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ESTIMATION OF SEISMIC AZIMUTHAL ANISOTROPY PARAMETERS OF THE UPPER MANTLE OF THE CENTRAL PART OF THE EAST-EUROPEAN CRATON ACCORDING TO THE DATA OF THE "OBNINSK" AND "MIKHNEVO" SEISMIC STATIONS

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Abstract. The results of determining the parameters of seismic anisotropy of the upper mantle of the central part of the East-European craton are given. According to the tectonic concepts actively developing in recent decades, the East-European craton consists of megablocks (microplates) of different age: there are three main megablocks – Fennoscandia, Volga-Uralia and Sarmatia. The area of their triple junction is the subject of this article. The SKS/SKKS anisotropy method was applied. Its essence is to use SKS phases in order to obtain delay times for the arrival of two quasi-shear waves that are formed during the trace of a shear wave through an anisotropic medium and gets through it with different velocities. The result is to simulate the azimuth of the maximum velocity axis along which "fast" quasi-shear wave trace and to get the delay time between "fast" and "slow" waves. The technique does not allow to obtain accurate estimates of the depth of the anisotropic layer, however, taking into account the long periods of the SKS wave and the pronounced anisotropic properties of olivine, as the main material composing the upper mantle, it is assumed that these effects are related to the mantle processes. Authors used the data from "Obninsk" (OBN) and "Mikhnevo" (MHV) stations that are located in the zone of the triple junction of blocks. For Obninsk station – 1266 events were used, for Mikhnevo station – 472. For each station, we obtained estimates of the azimuth of the maximum speed axis and the delay time of arrival of quasi-shear waves. As a result of the study, the mantle anisotropy of the region is assessed as weak, which is an expected result for tectonically stable platform regions (delay time 0.4 s for the OBN station and 0.2 s for the MHV station). The direction of the maximum speed axis is strictly sub-latitude (90° for the OBN and 100° for MHV station), which is in accordance with the known the East-European lithospheric plate motion. For the OBN station, two groups of events were identified, with significantly different results, structured by azimuth. For events mainly with western azimuths of arrival of seismic waves, the solution is 90° and 0.4 s, while processing events from the eastern direction of arrival, along with a coordinated solution, a second pronounced local extremum is detected, corresponding to angles and delay time about 0.5–1.0 s. According to the results of MHV data processing, a second local extremum was also found, corresponding to similar angles of about 160°, however, with a shorter delay time (about 0.1–0.2 s). It can be assumed that the presence of two extrema is associated with the anisotropic parameters of two different megablocks, near the junction boundary of which are located the OBN and MHV stations.

Keywords: anisotropy, seismology, tectonics, SKS/SKKS, shear waves.

Introduction

Studies on the estimation of azimuthal elastic anisotropy of the upper mantle from observations and analysis of seismic *SKS*/*SKKS*-waves from distant earthquakes began in 1984, when the authors of [*Vinnik*, *Kosarev*, *Makeyeva*, 1984] proposed the use of the splitting of a transverse wave propagating in an anisotropic medium into two quasi-transverse. *SKS*/*SKKS*-transverse waves polarized in *SV* are split into fast and slow quasi-transverse waves, each of which has *SH*- and *SV*- components. An analysis of the ratio of *SH*- and *SV*- components in the records of *SKS*/*SKKS*-waves allows us to study the azimuthal anisotropy in the vicinity of the observation point (seismic station). At least two anisotropic parameters are determined at each seismic station: α is the azimuth of the propagation direction of the quasi-transverse "fast" wave and δt is the delay of the "slow" wave relative to the "fast" when they pass through the anisotropic medium. Due to the close relationship of tectonic phenomena in the crust with processes occurring in the upper mantle, these studies are widespread and are still ongoing in the world (see, for example, [*Becker et al.,* 2015]).

In the early nineties of the last century, two research groups published the results of extensive work on the analysis of anisotropic parameters for hundreds of stations around the world [*Silver, Chan,* 1991; *Vinnik et al.,* 1992; *Helffrich, Silver, Given,* 1994]. For the East European craton, studies of anisotropy based on *SKS*/*SKKS*-phases were carried out according to "Obninsk" station (OBN). In [*Silver, Chan,* 1991], δt = 0.5 s and α = - 5 ° were obtained for this station from an unspecified set of events. Later, for the same station, the values of δt = 0.68 s and α = –19 ° were obtained from 12 events [*Helffrich, Silver, Given,* 1994]. Other authors [*Vinnik et al.,* 1992; *Vinnik, Kosarev,* 1997] obtained values of δt=0.5 s, α=160° for the OBN station from 6 events. The presented results can be considered independent, since the authors of these works used different sets of initiating events. So, in Fig.1 it can be seen that one group of researchers [*Helffrich, Silver, Given,* 1994] analyzed events concentrated in the eastern direction (9 events out of 12). The results of another group [*Vinnik et al.,* 1992] are based on smaller number of events (6 paths), but more evenly distributed in azimuthal directions.

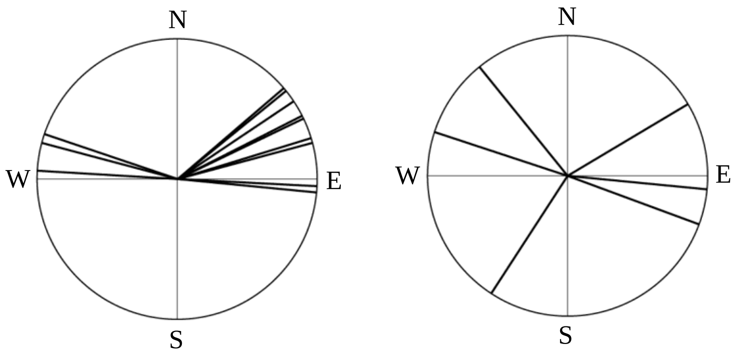

Fig. 1. Diagrams of the azimuthal distribution of events for the OBN station: *left* – according to [*Helffrich, Silver, Given,* 1994], *right* – according to [*Vinnik et al.,* 1992]

In the discussed papers, different but always submeridional directions of the maximum velocity axis were obtained. In one of the later works [*Vaganova,* 2012] its sub-latitudinal direction is recorded, however, this work focuses on studies of the northern regions of the East European craton and does not contain information on the quantity and quality of the material used for the OBN station.

To date, a significant amount of new seismic information is accumulated, which, in particular, makes it possible not only to reevaluate seismic anisotropic parameters for the OBN, but also to perform for the first time the same estimations for nearby station MHV (54.95 °N, 37.76 °E).

The reevaluation results of the anisotropic properties of the medium for the OBN seismic station

The OBN seismic station is equipped with a *STS*-1 broadband velocimeter [The Earthquakes…, 2010] with a limit period of 300 s. For the study, 1266 events from the *Global Centroid Moment Tensor Catalog* (*CMT*) were used [*Dziewonski et al.,* 1981; *Ekstrom et al.,* 2012] from the period of 2001–2015 in the range of epicentral distances 65°–120° with magnitudes greater than 5.5. For the analysis, events with isolated, non-interfering with any other, *SKS/SKKS*-phases were selected, on which the horizontal components the signal-to-noise ratio is not lower than 3. In most cases, the *SKS*-phase was processed (Fig. 2, *top*). For each event, a transition was made from the *ZNE* coordinate system (*Z* is the vertical recording component, *N* is the horizontal component, oriented in the north-south direction, *E* is the horizontal component, oriented in the east-west direction) to the *ZRT* coordinate system where *R* is the radial component, coinciding with the direction from the source to the station, *T* is the transverse (tangential), obtained by turning *R* in the plan through 90°clockwise. When evaluating the isolation of the target phases, in addition to visual determination, the criteria were low amplitudes on the *Z*-component of the seismogram and a characteristic elliptical particle trajectory on the surface, with a major axis parallel to the direction of the *R*-component (Fig. 2, *bottom*, *right*).

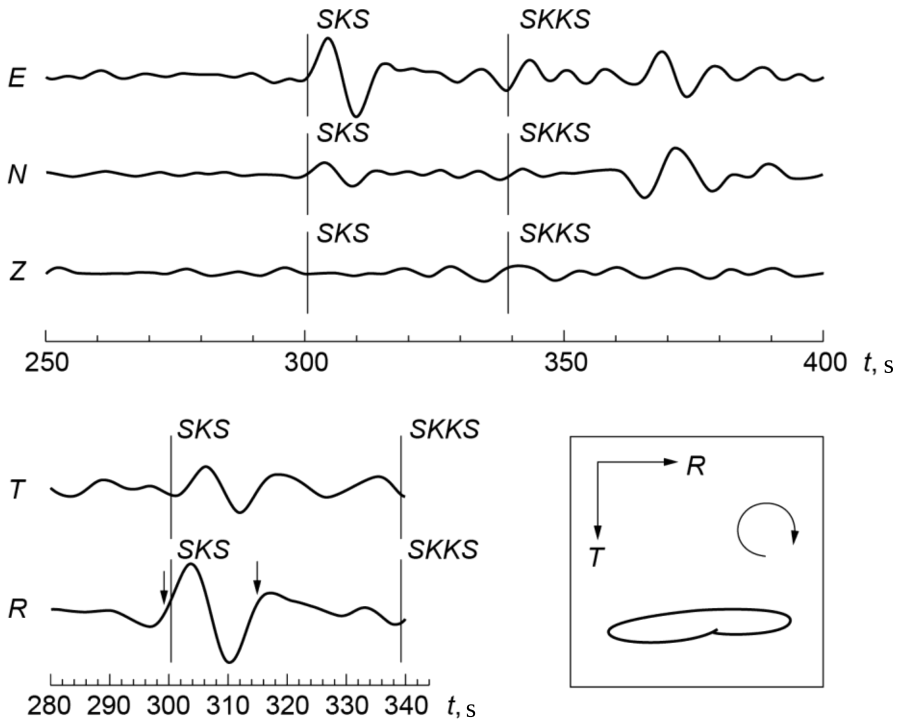

Fig. 2. *Top*: Example of the filtered event record processed for the OBN station. *Bottom:* seismograms of *T*- and *R*-components, the arrows indicate the time range chosen for the inversion; the amplitude of the *T*-component is 5 times increased for the clarity (*left*); trajectory of particle motion in the chosen range (in plan for the SKS-phase, *right*)

As a result, 46 best events were selected for the OBN station (Table 1), satisfying the above criteria. An asterisk in the table marks 36 events remaining after deleting records from $\alpha \geq 3.0$ s.

Records with $\alpha \geq 3.0$ s were deleted, since such a large value of this parameter can be obtained only in tectonically active regions and is not typical for the central part of the platform area. The spatial distribution of the sources used for the analysis of events is shown in Fig. 3.

Table 1. Events used to estimate the anisotropy parameters for OBN station

Date	Distance, °	Azimuth, °	Magnitude	α, °	δ*t*, s
13.01.2001	98.01	306.5	6.4	120	3.0
29.01.2001	94.43	84.84	5.9	70	3.0
19.03.2001	94.11	91.11	6	90	3.0
04.04.2001*	97.54	88.21	5.9	10	0.8
20.05.2001*	99.24	322.86	5.5	50	1.9
23.08.2001*	103.98	75.53	5.8	140	1.0
07.10.2001	102.03	78.36	5.7	80	3.0
10.01.2002*	101.67	78.73	6	160	1.0
17.03.2002	99.97	181.05	5.5	170	3.0
06.06.2002*	103.03	72.39	5.7	150	1.0
06.06.2002*	103.03	72.39	5.7	140	0.9
07.08.2002*	99.72	298.93	5.6	90	0.6
08.09.2002*	102.04	78.34	6.5	160	2.2
16.09.2002*	101.9	78.57	5.9	160	1.7
17.09.2002*	101.92	78.48	5.7	160	1.6
20.12.2002*	104.64	73.97	5.8	150	2.6
02.03.2003	104.03	224.1	5.6	130	3.0
25.08.2003	100.26	324.78	5.5	50	3.0
22.09.2003*	83.4	295.12	6.2	100	1.2
22.12.2003	87.53	341.97	6.1	160	3.0
11.01.2004*	92.58	166.57	6.1	160	2.4
17.04.2004*	97	92.74	6.1	80	1.4
29.04.2004*	98.7	303.11	5.6	120	2.9
29.06.2004	99.26	303.98	5.8	120	3.0
15.11.2004*	99.61	292.64	6.6	100	1.3
20.11.2004*	98.86	300.92	6.2	110	2.4
11.04.2005*	103.85	75.93	5.9	10	0.1
04.06.2005*	97.15	175.66	5.7	110	2.0
05.02.2006*	87.61	65.29	6.3	150	1.4
09.06.2006*	102.55	182.73	5.6	170	1.6
11.08.2006*	98.26	319.76	6	20	0.1
16.08.2006*	86.34	158.04	5.6	150	1.8
15.10.2006*	104.55	12.15	6.2	180	1.9
10.09.2007*	101.3	292.11	6.1	80	0.8
26.11.2007	98.42	320.36	5.7	50	3.0
26.06.2011*	97.1	83.09	6.4	160	1.9
15.08.2011*	105.4	288.5	5.7	50	0.9
30.08.2011*	94.6	95.28	6.9	180	0.9
12.09.2011*	102.4	77.49	6.0	160	2.7
13.10.2011*	90.2	105.05	6.2	20	1.5
14.11.2011*	90.3	90.26	6.4	100	0.2
18.01.2012*	90.2	90.26	5.8	90	0.5
20.03.2012*	99.5	316.41	7.4	50	1.4
21.04.2012*	95.1	84.6	6.7	80	2.9
01.06.2012*	93.8	84.92	5.8	170	2.2
04.06.2012*	102.3	297.39	6.3	50	0.5

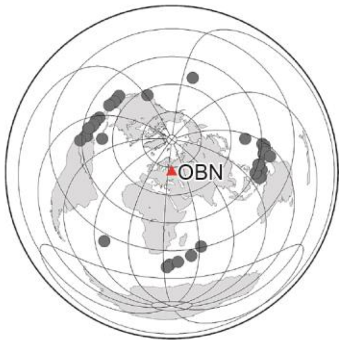

Fig. 3. The spatial distribution of the sources of events used in the analysis for the OBN station (triangle)

Individual solutions for the 36 events remaining after deletion by the α parameter are clearly divided into two groups: one with $\alpha \approx 100°$ (21 events), the other with $\alpha \approx 160°$ (15 events). In this regard, the azimuthal distributions were analyzed separately for a complete set of 36 events, for 21 events with $\alpha \approx 100°$ and for 15 events with $\alpha \approx 160°$ (Fig. 4). The different color of the lines in Fig. 4 shows the direction of rotation of particles on the surface: red - clockwise (right rotation), blue - counterclockwise (left rotation). Theoretically, when the azimuth of an event passes through the azimuth of the axis of the maximum velocity, the observed direction of rotation of the particles on the surface should be changed to opposite.

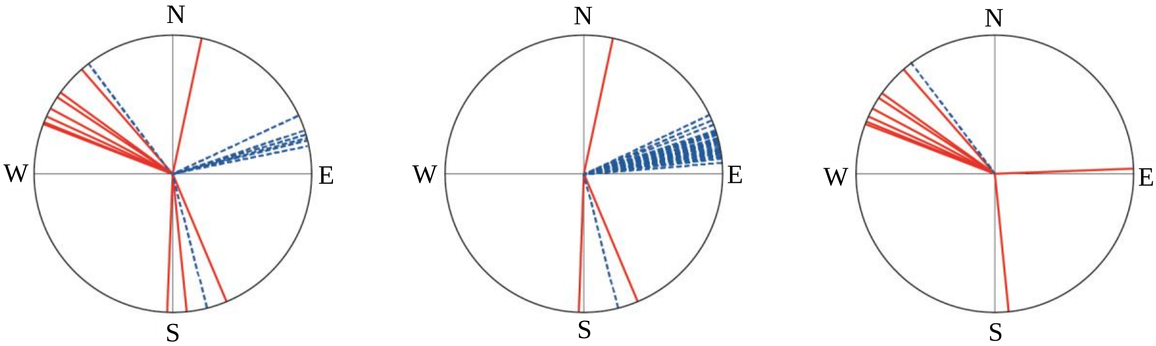

Fig. 4. Diagrams of azimuthal distribution for 36 events (*left*), for 21 events with $\alpha \approx 100°$ (*center*), and for 15 events with $\alpha \approx 160°$(*right*). Red lines – right rotation of particles on the surface, blue – left rotation

The solution was sought in the form of a minimum of the objective function depending on the parameters α and δt, as was described, for example, in [*Vinnik et al.*, 1992]:

$$E(\alpha, \delta t) = \left[\frac{1}{N} \sum_{n=1}^{N} \frac{\int \left(T_n(t) - T_n^*(t, \alpha, \delta t) \right)^2 dt}{\int R_n^2(t) dt} \right]^{1/2},$$

where α is the test azimuth of the "fast" axis; δt is the delay of the "fast" quasi-transverse wave relative to the "slow" one; n is the event number; N is the total number of events; $T_n(t)$ and $R_n(t)$ are the observed components, while $T_n^*(t, \alpha, \delta t)$ is the synthetic transverse component. The synthetic component was calculated as $T^*(t) = F(t) * R(t)$, where $F(t)$ is the result of the inverse Fourier transformation of

$$f(\omega) = -0.5 \sin 2\alpha \frac{1 - e^{-i\omega\delta t}}{\cos^2 \alpha + e^{-i\omega\delta t} \sin^2 \alpha}.$$

Test angles of α ranged from 0° to 180° (in increments of 10°), and delay times of δ*t* ranged from 0.1 to 3.0 in increments of 0.1 s. The step size is due to limitations in the accuracy of the used method.

The contour plot of the values of the objective functions *E* (α, δ*t*) for the three data sets mentioned above are presented in Fig.5. It can be seen that in each of the distributions a zone of the absolute minimum is traced in the range of α from 80° to 110° and δ*t* from 0.3 s to 0.5 s. As a solution, the authors propose to use the data obtained for the maximum set of events, namely, α=90°, δ*t*=0.4 s (see. Fig. 5, *left*). It is also important to note that for events with predominantly eastern azimuths, a second distinct minimum is detected with α≈160° and δ*t* ≈0.5 s.

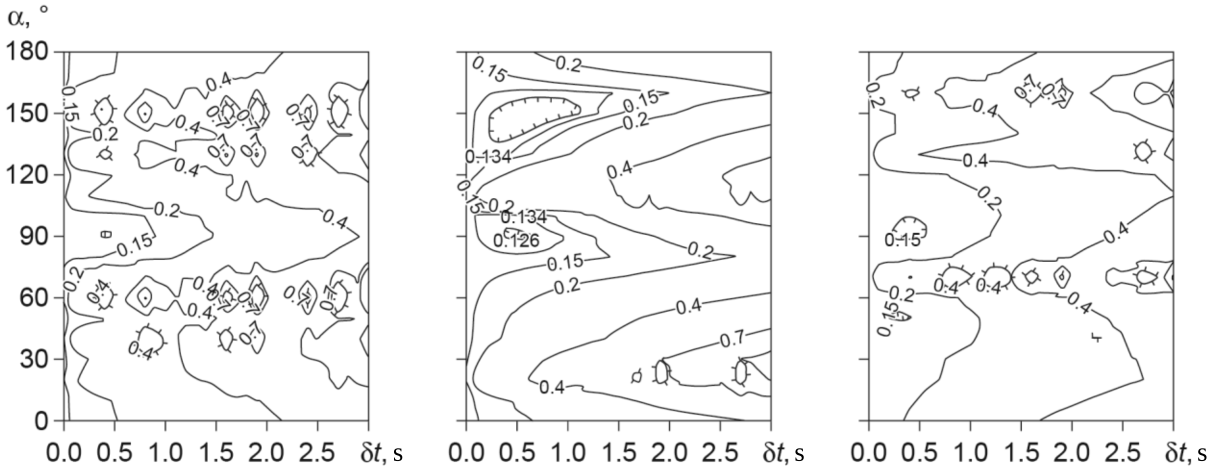

Fig. 5. The contour plot of the values of the objective function *E*(α, δ*t*) according to the data of the OBN station. The solution obtained for the complete set of 36 events (*left*, α=90°, δ*t*=0.4 s); for 21 events with individual solutions α≈160° (*center*, α=100°, δ*t*=0.3 s); for 15 events with individual solutions α≈90° (*right*, α=90°, δ*t*=0.4 s)

The evaluation results of the anisotropic properties of medium for the MHV seismic station

The MHV seismic station is located in 80 km from the OBN station and equipped with a *STS*-2 velocimeter [The Earthquakes ..., 2010] with a limit period of 120 s. Anisotropic parameters were estimated using *SKS/SKKS*-phases for the first time for this station and were carried out according to a procedure similar to that described for the OBN station.

417 events satisfying the criteria of magnitude and distance were used; 37 events presented in Table. 2, correspond to a complete set of criteria. As in the analysis of data for the OBN station from selected events were excluded events with the delay ≥3.0 s. The azimuthal distribution for the 16 paths remaining after this (marked in the table with an asterisk) is shown in Fig. 6, *on the left*; the location of their sources - in Fig. 6, *on the right*.

The local minimum with α=90° and δ*t*=0.2 s is clearly traced on the scheme of contour plot of the objective function *E*(α, δ*t*) constructed for events recorded by the MHV station presented in Fig. 7. In addition, as well as for the OBN station, a second local minimum with α≈160° and δ*t*≈0.1–0.2 s is allocated.

Table 2. Events used to estimate the anisotropy parameters for the MHV station

Date	Distance, °	Azimuth, °	Magnitude	α, °	δ*t*, s
06.03.2011*	114.3	273.2	6.3	100	0.9
07.04.2011	97.3	314.3	6.7	60	3.0
20.06.2011*	116.6	269.8	6.5	80	0.4
26.06.2011*	97.1	84	6.4	170	1.9
15.08.2011	105.4	289.5	5.7	30	3.0
24.08.2011	108.9	284.1	7.0	20	3.0
30.08.2011*	94.6	94.4	6.9	100	0.3
12.09.2011	102.4	78.5	6.0	160	3.0
13.10.2011	90.2	106	6.2	110	3.0
14.10.2011	106.9	77	6.5	160	3.0
14.11.2011*	90.3	91.2	6.4	100	0.2
22.11.2011*	109.8	271.4	6.6	10	0.8
14.12.2011	107.1	78.5	7.1	160	3.0
14.01.2012*	70.8	83.9	5.8	160	1.3
18.01.2012*	90.2	91.2	5.8	120	0.4
11.02.2012*	90.3	91.3	5.6	10	2.8
14.03.2012*	107.8	73.7	6.2	180	0.3
20.03.2012	99.5	307.4	7.4	50	3.0
21.03.2012	105.5	78.5	6.6	160	3.0
21.04.2012	95.1	85.5	6.7	90	3.0
14.05.2012*	114.2	273.7	6.2	180	0.3
28.05.2012*	118.5	261.3	7.8	160	1.8
01.06.2012*	93.8	85.8	5.8	100	0.9
04.06.2012	102.3	298.4	6.3	40	3.0
09.02.2013	103.2	291.6	6.9	30	3.0
18.02.2013	74.5	257.1	5.6	30	3.0
23.02.2013	96.7	95	5.9	10	3.0
06.04.2013	99	83.2	7.0	80	3.0
16.04.2013	101.1	79.6	6.6	70	3.0
19.04.2013	96.3	101.8	5.8	20	3.0
07.07.2013	108	70.2	7.3	150	3.0
12.08.2013*	97	92.4	6.1	180	1.2
12.08.2013	111.1	292	6.3	40	3.0
13.08.2013	99.7	294.8	6.7	40	3.0
21.09.2013*	91.5	100.5	6.1	20	2.5
19.11.2103*	88.3	87.9	6.0	10	0.6

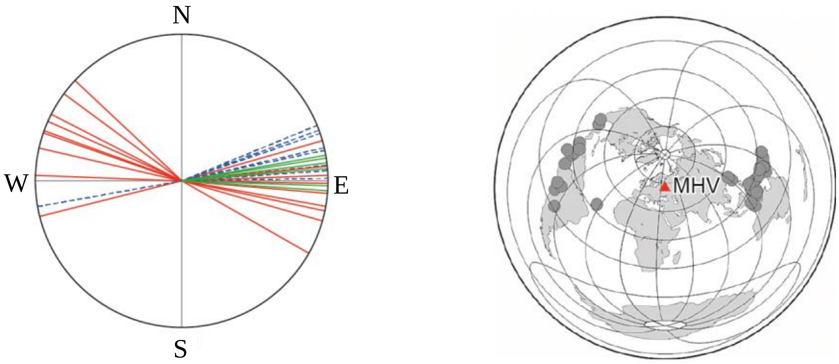

Fig. 6. Diagram of azimuthal distribution of events used for the MHV station (*left*) and the location of the sources of events (*right*). Red lines on the diagram – right rotation of particles on the surface; blue – left rotation; green – linear rotation

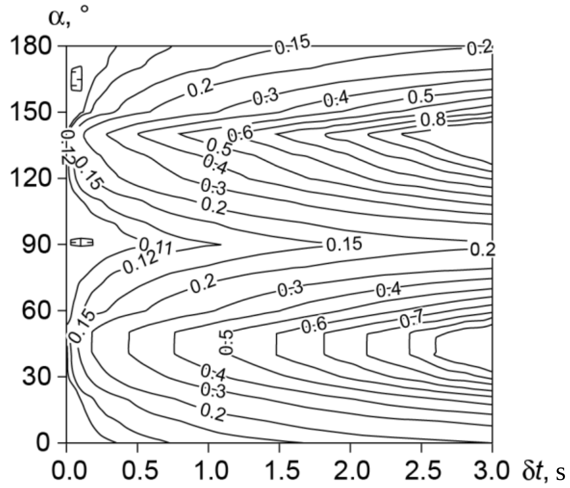

Fig. 7. Isolines of the values of the objective function $E(\alpha, \delta t)$ according to the data of the MHV station. The solution obtained for 16 events – α=90°, δt=0.2 s

Taking into account the difference between the results obtained in the framework of this study and previously published estimates and also the close proximity of the MHV and OBN stations, the authors conducted an additional study. From the lists given in Table 1, 2, were selected events recorded at both stations - there were only 11 such events. Diagram of the azimuthal distribution of these events and the layout of their epicenters are shown in Fig.8. OBN and MHV stations are marked by one triangle, which is due to their close proximity and scale of the picture.

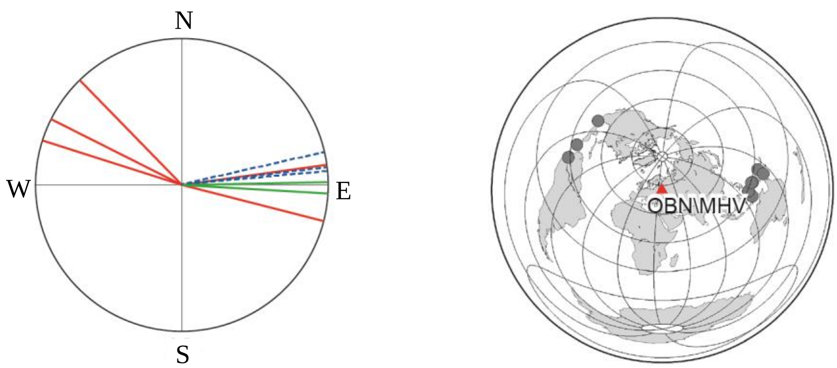

Fig. 8. Diagram of the azimuthal distribution of events recorded simultaneously at the OBN and the MHV stations (*left*), and the location of sources of the events (*right*). Notations see in Fig. 6

Independent processing of the same events recorded by two different stations showed complete consistency of the results: a solution according to the OBN station data – α=90°, δ*t*=0.3 s, according to the MHV station data – α=100°, δ*t*=0.3 s (Fig. 9).

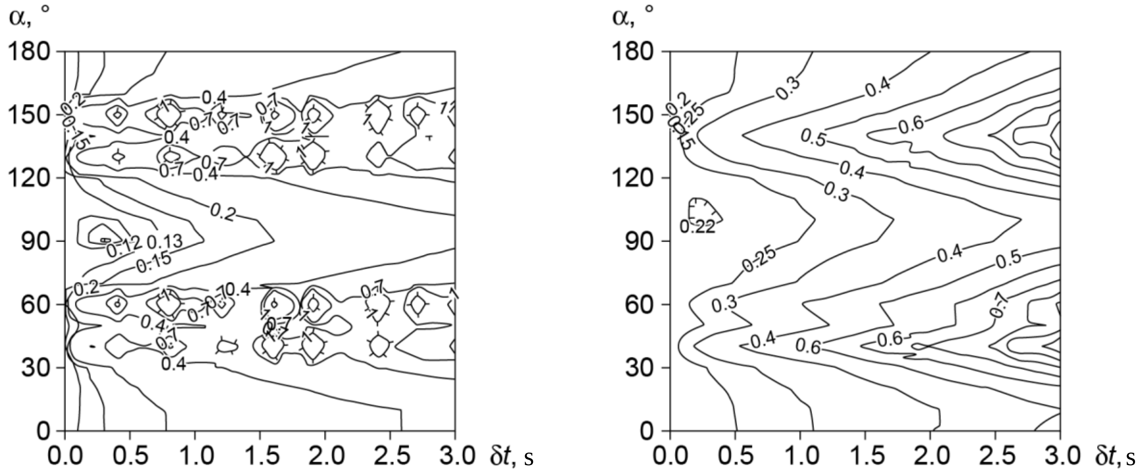

Fig. 9. The contour plot of the values of the objective function *E*(α, δ*t*) for events recorded simultaneously by the OBN and the MHV stations. *Left*: the solution obtained from the OBN station data; *right*: the solution obtained from the MHV station data

Conclusions

The paper presents the results of a reevaluation of the anisotropic parameters (the directions of the main axis of symmetry α and the delay δ*t*) performed for the central part of the East European craton by the *SKS/SKKS* method according to the data from the Obninsk (OBN) and Mikhnevo (MHV) seismic stations.

Estimates for the OBN seismic station were obtained from a data set that is more representative compared with previously used in similar studies; for the MHV seismic station, the anisotropic parameters were estimated using the *SKS/SKKS* method for the first time.

For the OBN station, the azimuth of the direction of the main axis of symmetry α is 100°; the delay δ*t*, characterizing the value of anisotropy, is 0.4 s. For this station, two groups of events with different individual solutions were identified - for one α≈90°, for the other α≈160°.

A more detailed analysis showed that in the joint processing of events group with individual solutions close to 160°, we obtain a general solution α=100°, δ*t*=0.3 s. However, in this case, a pronounced side local minimum is detected, corresponding to α≈160°and δ*t*≈0.5 s. In addition, the epicenters of most events of this group are located to the east of the OBN station. Note that the result given in [*Helffrich, Silver, Given,* 1994] α= –19° (161° taking into account 180-degree periodicity) was also obtained from events mainly from the east direction relative to the OBN station (see Fig. 1). The reason for the apparent separation of events into two groups with opposite azimuths and significantly different results is currently unclear - for example, we can assume the existence of at least two anisotropic layers.

For the MHV seismic station, located at a distance of 80 km from the OBN station, a solution is obtained that is in good agreement with the solution for the OBN station – α=90°, δ*t*=0.2 s. Moreover, according to the results of analysis of the experimental material for the

MHV station, a second local minimum is also traced, corresponding to α~160° and δt~0.1–0.2 s.

The OBN and MHV seismic stations are located in the junction zone of megablocks (Fig. 10), which thicknesses and features of the deep structure, as shown in [*Bogdanova, Gorbatschev, Garetsky,* 2016], are not yet established.

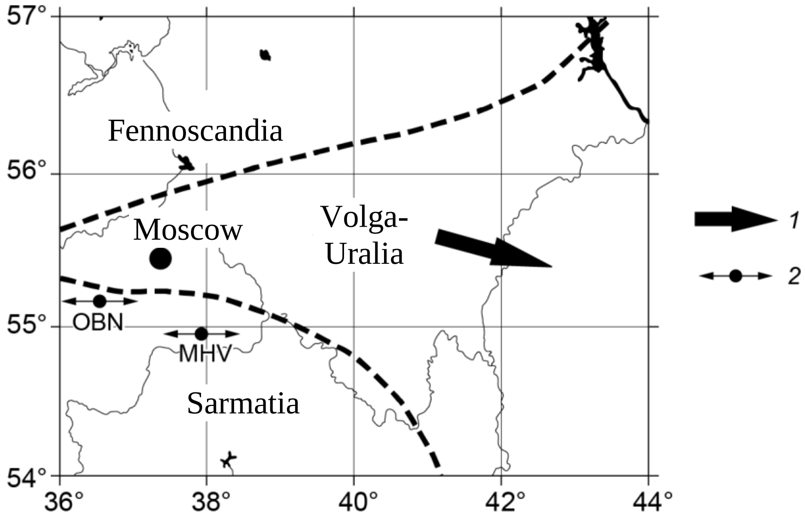

Fig. 10. A tectonic scheme (according to [*Bogdanova, Gorbatschev, Garetsky,* 2016]) of the central part of the East European craton with locations of the OBN and the MHV stations and the directions of the axis of anisotropy. *1* – direction of movement of the East European craton (by [*Khain, Lomize,* 1995]); *2* – location of stations, arrows – direction of the axis of anisotropy

It can be assumed that, since both stations are located near the junction of megablocks, the two local minima identified in this work with α of 90° and 160° characterize the "frozen-in" anisotropy of different megablocks and, possibly, reflect the effect of the asthenospheric flow of mantle material associated with the direction of movement of the lithospheric plate, which is established according to *GPS,* geotectonic and paleomagnetic modeling [*Khain, Lomize,* 1995]. Fig. 10 shows that the direction of the lithospheric plate motion coincides with the main direction of the axis of symmetry of the mantle material.

It should be noted that the factors causing the presence of anisotropy can be divided into two groups. The first group is "relict", that occurred as a result of ancient geodynamic processes, the second group is "modern", caused by convective processes and the movement of lithospheric plates. Based on the obtained results, we can assume that in this case we observe the integral effect of the interaction of these groups of factors.

Acknowledgments

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References

Becker T.W., Schaeffer A.J., Lebedev S., and Conrad C.P., Toward a generalized plate motion reference frame, *Geophys. Res. Lett.*, 2015, no. 42, pp. 3188-3196.

Bogdanova S.V., Gorbatschev R., Garetsky R.G. *Europe/East European Craton, Reference Module in Earth Systems and Environmental Sciences,* Elsevier, 2016, pp. 1-18.

Dziewonski A.M., Chou T.-A. and Woodhouse J.H., Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res.*, 1981, no. 86, pp. 2825-2852.

The Earthquakes of Russia in 2008, Editor A.A. Malovichko et al. Obninsk: GS RAS, 2010. 224 p.

Ekström G., Nettles M., and Dziewonski A.M., The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes, *Phys. Earth Planet. Int.*, 2012, no. 200-201, pp. 1-9.

Helffrich G., Silver P.G., Given H., Shear wave splitting variation over short spatial scales on continents, *Geophys. J. Int.*, 1994, no. 119, pp. 561-573.

Khain V.E., Lomize M.G., *Geotectonic with basics of geodynamics*, Study book for students of the geosciences departments of universities. M.: MSU, 1995, 480 p.

Kosarev G.L., Makeyeva L.I., and Vinnik L.P., Inversion of the P wave particle motion for crystal structure in Fennoscandia, *Phys. Earth Planet. Int.*, 1987, no. 47, pp. 11-24.

Silver P.G., Chan W.W., Shear wave splitting and subcontinental mantle deformation, *J. Geophys. Res.*, 1991, no. 96, pp. 1449-1454.

Vaganova N.V., Measurement of azimuthal seismic anisotropy parameters of the East European platform based on observations of exchange SKS waves, in *Sovremennye metody obrabotki i interpretatsii seismologicheskikh dannykh. Mater. VII Mezhdunarodnoi seismologicheskoi shkoly* (Modern methods of processing and interpretation of seismological data. Proc. VII Intern. Seismological Workshop), Obninsk, GS RAS, 2012, pp. 74–78.

Vinnik L.P., Farra V., Romanowicz B., Azimuthal anisotropy in the Earth from observations of SKS at Geoscope and NARS broadband stations, *Bull. Seismol. Soc. Am.*, 1989a, no. 79, pp. 1542-1558.

Vinnik L.P., Kosarev G.P., Makeyeva L.I., Anisotropiya litosfery po nablyudeniyam voln SKS and SKKS, *Dokl. Akad. Nauk SSSR*, 1984, vol. 278, no. 6, pp. 1335-1339.

Vinnik L.P., Makeyeva L.I., Milev A., Usenko A.Yu. Global patterns of azimuthal anisotropy and deformations in the continental mantle, *Geophys. J. Int.*, 1992, no. 111, pp. 433-447.

Vinnik L.P., Kosarev G.L., Shear wave splitting in the mantle transition zone, *Dokl. RAS*, 1997, vol. 353, no. 4, pp. 531-534.