; Figs 1, 4).

The deep facies depocentre with the thickest Ordovician units concentrating around the subsiding LeRPFZ area outlines in the lithofacies/isopach maps at the end of Darriwilian (Uhaku) time (Männil 1966). However, in Sandbian–earliest Katian (Kukruse–Keila) time, the area with the largest thicknesses starts to shift

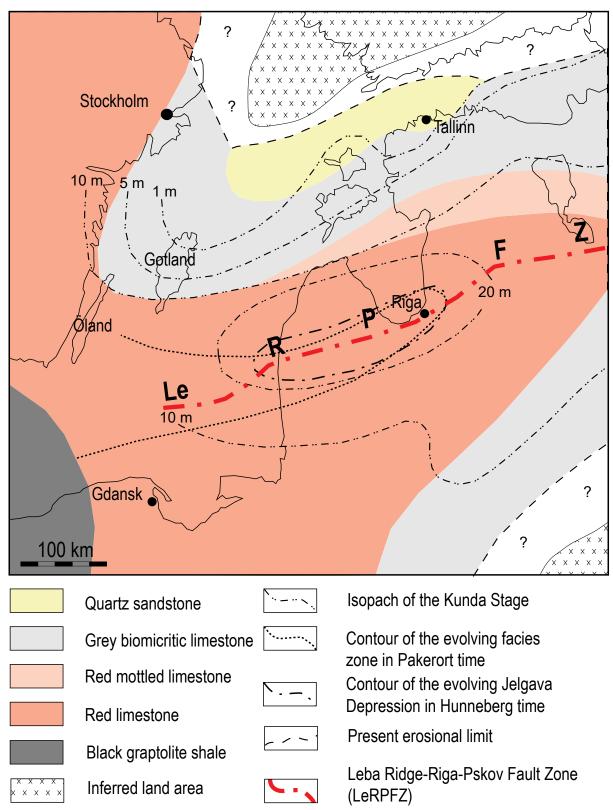

Fig. 3. Distribution and thicknesses of the facies of the Ordovician Darriwilian (Kunda) sediments within the Baltic Basin (modified after Männil 1966), the location of the LeRPFZ and the contours of the earliest Ordovician Livonian Tongue and Jelgava Depression during the Tremadocian (Pakerort) and at about the Tremadocian–Floian (Hunneberg) transition, respectively.

[1] Here and henceforth the corresponding O/S regional stage name for the Baltic Basin is given in brackets.

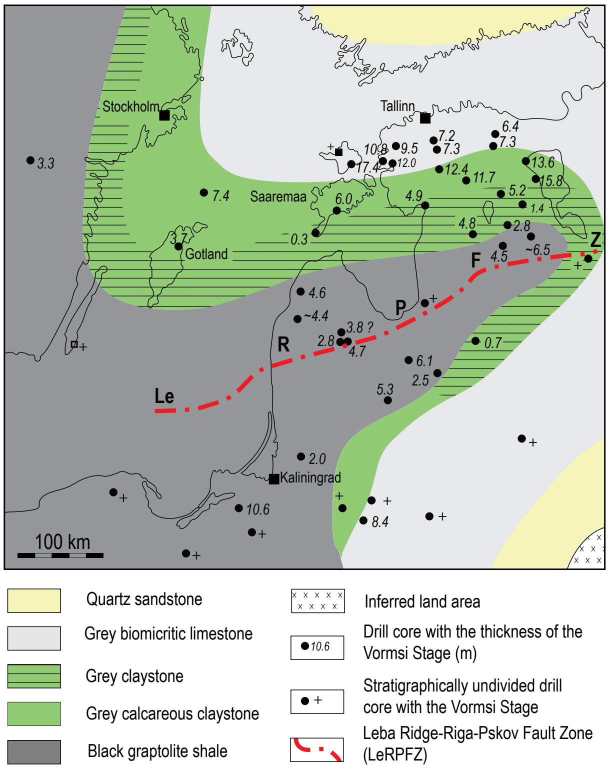

Fig. 4. Sketch of the facies and thickness distribution of the Baltic Basin with the evolving Livonian Tongue around the LeRPFZ in late Katian (Vormsi) time (modified after Männil 1966).

from the LeRPFZ area towards the margins of the Ordovician Baltic Basin. This might point to nearshore sediment progradation in the starving sedimentary basin. Alternatively, it reflects the onset of differentiated tectonic movements with bathymetric rearrangements that led to the formation of a gradually steepening basinal slope towards the Silurian (Nestor & Einasto 1997). A similar thickness distribution is evident, in most part, for the Late Ordovician (Männil 1966; Fig. 4). Exceptional reactivation of the LeRPFZ with the re-emergence of the Jelgava Depression and rejuvenation of the deposition of red-coloured sediments in the LT extending beyond the Smiltene–Ape fault occurred at the end of Katian (Pirgu) time (Männil 1966; Ulst et al. 1982).

LIVONIAN TONGUE AT THE ORDOVICIAN–SILURIAN TRANSITION AND IN THE SILURIAN

Due to extensive erosion the Ordovician–Silurian boundary layers in the Baltic region show widespread inconsistency in stratigraphic completeness and thicknesses that even reach deeper sections of the basin. Thus, two major hiatuses with varying periods and lateral extents are known from the Ordovician–Silurian boundary sequence (from the latest Katian (Pirgu) to the earliest Telychian (Adavere) layers) in the Baltic countries (Kaljo et al. 1988, 2004, 2008; Kaljo & Hints 1996; Nestor & Einasto 1997; Paškevičius 1997; Loydell et al. 1998, 2003, 2010; Lukševičs et al. 2012; Männik 2014; Meidla et al. 2014), below the Central Baltic Sea (Tuuling & Flodén 2000, 2007, 2009a, 2009b) and on Gotland (Martinsson 1968; Grahn 1982, 1995; Grahn & Nõlvak 2010).

Assessing the role of tectonic upheaval in the erosion/non-sedimentation of the late Ordovician layers in the Baltic Basin is problematic because of the abrupt sea-level fall due to the global Hirnantian glaciation (Kaljo et al. 1988, 1991; Nestor & Einasto 1997; Brenchley et al. 2003). However, considering the concurrently progressing Caledonian orogeny with collision(s) at the nearby EEC margins, it is likely that the cratonic interior around the LeRPFZ was also affected by tectonic movements. Nevertheless, towards the LT, a deepening sedimentary environment with the input of the nearshore sandy material (Ainsaar 1995; Nestor & Einasto 1997) suggests that the facies zonation in the Baltic Basin was still largely controlled by the LeRPFZ during the extensive mainland erosion in the latest Ordovician (Fig. 5).

Progressing differentiated movements in the LeRPFZ in the early Silurian led to the formation of the South Estonian depression just WNW of the VLU and to the formation of another extensive hiatus at the end of Aeronian (Raikküla) time. This evolving depression, filled with abnormally thick deposits belonging to the Raikküla Stage (Kaljo & Jürgenson 1977), marks a remarkable rearrangement in the general thickness trends and sediment distribution in the Baltic Silurian Basin at the Estonian–Latvian borderland (Fig. 6). However, when the stratigraphic gap of the latest Ordovician period grew, as expected, towards the margins of the Baltic Basin, the hiatus at the Aeronian–Telychian boundary (Raikküla–Adavere stages) persisted between Central Estonia and the LeRPFZ, denoting the transition between the shallow and deep basin areas. Thus, from the Estonian mainland, across the West Estonian islands, and towards the Central Baltic Sea, the Aeronian–Telychian boundary hiatus was not shaped by extensive regression-initiated subaerial erosion but was possibly controlled by tectonic movements within the LeRPFZ. A similar trend is also ascertained in the high-resolution seismic profiles in the Central Baltic Sea, where, towards Gotland, the deepening erosional surface at the boundary of the Adavere and Raikküla regional stages occasionally intervenes even with the latest Ordovician erosional surface (Tuuling & Flodén 2007, 2009a). Hence, as suggested by Tuuling & Flodén (2009a), the Aeronian–Telychian boundary hiatus

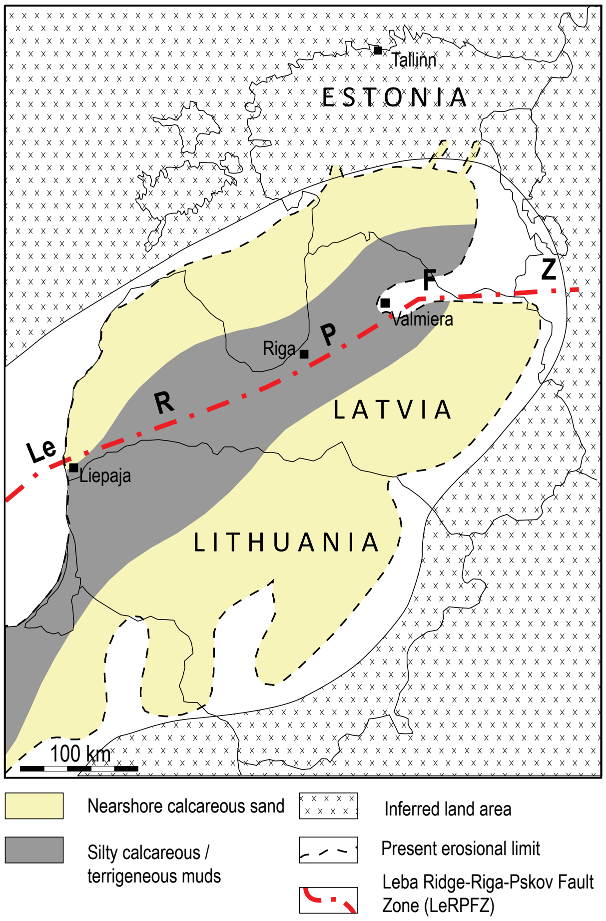

Fig. 5. The facies distribution of the Baltic Basin with the Livonian Tongue around the LeRPFZ during late Hirnantian (Porkuni) time (modified after Nestor & Einasto 1997).

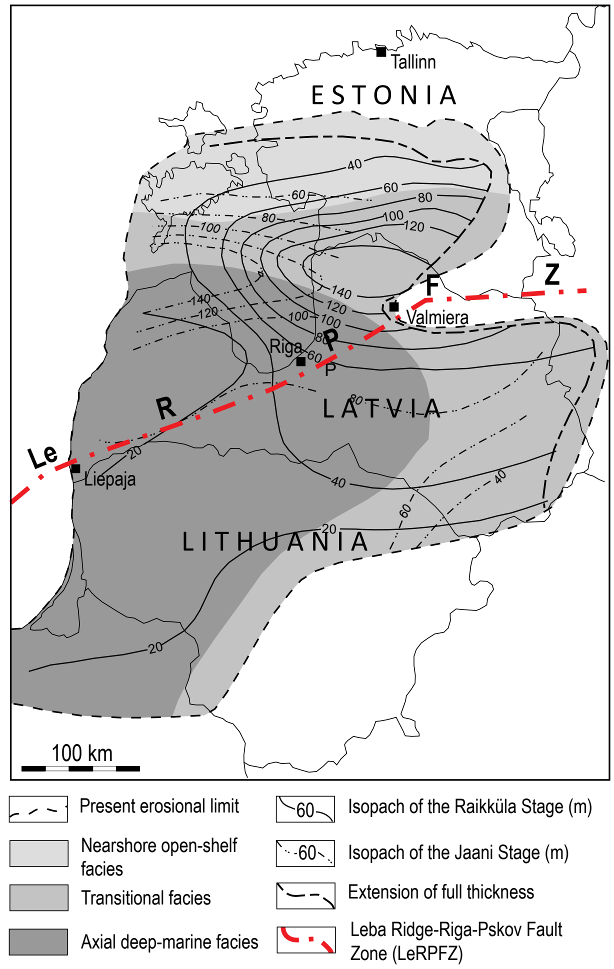

Fig. 6. The facies/thickness distribution of the Baltic Basin with the Livonian Tongue around the LeRPFZ in Aeronian (Raikküla) time and locations of the early Silurian Raikküla and Jaani time depressions on the Scandinavian side of the LeRPFZ (modified after Kaljo & Jürgenson 1977).

developed in the progressing, tectonically unstable basin slope area that was prone to extensive submarine ramp slides and erosion or even non-deposition.

The next tectonic activity pulse with an extensive transgression and major bathymetric rearrangements north of the LeRPFZ arose at the Telychian–Sheinwoodian transition, when a narrow E–W-elongated depression with thickening sediments of the Jaani Regional Stage evolved in the area of the northern Kurzeme Peninsula (Kaljo & Jürgenson 1977; Fig. 6). Considering the northerly extent of clayey deep-water facies in Estonia, the later transgression inundated most of the LeRPFZ last time (Nestor & Einasto 1997). Due to the intensifying uplift of the southern slope of the Baltic Shield along with the significant subsidence of the EEC margin bordering the Trans European Suture Zone (TESZ) (Lazauskiene et al. 2003; Figs 1, 2), the southwesterly regression of the Baltic Silurian Basin became increasingly dominant. As a result, compared to Aeronian (Raikküla) time, a depression near the northern flank of the LeRPFZ with the LT was shifting further WSW in Telychian (Jaani) time (Fig. 6).

The LT, with a depression located on the northern flank of the LeRPFZ in the area of the present-day Kurzeme Peninsula in western Latvia, can still be followed in mid-Homerian (Jaagarahu) time (Kaljo & Jürgenson 1977). However, the outlines of the LT further towards the end of the Silurian, and the role of the LeRPFZ in its development, are difficult to recognize because of the lack of data. The uplifted areas around the LeRPFZ in southeastern Estonia and Latvia became increasingly exposed to erosion and the Baltic Silurian Basin regressing towards the SW shifted largely to the area presently covered with the Baltic Sea, which is very poorly drilled and studied (Kaljo & Jürgenson 1977; Kleesment et al. 1980; Nestor & Einasto 1997). Hence, a large amount of the uppermost Silurian layers was removed later by erosion from the areas surrounding the eastern segment of the LeRPFZ or, alternatively, was never deposited at the most elevated sections of this major fault zone (Misans & Brangulis 1979). Furthermore, starting from Gorstian (Paadla) time, the facies zones in the Baltic Basin attained a trend which is increasingly sub-longitudinal, that is, traversing the LeRPFZ (Kaljo & Jürgenson 1977; Nestor & Einasto 1997; Fig. 7). Hence, along with the substantial rearrangements in the regional structural setting, the LeRPFZ with adjacent areas gradually lost its role as a cratonic interior subsidence centre and underwent inversion in the tectonic regime. Instead, the former axial area of the LT along the LeRPFZ emerged by the earliest Devonian as the most notably raised and intensively eroded zone in the NW EEC interior. 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; Fig. 1).

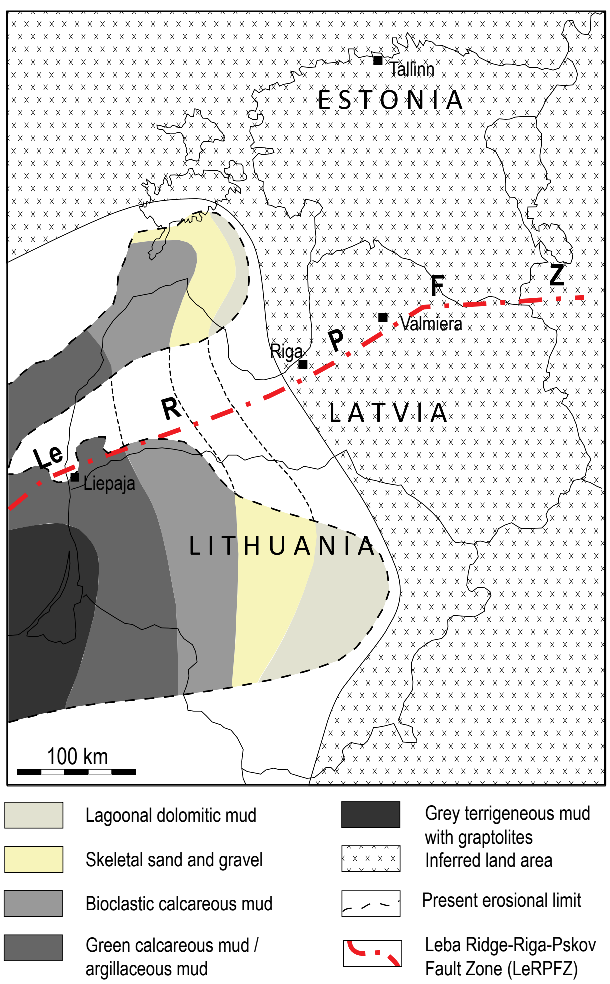

Fig. 7. The facies distribution of the Baltic Basin with the Livonian Tongue around the LeRPFZ in earliest Přidoli (Kaugatuma) time (modified after Nestor & Einasto 1997).

INDICATION OF FAULTING ACTIVITIES IMPRINTED IN THE ORDOVICIAN–SILURIAN SEQUENCE OF THE BALTIC BASIN

Given that the evolvement of the deep-facies LT was induced by the LeRPFZ tectonics with significant strike-slip movements, we may also expect signs of possible earthquake indications imprinted into the Ordovician–Silurian sedimentary succession of the Baltic Basin. Indeed, the Ordovician–Silurian succession reveals a number of signs of possible earthquake activities: (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) a vast area with sediment liquefaction structures accompanied locally by polygonal set(s) of sedimentary dikes (up to 1 m in width) and breccias within the calcareous sandstones – sandy limestones of the Darriwilian (Kunda) successions in NW Estonia (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, 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).

CONCLUSIONS

We conclude that the LeRPFZ started to act as a regional-scale intracratonic dislocation zone with the onset of the Caledonian orogeny. Its development has largely determined the structural setting and formation of the platform cover during the Ordovician–Silurian period in the large areas of the NW EEC extending from the intracratonic East Baltic countries to the pericratonic Scandinavian–Poland region.

Being induced by the Caledonian orogeny far-field stresses, the LeRPFZ shaped the outlines of a vast NW EEC depression, the Baltic Syneclise, which became submerged and to a great extent filled with the sediments of the Baltic Ordovician–Silurian Basin. The SW–NE-oriented and >700 km long LeRPFZ that developed at about the right angle with respect to the Trans European Suture Zone marks the axis of the Baltic Syneclise.

Regional subsiding/rising trends along the LeRPFZ directly controlled the depth and facies distribution with the thicknesses of the accumulating sediments in the Baltic Ordovician–Silurian Basin inundating the Baltic Syneclise. This structural setting with the LeRPFZ activities is best reflected in the emergence and development of the deep-facies filled depression (LT) that extended deeply into the NW EEC interior and divided the Estonian and Lithuanian shallow marine shelves of the Baltic Basin through most of the Ordovician–Silurian period.

The development of the LeRPFZ was governed by the progressing Baltica–Avalonia–Laurentia collision. The complex pattern, varying kinematics and striking offsets of the LeRPFZ faults reveal highly complex and changing stress field conditions in the NW EEC during the Ordovician–Silurian period. Besides determining the outlines of the regional tectonic setting, the changes in the stress field controlled chiefly also the development of the Baltic Ordovician–Silurian Basin with the deep-facies LT.

In the Ordovician–early Silurian, when Avalonia was nearing/colliding with Baltica from the southwest, the LeRPFZ expressed a high shear stress component with significant horizontal/oblique faulting towards the NE (Fig. 2). This facilitated subsidence around the LeRPFZ with the emergence and development/widening of the deep-facies LT.

When Laurentia was nearing Baltica at a right angle from the NW towards the end of the Ordovician and finally collided with it in the mid-Silurian, the LeRPFZ tectonics became increasingly affected by the compression from the northwest. As a result, the subsidence around the LeRPFZ became gradually inverted to elevation and the Baltic Silurian Basin with the LT started to retreat from the East Baltic region towards the NW EEC margin in the southwest.

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Łeba Kerke-Liepāja-Riia-Pihkva murranguvööndi tektoonikast tulenev süvafatsiaalse Liivi Keele teke ja areng Ordoviitsiumi-Siluri Balti basseinis: ülevaade

Igor Tuuling ja Kairi Põldsaar

Eelmise sajandi kuuekümnendate aastate algul avastati, et Rootsis Ölandi saarel esinev punavärviliste Ordoviitsiumi kivimite leviala jätkub keelelaadse vööndina teisel pool Läänemerd, ulatudes üle Läti Kagu-Eestisse. Seda Eestis ja Leedus esinevate rannalähedaste faatsieste vahele kiildunud süvaveelisema päritoluga Ordoviitsiumi-Siluri kivimite vööndit tuntakse tänapäeva geoloogilises kirjanduses Liivi Keelena. Ehkki sellise kaugele Ida-Euroopa kraatoni sisemusse välja sopistuva fatsiaalse vööndi tektooniline päritolu oli aimatav, puudusid tänini detailsemad käsitlused selle struktuuri arengust. Selle üheks põhjuseks võib olla fakt, et Liivi Keele keskossa jäävast murranguvööndist on

teada rida sadu meetreid üles kergitatud kristalse aluskorra plokke, mistõttu seda vööndit käsitleti pigem vajumist ja süvaveelisust välistava antiklinaalset tüüpi struktuurina. Läänemere lõunaossa jäävast Łeba Kerkest üle Liepāja, Riia ja kuni Pihkvani ulatuva murranguvööndi (LeRPFZ) detailsem analüüs (Tuuling 2019) näitas, et selle murrangute keeruline “muster” ja sagedasti vahelduv kineetiline taust tuleneb ennekõike muutlikust ning vahelduvast pingeväljast, mille üheks põhjuseks on ilmselt plokkide horisontaalsuunalist liikumist soodustav suur nihkepinge komponent. LeRPFZ ja sellest tulenevalt Liivi Keele areng on otseselt seotud Ordoviitsiumis-Siluris Baltika kontinendi loodeosa äärealadel aset leidnud Kaledoonia orogeneesiga. Selle esmases faasis Ordoviitsiumis-Vara-Siluris, mida dikteeris Avaloonia kontinendi lähenemine/põrkumine Baltikaga edelast, valitsesid LeRPFZ-i piires nihkepinged ja selle murranguplokkide nihkumisel kirdesse toimus murrangvööndit ümbritseva ala vajumine, Liivi Keele teke ning laienemine. Kaledoonia orogeneesi teises faasis, kui Ida-Euroopa kraatoni loodeosa pingeväljas hakkas üha enam dikteerima Baltikale loodest lähenev Laurentia ja nende kontinentide põrkumine Kesk-Siluris, asendus vajumine LeRPFZ-i ümbruses aegamisi kerkimisega. Murranguvööndi, selle üksikute plokkide kerkimine tõi kaasa Liivi Keele järkjärgulise taandumise edelasse ja Devoni alguseks oli suur osa kunagisest Eesti ning Läti territooriumile ulatuvast süvaveelisest Liivi Keelest muutunud kontinentaalseks kulutusalaks.