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Modeling and observations of geyser activity in relation to catastrophic landslides–mudflows (Kronotsky nature reserve, Kamchatka, Russia)

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ABSTRACT

This study reports and interprets observational data of geyser cycling in the Valley of Geysers and Uzon hydrothermal systems between 2007 and 2015. The monitoring of the Velikan and Bolshoy Geysers after the catastrophic landslide on 3.06.2007 (which dammed and created Podprudnoe Lake, drowning some geysers) and before a mudflow on 3.01.2014 (which destroyed the dam and almost completely drained Podprudnoe Lake) shows that the interval between eruptions (IBE) of the Bolshoy Geyser decreased from 108 to 63 min and that the IBE of the Velikan Geyser slowly declined over three years from 379 min to 335 min. The seasonal hydrological cycle of the Velikan Geyser shows an increase in the IBE during winter (average of 41 min). The dilution of the chloride deep components of the Bolshoy (−23%) and Velikan Geysers (−12%) is also observed. A local TOUGH2 model of the Velikan Geyser is developed. This model is used to describe the transient thermal hydrodynamic and CO_2 changes in a Velikan Geyser conduit during the entire cycling process by using cyclic, time-dependent boundary mass flow conditions (major eruption discharge and sub-cyclically assigned CO_2 mass flow recharge into the base of the geyser conduit and water recharge at the mid-height of the geyser conduit) and a constant mass flow of water into the geyser at depth. This model also indicates a seepage element at the conduit's top to allow pre-eruptive discharge and a buffering isothermal reservoir below to compensate for pressure declines from major eruptions at earlier times. A local TOUGH2 model is successfully calibrated against temperature observations at both the mid-height and base of the conduit of the Velikan Geyser, which shows the essential role of the above parameters in describing the functionality of the geyser. A reservoir model of shallow production geysers is also developed. This 2D model is used to describe changes in the thermal hydrodynamic state and evolving chloride concentrations in the areas of most prominent discharge, both at steady state and when perturbed by cold water injection from Podprudnoe Lake and other cold water sources (after 3.06.2007). A "well on deliverability" option is used to model the geyser discharge features in the model. The modeled increases in geyser discharge that is caused by an increase in the reservoir pressure from cold water injection reasonably matches observations of IBE decreases in the Bolshoy (~58%) and Velikan Geysers (~9%). The modeling also shows the possibility of chloride dilution in the Velikan Geyser but no dilution in the Bolshoy Geyser. The latter observation is attributed to the presence of direct cold water inflow into the Bolshoy Geyser conduit.

1. Introduction

1.1. Brief history of the exploration of the Valley of Geysers

The Valley of Geysers is located in the Kronotsky State Nature Reserve on the Kamchatka Peninsula. This region was first discovered by T. I. Ustinova on April 14, 1941 (Ustinova, 1955) in the canyon of the Geysernaya river basin, which is 8 km long and 400 m deep. Geological and hydrogeological studies that were conducted 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.) revealed that the Valley of Geysers' hydrothermal system has the greatest natural discharge of the twelve highest-temperature Kamchatka hydrothermal systems, with an approximate discharge rate of 300 kg/s and water temperature of 100 °C. At least 57 geysers have been discovered (Sugrobov et al., 2009), and explorers have conducted systematic observations of the activity cycle of 13 geysers (Pervenetz, Troynoy, Konus, Maly, Bolshoy, Schel, Fontan, Velikan, Zhemchuzhny, Gorizontalny, Rozovy Konus, Burlyaschy, and Vosmerka). The Valley of Geysers has significant touristic, scientific and educational value because it is the only place in Russia where one can watch the activity of geysers, use these observations to

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understand the conditions of the formation of hydrothermal systems (discharge conditions, heat sources, reservoir structure, and role of the caprock), and explore the potential of geothermal energy.

The number of visitors to the Valley of Geysers reaches 3000 people annually. Therefore, identifying the mechanisms of geyser formation, the parameters of the hydrothermal system, and the factors that control hydrothermal explosions and landslides is important, as is monitoring these parameters to predict possible catastrophic natural phenomena and assess the impact of changes in the discharge/recharge conditions on the geyser regime, which survived disastrous landslides and mudflows in 2007 and 2014. This article describes and discusses recent results (from 2007 to 2014) of hydrogeological regime monitoring for the Velikan and Bolshoy Geysers and modeling approaches that explain the changes in the geyser activity.

1.2. Brief overview of the worldwide experience of geyser observations and modeling

Natural geysers (cyclically erupting springs of boiling water) are found in a few places around the world, the most famous of which are located in Iceland (Haukadalur basin), the United States (Yellowstone Park), New Zealand (Rotorua) and Russia (Kronotsky Reserve) (Rinehart, 1980). Geyser observations is a subject that involves numerous scientific research applications, which began from simply visually counting the number of cycles per day (since 1937 in Yellowstone) and progressed to continuous logging with temperature sensor records since 2003 (Hurwitz et al., 2008). The transient data that are used to understand the features of the cycling activity of geysers (geyser eruption intervals, GEI, or intervals between eruptions, IBE) include the height and duration of eruptions; the eruption volumes; the chemical composition of the discharged fluid; the local barometric pressure, temperature and wind; the reservoir water recharge conditions (estimated based on a local river's discharge); local, regional and global seismic events; and tidal and tectonic stress deformations (Rojastczer et al., 2003; Husen et al., 2004; Hurwitz et al., 2008, 2012, 2014). Despite the easy access to observations of the characteristics of surface eruptions, the geometry of geyser conduits has rarely been described in detail, with exceptions including the chamber-shaped dormant Te Waro geyser in Whakarewarewa, Rotorua (Rinehart, 1980) and the vertically shaped Old Faithful geyser in Yellowstone (Hutchinson et al., 1987).

The mechanisms of cyclic eruption are conceptually explained and experimentally verified in terms of three basic models: (1) a chamber (or bubble trap) model (Rinehart, 1980; Vandemeulebrouck et al., 2014), (2) a well model (Droznin, 1980; Ingebritsen and Rojstaczer, 1996; Lu et al., 2005), and (3) a mixing model (Steinberg et al., 1981).

The well model ("well" with a possibility of relatively cold recharge from the top) was numerically tested by Ingebritsen and Rojstaczer (1996) with the Hydrotherm program. Geyser cycling (cyclic increase in the flowrate at the top of up to 40 kg/s) was successfully performed in a highly permeable conduit at 200 m depth in a low permeability environment with a 2 MW heat source at the bottom and fixed state (1 bar, 100 °C) atmospheric conditions at the top. Some outputs of this study included the appearance of a steam phase at the bottom to initiate high discharge near the top and the sensitivity of the IBE to the conduit's porosity, permeability contrast, relative permeability (a change from linear to Corey relative permeabilities switched the cycling to a bimodal regime), top pressure and temperature, depth and cross-sectional area of the conduit. Another type of well model was tested by Lu et al. (2006), who found that adding a non-condensable gas (CO_2) component made 12-min cycling viable in a 70 m-deep and 0.1 m-diameter well that was recharged by fluids at a rate of 0.2 kg/s, temperature of 87 °C, and mass fraction of $CO_2 = 3000$ ppm at the bottom. These authors found that the IBE was sensitive to the mass fraction of CO_2 and the recharge flowrate.

The mixing model (conduit with the possibility of two contrasting recharges from the bottom) assumes that an eruption will occur when the water temperature in the chamber reaches the boiling point for the hydrostatic pressure that is produced by the water-filled conduit (Steinberg et al., 1981). This model was numerically tested by N.M. Saptadji (1995) with the AUTOUGH2 program. The model geometry was assigned as a vertical 12 m and 0.1 m^2 cross-section, highly permeable conduit ($8e-8$ m^2) that was connected to a less permeable ($2.5e-10$ m^2), large-volume "cold water" reservoir (75 °C, 2.1 bars) at the bottom. A "hot water" mass source of 1 kg/s and 853 kJ/kg (200 °C) was also specified at the bottom of the conduit (chamber). The above model successfully demonstrated cycling with an IBE $\approx$ 15 min and eruption flowrates of 9–16 kg/s. The model also reproduced the characteristics of the known Whakarewarewa geysers (Pohutu, Feathers and Waikorohihi) and checked the model's sensitivity to the input parameters (cold water reservoir recharge, pressure, temperature, etc.).

The chamber (or bubble-trap) model was recently supported by multiple instrumental (seismometer, tilt meter, and temperature radar) observations of the Lone Star geyser (Yellowstone) (Karlstrom et al., 2013; Vandemeulebrouck et al., 2014), which yielded estimates of various geyser parameters (a 3-hour IBE, a four-phase cycling period with a 28-min major eruption duration, and a 20.8 m^3 eruption volume that was discharged) and revealed continuous hydrothermal tremors in the geyser conduit and in an area to the northeast, where the source reservoir's "bubble trap" was assumed to be located. This trap suggested a compressed vapor store of thermal and mechanical energy that is released during eruptions and relaxation. The bubble trap model in the Valley of Geysers was discussed by Belousov et al. (2013).

Some laboratory experimental studies were designed to test conceptual models, including recent studies (Toramaru and Maeda, 2013; Adelstein et al., 2014). In particular, these models (Adelstein et al., 2014) provide insight into the roles of pre-play and the bubble-trap structure during the geyser eruption process (pure water component fluid). The transport of vapor up the conduit during pre-play events warms the conduit, moving the system closer to the required boiling state for eruption. The position of the bubble trap structure allows for vapor accumulation below the upper conduit and the episodic release of the vapor and its enthalpy.

The main outcomes of the long-term geyser monitoring studies at Yellowstone (Rojastczer et al., 2003; Husen et al., 2004; Hurwitz et al., 2008, 2012, 2014) are the following: (1) the IBE's (interval between eruptions) sensitivity to seasonal hydrological recharge conditions (more recharge and higher reservoir pressures shorten the IBE, while windier and colder winter conditions cause heat loss at the top and lengthen the IBE of pool geysers); (2) the IBE's sensitivity to neighboring hydraulically connected geyser eruptions; (3) the IBE's sensitivity to local, regional and global earthquakes (dynamic pressures greater than 0.1 MPa), which can significantly affect the permeability of geyser conduits (the IBE increases or decreases as earthquake effects accumulate); and (4) the IBE's lower sensitivity to short-period barometric (less than 5 mbars) and tidal deformations. Recently monitoring of the El Jefe geyser in Chile (Munoz-Saez et al., 2015) demonstrated the lack of responses to environmental perturbations (air pressure, temperature and probably Earth tides). This study also noted the periodic release of steam bubbles from the reservoir system below, which triggered geyser eruptions. Nevertheless, an example of a geyser that was sensitive to the atmospheric pressure was found in Waiotapu, New Zealand, where the Wai O Tapu geyser stops/starts cycling when the atmospheric pressure passes a threshold value of ~1010/1015 hPa (Davidson, 2014). New Zealand's experience with geysers and water level monitoring for the exploitation of Whakarewarewa-Rotorua shows the possibility to identify periodic variations for both anthropogenic and barometric disturbance in the range of 2.8–5.2 mm-H_2O when the Earth tidal amplitudes are less than 1 mm-H_2O (Leaver and Unsworth, 2007).