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Isotopes & Geochemistry: Tools For Geothermal Reservoir Characterization (Kamchatka Examples)

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Abstract. The thermal, hydrogeological, and chemical processes affecting Kamchatka geothermal reservoirs were studied by using isotope and geochemistry data: (1) The Geysers Valley hydrothermal reservoirs; (2) The Paratunsky low temperature reservoirs; (3) The North-Koryaksky hydrothermal system; (4) The Mutnovsky high temperature geothermal reservoir; (5) The Pauzhetsky geothermal reservoir. In most cases water isotope in combination with Cl^- transient data are found to be useful tool to estimate reservoirs natural and disturbed by exploitation recharge conditions, isotopes of carbon-13 (in CO_2) data are pointed either active magmatic recharge took place, while SiO_2 and Na-K geothermometers shows opposite time transient trends (Paratunsky, Geysers Valley) suggest that it is necessary to use more complicated geochemical systems of water/mineral equilibria.

1 Introduction

Active pore space limitation mass transport velocities are typically greater than heat transport velocities. That is a fundamental reason why changes in the isotope and chemistry parameters of geofluids are faster than changes in the heat properties of producing geothermal reservoirs, which makes them pre-cursors to production parameter changes. In cases of inactive to rock chemical species, they can be used as tracers of fluid flow and boundary condition estimation. Otherwise, chemical equilibriums between rocks, water and gas phases yield reliable chemical signatures of temperature and phase saturation parameters of geothermal reservoirs and internal condition estimation. A gas partial pressure rise reduces the boiling temperature, which may switch reservoirs into two-phase conditions and cycling.

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2 The Geysers Valley hydrothermal reservoirs

The Geysers Valley hydrothermal system (Kamchatka, Russia) is one of the five major geysers fields in the world. The 1941-2018 period of the Valley of Geysers monitoring (Kamchatka, Kronotsky Reserve) reveals a very dynamic geyser behavior in natural state conditions: significant changes of interval between eruptions (IBE) and power of eruptions, chloride concentration and that of other chemical components, and pre-eruption bottom temperature [1,2,3]. Nevertheless, the total deep thermal water discharge (that was estimated by the chloride method [1]) remains relatively stable implying that this dynamic behavior may be caused by a redistribution of the thermal discharge due to the Giant Landslide of June 3, 2007, the mudflow of January 3, 2014 and other events of geothermal caprock erosion and water injection into the geothermal reservoir. In some cases, water chemistry and isotope data suggest a local meteoric water influx into the geothermal reservoir and geyser conduits. A local TOUGH2 model of the Velikan geyser is developed and is successfully calibrated against temperature observations at both mid-height and base of the Velikan Geyser conduit, which indicates the essential role of CO_2 in the geyser functionality. TOUGHREACT V.3 modeling of the Velikan geyser chemical history confirms a 20% dilution of deep recharge water and CO_2 components after 2014. Temperature logging in the geysers Velikan (1994, 2007, 2015, 2016, 2017, 2018) and Bolshoy (2015, 2016, 2017, 2018) conduits shows pre-eruption temperatures below boiling at the corresponding hydrostatic pressure, which means the partial pressure of CO_2 and other non-condensable gases creating gas-lift upflow conditions in geyser conduits. The Velikan geyser IBE history is explained in terms of a gradual CO_2 recharge decline (1941-2013), followed by a CO_2 recharge significant dilution after the mudflow of January 3, 2014 also reshaped geyser conduit and diminished its power.

3 The Paratunsky low temperature reservoirs

The Paratunsky low temperature geothermal field has been operated since 1964. During the period of utilization from 1966-2014, 321 Mt of thermal water (Cl-Na, Cl-SO_4-Na composition, TDS up to 2600 ppm) with temperatures of 70-100^oC was extracted and used for district heating, balneology and greenhouses [4]. Water isotope and gas ($N_{2,}$ 96-98%) data analysis indicated that the main recharge region of the Paratunsky geothermal reservoirs is the Viluychinsky Volcano (2173 masl) and the adjacent highly elevated structures, located 25 km south from the geothermal field. TOUGH2 modeling of the thermo-hydrodynamic natural state and the history of utilization (involving pressure, temperature and chemical change response to utilization) between 1965 and 2014 yield estimates of hot water upflow rates (190 kg/s). Modeling of the chemical (Cl-) history of utilization provides an explanation of a gradual Cl- accumulation due to the inflow of chloride-containing water through the eastern (open) boundary of the geothermal reservoirs (NP & N sites).

An additional feature is a trend of T_{SiO2} increase (12 ^oC/50 years) and a trend of $T_{Na\text{-}K}$ decrease (-35 ^oC/50 years), while a pH drop (from 8.1 to 7.1 in 50 years) was observed at the SR1 site of the Paratunsky geothermal field (in the southwest part of the field) (Fig. 1), that may be associated with the influx of more acidic water.

4 The North-Koryaksky hydrothermal system

The Avachinsky-Koryaksky volcanogenic basin of an area of 2530 km^2, is located 25 km from Petropavlovsk-Kamchatsky City and includes five Quaternary volcanoes (two of which, Avachinsky (2750 masl) and Koryaksky (3456 masl), are active), and is located within a depression that has formed atop Cretaceous basement rocks [5]. Water isotope (δD, $\delta^{18}O$) data indicate that these volcanoes act as recharge areas for their adjacent thermal mineral springs (Koryaksky Narzans, Isotovsky and Pinachevsky) and the wells of the Bystrinsky and Elizovo aquifers. Carbon $\delta^{13}C$ data for CO_2 from CO_2 springs in the northern foothills of the Koryaksky Volcano reflect the magmatic origin of CO_2. Carbon $\delta^{13}C$ data for methane CH_4 reservoirs penetrated by wells in the Neogene-Quaternary layer around Koryaksky and Avachinsky volcanoes indicate a thermobiogenic origin for methane.

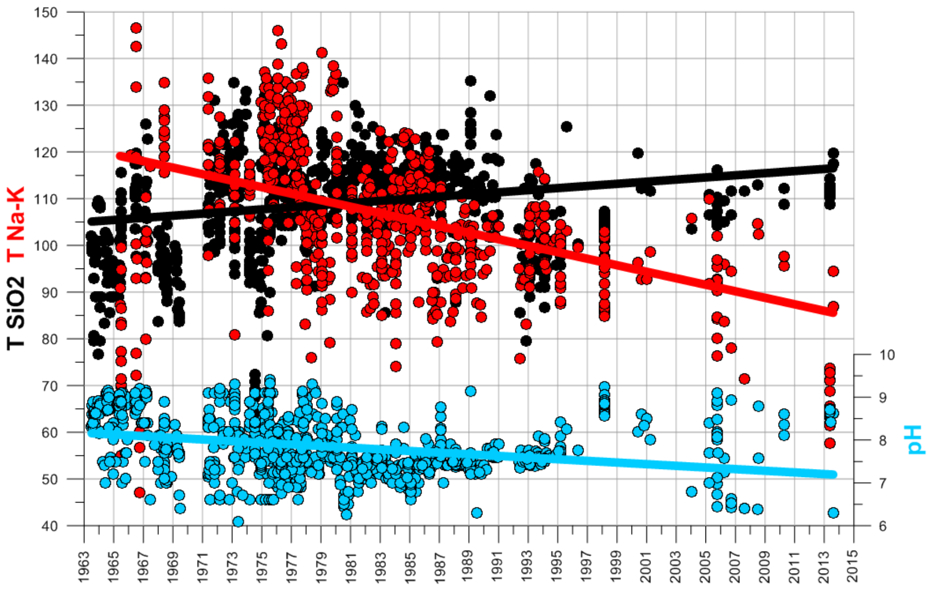

Fig. 1. Chemical history of the SR1 site Paratunsky geothermal field in terms of Na-K and SiO_2 geothermometers and pH.

5 The Mutnovsky high temperature geothermal reservoir

The Mutnovsky geothermal area is a part of the Eastern Kamchatka active volcano belt. Mutnovsky is 80 kY old, an aging strato-volcano (a complex of 4 composite volcanic cones), which acts as a magma- and water-injector into the 25-km-long North Mutnovsky extension zone [6]. Magmatic injection events (dykes) are associated with plane-oriented MEQ (microearthquake) clusters, most of whom occur in the NE sector of the volcano (2 x 10 km^2) at elevations from -4 to -2 km, while some magmatic injections take place at elevations from -6.0 to -4.0 km below the Mutnovsky production field. The Mutnovsky (Dachny) 260-310°C high-temperature production geothermal reservoir with a volume of 16 km^3 is at the junction of NNE- and NE-striking normal faults coincides with the current dominant dyke injection orientation. TOUGH2-modeling has been used to estimate the reservoir properties, including the deep upflow recharge of 80 kg/s with an enthalpy of 1420 kJ/kg. Modeling was used to reproduce the history of the Mutnovsky (Dachny) reservoir utilization since 1983 and shows that the predicted power is sensitive to local meteoric water influx during development.

Production geothermal well isotope(δD, $\delta^{18}O$) ratio data clearly indicate the following. 1. The melting glacier of the Mutnovsky volcano is the most probable water recharge area for the producing geothermal reservoirs in the Mutnovsky geothermal area, and 2. Some trends in isotope (δD, $\delta^{18}O$) ratios increases during the 12-year utilizationn period (5.5‰ in δD) may have been caused by heavy local groundwater infiltration into the producing geothermal reservoirs (which coincide with chloride dilution trend in production wells and adjacent hot springs). It is noteworthy that the Giggenbach (1988) geo-indicator plot (K/100, Na/1000, sqrt(Mg)) also shows some nonequilibrium trends in recent years for wells 048, Geo-1, 022, and 035 and thermal features. Chloride water dilution trend, which is similar to that in production wells, is observed in the Nizhne-Zhirovskoy hot spring, where chloride concentration declined from 120 to 80 ppm from 1985 to 2016. We do not discuss possible additional mechanisms of isotope (δD, $\delta^{18}O$) ratios enrichment here, since no indications of reinjected water return to production wells or significant production reservoir boiling have been observed recently. Sodium chloride hot springs in the Mutnovsky geothermal area (Nizhne-Zhirovskoy and Vilyuchinsky springs) seem to be a product of the separation of high-temperature geothermal fluids being recharged from the producing geothermal reservoir. Its isotope (δD, $\delta^{18}O$) ratios vary in the range −103‰ < δD < −99.9‰ and −15.7‰ < $\delta^{18}O$ < −13.4‰ (Nizhne-Zhirovskoy), and −104.3‰ < δD < −102‰ and −14.3‰ < $\delta^{18}O$ < −13.8‰ (Vilyuchinsky, well R27). If phase corrections (steam losses at an initial enthalpy of 1260 kJ/kg and atmospheric pressure) are applied, these springs (−111.3‰, −15.9‰) match the isotope (δD, $\delta^{18}O$) ratios of the Mutnovsky glacier melting water (−108‰, −14.9‰).

We also report the magmatic signs in the gas composition sampled in the Mutnovsky production wells and thermal features, especially in the production reservoir parts adjacent to the Mutnovsky volcano dyke injection zones. The $\delta^{13}C$ (CO_2) values in wells 022, 031, 035, A4, and R27 and thermal features Medvejy and Verkhne-Mutnovsky vary in the range −8.4‰ to −5.6‰, which is indicative of a magmatic origin for the CO_2.

6 The Pauzhetsky geothermal reservoir

The initial chemistry of the geothermal fluids produced is characterized by its NaCl and CO_2–N_2 concentrations, with a total dissolved solids concentration of 2.7–3.4 g/kg, and a non-condensable gas concentration of 0.04–0.08% (by weight). The stable isotope (δD, $\delta^{18}O$) ratios of the hot fluids correspond to the range determined in Kurile Lake waters (at 110 masl) and in the cold springs on the Kambalny Ridge (at 600–700m asl), which demonstrates their meteoric origin [7,8]. The fluid enthalpy versus chloride diagram [7] illustrates the integrated effect of reservoir fluid dilution and reservoir temperature decline during utilization. The chloride concentrations (Cl^-) were corrected to compensate for the steam loss. All fractions shown in the diagram originate from the geothermal source parent fluid, which was estimated to have a chloride concentration of 1600 ppm and an enthalpy of 870 kJ/kg (corresponding to 204 ◦C). The most diluted well waters are 106, 108, and RE1, where the meteoric water fraction is estimated to be 40–62.5%, and the fluid enthalpy drops to 680–730 kJ/kg. Wells 121, 122, 123 and 103 are less sensitive to meteoric water inflows; the dilution rate is estimated to be 30–39.5%, and the enthalpy decline to 740–850 kJ/kg. Wells GK3 and 120 indicate a dilution of 13–39.5%, with fluid enthalpies in the 790–890 kJ/kg range, and a relatively slow decline rate. Stable isotope data (δD, $\delta^{18}O$) and tritium data confirm a significant meteoric inflow into the geothermal reservoir during utilization.

Hence, the key feature of the Pauzhetsky field behavior is the cooling of the production wells, accompanied by a change in fluid chemistry and temperatures along streamlines which starts at the recharge areas. The cooling rates can be approximately correlated with the relative horizontal distances between the producing wells and the recharge areas, rather than the depths of the feed zones in the wells. For example, Wells 106, 108, and RE1, which are located closer to the recharge areas, show faster enthalpy and chloride declines than wells 121, 122, 123 and 103, which are farther away from the infiltration zones. The location of meteoric water inflows basically coincides with pre-utilization discharge areas, i.e. fractured and/or faulted zones that allow a hydraulic communication between the geothermal reservoir and the water-saturated alluvial deposits of the Pauzhetka River and tributary creeks. The pressure drop caused by utilization turned these areas into distinct infiltration/recharge zones in the northern, western, and eastern parts of the field, surrounding the production zone in the center. There is also a possibility that some abandoned, poorly cemented wells allow the inflow of shallow groundwater into the geothermal reservoir.

7 Conclusions

Mechanisms of Kamchatka geothermal reservoir functionality were studied by using isotope and geochemistry data: (1) The Geysers Valley hydrothermal reservoirs shows a key role of cyclic CO_2 inflow on geysers functionality; (2) The Paratunsky low temperature reservoirs recharge areas were indicated by water isotope data, while a chloride rise pointed to utilization-induced recharge from the west boundary, where a potential adjacent geothermal reservoir may exist; (3) The North-Koryaksky hydrothermal system is recharged by meteoric water from the Koryaksky volcano glaciers and magmatic CO_2, as revealed by isotopes of water and carbon-13 (in CO_2) data; (4) The Mutnovsky high temperature geothermal reservoir is initially fed by the water from the Mutnovsky volcano glacier, then utilization triggers a local meteoric water inflow (water isotope data, Cl^- transient data); (5) The Pauzhetsky medium temperature geothermal reservoir is significantly diluted by local meteoric waters, which used former discharge channels to flow in (Cl^- transient data).

We also mentioned SiO_2 and Na-K geothermometers as useful tools to predict temperatures in all the above mentioned reservoirs, but opposite time transient trends of these geothermometers (Paratunsky, Geysers Valley). This points to the necessity of using additional geothermeters in the future, such as more sophisticated methods relying on multicomponent water/mineral equilibria.

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