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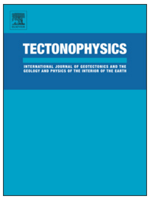

Spatial changes of seismic attenuation and multiscale geological heterogeneity in the Baikal rift and surroundings from analysis of coda waves

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ABSTRACT

The Baikal rift system is undergoing an active tectonic deformation expressed by a high level of seismic activity. This deformation leads to physical and mechanical changes of crustal properties which can be investigated by the seismic quality factor and its frequency dependence. Using a single backscattering model, a seismic quality-factor (Q_C), a frequency parameter (n) and an attenuation coefficient (δ) have been estimated by analyzing coda waves of 274 local earthquakes of the Baikal rift system for nineteen lapse time windows (W) from 10 to 100 s every 5 s and for six central frequencies (0.3, 0.75, 1.5, 3, 6 and 12 Hz). The average Q_C value increases with the frequency and lapse time window from 46 ± 52 (at 0.75 Hz) to 502 ± 109 (at 12 Hz) for $W = 10$ s and from 114 ± 49 (at 0.3 Hz) to 1865 ± 679 (at 12 Hz) for $W = 100$ s. The values of $Q_C(f)$ and δ were estimated for the whole Baikal rift system and for separate tectonic blocks: the stable Siberian Platform, main rift basins, spurs and uplifts. Along the rift system, the Q_0-value (Q_C-factor at the frequency $f = 1$ Hz) varies within 72–109 and the frequency parameter n ranges from 0.87 to 1.22, whereas Q_0 is 134 and n is 0.48 for the stable Siberian Platform. Vertical variations of attenuation reveal that sharp changes of δ and n are confined to the velocity discontinuities. The comparison of lateral variations of seismic wave attenuation and geological and geophysical characteristics of the Baikal rift system shows that attenuation is correlated with both seismic activity and heat flow and in a lesser degree with the surface fault density and the age of the crust. Seismic wave attenuation found across the main shear zones of the south-western Baikal rift (Main Sayan strike-slip fault zone and Tunka, Obruchev and Primorsky normal faults) is increased by more than 25–60% compared to the neighboring areas.

1. Introduction

The attenuation of seismic waves is referred to as the decrease in the amplitude (or the energy) when the seismic wave propagates within the geological medium. Seismic wave energy decreases because of multiple scattering and intrinsic attenuation (e.g. Sato et al., 2012 and references therein). Seismic wave scattering reflects elastic properties of the medium and is produced by irregular topography, complex surface geology, faults and cracks and other small-scale heterogeneities of crustal or mantle rocks. These heterogeneities generally decrease with depth and are hardly resolved by conventional tomographic methods. Conversely, absorption depends on anelastic properties of the medium such as viscous dissipation or fluid flow within the fault network (Mavko et al., 2009; Sato et al., 2012). In order to describe the seismic wave attenuation, a non-dimensional parameter Q (quality factor) is commonly used, which is defined as the ratio of the wave energy to the energy dissipated per cycle of oscillation (Knopoff and Hudson, 1964; Aki and Chouet, 1975).

Several methods of Q-factor determination were developed, based either on active or on passive seismic experiments. In the latter case, the seismic Q-factor may be obtained for direct P-(Q_P), S-(Q_S) or coda waves (Q_C). Coda wave analysis is the widely used method (see e.g. Aki and Chouet, 1975; Rautian and Khalturin, 1978; Singh and Herrmann, 1983; Pulli, 1984; Gusev, 1995; Sato et al., 2012; Mak et al., 2004; Ma'hood and Hamzehloo, 2009; Dobrynina, 2011; Kopnichev and Sokolova, 2012). Aki (1969) and Aki and Chouet (1975) were among the first ones to have determined the seismic quality factor using coda waves. For explaining the coda wave pattern, Aki suggested a single backscattering model which explains the coda waves as a superposition of secondary waves reflected by the heterogeneities randomly distributed in the crust and the upper mantle (Aki, 1969; Aki and Chouet, 1975; Rautian and Khalturin, 1978). Seismic wave attenuation

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is strongly dependent on the frequency; this dependence is typically described by a power law (Mitchell, 1981):

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

where Q_C is the quality-factor for the coda waves, Q_0 is the Q_C value at the reference frequency f_0 (usually $f_0 = 1$ Hz), and n is the frequency parameter, which varies from place to place depending on the heterogeneity of the medium (Aki and Chouet, 1975). The Q_C and n values are assumed to partly reflect the tectonic activity of the corresponding region: indeed, for tectonically active regions, Q_C decreases in the frequency range 0.1–25 Hz (Aki, 1982) and has a strong dependence on n-value in the frequency range 1.5–25 Hz (Aki and Chouet, 1975).

Since the development of dense seismic arrays in the 90's, coda wave analyses at high frequencies have been used to quantify the spatial changes of absorption and scattering properties of the continents, leading to a better understanding of the origin of attenuation (e.g. Calvet et al., 2013; Mayor et al., 2014, and references therein). The comparison of attenuation parameters for different tectonic settings has shown that (1) active tectonic areas are characterized by low Q_C-values ($Q_C < 200$) and high n-values ($n > 0.8$), (2) stable tectonic regions are characterized by high Qc-values ($Qc > 600$) and low n-values (<0.5), and (3) Qc-values for areas with moderate tectonic activity vary within these values (Sato and Fehler, 1998; Mak et al., 2004).

In this work, the seismic quality-factors (Q_S and Q_C), their frequency dependence (n) and the attenuation coefficient (δ) are studied by analyzing the body S- and coda waves of local earthquakes of the Baikal rift system (BRS, Fig. 1). Not many studies of quality factor have been done in the Baikal rift system: the Q-factor is known only for some local areas of the Baikal rift system. Earlier, using the method of the predominant periods, the Q_S value was obtained for the Olkhon island ($Q_S = 1000–2000$), the Barguzin, Muya and Chara basins ($Q_C = 140–700$, periods $T = 0.6–1.7$ s), the south-western part of BRS ($Q_C = 150$), and qualitative map of the coda wave attenuation in the upper mantle was estimated (Dobrynina, 2011, and references therein). Values of the quality-factor from direct P- and S-waves were obtained using local, temporary seismic networks for some local areas such as the central part of the Baikal rift ($Q_S = 400$ and $Q_S = 1400$ for frequencies $f = 2$ and 8 Hz), the Barguzin ($Q_P = 500$, $Q_S = 400$) and the North-Muya ($Q_S = 250$) regions (Dobrynina, 2011 and references therein). Finally, an active seismic experiment has provided attenuation parameters of P- and S-waves for the crust and the upper mantle of the Siberian Platform ($Q_P = 168$, $Q_S = 340$, $f = 1–6$ Hz, epicentral distances $\Delta = 18–181$ km, $Q_P = 154$, $Q_S = 508$, $f = 1–8$ Hz, $\Delta = 9–148$ km) and the quality-factor for P-waves propagating along ($Q_P = 157$) and across ($Q_P = 82$) the active faults of the Transbaikal area (Dobrynina, 2011, and references therein). Attenuation parameters were also approximated for the SW Baikal rift system and for the whole rift system on the basis of a limited data set (Dobrynina, 2011; Dobrynina et al., 2011). However, the use of different methods for attenuation parameter determination results into some important discrepancies or inaccuracies. Actually, there have been no data on the quality-factor for the whole Baikal rift system until now.

Values of seismic quality factor, frequency parameter, attenuation coefficient and their variations with depth have also been obtained worldwide, for instance in the southern part of the Kenya rift and in the northern Basin and Range Province (Dobrynina et al., 2012;

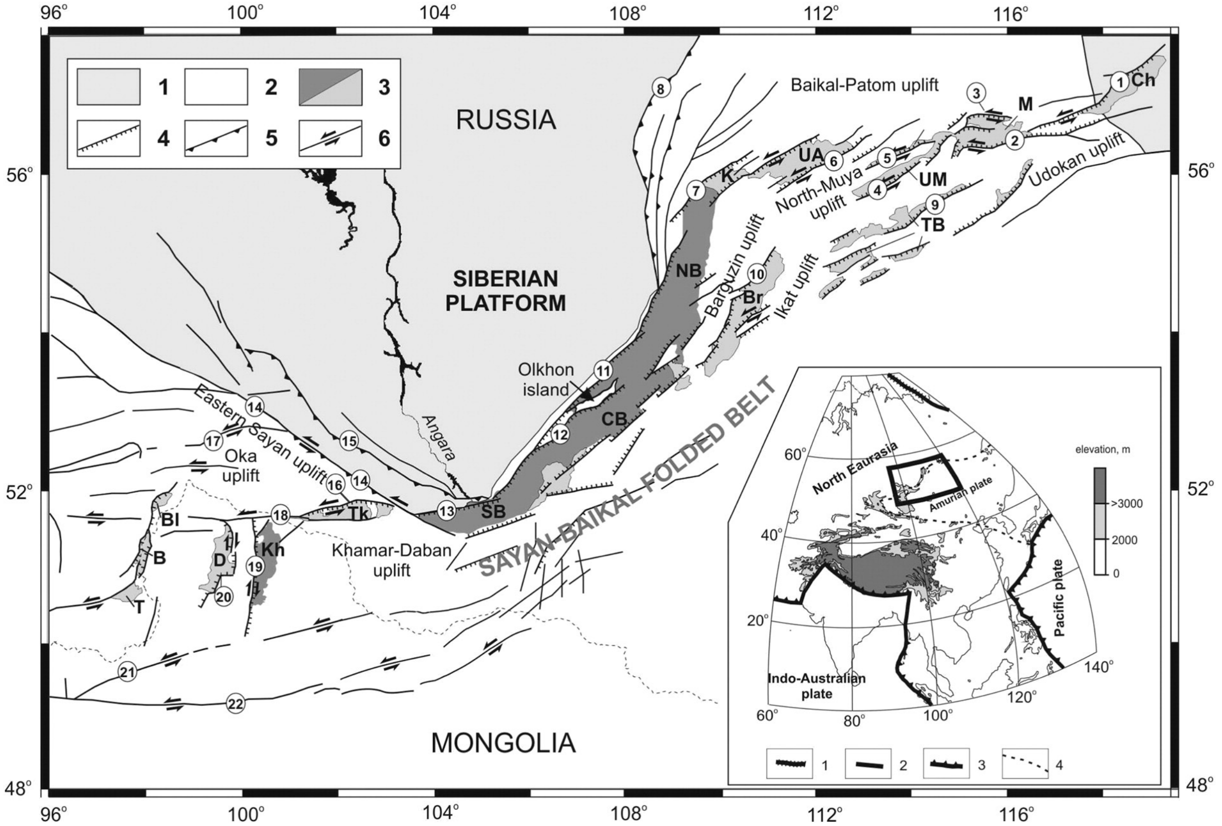

Fig. 1. Neotectonic scheme of the Baikal rift system and surroundings. 1 — Siberian platform; 2 — Sayan-Baikal folded area; 3 — Cenozoic rift basins: Ch — Chara, M — Muya, UM — Upper Muya; TB — Tsipa-Baunt; UA — Upper Angara; K — Kitchera; NB — North Baikal; Br — Barguzin; CB — Central Baikal; SB — South Baikal; Tk — Tunka; Kh — Khubsugul; D — Darkhat; Bl — Belinskaya; B — Busingol; T — Terekhol; 4–6 — faults: 4 — normal; 5 — thrust and reverse; 6 — strike-slip. Numbers within circles denote main faults: 1 — Kodar; 2 — South-Muya; 3 — North-Muya; 4 — Upper Muya; 5 — Muyakansky; 6 — Upper Angara; 7 — Kitchera; 8 — Akitkan; 9 — Tsipa-Baunty; 10 — Barguzin; 11 — Primorsky; 12 — Morskoy; 13 — Obruchev; 14 — Main Sayan Fault; 15 — Peredovoy; 16 — Tunka; 17 — Okino-Zhombolok; 18 — Baikal-Mondy; 19 — Khubsugul; 20 — Darkhat; 21 — Tsetserleg; 22 — Bolnai (Khangai). Inset locates the study region within Asia: 1 — study zone; 2 — mains strike-slip faults; 3 — subduction zones; and 4 — Amurian plate boundary.