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GEOPHYSICS

Heterogeneities of the Shear Wave Attenuation Field in the Lithosphere of East Tien Shan and Their Relationship with Seismicity

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Abstract—The shear wave attenuation field in the lithosphere of Eastern Tien Shan has been mapped. The method based on analysis of the ratio between amplitudes of *Sn* and *Pn* waves was used. On aggregate, about 120 seismograms made at the Makanchi station (MKAR), mainly in the period of 2003–2009, at epicentral distances of about 350–1200 km were analyzed. It was found that shear wave attenuation in the lithosphere of Eastern Tien Shan is weaker than that in the region of Central Tien Shan. This agrees with the fact that the rate of deformation of the Earth's crust in Eastern Tien Shan is lower (based on GPS data), as is the seismicity level, in comparison to Central Tien Shan. The zones of high attenuation, where strong earthquakes with $M > 7.0$ have not occurred for the last 200 years, have been identified: first of all, these are the area west of Urumqi and that of the Lop Nur test site. It is suggested that in the first zone, where an annular seismicity structure has formed over the last 30 years, a strong earthquake may be being prepared. The second zone is most probably related to the uplift of mantle fluids resulting from a long-term intensive technogenic effect, analogous to what has occurred in areas of other nuclear test sites (Nevada and Semipalatinsk).

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The shear wave attenuation field in the lithosphere of Eastern Tien Shan has been mapped. The method based on analysis of the ratio between amplitudes of *Sn* and *Pn* waves was used. The records of local earthquakes, made at the Makanchi station (MKAR) at the epicentral distances of about 350–1200 km, were analyzed. Zones of high attenuation, where strong earthquakes with $M > 7.0$ have not occurred over the last 200 years, have been identified: first of all, these are the area west of Urumqi and that of the Lop Nur test site. It is suggested that in the first zone, where an annular seismicity structure has formed over the last 30 years, a strong earthquake may be being prepared. The second zone is most probably related to the uplift of mantle fluids resulting from a long-term intensive technogenic effect, analogous to what has occurred in locations of other nuclear test areas.

Investigation of the characteristics of the shear wave attenuation field is important for solution of different geophysical problems, first of all, for detection of preparation zones of strong earthquakes [1–5]. In the present work, we mapped the shear wave absorption field in Eastern Tien Shan for this purpose. Here is located the large city of Urumqi, the capital of Xinjiang Uyghur Autonomous Region, People's Republic of China, of about 2 500 000 inhabitants. Additionally, there is the Lop Nur test site in the region of Eastern Tien Shan. Investigation of the characteristics of the attenuation field is required for analysis of geodynamical processes in the neighborhood of the test area [6], and for recognition of underground nuclear explosions (UNE) and earthquakes [7].

Since 1812, there have been four earthquakes with $M > 7.0$ in the discussed region (table). Figure 1 presents the map of the region with epicenters of strong earthquakes, including the epicenter of the 1931 Mongolian earthquake ($M_w = 7.9$) and its strongest aftershocks. It follows from the map that the absolutely predominant part of the epicenters is located on the

Strong earthquakes in the region of Eastern Tien Shan

Date (DD.MM.YYYY)	N	E	*M*
08.03.1812	43.70°	83.00°	7.5
22.12.1906	43.50	85.00	7.2
04.08.1914	43.50	91.50	7.2
23.02.1949	41.00	83.50	7.3

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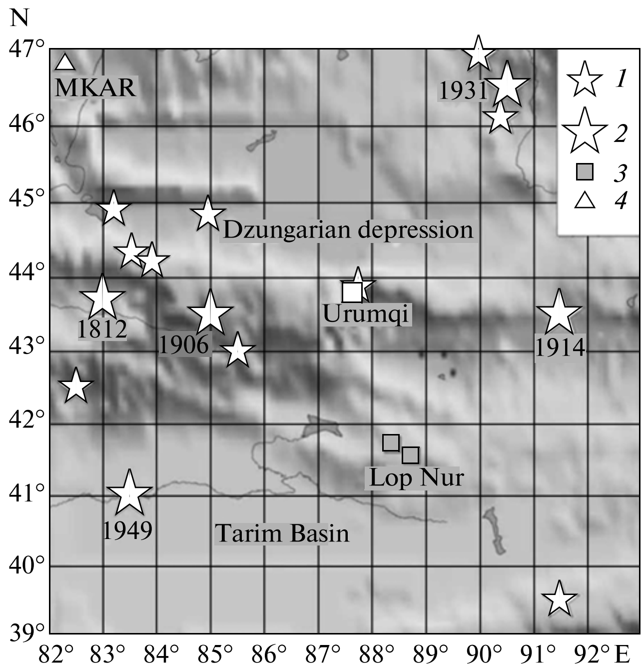

Fig. 1. The map of the study area showing the epicenters of the strongest earthquakes (with years of the events). *1*, $6.0 \le M < 7.0$ (since the early 20th century); *2*, $M > 7.0$ (since the early 19th century); *3*, Lop Nur test site objects; *4*, seismic station.

western side of the region (west of 86° E). The last quite strong earthquake in the region of Eastern Tien Shan occurred in 1949, and, after this, earthquakes of $M \ge 7.0$ have not occurred here for more than 60 years. Note that no earthquakes with $M \ge 6.0$ have been recorded here since 1966 in the region of Eastern Tien Shan, whereas in the period of 1969–1996, at the Lop Nur test site, 22 UNE were made and their magnitudes were $mb = 4.5–6.5$ [8].

For the attenuation field mapping, we used the method based on analysis of the ratio between maximal amplitudes in *Sn* and *Pn* waves and the parameter $\log\frac{A_{Sn}}{A_{Pn}}$, which we will call briefly *Sn*/*Pn*. It has been formerly found that the *Sn* group is formed by shear waves reflected from numerous subhorizontal boundaries in the upper mantle [9]. By analysis of *S* coda of close earthquakes, it has been shown that in the Tien Shan region the strongest attenuation of shear waves is observed usually in the lower crust and upper mantle, in the layer confined by depths of about 30 and 70 km [10]. The estimates indicate that, for the sources located at zero depth, deviation of rays in this layer is about 30–100 km [3]. In this case, the main absorption of shear waves takes place in the uppermost mantle. The parameter *Sn*/*Pn* was used for normalization, because the *Sn* and *Pn* waves propagate along close traces. Attenuation substantially depends on frequency; therefore, we used narrow band filtering during analysis: a filter with the central frequency of 1.25 Hz and a bandpass of 2/3 octave [11].

Mapping of the attenuation field in the discussed area was made based on the records of local earthquakes, acquired at the Makanchi station (MKAR) at the epicentral distances of about 350–1200, mainly for the period of 2003–2009 (Fig. 1). About 120 records in aggregate have been processed for the region within

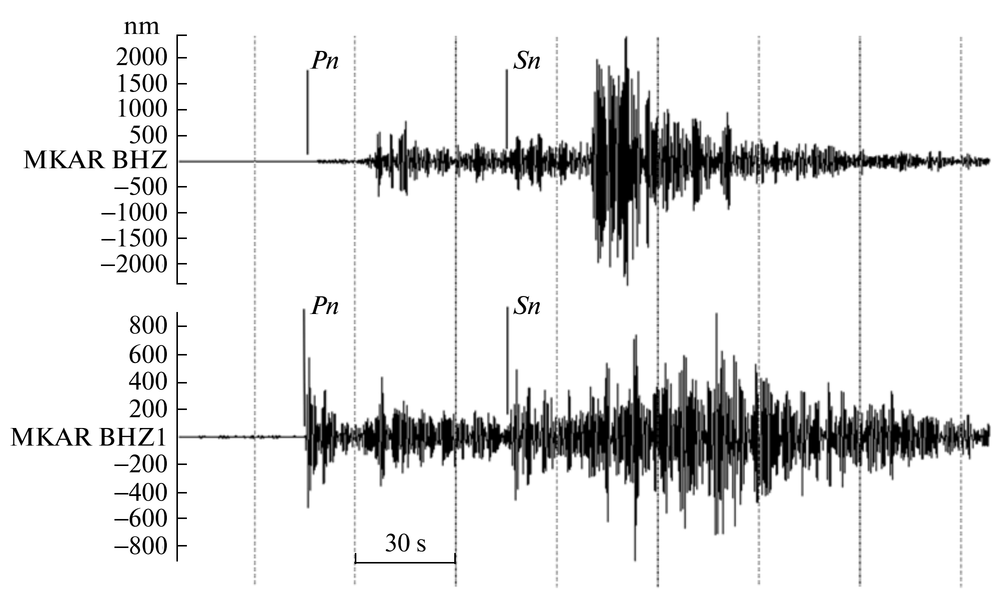

Fig. 2. Examples of seismograms for the earthquakes in the region of East Tien Shan. The lower trace is for the March 29, 2007, event (43.49° N, 87.96° E, $\Delta = 578$ km); the upper one, for the December 15, 2004, event (42.10° N, 85.02° E, $\Delta = 565$ km). The records are made at the MKAR station; vertical component, 1.25 Hz channel. The arrivals of *Sn* and *Pn* waves are designated.

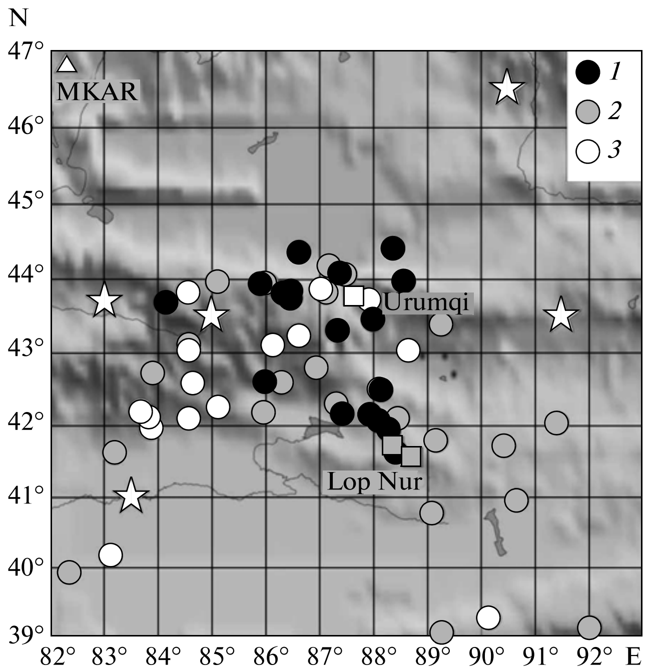

Fig. 3. Map showing the attenuation field in the region of Eastern Tien Shan. Attenuation: *1*, higher, *2*, intermediate, *3*, lower. For other designations, see Fig. 1.

the coordinates 39°–45° N and 82°–93° E. To eliminate the effect of azimuthal directivity of *S*- and *P*-wave radiation, we implemented averaging of *Sn*/*Pn* values for close epicenters (usually for the sites with linear sizes of several tens of kilometers).

Figure 2 demonstrates the examples of seismograms for the earthquakes that occurred in the Eastern Tien Shan region at close epicentral distances. It is seen that, for the epicenter of an event that occurred south of the 1906 earthquake, the amplitudes of *Sn* waves are larger than those of *Pn* waves by more than an order of magnitude. However, these parameters are close in the level for the epicenter located on the boundary of the Dzungarian depression, east of the city of Urumqi. In addition, note the very high relative level of the *Lg* group for the upper seismogram, which indicates a quite low attenuation of shear waves in the Earth's crust along the whole trace from source to station [9, 11].

Our analysis has shown that in the region of Eastern Tien Shan, the average (for small sites) *Sn*/*Pn* values vary from 1.66 to –0.06, whereas their interval for the region of Central Tien Shan is from 0.95 to –0.23 [3]. We analyzed the dependence of *Sn*/*Pn* values on epicentral distance. In the range Δ of about 350–1200 km, the average *Sn*/*Pn* values decrease with distance; the equation of linear regression is described by the formula

$$Sn/Pn \sim 1.31 - 0.0011\Delta(\text{km}). \qquad (1)$$

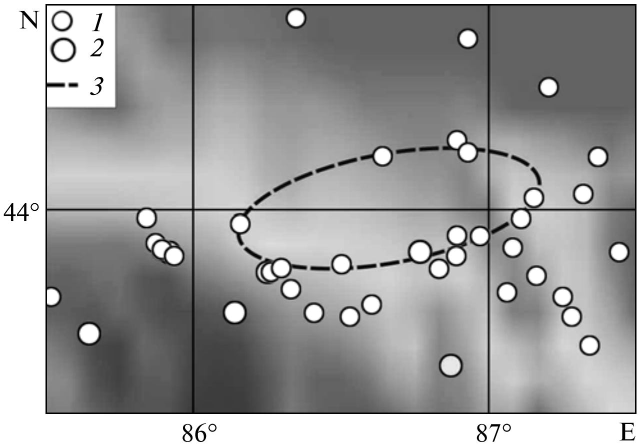

Fig. 4. Characteristics of seismicity in the region west of Urumqi. *1*, *2*, epicenters of earthquakes: *1*, $4.0 \le M < 5.0$, *2*, $M \ge 5.0$; *3*, annular seismicity structure.

In general, the regression line is located significantly higher (especially for the distances of up to 800 km), but its inclination is slightly more than that for the region of Central Tien Shan [3].

Figure 3 shows the map of the attenuation field for the region of Eastern Tien Shan. The whole range of $\Delta Sn/Pn$ variations (deviations from dependence (1)) is subdivided into three grades corresponding to lower ($\Delta Sn/Pn > 0.12$), intermediate ($0.12 \ge \Delta Sn/Pn \ge -0.12$), and higher ($\Delta Sn/Pn < -0.12$) attenuation. It follows from the map that Tarim Region (based on a small volume of data) corresponds to the zone of intermediate and lowered attenuation. All the zones of higher attenuation are situated in the regions of Eastern Tien Shan and the south end of the Dzungarian depression. The absolutely predominant part of low values of the $\Delta Sn/Pn$ parameter is concentrated in the area between 85.5° and 89° E. An explicit zone of high attenuation is situated in the area of the Lop Nur test site and northwest of it. Finally, there is a zone of higher and, in part, intermediate attenuation between 43.5° and 44.5° N (on the northern boundary of Eastern Tien Shan, in the neighborhood of the city of Urumqi). In general, the zones of high attenuation are seen as three narrow interrupted bands: one of a west-northwest strike and two of east-northeast strike. The highest contrast in attenuation at small distances is observed west of the city of Urumqi: the average *Sn*/*Pn* values vary here from 0.26 to 0.94. Most of the high $\Delta Sn/Pn$ values are concentrated in the ENE-striking band, which divides the bands of high attenuation.

Figure 4 demonstrates the characteristics of seismicity on the northern boundary of Eastern Tien Shan, in the zone of high contrast in attenuation, between 85.5° and 87.5° E. The map contains epicenters of earthquakes with $mb \ge 4.0$ and depths less than 40 km, recorded in the period from January 1, 1979, to July 1, 2011. It is seen that the epicenters form an annular structure with the large axis being about 85 km long and stretched in the sublatitudinal direction.

The higher attenuation of shear waves can be caused by the presence of partially melted rocks or fluids. However, the absence of juvenile igneous rocks in this region argues for the fact that zones of relatively high attenuation are not related to rocks melting in the Earth's crust and the upper mantle.

Higher average *Sn*/*Pn* values indicate that absorption of shear waves in the lithosphere of Eastern Tien Shan is significantly weaker than that in the region of Central Tien Shan. This argues for a decrease in the fluid content in the Earth's crust and upper mantle east of 82° E. A decreased fluid content in the lithosphere causes its higher viscosity, which, in turn, leads to a lower rate of deformation. This does not contradict the GPS data that indicate the rate of deformation of the Earth's crust in Eastern Tien Shan, being several times less than in the region of Central Tien Shan [12].

The relatively low fluid content also allows us to explain the substantially less intensive seismicity of the region of Eastern Tien Shan, in comparison to the Central one, where 11 earthquakes with $M = 7.0–8.3$ have occurred since 1887 [3]. For the past 10–15 years, a great volume of data has been acquired, arguing for the significant role played by deep fluids in processes of preparation for strong crustal earthquakes [1–5]. There are grounds to think that generation of the strongest intràcontinental earthquakes requires a certain content of free fluids in the lower part of the Earth's crust [1–5].

An interconnected network of fluids provides concentration of stresses in the roof of the two-phase layer [13], lightening slip initiation in an earthquake focus. A relatively low fluid content in the lithosphere substantially lengthens the period required for achievement of the critical level of their content in the lower crust and, therefore, generally sharply decreases the level of seismic activity.

A quite low attenuation of shear waves west of 86° N, where three earthquakes with $M > 7.0$ occurred before the mid-20th century, is in agreement with the formerly acquired data indicating the gradual uplift of fluids from the upper mantle during several tens of years after large seismic events [1, 14].

The prolonged zones of higher attenuation, where strong earthquakes have not occurred (based on both historical and instrumental data), are of special interest. One such zone is located on the boundary of the Dzungarian depression, and the second one coincides with the region of the Lop Nur test site and northwest of it. Note that the conclusion about the higher shear wave attenuation in the region of the test area verifies the results acquired in [6] from analysis of the data from the KKAR station, which is located in the region of Western Tien Shan. It is substantial that the northern zone coincides with a large annular seismicity structure, which is a kind that formed prior to strong earthquakes [4]. The available data indicate that shallow rings of seismicity outline relatively rigid lithospheric blocks, at whose boundaries stresses accumulate and uplift of deep fluids occurs [4]. All the data on the attenuation field's heterogeneities and on the characteristics of seismicity may indicate preparation of a strong earthquake west of the city of Urumqi. There should be continual monitoring of geodynamical processes in this area, for the purpose of mid-term prognosis of a strong seismic event.

The higher attenuation of shear waves in the upper mantle in the neighborhood of the Lop Nur test site agrees with the formerly made conclusions about active geodynamical processes related to uplift of mantle fluids in the areas of three large nuclear test areas [15]. These processes are caused by a long-term intensive technogenic effect on the geological medium. The acquired characteristics of the absorption field must also be taken into account in the works dealing with UNE and earthquake recognition in the region of Eastern Tien Shan [7].

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