ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2020, Vol. 56, No. 8, pp. 869–886. © Pleiades Publishing, Ltd., 2020.
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Historical and Modern Seismicity of the Semipalatinsk Test Site

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Received December 11, 2019; revised March 19, 2020; accepted March 20, 2020

Abstract—According to the current maps of general seismic zoning of the Republic of Kazakhstan (2006), the territory of the Semipalatinsk Test Site (STS) is considered an aseismic region. However, recent investigations and an analysis of archived data have shown that the Test Site territory and its vicinity have experienced and still experience tectonic and induced earthquakes. The maximum magnitude of recorded earthquakes is 5–5.9. An analysis of global seismological bulletins and data on historical seismicity from literature sources is performed to solve the problem of seismicity in the STS region. Historic analog seismograms of earthquakes have been collected since 1925; the earthquake parameters are estimated more precisely. Modern instrumental seismic data of the Kazakhstan monitoring network since 1994 are processed, as is the data of temporary networks of seismic stations operating on the territory of the test site in 2005–2010 in the region of the Sary-Uzen, Balapan, and Degelen test sites. These works resulted in the creation of a common earthquake catalogue for the STS territory and its vicinity from 1783 up to the present. Macroseismic data of the felt earthquakes have been collected; strong motion records have been analyzed. Deep faults dividing Earth's crust blocks have been marked out. Tectonic elements are located by decoding the Landsat space images and using materials of geologic and topographic surveys. The calculations show that the STS territory can experience events with intensity 6 based on the MSK-64 scale.

Keywords: Semipalatinsk Test Site, seismic hazard, induced seismicity

DOI: 10.1134/S0001433820080058

INTRODUCTION

The Semipalatinsk Test Site (STS) is one of the largest test sites for nuclear weapons in the world. The decision of the need to build a special training ground was adopted by the Soviet government on November 14, 1946. For this purpose, a test site of 15500 km^2 was allocated on the territory of the Kazakh SSR. The first explosion of a Soviet atomic bomb with a power of 22 kt was carried out on August 29, 1949. Since then, 456 nuclear tests have been carried out on this territory, including 116 atmospheric and 340 underground explosions. On August 29, 1991, the Semipalatinsk Test Site was closed by decree of President of the Kazakh SSR N.A. Nazarbayev.

Since then, new life has begun at the test site. The National Nuclear Center of the Republic of Kazakhstan was opened, which unites several research institutes. For scientific purposes, three research reactor facilities are currently operating. The world's first specialized tokamak for testing materials of future thermonuclear power plants has been launched. In addition, at present, the region of the town of Kurchatov, located almost within the STS, is considered as one of the possible places for the construction of a nuclear power plant in Kazakhstan. There are boreholes and tunnels in the test site in which nuclear tests were previously conducted. It is likely that processes are currently taking place in the Earth's interior that may be accompanied by seismic phenomena. In this regard, the question of studying the seismic situation and assessing the seismic hazard of the area are of particular interest.

In Soviet time, the processing of seismic events from the STS region at regional seismic stations was not performed, regardless of the nature of the source of the recorded event. These events were not included in the catalog of earthquakes, for example, in Kazakhstan. The data of Soviet special control service stations existing at that time were not available for the use in compiling seismic bulletins at processing centers of seismological institutes. However, seismologists around the world were always interested in studying seismic records of events from the STS region, which was primarily determined by monitoring nuclear tests and the seismic discrimination of underground nuclear explosions and earthquakes (Pooley et al., 1983).

Of course, the most important issue is the question of the existence of natural seismicity in this region, particularly on the territory of the test site. Were there earthquakes in the historical period before the start of nuclear testing at the test site? Has their activity changed in connection with a series of large nuclear explosions?

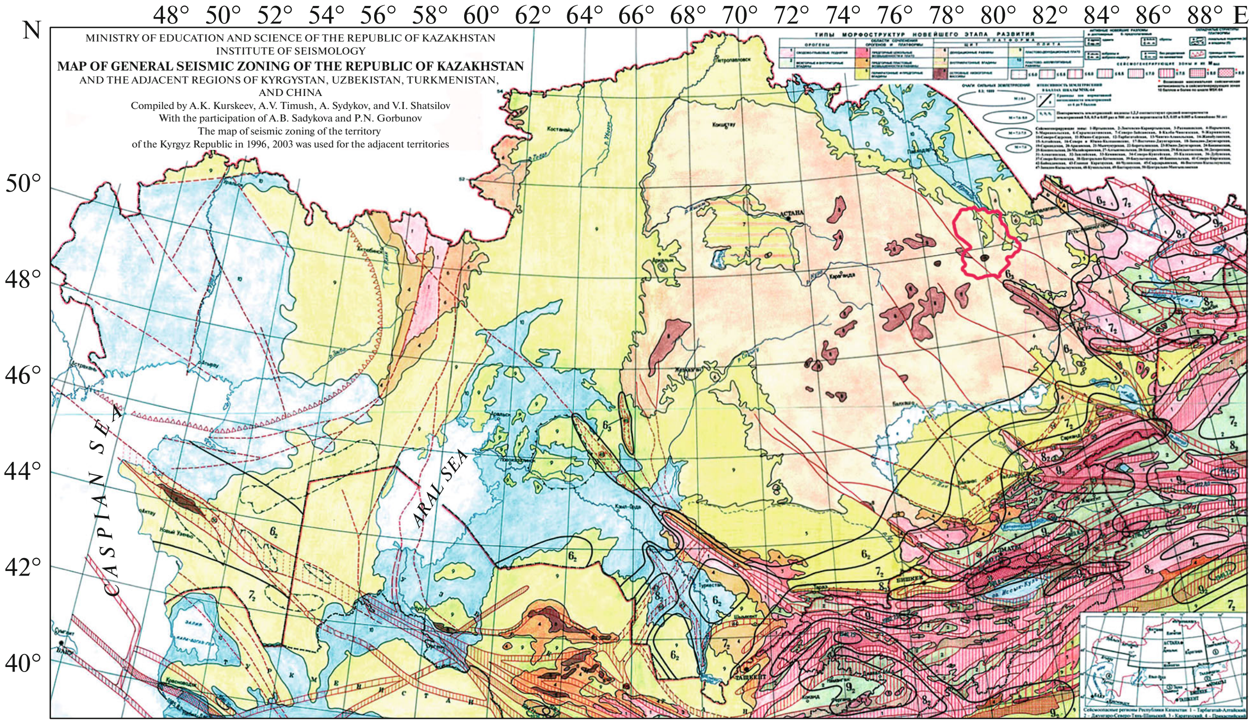


Fig. 1. Map of the general seismic zoning of the Republic of Kazakhstan.

Another aspect of the seismic hazard problem is the question of the presence of induced seismicity on the STS, which is a result of numerous nuclear tests here (Sokolova et al., 2017). Do postexplosive geodynamic processes exist here that can be reflected in the activity of weak earthquakes near the test sites?

This work is aimed at finding answers to these questions.

Until recently, a chart included in the Building Regulations and Rules of the Republic of Kazakhstan “Construction in Seismic Areas” (SNiP RK 2.03-30-2006) (Almaty: LEM Publishing House, 2006. 80 p.) compiled by a team of authors at the Institute of Seismology of the Ministry of Science–Academy of Sciences of the Republic of Kazakhstan in 2003 (updated in 2006) has been a valid map of Kazakhstan’s general seismic zoning. A set of geological–tectonic, geophysical, and seismological data was used to prepare this chart: the data on geodynamic processes occurring in the interior of the Earth’s crust and upper mantle. As a result of the coupled analysis of data, the main seismic-generating zones have been identified that are responsible for the occurrence of foci of large earthquakes, their seismic potential has been estimated in the units of magnitudes, and the areas of possible shocks of varying units of seismic intensity on the MSK-64 scale have been calculated. If one looks at this map (Fig. 1), it is possible to see that the entire STS region is located on an aseismic territory that is not seismically hazardous. No seismic-generating zones were identified in this region of East Kazakhstan; no occurrence of earthquakes with a shock intensity of more than 5 units has been predicted.

This paper presents the results of studies in three fields:

(1) solving the problem of historical natural seismicity in the STS region based on an analysis of global seismological bulletins, existing catalogs, and literature data, as well as the search for and processing of old analog seismograms;

(2) the study of modern seismicity based on the instrumental data from the stations of the Institute of Geophysical Research, National Nuclear Center of the Republic of Kazakhstan (IGR NNC RK) since 1994;

(3) a detailed study of possible induced seismicity on the STS territory using field observations by a network of seismic stations directly near the locations of previous nuclear explosions.

Geological and Tectonic Characteristics of the STS Territory and Adjacent Areas

The Semipalatinsk Test Site (STS) is located in the northeastern part of Kazakhstan at the junction of three regions: Karaganda, Pavlodar, and East Kazakhstan. According to the geological structure, the STS territory is located in the central part of the junction of two large geotectonic structures: the Chingiz-Tarbagatai caledonites (meganticlinorium) and Hercynian Zharma-Saursky (megasynclinorium) geotectonogens, which are structurally related to the Altai-Chingiz folded region, which is more often now called Great Altai (Fig. 2a).

The geological structure of these structures has been studied since the 19th century. The first descriptions are given in the works of A. Tatarinov (1851, 1864), I.V. Mushketova (1878–1884), and V.A. Obruchev (1905–1909). Intense research began in the 1930s. The main work was carried out by expeditions of Moscow State University; the Karpinsky All-Russian Research Geological Institute (VSEGEI); the Satpayev Institute of Geological Sciences; the Kazakhstan Institute of System Modeling, Ministry of Geology of the Republic of Kazakhstan; and CenterKazGeology and EastKazGeology regional production or territorial geological associations (PGA or TGA). From the end of the 1940s until 1992, the geological structure of the STS territory was studied by specialized geological organizations: Survey Expedition No. 113 and Geological Party No. 27 of the State Expertise 16 of the Gidrospetsgeologiya PGA region. Since 1993, work on the geological structure of the study site has been carried out by the IGR NNC RK.

As a result of a generalization and analysis of available materials—using remote methods for the analysis of satellite images using the "Scheme of Discontinuous Structures of Great Altai," compiled by B.A. Dyachkov (Shcherba et al., 1998) as a basis—a diagram of discontinuous structures of the STS territory and adjacent areas has been built (Fig. 2b).

The southwestern part of the STS region is part of the Chingiz-Tarbagatai geotectonogene, which is the northeastern marginal part of the caledonites of the Kazakhstan subcontinent, and composes the southwestern side of the hercynian structure of Great Altai. The northeastern part of the STS occupies the southwestern margin of the Zharma-Saur geotectonogene, which is the marginal (southwestern) part of the Irtysh-Zaysan folded system that was formed during the Hercynian era of folding.

Hercynides of Zharma-Saur are separated from the caledonites of Chingiz-Tarbagatai by the Chingiz-Saur (also known as Kalba-Chingiz) deep fault with a northwestern direction and a length of more than 500 km.

Both structures of the northwestern direction acquired a complex structure as a result of long active tectonic development. The intense superimposed folding of different orders, deep rock metamorphism, and extremely wide development of discontinuous faults from deep faults to intense tectonic fracturing are their characteristic features.

The following structures are distinguished on the basis of the geological and geophysical data: (1) subcrustal (mantle) faults penetrating to a depth of 200–250 km, delimiting the structures of the Great Altai and large blocks of the Earth's crust; they are located at a distance of 30–50 km from each other and can be traced for hundreds of kilometers (Main Chingiz, Chingiz-Saur, and Charsko-Gornostaevsky); (2) intracrustal faults dissecting the layers of the Earth's crust in the vertical and horizontal directions, which determines the heterogeneity of geotectonogenes. They are the main magma-leading channels (Aleysky, Sirektassky, Chinrausky, Znamensky, etc.).

Two orthogonal systems of deep faults are distinguished in the prevailing directions of disturbances: longitudinal–transverse (northwestern and northeastern) and longitudinal–latitudinal. In addition, there are ruptures in the other directions (see Fig. 2b).

Deep faults of the orthogonal system of the sublatitudinal and submeridional directions are the structures of the pre-Caledonian and Caledonian formations weakly manifested in the upper structural stages. The distance between the main faults is quite constant—45–55 km. This discontinuity system is distinguished mainly from the geophysical data and decoding of satellite images. The ruptures reach the surface of the "basalt" layer and in some cases the Moho surface, being subcrustal structures.

Maps of seismic-generating zones have been constructed within the works on the general seismic zoning of Kazakhstan (see, for example, (Timush et al., 2012)). The seismic-generating zones closest to the STS are the Irtysh, Chingiz-Alakol, and Zharminskaya. They are associated with regional faults of the same name (Fig. 3). All zones have a seismic potential of $M_{\max} = 5–5.5$; however, they do not reach the STS territory, terminating southeast of the test site. These zones, as a rule, are described very briefly, since sufficiently detailed seismological data are missing. This is due to the fact that for decades instrumental observations by a network of seismic stations have not been carried out in this region, and the data of global observation networks were not available at the time the map was compiled. According to the general seismic zoning map, the maximum expected shock intensity on the STS territory should not exceed 5 units on the MSK-64 scale.

However, it should be noted that large faults such as the Main Chingiz and Zharminsky can be actually traced within the territory of the STS, crossing it from southeast to northwest. Therefore, it is quite realistic to expect the existence of focal zones of earthquakes in this territory.

Seismic Observation Systems Whose Data Were Used in the Work

In the 18th–19th centuries, when felt earthquakes occurred near Semipalatinsk, there were no seismic stations on the territory of the Russian Empire. The only source of information about the earthquakes at that time was macroseismic data (Chekaninsky, 1927; *Novyi*..., 1977).

Figure 4 shows the location of the first seismic stations in the study region: PUL (1906), TIF (1899),

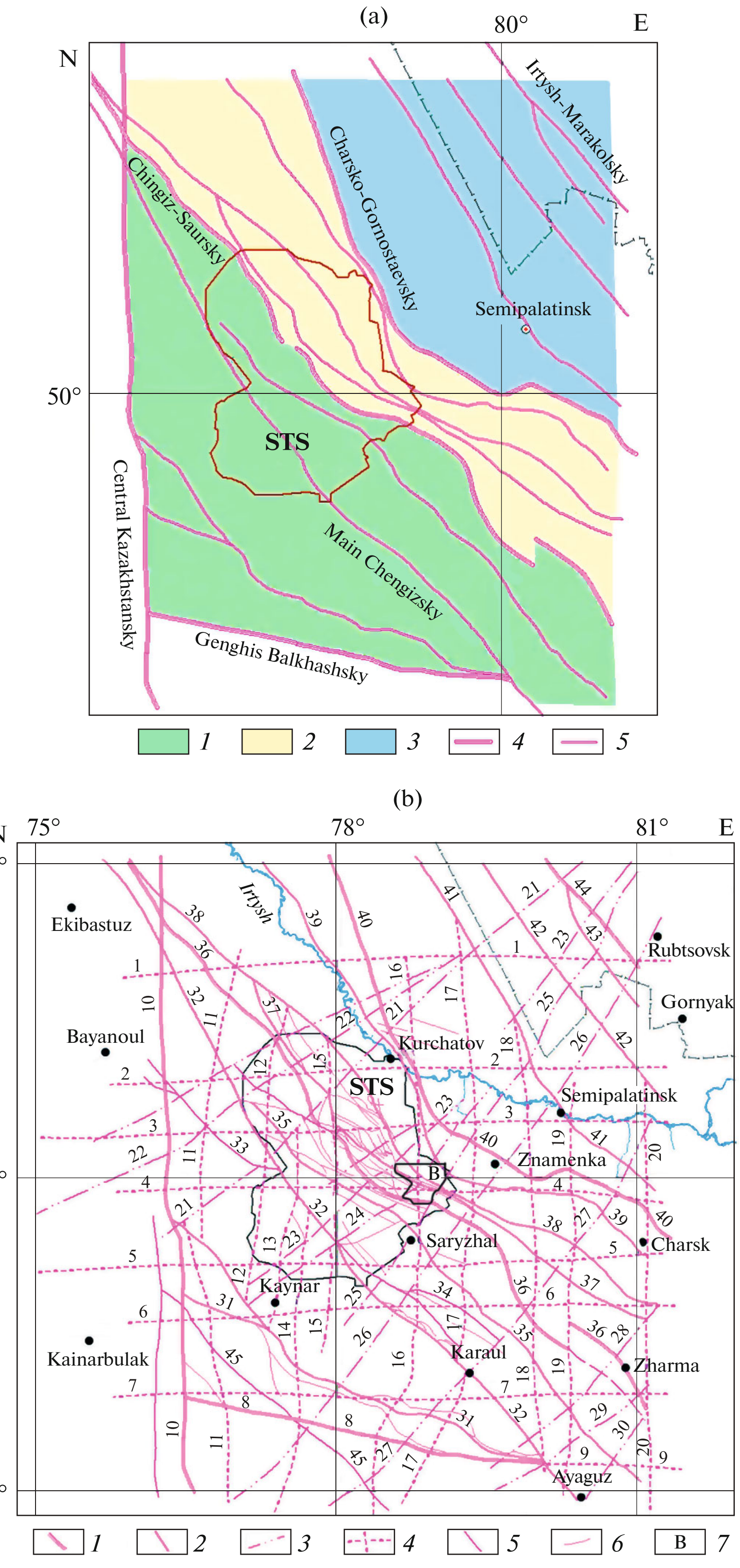

(a)
80°
E
N
50°
Irtysh-Marakolsky
Charsko-Gornostaevsky
Chingiz-Saursky
Semipalatinsk
STS
Central Kazakhstansky
Main Chengizsky
Genghis Balkhashsky
1
2
3
4
5
(b)
N
75°
78°
81°
E
52°
50°
48°
Ekibastuz
Irtysh
Rubtsovsk
Gornyak
Bayanoul
Kurchatov
STS
Semipalatinsk
Znamenka
B
Saryzhal
Charsk
Kaynar
Kainarbulak
Karaul
Zharma
Ayaguz
1
2
3
4
5
6
B
7

Fig. 2. Scheme of the locations of geotectonogenes in the Altai-Chingiz region (Great Altai) (a) and a scheme of the discontinuous structures of the STS region and adjacent territories (northwest of the Altai-Chingiz region) (b). (a) Geotectonogenes: (*1*) Chingiz-Tarbagatai; (*2*) Zharma-Saursky; and (*3*) Altai. Ruptures: (*4*) main: boundaries of geotectonogenes; (*5*) main. (b) (*1*) Main deep faults, which are the boundaries of geotectonogenes; (*2*) main deep faults of the northwestern direction; (*3*) main deep faults of the northeastern direction; (*4*) main deep faults of the longitudinal–latitudinal orthogonal system; (*5*) minor deep faults; (*6*) minor faults; and (*7*) Balapan platform. The numbers denote faults: (1) Rubtsovsky, (2) Aleisky, (3) Semipalatinsk, (4) Znamensky, (5) Georgievsky, (6) Chingiz-Narymsky, (7) Abralinsky, (8) Chingiz-Balkhashky, (9) Zaysansky, (10) Central Kazakhstansky, (11) Zhanaakshimansky, (12) Saryozeksky, (13) Kaynarsky, (14) Burlyugansky, (15) Degelensky, (16) Kyzyl-Adyrsky, (17) Belokamensky, (18) Kaskabulaksky, (19) Akbulaksky, (20) Novo-Taubinsky, (21) Mikhailovsky, (22) Severo-Mikhailovsky, (23) Degelen-Irtyshsky, (24) Alambaysky, (25) Voznesensky, (26) Kokonsky, (27) Delbegeteiky, (28) Dungalinsky, (29) Kandygataysky, (30) Zholdybaisky, (31) Zhaurtaginsky, (32) Main Chingizsky, (33) West Chingizsky, (34) East Chingizsky, (35) Arkalyksky, (36) Chingiz-Saursky (Kalba-Chingizsky), (37) Sirektassky, (38) Chinrausky, (39) Baiguzin-Bulaksky, (40) Charsko-Gornostaevsky, (41) West Kalbinsky, (42) Terektinsky, (43) Kalba-Narymsky, (44) Irtysh-Markakolsky, and (45) Kaindinsky.

TAS (1901), IRK (1901), SVE (1906), AAA (1927), FRU (1927), CHM (1932), and SEM (1934). Regular seismic observations started in Central Asia and Kazakhstan in 1901 with the opening of the Tashkent seismic station in Uzbekistan, the Samarkand seismic station (Uzbekistan) was opened in 1913, the Alma-Ata (Kazakhstan) and Frunze (Kyrgyzstan) seismic stations were opened in 1927, the Andizhan seismic station (Uzbekistan) in 1929, the Chimkent seismic station (Kazakhstan) in 1932, the Semipalatinsk seismic station (Kazakhstan) in 1934, and the Dushanbe seismic station (Tajikistan) in 1939. These stations were located in cities with a fairly high level of anthropogenic noise, and therefore the equipment that was installed on them (Nikiforov seismometer, SKD, etc.) had low magnification. Later, these stations became part of the Unified System of Seismic Observations (USSO) of the Soviet Union. Only the Semipalatinsk station was located near the study region. All other seismic stations operating at that time were located far from the STS. Since the equipment had low magnification, it was possible to record only the largest earthquakes with magnitudes greater than 4.5.

Since the 1950s, networks of detailed seismic observations have been deployed in the Northern Tien Shan region to study the seismic regime in the south and southeast of Kazakhstan and in the north of the Kyrgyz SSR. The SKM-3 seismometers with a high magnification were generally used at the seismic stations of the Schmidt Institute of Physics of the Earth

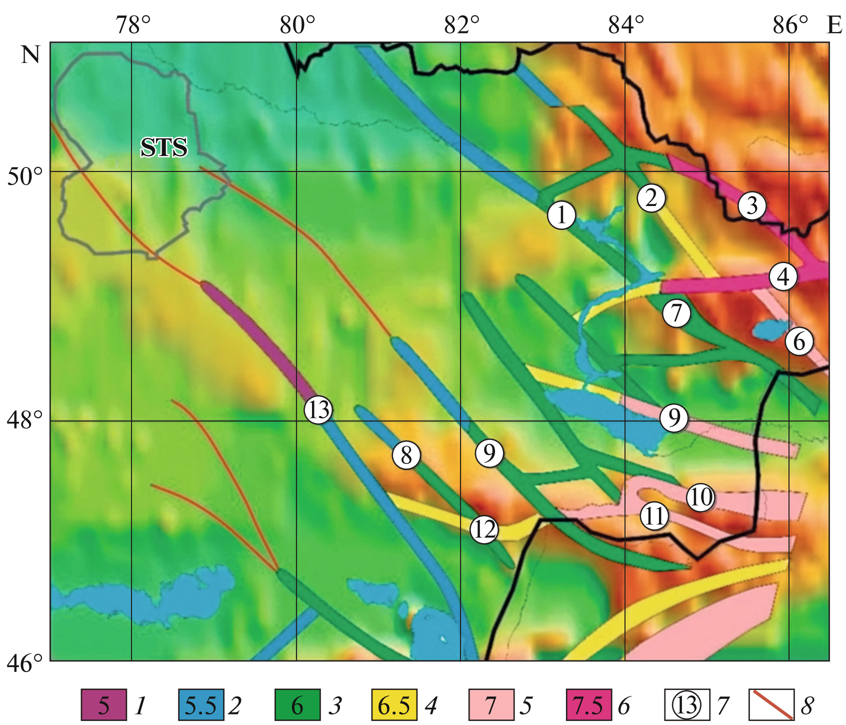


Fig. 3. Seismic-generating zones of the Tarbagatai-Altai region; (*1–6*) seismic potential (magnitude is shown in the legend); (*7*) zones (numbers in circles): (1) Irtyshskaya, (2) Loktev-Karairtyshkaya, (3) Rakhmanovskaya, (4) Narymskaya, (5) Markakolskaya, (6) Sarymsaktinskaya, (7) Severo-Zaysanskaya, (8) Kalba-Chingizskaya, (9) Zharminskaya, (10) Severosaurskaya, (11) Yuznosaurskaya, (12) Tarbagataiskaya, (13) Chingiz-Alakolskaya, and (*8*) tectonic faults.

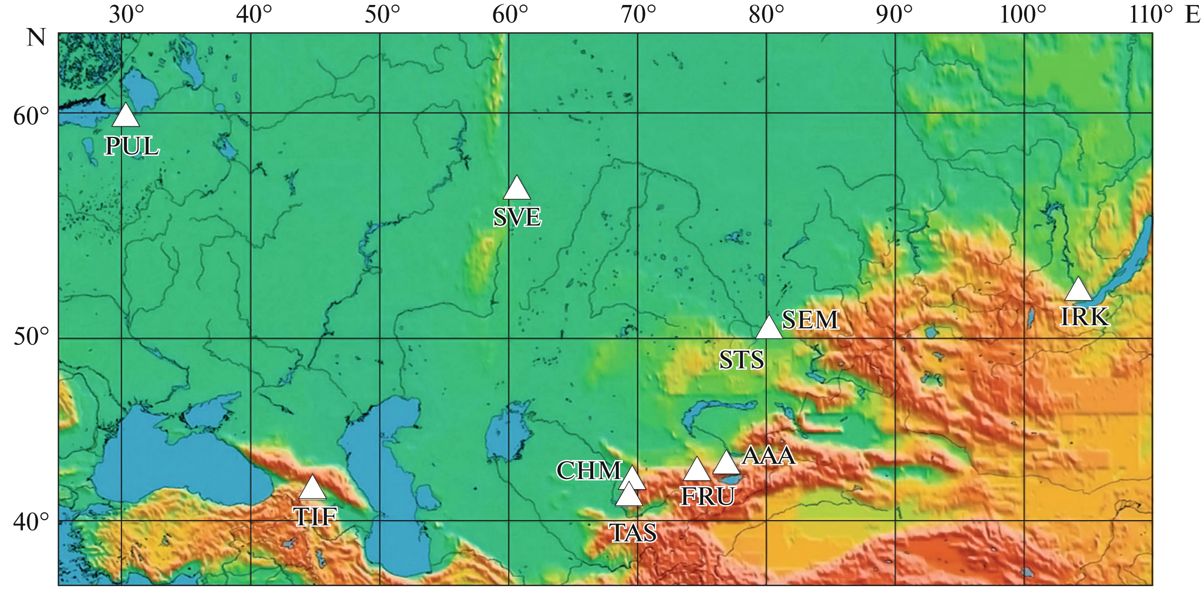


Fig. 4. Network of seismic stations in Kazakhstan organized before 1935.

(Academy of Sciences of the Soviet Union), but the parameters of seismic events were determined only for seismically active regions of the Tien Shan. A bulletin of events for the territories of northeastern, northern, central and western Kazakhstan was not compiled.

In 1961, the Institute of Physics of the Earth (Academy of Sciences of the Soviet Union) organized the Complex Seismological Expedition (CSE) in the town of Talgar near Alma-Ata. The main tasks of the CSE were to study the structure of the lithosphere, monitor nuclear tests using seismic methods, etc. A large number of seismic stations were opened by the CSE on the territory of the Soviet Union, both permanent and temporary. All stations were equipped with sensitive devices such as SKM-3, USF, KSE, and RVZT with magnification in V from 40000 to 120000. In 1961–1963, the CSE opened the Pamir–Baikal profile stations (Nersesov and Rautian, 1964). The total length of the profile of the highly sensitive Pamir–Baikal seismic stations was approximately 3500 km. The total number of stations on the profile was 54 and the average distance interval between stations was 70–120 km (Nersesov and Rautian, 1964) (Fig. 5). The profile crossed Central Asia, Kazakhstan, Altai, Sayany, and Cis-Baikalia. Some stations were located near the STS; they recorded 19 earthquakes in the study area with energy classes $K = 7–9$.

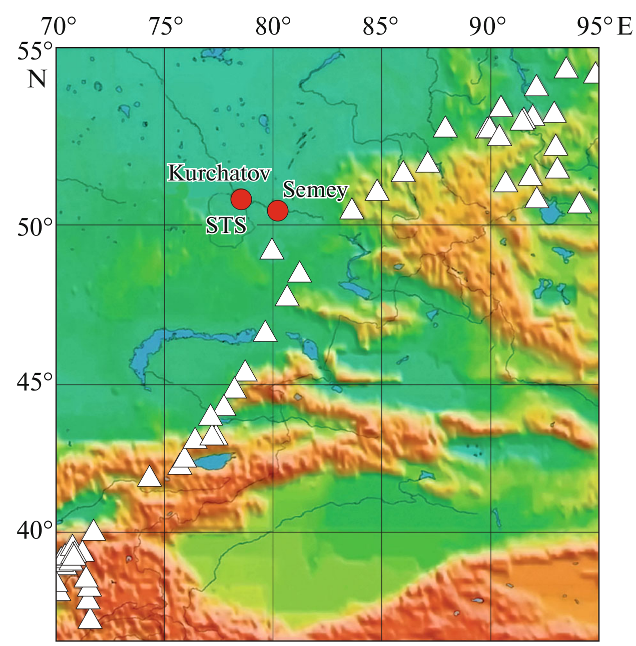


Fig. 5. Location of seismic stations of Complex Seismological Expedition of the Institute of Physics of the Earth, Academy of Sciences of the Soviet Union (1961–1963).

After 1969, the CSE signed over most of the northern Tien Shan stations located on the territory of Kazakhstan to the Institute of Geological Sciences, Academy of Sciences of the Kazakh SSR. Since 1969, the CSE has ceased to compile bulletins of the seismic events in Central Asia. Hence, to study the seismicity of the STS region over the next period (1969–1991) we used the annual Earthquakes in the USSR (*Zemletryaseniya*..., 1962–1991) data collections, in which catalogs were compiled based on the Altai-Sayany region network of stations of the Altai-Sayany experimental–methodical seismological expedition (Fig. 6).

Since mid-1994, a new modern digital seismic network of the IGR NNC RK stations has been operating in Kazakhstan (Fig. 7). Until 2002, most stations operated in real time; the data were collected and

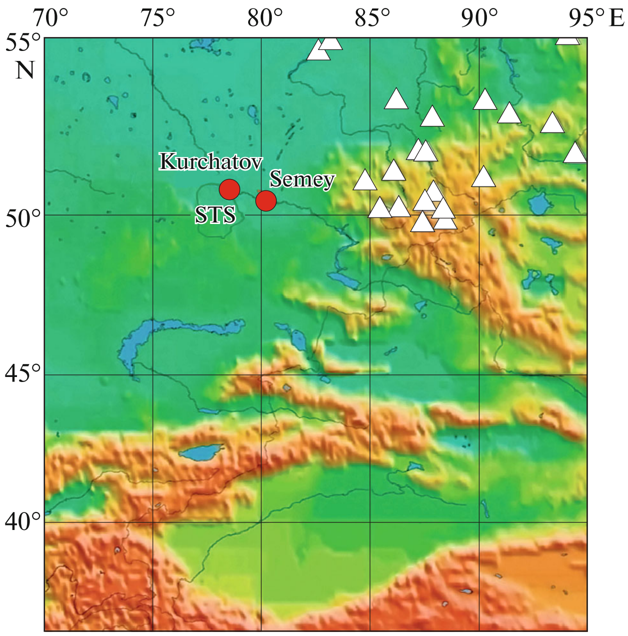


Fig. 6. Location of seismic stations of the Altai-Sayany experimental–methodical seismological expedition of the Siberian Branch, Academy of Sciences of the Soviet Union (1969–1991).

archived after a long period of time, while joint routine processing was not performed. We analyzed the data from international seismological centers over this period of time; the events in the STS region found in these data were reprocessed, and their parameters were updated using the data from the Kazakhstan monitoring network (*Zemletryaseniya*..., 1992–2004; Mikhailova et al., 2007). Starting in mid-2002, a seismic bulletin for the Central Asian region began to be prepared on a regular basis. The bulletin of the Kazakhstan National Data Center (KNDC) of the Institute of Geophysical Research, National Nuclear Center of the Republic of Kazakhstan, includes not only the parameters of tectonic earthquakes, but also the parameters of events of various nature, such as quarry explosions; therefore, much work is being done on seismic discriminating of the nature of event sources (Velikanov et al., 2012).

Monitoring of the local network of seismic stations is required for a detailed study of seismicity near the sites of previously conducted nuclear tests. In 2005–2010 (no research was conducted in 2009), a network of field stations was organized on the STS territory during the field season. Temporary networks were set on each of the sites: Balapan (2005–2006, 2010), Degelen (2006, 2007, 2010), and Sary-Uzen (2007, 2008, 2010). They included from one to five field stations equipped with SK-1P seismometers and DAS-6102-16 digitizers (PMD/eentec Scientific, Inc., United States) (Morgovskaya et al., 2006). A 24-h continuous recording of seismic events was carried out during the field seasons. Figure 8 shows a network of field seismic stations on the STS territory in 2010.

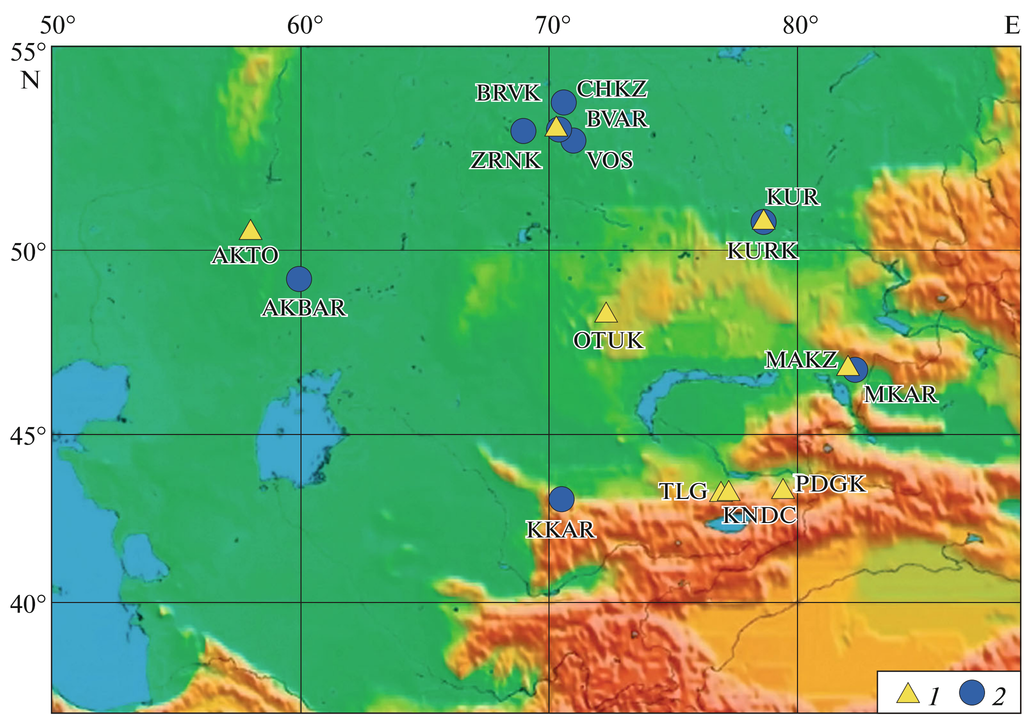


Fig. 7. Location of seismic stations of the Institute of Geophysical Research Institute, National Nuclear Center of the Republic of Kazakhstan; data processing is carried out in the Kazakhstan National Data Center (KNDC). (*1*) Three-component station; (*2*) seismic array.

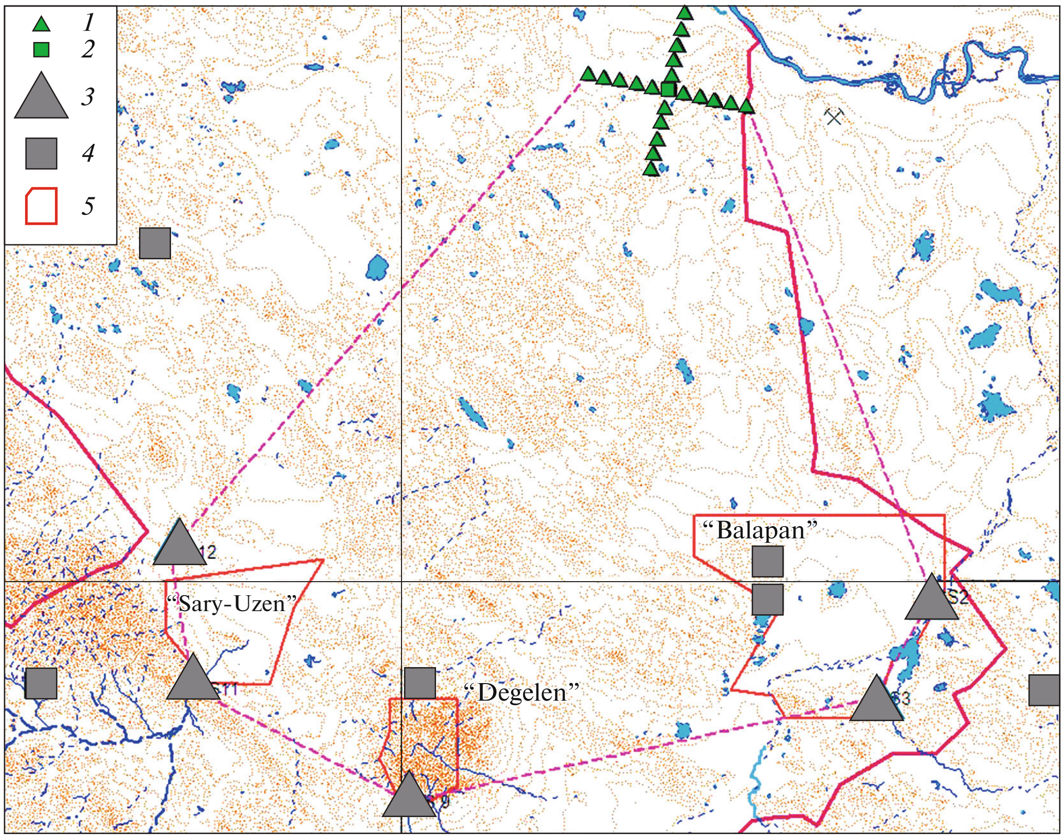


Fig. 8. Location of field seismic stations at STS in 2010. (*1*) Elements of the Kurchatov-Cross array, (*2*) central element of the Kurchatov-Cross seismic array, (*3*) seismic field stations, (*4*) current quarries, and (*5*) boundaries of the test sites.

A total of 1613 seismic events were recorded during seismic monitoring of the STS region and adjacent territories by a temporary network of field seismic stations installed at the Balapan, Degelen, and Sary-Uzen sites in the 2005–2008 field seasons and 2010 for 546 days of continuous observations. Most of them were identified as quarry explosions, and only 36 events were attributed to earthquakes. Most earthquakes were recorded only by stations in the field observation network and only less than 30% of events were recorded by the IGR NNC RK permanent observation network.

Seismicity of the STS Territory

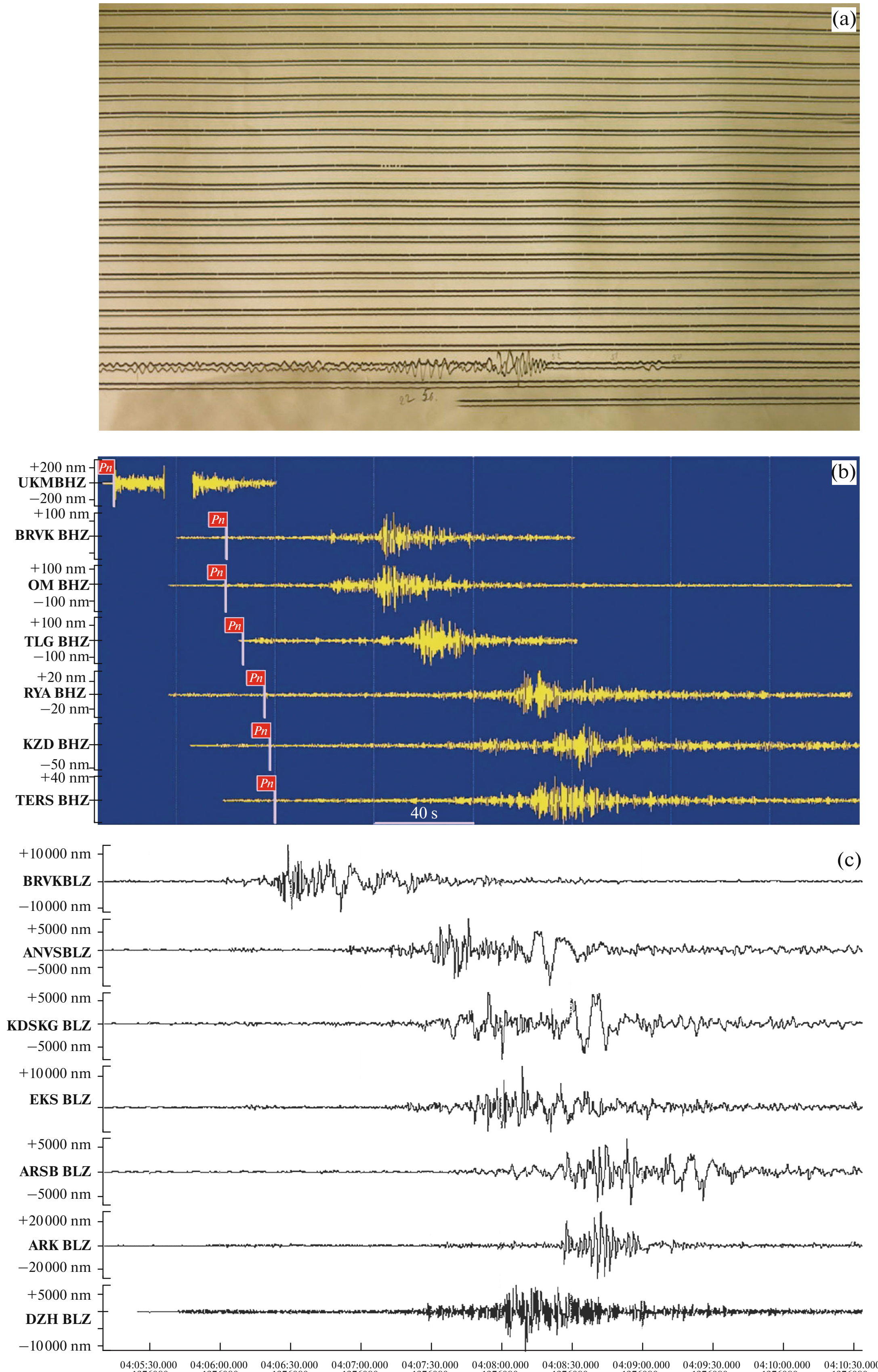
A region limited by coordinates 48°–52° N, 75°–81.1° E was chosen for research. The first issue to be resolved was the question of the presence of natural seismicity in the STS. Various sources of information were involved to solve this.

(1) An analysis of seismological bulletins of international data centers (www.isc.ac.uk; www.earthquake.usgs.gov), as well as a data analysis on historical seismicity from literature sources (Chekansky, 1927; Pooley et al., 1983; Khalturin et al., 2001; Mukambaev and Mikhailova, 2015), has been performed.

(2) Historical analog earthquake seismograms were collected since 1925, and the parameters of instrumentally recorded earthquakes were updated.

(3) Digital seismic records of stations of the Kazakhstan regional permanent network since 1994, when seismic bulletins were not compiled, have been processed

Fig. 9a. Fragment of historical analog seismogram on September 9, 1925 (t_0 = 21:42:40; 50° N; 77° E; M_S = 5.8; IRK seismic station, Irkutsk) (a); digitized earthquake seismograms on December 26, 1966 (t_0 = 17:39:38.5; 49.52° N; 78.71° E; *mpv* = 4.3, *Z* component. According to archival data from the Multidisciplinary Seismological Expedition of the Institute of Physics of the Earth, Academy of Sciences of the Soviet Union) (b); and the earthquake of March 20, 1976, in the region of the Murzhik Ridge. (50.02° N; 77.37° E; M_S = 5.1, *Z* component. Analog records from the archives of the IGR NNC RK, Institute of Seismology of the National Academy of Sciences of the Kyrgyz Republic, Seismological Experimental and Methodical Expedition (SEME) of the Ministry of Education and Science of the Republic of Kazakhstan) (c); the earthquake of July 20, 1988 (48.3° N; 81.1° E; M_S = 5.1, *Z* component. Analog records from the SEME archive of the Ministry of Education and Science of the Republic of Kazakhstan) (d), and the earthquake of January 20, 2015 (48.982° N; 78.759° E; *mpv* = 5.3, *K* = 12.2, *Z* component. Records of the IGR NNC RK network stations) (e).


(a)
(b)
+200 nm
UKMBHZ
−200 nm
+100 nm
BRVK BHZ
+100 nm
OM BHZ
−100 nm
+100 nm
TLG BHZ
−100 nm
+20 nm
RYA BHZ
−20 nm
KZD BHZ
−50 nm
+40 nm
TERS BHZ
Pn
40 s
(c)
+10000 nm
BRVKBLZ
−10000 nm
+5000 nm
ANVSBLZ
−5000 nm
+5000 nm
KDSKG BLZ
−5000 nm
+10000 nm
EKS BLZ
+5000 nm
ARSB BLZ
−5000 nm
+20000 nm
ARK BLZ
−20000 nm
+5000 nm
DZH BLZ
−10000 nm
04:05:30.000 1976080
04:06:00.000 1976080
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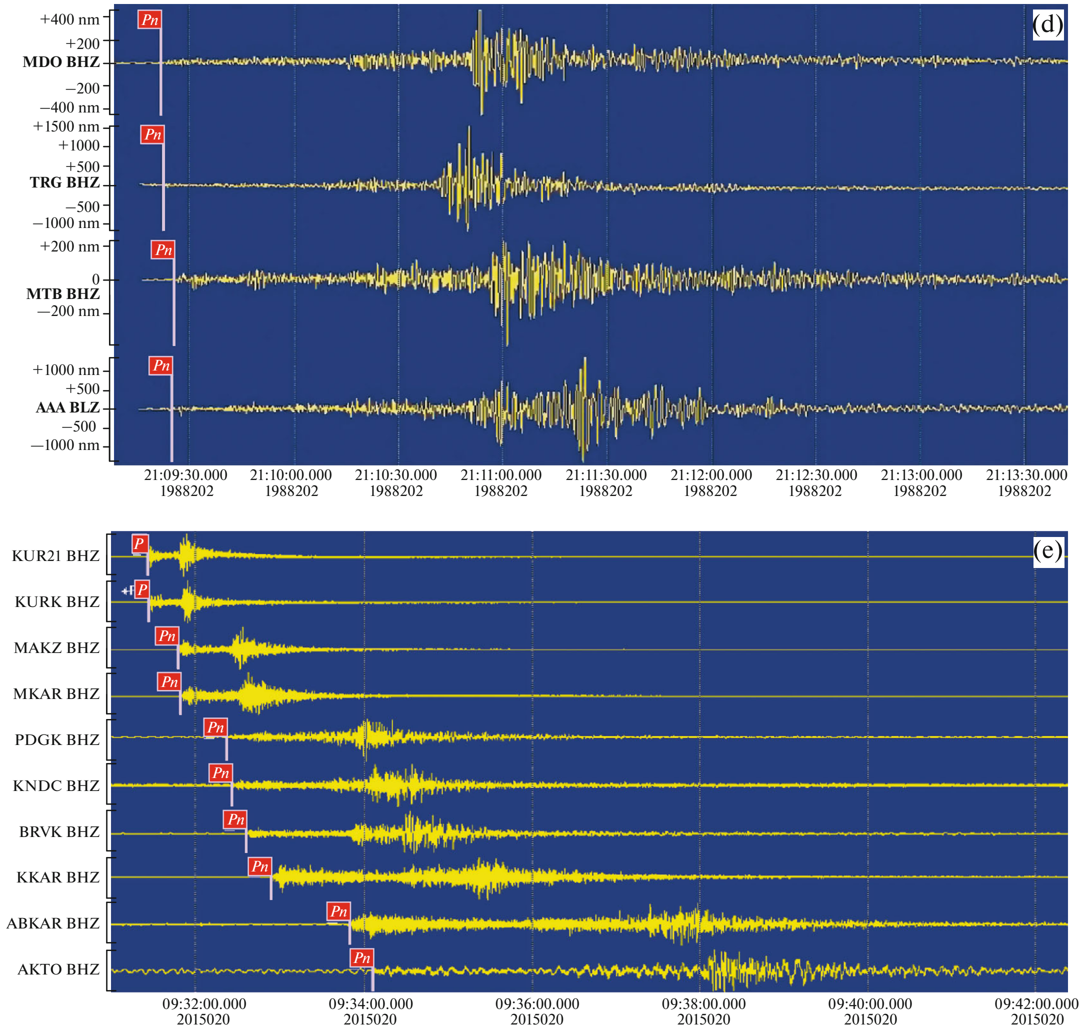

Fig. 9 (Contd.)

(*Zemletryaseniya*..., 1992–2004; Mikhailova et al., 2007; Morgovskaya et al., 2006).

(4) The data on seismicity of the STS region based on the permanent network of monitoring stations IGR NNC RK in 2004–2019 were collected. Within this goal, seismic bulletins and waveforms of seismic events were analyzed, the work on seismic discrimination was carried out (Velikanov et al., 2012; Mukambaev and Mikhailova, 2015; www.kndc.kz).

(5) The data on the STS seismicity obtained in the period of 2005–2010 by the field observation network set at the Balapan, Degelen, and Sary-Uzen sites were collected (Morgovskaya et al., 2006; Mikhailova et al., 2007).

Figure 9 presents seismograms of the largest earthquakes with epicenters near the STS revealed in this work. The earthquake of 1925 with magnitude M_S = 5.8 (Fig. 9a), the earthquake of 1966 with mpv = 4.3, the earthquake of 1976 with M_S = 5.1 (Fig. 9b), the earthquake of 1988 with M_S = 5.1 (Fig. 9c), and the earthquake of 2015 with mpv = 5.3 (Fig. 9d). Analog seismograms were digitized for further storage and processing. It should be noted that the earthquake of September 28, 1925, occurred long before the beginning of nuclear tests. Its parameters were t_0 = 21:42:40 (±20 s), and coordinates were 50 ± 1° N, λ = 77 ± 1° E. The epicenter was located in the region of the Main Chingiz Ridge. The magnitude was M ~ 5.8 ± 0.5 (see Fig. 9a). Such an earthquake (depending on the depth of the focus) can cause oscillations in the epicentral zone with an intensity of 7 or even 8, depending on the depth of the focus.

Earthquake records near the STS were also found in a later period of time. The seismic records of the IGR NNC RK stations on March 26, 1996, identified signals from an earthquake with magnitude 4.3. Its epicenter was in close proximity to the Degelen massif. Geographically, this area belongs to the northern

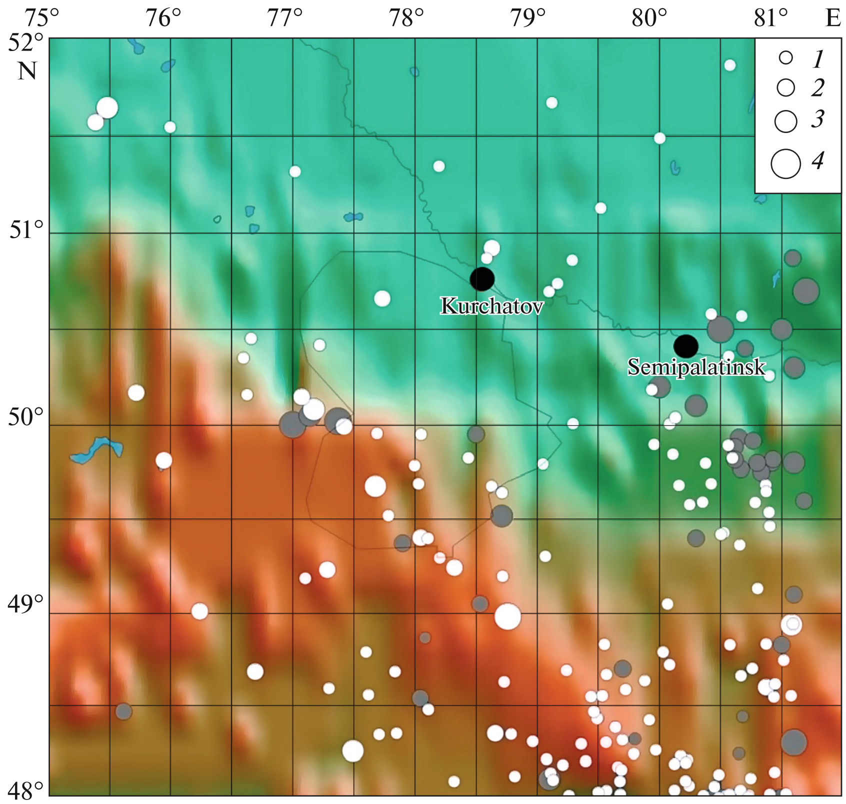

Fig. 10. Map of the earthquake epicenters of the STS region and its vicinities. The size of the circle corresponds to magnitude: (*1*) $mb < 3$, (*2*) $3 \le mb < 4$, (*3*) $4 \le mb < 5$, and (*4*) $mb \ge 5$. Tone circles denote epicenters of earthquakes up to 2004; white circles are after 2004.

slopes of the Murzhik Ridge, which is the region of the deep Main Chingiz fault. In the town of Kurchatov, an earthquake was felt with an intensity of 3 units.

This event was of great interest among the researchers involved in the problems of seismic monitoring of nuclear explosions, since its epicenter was located near the epicenters of the nuclear test site. A detailed analysis of the records allowed foreign experts to make sure that this event was an earthquake caused by deep tectonic processes in the Earth's crust. A similar earthquake had been noted earlier in this region (March 20, 1976, $M = 5.1$, see Fig. 9c). This event was also thoroughly analyzed by foreign scientists with the goal of clarifying the nature of this event, i.e., to the question of whether it was a nuclear explosion (see, for example, (Pooley et al., 1983)).

It is considered that one of the recent largest earthquakes in this region is the earthquake of January 20, 2015, which occurred at 09:30 GMT. Event coordinates were 48.982° N; 78.759° E; $mpv = 5.3$, $K = 12.2$. All stations of the IGR NNC RK network recorded this earthquake; Kurchatov and Makanchi stations were the closest to its epicenter (see Fig. 5d). The earthquake source was located in the region of the Main Chingiz Ridge in the Chingiz-Alakol seismic-generating zone (Mukambaev and Mikhailova, 2015). The earthquake was felt at a distance of up to 300 km from the epicenter. In the town of Kurchatov, it had an intensity of 4 units, in the town of Semey it was 2–3 units, and it was 2 units in the town of Ust-Kamenogorsk. On February 2, 2015, at 06:55 GMT, another earthquake occurred in this region. It was weak in energy; hence, it was recorded only by the Makanchi and Kurchatov stations. Based on the results of localization and the good correlation of the waveforms of this weak event (see Fig. 9e) and on the investigation of the earthquake of January 20, 2015, as well as on the insignificant time interval between the two shocks, this event was defined as the aftershock of the earthquake of January 20, 2015.

Figure 10 is a summary map of the earthquake epicenters on the STS territory and its surroundings since historical times (since 1783) up to 2019. The largest earthquakes are grouped into two zones: near the town of Semey (former Semipalatinsk) and in the region of the Murzhik Ridge in the western margin of the STS. The STS territory is seismic in its southern part. The epicenters of earthquakes near the Main Chingiz Fault are clearly detected; this is a seismically dangerous lineament. In different periods, the representative magnitude of recorded earthquakes was different, which was associated with the presence or absence of seismic

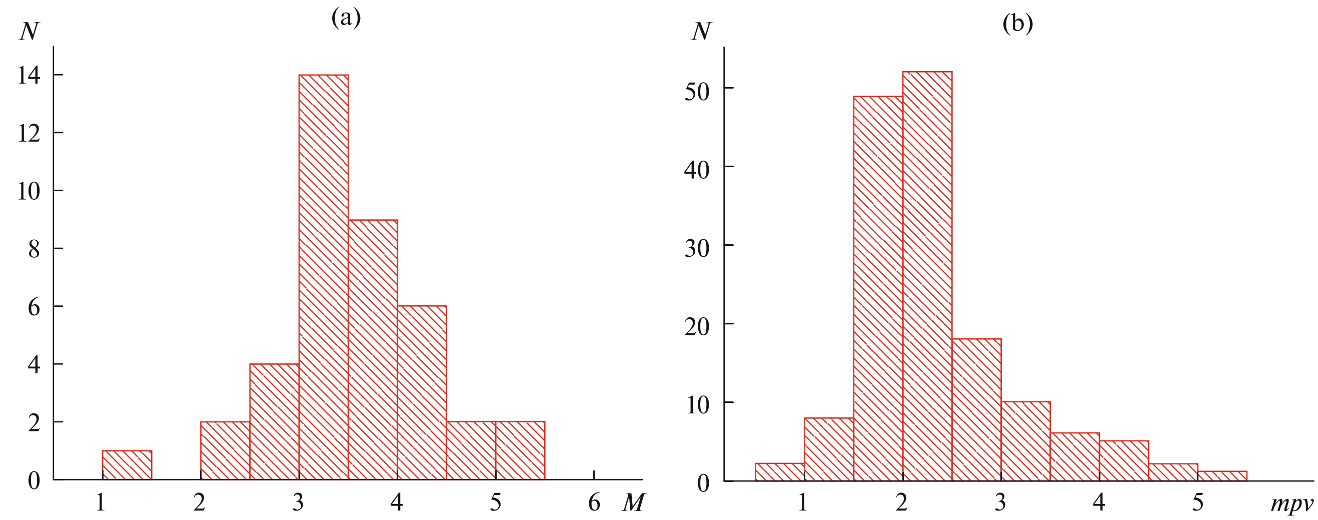

Fig. 11. Histograms of the distribution of seismic events in the STS region by magnitude over the periods up to 2004 (a) and in 2004–2019 (b).

recording stations, various network configurations, and the technical equipment of seismic monitoring stations.

Figure 11 shows histograms of the distribution of seismic events by magnitude in the STS region over different time periods. Before 2004, the largest number of recorded events had magnitudes of M = 3–4; in the period of 2004–2019, most events had magnitudes of 1.5–2.5. Figure 12 presents a graph of the recurrence frequency of earthquakes in the STS territory in the period 2004–2019; the representative magnitude for this period is mpv = 2.

Discrimination of Earthquakes and Quarry Blasts

In the routine processing of seismic records, the challenge is to determine the nature of the sources. This is very important for further work on assessing seismic hazard. Ultimately, the catalog of earthquakes needs to consist only of natural events and include no explosions.

After the end of nuclear tests on the territory of the STS, intense mining of various minerals began, which was accompanied by explosions of different yield and frequency. Seismic data analysts are faced with the problem of identifying the nature of the recorded seismic signals. Often, only seismic methods can be used to discriminate them, since it is not possible to obtain information about the blasts from mining enterprises. In the process of studying the seismicity of the test site, a catalog of existing quarries was compiled, and reference records of blasts from each quarry were collected, which were necessary to recognize the nature of seismic events recorded during seismic monitoring (Velikanov et al., 2012). Currently, the STS has a large number of active quarries (Fig. 13): Karazhira (coal), Naimanzhal (gold), Esymzhal (manganese), Karazhal (fluorite), Shorskoye (molybdenum), Zhanan (gold), Suzdal (gold), Central Mukur (gold), Zherek (gold), Far and Middle Novotubinsky (limestone for cement), Abyz (gold, polymetals), etc.

The following set of parameters is studied to discriminate seismic events from records of seismic stations: (1) the coordinates of the epicenter of the event and their proximity to the known quarries, (2) depth of the event, (3) properties of the wave pattern of seismograms, (4) time of the event (working or nonworking hours), (5) presence of a signal recorded by the infrasound station (Belyashov et al., 2013), (6) range of energy classes, (7) spectral ratio of amplitudes in various wave trains, and (8) characteristics of the spectra

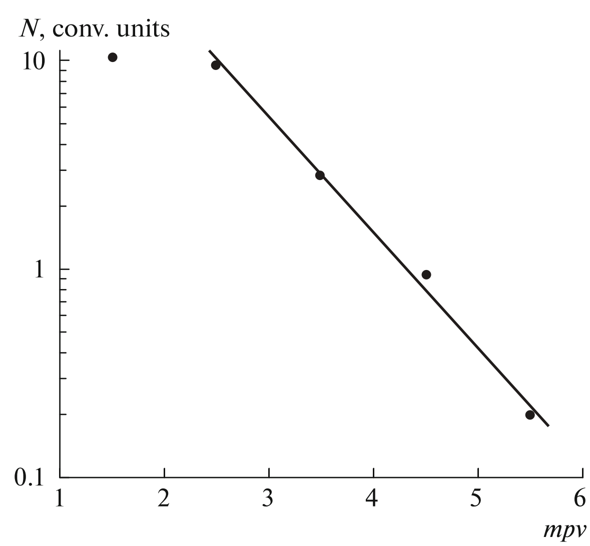

Fig. 12. Recurrence of the magnitudes of seismic events in the STS region for the period 2004–2019.

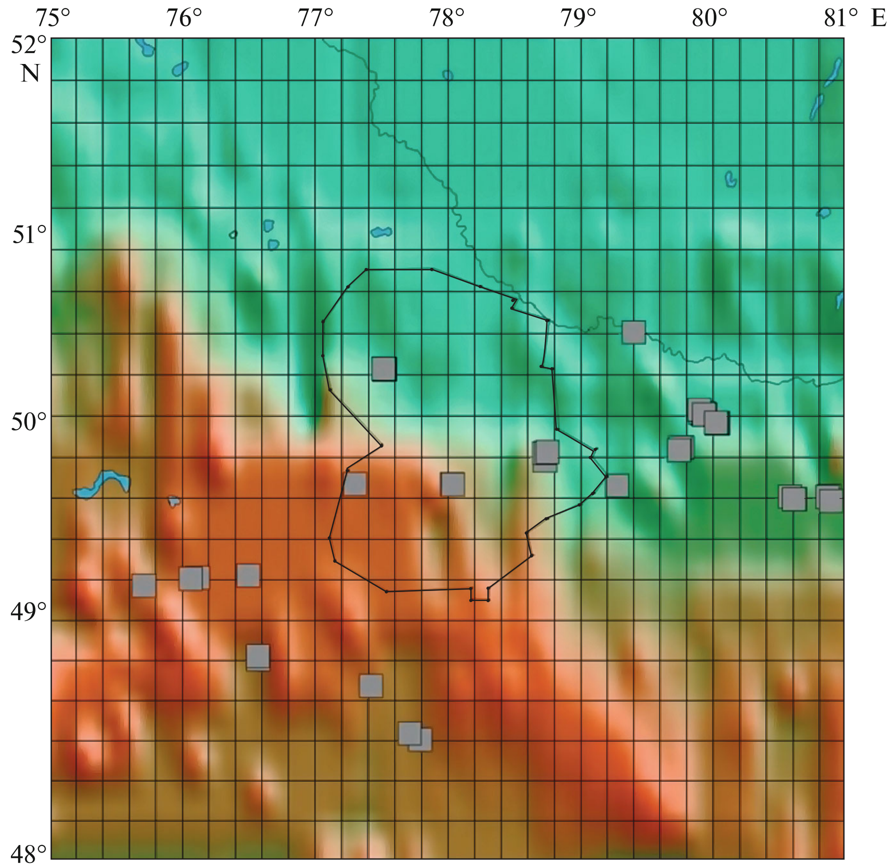

Fig. 13. Map of the location of quarries (squares) in the STS territory.

of different wave trains. In 2010, a modern KURIS infrasound array with an aperture of 1 km was put into operation in the town of Kurchatov (near technical site no. 2). The array consisted of four points (three at the vertices of an equilateral triangle and the fourth at its center) (Belyashov et al., 2013). The installation of KURIS greatly facilitated the discrimination of quarry blasts.

Each of the listed parameters separately cannot be a sign for the confident division of seismic events into explosions and earthquakes. A joint analysis of several properties, for example, the proximity of the location of the event epicenter to a known quarry, the shallow depth of the event, the characteristic recording of this event by the infrasound station, and the time of the event related to the working time of the day increase the chance of attributing the recorded seismic event to the class of quarry blasts. The spectral ratios of shear and longitudinal waves and properties of the wave pattern of the event recording have the greatest efficiency in discrimination. The ranges of energy classes characteristic of each quarry are considered additional criteria. Note that the specific quantitative discrimination criteria are different for different regions of Kazakhstan, as well as for different recording stations, which necessitates a detailed study.

Below is an example of such an analysis for the Karazhira coal mine located on the territory of the STS Balapan site. The quarry coordinates are 50.018° N, 78.727° E; it is located near the Kurchatov seismic station (78 km) and the Kurchatov-Cross seismic array (69 km to the central point).

Most blasts at the Karazhira quarry have an explosive mass of 5–15 t (although there are individual blasts with a charge mass of about 50 t), the energy class is $K = 5$–7 (while single blasts have class $K = 9$), which corresponds to a magnitude of $mb = 3.8$. Such blasts are recorded by a large number of stations of the global monitoring network and fall into seismological catalogs from around the world. Almost all blasts are carried out at 7:00–8:00 GMT (13:00–14:00 local time) and 13:00–14:00 GMT (19:00–20:00 local time).

Figure 14 shows the seismograms of the blast at the Karazhira quarry on June 29, 2008, and the earthquake of April 18, 2004, recorded at the Kurchatov seismic station. An explosion record is significantly different from an earthquake seismogram. The blast has a clear *P*-wave arrival, a relatively small amplitude of the *S*-wave, and dominant low-frequency surface waves, while the earthquake has a completely different

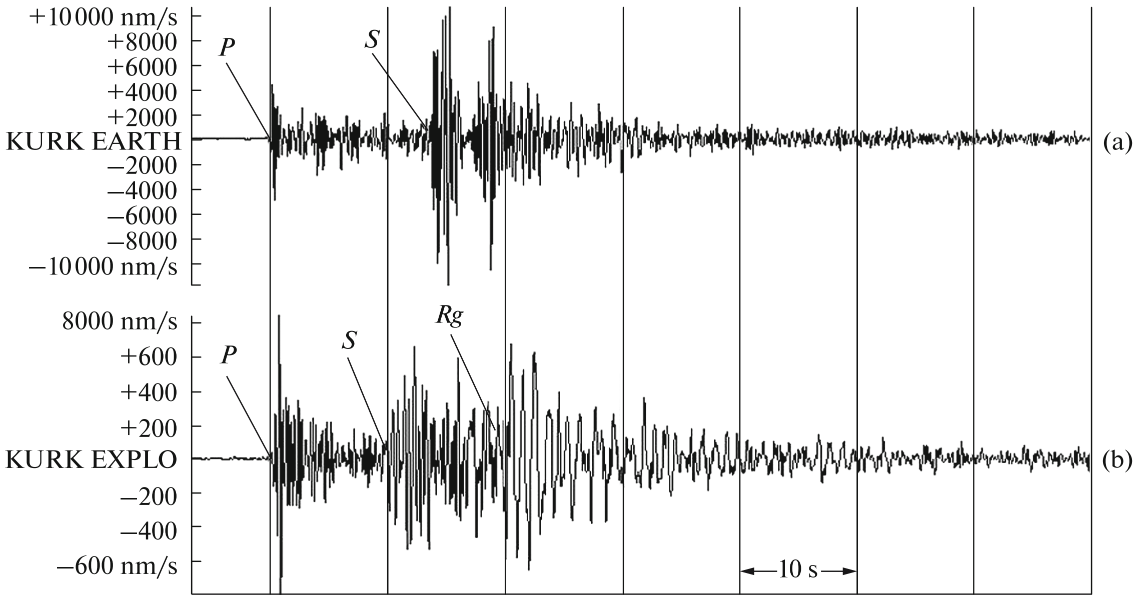

Fig. 14. Seismograms of the earthquake of April 18, 2004 (49.99° N; 77.42° E; *mb* = 3.8) (a) and the blast in the Kara-Zhyra quarry on June 29, 2008 (50.00° N, 78.63° E; *mb* = 3.3) (b).

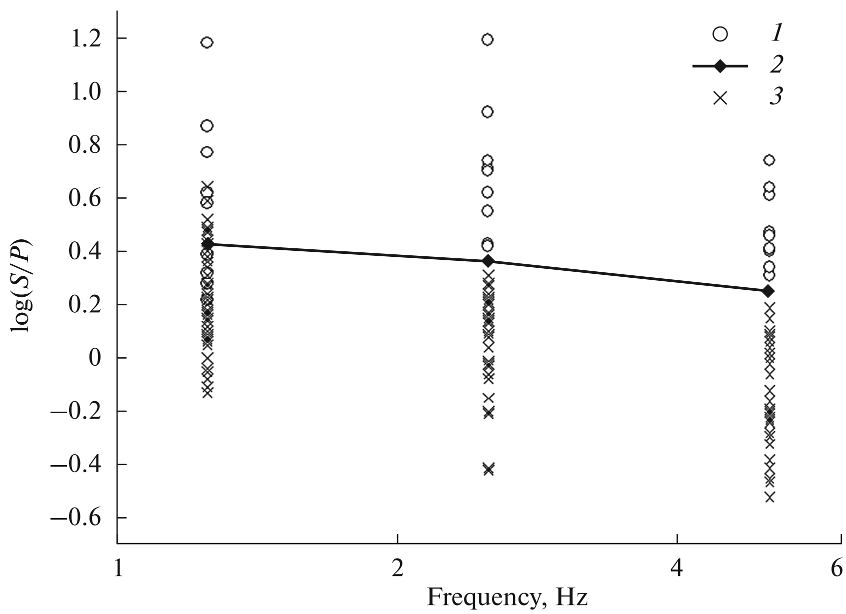

Fig. 15. Distribution of the spectral ratios of the maximum S/P-amplitudes of blasts and earthquakes. (*1*) Earthquakes, (*2*) blasts, and (*3*) dividing threshold. See the text for explanations.

pattern: surface waves are absent and the *S*-amplitude dominates.

Most attention in the analysis was paid to the method of amplitude relations between *S*- and *P*-waves as the most efficient and universal method for discriminating chemical explosions and earthquakes. The processing technique included measuring the decimal logarithms of the *S*/*P* amplitude ratios of the vertical component with narrow-band filtering. We used filters with center frequencies of 1.25, 2.5, and 5 Hz and a passband of 2/3 octaves at a level of 3 dB from the maximum. Figure 15 shows an example of such an analysis for the Karazhira quarry and related earthquakes. It is clearly seen that, at the Kurchatov station, the nature of the event can be quite confi-

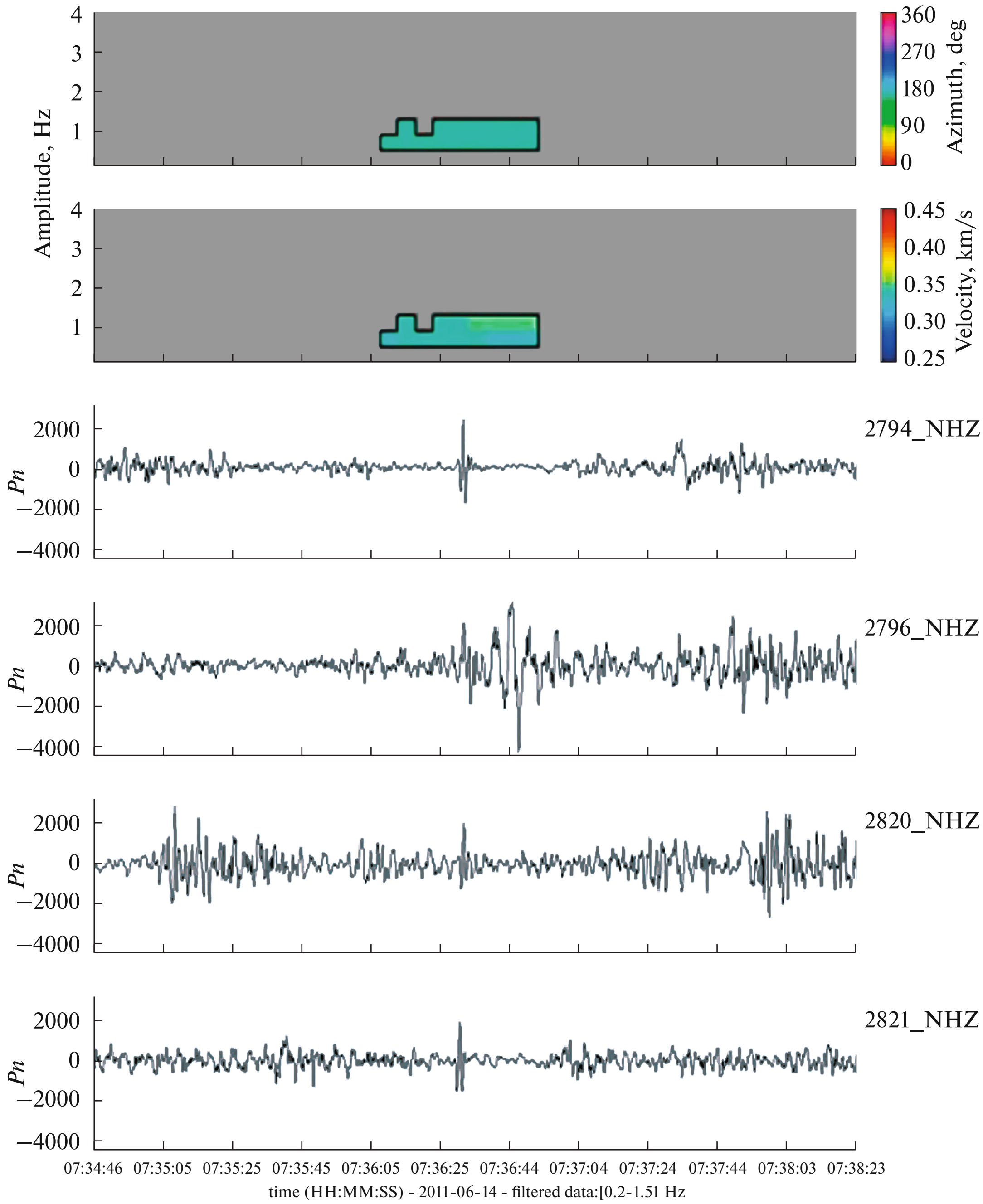

Fig. 16. Results of the records of blasts in the Karazhira coal mine (STS) on June 14, 2011, by the Kurchatov infrasound array.

dently identified by the spectral ratio of the amplitudes of *S* and *P* waves.

Figure 16 presents the results of recording and processing an explosion record at the Karazhira coal mine on June 14, 2011, by the KURIS infrasound array (Belyashov et al., 2013).

Industrial Earthquakes

During the operation of the test site, 340 underground nuclear explosions (UNEs) were conducted on its territory. It is known that, over a short period of time (several hours to several days) after the UNE, a collapse of the explosion cavity was recorded (Sokolova et al., 2017) (Fig. 17). At present, almost 30 years after the end of the tests, geodynamic activity is observed in the region of the test site infrastructure. One such manifestation is low energy seismic events. In 2010, the DEG1 field seismic station recorded nine small surface events, the recording form of which was similar to the collapse recording (Fig. 18). The magnitude of events was $mb < 1$. Figure 19 is an example of

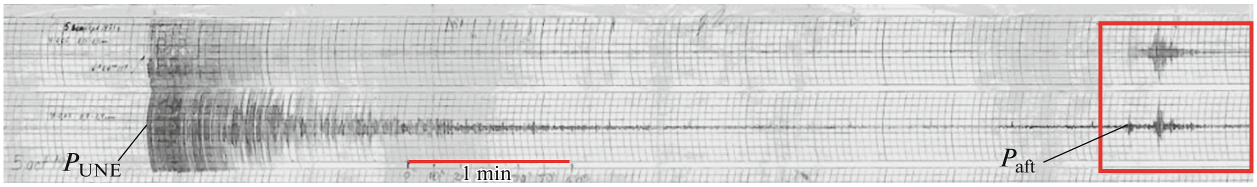

Fig. 17. Seismogram of an underground nuclear explosion on May 10, 1975 (t_0 = 04:27:00.0; 49.78306° N; 78.08667° E, Degelen site) recorded by the Kurchatov seismic station.

an earthquake record from a Degelen test site; the epicenters of such events are consistent with the location of the tunnels used on the site.

In recent years (2018–2020), a series of field work has been carried out at three sites where nuclear tests were previously conducted as part of a project supported by a grant from the Ministry of Science and Education of the Republic of Kazakhstan. These are the Degelen, Balapan, and Sary-Uzen sites. The goal of these works was to establish the geodynamic manifestations of seismicity at the test sites directly near the boreholes and tunnels.

Focal Mechanisms of the Earthquakes in the STS

Focal mechanisms were determined for seven centers of earthquakes that occurred from 1976 to 2016 (stereograms are shown in Fig. 20). The dislocations in most of the foci occurred under conditions of near-horizontal compression stress in the western–northwestern direction; the orientation of the tensile axes is more variable in terms of both the dip angles and the extension azimuths.

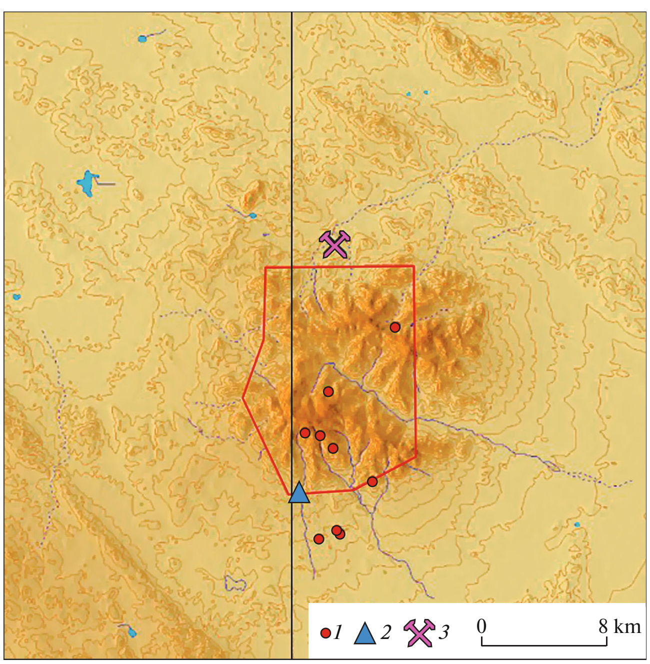

Fig. 18. Location of seismic event centers in the area of Degelen test site (STS). (*1*) Epicenter of the event, (*2*) seismic station DEG1, and (*3*) quarry.

A comparison of the parameters of the rupture planes in the centers of the investigated earthquakes with the tectonics of the region indicates that a structural explanation can be found for both nodal planes. Strike-strip faults with an insignificant upthrust component along the northwestern strike planes steeply falling to the southwest may reflect the seismic activity of the regional Main Chingiz fault. At the same time, the gentler planes of northeastern strike falling to the southwest are consistent with the orientation of the faults that cut the structures of the Kazakh Shield.

CONCLUSIONS

(1) A single catalog of earthquakes was prepared for the STS territory and its environs from 1783 to 2019 based on the set of all collected data; the most active seismic zones were identified. It is possible to confidently answer the question about the presence of natural tectonic foci of earthquakes in this region. Earthquakes associated with active tectonic processes have been recorded on the territory of the STS and its environs both in the historical past and in recent years.

(2) The current map of the general seismic zoning of the Republic of Kazakhstan does not reflect the actual pattern of the existing seismic-generating zones and should be specified for the STS territory.

(3) The records of microshocks near the tunnels of the Degelen site, where nuclear tests were previously made, indicate that the geodynamic processes at the sites of nuclear explosions have not been completed.

(4) An adequate assessment of quantitative seismic hazard in the study area requires developments of a permanent system of seismic observations.

(5) To assess the possible seismic impact, it is necessary to carry out special seismic and geological-tectonic work to study the activity of tectonic faults and establish their seismic potential. It would be very useful to conduct paleoseismological studies at the Main Chingiz fault.

(6) Preliminary calculations show that seismic impacts with an intensity of 6–7 units on the MSK-64 scale are actually possible in the study site.

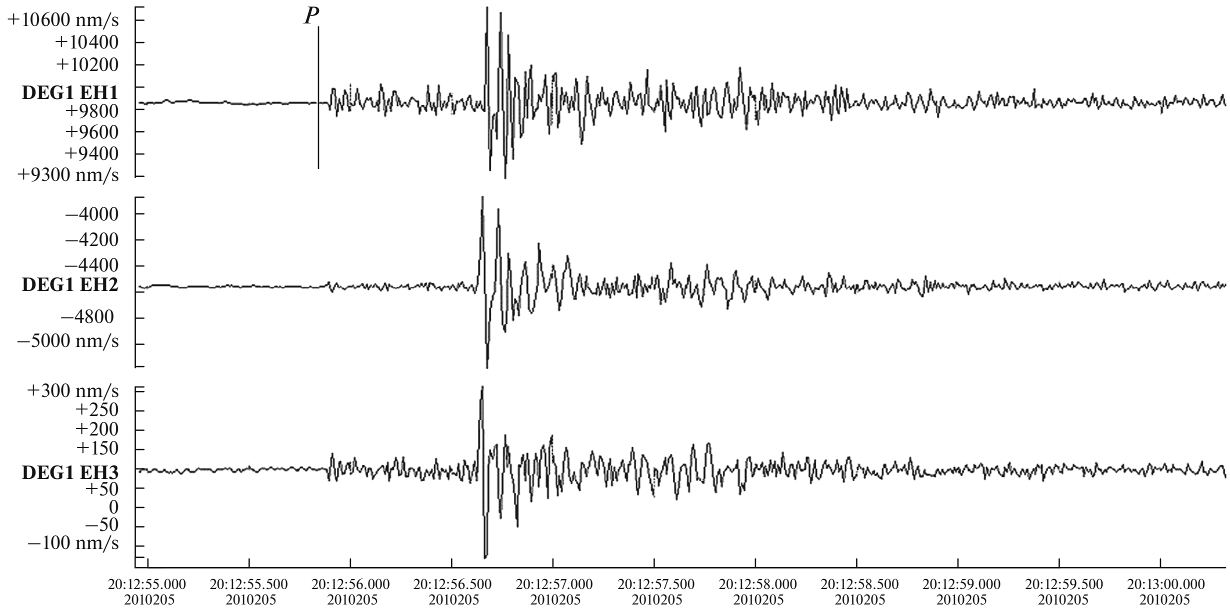

Fig. 19. Seismograms of a induced earthquake at the Degelen test site (STS) on July 24, 2010 (20:12:55.8 GMT; coordinates: 49.698° N; 78.044° E).

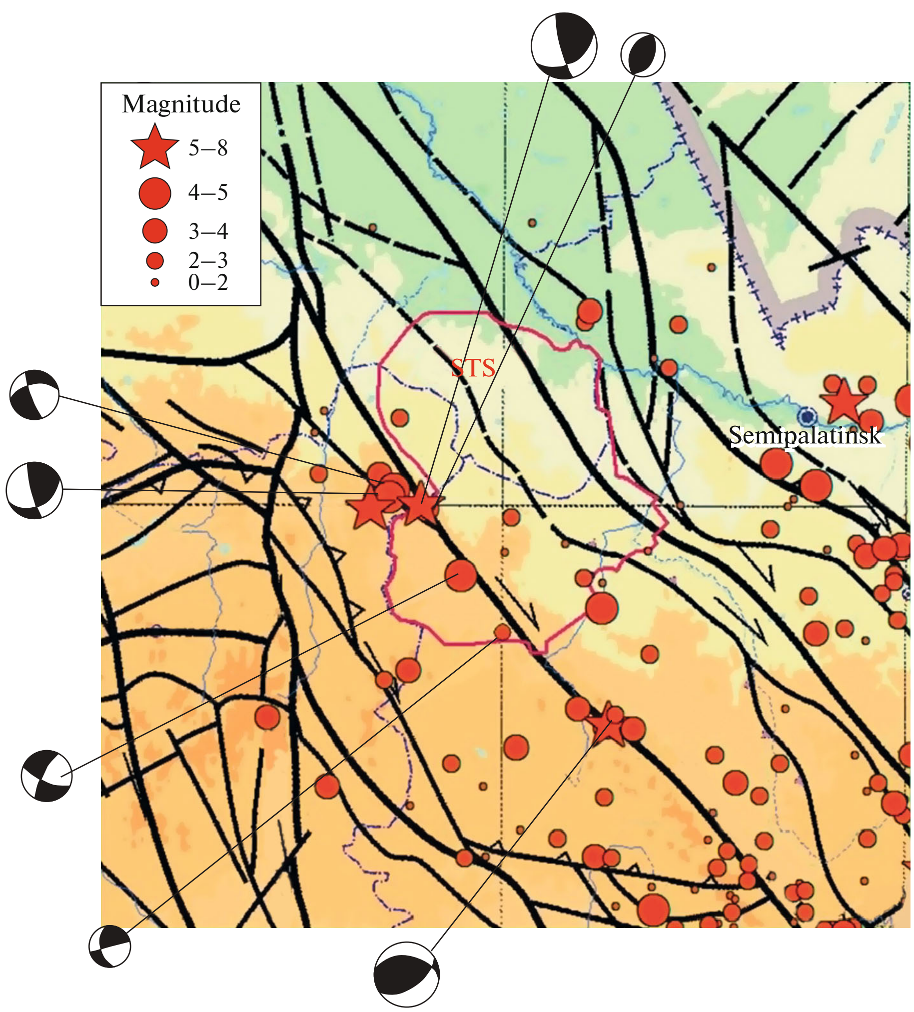

Fig. 20. Stereograms of the mechanisms of earthquake sources in the territory of the Semipalatinsk Test Site. Major faults are shown.

CONFLICT OF INTEREST

The authors claim that they do not have any conflict of interest.

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