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# Seismicity of the East Baltic region after the Kaliningrad earthquakes on 21 September 2004

*Valerijs Nikulins, Bela Assinovskaya*

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**Abstract** For a long time, the north-western part of the East European Craton, specifically the East Baltic region (EBR), was considered an aseismic territory. Historical earthquakes did take place in the EBR, but they occurred rarely and could not always be associated with tectonic conditions. The attitude towards seismicity of the region began to change after the Osmussaar earthquake on 25 October 1976 (M = 4.7) and especially after the Kaliningrad earthquakes on 21 September 2004 (*Mw* = 5.0; *Mw* = 5.2). In this study, the seismicity of the EBR was generalized over 13 years after the Kaliningrad region earthquakes on the basis of Scandinavian and our own data. In several cases focal mechanisms were solved for weak earthquakes. The study showed a tendency of seismic activity to decrease from northwest to southeast, a predominant concentration of earthquakes sources in the East Baltic coastal zone, and the activation of Ladoga-Bothnia, Vyborg, Olaine-Inčukalns, Võrtsjärv zones. The main problems are associated with a rare seismic network, high level of ambient seismic noise, and a large number of man-made sources.

***Keywords*** *· East Baltic region · Fennoscandian region · GEOFON · Baltic Virtual Seismic Network · earthquake focal mechanism · crystalline basement · man-made earthquake · seismotectonics*

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## INTRODUCTION

The East Baltic region is located in the north-western part of the ancient Precambrian Eastern European craton, within its Fennoscandian element (Bogdanova *et al*. 2006). The EBR covers Saint Petersburg, Pskov, part of the Novgorod region and the Kaliningrad region of Russia, Estonia, Latvia and Lithuania, as well as the southeast parts of the Baltic Sea and of the Gulf of Finland.

The East Baltic region belongs to territories with a low level of seismic activity. The Osmussaar earthquake of 25 October 1976 with a magnitude of 4.7 (Kondorskaya *et al*. 1988) changed the viewpoint on the EBR's aseismicity. The Kaliningrad earthquakes on 21 September 2004 with a magnitude of 5.0 and 5.2 (Gregersen *et al*. 2008) finally convinced sceptics that not only can the earthquakes in the EBR occur, but they can also cause significant damage. These earthquakes stimulated the development of instrumental observations in the EBR.

In 13 years that have passed since the Kaliningrad earthquakes, 19 weak ($M_L$ from –0.8 to 2.6) regional earthquakes occurred in the area of Lake Ladoga, the Karelian Isthmus, Estonia and the Gulf of Finland in the region. Perhaps this number is bigger, but identifying tectonic earthquakes is seriously hampered by the extensive technogenic explosions which formed a kind of a seismic background, as well as by a high level of the ambient seismic noise. It is important to establish a genetic connection between the earthquakes in the East Baltic region and the tectonic structure, as well as understand the underlying geodynamic processes.

This review is devoted to summarizing the results of regional instrumental observations in the East Baltic region after the Kaliningrad earthquakes of 2004 and their relationship to the tectonic structure and geodynamic conditions.

## MATERIALS AND METHODS

The geotectonic conditions of the East Baltic region are characterized by different elements of the crystalline basement and sedimentary cover. On the eastern side of Lake Ladoga, the crystalline basement is represented by the most ancient – Archaean complex (3.0–2.7 Ga). In the direction from northeast to southwest, the Proterozoic age of the crystalline basement decreases from 1.90 to 1.85 Ga (Saint Petersburg and Pskov regions, Estonia and eastern Latvia), from 1.85 to 1.80 Ga (central and south-western Latvia, Lithuania and the Kaliningrad region of Russia). The age of individual "fragments" of the crystalline basement (Kurzeme, southern part of the Kaliningrad region) is even younger – from 1.65 to 1.40 Ga (Bogdanova *et al*. 2006).

The East Baltic region is associated with the Fennoscandian segment of the Earth's crust which borders *Sarmatia* and the *Volga-Uralia* (Bogdanova *et al*. 2006). On the border of Sarmatia and Fennoscandia, there was a subduction of the Fennoscandian segment of the Earth's crust under the Sarmatian continent. These collision processes led to the formation of terranes – geological bodies (Bogdanova *et al*. 2006), limited by faults and having a significant regional extent: 1) the west Lithuanian granulite region; 2) the eastern Lithuanian–Latvian belt; 3) the Belorussian–Baltic granulite belt; and 4) the central Belorussian belt.

Within the East European Craton, there are all types of tectonic elements of the ancient platforms (Garetsky 2007). They include shields, slabs, anteclises, syneclises, pericratonic subsidence, aulacogens, etc. From northeast to southwest, the platform conditions of the EBR are characterized by the presence of Ladoga Aulacogen, Latvian Col, Baltic Syneclise and Belorussian Anteclise bordering the EBR in the south.

### Seismic observations

Seismic observation systems which consist of an international network GEOFON and national seismic networks exist in the East Baltic region. A part of the GEOFON network stations formed the basis of the

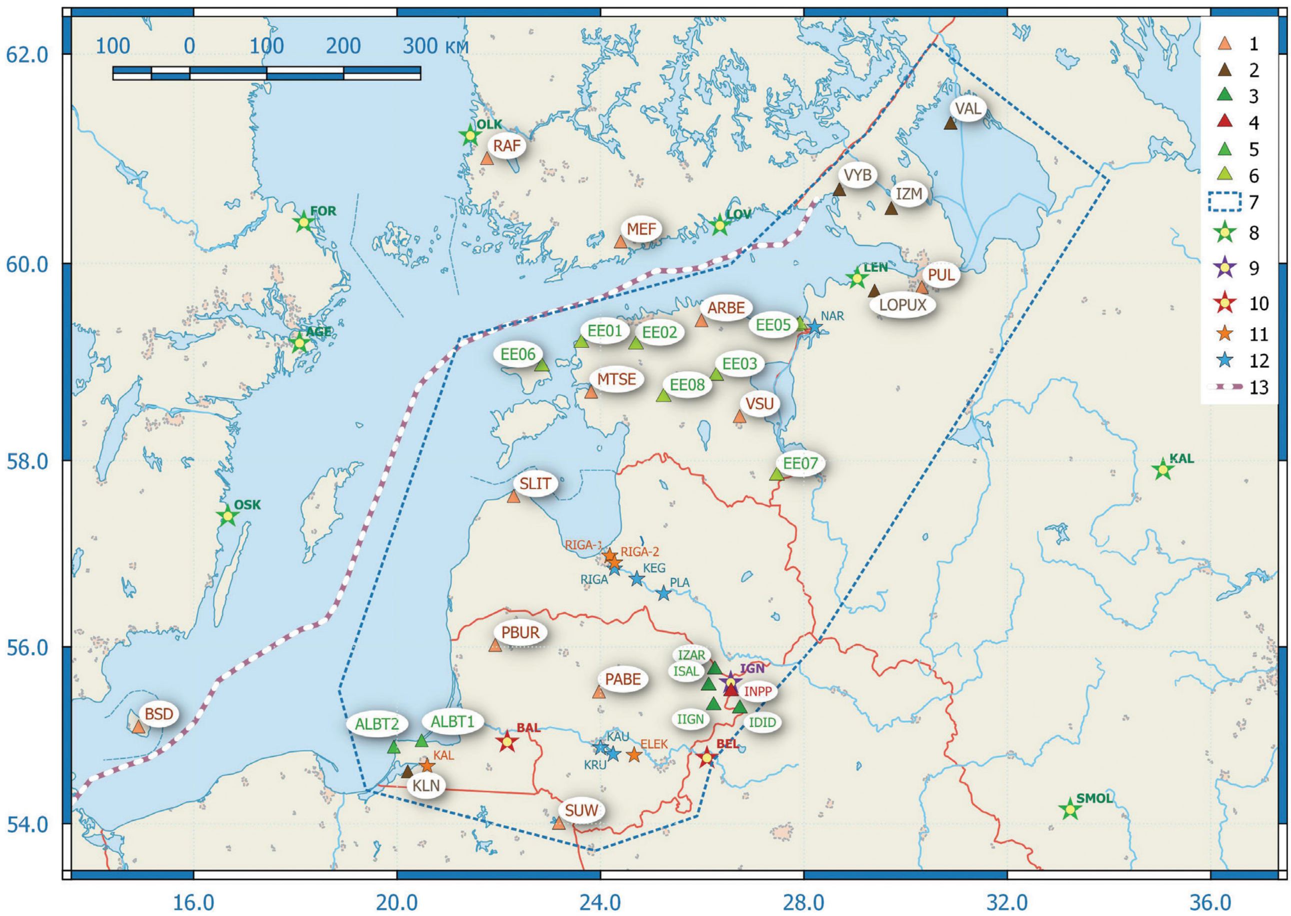


**Fig. 1** Systems of seismological observations in the East Baltic region and the most important infrastructural facilities: 1 – broadband seismic stations of the BAVSEN network; 2 – broadband seismic stations in the Russian part of the EBR; 3 – short-period seismic stations of the Ignalina local network; 4 – accelerometer of the Ignalina local network; 5 – short-period seismic stations in the Kaliningrad region of Russia; 6 – temporary seismic stations of the Estonian seismic network; 7 – border of the East Baltic region; 8 – operating nuclear power plants; 9 – closed nuclear power plants; 10 – projected nuclear power plants; 11 – combined heat and power plant; 12 – hydroelectric power station; 13 – Nord Stream gas pipeline

Baltic Virtual Seismic Network (BAVSEN) (Fig. 1) in the region. This network was organized by authors. The distances between the nearest stations of the network are quite large, about 150–200 km. Such a system makes it possible to detect and localize seismic events with local magnitudes $M_L$ ≥1.25.

In the Kaliningrad region, there are 3 seismic stations now. In the period from 2006 to 2015, a local seismic network comprised of 4 seismic stations was opened in the Saint Petersburg region. It covers the eastern part of the Gulf of Finland and the western part of Lake Ladoga.

The BAVSEN network, the SEISAN and WSG software and three different models of the seismic wave propagation velocity are used to localize seismic events. The authors of this article directly are engaged in carrying out seismic observations, processing seismograms and scientific analysis of the data.

## RESULTS AND DATA INTERPRETATION

In the period after the Kaliningrad earthquakes on 21 September 2004, there have been 19 seismic events in the East Baltic region identified with tectonic earthquakes. The local magnitudes $M_L$ of these events cover a range from –0.8 to 2.6. The depth of hypocenters varies from 1.4 to 12.2 km. The catalogue of earthquakes in the East Baltic region is presented in Table 1.

The greatest seismic activity in the East Baltic region manifested in 2014–2016, when there were 10 earthquakes with $M_L$ from 1 to 2.1 in the Vyborg region, of which 5 events occurred within a single day, on 18 December 2016. The epicentres of earthquakes and explosions in the East Baltic region for the period after the Kaliningrad earthquakes on 21 September 2004 are mapped in Fig. 2.

High technogenic activity of the East Baltic region is due to the extraction of mineral raw materials (granite, oil shale, dolomite, gypsum) by the explosive method. There are about 60 open quarries and 5 mines in the EBR that produce blasting operations (Nikulins 2017b). Identification of tectonic seismic events in the EBR is complicated due to the following circumstances: 1) a high level of ambient seismic noise, 2) low magnitudes of seismic events (0.8–2.1), 3) large distances between stations (150–200 km), 4) a large number of technogenic seismic events creating a peculiar background.

### *Seismic shocks in Riga and Riga region on 22 November 2010*

On 22 November 2010, at about 12 o'clock (GMT), in some places in Riga and Riga region, the population felt a number of shocks. In total, 7 ques-

**Table 1** Earthquakes in the East Baltic region from October 2004 to December 2017. Designations:* – probable tectonic earthquake; ** – probable man-made earthquake induced by getting of geothermal energy; $M_L$ – local magnitude; Area – position of the epicentre; B_S – the Baltic Sea; LAT – Latvia; EST – Estonia; LIT – Lithuania; RUS – Russia; Source – the source of information; HEL – University of Helsinki Institute of Seismology; LEGMC – Latvian Environment, Geology and Meteorology Center; PUL – Geophysical Service of Russian Academy of Science; Type – type of information; INST – instrumental recording; MCS – macroseismic method

| Date | Time (GMT) | Lat | Lon | H, km | $M_L$ | Area | Source | Type |
|---|---|---|---|---|---|---|---|---|
| 06.11.2006 | 01:11:40.3 | 59.68 | 24.86 | 3 | 1.1 | B_S | HEL | INST |
| 11.07.2007 | 15:45:27.9 | 60.10 | 28.84 | 2.9 | 2.0 | B_S | HEL | INST |
| 31.07.2010 | 01:47:45.9 | 61.35 | 30.84 | 1 | −0.8 | RUS | PUL | INST |
| 22.11.2010 | ~ 12 | ~56.9 | ~24.1 | | | LAT | LEGMC | MCS* |
| 04.02.2013 | 20:17:54.2 | 58.92 | 23.52 | 4.4 | 1.0 | EST | HEL | INST |
| 03.06.2014 | 09:06:08.2 | 60.76 | 28.84 | 0.9 | 1.0 | RUS | PUL | INST |
| 12.06.2015 | 08:18:26 | 55.52 | 21.42 | 0.9 | 2.6 | LIT | LEGMC | INST** |
| 07.10.2015 | 20:14:33.3 | 60.99 | 29.05 | 1.5 | 1.6 | RUS | PUL | INST |
| 07.10.2015 | 20:16:47 | 60.99 | 29.05 | 2.0 | 1.7 | RUS | PUL | INST |
| 11.07.2016 | 01:47:46 | 60.74 | 28.84 | 1.2 | 1.05 | RUS | PUL | INST |
| 11.07.2016 | 01:49:31 | 60.76 | 28.84 | 1.2 | 1.1 | RUS | PUL | INST |
| 12.11.2016 | 02:49:52.8 | 58.30 | 26.19 | 1.4 | 1.8 | EST | HEL | INST |
| 18.12.2016 | 00:20:19.5 | 60.75 | 28.85 | 2 | 2.1 | RUS | PUL | INST |
| 18.12.2016 | 00:30:27.1 | 60.75 | 28.84 | 1.2 | 1.4 | RUS | PUL | INST |
| 18.12.2016 | 02:35:13.9 | 60.74 | 28.84 | 1.2 | 1.3 | RUS | PUL | INST |
| 18.12.2016 | 02: 50: 6.1 | 60.73 | 28.84 | 1.2 | 1.3 | RUS | PUL | INST |
| 18.12.2016 | 18:04:23.8 | 60.76 | 28.84 | 0.6 | 1.25 | RUS | PUL | INST |
| 22.03.2017 | 03:00:27.5 | 59.34 | 24.36 | 4.0 | 1.2 | EST | HEL | INST |
| 15.07.2017 | 08:01:50.5 | 59.05 | 22.96 | 12.2 | 2.1 | EST | HEL | INST |

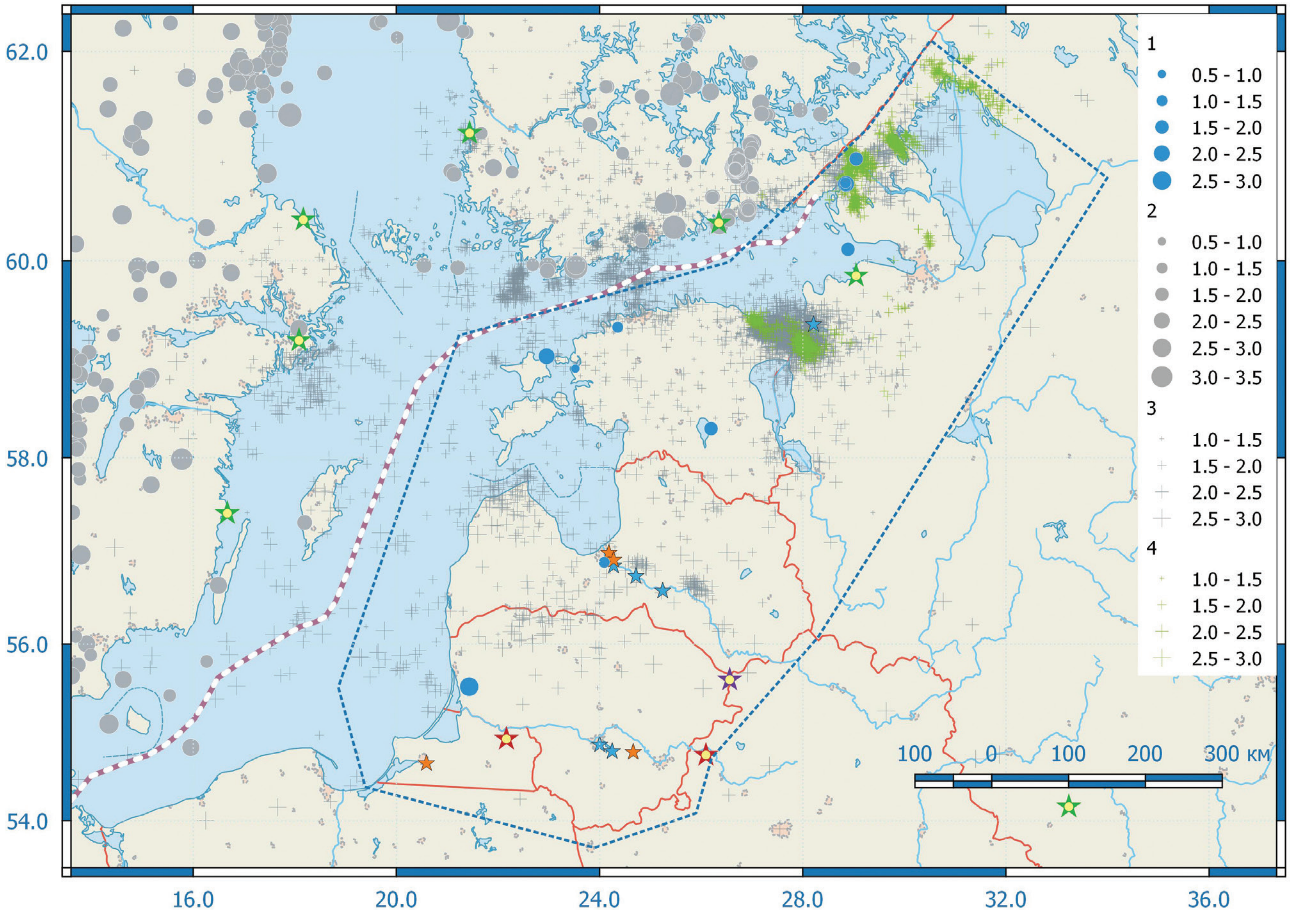


**Fig. 2** Map of epicentres of earthquakes and explosions from October 2004 to December 2017 and the main infrastructure facilities in the East Baltic region: 1– epicentres of earthquakes in the territory of the EBR; 2 – epicentres of earthquakes outside the EBR; 3 – epicentres of explosions according to the BAVSEN data; 4 – epicentres of explosions according to the Russian data in the Saint Petersburg region. The remaining notations are similar to those shown in Figure 1

tionnaires were received from eyewitnesses of this seismic tremor. Three points (points 1 to 3 in Fig. 3) where the shocks were felt are located in the northwest of Riga, in the districts of *Iļģuciems*, *Kurzeme* avenue and *Ulņama* avenue. In some of the points, the shock was felt with a much greater delay than the average time (~12 hours) registered at other points.

The four points where the tremor was felt are located in the tectonic zone formed by the Olaine-Inčukalns and Berģu faults (4–7 in Fig. 3).

The Olaine-Inčukalns fault is the longest fault of Latvia, stretching more than 130 km from southwest to northeast and in the Cēsis area changing its direction to the east towards Pskov. This fault, unlike other tectonic faults, was better studied in connection with the creation of an underground gas storage facility adjacent to it in the Ragana area. The Olaine-Inčukalns fault is a *predominant thrust mechanism with a strike-slip component*, while most of other faults in Latvia are *normal* (Brangulis, Kanevs 2002) or *prevailing normal faults with a strike-slip component*.

The following factors confirm the geodynamic activity of the Olaine-Inchukalns fault (Nikulins 2017a): 1) a change in the colour of the water sources of *Kaļkugrāvas*, Allažu region (point 8 in Fig. 3); 2) an anomaly of increased radon concentration at point 12 (Nikulins 2017b) on the basis of technical report from Gilucis; 3) an anomalous velocity of movement for points 14 and 15 located on opposite sides of the Cīrulīši fault at a distance of about 80 m from each other (Fig. 3) on the basis of data from *PanGeo* Project; 4) deformation processes developing within the tectonic zone formed by the Olaine-Inčukalns and Berģu faults (Nikulins 2017a).

Thus, the detected abnormal factors confirm the tectonic cause of macroseismic manifestations in the zone formed by the Olaine-Inčukalns and Berģu faults. Shakes on 22 November 2010 are quite likely to have been caused by tectonic reasons.

### *Probable earthquake near the Curonian Lagoon on 12 June 2015*

On 12 June 2015, near the Curonian Lagoon, a seismic event occurred with a magnitude of $M_L = 2.6$ and the depth of the hypocenter of 1.0 km, which had signs of an earthquake. The epicentre of the seismic

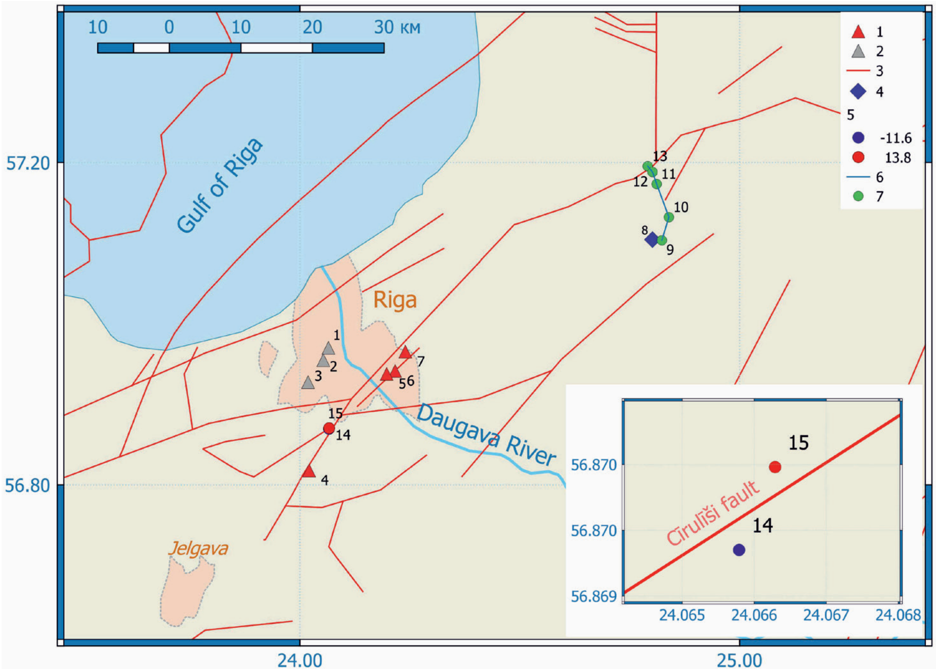


**Fig. 3** Seismic shocks in Riga and Riga region on 22 November 2010: 1 – points in which shakes were felt along the Olaine-Inčukalns and Berģu faults; 2 – points in which shakes were felt in other parts of Riga; 3 – tectonic faults in the Caledonian structural complex; 4 – Kaļkugrāvas spring; 5 – points for measuring the velocity of the Earth's surface displacement by the PSI method; 6 – radon survey profile; 7 – points of measurement of radon anomalies. The sidebar shows points 14 and 15 on either side of the Cīrulīši fault

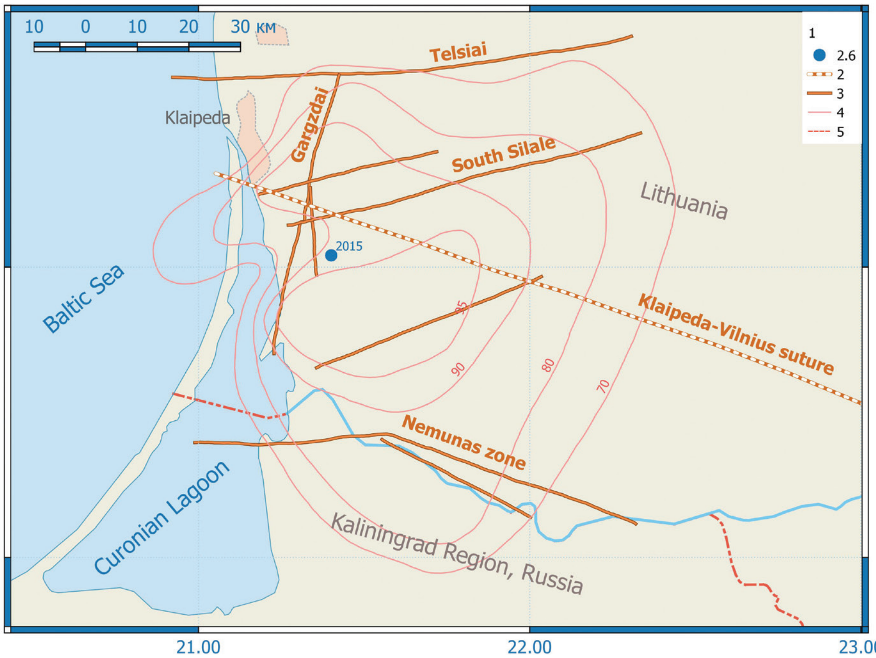


**Fig. 4** Probable tectonic (technogenic) earthquake near the Curonian Lagoon, in Lithuania on 12 June 2015: 1 – the epicentre of the seismic event of 12 June 2015; 2 – the fault of a super-regional scale – Klaipeda–Vilnius suture (Stirpeika 1999); 3 – tectonic faults in the crystalline basement: Telšiai, South of Šilalė, Gargždai and Nemunas fault zone (Paškevičius 1997); 4 – isotherms in °C; 5 – the state border of Lithuania and the Kaliningrad region of Russia

event was located near the tectonic node formed by the Gargždai and South Šilalė faults (Fig. 4).

The Klaipeda–Vilnius suture of a super-regional scale crosses this tectonic node. This suture border coincides with the outwardly stretching northern edge of the deep depression found in the Baltic Sea (Ostrovsky *et al.* 1994). It is also where the Klaipeda geothermal anomaly is located, with a geothermal gradient up to 4°C/100 m. The geothermal resources of Lithuania are mainly concentrated in the Cambrian and the Lower Devonian, i.e. in the sedimentary thickness of about 2 km. Their development began in 2000 and is accompanied by increase in the number of heat pumps (5500). In 2015, the total heat pump capacity reached a maximum of 76.6 Mw.

For the seismic event detected on 12 June 2015, the azimuthal gap is sufficiently large (272°). In this case, the precision of the earthquake source mechanism is not reliable, since none of the 4 stations has a satisfactory identification of the polarity of the first arrivals of P-waves (Fig. 5).

The relationship between the exploitation of geothermal deposits, technogenic seismicity and subsidence of the Earth's surface is known due to decrease in pressure. The results of monitoring at Rotokawa (New Zealand) from 2008 to 2012 revealed over 1000 events with $M_L > 0.8$ and 50 events with $M_L > 2$ (Sherburn *et al*. 2013).

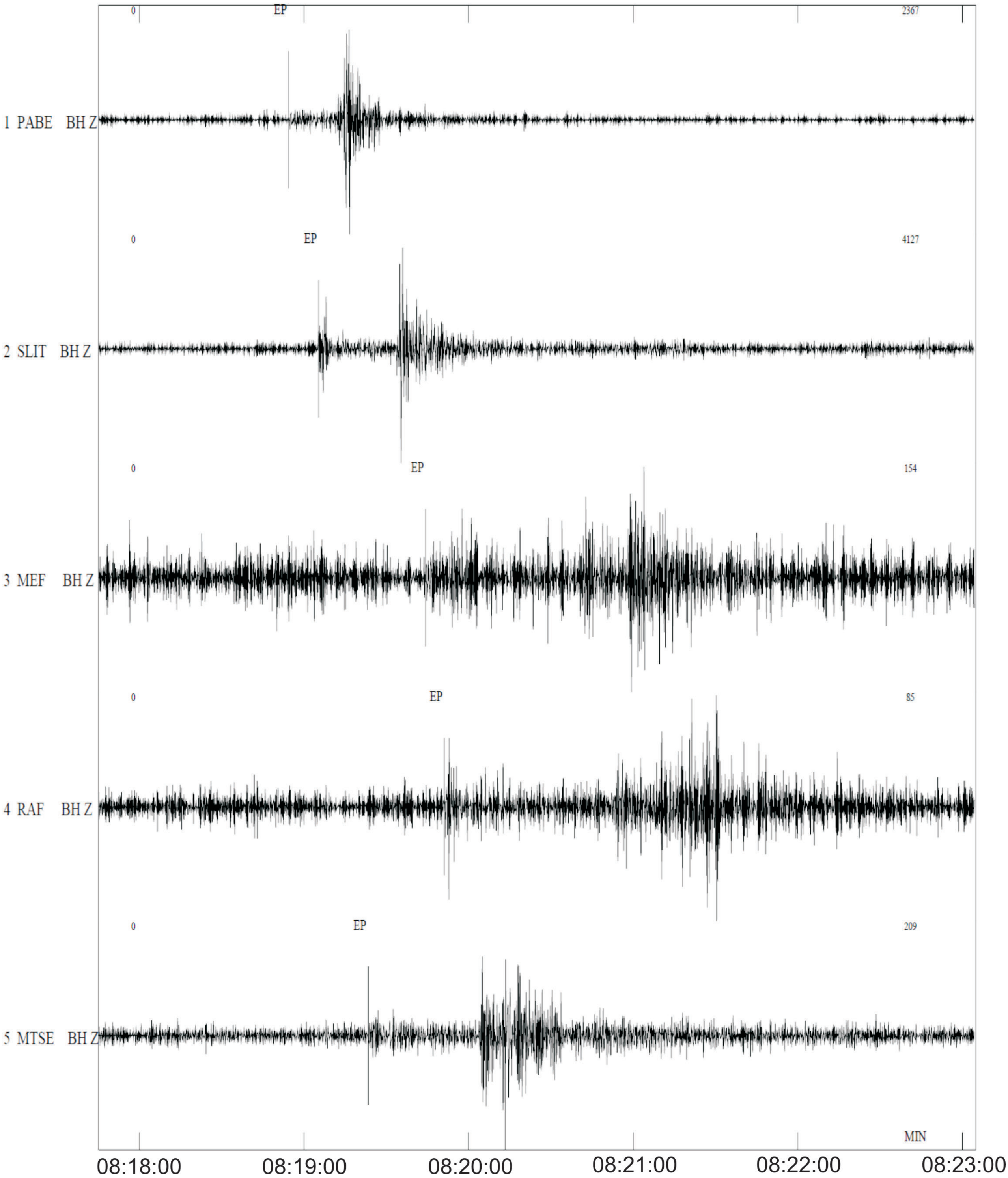


**Fig. 5** Records of seismic event with signs of an earthquake near the Curonian Lagoon (Lithuania) on 12 June 2015. Notes: filtering 3.0–8.0 Hz; only the Z-components are shown

There is no complete clarity about the actual type of event: whether it is a tectonic or probable man-made earthquake induced by getting of geothermal energy. The location of the epicentre on 12 June 2015 in the area of the Klaipeda geothermal anomaly suggests that this event can be qualified as an induced earthquake type.

***Earthquake near Lake Võrtsjärv in Estonia on 12 November 2016***

On 12 November 2016, a tectonic earthquake occurred near Lake Võrtsjärv in Estonia. According to the HEL data *(University of Helsinki Institute of Seismology – UHIS)*, the magnitude of the earthquake was $M_L$ = 1.8 and the depth of the hypocenter was $H$ = 1.2 km. As a result of the location with the help of the *BAVSEN* network (*LEGMC*), the following earthquake parameters were obtained: magnitude $M_L$ = 2.4 and hypocenter depth $H$ = 1.1 km (Fig. 6).

For 5 stations (VSU, ARBE, MTSE, MEF, SLIT), the quality of the recordings made it possible to determine the polarity of the first P-waves and determining the mechanism of the earthquake source. The solution of the focal mechanism gave the following results: *STRIKE* = 41.6; *DIP* = 45.3; *RAKE* = –97.5. Negative sliding angle *RAKE* indicates that the slip of the hanging wall relative to the foot wall goes downward. The solutions, the mechanism of the source of this earthquake corresponds to the regime of the prevailing normal fault with a small strike-slip component.

The epicentre of the earthquake of 12 November 2016 was located on the site where the Paldiski-Pskov tectonic zone intersects with the alleged tectonic fault (Vaher 1983; Tuuling 1990).

In the area of Lake Võrtsjärv, not only did historical earthquakes occur in 1823 and 1909 (Mushketov, Orlov 1893; Doss 1898, 1909), but also a modern sensitive earthquake occurred in 1987 (Nikonov, Sildvee 1991). Its epicentre is connected to the Paldiski-Pskov tectonic zone. Therefore, within the southern slope of the Baltic Shield, the Lake Võrtsjärv region is characterized by increased seismic activity compared to other EBR areas.

***Seismicity of the Saint Petersburg region***
***Earthquake on 11 July 2007***

The intensification of seismic activity caused by the Kaliningrad earthquake at the beginning of the

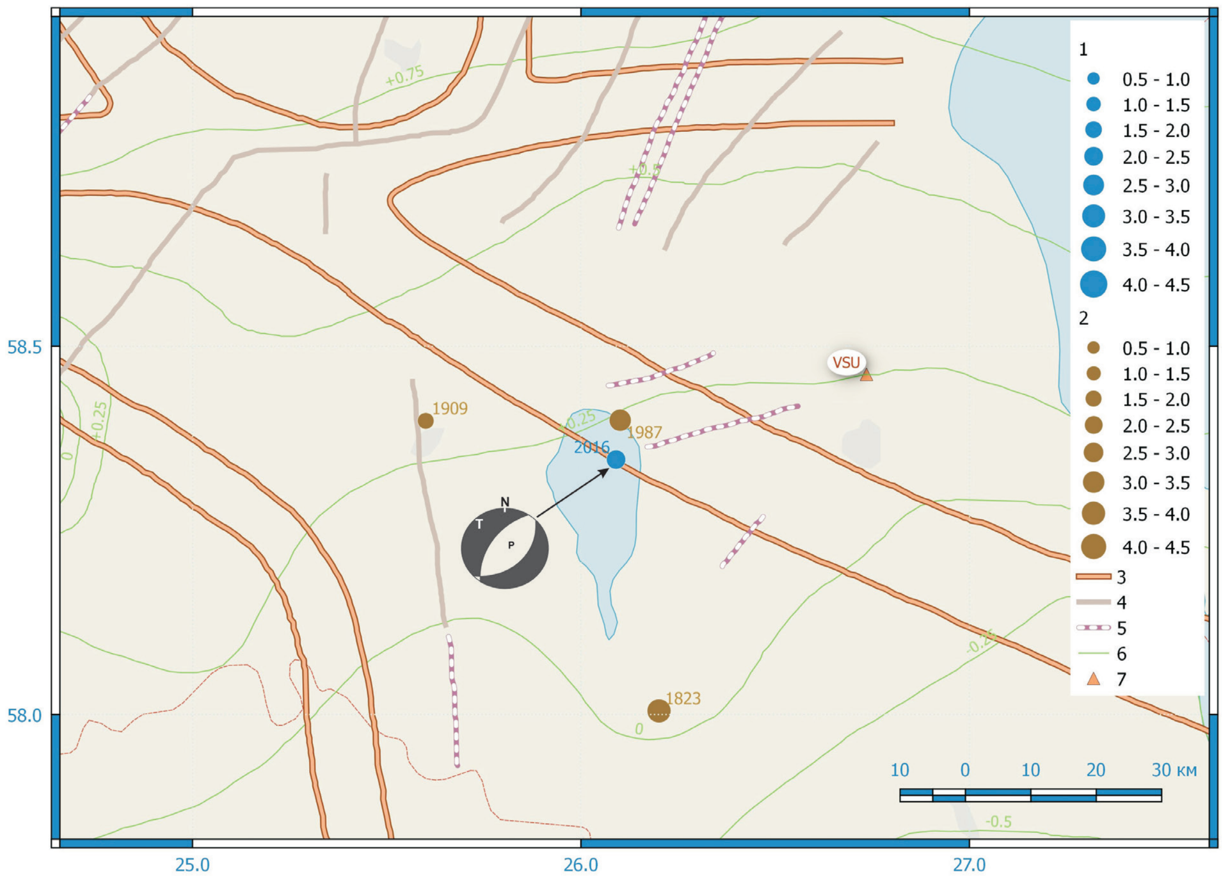


**Fig. 6** Seismotectonics of Lake Võrtsjärv area, Estonia: 1 – magnitude of modern earthquakes; 2 – magnitudes of historical earthquakes; 3 – deeply located zones of dislocations in the crystalline basement from geophysical data (Pobul, Sildvee 1975); 4 – zones of dislocations in the crystalline basement and sedimentary cover according to drilling data (Vaher 1983; Tuuling 1990); 5 – alleged zones of dislocations; 6 – the model of velocity of vertical crustal movements EST2015LU (Kall *et al*. 2016); 7 – seismic stations of the BAVSEN network

21st century was also noted in the Gulf of Finland, including its eastern part.

The earthquake on 11 July 2007 (60.104°N, 28.84°E, H 2.9 km, $M_L$ 2.0) $T_0$ = 15 h 45 m 27.9 s) occurred in the east of the Gulf in the area of its narrowing. The event was recorded by all stations of the Fennoscandian region, and the position of the hypocenter was determined with the help of the nearest Russian and Finnish seismic stations VAL, VYB, JOF, VAF, RAF, MEF, etc.

The seismotectonics of the region is determined by the heterogeneous structure of the crystalline basement which is represented here by deeply metamorphosed Archean and predominantly Early Proterozoic rocks penetrated by intrusions of various genesis; they are represented mainly by rapakivi granites in association with gabbro-anorthysites. Various fractures of the Gulf have small linear dimensions and amplitudes of vertical displacement not exceeding 20 m, they are nonlinear, segmented in plan, and are revealed both in the basement and in the cover. Discontinuities have mainly northeast and northwest directions (Fig. 7).

The earthquake focal zone is confined to the tectonic node (Fig. 7) formed by the faults of north-western and north-eastern directions, not exceeding 20 km in length. The faults are developed within the Vyborg rapakivi batholith near the border of the latter with the enclosing rocks (Amantov *et al*. 2002).

The investigated earthquake source mechanism follows the morphology of the faults. According to the data obtained, a strike-slip movement with a small fault component along the possible planes of rupture occurred in the source.

A more suitable plane dips vertically and is orientated to the east-north-east; the second plane is of submeridional strike with a dip of 60° to the north-east. The first plane of the rupture coincides with the faults shown on the map, from which it can be concluded that these ruptures may be active at the present stage. Meridional directions are also probably active, as they mark the ancient orographic network.

In general, the 11.07. 2007 earthquake in the centre of the eastern part of the Gulf of Finland indicates the mobility of the southern boundary of the rapakivi massif.

Two areas of 2003 and 2011 earthquake swarms of a hundred events ($M_L$ from 0.4 to 2.8) are known in Anjalankoski and Kouvola within the Vyborg rapakivi intrusion on the northern shore of the Gulf of Finland (Uski *et al.* 2006; Smedberg *et al.* 2012). The events belong to the northeast-oriented zones with a length of 1 km at a depth of ~2 km. The focal mechanism is also defined as a normal strike-slip over the vertical fault plane with a strike of 250°.

### *Earthquake on 31 July 2010 in Ladoga Lake*

The earthquake occurred in the evening at 18:44 GMT in Ladoga Lake near the south-western cape of the Valaam Island. It is described in detail (Assi-

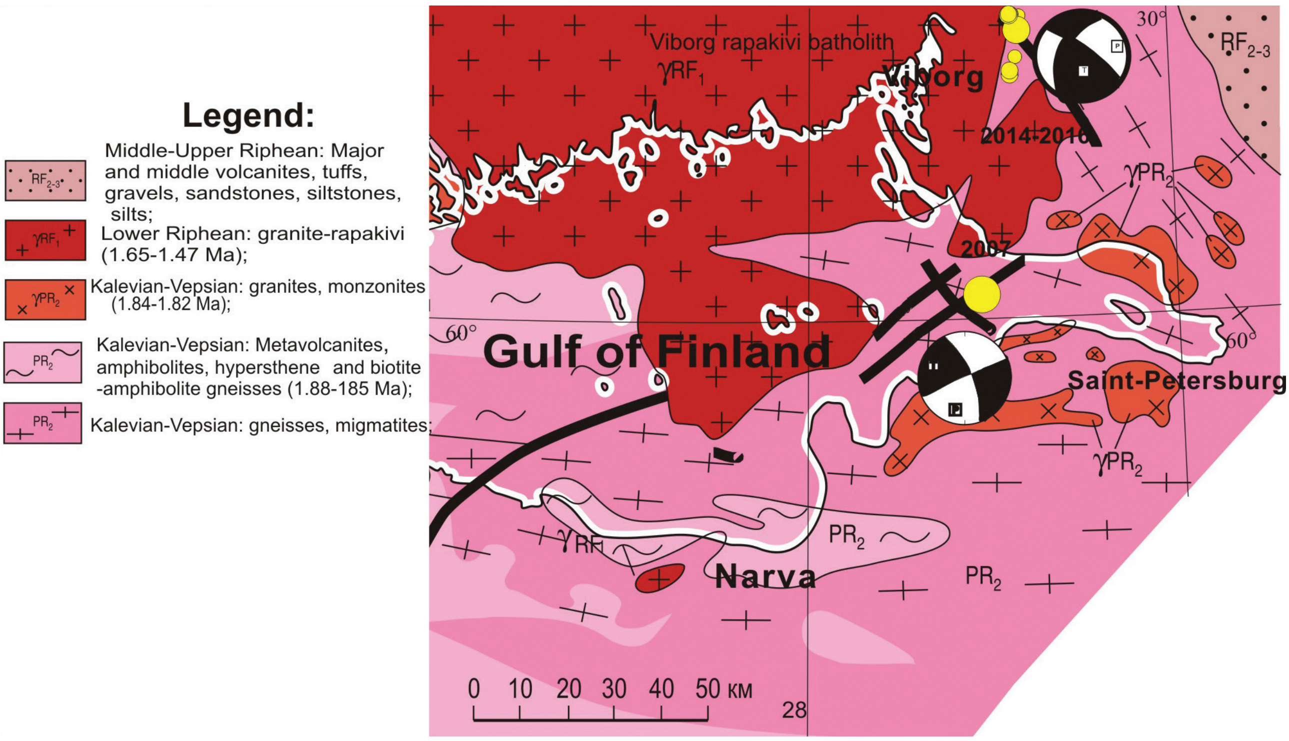


**Fig. 7** Map of the geological structure of the pre-Vendian formations of the eastern part of the Gulf of Finland and adjacent areas and earthquakes of the region. It was compiled on the basis of the map of the Precambrian basement of the Gulf of Finland (Koistinen 1994), with refinements and additions (Geology and minerals …2006; Kirikov 2012; Kirs *et al*. 2009; Soesoo *et al.* 2004; Amantov *et al*. 2002). Epicentres of earthquakes are indicated by yellow circles, the size of the sign is proportional to M/10. The figure shows 11.07.2007 and 18.12.2016 earthquake focal mechanisms

novskaya *et al.* 2011). Despite a small magnitude of M~1, the event was recorded instrumentally and was felt macroseismically (Figs. 8, 9). It can be considered the first earthquake from this region recorded by specialized seismic equipment. In addition, there are reasons to believe that this seismic activity also manifested in a swarm of accompanying microearthquakes (32 events with M from –0.8 to 3 only). One event preceded the main event, and more than three dozen that occurred after it constituted a seismic swarm.

Localization of the earthquake source, as well as several others where the main phases were definable was carried out using the azimuth to the epicentre and the distance (Fig. 10). A fixed depth of 1 km was used. The analysis of longitudinal and shear wave velocities, based on the known lithological rock composition leads to values of epicentral distances equal to 2–3 km. The instrumental magnitude $M_L$ is –0.8 for the main shock and from –1 to –2.5 for the rest (Joswig 1999).

From the macroseismic point of view, the event manifested itself in the form of a push and shaking, the vibration of the floor and furniture felt by all people inside the buildings, by the fall of individual objects, and light panic (some people ran out into the street). Under the open sky, shaking was not felt, but all observers describe sound phenomena in the form of a blow, cotton from under the ground, thunder, an explosion with a long train, the noise of a fallen object that came from the southwest of the rocky shore, from the side of the

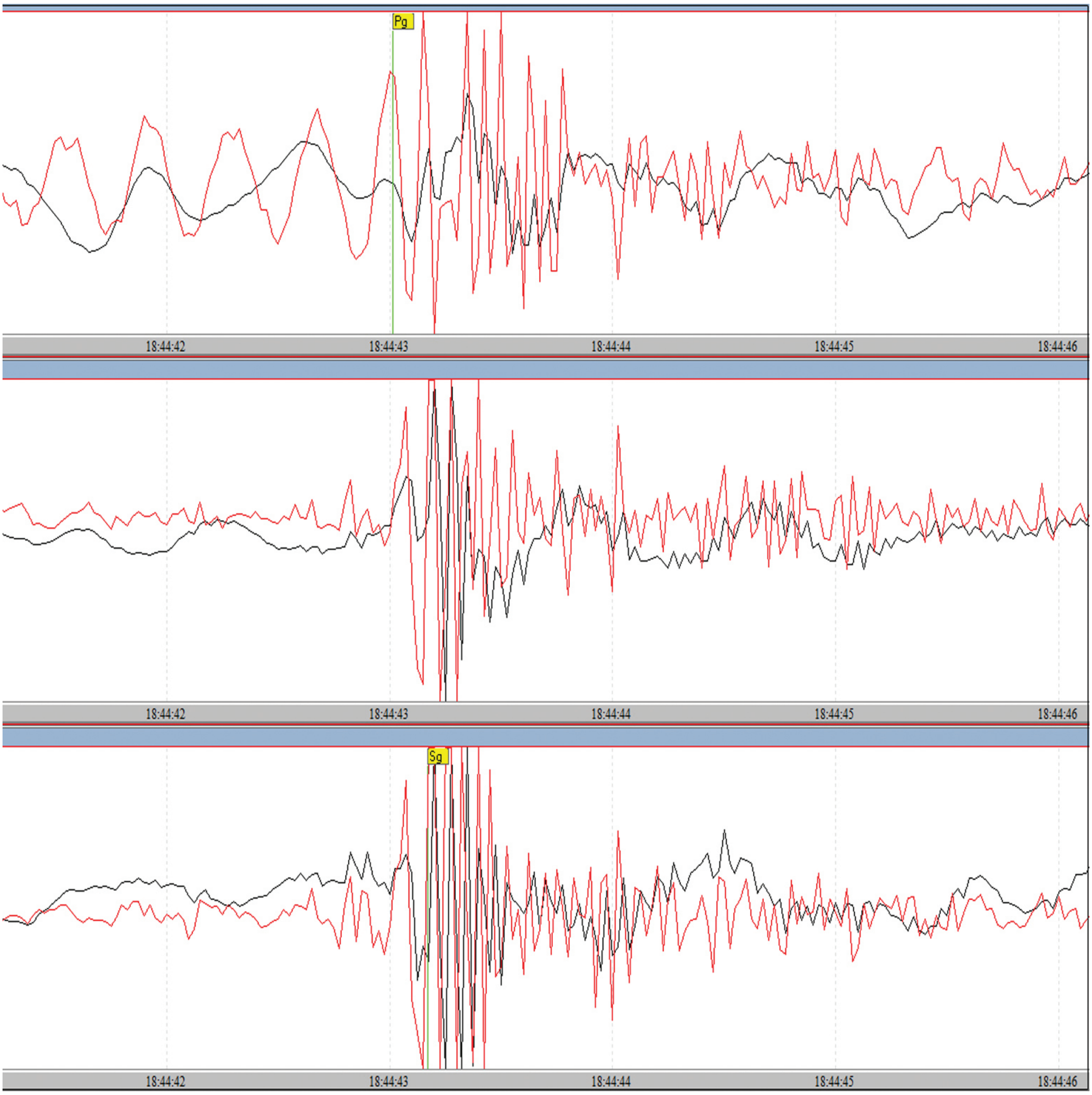


**Fig. 8** Recording of the ground movement velocity in μm/s of the Valaam seismic station (VAL) during the earthquake on 31 July 2010 at 18:44 GMT (the components of the top-down recording are Z, EW, NS)

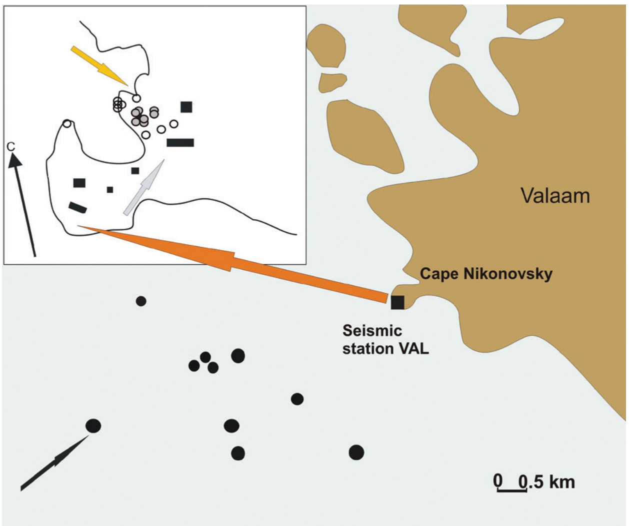


**Fig. 9** Earthquakes from 31.07.2010 18:33 GMT to 31.07.2010 23:17 GMT with $M_L$ from –0.8 to –2.6 in the area of Cape Nikonovsky. The strongest event is shown by a black arrow. The average azimuth is 234.7°, the average distance is 2.19 km. The macroseismic map is shown additionally. On the map: the seismic station is shown by the orange arrow; the place of geodynamic manifestations is marked by the yellow arrow, points with intensity 3–4 EMS and 2 EMS are shown by the gray and white circles, respectively; direction of arrival of sound is marked by the grey arrow

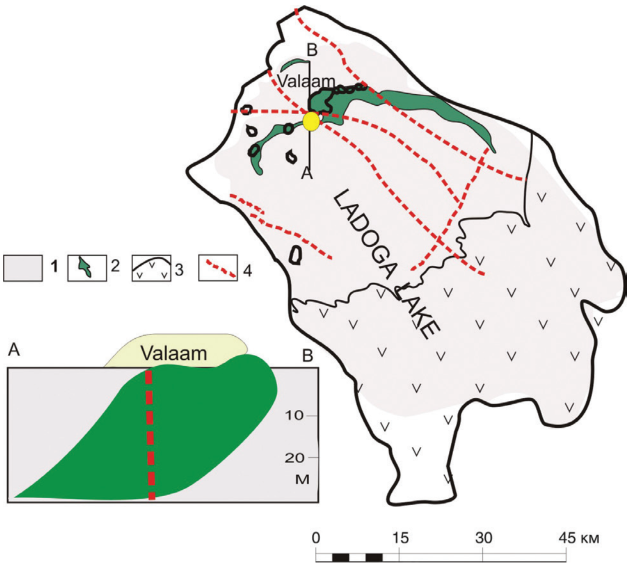


**Fig. 10** Earthquake position on the geological map of the region; the section has 4 times enlarged size, it shows the part of the Valaam sill (after modified Schematic ... 1991). Number 1 denotes Riphae deposits; number 2 indicates Valaam sill; number 3 denotes Vend and Palaeozoic deposits; fault is denoted by number 4

lighthouse. Some people were scared even on the street, they wrote: "Everyone immediately realized that this is a natural phenomenon of a large scale, it was like the beginning of the end of the world." All these observations clearly correspond to the level of macroseismic intensity of 3 to 4 MSK-64 (EMS-98).

Thus, the earthquake source according to instrumental data was definitely within the lake at a distance of 2–3 km from the shore, and its intensity reached 4 EMS in a narrow coastal strip. One more important and unusual circumstance can be noted: the most powerful seismic event of the swarm was preceded by a hydrodynamic precursor in the form of a funnel on the surface of water that suddenly appeared near the shore: some objects were drawn into the crevice (the place of these manifestations is noted in Fig. 9). We consider it is important to note that the described earthquake swarm occurred two days after the hurricane on 29 July 2010 in the north-western regions of Russia with a centre in the Priozersky district of the Saint Petersburg region [http://www.meteo.nw.ru/articles].

The hurricane had an impact on the water level in Lake Ladoga. In the evening on 30 July, according to observer's reports who were close to Island Nikolsky located near the northern shore of Valaam, "the water in the lake in the form of a long-period wave left the shore, and then returned." It can be assumed that its height was probably less than the height of the shore of 8 meters. According to other visual observations, this wave had enough strength to pass through the inner channels of the island of Valaam and to move the submerged logs over a certain distance. These hydrodynamic phenomena are almost certainly associated with the phenomena of the appearance of a seiche. Seiches on Lake Ladoga have been studied in sufficient detail (Kalesnik 1968). If this process is to be considered in detail, it should be pointed out that it began one day after the seiche. In the geodynamic aspect, it appears that a long wave passing through the whole island upset the hydrodynamic and, consequently, hydrostatic balance, which, as is known, led to the occurrence of additional stresses, which in this case were released as a series of microearthquakes.

The tectonic reason for earthquake occurrence is due to the geological structure of the region and its recent geodynamics. The map of the stress state drawn from GPS data is given in the work (Assinovskaya *et al*. 2011). From the geological point of view, the specific structure of the basin of the northern half of Lake Ladoga is the regional negative structure like the large Riphean Ladoga-Pashsky graben-syncline (Amantov 1992) or the Ladoga Aulacogen. At the same time, the most important feature of the tectonics of the region appears to be the Riphean trapping, which was expressed in the formation of a large Valaam layered sill with the predominance of rock formations in the form of gabbroids with a thickness of up to 150–200 m near the island of Valaam (Amantov *et al*. 1992). (Fig. 10). In addition, there are a lot of linearly extended north-western fault zones oriented meridionally (330°–350°) in the area of the Ladoga structure. Figure 10 shows the intersection of the two long faults and the Valaam sill where 31 July 2010 events occurred. The earthquake swarm of 2010, registered instrumentally, confirmed the potential seismic activity of the southern end of the Ladoga-Bothnic seismogenic zone, and the fact of the absence of instrumental period earthquakes in the Russian part of the Ladoga region is probably associated with a short interval of permanent seismic observations. There is an established connection between seismic and natural hydrodynamic phenomena on Ladoga (Assinovskaya *et al.* 2011).

***Induced earthquakes of 2014–2016 on the Karelian Isthmus***

The northern half of the Karelian Isthmus with dimensions of 90–100 km is predominantly characterized by outcrops of hard rock represented by granitites of various origins. They are intensively developed by the explosive method (1500 explosions per year). Such an intensive impact on the geological environment led to the appearance of additional stresses in some blocks of the Earth's crust, which are currently discharged seismically. Recently the Saint Petersburg network of seismic stations has been recording weak seismic events. The seismic process of March 2014 – December 2016 was studied in detail. Event epicentres were located on the Karelian Isthmus; they differed from the explosions dramatically and concentrated locally in the form of swarms in the vicinity of the Erkilja quarry (only 10 earthquakes in 2014–2016 with $M_L$ from 1 to 2.1 are shown in the catalogue). These events are similar to the swarms of 2003 and 2011 in Finland. The events are characterized by different signs of the first arrivals of body waves on seismograms, which consequently made it possible to construct the focal mechanism of the main event. As an example, Fig. 11 shows the earthquake seismograms of 01.18.2016 at 00:30 with $M_L$ 1.4 from the specified swarm. The distances from the epicentre were 8 km to the station VYB, 53 km to IZM, 122 km to LOPUX, and 129 km to VAL.

The main features of the recordings are, firstly, characterized by the presence of sP waves at the VYB station and often also at the remaining stations 0.3–0.7 seconds after the first arrival, secondly, by the presence of a characteristic high-amplitude and high-frequency group of vibrations with a duration of about 5 s in the structure of the S wave, and, thirdly, by a relatively low-amplitude Rayleigh wave (Panas, Assinovskaya 2017). To determine the main parameters of the earthquake hypocenters and their magnitudes, the WSG and SEISAN software complexes were used, the errors were estimated using the HYPODD program. They were in the range of 0.5 km × 0.9 km for the strongest earthquakes and 0.5 km for 0.9 km in depth. The earthquake focal mechanism was built for the strongest event registered on 18 December 2016 at 00:20 using the first arrivals of P waves of the Saint Petersburg network stations, as well as Finnish and Estonian stations. The solution obtained indicates a thrust-strike-slip movement along the plane with a dip of 75° and a north-western strike of the rupture plane of 308°. Judging by the similarity of waveforms and the polarity of the first arrivals, the focal mechanisms of all the earthquakes of the recorded swarm will be similar, and the geodynamics of the region is determined by the prevailing compressive

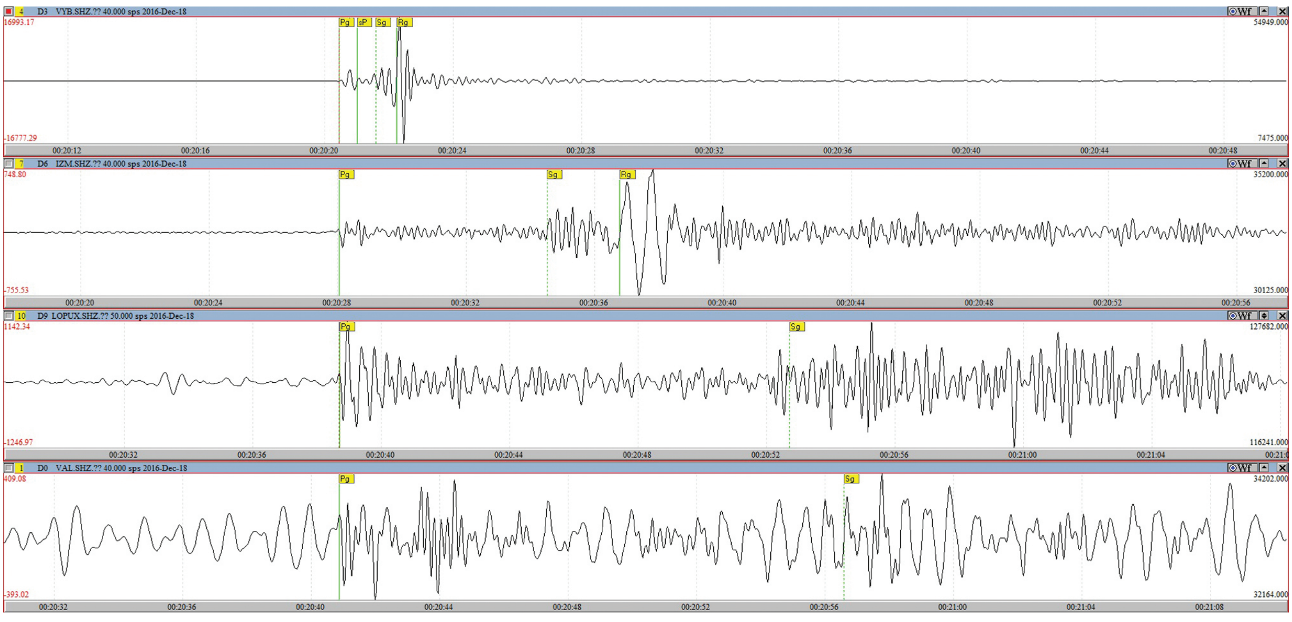

**Fig. 11** Records of the vertical component of VYB, IZM, LOPUX, VAL stations (top-down, respectively) filtered in the 2–8 Hz band (Butterworth, 3rd order) of the event of 18.12.2016 at 00:20 with $M_L$ 2.1. The records are aligned for the first arrival of Pg

stress in the north-western direction and submeridional near-vertical dilatation (Fig. 7). Sequences of earthquakes often appeared with a very short time interval one after another with the superimposition of waveforms. The time of occurrence of events is distributed uniformly enough throughout the day, the interval of magnitudes $M_L$ being from –0.6 to 2.1. The swarm type event sequences form a linear zone with a length of about 4 km of submeridional strike, as is shown on the map (Fig. 7). Interestingly, the orientation of the zone as a whole does not coincide with the direction of a possible plane of rupture in the focal mechanism, which might suggest that, perhaps, the swarms activated smaller ruptures in the other direction. It can also be assumed that the faulting occurred in the vertical direction. From the geological point of view, the region can be distinguishingly characterized by the presence of the eastern side of the Vyborg rapakivi granites intrusion, which is a thick plate-like body stretching over 180 km in length from north to south and 60 to 130 km in width from west to east (Kiselev *et al.* 1997). It is worth nothing that batholith is rich in lithological and structural homogeneities, rapakivi granites themselves are represented by several petrographic varieties such as viborgites, piterites and large-ovoid porphyry formations. The structure is faulted by numerous sub-parallel tectonic dislocations, mainly of northwest strike (http://www.geolkarta.ru/list_200.php?idlist=P-35-XXIX). In some places, including the source zones and around, there are faults and vein formations of the orthogonal north-western orientation, both pegmatite-aplite and pure quartz in composition. It can be assumed that the identified areas of seismic activity are confined to local tectonic nodes. The same fault structures are found inside the rapakivi massif in the areas of the Anjalankoski swarms described above in 2003 and Kouvola in 2011 in Finland. The historical seismic activity of 1870, 1902, and 1926 on the Karelian Isthmus (Renquist 1930) is confirmed by modern instrumental data, namely, by the occurrence of a sequence of earthquakes such as swarms. It is also impossible to exclude the induced nature of modern seismicity, since this region had never experienced such a strong explosive load earlier.

## DISCUSSION

Long-term stationary seismic observations are required to assess the seismic hazard. The seismic network described in this paper is intended to be a solution to this problem. Strong earthquakes in 1976 and 2004 do not give a complete picture of the seismic activity of the East Baltic region, since until 2004 there were no comprehensive systems of seismological observations. However, the seismic stations created after 2004 within the GEOFON network are not sufficient for the entire region due to their scattered location, large distances between them, a high seismic noise level and unfavourable geological conditions in the central and south-western part of the EBR. National networks of stations address the problems of studying seismicity in local areas, such as, for example, the Karelian Isthmus or Estonia.

Consequently, there is a difficulty in identifying the genesis of seismic events, especially in the central and south-western parts of the EBR. Unlike the north-western part of the EBR (Saint Petersburg region of Russia and northern Estonia), where the stations are compactly located on the Baltic shield or its southern slope with the minimum thickness of the sedimentary cover, the seismic stations located in the Baltic Syneclise have a high level of seismic noise. The sedimentary cover significantly affects the polarization of seismic waves. This is especially true for high frequencies, which are typical of regional and local seismic events. It is precisely due to the difficulty in determining the polarization of the first arrivals that it turned out impossible to obtain an estimate of the focal mechanism of the seismic event on 12 June 2015 in Lithuania. This event was recorded by the stations located on the sedimentary cover. The Baltic Shield creates more favourable conditions for assessing the polarization of the first arrivals.

The sources of strong earthquakes in 1976 and 2004 are located in the coastal zone of the Baltic Sea. It is characteristic that the majority of earthquake epicentres for the analyzed period (2004–2017) in the EBR are also located in the coastal zone, especially on the north and west coasts of Estonia. There is a tendency towards a lower level of seismic activity from northeast to southwest. Evidence suggests that the inherited nature of the seismic activity manifested in the coastal zone of the EBR is associated with an elevated horizontal gradient (Nikulin 2007) of vertical neotectonic movements, starting from *Rupelian* (Garetsky *et al*. 1999) in the Baltic Sea basin.

The mechanism of the earthquake in the area of Lake Võrtsjärv is defined to correspond to the regime of the prevailing normal fault with a small strike-slip component. According to other results, the mechanism of the earthquake focus in the area of Lake Võrtsjärv is in line with the mechanism of the source of the Osmussaar earthquake of 1976 (Assinovskaya *et al*. 2013). In the seismotectonic scheme presented in the study of an international group (Kondorskaya *et al*. 1988), the epicentre of the Osmussaar earthquake of 1976 is located on the fault in the crystalline basement and Palaeozoic deposits, which extend in the east-north-east direction in the form of isoseists of 6 and 5 points. In terms of the earthquake focal mechanism in the area of Lake Võrtsjärv, its nodal planes are directed northeast, i.e. very close to the direction of the extension of the seismogenic fault for the Osmussaar earthquake.

## CONCLUSIONS

The study of the seismicity in the EBR after the Kaliningrad earthquakes of 2004 showed that: 1) the epicentres of the registered earthquakes are mainly concentrated in the coastal zone characterized by an elevated horizontal gradient of vertical neotectonic movements, 2) in addition to the naturally occurring earthquakes caused by the drop of tectonic stresses, on 12 June 2015 the zone of the Klaipeda geothermal anomaly probably experienced an induced earthquake triggered by the exploitation of geothermal resources, 3) as for the earthquake in the area of Lake Võrtsjärv on 12 November 2016, its focal mechanism was estimated as a very insignificant right lateral slip and corresponded to the regime of the prevailing normal fault with a small strike-slip component, 4) in the conditions of the sedimentary cover of the central and south-western parts of the EBR, it is difficult to estimate the polarization of the first P-waves and solve the focal earthquake mechanics, 5) during 2004–2017 there was a decrease in seismic activity in the EBR from northeast to southwest, 6) seismic stations do not cover the area of the EBR evenly, forming voids in the central (Latvia) and western (western Lithuania) parts, and 7) during the period under study, there was a seismic activation of the southern end of the Ladoga-Bothnic zone and faults marking the boundaries of the Vyborg batholith of rapakivi granites in the south and east of the structure.

A high rate of mineral extraction carried out by the explosive method may also have contributed to the emergence of technogenic-tectonic earthquakes on the Karelian Isthmus of the Saint Petersburg region.

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