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LOCAL DEFORMATION AND RHEOLOGICAL PARAMETERS BY MEASUREMENTS IN TALAYA STATION GALLERY (BAIKAL REGION)

V. Yu. Timofeev[1], O. K. Masalsky[2], D. G. Ardyukov[1], A. V. Timofeev[1]

[1] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of RAS, Novosibirsk, Russia*
[2] *Baikal Branch of Geophysical Survey, Siberian Branch of RAS, Irkutsk, Russia*

Abstract: Tilt measurements have been taken in the underground gallery at Talaya Seismological Station for almost three decades, from March 1985 till 2014. Based on such data, deformation curves were constructed and analysed in the frame of elastic and viscous-elastic models of the geological medium. From estimated annual deformation rates, it became possible to reveal deformation cycles ranging from 3 to 18 years with amplitudes up to 5 arc-seconds ($2\cdot10^{-5}$). For the bedrock in the Talaya stream valley, the elastic modulus was estimated at 20 GPa. In frame of the Kelvin visco-elastic model, the apparent viscosity of the medium was estimated at 10^{19} Pa·sec by deformation delay curve for 1989–2014 epoch. Observed vertical rates were used to estimate the size of the studied area (from 0.1 km to 6.0 km). The values estimated in our experimental investigation are used in a wide range of geophysical studies: modelling tectonic, co-seismic and post-seismic processes.

Key words: tidal quartz tiltmeter, viscoelastic model of deformation, apparent rheological parameters, Baikal region.

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ЛОКАЛЬНОЕ ДЕФОРМИРОВАНИЕ И РЕОЛОГИЧЕСКИЕ ПАРАМЕТРЫ ПО ИЗМЕРЕНИЯМ В ШТОЛЬНЕ (СЕЙСМОСТАНЦИЯ ТАЛАЯ, БАЙКАЛЬСКИЙ РЕГИОН)

В. Ю. Тимофеев[1], О. К. Масальский[2], Д. Г. Ардюков[1], А. В. Тимофеев[1]

[1] *Институт нефтегазовой геологии и геофизики им. А.А. Трофимука СО РАН, Новосибирск, Россия*
[2] *Байкальский филиал Геофизической службы СО РАН, Иркутск, Россия*

Аннотация: Наблюдения наклонов в штольне сейсмостанции Талая ведутся уже около трех десятилетий (с марта 1985 года по настоящее время). В работе представлены результаты измерений. Полученные графики хода деформаций анализируются с использованием упругих и упруговязких моделей геологической среды. Определены годовые скорости деформирования, выявлен его циклический характер с периодами от 3 до 18 лет и амплитудами до 5 секунд дуги ($2\cdot10^{-5}$). Различными методами определен упругий модуль коренных пород, слагающих долину р. Талой, его величина составила 20 ГПа. С использованием кривой затухания деформации за период 1989–2014 гг., в рамках вязкоупругой модели Кельвина получено значение эффективной вязкости среды 10^{19} Па·с. С привлечением данных о скоростях вертикальных движений проведена оценка области, представительной для полученных параметров (от 0.1 до 6.0 км). Экспериментально определенные параметры могут быть использованы при моделировании тектонических, косейсмических и постсейсмических процессов.

Ключевые слова: приливные кварцевые наклономеры, вязкоупругие модели деформирования, эффективные реологические параметры, Байкальский регион.

1. Introduction

In studies of recent movements, which are an integral part of geophysical monitoring of the Earth's crust, recent deformation of the crust and mantle is described by elastic, plastic, viscoelastic models and combinations of such models. Obtaining field experimental results is essential for development of theoretical models of recent shear and deformation fields. Variations of such fields are determined for periods from a few days to decades. In such studies, measurements by extensiometers and the horizontal pendulums installed in special underground gallery is one of the common methods. Upon analyses of strain variations in time, a model showing deformation and rheology is selected, and it becomes possible to reveal factors and forces that influence the process of deformation. Interpreting of the obtained data can be challenging due to the fact that strain measurements are taken at the surface of the Earth and may be distorted by local impacts. Besides, there is an uncertainty of a total value of accumulated strain. Actually, accumulated strain can be estimated only at the qualitative level from neotectonic reconstructions, knowledge of the stage of seismic activation, and structural models of the region. Observed periods of deformation are indications of current regional activity; for instance, in the Baikal rift, i.e. in the intracontinental area, representative earthquakes occur in periods of 3 to 150 years. Determination of rheological parameters of the geological medium and estimation of deformation or strain rates are major objectives of our studies. We study processes on the data basis collected by long-term observations using tidal quartz tiltmeters that were installed in the underground gallery at Talaya Seismological Station (TSS, 51.68°N, 103.65°E) in March 1985 and ensure non-stop data recording. TSS situated near the northern boundary separated of the south-western part of the Baikal rift zone and the Siberian platform. The Main Sayan fault, being the boundary between the Siberian platform and the mobile area [*Levi et al., 1997; Solonenko, 1993*], is located a few kilometres to the north. In this region, lateral inhomogeneities of the crust and upper mantle cause deviatoric stresses of 35–40 MPa, according to calculations published in [*Kaban, Yunga, 2000*], and such stress values are close to maximum stresses estimated for the Baikal Rift. Left-lateral shift motion takes place at the Main Sayan fault. According to the available geological data and tectonic models of south-western part of the Baikal rift zone, horizontal displacement rates are from 0.8 to 2.0 mm per year, and displacements are mainly directed to the east [*San'kov et al., 1999, 2000; Calais et al., 2002; Lukhnev et al., 2010; Timofeev et al., 2012, 2013*].

2. Quartz tiltmeters, calibration methods, and strain record

The first measurements of tidal and technogenic tilting were obtained in 1960s when a tiltmeter designed by A.E. Ostrovsky was used; the tiltmeter mechanism included steel springs [*Ostrovsky, 1978*]. A pilot quartz tiltmeter NK-1 (Zöllner suspension type) was designed in 1973, manufactured and tested in 1974; it provided for photoelectric recording, and a new calibration method was proposed for calibration of the tiltmeter [*Bulanzhe et al., 1975*]. Stations in Siberia used pilot NK-1 units and sets of tools manufactured at the pilot plant of the Siberian Branch and in the Institute of Geology and Geophysics SB. In the TSS gallery, quartz horizontal pendulums have been in use since March 1985 [*Gridnev et al., 1990*]. Analogue records of measurements were collected from 1985 to 1998. Digital records are available since 1998. The tiltmeter is calibrated in laboratory conditions under the impact of elastic force of a quartz spring, and regular calibration checks are conducted on the permanent measurement inside the TSS tunnel. In the laboratory conditions, the calibration error amounts to 0.1 %. In situ conditions, when operator approaches the tiltmeter installed in the underground gallery (Fig. 1), an error may increase to a few percent. Maintaining stable recording of metrological parameters in time is challenging as measurements are impacted by the following factors: the electric

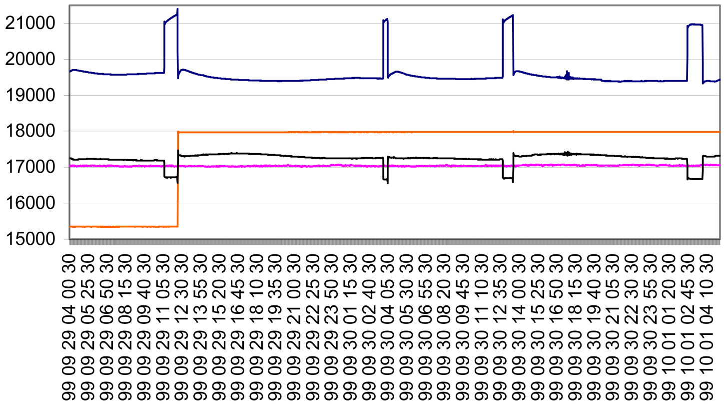

Fig. 1. Calibration pulses at the background of tidal variations of slope (underground gallery, Talaya seismic station). Minute interval of record.

Рис. 1. Калибровочные сдвиги на фоне приливных вариаций наклона (штольня сейсмостанции «Талая»).

power network of the seismic station is unstable, elements of the photo-electric sensor need to be periodically replaced, voltage may vary, it may be needed to disconnect the tiltmeter when seismological and geophysical equipment is in service operation. Such factors cause gaps in records and disturb stabilization of temperatures inside the TSS tunnel (+1°±1°C).

At Talaya Seismological Station, the tiltmeters were calibrated with the use of a quartz-spring micrometer or an electromagnetic calibration device [*Gridnev, Timofeev, 1990*]. For example, calibration for the period from 29 September 1999 to 01 October 1999 was done by shifting with a quartz spring, as shown in Figure 1. Figure 2 shows examples of tiltmeter calibration and attenuation of natural oscillations of the pendulum after shifting. The tiltmeter base ranges from 300 to 100 millimetres. Measurements are conducted on a pedestal (0.7 m × 1.4 m) mounted on the bedrock.

The horizontal pendulums were installed in two azimuths, N-S and E-W. Examples of digital records of tilting for every component are shown in Figures 3 and 4. Tidal tilt amplitudes amounted to 0.03 arc-seconds.

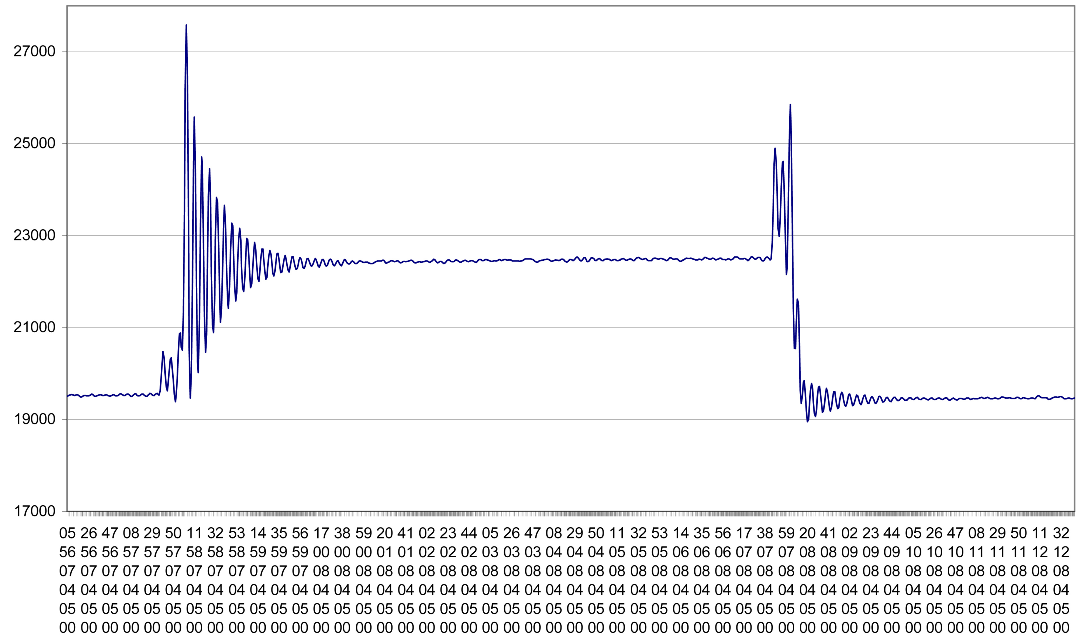

Fig. 2. Calibration pulses and inclinometer pendulum attenuation. A typical own period ranged from 8 to 18 seconds. Plotted time from 05 sec-56 m-07 h to 32 sec-12 m-08 h, 04 May 2000.

Рис. 2. Калибровочный сдвиг и затухание маятника наклономера. Обычно собственный период составлял от 8 до 16 секунд. Время на графике с 05 с-56 мин-07 ч по 32 с-12 мин-08 ч 4 мая 2000 г.

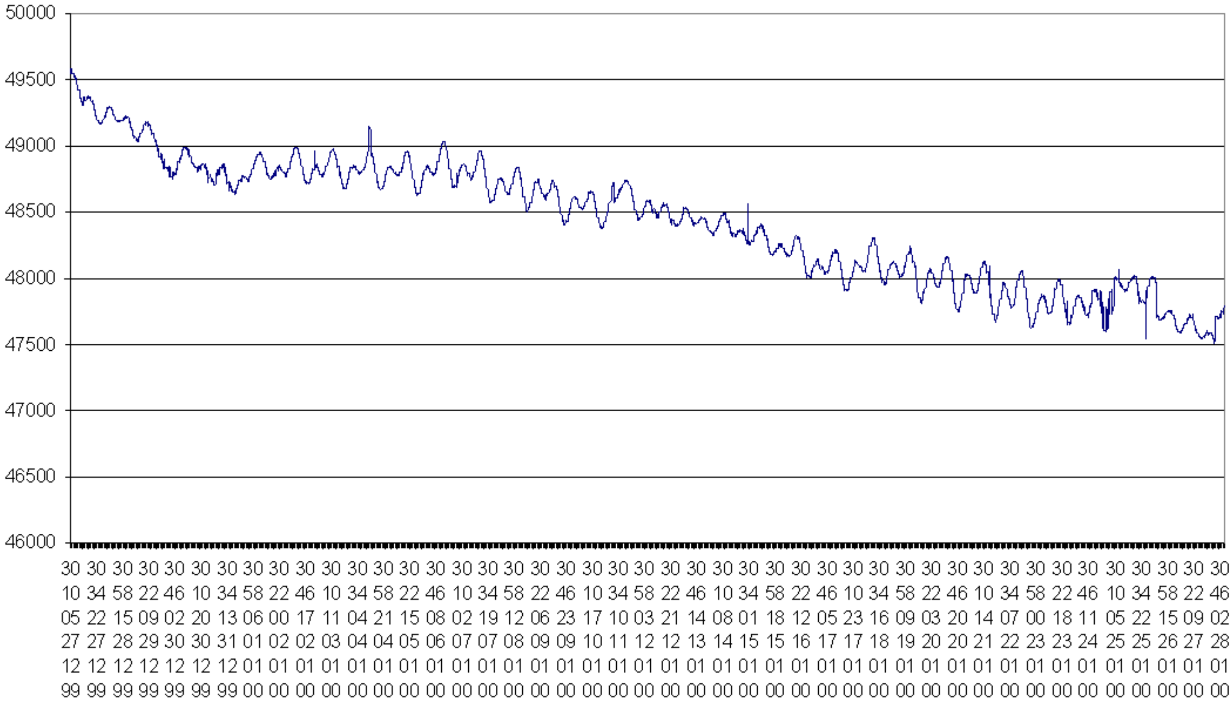

Fig. 3. Tidal variations and systematic tilt run (E-W) from 27 December 1999 to 28 January 2000.

Рис. 3. Приливные вариации и систематический ход наклона (В-З) за период 27.12.1999 г. – 28.01.2000 г.

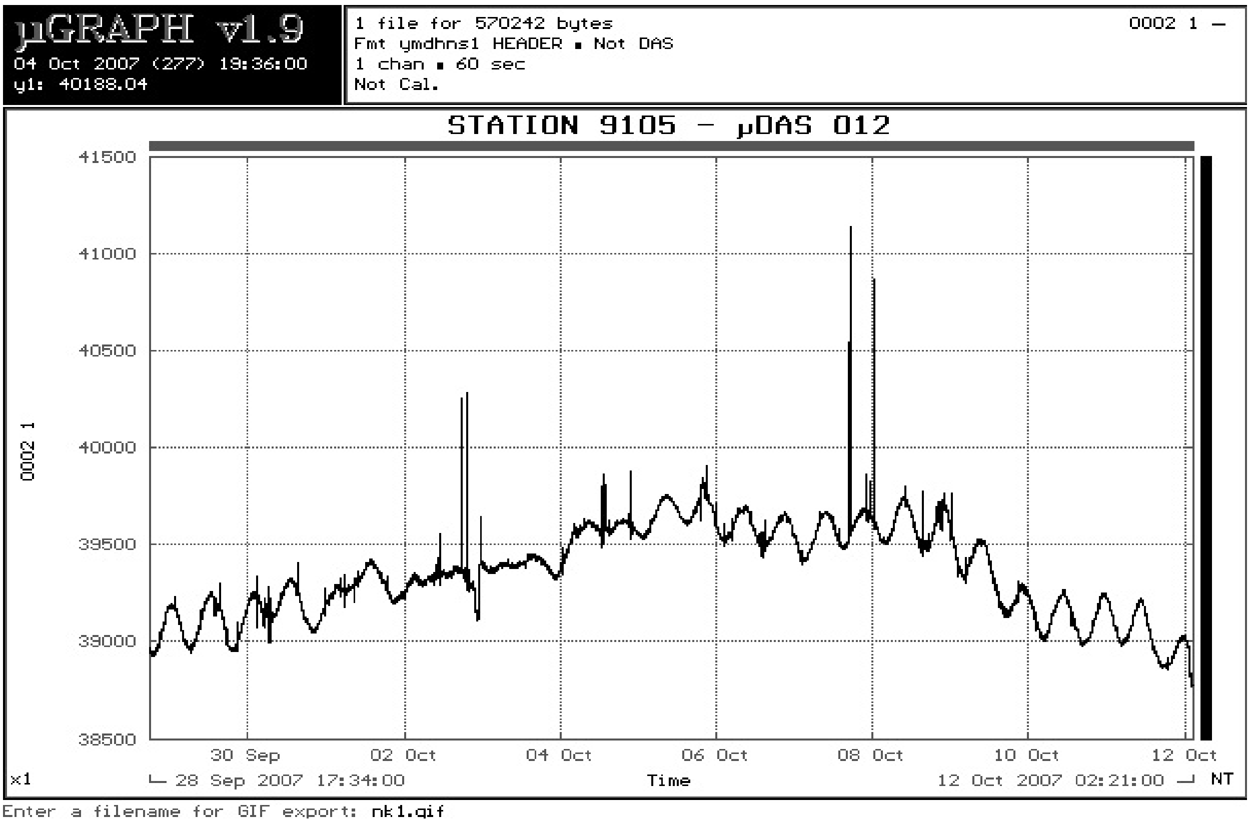

Fig. 4. Tidal variations and systematic tilt run (N-S) from 28 September 2007 to 12 October 2007. Tilt azimuth East-West. Time counters across 3 minutes. Tilt at East (1 sec.arc = 4000).

Рис. 4. Приливные вариации и систематический ход наклона (С-Ю) за период 28.09.2007 г. – 12.10.2007 г.

Tilt records in analogue and digital formats were analysed at the IPGG SB RAS, and the Royal Observatory of Belgium [*Timofeev et al., 2000, 2008*]. Then tidal parameters, i.e. amplitude and phase-lag factors, were compared with models of tidal deformations of the Earth. A good correlation was revealed with the DDW99 tidal model (static part) and SCW80 tidal ocean model (dynamic part) [*Schiwiderski, 1983; Dehant et al., 1999; Ducarme et al., 2008*]. Deviations from the global tidal tilt model amounted to 7 % for amplitudes (E-W) and +9° for phases (N-S), which can be explained by the effect of the geological structure of the Main Sayan fault. This fault is located 3 km to the north of Talaya Station and strikes sub-latitude the region where the station is located.

3. Short-period variations and effective elastic moduli

Based on measurements of short-period variations associated with atmospheric pressure drops, we calculated effective elastic moduli of rocks in situ [*Gridnev, Timofeev, 1989a, 1989b*]. Variations were recorded in periods from a few minutes to hours in case of rapid air pressure variation. A simple Young modulus (E) ratio was used for interpretation:

$$E = \Delta P / \Delta \varepsilon, \qquad (1)$$

where ΔP is an atmospheric pressure drop; Δε is a corresponding variation of vertical strain.

The first data were received using a vertical quartz extensometer, quartz tiltmeters and a quartz microbarograph [*Gridnev, 1975*]. Calculations based on records by the vertical strain meter yielded an effective elastic modulus of the rocks which is quite low, E=4.7·10^9 Pa. In this case, significant impacts of cavity effects should be noted as such effects are maximum when the tool is installed (in a vertical or horizontal position) across the tunnel. According to calculations reported in [*Harrison, 1976; Blair, 1977*], horizontal strain is variable:

$$e_{xx\text{п}} = (3e_{xx} + 0.5e_{yy}), \qquad (2)$$

where e_{xx} and e_{yy} are horizontal strain values for the homogeneous medium.

A similar reduction of the modulus value is due to the strain value as follows:

$$e_{zz\text{п}} \cong 3e_{zz}. \qquad (3)$$

The effect of the triple increase of the tidal amplitude of vertical strain was also revealed in Osakayama (Japan), an old tunnel where vertical strain meters were installed [*Ozawa, 1967, 1974; Melchior, 1982*]. The effect disappears when a vertical strain meter is installed in the tunnel in a specially drilled hole.

In case of short-period pressure variations (half a minute, less than 1 hour), it is possible to determine the effective modulus from records by tidal tiltmeters. In such cases, the following ratio is used:

$$E_{ef} = (2\Delta P_i \ln r_i)/(\pi \Delta \psi_i), \qquad (4)$$

where: ΔP_i ΔP_i is a load; r_i is a distance between tilt and load measurement points (in case of rapid variations, frontage orthogonally to isolines) normalized to the tiltmeter base; $\Delta\psi_i$ is a tilt balance in the azimuth, orthogonal to the atmospheric front, i-th individual determination.

Our experiments show that the accuracy in this case is low because of difficulties in determining the position of the atmospheric front and challenges related to local mapping of pressure isolines in case of rapid variations (errors from 50 to 100 %). The effective modulus calculated from the tilt measurements is much closer to that estimated from petrophysical data, E=1.5·10^{10} Pa.

Based on petrophysical studies of core samples (Archean marble from Well 1608 located 100 m from the tunnel entrance in the TSS territory) (Fig. 5), the following values were estimated: density ρ=2.87·10^3 kg/m^3; seismic velocity $Vp = \sqrt{(\lambda+2\mu)/\rho} = \sqrt{(K+4/3\,\mu)/\rho} = 4.16\,km/sec$, velocity $Vs = \sqrt{\mu/\rho} = 2.62$ km/sec; and ratio Vs/Vp = 0.63. Core studies were conducted at IPGG SB RAS.

The obtained values are as follows: for Poisson ratio, ν=0.17; for bulk modulus, К=2.34·10^{10} Pa; for shear modulus, $\mu = G = E/[2(1+\nu)] = 1.97 \cdot 10^{10}$ Pa From ratio $K = E/[3(1-2\nu)]$, Young modulus is E=4.63·10^{10} Pa, and Lamé parameter is

$$\lambda = \frac{2\nu G}{1-2\nu} = \frac{E_\nu}{(1+\nu)(1-2\nu)} = 1.01 \cdot 10^{10} \text{ Pa}.$$

The most effective reference to short-period strain variations was demonstrated in the study of co-seismic deformations near earthquake locations. When an earthquake (M=5.5–5.7, 51.71°N, 102.70°E) took place on 29 June 1995, it was for the first time when a tilt change was recorded at a distance of 67 km to the west of the station. The anomalous tilt amounted to 0.25 microradian (extension, +2.5·10^{-7}) at azimuth 124°N, which correlates with the solution of the earthquake mechanism [*Melnikova, Radziminovich, 1998*]. The most striking example is the Kultuk earthquake of 27 August 2008 (M=6.5, 51.61°N, 104.07°E) which occurred at a distance of 25 km from the station [*Melnikova et al., 2009*], when extension of +1·10^{-6} was

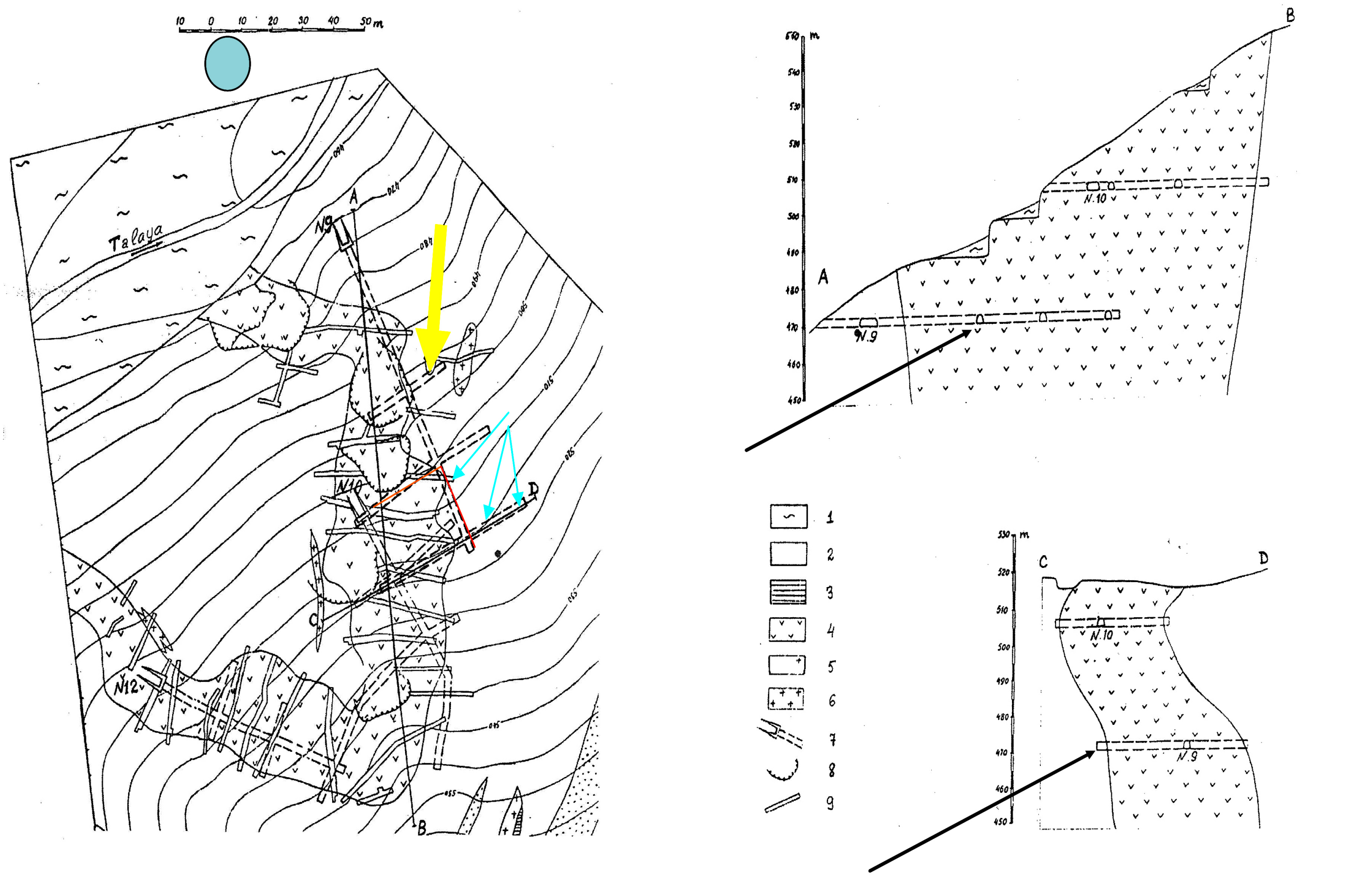

Fig. 5. Geological map and mining plan, underground gallery No. 9, Talaya seismic station. Scheme and cross section of the tunnels, Talaya seismic station.

The circle shows the location of Well 120; tilt meters were installed in the gangway, 50 m from the entrance; rod- and laser deformation meters were installed in distant gangways. *1* – alluvial deposits; *2* – marble; *3* – amphibole-piroxene crystalline schist; *4* – crystalline schist and skapolite-amphibole-diopside gneiss; *5* – garnet-biotite gneiss; *6* – garnet-pegmatite; *7* – shaft tunnels; *8* – quarries; *9* – trenches.

Рис. 5. Геологическая карта и совмещенный план горных выработок, штольня № 9 сейсмостанции «Талая». Схема и разрезы штольни сейсмостанции «Талая».

Кружком обозначена 120-метровая скважина, наклономеры установлены в штреке, в 50 метрах от входа, деформографы штанговые и лазерные, расположены в дальних штреках. *1* – аллювиальные отложения; *2* – мраморы; *3* – кристаллосланцы амфибол-пироксеновые; *4* – кристаллосланцы и гнейсы скаполит-амфибол-диопсидовые; *5* – гнейсы гранат-биотитовые; *6* – гранит-пегматиты; *7* – штольни; *8* – карьеры, *9* – канавы.

registered [*Boiko et al., 2012*]. This result is in good agreement with the model making by seismological data of the Baikal Branch GS SB RAS, Irkutsk.

4. Long-term tilt variations and local rheology

We consider long-term tilt variations by individual components of the tilt vector (N-S and E-W, Fig. 6 and 7). Dates of strong regional earthquakes are marked by changes in directions and rates of tilting at the curve. Arrows show dates of strong regional earthquakes as follows: 13 May 1989 (M=5.9, 50.2°N, 105.5°E), 27 December 1991 (M=6.5–7.0, 50.98°N, 98.08°E), 29 June 1995 (M=5.5–5.7, 51.71°N, 102.70°E), 25 February 1999 (M = 5.7–6.0, 51.63°N, 104.89°E), and 27 August 2008 (M=6.3, 51.61°N, 104.07°E).

Tilting runs manifest strain recurrence from 3 to 18 years (Fig. 6, 7, 8, and 9). In the vector diagram, this is reflected in the time period from 1985 to 2003 (Fig. 8). The average annual strain rate in some periods is variable from 0.05 second of arc to 2 second of arc per year ($10^{-8}\div10^{-6}$), and such values are consistent with data obtained by space geodesy techniques in this region [*San'kov et al., 1999; Lukhnev et al., 2010, Timofeev et al., 1994, 1999, 2012*].

Tilting as local deformation of the geological medium can be caused by stress variations due to seismic

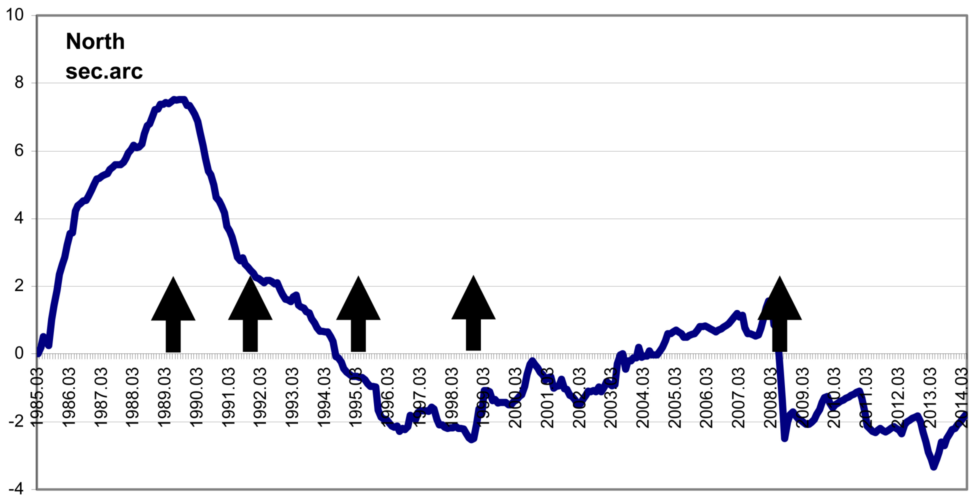

Fig. 6. Tilt variations at N-S azimuth (1 arc-second = $4.8 \cdot 10^{-6}$). Observations from March 1985 to April 2014. Arrows show time of strong regional earthquakes.

Рис. 6. Вариации наклона в азимуте север-юг в секундах дуги (1 секунда дуги = $4.8 \cdot 10^{-6}$). Период наблюдений с марта 1985 г. по апрель 2014 г. Стрелками показаны моменты сильных региональных землетрясений.

activity in the region. In the vector diagram (Fig. 9), all the registered events are shown: M≥3 at a distance of 50 km (L), M≥4.5 at 50 km < L < 100 km, and M≥5 at 100 km < L < 200 km. At the start period the tilt curve shows that northward motion when a strong earthquake occurred to the south of the station on 13 May 1989 (M=5.9, 50.2°N, 105.5°E). It was followed by strong aftershocks that occurred within a few months. In the area where in 13 May 1989 earthquake took place, several strong events were recorded in the past: M=5.6 on 10 May 1929, M=6.5 on 06 February 1957, and M=5.1 on 01 March 1987.

After the earthquake, the stress state changed. The measurements had lasted for ten years before the next group of strong earthquakes (M>5) was registered to the west and east of the station. The first strong event occurred on 29 June 1995 (M=5.5), and the second on 25 February 1999 (M=5.8). For 50 km zone around the

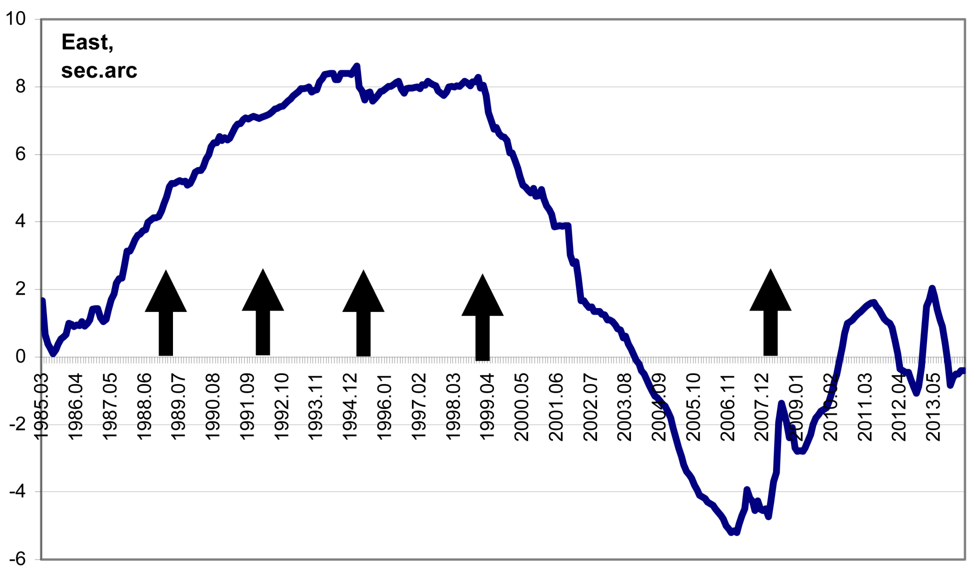

Fig. 7. Tilt variations at E-W azimuth (arc-second) from March 1985 to April 2014.

Рис. 7. Вариации наклона в азимуте восток-запад в секундах дуги (03.1985 г. – 04.2014 г.).

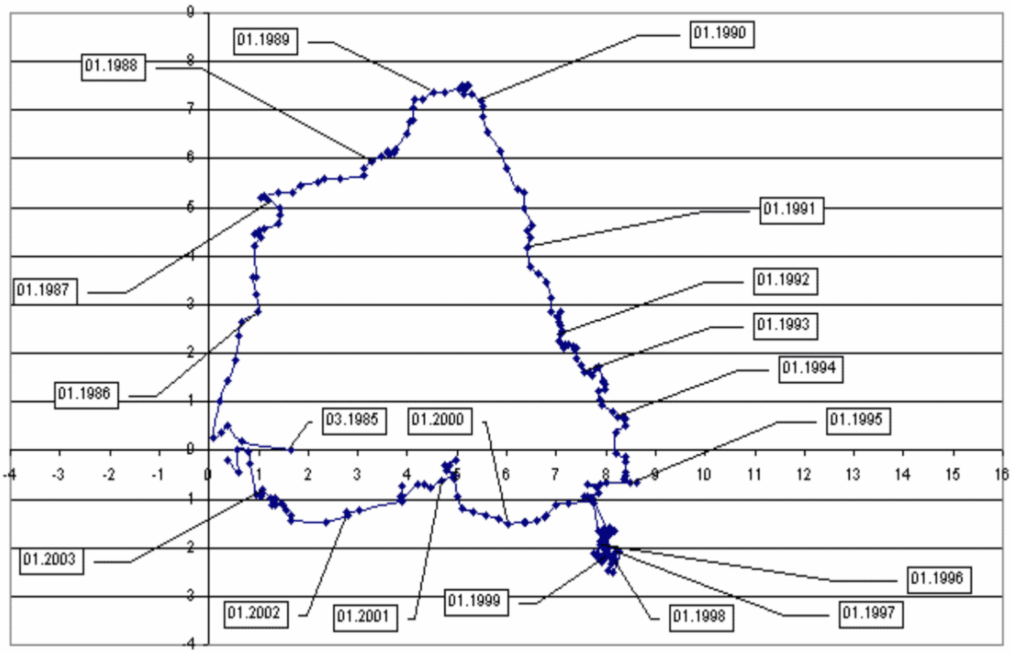

Fig. 8. Vector diagram of tilt run (arc-second) from 1985 to 2003 as per monthly data. January dates are shown for each year.

Рис. 8. Векторная диаграмма хода наклона в секундах дуги за период 1985–2003 гг., построенная по ежемесячным данным, показаны январские даты каждого года.

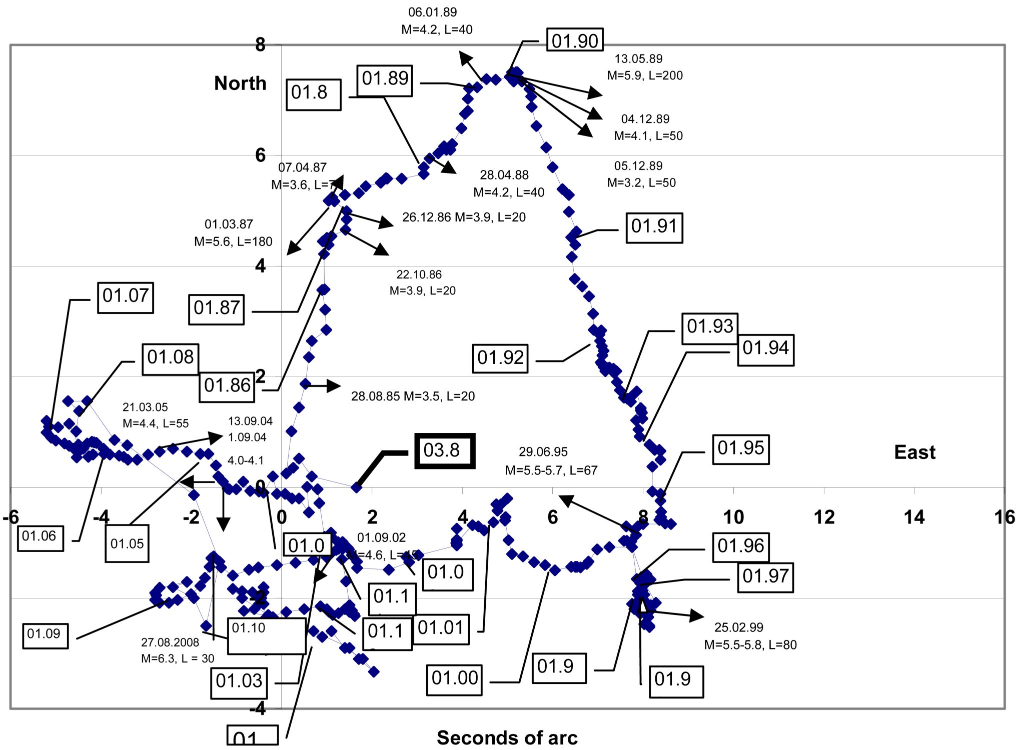

Fig. 9. Vector diagram of tilt run (arc-second) as per monthly data. January dates are shown in the box. Arrows show time of neighbouring earthquakes (magnitude and distance, km).

Рис. 9. Векторная диаграмма хода наклона в секундах дуги. График построен по ежемесячным данным. Время (январь каждого года) показано в рамке. Стрелками отмечены моменты близких землетрясений (магнитуда и расстояние в километрах).

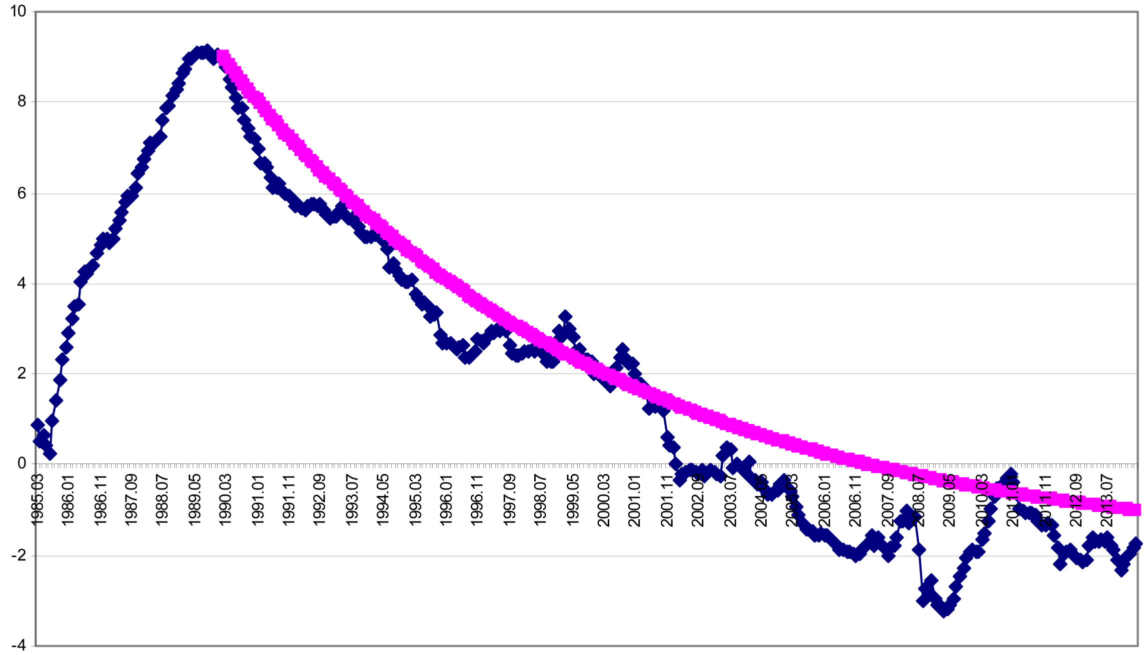

Fig. 10. Tilt variations at –33°NE azimuth (arc-second). Observations from March 1985 to April 2014. Theoretical calculations of shear deformation release (arc-second) are plotted: $\Psi(t)=[11\cdot e^{(-t/T)}-2]$.

Рис. 10. Вариации наклона в азимуте –33 °N в секундах дуги. Период наблюдений с марта 1985 года по апрель 2014 года. Приведен теоретический график разгрузки сдвиговой деформации в секундах дуги: $\Psi(t)=[11\cdot e^{(-t/T)}-2]$.

station, it is possible to distinguish two periods: the first period until 1990 (weak earthquakes, M=3.5÷4.0; one or two events per year), and the second period from 1990 to 1994 (no earthquakes) (Fig. 9).

Continuous tilt underground sites measurements allow us to estimate both elastic and viscous parameters of the geological medium. Structural rock mass elements are known to have rheological properties, i.e. they can be deformed with time under constant loading or release stresses in case of constant deformation. In simulations, equations of state generally include elastic and viscous elements. The number of such elements and their combinations (serial, parallel) are determined by the available experimental data. Definitely, the basic model envisages elastic deformation (Hooke body). As shown above, the elastic response is clearly manifested in case of rapid pressure changes and nearby strong earthquakes (co-seismic effect). Data on long-term variations of strain provide for estimation of effective viscous parameters, and the simplest viscoelastic models consisting of two elements are analysed as follows:

Maxwell body $\acute{\varepsilon} = \sigma/\mu + \sigma/\eta$, $\varepsilon' = \sigma'/\mu + \sigma/\eta$ (5)

and

Kelvin body $\sigma = \eta \cdot \acute{\varepsilon} + \mu \cdot \varepsilon$, $\sigma = \eta\cdot\varepsilon' + \mu\cdot\varepsilon$, (6)

where σ and ε are tangential stresses and strain; μ is shear modulus; η is viscosity; ε' is differentiation of strain in time, t. The deviatoric form of (5) and (6) is due to the fact that viscous deformation does not change the volume.

Based on the experimental results concerning shear deformation progress / tilting and the simple concepts of stress changes from 1985 to 1989 $\sigma \neq 0$ and later on $\sigma = 0$, we use the Kelvin model and consider the strain attenuation curve at azimuth –33°N in the main gangway of the shaft tunnels; this direction is orthogonal to the Talaya stream valley, where in a zone of fracturing is revealed [*Timofeev et al., 2012*], and to the Main Sayan fault located a few kilometres to the north of the station (Fig. 10). There is an approximate correlation between the notion of the zero component at azimuth –33°N and principal strain orientations in the given period according to strain data obtained by rod- and laser measurement systems.

The rheological equation for a solid Kelvin body is obtained from a simple algebraic combination of equations for a solid Hooke and a Newtonian fluid. For strain, it can be written as follows:

$$e(t) = e_o \cdot \exp(-t/T)\,[e_o + 0.5\eta \int P_o \cdot \exp(t/T)dt], \quad (7)$$

where *e* is deformation at time t; e_o is initial deformation; P_o is instant stress; η is viscosity; t is time;

Рис. 11. Gangway located 50 m from the entrance to the shaft tunnel.

Quartz tidal slope meters installed on the pedestal (April 2014). In the zone of intrusion, the shaft tunnel walls are composed of crystalline schist and skapolite-amphibole-diopside gneiss. See zoomed-in photos of points marked by arrows in Fig. 12 and 13.

Рис. 11. Штрек в 50 метрах от входа в штольню.

Кварцевые приливные наклономеры на постаменте (апрель 2014 года). Породы, слагающие стены штольни в зоне интрузии – кристаллосланцы и гнейсы скаполит-амфибол-диопситовые. Увеличенное изображение точек, указанных стрелками, показано на рис. 12 и 13.

$T = \eta/\mu$ is time constant or lag time for rigid-viscous movement; μ is shear module.

In case of permanent stress (1985–1989), P_o = const, and equation (6) is as follows:

$$e = \frac{P_o}{2\mu_s} + \left(e_o - \frac{P_o}{2\mu_s}\right) \cdot exp\left(\frac{t}{T}\right). \quad (8)$$

After 1989, $P_o = 0$:

$$e = e_o \cdot exp(-t/T). \quad (9)$$

A value of viscosity, η_s is determined from the strain attenuation curve and equation (9) as follows:

$$\psi(t) = \left[11 \cdot e^{(-t/T)} - 2\right], \quad (10)$$

where $\psi(t)$ is deformation (tilt of the ground surface at azimuth –33°N).

Figure 10 shows attenuation in case of recalculations of variations for azimuth –33°N in the N-S and E-W directions, and the curve based on experimental data covering 30 years of observations at Talaya Seismological Station. In our analysis of these data, time constant, T is 10 years. For μ_s = 20GPa, the effective viscosity of the crustal material, η_s amounts to $6.3{\cdot}10^{18}$ Pa·sec.

Based on the available measurement data, it is possible to estimate an additional local stress of the crust from the maximum tilt value:

$$\sigma_{zx} = \mu_s \cdot e. \quad (11)$$

For $e = 5 \text{ x } 4.8 \cdot 10^{-6}$ and μ_s = 20GPa, the variable portion of the tectonic crustal stress, σ_{zx} amounts to 5 bar (0.5 MPa).

Estimating the size of the area being representative for tilt observations is complicated due to the following factors: in the area of Talaya Seismic Station, the terrain is strongly dissected; a zone of fracturing strikes along the Talaya stream valley; the Main Sayan fault zone is located 3 km to the north of the station. Based on the recorded tilt variations (from 0.1 to 3 arc-seconds per year) and velocities of vertical movements (according to space geodesy techniques, 1–3 mm per year) [*Timofeev et al., 2013*], the size of the zone can be estimated from the following ratio of the annual tilt rate:

$$\Delta\psi = \Delta h/1, \quad (12)$$

where l is size of deformation area; Δh is velocity of vertical movements.

For different rate, the estimated size of the deformation zone varies from 100 m to 6 km.

Fig. 12. Crystalline schist and gneiss in the shaft tunnel wall.

Рис. 12. Породы, слагающие стену штольни, – кристаллосланцы и гнейсы.

Fig. 13. Large mica inclusions in the shaft tunnel wall.

Рис. 13. Породы, слагающие стены штольни, – крупные включения слюды.

5. Conclusion

Determining the rheological parameters of rocks *in situ* is discussed. In the shaft tunnel of Talaya Seismological Station, it is possible to measure deformations from 0.1 nanostrain level (1 nanostrain = 10^{-9}). However, cavity and thermal effects can distort the obtained parameters. Such effects should be taken into account during developing observation in well or in tunnel. The petrophysical studies of the core samples yielded elastic parameters of the bedrocks in the Talaya stream valley (Archean marble) as follows: $\mu=G=2\cdot10^{10}$ Pa for the shear modulus, and $\nu=0.17$ for the Poisson ratio. The tilt measurement database covering 30 year period provided for strainattenuation analyses. Using the viscoelastic Kelvin model and the experimental curve, we estimated the apparent viscosity of rocks in the shaft tunnel: $\eta s\approx10^{19}$ Pa·sec.

In our experiments, the obtained parameters are representative for the area ranging from 0.1 km to 6.0 km, i.e. may be valid to the underground gallery, the Talaya stream valley and the Main Sayan fault zone. In the shaft tunnel, viscoelastic behaviour of the rocks may be outcome of their composition and fine structure (see Fig. 5, 11, 12 and 13). In the Talaya stream valley and the Main Sayan fault zone, viscoelastic behaviour may be caused by the impact of the linear fracturing zone (striking along the valley and along the fault strike) which is characterized by high water-cut. The reported rheological parameters of the geological medium can be useful for modelling of tectonic, coseismic and post-seismic effects.

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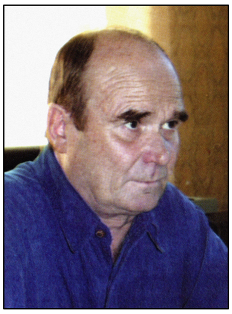
Timofeev, Vladimir Yu., Doctor of Physics and Mathematics, Head of Laboratory
A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of RAS
3 Akademika Koptyuga Prosp., Novosibirsk 630090, Russia
Tel.: (383)3356442; ✉ e-mail: timofeevvy@ipgg.nsc.ru

Тимофеев Владимир Юрьевич, докт. физ.-мат. наук, заведующий лабораторией
Институт нефтегазовой геологии и геофизики им. А.А. Трофимука СО РАН
630090, Новосибирск, пр. Академика Коптюга, 3, Россия
Тел.: (383)3356442, ✉ e-mail: timofeevvy@ipgg.nsc.ru



Masal'sky, Oleg K., Director
Baikal Branch of Geophysical Survey, Siberian Branch of RAS
128 Lermontov street, Irkutsk 664033, Russia
Tel.: 8(3952)428782

Масальский Олег Константинович, директор
Байкальский филиал Геофизической службы СО РАН
664033, Иркутск, ул. Лермонтова, 128, Россия
Тел.: 8(3952)428782

Ardyukov, Dmitriy G., Senior Researcher
A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of RAS
3 Akademika Koptyuga Prosp., Novosibirsk 630090, Russia
Tel.: (383)3356442; e-mail: ardyukovdg@ipgg.nsc.ru

Ардюков Дмитрий Геннадьевич, с.н.с.
Институт нефтегазовой геологии и геофизики им. А.А. Трофимука СО РАН
630090, Новосибирск, пр. Академика Коптюга, 3, Россия
Тел.: (383)3356442, e-mail: ardyukovdg@ipgg.nsc.ru

Timofeev, Anton V., Engineer
A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of RAS
3 Akademika Koptyuga Prosp., Novosibirsk 630090, Russia
Tel.: (383)3356442; e-mail: timofeevav@ipgg.nsc.ru

Тимофеев Антон Владимирович, инженер
Институт нефтегазовой геологии и геофизики им. А.А. Трофимука СО РАН
630090, Новосибирск, пр. Академика Коптюга, 3, Россия
Тел.: (383)3356442; e-mail: timofeevav@ipgg.nsc.ru