ISSN 1028-334X, Doklady Earth Sciences, 2011, Vol. 437, Part 1, pp. 363–367. © Pleiades Publishing, Ltd., 2011.
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GEOPHYSICS

Heterogeneities of the Field of Short-Period Shear Wave Attenuation in the Lithosphere of Central Asia and Their Relationship with Seismicity

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Presented by Academician A.O. Gliko July 1, 2010

Received July 2, 2010

Abstract—The characteristics of the short-period shear wave attenuation field in the lithosphere of the Turanian Plate, West Tien Shan, Pamir, and Hindu Kush have been studied. The method based on analysis of the logarithm of the ratio between maximal amplitudes of Sn and Pn waves (*Sn*/*Pn* parameter) has been applied. More than 400 records of earthquakes, obtained at distances of ~400–1000 km from the AAK digital station, have been processed. It has been found that relatively weak attenuation is observed in the regions of the West Tien Shan and Pamir. The largest area of strong attenuation is located in the region of the Afghan–Tadjik Depression adjacent to Hindu Kush. A wide band of low *Sn*/*Pn* parameter values, stretched northeastwards, has been distinguished. Along with the analogous band of strong attenuation, distinguished before in the regions of Central Tien Shan and Dzungaria, it is the continuation of the largest Chaman Fault, which stretches 850 km along the boundary of the Indian Plate. Source zones of strong earthquakes with $M \geq 7.0$ that occurred in the first half of 20th century correspond to relatively weak attenuation. Areas of high attenuation, where strong seismic events have not occurred for the last 110 years, are outlined. Analogously to other seismoactive regions, it is supposed that these areas are related to preparation of strong earthquakes.

DOI: 10.1134/S1028334X11030044

The mapping of the shear wave attenuation field for the lithosphere of the Turanian Plate, West Tien Shan, Pamir, and Hindu Kush is carried out. The method based on analysis of the ratio between maximal amplitudes of *Sn* and *Pn* waves is used. Earthquake records derived at distances ~400–1000 km at the AAK station were processed. It has been found that relatively weak attenuation is observed in the areas of Turanian Plate, West Tien Shan, and Pamir. The largest area of strong attenuation is located in the region of the Afghan–Tadjik Depression, which is adjacent to Hindu Kush. Areas of high attenuation are distinguished, where strong seismic events ($M \geq 7.0$) have not occurred for the last 110 years. Analogously to the other seismoactive regions, it is supposed that these areas are related to preparation of strong earthquakes.

It was shown previously that a high attenuation of short-period *S* waves is observed in the lower crust and upper mantle in source zones of strong earthquakes in varied regions of the globe [1–4]. This enables us to use the data on heterogeneities of the attenuation field for distinguishing zones where sources of strong earthquakes are prepared. In [4], the heterogeneities of the *S* wave attenuation field for the lithosphere of Central Tien Shan and Dzungaria were studied. In the present paper, the results of mapping of the attenuation field in the areas south and west of the Central Tien Shan are given.

The considered region, which includes West Tien Shan, the eastern margin of the Turanian Plate, the Afghan–Tadjik Depression, Pamir, and Hindu Kush, is characterized by a quite high seismicity. Since 1900, seven crustal earthquakes with $M \geq 7.0$ have occurred in this region, namely, south of 40° N (Fig. 1). In addition, most of the strong earthquakes were recorded in the region of Tien Shan, while regions of Pamir and Hindu Kush each contain a single event of such kind (in 1911 and 1956, respectively). Moreover, the Hindu Kush and Pamir regions include the only active zone of deep-focus seismicity in Central Asia, where earthquakes occur in the range of depths of 70–300 km (see Fig. 1).

The technique used is based on analysis of the ratios between maximal amplitudes of *Sn* and *Pn* waves; this is parameter $\log\frac{A_{Sn}}{A_{Pn}}$, which we will briefly designate as *Sn*/*Pn*. It was found previously that the *Sn* group is formed by shear waves reflected from numerous subhorizontal boundaries in the upper mantle [5].

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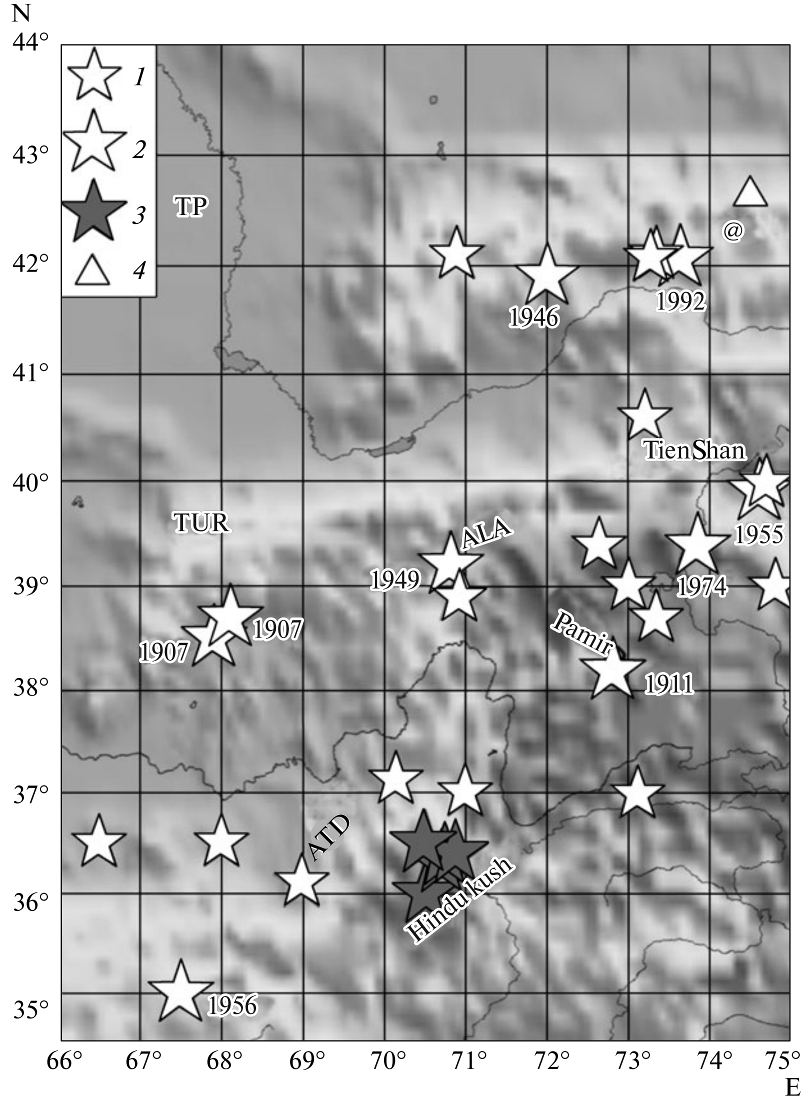

Fig. 1. Map of the study area. TP is Turanian Plate; TUR and ALA are Turkestan and Alai Ranges, respectively; ATD is Afghan–Tadjik Depression. Epicenters of strong earthquakes (since 1900): (*1*) $M = 6.5–6.9$, (*2*) $M \geq 7.0$ (with years when events occurred), (*3*) epicenters of strong deep-focus earthquakes ($M \geq 7.0$), (*4*) seismic station.

By analysis of records of *S* coda for local earthquakes, it was shown that the strongest attenuation of short-period waves in seismically active regions of Central Asia is observed usually in the lower crust and uppermost mantle, in the layer located at depths of ~30–70 km [6]. Estimates show that in the case of sources located at zero depth, the drift of rays is ~30–100 km for the *Sn* group. In this case, the main attenuation of *S* waves corresponds to the uppermost mantle. The *Sn*/*Pn* parameter was used for normalization, because *Sn* and *Pn* waves are propagated in close paths. In order to take variations of radiation pattern in sources into account, averaging of *Sn*/*Pn* values was performed in small areas with linear sizes, usually, of several tens of kilometers. Because attenuation strongly depends on frequency, a narrow-band filtering was used for analysis of records (a filter with a central frequency of 1.25 Hz and bandpass of 2/3 octaves [7]).

Study of the attenuation field in the considered region was carried out by the records of local earthquakes obtained by the digital station AAK at epicentral distances of ~400–1000 km in 1994–2009. In total, more than 400 records of earthquakes with depths of 0–33 km from the region bounded by coordinates 35°–43° N and 66°–75° E were processed.

Figure 2 shows typical examples of seismograms for earthquakes from two regions, derived at almost the same epicentral distances. It is seen that in the source zone of two Karatag earthquakes that occurred in 1907 ($M = 7.4$ and 7.3), almost a hundred years after these events, the amplitude level of the *Sn* group is significantly higher than that of the *Pn* group. At the same

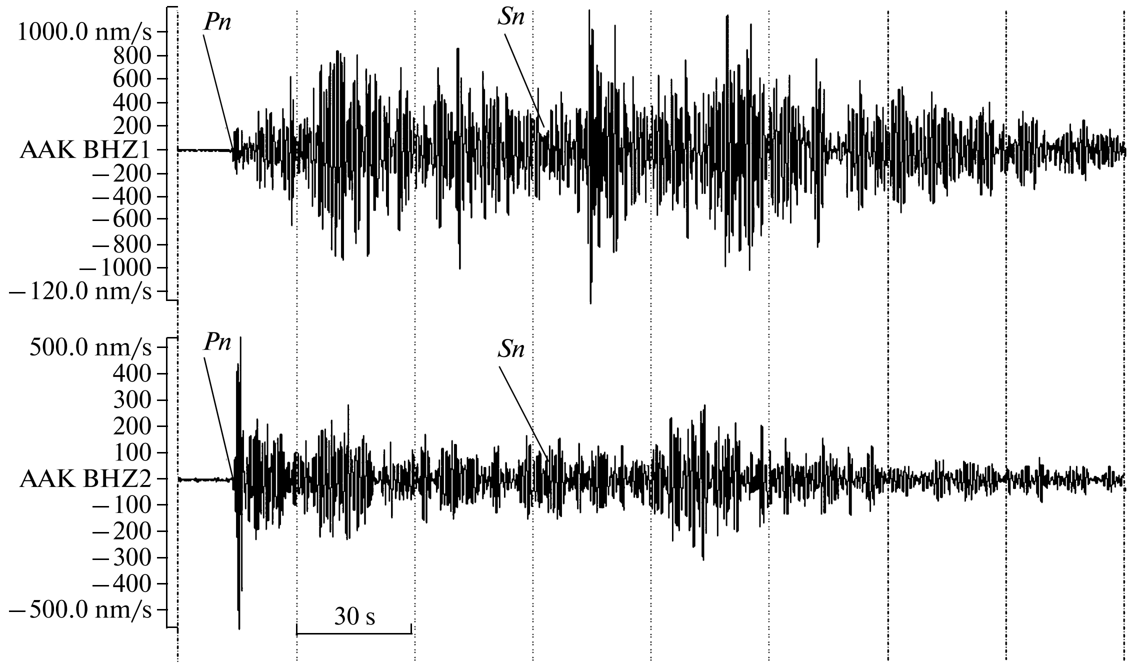

Fig. 2. Examples of earthquake seismograms. The upper trace is for the event of March 23, 2001, 38.56° N, 68.22° E, $\Delta = 698$ km. The lower trace is for the event of May 30, 1998, 37.29° N, 70.04° E, $\Delta = 705$ km. AAK station, channel 1.25 Hz. Arrows correspond to first arrivals of *Pn* and *Sn* waves by travel-time data.

time, a contrast pattern is seen for the aftershock of the earthquake that occurred on May 30, 1998 ($M = 6.7$), where *Sn* wave arrivals cannot be distinguished against the background of the *Pn* coda.

Figure 3 gives the dependence of the Sn/Pn parameter on the epicentral distance Δ. Standard deviations σ for mean values vary from 0.02 to 0.36. Despite the data averaging, a great spread of Sn/Pn values is observed (from 0.79 to –0.33). In general, Sn/Pn values decrease with distance, analogously to the region of Central Tien Shan [4], and the equation of linear regression is written as

$$Sn/Pn = 0.58 - 0.00053\Delta \text{ (km)}. \quad (1)$$

Figure 4 demonstrates the map of the *S* wave attenuation field in the lithosphere of the considered area. It contains values of Sn/Pn parameters with correction to the epicentral distance (deviations from the mean dependence (1)). All the values of the Sn/Pn parameter are subdivided into three levels corresponding to lowered ($Sn/Pn > 0.12$), intermediate ($-0.12 \le Sn/Pn \le 0.12$), and high ($Sn/Pn < -0.12$) attenuation. It follows from Fig. 4 that the attenuation field of short-period shear waves in the studied area is characterized by a great heterogeneity. In general, lowered and intermediate attenuation corresponds to regions of the Turanian Plate, West Tian Shan, and Pamir. The strongest attenuation is observed in the southern part of the studied territory. A clear anomaly of low Sn/Pn values is distinguished in the region of the Afghan–Tadjik Depression, which is adjacent to the Hindu Kush zone of deep-focus seismicity. Note that this anomaly consists of two relatively narrow submeridionally stretched bands. A narrow area of high attenuation, which stretches north–northeastwards, is located in the eastern boundary of the Hindu Kush zone. Another domain of high attenuation, which is oriented close to latitudinal direction, is observed in the boundary between Pamir and Tien Shan, south of

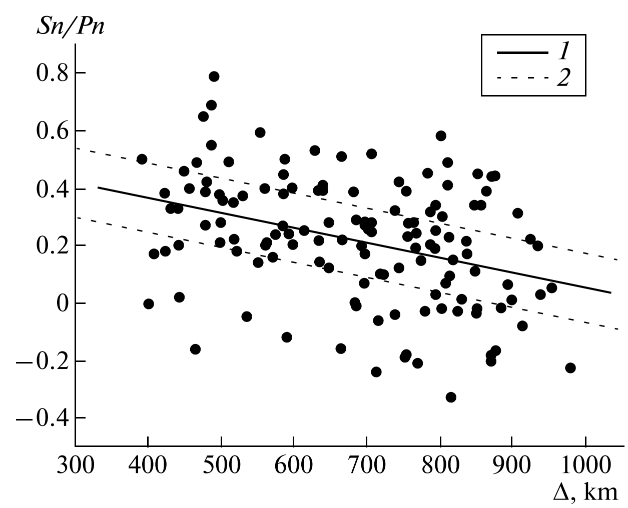

Fig. 3. Dependence of the Sn/Pn parameter on distance. Points are individual values, (*1*) correlative dependence, (*2*) boundaries of intermediate attenuation area.

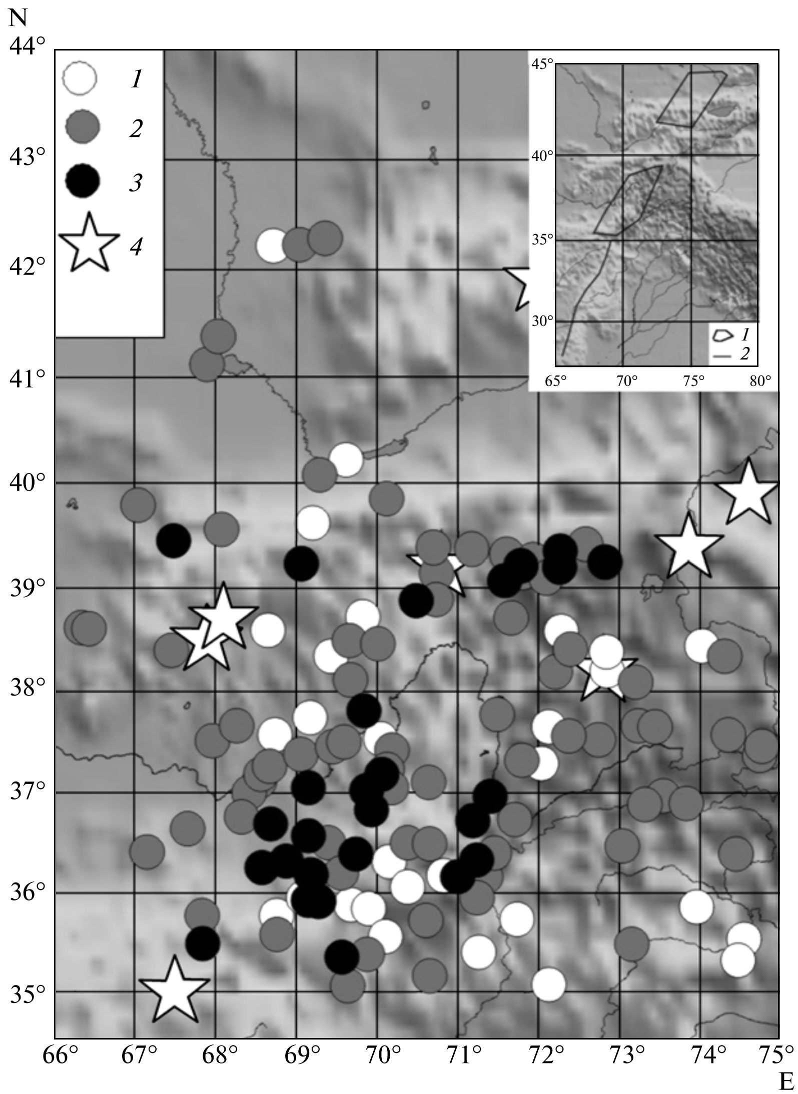

Fig. 4. Heterogeneities of the *S* wave attenuation field in the studied area. Attenuation: (*1*) lowered, (*2*) intermediate, (*3*) high; (*4*) epicenters of strong crustal earthquakes ($M \geq 7.0$). In the inset: (*1*) northeastward-striking bands of high attenuation, (*2*) Chaman Fault.

Alai Range, between 71.5° and 73° E. (Note that this anomaly was distinguished previously by the data of MKAR station [4], which can be additional evidence for the reliability of the method.)

In general, the main part of the high attenuation area occupies a band of about 200 km width stretching 600 km northeastwards. The structure of this band is quite complicated: it contains portions of both lowered and high attenuation.

An additional, narrower band of strong attenuation is outlined; it stretches northwestwards, from the Turkestan Range to Hindu Kush, and crosses the first band.

Note that the greatest contrast of *Sn*/*Pn* values at small distances (up to 0.6–0.7) is observed in the regions of Hindu Kush and the Turkestan Range.

Comparison with seismicity of the region shows that source zones of two Karatag earthquakes, as well as those of the Sarez (1911, $M = 7.0$) and Khait (1949, $M = 7.4$) earthquakes, correspond to areas of lowered and intermediate attenuation of *S* waves. Along with this, source zones of these events, and of the 1956 Afghan earthquake ($M = 7.2$) as well, are drawn to gaps in the mentioned bands of strong attenuation or to their continuations. It is important to note that zones of strong attenuation coincide with the areas where earthquakes with $M \geq 7$ have not occurred for the last 110 years. At the same time, several weaker events with $M = 6.5$–6.8 had occurred in these zones (Fig. 1).

We emphasize that the strongest attenuation is observed in the regions of Alai Range, the Afghan–Tadjik Depression, and Hindu Kush, where relatively young magmatic rocks are absent. This allows believing that low *Sn*/*Pn* values here, as in the regions of Altai and Central Tien Shan [3, 4], are related, first of all, to the presence of a visible fraction of fluids rather than partially melted rocks. Analogously to the Central Tien Shan [4], one can suppose that the strongest attenuation of *S* waves corresponds to depths of ~30–70 km.

It is interesting that a wide band of strong attenuation is a continuation of an analogous band distinguished previously in the regions of Central Tien Shan and Dzungaria and stretching with gaps from 39° to 45° N (Fig. 4) [4]. It was noted in the mentioned paper that bands of strong attenuation are related, most probably, to gradual uplift of fluids in the upper mantle and the Earth's crust under the effect of shear stresses [8, 9]. One can believe that in the present case an analogous effect is observed, because the location of the largest zones of strong attenuation in the regions of the Afghan–Tadjik Depression and Hindu Kush approximately coincide with the orientation of maximal shear stresses in the lithosphere of these regions [10]. The argument for such a conclusion is that northeastern-course bands of strong attenuation in the regions of the Afghan–Tadjik Depression, Hindu Kush, Central Tien Shan, and Dzungaria are located in the continuation of the largest Chaman left-lateral strike-slip fault stretched along the boundary of the Indian Plate from 28° to 35° N (Fig. 4).

The obtained results agree with the conclusions made previously that uplift of fluids from the upper mantle into the Earth's crust is observed after sufficiently strong ($M \geq 7.0$) crustal earthquakes [2–4, 11–14]. This enables us to explain the relatively weak attenuation in the source zones of two Karatag, Sarez, and Khait earthquakes.

Zones of strong attenuation, which are not related to sources of strong earthquakes with $M \geq 7.0$, such as in the regions of Altai and Central Tien Shan [3, 4], are of special interest. In accordance with the model of formation of a strong crustal earthquake proposed previously [15], preparation of strong seismic events can be implemented in such zones. This is related, first of all, to the eastern margin of the Afghan–Tadjik Depression. Note that two quite strong earthquakes with $M = 6.7$ were recorded here in 1982 and 1998. Most probably, a new strong event may occur in the area between sources of these earthquakes (between 36° and 37° N). In addition, preparation zones of strong seismic events are probably related to areas of low *Sn*/*Pn* values in the regions of the Turkestan Range and south of Alai Range, and in the eastern margin of Hindu Kush as well. It is reasonable to conduct continuous monitoring of geodynamic processes in these regions for the purpose of middle-term earthquake prediction.

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