

Evaluation of the Detection and Location Capability of the Seismic Network in the Western Part of the North Caucasus Using Network Layout and Local Microseismic Noise Level

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Abstract—The power spectra of microseismic noise were investigated at 20 stations in the western part of the North Caucasus. The seismic stations are located on the eastern coast of the Black Sea and adjacent territories, covering various tectonic structures from the Greater Caucasus to the Scythian Platform. The night and day levels of microseisms were studied at different times of the year. The annual median seismic noise spectra were calculated. The most sensitive stations with the lowest and least differing day and night noise levels were identified, which are located in protected areas far from populated areas—Guzeripl, Gornoye, and Krasnaya Polyana. Most of the stations have an average noise level compared to the global average Peterson noise curves; at these stations, at frequencies above 1 Hz during the day, the noise level increases by at least an order of magnitude due to anthropogenic activity. Average noise levels in the 1–10 Hz frequency band were used to construct network capability maps according to the our method, with the application of empirical seismic wave attenuation curves, which are used to calculate the magnitudes of seismic sources in the region. The two areas of highest network sensitivity are visible on the maps of representative $K_{P_{\min}}$ values: Anapa, with a level of $K_{P_{\min}} = 6.0$ during the day and $K_{P_{\min}} = 5.5$ at night, and Sochi–Krasnaya Polyana, with a level of $K_{P_{\min}} = 5.5$ during the day and $K_{P_{\min}} = 5.0–5.5$ at night.

Keywords: microseismic noise, seismic station, seismometer, median power spectrum, seismic network sensitivity, western part of the North Caucasus

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INTRODUCTION

The seismic network is a tool for continuous monitoring of seismic activity and is constantly changing and developing. Therefore, the sensitivity of a seismic network is evaluated regularly. Capabilities of the seismic network the whole Caucasus and the North Caucasus as part of it were determined using two approaches study of dynamic detection range of a certain energy class earthquakes by seismic stations and using statistical analysis of earthquake catalogs (Aranovich and Fabricius, 1980; Smirnov and Gabsatarova, 2001; Gabsatarova et al., 2008; Burmin, 2019a).

The present study is aimed at assessing the efficiency of the seismic network for detecting and locating earthquakes in the western zone of the North Caucasus, which has undergone significant development in the last decade. Since this area has developed only in the last decade, in the studies considered earlier, this area was practically not studied or was studied in part due to the small number of seismic stations.

It is proposed to estimate the network detection capability by applying new empirical seismic wave

attenuation curves used to calculate the magnitudes of seismic sources in the region. At the same time, variations in the seismic noise level (microseisms) where equipment is installed are taken into account: they affect the amplitude threshold for recording oscillations for each individual station.

Over the past decade, earthquakes in the North Caucasus have been recorded with digital equipment, which in many respects is technically superior to the previous generation. The significant expansion of the frequency and dynamic range for detecting vibrations led to a significant increase in the number of recorded seismic events. The transition to effective digital signals processing methods also had a significant positive effect. As a result, more accurate and representative data on the nature of seismic wave propagation, expressed in the updated calibration functions of the magnitude scales M_L used were obtained in the region (Zaklyukovskaya and Gabsatarova, 2015).

The local magnitude is calculated by an empirical dependence of the form

$$M_L = \frac{\sum_{j=1}^m \log A_j + a \log R_j + b R_j + S_j}{m} + c, \quad (1)$$

where M_L is the local earthquake magnitude; A_j is the maximum displacement amplitude in the S -wave (in nm) measured at the j th seismic station; R_j is distance of the hypocenter (in km) from the source to the j th station; S_j is the station magnitude correction for the j th observation point; a , b , and c are the calibration constants; $j = 1, \dots, m$, where m is the number of stations.

Zaklyukovskaya and Gabsatarova (2015) found the calibration constants a , b , and c for the western zone of the North Caucasus. Their values were $a = 1.22 \pm 0.3$; $b = 0.00175 \pm 0.00025$; and $c = -2.29$. A station correction was not used. Formula (1) is applied in the present research and in calculating the network sensitivity estimates.

Much greater opportunities have arisen with the transition to a digital seismic network to study the local microseismic background. Microseismic vibrations recorded by seismic stations are caused by the total impact of many seismic sources, which can be both natural (variations in atmospheric pressure, waves in the ocean, wind, atmospheric precipitation, etc.), and anthropogenic–technogenic (industrial production, transport, and other human activity) (Bormann and Wielandt, 2013).

The frequency range of microseisms is very broad, from fractions to hundreds of hertz. Microseisms associated with ocean storms have maximum amplitudes; their periods range from 5 to 6 s. The seasonal variability of microseisms is characterized by the difference between the average monthly and average annual values. Usually the most quiet season is summer (May–August in the Northern Hemisphere), and noisiest is winter (November–February) (Aptikaev, 2012).

J. Peterson (1993) developed a new of global seismic noise model in acceleration units. It is in fact two models: the upper and lower boundaries of the envelope of the total set of spectral power densities of typical ground acceleration, determined for different periods at 75 digital stations around the world. The models are commonly referred to as the New High Noise Model (NHNM) and New Low Noise Model (NLNM), respectively, and are the currently accepted standard for the expected seismic noise limits at seismic stations (Bormann and Wielandt, 2013). In comparison with these generalized noise limits, the real noise at the stations of the western zone of the North Caucasus was investigated.

The network detection capability also depends on its configuration. In a recent work, V.Yu. Burmin (2019b) showed that, on the whole, the entire seismic network in the Caucasus, despite its significant quan-

titative representativeness (more than 300 stations), is not optimal for ensuring uniform observations of any one value of the energy class of earthquakes, e.g., $K = 9.0$. In his calculations, the author assumed that the increase at all stations is the same: 50000. It was concluded that in order for the observation system to record events occurring at different points of the Caucasus with the same accuracy and same minimum energy class, it is necessary to arrange the seismic stations more evenly throughout the entire territory, i.e., the observation system must be optimally configured. However, practice shows that this is impossible for the Caucasus network for a number of reasons described below.

The seismic network of the western zone of the North Caucasus has undergone significant changes in the last decade. Until 2008, only two stations “Sochi” and “Anapa” operated on the Black Sea coast, built according to the standard approach in the 60-s of the last century (Gabsatarova et al., 2008). Over time, these stations ended up in the central part of rapidly developing resorts, which was reflected in the level of recorded seismicity in this area: these stations recorded earthquakes with $K_p = 8.5$ occurred in the immediate vicinity, while further north, only with, $K_p = 9.0–10.0$. By 2012, the number of stations had grown to 12, but most of them were grouped near the Sochi and Krasnaya Polyana zones, which was explained by the need to ensure continuous seismic monitoring near facilities under construction for the 2014 Olympics (Malovichko and Gabsatarova, 2012).

It should be noted that the Black Sea coast and adjacent territories are a very complex area for placing seismic stations (observation points), since they are characterized by:

- (1) a high level of seismic noise, both natural and technogenic;
- (2) complex soils, rarely hard basement rock, often composed of sedimentary sandy-clayey rocks, sometimes filled or watered;
- (3) a large number of transport roads of different levels;
- (4) state- and privately owned closed territories over vast areas.

Choosing an installation site for a seismic station and creating an optimal operating environment is an important task. It should be noted that a modern seismic station is an unmanned observation post that operates autonomously. For this reason, it is necessary to ensure conditions for equipment safety, as well as the possibility of uninterrupted power supply and continuous data transmission via satellite or mobile communication channels, since rapid access to data, is a requirement of paramount importance. It is expedient to place seismic stations in areas as far as possible from



Fig. 1. Map of seismic stations in the western zone of the North Caucasus. Yellow lines show the boundaries of tectonic elements after (Khain, 1973).

any human activity, but in practice one has to compromise between remoteness and ease of access.

All this was taken into account in the initial preliminary selection of the locations for new stations. Teams of specialists conducted field trips to these areas prior to installation. Preliminary works included microseismic noise studies at several promising points of the selected area, as well as in several nearby populated areas, assessment of a possible uninterrupted power supply and stable communication and, importantly, the obtaining of consent from the owners of private property to place a small concrete pedestal on their territory, isolated from residential buildings and enclosed in a metal housing.

The aim of this study was to assess the sensitivity of the network in the western zone of the North Caucasus based on the results of studying the microseismic level noise at seismic stations in different seasons and times of day, as well as seismic wave attenuation in this zone.

COMPOSITION OF THE SEISMIC NETWORK AND INSTALLED EQUIPMENT

Despite the short development time for the seismic network in the western zone of the North Caucasus (Fig. 1), it has a rich history of events. Some of the stations that had been installed and were operating for a certain time were subsequently decommissioned or

Table 1. Information on operating stations of GS RAS in western zone of North Caucasus

Seismic station		Coordinates and height above sea level		Characteristics of equipment installation site	Digital equipment (date of installation of new equipment)
station name and code	commissioning date	φ , °N, λ , °E	h , m		
1	2	3	4	5	6
Anapa ANN	07.03.1968	44.881, 37.314	58	The central part of Anapa, the seismometer is installed in a remote pavilion; 0.5 km to the west, Black Sea. Rocks: loam, alluvium, clays, sandstones	SM-3OS + SDAS (11.07.02); SM-3OS + UGRA (29.08.2019)
Arkhyz ARXR	17.11.2006	43.562, 41.275	1501	Outskirts of village of Arkhyz, 100 m from highway, 500 m from mountain river B. Zelenchuk	SM-3KV + SDAS SM-3KV + UGRA (8.12.2015)
Veseloe VSLR	27.10.2014	43.461, 40.032	340	Eastern outskirts of village of Nizhnyaya Shilovka; 8 km, Adler airport; 10 km, city of Adler	SM-3KV+UGRA
Gelendzhik GL1R GELR	01.05.2013 17.07.2017	44.549, 38.070 44.580, 37.987	60 70	Western outskirts of city, 0.5 km from sea (Golubaya Bay), 2 km from runway of Gelendzhik airport, 5 km from Sukhum highway	SM-3KV + UGRA SPV-3K + UGRA (25.04.2018)
Gladkovskii GLDR	07.10.2018	44.983, 37.721	230	Southern outskirts of Gladkovskaya station, 3 m from local road, 1.3 km east of Lake Bam, 22 km from Krymsk. Rocks: sandy–clayey sedimentary	SM-3KV + UGRA
Goytkh GOYR	29.09.2015	44.247, 39.377	300	Northeast suburb of village of Goytkh, 30 km northeast of Tuapse, 200 m from local road, 500 m from Pshish River. Rocks: limestone	CM-3KB + UGRA SPV-3K + UGRA (14.07.2017)
Golovanovskii GLVR	06.06.2019	46.848, 40.981	96	Veselovskoye Reservoir 24 km northeast; town of Salsk 60 km southeast. Around lie arable fields and pastures	SM-3KV + UGRA
Gornoye GRYR	12.11.2017	44.117, 41.094	740	Northern outskirts of village of Gornoye, 4 km from deep Laba River Rocks: limestone	SM-3KV + UGRA
Guzeripl GUZR	15.06.2012	43.996, 40.118	822	4 km from village of Guzeripl, on territory of branch of Caucasian Reserve. Deep Belaya River, 800 m; creek, 20 m. Rocks: limestone	SM-3KV + UGRA
Dombay DOMR	25.10.2006	43.292, 41.624	1608	Northwest outskirts of resort village of Dombay, less than 100 m from mountain river Amanauz; 150 m, lift station	SM-3KV + SDAS SM-3KV + UGRA (16.01.2016)
Eremizino-Borisovskaya ERBR	07.10.2009	45.715, 40.484	286	Northern outskirts of large rural settlement; 1 km, Borisovka River	SM-3KV + SDAS TC120-SV1 + UGRA (1.08.2017)
Krasnaya Polyana RPOR	24.02.2010	43.699, 40.266	600	Cordon Laura, 1.5 km from main settlement of Estosadok and Mzymta River	SM-3KV + UGRA
Labinsk LABN	26.09.2008	44.641, 40.724	290	Central part of city of Labinsk; 1.5 km, Laba River	SM-3KV + UGRA TC120-SV1 + UGRA (13.08.2017)

Table 1. (Contd.)

Seismic station		Coordinates and height above sea level		Characteristics of equipment installation site	Digital equipment (date of installation of new equipment)
station name and code	commissioning date	φ , °N, λ , °E	h , m		
1	2	3	4	5	6
Maryino MRNR	17.11.2017	43.937, 39.479	360	Southwestern outskirts of Maryino; 3 km to west, Psezuapse River, 8 km from LZRR station, 10 km from sea	SM-3KV + UGRA
Nevinnomyssk NVN	19.02.2007	44.614, 41.964	340	On territory of meteorological station; 1.7 km west, Kuban River; 3 km west, B. Zelenchuk River; 2 km, highway P217	SM-3KV + SDAS (19.02.2007)
Novopoltavsky NVPR	03.06.2019	46.877, 39.140	28	In center of village of Novopoltavsky, Rostov oblast; 16 km southeast of Taganrog Bay of Sea of Azov, 33 km from city of Azov, 40 km from highway E50	SM-3KV + UGRA
Sochi SOC	1928	43.570, 39.763	180	Bytkha mountain area, densely built up area, 1.5 km from sea. Rocks: clay shale	SM-3OS + SDAS (16.06.2001) SM-3OS + UGRA (30.11.2014)
Sergievskii SRGR	04.10.2018	45.418, 39.181	15	Western outskirts of Sergievskaya station, in bend of Kirpili River, 22 km east of Korenovsk, 45 km north of Krasnodar. Rocks: chernozem	SM-3KV + UGRA
Sukko SUKR	15.10.2018	44.799, 37.429	41	4 km from sea, 500 m from Utrish nature reserve. Rocks: gravel	SM-3KV + UGRA (15.10.2018)
Tamanskii TMNR	11.10.2018	45.155, 36.785	14	Northern outskirts of village, 5 km from highway E97 to Crimea Bridge (15 km), 5 km to Black Sea, 10 km to Taman Bay, large estuaries 5 and 10 km to east. Sandy–clayey sedimentary rocks	SM-3KV + UGRA
Shapsug SPGR	08.09.2015	44.742, 38.073	100	On southern outskirts of village of Shapsugskaya, 15 km north of Tsemesskaya Bay, 20 km from Gelendzhik, between small Adeгой and Abin rivers Rocks: dense loam, low-moisture, with inclusions of rubble and pebbles	SM-3KV + UGRA SPV-3K + UGRA (6.07.2018)

moved. Information about all of the stations is given in Tables 1 and 2. The records of the operating stations are continuously transmitted to the data centers and are stored in the archives of the Federal Research Center of GS RAS.

To develop the network in such difficult conditions on the territory of the Greater Sochi resort, the route was initially used to duplicate the stations in terms of operating time and their location at a short distance from each other, in order to subsequently choose the optimal stations for this territory. Such duplicating groups are Tuapse–Agoy–Goytkh, Lazarevskoe–

Maryino, Akhmetovskaya–Gornoye, and Esto-Sadok–Krasnaya Polyana (see Tables 1, 2).

BRIEF DESCRIPTION OF SEISMIC EQUIPMENT INSTALLED AT STATIONS

The stations are equipped with various seismometers (velocimeters) (see Table 1):

(1) Russian SM3-OS broadband seismometers (velocimeters) (Anapa and Sochi stations) with an operating band (at a 3 dB level) of 0.02–10 Hz and Canadian Trilium TC120-SV1 seismometers (Fig. 2)

Table 2. Information about stations of FRC GS RAS in western zone of North Caucasus that have been moved or whose operation has been terminated to date

Seismic station		Coordinates and height above sea level		Characteristics of equipment installation site	Seismometer and type of digital equipment
station name and code	commissioning date—decommissioning date	φ , °N, λ , °E	h , m		
1	2	3	4	5	6
Agoy AGYR	09.08.2012— 22.08.2014	44.148, 39.037	55	Western outskirts of Agoy, 250 m from road with heavy traffic, 500 m from river, 2 km from seacoast, 10 km from Tuapse	SM-3KV + UGRA
Aibga Moved to Veseloe	14.10.2013— 20.10.2014	43.588, 40.185	680	Northwest outskirts of Aibga, 1.5 km from Abkhazia border, 11 km south of Krasnaya Polyana. Impossibility of automatic information transmission	SM-3KV + UGRA
Akhmetovskaya AHMR Moved to Gornoe	19.10.2012— 09.11.2017	44.158, 41.044	640	On Laba River, in center of village	SM-3KV + UGRA
Vozrozhdenie VOZR Moved to Gelendzhik	28.09.2008— 11.03.2013	44.553, 38.223	92	Outskirts of village on hillside, 0.4 km from motorway; Black Sea, 9 km southwest. Unstable power supply and communications	SM-3KV + UGRA
Lazarevskoe LZRR Moved to Maryino	31.07.2011— 16.11.2017	43.935, 39.380	180	Eastern outskirts of Alekseevskoe, suburban area, 500 m from Psezua-pse River, 5 km from village of Lazarevsky, 6 km from sea	SM-3KV + UGRA
Tuapse TPSR Moved to Goytkh	31.10.2010— 28.09.2015	44.078, 39.096	80	Village of boarding house Vesna, 150 m from sea and railway, 2.5 km from seaport	SM-3KV + UGRA
Fisht FSTR	07.05.2013— 31.10.2018	43.944, 39.871	1760	Caucasian Biosphere Reserve, on Mt. Fisht, research area of scientific center Biosphere. 37 km northwest of Krasnaya Polyana, 6 km east of deep Belaya River Rocks: limestone	SM-3KV + UGRA
Esto-Sadok RP2R	12.08.2012— 03.05.2014	43.683, 40.2722	550	On northeastern outskirts of village of Estosadok, 250 m from Mzymta River, 0.5–2 km from lift stations	SM-3KV + UGRA

with a 0.008–100 Hz frequency range (Labinsk and Eremizino-Borisovskaya stations);

(2) short-period seismometers (velocimeters): small-sized SPV-3Ks with a 0.5–65 Hz operating frequency range at the Gelendzhik, Goytkh, and Shapsug stations and SM-3KV with a 0.5–70 Hz operating frequency range at the other stations (Fig. 3).

The number of recording channels is a multiple of three, since all three ground components motion are of interest in seismic observations. Sets of uniaxial sensors (SM3-KV Z, N–S, E–W, see Fig. 3) and triaxial sensors in one housing are used (SPV-3K and Trilium TC120-SV1, see Fig. 2).

Only two stations in the western zone of the North Caucasus, established in Soviet times according to a special project for southern stationary stations—Anapa and Sochi—have specially built portable pavilions with equipment pedestals; therefore, the CM3-OS temperature- and pressure-sensitive devices were installed. For all other stations/observation posts, pedestals were set up in places separated spatially from residential rooms and were encased in metal boxes (Figs. 4, 5). The Labinsk and Eremizino-Borisovskaya stations were equipped with Trilium TC120-SV1 seismometers under the international project Deep-Seated and Seismic Structure of the Greater Caucasus (Sandvol et al., 2019).



Fig. 2. General view of bunker with Trilium TC120-SV1 seismometer in standard housing. Eremizino-Borisovskaya Station.



Fig. 3. Set of SM-3KV short-period seismometers on pedestal in metal cover. Veseloe station.

Referencing to the time scale at all stations is done with GPS receivers. Arrays were usually installed at the corners of buildings.

The recording equipment consists of UGRA type seismometers. Digital seismic station UGRA digital seismic station produced by RPE Geotech + and LLC Microseism (Russia) is scientific equipment designed for regional and teleseismic observations in stationary conditions.

The stations are equipped with 24-bit recorders with a sampling rate of 50 or 100 readings per second and have a dynamic range of at least 130 dB, which makes it possible to simultaneously record both low-energy seismic events and strong earthquakes without distortion.

METHODOLOGY FOR STUDYING SEISMIC NOISE

Seismic noise was studied using microseismic noise power spectra, calculated using MicroNoise v. 1.3 software (author R.A. Dyagilev). To obtain spectral estimates, we used experimental data (seismic records free of earthquake records) for 2019–2020 (hereinafter, the first half of 2020); for each station, samples were taken from at least 20 seismic record fragments, each about 1.5 h long. There were separate fragments for studying daytime (from 04:00 to 18:00 UTC) and night (from 19:00 to 03:00 UTC) noise, as well as for studying seasonal noise variations.

All power spectra were calculated using Bartlett's spectral estimate (Kanasevich, 1985), with averaging of the power of individual harmonics over a series of



Fig. 4. General view of bunker encased in metal housing at Guzeripl station.



Fig. 5. General view of bunker encased in metal housing at Gornoye station.

spectra obtained from short (about 20 s) consecutive segments of the original time series. This made it possible to reduce the variance of the ultimate spectral density estimates for each record fragment by about 16 times. The spectrum in each data segment was calculated by fast Fourier transform, while the calculated window was filled to a length that is a multiple of a power of two entirely based on data from the initial series. The distorting effects associated with the finiteness of the time series in each segment were compensated by Hann window functions.

The spectra for each component of the record were analyzed separately. This paper presents the results of estimating the noise parameters only for vertical oscillations (Z component).

Golden Software Grapher v8.0.278 software was used to plot the noise power spectra.

STUDY OF SPECTRAL NOISE MODELS FOR NETWORK STATIONS

A series of seasonal spectra for four stations in the region— Anapa, Sochi, Labinsk and Eremizino-Borisoovskaya—equipped with broadband equipment give an idea of the variability of natural microseisms associated with storm impact in the ocean and Black Sea: The microseismic spectra differ somewhat at the coastal (ANN, SOC, Figs. 6, 7) and continental (ERBR, LABN, Figs. 8, 9) stations.

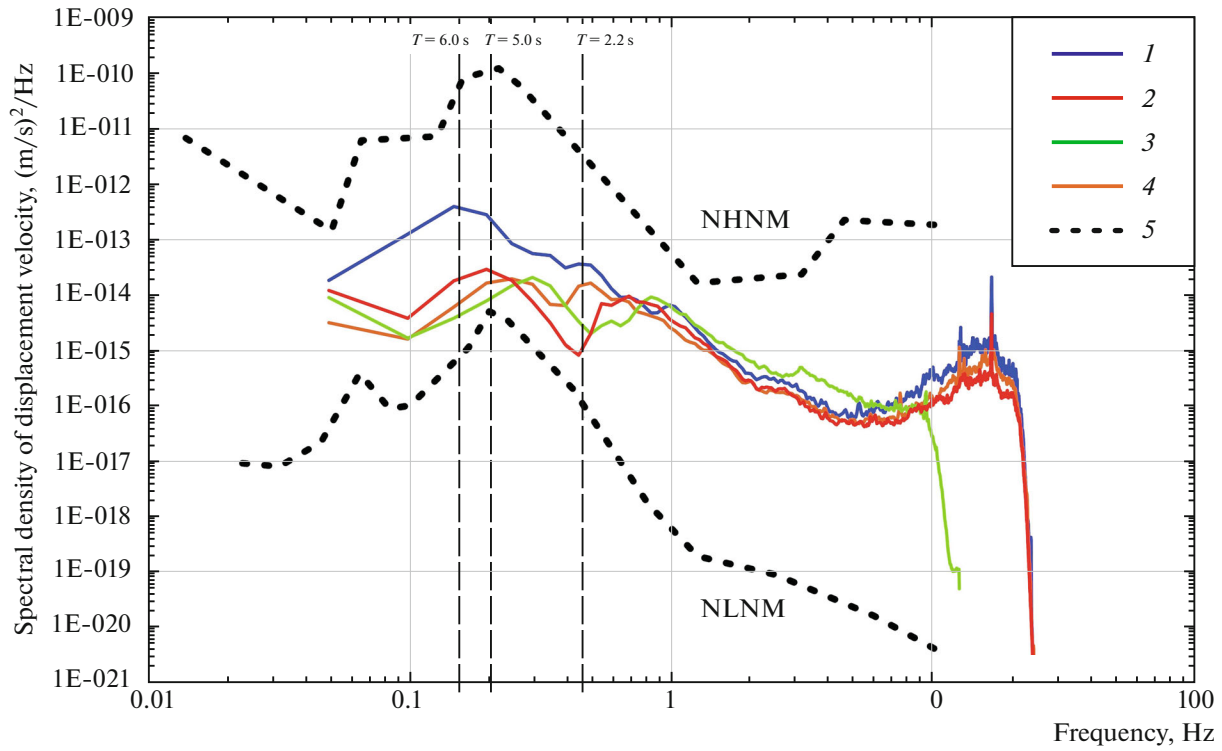


Fig. 6. Seasonal nighttime noise power spectra of seismic station ANN: (1) winter; (2) spring; (3) summer; (4) autumn; (5) curves of new high noise model (NHNM) and new low noise model (NLNM) (Peterson, 1993).

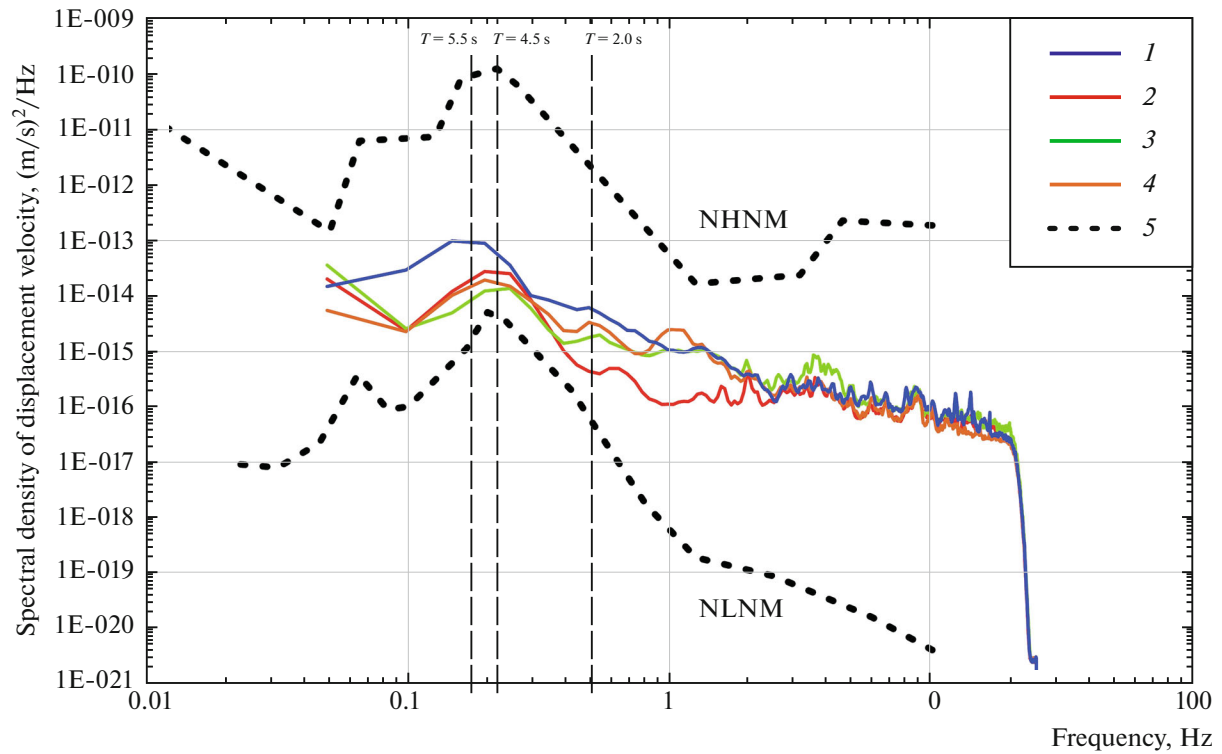


Fig. 7. Seasonal nighttime noise power spectra of seismic station SOC: (1) winter; (2) spring; (3) summer; (4) autumn; (5) curves of new high noise model (NHNM) and new low noise model (NLNM) (Peterson, 1993).

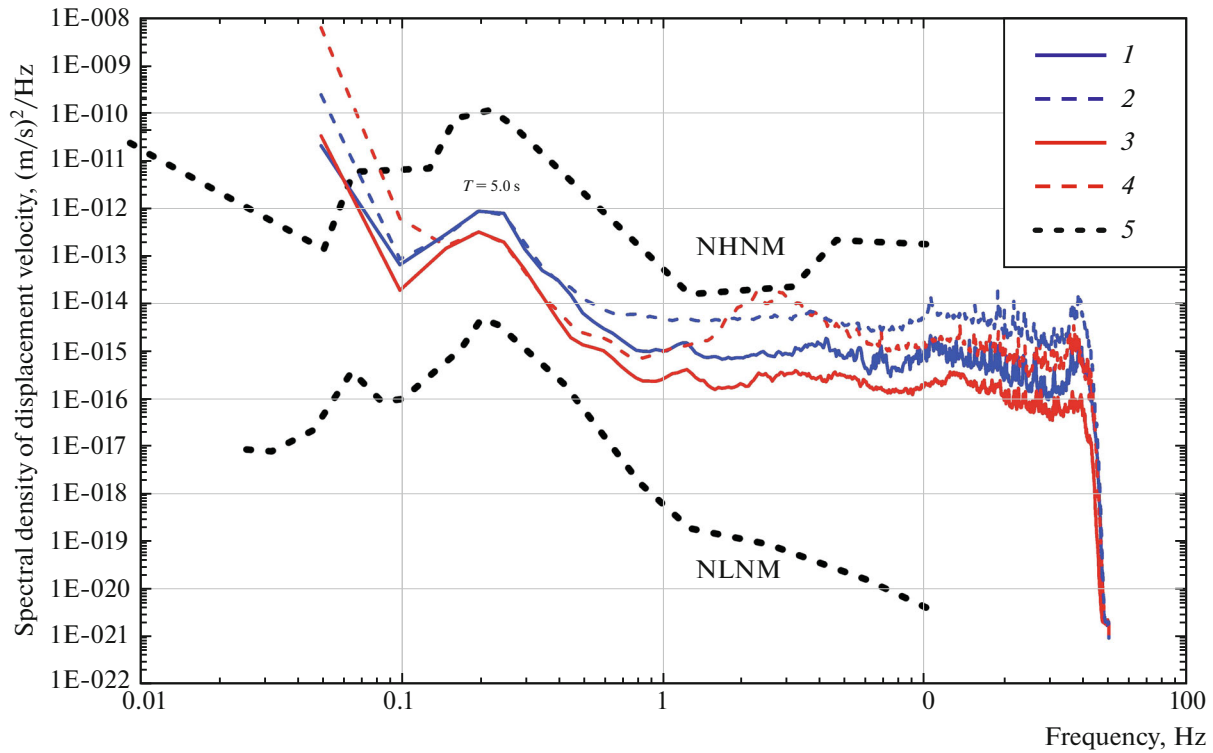


Fig. 8. Power spectra of night- and daytime noise at seismic station ERBR in winter and spring: (1) nighttime noise in winter; (2) daytime noise in winter; (3) nighttime noise in spring; (4) daytime noise in spring; (5) curves of new high noise model (NHNM) and new low noise model (NLNM) (Peterson, 1993).

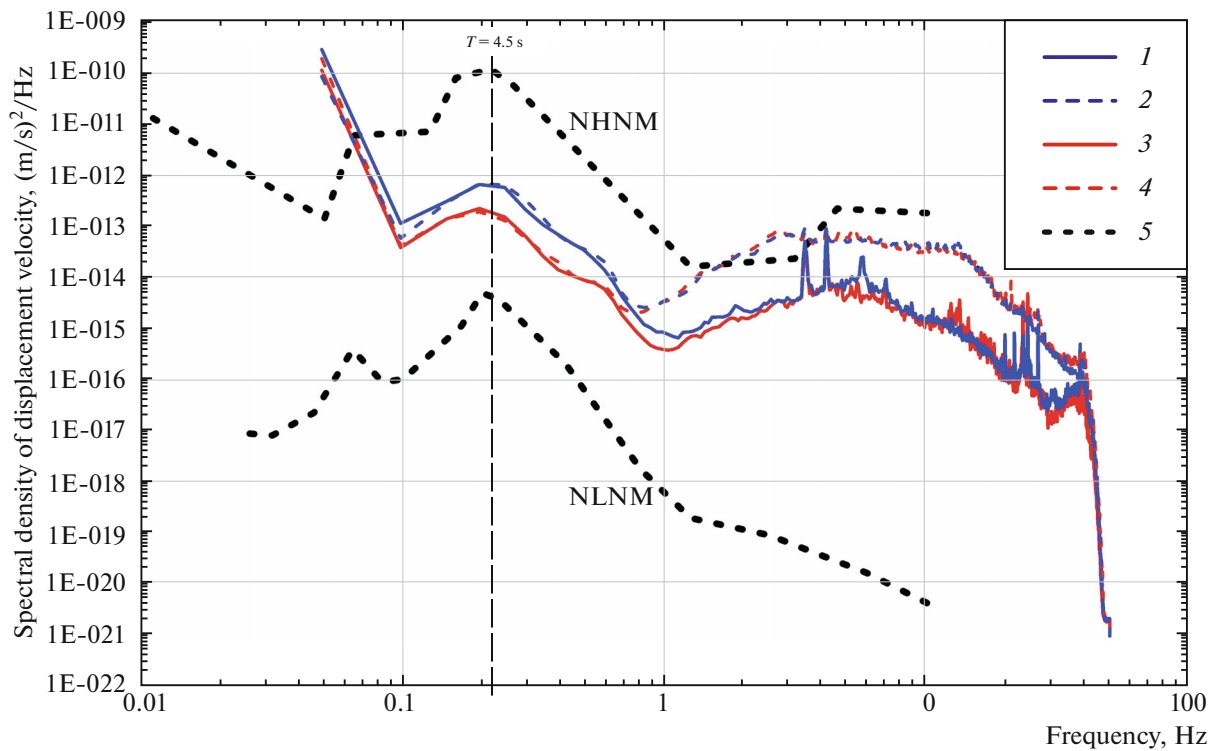


Fig. 9. Power spectra of nighttime and daytime noise in winter and spring for seismic station LABN: (1) nighttime noise in winter; (2) daytime noise in winter; (3) nighttime noise in spring; (4) daytime noise in spring; (5) curves of new high noise model (NHNM) and new low noise model (NLNM) (Peterson, 1993).

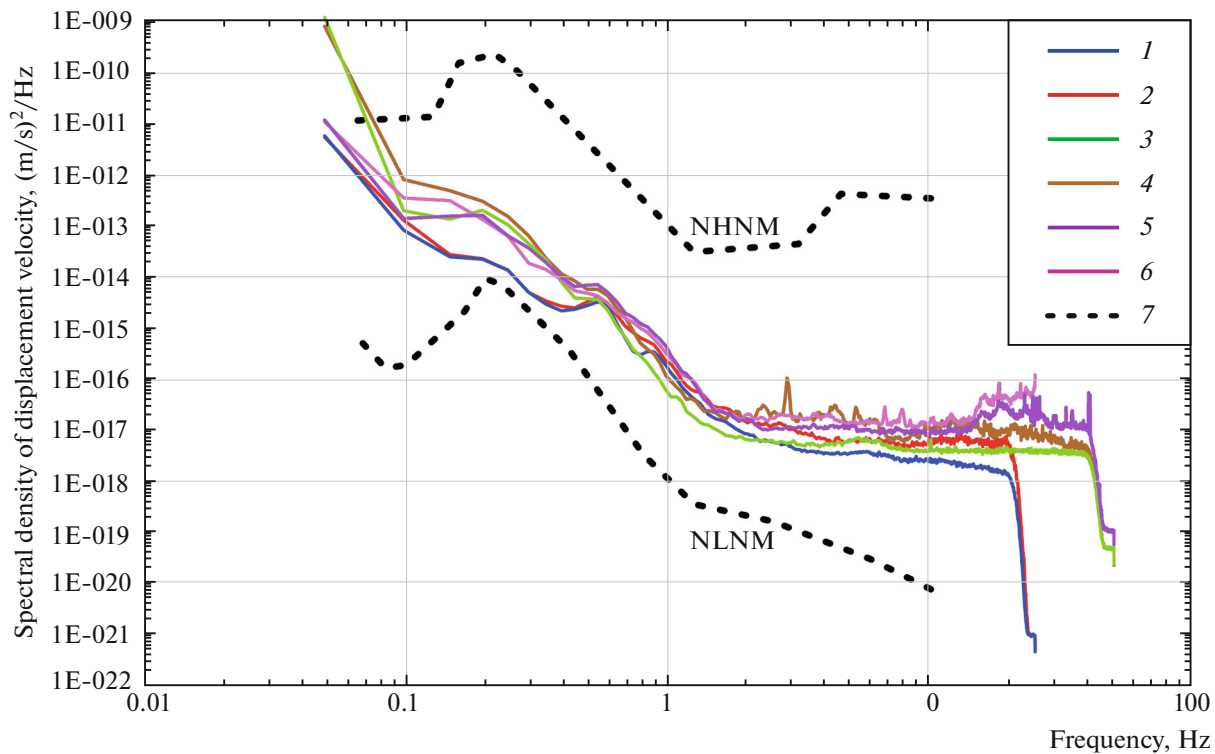


Fig. 10. Power spectra of nighttime and daytime noise of three quietest stations in western part of North Caucasus. GUZR: (1) night, (2) day; GRYR: (3) night, (4) day; RPOR: (5) night, (6) day; (7) curves of new high noise model (NHNM) and new low noise model (NLNM) (Peterson, 1993).

The coastal stations, as is distinctly seen in the noise power at spectrum of station Anapa (ANN, see Fig. 6), have two maxima: in the range of periods $T = 5-6$ s and $T \cong 2$ s. The maximum storm microseisms of the World Ocean with a period of about 5 s are manifested in winter, and the Black Sea microseisms ($T \cong 2$ s), in autumn. In summer and spring, storm microseisms are less pronounced. On the noise power spectrum of the Sochi station (SOC), microseisms from storms in the Black Sea are poorly distinguished even in winter (see Fig. 7).

The continental stations (far from the Black Sea at distances $\Delta \geq 100$ km) contain in their power spectra a typical increase in spectral amplitudes for oceanic microseisms with a period of 5 s and are hardly contain influenced by the Black Sea (period ~ 2 s), as shown, e.g., in Figs. 8 and 9 for the Eremizino-Borisovskaya (ERBR) and Labinsk (LABN) stations.

The high-frequency noise range is usually associated with anthropogenic activity and the seismic properties of the ground on which the equipment is installed. The level of human influence on microseisms can be seen in daytime noise; the ground influence of soils is better observed at night.

In terms of seismic noise, the quietest stations equipped with short-period equipment are Guzeripl, Gornoye, and Krasnaya Polyana. Their microseismic power spectra are virtually unaffected by anthropo-

genic and technogenic factors, because the levels of the median annual spectrum of the night and daytime records are very close and lie below the conditional middle line of Peterson models (Fig. 10). These three stations are located in the Caucasian Reserve in a sparsely populated area, and the instruments are installed on rocky ground.

Several more stations are close to them in terms of noise level: Maryino, Goytkh, Sukko, and Shapsug (Fig. 11), where the underlying rocks are mainly dense sedimentary. The presented spectra characterize the nighttime interval; therefore, anthropogenic influence on them is minimal.

Nighttime noise looks different at platform stations (see Fig. 1): Gladkovskii on the southern side of the West Kuban trough, Sergievskaya on the Scythian platform, Novopoltavskii on the Rostov scarp of the Ukrainian Shield, and Golovanovskii in the Kumobnychsky trough. The stations are installed on looser soils, in areas with a thick sedimentary layer. When compared with the quietest station, Guzeripl, it is noticeable that noise at frequencies of $f > 1$ Hz are about two orders of magnitude higher even at night (Fig. 12).

The Labinsk and Nevinnomyssk stations, located in cities, are distinguished by a high microseism level; their microseismic power spectra show high noise in a wide frequency band of $f \geq 1$ Hz, attributable to

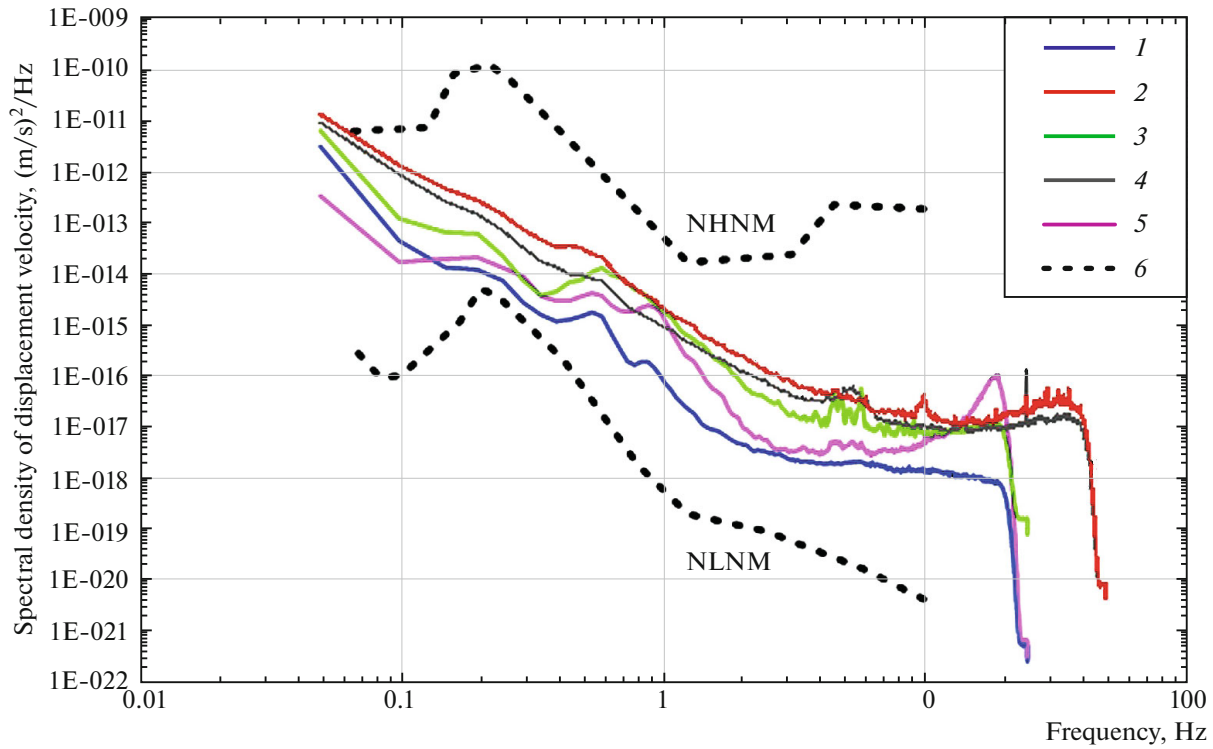


Fig. 11. Power spectra of nighttime noise of four stations in western part of North Caucasus compared to the spectrum of the quietest station (GUZR): (1) GUZR; (2) SPGR; (3) SUKR; (4) GOYR; (5) MRNR; (6) curves of new high noise model (NHNM) and new low noise model (NLNM) (Peterson, 1993).

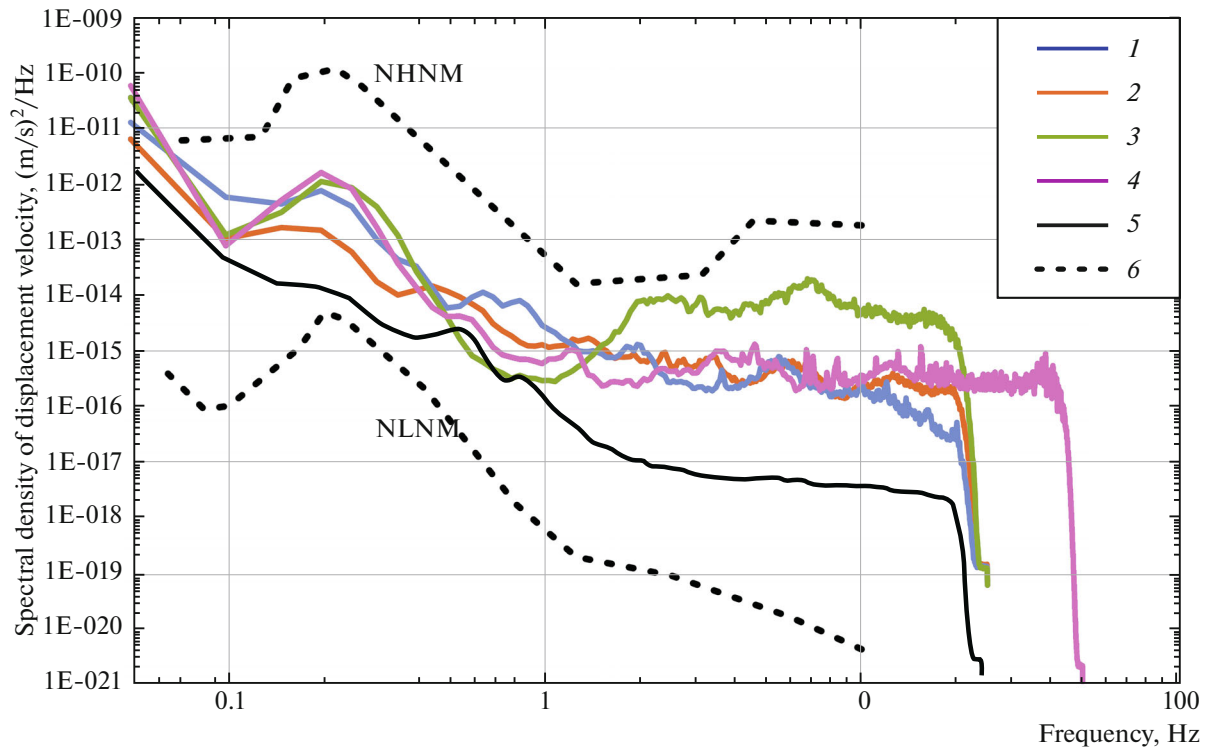


Fig. 12. Nighttime noise power spectra of platform stations in western part of North Caucasus (1) NVPR, (2) SRGR, (3) GLVR, (4) ERBR compared to (5) the spectrum of the quietest station, GUZR, and (6) levels of new high noise model (NHNM) and new low noise model (NLNM) (Peterson, 1993).

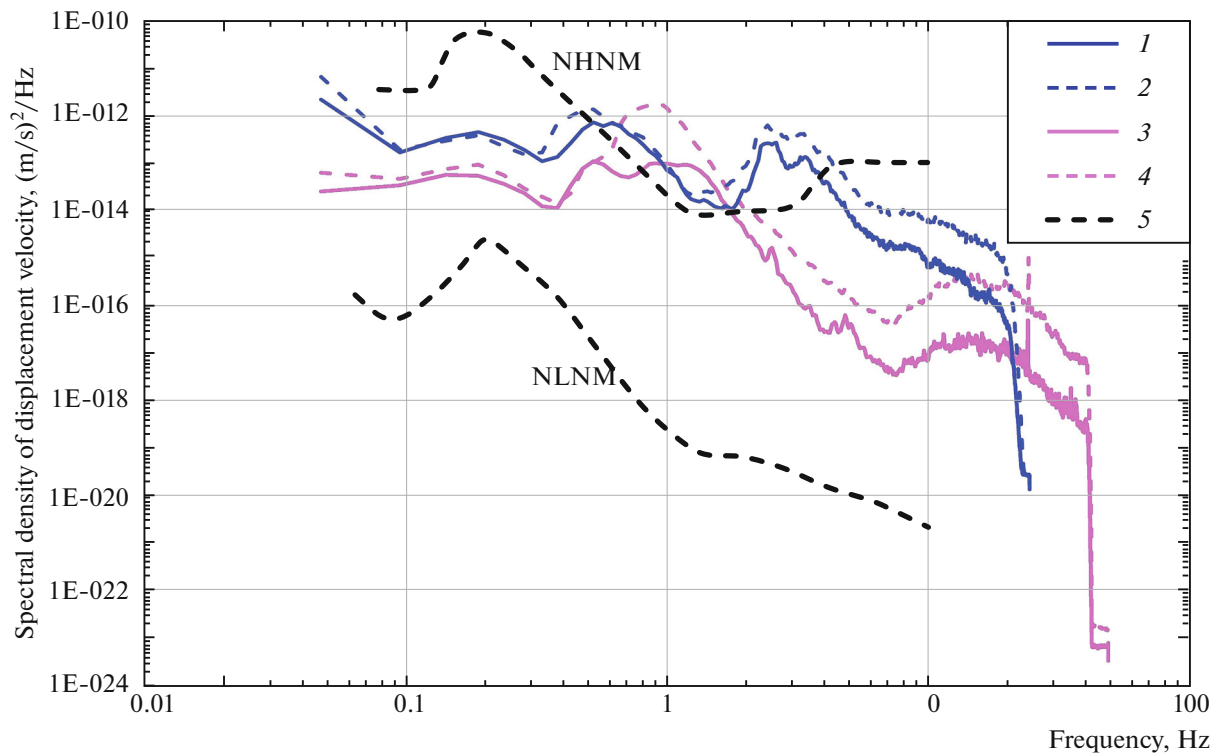


Fig. 13. Average power spectra of night- and daytime noise from Kerch and Taman stations: (1) Taman, night; (2) Taman, day; (3) Kerch, night; (4) Kerch, day; (5) curves of new high noise model (NHNM) and new low noise model (NLNM) (Peterson, 1993).

anthropogenic activity. Thus, in Labinsk, at a distance of 1–1.5 km from the station, there are at least three large production facilities: a mechanical plant producing metal products for construction organizations, the Kubanmash machine building plant, and a wood-processing plant. Less than 1 km from the station is a railway with heavy freight traffic both day and night. Nevinnomyssk station is also located in the city center on the territory of a meteorological station. The location of Labinsk and Nevinnomyssk stations is important for monitoring seismicity at the Stavropol arch and in the vicinity of the Caucasian mineral waters, but they need to be moved to a quieter place in the suburbs of these cities.

The Taman and Golovanovskii stations occupy a special place among the noisy ones, since they are located in extremely important places: The Taman is closest to Crimea Bridge on the Taman Peninsula; Golovanovskii is closest to the source zone of the rather strong, perceptible Salsky earthquake on May 22, 2001 (Tatevossian et al., 2002; Gorbatikov et al., 2019).

These stations have been commissioned for research purposes, and it is too early to draw conclusions about their efficiency. Both of them have a high noise level due to loose sedimentary soils, which in one case (Taman) are inundated due to vast surrounding estuaries, while in the other (Golovanovskii), the

underlying rocks consist of thick chernozem in the form of arable land.

Taman station is located in a place where, west of the Anapa flexure, the fold structure of the Greater Caucasus plunges under Oligocene–Quaternary molasse of the Kerch–Taman transverse trough separating the Greater Caucasus from the Crimea Mountains. The trough consists of thick clay deposits. Despite the unfavorable ground conditions, the position of the Taman observatory is important for more accurate determination of the coordinates of the epicenters and depths of earthquakes near the Taman Peninsula in the Azov and Black Seas, especially for the most significant earthquakes in magnitude, affecting the seismic hazard level of the territory.

Seismic monitoring of the Crimean Bridge zone is of great importance. On its Crimean side is Kerch station, the records of which have been received by the Obninsk data exchange center since April 2020. The necessary data series have not yet been accumulated for the same analysis of Kerch station noise as was done for the stations in the North Caucasus. A preliminary comparative assessment of the power spectra of microseisms in spring and summer 2020 at two stations from different sides of Crimea Bridge shows (Fig. 13) that Kerch station, installed near the Pavlovsky lighthouse, has a significantly lower noise level in the 2–20 Hz band, but in the 0.5–2 Hz band, its noise

Table 3. Estimates of day- and nighttime seismic noise level from median annual power spectrum for vertical component of stations in western zone of North Caucasus in different frequency bands with and without Wood–Anderson (WA) instrument simulation

Station name and code	Displacement (WA), mm $f=1-10$ Hz, night	Displacement (WA), mm $f=1-10$ Hz, day	Displacement, $\mu\text{m} \times 10^{-3}$ $f=0.7-1.4$ Hz, night	Displacement, $\mu\text{m} \times 10^{-3}$ $f=1-10$ Hz, night	Displacement, $\mu\text{m} \times 10^{-3}$ $f=1-5$ Hz, night	Displacement, $\mu\text{m} \times 10^{-3}$ $f=5-10$ Hz, night
ANN	0.00899	0.01239	9.6002	4.3228	4.3035	0.47161
ARXR	0.0043	0.01731	5.1033	2.0663	2.0451	0.38809
VSLR	0.00408	0.00973	11.699	4.6793	4.6659	0.48096
GLDR	0.00429	0.00770	4.7691	2.0606	2.0419	0.40219
GLVR	0.02075	0.03558	3.9479	9.9760	8.8965	5.3177
GOYR	0.00481	0.00511	4.7500	2.3115	2.3087	0.25100
GRYR	0.00081	0.00121	1.0794	0.39020	0.38471	0.087599
GUZR	0.00111	0.00138	1.3888	0.53275	0.53028	0.067512
DOMR	0.00208	0.00421	0.75792	1.0000	0.77791	0.72126
ERBR	0.00710	0.26340	4.0984	3.4155	3.3462	0.99953
RPOR	0.00157	0.00158	2.3445	0.75280	0.74778	0.11861
LABN	0.01977	0.05975	5.6882	9.5039	8.9876	4.4805
MRNR	0.00369	0.00373	4.8899	1.7722	1.7704	0.10234
NVNR	0.02383	0.04451	10.559	1.1457	11.614	2.5595
NVPR	0.00900	0.02213	8.9636	4.3270	4.2683	0.97096
SRGR	0.00918	0.01984	6.8032	4.4141	4.3432	1.0034
SOC	0.00759	0.01181	6.0675	3.6486	3.6276	0.59326
SUKR	0.00555	0.00616	6.9583	2.6683	2.6642	0.18373
TMNR	0.09613	0.14865	7.0656	46.217	46.251	2.5538
SPGR	0.00694	0.00844	7.5127	3.3386	3.3329	0.26413

level exceeds not only that at Taman station, but also the curve of the global average new high noise model (NHNM). This can complicate the recording of weak near-surface events occurring in the Kerch–Taman trough. As is known, the Earth's crust is represented here by a thick layer of sedimentary rocks that contribute to the rapid attenuation of high-frequency oscillations.

METHODOLOGY FOR CONSTRUCTING A MAP OF NETWORK CAPABILITIES

The capabilities of the seismic network was calculated with SArra v1.0 software (Dyagilev, 2020), which for solving this problem relies on theoretical wave

propagation concepts used in their recording, location of hypocenters, and calculation of the energy parameters of sources. The capabilities are characterized by maps of minimum recorded (representative) magnitudes and maps of expected errors in the location of the source.

Maps of the minimum recorded magnitudes of the seismic network are calculated for conditional sources located on a certain plane, taking into account the noise situation at the location of stations. The calculation algorithm is as follows:

Let there be a seismic network consisting of N elements (stations or signal reception points). Each net-

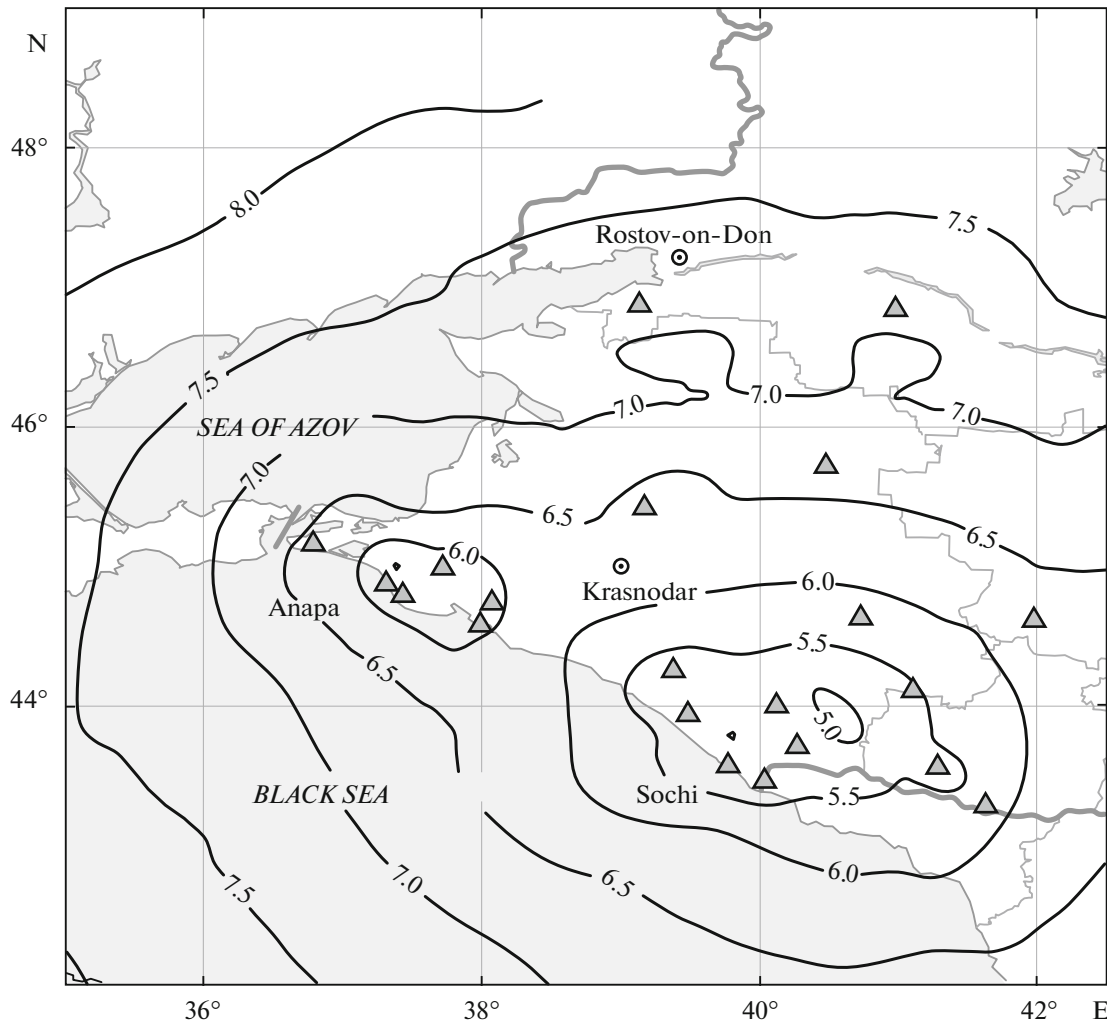


Fig. 14. Map of minimum detected (representative) energy classes (K_{Pmin}) taking into account daytime noise conditions at station locations.

work element is characterized by the following set of values:

- (1) x, y, z coordinates determining the location of the reception point;
- (2) the dependence that determines the seismic wave attenuation;
- (3) root-mean-square level of microseismic noise A_p in the useful frequency range.

The minimum detectable magnitude is determined according to the following rules:

- (1) a seismic event is considered recorded by one station if the amplitude of the recorded oscillations exceeds the level of external noise by SNR times (here SNR is the signal-to-noise ratio, in our case, $SNR = 4$);
- (2) a seismic event is considered registered by a network of stations if it is recorded by a certain minimum number of stations (N_{min}) sufficient to determine

the parameters of the source (we have established $N_{min} = 3$).

Thus, based on the law of wave attenuation and the noise level, at each point of the monitored area, it is possible to establish the limiting sensitivity of the seismic network, which in magnitude (M) or energy class (K) will be the maximum estimate of this quantity (M or K) given by N_{min} the stations with the lowest estimates M or K . With the same wave attenuation parameters and noise pattern at all stations, these will be the nearest recording points. If this is not the case, then this approach makes it possible to take into account the situation when a remote quiet station will be more sensitive than a near, but noisy one.

When using the local magnitude (Richter) scale, seismic attenuation is taken into account with the calibration curve for a particular region. In the general case, it can be represented as

$$M = \log A + a_1 \log R + a_2 R + a_3, \quad (2)$$

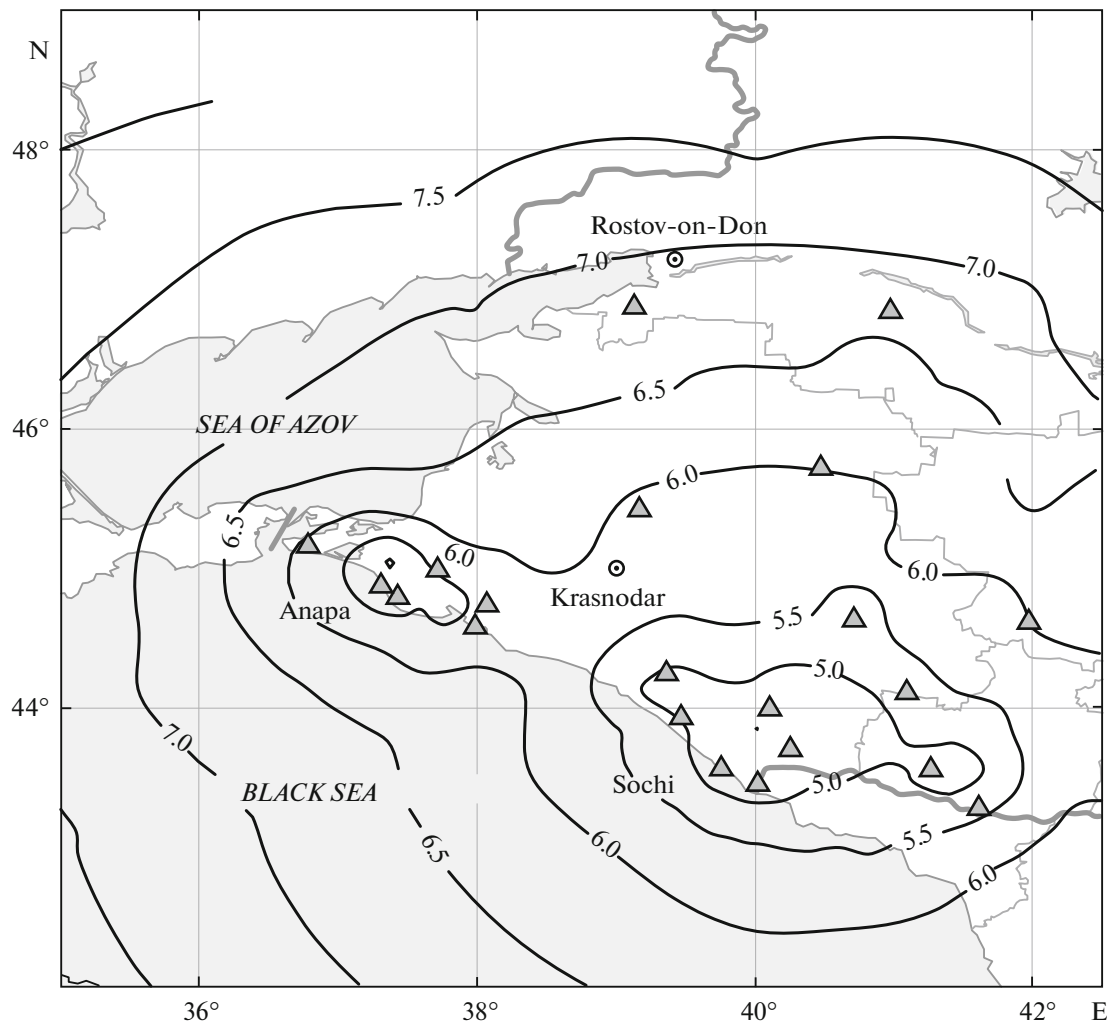


Fig. 15. Map of minimum detected (representative) energy classes ($K_{p_{\min}}$) taking into account nighttime noise conditions at stations' locations.

where A is the displacement amplitude (mm) on the record of a Wood–Anderson seismograph; R is the hypocentral distance (km); a_1 , a_2 , and a_3 are empirical coefficients. The values of coefficient a_1 , a_2 , a_3 for the western part of the North Caucasus were determined earlier in (Zaklyukovskaya and Gabsatarova, 2015).

Using the above rules that determine the detection of a seismic event, one can easily reduce Eq. (2) to a form for estimating the minimum detected magnitude (M_{\min}):

$$M_{\min} = a_0 \log(SNR \cdot A_d) + a_1 \log R + a_2 R + a_3. \quad (3)$$

Additional empirical coefficient a_0 here is needed in order to use alternative magnitude scales, including for describing in a general form the calibration curve for calculating the energy class K_{\min} . For the local magnitude scale $a_0 = 1$; when alternative scales are used, it is obtained from empirical dependences that relate them to

the M_L scale. In this study, T.G. Rautian's formula (Rautian, 1969) $\log E = K = 1.8M + 4.0$ was used, which characterizes the regions of the North Caucasus and Central Asia.

In calculating the maps of expected location errors, a fairly simple approach was used, according to which the location error at each map node was taken equal to 5% of the maximum hypocentral distance to N_{\min} stations where recording of a seismic event was noted. The 5% threshold is an empirical value obtained from a sampling of data formed as a result of seismological observations in mines and developed ore workings, where it is often possible to reliably determine the actual location error.

To construct the maps, Golden Software Surfer v9.5.510 was used.

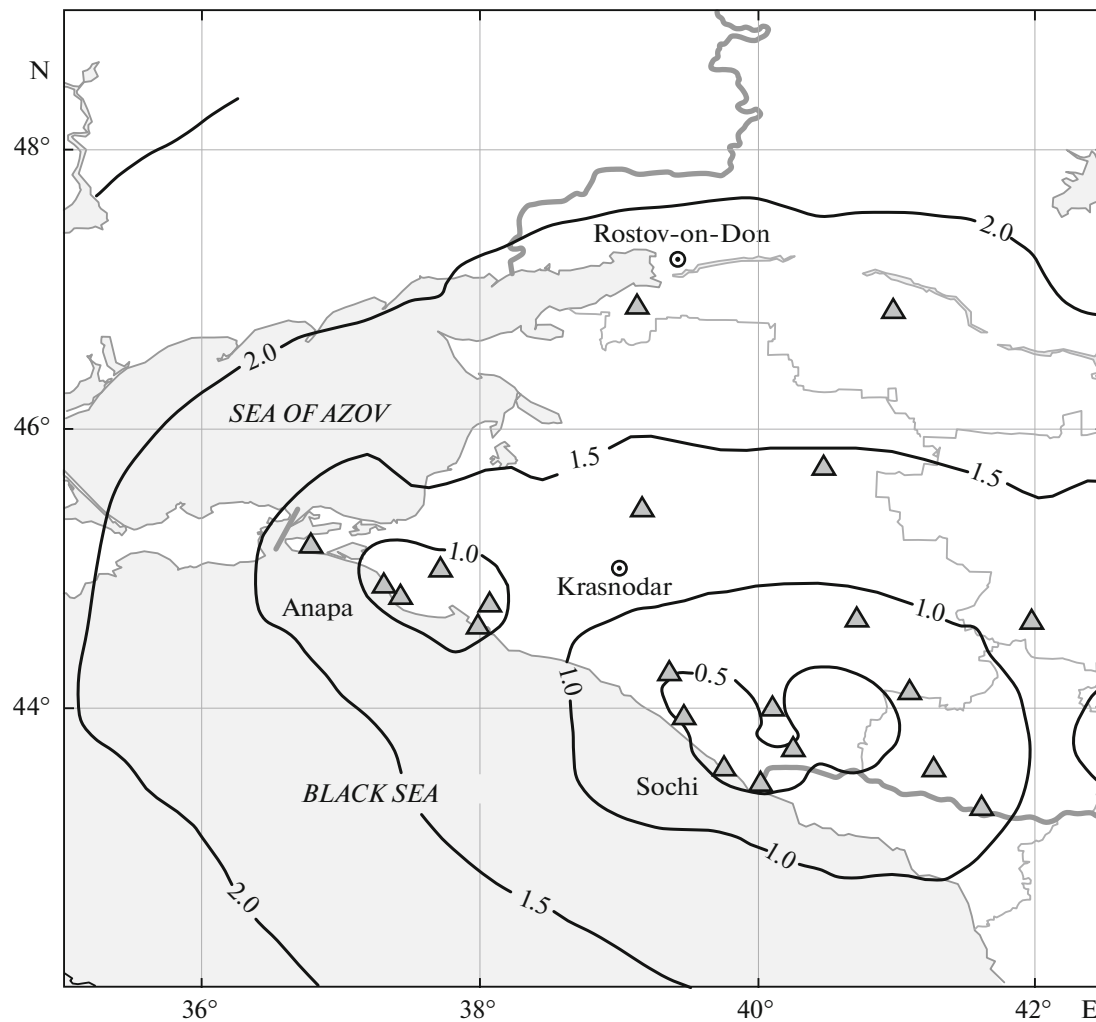


Fig. 16. Map of minimum detected (representative) magnitudes, taking into account daytime noise conditions at stations' locations.

MAPS OF NETWORK CAPABILITIES

To assess the sensitivity of the seismic network in the western zone of the North Caucasus created by 2020, we used the average microseismic noise levels according to the level of the power spectrum of median annual displacement on the vertical (Table 3). Highly sensitive stations were distinguished by noise level: Guzeripl, Gornoye, Krasnaya Polyana; medium sensitivity stations: Anapa, Gladkovskaya, Maryino, Shapsug, Sergievskaya, Goytkh, Veseloe, Sukko, Sochi, Eremizino-Borisovskaya, Novopoltavskii; and low-sensitivity stations: Labinsk, Golovanovskii, Taman, and Nevinnomyssk.

To construct a map of the minimum detected (representative) magnitudes (energy classes), taking into account the noise situation at the station location and maps of the expected errors in the location of the foci, WA offsets were used in the 1–10 Hz band at night and during the day (Table 3, Figs. 14–16).

On the K_{Pmin} maps (Figs. 14, 15), constructed taking into account the day- and nighttime noise conditions at the stations' locations, two areas of highest network sensitivity are clearly distinguished: Anapa (stations Anapa, Sukko, Shapsug, Gladkovskaya, and Gelendzhik), with a level $K_{Pmin} = 6.0$ during the day and $K_{Pmin} = 5.5$ at night, and Sochi–Krasnaya Polyana (Goytkh, Maryino, Guzeripl, Krasnaya Polyana, Veseloe, Sochi), with a level $K_{Pmin} = 5.5$ during the day and $K_{Pmin} = 5.0$ – 5.5 at night. They are bounded by the $K_{Pmin} = 6.5$ isoline during the day and $K_{Pmin} = 6.0$ at night. North of these zones, over most of the territory, the network yields K_{Pmin} from 6.5 to 7.5, and in the far north $K_{Pmin} = 7.5$ – 8 . The areas of the zones outlined by the eponymous isolines are approximately 25% larger at night than during the day.

In local magnitude M_L (Fig. 16), the map also preserves two minima corresponding to $M_L = 1.0$ for the Anapa zone and $M_L = 0.5$ – 1.0 for the Sochi–

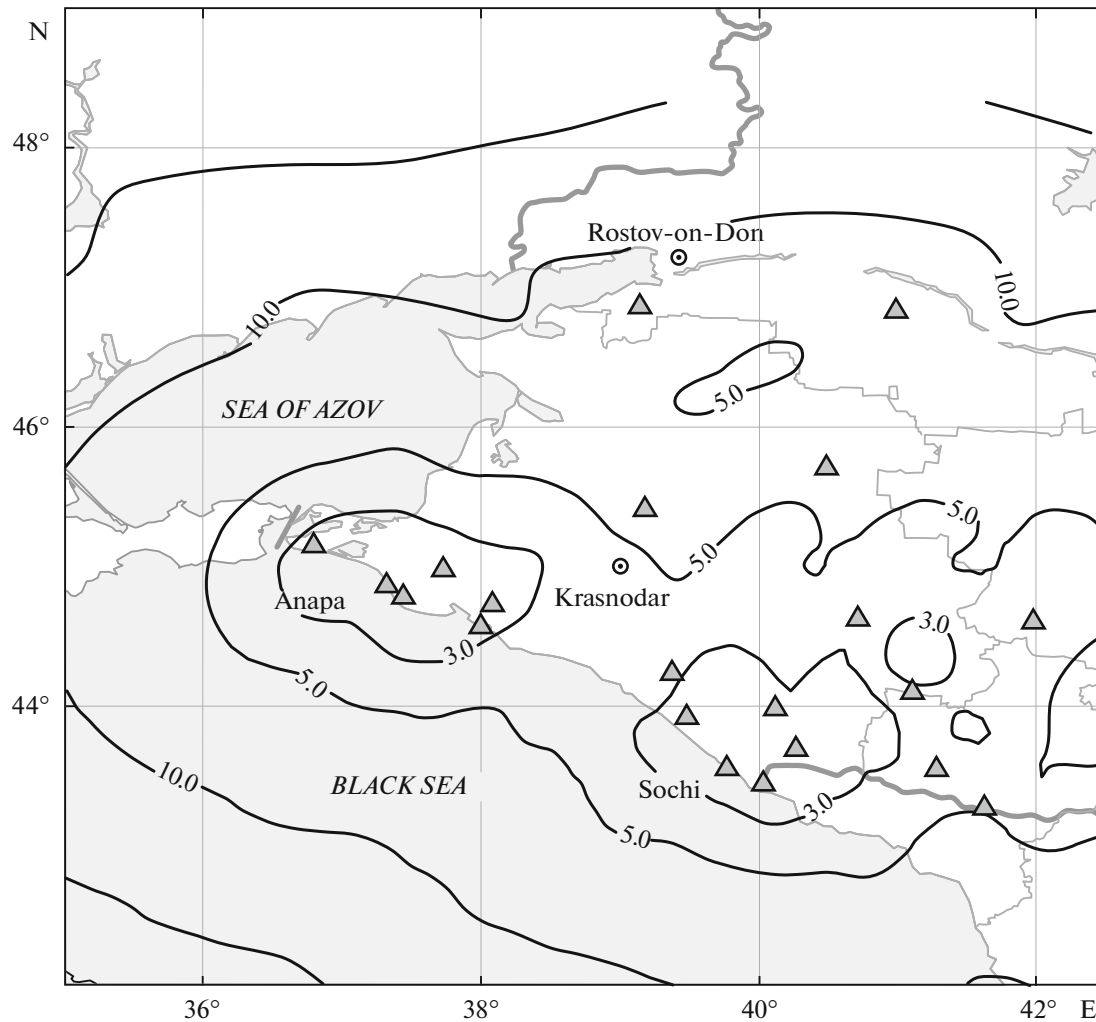


Fig. 17. Map of expected errors in locating sources $\delta_{\phi\lambda}$ taking into account daytime noise conditions at stations' locations.

Krasnaya Polyana zone. The most widespread in the area of the coastal zone and closest part of the Black Sea is the minimum magnitude $M_L = 1.5$. For the territory of the Sea Azov, $M_L = 2.0$.

The expected location errors from the SARRa program (Dyagilev, 2020) and presented on the map (Fig. 17) show that the minimum estimates $\delta_{\phi\lambda}$ are 3 km in the Anapa and Sochi zones, where the stations are the densest. Zones with such estimates are outlined by the isoline with $\delta_{\phi\lambda} = 5$ km; in the rest of the territory $\delta_{\phi\lambda}$ can reach 10 km; in the north, 15 km.

DISCUSSION

To confirm the reliability of these data on the network detection capability and probable error in determining the coordinates of epicenters, we present the results of a study by other independent methods.

Analysis of the earthquake catalog for 2019–2020 showed on the cumulative frequency curves that for the Anapa ($N = 199$) and Sochi ($N = 353$) zones, earthquakes with a minimum energy class $K_R = 6$ and $K_R = 5$, respectively, are representative (Fig. 18). This confirms the result obtained with the SARRa program, taking into account the daytime noise level at the stations.

The capability of the network in the western zone of the North Caucasus depends on interaction with the Crimean network. The level of representative earthquake detection by the seismic network in Crimea, based on the actual recording ranges of stations, is estimated in (Kalinyuk et al., 2019): the network records earthquakes ranging from $K_{\min} = 7$ to $K_{\min} = 9$. Representative recording of earthquakes from $K_p = 9.0$ (according to the regional classification (Pustovitenko and Kulchitskii, 1974)), as before, is ensured for almost the entire region, and at a level $K_p = 8.0$ for the main seismic zones: Sevastopol, Yalta, Alushta,

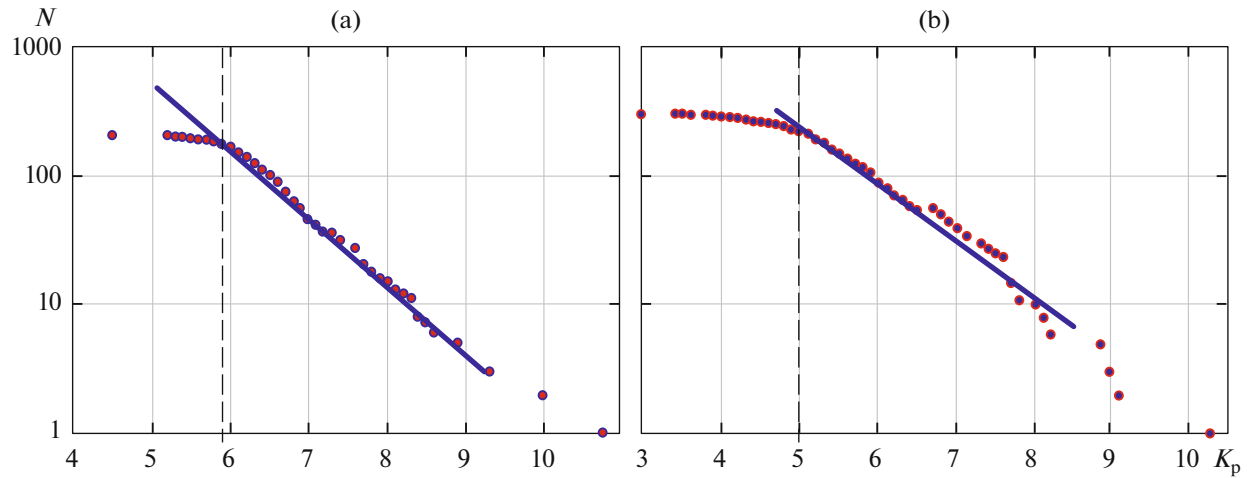


Fig. 18. Cumulative earthquake recurrence graphs for (a) Anapa and (b) Sochizones according to earthquakes catalog of North Caucasus for 2019–2020.

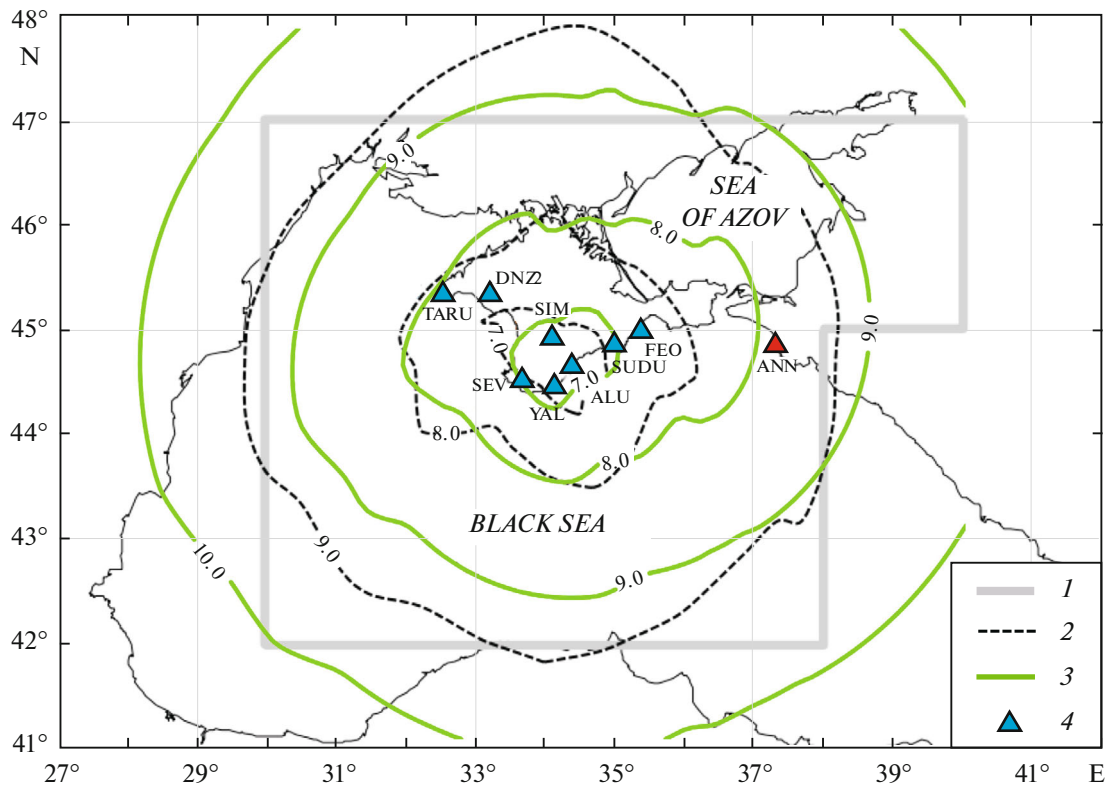


Fig. 19. Comparison of earthquake energy completeness in isolines K_{pmin} (by (Kalinyuk et al., 2019)) and K_{pmin} , obtained using SArRa program, taking into account conditional noise level in daytime (focusing on noise of ANN station Anapa): (1) boundary of region; (2) isolines K_{pmin} ; (3) isolines K_{pmin} ; (4) seismic stations.

Sudak, and the northern part of the Crimean Peninsula.

Let us assume that the noise level of the rest of the Crimean stations (except for Kerch station) is close to the level of microseisms at Anapa station; we use it to calculate and construct a detection capability map of

the Crimean network according to the above methodology. Comparison of the obtained isolines of representative energy classes K_{min} and earthquake energy completeness maps in isolines K_{pmin} from (Kalinyuk et al., 2019) shows their similarity (Fig. 19). Within distances comparable to the size of the network, the

network sensitivity estimates are almost the same. At large distances, our methodology yields more conservative K_{\min} estimates.

It is also necessary to mention the slight eastern elongation of the isoseism with $K_{\min} = 8$ and $K_{\min} = 9$, which is due to introduction of the Anapa station into the analysis, which, possibly, was not taken into account in (Kalinyuk et al., 2019). Undoubtedly, the use of real noise levels of the Crimean network will allow a more accurate configuration of K_{\min} isolines; however, at present we do not have all the necessary data for such a calculation. Despite this, the obtained K_{\min} maps for stations in the western zone of the North Caucasus, when compared with an independent source, give grounds to consider our capability calculation methodology using quantitative estimates of variations seismic noise level (microseisms) at each individual station (Dyagilev, 2020) acceptable, yielding reliable results.

To confirm the obtained calculated errors in determining the coordinates of epicenters, a sampling of earthquakes for 2019–2020 ($N = 410$) was refined using the hypoDD program based on the double difference method (Waldhauser and Ellsworth, 2000; Waldhauser, 2001). This method assumes that if there are two earthquakes the sources of which are distanced from each other by less than the distance from the hypocenter of each event to the station, then the seismic wave propagation paths from the two earthquakes to the station can be considered the same. In this case, the difference in the arrival time of seismic phases from these events observed at one station can be attributed to the spatial displacement between events with high accuracy. The helps to concentrate seismicity, which has a scattered character during preliminary location, into certain clusters due to the identical natural and possibly technogenic causes (Czeczé and Bondar, 2019).

The analyzed sampling of earthquakes in the western zone of the North Caucasus after application of the double differences method was divided into 33 clusters, but to assess the accuracy in calculating coordinates, we used only clusters that included $N \geq 10$ seismic events. Thus, for the Anapa zone, on average, the accuracy in locating the epicenter was $\delta\Delta = 4.98 \pm 2.32$ km, and in the cluster closest to Sukko station, $\delta\Delta = 1.46 \pm 0.24$ km; in the Sochi zone $\delta\Delta = 4.13 \pm 2.67$ km, but in individual clusters within the seismic network, $\delta\Delta = 1.08 \pm 0.16$ km. This agrees well with the map of expected epicenter errors obtained using the SARra program (see Fig. 17).

In the Novorossiysk–Gelendzhik zone (the nearest stations are Gelendzhik and Shapsug) in 2019–2020, more than ten industrial blasts were recorded in quarries for the extraction of marl for cement plants in Novorossiysk. The deviations of the epicentral coordinates of the of these events obtained during routine processing from the positions of the quarries did not

exceed 3–5 km, which also confirms the calculated expected errors in locating the sources, obtained with allowance for the daytime noise conditions at the location of the stations.

In the Sochi–Krasnaya Polyana and Arkhyz–Dombay zones, the network configuration provides a close location ($D_{\min} \leq 30$ km) and good surrounding by epicentral stations ($GAP \leq 130^\circ$), which allows the GT05 (Ground Truth 5 km) condition to be met; i.e., errors in calculating epicenters will not exceed ± 5 km, in accordance with the recommendations (Bondar et al., 2004).

CONCLUSIONS

For the first time, quantitative estimates of variations in the seismic noise level (microseisms) at each individual station of the seismic network of the western zone of the North Caucasus were studied in detail. The median power spectra of daytime and nighttime seismic noise at the stations operating in this zone were constructed. They are digital noise models and can be used in the automatic processing of digital records to reliably identify the arrivals of seismic phases.

The stations in the western zone of the North Caucasus are divided into three groups by noise level:

The three most sensitive stations are Guzeripl, Gornoye and Krasnaya Polyana. They are located in protected areas, far from populated areas, their equipment is installed on rocky soils. Noise at the stations has the same level of microseisms at night and in the daytime.

Stations with a medium sensitivity level are Maryino, Anapa, Gladkovskii, Shapsug, Sergievskaya, Goytkh, Veseloe, Sukko, Sochi, Eremizino-Borisovskaya, Novopoltavsky They are characterized by a significant difference between the night- and daytime levels of microseisms in the high-frequency range ($f \geq 1$ Hz), by about an order of magnitude.

Stations with low sensitivity are Labinsk, Golovanovskii, Taman, Nevinnomyssk. The level of microseisms for these is close to the global average new high noise model (NHNM). The difference in the level of microseisms during the day and at night at frequencies above 1 Hz is 1.5–3 times.

The difference in the noise level at stations located in orogenic structures on rocky soils and within platform structures on loose soils in areas with a thick sedimentary layer was established. Comparison with the quietest station, Guzeripl, showed that the noise of platform stations at frequencies of $f > 1$ Hz is about two orders of magnitude higher even at night. However, the position of these stations significantly improves the geometry of the network and affects its sensitivity and location accuracy, especially for relatively strong earthquakes ($K_p \geq 8$).

Based on the law of wave attenuation, expressed in the equation for calculating the local magnitude M_L for the western zone of the North Caucasus, and on estimates of the power spectra of microseismic noise characterizing the noise level at individual stations, the ultimate sensitivity of the network has been established, which in magnitude (M) or energy class (K) will be the maximum estimate of this quantity (M or K) provided by $N_{\min} = 3$ stations. $K_{P\min} = 8.0$ is representative of the entire considered territory of the western zone of the North Caucasus.

On $K_{P\min}$ maps, constructed taking into account the day- and nighttime noise conditions at the stations' locations, two zones of the highest network capability are clearly distinguished: Anapa (stations Anapa, Sukko, Shapsug, Gladkovskaya, and Gelendzhik) with a level of $K_{P\min} = 6.0$ during the day and $K_{P\min} = 5.5$ at night, and Sochi–Krasnaya Polyana (Goytkh, Maryino, Guzeripl, Krasnaya Polyana, Veseloe, Sochi) with a level of $K_{P\min} = 5.5$ during the day and $K_{P\min} = 5.0$ – 5.5 at night. They are bounded by the isoline $K_{P\min} = 6.5$ during the day and $K_{P\min} = 6.0$ at night. North of these zones, in most of the territory, the network ensures reliable recording of events with $K_{P\min}$ from 6.5 to 7.5, and in the northernmost part of the area under consideration, $K_{P\min} = 7.5$ – 8 . The areas of the zones outlined by the eponymous contours are about 25% larger at night than during the day.

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CONFLICT OF INTEREST

The authors declare they have no conflict of interest.

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