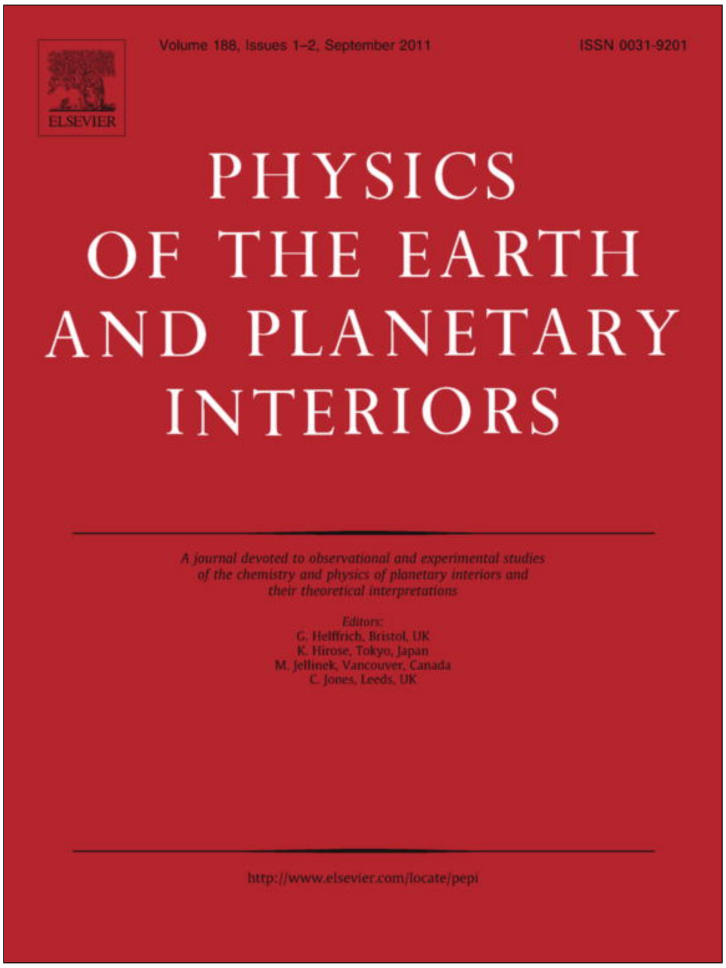

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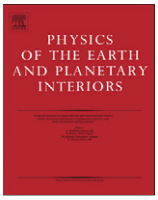

Short communication

Coda-wave attenuation in the Baikal rift system lithosphere

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A B S T R A C T

Using the single backscattering model a seismic quality factor (Q_C), a frequency parameter (n) and an attenuation coefficient (δ) have been studied by analyzing the coda waves of local earthquakes of Baikal rift system. The Q_C values were estimated at 6 central frequencies and for 8 lapse time windows W from 20 to 90 s. The average Q_C varies with frequency from 46 ± 45 (at 0.3 Hz) to 1025 ± 221 (at 12 Hz). The δ values show significant variations from 0.009 km^{-1} (for $W = 20$ s) to 0.003 km^{-1} (for $W = 90$ s). Increasing of Q and decreasing of n values with lapse time windows show that the lithosphere upper part is more heterogeneous as against its lower layers.

1. Introduction

The seismic quality factor Q is a non-dimensional parameter describing the attenuation of the seismic energy when the seismic wave propagates in the geological medium. For the first time the possibility of determination of the seismic quality factor using the coda waves (as the nature of the coda wave) was considered by Aki (1969) and Aki and Chouet (1975). For explaining of the coda waves existing Aki suggested a single backscattering model which explains the coda waves as a superposition of the secondary waves reflected from heterogeneities randomly distributed in the crust and the upper mantle. The decrease of the seismic energy in the coda wave is due to energy attenuation, scattering and geometrical spreading; it's independent on source pattern, path effect and site amplification and gives a chance to numerically calculate of the seismic quality factor.

At present the coda waves are widely used for computation of the seismic wave attenuation in the crust and the mantle. Comparison of the attenuation parameters for different tectonic settings showed that active tectonic areas are characterized by the low values of the quality factor ($Q < 200$), stable tectonic regions are characterized by the high Q-values ($Q > 600$) while for areas with moderate tectonic activity the Q values varies within 200–600 (Mak et al., 2004).

In this work the seismic quality factor (Q_C) has been studied by analyzing the coda waves of 274 local earthquakes of Baikal rift system. In spite of the high seismic activity of the region, the Q-factor is known only for the some local areas of Baikal rift system. Using the dominant period method the Q value was obtained for Tyva republic and Olkhon island (Zhadin and Dergachev, 1973). The method of the coda-wave was used for the calculations of the Q-factor for Barguzin and Muya-Chara basin region, for south-western part of rift system (Rautian et al., 1981; Kopnichev, 1991; Potapov et al., 1997). The values of the quality factor for the direct P- and S-waves were obtained using the local temporary seismic station networks for the some local areas such as central part of Baikal rift, Barguzin and North-Muya regions (Dergachev, 1982; Bukina et al., 1983; Kochetkov et al., 1985). During active seismic experiments the attenuation parameters of P- and S-waves for the crust and the upper mantle of Siberian platform (Egorkin et al., 1981) and P-waves propagating along and across an active faults of Transbaikal area (Emanov et al., 1999) were computed. The highly sensitive digital instrumentation of the seismic stations of the region in 1998–2003 improved appreciably the conditions of the recording of seismic events in the Baikal rift system and made it possible to estimate the quality factor of the lithosphere of Baikal rift system by the coda wave method (Dobrynina et al., 2010).

2. Tectonic settings

Baikal rift system is located in North Eurasia (Fig. 1) and is the second largest continental rift system in the world. It stretches along the edge of the Siberian platform, 1600 km from North Western Mongolia, through the mountain structures of East Siberia to South Yakutia and consists of a linear system of the uplifts and the basins, bordered by the faults of the predominantly normal faulting kinematic type (Logatchev and Florensov, 1978). In

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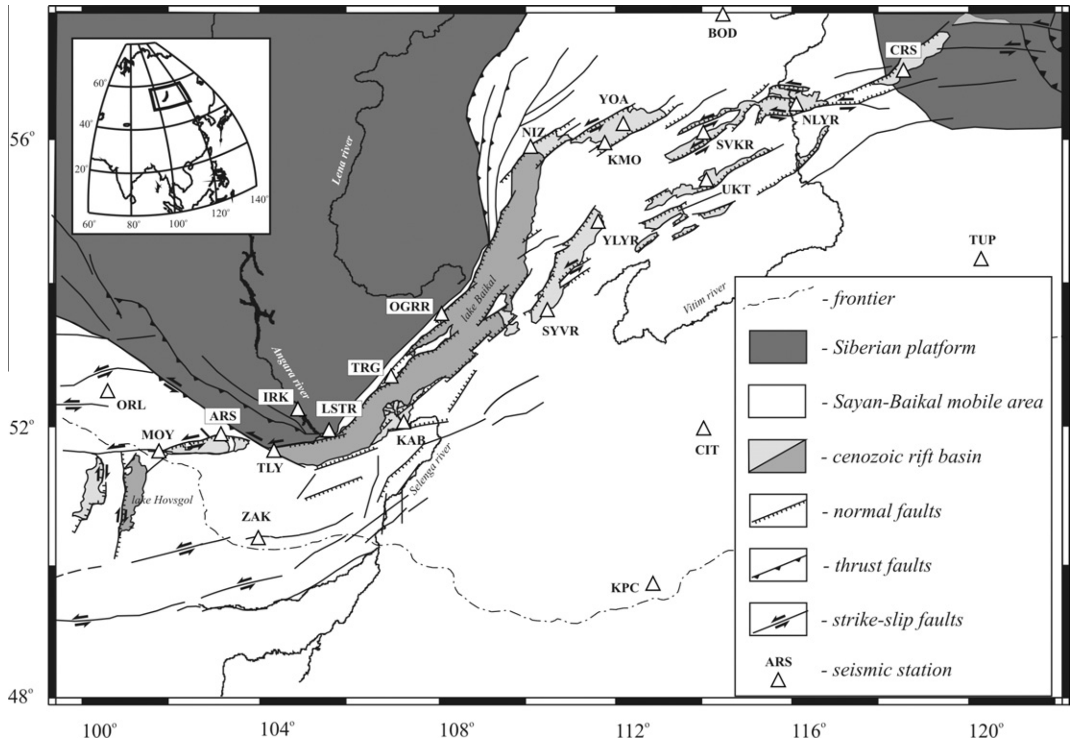

Fig. 1. Baikal rift system, in the inset the study region location is shown.

neotectonic sense Baikal rift system is confined to the boundary of North Eurasian and Amurian lithospheric plates. The high contemporary mobility in between the plates determines the high level of the seismic activity taking place there: since 1950 the 13 earthquakes with magnitude $Ms \geqslant 6.0$ occurred here according to the data of Baikal Regional Seismological Center of Geophysical Survey of Siberian Branch of Russian Academy of Sciences (BRSC GS SB RAS). The maximum quantities of earthquakes are confined directly to the rift system, Siberian platform is practically aseismic area and Transbaikalia region is characterized by a low level of seismic activity. The earthquakes are localized in the upper crust with the maximum in the range of 10–20 km (Radziminovich, 2010, references herein). According to the deep sounding data (Mats et al., 2001) the crustal thickness under South Baikal basin varies within 35–57 km, under North Baikal basin – 40–42 km, under uplifts of the NE part of the rift system – 43–55 km, under uplifts of for the SW part of Baikal rift system – 43–55 km and under Siberian craton – 37–43 km. The results of the structural studies (Sherman and Dneprovsky, 1989; San'kov et al., 1997), the GPS geodesy measurements (Calais et al., 2003) and the calculations of the seismotectonic deformations (Petit et al., 1996) indicate that the extension regime is dominate at the central part of the rift system. For its wings, increasing of the role of the strike-slip type of tectonic stresses is characteristic. An oblique extension relative to the axis of the rift structures is established for the northeastern part of the rift system and a strike-slip with compression is revealed for its southwestern part.

3. Methods

For the quality factor estimation the single backscattering model was used (Aki, 1969; Aki and Chouet, 1975). According to this model the coda waves have been explained as a superposition of the secondary waves reflected from heterogeneities randomly distributed in the lithosphere. The attenuation of the seismic waves is due to energy attenuation and geometrical spreading and independent on earthquake source, path effect and site amplification (Aki, 1969). Generally, the Q-factor increases with the frequency following the next relation (Mitchell, 1981):

$$Q_C(f) = Q_0 \cdot \left(\frac{f}{f_0}\right)^n, \tag{1}$$

where Q_C – the quality factor for coda waves, Q_0 – the Q_C value at reference frequency f_0 (generally $f_0 = 1$ Hz), n is the frequency parameter, which is close to 1 and varies from region to region (Aki, 1981). The frequency parameter n characterizes the medium and increases with tectonic activity of the region: $n < 0.5$ for stable tectonic regions, $n = 0.3$–0.8 for moderate areas and $n > 0.8$ for active tectonic regions (Mak et al., 2004). The relation (1) indicates that the attenuation of the seismic waves with the distance from the source is different for different frequencies. The amplitude of the coda wave A at lapse time t seconds from the origin time for a bandpass-filtered seismogram at the central frequency f is related to the attenuation parameter Q_C by the following equation:

$$A(f,t) = S(f) \cdot t^{-\alpha} \cdot \exp\left(\frac{-\pi \cdot f \cdot t}{Q_C(f)}\right), \tag{2}$$

where $S(f)$ – the coda wave source factor at frequency f, α – the geometrical spreading parameter, $\alpha = 1$ for the body waves (Sato and Fehler, 1998). Eq. (2) can be rewritten as:

$$\ln(A(f,t) \cdot t) = \ln(S(f)) - \frac{\pi \cdot f \cdot t}{Q_C(f)}, \tag{3}$$

The Q_C value is determined from the slope of a least-squares straight-line fit between $\ln(A(f,t)\,t)$ versus time t. According to Rautian and Khalturin (1978), the above relations are valid for lapse times greater than twice the S-wave travel time.

4. Data

The digital data used in the present work were obtained by the permanent regional network of the short-period digital seismic stations of BRSC GS SB RAS (network code BYKL). The network consists of 23 stations, nineteen of which are located directly within the rift system (Fig. 1). For the Q-factor estimation 274 local events with magnitude $M_L = 3.1–5.4$ occurred within Baikal rift system were selected (Fig. 2). The hypocentral distances of the events mainly range within 15–300 km. The covering of the study region by the seismic traces "source – receiver" is shown on Fig. 2. The most of them are crossed the rift structures. The Q values are calculated through the CODAQ subroutine of SEISAN (Havskov and Ottemoller, 2006). The time of the processing beginning is taken at twice the S-wave travel time. The Q values were estimated at the six central frequencies 0.3, 0.75, 1.5, 3, 6, 12 Hz and for the eight lapse time windows: 20, 30, 40, 50, 60, 70, 80 and 90 s.

5. Results and discussion

The final Q-factor determination is based on about 15,500 individual measurements. The average Q_C value increases with increasing of the frequency and the lapse time window length from 46 ± 45 (at 0.3 Hz) to 1025 ± 221 (at 12 Hz) for $W = 20$ s and from 113 ± 48 (at 0.3 Hz) to 1995 ± 751 (at 12 Hz) for $W = 90$ s (Fig. 3a).

There is no unique opinion about the depths producing of coda waves. The single backscattering model assumes that the scattering wave field is weak and does not produce secondary scattering when it encounters another scatterers; it gives the possibility to approximately estimate the depths of the coda waves forming (Pulli, 1984). At the same time opinion about the coda forming due to the multiple scattering within the upper crust exists (Gao et al., 1983). According to Pulli (1984) the obtained value of Q characterizes some volume of the lithosphere, presumably an ellipsoid. The source and the seismic station are located in its foci. Ellipsoid equation can be written as:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1, \tag{4}$$

where x, y, z – the ellipsoid coordinates, a, b, c – the ellipsoid's semi-axes, a, b – the largest and the smallest axes of the surface projection of ellipsoid, c – the lower border of the ellipsoid.

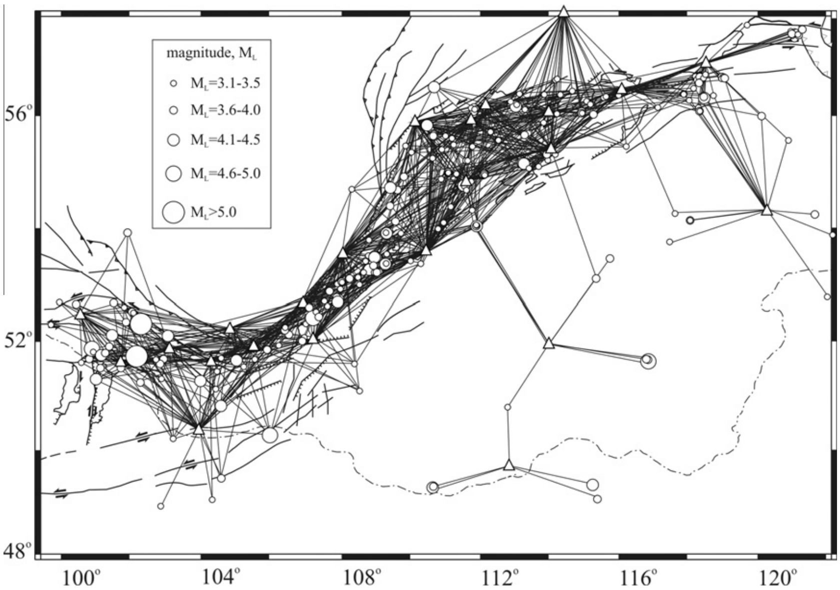

Fig. 2. Map of the covering of the study area by the seismic traces "source – receiver".

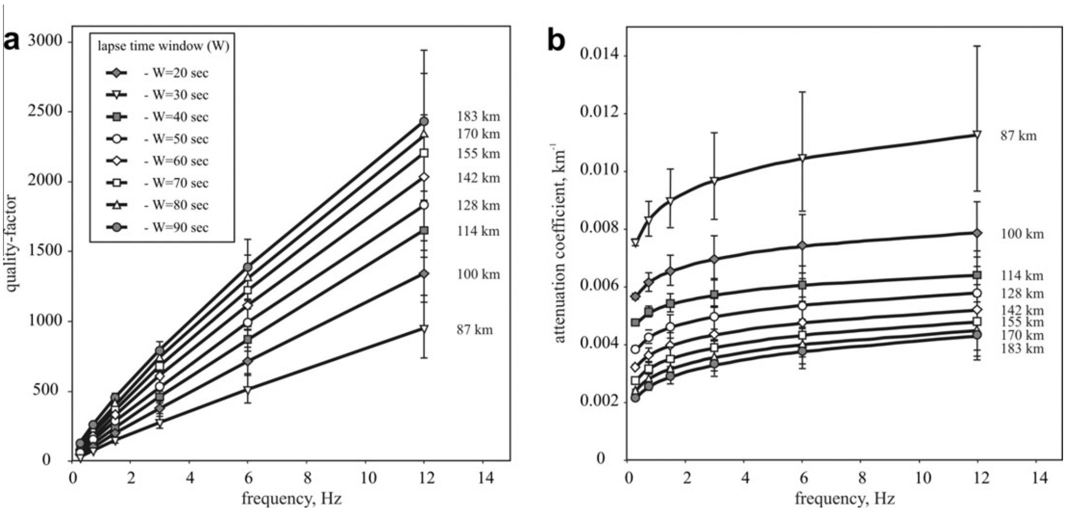

Fig. 3. Plots of the mean Q_C (a) and δ (b) values of the each lapse time window as a function of the frequency. For each W the respective ellipsoid lower border c (km) is shown (on right). The standard deviations are shown by the bars.

$$a = \frac{V_C \cdot t_a}{2}, b = \sqrt{a^2 - \frac{r^2}{4}}, c = h + b, \tag{5}$$

where V_C – the coda-wave velocity, generally it's equal the *S*-wave velocity (V_C = 3.55 km/sec), *r* – the distance "source – receiver", *h* – the earthquake depth, t_a – the average length of the time window which are determinate as:

$$t_a = t_{start} + \frac{W}{2}, \tag{6}$$

where t_{start} – the origin time for the coda processing, *W* – the length of the lapse time window.

In other words the sizes of the study area are dependent on the lapse time window and on the distance from the source to the receiver. Thus, changing lapse time window *W*, we can see the changing of the $Q_C(f)$ with the depth. In the present study the average epicentral distance *r* for the selected events is equal 140 km, the average value t_{start} = 77 s. Since there are no the reliable earthquake depth determinations for the selected events, the average depth *h* = 15 km according to (Radziminovich, 2010) was used. The estimated sizes of the ellipsoid axes are presented in Table 1.

The relation between the quality factor and the frequency for the different lapse time are shown on Fig. 3a. The empirical relations $Q_C(f)$ according to Eq. (1) were obtained for the all *W* values (see Table 1). The Q_0 values vary from 103 to 325 and *n* values range between 0.92 and 0.81 for the different lapse time windows.

The attenuation coefficient δ is determinate from the Q_C as:

$$\delta = \frac{\pi \cdot f}{V_C \cdot Q_C}, \tag{7}$$

The attenuation coefficient's dimension is (km^{-1}). The obtained δ values vary from 0.0086 ± 0.0008 to 0.0027 ± 0.0002 km^{-1} depending on *W* (see Table 1). The best fit of the frequency dependence of the attenuation coefficient is the power-law (Fig. 3b):

$$\delta(f) = (\delta_0 \pm \sigma_\delta) f^{(\eta \pm \sigma\eta)}, \tag{8}$$

where δ_0 – the attenuation coefficient at frequency 1 Hz, η – the frequency dependence of δ and σ_X – the standard deviation. The variation of the attenuation coefficient with depth may be present by the power-law also:

$$\delta = 7.03c^{-1.52} \quad \text{for } f = 1 \text{ Hz} \tag{9}$$

On Fig. 4 the variations of the attenuation coefficient δ for different frequencies with increasing of the depth of the ellipsoid lower border *c* are shown. The regression coefficients in Eq. (9) vary for different frequencies from 12.68 (at 0.3 Hz) to 2.08 (at 12 Hz) for the multiplier and for the exponent from −1.67 (at 0.3 Hz) to −1.20 (at 12 Hz).

In spite of significant quantity of studies of the quality factor of lithosphere the reason of the frequency dependence of *Q* is not clear. According to Aki's hypothesis (Aki, 1980) the frequency variations of *Q*-factor is related to the heterogeneities randomly distributed in the lithosphere. In the latest investigations (Sato and Fehler, 1998; Mak et al., 2004) it is shown that there is a consistent relation between the frequency dependence of *Q* and tectonic framework in the studied areas. It's also shown that regional variation of *Q*-factor is related to the age of crust and the level of tectonic activity of studied areas; higher attenuation correlates with lower crustal and upper mantle *Pn* velocities (Cormier, 1982). The fact that the attenuation in direction normal to the main direction of faults and cracks in lithosphere is stronger than other ones may be an additional evidence of Aki's assumption. Recently a new geometrical attenuation model is suggested as an alternative to the conventional power-law $Q(f) = Q_0(f/f_0)^n$ (Morozov, 2008). This model divides between the geometrical attenuation (correlates with crustal tectonic types and age of Earth's crust) and effective attenuation (it's frequency-independent and shows no significant correlation with tectonic age) which includes the intrinsic attenuation and small-scale scattering. Using of this new geometrical model may results in significant changes in the interpretations (Morozov, 2008). In our study for interpretation of obtained results the "standard" Aki's single backscattering model was used (Aki and Chouet, 1975). According to this model the frequency dependence of *Q* shows the level of tectonic activity of the studying region. The high frequency parameter (*n* = 0.89) and low quality factor (Q_C = 103) values denote a high tectonic activity in Baikal rift.

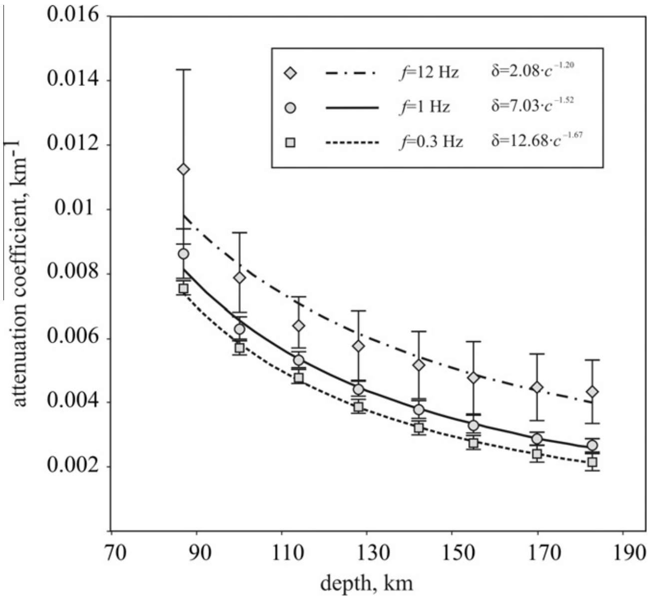

Fig. 4. Plot of the attenuation coefficient δ versus the depth of the ellipsoid lower border. The standard deviations are shown by the bars.

The power dependence between δ and *c* (Fig. 4, Eq. (9)) is the evidence of the fact that decreasing of the attenuation with the depth in the upper part of the lithosphere is faster than in its lower part. According to the obtained attenuation characteristics for the

Table 1
Length of ellipsoid's axes and attenuation parameters (Q_0, *n*, δ) for study region.

W (s)	*a* (km)	*b* (km)	*c* (km)	Q_0	σ_Q	*n*	σ_n	δ (km^{-1})	σ δ (km^{-1})	η	σ_η
20	154	72	87	103	9	0.89	0.06	0.0086	0.0008	0.11	0.06
30	149	85	100	140	9	0.91	0.04	0.0063	0.0004	0.09	0.04
40	156	99	114	168	8	0.92	0.03	0.0053	0.0003	0.08	0.03
50	165	113	128	201	14	0.89	0.05	0.0044	0.0003	0.11	0.05
60	178	127	142	234	18	0.87	0.05	0.0038	0.0003	0.13	0.05
70	190	140	155	267	22	0.85	0.06	0.0033	0.0003	0.15	0.06
80	204	155	170	298	24	0.83	0.06	0.0029	0.0002	0.17	0.06
90	217	168	183	325	25	0.81	0.06	0.0027	0.0002	0.19	0.06

σ_X – standard deviations of the respective value.

different lengths of the lapse time window the frequency parameter n decrease from 0.89 to 0.81 with increasing of the depth or the ellipsoid lower border (see Table 1); this fact shows that the upper crust is more heterogeneous than the lower part. Additionally, the most earthquakes of Baikal rift are localized in the upper crust with the maximum in the range of 10–20 km (Radziminovich, 2010, references herein). And obtained low Q_C and high n values reflect the faulted structure of the upper crust. Increasing of the Q_C values and decreasing of the attenuation coefficient δ and the frequency parameter n with increasing of the length of the lapse time window (and, correspondently, the depth) show that heterogeneity of the lithosphere decreases with the depth since a high pressure in the lower part of the crust reduces to closing a cracks and to appearance of a plastic deformation.

The empirical relations $Q_C(f)$ (according to Eq. (1)) were obtained also for three parts of the study region: Siberian platform (seismic station IRK), Transbaikalia area (seismic stations TUP, CIT and KPC) and rift system (all the rest seismic stations). For stable ancient Siberian platform the quality factor dependence on the frequency is: $Q_C(f) = (134 \pm 26)f^{(0.48\pm0.12)}$; for Transbaikalia area characterized by low level of seismic activity: $Q_C(f) = (115 \pm 10)f^{(0.90\pm0.06)}$ and for seismically active rift system: $Q_C(f) = (100 \pm 9)f^{(0.91\pm0.06)}$. The frequency parameter n characterizing of heterogeneity of the medium is high for rift system and Transbaikalia area ($n = 0.90$–0.91) that agrees with destruction of the lithosphere by an active faults within these areas while the low value of the frequency parameter for Siberian platform ($n = 0.48$) agrees with a low level of the lithosphere's destruction in this region.

Comparison of the attenuation parameters for Baikal rift system and different tectonic region of the World shows that the relation $Q_C(f)$ for study area agrees with ones for tectonic active regions such as Himalaya ($Q_C(f) = 110f^{1.02}$) (Gupta and Kumar, 2002), Central Iran ($Q_C(f) = 101f^{0.94}$) (Ma'hood and Hamzehloo, 2009) and south of Central Alaska ($Q_C(f) = 158f^{0.79}$) (Dutta et al., 2004). At the same time the frequency parameter for Siberian platform ($n = 0.48$) agrees with ones for tectonically stable and moderate areas: North Iberia ($n = 0.45$) (Pujades et al., 1991), Canadian Shield ($n = 0.35$) (Hasegawa, 1985) and New England ($n = 0.40$) (Pulli, 1984).

The attenuation parameters obtained in this study are an evidence of the high tectonic activity of the investigated region (Mak et al., 2004). This fact agrees with the high seismic activity of Baikal rift system and the high velocity of the contemporary horizontal tectonic movements according to the data of the GPS measurements (Calais et al., 2003). Thus the lithosphere under the Baikal rift system's structures is characterized by the high level of the attenuation and heterogeneity that may be closely connected with an active process of the contemporary destruction of the lithosphere (Sherman, 1978) and with the high heat flow of the Earth's interior (Lysak, 1978).

6. Summary

Using the coda waves of 274 local earthquakes the seismic quality factor (Q_C), the frequency parameter (n) and the attenuation coefficient (δ) have been studied for the lithosphere of Baikal rift system and surroundings. The relations between the quality factor and the frequency were obtained for three main area of the study region: stable Siberian platform, Transbaikalia area with moderate tectonic activity and seismically active rift system. Increasing of the quality factor value and diminution of the frequency parameter with increasing of the lapse time windows (or depth) show that the upper part of the lithosphere is more heterogeneous as against its lower layers. The empirical relation between the attenuation coefficient and the depth of the ellipsoid lower border characterizing of the distribution of the structural heterogeneities in the different deep levels in the lithosphere is obtained.

7. Data and resources

Waveforms, catalogs and bulletins of earthquakes used in this study were collected by Baikal Regional Seismological Center of Geophysical Survey of Siberian Branch of Russian Academy of Sciences (http://www.seis-bykl.ru/).

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