Doklady Earth Sciences, Vol. 395A, No. 3, 2004, pp. 461–464. Translated from Doklady Akademii Nauk, Vol. 395, No. 6, 2004, pp. 818–821.

GEOPHYSICS

Spatiotemporal Variations of the S-Wave Attenuation Field in Source Zones of Strong Earthquakes in the Tien Shan Region: Evidence from the Records of Underground Nuclear Explosions

Yu. F. Kopnichev[1] and I. N. Sokolova[2]

Presented by Academician V.V. Adushkin December 11, 2003

Received December 16, 2003

Spatiotemporal variations of the S-wave attenuation field in the Earth's crust of the Tien Shan region were studied from the records of underground nuclear explosions (UNE) at the Semipalatinsk nuclear test site (SNTS). It is shown that anomalously strong changes in the attenuation field structure are observed for the paths that cross or pass near the source zones of strong earthquakes ($M \geq 6.8$). We suggest that this phenomenon is related to the ascent of mantle-derived fluids (first of all, water) into the Earth's crust before strong earthquakes and their subsequent lateral migration from the source zones.

As is known, the short-period waves *Lg* and *Pg* represent a set of S- and P-waves, respectively, that are postcritically reflected from the M boundary [1]. Therefore, the ratio of their amplitudes, i.e., parameter $\log(A_{Lg}/A_{Pg})$, designated for sake of brevity as *Lg*/*Pg*, is a measure of integral attenuation of S-waves in the Earth's crust on the path from a source to the seismic station, all other things being equal. As was shown in [2], the differences of *Lg*/*Pg* values of UNE records at the SNTS, especially for the Degelen site, where explosions were conducted in adits, is much smaller than for earthquakes. This makes it possible to reliably identify spatiotemporal variations of the S-wave attenuation field in the Earth's crust of different regions. In this work, the UNE records are used to study attenuation field variations in the Earth's crust of the Tien Shan region, first and foremost, for the paths that cross or pass near the source zones of strong earthquakes.

We analyzed the UNE records at the Degelen site in 1964–1989 obtained by 15 seismic stations in the Tien Shan and Turan Plate regions (Fig. 1). The majority of the data correspond to the TLG, KRM, and GRM stations. Records from the NVS station, where the paths from the SNTS transect the southern margin of the West Siberian Plate, were used for purposes of comparison. The epicentral distances varied from 730 to 1600 km.

We mainly processed records of analog frequency-selective seismic stations (FSSS [3]) with central frequencies of ~1 Hz. For some stations, we also used the records of vertical SKM-3 channels digitized with a frequency of 20 Hz and equipped with a filter (filter with central frequency = 1.25 Hz, width = 2/3 octave at the level 0.7 of the maximum, similar to the FSSS filter).

Figure 2 shows the *Lg*/*Pg*–time relationship established from the records of seismic stations NVS, KRM, and GRM. The plots demonstrate that Station NVS, the path to which is transected by the regions of low seismic activity, is characterized by insignificant variations of *Lg*/*Pg* (mainly, within 0.2–0.3). The *Lg*/*Pg* value decreased by ~0.1 in 1973–1981.

According to the data from Station KRM, situated ~10 km from the source zone of the Zhalanash–Tyup earthquake of March 24, 1978 ($M = 6.8$), the *Lg*/*Pg* value dropped markedly by 0.15–0.20 before this event (in 1976–1977). After the earthquake, the value of this parameter gradually increased, and the increment was ~0.35 in 1988–1989.

The paths from Degelen to GRM cross the source zones of the following three strong earthquakes: Garm (1941, $M = 6.5$), Khait (1949, $M = 7.4$), and Chatkal (1946, $M = 7.5$). As is evident from Fig. 1, the paths also pass at a distance of ~40 km from the Susamyr earthquake zone (August 19, 1992; $M = 7.3$). It should be noted that the curve $Lg/Pg(T)$ for Station GRM is very rugged in comparison with the curve for other stations (first of all, NVS), although the data on some time intervals were averaged over 2–3 yr. In this case, the average increment of the *Lg*/*Pg* value was ~0.55 in 1965–1978, remained at a nearly constant level until 1983, and then dropped by ~0.25 in 1987–1989 (Fig. 3). It is notable that a substantial decrease of *Lg*/*Pg* was recorded in 1965, 1966, and 1974, when the strongest

[1] *Schmidt Joint Institute of Physics of the Earth, Russian Academy of Sciences, Bol'shaya Gruzinskaya ul. 10, Moscow, 123995 Russia*

[2] *Institute of Geophysical Research, National Nuclear Center of Kazakhstan, Almaty, Kazakhstan; e-mail: sokolova@kndc.kz*

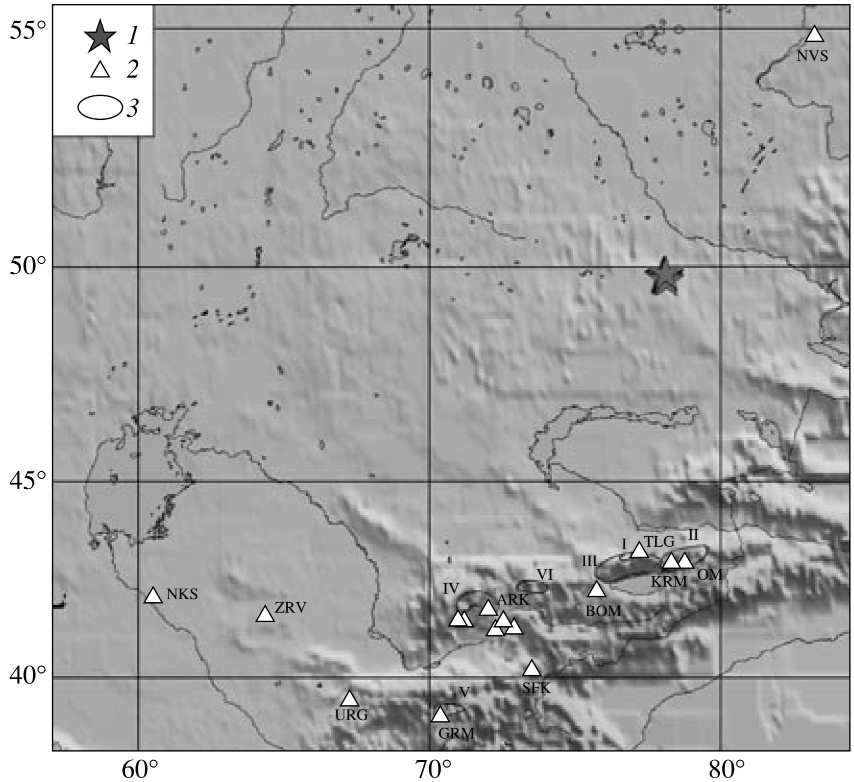

Fig. 1. Map of the study region. (*1*) UNE epicenter; (*2*) seismic stations; (*3*) source zones of strong earthquakes: (I) Verny, (II) Chilik (9-intensity isoseists), (III) Kemin (8-intensity isoseist), (IV) Chatkal (9-intensity isoseist), (V) Khait (8-intensity isoseist including a 8-intensity isoseist of the Garm earthquake), (VI) Susamyr (aftershock region). The 9-grade Zhalanash–Tyup earthquake zone (~35 km long) is localized within zone II.

deep-focus earthquakes (M = 7.7, 7.2, and 7.3, respectively) occurred in the Hindu Kush region. In contrast, an abrupt increase of this parameter was recorded approximately 1 yr after the strong crustal earthquakes in Sarykamysh (June 5, 1970; M = 6.8), Markansu (August 11, 1974; M = 7.3), and Zhalanazh–Tyup and Alai (November 1, 1978; M = 6.8).

The paths from the SNTS to the TLG station largely extend across the Kazakh Platform, which is characterized by a relatively low seismic activity. At the same time, three very strong earthquakes took place ~100 yr ago near this seismic station (Verny 1887, M = 7.3; Chilik 1889, M = 8.3; and Kemin 1911, M = 8.2). According to [2], the Lg/Pg value increased from 0.50 in 1964 to 0.75 in 1976 and then remained approximately at the same level (with small variations) until 1989.

Figure 3 shows the Lg/Pg–epicentral distance relationship. We used data from 1965–1966 for most of the stations and data from 1970–1971 for seismic stations SFK, ZRV, URG, and NKS. Data on both these time intervals were considered for Station GRM. As can be seen from the figure, the Lg/Pg values for Station TLG over 1965–1966 were much lower than for stations KRM, OM, and BOM situated to the east and west, respectively, from the Verny earthquake zone and near the 8-intensity isoseist of the Kemin earthquake at greater epicentral distances.

In 1965–1966, the ARK–GRM segment, which crosses the source zones of two earthquakes with M > 7.0, was marked by an anomalously rapid decrease of Lg/Pg with a distance relative to the average relationship for the Tien Shan and Turan Plate regions (based on the data reported in [4]). Moreover, even in 1970–1971, when this parameter markedly grew at Station GRM, it was 0.3–0.4 log units lower than for stations ZRV, URG, and NKS, where the paths bypass the source zones of the known strong earthquakes. It should also be noted that the paths to the aforementioned stations partly extend across the Turan Plate, which is characterized by relatively strong attenuation in comparison with the Kazakh Platform [5].

Since the Lg/Pg parameter characterizes the S-wave attenuation in the Earth's crust, its relatively rapid changes may be related only to variations in the free fluid content on the path from a source to the seismic station. Comparison of data for Group 1 (stations TLG, KRM, OM, and BOM) and Group 2 (stations GRM, ARK, RYA, YARD, TERS, KZD, and URG), with ranges azimuths to Degelen no more than 17° and 14°, respectively, shows that the main temporal change of the fluid field structure occurs at a relatively short dis-

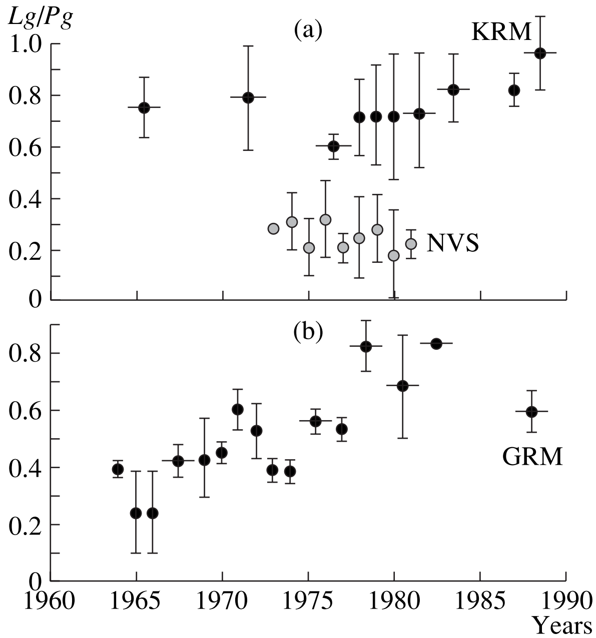

Fig. 2. The *Lg*/*Pg* vs. time relationship. (a) Stations NVS and KRM; (b) Station GRM. The average values, standard deviations, and averaging intervals are shown (the averaging interval equals 1 yr in other cases). The standard deviations do not exceed the size of symbols in two cases without the interval designation.

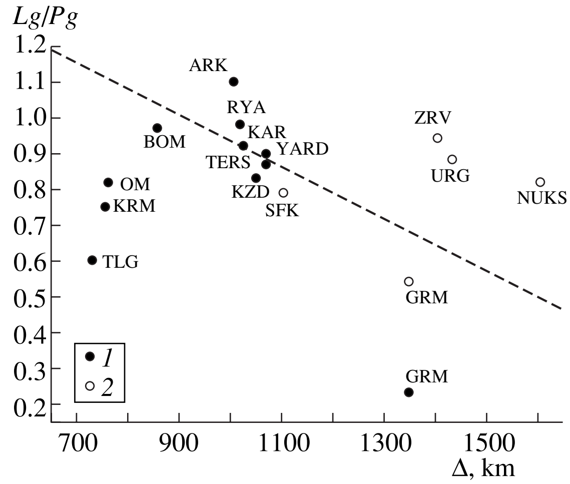

Fig. 3. The *Lg*/*Pg* vs. epicentral distance relationship for (*1*) 1965–1966 and (*2*) 1970–1971. The dashed line designates the average trend for the Tien Shan and Turan Plate regions.

tance from stations TLG, KRM, and GRM. The nearly constant *Lg*/*Pg* value for Station NVS, in combination with the relatively high values of this parameter for the stations situated in the Tien Shan and Turan Plate, where the paths do not pass near the sources of tectonic events with $M > 6.5$ that have taken place over the last century, testifies that the temporal *Lg*/*Pg* variations are, first of all, related to the variation of fluid content in and near the source zones of strong earthquakes and in close proximity to them.

Data on Station KRM indicate an increase of attenuation 1–2 yr before the Zhalanash–Tyup earthquake. Data on Station GRM suggest the possibility of a similar effect a few years before the Susamyr earthquake. These data are consistent with the previously drawn conclusions about the supply of mantle-derived fluids into the lower crust during the preparation of strong crustal events.

The mantle fluids also continue to ascend into the crust over 20–30 yr after the strong earthquakes [7], providing a high concentration in and near the source zones. At the same time, our data indicate that the fluid concentration is accompanied by a lateral fluid migration that reduces its average content in the source zones. Judging from the available data on the Zhalanash–Tyup earthquake zone, this process continued at least 11 yr after the event mentioned above. The respective estimates for the Chatkal and Khait earthquakes are ~30 and 60–65 yr, respectively.

The relatively high *Lg*/*Pg* values for stations KRM and OM, where the paths intersect the source zone of the Chilik earthquake, show that fluid migration most likely continued here for no longer than 75 yr.

The available geochemical data also testify to the spreading of the fluid spot with time. For example, submantle values of the helium isotope ratio were detected in the nearly latitudinal (~100-km-wide) belt, which includes the Zailii Alatau Range and a considerable part of the Ilii Basin [8], in the northern Tien Shan region near the source zones of two earthquakes with $M > 8$.

The discovered effect is basically similar to the lateral magma flow along fractures during volcanic eruptions [9]. However, the fluid spreading rate is several orders of magnitude lower. This can be explained by a much larger volume of erupted magma and its higher density and pressure relative to the respective parameters of the juvenile water [10].

It may be suggested that diffusion of fluids (largely, water) mainly occurs in the uppermost crust with a high permeability. In this connection, let us note that the S-wave velocity drops by nearly 30% at a depth of 0–5 km due to the presence of free water over the vast area in the central Tien Shan [11].

The relatively short-term (1–2-yr-long) variations of the *Lg*/*Lp* value recorded by Station GRM may locally be related to the supply of additional portions of fluid from the upper mantle into the Earth's crust in the Garm test area after the strongest deep-focus Hindu Kush earthquakes [12], with sources localized ~250–300 km away from the seismic station. The variations might also be caused by acceleration of lateral fluid migration after the strong crustal events due to the increase in permeability under the impact of seismic waves [13].

In conclusion, let us note that lateral water diffusion may also occur in the upper crust of regions with a low seismic activity due to long-term and intense technogenic impacts (e.g., numerous underground nuclear explosions at the SNTS). In particular, this is confirmed by the detection of a thermal anomaly that is several times wider (relative to the test site area) near the SNTS region [2, 14].

ACKNOWLEDGMENTS

This work was partly supported by the Ministry of Science and Technology of the Russian Federation, project no. KR-837).

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