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Temporal Variations of the *S*-Wave Attenuation Field in the Area of the Lop Nor Nuclear Test Site

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Abstract—The characteristics of the shear wave attenuation field in the area of the Lop Nor nuclear test site, China, are considered. Methods are used that analyze the relative level of S_n and P_n waves (parameter S_n/P_n) and the slope of *P*-coda envelopes. An S_n wave is formed by shear waves reflected from multiple boundaries in the upper mantle, while *P*-coda is formed by *S*–*P* type conversion in the lithosphere of the source region. Twenty-six records of underground nuclear explosions (UNEs) and earthquakes obtained by station BRVK at epicentral distances of ~1800–2000 km have been processed. It is found that from the late 1960s until the mid-1990s, the mean S_n/P_n values in the records of UNEs have substantially decreased and the slope of the *P*-coda envelope has increased in the area of the test site. These effects indicate an increase in *S*-wave attenuation in the lithosphere of the source region. A decrease in S_n/P_n with time in earthquake records for the test site region has also been observed after the termination of UNE series. Similar results were obtained earlier for the areas of the Semipalatinsk and Nevada nuclear test sites. The revealed effects are supposedly caused by deep fluid migration as a result of intensive long-term anthropogenic impact.

Keywords: Lop Nor nuclear test site, S_n group, *P*-coda, *S*-wave attenuation, deep-seated fluids

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INTRODUCTION

The significant temporal variations in the attenuation field of short-period shear waves in the areas of the Semipalatinsk and Nevada nuclear test sites, attributed to migration of deep-seated fluids as a result of long-term anthropogenic impact on the geological medium, were revealed in (Kopnichev and Sokolova, 2001; Kopnichev et al., 2013). In the present work, we consider these variations in the area of the Lop Nor nuclear test site in China.

OBSERVATION SYSTEM AND DATA USED

The Lop Nor nuclear test site is located in the seismoactive zone of the East Tien Shan, where the earthquakes with $M \geq 7.0$ have been recorded. From 1969 to 1996, 22 underground nuclear explosions (UNEs) with m_b = 4.5–6.5 were detonated here (Fig. 1) (Fisk, 2002). Explosions were no more than 700 kt in power. Additionally, beginning from 1969, 15 earthquakes with m_b = 4.5–5.9 have been recorded in the region and nearest vicinity of this test area (within the boundaries of the map shown in Fig. 1). We processed the records of underground nuclear explosions made in 1969–1996, and also those of earthquakes occurred in the vicinity of this test area, recorded by the BRVK station in northern Kazakhstan (Fig. 1). Totally, we processed 26 seismograms of 1969–2010 recorded at epicentral distances of ~1800–2000 km.

METHODS

We used the method based on analysis of the ratio between maximal amplitudes in S_n and P_n waves (parameter $\log(AS_n/AP_n)$) (Kopnichev and Sokolova, 2008). It was shown in (Kopnichev and Arakelyan, 1988) that the S_n group is formed mainly by shear waves reflected from subhorizontal boundaries in the upper mantle. The amplitude ratio is used for normalizing because S_n and P_n waves travel along close paths.

In addition, we analyzed the slope of *P*-coda envelopes. As was found earlier, *P*-coda within the considered range of distances is formed mainly by the waves traveling near the ray plane, as a result of *S*–*P*-type conversion scatter in the source zone (Koper and Fatehi, 2009). In this case, coda waves cross the crust and upper mantle in the epicentral zone at a steeper angle that S_n does (Aki and Richards, 1980; Kopnichev and Arakelyan, 1988; Koper and Fatehi, 2009). We considered the parameter $\log(A_c/A_p)$, where A_c is the level of the coda envelope at some fixed lapse time t_c. Below, we denote these parameters S_n/P_n and C/P, respectively, for brevity.

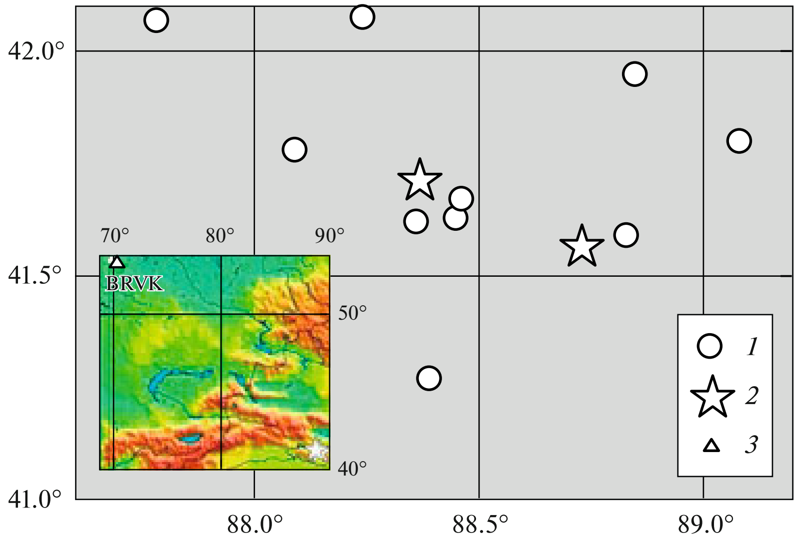

Fig. 1. Map of area of Lop Nor nuclear test site (LTS): (*1*) earthquake epicenters, (*2*) main sites of underground nuclear explosions (UNEs). Locations of LTS (*2*) and BRVK station (*3*) are shown in inset.

Since attenuation considerably depends on frequency, the vertical components of the records preliminarily underwent narrowband filtering. For this purpose, we used a filter with central frequency of 1.25 Hz and a 2/3 octave width.

DATA ANALYSIS

Figure 2 shows the records of UNEs detonated at the Lop Nor nuclear test site. In the record of UNE of October 27, 1975, the S_n group has a relatively high amplitude. However, a UNE recorded 20 years later (August 17, 1995) has a significantly lower S_n/P_n, as well as an increased rate of *P*-coda amplitude attenuation.

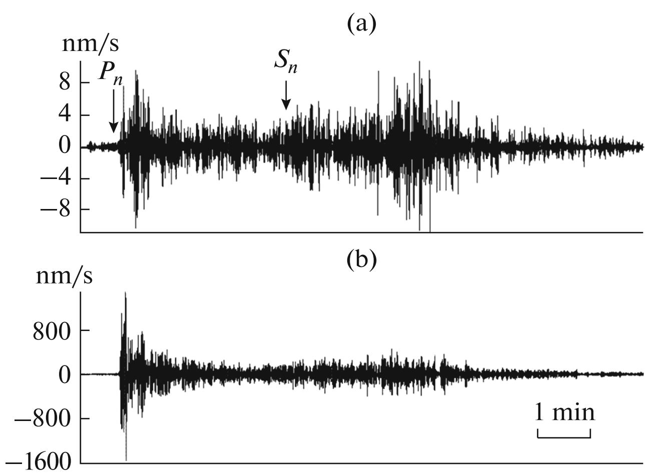

Fig. 2. Examples of records of UNEs made at LTS: (a) explosion of October 27, 1975, (b) explosion of August 17, 1995. BRVK station, *Z*-channel 1.25 Hz. Arrivals of P_n and S_n waves are indicated with arrows.

Figure 3 shows the dependences of S_n/P_n on time for UNEs and earthquakes. These dependences suggest that the S_n/P_n values in the records of UNEs decrease with time, and in 1993–1996 it became generally lower than in 1969–1978 by 0.26 logarithmic units. Interestingly, after the termination of nuclear tests, a similar trend was observed in earthquake records: in 2007–2010, compared to the period of 1994–1995, the mentioned parameter dropped by 0.13 logarithmic units overall. Note that in the period of 1993–1996, the S_n/P_n value for earthquakes is higher than for UNEs by 0.29 logarithmic units.

Figure 4 shows the common *P*-coda envelopes for UNEs and earthquakes in different periods. The slope of the envelopes for UNE records considerably increases with time, so that the mean *C*/*P* values at t_c = 380 s decrease from –0.54 in 1969–1978 to –0.74 in 1994–1996. For earthquake records, the *C*/*P* parameter decreases from –0.62 in 1994–1999 to –0.72 in 2007–2010. Note that this parameter decreases with time to a relatively lesser degree than S_n/P_n for both UNEs and earthquakes.

DISCUSSION

The obtained data indicate that attenuation of *S*-waves along paths between the Lop Nor nuclear test site and the BRVK station has significantly increased with time. Since the station is located in a low seismicity zone, with the lithosphere being characterized by relatively weak *S*-wave attenuation (*Glubinnoe stroenie*..., 1987), it should be accepted that the main vari-

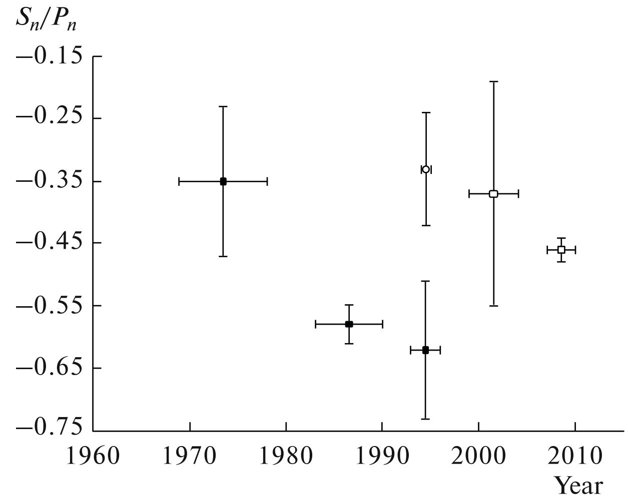

Fig. 3. Dependence of mean S_n/P_n values on time for the LTS region. Mean values and standard deviations for UNEs (filled circles) and earthquakes (empty circles) are shown. Horizontal bars are intervals of data averaging.

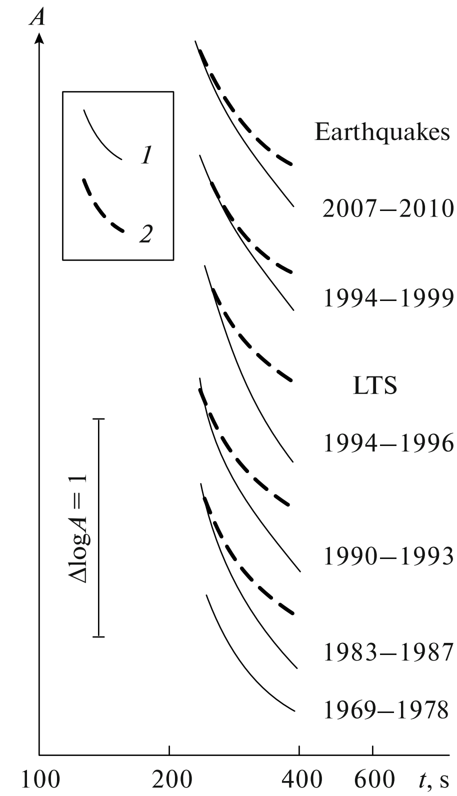

Fig. 4. Common *P*-coda envelopes for UNEs and earthquakes in the LTS region in different time intervals (*1*) compared to the UNEs envelope for the period of 1969–1978 (*2*). Time *t* is measured from the beginning of seismic wave radiation in the source.

ations in the attenuation field should be in the crust and uppermost mantle of the test site area.

Analysis of attenuation of the *Lg* crustal phase with distance in the region of the East Tien Shan (Kopnichev and Sokolova, 2008) shows that *S*-wave attenuation is relatively weak in the crust of the area hosting the Lop Nor nuclear test site. However, the relative level of the S_n group that penetrate to the upper mantle abruptly decreases in the vicinity of the test site (Kopnichev and Sokolova, 2008). Hence, the main changes in the attenuation field are observed here in the upper mantle.

The most obvious and natural explanation for the revealed effects is related to the migration of deep-seated fluids in the lithosphere (Kopnichev and Sokolova, 2001, 2008; Kopnichev et al., 2009): partially molten material, which also results in high *S*-wave attenuation, cannot ascend relatively quickly due to the high viscosity in comparison to fluids. Fluid migration is likely caused by an abrupt increase in the permeability of rocks under the effect of vibration, which even model experiments revealed (Barabanov et al., 1987). At depths of the lower crust and upper mantle, this effect is considerably intensified due to the buoyancy force pushing fluids upward. Note that an increase in permeability of the lower crust leading to the faster ascent of mantle fluids was observed in southwestern Japan during the passage of low-frequency Rayleigh waves from great earthquakes even at epicentral distances of ~4000–5000 km (Miyazawa and Mori, 2006).

It follows from Fig. 4 that the ascent of fluids in the area of the Lop Nor nuclear test site continued after the nuclear tests were stopped, despite the fact that the seismic energy of earthquakes in this region was considerably lower than the energy of UNEs. A similar effect was revealed earlier for the area of the Semipalatinsk nuclear test site (Kopnichev and Sokolova, 2001, 2009). This can be explained by the inertial character of fluid ascent after intensive technogenic disturbance of equilibrium condition.

The larger variation range of S_n/P_n compared to C/P is most probably because fluids ascend more intensively in the area northwest of the test site; therefore, the dynamic characteristics of waves that pass through the crust and upper mantle at gentler angles change to a higher degree. This agrees with the data on attenuation field anomalies in the East Tien Shan (Kopnichev and Sokolova, 2012) obtained from analysis of records of the Makanchi (MKAR) station.

The results furnish new evidence that long-term intensive technogenic impact can change the characteristics of the geological medium at quite large depths of the crust and even upper mantle. Such evidence was obtained earlier for the areas of the Semipalatinsk and Nevada nuclear test sites (Kopnichev and Sokolova, 2001; Kopnichev et al., 2013). It should also be noted that the existence of temporal variations in the shear wave attenuation field should be taken into account when studying discrimination of UNEs and earthquakes (Kopnichev et al., 2001).

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