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CodaNorm: A software package for the body-wave attenuation calculation by the coda-normalization method

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ABSTRACT

The presented software package *CodaNorm* is an open source seismological software and allows the estimation of the seismic quality factor (Q_P, Q_S), its frequency dependence (n) and attenuation decrement (γ) for body P- and S-waves by the coda-normalization method for different frequency ranges selected by a user. Obtained data about the seismic wave attenuation are necessary to correct the decay shake model from the earthquakes on the traces from the seismically active zones in the main urban areas, as well as for the further calculation of synthetic accelerograms and the evaluation of the parameters of the vibration for the possible strong earthquakes and etc.

The software package *CodaNorm* was applied for the estimation of the attenuation of the body P- and S-waves in the area of the South and Central Baikal (Baikal rift system, Southern Siberia, Russia) using 185 regional earthquakes with magnitude $Ml = 2$–5. The calculations were carried out for eight traces crossing the rift system in different directions and for the frequency range from 0.5 to 16 Hz. In the low frequency area the coincidence of the values of the seismic quality factor for P- and S-waves (Q_P and Q_S, respectively) is observed while for the high frequencies (8–16 Hz) the ratio between quality factors is $Q_S \approx 1.7Q_P$. Such difference is the evidence of different absorption of longitudinal and transverse waves by geological medium. The comparison of the attenuation parameters for different azimuthal traces showed that higher attenuation is observed for the traces crossing the rift system in normal direction to the main tectonic structures. This fact may reflects the differences between the local elastic properties of the crust of the Baikal rift system and the high heterogeneity of the medium.

Code metadata

Current code version	*0.1*
Permanent link to code/repository	https://github.com/ElsevierSoftwareX/SOFTX-D-15-00038
Legal Code License	*GNU General Public License, Version 2*
Code versioning system used	*Git*
Software code languages, tools	*Python*
Compilation requirements	*None*
Link to developer documentation/manual	https://github.com/cormorant/CodaNorm/wiki
Support email for questions	crmpeter@gmail.com

Software metadata

Current software version	*0.1*
Permanent link to executables of this version	https://github.com/cormorant/CodaNorm/
Legal Software License	*GNU Lesser General Public License*
Computing platforms/Operating Systems	*Crossplatform*
Installation requirements & dependencies	*Python 2, Numpy, Scipy, Matplotlib, Obspy*
Link to user manual	https://github.com/cormorant/CodaNorm/wiki
Support email for questions	crmpeter@gmail.com

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1. Motivation and significance

The information on the regional attenuation parameters (the seismic quality factor, its frequency dependence and attenuation decrement) is necessary to correct the decay shake model from the earthquakes on the traces from the seismically active zones in the main urban areas, as well as for the further calculation of synthetic accelerograms and the evaluation of the parameters of the vibration for the possible strong earthquakes, for the estimation of the earthquake source parameters and etc. The attenuation of the seismic wave is a decrease of the amplitude (or energy) of the wave during it propagation in the geological medium due to the geometrical spreading, scattering by inhomogeneities, loss of heat, and others. 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 [1]. Also the frequency dependence of Q-factor (or the frequency parameter, n) and attenuation decrement (γ) are used.

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 is the continuous wave trains in the tail portion of seismograms after the arrival of all the direct waves [2] (Fig. 1). The coda wave is caused by the body S-waves scattered from random heterogeneity in the earth's lithosphere.

The aim of the present work is a design of a software for an estimation of the body-wave attenuation of local and regional earthquakes and explosions. There are the number of seismological softwares allowing obtain the estimates of attenuation of seismic waves along with an another routine procedures. For example, the *CodaQ* subroutine of *Seisan* [3] allows calculate the attenuation using coda waves. The SGRAPH program [4] has a tool for calculating of two component of the attenuation (intrinsic and scattering seismic attenuation) by the MLTW method [5]. The presented software package *CodaNorm* is an open source seismological software and allows the estimation of the seismic quality factor (Q_P, Q_S), its frequency dependence (n) and attenuation decrement (γ) for body P- and S-waves by the coda-normalization method [1] for different frequency ranges selected by a user. The initial data used are:

1. The earthquake (or explosion) waveforms (seismograms) in the GSE2 format;

2. The text file containing the information on the earthquake origin time, coordinates, arrival times of direct body-waves (P- and S-waves), and the path to the waveform database as well.

The main advantages of the software package *CodaNorm* are the ease of installation (the program does not require of installation any addition softwares); it runs in Windows and there is the possibility of the control of the calculation procedure by user at each stage (for details, please, see the Section 3 – Software Description).

2. The extended coda-normalization method

We used the extended coda-normalization method [6] to estimate the attenuation of body-waves. The coda-normalization method is based on the assumption that the coda energy is uniformly distributed in the region surrounding the source. In this method, the spectral amplitudes of direct P- and S-waves (A_P and A_S, respectively) are divided by the coda–spectral amplitude (A_C) to remove the effect of instrument gain, source excitation and site amplification effects. The method enables us to estimate Q_P- and Q_S-values from a data set by normalizing the direct P- and S-wave spectral amplitude by the coda–spectral amplitude measured at a fixed lapse time, roughly twice greater than the direct S-wave travel time measured from the earthquake origin time:

$$\ln\left[\frac{A_P(f,\ r)\,r^{\alpha}}{A_c(f,\ t_c)}\right]_{r\pm\Delta r} = -\frac{\pi f}{Q_P(f)\,V_P}r + const(f), \quad (1)$$

$$\ln\left[\frac{A_S(f,\ r)\,r^{\alpha}}{A_c(f,\ t_c)}\right]_{r\pm\Delta r} = -\frac{\pi f}{Q_S(f)\,V_S}r + const(f), \quad (2)$$

where $A_{P,S}$ are the spectral amplitudes of the body P- and S-waves at distance r; $Q_{P,S}$ are the quality factors of P- and S-waves, respectively; and $V_{P,S}$ are the average P- and S-wave velocities, respectively; α is the geometrical spreading parameter. The slope of the regression lines plotted between the left-hand side of Eq. (1) versus hypocentral distance are used to estimate Q-values (Fig. 2).

3. Software description

The software package consists of two components: the converter *baikal2gse* and program *CodaNorm* for calculating the seismic quality factor. Herewith the program *CodaNorm* is independent products and can be used separately while the converter *baikal2gse* is the additional supplement designed specially for the conversion of the waveforms from regional data format used by seismological agencies in the South Siberia and Yakutia (Russia) to the standard format GSE2.

To write software package an interpreted programming language Python was used. To link the different modules of the program the Obspy package [7] was used. Python framework for processing seismological data, which provides parsers for common file formats and different seismological signal processing routines in order to facilitate rapid application development for seismology.

Converter *baikal2gse*. In the present time, there are many formats of the seismic waveforms (MSEED, SAC, GSE, SAF, SEGY etc.). Some of them are conventional and widely used in the different seismological software (such as PITSA, SEISAN, Computer Programs in Seismology, SGRAPH etc.) for visualizing, processing and analyzing seismic data. But others are original and used only by regional seismic station networks. As a result, there are difficulties with the conversion of data and their further processing.

There are five permanent seismic station networks (four regional and one local) on the territory of South Siberia and Yakutia (Russia). These are the networks of the Altai-Sayan, Baikal, Buryatia and YakutskRegional Seismological Centers of the Geophysical Service of the Russian Academy of Sciences and Krasnoyarsk research Institute of geology and Mineral Resources (KRAR). The stations are usually equipped by three-component recording instruments Baikal-10 (11), Baikal-7HR (analog of Quanterra Q330HR), developed in GS SB RAS. The stations are equipped with short-period seismic receivers (SM-3, SM-3KV), oriented in vertical, north–south, and east–west, and operating in the frequency range from 0.5 to 20 Hz. The sampling frequency is 100 samples per second. Waveforms are recorded in the Baikal-5 format.

Converter *baikal2gse* was written to adapt the regional format Baikal-5, which allows records of the regional networks of stations in the format GSE2 to be obtained.

Waveforms of earthquakes recorded are stored in a regional format Baikal-5. The script baikal2gse for the conversion of data from Baikal-5 format to GSE2 format was written that reads the original input data from a file according to the original format (Fig. 3).

The script reads the number of recorded channels and other general settings from the main headline of the file, then — the headlines of channels and the data in the multiplexed form until the end of the file. A stream of traces according to the channels in

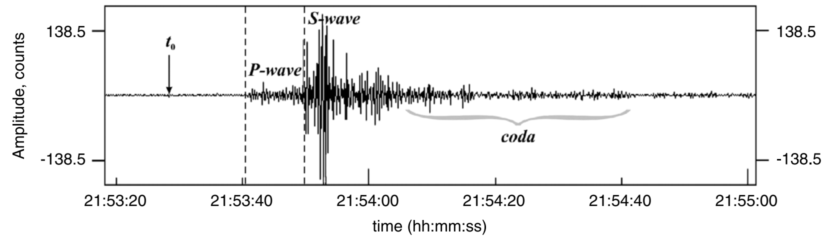

Fig. 1. The example of typical seismogram of the Baikal regional earthquake. The origin time of earthquake (t_0) is shown by arrow; the arrival times of P- and S-waves are shown by dashed lines and the coda waves are indicated by the gray bracket.

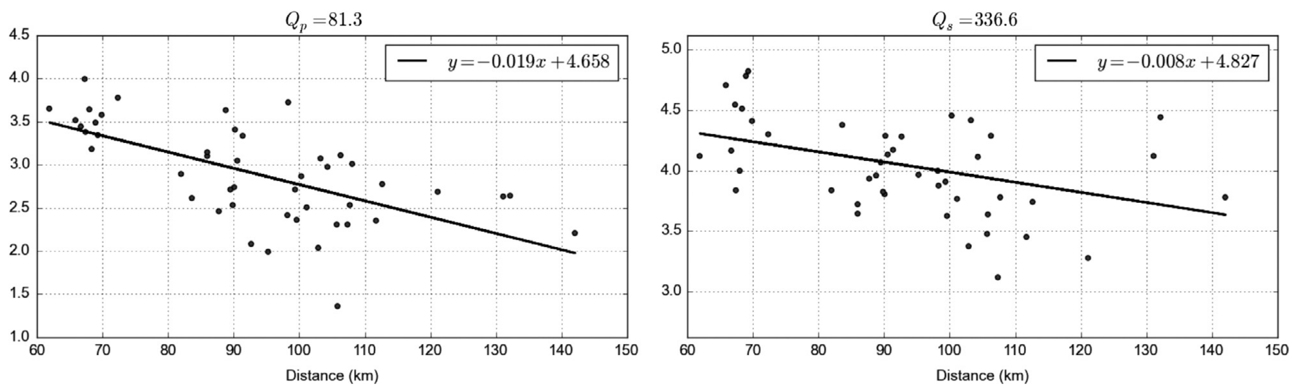

Fig. 2. Example of calculating the values of the quality factor Q_P, Q_S for the frequency of 3 Hz.

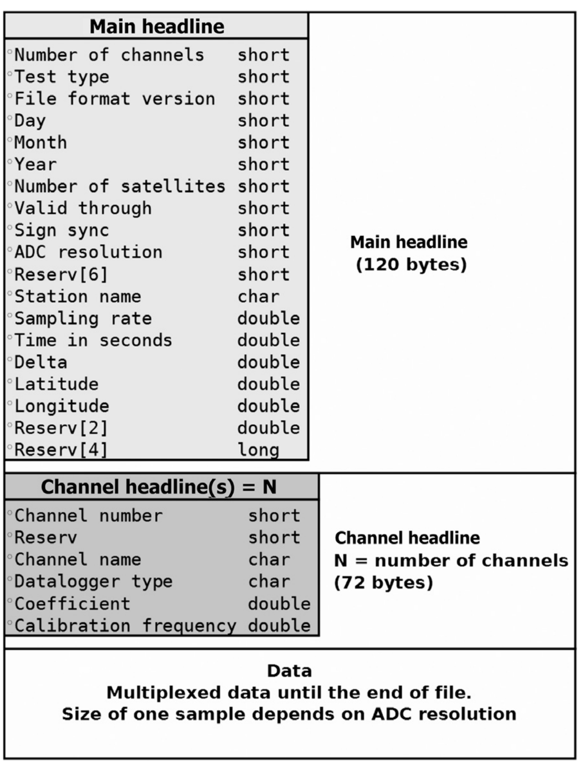

Fig. 3. Description of the data format Baikal-5.

the source file from the data read and the output file in the format GSE2 is recorded using packet Obspy.

Program *CodaNorm*. The *CodaNorm* program allows calculate the seismic quality factor using the coda-normalization method [6]. The calculation is made on the base of earthquake records obtained at the same seismic station. The program is implemented in the programming language Python (v.2) and to run it libraries of numerical calculations Numpy (www.numpy.org), Scipy (www.scipy.org) and Python framework for processing seismological data (www.obspy.org) are required to be installed besides the standard libraries. The Matplotlib library is required to visualize the process of calculating (www.matplotlib.org). Installing the libraries and of all the necessary is possible using Python Setuptools (https://pypi.python.org/pypi/setuptools) and Obspy settings: the command easy_install obspy.

The algorithm of the program *CodaNorm*: when you start the program, *CodaNorm* reads the configuration file coda.conf, its main parameter is the name of the input file with the separator of columns (by default, any consecutive whitespaces act as delimiter). This file contains the necessary input data: earthquake origin time, arrival times of P- and S-waves at seismic stations, those parameters (international code and coordinates) are also inputted into the configuration file. Also, the path to the directory with the waveforms is specified in the input file.

The values of lapse time windows for P-, S-wave and coda (in seconds) and the coefficient for calculating of the beginning of coda (*coef*) are specified in the configuration file. The *coef*-value is usually taken to be equal to 2 which corresponds to twice the S-wave travel time [8]. In addition, the configuration file has a debug option of drawing graphs with drawing marks of seismic wave arrivals on the origin/filtered seismogram. The central frequencies are directly specified as a string of integers, eq. '1 2 4 6 8', separated by space or tabs, where the numbers determine the central frequencies with respect to which the lower and upper limits of the frequency domain are calculated.

The program has a choice between obtaining of normalized values of the original amplitudes of the seismogram or values of amplitude spectrum, which is also defined in the configuration file (please, see Listing 1 for example).

Listing 1. Example of configuration file:

```
[main]
# Any line begins with # is ignored
input_file = inputSTATION.dat
# Station code
station = STATION
# coords
```

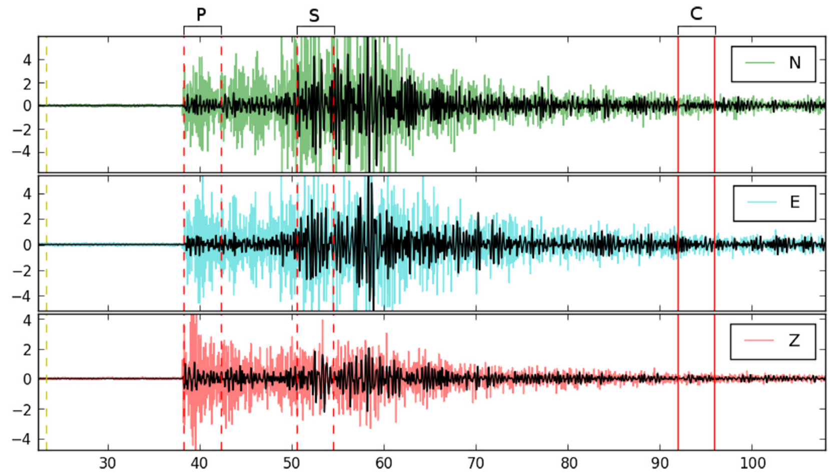

Fig. 4. The example of earthquake waveform processing. The upper line: the date and origin time of the earthquake in the 'year–month–day–hour, minute' format, seismic station name, as well as the central frequency and (in parentheses) the frequency range for which the calculation was carried out. The waveforms obtained on different channels: HON (orientation north–south), HOE (orientation east–west) and HOZ (vertical orientation), black curves show waveforms filtered in frequency range selected. Dotted lines show the origin time of the earthquake and the lapse time windows for body the *P*- and *S*-waves, and solid lines — the lapse time window for coda wave, for which calculations of seismic quality factor were carried out.

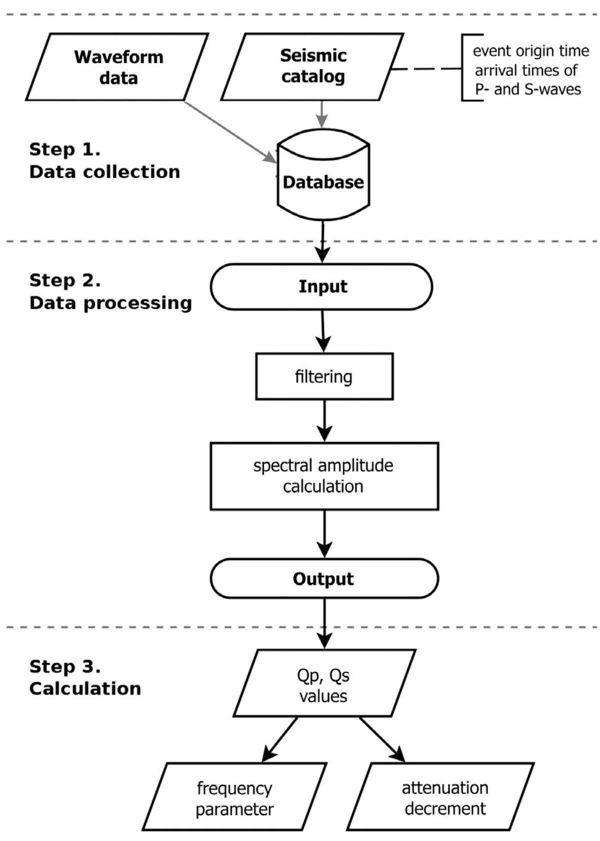

Fig. 5. The algorithm of the program *CodaNorm*.

station_lat = 55.45
station_lon = 37.36
# window size of P-, S-, coda-wave (in seconds)
sd = 8
# coefficient (* time of S)
coef = 2.5
# draw
plot = True
# Frequencies
freqs = 0.5 1 3 9 12
# algorithm (SQRT_SUM_ SPECTRUM_AMP or NORMALIZE)
algorithm = SQRT_SUM_SPECTRUM_AMP

The attenuation parameter calculation consists in the following steps: 1. Reading the initial data: events from the catalog and the arrival times of the direct wave; 2. The search of waveform data in the GSE2 format; 3. Seismogram filtering using a four-pole Butterworth band-pass filter with octave frequency bands centered at frequencies selected by a user. After filtering, RMS values of amplitudes of body *P*- and *S*-waves and coda waves for horizontal and vertical components are estimated. Optionally, an image with the visualization of calculation in the output folder is created (Fig. 4). The algorithm of the program is shown in Fig. 5.

For convenience of the output of large data volume, a file in the format of Excel at the output of the program is created, in which a separate worksheet is generated for each central frequency, where all normalized amplitudes for all windows are recorded. The calculation results are saved in database, the final calculation is made by means of Microsoft Excel (please, see Table 1 for example).

4. Impact

The software package *CodaNorm* was tested by the authors to evaluate the attenuation of seismic waves in the central part of the Baikal rift system. Selected area is the oldest part of the Baikal rift system and is characterized by a complex structure — it is here where the rift system changes its orientation from the sublatitudinal (the south-western flanc of the rift) to the north-eastern (the central part of the rift, Fig. 6). Cenozoic rift basins (South and Central Baikal) from the NW adjacent to the stable Siberian Platform with thick lithosphere, and from SE — to the Amurian lithospheric plate moving to the SE. The rate of the divergence is about 3.4 ± 0.7 mm per year and it defines the high intensity of seismic processes occurring here [9].

For the attenuation parameter estimation the 185 earthquakes with magnitude $Ml = 2$–5 recorded by the seismic station Huramsha (HRM, Fig. 6) at the epicentral distances from 100 to 250 km were selected. The epicenters locate along eight traces crossing the rift system in different direction. This approach allows estimate the attenuation parameters of the seismic waves, taking into account local peculiarities of the geological structure along the seismic traces.

The seismic traces were threated by Butterworth filter at four central frequencies: 1, 3, 6 and 12 Hz. Using the *CodaNorm* program

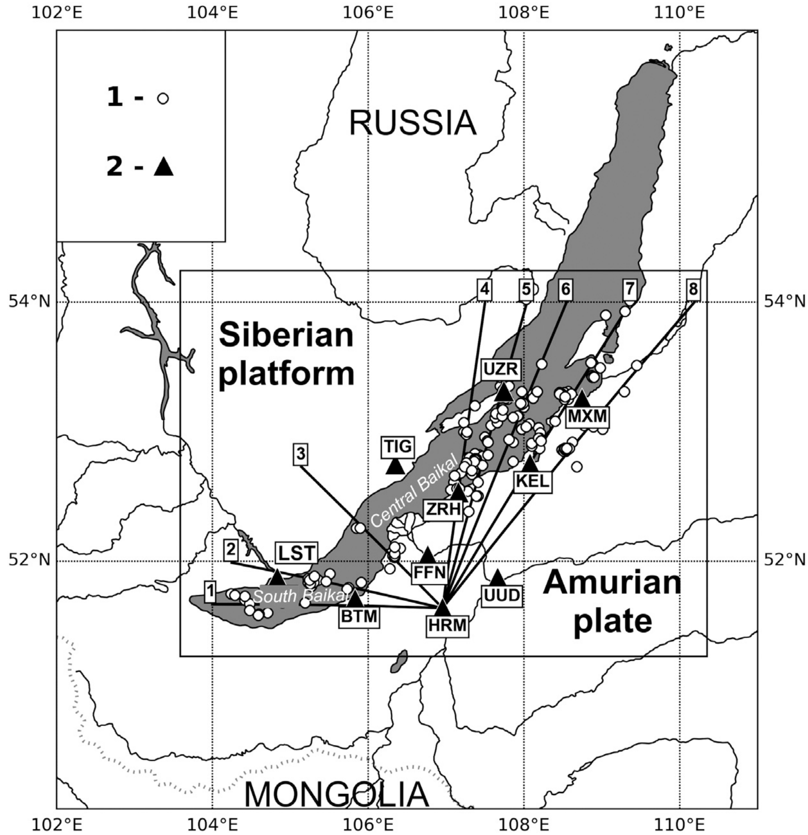

Fig. 6. Location of seismic traces (shown by lines, each trace is numbered), epicenters of the selected events (1) and regional seismic stations (2). Study region is indicated by rectangle.

Table 1
Output example headline.

DATE	TIME	LAT	LON	TIME_P	TIME_S	DIST	P	S	C	P_Z	S_Z	C_Z
040124	14:18:23.7	52.5	106.8	14:18:38.9	14:18:50.0	92	5202	43119	2042	7115.2	18058	1173.
050321	18:04:55.2	51.7	104.4	18:05:24.5	18:05:46.3	178	3686	31570	817.2	4847.8	16988	341.1
060929	17:28:52.7	52.1	106.4	17:29:04.2	17:29:12.7	67	1546	7377	624.0	1621.7	3295.9	337.3
070708	13:43:44.3	52.4	106.4	13:43:58.5	13:44:09.1	91	2812	14570	746.2	2648.4	6933.4	353.6
080112	20:32:24.2	51.7	104.6	20:32:50.4	20:33:12.3	163	39.2	492.3	13.7	47.6	200.5	6.0

Note. Output information: earthquake information — date (the column DATE), origin time (TIME) and coordinates, in degree (latitude — LAT and longitude LON); arrival times of *P*-wave (TIME_P) and *S*-wave (TIME_S), epicentral distance, in km (DIST) and RMS values of amplitudes estimated for horizontal components of *P*-, *S*- and coda waves (P, S, C) and for vertical ones (P_Z, S_Z, C_Z).

for each frequency diapason the root mean square values of the amplitude of *P*-, *S*- and coda waves were estimated. For amplitude estimation the portions of seismograms from onset of seismic wave and a few seconds long, containing the peak amplitudes of seismic waves, were used (Fig. 3). The values Q_P and Q_S were estimated for each frequency and for each trace. According these data the empirical relations between the seismic Q-factor and the frequency were obtained [10]:

$$Q_{P,S}(f) = Q_0 \cdot \left(\frac{f}{f_0}\right)^n, \quad (3)$$

where $Q_{P,S}$ is the quality-factor for the body *P*- and *S*-waves, Q_0 is the Q-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 [11].

The analysis of obtained attenuation parameters revealed the next tendencies:

1. The comparison of empirical relations (3) for *P*- and *S*-waves showed that at low frequency (~1 Hz) the values Q_P and Q_S are comparable while for higher frequencies (~12 Hz) the ratio between quality factors is $Q_S \approx 1.7 Q_P$. Such difference is the evidence of different absorption of longitudinal and transverse waves by geological medium.

2. The seismic Q-factor increases with increasing of frequency. Thus, for the South Baikal (traces 1–2) obtained Q_P-values are 84 (1 Hz), 297 (3 Hz), 813 (6 Hz) and 1188 (12 Hz) and Q_S-values are 236 (1 Hz), 709 (3 Hz), 1346 (6 Hz) and 2032 (12 Hz). For comparison, for traces oriented in NE direction (traces 6–8) obtained Q_P-values are 151 (1 Hz), 552 (3 Hz), 1426 (6 Hz) and 1873 (12 Hz) and Q_S-values are 199 (1 Hz), 1122 (3 Hz), 2154 (6 Hz) and 2762 (12 Hz).

3. For the traces oriented in NE direction (along the Baikal rift system) the more expressed dependence of Q-factor on the frequency is characterized (Table 2). Smaller values of Q-factor and higher values of frequency parameter, n, are characterized for the area of the Central Baikal (for the traces oriented normal to the main tectonic structures). This fact may reflects the differences between the local elastic properties of the crust of the Baikal rift system and the high heterogeneity of the medium.

Obtained values of the seismic quality factor for *S*-waves for low frequencies (150 ± 30) are agree with results obtained earlier for the South Baikal on the base of the coda waves [12]. The n-values

Table 2
The frequency parameter and attenuation coefficient.

No of trace	Frequency parameter, $n \pm \delta n$	Attenuation decrement, $\gamma \pm \delta\gamma$
1–2	1.16 ± 0.11	0.0051 ± 0.001
3–5	1.25 ± 0.01	0.018 ± 0.0069
6–8	1.15 ± 0.1	0.0029 ± 0.0006

obtained ($n > 1$) agree with those determined for areas with high tectonic activity, including the Baikal rift [12, references herein].

5. Conclusions

Using *CodaNorm* software allows us to get the value of seismic quality factor for local and regional earthquakes and explosions, to calculate the frequency dependence of attenuation, to evaluate temporal attenuation variations in the focal areas of strong earthquakes. The frequency dependence of quality factor $Q_{P,S}(f)$ is used to take into account attenuation parameters for earthquake source parameter calculations.

The *CodaNorm* software can significantly accelerate the process of data processing and calculating the parameters of attenuation of seismic waves, and also allows us to convert waveforms from regional format Baikal-5 in the standard GSE2 format for specialized seismic programs. Writing a program in Python makes it possible to further develop programs to integrate existing packages and GIS processing of seismic data.

Using the presented software package *CodaNorm* the attenuation of the body *P*- and *S*-waves in the area of the South and Central Baikal (Baikal rift system, Southern Siberia, Russia) was estimated on the base of 185 regional earthquakes with magnitude $Ml = 2–5$. The calculations were carried out for eight traces crossing the rift system in different directions and for the frequency range from 0.5 to 16 Hz. In the low frequency area the coincidence of the values of the seismic quality factor for *P*- and *S*-waves (Q_P and Q_S, respectively) is observed while for the high frequencies (8–16 Hz) the ratio between quality factors is $Q_S \approx 1.7Q_P$. Such difference is the evidence of different absorption of longitudinal and transverse waves by geological medium. The comparison of the attenuation parameters for different azimuthal traces showed that higher attenuation is observed for the traces crossing the rift system in normal direction to the main tectonic structures. This fact may reflects the differences between the local elastic properties of the crust of the Baikal rift system and the high heterogeneity of the medium.

At present time the software package CodaNorm is actively used by the authors and their colleagues in the study of the attenuation characteristics of the seismic waves in Southern Siberia and Yakutia.

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