Izvestiya, Physics of the Solid Earth, Vol. 37, No. 11, 2001, pp. 928–941. Translated from Fizika Zemli, No. 11, 2001, pp. 73–86.

Space–Time Variations in the Attenuation Field Structure of *S* Waves at the Semipalatinsk Test Site

Yu. F. Kopnichev and I. N. Sokolova

Schmidt United Institute of Physics of the Earth, Russian Academy of Sciences, Bol'shaya Gruzinskaya ul. 10, Moscow, 123810 Russia

Received January 25, 2001

Abstract—The attenuation field structure of the Earth's crust and upper mantle in the Degelen and Balapan areas is studied using near-station records of calibration chemical explosions at the Semipalatinsk test site (STS) obtained by near stations. The characteristics of the envelope curves of the short-period coda are analyzed at frequencies of 1.25 and 5 Hz. Abnormally strong attenuation of *S* waves is observed at depths of 10 to 120 km in the Balapan area, where two large fault zones are located. The attenuation in the Degelen area is much weaker at these depths. The *Q* factor sharply increases at depths greater than 200 km in the test site region. The time variations of the amplitude ratio of Lg and Pg waves are studied from the records of more than 260 underground nuclear explosions obtained at the North Tien Shan TLG station located at epicentral distances of 730–770 km. Variations in this parameter with time are shown to be significantly different in the Murzhik, Degelen, and Balapan areas. An abrupt increase in the *S* wave attenuation in the crust is established from records of explosions detonated at the Balapan area in the 1980s. The time–space variations in the attenuation field structure are presumably associated with the ascent of juvenile fluids through large fault zones due to the long-term strong effect of high-yield explosions. Such a mechanism can also account for the existence of a large thermal anomaly in the northeastern Kazakhstan region including STS.

INTRODUCTION

The detonation of underground nuclear explosions (UNEs) results in a significant restructuring of the medium in the immediate vicinity of sources: cavities and fractured zones form, and the groundwater level noticeably changes. On the other hand, until now little has been known about possible structural changes at comparatively large depths in the crust and particularly in the upper mantle. In this work, the time-space variations of the *S* wave attenuation in the northeastern Kazakhstan region including the Semipalatinsk nuclear test site (STS) are examined.

From 1949 through 1989, 466 nuclear tests, including 30 surface, 88 atmospheric, and 348 underground nuclear explosions, were conducted at STS [Mikhailov, 1996]. The UNEs were detonated from 1961, and their maximum yield was about 150 kt of the TNT equivalent. With regard to the number of tests, STS is second only to the Nevada test site. In this connection, the STS region is a unique natural laboratory for studying the effects caused by a strong and relatively long-term anthropogenic effect on the geological medium in a tectonically quiet region.

GEOLOGICAL AND GEOPHYSICAL CHARACTERISTICS OF STS

The STS is located at the northeastern margin of the vast Kazakh platform. Its territory coincides with the junction area of two large regional structures, namely, the Caledonian Chingiz-Tarbagatai and Hercynian Irtysh-Zaisan structures. The Kalba-Chingiz deep fault, which is actually an area of intense tectonic movements active throughout the geological history, separates these structures.

This region is characterized by a wide development of intrusive magmatism. Intrusive rocks are represented by a wide spectrum of igneous varieties ranging in composition from ultrabasic rocks to alkalic granitoids. The Paleozoic basement in most of the territory of the test site is overlain by a comparatively thin cover of Paleogene and younger sedimentary rocks. Their maximum thickness attains a few hundreds of meters.

The majority of the STS UNEs were detonated in the Degelen (over 200 explosions) and Balapan (over 100 explosions) areas. In addition, 25 explosions were detonated in the Murzhik area [Mikhailov, 1996] (Fig. 1). The charges were placed in tunnels driven in a rock mass in the Degelen area and in boreholes drilled below the thin sedimentary cover in the two other areas.

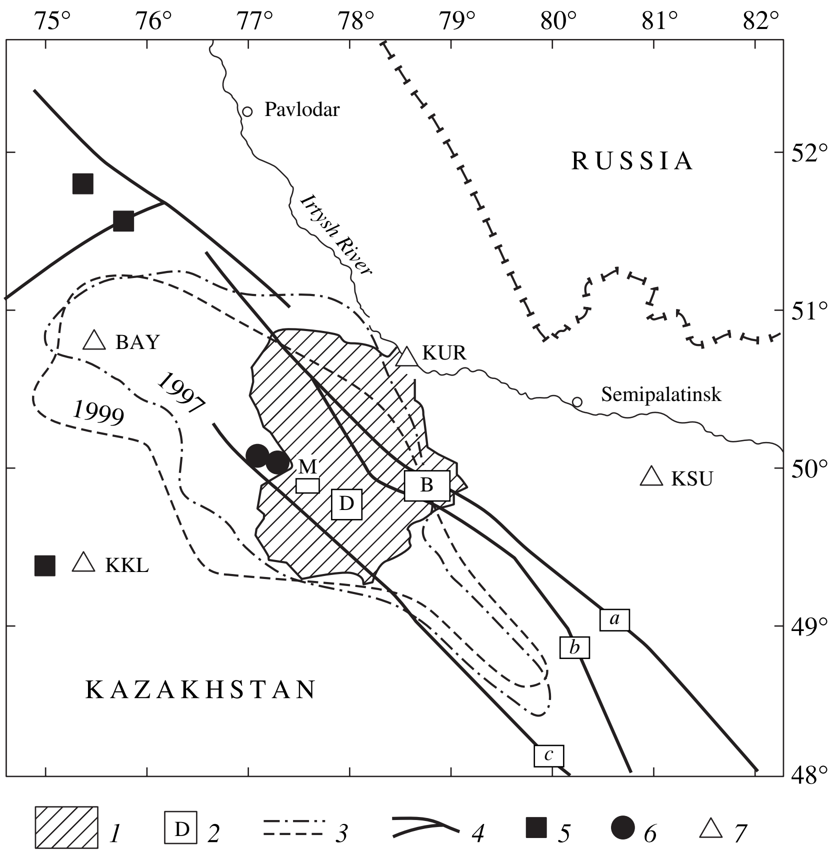

Fig. 1. Map of the study region: (*1*) STS; (*2*) STS areas: M, Murzhik, D Degelen, B Balapan; (*3*) boundaries of the temperature anomaly in 1997 and 1999; (*4*) main fault zones: (*a*) Chinrau, (*b*) Kalba-Chingiz, (*c*) Main Chingiz; (*5*) largest quarries in the vicinity of STS; (*6*) epicenters of local earthquakes; (*7*) seismic stations.

From 1976, nearly all large (over 20 kt) explosions were detonated in the Balapan area.

It is significant that the Balapan area includes the large Kalba-Chingiz and Chinrau faults [Peive and Mossakovskii, 1982], reaching Moho according to geophysical data (Fig. 1). Small fractures have only been recognized in the Degelen and Murzhik areas [Peive and Mossakovskii, 1982]. The large Main Chingiz fault is located just south of these areas (Fig. 1).

The average thickness of the STS crust is 44 km [Belyashova *et al.*, 2000].

It is important that, from 1997 to 1999, a relatively large STS-including region of northeastern Kazakhstan was characterized by a very intense thermal anomaly (Fig. 1) [Sultangazin *et al.*, 1998]. The snow cover was absent in this region in winter, and the surface temperature was higher than in the surrounding areas by about 10°C. As is evident from Fig. 1, the area of the thermal anomaly is nearly three times as large as the STS area. The anomaly is asymmetrical and extends in the NW–SE direction; its center is markedly displaced toward the northwest with respect to the STS center.

The present seismic activity of the region is weak. The only known earthquakes that occurred within the STS territory are the March 20, 1976 (m_b = 5.1) and March 26, 1996 (m_b = 4.2) events [Pooley *et al.*, 1983] (Fig. 1).

Various industrial quarries are located in the STS vicinity (within 300 km from the KUR station). Among them, the Ekibastuz and Maikain areas northwest of STS are undoubtedly most distinguished by the intensity of blasting operations (Fig. 1). Comparatively large (a few tens of tons) chemical explosions have often been detonated here until the early 1990s. Relatively large (to 50 t) explosions were regularly detonated during these years at the GOK Karagaily quarry (26 km west from the KKL station). The number and yield of explosions at these and other quarries were considerably reduced in the 1990s.

DATA

We used records of six calibration chemical explosions with yields of up to 100 t, which were detonated

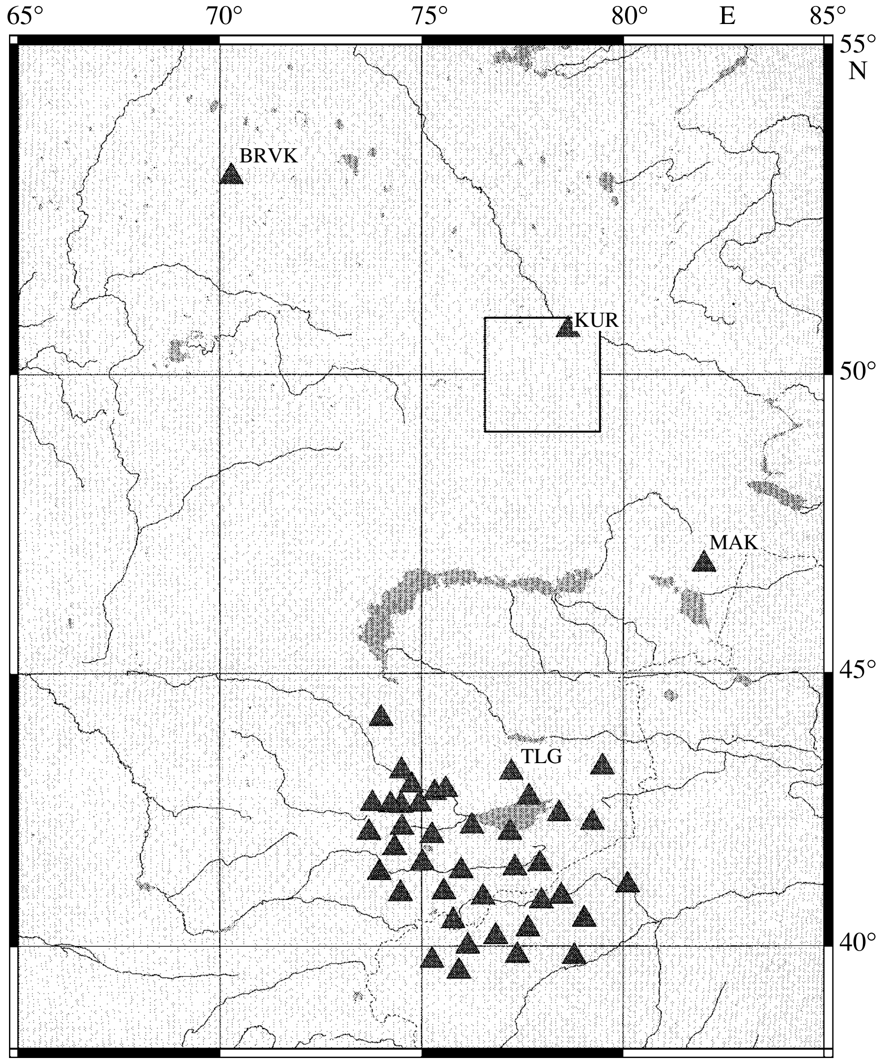

Fig. 2. Location of digital seismic stations whose records were used in this work. The rectangle is STS.

from 1997 to 2000 at STS (see the table) [Belyashova *et al.*, 2000].

The seismograms were obtained at three-component digital REFTEC stations at epicentral distances of up to 250 km. The stations were equipped with the STS-1, STS-2, CMG-3, CMG-40T, K213-S, and L4C seismometers.

Parameters of calibration explosions

Date	Time	Latitu-de, °N	Longi-tude, °E	Charge mass, kg
August 3, 1997	8:07:20.040	49.9412	78.7860	25000
August 31, 1997	7:08:38.750	49.8837	78.8148	25000
August 22, 199	5:00:18.904	49.7667	77.9908	100000
September 17, 1998	7:19:40.551	49.9810	78.7559	25040
September 25, 1999	5:00:05.800	49.7819	77.9663	100000
July 29, 2000	6:10:04.250	49.7819	77.9663	100000

We also used records of three digital stations (BAY, KKL, and KSU; see Fig. 1) equipped with the GS-13 seismometers and installed within the framework of the Soviet–American project on the seismic UNE monitoring in 1987 and 1988 [Nersesov and Sidorin, 1991]. The records of chemical and nuclear calibration STS explosions were analyzed.

In addition, records of 261 UNEs obtained from 1964 through 1989 at the North Tien Shan TLG station at epicentral distances of 730 to 770 km (Fig. 2) were processed. Records of the analog frequency-selective station [Zapol'skii, 1971] (FSS; the vertical channel with a center frequency of 1.25 Hz and a width of 2/3 of octave at a level of 0.7 of the maximum) and the broadband channel SKM-3 (0.7- to 10-Hz bandpass) were analyzed.

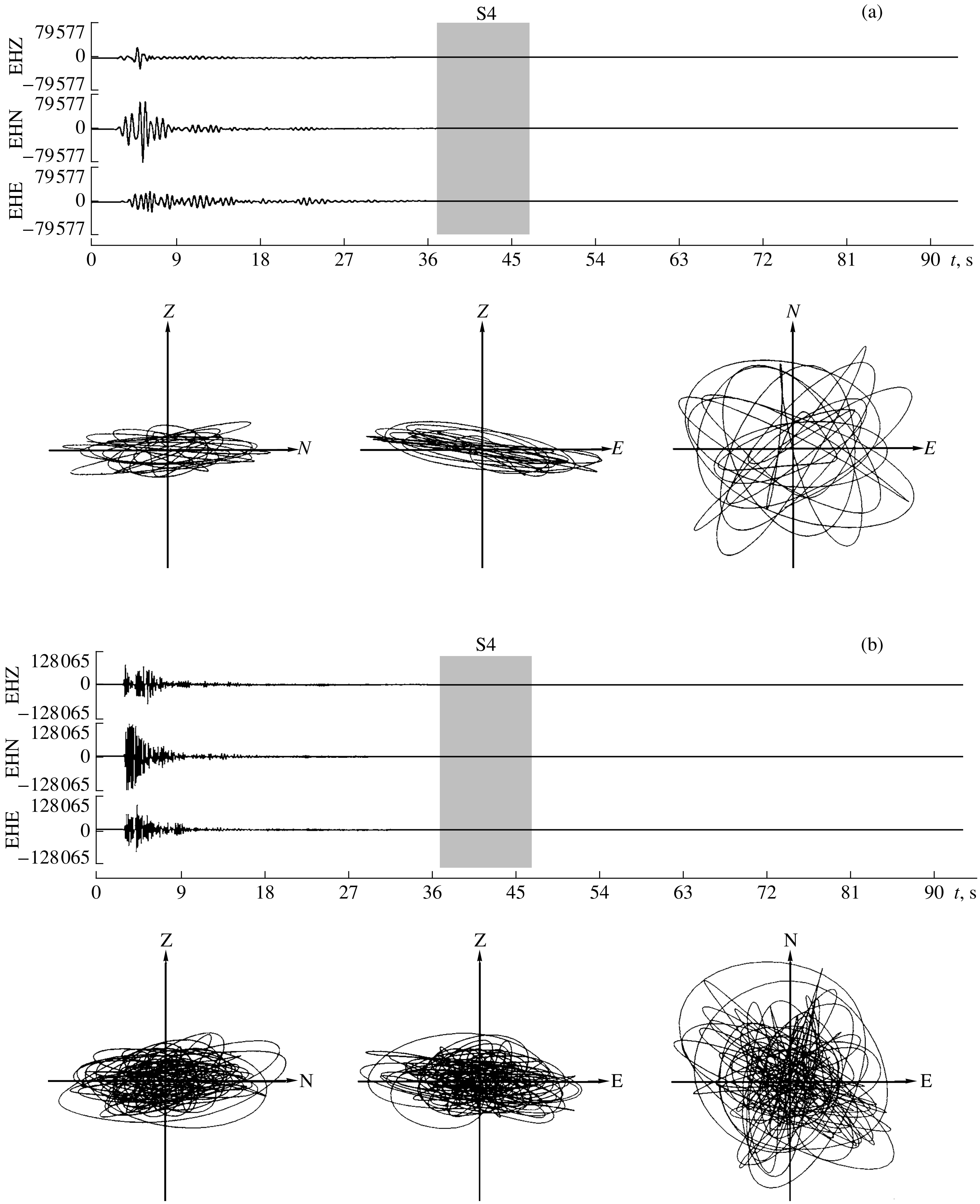

Fig. 3. Polarization characteristics of the record of the Balapan calibration explosion from station 4 (see Fig. 6) with FSS channels: (a) 1.25 Hz; (b) 5 Hz.

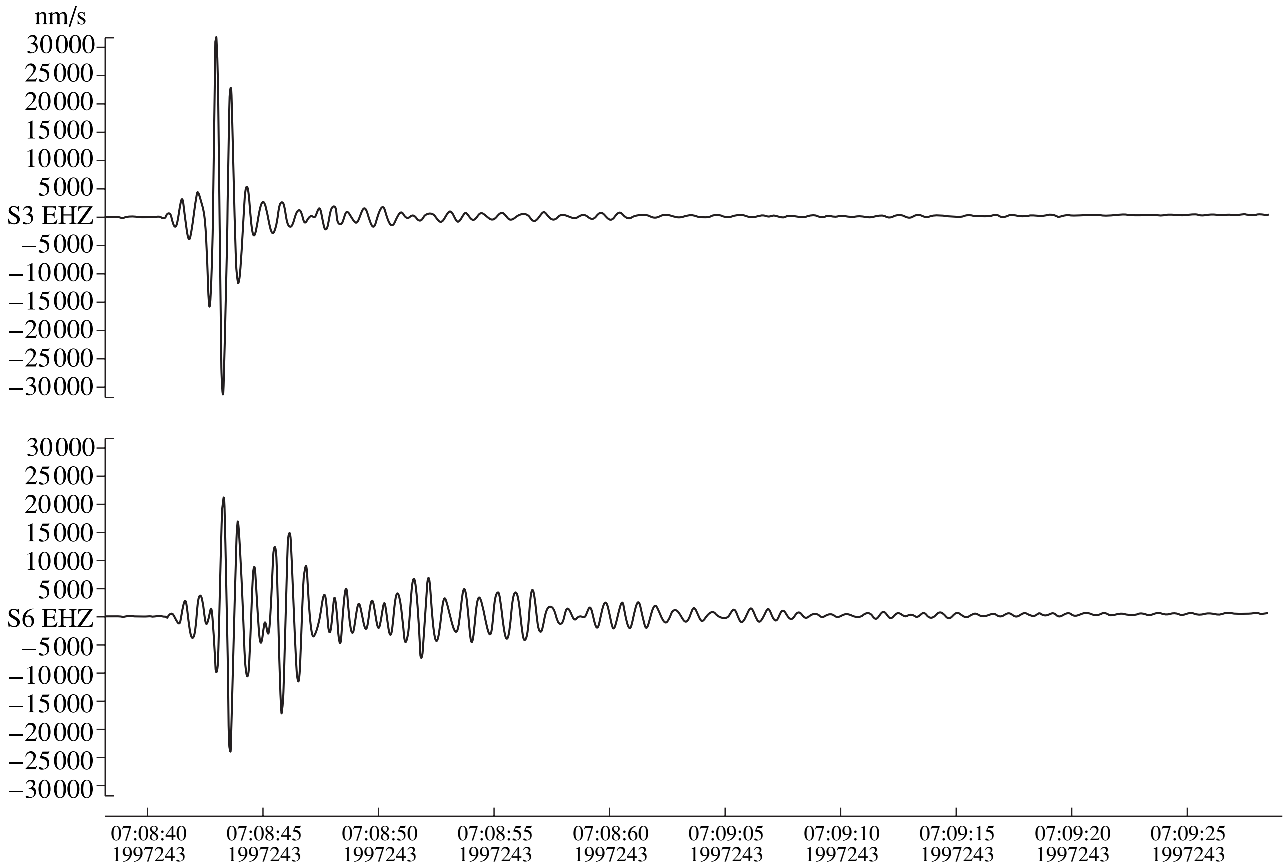

Fig. 4. Examples of vertical component records of a Balapan calibration explosion made at stations 3 and 6 (see Fig. 6) with a 1.25-Hz FSS channel.

Finally, for comparison, records of local earthquakes and quarry blasts obtained at 40 digital REFTEC stations within the Central Tien Shan region and at the BRVK and MAK stations located at the northern and eastern margins of the Kazakh platform were analyzed (Fig. 2). Overall, more than 500 records of explosions and earthquakes were processed.

DATA PROCESSING TECHNIQUE

Analysis of Records from Local Explosions and Earthquakes

The method based on the analysis of the short-period *S*-coda characteristics was used for the interpretation of records from near explosions. The comprehensive analysis of experimental data in Central Asia (arrival direction, apparent velocities, polarization of coda wave groups, space–time characteristics of envelopes, and so on [Kopnichev, 1985; Aptikaeva and Kopnichev, 1993; Kaazik *et al.*, 1990]) showed that, at frequencies of about 1 Hz, the coda of local earthquakes and quarry blasts is mainly formed by *S* waves reflected from numerous subhorizontal interfaces in the crust and upper mantle. (Below, we present additional evidence supporting the validity of this model for the coda of records from STS explosions). Given such a scheme of the coda formation, the intervals of relatively fast and slow amplitude attenuation in the coda are related to the *S* wave penetration into layers of strong and weak attenuation, respectively. The depths of these layers are determined under assumption that the coda is formed by primary reflections. Attenuation was characterized by an effective Q factor Q_S determined from the amplitude attenuation in the coda with the use of the formula: $A(t) \sim \exp(-\pi t/Q_S T)/t$, where T is the period of waves and t is the lapse time [Kopnichev, 1985].

Due to the unique character of the STS area, it is necessary to take into account the possible influence of structural variations in the uppermost part of the cross section on wave fields. For example, it is known that an UNE gives rise to cavities and a fractured zone, with their sizes depending on the detonation yield. However, experimental data show that, even with a yield on the order of 150 kt, the fractured zone radius is only 0.5 km [Adushkin and Spivak, 1993].

The UNE-induced local variation in the groundwater regime in the upper part of the cross section is observed in an area exceeding in linear size the

UNE-induced fractured zone by an order of magnitude. However, this effect lasts for a comparatively short time: the hydrogeological regime is usually recovered a year after a nuclear test [Adushkin and Spivak, 1993].

We should also note that structural variations in the uppermost crust can affect only the general coda level but not the envelope shapes. Therefore, structural variations in the upper part of the STS cross section are not an obstacle to the study of the attenuation field at relatively large depths using the method described above.

Analysis of UNE Records

Using records of the TLG station, we examined the maximum amplitude ratio of Lg and Pg waves ($\log(A_{Lg}/A_{Pg})$) designated for brevity as Lg/Pg. These waves propagate in the crust, and their amplitude ratio serves as a measure of the *S* wave attenuation all along the source-to-station trace.

A narrow-band frequency filtering was used for seismogram processing in order to eliminate from the analysis the effects caused by distinctions between the source radiation spectra of different events, frequency dependence of the effective *Q* factor, and so on [Kopnichev, 1985; Aptikaeva and Kopnichev, 1993]. The filters with center frequencies of 1.25 and 5 Hz and a width of 2/3 of octave at a 0.7 level, similar to the FSS channels, were used. Records of the SKM-3 channel included in the analysis were preliminarily digitized with a frequency of 32 Hz.

ANALYSIS OF THE EXPERIMENTAL DATA

First, we present additional data providing constraints on the origin of the short-period coda in records of STS explosions.

Coda Polarization Characteristics of Explosion Records

Typical examples of the coda polarization from the station-4 record of the August 3, 1997, explosion obtained at an epicentral distance of 7 km are shown in Fig. 3. The record was subjected to preliminary frequency filtering (FSS channels at 1.25 and 5 Hz). It is evident that the coda is dominated by horizontally polarized oscillations in the interval t = 35–45 s. The major-to-minor axis ratio of the polarization ellipse in the Z–E plane γ is greater than 5 at a frequency of 1.25 Hz. The 5-Hz value of γ is considerably smaller but exceeds 2.5 in both vertical planes. A similar structure of records is observed in an interval of at least $t \sim$ 10–100 s at 1.25 Hz and even at shorter times ($t > 5$ s) at a frequency of 5 Hz. Due to weaker scattering of *S* waves in the STS region, the horizontal polarization of the coda is more pronounced and is observed within a wider frequency range than in tectonically active regions [Kopnichev, 1985]. Therefore, the polarization

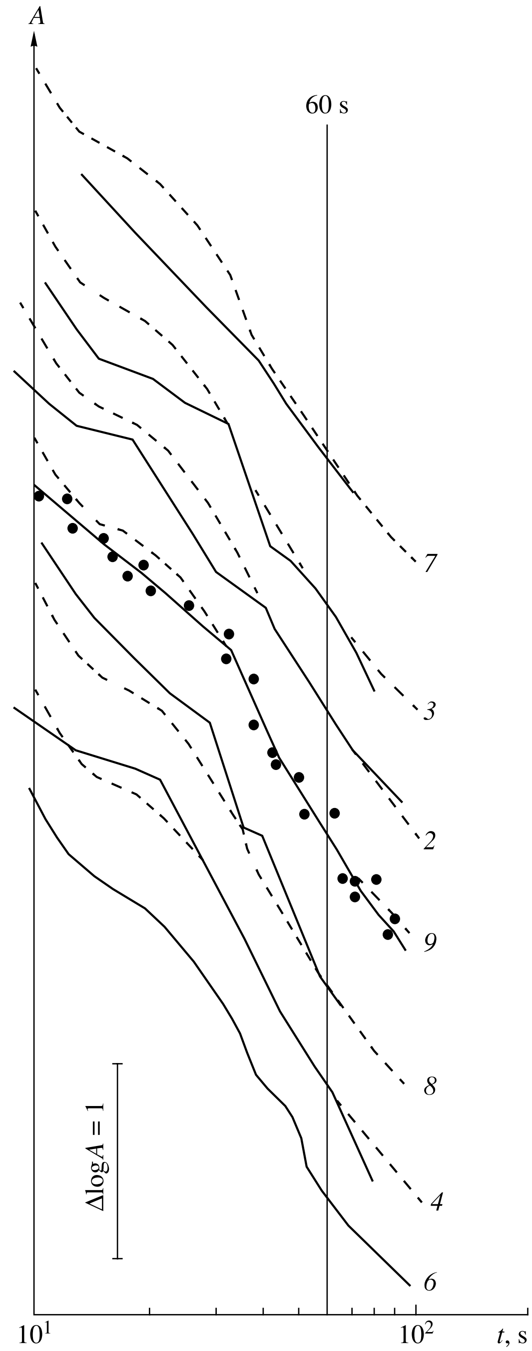

Fig. 5. General coda envelopes from records of Balapan calibration explosions (1.25-Hz FSS channel). Station numbers (see Fig. 6) are shown at respective curves. The broken lines are station-6 coda envelopes. The scatter in envelope data is shown for station 9.

characteristics of the STS records confirm the above conclusion that the short-period coda is formed by reflections of *S* waves from subhorizontal interfaces in the crust and upper mantle. We do not consider here other arguments in favor of this model of the *S* coda formation, which were discussed in detail in [Kopnichev,

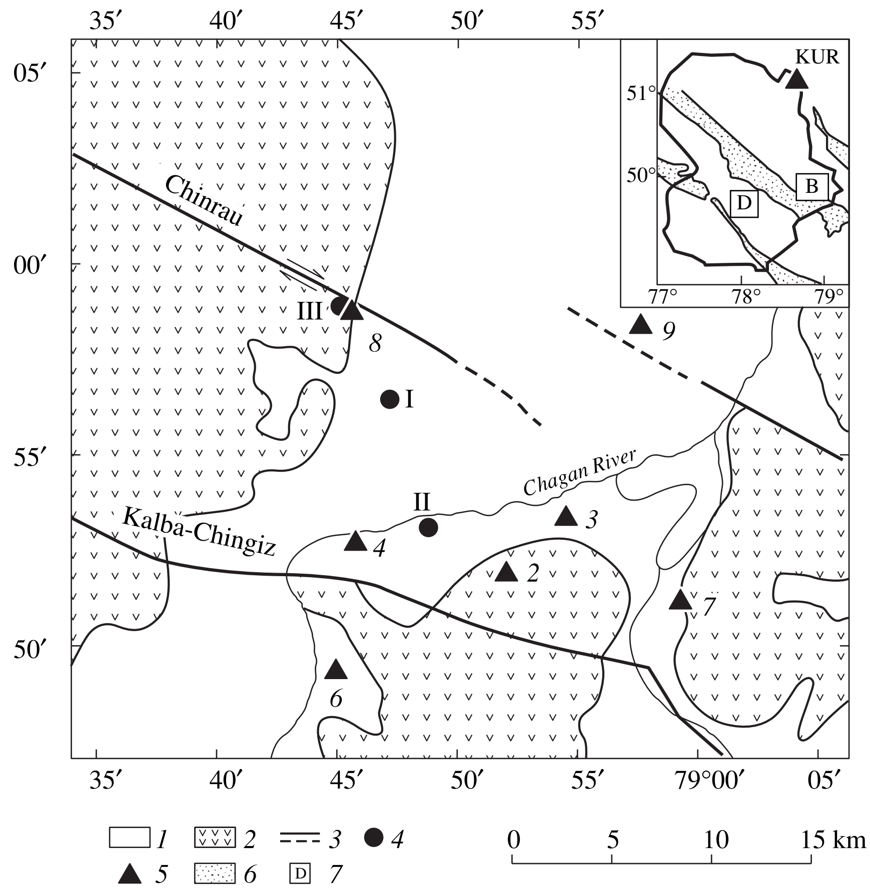

Fig. 6. Map of the Balapan area (modified and complemented after [Ringdal *et al.*, 1992]): (*1*) young sedimentary rocks; (*2*) outcrops of the Paleozoic basement; (*3*) fault zones; (*4*) epicenters of calibration explosions (see the table); (*5*) seismic stations. The inset shows the KUR station, (*6*) anticlinoriums, and (*7*) Degelen (D) and Balapan (B) areas.

1985; Aptikaeva and Kopnichev, 1993; Kaazik *et al.*, 1990].

The Structure of the S wave Attenuation Field in the STS Region

Examples of records from Balapan calibration explosion obtained at various digital stations (1.25-Hz FSS channel) are presented in Fig. 4. The amplitude attenuation rate in the coda is seen to be station dependent.

Coda envelopes were constructed from 1.25- and 5-Hz FSS records of Balapan and Degelen explosions obtained at various stations. Figure 5 shows that the Balapan 1.25-Hz envelope shapes noticeably vary even for stations spaced 6 km apart (nos. 4 and 6 in Fig. 6). The most conspicuous feature of the envelopes is a very rapid attenuation of amplitudes in the interval t = 10–60 s observed in the records of stations located in the close vicinity of deep fault zones (nos. 4, 6, and 8) as distinct from other stations. The only exception seems to be the envelope from station 9, but the fault in the area of this station is identified insufficiently reliably. Within an interval of 20–60 s corresponding to depths of 35–120 km, Q_S (effective Q factor) varies from 55 (station 8) to 115 (station 7).

Figure 7 presents the general coda envelopes from Degelen explosions (Fig. 8). In this case, coda envelopes from various stations in the time interval t = 20–60 s attenuate much weaker compared to the Balapan station 6. The amplitudes in the station-8 coda also decrease much slower in the interval 60–100 s as compared with the Balapan area. Within the range t = 20–60 s, Q_S varies from 85 (station 7) to 110 (stations 1 and 6).

Within an interval of 10–20 s, corresponding to the middle and lower crust (depths of about 20–35 km), the amplitude decrease rate in the coda is rather high (particularly for station 5) and is not lower than in the Balapan area.

For comparison, Fig. 9 shows the scatter range of data for the coda envelopes from local earthquakes and quarry blasts, calculated from the records of 40 digital stations in the Central Tien Shan region bounded by 39–44° N and 73–80° E (Fig. 2). As seen from the figure, if the envelopes are superposed at t = 60 s, all Tien

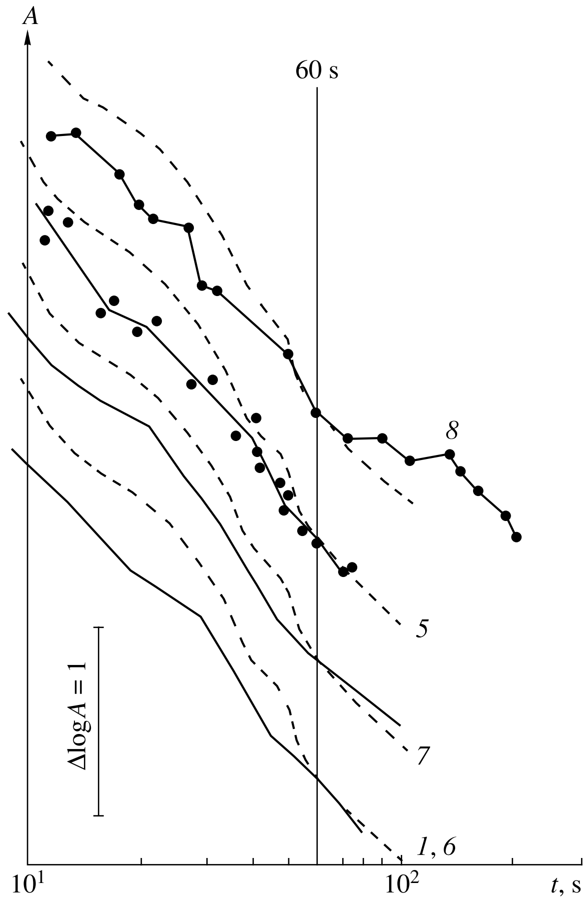

Fig. 7. General coda envelopes from records of Degelen calibration explosions (1.25-Hz FSS channel). Station numbers (see Fig. 8) are shown at respective curves. The broken lines are station-6 coda envelopes (Balapan area, Fig. 5). The scatter in station-5 envelope data is shown. The individual envelope is shown for station 8.

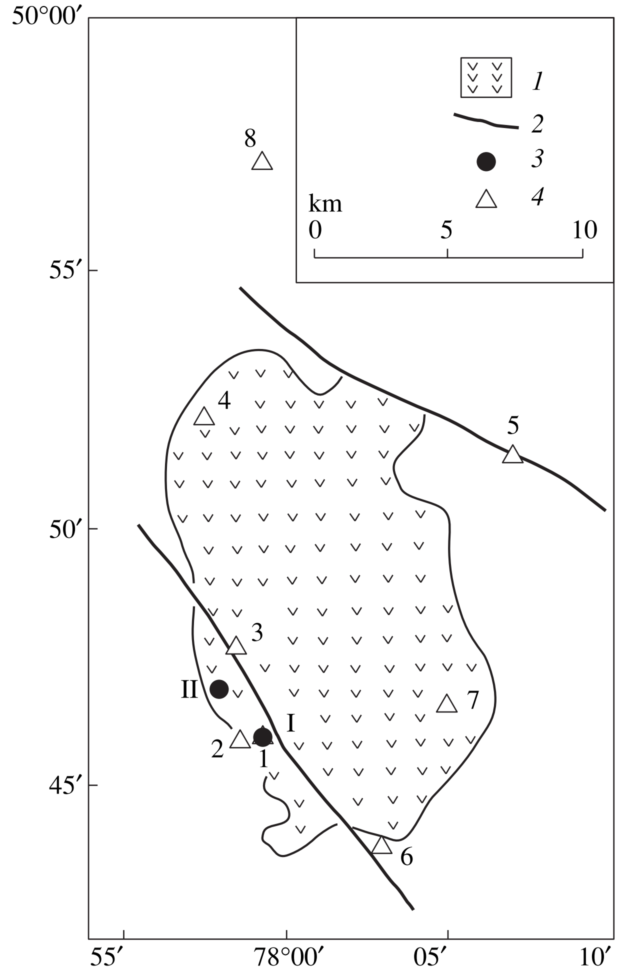

Fig. 8. Map of the Degelen area: (*1*) Degelen massif (Paleozoic rocks); (*2*) faults of the second order; (*3*) epicenters of calibration explosions (two explosions were detonated at point II, see table); (*4*) seismic stations.

Shan envelopes within the interval from 10 to 60 s (depths of about 20 to 120 km) attenuate considerably slower compared to the Balapan station 6.

The same figure shows the data scatter within a range of 100–300 s for the envelopes superposed at t = 100 s (records of 29 digital stations in the same region were used). In this case, the coda in the Central Tien Shan region attenuates, as a rule, stronger compared to the KUR station located ~90 km to the north from the epicenters of the Balapan calibration explosions. The KUR value of Q_S is 2800 within a range of 100–300 s (depths of about 230–700 km).

The coda envelopes constructed from records of the nearest stations ($\Delta < 7$ km) are presented in Fig. 10 for the filter with a center frequency of 5 Hz. At such distances and relatively high frequencies, the coda attenuation can be studied for very short times ($t < 10$ s), corresponding to the upper crust. Figure 10 shows that, similar to a frequency of 1.25 Hz, the Balapan envelopes strongly vary in shape at $t > 10$ s, and the strongest coda attenuation is again observed at station 4 located near the fault zone.

On the contrary, at t = 5–10 s (depths of about 10–20 km), the envelopes are relatively stable in shape, the coda amplitudes attenuate very rapidly, and Q_S is 50. For comparison, Fig. 10 also shows the coda envelope in the Zailiiskii fault zone (North Tien Shan) constructed from the TLG (Δ = 10 km) records of blasts at the small Kotur–Bulak quarry. The S wave attenuation is rather high in this zone. However, as seen from Fig. 10, the 5-Hz coda envelope attenuates considerably weaker compared to the Balapan area (Q_S = 480 in an interval of 5–10 s).

The Degelen coda attenuation at t = 5–10 s is somewhat weaker as compared with the Balapan area (Fig. 10), but Q_S is still small (~80). The envelope shape is very stable compared to the Balapan area.

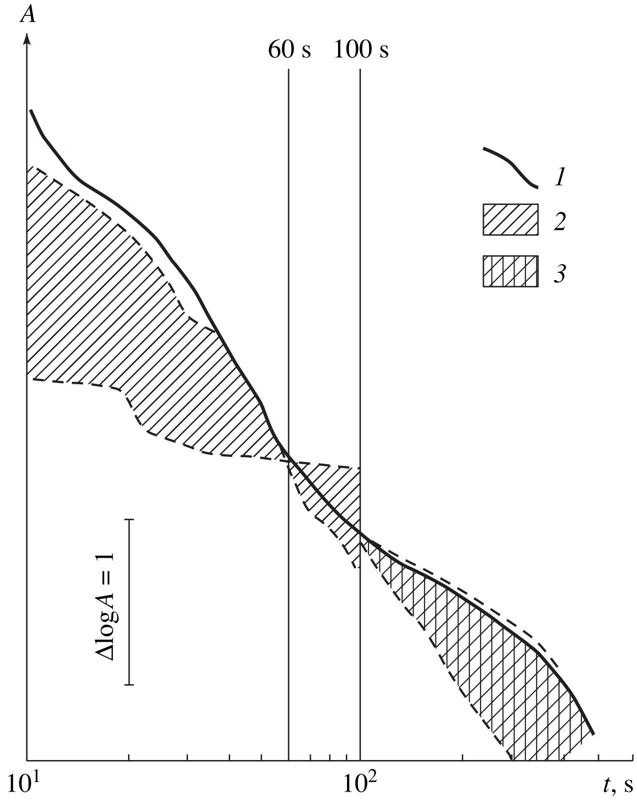

Fig. 9. The data scatter range of coda envelopes constructed from records of 40 digital stations in the Central Tien Shan (Fig. 2): (*1*) coda envelope from records of stations 6 (Balapan) and KUR; (*2*)–(*3*) envelopes are superposed at (*2*) t = 60 s and (*3*) t = 100 s.

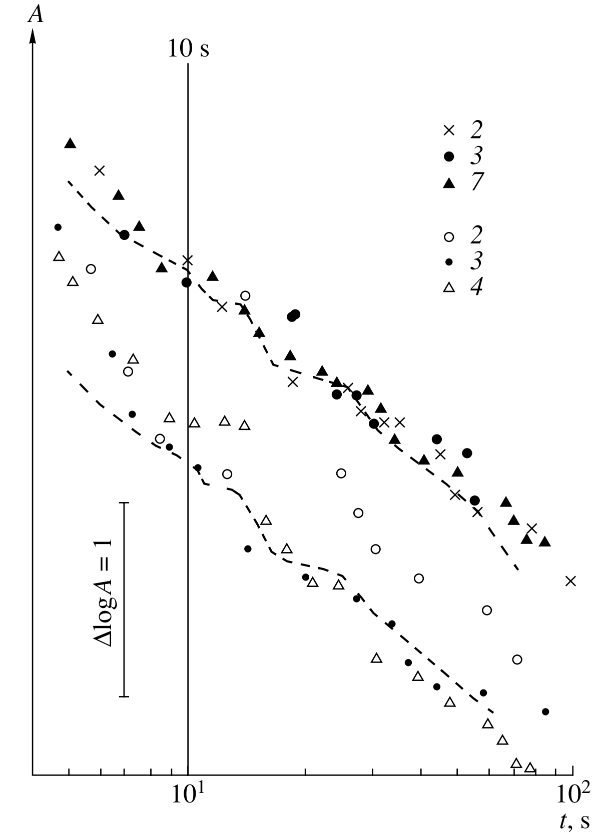

Fig. 10. Coda envelopes for the 5-Hz channel from records of calibration explosions in the Degelen (upper plot) and Balapan areas. Station numbers are shown at respective symbols. The dotted line is the coda envelope for Kotur-Bulak quarry blasts (station TLG, Δ = 10 km).

Thus, the *S* wave attenuation in the crust and upper mantle of the Balapan area was very strong during the period from 1997 through 2000. In contrast, the attenuation is considerably weaker in the Degelen area at depths of 35 to 230 km. Very weak attenuation in the lower part of the upper mantle is characteristic of the whole STS region.

Dimensions of Zones of Abnormally Strong and Weak Attenuation in the Crust and Upper Mantle

We can approximately estimate the dimensions of zones of strong attenuation at depths of up to 120 km in the Balapan area only from records of the nearest stations. The Fresnel zone radius for reflected waves is determined by the formula $R_f = \sqrt{H}\lambda/2$, where H is the reflector depth and λ is the wavelength. Given H = 120 km and λ = 3.8 km, we obtain $R_f \sim 20$ km. Taking into account the distance between stations 6 and 8 yielding strong attenuation in the depth range mentioned above and the position of the calibration explosion epicenters, we find that the maximum linear dimension of the strong attenuation zone is on the order of 50 km. This value is somewhat smaller than the distance between the centers of the Degelen and Balapan areas, sharply differing in the upper mantle (~60 km) attenuation, which indicates that our estimate is realistic.

Figure 11 presents 1.25-Hz coda envelopes for various traces in the STS vicinity constructed from records of calibration explosions detonated in 1987 and 1988 [Nersesov and Sidorin, 1991] and from 1997 through 1999 [Belyashova *et al.*, 2000], as well as from records of local quarry blasts and earthquakes at distances of up to 40–50 km (BRVK, KKL, KSU, and MAK stations). As seen from the figure, the coda envelopes very weakly attenuate in a range of 100–300 s along the traces in and near the STS area. The coda amplitude attenuation rate dramatically increases at greater distances from the Degelen and Balapan areas. It is interesting to note that the coda from BAY records of the Degelen explosions attenuate much stronger compared to the KKL station, although their epicentral distances differ insignificantly (209 and 194 km, respectively). Strong attenuation is obtained from records of local events and from the most remote stations (BRVK and MAK).

Figure 12 summarizes the data on traces constraining weaker or strong attenuation zones of coda amplitudes at t = 100–300 s in and near the STS region. The circles in the figure are centered at midpoints of respective traces. The weak attenuation zone is seen to extend in the ENE direction, approximately along the line connecting the centers of the two main STS areas, Degelen and Balapan. The available data indicate that the maximum linear size of this area is on the order of 200 km.

Time variations of Lg/Pg

To study the time variations of attenuation in the STS area, we analyzed the TLG records of 261 UNEs. Figure 13 shows that the Balapan variances of Lg/Pg data are usually larger than Degelen and Murzhik variances. This is largely related to the fact that the explosions detonated near the fault zones (at distances not larger than 2–3 km from the fault axes) yielded much lower values of Lg/Pg (on average, by 0.3–0.4 log units) compared to the other events in the Balapan area.

The Lg/Pg averages over the Degelen area and particularly over Murzhik area (smaller amount of data) are considerably larger than in the Balapan area.

The ratio significantly varies with time for all three areas. Thus, Degelen explosion data indicate that Lg/Pg noticeably increased from the mid-1960s to the end of the 1970s, after which it remained approximately at the same level until the end of the 1980s. An increase in this parameter, as constrained by Murzhik explosions (from 1965 to 1980), was even more pronounced. From 1980, the Balapan values of Lg/Pg gradually decreased: in 1988–1989, their decrease averaged 0.4–0.5 log units. The difference between the Degelen and Balapan averages reached 0.6 log units at the end of the 1980s.

It is interesting to note that this conclusion is in qualitative agreement with the results obtained by Ringdal *et al.* [1992], who examined the constraints of Balapan explosions on the parameter m_b–$m_{\rm Lg}$ (NORSAR magnitude determinations from Lg waves were used). Using their initial data, we obtained annual averages and found that the 1989 Balapan average of m_b–$m_{\rm Lg}$ is considerably larger (by 0.15–0.20 log units) than the values of the 1970s.

The differences between the Lg/Pg values as constrained by the three areas are unrelated to the source type because the differences between the Degelen (explosions in tunnels) and Murzhik (explosions in boreholes) values are much smaller than between the Balapan and Murzhik values.

DISCUSSION

The results obtained indicate very strong time–space variations in the *S*-wave attenuation field structure in the crust and upper mantle in and near the STS area.

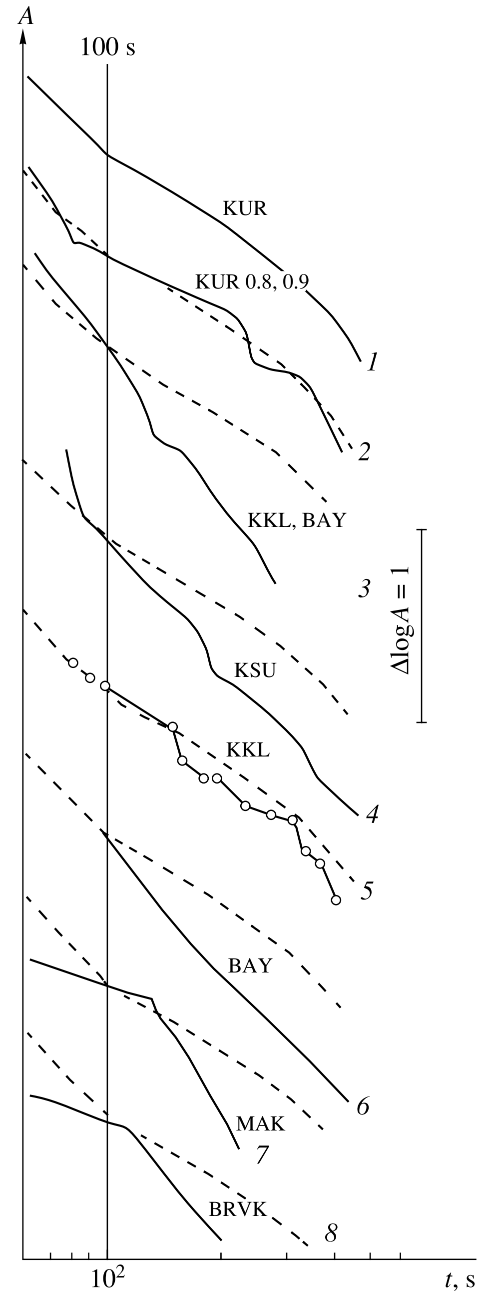

Fig. 11. Coda envelopes from records of calibration explosions detonated in 1997–1999 (curves *1*, *2*, *5*, and *6*) and in 1987–1988 (curves *3* and *4*) and local earthquakes (curves *7* and *8*). The KUR08 and KUR09 stations are located about 19–21 km southwest of the KUR station (Fig. 12).

One of the most surprising results is the abnormally strong attenuation of *S* waves in the crust and upper mantle of the Balapan area. It is known that the typical average velocities of seismic waves in the crust and upper mantle under seismically passive regions of Central Asia (including the Kazakh platform) are noticeably higher and attenuation is weaker than in tectonically active areas [Kopnichev, 1985; Nersesov and Sidorin, 1991; Roecker *et al.*, 1993; Belyashova *et al.*,

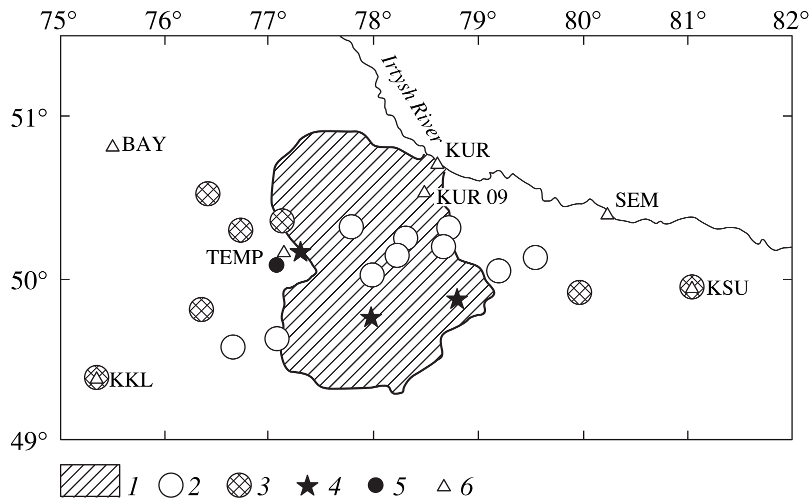

Fig. 12. Zones of (*2*) weak and (*3*) strong attenuation from the coda attenuation in the interval 100–300 s in (*1*) the STS region and its vicinities. The circles are centers of traces from epicenters of (*4*) calibration explosions and (*5*) an earthquake to stations (*6*). KKL and KSU records of local quarry blasts were used. Attenuation in station areas is shown.

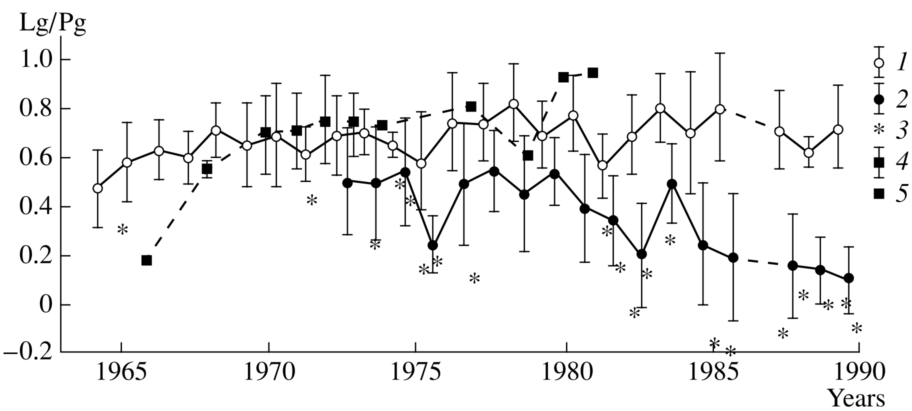

Fig. 13. Variations in Lg/Pg from TLG records of STS UNEs (1.25-Hz FSS channel). Yearly averages and standard deviations are shown for (*1*) Degelen, (*2*) Balapan, and (*4*) Murzhik areas. Also shown are data from (*3*) individual Balapan explosions with epicenters near fault zones and (*5*) individual Murzhik explosions.

2000]. Nevertheless, as has already been demonstrated above, the attenuation of *S* waves at depths of ~20–120 km in the Balapan area is significantly stronger than in the Central Tien Shan region (even in its southeastern part, which is characterized by the lowest velocities of *P* waves in the upper mantle [Roecker *et al.*, 1993]).

The records of the STS calibration explosions fail to accurately constrain the time of such a strong change in the attenuation field structure. The pertinent information can be recovered from the analysis of temporal variations in the Lg/Pg ratio. First, the traces of waves arriving at the TLG station from different STS areas being very close (their azimuths differ by no more than 7°), large divergences between the temporal variations in this parameter as constrained by explosions in different STS areas indicate that variations in the attenuation field structure were largest in the crust immediately under the STS areas.

The results obtained indicate that the integral attenuation of *S* waves significantly decreased in the crust of the Degelen and Murzhik areas from the mid-1960s up to the end of the 1970s and considerably increased in the Balapan area in the 1980s.

Note that, prior to nuclear tests, the STS region did not differ from other regions of the Kazakh platform with similar tectonic conditions (in particular, no information on local earthquakes in this region had been available until 1976). Taking into account this fact, as well as the existence of a bright thermal anomaly in this region, it is natural to suppose that the variations in the attenuation field structure is a result of long-term and intense action of high-yield explosions on the geological medium.

In our opinion, the only possible interpretation of the inferred effects is related to fluids ascending from the lower crust and upper mantle. As has previously been shown, active migration of fluids along the Zailiiskii fault zone in the North Tien Shan took place after low-yield (up to a few kilotons) chemical explosions [Kopnichev, 1998]. Such behavior might naturally be expected in the STS region, where more than 10 nuclear tests per year on average were detonated during 40 years, and many of them had yields exceeding 100 kt [Mikhailov, 1996; Ringdal *et al.*, 1992].

The inflow of fluids is known to drastically change the parameters of *S* wave propagation: their velocities appreciably decrease and attenuation sharply increases (in contrast to *P*-waves). Under these conditions, the attenuation rate of amplitudes in the short-period coda significantly increases and the amplitude ratio of *S* and *P* waves decreases (giving rise to variations in Lg/Pg at large distances).

Characteristically, the ascent of fluids produced most pronounced effects in the Balapan area, where two large faults penetrate into the upper mantle. Deep fault zones containing an appreciable fluid fraction are, according to terminology of Prigogine [Nikolis and Prigogine, 1979] dissipative structures characterized, in particular, by a high sensitivity to external effects [Rodkin, 1993]. The seismic vibrations from high-yield explosions lead to the opening of cracks and pores of various scales, which facilitates the ascent of fluids through fractured zones from the lower crust and upper mantle. (The impulsive acoustic action on a porous medium can increase its permeability by a few orders of magnitude [Barabanov *et al.*, 1987].) The data obtained on the attenuation field structure indicate that fluids can move upward from depths of more than 200 km.

The lack of large faults in the Degelen area precluded direct fluid motion from the upper mantle. Fluids in this area entered the upper crust mostly from the lower crust waveguide [Vanyan and Hindman, 1996], and the *S* wave attenuation in the upper mantle of the Degelen area is much weaker than under the Balapan area.

There are grounds to suppose that mantle fluids actively ascended through the Main Chingiz fault zone. The point is that the nearest epicenters of Degelen and Murzhik UNEs are only ~10–15 km from this fault. In addition, regular explosions in the Degelen area were started 8 years earlier than in the Balapan area. This is indirectly indicated by the elongation of the thermal anomaly zone in the SE direction along the fault, as well as by the fact that the epicenters of the two known local earthquakes are located in the fault zone (Fig. 1).

Judging from the attenuation field structure, channels of fluid migration in the Balapan area have existed for ten years after the termination of nuclear tests. This is consistent with the data available on the ascent of mantle fluids in source zones of Tien Shan strong earthquakes: the upward motion of the fluids persisted for at least a few tens of years after $M > 6.5$ events [Kopnichev *et al.*, 2000].

Penetrating into the upper crust, fluids diffuse through fractured zones over vast territories. In particular, this fact is demonstrated by the high attenuation of *S* waves in the upper crust of the Degelen area, even though the integral attenuation in the crust significantly decreased here from the mid-1960s to the end of the 1980s.

Now, we discuss the origin of the temperature anomaly in the region including STS. First, note that a certain contribution to this anomaly can be made by long-lived sources of thermal energy associated with the UNE-induced cavities. It is known that the mean air temperature in these explosion cavities can remain at a level of 30–50°C for many years [Busygin *et al.*, 1999]. However, the attenuation field structure yields evidence that the total volume of these cavities in the STS region is negligibly small compared to the volume of the crust and upper mantle involved in the rearrangement of the fluid field. Moreover, the temperature of deep fluids is rather high. For example, the Kola ultradeep borehole drilled through the most ancient rocks of the Baltic Shield revealed that the groundwater temperature at a depth of 7200 m was 120°C [Kozlovskii, 1984].

In view of the above results, it is natural to relate the temperature anomaly in northeastern Kazakhstan to the ascent of juvenile fluids in the STS area. The rapidly ascending fluids mix with subsurface water and raise its temperature, thereby producing a thermal anomaly over a vast area.

Now, we address the spatial structure of the thermal anomaly discussed. The anomaly is obviously elongated along the strike of major fault zones. However, its width significantly varies: being widest in the area of the western STS boundary, it is 1.5 to 2 times narrower at the northwestern STS margin and 4 to 5 times narrower at its southeastern margin.

One may suggest that such irregularity of the thermal anomaly area can be due to, first, the motion of fluids along major fault zones and, second, the effect of blast sources in the quarry areas northwest and west of STS. After fluids penetrated into the upper crust, even comparatively weak but regular vibration effects of quarry blasts largely affect the permeability of the porous medium and must result in gradual fluid migration, primarily toward these quarries.

The available data do not allow one to determine the exact formation time of the thermal anomaly in its present form. However, taking into account the fact that the intensity of blasting operations in the quarries west and northwest of STS has dramatically reduced since the early 1990s, we may suggest that the anomaly had mainly formed by 1990. The fact that the anomaly area remained virtually unchanged from 1997 through 1999 supports this inference.

CONCLUSIONS

1. The space–time variations in the attenuation field structure of *S* waves in the crust and upper mantle of the STS region were studied from records of 24 digital and analog seismic stations.

2. The analysis of coda in records of local earthquakes at frequencies of about 1 Hz showed that the attenuation field of *S* waves in the study region is characterized by significant spatial inhomogeneity. The *S* wave attenuation at depths of 35 to 120 km is very strong in zones of large deep faults in the Balapan STS area and is much weaker in the Degelen STS area, where only small fault structures are known.

3. The analysis of *S* coda records at a frequency of 5 Hz showed that strong attenuation characterizes the upper crust at depths of 10 to 20 km in the Balapan and Degelen areas.

4. The *S* wave attenuation in the Balapan area at depths of 20 to 120 km is found to be much stronger compared to data from 40 seismic stations located in the Central Tien Shan. On the other hand, the attenuation at depths of more than 200 km in the upper mantle in the STS region is commonly weaker than in the vicinity of various stations in the Central Tien Shan.

5. The analysis of the amplitude ratio of Lg and Pg waves from more than 260 UNEs recorded at the TLG station showed that the crustal attenuation of *S* waves appreciably decreased in the Degelen and Murzhik STS areas from the mid-1960s to the end of the 1970s and markedly increased in the Balapan area in the 1980s.

6. An interpretation of the effects revealed is proposed in terms of the ascent of fluids through large fault zones from the upper mantle under the STS region due to a long-term intense action of high-yield explosions on the geological medium.

7. The rise of fluids from the upper mantle into the upper crust and their further diffusion through small fractures can account for the existence of the large temperature anomaly in the northeastern Kazakhstan region including STS.

ACKNOWLEDGMENTS

We are grateful to N.N. Belyashova, W.-Y. Kim, and S.W. Roecker, who provided us with digital records of calibration explosions and local earthquakes in the Tien Shan region.

REFERENCES

Adushkin, V.V. and Spivak, A.A., Groundwater Level Variations Induced by Underground Nuclear Explosions, *Byull. TsOIAE*, 1993, no. 9, pp. 38–43.

Aptikaeva, O.I. and Kopnichev, Yu.F., Space-Time Variations of the Coda Wave Envelopes of Local Earthquakes in the Region of Central Asia, *J. Earthquake Prediction Res.*, 1993, vol. 2, no. 4, pp. 497–514.

Barabanov, V.L., Grinevskii, A.O., Kissin, I.G., and Nikolaev, A.V., Vibratory Seismic Effects on a Water-Saturated Medium and Their Comparison with Effects of Remote Strong Earthquakes, *Dokl. Akad. Nauk SSSR*, 1987, vol. 297, no. 1, pp. 52–56.

Belyashova, N.N., Shatsilov, V.I., Mikhailova, N.N., *et al.*, The Use of Calibration Explosions at the Semipalatinsk Test Site for Updating the Velocity Structures of the Crust and Upper Mantle, *Geofizika i problema nerasprostraneniya* (Geophysics and Non-Proliferation Problems), 2000, issue 2, pp. 45–52.

Busygin, V.P., Andreev, A.I., and Kosolapov, S.A., Thermal Regime of the Earth's Surface in the Epicentral Zone of Underground Nuclear Explosions, *Fiz. Zemli*, 1999, no. 11, pp. 68–74.

Kaazik, P.B., Kopnichev, Yu.F., Nersesov, I.L., and Rakhmatullin, M.Kh., Fine Structure Analysis of Short-Period Seismic Fields from a Seismic Array, *Fiz. Zemli*, 1990, no. 4, pp. 38–49.

Kopnichev, Yu.F., *Korotkoperiodnye seismicheskie volnovye polya* (Short-Period Seismic Wave Fields), Moscow: Nauka, 1985.

Kopnichev, Yu.F., The Effect of High-Yield Explosions on the *S* Wave Attenuation Field Structure in the Crust and Upper Mantle, *Dokl. Ross. Akad. Nauk*, 1998, vol. 363, no. 6, pp. 819–822.

Kopnichev, Yu.F., Sokolova, I.N., and Shepelev, O.M., Temporal Variations in the *S* Wave Attenuation Field in Strong Earthquake Source Zones, *Dokl. Ross. Akad. Nauk*, 2000, vol. 374, no. 1, pp. 99–102.

Kozlovskii, E.A., Ed., *Kol'skaya sverkhglubokaya* (Kola Overdeep Borehole), Moscow: Nedra, 1984.

Mikhailov, V.N., Ed., *Ispytaniya yadernogo oruzhiya i yadernye vzryvy v mirnykh tselyakh SSSR, 1949-1990 gg.* (Nuclear Weapon Tests and Peaceful Nuclear Explosions in the USSR in 1949–1990), Sarov: RFYaTs–VNIIEF, 1996.

Nersesov, I.L. and Sidorin, A.Ya., Eds., *Sovetsko-amerikanskie raboty po seismicheskomu kontrolyu yadernykh vzryvov* (Soviet-American Studies on the Seismic Monitoring of Nuclear Explosions), Moscow: Nauka, 1991.

Nikolis, G. and Prigogine, I., Translated under the title *Samoorganizatsiya v neravnovesnykh sistemakh. Ot dissipativnykh struktur k uporyadochennosti cherez fluktuatsii* (TRaNSl), Moscow: Mir, 1979.

Peive, A.V. and Mossakovskii, A.A., *Ob"yasnitel'naya zapiska k tektonicheskoi karte Kazakhstana* (Explanatory Note to the Tectonic Map of Kazakhstan), Moscow: Nauka, 1982.

Pooley, C., Douglas, A., and Pearce, R., The Seismic Event of 1976, March 20, East Kazakhstan: Earthquake or Explosions?, *Geophys. J. R. Astron. Soc.*, 1983, vol. 74, pp. 621–631.

Ringdal, F., Marshall, P., and Alewine, R., Seismic Yield Determination of Soviet Underground Nuclear Explosions at the Shagan River Test Site, *Geophys. J. Int.*, 1992, vol. 109, pp. 65–77.

Rodkin, V.V., *Rol' glubinnogo flyuidnogo rezhima v geodinamike i seismotektonike* (Geodynamic and Seismotectonic Implications of the Deep Fluid Regime), Moscow, 1993.

Roecker, S.W., Sabitova, T.M., Vinnik, L.P., *et al.*, Three-Dimensional Elastic Wave Velocity Structure of the Western and Central Tien Shan, *J. Geophys. Res.*, 1993, vol. 98, no. B9, pp. 15779–15795.

Sultangazin, U.M., Zakarin, E.A., Spivak, L.F., *et al.*, Monitoring of Temperature Anomalies in the Former Semipalatinsk Test Site, *Method. Instrum. Acad. Sci. Paris*, 1998, vol. 326, pp. 135–140.

Vanyan, L.L. and Hindman, R.D., On the Origin of Electrical Conductivity in the Consolidated Crust, *Fiz. Zemli*, 1996, no. 4, pp. 5–11.

Zapol'skii, K.K., Frequency-Selective Stations, *Eksperimental'naya seismologiya* (Experimental Seismology), Moscow: Nauka, 1971, pp. 20–36.