

Hydrogeological Regime of the Geysers (Kronotsky Nature Reserve, Kamchatka) After Landslide 3.06.2007

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ABSTRACT

This study views the results of the Valley of Geysers hydrogeological regime monitoring in 2007-2013 on geysers Velikan, Bolshoy, major geysers and springs following the disastrous landslide of 3.06.2007. According to the observations of geyser Bolshoy, its average eruption period has decreased after the landslide almost twofold and is 63 min, while its activity was defined by the level of Podprudnoye Lake. Geyser Velikan observations expose essential decrease of eruption period from its average annual value of 379 min (2007) to 335 min in the first three years following the disastrous landslide, whereupon its average annual value has stabilized. It has been found out that geyser Velikan within hydrogeological cycle shows eruption period increase in winter (on the average 41-45 min). Average annual value of the deep discharge component (defined by the chloride method) of the hydrothermal system is estimated at 215 kg/s, its decrease (by 30%) is observed during the spring-summer flood. Meteoric water injection from Podprudnoye Lake has not effected significant hydrochemical changes in geysers Velikan and Pervenetz, but geyser Bolshoy displays dilution according to the fluid major chemical components analysis. TOUGH2-modeling shows that the eruption period of the geysers is sensitive to the local surface waters level. The study examines seismic effect on the eruption regime of geyser Velikan.

1. INTRODUCTION

The Valley of Geysers is located in Kronotsky State Nature Reserve on the Kamchatka Peninsula. It was first discovered by T. I. Ustinova in April 14, 1941 (T. I. Ustinova, 1955) in the canyon of the Geysernaya river basin, 8 km long and 400 m deep. As a result of geological and hydrogeological studies carried out in 1960-1970 (V. V. Averiyev, V. I. Belousov, B. V. Ivanov, V. I. Kononov, V. M. Sugrobov, V. A. Droznin, V. L. Leonov, N. G. Sugrobova, etc.) it was found that the Valley of Geysers hydrothermal system has the greatest natural discharge of the 12 highest-temperature Kamchatka hydrothermal systems with an approximate rate of 300 kg / s and water temperature of 100°C. 57 geysers at least have been discovered (Sugrobov et al, 2009), at 13 of which there have been carried out systematic observations of activity cycle (Pervenetz, Troynoy, Konus, Maly, Bolshoy, Schel', Fontan, Velikan, Zhemchuzhny, Gorizontal, Rozovy Konus, Burlyaschy, Vosmerka). The Valley of Geysers is of significant tourist, scientific and educational value, as it is the only place in Russia where you can watch the activity of geysers, understand the conditions of the hydrothermal system formation (discharge conditions, heat sources, the reservoir structure, the role of the caprock), as well as explore the potential of geothermal energy.

The number of visitors to the Valley of Geysers reaches 3,000 people annually. It is therefore important to identify the mechanism of formation and parameters of the hydrothermal system, controlling hydrothermal explosions and landslides, to monitor these parameters in order to predict possible catastrophic natural phenomena and assess the impact of changes in the conditions of discharge / recharge on the regime of geysers, which survived the disastrous landslide of June 3, 2007 Kiryukhin et al (2011, 2012). This article describes and discusses recent results of hydrogeological regime monitoring in 2007-2013 on geysers Velikan, Bolshoy, Podprudnoye Lake and the principal geysers and springs.

2. GEYSERS CYCLING AND HOT SPRINGS DISCHARGE IN 2007-2013 YEARS

2.1 Methods of measurements

To register the recurrence of eruptions of geysers Velikan and Bolshoy, beginning from July 2007 temperature loggers HOBO U12-015 were used. The loggers, which are installed in the channels of water discharge from the geysers, record the temperature of water outflow every 5 min. The eruption time of geysers was estimated according to the time of absolute maximum temperature prior to its absolute minimum.

To register the level of Podprudnoye Lake, a pair of loggers HOBO U20-001 -04 was used with set interval measurements 20-30 min. One logger recorded barometric pressure, and the other was installed in the lake to record the total pressure of the water column above it and atmospheric pressure. The relative level of the lake was determined by the difference of pressure records at the two loggers. Since Podprudnoye Lake is recharged by the Geysernaya river, its level is linked with the river discharge. Calibration of a calculating formula to determine the river discharge by the level of the lake was carried out according to the results of hydrometric observations at the river cross sections "Plotina" and "Schel'". The value of hidden discharge of thermal springs is estimated by the chloride method at the observation cross section "Plotina". Beginning from May 2012, for continuous recording of the solution conductivity at the cross section "Plotina", a logger HOBO U24-001 (range 0 - 10,000 μ S / cm, the set recording interval of 20 min.) has been used, which enables simultaneous assessment of the changes in chloride ion and thereby the changing dynamics of a hidden discharge value and the thermal power of the hydrothermal system.

The boiling spring Avery (about 12 kg/s) has the highest stable value of discharge at the Lower Geyser section. Velikan is the most powerful geyser in the Valley of Geysers (Kiryukhin et al, 2011, Table 3), hence they were selected for monitoring the gas and hydrochemical regime of the hydrothermal reservoir in the first place. In addition, this list includes large and boiling hot springs

and geysers at different sites of the hydrothermal system: Pervenetz, Bolshoy, Truby, Verkhniy, Chloridny, N16 and N17 (last two boiling springs discovered after the landslide 3.06.2007), 56 – Kisly Kotel, M – Mladenetz (Krepost'), N37 – a boiling spring on the tip of the lake, which arose after the landslide in the locality of the site of Artefact (2011) and moved in 2012 to the position of Skalisty (Fig. 1). All of the above-mentioned sources undergo gas and hydrochemical testing for the purpose of diagnosis and analysis of the hydrothermal reservoir condition. In 2012 geyser Burlaschy, springs in the upper streams Goryachy and Teply as well as a spring in the exit point of the landslide in 2007 were also tested.

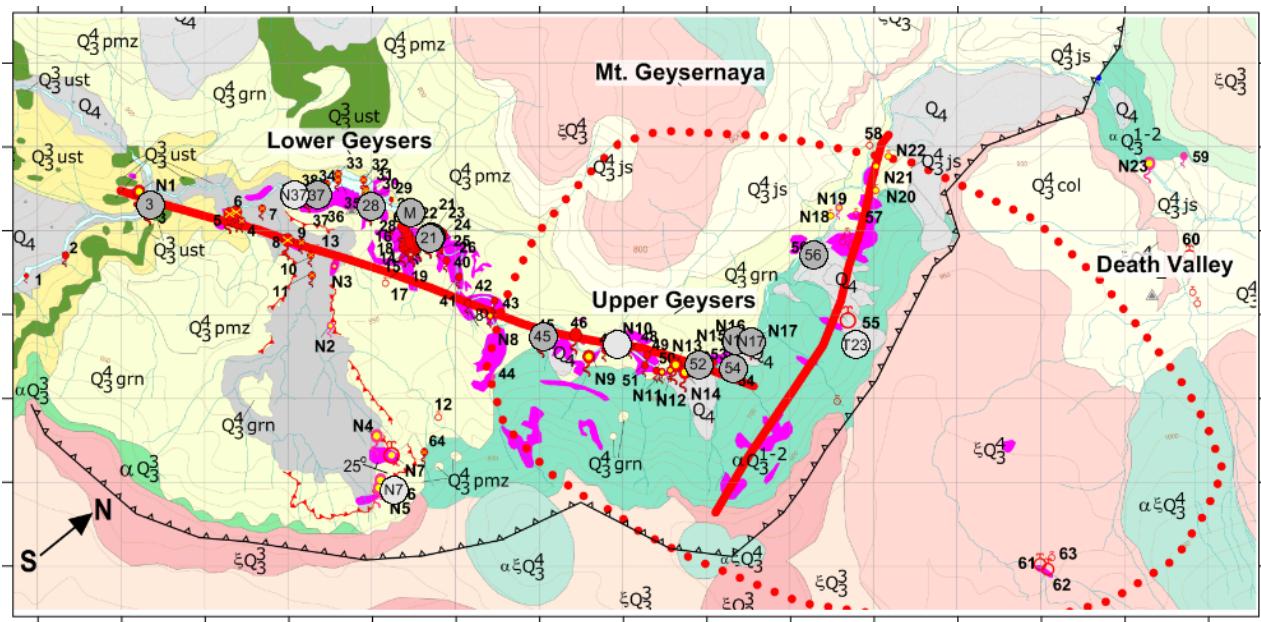


Figure 1: Monitoring points of hydrogeological regime of geysers and hot springs in the Valley of Geysers in 2012 – are designated by gray circles with numbers inside (3 – Pervenetz, 28 – Bolshoy, 21 – Avery, 23 – Velikan, 45 - Truby 52 – Verkhniy, 54 - Chlordiny, N16 and N17 - boiling springs discovered after the landslide 3.06.2007, 56 – Kisly Kotel, M - Mladenetz (Krepost'), N37 – a boiling spring on the nip of the lake, which arose after the landslide and in 2011 is in the locality of the Artifact point). Additional sampling points are shown with open circles (T23 – a spring in the Teply upper river, N7 – a spring in the exit point of the landslide 3.06.2007, N37 – a boiling spring on the nip of the lake, which arose after the landslide 3.06.2007 and in 2012 moved to the position in the locality of geyser Skalisty; without number – a pulsating high-output spring at the confluence of the Igrushka riv. and the Geysernaya riv. Numbers correspond to names (Kiryuhin et al , 2011, p.243) and (Kiryukhin et al, 2012, Table 2 and 3); symbols used on the map correspond to Fig. 2 (Kiryuhin et al, 2011, Kiryukhin et al, 2012). Grid – 500 m.

2.2 Cycling of Bolshoy and Velikan (2007-2013)

2.2.1 Geyser Bolshoy (Fig. 2)

Observations of 2008-2010 showed that the regime of geyser Bolshoy is most sensitive to the position of Podprudnoye lake level. The eruptions of geyser Bolshoy ceased when the relative level of the lake was above the lower edge of the geyser pool and cold water from the lake penetrated the geyser pool (June 2010). When the lake level fell below that of the pool edge (25-30 cm), geyser Bolshoy started erupting again with a period from 45 to 85 min. In addition, observations in 2011-2013 also demonstrated the termination of geyser Bolshoy eruptions during spring- summer flood (18 June - 9 July 2011, June 22-24 and July 2-3, 2012, June 5 - July 10, 2013) and during autumn typhoon - flood (18-20 October 2013), although the lake level was below the edge of the pool, which is probably indicative of incomplete sealing of the geyser pool walls as deteriorating with time. The average eruption period of geyser Bolshoy during the observation period of 2007-2013 was 63 min, where 19712 geyser eruptions were registered (Fig. 2). Note that before the disaster, according to the results of measurements in August-October 2003, the average value of geyser Bolshoy eruption period was 108 min. (V. A. Droznin , 2007).

2.2.2 Geyser Velikan

In the period from June 3, 2007 to September 2013, the average eruption period of geyser Velikan amounted to 340 min, where 8216 geyser eruptions were registered (Fig. 3). The decrease in the average eruption period shows a tendency of stabilization after its reduction in the first three years after the disastrous landslide: 379 min (2007), 359 min (2008), 323 min (2009), 334 min (2010), 337 min (2011), 337 min (2012), 334 min (2013). The observation results show that recurrence of geyser Velikan activity depends on the amount of precipitation falling in the geyser pool. Heavy snowfall and typhoons may delay eruptions and result in longer cycles. Maximum observed period of eruptions was 32 hours during a heavy snowfall of February 29, 2008. Analysis of the relationship between the recurrence of geyser Velikan eruptions and atmospheric pressure shows that this relationship is absent (Fig. 4). The cloud of points is fairly evenly distributed in an ellipse, covering a range of changes in atmospheric pressure 91.5–98.5 kPa and 150–500 min period of eruptions. Some instances of abnormal increase in the period of eruptions are recorded over the entire range of atmospheric pressure change.

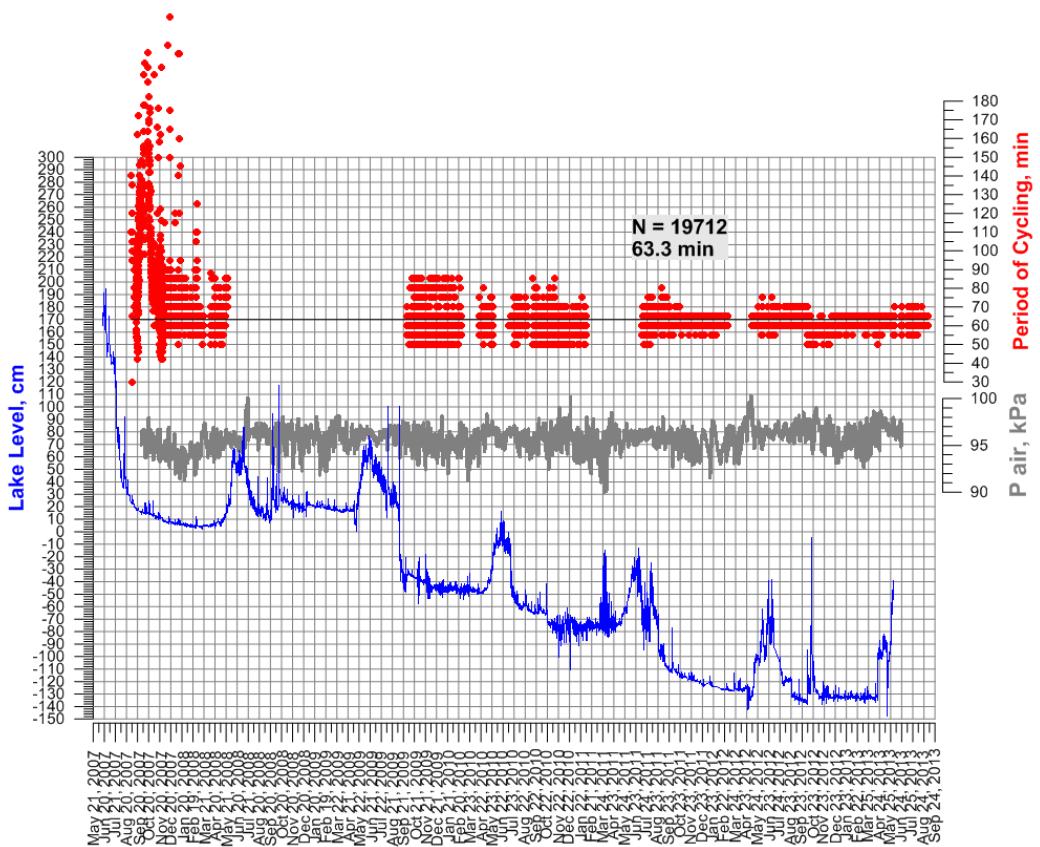


Fig. 2. Eruption period (min.) of geyser Bolshoy (upper graph) and the relative level (cm) of Podprudnoye lake (lower graph).

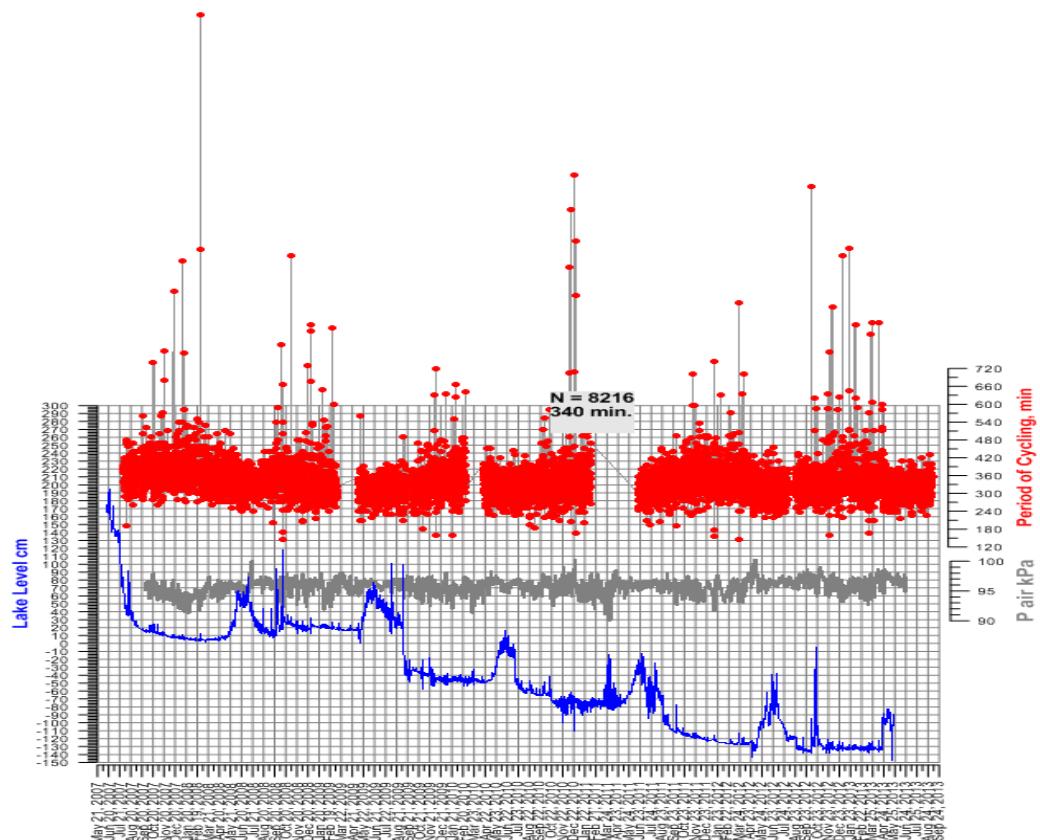


Fig. 3. Eruption period (min.) of geyser Velican (upper graph), the relative level (cm) of Podprudnoye lake (lower graph), and barometric pressure (kPa) (middle graph).

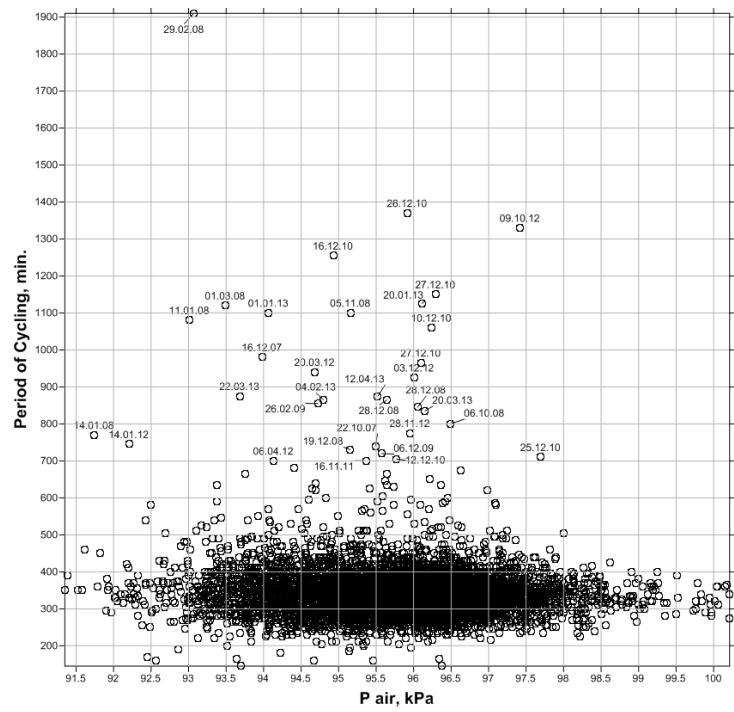


Fig. 4 Relationship between the eruption period (min.) of geyser Velikan and atmospheric pressure (kPa) according to observations in 2007-2013.

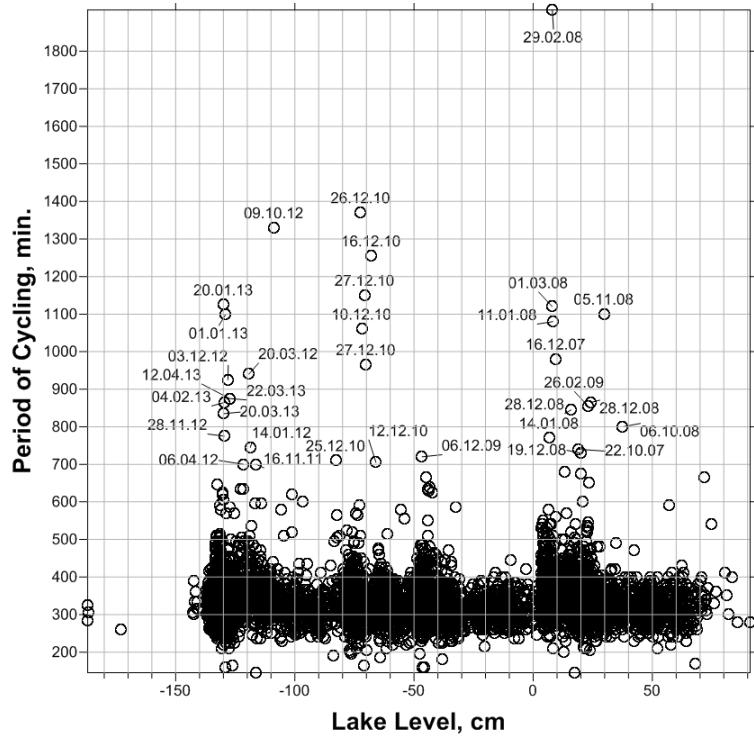


Fig. 5 Relationship between the eruption period (min.) of geyser Velikan and the level of Podprudnoye lake (cm) according to observations in 2007-2013.

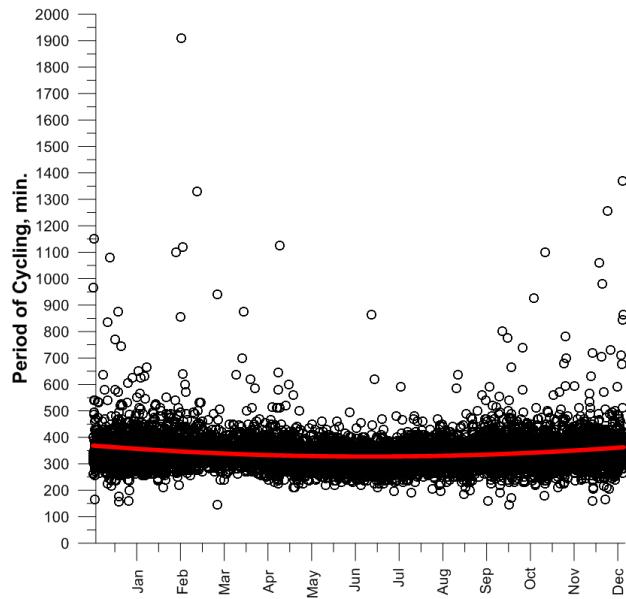


Fig. 6 Change in the eruption period (min.) of geyser Velikan in the annual hydrological cycle, according to observations in 2007-2013.

In the process of the destruction of the dam by the Geysernaya river there is systematic lowering of water level in Podprudnoye lake (130 cm during 4 years, or about 33 cm per year), this decrease is superimposed on the seasonal changes of the lake level (Fig. 2 and 3). The relationship diagram of the periodicity of geyser Velikan eruptions with a level change in Podprudnoye lake appears more complicated (Fig. 5). It clearly shows that the abnormal increase in the period of geyser Velikan eruptions occurred at discrete values of Podprudnoye lake level 10-20 cm, -45 cm, -70 cm, -120 cm. These levels correspond to the winter seasons 2007/2008 - 2008/2009, 2009/2010, 2010/2011, 2011/2012 and 2012/2013 (Fig. 3).

Schedule changes of the eruption period of geyser Velikan within a hydrological cycle from January to December for the entire observation period 2007-2013, shows that the abnormal increase in the period of eruptions over 600 min. and reduction in the period of less than 200 min. only occur in the winter, i.e. have a pronounced seasonal pattern (Fig. 6). On average, the increase in the period of eruptions in the winter compared with the summer period is about 42 min.

Likely reasons for this seasonality are: (1) Increased heat loss from the surface of the Velikan pool, having an area of approximately 12 m², in the period of low temperatures, strengthening winds (according to V. M. Stepanenko (2012)) the average value of the wind energy potential in the winter is 4.4 times higher than the analogous value in the summer (weather station "Semyachik") and snowfall; (2) Reduction in the overall recharge of the hydrothermal system during winter due to the freezing of water supply areas; (3) Local surface water level changes affect boundary condition in the thermal fluids discharge areas.

Note, that prior to the catastrophic landslide, a mean period of Velican eruptions amounted to 375-379 min., according to the measurement data, 1991-2004 (Droznin V. A., 2007). Thus after the landslide and Podprudnoye lake formation, Velikan's period on an average decreased by 41-45 min.

2.3 Hot springs discharge

To estimate the discharge of a deep thermal component (Q_d , kg / s) of the hydrothermal system of the Valley of Geysers the chloride method was used (Fournier, R., 1989, Sugrobov V. M. et al, 2009). As the initial data were employed the river discharge (Q_r , kg / s) and the chlorine concentration in the river water (Cl_r , mg / l). The chloride method automatically compensates for the evaporation and dilution of thermal waters. For record of the background concentration of chlorine in the meteoric water (1 to 2 mg/l) some adjustment is employed. Chlorine discharge is linked with the deep component of the thermal springs and rated as $Q_d \cdot (Cl_r - Cl_b)$, where Cl_r – is chlorine concentration in the river water, Cl_b – background concentration of chlorine in the meteoric water. Chlorine concentration in the deep water of the hydrothermal system (parent fluid – Cl_d , mg/l) is estimated by the maximum value of chlorine content in the hot springs (for the Valley of Geysers 900 mg/kg). To calculate the discharge of the deep component of the hot springs, runs the following formula derived from the mass balance relations:

$$Q_d = \frac{Q_r \cdot (Cl_r - Cl_b)}{Cl_d} \quad (1)$$

The discharge of the deep thermal component in Yellowstone hydrothermal system (U.S.) is estimated to be 3000 kg/s, and varies by 25-50% within the hydrological year. The discharge also depends on the seismicity, which determines the degree of penetration of meteoric water into the main magma chamber (Fournier, R., 1989).

In the Valley of Geysers, the discharge of the thermal deep component is measured directly at the output (Plotina) and input (Schel') in Podprudnoye lake, in total, over the observation period from 2007 onwards, 19 direct measurements were conducted at the lower cross section (Table 1). The average value of the thermal discharge at the cross section "Plotina", which was fixed by the

chloride method, amounts to 215 kg/s (Fig. 7). The discharge of the thermal deep component can be expressed in terms of the thermal power of the hydrothermal system W (MW), which is a product of Q_d and deep fluid enthalpy (deep fluid enthalpy is accepted as 900 kJ / kg, according to the geothermometric data (Kiryukhin et al., 2012). Mean value of the thermal power discharge of the hydrothermal system is estimated at 194 MW.

Logger HOBO U24-001 was used since May 2012 to continuously record (1 record in 20 min.) the solution conductivity at the cross section "Plotina" allowing assessment of continuous changes in chloride ion and thus the dynamics of change of the latent discharge value and the heat discharge of the hydrothermal system by formula (1). For this, the conductivity logger was calibrated according to the chlorine ion values, estimated in the three samples taken from the Geysernaya river at the lower cross section (20.04.2012, 8.05.2012, 24.08.2012), which allowed to continuously define Cl_r . To determine the discharge of the Geysernaya river at the lower cross section, at the appropriate times there was used the relationship between the level of Podprudnoye lake recorded in automatic mode (1 record in 20 min.) and the river discharge rates according to hydrometric measurements (8.05.2012, 24.08.2012), that allowed to continuously determine Q_r . Fig 7a shows that the thermal deep component discharge of the hydrothermal system is characterized by a local minimum during spring- summer flood (May-June).

Fig. 7b even more clearly illustrates the seasonal dependence of the deep component discharge of the hydrothermal system (for chlorine-ion), where this dependence is shown in the format of the annual hydrological cycle with the data usage for the entire observation period 2007-2013. A relative decrease in the deep component (during spring-summer flood), based on the average graph shown in Fig. 7b, is estimated at 31%.

Table 1. Evaluation of discharge rate of the thermal springs by the chloride method at the cross section "Plotina". Calculations of heat and mass flows were performed by Kiryukhin A. V., hydrometric measurements – by A. V. Kiryukhin, Rychkova T. V., Chernykh Ye. V., chemical analysis – by Marynova V. K., Kartashova Ye. V., Dunin-Barkovskaya V. V., O. V. Shulga in Center for the Chemistry in the Institute of Volcanology & Seismology FEB RAS. Q_r – discharge of the Geysernaya riv., kg/s, T –temperature of the Geysernaya riv., °C, C_{Cl} – concentration of chloride ion in the Geysernaya riv., mg/kg, Q_{Cl} – mass discharge of chloride ion, g/s, Q_d – thermal spring hidden discharge rate, kg/s W – power of thermal spring discharge, MW. Note: For calculating, the concentration of chloride ion in the parent fluid was assumed to be equal to 900 mg/kg, enthalpy - 900 kJ/kg.

Date	Q_r kg/s	T°C	C_{Cl} mg/kg	Q_{Cl} g/s	Q_d kg/s	W MWt
01.10.2007	1770	21.5	156	276.1	306.8	276.1
08.04.2008	1268	24.5	229.8	291.4	323.8	291.4
21.07.2008	3640	16.5	46.5	169.3	188.1	169.3
22.07.2008	3520	16.5	46.1	162.3	180.3	162.3
23.07.2008	3410	17	46.8	159.6	177.3	159.6
24.07.2008	3510	19.1	53.9	189.2	210.2	189.2
25.07.2008	3290	17.7	53.9	177.3	197.0	177.3
26.07.2008	2920	18	54.6	159.4	177.1	159.4
27.07.2008	2820	18.2	53.2	150.0	166.7	150.0
07.10.2008	3040	18	71	215.8	239.8	215.8
08.10.2008	2830	18.9	76.7	217.1	241.2	217.1
09.10.2008	2460	17.2	71	174.7	194.1	174.7
10.10.2008	2590	17.6	80.2	207.7	230.8	207.7
07.05.2009	1230	26	208	255.8	284.3	255.8
16.10.2011	1675	17.8	138	231.2	256.8	231.2
08.05.2012	1250	19.3	113	141.3	156.9	141.3
24.08.2012	1331	27	128	170.4	189.3	170.4
18.04.2013	800	23.5	163.1	130.5	145.0	130.5
05.09.2013	2930	19	68	199.2	221.4	199.2

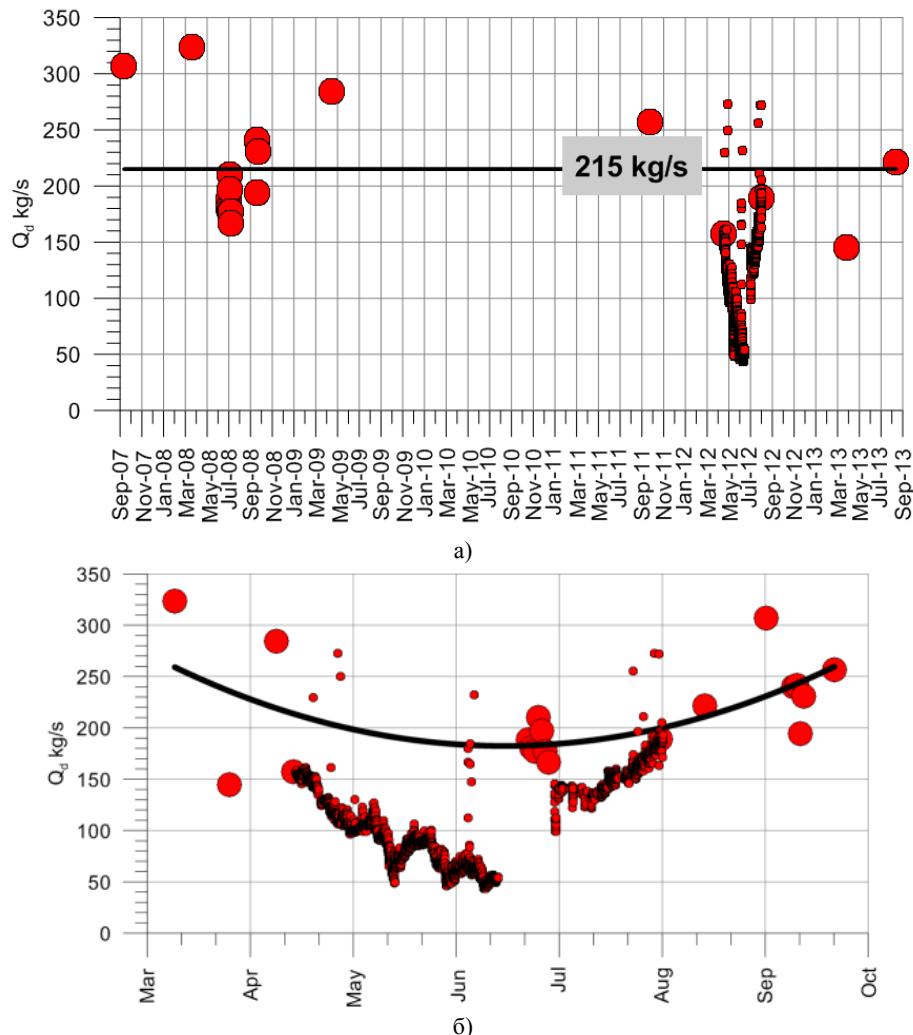


Fig. 7. Change in the thermal deep component discharge (Q_d , kg/s) according to measurements at the cross section "Plotina": a) – in real time, b) – in the annual hydrological cycle. Large circles show direct measurements, small circles – calculated values according to the continuous records of conductivity at the cross section "Plotina" with the usage of logger HOBO U24-001.

2.4 Geysers and hot springs geochemistry transient data

The discharge of geysers and hot springs in the Valley of Geysers is presented by subalkalic low-mineralized chloride-sodium waters, the data on chemical composition prior to the catastrophic landslide and the results of testing in 2010 are given in the study (Kiryukhin et al., 2012). The results of hydrochemical sampling of geysers and springs in 2011–2012 are shown in Tables 2 and 3 in the form of analyses of chemical composition. Fig. 8 displays the results of chemical analyses of 12 key geysers and boiling springs in the form of graphs of the comparative distribution of the content of chloride ion, sulfate ion Na-K and SiO₂ geothermometers for the entire observation period 2007–2013, taking into account the available data prior to the catastrophic landslide of 2007.

For the geysers, with the data up to 2007 (Velikan, Bolshoy and Pervenetz), on the basis of Fig. 8, the following conclusions can be made. The dynamics of changes in chloride ion (Fig. 8a) is explicitly manifested only for geyser Bolshoy, with a fixed dilution of 20% compared with the data before 2007, Velikan and Pervenetz show quite stable values of chloride ion. Changes of sulfate ion (Fig. 8b) for the above three geysers are insignificant and do not go beyond the errors in the determination. With regard to Na-K and SiO₂ geothermometers (Fig. 8c, 8d), there have not yet been identified significant systemic changes.

It should be noted that all the samples discussed above were taken during the period from August to October, so they do not reflect the possible seasonal changes during the annual hydrological cycle. Comparison of the chemical analysis results of water samples from geyser Velikan in April and September 2013 (in each case three samples were selected) shows a slight decrease in chloride ion and an increase in sulfate ion in the samples collected in April, compared with the samples taken in September (Table 4, geyser number - 23), which may reflect seasonal variations in the deep component discharge of the hydrothermal system during the annual cycle (Fig. 7).

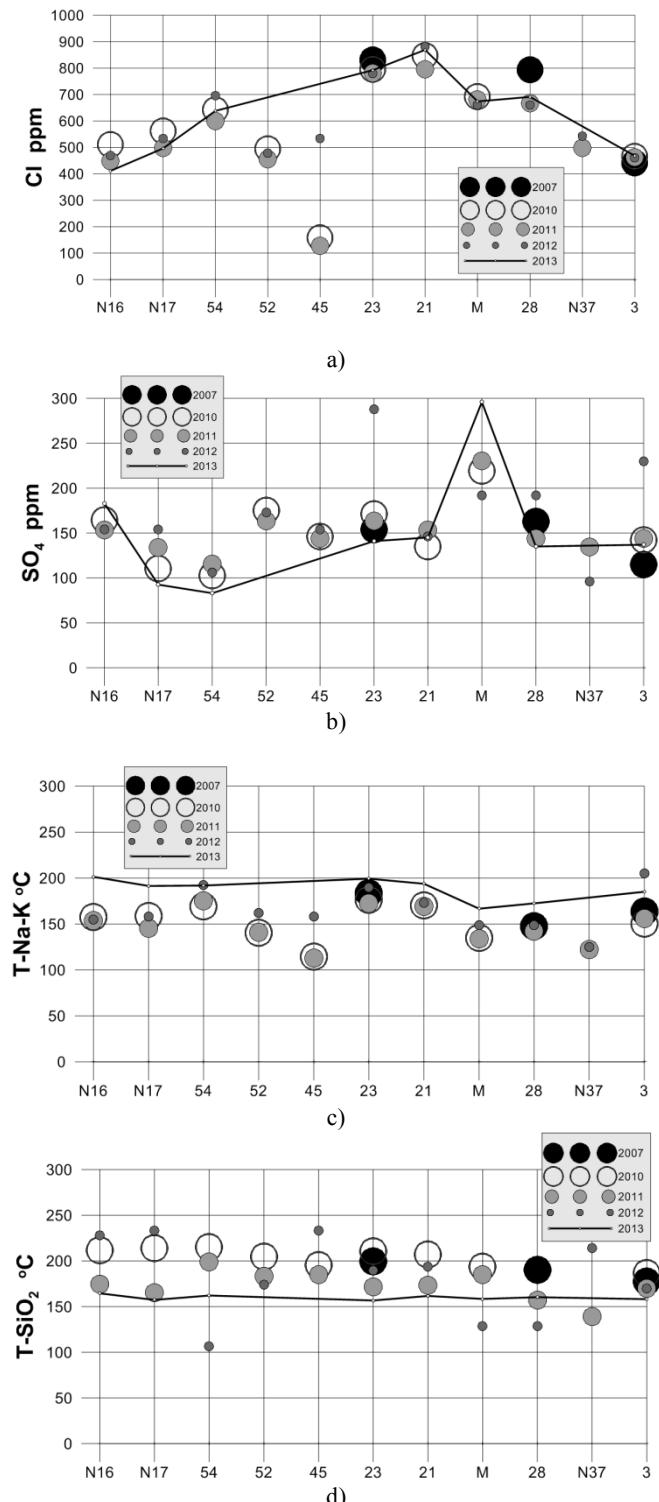


Fig. 8 Change in the contents of chloride ion (a), sulfate ion (b), values of SiO₂ geothermometer (c) and Na-K geothermometer (d) in regime geysers and springs (numbers correspond to Fig. 1). Data prior to 2007 (Sugrobov V. M. et al., 2009).

Prior to the catastrophic landslide, the thermal fluid was characterized by the following gas composition: CO₂ - 54.8 o6%, N₂ - 44.2 o6%, CH₄ - 1.0 o6% (Kononov, 1983) (probably with subtracting the atmospheric component).

In September 2013, two samples of free gas were selected from a hot (40°C) gassing spring at 8 m from the pool of geyser Velikan. These samples mostly characterize gas composition of the reservoir, that feeds the geyser, and they are less polluted with the atmospheric gases out of the channel of the geyser itself (Table 7). Sample №2, virtually not contaminated with oxygen, shows that the hydrothermal reservoir, feeding geyser Velikan, is dominated by the content of carbon dioxide CO₂ (61.5%) and nitrogen N₂ (32.1%), and there is also a significant content of methane CH₄ (5.8%) and hydrogen H₂ (0.4%).

Table 7. Chemical composition of free gas (vol. %), which characterizes the feeding reservoir of geyser Velikan. The sample is taken from a griffin of a hot gassing spring at 8 m from geyser Velikan in 2012. The samples were taken by A.V. Kiryukhin (Sept. 4 and 5. 2013), sample #1 was analyzed by V. I. Guseva in Center for the Chemistry in the IVS FEB RAS, sample #2 was analyzed by V. Yu. Lavrushin in GIN RAS.

Sample #	H ₂	Ar	O ₂	N ₂	CO ₂	CO	CH ₄	H ₂ S	Sum %
1		0.9	6.6	48.9	32.7	0.3	9.2	0.03	98.6
2	0.45		0.02	32.1	61.5	0.003	5.8		99.6

2.5 Isotope composition (δD , $\delta^{18}\text{O}$) of hydrothermal fluids

In 1985 and 2013 we performed testing of the boiling springs in the Valley of Geysers for determining the isotopic composition of water. Samples G1 - G6 were selected in 1985 from small boiling springs in the Geysernaya river basin between the springs 7 and 24. Samples 3, M, 21, 23, 45, 52, 54, N16, N17, 56 and 59 were selected in 2010 throughout the discharge area of the Valley of Geysers (names and numbers correspond to the names in the papers (Kiryukhin et al, 2011, p.243, Kiryukhin et al, 2012, Tables 2 and 3). The results of isotopic analysis of oxygen and hydrogen in the tested waters are shown in Fig. 9.

The proximity of imaging points, obtained for the thermal springs in the diagram δD - $\delta^{18}\text{O}$ to the line of Craig meteoric water, suggests that these waters are of predominantly meteogenic origin. The parameters, which we have set to make a formula of the local meteoric water line for this region, differ from that of the Craig line by the value of deuterium excess:

$$\delta D = \delta^{18}\text{O} \times 8 + 10$$

With respect to this line there were calculated shifts in the isotopic composition of oxygen for a group of springs, that deviate from the right line of meteoric waters.

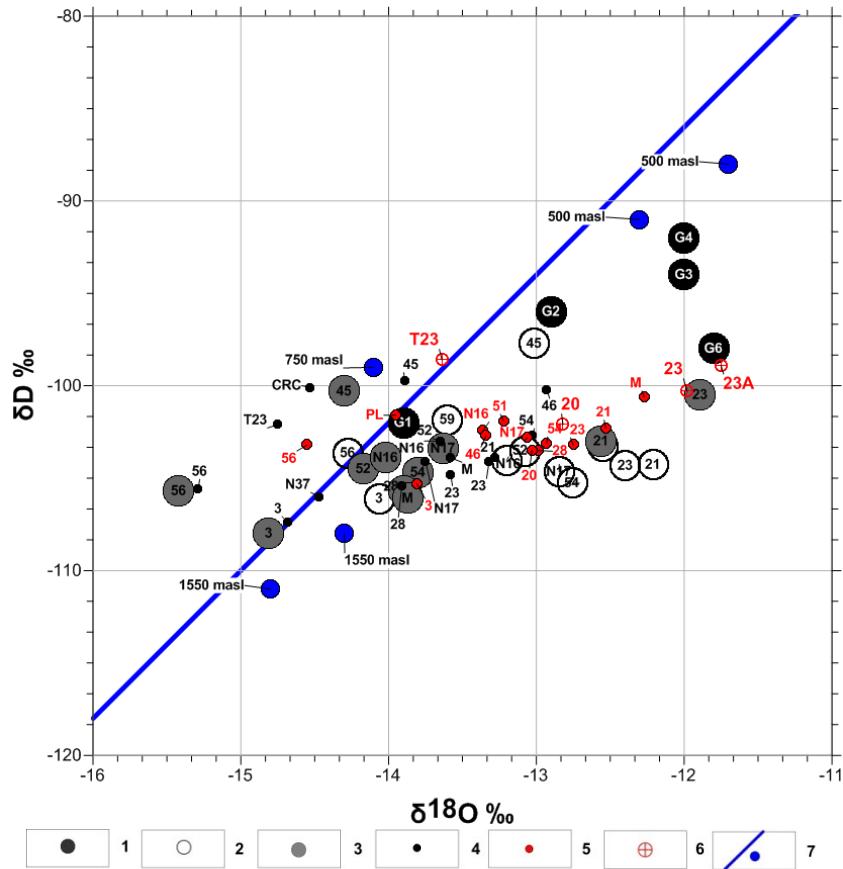


Fig. 9 The water isotopic composition of the boiling and hot springs of the Lower Geyser and Upper Geyser fields, according to the 1985 and 2010-2014 data, in contrast to Kamchatka meteoric waters at different absolute elevations (rivers, streams). Legend: years of sampling 1- 1985, 2 – 2010, 3 – 2011, 4 – 2012, 5- 2013, 6 – 2014, 7 – line and meteoric waters from different elevations (cr. Dachny, +800 m.a.s.l., r. Zhirovaya and r. Falshivaya, +500 m.a.s.l., Mutnovskiy crater, +1550 m.a.s.l.). The samples were collected by A.V. Kiryukhin and analyzed by V. A. Polyakov (VSEGINGEO, 1985), Ye. Dubinina (IGEM RAS, 2011), P.O. Voronin and A.Y. Polyakov (2011-2014) using LGR IWA 45EP in IVS FEB RAS.

The range of set values δD from -92 to -102 ‰ (data 1985) and from -100 to -107 ‰ (data 2010-2014) corresponds to the location of nutrition of the hot springs hydrological system on the absolute height of +500 to +900 m, according to the data of 1985, and from +750 to +1500 m, according to the data of 2010-2014. Apparently, the most favorable areas of water supply are those of dissemination of rhyolitic extrusions with permeable deep roots (ξQ_3^4) and the boundary of the caldera, especially within the

thermal areas, allowing all season infiltration. One of these extrusions is the Geysernaya rhyolite extrusion (Fig. 1) with a surface area of more than 6 km², having elevation points from +600 to +1085 m.

A group of boiling springs and geysers (M, 21, 23, 52, 54, N16, N17) displays a shift of $\delta^{18}\text{O}$ values to the right with respect to the meteoric water line. Such a shift is characteristic of the water passing a stage of high temperature interaction with silicate or carbonate rocks (Sheppard, 1986). The value of the oxygen-isotope shift $\Delta\delta^{18}\text{O}$, calculated according to the equation of the local meteoric water line, for these springs is from 0.6 to 1.6 ‰. There is positive correlation of $\Delta\delta^{18}\text{O}$ values with the content of chlorine and boron, as well as the content of cations (Na, K and Ca), which may indicate the involvement of magmatic fluids in water infiltration at considerable depths. In this regard, a distinct relation between these values and the content of SiO₂ and sulfate ion is not established.

Perhaps, the waters of these springs and geysers contain a meteoric component, which is infiltrated at considerable depth, and undergoes the process of oxygen isotope re-equilibration with rocks at elevated temperatures. The outflow of heated infiltration water in the form of upflows and their dilution with water of isotopic parameters of current precipitation may lead to the formation of compounds corresponding to those observed in the diagram of Fig. 9. The points of condensate type springs (59 and 56), the waters whereof are characterized by low content of chlorine, are close to the line of meteoric waters, and along the line of meteoric waters there are waters of geysers Petvenetz (3) and Truby (45), indicative of the significant dilution of these waters by the meteoric component, which did not go through stages of isotopic exchange with silicate or carbonate rocks.

Some negative shift about -1‰ of $\delta^{18}\text{O}$ values in 2011-2012 years compared to years 2010 and 2013 may reflect either Podprudnoe Lake cold water injection effect or heat up of the deep roots of hydrothermal system in 2013 year.

3. TOUGH2-MODELING OF THE VELIKAN CYCLING SENSITIVITY FROM THE LOCAL SURFACE WATER LEVEL

To analyze the Podprudnoye lake effect (formed after the disastrous landslide of June 3, 2007) on the hydrogeological regime of geyser Velikan TOUGH2-EOS3 modeling was employed (K. Pruess et al, 1999). On a numerical thermohydrodynamic model (full description of the model assembly and testing is given in the study Kiryukhin et al, 2012) there was defined the internal area, coinciding with the Podprudnoye lake contours, with Dirichlet boundary condition (corresponding to the water level in the lake +423 m).

The model discharge of the model element, corresponding to geyser Velikan, was connected with the period of geyser eruptions τ by the formula $\tau = M/Q$, where M is the mass of Velikan eruption (kg), Q – model discharge of Velikan (kg/s). Fig. 10 shows that Podprudnoye lake has a positive hydrodynamic effect on the activity of Velikan - its average discharge should increase by 10.3%, and the period of eruption should be reduced by 9.4% respectively. This phenomenon is associated with an increase in pressure in the hydrothermal reservoir as a result of appearance of secured recharge boundary on its top in the circuits of Podprudnoye lake. The obtained model results are generally consistent with the observed 11% decrease in the eruption period of geyser Velikan during 2007-2013.

N. G. Sugrobova's study (1982) presents factual data on the reduction in the period of geyser Velikan activity by 30 min. with water level increase in the Geysernaya river by 80 cm during the flood in June 1975. This phenomenon is explained by the afflux of the hydrothermal reservoir with groundwater following the increase in the river level. Modeling results demonstrate that a similar effect was exerted on the geysers by the newly formed Podprudnoye lake, depending on the distance and the hydraulic connection between the lake and the specific geyser.

Note that the mass of Velikan eruption, used in modeling, is estimated as the mass of water in its channel, for it is completely emptied during the eruption. Previously, the channel volume of Velikan was estimated as V=20 m³, according to the volume of water poured into it after the eruption (N. G. Sugrobova, 1982).

These estimates were generally confirmed by using 4.8 kg of tracer (NaCl) during a cycle of geyser Velikan eruption from 13-00 to 17-10, April 18, 2013. Before the tracer was introduced in the geyser channel (Fig. 11), the concentration of chloride ion in the channel was C₁=744 mg/L (average of three samples), after stirring and dissolving during intermediate boiling in the geyser channel, chloride ion concentration in the channel amounted to C₂=904 mg/L (average of three samples). Hence the volume of the channel is determined by the formula V=0.60684·10³·m/(C₂-C₁) = 18.13 m³, and the water mass, given its density 958 kg/m³, at boiling temperature (100°C) is M=17400 kg. To this we must add a further 4210 kg of water poured out of the geyser during 6 intermediate boiling events (level lowering in the geyser pool by intermediate discharge was 6 cm at 12.2 m² area of the pool, so at each intermediate boiling out of the geyser flowed 0.073 m³ or 701 kg of water). As a result, the actual average discharge of geyser Velikan during the relevant eruption cycle of 4 hours 10 minutes is estimated at 1.44 kg/s.

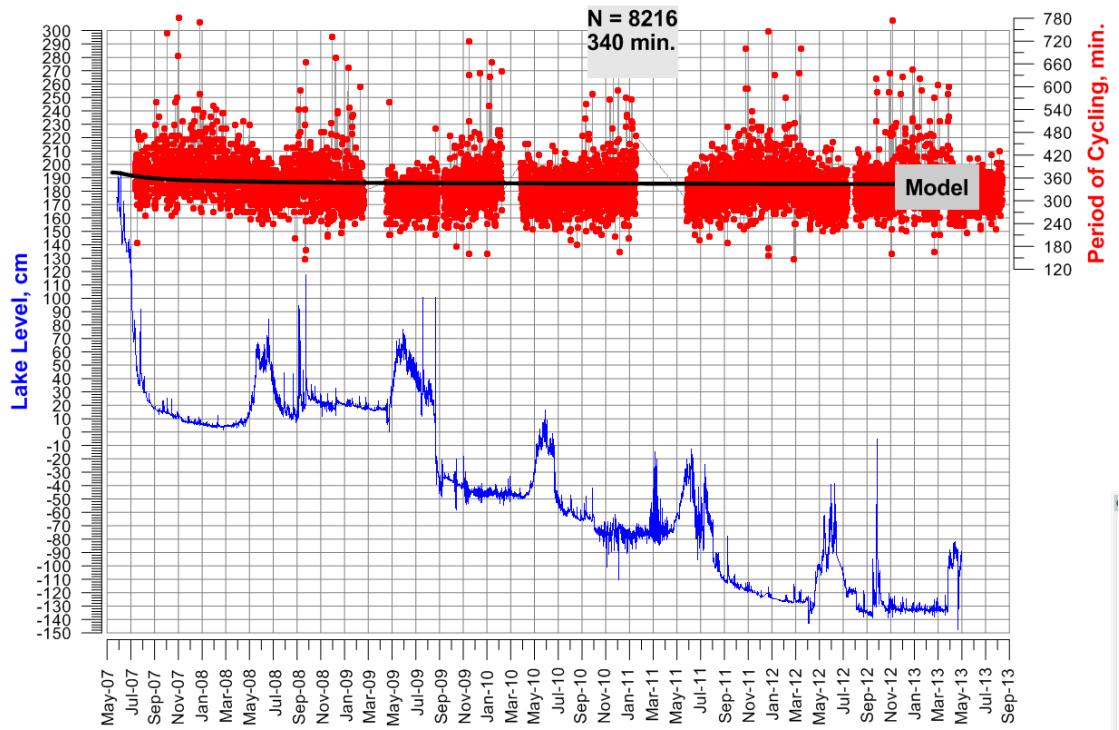


Fig. 10 Forecast of eruption period change of geyser Velikan, according to TOUGH2-EOS3 modeling data, is shown by a thick black line (Kiryukhin, 2011). The figure also shows the actual eruption period of geyser Velikan (upper graph) and the relative level of Podprudnoye lake (lower graph).

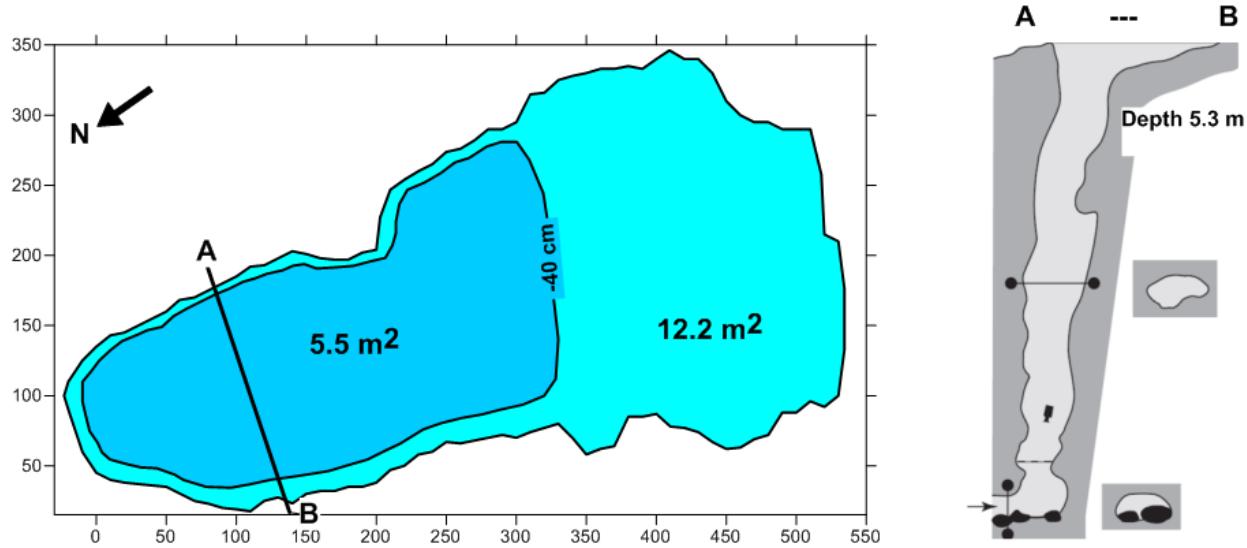


Fig. 11 Geometry of the channel of geyser Velikan. Left figure – surface area and section at 40 cm depth (scale in cm) as measured in Sept., 2013; right figure – cross section based on video observations inside conduit (Belousov et al, 2013) with depth corrected value 5.3 m accordingly to measurements of Aug. 2007.

4. GEYSERS CYCLING VS SEISMICITY

Seismicity is a factor influencing the eruption period of geysers. Proof of this were the changes that occurred in the Yellowstone hydrothermal system within an hour after the devastating earthquake Denali on November 3, 2002 in Alaska M7.9 (S. Husen et al, 2004, S. Rojstaczer et al, 2003). Hydrothermal changes were observed at 100 thermal areas, in the system of hot springs in the Norris Geyser Basin (Yellowstone Park, USA). Several small hot springs, which did not show up earlier as geysers, suddenly began to boil and erupt, the temperature in one of these springs rapidly increased from 42 to 93°C. In some geysers there was increase in the period, in others, on the contrary, there was decrease, and some geysers, such as Old Faithful and Grand, being under the influence of recent preceding earthquakes, did not react to the earthquake Denali at all.

Comparison of the cumulative graph of seismic energy (by regional and global directories) with the dynamics of change of the eruption period of geyser Velikan (The Valley of Geysers, Kamchatka) during the period of our observations from 2007 to 2013 so far does not enable to discover the unique timing of these changes with seismic events (Fig. 12 and 13). We can only indicate (Fig. 11), that one of the powerful regional earthquakes (Nov. 27, 2010, M = 5.2), which happened 40 km NE from the Valley of

Geysers, could trigger a slowdown in periodicity of Velikan. Of the three powerful ($M > 7$) earthquakes within 3500 km - one is synchronized according to Velikan's periodicity slowdown during the same time period.

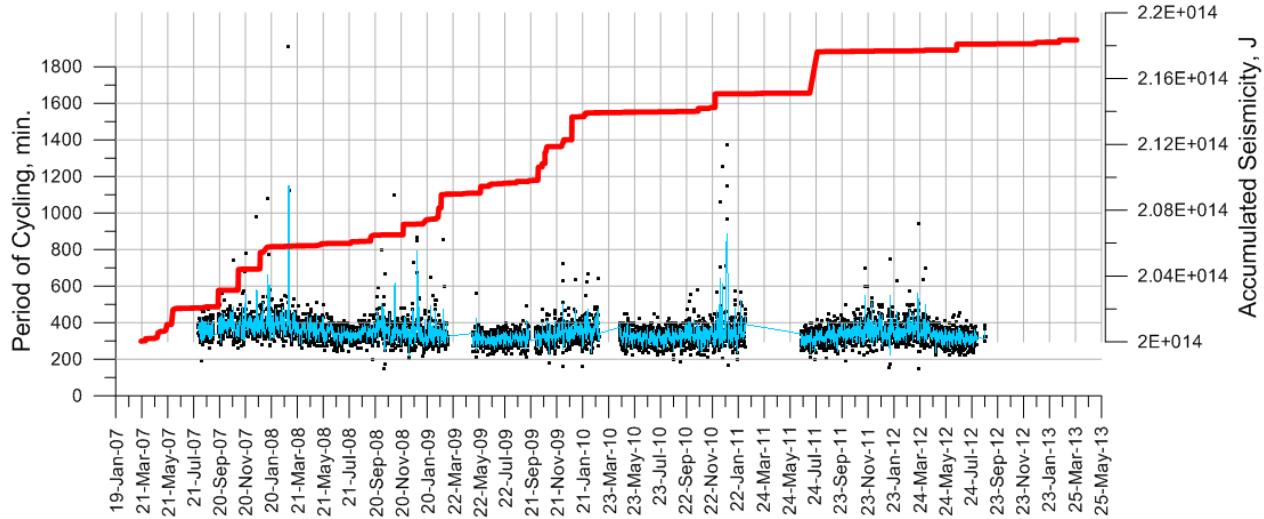


Fig. 12 Eruption period of geyser Velikan and regional seismicity (radius of 200 km, depth to 40 km).

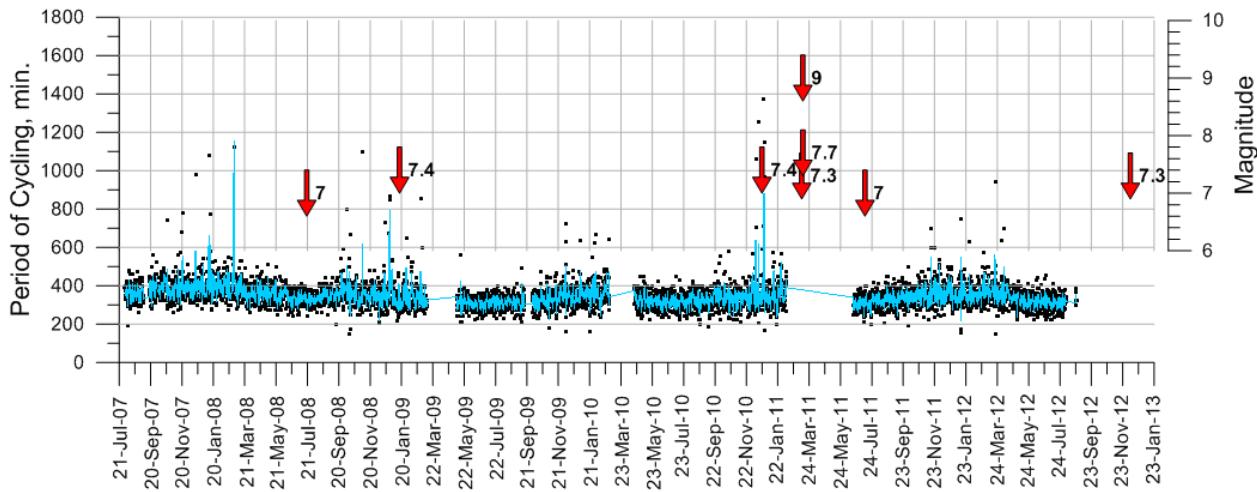


Fig. 13 Eruption period of geyser Velikan and global seismicity (radius of 3500 km, depth to 40 km, $M \geq 7$).

5. CONCLUSIONS

The monitoring results of the hydrogeological regime of the Valley of Geysers in 2007-2013 in respect of geysers Velikan, Bolshoy, key geysers and springs, and Podprudnoye lake after the catastrophic landslide of 3.06.2007 show that their characteristics have undergone significant changes.

The average eruption period of geyser Bolshoy is 63 min. (before the disaster, in 2003, the period was 108 min., V. A. Droznin, 2007), its activity is determined by the level of Podprudnoye lake: increase in the lake level may cause cease in geyser activity.

With regard to geyser Velikan, we have discovered a significant decrease in the period of eruptions from an average value of 379 min. (2007) to 335 min. Reduction in the period occurred in the first three years after the disastrous landslide, after which its annual average eruption period was stabilized (2010-2013 years). We have found that geyser Velikan within the hydrological cycle shows increase in the eruption period in the winter (on average about 50 min.). Most likely, the increase in the period of Velikan in the winter is due to more intensive cooling of the geyser pool.

The average value of the deep component discharge of the hydrothermal system (defined by the chloride method) at the Podprudnoye lake dam is estimated at 215 kg/s. There is evidence of its decline (up to 30%) during the spring-summer flood. The injection of meteoric waters out of Podprudnoye lake was not reflected in significant hydrogeochemical changes in geysers Velikan and Pervenetz, while with regard to geyser Bolshoy, there is dilution by the main component of the deep fluid. In general, gas composition of the channels of geysers and boiling springs is dominated by the atmospheric component, while the parent reservoir, feeding geyser Velikan, is characterized by the dominance of CO_2 and N_2 , with a substantial content of methane and hydrogen.

TOUGH2-modeling was employed to analyze the effect of cold water injection out of Podprudnoye lake on the regime of geyser Velikan eruptions. This model show the reduction in the period of its eruptions by 11% due to increase in pressure in the reservoir as a result of Podprudnoye lake hydrodynamic effect.

A new disastrous landslide hit Geysers Valley on January 4, 2014. This significantly changed geysers cycling again, but this is a new story.

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