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Formation of the hydrothermal system in Geysers Valley (Kronotsky Nature Reserve, Kamchatka) and triggers of the Giant Landslide

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ABSTRACT

The Geysers Valley hydrothermal system is hosted within a system of two permeable faults (revealed by mapping thermal features), located above a suggested partially melted magmatic body and recharged by meteoric water along the outcrops of rhyolite–dacite extrusions. Fast erosion is stimulating the significant discharge rate, the geyser's cycling mode and landslide events. Natural state thermal hydrodynamic modeling shows that 20–30 ka of high temperature upflow of 250 kg/s and an enthalpy of 900 kJ/kg could build up the hydrothermal system in the Geysers Valley basin with output discharge parameters comparable to those at the current level. Modeling also shows that steam accumulation below an inclined caprock may have hydrothermal eruption potential. The Giant Landslide took place on June 3, 2007, when 20×10^6 m^3 of rocks were shifted 2 km downstream, more than 23 geysers were buried or submerged, and Podprudnoe Lake was dammed, injecting cold water into submerged geysers. Possible triggers of the Giant Landslide include the inclination of the sliding plane towards the Geysernaya river basin, a pressure increase in the fluid-magma system, hanging block saturation by water during spring flooding, hydrothermal alteration weakening of the sliding plane, and steam explosions. Recent geysers cycling activity monitoring data (2007–2010), hydrogeochemical sampling, and thermal area infra red (IR) survey data are also discussed.

1. Introduction

The Geysers Valley is located in the Kronotsky State Reserve of the Kamchatka Peninsula, Russia. It was discovered by T.I. Ustinova on April 14, 1941 (Ustinova, 1955) in a 400 m deep and 8 km long canyon of the Geysernaya river basin. Geological and hydrogeological studies during 1960–1970 confirmed, that the Geysers Valley hydrothermal system has the highest natural discharge rate of the 12 high-temperature systems in the Kamchatka region; it has an approximate flow rate of 300 kg/s with 100 °C water and a minimum of 57 geysers (Sugrobov et al., 2009), from which 13 were monitored for their cycling activity (Pervenetz, Troynoy, Conus, Maly, Bolshoy, Shel, Fontan, Velikan, Zhemchuzhny, Horizontalny, Rosovy Conus, Burlyashy, Vosmerka). The Geysers Valley has significant interest for tourism and educational purposes, since this is the only place in Russia, where geyser activity can be observed. This is a good location for understanding the formation of a hydrothermal system (recharge/discharge conditions, heat sources, fault structure of reservoir, caprock, etc.) as well as investigating the potential for geothermal hazards. The Velikan (Giant) geyser is a symbol for the Geysers Valley, as its regular activity is one of the "seven Russian miracles". Velikan is the most powerful in the Geysers Valley, with a production cavity volume of 13.5 m^3 (6 m deep $\times$ 4.5 m^2) and a total erupting water volume of 20 m^3.

The objectives of the present study are to integrate available hydrogeological data (Kiryukhin and Rychkova, 2010, 2011; Kiryukhin et al., 2010a,b) into a conceptual model of the Geysers Valley hydrothermal system, to develop 3D thermal hydrodynamic (chemical) models to deduce a mechanism for the formation of the hydrothermal system and its response to changing recharge/discharge conditions after the Giant Landslide of June 3, 2007, and to understand triggers of such catastrophic events in order to forecast future ones.

It is worth noting that the Giant Landslide of June 3, 2007 was larger than other examples worldwide (M. Stark, 2010, pers. comm.); for example: (1) The slide at the Geysers geothermal field in California, long before development which blocked the main creek that drains the field and created a temporary lake, (2) The landslide 20 years ago in Zunil, Guatemala, that wiped out a village and killed dozens of people (possibly related to a shallow wellbore failure), (3) A fairly major slide in the Tongonan geothermal field early in its history.

Landslides in geothermal fields sometimes occur in coincidence with hydrothermal eruptions (steam explosions). Thirty-one cases of hydrothermal explosions are documented by Brown and Lawless (1998). These include the prehistoric hydrothermal eruption at Kawerau, New Zealand with breccia and lahar products whose

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volume amounted to $20 \times 10^6\,m^3$, hydrothermal explosions in Dieng, Indonesia in 1979 with a 3 km long lahar followed by gas emissions, which left 142 people dead and landslide/steam explosions in 1995 during road construction in the vicinity of Nakano-Yu hot springs in Japan, which killed four people.

Landslides with hydrothermal explosions create unsafe conditions for visitors to Geysers Valley, of which there are 3000 people annually. Hence it is important to understand what hydrothermal system parameters are responsible for landslides/hydrothermal eruptions in order to set up proper monitoring to recognize precursors of such events.

2. Formation of the hydrothermal system in the Geysers Valley

2.1. Geological setting

The age of Uzon–Geysernaya caldera (Fig. 1) has been estimated to be 39.6 ± 1 ka using radiocarbon dating of soil samples covered by caldera forming ignimbrites (Leonov, 2009). Uzon–Geysernaya pre-caldera deposits are comprised of dacite–andesite tuffs and lavas that are 40–140 ka old (Fig. 2, $\alpha Q_3^{1-2}, \alpha Q_3^3, Q_3^3$ust). Initially this caldera was an isolated hydrological basin, where volcanogenic and sedimentary lake deposits were formed (Q_3^4 grn, pmz, js, col). These deposits with thicknesses up to 400 m near the caldera rim, are represented by layered pumice tuffs and minor breccias and conglomerates. Caldera lake deposits are overlain by 15–20 ka old rhyolite–dacite lavas, which formed large domes and adjacent lava flows up to 100–150 m thick ($\xi Q_3^4, \alpha\xi Q_3^4$).

Approximately 9–12 ka ago, the SE wall of the caldera was eroded by the Shumnaya and Geysernaya rivers, and drainage of the hydrological basin started. The ultimate lake below the Upper Geyserny field was drained as a result of the Geysernaya river erosion that took place about 5–6 ka ago. Hence, a 400–500 m elevation drop in the discharge area took place in the Geysernaya river basin. The absence of recent basaltic volcanism in the upper stream of the Geysernaya River may indicate the existence of shallow partially melted magma bodies there, which trap emerging basaltic dykes (Leonov, 2009).

2.2. Hydrogeological stratification

The following hydrogeological units were identified in the Uzon–Geyzernaya caldera: 1 – aquifers of alluvial and glacial deposits, 2 – relatively low permeability units of caldera lake deposits (Q_3^4 grn, pmz, js, col) including pumice tuffs, sandstones and breccias, 3 – permeable units of rhyolite, dacite and andesite extrusions ($\alpha\xi Q_3^4$), 4 – pre-caldera upper Pleistocene permeable units of lake tuffs and sedimentary deposits, complicated by a dyke complex (Q_3^3 ust), andesite lavas (αQ_3^3), pumice breccias (ξQ_3^3) and caldera rim dacite and rhyolite extrusions (ξQ_3^3), 5 – aquifer of basalts, andesites, dacites lavas and pyroclastics (αQ_3^{1-2}), 6 – aquifer ($\alpha\beta Q_{1-2}$) basalt lavas, 7 – aquifer of Pliocene tuffs, basalts and sandstones, 8 – basement, composed of Tertiary sedimentary basins (Fig. 2).

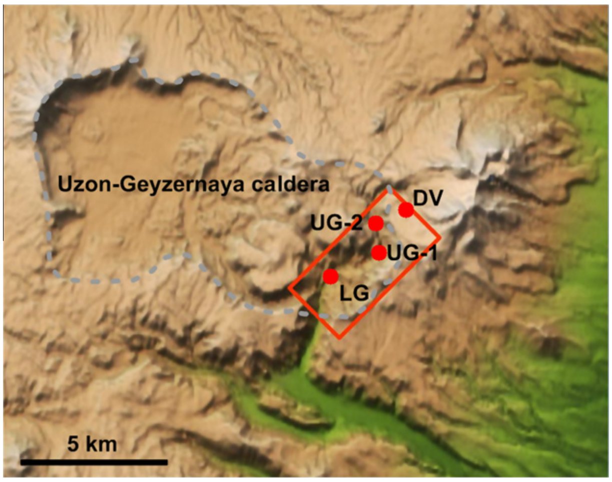

Fig. 1. Uzon–Geyzernaya caldera radar image, rectangle is the Geysers Valley mapped area (see Fig. 2 below). LG – Lower Geysers Field, UG – Upper Geysers Field (1 – hot water discharge, 2 – steam discharge), DV – Death Valley.

2.3. Thermal discharge conditions

The Geysers hydrothermal system includes three discharge areas: Lower Geysers Field (geysers and boiling springs), Upper Geysers Field (including geysers, boiling springs, and steam jet areas), and Death Valley (steam and gas jets area). The main thermal discharge zone strikes in a WSW–ENE direction and is hosted in pre-caldera Upper Pleistocene units of lake tuffs and sedimentary deposits complicated by a dyke complex (Q_3^3 ust). This zone is traced by boiling springs and geysers that discharge at a total estimated rate of 260–300 kg/s. There is another significant thermal discharge zone to the NNW–SSE (parallel to the caldera rim) which is traced by fumaroles and steaming ground in the Upper Geysers Field. These two permeable fault zones are the main elements in heat and mass transfer of the Geysers Valley hydrothermal system.

The caprock of the hydrothermal reservoir is composed of the Geysernya unit (Q_3^4 grn), formed by caldera lake deposits, and dips at an angle of 8–25° in a NW-direction towards the Geyzernaya river basin. When thermal fluid upflow reaches this inclined caprock layer, it separates into steam and liquid phases. Steam and liquid discharge towards the SE and W, respectively, with geysers and hot springs discharging along the Geysernaya river valley (Fig. 2). This acts as a kind of natural separator due to different fluid densities, which is confirmed the Cl^- hot springs.

The geyser and hot spring fluids have neutral pH and low NaCl mineralization in the Lower Geysers and most of the Upper Geysers (Tables 1 and 2), and are characterized by the following composition of free discharged gases (in vol.%): CO_2 – 54.8, CH_4 – 1.0, N_2 – 44.2 (Kononov, 1983). Upstream hot springs in the Upper Geysers (#56) and Death Valley (#59) have lower pH and very low Cl^- values reflecting a change from water dominated reservoir conditions to two-phase zone reservoir conditions in the upper part of Geysernaya river basin. Chemical geothermometers (T_SiO_2 and T_Na–K, Fournier, 1981) were used to estimate reservoir temperatures. It was found that recently estimated T_Na–K values are 15–30 °C lower than estimates performed before the Giant Landslide of June 3, 2007. By contrast, recently estimated T_SiO_2 values are 15–30 °C higher than the estimates made before landslide. This seems to be an effect of reinjection of cooler but oversaturated separated waters, observed in some exploited geothermal fields (Mimura et al., 1995). In the case of the Podprudnoe Lake (created after the Giant Landslide of June 3, 2007) at the Geysers Valley hydrothermal system no significant changes in the Cl^- content of geysers and hot springs indicate that no dilution/enrichment processes have occurred.

The maximum estimated values of geothermometers applied to geysers and hot springs on the Lower and Upper Geysers were 205 °C (T_Na–K) and 207 °C (T_SiO_2) (Table 1, before the Giant Landslide of June 3, 2007). These values indicate possible high temperature upflows that recharge the Geysers Valley hydrothermal system. The Avery site (#21) with 12 kg/s has the highest stable flow rate of surviving boiling springs and geysers in the Lower Geysers Field (Table 3). Velikan (#23) is the largest geyser in Geysers

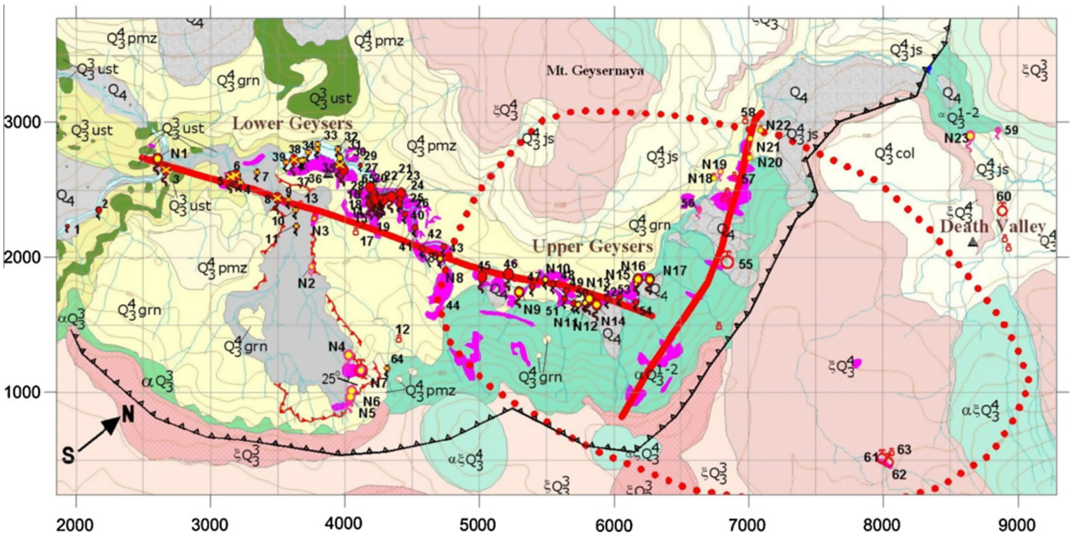

Fig. 2. Geological map of the Geysers Valley (lithology units after Leonov, 2009) with thermal and hydrogeological features. Geological units are identified by symbols. Gray filled contour on left side of the map – Giant Landslide of June 3, 2007; red dotted line – suggested lateral extent of the partially melted magma body; thick red lines – thermal discharge faults; magenta filled areas – infra red (IR) ground temperature anomalies revealed by a helicopter survey performed on August, 5, 2010; symbols with numbers – hot springs, geysers and fumaroles (new thermal features emerging after Giant Landslide filled by yellow, buried and submerged geysers are yellow-crossed); black hatched line – caldera rim. Sliding plane coincides with the bottom of the Geyzernaya tuff unit (Q_3^4 grn). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Chemical composition (in mg L^{-1}) of boiling springs and geysers before the Giant Landslide of June 3, 2007 (Sugrobov et al., 2009). Surviving geysers are shown in bold. T_SiO_2 and T_Na–K are chemical geothermometers (T_SiO_2 = 1309/(5.19 – LOG10 (SiO_2)) – 273 and T_Na–K = 855.6/(LOG10 (Na/K) + 0.8573) – 273 – Fournier, 1981).

##/Name	Cl^-	$HCO_3^- + CO_3^{--}$	SO_4^{--}	Na^+	K^+	Ca^{++}	B	SiO_2	T_Na–K	T_SiO_2
23 (Velikan)	831.0	76.5	154.0	572.0	55.0	23.0	18.2	263.2	183	200
3 (Pervenets)	440.0	70.6	115.0	330.0	26.0	18.0	11.4	192.5	163	178
5 (Troinoy)	659.0	77.6	138.0	460.0	46.0	13.0	18.0	248.7	188	195
36 (Conus)	596.0		125.0	436.0	32.0	16.0	15.4	169.4	157	169
29 (Maly)	567.0	73.7	106.0	412.0	25.0	14.0	13.8	187.5	139	176
28 (Bolshoy)	794.0	59.1	163.0	555.0	37.0	23.0	22.0	231.2	148	190
65 (Shell)	823.0	60.8	144.0	546.0	44.0	18.0	16.8	230.0	166	190
19 (Fontan)	780.0	68.6	92.0	488.0	57.0	18.0	20.0	173.8	205	171
25 (Zhemchuzhny)	868.0	79.0	154.0	660.0	51.0	22.0	26.1	291.2	161	207
26 (Horizontalny)	809.0	64.0	131.0	541.0	57.0	19.0	19.8	228.8	193	189
40 (R. Conus)	702.0	69.6	106.0	482.0	36.0	18.0	17.7	223.1	158	188
46 (Burlyashhy)	486.0	54.6	115.0	345.0	20.0	23.0	13.1	173.8	136	171
63 (Vosmerka)	702.0	63.3	144.0	482.0	29.0	30.0	21.0	238.1	139	192

Table 2
Chemical composition (in mg L^{-1}) of hot springs and geysers after the Giant Landslide of June 3, 2007. Samples collected by A.V. Kiryukhin (September 2010), analyzed by L.I. Gartseva in Central Chemical Lab Institute of Volcanology and Seismology. T_SiO_2 and T_Na–K are chemical geothermometers (Fournier, 1981).

##/Name	pH	Cl^-	F^-	HCO_3^-	CO_3^{--}	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	SiO_2	T_Na-K	T_SiO_2
N17	8.79	562.7	1.48	25.6	0.9	110.4	400.2	30.0	19.2	1.0	0.9	317.7	159	214
56 (Kisly Kotel)	6.33	1.4	<0.18	108.0	0.0	67.2	26.6	12.4	41.7	3.9	0.3	217.6		
N16	8.29	511.2	<0.18	65.9		164.2	393.4	29.1	13.6	3.9	0.9	308.3	157	212
54 (Chloridny)	8.71	642.6	<0.18	26.8	0.9	102.7	440.8	36.8	21.6	0.7	0.9	322.7	169	215
52 (Verkhny)	8.94	494.1	0.69	51.9	2.8	175.1	377.4	23.1	14.8	5.4	0.6	282.3	140	205
45 (Truby)	9.34	158.4	0.69	154.9	13.8	145.9	218.2	9.7	3.2	2.9	0.6	247.4	114	195
59 (Neozhidanny)	5.83	1.1	<0.18	323.3		134.9	26.0	3.8	106.8	26.8	0.2	116.9		
21 (Avery)	8.76	846.4	1.73	58.6	1.8	134.9	568.2	48.0	16.8	7.8	0.1	290.5	170	207
23 (Velikan)	8.34	794.4	1.3	45.1	0.6	171.4	554.4	49.8	18.0	6.8	0.3	303.4	176	210
Mladenets	8.28	692.2	1.3	45.1	0.6	218.9	508.2	29.3	16.0	6.1	1.2	243.3	135	194
3 (Pervenets)	8.72	465.7	1.05	61.0	0.9	142.2	342.1	23.5	20.8	5.4	1.6	220.0	150	187

Valley. Therefore, sites #21 and #23 were selected as the most reliable for monitoring chemical and thermal hydrodynamic changes.

In spite of numerous field surveys performed in Geysers Valley since 1941, mapping of existing geysers and hot springs is difficult due to limited access. Nevertheless, Table 3 lists significant geyser and hot spring characteristics known before the Giant Landslide of June 3, 2007. New sets of thermal features were found after the Giant Landslide took place (see Fig. 2 and Table 4).

The following thermal features (with a total boiling springs flow rate estimated at around 8 kg/s) occurred in the Upper Geysers Field: N23 – hot spring with a temperature of 25°C and flow rate of 2 kg/s on the right bank of the Geysernaya river, 1 m above

Table 3
Major hot springs and fumaroles of the Geysers Valley hydrothermal system: *X*, *Y*, *Z* – relative coordinates m (Fig. 2), *t* – temperatures (°C) and *Q* – flow rates (kg/s) known before the Giant Landslide of June 3, 2007 according to O. Bataeva (2002, pers. comm.), ## corresponds to numbers on Fig. 2.

##	NAME	*X*	*Y*	*Z*	*t*, °C	*Q*, kg/s	##	NAME	*X*	*Y*	*Z*	*t*, °C	*Q*, kg/s
1		1934	2232	315	96	0.01	33	Romeo & Julleta	3799	2839	396	98	0.1
2		2168	2353	346	90	0.2	34	Kamenka	3729	2778	390	98	1
3	Pervenets	2682	2674	357	98	2	35	Buratino	3796	2803	394	98	1
4		3222	2558	386	98	0.1	36	Conus	3696	2721	396	98	0.36
5	Troinoy	3149	2599	384	98	1.2	37	Artefact	3676	2717	369	98	0.8
6	Sakharny	3188	2610	381	98	2	38	Scalisty	3622	2725	400	98	3
7	Vodopad	3344	2632	381	98	0.3	39		3558	2705	386	98	0.1
8	Drevny	3496	2443	424	96	2	40	Ros. Conus	4394	2346	453	98	0.2
9	Malutka	3579	2430	428	98	0.1	41		4545	2118	453	98	0.1
10	Teremok	3635	2354	448	98	0.2	42		4632	2071	470	98	0.1
11	Vorota	3642	2233	446	97	0.5	43		4699	2002	470	94	0.5
12	Drozninsky	4398	1388	640	98	0	44		4725	1630	555	96	0.01
13		3675	2384	432	100	0	45	Truby	4982	1852	490	98	4
14	Vanna	4161	2412	450	93	1.2	46	Burlyashy	5263	1878	500	98	2
15	Kovarny	4181	2410	451	98	1.5	47	Peshera	5412	1780	505	98	0.5
16	Pravy Kotel	4062	2479	456	98	0	48	Vosmerka	5586	1807	515	98	0.2
18	Leshy	4219	2458	424	98	1.2	49	Plachushy	5696	1724	530	98	0.3
19	Fontan	4267	2418	446	98	8	50		5707	1646	550	90	0.5
20	Grot	4237	2426	446	98	3	51		5650	1666	520	98	0.3
21	Avery	4320	2429	444	98	12	52	Verkhny	5961	1706	560	98	0.2
23	Velikan	4354	2409	443	98	1.5	53		6117	1676	570	98	0.2
24	Paryashy	4386	2478	440	98	2.3	54	Chloridny	6147	1662	580	98	0.2
25	Zhemchuzhny	4389	2398	444	98	1	55	Kipyashy Kotel	6847	1965	770	98	0.25
26	Horizontalny	4387	2382	442	98	1	56	Kisly Kotel	6635	2358	660	70	2
27	Mal Pech	4117	2685	426	98	0.02	57	Bolshaya Fumarola	6957	2603	690	110	
28	Bolshoy	3999	2620	423	98	4	58		6994	3050	660	96	0
29	Maly	3962	2689	411	98	7	59	Neozhidanny	8856	2944	900	26	1
30	Pesherny	3966	2732	402	98	1	64		4314	1181	680	45	0.5
31	Krasny	3960	2752	402	98	1	65	Shell	4190	2524	423	98	0.01
32	Ustyevoy	3950	2803	402	98	0.8							

Table 4
New hot springs and fumaroles found in the Geysers Valley hydrothermal system after the Giant Landslide of June 3, 2007: *X*, *Y*, *Z* – relative coordinates m (Fig. 2), *t* – temperatures (°C) and *Q* – flow rates (kg/s), ## corresponds to numbers in Fig. 2.

##	NAME	*X*	*Y*	*Z*	*t*, °C	*Q*, kg/s	##	NAME	*X*	*Y*	*Z*	*t*, °C	*Q*, kg/s
N1	t98Q2	2608	2733	464	98	2	N13	t52Q3R	5817	1715	553	52	3
N2	t15q01	3753	1934	584	15	0.1	N14	t60Q4L	5882	1647	576	60	4
N3	Steam	3776	2288	522		0.01	N15	t98Q005	6181	1838	611	98	0.05
N4	t26q10	4029	1277	584	26	10	N16	t98Q3R	6208	1862	611	98	3
N5	t18q6	4042	967	629	18	6	N17	t98Q3L	6227	1835	611	98	2
N6	t25q12	4052	1014	608	25	12	N17A		6250	1841	611	98	1
N7	F-Podryva	4118	1162	626		0.1	N18		6764	2593	665		0.01
N8	t24Q05	4740	1895	484	24	0.5	N19	t41Q02L	6887	2594	682	41	0.2
N9	t98Q2	5300	1757	518	98	2	N20		7005	2656	700		0.01
N10	t98Q02	5529	1834	521	98	0.2	N21		6962	2799	675		0.01
N11	t98Q01	5738	1644	538	98	0.1	N22		6988	2844	675		0.01
N12	t98Q01	5781	1652	548	98	0.1	N23	t25Q2R	8649	2901	813	25	2

water level; N20–N22 – fumaroles on the left bank of the Geysernaya river 200–400 m upstream of known fumaroles #57, and fumaroles N18 on the right bank opposite fumaroles #57; N19 – condensate steam spring with a temperature of 41 °C and flow rate of 0.15 kg/s on the left bank of the Geysernaya river below the travertine dome; hot spring #56 (59 °C, 1 kg/s) on the left bank, was earlier reported as on the right bank of Geysernaya river; N15–N17 – boiling springs (98 °C) with a total flow rate of about 6 kg/s; N11–N14 – hot springs downstream of Triple waterfall (geyser Verkhny #52), they include N11, N12 – boiling springs (98 °C) with a flow rate of 0.1 kg/s, N13 – 52 °C, 3 kg/s on the right bank, N14 – 60 °C, 4 kg/s – on the left bank; N10 – boiling spring (98 °C) with a flow rate of 0.2 kg/s on the right bank 80 m downstream of geyser Vosmerka #63; N9 – boiling spring (98 °C) with a flow rate of 2 kg/s; N8 – 24 °C hot springs with a flow rate of 0.05 kg/s on the left bank at the bottom of caprock Q_3^4 grn unit.

On the Giant Landslide of June 3, 2007 cut off – a new fumarole field and group of hot springs arose, N4 – 26 °C hot spring with a flow rate of 10 kg/s, N5 – 18 °C hot spring with a flow rate of 6.0 kg/s discharging at the bottom of caprock Q_3^4 grn unit, N6 – 25 °C hot spring with a flow rate of 12.0 kg/s, N7 – fumarole Podryva (blasting fumarole), which disappeared in 2008.

A major group of boiling springs, N1, arose at the SW end of the thermal conducting fault on the right bank of Shumnaya River, located opposite buried geyser Pervenets (#3).

In summer 2008 significant cold spring discharges were recorded in the bottom of the tension crack wall of the Giant Landslide. This discharge caused displacement of the wall by 150–200 m. The drainage probably indicates the cold-water recharge boundary which occurs from rhyolite extrusions ($\alpha\xi Q_3^4$) along the caldera rim (Fig. 2).

2.4. Infra red (IR) survey results

On August 5, 2010 a helicopter IR survey of the Geysers Valley hydrothermal system was performed (S.A. Chirkov, A.V. Kiryukhin,

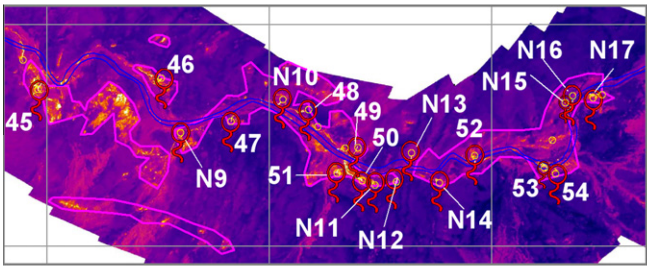

Fig. 3. IR-mapped hot springs (yellow circles) and interpreted ground temperature anomalies (magenta color polygons) in Upper Geysers. Field mapped hot springs are shown by red circles with numbers. Spring numbers and thermal anomaly shapes correspond to Fig. 2. All hot springs identified by IR-survey (including those not shown on Fig. 2) are indicated by yellow circles. Grid spacing is 500 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

640 × 480 SC640 infra red camera used, about 10 km^2 of thermal discharge area was covered with space resolution of 0.5–1.0 m). All significant hot springs and geysers, and most ground temperature anomalies (associated with steam ground areas) were identified on IR-images. Fig. 2 shows the distributions of ground temperature anomalies interpreted from IR survey images and Fig. 3 compares an IR-image to the mapped discharge distributions.

Structural elements of the Geysers Valley hydrothermal system are shown on Fig. 2; they include: two thermal discharge fault lines, the caprock boundary following the hot spring distributions, and ground temperature anomalies (inside the suggested horizontal extent of the magma body, see Section 2.6) as identified by IR-survey.

2.5. Recharge conditions

The elevation of recharge areas for meteoric waters was identified based on the isotopic composition of thermal fluids (δD, $\delta^{18}O$). Sampling of boiling springs from the Lower Geysers Field was performed in 1985 and 2010. Samples G1 to G6 were collected in 1985 from small boiling springs in the Geysernaya river basin between #7 and #24 (Table 3). Samples 3, M(Mladenets), 21, 23, 45, 52, 54, N16, N17, 56 and 59 (names and numbers correspond to Tables 2–4) were collected in 2010 throughout the Geysers Valley discharge area.

The convergence of the meteoric water line with data points from geothermal fluids (δD, $\delta^{18}O$) confirm their meteoric origin, while the δD values, which range from −92‰ to −102‰ (data from 1985) and from −98‰ to −106‰ (data from 2010) correspond to an elevation of the recharge area from +500 to +900 m.a.s.l. (data from 1985) and from +700 to +1200 m.a.s.l. (data from 2010) (Fig. 4). The most favorable recharge zones coincide with the outcrops of rhyolite extrusions with deep high permeability roots (ξQ_3^4) and with the caldera boundary, especially within heated parts which allow infiltration throughout the seasons. One of the possibilities is the Geysernaya Mt. (Fig. 2) rhyolite extrusion with an elevation from +600 to +1085 m.a.s.l. and a surface area of more than 6 km^2.

The $\delta^{18}O$ shift (1 to 2‰) observed in Fig. 4 for some of the boiling springs and geysers (M, 21, 23, 52, 54, N16, N17) may be attributed to dilution and rock interaction with geothermal water in higher temperature parts of the hydrothermal system. Larger $\delta^{18}O$ shifts are associated with higher Cl^- concentrations. Lower Geysers hot springs (21-Avery, 23-Velikan, M-Mladenets) show higher proportions of the deeper fluid component (less dilution) compared to the Upper Geysers (N16, N17, 52-Verkhny, 54-Chloridny). Low Cl^- springs (59 and 56) plot along the meteoric line and seem to be steam heated meteoric waters. Geysers (3-Pervenets and 45-Truby) are significantly diluted and are also located close to the meteoric water line (Fig. 4).

2.6. Heat sources

The primary heat source of the Geysers Valley hydrothermal system is suggested to be a partially melted magma chamber below the Upper Geysers Field. Its uplift was revealed by positive

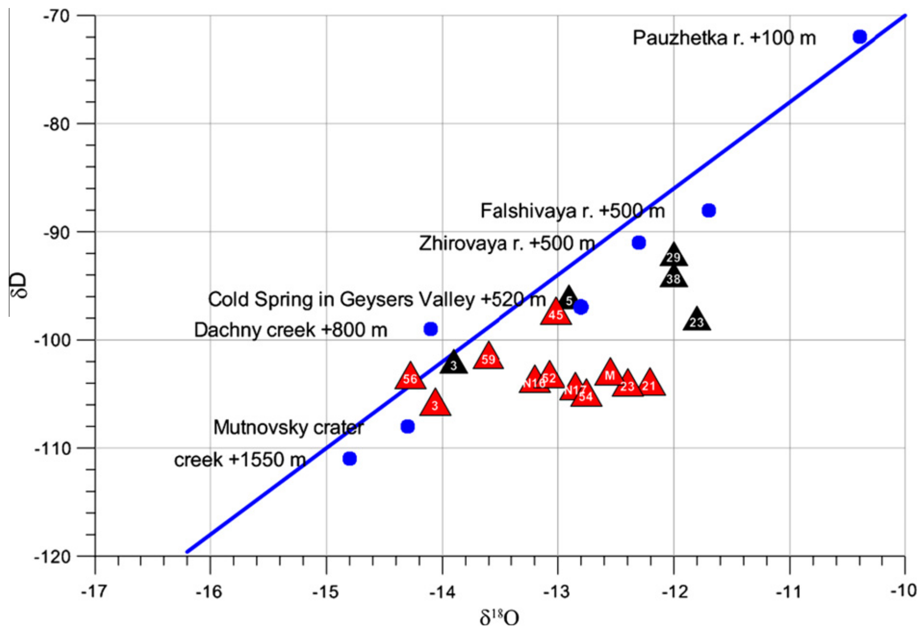

Fig. 4. Isotopic characteristics of boiling and hot springs from the Lower Geysers Field (black triangles with numbers, data from 1985), and the Lower and Upper Geysers Field (red triangles with numbers, 2010 year data) matched with meteoric waters (rivers and creeks) from different elevations (blue filled circles). Blue line is the global meteoric line. Numbers in triangles correspond to Tables 3 and 4. Samples collected by A.V. Kiryukhin, and analyzed by V.A. Polyakov (VSEGINGEO, Moscow, 1985) and E.O. Dubinina (IGEM, Moscow, 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

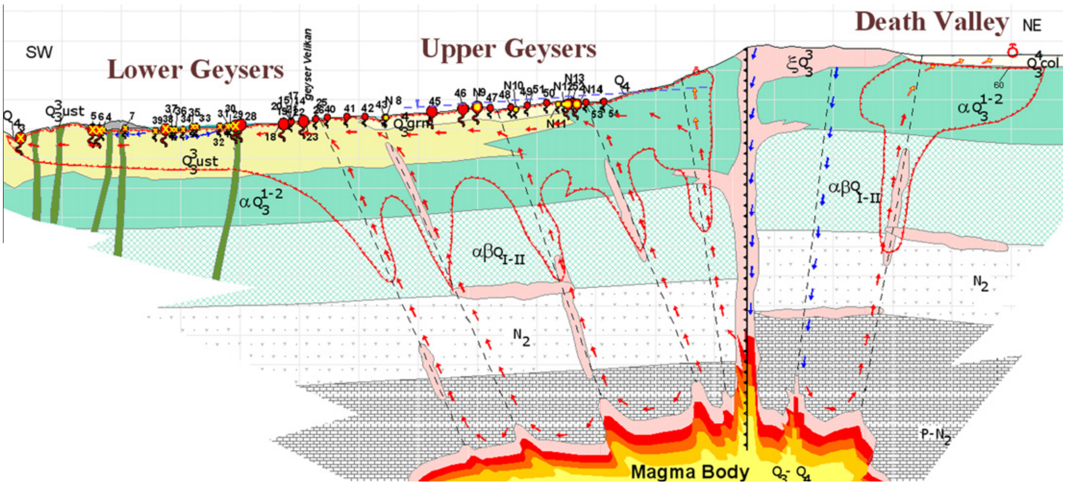

Fig. 5. Geysers Valley hydrothermal system conceptual model (SW–NE cross section). Grid scale is 500 × 200 m.

deformations with an amplitude of up to 15 cm from 1999–2003 (around 4 cm/a), identified by radar interferometry data analysis (Lundgren and Lu, 2006). The horizontal extent of the suggested magma body, shown as a red dotted line in Fig. 2 corresponds to a deformation of the contour line of approximately 10 cm.

The contours of the suggested magma body extent coincide with some ground temperature anomalies (steaming grounds) identified by IR-survey (Fig. 2 and 16). Some look like recently emplaced dykes (for example long shape below N9 in Fig. 3).

The magma system supplies heat to waters with meteoric origin and generate high temperature fluid upflows with base temperatures of 205–215 °C (see Cl^- springs ##21, 23, 52, 54, N16, N17, T-SiO_2 geothermometers estimates in Table 2).

The upflow rate corresponds to the discharge mass flow rate which was estimated as 300 kg/s by the Cl^- method in 1989 (Sugrobov et al., 2009), and re-estimated by the same method to be 260 kg/s in 2008 (see Section 3.2).

2.7. Conceptual hydrogeological model

Figs. 2 and 5 explain the formation of the Geysers Valley hydrothermal system, which is hosted in a fractured volume above a partially melted magmatic body and recharged along the caldera rim and outcrops of rhyolite extrusions with deep-seated high permeability roots ($\xi Q_3^3 - \xi Q_3^4$). The fractured system is suggested to be comprised of two faults with thermal discharges, shown as red lines in Fig. 2 and inferred from the distribution of thermal features both mapped and as shown by the IR survey of 2010. High temperature upflows are believed to occur along these faults above the partially melted magma body (Fig. 2). The inclined (8–25°) local caprock is composed of caldera lake tuffs (Q_3^4 pmz, grn) which change the upflow direction to lateral. There are significant hot spring discharges down from the fault axis in a NW direction, while the steam phase ascends in a southerly direction following the dip of the bottom caprock.

2.8. 3D thermal hydrodynamic modeling (natural state before June 3, 2007)

2.8.1. Thermal hydrodynamic model setup

The aim of this modeling study is to numerically reproduce thermal hydrodynamic processes during the formation of the hydrothermal system. The TOUGH2-EOS3 simulator (Pruess et al., 1999) was used for these purposes. The equation-of-state module EOS3 describes two-phase (liquid and gas) two-component (water and air) conditions prevalent in the unsaturated zone in the elevated parts of the Geysers Valley. The model boundary was defined so as to include the main thermal features: the Lower Geysers Field and the Upper Geysers Field, where most of the deep thermal discharge of 260–300 kg/s was estimated by the Cl^- method, following the main structural and hydrodynamic boundaries. Boundary lines are, in a clock-wise direction, following the Uzon–Geysernaya caldera rim, the Shumnaya River (#1–#3), the watershed of the Geyseranaya and Shumnaya rivers basins, the Geysernaya river basin upstream of the Upper Geysers Field, eventually closing the model along the caldera rim boundary (Fig. 6).

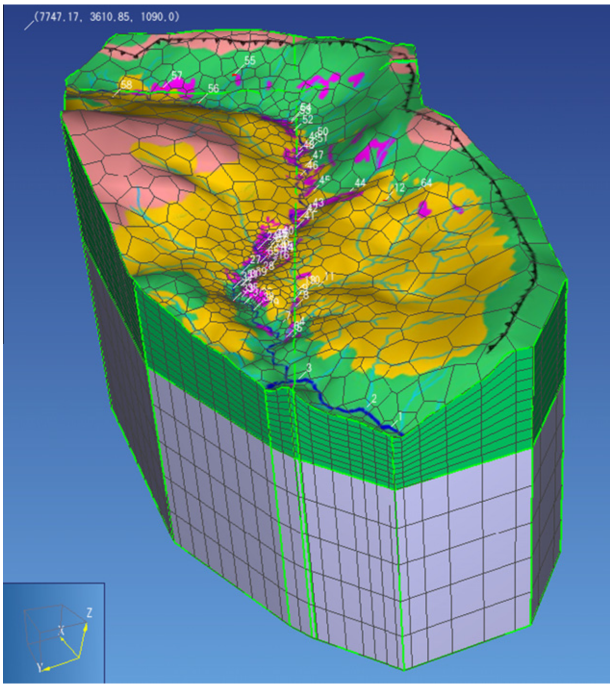

Fig. 6. Grid geometry used for the thermal hydrodynamic modeling of the natural state of the Geysers Valley hydrothermal system. Numbers on the surface correspond to thermal features listed in Table 3. Basement layer – gray; volcanogenic layer – green; top surface: rhyolite extrusions outcrops (recharge areas) – pink; caprock composed of rhyolite tuffs – brown; thermal anomalies areas revealed by the IR-survey conducted on August, 5, 2010 – magenta. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 5
Material properties assigned in the model as initial approach.

Model domain	Grain density, kg/m^3	Porosity	Vertical permeability, m^2	Horizontal permeability, m^2	Heat conductivity, W/m °C	Specific heat, J/kg °C
CAP_1	1E20*	0.2	1E−18	1E−18	1.6	1000
RES_1	2300	0.2	2E−15	2E−15	1.6	1000
RES_F	2300	0.1	1E−13	1E−13	1.6	1000
RESF2	2300	0.1	1E−13	1E−13	1.6	1000
BASE1	2800	0.02	1E−16	1E−16	2.1	1000
BASEF	2800	0.05	5E−15	5E−15	2.1	1000
RES1D	1E20*	0.2	2E−15	2E−15	1.6	1000

* Set to a high value to specify constant temperature boundary conditions.

The top of the model coincides with the topographic elevations; the model is bounded at the bottom at 2000 m.a.s.l. The two main geological units (layers) defined in the model are – (1) the Plio-cene–Quaternary volcanogenic reservoir, and (2) the Tertiary sedimentary basement (Fig. 6). The bottom of the reservoir (i.e., the top of the basement) is defined at 150 m.a.s.l. Two vertical structures, corresponding to the permeable fault zones shown in Fig. 2, were explicitly included in the model as high permeability zones.

The model domain was discretized using a polygonal Voronoi mesh, whereby the upper layer was divided into 10 sub layers, while the lower layer was divided into 5-mesh sub layers. The total number of grid elements is 10,500.

Model zonation includes the following domains with different material properties: CAP_1 – caprock units, composed of caldera lake tuffs; RES_1 – host reservoir; RES_F – fractured reservoir (two permeable fault zones); RESF2 – more permeable lateral contact zone in the reservoir (contact between caldera lake tuffs and pre-caldera volcanic units); BASE1 – host basement; BASEF – fractured basement (two permeable fault zones); RES1D – interface between reservoir and land surface; the top sub layer is used to assign atmospheric boundary conditions. Material properties of each domain are listed in Table 5, where the Grant function relative permeabilities with residual liquid saturation S_{lr} = 0.3 and residual gas saturation S_{gr} = 0.05. Note that according to National Park Reserve requirements, no drilling is permitted in the Geysers Valley hydrothermal system, hence material properties assigned to the model are based on known properties of analog Kamchatka geothermal fields, such as Pauzhetsky (Kiryukhin et al., 2008). Limited sampling of the Uzon–Geysernaya caldera tuff unit shows porosity ranges from 0.16 to 0.52, and grain density from 2.66 to 2.28 g/cm^3 (O. Topchieva, pers. comm., 2009).

A constant pressure of 1 bar specified at the land surface allows discharge at lowlands. Cold water recharge zones were assigned to outcrops of the Mt. Geysernaya rhyolite extrusion ξQ_3^4 on the right bank of the Geysernaya river and to the caldera rim at elevations above 700 m.a.s.l. (Figs 2 and 6), according to δD and δ^{18}O isotope data (see Section 2.4) and taking into account vertical channeling associated with extrusions. Cold water recharge rates were assigned to model elements at the top of extrusions.

Discharge conditions were assigned to the 38 most significant hot springs and fumaroles known before the Giant Landslide of June 3, 2007 (Table 4). Initially, all thermal discharge features were represented by 10 m deep wells on deliverability with well pressures of 1 bar and productivity indices of 10^{-12} m^3.

Initial conditions correspond to a steady state, with a temperature distribution in response to conductive heat flow of 60 mW/m^2 at the bottom of the model and a hydrostatic pressure distribution.

Heat and mass sources (high temperature upflow recharge) were assigned in the 20 elements at the bottom of the model basement layer along permeable fault zones within the area above the suggested magma body (Fig. 2). A total injected mass flow rate of 250 kg/s, with an enthalpy of 900 kJ/kg was distributed through all source elements. Upflow enthalpy corresponds to a temperature of 209 °C, as based on Na–K and SiO_2 geothermometry applied to representative Cl^- hot springs (Table 2).

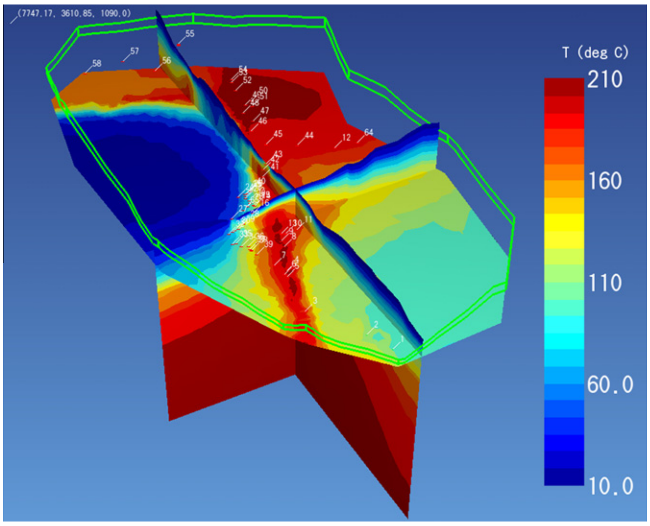

Fig. 7. Modeled temperature distribution in the Geysers Valley hydrothermal system 30 ka after the upflow of high temperature fluids started (slice planes Z = 200 m, X = 4100 m, Y = 2000 m). RUN DG02-J. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.8.2. Natural state thermal hydrodynamic modeling

Modeling runs were completed with outputs after 1, 3, 5, 10, 20, 30 and 100 ka, in order to explore the possible timing of the Geysers Valley formation process.

Based on modeling, natural temperature and discharge rate distributions of the Geysers Valley hydrothermal are postulated to be formed within 20 and 30 ka (modeling scenario #DG-02J). By that time, the 100 °C temperature isoline approximately covered the area of the Geysers Valley where boiling springs are observed, and the reservoir (RES_F + RESF2 + BASEF) temperatures reached 200 °C (Fig. 7). Most of modeled springs became boiling with enthalpies of 500–700 kJ/kg and quasi-stable flow rates, while higher thermal features turned into two-phase conditions. The total discharge flow rate is then close to the upflow rate at the basement bottom. The shape of the temperature anomaly covers the known thermal features and most of the permeable reservoir maintains a temperature of around 210 °C, which corresponds to geothermometry estimates (Fig. 8). It was found in the model (run DG02-J) that most of meteoric recharge (50 kg/s, 10 °C) took place on the outcrops of Mt. Geysernaya rhyolite extrusion ξQ_3^4 on the right bank of the Geysernaya river. Caldera rim recharges at elevations above 700 m.a.s.l. should be excluded from the model, otherwise numerous fumarole fields on the left bank of Geyser-

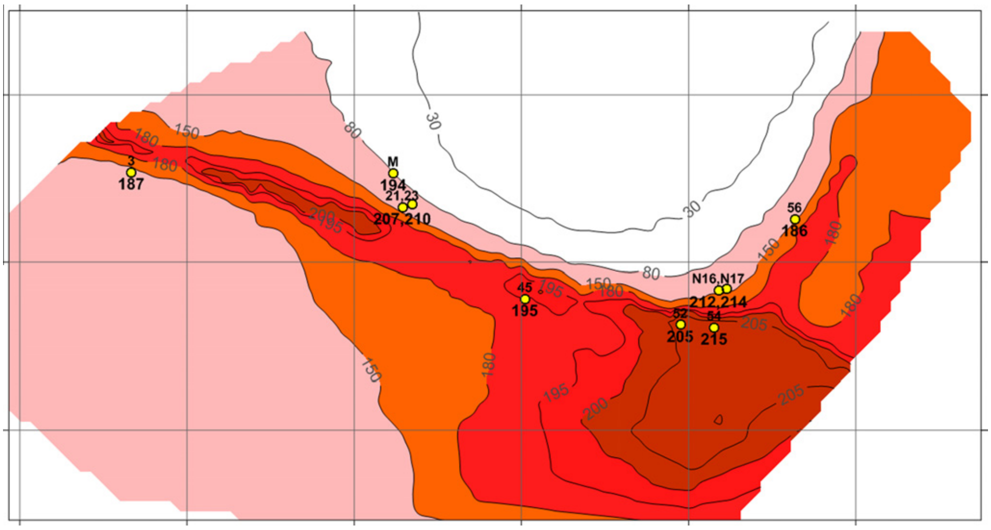

Fig. 8. Modeled temperature distribution at elevation $Z = 200$ m.a.s.l. (run DG02-J) compared with silica geothermometry data (Table 2). Sampled geysers and hot springs are displayed as yellow filled circles with spring numbers (Table 3) shown above circles and silica geothermometry values (Table 2) shown below circles. Grid scale is 500 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

naya River cannot be reproduced. Modeling also reveals that separation of the total upflow into two individual upflow zones below the Lower Geysers and the Upper Geysers Fields provides a better convergence by observed temperature distributions.

It is worth noting that a two-phase reservoir forms below the caprock. As a result of this, steam pressure below the caprock increases, which may trigger a hydrothermal eruption (Brown and Lawless, 1998), and (or) accelerate landslides (Fig. 8 and 13). Line-plot analysis of the model results shows that steam pressure in the wide two-phase zone reaches 7.0–8.5 bars at a depth of 150–250 m between N7, known as the "Fumarola Podryva" (steam vent, backing Giant Landslide of June 3, 2007) and #23 (geyser Velikan). These conditions, in which steam pressure transmits to shallower levels (see Section 3.3) may trigger steam explosions.

Inverse modeling capabilities of iTOUGH2-EOS3 (Finsterle, 1999) were used to estimate the total upflow rate, reservoir permeabilities (RES_F, RESF2, RES1D) and productivity indices of the 38 most significant springs against their individual flow rates (Table 3) at time 30 ka.

The first inversion (RUN DG02-K) includes estimates of the 40 model parameters (38 productivity indices, reservoir permeability (RES_F, RESF2) and surface sub layer permeability (RES1D)). In spite of over parameterization, this model helps to get initial parameter estimates with standard deviation of the flow rate of 1.03 kg/s, and a mean of the residuals of -0.495 kg/s. This bias points towards oversimplifications in the conceptual model parametrization used for this first inversion. Specifically, the upflow mass rates are not included in the estimation. Furthermore, simultaneous estimation of the hot springs production indices and reservoir permeability is not possible due to strong correlations. Nevertheless, the estimates of surface sub layer permeability (RES1D) of 0.03×10^{-15} m^2, and hot springs productivity indices (ranging from 2.2×10^{-13} to 5.0×10^{-9} m^3) are used in the updated model.

A second inversion (RUN DG02-K3) includes the estimation of the upflow mass rate and reservoir permeability (RES_F, RESF2) as model parameters. The following estimates for model parameters were obtained (with less standard flow rate deviation of 0.517 kg/s and mean -0.185 kg/s) (RUN DG02-K3): total upflow rate – 272 kg/s, reservoir permeability (RES_F, RESF2) – 435×10^{-15} m^2.

3. The Geysers Valley System after June 3, 2007 hydrothermal triggers of the Giant Landslide

3.1. Giant Landslide on June 3, 2007

On June 3, 2007, a catastrophic landslide took place in the Geysers Valley, Kamchatka. It occurred synchronously with a steam explosion (at point N7, Fig. 2) and was later transformed into a debris mudflow. Within a few minutes, 20×10^6 m^3 of rocks were shifted 2 km downstream in the Geysernaya river, which created a dam with Podprudnoe lake behind, and buried more than 23 geysers, including five famous geysers (Pervenetz, Troinoy, Conus, Maly and Bolshoy). The 20–30 m deep Podprudnoe lake started to inject cold water into the remaining part of the Geysers Valley hydrothermal system (Fig. 2 and 9).

3.2. Monitoring of Geysers cycling and deep component thermal discharge

Since July 2007, temperature loggers HOBO U12-015 were used to monitor the periodicity of the Velikan and Bolshoy geysers. Temperatures are recorded at intervals of 2–5 min by the loggers, which were installed at hot water discharge channels of the geysers. The time of the absolute maximum before absolute minimum temperature marks the period of the geyser Velikan's eruption.

To monitor the Podprudnoe lake level, HOBO U20-001-04 water level loggers were used. One logger recorded barometric pressure, while another one was lowered into the lake to record water pressure. The relative lake level was estimated from the pressure difference. Since Podprudnoe Lake is fed by the Geyzernaya River, it is possible to calibrate transient level data versus river flow rate. Hydrometric measurements and chemical sampling were conducted at the entry (Schell point) and exit (Dam point) of Podprudnoe Lake (Fig. 9). Deep component thermal discharge rates (estimated by the Cl^- rate method at the dam and entry points) are related to Podprudnoe lake levels as higher levels buffer the discharge of the hydrothermal system.

Bolshoy's cycling activity depended heavily on the level of the Podprudnoe Lake. Bolshoy was disabled when the relative level rose above 25 cm in summer, as cold water recharge took place

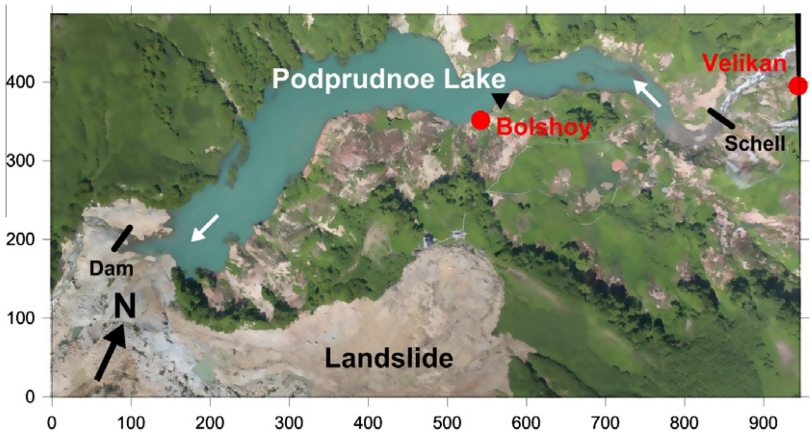

Fig. 9. Podprudnoe lake aerial view. Circles show the location of the Bolshoy (#28) and Velikan (#23) geysers; Dam Point and Schell Point are flow rate measurement positions at the entry and exit of the Geysernaya river in and from Podprudnoe lake, respectively. Triangle is the site of Podprudnoe lake level measurements.

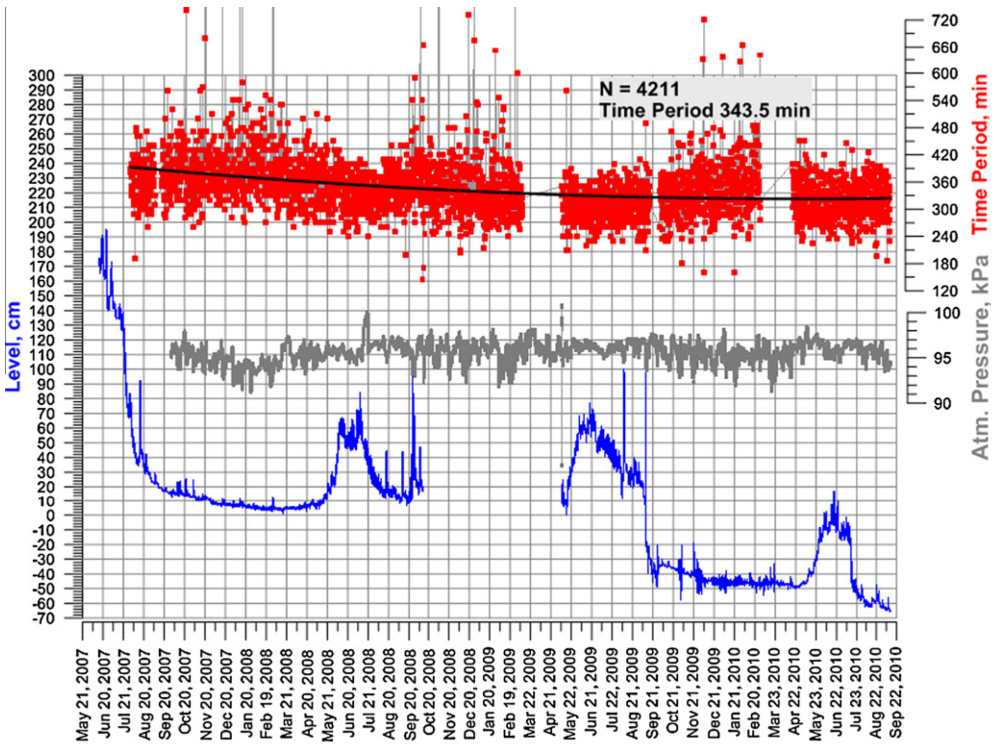

Fig. 10. Time period for eruption of the Velikan geyser (upper graph, cut off by maximum 720 min), relative level of Podprudnoe Lake (lower graph), and barometric pressure (middle graph) – vs. time after the 03-06-2007 Giant Landslide.

from the lake into the geyser channel. The Bolshoy geyser restarted to cycle, when the lake level dropped below 25 cm with an average period of cycling from 64 to 85 min.

From June 3, 2007 until September 2010, Velikan's average period of cycling gradually dropped from 392 to 327 min, and matched the value of 339 min, that was estimated as the value before the Giant Landslide (August 2003–October 2003, Droznin, 2007). The average period of cycling for the Velikan geyser during the entire observation time is 343.5 min (Fig. 10). Velikan's cycling is sensitive to direct recharge by meteoric water into the pool. Heavy snowfall and typhoons may delay eruptions and correspondingly increase the period of cycling. The maximum period of observed cycling was 32 h during heavy snowfall on February 29, 2008.

To estimate the total discharge of the deep component of thermal water (Q_d, kg/s) – the river Cl^- inventory method (Fournier, 1989) was applied to the Geysers Valley hydrothermal system. Measured rates of discharge of the rivers (Q_r, kg/s) and the Cl^- concentrations carried by those river waters (Cl_r, mg L^{-1}) were used. This method automatically compensates for boiling and mixing of rising thermal waters. Corrections are required for background Cl^- (Cl_b, mg L^{-1}), which generally amounts to 1–2 μg L^{-1}. The Cl^- flux associated with the deep component of the hot spring water was estimated as $Q_r * (Cl_r - Cl_b)$. The Cl^- concentration of deep water from the hydrothermal system (parental thermal fluid, C_d, mg L^{-1}) is estimated by the Cl^--enthalpy correlation (Fournier, 1989) or assumed to be the maximum before dilution (Sugrobov et al., 2009). Mass balances can be used to deduce the rate of total

Table 6
Estimates for the total discharge of a deep thermal component at Dam Point (Fig. 9). Flow rate measurements and sampling performed by Kiryukhin A.V., Rychkova T.V., and Chernykh E.V., chemical analysis performed by Marynova V.K., Kartasheva E.V., and Dunin-Barkovskaya V.V. in Central Chemical Laboratory Institute of Volcanology and Seismology.

Data (dd/mm/yyyy)	Q_r, kg/s Geysernaya river flow rate	*T*, °C Geysernaya river temperature	Cl_r, mg L^{-1}	Cl^- flux, g/s	Total discharge of deep component of thermal water (Q_d, kg/s)
01.10.2007	1770	21.5	156	276.1	306.8
08.04.2008	1268	24.5	229.8	291.4	323.8
21.07.2008	3640	16.5	46.5	169.3	188.1
22.07.2008	3520	16.5	46.1	162.3	180.3
23.07.2008	3410	17	46.8	159.6	177.3
24.07.2008	3510	19.1	53.9	189.2	210.2
25.07. 2008	3290	17.7	53.9	177.3	197.0
26.07.2008	2920	18	54.6	159.4	177.1
27.07.2008	2820	18.2	53.2	150.0	166.7
07.10.2008	3040	18	71	215.8	239.8
08.10.2008	2830	18.9	76.7	217.1	241.2
09.10.2008	2460	17.2	71	174.7	194.1
10.10.2008	2590	17.6	80.2	207.7	230.8
07.05.2009	1230	26	208	256.5	285.0

discharge for deep components of the hot spring: $Q_d = Q_r * (Cl_r - Cl_b)/C_d$. The discharge of the deep component of thermal water in Yellowstone was 3000 kg/s, and varied by 25–50% within a "water year". Discharge also depends on seismicity, which favors infiltration of meteoric waters into the underlying magma chamber (Fournier, 1989).

For the Geysers Valley, the total discharge of the deep component of the thermal water (with a Cl^- concentration of 900 μg L^{-1} assumed for the parental geothermal fluid (Sugrobov et al., 2009) was directly measured at the exit (Dam point) and entry (Shell point) points for Podprudnoe Lake (Fig. 9). The deep component of the thermal water at Dam Point is characterized by seasonal variations with a maximum recorded rate of 324 kg/s (April 2008) and minimum rates of 159 kg/s (July 2008 during spring–summer flooding, Table 6). Annually averaged, the total discharge of the deep component of the thermal water at Dam Point was 263 kg/s. The total discharge of the deep component at Schell point is sensitive to seasonal and individual nearby geyser discharge fluctuations; its recorded maximum was 229 kg/s (September 2008) and the minimum was 109 kg/s (July, 2008).

The maximum of the total discharge of the deep component of thermal water corresponds to the minimum level of the Podprudnoe Lake in winter–spring, while the minimum discharge corresponds to a maximum level during summer flooding times (Fig. 10). This shows that the lake level acts as a Dirichlet boundary condition for adjacent hydrothermal systems according to observations from the 2007/2008 seasonal cycle.

As the dam is eroded by the Geysernaya River, systematic lake level drawdowns (90 cm in 3 years, or 30 cm in a year) add to seasonal lake level variations (Fig. 10). Nevertheless, for this type of Dirichlet time dependent boundary condition, the output of the total discharge of the deep component will have a local maximum in winter/early spring, and a local minimum during summer flooding times.

3.3. New thermal discharge after the Giant Landslide as indications of fluid pressure increase and steam explosion conditions

Newly formed boiling springs (N9, N11, N12, N15–N17) with flow rates of 8.3 kg/s were found in the Upper Geysers Field as mentioned in Section 2.3. The upstream shifting (+20–+30 m elevation rise) of the boiling Cl^- springs (N15, N16, N17, see Figs. 2 and 3) corresponds to a water table rise of +20–+30 m and a corresponding pressure increase of 2–3 bars in the hydrothermal system.

Fig. 11. Photograph of steam explosion at point N7 (Fumarola-Podryva or "Blasting" fumarole) on June, 3, 2007 at 2:20 PM in the Giant Landslide cut off zone. Photo by courtesy of the Kronotsky State Reserve.

A new group of boiling springs emerged at the SE end of the upflow axes zone on the right bank of the Shumnaya river, near its junction with the Geyzernaya river (N1). This also indicates a fluid pressure increase in the hydrothermal system at the time of the Giant Landslide.

New fumaroles and hot springs arose in the Giant Landslide cut off zone. The total discharge of those springs with temperatures from 12 to 26 °C was estimated to be 30 kg/s. The chemical composition corresponds to steam heated meteoric water. Steam explosions rose to a height of 250–300 m on the site of the new fumaroles field, which has been documented by a video taken at the time of the Giant Landslide (Fig. 11).

The video quality is low, but ~300 m high steam clouds are clearly seen around the Giant Landslide cut off point (N7). N7 (Fumarola Podryva or "Blasting" fumarole) itself occurs in a 60°NE fracture dipping with a length of 20 m and a width of 10 cm. This fracture orientation dip coincides with the direction to the suggested magma body below the Upper Geysers Field (see Section 2.6 and Fig. 2). The cover thickness above the N7 cavity is estimated to have been less than 20 m before the landslide, hence just 2–3 bars of steam pressure are required to cause a shift (Fig. 12). Mordenite is one of the dominant secondary minerals in

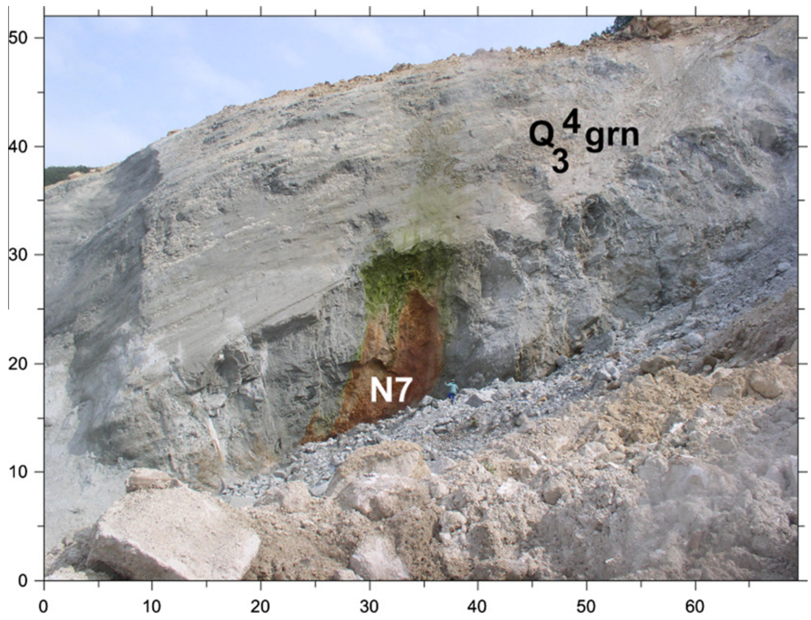

Fig. 12. Photograph of N7 (Fumarola-Podryva or "Blasting" fumarole) site. Scale in meters, man right of the fumarole for scale as well. Photo by A. Kiryukhin, July, 22, 2007.

N7 (F-Podryva) (Fig. 14), which corresponds to TOUGHREACT modeling of the site temperature being 160 °C with steam saturation pressures of up to 6.2 bars (see Section 3.5, Fig. 15). TOUGH2-EOS3 modeling outputs (Section 2.7) also show a potential for local hydrothermal explosions (Fig. 13). Moreover, Na–K and SiO_2-geothermometer values (Tables 2 and 3) correspond to a saturation pressure of up to 20.7 bars, which is enough to lift the 100 m thick caprock tuff unit (Q_3^4 pmz, grn).

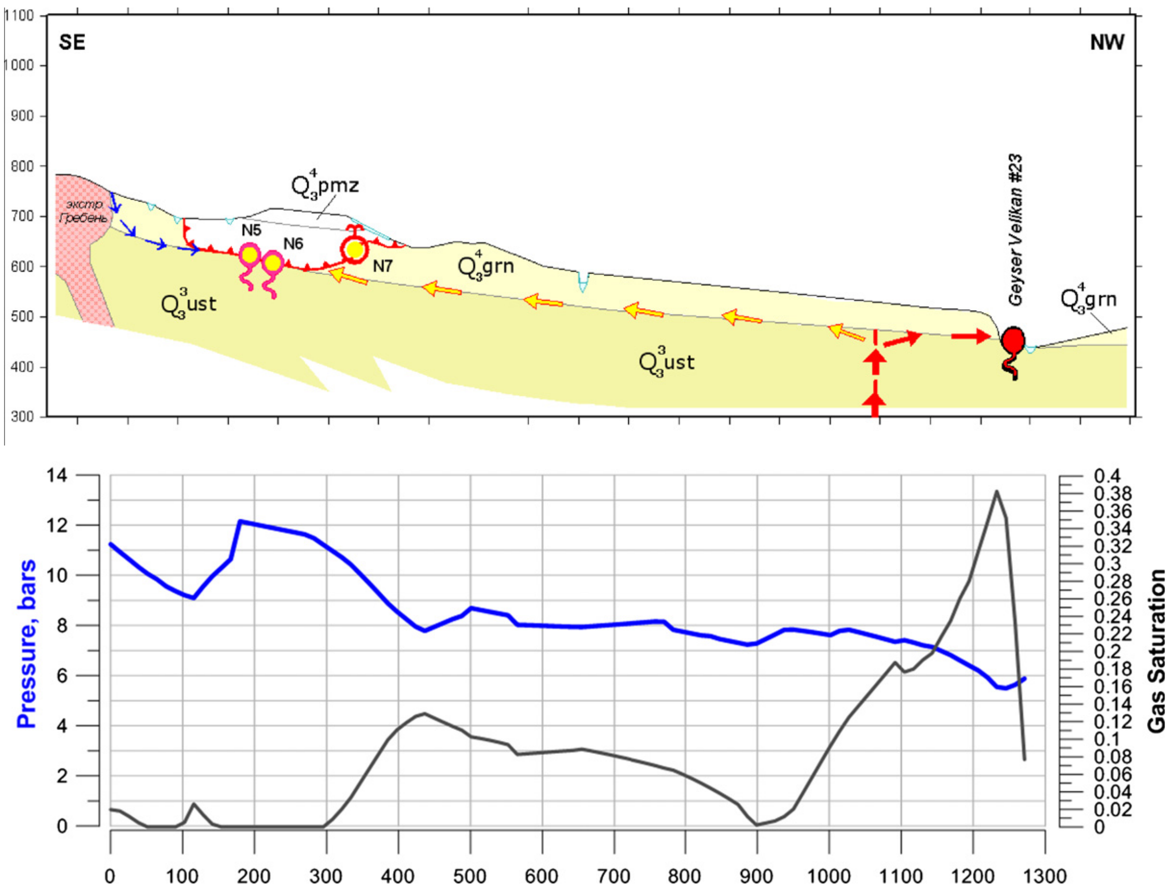

Fig. 13. Above: hydrogeological SE-NW cross section from Giant Landslide cut off zone (N5, N6, N7) to geyser Velikan (#23). Geological symbols are the same as in Fig. 2, horizontal axes tick spacing at 100 m. Below: TOUGH2-EOS3 modeling pressure and gas saturation line plot distribution from point (x_1 = 4123 m, y_1 = 1159 m, z_1 = 400 m.a.s.l.) (250 m below from N7, Fumarola–Podryva) to point (x_2 = 4354 m, y_2 = 2409 m, z_2 = 400 m.a.s.l.) (45 m below geyser Velikan, #23). RUN DG02-J.

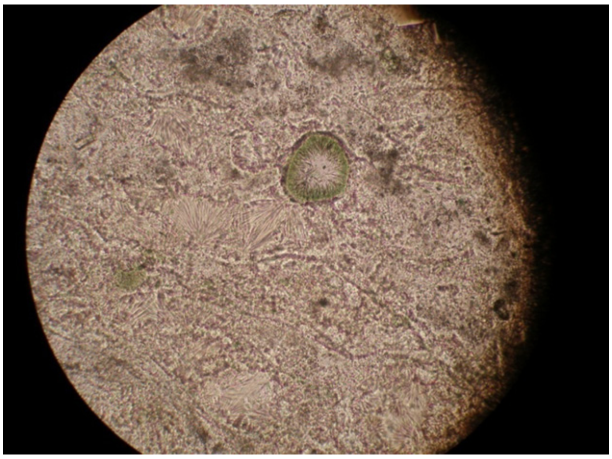

Fig. 14. Hydrothermal alteration example: Slice2a, diam. 0.6 mm. Radial mineral aggregates of mordenite (Vergasova et al., 2011) replace tuff cement and fill microcavities. This sample was collected by A.V. Kiryukhin directly from the Podryva fumarole (N7, Figs 2 and 12).

Two to three days before the Giant Landslide event, unusual gas smells were noticed on Gornoe Plato (500 m east from N7, see Fig. 2) by V. Zlotnikov (pers. comm., 2007). Nevertheless, regional seismic catalog data show no seismic events during that time. The hot spring N6 (temperature 25 °C, flow rate 12 kg/s), which drained the fumarole field where the Giant Landslide cut off occurred was sampled on July, 22, 2007. The chemical composition of the water is as follows: pH 7.78, Cl^- 1.4, F^- 0.2, HCO_3^- 23.2, SO_4^{--} 7.7, Na^+ 11.7, K^+ 0.2, Mg^{++} 8.5, NH_4^+ 0.3, and SiO_2 36.5 (in mg L^{-1}). No fumarole gas samples were taken, but a strong NH_3 smell was noticed. This may have been due to the reaction $N_2 + 3H_2 \rightarrow 2NH_3$, if H_2 generation in the magma–hydrothermal system increased at that time.

Steam explosions (hydrothermal eruptions) in geothermal fields are recognized worldwide (Brown and Lawless, 1998). Such explosions are caused by a fast transmission of steam pressure from a deeper two-phase zone to shallower levels, as fractures propagate from depth towards the surface. Steam pressure then causes fracturing, pushing breccias apart in an explosive way. Tension cracks may then evolve into landslide events, if steam pressure transmits upwards.

3.4. Hydrothermal alteration on sliding plane

According to Vergasova et al. (2011), the matrix of the tuff sliding plane that was originally composed of glass is now completely altered and contains hydrophilic, highly silicified zeolites (mordenite and clinoptilolite) and smectites (Fig. 14). In some samples, relatively fresh oligoclase (up to 15 vol.%) was found as well. This secondary mineral association was produced by a liquid phase, typical of hydrothermal alteration of the argillitic zone, that may form an impervious cover by self-sealing. The abundance of sulfides, gypsum, and Fe-hydroxides in fractures indicates the possibility of some meteoric water infiltration at the time of fracturing after the caldera wall eroded and reservoir drainage started.

3.5. Thermal hydrodynamic chemical modeling

TOUGHREACT modeling (Xu et al., 2006) was used to verify caprock hydrothermal alteration, identify a possible weakening mechanism, and determine the temperature of the secondary mineral generation. The following assumptions were made: (1) one element model with element volume 1 m^3, (2) initial caprock (rhyolite tuffs) mineral volume fractions were assumed: glass 90% and porosity 10% (Puzankov M.Y., pers. comm., 2011), (3) inflow and outflow fluid rate of 10^{-5} kg/m^2 s, chemical composition of inflow fluid corresponds to geyser Velikan (Table 1), (4) time of fluid

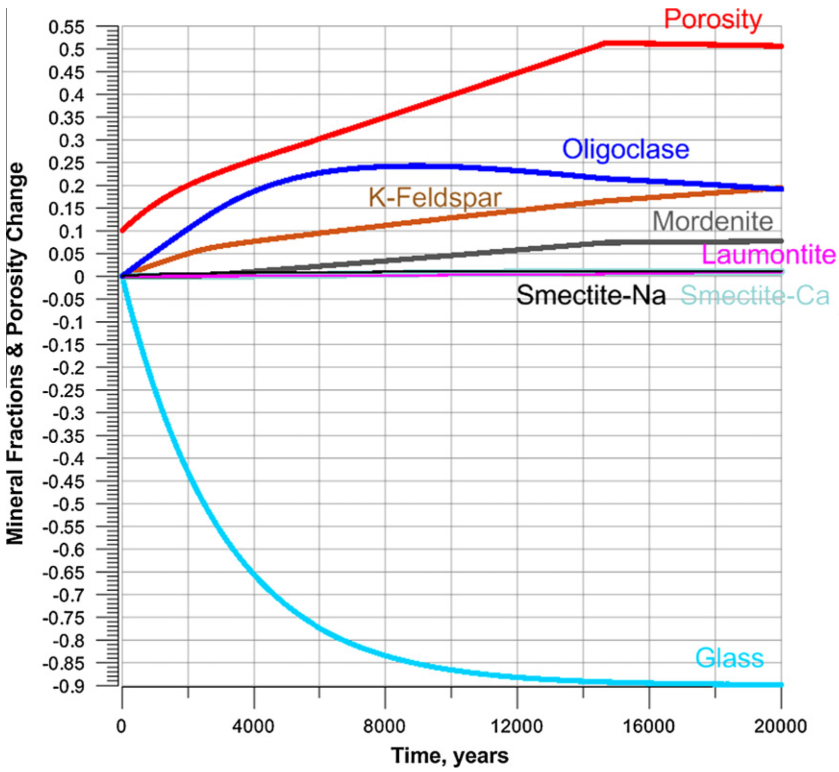

Fig. 15. Output of TOUGHREACT modeling (#2E-160-PUZ-CA): Time-transient change of porosity and mineral fractions in the model element (temperature 160 °C).

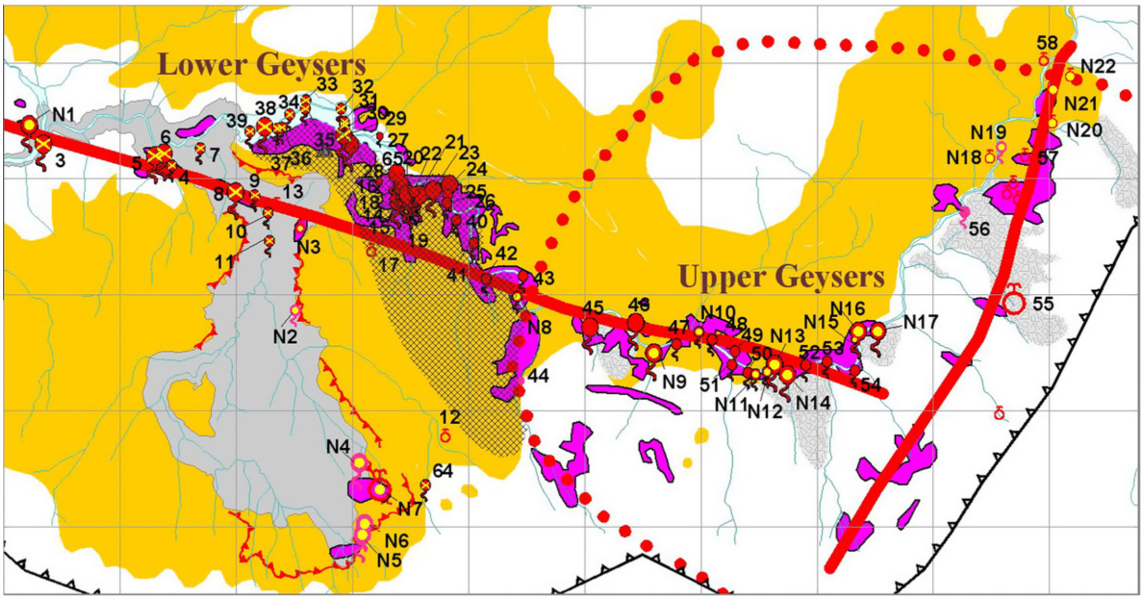

Fig. 16. Ground temperature anomalies (steam grounds) identified by IR-survey (August 2010) shown by magenta filled areas; cross hatched – potential hazards area (hydrothermal explosions associated with landslides); caprock of Geysernaya Unit – filled brown area; other symbols – see Fig. 2. Scale – 500 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

circulation is 20 ka, (5) the following mineral phases are included in modeled geochemical system: quartz, K-feldspar, clinochlore, cristobalit, laumontite, mordenite, sio2(am), wairakite, glass3, kaolinite-a, smectite-ca, smectite-k, smectite-mg, smectite-na, illite-a1, oligoclase, (6) kinetics of fluid rock chemical interaction taken into account, and (7) single phase liquid conditions at 12 bars pressure.

TOUGHREACT modeling was performed at different temperatures ranging from 80 to 170 °C. This reveals that mordenite generation occurs at temperatures of up to 160 °C (corresponding to a saturation pressure of 6.2 bar), while at higher temperatures, wairakite appears as well. Hence, a temperature of 160 °C and a saturation pressure of 6.2 bars may be considered as an upper threshold of mordenite for given caprock conditions. The following changes of mineral fraction volumes were observed in the model during 20 ka of fluid circulation: significant porosity increase (from 10% to 50.6%), complete glass dissolution (-89.9%), and growth of secondary minerals: mordenite (+7.7%), laumontite (+0.9%), K-feldspar (+19.4%), oligoclase (+19.1%), and Ca- and Na-smectites (+2.1%) (Fig. 15).

3.6. Geomechanical estimates of slope stability above geyser Velikan (#23)

A preliminary estimate of slope stability equilibrium theory analysis was applied to sliding along the bottom surface (failure plane) of the caprock (Figs. 13 and 16), which is composed of impermeable units of caldera lake deposits (Q_3^4 pmz, grn, corresponding to pumice tuffs, sandstones and breccia) using RockPack III (Watts et al., 2003) and assuming a factor stability FS a ratio of resisting forces to driving forces. A value for FS of 1.3 was considered as a minimum for slope use.

The following input data for the FS estimate was used (see Figs. 13 and 16): H – height of slope face, 50 m; SF – inclination of slope face, 45°; SS – inclination of upper slope, 5.4°; SP – inclination of failure plane, 4.5°; CO – cohesive strength of failure surface, 30.0 kPa; PH – friction angle of failure surface, 9° (standard parameter for clays with 0.5 porosity); GR – rock density, 1600 kg/m^3; GW – water density, 1000 kg/m^3; TZ – amount of discontinuity saturated, 1.0; AC – horizontal acceleration, 0.0 m/s^2; assumed tension crack data, B – horizontal distance of tension crack from crest, 830 m (Medvezhy creek); DZ – relative height of water in tension crack, 1.0.

RockPack III estimations show FS = 1.01 with the given input data. If horizontal acceleration reaches 0.1 g (M = 7 earthquake under scale MSK64), then FS drops to 0.51. This may trigger 1.09×10^6 tons of rock slide material, in the case of a landslide 500 m wide. Hydrothermal eruptions may be triggered by a similar acceleration factor.

4. Conclusions

The Geysers Valley hydrothermal system is hosted within a system of two permeable faults (confirmed by mapping thermal features), adjacent to a partially melted magmatic body and recharged by meteoric water along outcrops of rhyolite–dacite extrusions (ξQ_3^4). Fast erosion is stimulating the significant discharge rate, the geyser's cycling mode and landslide events. Natural state thermal hydrodynamic TOUGH2-EOS3 modeling shows that 20–30 ka with a high temperature upflow of 250–270 kg/s and an enthalpy of 900 kJ/kg can build up a hydrothermal system in the Geysers Valley basin with the observed output discharge. Modeling also shows that high temperature upflow includes two roots (below Lower Geysers and Upper Geysers Fields), whereby meteoric recharge occurs mainly through outcrops of the Mt. Geysernaya rhyolite–dacite extrusion (ξQ_3^4). Accumulated steam below the inclined caprock (SE from the Lower Geysers Field) may have hydrothermal eruption potential. Model parameters are verified by the distribution of hot spring flow rates, the isotopic composition of thermal fluids (δD, δ^{18}O), and silica geothermometry.

Monitoring of key geysers, hot springs and Podprudnoe Lake parameters conducted in 2007–2010 shows a gradual decline of geyser Velikan's time period of cycling from 392 min to 327 min, a strong sensitivity of Bolshoy geyser to Podprudnoe Lake level, seasonal variations of the total discharge of the deep thermal water component (Cl^- method estimation) with an annually averaged estimate of 263 kg/s, and a drop of Na–K and increase of SiO_2 geothermometer values compared to estimates made before the Giant

Landslide. The study of the new thermal discharge features that arose at time of the Giant Landslide of June 3, 2007 reveals a significant fluid pressure increase (rise of the thermal water level of 20–30 m detected by the emerging of the N16 and N17 hot springs at higher elevations). Additionally, the sliding unit bottom is completely altered into highly silicified zeolites at temperatures of up to 160 °C (fumaroles field at the Giant Landslide cut-off zone).

The remnants of the Geysernaya unit on the slopes of the caldera wall (Fig. 2 and 16) demonstrate that the Giant Landslide was a repetitious event due to sliding processes on the hydrothermally altered Geysernaya unit into the Geysernaya river basin. Possible triggers of such landslides are: (1) The inclination of the bottom of the Geysernaya unit (sliding plane) towards the Geysernaya river basin; (2) A pressure increase by 2–3 bars in the fluid–magma system; (3) Over-saturation of the hanging block by water and snow during spring flooding; (4) Hydrothermal alteration and weakness of the sliding plane; and (5) Steam explosions along the sliding plane.

The continuing development of 3D thermal hydrodynamic and chemical models of the Geysers Valley hydrothermal system will be the target of the following issues: (1) Natural state inverse modeling calibration based on individual hot springs; (2) Discharge and geyser activity sensitivity studies to define the rate of erosion of the Geysernaya river basin, the reservoir fluid pressure build up, Podprudnoe Lake level variations and cold water injection; (3) Modeling outputs for underground steam pressure and two-phase condition mapping for early detection of potential areas of hydrothermal explosions associated with landslides; (4) Understanding the chemical evolution of the hydrothermal system as a whole.

Monitoring key geysers, hot springs and Podprudnoe Lake thermal, hydrodynamic and chemical parameters combined with repeated helicopter infra red (IR) surveys and thermal hydrodynamic modeling will help to map and forecast underground steam pressure build up in areas of potential hydrothermal explosions (Fig. 16).

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