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Heterogeneities of short-period S wave attenuation field in the earth's crust and uppermost mantle of the Eastern Tien Shan

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Investigation of characteristics of the shear wave attenuation field is important for solution of different geophysical problems, first of all, for detection of preparation zones of large earthquakes and for discrimination of underground nuclear explosions (UNEs) and earthquakes [1–5]. In the present work, we mapped the shear wave field attenuation in the 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 2.5 million inhabitants. Additionally, there is the Lop Nor nuclear test site (LNTS) in the region of the 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].

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 large earthquakes, including the epicenter of the 1931 Mongolian earthquake (Mw = 7.9) and its strongest aftershocks. It follows from the map that the absolutely predominant part of the epicenters is located on the western side of the region (west of 86° E). The last large earthquake in the region of the Eastern Tien Shan occurred in 1949, and, after this, earthquakes of M ≥ 7.0 have not occurred here for more than 70 years. Note that no earthquakes with M > 6.0 have been recorded since 1966 in the region of the Eastern Tien Shan, whereas in the period of 1969–1996, at the Lop Nor test site, 22 UNEs were made and their magnitudes were mb = 4.5–6.5 [8].

We considered recordings of shallow earthquakes and UNEs, obtained by stations MAKZ and KKAR in 1994-2009 at epicentral distances of ~350-1500 km (Fig.2). More than 60 seismograms have been processed.

We used methods connected with an analysis of amplitude ratios of Lg and Pg (Lg/Pg), Sn and Pn (Sn/Pn) waves, and also Lg coda decay velocity [9, 10, 11]. Lg and Pg waves are formed by shear and longitudinal waves reflected from M boundary beyond critical angles, so Lg/Pg parameter characterizes S wave attenuation in the earth's crust at the whole path from the source to the station [9, 12]. At the same time, the Sn/Pn parameter is a measure of S wave attenuation in the uppermost mantle [10].

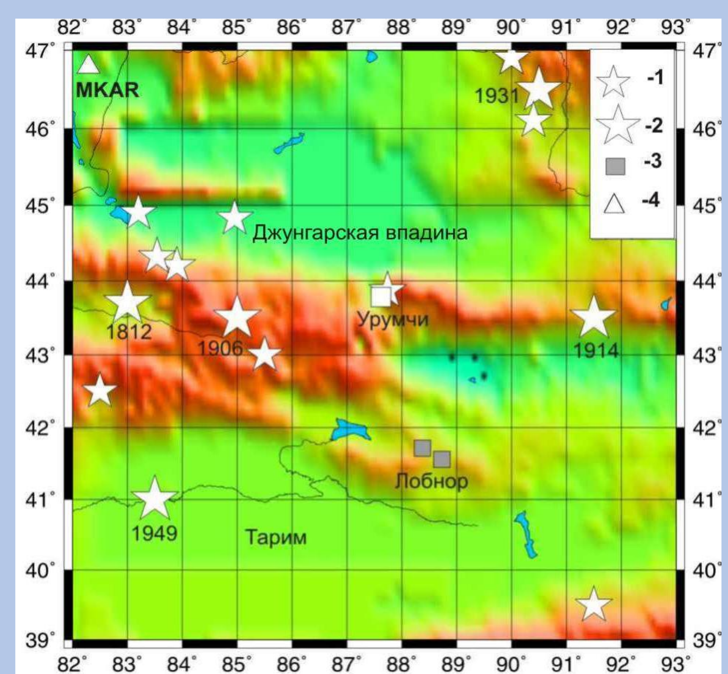

Fig. 1. The map of the study region showing the epicenters of large earthquakes (with years of the events). 1, 6.0 ≤ M < 7.0 (since the early 20th century); 2, M > 7.0 (since the early 19th century); 3, Lop Nor test site objects; 4, seismic station.

Large earthquakes in the region of the Eastern Tien Shan

Date	° 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

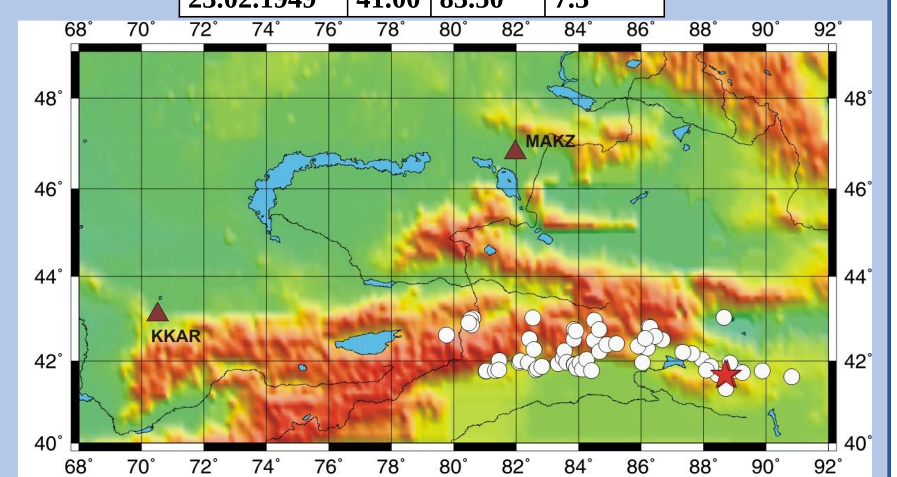

Fig.2. A map of the region. Earthquake epicenters (circles) and UNEs (stars) are shown. Triangles are seismic stations.

The Lg coda is formed by S waves reflected from numerous subhorizontal boundaries in the upper mantle [11,12]. Based on the attenuation rate of amplitudes in the initial part of the 70-s long coda using formula $Ac(t) \sim t^{-1}\exp(-\pi t/QT)$ (t is the lapse time and T is the wave period [11], we determined the effective Q factor in the uppermost mantle corresponding to the epicentral region. If the data from the only station are used, this parameter characterizes attenuation of S waves in the epicentral region at depths up to 200-250 km [11]. Since the short-period S wave attenuation depends strongly on frequency, we performed preliminary frequency filtering of the vertical component of records (we used the filter with the central frequency of 1.25 Hz and width of 2/3 of an octave at a level of 0.7 of the maximum [12].

Attenuation peculiarities in the area of the LNTS. Figure 3 illustrates the dependence of the mean value of Lg/Pg from the epicentral distance for the eastern Tien Shan profile (in the band between 41.3° and 43.0° N) obtained from the analysis of earthquake records (station KKAR). In general, the Lg/Pg value gradually decreases by approximately 0.25 logarithmic unit in the distance range 760-1520 km and no sharp drop of this parameter is observed over the interval corresponding to the LNTS (~1450-1520 km).

Figure 4 illustrates a similar dependence obtained for parameter Sn/Pn. In this case, mean values of Sn/Pn vary much more strongly in the same distance interval (from 0.76 to 0.03). Two segments of sharp drops of these values are distinguished (980-1130 and 1380-1520 km). The Sn/Pn value decreases by 0.47 and 0.39 log.units over the first and second intervals, respectively. We note that the second interval corresponds to the LNTS region and its close vicinities (87.3°-89.0° E).

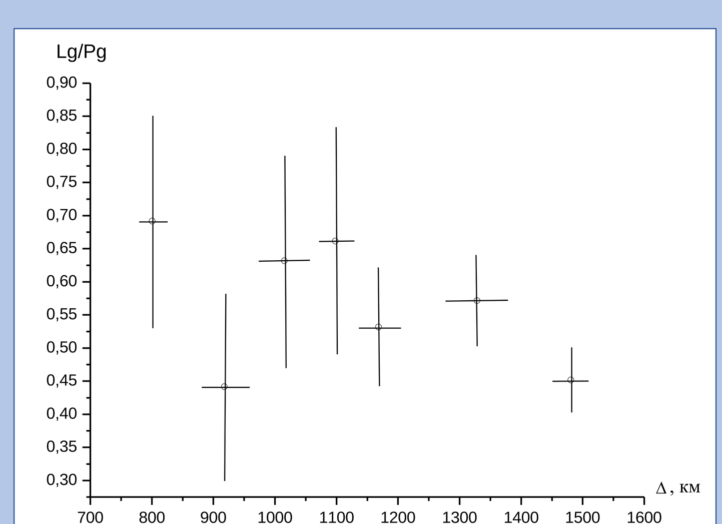

Fig.3. Dependence of Lg/Pg ratio on distance. Mean values and standerd deviations are shown. Horizontal lines denote intervals of epicentral distances.

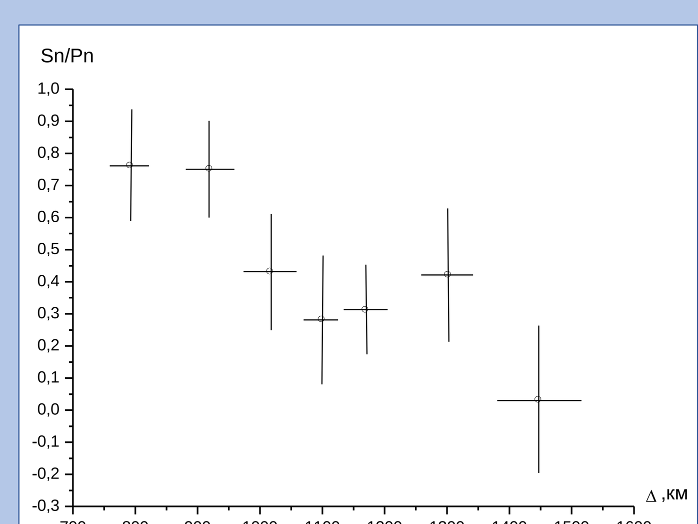

Fig.4. Dependence of Sn/Pn ratio on distance. Notations are the same as in Fig.3.

Figure 5 shows the envelope curves for the Lg coda at the test site and its close vicinities plotted from the records at station MAKZ. Records of UNEs and earthquakes show that the effective Q factor corresponding to the initial part of the coda decreases strongly with decreasing distance to the LNTS: from 350-370 (at distances up to 150 km northwest and east of the LNTS to 240 (in the test site region). At the same time, the Q factor for the more remote coda (t=350-500s), which corresponds to the deeper levels of the upper mantle, remains practically constant (580-630).

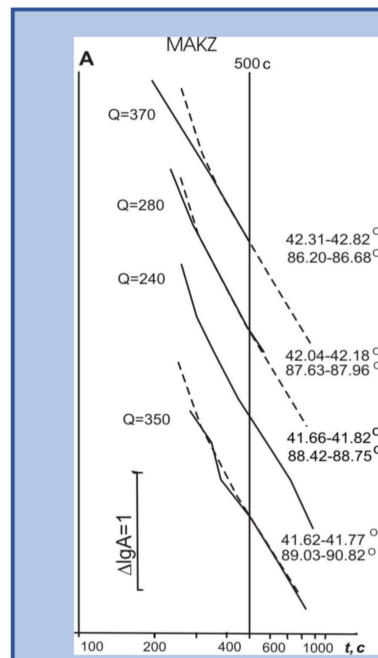

Fig.5. Lg coda envelopes for the test site area (the second from below curve and dashed line) and its close vicinities. Station MAKZ, filter 1.25 Hz.

The data obtained evidence that very high attenuation of S waves in the uppermost mantle (as compared to the surrounding regions) corresponds to the LNTS region. At the same time, no notable anomalous attenuation in the earth's crust is observed in the test site region.

It was shown earlier that S wave attenuation in the earth's crust increased essentially in the northern and eastern parts of the Semipalatinsk test site (SNTS). First of all this corresponds to paths from the Balapan area, where the most part of the largest UNEs were produced (up to 150 kt) [9, 13]. In the Balapan area, where two large regional deep fault zones are traced, very high attenuation is observed also in the uppermost mantle, at depth up to 120 km [9, 14]. At the same time, S wave attenuation is relatively low in the earth's crust and uppermost mantle in the Degelen area, where mainly much weaker UNEs were produced. Besides, as a whole, abnormally weak attenuation in the SNTS area is observed in the upper mantle, at depths more than 200 km [9].

According to our data, increased attenuation in the earth's crust and decreased one in the uppermost mantle corresponded to the Nevada test site (NNTS) in comparison to its close vicinities in 1990-s [13].

Earlier we noted, that most natural explanation of the spatio-temporal variations of S wave attenuation field in the regions of SNTS and NNTS is connected with rising of mantle fluids into the earth's crust, stipulated by protracted intense artificial influence on the geologic medium [9, 13, 14]. Note that manifestations of fluid migration within the large fault zone in the region of the North Tien Shan were observed even after relatively weak chemical explosions [15]. Mechanism of this effect, most probably, is connected with sharp increase of rocks permeability by vibration influence, which was observed even in model experiments [16] (and it grows stronger in conditions of the lower crust and uppermost mantle due to Archimedes force, conditioned by big difference of fluid and rock densities). Note that permeability increase in the lower crust, which leaded to acceleration of mantle fluid ascending, was observed in the region of southwest Japan by passage of low-frequency Rayleigh waves from great earthquakes at distances of ~4-5 thousand km [10].

It follows from this discussion that the rate of fluid ascent process should depend, first of all, on permeability of the crustal rocks and also on power and number of UNEs produced. Taking this into account, it's possible to explain, why this process advanced further in the region of the NNTS, where data on heterogeneities of the attenuation field show that uppermost mantle is "dried" to some extent and simultaneously the crust is saturated by fluids. It is connected with relatively high permeability of the crust and uppermost mantle of this region, situated within the rift zone of the western USA, and also with the biggest number of powerful UNEs (more than 800).

Geodynamic processes in the region of SNTS, situated on the weak-seismicity Kazakh platform, which is characterized by essentially lower permeability, and also smaller number of UNEs produced (about 340), were not so intensive. For this reason saturation of the earth's crust by fluids, for example, occurred not at the whole test site territory, but, first of all, in the vicinities of large fault zones [9, 13, 14]. Besides that, high fluid concentration is preserved here in the uppermost mantle under Balapan area [9].

LNTS is located in seismically active region of the Eastern Tien Shan, which is characterized by intermediate permeability relatively to the rift zone of the western USA and Kazakh platform. But small number of UNEs were conducted here in comparison with two other test sites [15]. We believe that essentially less intensive total artificial influence in the region of LNTS was the reason of the initial stage of fluids ascending, which are concentrated in the uppermost mantle and did not ascend into the earth's crust in considerable amount.

Mapping of the attenuation field in the Eastern Tien Shan region was made based on the records of local earthquakes, acquired at the Makanchi station (MKAR) at 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 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 6 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 rupture zone, 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 case 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 [2, 10].

Our analysis has shown that in the region of the Eastern Tien Shan, the mean (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 (fig.7); the equation of linear regression is described by the formula

$$Sn/Pn \sim 1.31–0.0011\,\Delta\,(km) \quad (1)$$

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 the Central Tien Shan [3].

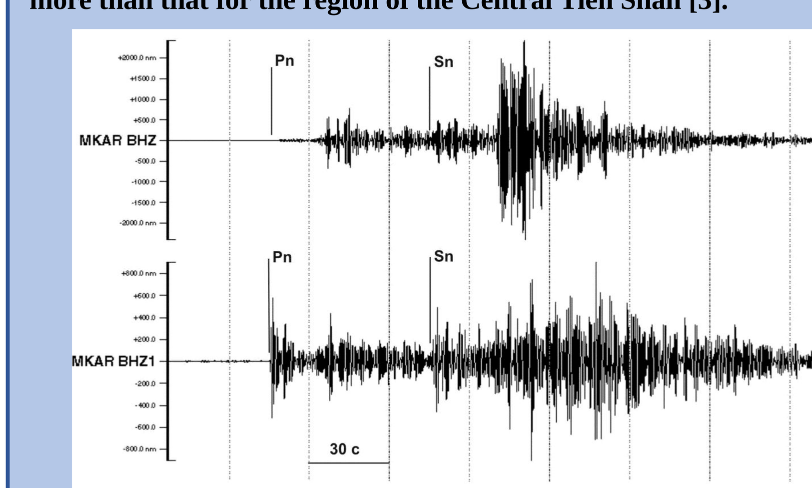

Fig. 6. Examples of seismograms for the earthquakes in the region of the Eastern Tien Shan. The lower trace is for the March 29, 2007, event (43.49° N, 87.96° E, Δ = 578 km); the upper one, for the December 15, 2004, event (42.10° N, 85.02° E, Δ = 565 km). The records are made at the MKAR station; vertical component, 1.25 Hz channel. The arrivals of Sn and Pn waves are designated.

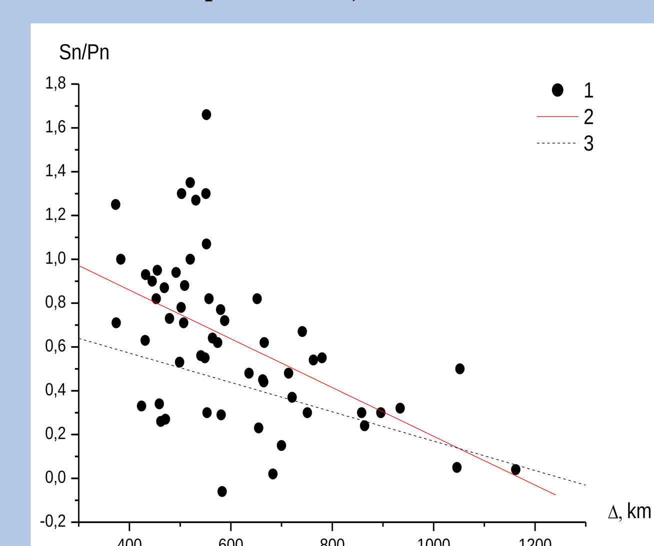

Fig. 7. Dependence of Sn/Pn parameter on distance for the Eastern Tien Shan (1,2) and Central Tien Shan (3).

Figure 8 shows the map of the attenuation field for the region of the Eastern Tien Shan. The whole range of ΔSn/Pn variations (deviations from dependence (1)) is subdivided into three grades corresponding to lower (ΔSn/Pn > 0.12), intermediate (0.12 ≥ ΔSn/Pn ≥ –0.12), and higher (ΔSn/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 ΔSn/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 Nor 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 the 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 ΔSn/Pn values are concentrated in the ENE striking band, which divides the bands of high attenuation.

Figure 9 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 ≥ 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.

Note that epicenter of strong earthquake of 08.12.2016 (Mw 6.0) is connected with this ring-shaped structure. This means that place of this event was successfully predicted in 2012 [Kopnichev, Sokolova, 2012a] based on the data on attenuation and seismicity rings.

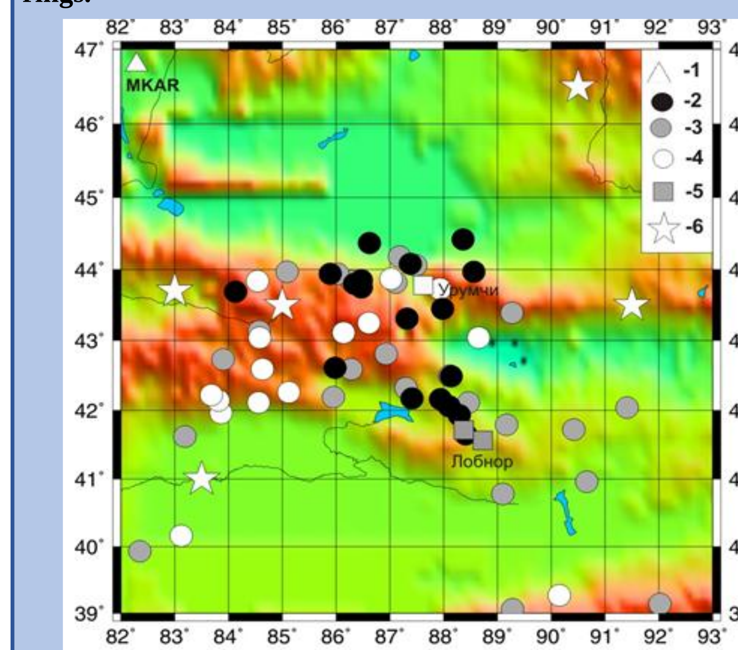

Fig. 8. Map showing the attenuation field in the region of the Eastern Tien Shan. Attenuation: 1, higher, 2, intermediate, 3, lower. For other designations, see Fig. 1.

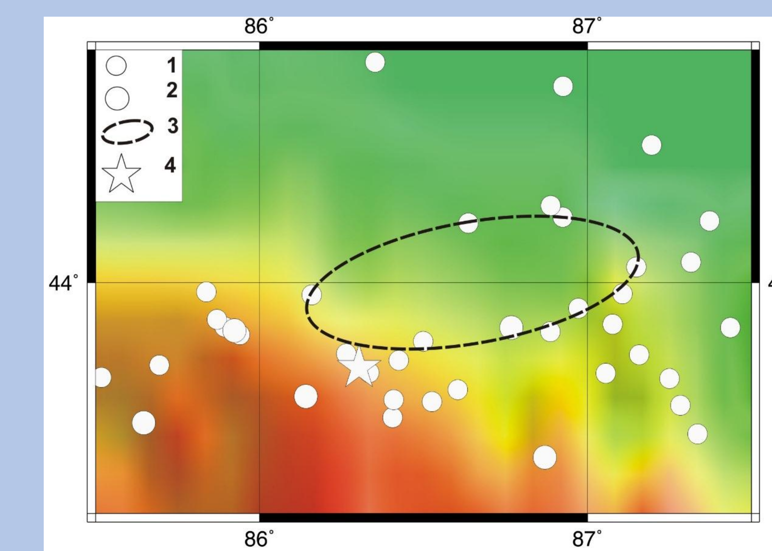

Fig. 9. Characteristics of seismicity in the region west of Urumqi. 1, 2, epicenters of earthquakes: 1, 4.0 ≤ M < 5.0, 2, M ≥ 5.0; 3, annular seismicity structure, 4 – earthquake epicenter 08.12.2016 y. (M=5.9).

Higher average Sn/Pn values indicate that attenuation of shear waves in the lithosphere of the Eastern Tien Shan is significantly weaker than that in the region of the Central Tien Shan. This suggests 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 the Eastern Tien Shan, being several times less than in the region of the Central Tien Shan [12].

The relatively low fluid content also allows us to explain the substantially less intensive seismicity of the region of the 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-seated fluids in processes of preparation for strong crustal earthquakes [1–5]. There are grounds to think that generation of the large 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. 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, 16].

The prolonged zones of higher attenuation, where large 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 Nor 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 presented above from analysis of the data from the KKAR station, which is located in the region of Western Tien Shan. It is essential that the northern zone coincides with a large annular seismicity structure, which is a kind that formed prior to large 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 for large 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 possible large seismic event.

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