Tidal and long-period variations observed with tiltmeters, extensometers and well-sensor (Baikal rift, Talaya station).

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Abstract

The paper presents results of measurements with tidal tiltmeters and extensometers in Talaya underground gallery (51.64°N, 103.68°E, western part of Baikal rift) from 1985 to 2007. The station is located in a narrow mountain valley, near Tunka-Sayan fault zone, on the boundary between Siberian platform and Baikal rift zone. Tidal analyses of tilt and strain data allow to separate cavity and geological effect. Quartz horizontal pendulums, well-sensor, tube and laser extensometer (25 m) were used with EDAS and other digital systems. Well-sensor was situated in a 120 m borehole at the bottom of the valley (200 m from underground gallery). Water tidal signal was analyzed by strain-program. It is influenced by the valley orientation (40°N). Long-term tilt variation shows a 18 year loop followed by a westward drift. Strain observations along three directions allow to determine the main strain axes. Long-term behavior is compared with regional seismological data. Laser extensometers data was used for tidal analysis. Time variation of tidal amplitude and phase are presented. Finally, after removing local effects, the Love and Shida numbers computed from combined data are h = 0.6077 ± 0.0008, k = 0.3014 ± 0.0004 and l = 0.0841± 0.0001.

Key words: quartz tiltmeters, tube and laser extensometers, borehole sensor, tidal parameters, long-period variation, Baikal rift, earthquakes.

1. Introduction

The measurements were made in the geodynamic observatory Talaya (coordinates 51.68° N, 103.65° E) located 7 km to the west of the Southwest extremity of the Baikal lake and 3 km to the South of the Main Sayan fault. Tilt and strain measurements are carried out in the 90m long underground gallery of the Talaya seismic station. The main gallery and the six perpendicular drifts have a cross section of 2x2 m^2. Water well is situated at 200 m from underground gallery. Results received at this station were published [Timofeev et al., 2000a, 2000b; Timofeev et al., 2006; Ducarme et al., 2008]. Tidal gravity measurements were performed in a special cellar. Observations with digital tidal gravimeter LCR-402

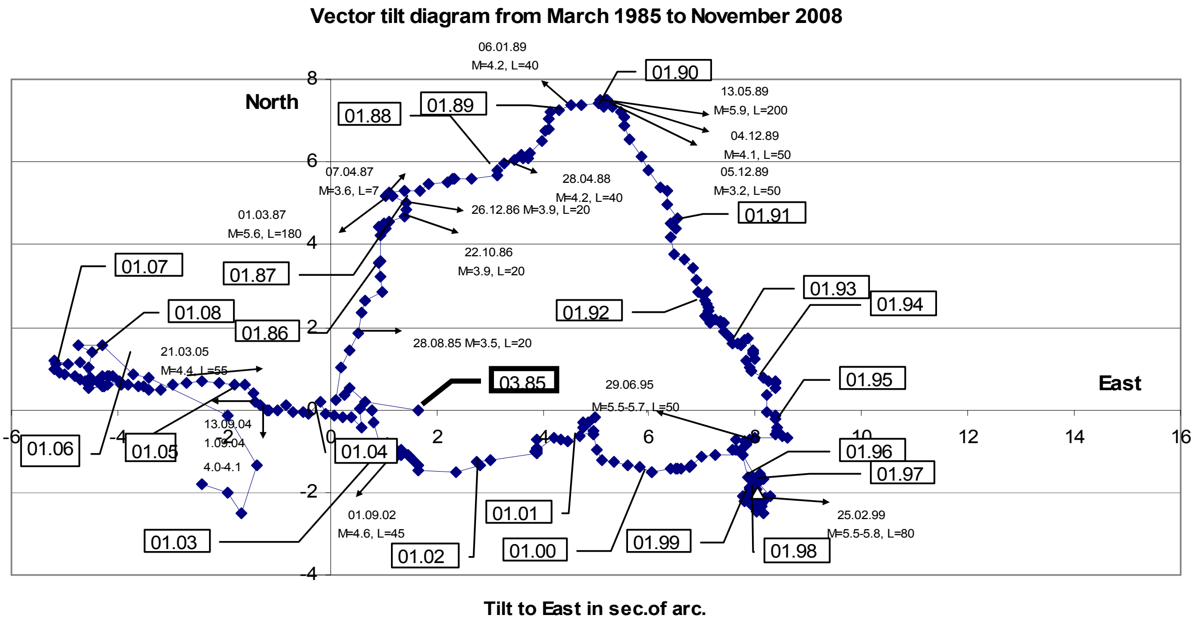


Figure 1. Tilt vector diagram from March 1985 to November 2008 (temp – one month), arrows – regional earthquakes, big arrow – last earthquake (1:35:31 27/08/2008, 51°.61, 104°.07, M = 6.1).

Table 1. Main strain orientation for Talaya station since 1989 deduced from extensometer data.

Year	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Compression (1), $\varepsilon_1 \cdot 10^6$	0.0	6.9	6.7	2.7	7.8	9.0	11.3	12.8	12.9	13.3	12.5	13.0	14.8	15.3	15.7	15.4	16.0	17.5	18.2
Extension (2), $\varepsilon_2 \cdot 10^6$	0.0	-5.8	-0.4	0.6	-2.1	-4.3	-5.1	-3.0	-4.8	-3.3	-2.2	-3.2	-2.8	-3.9	-3.5	-3.1	-2.2	-2.1	-2.5
Vertical strain, $\varepsilon_3 \cdot 10^6$	0.0	-0.4	-2.1	-1.1	-1.8	-1.5	-2.1	-3.2	-2.7	-3.3	-3.5	-3.2	-4.0	-3.8	-4.1	-4.1	-4.6	-5.1	-5.2
Orientation (ε_1)	0.0	-45.1	22.5	18.5	41.8	43.4	42.2	45.1	46.6	50.9	49.8	48.5	48.1	47.8	48.7	51.3	50.4	47.6	46.7
Orientation (ε_2)	0.0	44.9	112.5	108.5	131.8	133.4	132.2	135.1	136.6	140.9	139.8	138.5	138.1	137.8	138.7	141.3	140.4	137.6	136.7
Volume strain, $\theta \cdot 10^6$	0.0	0.7	4.2	2.2	3.7	3.1	4.1	6.5	5.4	6.6	6.9	6.4	8.0	7.6	8.1	8.2	9.2	10.2	10.4
Shift strain, $\gamma \cdot 10^6$	0.0	12.7	-7.1	-2.1	-10.0	-13.3	-16.4	-15.8	-17.7	-16.6	-14.7	-16.2	-17.6	-19.2	-19.2	-16.5	-18.2	-19.6	-20.7

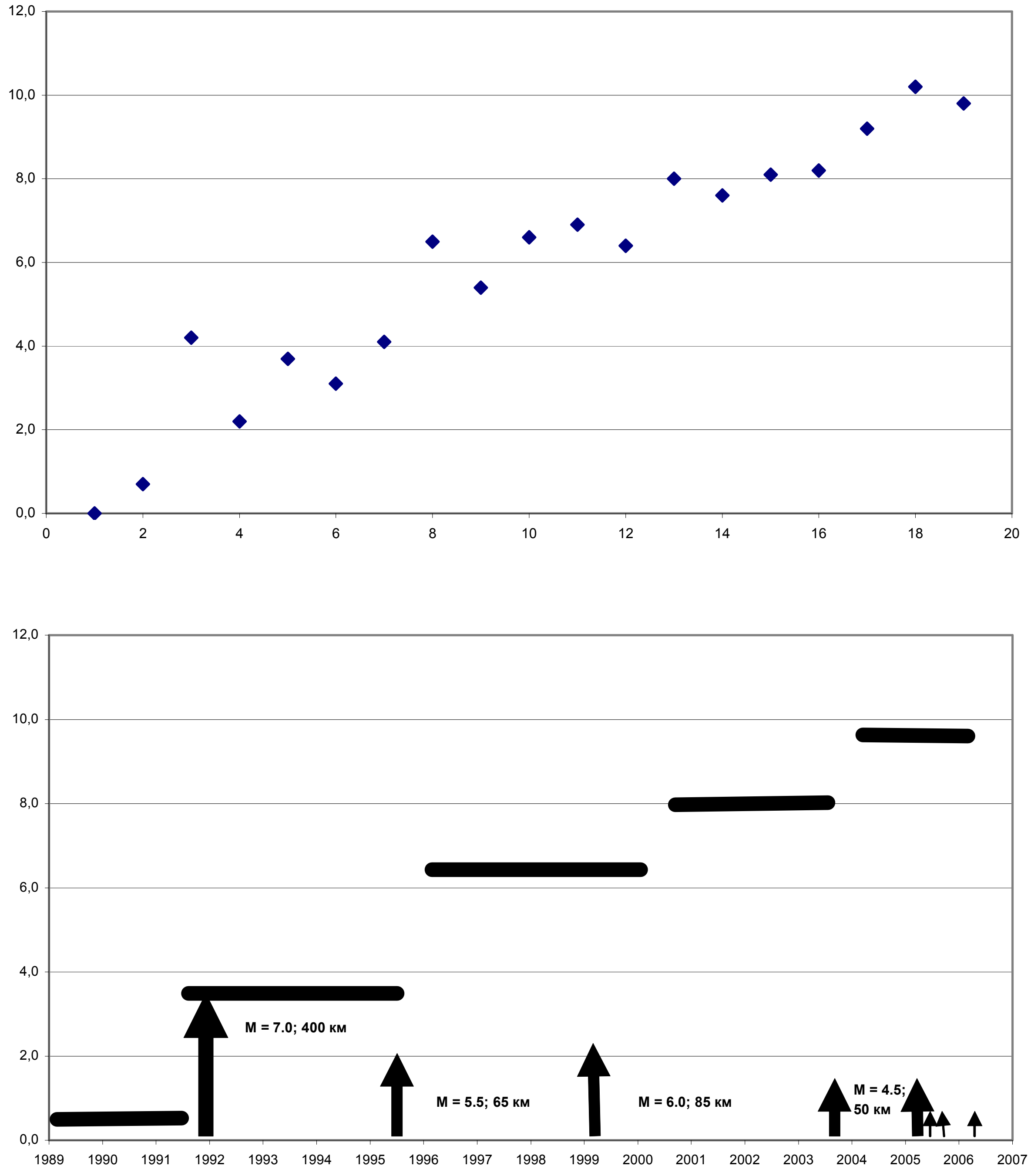


Figure 2. Volume strain variation (x10^6, 1989-2007 yy.) and earthquakes (see Table 1 and 2)

Table 2. List of earthquakes located 200km around Talaya station

Time and coordinates	Magnitude	Distance to epicenter (km) and magnitude range		
		0 < L < 50 M > 3.0	50 < L < 100 M > 4.5	100 < L < 200 M > 5.0
18h 27m 33.40s, 23/11/1994; 51.36°N, 104.14°E	3.0	50 km to SE		
04h 51m 14.80s, 20/02/1995; 51.28°N, 103.25°E	3.1	52 km to SW		
23h 02m 28,20s 29/06/1995; 51.71°N, 102.70°E	5.5-5.7		67 km to W	
05h 52m 31,40s 19/09/1996; 51.49°N, 103.95°E	3.0	30 km to S		
05h 00m 35,40s, 09/12/1997; 51.77°N, 103.39°E	3.9	20 km to W		
08h 05m 31,50s 10/02/1999; 51.64°N, 104.85°E	4.6		85km to E	
18h 58m 28,22s 25/02/1999; 51.63°N, 104.89°E	5.5-5.8		86 km to E	
19h 11m 07,00s 25/02/1999; 51.65°N, 104.80°E	5.3		86 km to E	
20h 24m 31,10s 25/02/1999; 51.58°N, 104.78°E	4.6		87 km to E	
00h 12m 28,30s 26/02/1999; 51.71°N, 104.79°E	4.5		86 km to E	
16h 28m 08,70s 31/05/2000; 51.71°N, 104.84°E	5.1		86 km to E	
07h 16m 31.60s 06/10/2001; 51,73 °N, 103,78° E	2.9	11 km to NE		
05h 19m 13.90s, 01/09/2002; 51,29°N, 103,33° E	4.6	49 km to SW		
02h 59m 56.00s, 17/09/2003; 51,75°N, 101,46° E	5.3			155 km to W
19h 55m 11.2s 23/02/2005 52.35°N, 101.59° E	5.3			160 km to NW
18h 04m 55.10s, 21/03/2005; 51,73°N, 104,40° E	4.5		52 km to E	
17h 05m 51.80s, 11/06/2005; 51,71°N, 103,94° E	3.4	22 km to E		
07h 34m 44.9s, 21/09/2005 51.72°N, 103.79° E	2.9	12 km to E		
01h 52m 17.3s, 18/02/2006 50.26°N, 105.37° E	5.0			200 km to SE
17h 15m 25.9s 06/03/2006 51.47°N, 103.82° E	3.1			25 km to SE
01h 35m 31s 27/08/2008 51.61°N, 104.07° E	6.1	25 km to E		

Table 3 : Tidal analysis results in NS component - from 05/1999 to 07/2003 by Program ANALYZE, version 3.40.

```
######################################################################
# Earth Tide Station Talay No. 1301 RUSSIA                           #
# BEMSE GS SB RAS                                                    #
# Institute of Geophysics SB RAS, Novosibirsk, Russia.               #
# 51.6810N  103.6440E  H550M                                         #
# Tilt NS                                                            #
# Calibration used.                                                  #
######################################################################
 19990503...20030717    Recorded days in total: 379.208
 Tamura (1987) 1200 waves.
```

Adjusted tidal parameters :

from [cpd]	to [cpd]	wave	theor. ampl. [mas]	ampl.fac.	stdv.	ph.lead [deg]	stdv. [deg]
0.501370	0.911390	Q1	0.3136	0.86573	0.15735	1.9780	7.7010
0.911391	0.947991	O1	1.6379	0.88325	0.03022	8.7692	1.4487
0.947992	0.981854	M1	0.1288	1.00597	0.25654	-0.6483	10.8175
0.981855	0.998631	P1	0.7621	0.90122	0.09438	4.6423	4.4383
0.998632	1.001369	S1	0.0180	30.26110	6.51725	156.7548	9.1498
1.001370	1.004107	K1	2.3035	0.74189	0.03799	0.0298	2.1742
1.004108	1.006845	PSI1	0.0180	18.17157	4.55190	174.9287	10.6114
1.006846	1.023622	PHI1	0.0328	6.23346	2.14210	-111.0360	14.5718
1.023623	1.057485	J1	0.1288	0.75018	0.36217	27.2119	20.4192
1.057486	1.470243	OO1	0.0705	1.03030	0.58887	-97.8232	24.1928
1.470244	1.880264	2N2	0.2367	1.28854	0.17086	-4.7379	5.6319
1.880265	1.914128	N2	1.4823	0.74683	0.03209	1.4791	1.8227
1.914129	1.950419	M2	7.7420	0.69775	0.00650	7.3366	0.3950
1.950420	1.984282	L2	0.2188	0.49144	0.24550	-78.0754	21.1776
1.984283	2.002736	S2	3.6020	0.69779	0.01462	9.8926	0.8888
2.002737	2.451943	K2	0.9792	0.35981	0.05061	22.2757	5.9668
2.451944	7.000000	M3M6	0.0944	0.60844	0.44718	0.6115	31.1835

Standard deviation on unit weight: 2.736

Table 4 : Tidal analysis results in EW component - from 05/1999 to 01/2000 by Program ANALYZE, version 3.40.

```
##########################################################################
# Earth Tide Station Talay No. 1301 RUSSIA                               #
# BEMSE GS SB RAS                                                        #
# Institute of Geophysics SB RAS, Novosibirsk, Russia.                   #
# 51.6810N  103.6440E  H550M                                             #
# Tilt EW                                                                #
# Calibration used.                                                      #
##########################################################################
```

19990510...20000124 7 blocks. Recorded days in total: 138.083
Hartmann+Wenzel (1995) 434 waves.

adjusted tidal parameters :

from [cpd]	to [cpd]	wave	theor. ampl. [mas]	ampl.fac.	stdv.	ph. lead [deg]	stdv. [deg]
0.501370	0.911390	Q1	0.9783	0.72995	0.18116	-23.9031	13.0968
0.911391	0.947991	O1	5.1095	0.56303	0.04368	2.7758	4.0890
0.947992	0.981854	M1	0.4016	1.32675	0.67244	66.3159	26.6897
0.981855	1.023622	P1K1	7.1829	0.64644	0.02569	1.3367	2.0947
1.023623	1.057485	J1	0.4018	0.75163	0.46944	9.0651	32.9707
1.057486	1.470243	OO1	0.2198	0.37185	1.42737	63.9568	201.6397
1.470244	1.880264	2N2	0.2999	1.03288	0.20150	15.7361	10.2850
1.880265	1.914128	N2	1.8778	0.77600	0.04911	-1.6245	3.3346
1.914129	1.950419	M2	9.8077	0.70702	0.01102	-1.6375	0.8221
1.950420	1.984282	L2	0.2772	0.29072	0.43553	46.8611	78.8911
1.984283	2.451943	S2K2	4.5626	0.68071	0.02592	-2.5299	2.0063
2.451944	7.000000	M3M6	0.1196	0.23136	0.52132	41.1160	118.6749

Standard deviation on unit weight: 1.793 mas agree well with the DDW99 (Dehant et al., 1999) model. The objective of our study is to estimate current surface deformation in the south-west part of Baikal rift using local deformation measurement. The last data processing and tidal analysis of these long series are described in this paper.

2. Tilt and strain long-term variations

The long series of quartz tiltmeter data have been obtained in the underground gallery of Talaya seismic station starting from 1985 until present day. Long-term tilt variation shows a 18 year loop followed by a linear drift to the West (Figure 1). Long series of extensometers data have been observed in the underground gallery starting from 1990 until present day. The equipment consists primarily of two short quartz tube extensometers and an invar rod strainmeter with induction sensors (Timofeev et al., 2000b). Later on a laser extensometer with two 25m orthogonal legs was also installed. This set of extensometers was installed in different drifts and directions (-24° N, -22.5° N, 0° N, 90° N, 66° N), as we need at least three different directions to calculate the variations of main strain axes for long term study of the tectonic activity (Table 1, Figure 2). Long-term tilt and strain variation reflects the regional seismic activity (Table 2).

3. Earth Tide Analysis of Tilt Data

The earth tide analysis of the quartz tiltmeters data set 1988-1998 has been carried out not only with method VEN66 (Venedikov, 1966) using the CTE550 tidal potential and filtering on 48 hours blocks but also with ETERNA 3.4 (Wenzel, 1996) using the Tamura tidal potential and Pertsev numerical filters (Gridnev et al., 1993, Timofeev et al., 2000a). The adjusted tidal parameters are given in Table 3 for North-South component and in Table 4 for East-West component. The standard deviation of unit weight for different components and for different periods reaches 2 to 2.5 mas. The results of tidal analysis by the two methods are similar in amplitude and in phase. The discrepancies are due to the different filtering techniques interfering with the gaps.

Slight changes are observed between successive partial analysis. They can be due to temporal variations of the calibration factor and temporal variations of the signal cable impedance. This last effect is probably responsible of the large S_1. Tidal analysis of barometric pressure shows a diffuse effect in the diurnal band with a maximum at S_1 frequency and only one peak on S_2 in the semi-diurnal band. Local cavity effect (Harrison, 1976) is perturbing M_2 (NS) phase lag result (9°) but this effect is absent on EW results. Tilt-strain coupling effect for M_2 wave is absent in EW direction at Talaya.

4. Strain difference

The best results for the laser system have been observed for differential strain as in this case we obtain the best elimination of the air pressure influence

(Table 5). We used for tidal analyses of strain difference between two orthogonal directions the version “0” (gravity) of the ETERNA analysis programs with a convenient renormalisation to convert it to strain evaluation i.e. potential divided by g (absolute gravity) and by R (Earth radius at the observation point).

As known [Melchior, 1976, Timofeev et al., 2000b] for strain in two directions of azimuth *a1* and *a2* we have:

$$e_{d1} = \cos^2 a1 \cdot e_{\theta\theta} + \sin^2 a1 \cdot e_{\lambda\lambda} + \cos a1 \cdot \sin a1 \cdot e_{\theta\lambda},$$

$$e_{d2} = \cos^2 a2 \cdot e_{\theta\theta} + \sin^2 a2 \cdot e_{\lambda\lambda} + \cos a2 \cdot \sin a2 \cdot e_{\theta\lambda},$$

We have for strain difference:

$$\Delta e = e_{d1} - e_{d2}$$

$$= e_{\theta\theta} \cdot (\cos^2 a1 - \cos^2 a2) + e_{\lambda\lambda} \cdot (\sin^2 a1 - \sin^2 a2) - e_{\theta\lambda} \cdot (\cos a1 \cdot \sin a1 - \cos a2 \cdot \sin a2)$$

When the first direction is perpendicular to the second one:

$$a2 = a1 + 90°$$

and we can use only one angle $a1 = \alpha$ to express the strain difference:

$$\Delta e = (e_{\theta\theta} - e_{\lambda\lambda})(\cos^2\alpha - \sin^2\alpha) - 2 e_{\theta\lambda} \cdot \sin\alpha \cdot \cos\alpha$$
$$= (e_{\theta\theta} - e_{\lambda\lambda}). \cos 2\alpha + e_{\theta\lambda} \cdot \sin 2\alpha$$

For the different tidal waves we have:

<u>Sectorial waves –</u>

$$e_{\theta\theta} = [h + 2((1-2\sin^2\theta)/\sin^2\theta) \cdot l] \cdot J_2/a \cdot g$$

$$e_{\lambda\lambda} = [h - 2((1+\sin^2\theta)/\sin^2\theta) \cdot l] \cdot J_2/a \cdot g$$

$$e_{\theta\lambda} = 4l[(\cos\theta / \sin^2\theta) \cdot \tan 2H] \cdot J_2/a \cdot g$$

<u>Tesseral waves -</u>

$$e_{\theta\theta} = (h - 4l) \cdot T_2/a \cdot g$$

$$e_{\lambda\lambda} = (h - 2l) \cdot T_2/a \cdot g$$

$$e_{\theta\lambda} = - 2l \cdot (tgH/\cos\theta) \cdot T_2/a \cdot g$$

where h and l are tidal number, J_2 and T_2 - tidal potential, *a* - radius of Earth, *g* – gravity,
θ - colatitude, *H* - hour’s angle.

Using these formulas for computing the strain difference, we get

.

Table 5 (a). Tidal analysis of differential laser strain data - from 01/1995 to 11/2003 by ETERNA 3.4 (gravity version).

Wave	Ampl. Observ (nstr)	Ampl. Error (nstr)	Ampl. Factor Obser.	Ampl. Factor Error	Phase Observ	Phase error
O1	2.950	0.018	0.1952	0.0012	-60°.57	0°.07
K1	3.830	0.017	0.1777	0.0008	-72°.30	0°.05
N2	1.702	0.016	0.6518	0.0061	66°.48	0°.35
M2	9.970	0.017	0.6901	0.0012	65°.36	0°.07
S2	5.008	0.016	0.7451	0.0024	68°.08	0°.14

Table 5 (b). Azimuth, phase, coefficient and Love number.

AZ	phase d	F1/l	l(O1)	phase sd	F2/l	l(M2)
-22.75	-52.37	2.29587	0.08502	44.66	8.28210	0.08332
-23.00	-52.85	2.30061	0.08485	45.17	8.27999	0.08334
-23.25	-53.33	2.30534	0.08467	45.67	8.27789	0.08336
-23.50	-53.81	2.31005	0.08450	46.17	8.27578	0.08339
-23.75	-54.29	2.31475	0.08433	46.67	8.27368	0.08341
-24.00	-54.76	2.31944	0.08416	47.17	8.27158	0.08343
-24.25	-55.23	2.32410	0.08399	47.67	8.26948	0.08345
-24.50	-55.71	2.32875	0.08382	48.17	8.26739	0.08347
-24.75	-56.17	2.33337	0.08366	48.67	8.26530	0.08349
-25.00	-56.64	2.33798	0.08349	49.18	8.26322	0.08351
-25.25	-57.11	2.34256	0.08333	49.68	8.26114	0.08353
-25.50	-57.57	2.34711	0.08317	50.18	8.25907	0.08355
-25.75	-58.03	2.35164	0.08301	50.68	8.25701	0.08358
-26.00	-58.49	2.35615	0.08285	51.19	8.25495	0.08360
-26.25	-58.95	2.36062	0.08269	51.69	8.25290	0.08362
-26.50	-59.41	2.36507	0.08253	52.19	8.25087	0.08364
-26.75	-59.86	2.36948	0.08238	52.70	8.24884	0.08366
-27.00	-60.32	2.37387	0.08223	53.20	8.24682	0.08368
-27.25	-60.77	2.37822	0.08208	53.71	8.24481	0.08370
-27.50	-61.22	2.38253	0.08193	54.21	8.24282	0.08372
-27.75	-61.67	2.38682	0.08178	54.72	8.24083	0.08374
-28.00	-62.11	2.39106	0.08164	55.22	8.23886	0.08376
-28.25	-62.56	2.39527	0.08149	55.73	8.23691	0.08378
-28.50	-63.00	2.39944	0.08135	56.23	8.23496	0.08380
-28.75	-63.44	2.40357	0.08121	56.74	8.23303	0.08382
-29.00	-63.88	2.40766	0.08107	57.24	8.23112	0.08384
-29.25	-64.32	2.41171	0.08094	57.75	8.22922	0.08386
-29.50	-64.76	2.41571	0.08080	58.26	8.22734	0.08388
-29.75	-65.20	2.41968	0.08067	58.76	8.22548	0.08390
-30.00	-65.63	2.42360	0.08054	59.27	8.22363	0.08391
-30.25	-66.06	2.42747	0.08041	59.78	8.22180	0.08393
-30.50	-66.50	2.43129	0.08029	60.29	8.21999	0.08395
-30.75	-66.93	2.43507	0.08016	60.79	8.21820	0.08397
-31.00	-67.36	2.43880	0.08004	61.30	8.21643	0.08399
-31.25	-67.78	2.44248	0.07992	61.81	8.21468	0.08401
-31.50	-68.21	2.44611	0.07980	62.32	8.21295	0.08402
-31.75	-68.64	2.44969	0.07968	62.83	8.21124	0.08404
-32.00	-69.06	2.45322	0.07957	63.34	8.20955	0.08406
-32.25	-69.48	2.45670	0.07946	63.85	8.20789	0.08408
-32.50	-69.91	2.46012	0.07935	64.35	8.20625	0.08409

-32.75	-70.33	2.46349	0.07924	64.86	8.20463	0.08411
-33.00	-70.75	2.46680	0.07913	65.37	8.20304	0.08412
-33.25	-71.16	2.47005	0.07903	65.88	8.20147	0.08414
-33.50	-71.58	2.47325	0.07892	66.39	8.19992	0.08416
-33.75	-72.00	2.47640	0.07882	66.90	8.19841	0.08417
-34.00	-72.41	2.47948	0.07873	67.41	8.19691	0.08419
-34.25	-72.83	2.48250	0.07863	67.92	8.19545	0.08420
-34.50	-73.24	2.48547	0.07854	68.44	8.19401	0.08422
-34.75	-73.65	2.48837	0.07844	68.95	8.19260	0.08423
-35.00	-74.06	2.49122	0.07836	69.46	8.19121	0.08425

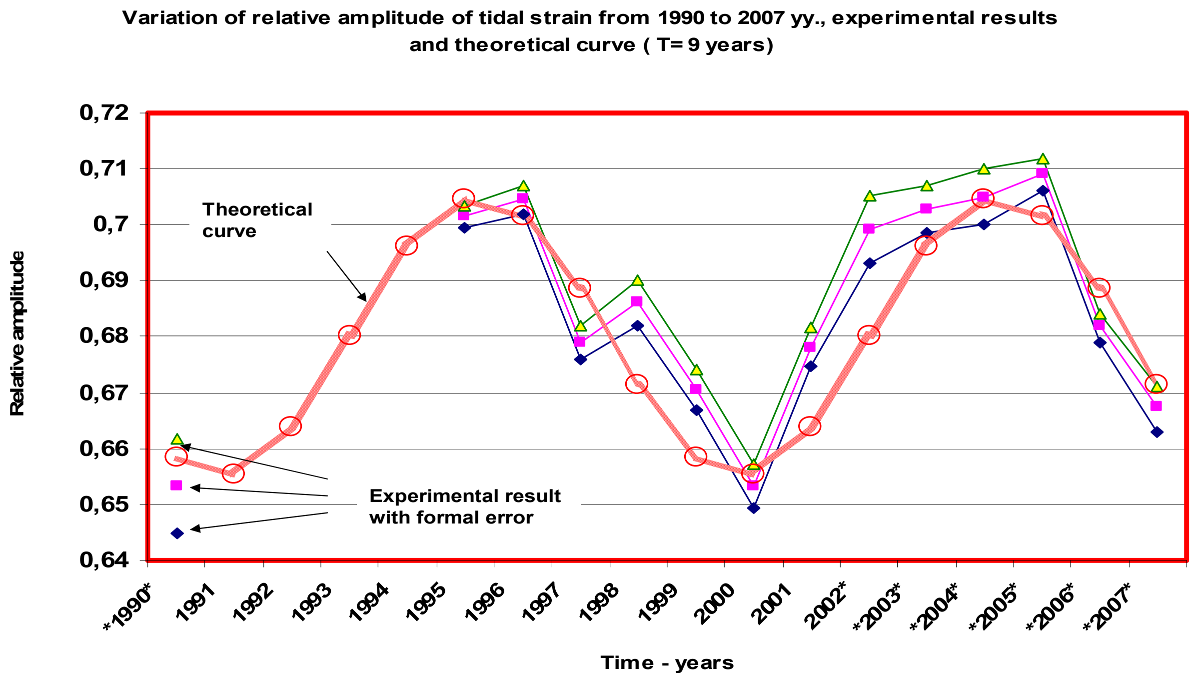
Table 6. Tidal analysis of water well data by "Strain version" (130°N).
Period: from 5h 11/06/2007 to 18h 17/01/2008.

Azimuth from north direction 130.0 deg
Adjusted tidal parameters :

from	to	wave	ampl. [nstr]	signal/ noise	ampl.fac.	stdv.	phase lead [deg]	stdv. [deg]
286	428	Q1	0.041	4.1	0.03590	0.00884	136.7197	0.5069
429	488	O1	0.347	32.9	0.05790	0.00176	47.6414	0.1008
489	537	M1	0.058	7.0	0.12384	0.01773	60.0412	1.0166
538	592	P1SK1	0.383	27.1	0.04548	0.00168	68.3259	0.0983
593	634	J1	0.033	3.4	0.07114	0.02110	76.8102	1.2088
635	736	OO1	0.031	5.1	0.11973	0.02357	126.3101	1.3471
737	839	2N2	0.025	2.7	0.12430	0.04596	-14.3450	2.6347
840	890	N2	0.125	10.7	0.09842	0.00921	14.4761	0.5276
891	**947**	**M2**	**0.676**	**54.6**	**0.10164**	**0.00186**	**2.4094**	**0.1066**
948	987	L2	0.006	0.5	0.03168	0.06786	-12.3562	3.8808
988	1121	S2K2	0.299	30.8	0.09677	0.00314	14.3476	0.1764
1122	1214	M3	0.016	1.3	0.52895	0.39395	-11.0200	22.5727

Standard deviation of weight unit: 0.333
degree of freedom: 1578
Adjusted meteorological or hydrological parameters:

no.	regr.coeff.	stdv.	parameter	unit
1	**2.36523**	0.10444		mm / KPa



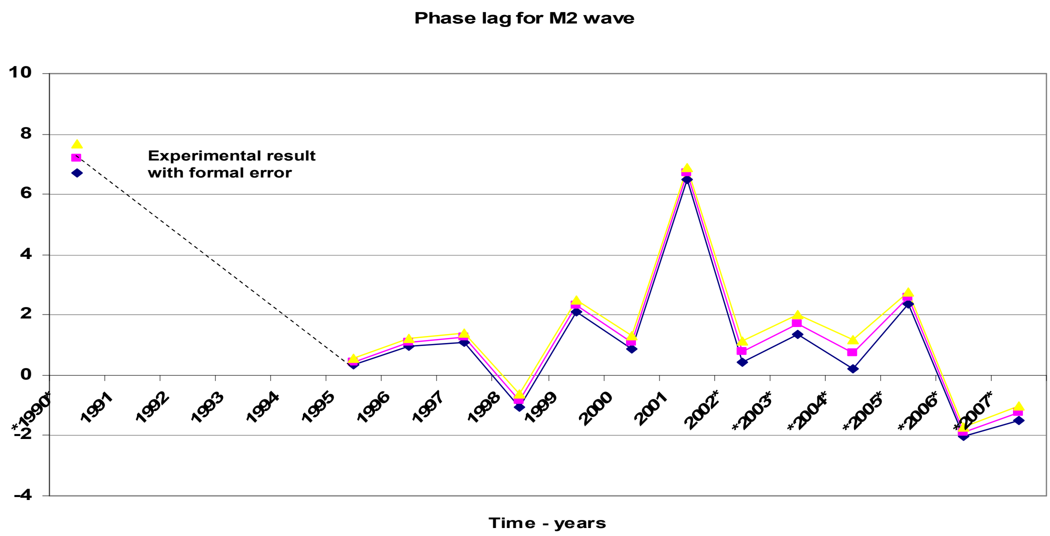


Figure 3. Tidal amplitude and phase variation (1990-2007 yy.) by laser extensometer consecutive annual analyses (M2, differential strain, annual analysis results).
Top - Relative tidal amplitude and theoretical curve: $f = A \sin(\omega t + \varphi)$, where A = 0.025 (3.6% of mean amplitude), $\omega = 2\pi/T$, T = 9 years and t – time.
Bottom - phase variation by laser extensometer annual data in degrees (difference from mean value).

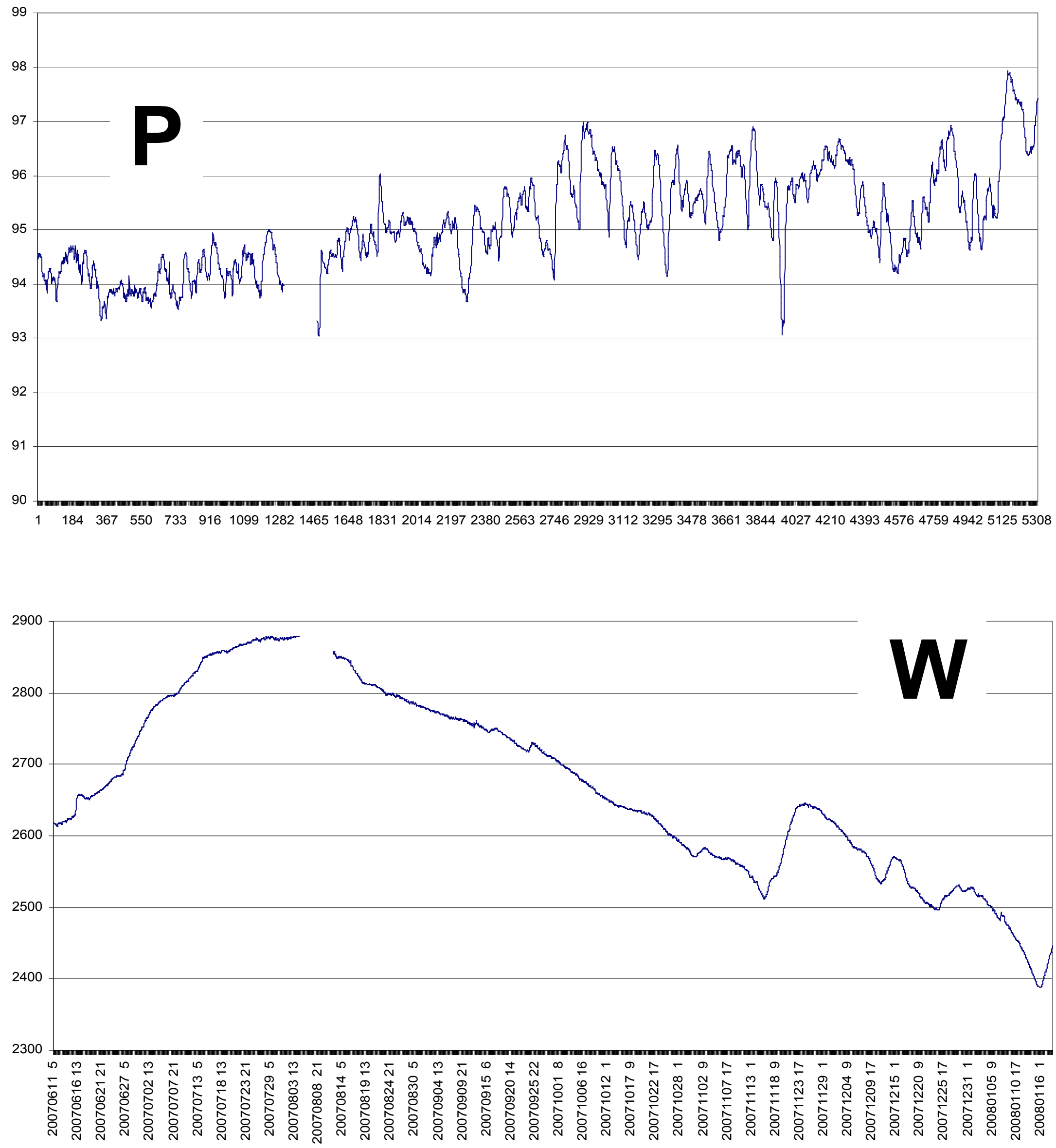


Figure 4. Variation of air pressure (P) and water level (W) for Talaya well from 5h 11/06/2007 to 18h 17/01/2008. (P in KPa and W in mm).

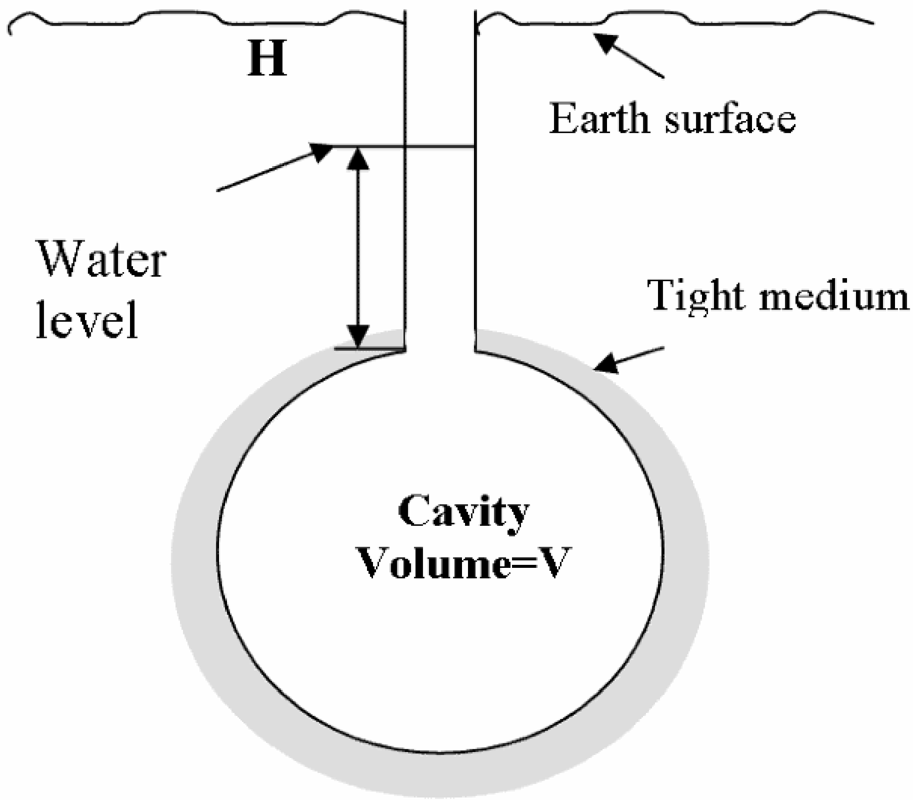


Figure 5. Finite cavity model of well.

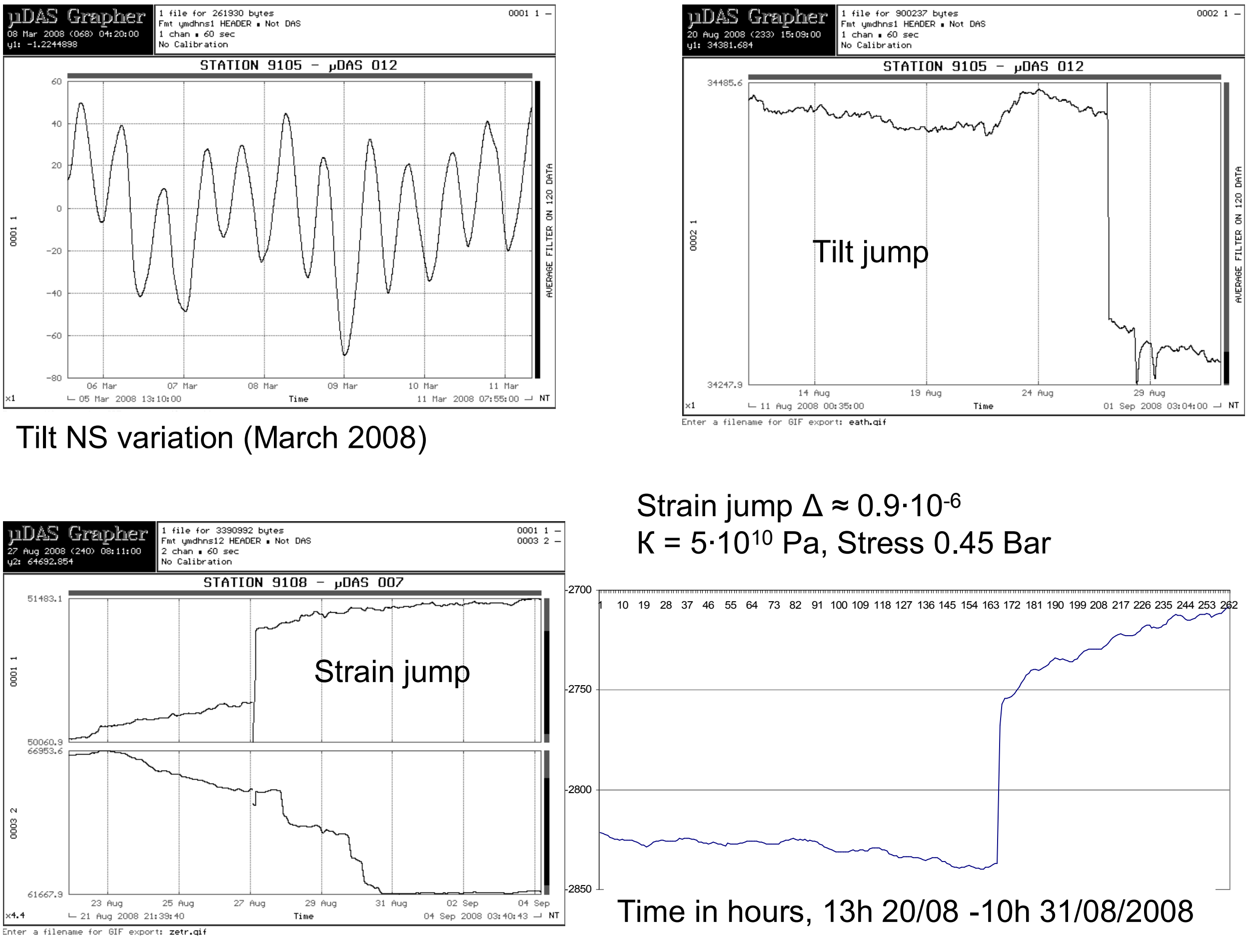


Figure 6. Tidal variation and earthquake jump on 27/08/2008
Top: tilt normal curve(left) and reaction to earthquake (right),
Bottom: strain (left) and water level variations (right).

Seismology station Talaya with underground gallery – orientation of Talaya valley 40°N, it situated to south from fault zone, 7 km to west from Baikal Lake.

Figure 7: Talaya station (star) and Baikal Lake.

Sectorial waves

$\Delta e_2 = \cos 2\alpha \cdot (e_{\theta\theta} - e_{\lambda\lambda}) + \sin 2\alpha \cdot e_{\theta\lambda} =$

$\{[2l\cdot \cos 2\alpha \cdot(2 - \sin^2\theta) / \sin^2\theta)] + [4l\cdot \sin 2\alpha \cdot (\cos\theta / \sin^2\theta)\cdot \tan 2H]\}\cdot J_2 /a\cdot g$

Tesseral waves

$\Delta e_1 = \cos 2\alpha \cdot (e_{\theta\theta} - e_{\lambda\lambda}) + \sin 2\alpha \cdot e_{\theta\lambda} =\{(-2l\cdot \cos 2\alpha) - [2l\cdot \sin 2\alpha \cdot(tgH/\cos\theta)]\}\cdot T_2 /a\cdot g$

After the calculation we obtain the theoretical values for amplitude factor and phase :

Sectorial waves

Amplitude factor $F_2 = (2l /\sin^2\theta)\cdot\sqrt{[(2\cos\theta \cdot\sin 2\alpha)^2 + \cos^2 2\alpha\cdot(2 - \sin^2\theta)^2]}$

Phase $\Delta\varphi_2 =$ -arctg$[2\tan 2\alpha.\cos\theta /(2 - \sin^2\theta)]$

Tesseral waves

Amplitude factor $F_1 =[2l/(\cos\theta)]\cdot\sqrt{(\cos^2 2\alpha\cdot\cos^2\theta +\sin^2 2\alpha)}$

Phase $\Delta\varphi_1 =$ arctg $[\tan 2\alpha/ \cos\theta)]$

For laser extensometer we have α = -24°N and θ = 38.32° (Semibalamut et al., 2000). However an apparent azimuth can be deduced directly from the observed phase differences. In our case the phase lag of M_2 (65.4° in Table 5) fits perfectly $\Delta\varphi_2$ for a value α = -33°N and the value for K_1 agrees reasonably well with the corresponding value $\Delta\varphi_1$=-71°. This apparent azimuth is thus shifted of –9°. It is probably related to the phase lag of 9° observed for M2 in our tiltmeter results due to cavity effect. In this direction the theoretical phase value of the amplitude factor is $F_2/\mathbf{l}$ = 8.203 and, as we get in Table 5 $F2_{(M2)}$=0.6901±0.0012, we can derive the corresponding Shida number $\mathbf{l}_{(M2)}$ = 0.0841±0.0001.

Annual analysis of strain data from 1990 to 2007 is presented on Figure 3. A nine years variation is apparent on the graph. Variations are associated with strong seismic activity in 1991, 1999 and 2008.

5. Tidal Analysis of Water Level Variation

Water level in the well (120 m depth, 2-3 m morena deposit over white marble) was sensitive to rainfall and reflects its seasonal variation (Figure 4). As tidal amplitude is very small, we use finite cavity model (Melchior, 1960**;** Figure 5):

$$dH = dV / [\pi\cdot r_w^2 + (\rho\cdot g\cdot V / K_w)]. \quad (1)$$

If the radius r_w is small we get: $dH = \Delta\cdot K_w / \rho\cdot g$, where $\Delta = dV / V$ is the cubic dilatation and K_w the elastic modulus of water. Using ETERNA program on the data of the second part of 2007 y. for volume variations, we got a phase disagreement. Phase agreement was obtained for horizontal strain with orientation 130°N (Table 6). It may be the result of crack system orientation along Talaya valley (40°N). Volume of crack can be estimated by adjusting the model. If we have for M_2 an experimental amplitude of 0.675 mm and a theoretical amplitude of 1.56 mm from the model ($dH = \Delta \cdot K_w / \rho \cdot g$), the amplitude reduction is connected with well size r_w. When relation (1), including crack volume and a well radius of 10cm, gives a correct estimation of the observed tidal amplitude, we can estimate parameters of crack system: crack depth – 100 m, crack width – 0.01 m, 30-50 cracks and crack length – 200 m. Formal use of Biot theory for confined aquifers for $dH/d\varepsilon = 0.10$ mm/nstr and barometric efficiency $\gamma = 2$ mm/KPa, allows to estimate elastic modulus $K_w = 0.2 \cdot 10^{10}$ Pa. for water. Orientation of crack system (40°N) is connected with Talaya valley orientation (Figure 7). Analysis results were used to estimate the effect of last earthquake (27/08/2008) on well level variation (Cooper et al., 1965, Figure 6). Stress jump was 0.045 MPa at 20 km distance from the epicenter.

6. Conclusions

We present results of tidal measurements with tiltmeters and extensometers in Talaya underground gallery (Baikal rift). The station is situated in a narrow mountain valley, on the boundary between Siberian platform and Baikal rift zone. Tidal analyses of tilt and strain data allow to separate cavity and geological effect. Quartz horizontal pendulums, well-sensor, tube and laser extensometers (25 m) were used with EDAS and other digital systems. Long-term tilt variation shows a loop with 18 year period followed by a westward drift. Three direction strain observation allow calculate main strain axes. Long-term variations were compared to regional seismological data. Laser extensometers data have been used for tidal analysis. Time variation of tidal amplitude and phase is presented. Then, after correction of local effect, the Love and Shida numbers calculated from combined strain tilt and gravity (Timofeev et al., 2000a, 2000b; Ducarme et al., 2008) data are $h = 0.6077 \pm 0.0008$, $k = 0.3014 \pm 0.0004$ and $l = 0.0841 \pm 0.0001$. Well-sensor was installed in a 120 m borehole at the bottom of the valley (200 m from underground gallery). Water tidal signal (M_2 – 0.67 mm) was analyzed by strain-program. Its phase is related with the valley orientation (40°N). Analysis results were used for estimations of last earthquake (27/08/2008) effect on well level variation. Stress jump was 0.045 MPa at 20 km distance from the epicenter.
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