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Is the Proterozoic Ladoga Rift (SE Baltic Shield) a rift?

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ABSTRACT

The southern part of the Baltic Shield hosts a series of mafic dykes and sills of Mesoproterozoic ages, including a ca. 1.53–1.46 Ga sheet-like gabbro-dolerite sills and the Salmi plateau-basalts from the Lake Ladoga region. Based on chiefly geochemical data, the region is conventionally interpreted as an intracratonic Ladoga rift (graben). We question the validity of this geodynamic interpretation by analyzing regional geophysical data (crustal structure, heat flow, Bouguer gravity anomalies, magnetic anomalies, and mantle Vs velocities). We provide a complete list of tectonic, magmatic, and geophysical characteristics typical of continental rifts in general and demonstrate that, except for magmatic and, perhaps, some gravity signature, the Lake Ladoga region lacks any other rift features. We also compare the geophysical data from the Lake Ladoga region with similar in age Midcontinent and Valday rifts, and provide alternative explanations for Mesoproterozoic geodynamic evolution of the southern Baltic Shield. We propose that Mesoproterozoic mafic intrusions in southern Fennoscandia may be associated with a complex deformation pattern during reconfiguration of (a part of) Nuna (Columbia) supercontinent, which led to magma intrusions as a series of mafic dykes along lithosphere weakness zones and ponding of small magma pockets within the cratonic lithosphere. Consequent magma cooling and its partial transition to eclogite facies could have led to the formation of a series of basement depressions, similar to intracratonic basins of North America, while spatially heterogeneous thermo-chemical subsidence, with phase transitions locally speeded by the presence of (subduction-related) fluids, could have produced a series of faults bounding graben-like structures.

1. Introduction

Geodynamic interpretation and reconstruction of paleotectonic environments is strongly non-unique. The existing models are derived from regional geology, structural geology, and sedimentology, combined with isotope geochronology and geochemistry, which provide insights into the interplay of surface and deep processes. For Precambrian regions, many tectonic settings are inferred from geochemical data alone. Such interpretations can be inaccurate and inadequate because of (i) non-unique links of geochemical signatures to tectonic settings and (ii) distinctive composition and emplacement conditions for many Precambrian, particularly Archean, rocks that differ from those in the Phanerozoic (Hamilton, 2007).

As a result, despite impressive progress in our understanding of Precambrian geology and geodynamics, there is a significant divergence in the interpretations, concepts, and understanding of many processes, especially on a regional scale. In this study we focus on the so-called Ladoga Rift (e.g. Bogdanova et al., 1996; Velichkin et al., 2005; Nikishin et al., 2011) in the south-eastern part of the Baltic shield (Fig. 1b), and present geophysical arguments against such a geodynamic interpretation of this tectonic structure.

The Ladoga Rift (or Graben, which includes the intracratonic Ladoga riftogenic basin, Bogdanova et al., 1996) is located between the largely Archean Karelian Province of the Baltic Shield to the east and the Paleoproterozoic Sveco-Fennian Province to the west (Bogdanova et al., 2008), all parts of the East European Craton (Fig. 1a). Proterozoic basement outcrops in the northern part of the Lake Ladoga region, while the southern part is covered by glacial sediments, and their northern extent marks the border between the Baltic Shield and the East European (Russian) Platform. Lake Ladoga has a pronounced depression in bathymetry (100–200 m deep) in the north (Fig. 2a). It its likely that the depth to the basement in

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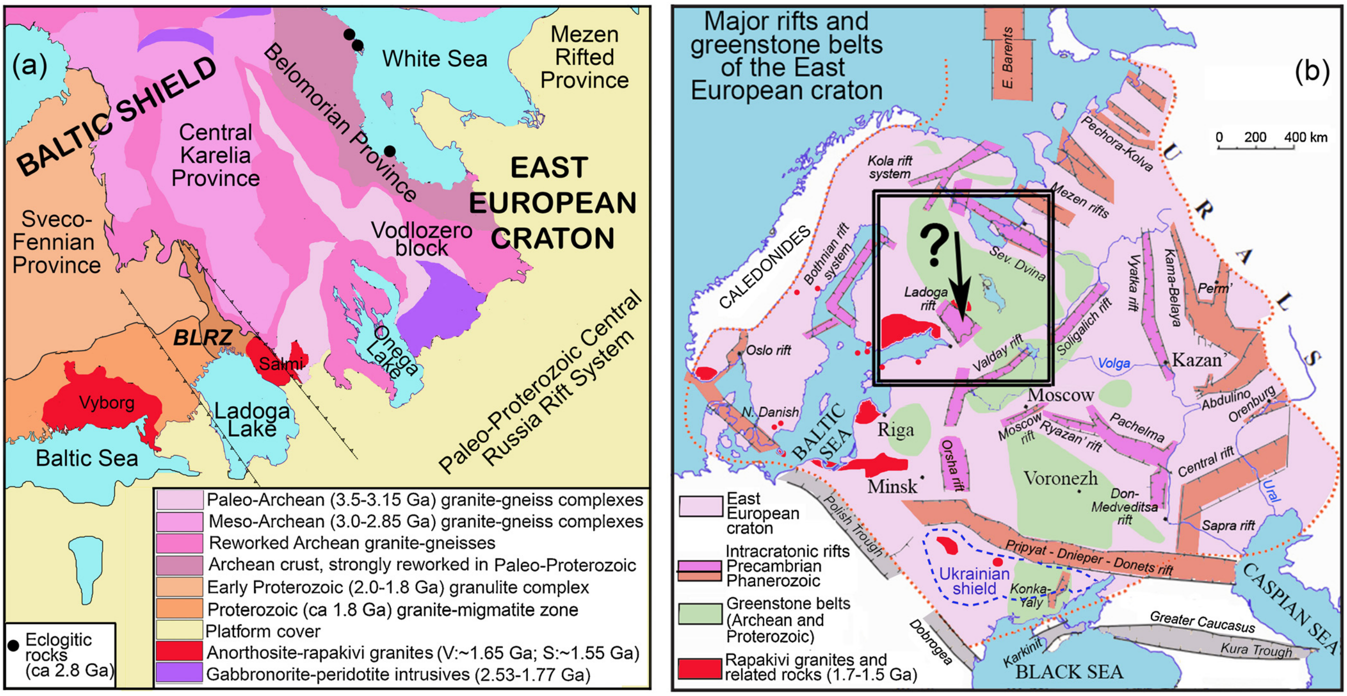

Fig. 1. Simplified tectonic map: (a) of the Ladoga region (based on Gaal and Gorbatschev, 1987; Korsman et al., 1997; Koistinen et al., 2001; Slabunov et al., 2006); BLRZ – the Bothnia-Ladoga rift zone (after Velichkin et al., 2005); (b) of the East European craton; major rifts are based on Nikishin et al. (2011); greenstone belts – after Lobach-Zhuchenko (1988); rapakivi granites and related rocks – after Elming et al. (2001). Red dotted line – outline of the craton boundaries; blue dotted line – outline of the Ukrainian shield, black box – region of study (shown in (a) and in the following figures).

the northern and southern parts is similar, given that the transition from deep to shallow (<70 m) water corresponds to the on-shore boundary of the sedimentary cover, and the thickness of sediments in Lake Ladoga is unknown.

No drilling has been done in Lake Ladoga; its geology (Fig. 2b) is inferred from potential field data and geochemical and petrological studies of volcanic rocks in the chain of islands in the northern part of the lake. The largest, Valaam island, is dominated by gabbro-dolerite sheet-like sills with the age of ca. 1.457 Ga (Rämö et al., 2004). Other islands are genetically similar and are interpreted as fragments of a ca. 200 m thick sheet-like intrusive body. Plateau-basalts (1.477 Ga, Kuptsova et al., 2011) totaling more than 100 m in thickness are exposed along the northern rim of the basin, while the Salmi basalts at the NE margin of the Lake Ladoga have Sm–Nd age of 1.499 Ga (Amelin et al., 1997; Golubev et al., 2003).

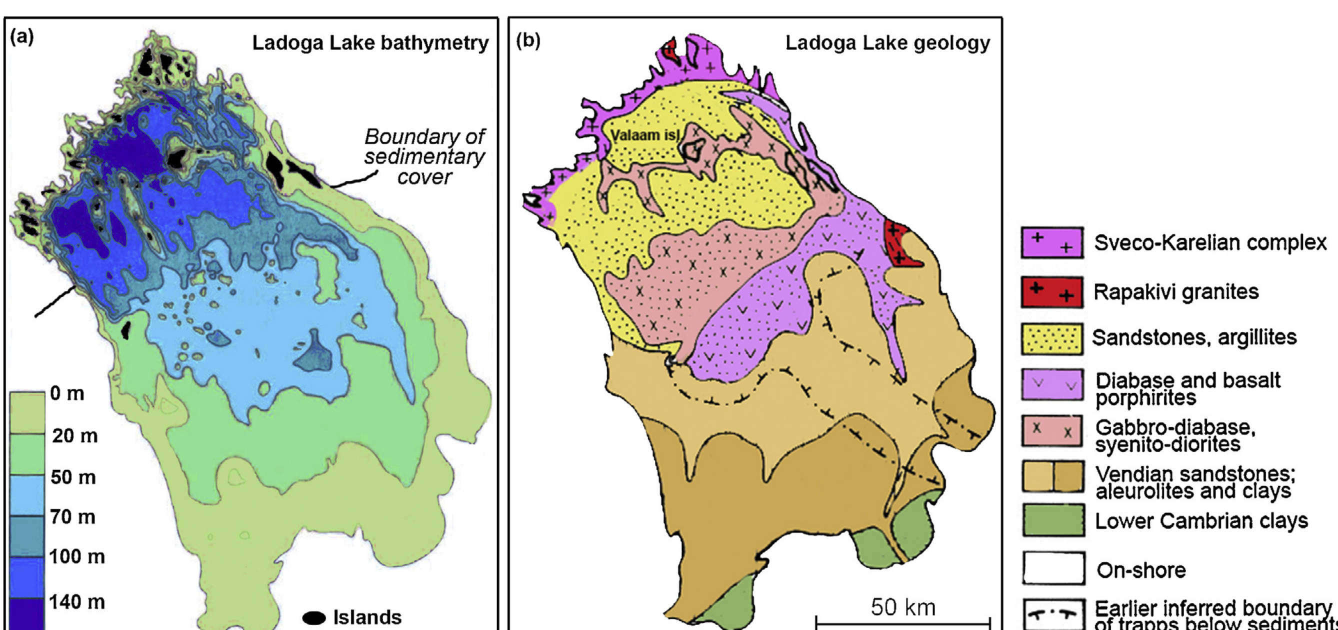

Fig. 2. Bathymetry (a) and geology (b) of Lake Ladoga

Modified after Amantov and Spiridonov (1989).

This geochemical data forms the primary basis for interpreting the tectonic origin of the basin as an intracratonic paleorift (e.g. Bogdanova et al., 1996; Amelin et al., 1997; Velichkin et al., 2005). We next discuss typical characteristics of continental rifts and examine whether geophysical observations from the Lake Ladoga region support its geodynamic interpretation in terms of intracratonic rifting.

2. What defines an intracontinental rift?

Classical definitions of a continental rift are based on a set of tectonic, magmatic, and geophysical features. We first list these general characteristics with some comments on their worldwide observations and then discuss them in relation to the Lake Ladoga region (Table 1).

(1) Based on surface observations, rifts may have different morphology and dimensions, but are usually defined as (Olsen, 1995):
- T1: elongated narrow extensional features
- T2: with a central depression (graben) and shoulder uplifts;
- T3: commonly bordered on one or both sides by normal fault systems as reported for tectonically active rifts (Ebinger et al., 1999). However, this feature may not be preserved in tectonically "dead" Proterozoic rifts;
- T4: with lithosphere extension expected in continental rift zones. However, its extent may vary significantly depending on tectonic forces and lithosphere rheology (Buck, 1991). In case of "passive rifting" lithosphere extension caused by far-field lithospheric stresses is the primary cause of rifting, while during "active rifting" triggered by mantle convective instabilities lithosphere extension is a secondary process caused by local surface uplift and crustal doming (Sengör and Burke, 1978; Bott, 1995).

(2) Regarding magmatism, continental rifts typically have:
- M1: some magmatic activity, particularly at the early stages of rifting (White and McKenzie, 1989). However, the amount of magmas may vary significantly and is essentially controlled by lithosphere rheology, extensional tectonic forces, and magma influx (e.g. Buck, 2004; Kendall et al., 2005; Bialas et al., 2010);
- M2: alkali basalts and bimodal volcanism as common products (McKenzie and Bickle, 1988; Farmer, 2005);
- M3: magmatic underplating at around the Moho as observed in many continental rifts (Thybo and Nielsen, 2009; Thybo and Artemieva, 2013).

(3) Conventional geophysical models predict:
- G1: Moho shallowing due to extension and crustal thinning (Wernicke, 1985). However, recent seismic studies from Cenozoic (Thybo and Nielsen, 2009) and Paleozoic rifts (Lyngsie et al., 2007) have demonstrated that magmatic underplating may result in a flat Moho beneath many (if not most) continental rifts;
- G2: in tectonically active rifts, low seismic velocities in the upper mantle caused by high mantle temperatures and a likely presence of partial melts; recent studies demonstrate that absolute seismic velocities may, however, still be high (Achauer and Masson, 2002), G3: in paleorifts, basalt-eclogite phase transition would increase seismic velocities in the subMoho mantle (Ringwood and Green, 1966), however such eclogitized material will be seismically indistinguishable from the upper mantle; in particular the pattern is not observed in the Midcontinent rift of North America (Shen et al., 2013), G4: in tectonically active rifts, high mantle temperatures and the presence of partial melts should lead to low mantle density and produce negative Bouguer gravity anomalies (Artemjev and Artyushkov, 1971), G5: in case of paleorifts, basalt-eclogite phase transition may, on the contrary, cause a significant density increase in the upper mantle (Artyushkov et al., 1990) with a characteristic gravity high such as in the Midcontinent rift (King and Zietz, 1971); the transformation rate can be significantly increased by an inflow of catalyzing fluid (Ahrens and Schubert, 1975; Austrheim, 1987), G6: high heat flow is expected in case of both active rifting (e.g. caused by mantle convective instability) and passive rifting (due to adiabatic melting associated with lithosphere extensional thinning) (McKenzie and Bickle, 1988), but heat flow anomaly should long have vanished in Precambrian paleorifts, G7: both lithosphere extension and mantle convective instability are expected to produce a significant thinning of the lithosphere (Artyushkov, 1981; Ruppel, 1995), however thermal cooling, particularly in paleorifts, could have led to lithosphere thickening by growth of the conductive boundary layer, G8: Fe-rich basaltic intrusions may produce linear magnetic anomalies along the rift valley because the igneous rocks are often strongly magnetized (Ferré et al., 2014); such anomaly is characteristic of the North American Midcontinent rift (Hinze et al., 1992), similar linear patterns of magnetic anomalies are typical for mid-ocean ridges.

3. Can the Lake Ladoga region be a rift?

We now address rift characteristics as listed in the previous section in relation to the Lake Ladoga region. The results are summarized in Table 1.

3.1. Topographic expression

The Lake Ladoga region is located at the border between the, largely sediment-free Baltic Shield and the East European (Russian) Platform (Fig. 3a). It is covered in its northern part by 0.5–3 km of sediments which fill-in the southern part of the lake depression (Fig. 2a). The topography (including the basement topography) does not show elongated narrow features, nor the presence of a central graben bordered by shoulder uplifts. The only pronounced topographic feature is a semi-circular, 100–200 m deep, depression of Lake Ladoga (Fig. 4), ca. 150 km in diameter, similar in shape to the Paleozoic intracratonic basins of North America, but smaller both in size and depth. The origin of the Hudson Bay, Michigan, Illinois and Williston basins has been explained by a plume-lithosphere interaction, followed by the emplacement of compositionally denser mantle into the cratonic lithosphere and localized lithospheric thinning (Kaminski and Jaupart, 2000). By similarity, the small size and depth of the Lake Ladoga depression suggests a shallow, probably sub-Moho, local thermo-compositional anomaly as its origin. A series of known faults bounding graben-like structures could be a result of crustal doming and extension during magma ascent, followed by spatially heterogeneous thermo-chemical subsidence, associated with magma cooling and possible metamorphic and phase transitions.

3.2. Magmatism

The Mesoproterozoic evolution of the southern Baltic Shield is marked by alkaline magmatism in the form of plateau-lavas (Salmi basalts), gabbro-dolerite sills (Valaam island in the northern part of Lake Ladoga, Fig. 2a), and dykes (hyalobasalt and dolerite-sortavalite) (Slabunov, 2013). Given that such magmatism is typical of continental rift zones, its presence gave raise to tectonic interpretations of the Lake Ladoga region as a Mesoproterozoic rift, with NW-orientation, similar to the White Sea rift system (Fig. 1b).

Table 1
Rift features in the Lake Ladoga region.

Feature	Feature description (see Section 2 for details)	Observations in the Lake Ladoga region (see Section 3 for details)	Fig.	Rift or not
T1	Linear surface expression	Rounded basin, ca. 200 km × 160 km	Fig. 2	No
T2	Horst-graben topography	No shoulder uplift	Fig. 4a	No
T3	Normal border faults	Insufficient data	–	?
T4	Crustal extension	No data	–	?
M1	Early magmatism	No data	–	?
M2	Magma composition	Plateau-basalts, gabbro-dolerite sills	–	Yes
M3	Magmatic underplating	Not observed	Fig. 3b	No
G1	Crustal thinning	No data for Lake Ladoga, but no thinning is observed further north in the proposed Bothnian-Ladoga rift zone (see Fig. 1a for location)	Fig. 3d	No
G2	Low Vp, Vs in mantle as in active rifts	If existed, should have disappeared over 1.5 Ga	Fig. 6cd	n/a
G3	High Vp, Vs in mantle due to eclogitization	May not be observed (Fig. 5b)	Fig. 6cd	n/a
G4	Negative Bouguer anomaly	Slightly positive (0 + 20 mGal)	Fig. 4d	No
G5	High density eclogitic mantle	Contrast with the adjacent regions ca. +50 + 70 mGal	Fig. 4d	May be
G6	High heat flow	If existed, should have disappeared over 1.5 Ga. Heat flow is typical cratonic (20–35 mW/m^2), even despite U-deposits in the Salmi massif	Fig. 6a	n/a
G7	Thin lithosphere	If existed, should have disappeared over 1.5 Ga.	Fig. 6b	n/a
G8	Magnetic anomaly	Not observed	Fig. 4b	No

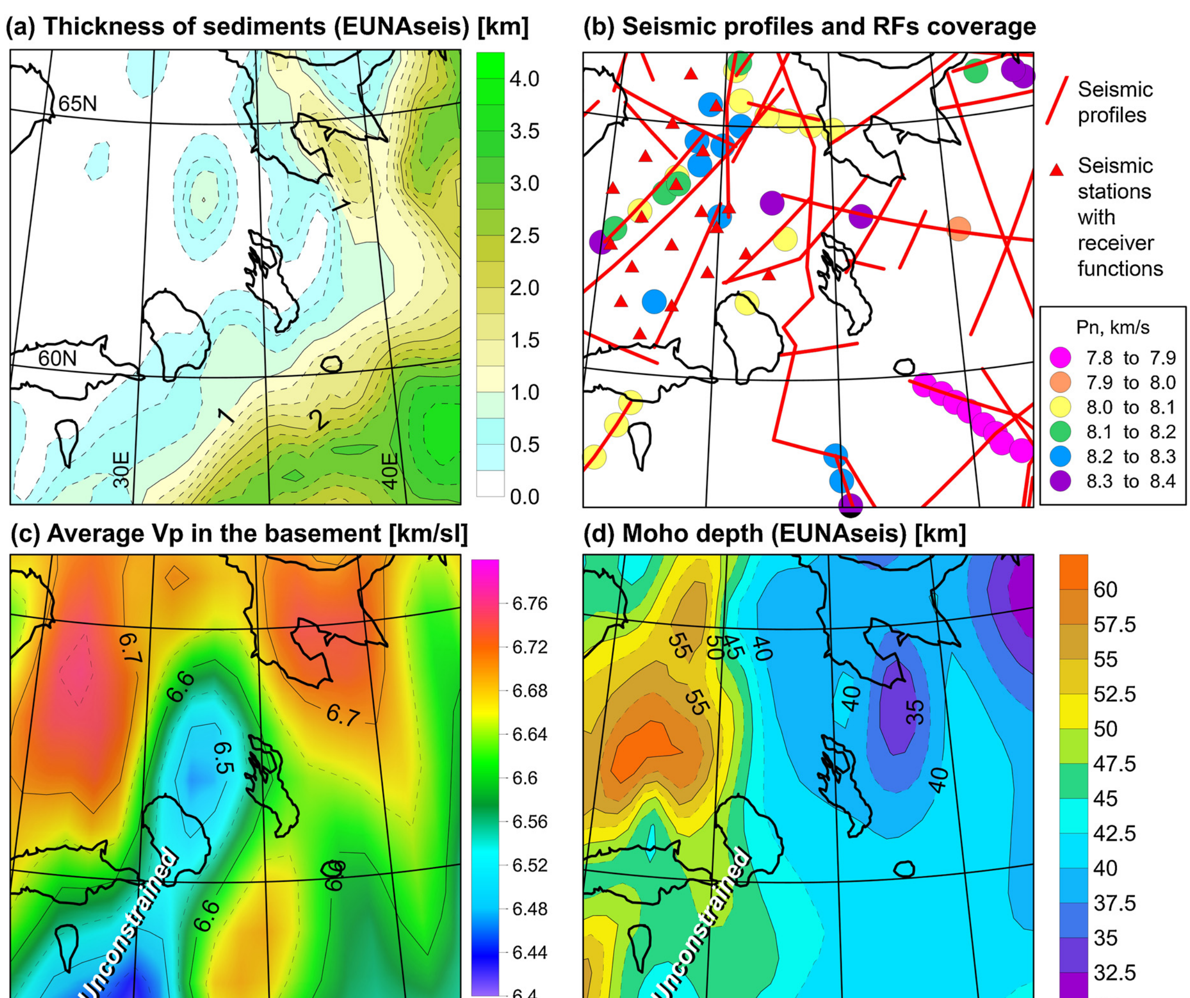

Fig. 3. Thickness of sediments (a), seismic data coverage and upper mantle Pn velocity (b); average Vp in the crystalline basement (c), and the depth to Moho (d) Based on Artemieva and Thybo (2013).

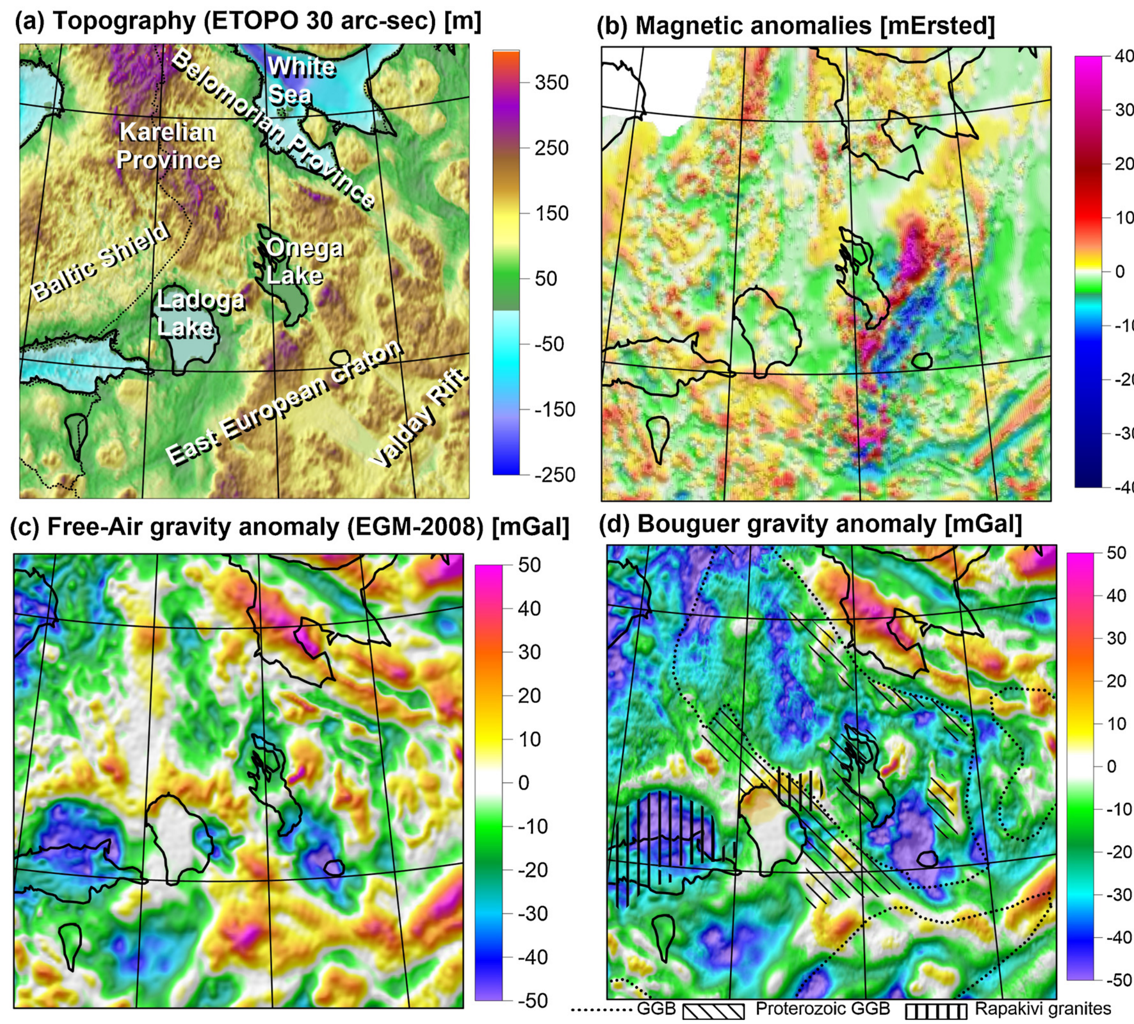

Fig. 4. Topography on a 30 arc-sec grid (a, based on ETOPO1 data), magnetic anomalies on a 1 arc-min grid (b, based on Racey et al., 1982), free-air gravity anomalies (c, based on EGM-2008, Pavlis et al., 2012), Bouguer anomalies (d, calculated from EGM-2008 assuming upper crustal density of 2.65 g/cc). GGB – Archean and Proterozoic granite-greenstone belts (after Lobach-Zhuchenko, 1988).

However, the presence of a large number of mafic dykes and sills of different ages (1.7–1.6 Ga, 1.53–1.46 Ga, ca. 1.3 Ga) along the Finnish Bay of the Baltic Sea and in the Sveco-Fennian province of the Baltic Shield indicates a complex pattern of post-Sveco-Fennian deformation in the region. Similar geochemical composition and ages (1.53–1.46 Ga) of the Kopparnäs basaltic dyke swarm in southern Finland and the Salmi basalts from the Lake Ladoga region have been interpreted recently as an indication of the presence of a single, ca. 1000 km wide, magmatic system at the Mesoproterozoic time beneath the southern Sveco-Fennian Province (Luttinen and Kosunen, 2006). Geochemical modeling of southern Finland basaltic dykes inferred a sublithospheric mantle source typical of plumes (Luttinen and Kosunen, 2006).

3.3. Crustal structure

Crustal structure of the region is known relatively well from a large number of seismic reflection/refraction profiles and recent receiver function seismic studies (Fig. 3b, Artemieva and Thybo, 2013). The depth to Moho is around 42–47 km, and no crustal thinning is observed along the proposed Bothnian-Ladoga rift zone (Fig. 3d). In fact, the proposed NW rift extent toward the Central Finland Province is marked by a well-established ca. 60 km deep crustal root at the Archean-Proterozoic suture (Korja and Heikkinen, 2005). However, as discussed in Section 2, the presence or absence of crustal thinning should not be considered as a characteristic feature of a continental rift. In case no crustal thinning is observed, magma underplating is expected at Moho. In such a case, the lower crust should have high seismic velocities (>7.2 km/s), as observed in the Baikal rift zone (Thybo and Nielsen, 2009) and in the Paleozoic Dnieper-Donetsk rift (Lyngsie et al., 2007). No such high-velocity anomaly is evident beneath the Lake Ladoga region from seismic data. Instead, the region ca. 100–200 km to the north has an unusually low average Vp in the crystalline basement (ca. 6.5 km/s) (Fig. 3c), suggesting that the lower crust is significantly thinned. Thus, the normal depth to Moho and the apparent absence of the high-velocity lower-crustal underplate are both inconsistent with a rift zone in the region.

3.4. Magnetic anomalies

The presence of a linear, alternating pattern of positive and negative magnetic anomalies is characteristic of a rift zone. While many other geophysical features may have vanished over 1.5 Ga, the pattern of magnetic anomalies should have been preserved, unless the region has been affected by a significant thermal process. For example, the ca. 1.1 Ga North American Midcontinent rift is seen only in gravity and magnetic anomalies (Hinze et al., 1992). In

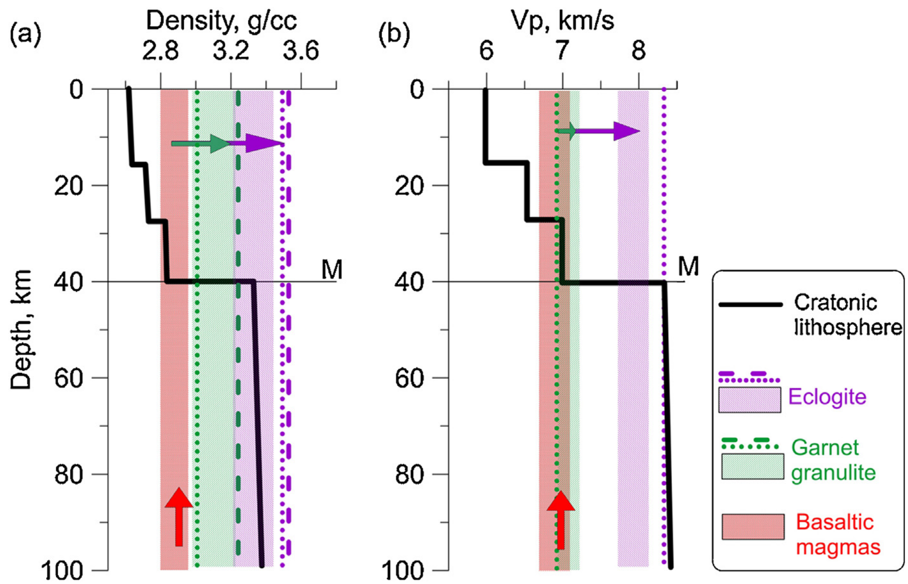

Fig. 5. Changes in lithosphere density (a) and Vp velocity (b) caused by injection of basaltic magmas and the consequent basalt → garnet granulite → eclogite phase transitions. Density values are based on Ringwood and Green (1966) (dotted lines), Ito and Kennedy (1971) (dashed lines, at $T = 1200\,^{\circ}C$), and Austrheim (1987) (shaded areas – for granulite and eclogite facies anorthositic rocks, with maximum values of 3.5–3.6 g/cc for two samples of mafic eclogites). Vp data are based on Ringwood and Green (1966) (dotted lines) and Christensen and Mooney (1995) (shaded areas). Basaltic magmas have density and Vp velocity similar to the lower crustal rocks. For granulite facies, Vp velocity remains similar to the lower crustal values, while density increases. For eclogite facies, both density and Vp velocity are significantly higher than the corresponding crustal values and overlap with the mantle values.

contrast, no linear magnetic anomalies are seen in the Lake Ladoga region (Fig. 4b), while they are present in the Valday rift of the Central Russia Rift system. Thus, magnetic data also do not support the rift origin of the Ladoga region magmatism.

3.5. Gravity anomalies

Free-air gravity anomalies show that the Lake Ladoga region is the only part of the southern Baltic Shield which is in near-isostatic equilibrium (Fig. 3c), although regional variations are not very large (ca. +50/−50 mGal). Bouguer anomalies show a complicated pattern of regional short-wavelength variations. It is outside the scope of this paper to discuss the details of regional tectonic evolution, but we note that linear belts of positive (+20 + 45 mGal) anomalies caused by high-density bodies at the crustal or subMoho depth (as suggested by their lateral dimensions) are associated with the Belomorian Province in the NE and the Riphean Valday rift in the SE. High-density anomalies associated with Proterozoic structures may be attributed to the presence of eclogites, either associated with paleosubduction zones or with eclogitization of lower crustal granulites or basaltic intrusions (Austrheim, 1987), as supported by the presence of eclogites along the White Sea margins (Fig. 1a).

Experimental studies of basalt → eclogite phase transition (Ito and Kennedy, 1971) indicate that phase transition to garnet granulite increases density from ca. 2.8 g/cc to ca. 3.0–3.2 g/cc, while a complete transformation of basalt to eclogite will increase density to ca. 3.5 g/cc, that is significantly higher than the density of the upper mantle (Ringwood and Green, 1966; Austrheim, 1987) (Fig. 5a). The rate of such transformation, particularly at low temperatures typical of cratonic lithosphere, is unknown, but it can be significantly increased by the presence of fluids (Ahrens and Schubert, 1975). Even for a partial transformation, which is more likely to take part at lithospheric conditions, the resultant density increase should be sufficient to be observed in the gravity field.

A small weakly-positive (ca. +5 + 15 mGal), but rounded in shape, Bouguer anomaly is observed around Lake Ladoga, with the maximum in its northern part (N Salmi massif) (Fig. 4d). Both the shape and the magnitude of the anomaly do not suggest the presence of an elongated magmatic intrusion as expected for rift zones. However, by comparison with negative background Bouguer anomalies (ca. −20 to 50 mGal) typical of the adjacent granitic plutons and granite-greenstone belts of the Central Karelia and the Vodlozero subprovince (Fig. 1a), the Bouguer gravity anomalies in the Lake Ladoga region are ca. 50–70 mGal higher and in the south merge with positive anomalies that mark the edge of the Central Russia rift system. Such interpretation suggests the existence of a tectonic feature parallel to the White Sea rift and the Belomorian Province, with an increased density approximately at Moho depth as suggested by the size of the anomaly. However, the amplitude of this anomaly is at least twice smaller than in the Midcontinent Rift.

3.6. Mantle Vs anomalies, heat flow and lithosphere thickness

The presence of a high-density, presumably partially eclogitized body in the upper mantle may not be seen in seismic velocities (Fig. 5b). Pn upper mantle velocity shows some velocity decrease (ca. 8.0 km/s) in the Lake Ladoga region as compared to typical cratonic Pn (8.2 km/s and higher), however the seismic data coverage is insufficient for any conclusions (Fig. 3b). Note that the Riphean Valday Rift is marked by low Pn velocities (7.8–7.9 km/s), apparently lower than below the Salmi Massif.

Seismic tomography (Fig. 6c and d) does not show any Vs anomalies around Lake Ladoga, but shows a pronounced localized high-velocity anomaly (+5 + 7%) centered around Lake Onega in the Vodlozero subprovince (Fig. 1a). Note that this subprovince has some of the oldest isotope ages reported so far for the Baltic Shield (ca. 3.25 Ga), so that the velocity anomaly may reflect the presence of a highly depleted lithospheric mantle, not affected by metasomatic reworking (Artemieva, 2009, 2011). However, the anomaly may also be, at least in part, caused by low mantle temperatures as suggested by anomalously low heat flow (15–20 mW/m^2, after paleocorrections are introduced, Artemieva, 2006, 2007) (Fig. 6a). The Lake Ladoga region is located at the edge of the high Vs anomaly in the upper mantle and at the zone of high gradient in lithosphere thickness (Fig. 6b). Since conductive cooling should have restored

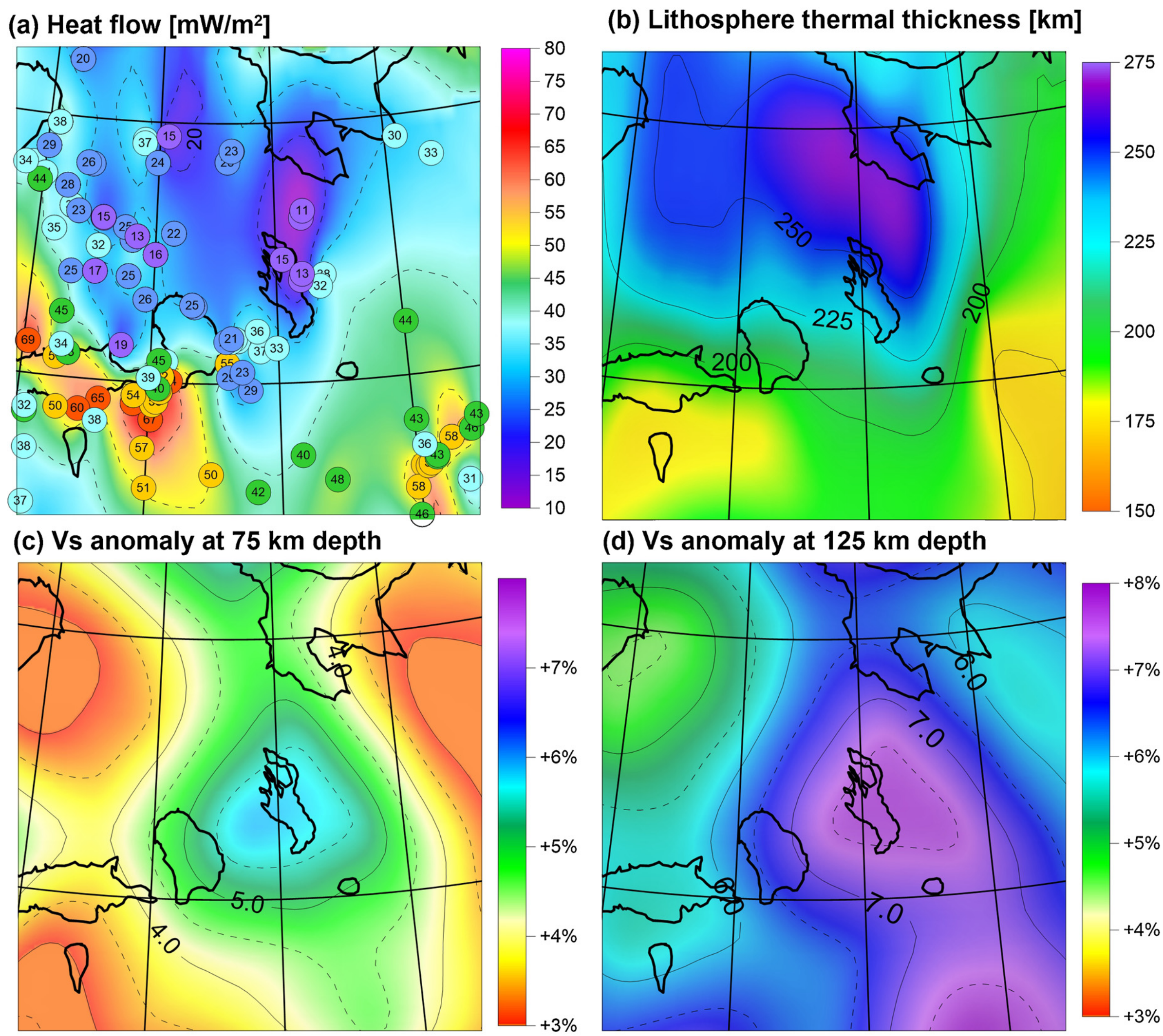

Fig. 6. Heat flow (a) based on IHFC-2011 compilation (without paleo-corrections); circles – sites of heat flow measurements with values in mW/m^2), lithosphere thermal thickness (b) based on Artemieva, 2003), relative Vs anomalies (c and d) at 75 km and 125 km depth based on SL2013sv tomography model (Schaeffer and Lebedev, 2013); the reference model has Vs = 4.4077 km/s at 75 km and 4.4195 km/s at 125 km depth.

lithosphere thickness since Proterozoic, the absence of lithosphere thinning cannot attest to the absence of the Mesoproterozoic rifting or plume–lithosphere interaction event.

4. Alternative mechanisms

Our analysis demonstrates that, except for magmatism and, possibly, a weak gravity anomaly, rift characteristics are not observed in the Lake Ladoga region neither in topographic nor in geophysical data (Table 1). This questions existing geodynamic interpretations of its origin as an intracratonic Riphean rift (e.g. Bogdanova et al., 1996; Amelin et al., 1997; Velichkin et al., 2005), since the younger ~1.1 Ga Midcontinent Rift in North America and the Riphean Central Russia Rift are well expressed in geophysical (gravity, magnetic, and seismic) anomalies, while also lacking surface expressions (Stein et al., 2014; Artemieva, 2003).

For most deep basins on continental crust, extension is insufficient to explain the subsidence by stretching (Artyushkov, 1987), and another mechanism is needed. Because of their similar shapes, we propose that geodynamic origin of the Lake Ladoga depression is similar to epicratonic basins of North America (Kaminski and Jaupart, 2000) and is caused by an infiltration of hot mantle material to shallow lithosphere. The shape of rising mantle bodies and the depth of their ascent are controlled by lithosphere rheology, viscosity contrast between the lithosphere and the basaltic magmas, the influx of mantle material, and tectonic stresses (Gerya and Burg, 2007; Bialas et al., 2010). In particular, tectonic stresses caused by far-field stresses associated with collision of lithospheric plates (Zoback, 1992) have long been proposed as a cause of intracontinental rifting (Gordon and Hempton, 1986).

Mafic magmatism in southern Fennoscandia at ca. 1.53–1.46 may be associated with reorganization of Nuna (Columbia) supercontinent (defined broadly as continent grouping) (Hoffman, 1997), which might have caused a complex deformation pattern along the cratonic margin. This pre-Rodinia supercontinent may have been assembled at ca. 2.1–1.8 Ga (Rogers and Santosh, 2002), and has undergone a subduction-related growth at 1.8–1.3 Ga by forming large magmatic accretionary belts along continental margins of North America, Greenland and Baltica (Karlstrom et al., 2001). In Fennoscandia these include the Kola-Karelia orogen (1.9–1.8 Ga), the Transscandinavian Igneous Belt (1.8–1.7 Ga), the Kongsberggian–Gothian Belt (1.7–1.6 Ga), and the Granitoid Belt (1.5–1.3 Ga) in Southwest Sweden (Zhao et al., 2004). Although a broad range of ages (ca. 1.6–1.2 Ga) has been proposed for the break up of Columbia (Zhao et al., 2004), these ages are also consistent with the age of Mesoproterozoic mafic (and anorogenic) magmatism in southern Baltica (Vigneresse, 2005).

Magma intrusion along the lithosphere weakness zones could produce a series of mafic dykes as observed in various parts of the Sveco-Fennian province, while ponding of small magma pockets within the "intact" cratonic lithosphere could have led to the formation of a series of small-size intracratonic basins, such as the Lake Ladoga basin, formed by magma cooling and its partial transition to eclogites. The rate of the phase transition could have been locally speeded by fluid injection (Austrheim, 1987), thus creating a strongly heterogeneous lithosphere structure with short wavelength, high-amplitude density anomalies. Due to a high density contrast between eclogite and mantle peridotite, these anomalies are well resolved in gravity field, but are not seen neither in seismic velocities because of similar velocities in two types of rocks, nor in thermal structure since the anomaly associated with magmatism has relaxed and conductive cooling has restored the cratonic lithosphere thickness.

5. Conclusions

Mesoproterozoic mafic magmatism at the southern part of the Baltic Shield (the Lake Ladoga region) is conventionally ascribed to epicratonic rifting. Our analysis of characteristics of continental rifts demonstrates that:

1. the topography of the region lacks a linear horst-graben structure typical of modern rifts, however this feature might have been lost by surface erosion;
2. the crust has neither shallow Moho, nor magmatic high-velocity underplated material, and thus is not typical of continental rifts;
3. weakly negative Bouguer gravity anomalies, especially by comparison with adjacent "background" anomalies suggest the presence of high-density material at shallow, near-Moho depths; however, the shape of the anomaly is rounded rather than linear, and may not attest to the paleorifting event;
4. seismic velocities in the upper mantle show a possible weak low-Pn anomaly near Lake Ladoga, and strong positive (+5 + 7%) Vs anomaly at 75–125 km depth to the NE of the lake, but not in the region of Mesoproterozoic mafic magmatism;
5. no thermal anomaly or lithosphere thickness anomaly is currently present in the lithosphere of the region, which instead is marked by extremely low heat flow; however, given the age of magmatism any thermal anomaly may have long ceased and thus its absence does not disprove rifting origin of magmatism;
6. the absence of linear magnetic anomalies which are preserved in other paleorifts provides strong evidence that this region has not been affected by rifting.

We conclude that a mechanism other than rifting is responsible for Mesoproterozoic mafic magmatism at the southern part of the Baltic Shield and propose that magma intrusion associated with deformation along the margins of Nuna (Columbia) supercontinent, and its transformation to eclogite facies, locally speeded by fluids, produced a highly heterogeneous density structure of the lithosphere.

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