Tidal modulation of weak seismic activity
(Baikal rift zone, Altay-Sayan region).

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Abstract

We show the tidal analysis of Earthquake's data bank for Baikal (1970-1993) and Altay-Sayan regions (1970-2001) by HiCum program. We research correlation of seismic activity in semi-diurnal, diurnal and long period tidal bands. As a result we got 10%-30% modulation for weak seismic process (magnitude M = 0.5÷ 2.0) for K1, S1, Mf and Mm tidal waves. Process modulation in time was analyzed for the Busingol earthquake (M =6.5-7.0, 1991/12/27 09-09-34.9, 51.12°N, 98.15°E) zone. Variation of modulation parameters is present in epicenter zone. Model of process in epicenter zone was discussed as crack genesis. Velocity of crack process is connected with the stress flow parameter i.e. "Stress•Strain Velocity". For weak energy seismic process tidal modulation appeared when this parameter reaches comparable values for tectonic process and for tidal forces. Modulation parameter reached 30% or more before a strong earthquake and after disappeared. When we analyze the Altay-Sayan seismic process we see the migration of process to south-west in the zone of preparation of Chuya earthquake (27/09/2003, M=7.3-7.5).

Key words: HiCum program, earthquake data bank, Baikal rift and Altay-Sayan region, tidal modulation, earthquake models.

1. Introduction

Research of relation between tidal strength and seismic process was made by different authors. Some results show correlation, some-don't [Aoki et al., 1997; Emter et al., 1985; Heaton 1975; Knopoff, 1964; Polumbo, 1986; Shlien, 1972; Simpson, 1967; Tanka et al., 2002; Van Ruymbeke, 1989; Weem&Perry, 1989].

The method of attack is based on the use of a maximum amount of information about earthquakes of the considered region (theoretically - all information). It is obvious, that we study process, on the weak energies, because most information about seismicity comes from weak energy events. For earthquakes data analysis we used a special software for tidal analysis called HiCum. Main topic of this article is research of modulation for seismic events in Baikal rift zone (1970-1993, about 90,000 events) and Altay-Sayan region (1970-2001, about 26,000 events), and its quantitative estimation (Figure 1). Different peculiarities of process in the different areas and its time variations were studied.

2. The HiCum method

The signals from periodic deformations such as earth tides are extremely small and any effects would be difficult to detect. In earlier studies spectral analysis has been the favorite tool for detecting such signals. In our case, we know the period of different components of the signal with an astronomical accuracy. In addition the very long series of records at our disposal gives us the potential to detect very weak signals with significant signal-to-noise ratio. The **Hi**stograms **Cum**ulating method [Bartels, 1938; Series et al., 1994] was originally developed at the Royal Observatory of Belgium for this purpose[Van Ruymbeke et al., 2003]. Its objective is to put forward a graphical display of the behavior of the non-linearities recorded by the sensors. To further simplify the analysis of the data, the HiCum method has been incorporated in the EDAS Grapher software package [Van Ruymbeke et al., 2001].

The inspiration for HiCum came from the field of meteorology where stacking data has been used for many decades. A signal, which at first sight appears like noisy signal, has its time base divided into a series of constant length time periods. The time period will be selected that is suspected to have an influence on the parameters in question e.g. the diurnal *S1* and semi-diurnal *S2* periods for climatic effects, the lunar *M2* period for tidal effects. This time period is, by definition, equivalent to an interval of width 2π or 360°.

For each period, a maximum of 360 sectors of 1° histogram are created and then the results from each time period are synchronized and added (stacked) resulting in an averaging effect producing a picture of the variations, in relation to the selected wave. Figure 2 is a schematic of the method for the wave *M2*.

HiCum has several advantages over Spectrum Analysis in extracting information when there are complex interactions in a multi parameter environment.

We can remove from the histogram the calculated fundamental sine wave and check for any non-linearity or harmonics present. We have the option of removing up to four harmonics from the main signal, leaving only the non-linear residuals.

The method is highly sensitive and has been shown to be capable of detecting non-linear hysteresis on raw data, which at first sight appears to be a white noise signal. This precision, obtained from analyzing the effects of tidal fluctuations on a weak signal from raw data records of a gravimeter, was possible because records were taken repeatedly over years and the results from the same time period each day were added, stacked, resulting in an averaging effect producing a picture of the daily variations. The accuracy of method has been tested on computer generated data. We can regard the background theory. Fourier's Theorem states that any periodic function can be expressed as a sum of sine waves.

$$F(x) = \sum(a \cdot \cos rx + b \cdot \sin rx) + \tfrac{1}{2} c \qquad (1),$$

where r takes integral values and a,b,c are constants.

This can be used as a method of determining the harmonic components of a complex periodic function. Since equation (1) is unchanged by replacing x by $x + 2k\pi$, where k is an integer, it necessarily represents a periodic function in x of period 2π. Consequently in discussing series of this type it is sufficient to consider any interval of width 2π or 360°.

Thus if we have a signal that varies over a period of time, and we can clearly define the frequency, $\omega/2\pi$, then we can equate that to the interval 2π (or 360°) and equation (1) becomes:

$$F(t) = \sum(a \cdot \cos \omega t + b \cdot \sin \omega t) + \tfrac{1}{2} c \qquad (2),$$

where t is the instantaneous time. With ω clearly defined, the various harmonics of the system can be found.

HiCum has been developed to analyze data linked with tidal phenomenon (e.g. *M2*) where the time period can be accurately defined and is stable. Using HiCum the parameters of the fundamental sine wave, the harmonics and any non-linearity in the signal can be detected on weak signals with high noise levels.

Statistic models of modulation method was discussed in article [Goldin et al., 2008] Let us consider a sinusoidal signal of amplitude B_0 superimposed on a background A_0.

$$F(t) = A_0 + B_0 \cdot \sin(\omega t + \varphi) \qquad (3)$$

or

$$F(t) = A_0 [1 + B_0/ A_0 \cdot \sin(\omega t + \varphi)] \qquad (4)$$

As

$(A_{max}+A_{min}) = 2A_0$

and

$(A_{max}–A_{min}) = 2 B_0$

we get

$$F(t) = A_0 [1 + m \cdot \sin(\omega t + \varphi)] \qquad (5),$$

with modulation m given by

$$m = (A_{max}–A_{min})/ (A_{max}+A_{min}) \qquad (6)$$

An example is given in Figure 3.

We can also write

$$F(t) = A_0 \cdot \cos\Omega t[1 + m\sin(\omega t + \varphi)],$$

or sum of low frequency signal and high frequency signal (noise)

$$F(t) = \lim_{\Omega\to\infty} \{A_0 \cdot \cos\Omega t[1 + m\sin(\omega t + \varphi)]\} \quad (7)$$

For statistic model we have [Goldin et.al., 2008]

$$m_S = [N \cdot \max L(\varphi)] / [\sum^{N}_{r=1} \cos^2(\omega \cdot r \cdot \Delta t - \varphi)] \quad (8)$$

where $N > 20$ (we have $N \geq 24$).

If we want to find estimation with signal/noise = 3 for m: 0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, we must have BANK of events: 180,000, 7,200, 1,800, 800, 450, 288 and 200.

3. Analysis of Altay-Sayan data as a function of the energy level

Earthquake data bank includes for 1970-2001 years period 26,126 events registered by Altay-Sayan seismology service and by Institute of Geophysics SB RAS (Novosibirsk). Latitude φ, longitude λ, and energy class K* of events are presented on Figure 4. Earthquakes are given from energy class 6 and up for period 1970-1991, and from 9-class for period 1992-2001. Analyses for Altay-Sayan territory are presented with separation in two blocks.

We start analyze for S1 wave with different steps for HiCum (1970-1991, Figure 5). When we check the data bank, we can see that more reliable level is near 7.6-class. Weak effect in longitude and in latitude appeared in result. Modulation for S1 wave (real daily period) is 14.6% ÷ 15.7%. Results for Mf, Mm and Sa waves presented in figure 6 and modulation are 3.2% ÷ 15.3%. For Mf wave (figure 6, 7) there is a dependence for longitude, latitude and energy.

Second part of Altay-Sayan data (1992-2001) is for class 9 and up and the more reliable level is near 9.5-class (figure 7). Analysis of the second part for S1 wave presented a reduction of modulation to 5.1% (figure 7). We can conclude that tidal modulation is maximum for weak energy events (from 6 to 8 class or M = 1.0 ÷ 1.5). This fact is illustrated on figure 8. When the energy of the events decreases the coefficient of modulation increases.

* For energy in Joule: $\log E = K$, $M = -3.64 + 0.70\,K$

4. Analysis of Baikal rift data including spatial distribution of modulation effect

Earthquake data bank includes for 1970-1993 period 90,220 events registered by Baikal seismology service and by Institute of Earth Crust SB RAS (Irkutsk). A first study of the "Tidal variation-Weak seismic activity" connection is presented here. Depth distribution of earthquakes for Baikal rift is presented on Figure 9. Energy of events for the 1970-1993 data bank is given from energy class 6 level up to 16 level or in other system – Richter magnitude – from M = 1 up to M = 7 (Figure 10). When we check the data bank, we can see that it is more reliable to use the lower level 7 ÷ 8 class or M=2. This level range was analysed by HiCum program. Geological & geophysical features of region allow us to cut the studied territory into three blocks according to stress condition, deep structure (depth of Moho) and kind of faults (Figure 11). We have three blocks delimited in longitude: 92°- 107°; 107°- 115°; 115°-126° (block 1, block 2 and block 3). The first one is the left flank of the rift with E-W lateral faults. The second one is the rift zone with SW-NE orientation of main features and the third one, corresponding to the right flank, is a zone with E-W lateral faults too. For the S1 wave (Doodson argument number 164.555) with 90 steps for HiCum, we can see different reactions in the first, second and third blocks (see the figure 11). In the first block is one kind of modulation and in the third one –other flank – there is

the opposite effect. Effect is strong on the left flank up to 17.0%. The modulation is reduced to 10.1% in the central block and in right flank to 3.6% (block 3). S2 modulation is different – first block – 9%, second block – 8%, and third block – 8%. The modulation is practically constant. When we try to estimate the situation as a function of latitude, longitude and energy (class of earthquake) we see the modulation on all these parameters for first block. We have a smaller effect for latitude, but real effect in longitude in second block. Effect is not significant for latitude, longitude and energy in third block. Relation between energy and number of earthquakes is linear for first block and without any correlation for other blocks.
Next step of analyze is the estimation of modulation for block 1. Smoothed data and seismology analyses show the source of such a strong effect (Figure 12). It is a strong earthquake at Busingol Lake, Mongolia (27.12.1991, 51.0°N, 98.0°E, M = 6.5 ÷ 7.0). This zone is present in Altay-Sayan data bank and in Baikal rift data bank. It is a territory where compression typical of Altay-Sayan region changes to Baikal rift extension condition. Testing of this territory showed the different effects before and after earthquake (Figure 13). Large modulation effect (30%) is existing during the four years period before earthquake. It is reduced to 12% within 6 months after Busingol earthquake (Figure 14).

Result of smoothing Altay-Sayan data bank (1992-2001) is presented in Figure 15.On the smoothing result (for 100 events) presented in longitude, latitude and energy we remark the migration of seismic process to south-west where Chuya earthquake happened (27.09.2003 г, M = 7.3, 50.064 °N, 87.731°E). An increasie of energy level can be seen in this graph too.

5. An attempt of theoretical understanding

As we see tidal effect is present in weak seismic activity. We can presuppose some control parameters in the medium. These parameters determine defects generation. Usually these parameters are the temperature, stress tensor and tensor of strain velocities [Zhurkov, 1983, Goldin et. al., 2008]. If tensor structure is fixed these parameters (T°, σ and $\dot{\varepsilon}$) can be used as a scalar. We can use stress flow ($\sigma d\varepsilon$), if temperature changes weakly. Our task is estimation of roles $\dot{\varepsilon}_{xz}, \dot{\varepsilon}_{zz}, \sigma_{xz}$ и σ_{zz} for tidal modulation. If seismic intensity $\lambda(t)$ reflects the growth of defect density (crack density) ψ: $\lambda(t) = d\psi(t)/dt$, the equation connecting defect density with control parameters is evolution type equation:

$$\frac{d\psi}{dt} = G(\psi, \nabla\psi, \mathbf{g}), \qquad (9),$$

where $\mathbf{g}$ -vector of control parameters, ψ - defect density.

If right side is proportional to defect value (ψ^q) and $q > 1$ we have speed unstable process, as fore-shock process. If *q = 0* or *q = 1*, we have process controlled by parameters, it may be periodic process when parameters have periodic character. When we have q < 0, the equation describes a delay-process, as after-shock process. For a very large area and for long period, it is a stationary process. For this territory the gradient $\nabla\psi$ is equal to zero as an average and we can use one dimension equation:

$$\frac{d\psi}{dt} = G(\mathbf{g}) \qquad (10)$$

If defect increment is proportional to energy increase:

$G(\mathbf{g}) = A[(\sigma^0_{zz} + \sigma_{zz})(\dot{\varepsilon}^0_{zz} + \dot{\varepsilon}_{zz}) + (\sigma^0_{xz} + \sigma_{xz})(\dot{\varepsilon}^0_{xz} + \dot{\varepsilon}_{xz})]^n$, where - σ_0 and $\dot{\varepsilon}_0$ - geodynamic stress and geodynamic strain velocity, *n* – structure parameter, A – constant for standardization. For tidal variation:

$$d\psi/dt = A[1 + \alpha_z \sin\omega t + \beta_z \cos\omega t + \gamma + \gamma\alpha_z \cos\omega t + \gamma\beta_x \sin\omega t + \cdots]^n =$$
$$= A'[1 + m\sin(\omega t - \varphi) + \cdots]$$

$$\gamma = (\sigma^0_{xz})(\dot{\varepsilon}^0_{xz})/(\sigma^0_{zz})^n(\dot{\varepsilon}^0_{zz})^n,\ \gamma < 1 \text{ (for Altay territory).} \qquad (9)$$

Geodynamic parameters:
by GPS: $4\cdot10^{-8}$/year or $4.6\cdot10^{-12}$/h or $1.3\cdot10^{-15}$/sec (rate of horizontal compression), $1\cdot10^{-8}$/year or $1.1\cdot10^{-12}$/h or $3.2\cdot10^{-16}$/sec (rate of vertical extension), 4 MPa (stress) ["Pre, co and post-seismic…", Timofeev et.al., 2008].
Parameter "Stress•Strain Velocity" $4\cdot10^{6}$ x $5\cdot10^{-12}$ Pa/h = $2\cdot10^{-5}$ Pa/h.
Tidal parameters:
Stress = (strain · elastic modulus) = $\varepsilon\cdot G$, max value for volume strain (Figure 16) $100\cdot10^{-9}$, if G = 55 GPa; we have $\varepsilon\cdot G$ = 5.5 KPa (maximum estimation for tidal stress).
Horizontal rate $100\cdot10^{-9}$/24h or $4.2\cdot10^{-9}$/h or $1.1\cdot10^{-12}$/sec.
Parameter "Stress•Strain Velocity" $5.5\cdot10^{3}$ x $4.2\cdot10^{-9}$ Pa/h = $2\cdot10^{-5}$ Pa/h.
As we used peak to peak amplitudes of the tidal variations, energy is only the fourth part of this estimation. We used the daily range of tidal effect (wave S1 as average frequency). As a matter of fact daily period can mix up with air pressure and surface temperature effects.
The ratio "Tidal parameter/Geodynamic parameter" is 25%, similar to experimental modulation.

6. Conclusions

We presented the tidal analysis of Earthquake's data bank for Baikal (1970-1993) and Altay-Sayan regions (1970-2001) by HiCum program. We are looking for seismic activity modulation for semi-diurnal, diurnal and long period tidal bands. As a result we have 10%-30% reaction (modulation) for weak seismic process (magnitude M = 0.5÷ 2.0) for K1, S1, Mf and Mm tidal waves. Process modulation in time was analyzed in Busingol earthquake zone (M =6.5÷7.0; 1991/12/27 09-09-34.9; 51.12°N, 98.15°E). Variation of modulation parameters is presented for epicenter zone. Model of process in epicenter zone was discussed as crack genesis. Velocity of crack process is connected with parameter "Stress•Strain Velocity". For weak energy seismic process modulation appeared when this parameter reaches comparable values for tectonic process and for tidal forces. Modulation parameter reached 30% or more before strong earthquake and after disappeared. Our investigation has been supported by grant RFBR 07-05-00077.

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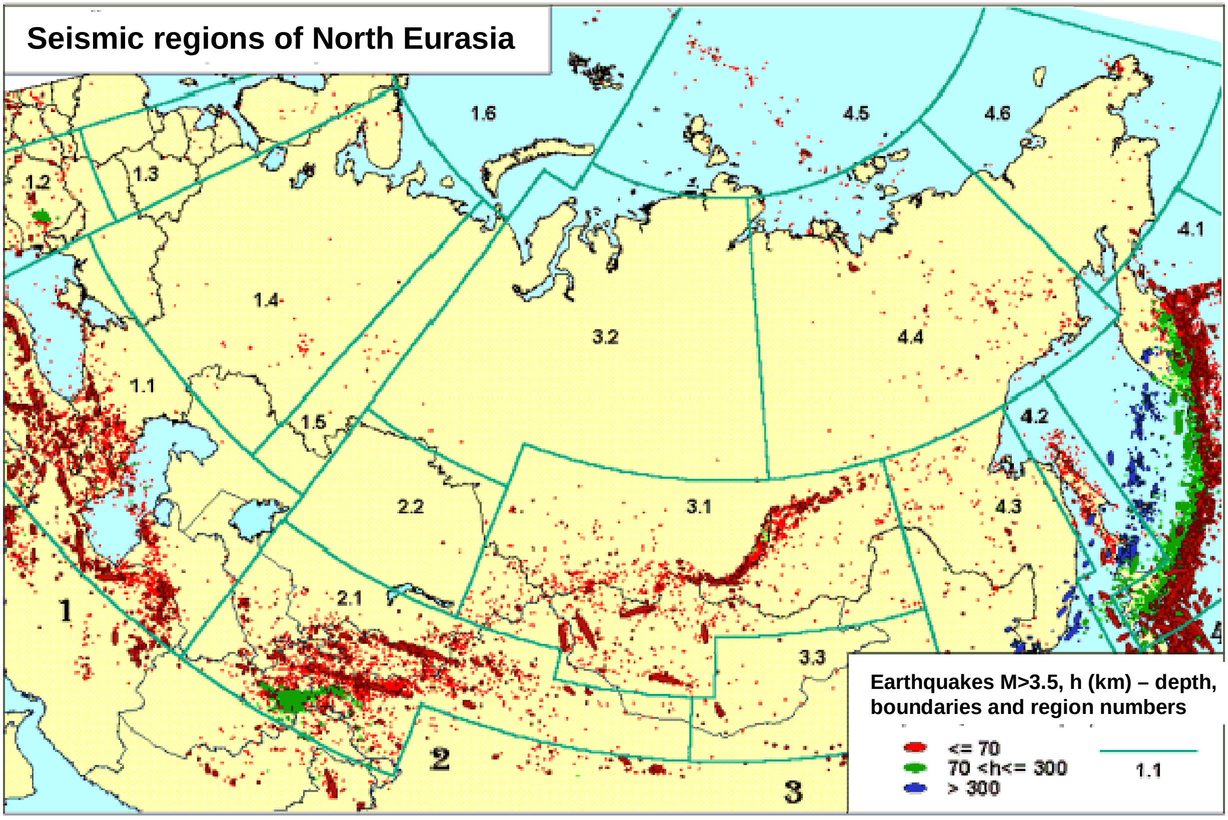
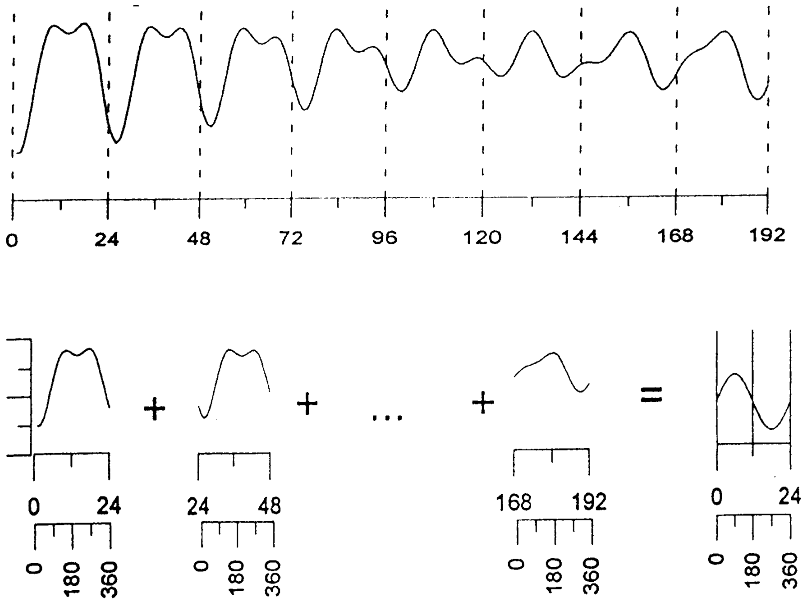
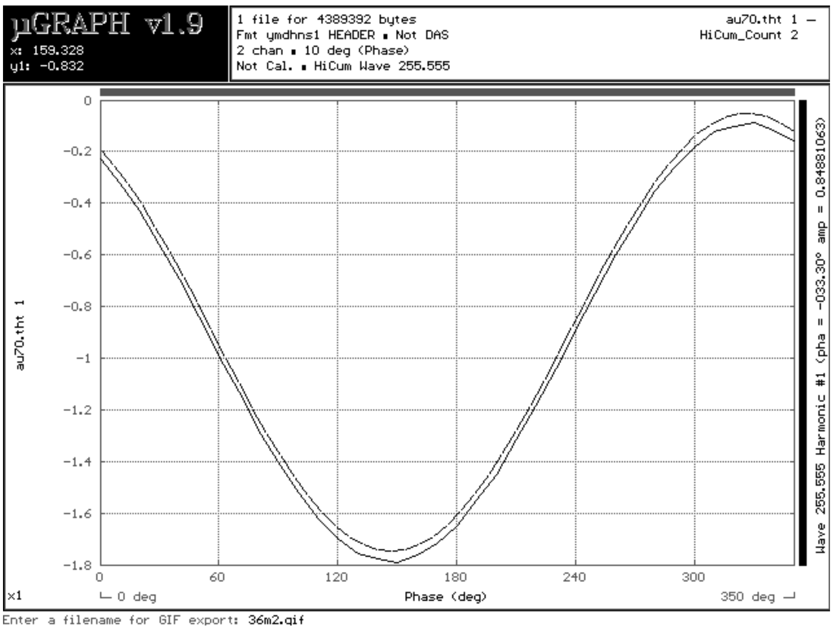


Figure 1. Seismic regions of North Eurasia. Our region is 3.1.



a)



b)

Figure 2. a) HICUM method and analysis of theoretical tide:
b) example on the 12h 25min period (wave M2)

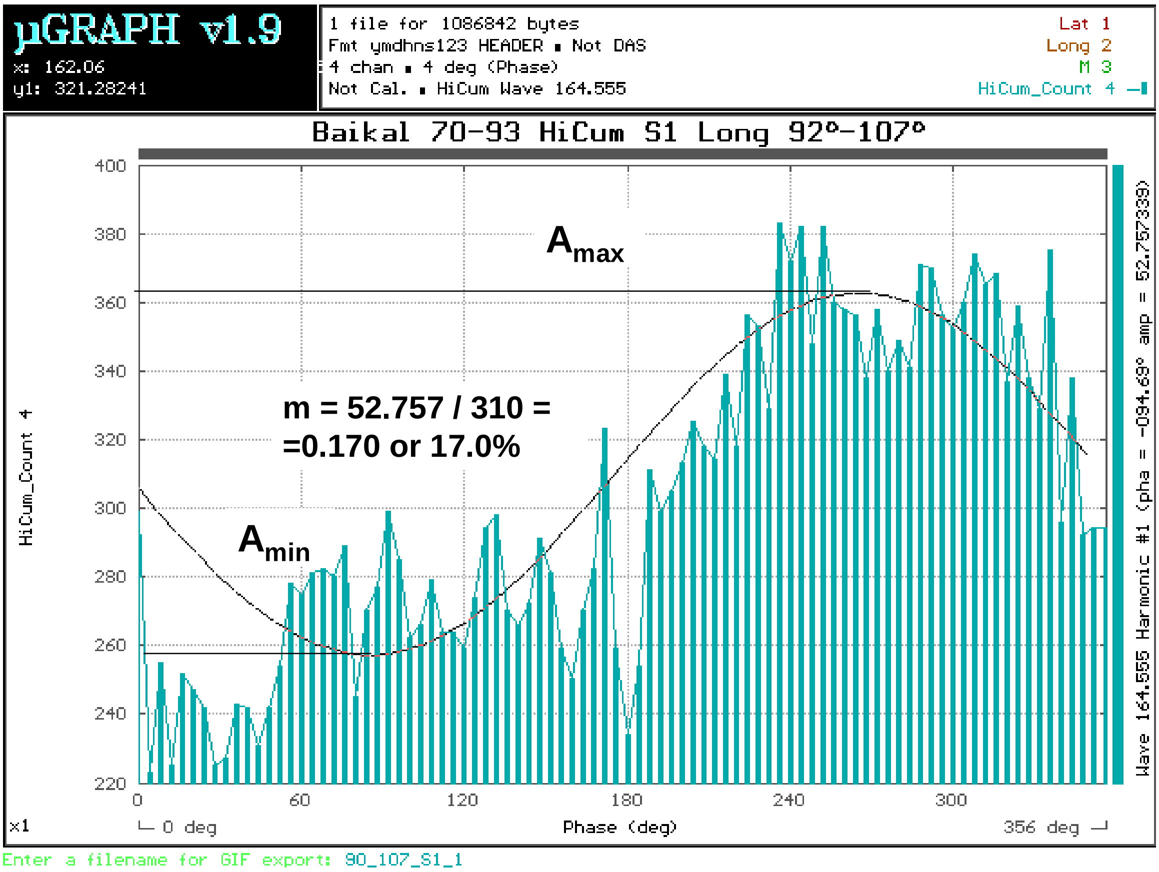


Figure 3. Analysis of Baikal seismic activity (wave S1), western part – 27,900 events. Quantity of sectors may be: N = 24÷360.

In case of random process we have 310 events for every sector (N = 90) and m = 0.

We observe a modulation m = (A_{max}-A_{min})/ (A_{max}+A_{min}) = 0.17 or 17%

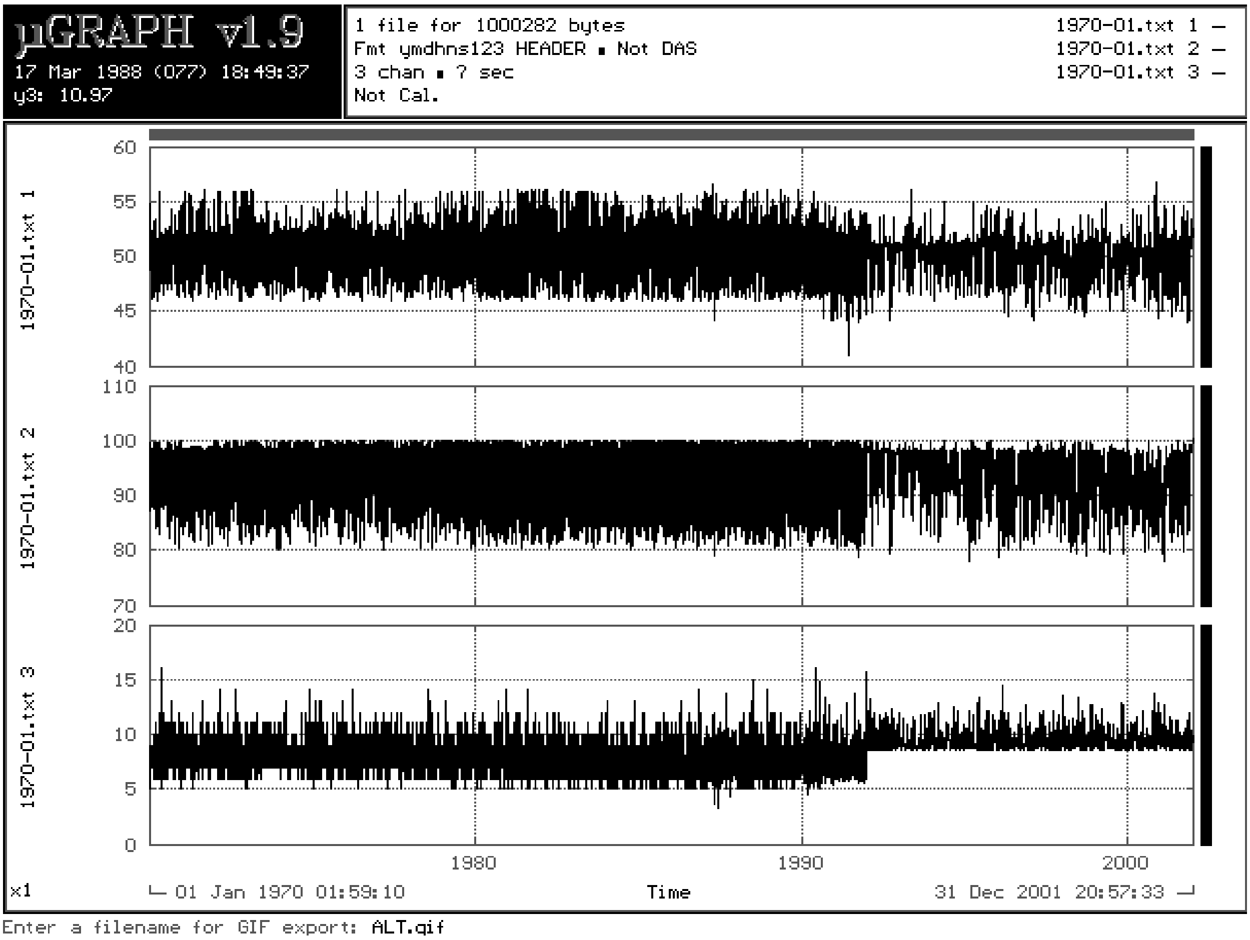
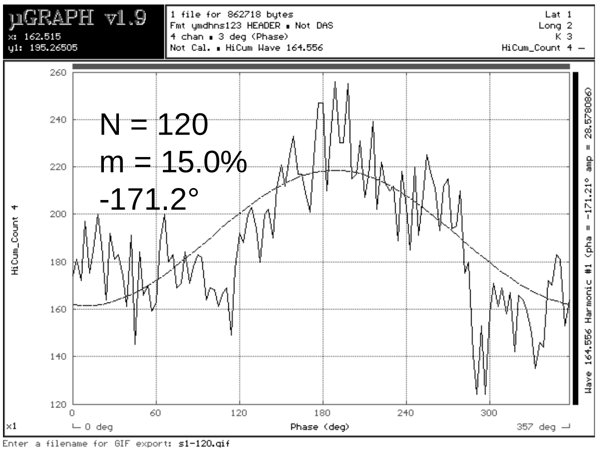


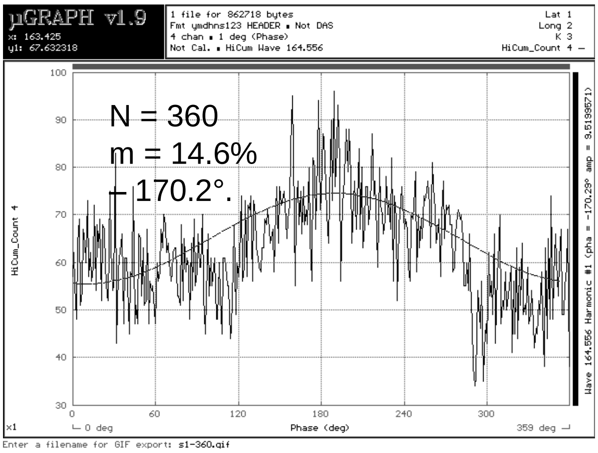
Figure 4. Altai-Sayan bank since 1970: parameters (φ, λ, K): latitude range 46°N÷56°N; longitude range 80°E÷100°E; energy K > 5 (M> 0.5).
Energy E^K Joule, log E = K, M = -3.64 + 0.70 K.



Altay-Sayan region,

near 25000 events, 1970–1991 yy.,
K > 5, wave S1 (really daily period),
quantity of sectors N =120 and 360,
modulation in percents
m = 15.0% and 14.6 %,
phase = -171.2°and – 170.2°.

Bank 1970-2001, (1970-1991, K >5;
1992-2001, K>8.5, M>2.5),
S1, N =72, m = 15.7%.



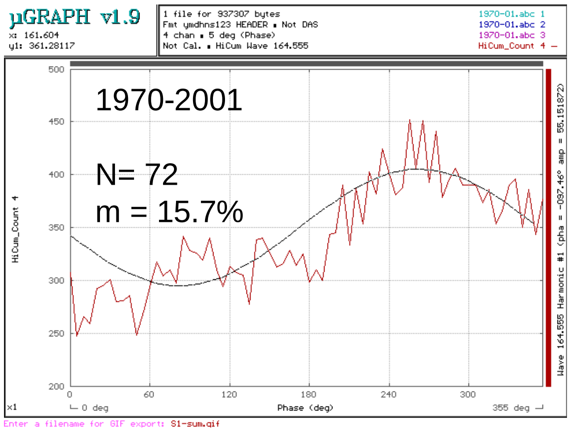


Figure 5. Altay-Sayan region –
left - 1970–1991 period, K > 5, wave S1 (daily period),
quantity of sectors N =120 and 360, modulation in percents m = 15.0% and 14.6 %, phase lag = -171.2°and – 170.2°;
right - 1970-2001 period, wave S1, N =72, m = 15.7%.

Altay-Sayan region, bank 1970 – 1991 yy. and bank 1970-2001, wave Mf, Mm and Sa. m = 3.2% - 15.3%.

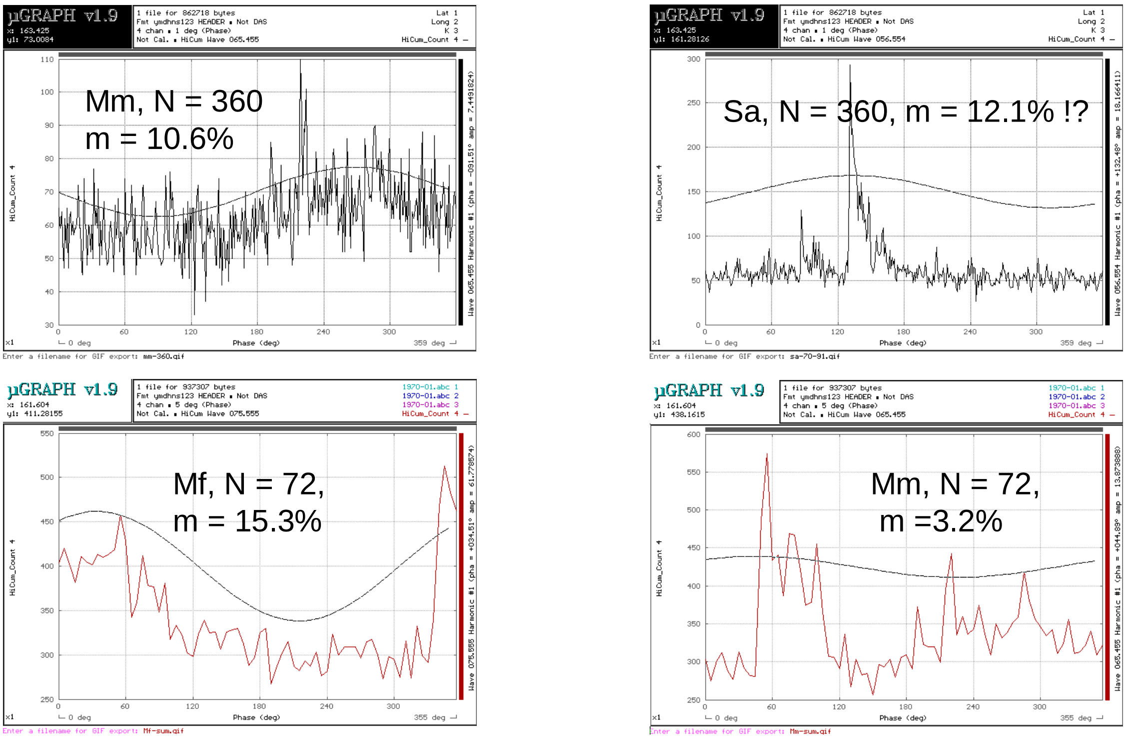


Figure 6. Altay-Sayan region – 1970–2001 period, quantity of sectors N = 72 (Mf, Mm) and 360 (Mm, Sa), modulation in percents from 3.2% to 15.3%.

Altay-Sayan region,

1500 events, 1992 – 2001 yy., K > 8.5, wave S1, Mf, K1, O1, N =72.

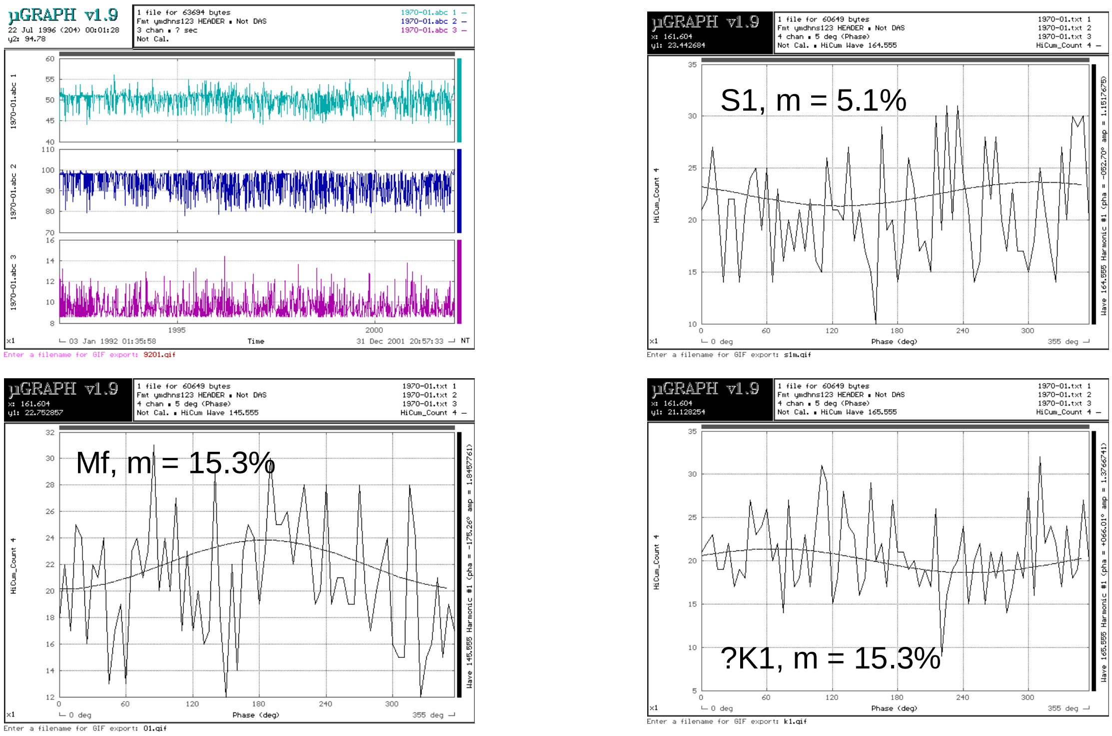
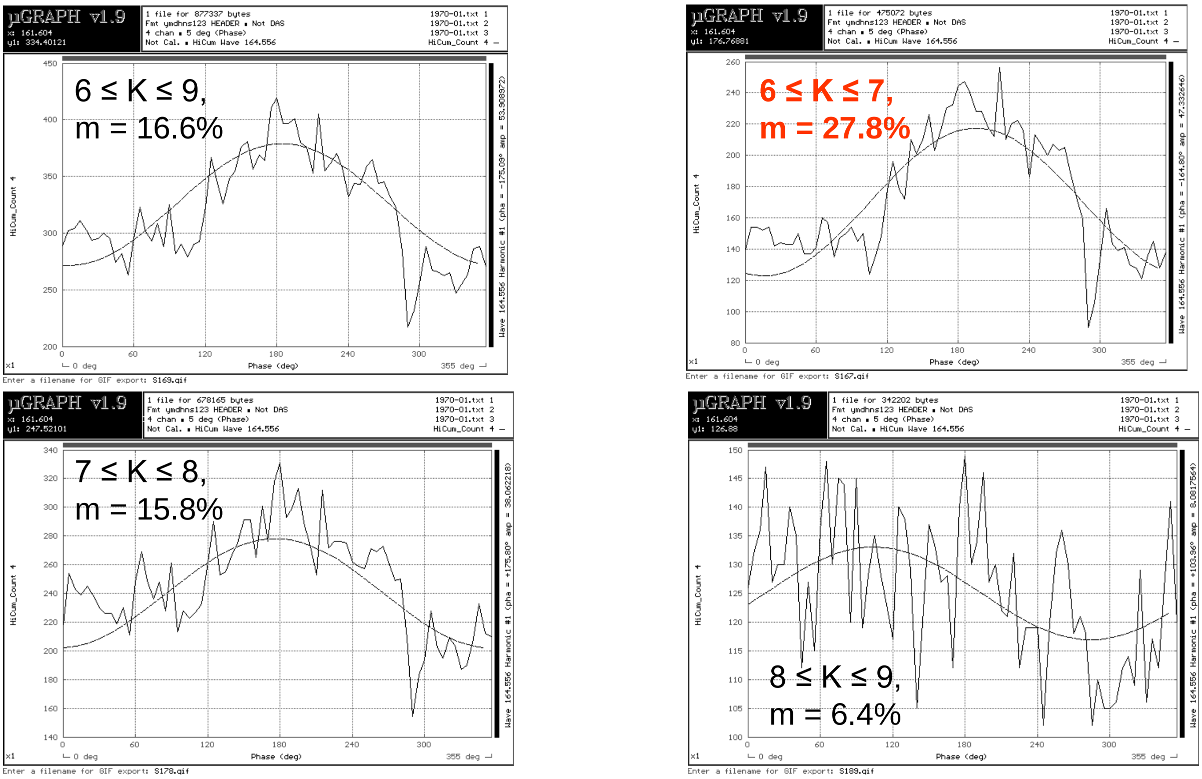


Figure 7. Altay-Sayan region – 1992–2001 period (ϕ, λ, K), energy K > 8.5, waves S1,Mf, K1, quantity of sectors N = 72, modulation in percents from 3.2% to 15.3%.

Energy Level

Altay-Sayan region, 1970 – 1991 yy., wave S1, N = 72,
6 ≤ K ≤ 9; 23400 events, m = 16.6%; 6 ≤ K ≤ 7; 12240 events, m = 27.8%;
7 ≤ K ≤ 8; 17280 events, m = 15.8%; 8 ≤ K ≤ 9; 9000 events, m = 6.4%



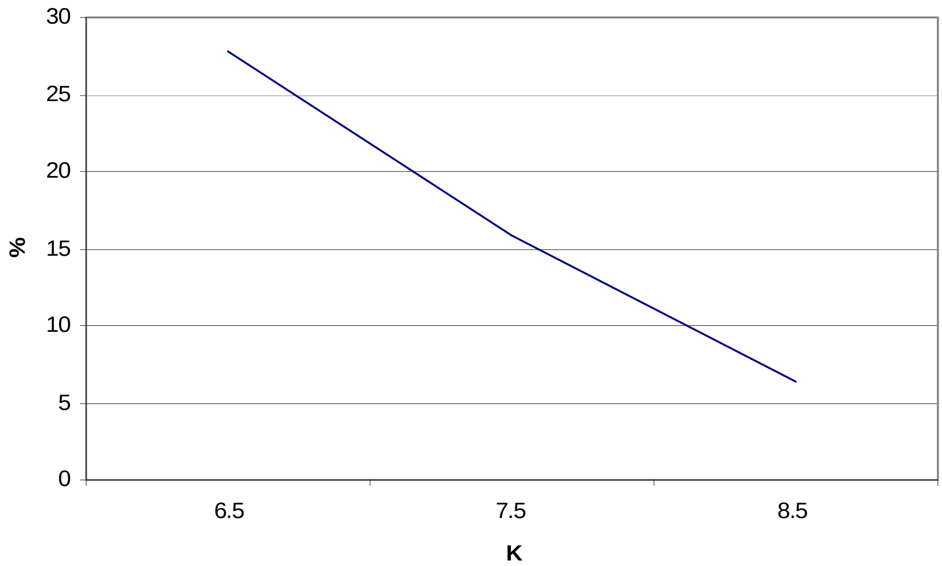
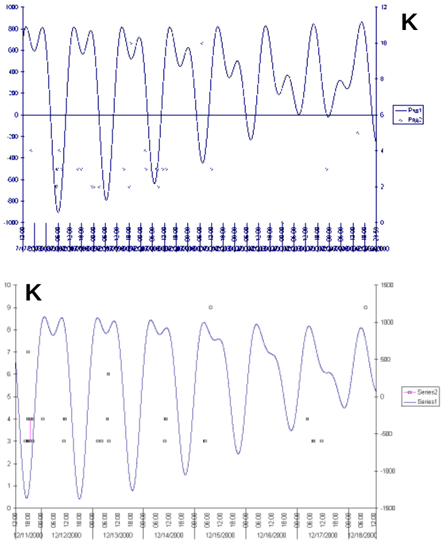


Figure 8. Modulation on S1 as a function of energy parameter K (crustal earthquakes, depth level 5÷25 km).

Tidal variation and weak seismic activity.

Baikal rift, Talaya station, borderland for Siberian platform and western part of Baikal Rift – July and December 2000 year. Series of feeble earthquakes (1-5 km distance), K > 2, July 2000 year; K > 3, December 2000 year. Theoretical tidal curves.



Baikal rift, depth distribution of earthquakes

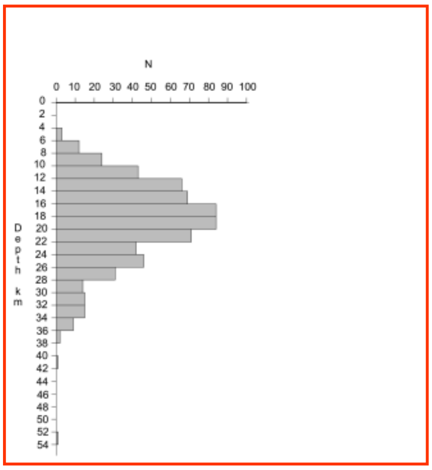


Figure 9. Tidal variation and weak seismic activity.
Baikal rift, Talaya station (51.681°N; 103.644°E; H = 550 m), borderland Siberian platform and western part of Baikal Rift –

Left) July and December 2000. Series of feeble earthquakes (1-5 km distance), K > 2, July 2000 and K > 3, December 2000 superimposed on theoretical tidal curves.

Right) Repartition of earthquakes with depth

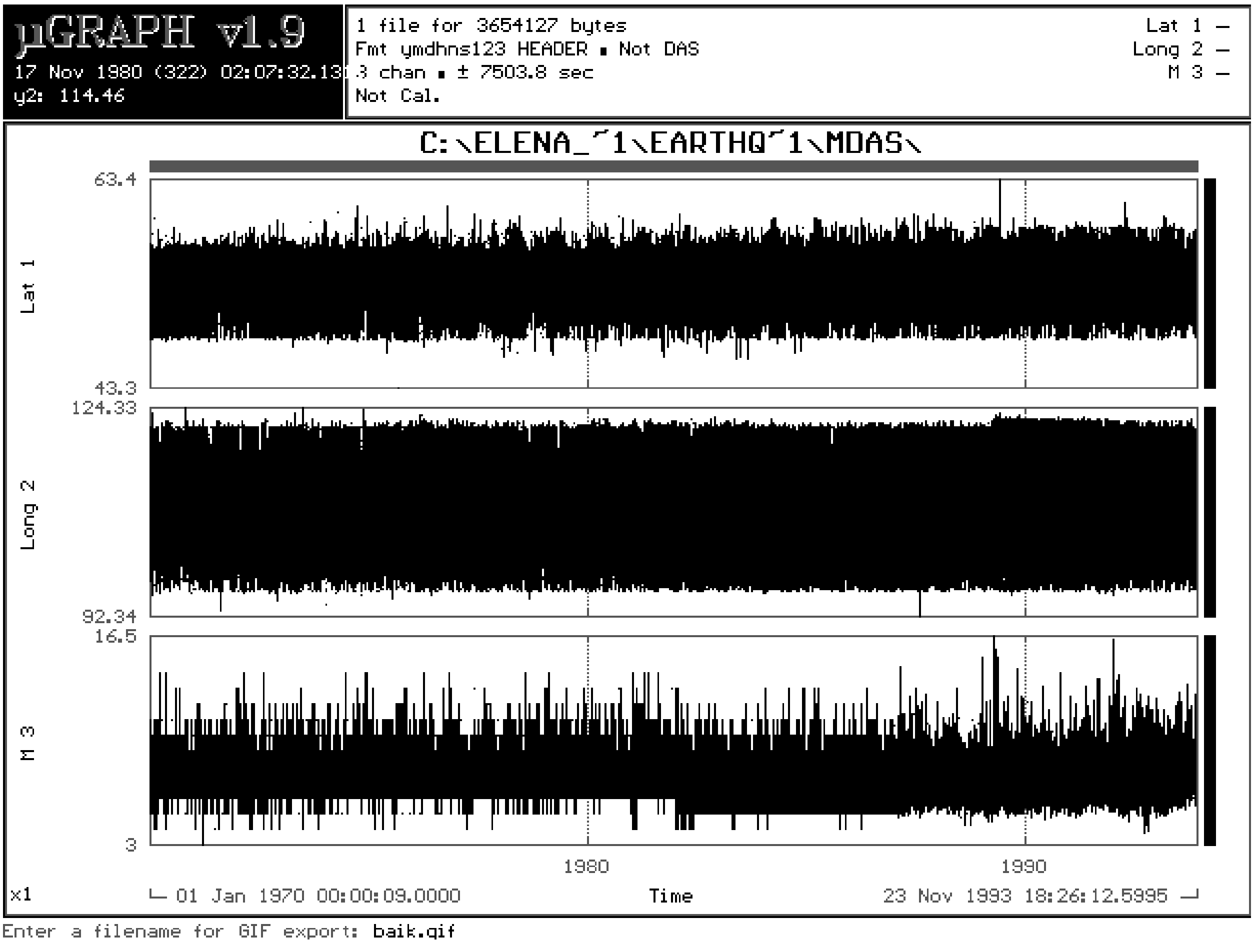


Figure 10. Baikal Rift data bank (φ, λ, K) from 1970 to 1993. Baikal rift territory: 48°N ÷ 59°N; 96°E ÷ 122°E; K> 5 (M>0.5).

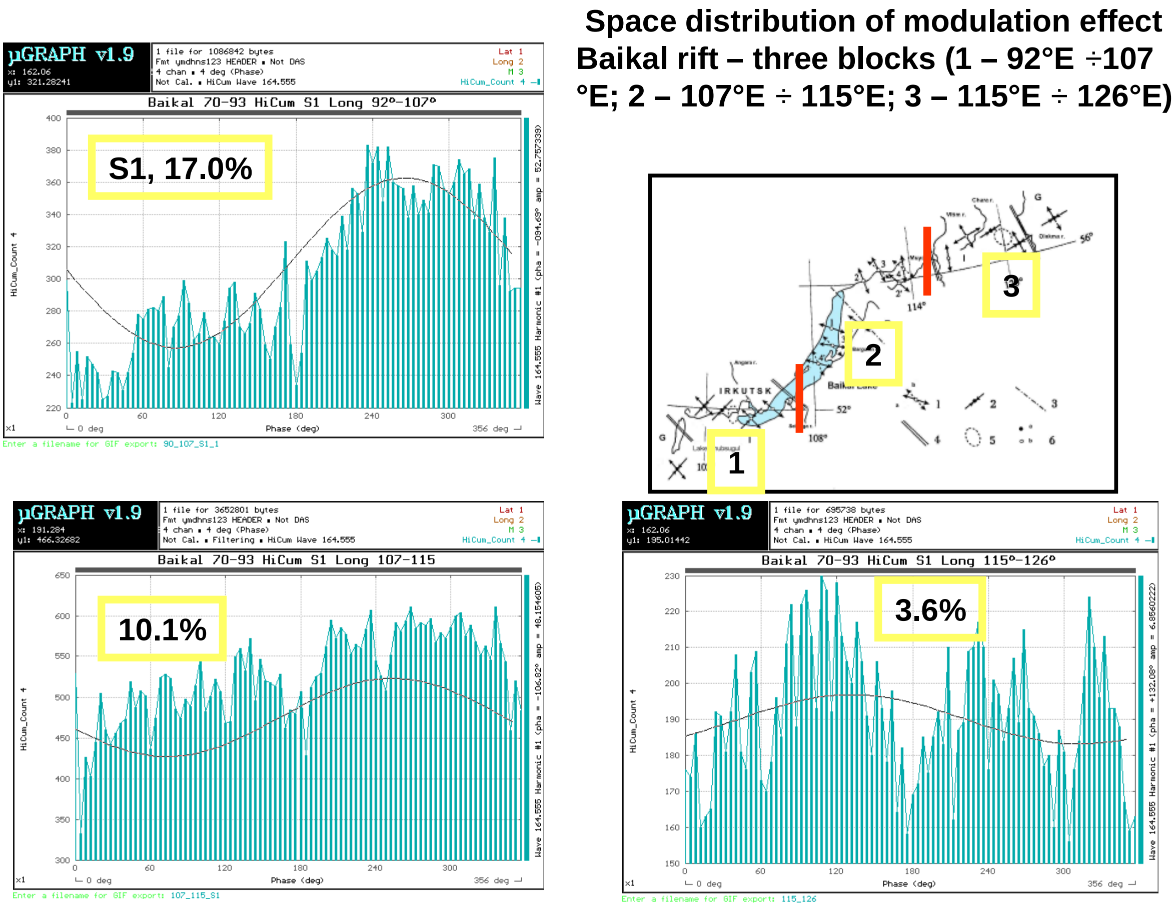
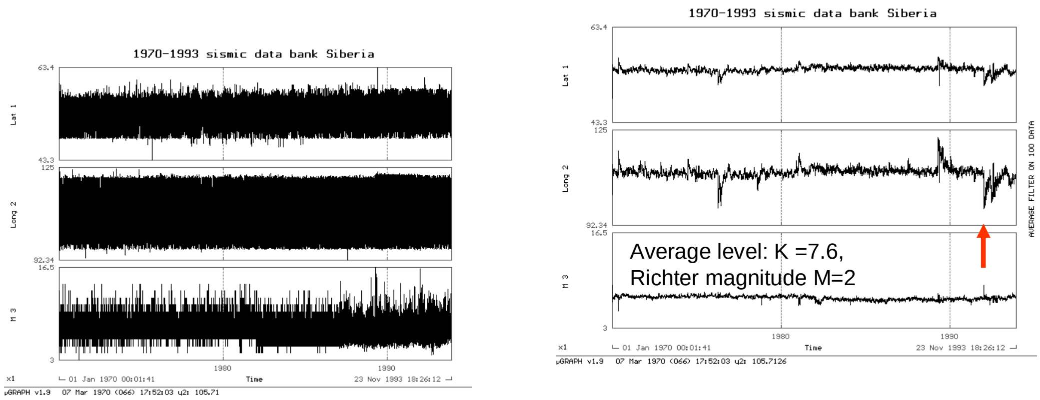


Figure 11. Separation of Baikal rift into three blocks (1 – 92°E ÷107 °E; 2 – 107°E ÷ 115°E; 3 – 115°E ÷ 126°E) based on seismological study [Solonenko, 1993]. Space distribution of modulation for wave S1:: block 1 – 17.0%, block 2 – 10.1%, block 3 – 3.6%.



First block - Strong earthquake 27.12.1991, 51.0°N, 98.0°E, M = 6.5 ÷ 7.0. Tested territory 50°N ÷ 52°N and 96.5°E ÷ 99.5°E, 1987-1993 yy.

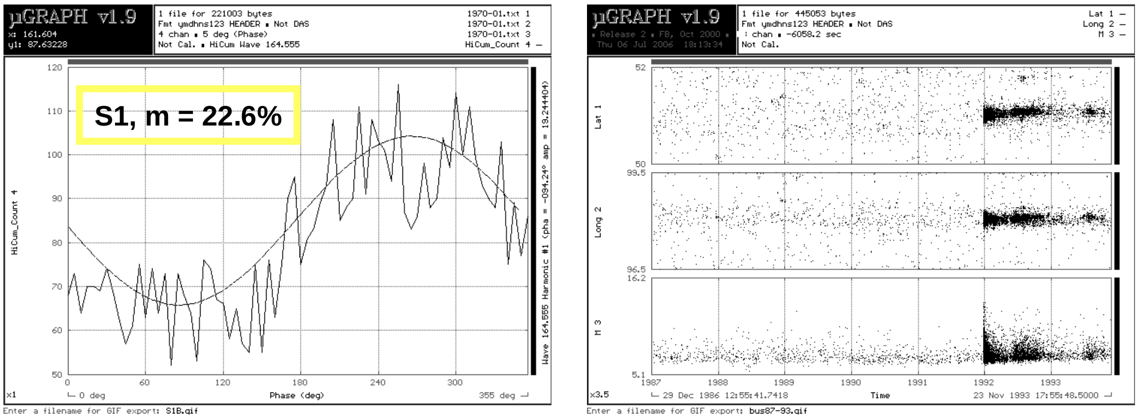
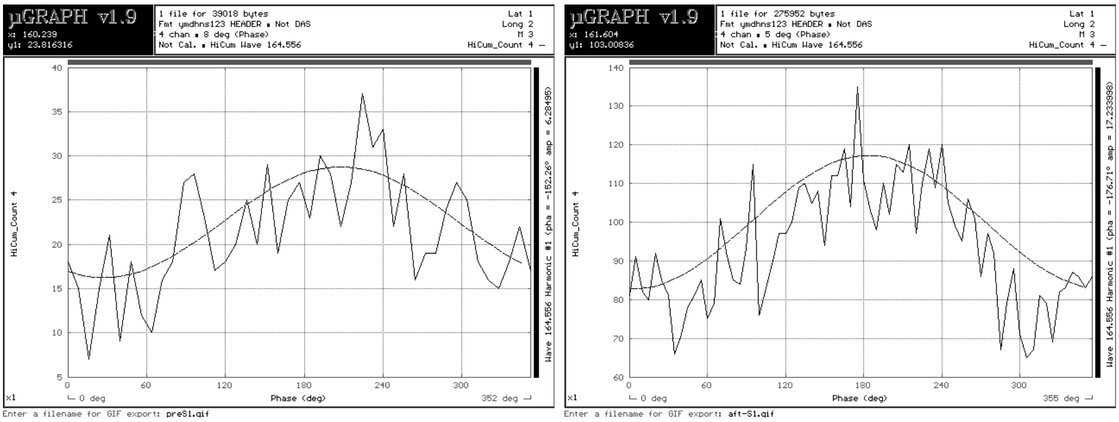


Figure 12. Top) Seismic data bank (φ-λ-K) 1970-1993, raw and smoothed (100); arrow indicates Strong earthquake 27.12.1991, 51.0°N, 98.0°E, M = 6.5 ÷ 7.0.

Bottom) Analysis of 1987-1993 series, tidal modulation (wave S1) , tested territory 50°N ÷ 52°N and 96.5°E ÷ 99.5°E.

Zone of Strong Busingol earthquake 27.12.1991, 51.0°N, 98.0°E,
(Busingol Lake, Mongolia), M = 6.5 ÷ 7.0.
Tested territory: 50°N ÷ 52°N and 96.5°E ÷ 99.5°E, 6.5< K< 8.5.
Modulation for S1 wave, before and after earthquake.



Before (1987-1991) 30.2% and after earthquake (1992-1993) 17.2% .

Figure 13. Zone of Strong Busingol earthquake 27.12.1991, 51.0°N, 98.0°E, (Busingol Lake, Mongolia), M = 6.5 ÷ 7.0. Tested territory: 50°N ÷ 52°N and 96.5°E ÷ 99.5°E, 6.5< K< 8.5. Modulation for S1 wave, before and after earthquake: Before (1987-1991) 30.2% and after earthquake (1992-1993) 17.2% .

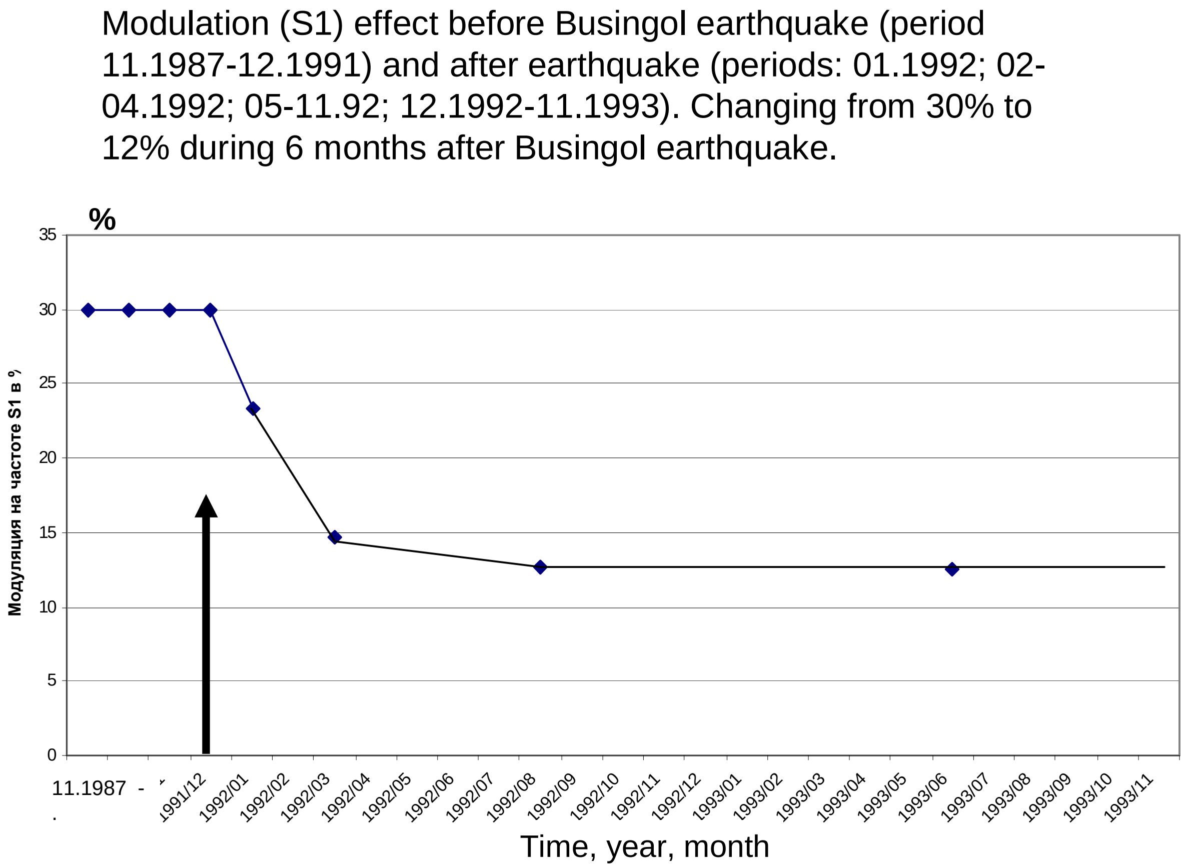


Figure 14. Evolution of S1 modulation before Busingol earthquake (period 11.1987-12.1991) and after earthquake (periods: 01.1992; 02-04.1992; 05-11.92; 12.1992-11.1993). Modulation is changing from 30% to 12% during the 6 months following Busingol earthquake.

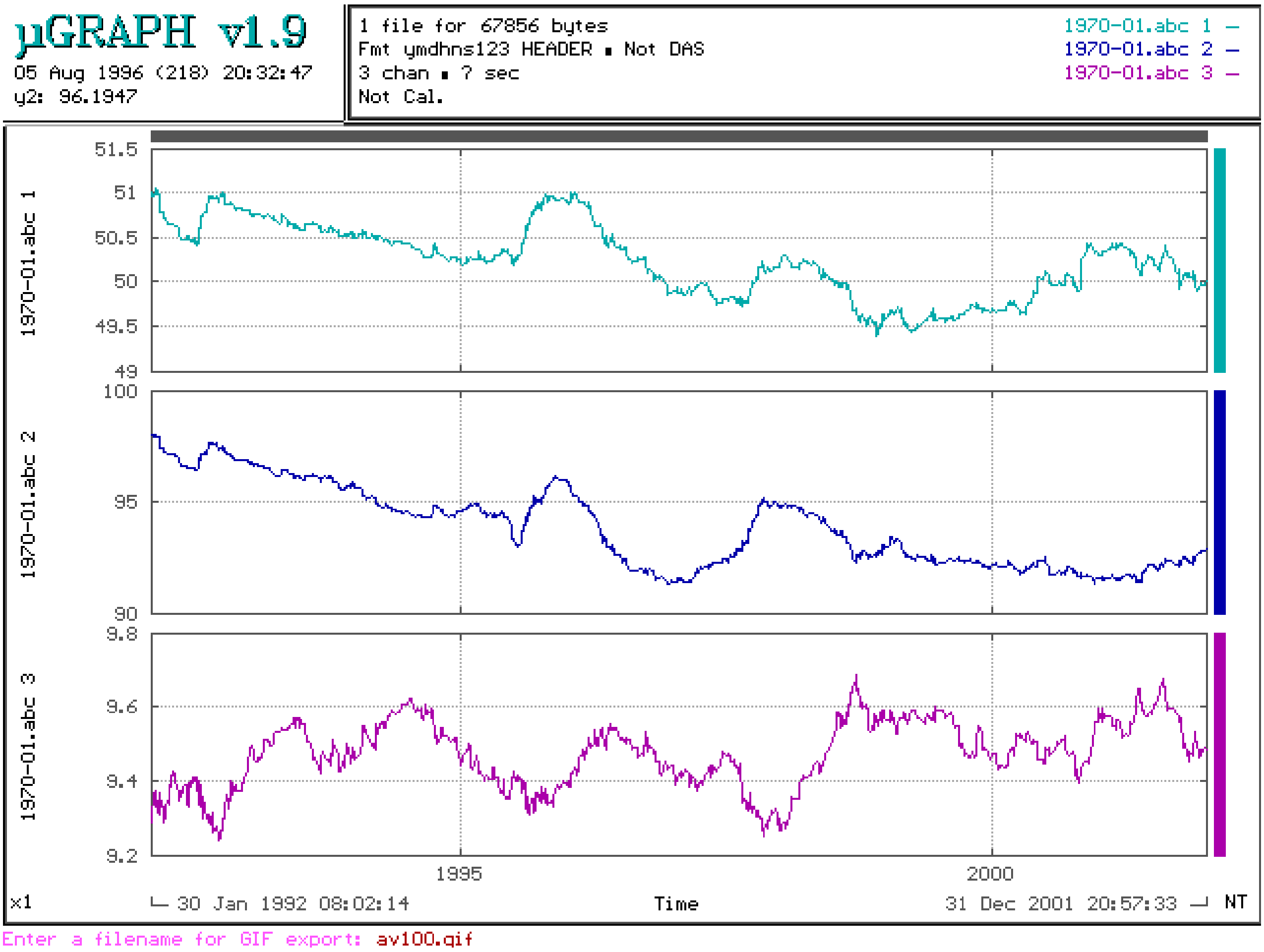


Figure 15. Migration of seismic activity (φ-λ-K) from Busingol earthquake zone (27.12.1991, 51.0°N, 98.0°E, M = 6.5 ÷ 7.0) to Chuya earthquake zone (27.09.2003, 50.0°N, 88.0°E, M = 7.2 ÷ 7.5).

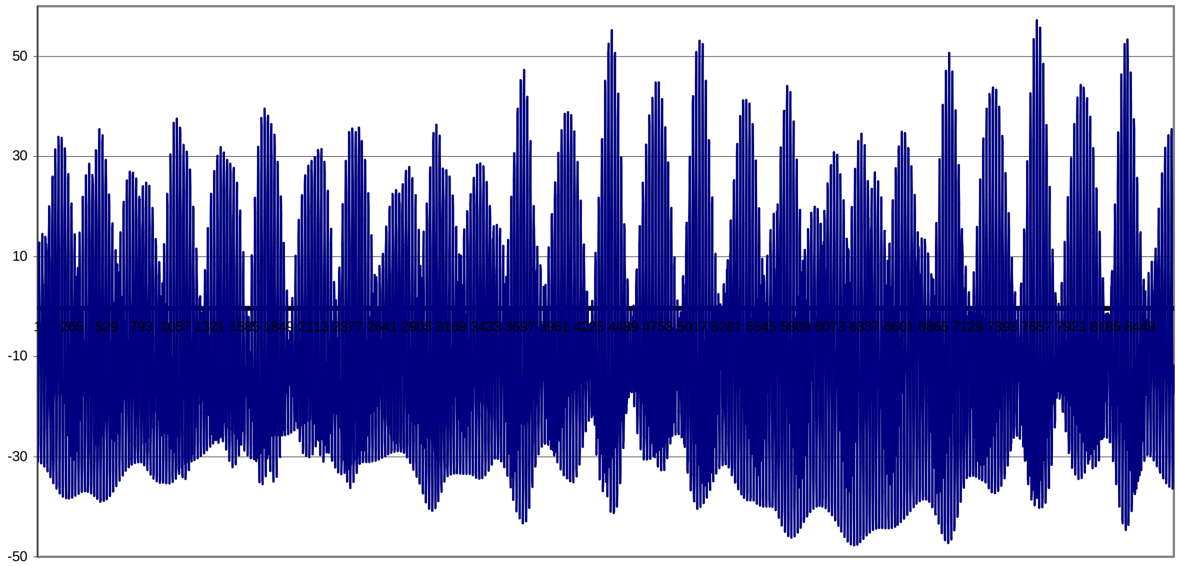


Figure 16. Volume strain for Talaya station (2008 year, in nstr).