Geophysica (1991), 27, 1-2, 79-93

Historical Earthquakes in Estonia and Their Seismotectonic Position

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Abstract

The earthquakes known to have occurred in Estonia since 1670 are reviewed on the basis of data available. Some moderate earthquakes were recorded in 1670, 1827, 1877, 1881 and 1976, with their intensity reaching from 3 to 6-7 units on the MSK-64-scale. Epicentre concentration within the western and northern parts of Estonia shows relatively intense tectonic activity in these areas during the last centuries. The earthquake epicentres are correlated with the tectonic setting of the area.

1. *Introduction*

The Osmussaar earthquake on October 25, 1976, with magnitude 4.7 (M_{LH} = 4.3 ± 0.5) and I_0 = 6-7 (*Slunga, 1979; Ananjin et al.*, 1980; Kondorskaya et al., 1988), was an unexpected event with respect to location and time. For a long time, Soviet seismologists were mainly engaged in the study of high-seismic territories, dealing with small and moderate earthquakes only if they were associated with destructive earthquakes. The territory of Estonia was considered a seismically inactive area. The map of seismic zones in the USSR (*Karta seismicheskogo...*,1983) and the map of maximum observed intensity in Europe (*Radu et al.*, 1983) present Estonia, like some Fennoscandian areas and the East-European Platform, as an aseismic area.

Such was the situation before the Osmussaar earthquake of 1976; it did not indicate the level of information about ancient seismic events in Estonia that can be seen from the earlier catalogues (*Hoff*, 1840; *Carlbom*, 1855; *Perrey*, 1846; *Mushketov* and *Orlov*, 1893) and also from some more recent publications (*e.g. Ananjin*, 1968; *Nikonov*, 1977a).

In this study the authors focus special attention on the material concerning historical earthquakes in Estonia with a view to studying the seismicity of this part of the East-European Platform more comprehensively.

Published by the Finnish Geophysical Society, Helsinki (1992)

2. *Macroseismic data*

There is a lack of earthquake data meeting the requirements of the present standards for Estonia, and the authors had to turn to old publications to compile their catalogue. B. Doss' works (1898, 1905, 1910, 1915), which were published at the turn of the century, turned out to be the most informative although they are not given the recognition they deserve in the Russian literature nowadays. As a result of the study, a list of earthquakes that had occurred in Estonia was compiled, including those noted by inhabitants since 1670, i.e. over a period in excess of 300 years (Table 1). In contrast to the three earthquakes (1670, 1823 and 1881) included in the map by *I. V. Ananjin* (1968) in accordance with the catalogue by *I. Musketov* and *A. Orlov* (1893), the list gives 14 seismic events, aftershocks omitted, among them that of 1976. Eight of these earthquakes took place during the 19th century and seven of them during the 20th century. Nine earthquakes were local shocks, being observed at one point only. The maximum intensities ranged from 3 to 6-7 (on the MSK-64 scale). Figure 1 shows the distribution of the earthquake epicentres.

Some data are available on the perceptions and observations by people in a number of places during several earthquakes. This information mostly concerns the earthquakes of 1827, 1877, 1881 and 1904 (the source of the latter was outside Estonia). As the primary information is virtually inaccessible, we are justified in presenting certain macroseismic descriptions after *B. Doss*.

<u>On September 28 (Sep. 16 according to the Julian calendar), 1827</u>, in Nukke parish (Vik Region) on Gutern Birkas, Lukholm and Rikholts, a slight noise reminiscent of a big and heavy passing carriage was heard at about midday for some seconds. Similar phenomena (shaking of floors, shock) were recorded simultaneously at Kleinnomkjull, a village not far from Nybi estate (Pjonal parish), at Veissenfeild (Rjotel parish) and Sallajogi (Pjonal parish) estates, and still farther away, at Padise and Kreitzhof (St. Mattias and Kreitz parish, Harrien region) (Doss, 1898). More than 70 years later, an eye-witness gave an account of a strong earthquake at Vasalemma, during which a little child fell off a boulder (*Doss*, 1905).

From this information we can define the felt area with an intensity of 4. It was located in north-westernmost Estonia (see Fig. 1), occupied about 2.7 thousand square kilometres (Table 2) and was oriented in a northeastern direction.

<u>October 16 (Oct. 4), 1877</u>. *B. Doss* (1905) has collected considerably more data on this earthquake. At 5.25 a.m. at Haapsalu a terrible dull rattle, like a volley of heavy calibre arms was heard, and a simultaneous shock from west to east was felt. The furniture started to clatter and all the window-panes jingled. The far-off rattle was immediately followed by a loud vibrating whistle ("vif-vif-vif"). During each sound a strong wave-like movement of the earth was felt. The sound and the movement ceased in about 7 seconds only to be repeated later with greater force. Beds collided and the movements took place from west to east. No cracks were noticed in small stone houses. There were high waves in the bay

and all the ships in port rocked. Their anchor chains rumbled. Both shocks lasted for 5 minutes, according to other information, with an interval of 10 seconds between them.

At Haapsalu, plaster fell from the ceilings. The way in which boxes were thrown off a shelf in one house gives evidence of the northwest - southeast direction of the shock, although the inhabitants perceived it as proceeding from southwest to northeast.

At a distance of 4-5 km to the southeast of Haapsalu, a carriage on a good road was shaken to and fro and sideways, trees swayed and struck each other although there was no wind.

Macroseismic data are briefly presented in Table 3.

The earthquake was felt at a distance of 50-60 km to the north, 23 km to the south, 31 km to the east and 18 km to the west of Haapsalu. Marking these points on a map and considering the intensity (see Fig. 1), we obtain the approximate range and location of intensity zones 5, 4 and 3 during the second shock (see Table 2).

January 28 (Jan. 16), 1881. At about 14.15 (local time) an earthquake was registered in Narva. It lasted for 3-4 seconds and was accompanied by an underground noise. Vibrations of the earth were noticed at 15 km to the south, 26 km to the east, 10 km to the north and 13 km to the west of Narva. At the station of Korf and in Laagna and Repnik plaster fell from the walls, and in villages the window panes clinked (*Mushketov* and *Orlov*, 1893; *Doss*, 1898). The above evidence suggests an intensity of 5-6 units. The area where the intensity was 2-3 units covered about 1600 km^2 (see Table 2).

The following data on local shocks were noted in 1912 on Keri Island, 30 km to the northeast of Tallinn (*Doss*, 1915). Shocks were felt on April 8 by a lighthouse keeper and his family inside and outside the house in the form of underground blows resembling a crackle (rattle). At the first shock the children indoors became frightened and ran outside. No accompanying jingle of dishes, shaking or damage to the buildings were observed.

Later on June 15, at the same place, shocks were followed by frequent strong shaking accompanied by underground noise. Note that the island constitutes a moraine ridge overlain by Quaternary deposits over 115 m thick.

The supposition that the shakings were caused by cracking marine ice or explosions of gas (*Doss*, 1915) have not been confirmed by facts. They were deduced from the extraordinary nature of the shocks, the accepted idea about the tectonic inactivity of the region and ignorance of similar events in other parts of Estonia (and Fennoscandia), including continental areas and those outside gas-bearing rocks.

The locations of epicentres (Table 1) show that they are mostly concentrated in northwestern Estonia, not far from the epicentre of the Osmussaar earthquake of 1976, which turns out to have been the most important seismic event in the area during the last 300 years (*Kondorskaya et al.*, 1988).

Table 1. Earthquakes in Estonia.

No.	Date	Local time	Epicentre	Felt area	I (MSK-64)	Macroseismic features	Sources
1	Feb 1. 1670	at night		4 km north of Pärnu	6	no serious damage or cracks in humid soil	Doss (1898, 1910) Amelung (1904)
2	Feb 5. 1823	at night	Kuikatse	Kuikatse station, 7 km SE of the southern coast of Lake Võrtsjärv	4-5	strong shocks noted by everyone inside building	Doss (1910)
3	Sep 28. 1827	about midday	north of Haapsalu		(5)		Doss (1898, 1905)
4	Jan 12. or 17. 1844	at night	Karuse villge	Upper Kuuramaa	4	shocks, various events possible	Hermann (1970) Doss (1910)
5	Mar 26. 1853	between 4 and 5 a.m.		some distance from Tallinn	(3)	people woke up because of noise, no shaking was felt	Doss (1910) Über... (1853)
6	Jan 15. 1858	14 h 10 m and 14 h 26 m	north of Hiiumaa Island		5	two waves (tsunami) on the northern coast of Hiiumaa Island	Doss (1898) Musketov and Orlov (1893)
7	Feb 15. 1869	at 3 a.m.	surroundings of Tallinn		4	China clinked, windows and doors rattled, sleepers woke up	Doss (1910)
8	Oct 16. 1877	5 h 25 m	near or north of Haapsalu	see Table 3	4 and 5	two shocks at an interval of 10 sec.	Über... (1877) Doss (1905, 1910)
9	Jan 28. 1881	14 h 15 m	town of Narva	surroundings of Narva	5-6	window-panes jingled, things fell to the floor plaster dropped	Bericht... (1881) Doss (1989, 1910)
10	Jun 2. 1909	11 h 30 m	surroundings of Viljandi	town of Viljandi	3		Hermann (1970)
11	Apr 8. 1912	between 4 and 5 p.m.	Koksher (Keri) Island, 30 km to NE of Tallinn	Koksher Island (Keri)	3		Doss (1915)
12	Apr 8. 1912	about 23 h 10 m	- " -	- " -	2-3		Doss (1915)
13	before Jun 15. 1912		- " -	- " -	3-4	frequent shaking and underground noise	Doss (1915)
14	Jul 12. 1931	at night	Anija village	35 km east of Tallinn	4-5	3-4 shocks in one hour	Kuuskand (1935)
15	Oct 25. 1976	11 h 39 m	59.3N, 23.5 E 3-7 km to the NE of Osmussaar	Major part of Estonia and southern Finland	6-7	3 shocks, shaking of ground, strong noise	Klaamann (1977) Slunga (1979) Ananjin et al. (1980) Kondorskaya et al. (1988)
16	Oct 25. 1976	11 j 49 m	- " -	NW Estonia	4-5	aftershock	- " -
17	Oct 25. 1976	12 h 07 m	59.3N, 23.5E	NW Estonia	3-4	aftershock	Klaamann (1977) Ananjin et al. (1980)
18	Nov 17. 1976	13 h 17 m	- " -	- " -	4-5	- " -	- " -
19	Nov 22. 1976	15 h 14 m	- " -	- " -	(2)	- " -	- " -
20	Apr 8. 1987	21 h 21 m	Lake Võrtsjärv	Towns of Tartu and Viljandi, Lake Võrtsjärv	4	windows and doors rattled, household utensils and china clinked, floors and walls of wooden houses creaked	Sildvee (1988)

Table 2. Comparison of macroseismic fields of main earthquakes in Estonia.

No.	Year	l_{max} (km)			l_{min} (km)			S (km^2)			H (km)	M	I (MSK-64)
		5	4	3	5	4	3	5	4	3			
1	1827		80			50			2700		14±2	4.0±0.3	5
2	1877 second shock	(15)		90	(10)	40	65	(150)	2000	4400	10±2	3.5±0.3	5
3	1881	10		70			30	70		1600	5±3	3.0±0.7	5-6
4	1976 main shock	275-325	450		60-75	325		16000-18000	98000		10±3	4.75	6-7

l_{max} - long axis of isoseismal; l_{min} - short axis of isoseimal; S - area of the isoseismal zone.
Approximate values in brackets.

Table 3. Macroseismic data on the earthquake in Oct. 16. 1877 in Estonia.

No.	Observation point	Intensity (MSK.64)	No. of observations	Remarks
1	Haapsalu	4 5	6	First shock Second shock. During both shocks, shaking spread from the west
2	St. Martens (Martna)	(4)	1	
3	Vormsi Island	4	3	
4	To the south of Matsalu Bay	3-4	1	The point in Matsalu Bay was not affected by the shock
5	Odinsholm Island (Osmussaar)	(3)	1	Two shocks were felt
6	4 km from Risti settlement	3	1	In Risti settlement the shock was not observed
7	Sen-Mattais, Padis (Harju-Madise)	3	1	
8	Hiiumaa Island, Putkaste (Keinas)	3	1	
9	Ditto, Pühalepa, Kärdla	2-3	2	

3. *Main parameters of Estonian earthquakes*

To determine the main parameters for the earthquakes we used the macroseismic field equations of N.V. Shebalin (*Novyi katalog*..., 1977). The focal depth was estimated from the size of the intensity areas and the magnitude was assessed with a standard procedure, using a monograph (*Novyi katalog*..., 1977; Fig. 10 b, 13). In the case of local shocks, when information was received from one point only, the radius of the felt area was calculated taking into account the lack of information of the events from the nearest big settlements.

Some discrepancies are apparent with respect to the coefficient of attenuation, which differs for the Fennoscandian Shield depending on the author. The *Novyi katalog* (1977) gives the value k= 3.5, Finnish scientists (*Ahjos* and *Arhe*, 1983) prefer the value k= 4. We have calculated the values M by both coefficients of attenuation. When k= 4, the depths increase by some kilometres and the values of M are by 0.3 - 0.5 units higher. The mean values of M have been considered the most reliable (Table 4).

For the northern part of the Fennoscandian Shield magnitude (M) was calculated using the formula of *G.D. Panasenko* (1977): M=2.7+lg S, where S is the felt area (I=3) over thousands of square kilometres. For earthquakes in 1827 and 1877, the same formula gives the following values: M = 3.5 and M = 3.3, i.e. the mean values are somewhat lower than those obtained with N.V. Shebalin's method; however they still remain within error limits.

Six of the earthquakes of our catalogue are included in the catalogue of Finnish authors (*Ahjos* and *Arhe*, 1983). They give higher magnitude values for the earthquakes of 1670, 1869, 1877 and 1881; 4.2, 3.6, 4.2 and 3.2, respectively, because of the higher estimated intensity. In their catalogue, the maximum intensities for the earthquakes of 1827 and 1853 are lower than ours. The values of magnitudes are correspondingly smaller, M=3 and M=2.5. The parameters determined in this study for Estonian earthquakes are presented in Table 4.

Assuming that the collected primary material represents the seismicity of the area exclusively, the following conclusions can be drawn. During the last 300 years, about 13 earthquakes have occurred in Estonia and surrounding water area; one with a maximum intensity of 6-7, four with 5 and at least 7-8 earthquakes with 4, when aftershocks of the event in 1976 are included.

The majority of epicentres were located in coastal areas of the northwestern part of Estonia. The epicentres of four earthquakes form a longitudinal line at the town of Haapsalu. However, the long axes of the isoseismals of the three strongest earthquakes (1827, 1877 and 1976) stretch in a northeastern direction.

The areas of intensity zone 5 were from ten to a few hundred square kilometres; only the zone of the earthquake in 1976 covered an area of 16-18 thousand km^2. The areas of intensity zone 4 were 2-3 thousand km^2 with the exception of the 1976 earthquake, which covered an area of about 100 000 km^2. All estimations were made taking into account the water area and, in the last case, the southern part of Finland, too. Most of the shocks were local, the radius of the felt area being some tens of kilometres.

The focal depth of most of the earthquakes is 10-12 km and of the local shocks 5 km.

Table 4. Catalogue of earthquakes in Estonia, 1670-1987.

No.	Date	Time (GMT)	Coordinates		Depth (km)	Magnitude	Maximum intensity	Isoseismals	Radius (km)
1	Feb 1. 1670	22±3 h	58.4N	24.5E ±0.2	(8±4)	(3.9±0.6)	6	(3)	(80)
2	Feb 5. 1823	22±3 h	58.0N	26.2E ±0.2	(7±3)	(3.9±0.5)	4-5	(3)	(40)
3	Sep 28. 1827	9±1 h	59.0N	23.5E ±0.2	14±2	4.0±0.3	5	4	65
4	Jan 12. or 17	22±3 h	58.6N	23.7E ±0.2	(6±2)	(2.5±0.3)	4	4	35
5	Mar 26. 1853	01.30 ±30 m	59.5N	24.7E ±0.2	(5±3)	1.2±0.7)	(3)	(3)	30
6	Jan 15. 1858	11.10 11.26	59.3N	22.6E ±0.2	(8±5)	(3.0±0.7)	(5)	(5)	(50)
7	Feb 15 1869	00±3 h	59.5N	24.7E ±0.2	(6±3)	2.5±0.3	4	4	30
8	Oct 16. 1877	02.25±0.5 m between shocks 10 sec	59.0N	23.5E ±0.2	10±2	3.0±0.3 3.5±0.3	4 5	first shock 4 second shock 4 3	30 40 70
9	Jan 28. 1881	11.15 ± 0.5 m	59.4N	28.2E ±0.1	5±3	3.0±0.7	5-6	5 3	10 50
10	Jun 2. 1909	08.30 ± 15 m	58.4N	25.6E ±0.2	(7±3)	(1.8±0.5)	3	(3)	(<60)
11	Apr 8. 1912	13.30 ± 30 m	59.7N	25.0E ±0.2	5±3	(2.0±0.5)	3	3	<30
12	Apr 8. 1912	20.15 ±	59.7N	25.0E ±0.2	(5±3)	(1.6±0.5)	2-3	3	<30
13	Until Jun 15. 1912		59.7N	25.0E ±0.2	(6±3)	(2.0±0.5)	3-4	(3-4)	<30
14	Jul 12. 1931	22±3 h	59.4N	25.3E ±0.1	(5±3)	(2.5±0.5)	4-5	(4-5)	24
15	Oct 25. 1976	08.39	59.3N	23.5	10±3	4.75	6-7	5 4	75-300 325-450
16	Oct 25. 1976	08.49	- " -	- " -		3.5	4-5	aftershock	
17	Oct 25. 1976	09.07	- " -	- " -		3.0	3-4	aftershock	
18	Nov 8. 1976	10.17	- " -	- " -	6-13	3.5	4-5	- " -	
19	Nov 22. 1976	12.14	- " -	- " -	13±2	(2.5)	(3)	- " -	
20	Apr 8. 1987	19.21	58.4N	26.1E	(7±3)	3.5	4	3	50-60

Approximate values are given in brackets.

4. *Geological structure and crustal movements in Estonia from the seismotectonic viewpoints*

Specifically seismotectonic studies have not been carried out in Estonia. In the light of present seismotectonic knowledge, the block structure of the crystalline basement in Estonia as revealed by geophysical data (*Pobul* and *Sildvee*, 1975) must be considered when determining the location and nature of earthquakes.

Study of the disjunctive tectonics of the basement of Estonia, taking into account geophysical data, has shown (*Pobul* and *Sildvee*, 1973) the presence of two orthogonal fault systems trending north-south and west-east and a diagonal orientation. Judging by the distribution of the strikes, the faults of the first and second order in the basement (evidently also in the Earth's crust) are dominated by northwestern (40 %) and latitudinal strikes (32 %), the northeastern and longitudinal strikes are in a subordinate position (15 % and 13 %, respectively). The faults of the third order, which are connected with local features of the tectonic structure of the basement, are dominated by latitudinal strikes (32 %). Such is the case also in the distribution of lineaments in the crystalline basement of southern Finland and water area, as revealed by satellite imagery (*Lahtinen*, 1984).

These patterns of the inner structure of the basement have not controlled the general distribution and characteristics of recent movements, including earthquakes.

Study of basement movements due to tectonic features of the Lower Palaeozoic sediment cover (younger rocks are lacking in Estonia) reveales two main features. First, gradual sinking of the basement surface to the south (started in the Vendian), i.e. uplift of the central and northernmost parts of Fennoscandia in post-Early Palaeozoic times (evidently Mesozoic and Cenozoic) with respect to the area of Estonia, see Figure 2. Second (and considerably more important from the seismotectonic point of view), the presence of a fault with a northeastern trend in the east and northwestern and longitudinal trends in the west. Several faults and their groups extend for tens of kilometres with the block displacement of up to 50 m. Imbricate dislocation zones without amplitude have also been recorded. The most important known dislocations in the cover are shown in Figure 2. The greatest, the Aseri zone, which extends from southwest to northeast with a length of over 75 km and a width of 1-4 km, constitutes a flexure with a sunken northwestern block. The displacement magnitude decreases at the base of each overlying formation (from 50 to 22 m). This suggests consedimentary development of the zone in the Palaeozoic and later (*Vaher et al.*, 1962). Apart from long-term evolution of the zones, there exists geological evidence for the change in the slip of the blocks.

Another large tectonic fault zone of Palaeozoic rocks and the underlying basement, trending northeast, occurs at the bottom of the Baltic Sea, extending approximately across Osmussaar Island to the west and southwest (*Gudelis* and *Emeljanov*, 1976; *Sildvee* and *Miidel*, 1978). At the northern and northwestern margins of Hiiumaa Island, unlike its other parts, terrestrial geological investigations have revealed faults in the Ordovician rocks, in a linear belt about 8 km wide and trending eastnortheast at an azimuth of 50-70 degrees. As the basement here lies at a depth of 200-250 m, it is very likely cut by the same faults. To the west-southwest of the western edge of Hiiumaa Island at the bottom of the Baltic Sea in an outcrop area of Ordovician rocks, a fault with the same strike cuts into the Ordovician and Cambrian rocks (*Gudelis* and *Emeljanov*, 1976). The fault, which has a southern footwall with a slip possibly of some hundred metres, likely cuts the basement at a depth of some kilometres.

As to the most recent epoch (Neogen-Quaternary) we infer only a slight general uplift of the Estonian area, which is however, greater in the north. Thus, there may be differentiated displacements by the faults, first of all by those intersecting Palaeozoic rocks.

During the last fifteen to five thousand years Estonia has been subjected to general uplift (the southeastern part excluded) the maximum being in the northwestern part. This process reflects more general glacioisostatic uplift over an extensive area of Fennoscandia with the maximum in the apical part of the Gulf of Bothnia at the site of the greatest thickness of the ancient ice sheet (*Sauramo*, 1958; *Nikonov*, 1977b).

In Estonia, as in adjoining parts of Finland, the isobases of the postglacial uplift are frequently parallel and run in a northeastern direction, whereas the isopachites (or isolines of the depth of the crystallinen basement) trend latitudinally. Note that there is no correlation between Holocene movements, the thickness of the Earth's crust and the known large structural units of the basement (*Sildvee* and *Miidel*, 1978).

Against the general background of the decline to the southeast of the uplift of the Earth's crust, tectonic fault lines with a northeastern orientation can be distinguished at the southeastern border of Fennoscandia in the Holocene (at a rate of up to 4-5 mm per year). In satellite imageries of the underwater relief in the Gulf of Finland, distinct lineaments of the first order are depicted along the lines: 1) trending northeast at Pärnu-Tapa-Kunda and across the bottom of the Gulf of Finland, 2) trending eastnortheast from Osmussaar Island along the northern coast of Estonia to the northeastern Gulf of Finland (*Lahtinen*, 1984). In position and strike, these lineaments coincide with the above geologically active dislocations in the sedimentary cover and the basement. The data available demonstrate that differentiated movements were intensified in the Holocene along these fault zones. On the southeastern line, these movements have been controlled in northern Estonia by geomorphological features such as anomalous inclination of coastlines, concentrations of esker and karst formations, and anomalous gradients of river beds (*Heinsalu* and *Sildvee*, 1971; *Gazizov*, 1973; *Kessel* and *Miidel*, 1973; *Sildvee* and *Miidel*, 1978).

Unlike the movements affecting Palaeozoic rocks, the northwestern block was uplifted along the whole length of the fault under consideration in the Holocene.

Our knowledge of Holocene movements along the northwestern line running mostly under the waters of the Baltic Sea is based on data obtained from east of Helsinki on the Finnish coast of the Gulf of Finland. Here the Early and Middle Holocene coastlines are distorted and the slope of the early Holocene coastline has changed, whereas the fault line proceeds to the northeast and the northwestern block has risen (*Okko*, 1967; *Donner*, 1970; *Lahtinen*, 1984). These features permit the distinction of hingelines surrounding the dome-like uplift of Fennoscandia in the Holocene (*Sauramo*, 1958; *Nikonov*, 1977b). Similar trends and expressions in the relief suggest that the above line, serving as a continuation of the geologically proved southwestern large fault zone, passes on its activity in the Holocene, too. In the Holocene, like in the post-Early Palaeozoic, the northwestern block rose to some extent. Although we can only make suppositions about the coherence and activity of the whole fault, features such as the common trend, the general extent of about 500 km, and the similarity of the movements of the footwall and hanging wall up to the Late Holocene, allow us to distinguish it as the greatest regional fault structure permitting penetration into the basement up to a depth of some tens of kilometres.

At present, as in the Holocene, uplift of the Earth's crust is taking place in the major part of Estonia, decreasing from 3 mm/year in the northwest, with a transition to slight subsidence in the southeast (*Zhelnin*, 1973; *Vallner* and *Zhelnin*, 1975). Such a regular pattern of recent crustal movements in Estonia and in the adjoining area of Fennoscandia reflects overall glasioisostatic uplift of Fennoscandia, inherited from the Holocene (*Kääriäinen*, 1953; *Nikonov*, 1977b). Contemporary vertical movements in Estonia and in the major part of Fennoscandia do not show clear relations with the block structure of the basement (*Nikonov*, 1977b; *Sildvee* and *Miidel*, 1978). An exception is the fault zone trending to northeast - Pärnu-Tapa-Kunda, being a hinge-line active in the Holocene (see above) and at present. In this zone, striking parallel to the general trend of uplift isobases in Estonia, the recent vertical movements have a maximum rate gradient, i.e. in this 20-40 km wide zone the Earth's crust has an anomalously steep inclination to the southeast. The similarity in the trend, structure and history of this zone, with the parallel zone running through Osmussaar Island, suggests similar present activity for the latter, too, considering its position and size and the features of previous activity. As the zone is mostly located under the Baltic Sea, this may be proved by direct geodetic measurements only on the northwestern coast of the Gulf of Finland.

In accordance with the general patterns of the present uplift of Fennoscandia and the character of movements across the hinge lines (*Nikonov*, 1977b), the northwestern block of the fault has to be rising with respect to the southern one.

4. *General conclusions*

Analysis of the above material demonstrates that the Estonian area, as a peripheral part of the Baltic Shield, has continuously experienced rare and weak earthquakes. This finding applies mostly to its northern and northwestern parts. Apart from more frequent slight local shocks (or their swarms), moderate earthquakes with a maximum intensity of 5-6 (three events in the 19th century) and with a felt area of tens and some hundreds of km^2 also occur. During the past 300 years, 15 earthquakes have been recorded (excluding aftershocks) but the Osmussaar earthquake of 1976 was the only one to reach the maximum intensity of 6-7, magnitude 4.75 and intensity area 5 (mostly in the water area) over 16-18 thousand km^2.

The present seismotectonic interpretation of the data from Estonia is mainly based on the spatial relations between the tectonic structure and the location of earthquakes. Thus, first of all, attention should be paid to the fact that all the earthquakes are related to the upper part of the Earth's crust, i.e. the granitic layer. They occur in the crystalline basement represented by magmatic and metamorphic rocks of Archaean and Proterozoic age.

The question arises why the earthquakes are concentrated in the northwestern part of Estonia, as the structure of the crystalline basement in this area does not differ much from the other parts; it is only somewhat more differentiated and fractured. To answer the question, we have to analyse the relations between the earthquakes and the basement structure. The heterogeneous nature of the basement, expressed in the form of large blocks and intervening zones which are dominated by the northwestern and latitudinal strikes according to geophysical data, is not reflected in the location of earthquake epicentres (Fig. 1).

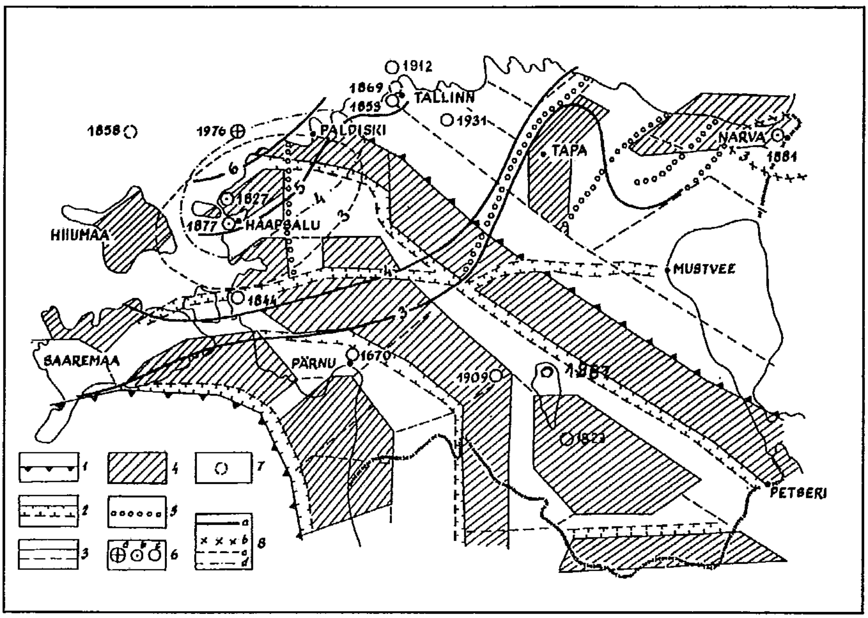

Fig. 1. Tectonic structure of Estonia. 1-4) Structural elements of the basement by geophysical data; 1) Boundaries of the largest blocks; 2) Zones of deep-seated faults; 3) Faults bounding the blocks; 4) Relatively compact blocks of the basement separated by gravity anomalies; 5) Tectonic elements by geological data; discontinuities in the Palaeozoic sedimentary cover; 6-8) Seismic elements; 6) Earthquake epicentres with maximum intensities: a) I_0 = 6-7, b) I_0 = 5-6, c) I_0 = 4; 7) Poorly located epicentre; 8) Isoseismals of earthquakes with a notice of intensity: a) 1976, b) 1881, c) 1877, d) 1827.

The elongated isoseismals with northeastern strike of the three strongest earthquakes also show unconformity with the block-zonal structure of the basement. In contrast, the locations of the epicentres, and the elongated sources of the strongest and most comprehensively studied earthquake of 1976, demonstrate a correlation with the fault in the basement and the Palaeozoic strata, which from geological data may be considered as having been relatively active during the later stages of geological history (Fig. 2).

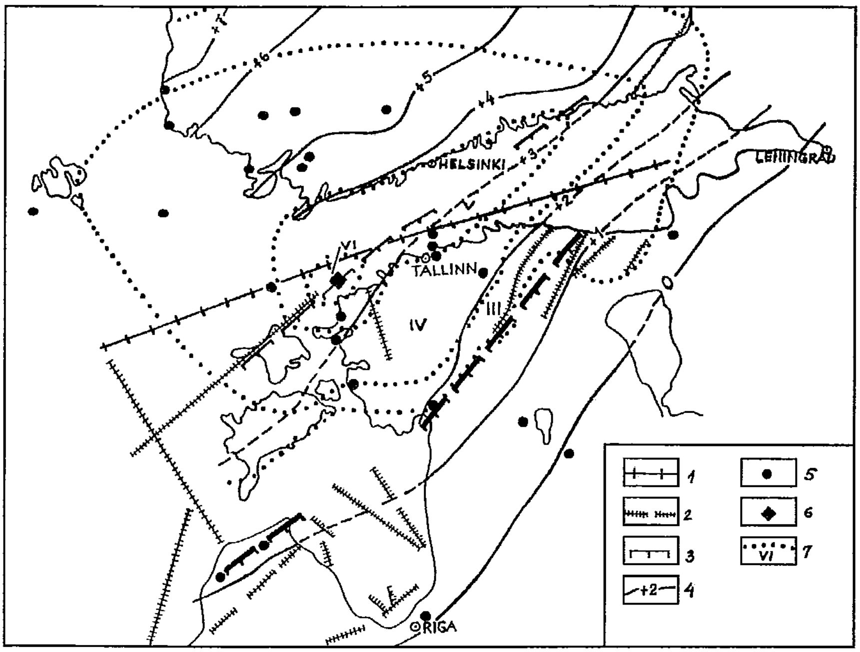

Fig. 2. Seismotectonic scheme of the Baltic Sea. 1-4) Elements of post-Early Palaeozoic tectonics: 1) Fault in the Pre-Cambrian basement (in the water area); 2) Faults in the Palaeozoic strata and in the basement; 3) Zones of contrast movements (hinge-lines) of the Post-Glacial and present times (stripes towards the footwall, in the water area inferred); 4) Isolines of the rate of recent movements, mm/year; 5) Epicentres of the recorded earthquakes (since 1670); 6) Epicentre of the Osmussaar earthquake, 1976; 7) Isoseismals and intensity zones on MSK-64 scale of the Osmussaar earthquake.

Thus, the earthquake of 1670 with a maximum intensity of 6 (like some other earthquakes farther southwest in Latvia) was located on a still active hingeline. The epicentres of the earthquakes of 1912 and 1976 extended along the northernmost parallel fault line showing signs of activity. The isoseismal axis of the earthquake of 1976 ran in the same direction and along the assumed fault (*Kondorskaya et al.*, 1988) (Fig. 2). The epicentres of the earthquakes of 1827, 1844, 1877 and 1976 (succession from south to north) were equally strong on a longitudinal line, parallel to the Vihterpalu fault and probably marked a similar active fault on the western coast.

These data on the concentration of earthquakes in northwestern and northern Estonia indicate that the marginal part of the Baltic Shield is seismically active, transitional to the East European platform. However this conclusion is not satisfactory unless we pay attention to the fact that at present especially the northwestern part of Estonia, which is separated from the rest of the country by a high-gradient line (the hinge line of M. Sauramo), is subject to considerable uplift. The uplift isolines and the hinge line trend northeast as do the relatively young faults in the basement and the isoseismals of the recorded earthquakes.

It appears that, in Estonia the marginal dissected part of the Baltic Shield is seismically active. That part participates in the inherited recent glasioisostatic uplift, thus differing from the passive adjoining part of the East European Platform.

References

Ahjos, T. and Arhe, K., 1983: Loviisan ympäriston seismisyys. Inst. of Seismology, Univ. of Helsinki. Report T-21. 48 p.

Amelung, F., 1904: Frühere Erdbeben in Livland. *Nordlivl. Zeit.*, 23. Okt. (5. Nov.).

Ananjin, I., 1968: Relation between seismicity and recent tectonic movements in Russian platform. In: Recent movements of the Earth's crust. No. 3, Moscow, 282-295. (in Russian).

Ananjin, I., Bulin, N. and Klaaman, E., 1980: The Osmussaar (Estonian) earthquake in October 25th, 1976. In: Zemletrjasenija v SSSR, v. 1976 (Earthquakes in the USSR in 1976). Moskva, 91-97. (in Russian).

Bericht über das Erdbeben in der Gegend von Narva am 16. Januar 1881., 1881: *Neue Dorptsche Zeitung*, 20. Jan. (1. Feb.).

Carlbom, J., 1855: Erdbeben in Estland. *Korresp. Bl. Naturf. Ver.*, Riga, 14. No. 1.

Donner, J., 1970: Deformed Late Weichselian and Flandrian shorelines in South-Eastern Fennoscandia. *Comment. Phys.-Math., Soc. Sci. Fenn.*, 40 p.

Doss, B., 1898: Übersicht und Natur der in den Ostseeprovinzen vorgekommen Erdbeben. *Korresp. Bl. Naturf. Ver.* Riga., **40**, 147-162.

Doss, B., 1905: Über ein unbeachtet gebliebenes Beben in Estland. *Korresp. Bl. Naturf. Ver.* Riga., **48**, 121-138.

Doss, B., 1910: Die historisch beglaubigten Einsturzbeben und seismisch-akustischen Phänomene der russischen Ostseeprovinzen. *Beit. zur Geophysik.*, X, 1-124.

Doss, B., 1915: Seismische Ereignisse in den Ostseeprovinzen vom Juni 1910 bis Ende 1912. Izv. postojannoi centralnoj seismicheskoj komissii. 6, Petrograd, 25-32 (in Russian).

Gazizov, M., 1973: On the methods of studying manifestations of neotectonic movements in the Baltic oil shale basin. In: Recent movements of the Earth's crust. No. 5, Tartu, 319-321 (in Russian, summary in English).

Gudelis, V. and Emeljanov, E. (Editors), 1976: Geologija Baltijskogo Morja (Geology of the Baltic Sea). Vilnius. (in Russian).

Heinsalu, U. and Sildvee, H., 1971: Die Abhangigkeit der Neotektonischen und der gegenwartigen differenzierten Bewegungen in Nordöstlichen Estland von den Störungszonen des Grundgebirges und der Tafeldecke. ENSV TA Toimitised. *Keemia, Geoloogia*, **20**, No. 3, 260-265 (in Russian, summary in German).

Herman, U., 1970: Maavärisemised Eestis ja Lätis (Earthquakes in Estonia and Latvia). *Eesti loodus*, Nr. **2**, 120 (in Estonian, summary in English).

Hoff, K. E. A., 1840: Chronik der Erdbeben und Vulkan-Ausbruche. I. Gotha.

Karta seismicheskogo rajonirovanija SSSR (The map of seismic zoning in the USSR), 1983: Moskva, (in Russian).

Kessel, H. and Miidel, A., 1973: On the late and post-glacial crustal movements in Estonia. ENSV TA Toimitised. *Keemia, Geoloogia*, **22**, No. 3, 257-264 (in Russian, summary in English).

Klaamann, E., 1977: Kõigi aegade tugevaim maavärin Eestis (The strongest earthquake in Estonian history). *Eesti Loodus*, No. **6**, 338-344 (in Estonian, summary in English).

Kondorskaya, N., Nikonov, A., Ananjin, I., Dolgopolov, D., Korhonen, H., Arhe, K. and Sildvee, H., 1988: The Osmussaar, Eastern Baltic earthquake. Izv. Acad. Nauk SSSR, *Ser. Fizika Zemli*, **5**, 3-11 (in Russian).

Kuuskand (Kuuskmann), J., 1935: Maavärinaist Harjumaal. *Loodusvaatleja*, Nr. 5, Okt. 1935, 158.

Kääriäinen, E., 1953: On the recent uplift of the Earth's crust in Finland. Helsinki.

Lahtinen, A., 1984: Seismotectonic studies for Loviisa power plant region. In: Proc. Symp. between Imatran Voima Oy and Acad. Sci. USSR on Fennoscandian Seismicity, in Moscow. 1-18.

Mushketov, I. and Orlov, A., 1893: Katalog zemletrjasenij Rossijskoi Imperii (A catalogue of earthquakes in Russian empire). *Zap. Imp. Russ. Geograf. Ove.*, **26** (in Russian).

Nikonov, A., 1977a: Earthquake in Estonia. *Priroda*, No. **3**, 143-144 (in Russian).

Nikonov, A., 1977b: Recent crustal movements. Geological-geomorphological and seismotectonic aspects. Moscow., 240 (in Russian, summary in English).

Novyi katalog silnykh zemletrjasenij na territorii SSSR s drevneishikh vremen do 1975 g (New catalogue of strong earthquakes in USSR from time immemorial till 1975). 1977. Moscow (in Russian).

Okko, M.,1967: The relation between raised shores and present land in Finland during the past 80 years. *Ann. Acad. Sci. Fenn.* Ser. A, III, No. 93.

Panasenko, G., 1977: Fennoscandian earthquakes in 1951-1970, Catalogue Materials of the World Data Center B. Moscow (in Russian).

Perrey, A., 1846: On earthquakes in northern Europe and Asia. Svod magnitnykh i meteorologicheskikh nabljudenij Nikolajevskoi glavnoj geofizicheskoj observatorii (Summary of the magnetic and meteorological observations in Main Geophysical Observatory of Nikolajev). 2, SPb., 205-235.

Pobul, E. and Sildvee, H., 1973: On the faults in the basement of Estonia. ENSV TA Toimitised. *Keemia, Geoloogia.*, **22**, No. 1, 51-57 (in Russian, summary in English).

Pobul, E. and Sildvee, H., 1975: About the block structure of the basement in Estonia. In: Sovremennye dvizhenija territorii Pribaltiki. Tartu, 64-73 (in Russian, summary in English).

Radu, C., Karnik, V., Polonic, Prochazkova, D., 1983: The map of maximum observed intensity in Europe.

Sauramo, M., 1958: Die Geschichte der Ostsee. *Acad. Sci. Fennicae*, Ser. A, III, No. 51.

Sildvee, H., 1988: Võrtsjärve maavärin (An earthquake under Lake Võrtsjärv). *Eesti Loodus*, No. **1**, 26-31 (in Estonian, summary in English).

Sildvee, H. and Miidel, A., 1978: Some results of the interpretation of recent crustal movements in Estonia. In: Sovremennye dvizhenija zemnoj kory. Novosibirsk., 138-143 (in Russian).

Slunga, R.S., 1979: Source mechanism of a Baltic earthquake inferred from surface wave recordings. *Bull. Seism. Soc. Am.* **69**, 1931-1964.

Zhelnin, G., 1973: Results of studying the recent movements of the Baltic area. In: Recent movements of the Earth's crust. No. 5, Tartu, 79-88 (in Russian, summary in English).

Vaher, R., Puura, V. and Erisalu, E., 1962: The tectonic pattern of northeast Estonia. Eesti NSV Teaduste Acadeemia Geoloogia Instituudi Uurimused X. *Geologija paleozoja*, 319-335 (in Russian, summary in English).

Vallner, L. and Zhelnin, G., 1975: New map of isobases on the territory of the Estonian SSR. In: Sovremennye dvizhenija territorii Pribaltiki. Tartu, 48-57 (in Russian, summary in English).

Über Erdbeben in Hapsal., 1877: Revalische Zeitung, 10/22. Okt.

Über ungewöhnliche Naturerscheinung., 1853: Inland, No. 14, Sp. 294.