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The Influence of Underground Nuclear Explosions on Regional Seismicity

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Abstract—The effect of underground nuclear explosions (UNEs) detonated at the Kazakhstan test site (KTS) from 1962 through 1989 on the seismic regime in a region of Central Asia and Kazakhstan about 1000 km from KTS is discussed. The total seismic energy flux through the unit volume at a distance of 1000 km from an UNE of 150-kt yield (the limiting value under the 1967 Threshold Test Ban (TTB) Treaty) is 3.4×10^{-7} erg/cm^3, and the total energy flux from all of the 338 KTS UNEs is on the order of 6×10^{-5} erg/cm^3, whereas an ultimate strain disturbing the continuity of the medium is about 3×10^3 erg/cm^3. The analysis of samples including 300 UNEs and about 40000 earthquakes with epicenters within the Central Asia and Kazakhstan region over the period from 1962 through 1989 shows that explosions had an insignificant effect on the seismic activity level in the study region, at least in relation to earthquakes of the energy class $K \geq 9$. Weak effects of nuclear explosions on natural seismicity were not studied in this work, because such an analysis requires conducting special monitoring of weak seismicity ($K \ll 9$).

INTRODUCTION

The influence of underground nuclear explosions (UNEs) on the seismic regime in regions located both near to and far from an UNE epicenter have been widely discussed not only in scientific publications but also in mass media because of its great practical importance. There are diametrically opposite opinions concerning this problem. In particular, Richards and Ekström [1995] note that no strong or destructive earthquake occurred near or shortly after a nuclear explosion over a 30-year period (from 1963 through 1992) when more than 1500 UNEs were detonated (i.e., nearly once every week). On the other hand, some investigators [Nikolaev and Vereshchagina, 1991; Nikolaev, 1994, 1995; Tarasov and Tarasova, 1995] suppose that, similar to earthquakes, UNEs can have a substantial effect on the level of natural seismic activity even in regions located at a distance of a few thousand kilometers from these sources.

Supposedly, the seismic energy of an explosion, propagating through a source region of a forthcoming a earthquake, can raise the stress level above its critical value and trigger an earthquake. Depending on specific conditions in a seismically active region, this UNE triggering effect can lead to either a strong earthquake or a series of weak shocks that, on the contrary, eliminate the danger of a strong earthquake. This concept was supported by the 1982, Landers (California), $M_s = 7.4$, earthquake, which gave rise to a series of strong earthquakes at a distance of more than 1000 km [Gomberg, 1995; Hough, 1995].

Kedrov and Steblov [1995] used data over a relatively short time interval (from 1984 through 1989) to analyze the problem of the relation between UNEs detonated at the Kazakhstan test site (KTS) and earthquakes that occurred in the Central Asia and Kazakhstan region.

The same problem is studied here on the basis of a considerably larger volume of empirical data. We used data on the seismic activity in a Central Asia and Kazakhstan region over the period from 1962 through 1991 reported in yearbooks [*Zemletryaseniya v SSSR*, 1962–1991] and the electronic version of the catalog of strong earthquakes in North Eurasia [Kondorskaya and Ulomov, 1997] and compared them with UNEs detonated at KTS over the period from 1962 through 1989 [Mikhailov, 1997].

AN EARTHQUAKE AND AN EXPLOSION AS THE SOURCES OF SEISMIC WAVES

According to current concepts [Kostrov, 1975], an earthquake source can be formally described as follows:

the source of a tectonic earthquake is a plane rupture of the Earth's material;

the rupture is produced by elastic shear stresses accumulated in the course of a tectonic deformation and leads to their complete or partial release on the fault plane;

the rupture first arises in a small area (point) and then propagates from the area at a rate not exceeding the P wave velocity (the causality principle);

the rupture in a tectonic earthquake source occurs as a slip motion, i.e., the relative displacement of fault walls along the normal to the fault plane (detachment) is zero;

the Earth's material outside the rupture area remains linearly elastic.

A lateral fault is a typical feature of tectonic earthquakes. The radiation pattern of seismic oscillations during an earthquake has a quadrupole shape for both P and S waves.

According to the theory of the avalanche-unstable fracturing [Myachkin *et al.*, 1975] confirmed by modeling results of the seismic process and precursors [Sobolev, 1993; Sobolev *et al.*, 2001], an earthquake proper occurs if some volume of the medium becomes mechanically unstable due to external effects.

The UNE energy released is transferred to the surrounding medium via compressional waves [Rodionov *et al.*, 1971]. Concurrent melting and evaporation of rocks occurs in the immediate vicinity of the explosion source, and an underground cavity forms due to the compression of melted rocks. Shock waves fracture rocks in the vicinity of the source and generate elastic seismic oscillations outside the zone of inelastic deformations. Linear dimensions of the cavity and fracture zone depend on the UNE yield, charge depth, and, to a lesser extent, properties of the medium.

An UNE is a spherically symmetric source that would excite compressional body waves alone, if the medium were ideal, homogeneous, isotropic, and unbounded. However, all types of waves are produced by an UNE detonated in the real medium, which can be represented as a heterogeneous layered half-space. Moreover, the UNE-related release of stresses accumulated in the medium can additionally complicate the observed seismic wave field.

The size and lifetime of an explosive source are appreciably smaller than those of an earthquake of comparable energy.

An essential distinction between these two types of seismic oscillations consists in that an earthquake occurs in a medium that has been subjected to the action of elastic shear stresses accumulated in the process of a tectonic deformation, whereas UNEs are detonated in media with various, but generally subcritical, stress levels. The explosion itself is an external factor releasing the stresses in the place of its detonation. The recurrence rate of postexplosion aftershocks depends on the prestress level and on the physical and mechanical properties of host rocks.

Despite the aforementioned distinctions, these sources have a common characteristic allowing their joint analysis. Such a characteristic is the source size, if this parameter is treated in terms of the zone encompassing aftershocks of the main shock. This definition of the source was proposed by Tsuboi [1956], discussed by Kasahara [1981], and corroborated by independent experimental data in [Sadovskii *et al.*, 1983a].

Using data on 99 strong earthquakes in various regions over the period from 1923 through 1968, Sadovskii *et al.* [1983a] showed that the relation between the volume V_s of the medium in which aftershocks are observed and the seismic energy E_s of the main shock is approximately described by the expression

$$\log E_s = \log V_s + 3, \qquad (1)$$

where E_s is the seismic energy (erg) and V_s is the volume (cm^3) containing aftershocks.

Some researchers [Crovely and German, 1971; Ryall and Sawage, 1962; Hamilton *et al.*, 1972; Engdahl, 1976; Adushkin and Spivak, 1995] showed that, similar to earthquakes, UNEs give rise to aftershock sequences. On the other hand, neither a strong earthquake nor a seismicity level increase that could be classified as one induced by the explosion was observed in regions where high-yield UNEs were detonated. This fact is of special importance for explosions detonated on Amchitka Island, because the level of natural seismic activity in this region is one of the highest levels in the world, and the Cannikin explosion detonated here in 1971 is the most powerful among all United States UNEs. The yield of this explosion was estimated at $Y <$ 5000 kt by Springer and Kinneman [1975] and at about 3000 kt by Kedrov[1994].

The fact that the relations between E_s and V_s are similar for UNEs detonated in dense rocks and earthquakes allowed Sadovskii *et al.* [1986] arrive at the two important conclusions:

the formation of an earthquake source and thereby of an observed wave field is mainly controlled by properties of the medium rather than the focal mechanism;

seismic effects of UNEs detonated in dense rocks and tectonic earthquakes are nearly the same and amount to a few percent.

SEISMIC EFFECTS OF EXPLOSIONS AND EARTHQUAKES

To estimate the seismic effect of UNE, we calculated the UNE seismic energy from the spectra of short-period P-wave records using the Golitsyn formula modified in such a way as to account for the frequency dependence of the P wave attenuation coefficient:

$$E_s = 2\pi R^2 G\rho c K^{-2}\exp(2\alpha_P L)\int_{t_1}^{t_2} v^2(t)dt. \qquad (2)$$

Here, the following notation is adopted: R, Earth's radius; G, geometrical divergence; ρc, acoustic stiffness of the medium in the station area; K, conversion coefficient of displacements on a half-space surface into displacements in an incident wave represented by a harmonic oscillation packet; $\alpha_P(f) = kf$, attenuation coefficient of P waves; L, length of the source-to-station ray path; $\nu(t)$, velocity of particles on the half-space surface.

Whenever digital records of UNEs were lacking, we estimated the energy by the formula [Sadovskii *et al.*, 1986]

$$\log E_s = 1.7M_{PV} + 9.3, \quad (3)$$

where M_{PV} is the magnitude estimated from short-period P waves with the help of the calibrating scale [*Instruktsiya o poryadke* ..., 1982]. Then, using the seismic energy values of UNEs with declared yields [Springer and Kinneman, 1971, 1975], we obtained relations between the seismic and total (E_0) energies:

$$\log E_s = 1.5\log E_0 - 11.5, \text{ for } \log E_s < 20.5, \quad (4)$$

$$\log E_s = \log E_0 - 2.1, \text{ for } \log E_s \geq 20.5 \quad (5)$$

in dense rocks and

$$\log E_s = 1.2\log E_0 - 6.6, \text{ for } \log E_s \leq 19.5 \quad (6)$$

in loose rocks

The values of the UNE seismic effect $\eta = E_s/E_0(\%)$ estimated by formulas (4)–(6) are presented in Table 1.

These estimates roughly show that the UNE seismic effect varies from 0.1 to 0.3% in loose rocks and from 1 to 5% in dense rocks. The 0.3–1% interval corresponds to intermediate conditions.

Variations in rock properties can change the coefficient η by an order of magnitude, and strong UNEs detonated in dense rocks can yield η values of about 5%, which are close to those characteristic of the near-field zone [Rodionov *et al.*, 1971]. The η dependence on the UNE yield, as derived from teleseismic data, is apparently caused by an increase in the high-frequency attenuation with the distance from the source. This effect noted by Latter *et al.* [1961] leads to underestimated values of the coefficient η and is most pronounced in the case of weak explosions.

Table 1. Estimates of the seismic effect of UNEs detonated in dense and loose rocks

E_0, erg	Y, kt	Seismic effect of UNE (η, %)	
		dense rocks	loose rocks
4.2×10^{19}	1	0.3	0.1
4.2×10^{20}	10	1.0	0.15
4.2×10^{21}	100	2.8	0.2
4.2×10^{22}	1000	4.2	0.3
4.2×10^{23}	10000	4.4	–

Moreover, the coefficient η appears to slightly increase with the UNE yield, because the acoustic impedance of rocks of the same type is higher at greater detonation depths. Averaged estimates of main source parameters that apply to both UNEs and tectonic earthquakes in dense rocks, provided that seismic efficiencies of these sources are comparable, are presented in Table 2.

EVALUATION OF THE SEISMIC ENERGY FLUX FROM AN EXPLOSION

To elucidate the UNE effect on the seismic regime in surrounding regions, we chose the Kazakhstan test site (KTS), where explosions were detonated over a long period of time, and a seismically active Central Asia and Kazakhstan region (Fig. 1).

It is appropriate to estimate the seismic energy flux for maximum yield UNEs detonated at the test site in the time interval under study, and the estimation area should have a high level of natural seismicity. Taking into account that the seismically active zone of Central Asia is about 1000 km from KTS, whereas the territory surrounding the test site is virtually aseismic, it is appropriate to estimate the flux at a distance of 1000 km from the test site. We assumed the maximum UNE yield to be 150 kt (the limiting vale under the 1967 TTB treaty).

Since the total, and thereby seismic, UNE energy are known, the estimation of the energy flux at a given point is simplified and does not require integration of the signal.

Denoting

$$W = 2\pi R^2 G\exp(2\alpha_P L), \quad (7)$$

$$E(t) = \rho c K^{-2}\int_{t_1}^{t_2}\nu^2(t)dt \quad (8)$$

in (2), we find

$$E_s = WE(t),$$

where W is a coefficient characterizing the geometrical divergence and the attenuation of the P wave energy, and $E(t)$ is the total energy flux through the unit area at the observation point.

Assuming $\eta \approx 3\%$ (see Table 1), the total energy of a 150-kt UNE is $E_0 = 6.3 \times 10^{21}$ erg, and its seismic energy is $E_s = 1.9 \times 10^{20}$ erg. Given $\Delta = 1000$ km, we have in this case $G = 0.378$ after data of Kogan [1975] and $\alpha_P(f) = 1.9 \times 10^{-3} f$ km^{-1} in the crust after data of Pasechnik [1970]. Assuming that the predominant frequency of the record is $f = 1$ Hz, we obtain

$$W = 4.6 \times 10^{18}\ \text{cm}^2,$$

$$E(t) = 41.2\ \text{erg/cm}^2 = 4.1 \times 10^{-2}\ \text{J/m}^2.$$

This estimate of $E(t)$ is gross, because we used average values of parameters in (3). Moreover, we supposed that the attenuation in the medium does not depend on the azimuth of the P-wave path from the source to the observation point. However, this estimate provides order of magnitude constraints on the energy. Note for comparison that Savarenskii *et al.* [1983] obtained $E(t) = 4.7 \times 10^{-2}$ J/m^2 using the record of a P wave propagating from an earthquake in the Sea of Okhotsk to the Obninsk station with due regard for the structure of the medium under the station.

According to estimates of Kasahara [1981], the critical strain energy above which the crust fractures is about 3×10^3 erg/cm^3. In order to compare this value with our estimate of the energy flux through the unit area (41.2 erg/cm^2), it should be normalized to the wave train length and velocity. Taking, as rough estimates, a velocity of about 6×10^5 cm/s and a total length of the body wave train of about 200 s, we find that the total energy flux through the unit volume is 3.4×10^{-7} erg/cm^3. Thus, the seismic effect produced by a 150-kt UNE at a distance of 1000 km is ten orders of magnitude smaller than the critical energy strain.

Note that the total energy release from all of the 338 KTS UNEs is on the order of 26 Mt [Mikhailov, 1997], which corresponds to a seismic energy of the order of 3.3×10^{22} erg. The total energy flux through the unit area at a distance of 1000 km from KTS is 7.1 J/m^2 or, in terms of the unit volume, 5.9×10^{-5} erg/cm^3, which is much smaller than the critical strain energy.

The question as to whether such small an effect can appreciably affect the seismicity level or serve as a triggering mechanism for a strong destructive earthquake is discussed below by comparing experimental data on seismicity in Central Asia and Kazakhstan with series of KTS UNEs.

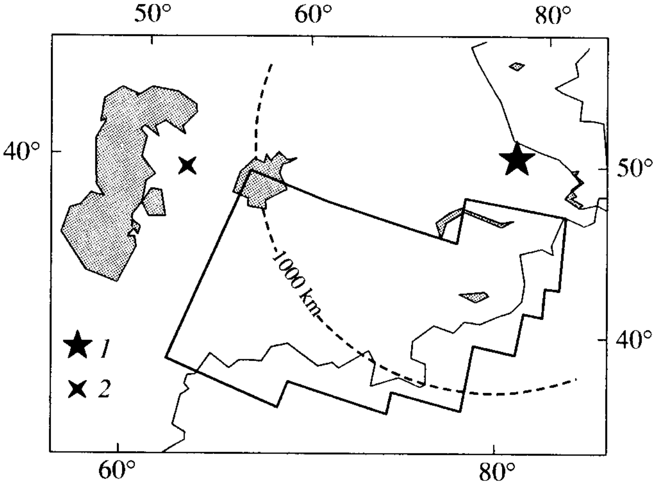

Fig. 1. Schematic map showing the position of the seismically active region under study in Central Asia and Kazakhstan: (*1*) KTS; (*2*) epicenters of two PNEs in the Mangyshlak area.

COMPARISON OF SEISMICITY IN CENTRAL ASIA AND KAZAKHSTAN WITH KTS EXPLOSIONS

Presently, numerous investigations devoted to estimating the seismicity induced by natural and controllable sources have been conducted [Console and Nikolaev, 1995]. Some factors that can be responsible for the induced or anthropogenic seismicity in a region raise no doubts. In particular, the creation of a large reservoir can induce seismicity in a previously aseismic region. The classical example is the Koine reservoir in India: numerous microearthquakes were recorded after its creation and a destructive, $M = 6.7$, earthquake occurred there in 1967 [Gupta *et al.*, 1972].

Another example is the mining of minerals. The underground development of coal deposits is known to induce microseismicity in a zone adjacent to the coal face [Kuznir *et al.*, 1980; McGarr, 1978]; the microseismicity migrates as the face advances.

Table 2. Averaged estimates of source parameters of UNEs and tectonic earthquakes under the assumption that their values of η are comparable

Source parameters	Total energy of source E_0, erg				
	4.2×10^{19}	4.2×10^{20}	4.2×10^{21}	4.2×10^{22}	4.2×10^{23}
E_0, erg	1.4×10^{17}	4.1×10^{18}	1.2×10^{20}	1.7×10^{21}	1.9×10^{22}
M_{PV}	4.6	5.5	6.3	7.0	7.6
η, %	0.3	1.0	2.8	4.2	4.4
L, km	0.9	2.7	8.3	20.4	45.1
V_s, cm^3	1.4×10^{14}	4.1×10^{15}	1.2×10^{17}	1.7×10^{18}	1.9×10^{19}

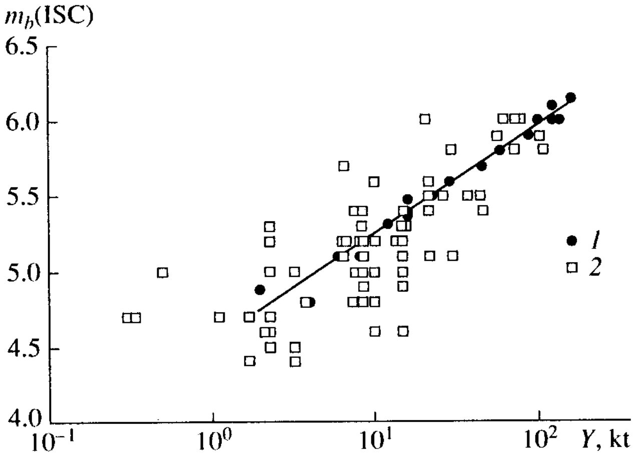

Fig. 2. The magnitude m_b (ISC) versus $\log Y$ (kt) for (*1*) KTS UNEs and (2) PNEs detonated within the territory of the former USSR.

Plotnikova *et al.* [1994] supposed that development of the Gazli gas field gave rise to two strong earthquakes with $M = 7$ (K = 17) in 1976 and 1984 in the region where earthquakes of such an intensity had not been predicted. Here, K is the energy class ($\mathrm{K} = \log E_s$, where E_s is seismic energy in joules).

According to Rautian [1969], the relation between the energy class and magnitude in Central Asia has the form

$$\mathrm{K} = 1.8M + 4.6. \tag{9}$$

Along with the aforementioned factors, the seismicity effect of explosions at distances of 1000–1500 km from the source has been widely discussed recently. Based on experimental estimates, some authors [Nikolaev and Vereshchagina, 1991; Nikolaev, 1994; Tarasov and Tarasova, 1995; and others] arrived at the conclusion that explosions have a triggering effect expressed as a small increase in seismicity at distances of up to 1000–1500 km during the first ten days after the explosion

The hypothesis of the KTS UNE effect on the seismic activity level was tested in the (35°–45° N, 65°–80° E) rectangle using the catalog of Central Asia and Kazakhstan earthquakes. Data on 300 UNEs ($m_b \geq 5$) and about 40000 earthquakes ($\mathrm{K} \geq 9$) over the period from 1962 through 1989 were analyzed.

To select UNE with $m_b \geq 5$, we derived the following relationship between the yield $\log Y$ (kt) and magnitude m_b as estimated at the International Seismological Center (ISC):

$$m_b(\mathrm{ISC}) = 0.72\log Y + 4.52. \tag{10}$$

The UNE yield data published in [Bocharov *et al.*, 1989] were used (Fig. 2).

The above relationship is approximate, because the magnitude m_b reported in the ISC Bulletins is accurate to the first decimal place, and it was not further refined here. However, formula (10) is acceptable for the approximate estimation of the explosion yield.

We also considered the expedience of using peaceful nuclear explosions (PNEs) detonated on the territory of the former USSR. Data on their yield were taken from [Mikhailov, 1997] and, as before, ISC magnitudes were used.

Calculations show that the regression curves obtained for the complete PNE sample (Fig. 2) and KTS UNEs virtually coincide. However, PNEs were detonated in rocks widely varying in their physical and mechanical properties [Sultanov *et al.*, 1999], which results in a wide scatter of points. Because most of these explosions were detonated at great distances from the region under study, their yield was small and the resulting seismic effect was weak, we did not use the PNE data, except for the two most powerful explosions detonated in the Mangyshlak area.

Aftershocks of strong earthquakes in this region were eliminated from the catalog manually by comparing the flux intensity of events after the main shock with the background level observed before it.

The reliable identification of aftershocks is a difficult problem, which is not completely understood. The existing algorithms and software designed for aftershock identification [Molchan and Dmitrieva, 1991; Smirnov, 1997] are based on the analysis of a large volume of information about the source parameters and regional geologic and tectonic conditions and are contingent on the quality of catalogs in use. This primarily refers to the accuracy of the source depth determination. The catalog of Central Asia and Kazakhstan earthquakes, used in our work, does not meet the numerical processing requirements to the source depth accuracy. For this reason, in order to reveal such fine effects as the induced seismicity, we used a simplified manual method for the elimination of intervals containing aftershocks of strong earthquakes from time series analyzed.

In order to assess the possibilities of the formalized aftershock recognition, we made use of the regional catalog of Kazakhstan and Kyrgyzstan earthquakes ($\mathrm{K} \geq 7$) over the period from 1975 through 1996, compiled by N.N. Mikhailova, staff member of the Institute of Seismology, Kazakh Academy of Sciences, and the Schmidt United Institute of Physics of the Earth, Russian Academy of Sciences.

Aftershocks of $\mathrm{K} \geq 10$ earthquakes were removed from this catalog by G.A. Sobolev. Since no earthquakes with $\mathrm{K} > 15$ occurred in this region during the aforementioned time period; only 16 earthquakes with $\mathrm{K} \geq 10$ accompanied by aftershocks were selected.

The total number of aftershocks per day during the first week after the main shock of each of the 16 earthquakes and the same parameter for aftershocks with

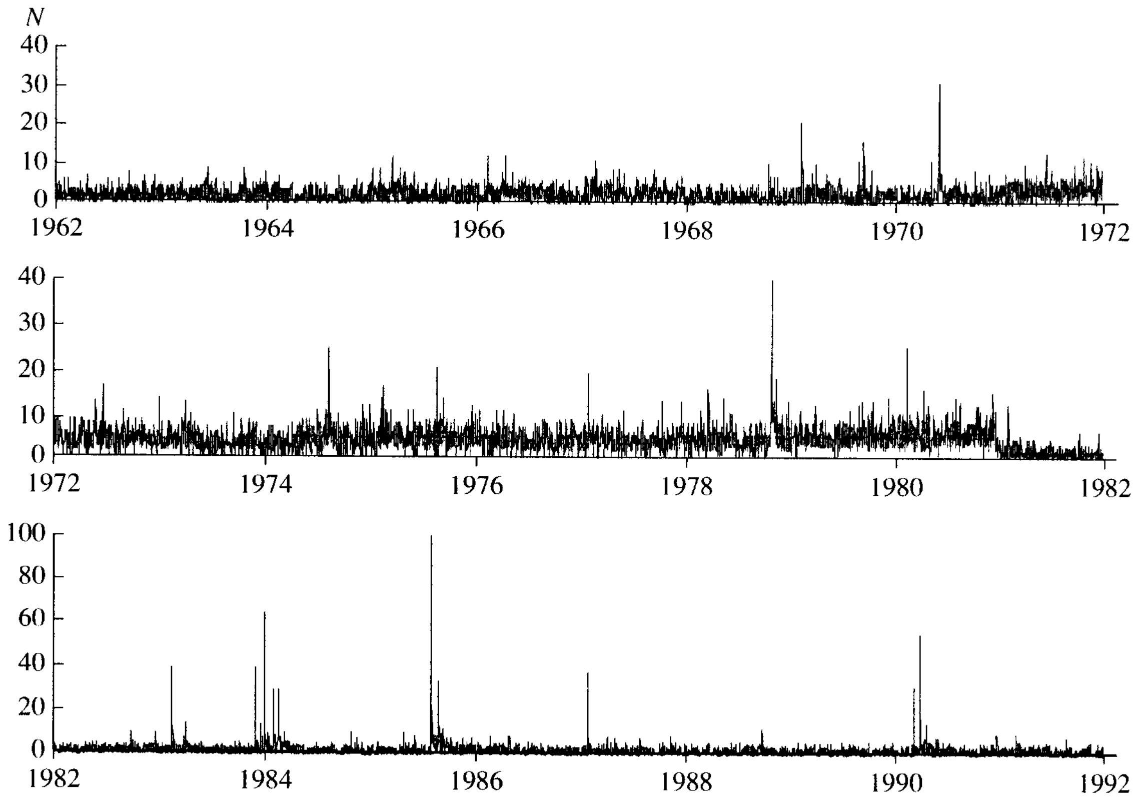

Fig. 3. Variations in the daily seismic activity in the study region for earthquakes with K ≥ 9 (1962–1980) and K ≥ 10 (1981–1991).

K ≥ 9 are characterized in the table of Appendix. It is easily seen that most aftershocks with K ≥ 9 occurred during the first few days after main shocks having K = 15, and they were virtually absent if the main shock had K < 15.

Since we used the catalog of K > 9 earthquakes, aftershocks of K = 15–17 earthquakes in the Central Asia and Kazakhstan region should be bounded by a few days after the main shock, implying that the manual method of the aftershock elimination is acceptable.

On the whole, considering that the time intervals under study should have included aftershocks of strong earthquakes, only 198 explosions (143 over the period from 1962 through 1980 and 55 over the period from 1981 through 1989) were analyzed. Overall, 22191 earthquakes (18536 with K ≥ 9 over the period from 1962 through 1980 and 3404 over the period from 1981 through 1989, when the catalog included K ≥ 10 earthquakes) were sampled by a 31-day time window.

Figure 3 shows the variation in the number of earthquakes per day in this region over the entire period from 1962 through 1991. A total of 37155 earthquakes were considered.

The variation in the number of earthquakes per day over 1970 is shown in Fig. 4 (a total of 1076 earthquakes). Arrows show the explosion detonation and earthquake occurrence times. An M = 5.7 KTS UNE was detonated on June 28, 1970, and two M = 6.0 PNEs were detonated on December 12 and 23, 1970, in the Mangyshlak area.

The only strong earthquake recorded in 1970 was the Central Tien Shan, June 5, 1970, earthquake (T_0 = 04:53:05; 42.48° N, 78.89° E; H = 12 km, M = 6.8, K = 15), which was followed by an aftershock sequence. Also, a small increase in the seismic activity was observed after the South Pamirs, May 9, 1970, earthquake (T_0 = 10:01:59; 38.3° N, 73.5° E; H = 140 km, M = 3.9).

The yearly average numbers of earthquakes per day (N_{av}) and their standard deviations (σ) in the study region over the period from 1962 through 1991 are presented in Table 3. These calculations were made without the elimination of aftershocks, which has resulted in somewhat overestimated values. Thus, if aftershocks were eliminated, the average level of the background seismicity N_{av} would be 2.7 earthquakes per day with σ = 1.8 (tabulated values of N_{av} and σ are 2.9 and 2.5, respectively).

The above data show that the yearly average number of earthquakes is a stable quantity exhibiting small-amplitude long-period smooth temporal variations. It is known that variations of this type correlate with the periodicity of temporal variations in kinematic and dynamic parameters of seismic waves and are related to geodynamic processes in the region [Gamburtseva *et al.*, 1988].

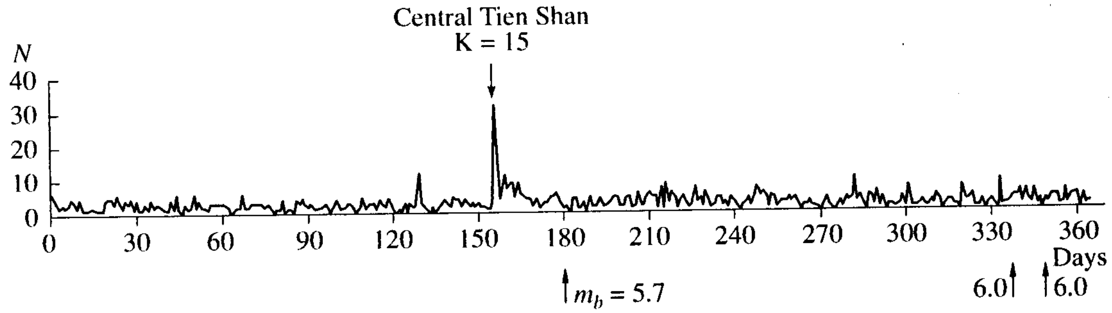

Fig. 4. Variations in the daily seismic activity in 1970. The time moments and magnitudes of a KTS UNE and two Mangyshlak PNEs, as well as the occurrence time and energy class of a Tien Shan earthquake, are shown.

However, the number of earthquakes per day varies strongly throughout a year. These variations do not allow one to reveal significant variations in the natural seismic activity by direct comparison of explosion time moments with the seismicity level variations observed during a few days after an explosion. Kitov *et al.* [1992] arrived at the same conclusion by analyzing the effect of an individual chemical underground explosion on the seismic process of the tectonic energy release in a region adjoining the explosion epicenter. In this connection, we applied the method described by Tarasov and Tarasova [1995] to the analysis of the UNE effect on seismicity.

Within the framework of this method, ±40-day intervals centered at the explosion time moment were used for the analysis of seismicity variations. The pertinent procedure consisted in the calculation of the average number of earthquakes per day (N_{av}) over a 40-day interval before each explosion, and all values of n_i over the common 81-day interval were normalized to N_{av}. The resulting normalized values n_i/N_{av} were averaged over the number of UNEs considered.

Table 3. Variations in the yearly average number of earthquakes per day in the Central Asia and Kazakhstan region over the period from 1962 through 1992

Year	N_{av}	σ	Year	N_{av}	σ	Year	N_{av}	σ
1962	2.5	1.7	1972	4.5	2.2	1982	2.0	1.5
1963	2.6	1.8	1973	4.1	2.2	1983	2.1	1.7
1964	2.2	1.6	1974	4.4	2.4	1984	2.0	1.5
1965	2.9	1.9	1975	4.8	2.2	1985	2.4	1.8
1966	3.1	1.8	1976	4.7	2.3	1986	2.2	1.6
1967	3.6	2.0	1977	4.3	2.2	1987	2.2	1.6
1968	2.3	1.5	1978	4.6	2.3	1988	2.1	1.5
1969	2.7	1.9	1979	5.6	2.4	1989	1.8	1.2
1970	2.7	1.8	1980	6.3	2.7	1990	2.3	1.7
1971	4.2	2.1	1981	1.8	1.4	1991	2.0	1.6

Analysis of large temporal series involves methodological problems related to the choice of parameters characterizing the seismicity level, statistical distribution law describing these parameters, and time interval adequate to the search for significant post-UNE variations in seismicity.

We suppose that variations in seismic activity induced by explosions should be sought within a few days after the UNE, because it is not clear which criteria should be applied in order to relate intervals remote in time to this effect. In view of these, we chose a somewhat conservative ±15-day interval centered at the explosion time moment.

The following parameters characterizing temporal seismicity variations were considered:

$q_i = n_i/N_{av}$, the number of earthquakes per day normalized to the average number of earthquakes over an N-day interval before an explosion;

$z_i = (n_i - N_{av})/\sigma$, the relative number of earthquakes per day that centers a sample at a zero average, i.e., the parameter used in the normalized normal distribution $N(z; 0; 1)$.

Figure 5 shows the daily histograms of q_i calculated in intervals of 15 days before (Fig. 5a) and after (Fig. 5b) the zeroth (detonation) day. Each histogram was obtained by averaging data over 143 explosions detonated from 1962 through 1980, but the actual number of earthquakes in such 31-day intervals varied from 134 to 141 due to the elimination of intervals containing aftershocks of strong earthquakes. These histograms slightly vary in shape and position of the distribution maximum. To a varying extent, each histogram is characterized by a positive asymmetry and an excess much smaller than 3 (the excess of the normal distribution is about 3, and the coefficient of asymmetry lies within ±0.5).

The analysis of z_i histograms showed that they are also similar in shape and position of maximum. The histograms of the zeroth and subsequent 15 days insignificantly differ in shape from the histograms of the days preceding explosions. For this reason, Fig. 6 presents average histograms over intervals of 15 days

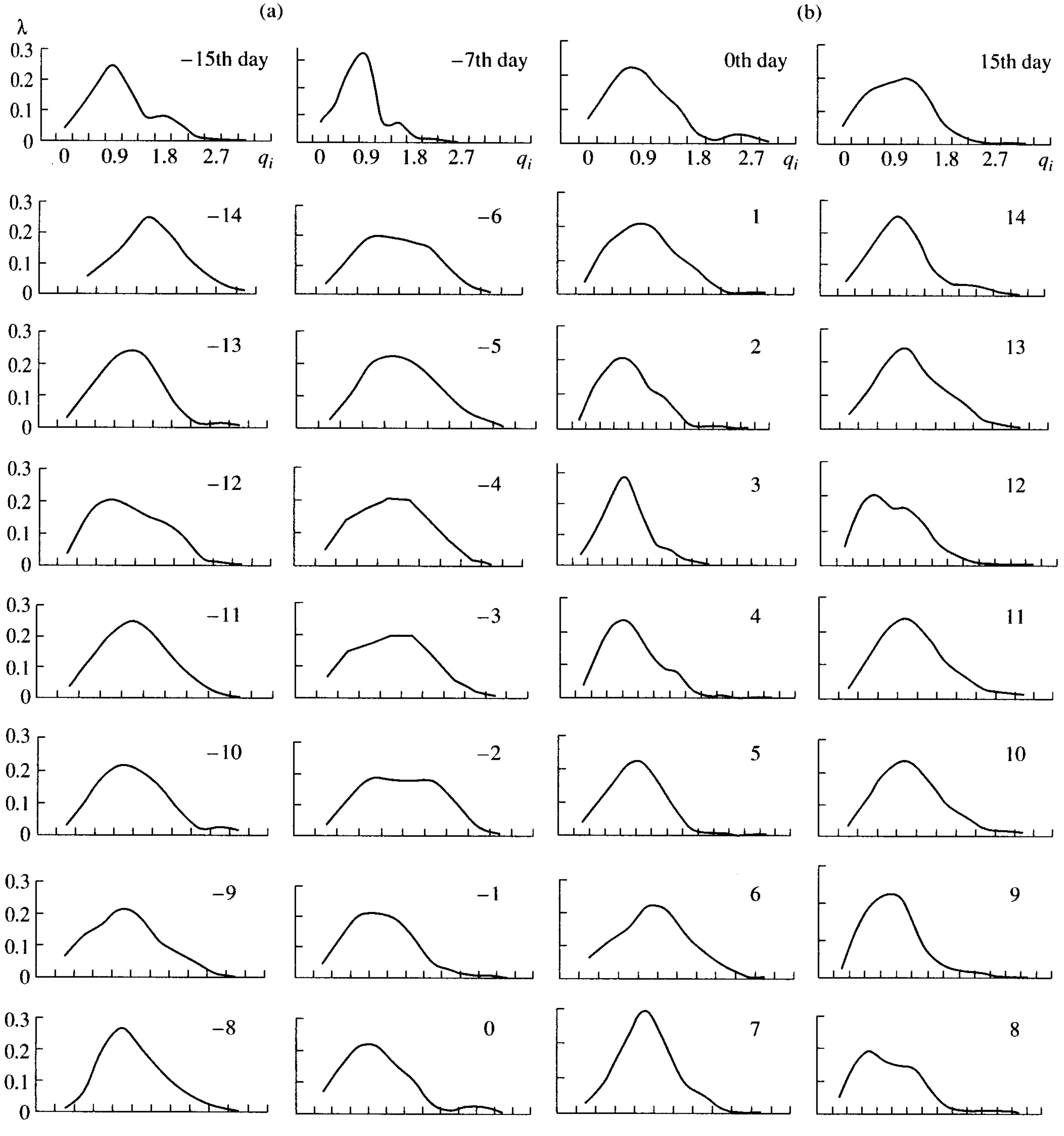

Fig. 5. Histograms of normalized number of earthquakes per day ($q_i = n_i/N_{av}$) on each day of (a) pre- and (b) postexplosion 15-day intervals, averaged over 143 explosions of the period from 1962 through 1980.

before (Fig. 6a) and after (Fig. 6b) explosions only for the parameter z_i.

Table 4 presents main statistical characteristics of q_i and z_i (N, X_{av}, σ, excess, and asymmetry estimated from the total dataset, and from its samples before and after explosion).

As seen from Table 4,the parameter z_i is close to the normal distribution $N(z, X_{av}, \sigma)$, because it has $X_{av} \approx 0$ and $\sigma \approx 1$, and the values of excess and asymmetry differ only slightly from the normal law values.

An important advantage of the parameter z_i consists in that it allows the joint analysis of samples with dif-

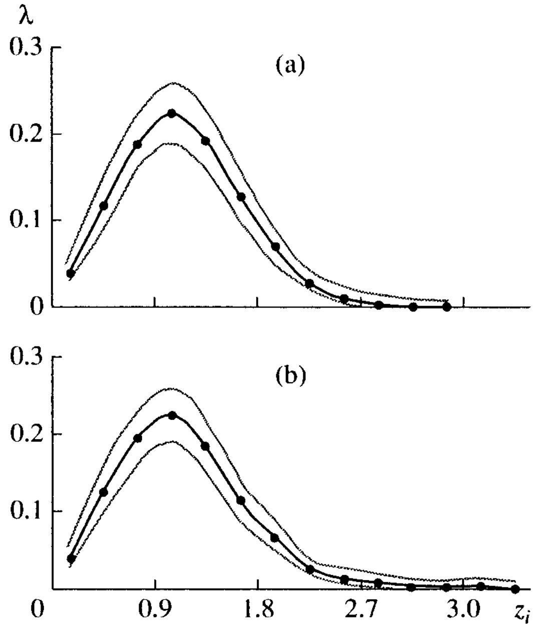

Fig. 6. Histograms of the normalized number of earthquakes per day ($z_i = (n_i - N_{av})/\sigma$) averaged over 15 days (a) before and (b) after explosion and using data of 143 explosion detonated over the period from 1962 through 1980. Confidence intervals on a 99% level ±3σ are shown.

ferent initial values of n_i and σ; however, the use of the parameter q_i is also admissible.

Figure 7 plots q_i variations over the whole ±15-day interval calculated from data recorded in periods of (a) 1962–1980 and (b) 1981–1989; the zero day is shown by an arrow.

Figure 8 presents similar plots of z_i calculated from data over periods of 1962–1980 (a) and 1981–1989 (b), as well as over the entire study period from 1962 through 1989 (c), because the parameter z_i allows such a procedure of data combination.

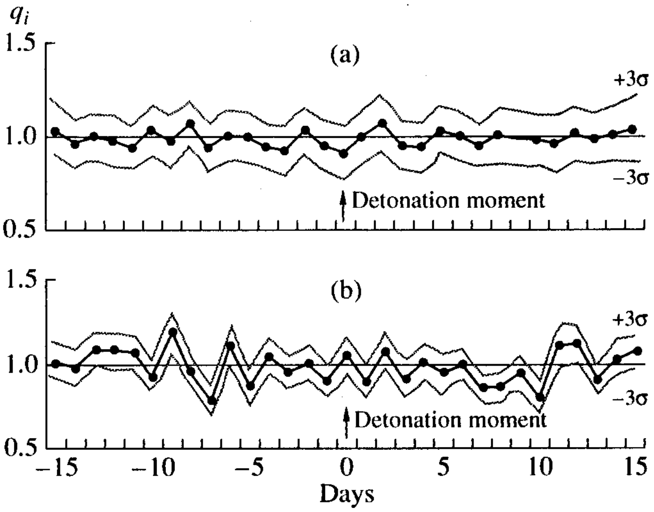

Fig. 7. Variations in the parameter q_i over a ±15-day interval centered at the explosion day (0th day in the figure) based on data samples covering the periods (a) from 1962 through 1980 and (b) from 1981 through 1989. The broken lines show confidence intervals of true averages of the parameter q_i on a ±3σ confidence level.

The broken lines in Figs. 6–8 show intervals of true averages on a 99% confidence level (±3σ).

Comparison of plots presented in Figs. 7 and 8 shows that, within a 99% confidence interval, the daily average seismic activity of K ≥ 9 earthquakes in the Central Asia and Kazakhstan region determined from all data on KTS UNEs over the period from 1962 through 1989 does not allow any reliable discrimination between 15-day intervals preceding and following the explosion.

This result agrees with the above estimates, according to which the total energy flux from all UNEs detonated at KTS over the 30-year period under study is

Table 4. Statistical characteristics of histograms of the parameters q_i, h_i, and z_i based on data samples from the catalog of Central Asia and Kazakhstan earthquakes over the period from 1962 through 1989 (K ≥ 9)

Parameter	Sample	N	X_{av}	σ	Excess	Asymmetry
n_i	Before UNE	2058	4.9	11.5		
	After UNE	2206	4.8	11.5		
	Total	4264	4.8	11.5	1.6	0.1
$q_i = n_i/N_{av}$	Before UNE	2058	0.99	0.51		
	After UNE	2206	0.93	0.58		
	Total	4264	0.96	0.55	1.9	0.7
$z_i = (n_i - N_{av})/\sigma$	Before UNE	2058	−0.03	0.96		
	After UNE	2206	−0.06	1.10		
	Total	4264	−0.05	1.03	2.7	1.1

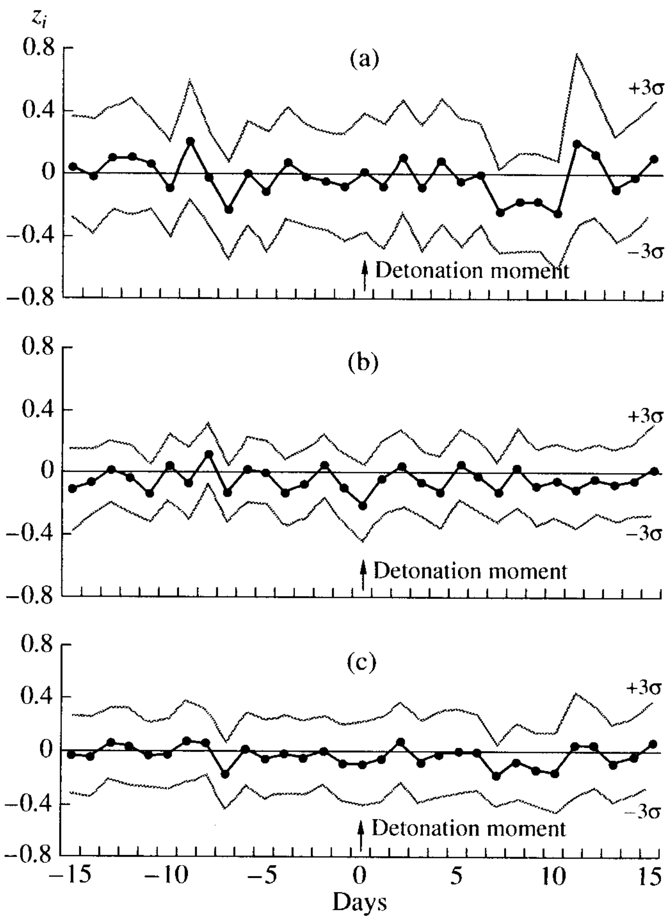

Fig. 8. Variations in the parameter z_i over a ±15-day interval centered at the explosion day (0th day in the figure) based on data samples covering the periods (a) from 1962 through 1980 and (b) from 1981 through 1989 and (c) the entire period studied (from 1962 through 1989). The broken lines show confidence intervals of true averages of the parameter z_i on a ±3σ level.

much smaller than the critical strain energy in the crust leading to fracture.

Apparently, data from catalogs of comparatively strong earthquakes ($K \geq 9$) fail to resolve fine effects of induced seismicity, if these take place.

We should note that Tarasov and Tarasova [1995] discovered the effect of explosions on seismicity from samples of both weak ($K \geq 3$) and strong ($K \geq 10$) earthquakes that occurred in a small region near the town of Garm whose area is 1% of that of the Central Asia and Kazakhstan region considered in this work. With regard to strong earthquakes, their result was not confirmed by the data of our work. However, there is no reason to believe that the size difference between the territories studied could be disadvantageous to the effectiveness of recognition of an increase in seismic activity after KTS explosions. Rather, the analysis of the entire territory of the Central Asia and Kazakhstan region decreased the probability to miss a postexplosion rise in activity, if this took place.

Thus, based on the above data, we can conclude that the long series of explosions detonated at KTS from 1962 through 1989 had no substantial effect on the seismicity pattern in the Central Asia and Kazakhstan region, at least with regard to $K \geq 9$ earthquakes. Moreover, throughout the study period of observations, no strong earthquakes that could be related to explosions occurred within a few days after any KTS explosion.

In this work, we did not consider finer effects of explosions on natural seismicity because this analysis requires special monitoring of weak seismicity ($K \ll 9$).

CONCLUSION

The seismic activity in a Central Asia and Kazakhstan region over the period from 1962 through 1989 was analyzed in this work in order to estimate the KTS UNE effect on the seismic activity level and to elucidate whether some of these explosions led to a strong earthquake.

The estimates obtained in this work show that the seismic flux through the unit volume of the medium induced by a 150-kt KTS UNE in the seismically active zone of Central Asia and Kazakhstan at a distance of 1000 km from KTS is of the order of 3.4×10^{-7} erg/cm^3, i.e., about ten orders of magnitude smaller than the critical strain energy.

The total seismic energy of all the 338 KTS UNEs detonated from 1962 through 1989 is $\sim 3.3 \times 10^{22}$ erg, which corresponds to a total energy flux through the unit volume of $\sim 6 \times 10^{-5}$ erg/cm^3. Some 300 KTS UNEs ($m_b \geq 5$) and 40000 earthquakes of $K \geq 9$ energy classes were analyzed.

The analysis was conducted by the method used in [Tarasov and Tarasova, 1995], according to which seismicity data in the region under study are summed in a given postexplosion time interval over all explosions under consideration.

A ±15-day window was chosen in this work, and temporal variations in seismicity were characterized by the normalized relative number of earthquakes per day $z_i = (n_i - N_{av})/\sigma$ centering a sample at the zero average. An important advantage of the parameter z_i consists in that it allows the joint analysis of samples with different values of standard deviation (σ) and N_{av}.

The analysis of the parameter z_i using the total sample of data showed that explosions insignificantly affect the seismicity level, at least in relation to $K \geq 9$ earthquakes. No strong disastrous earthquake was recorded in the first postexplosion days.

Fine effects of explosions on the natural seismicity were not discussed in this paper, because their analysis requires data on weak seismicity ($K \ll 9$).

APPENDIX.

Earthquake parameters and the number of aftershocks per day over the first week after the main shock identified numerically on the basis of Kyrgyzstan catalog over the period from 1975 through 1996 (K ≥ 7)

Parameters of the main shock			Number of aftershocks per day (including those with K > 9) over the first week after the main shock													
			1st day		2nd day		3rd day		4th day		5th day		6th day		7th day	
Data	H, km	K	total	K ≥ 9	total	K ≥ 9	total	K ≥ 9	total	K ≥ 9	total	K ≥ 9	total	K ≥ 9	total	K ≥ 9
February 12, 1975	23	12.6	3	–	3	3	–	–	–	–	1	1	–	–	1	–
March 24, 1978	15	15.0	13	6	31	9	15	7	4	1	4	–	2	–	4	1
April 6, 1979	25	13.3	12	4	4	1	–	–	–	–	–	–	–	–	–	–
November 10, 1982	–	11.1	3	–	–	–	1	–	–	–	1	–	–	–	1	–
March 24, 1985	15	11.0	5	–	3	–	2	–	–	–	–	1	1	–	–	–
February 14, 1986	20	12.7	1	–	–	–	–	–	–	–	–	–	1	–	–	–
January 24, 1987	–	15.3	165	63	77	28	34	8	32	6	20	6	10	1	8	4
June 1, 1987	15	10.9	12	2	2	–	–	–	–	–	1	–	–	–	1	–
March 13, 1988	8	11.8	–	–	–	–	–	1	–	–	–	–	–	1	–	–
September 29, 1990	–	10.6	3	–	2	–	4	2	1	1	–	–	–	–	–	–
November 12, 1990	20	15.3	32	1	10	–	6	–	7	–	4	–	–	–	5	–
July 24, 1991	15	11.4	5	–	–	–	1	–	–	–	–	–	1	–	–	–
December 30, 1993	20	15.0	31	3	9	–	7	–	3	–	2	2	–	–	1	–
November 1, 1995	–	13.1	6	1	–	–	–	–	1	–	–	–	–	–	–	–
January 18, 1996	5	13.2	1	–	–	–	–	–	–	–	–	–	–	–	–	–
December 16, 1996	20	12.2	1	–	1	1	1	–	1	–	1	–	1	–	1	–

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