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Water-Methane Geothermal Reservoirs in a South-West Foothills of Koryaksky Volcano, Kamchatka

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ABSTRACT

The Ketkinsky geothermal reservoirs appears to be the product of magma and water injection from the Koryaksky volcano. Actual thermal supply may be carried out by magma injections in the form of sills in the depth range of -6 to -3 km abs. from the SW sector of the Koryaksky volcano. Water supply according to the isotopic composition of water is mixed: it is carried out through the structure of the Koryaksky volcano from above 2 km abs. and at the expense magmatic fluids. The system of the identified productive faults and magma fracking system is geometrically conjugated through some of the existing faults. Well E1 located above of the magma-hydrothermal connection above mentioned demonstrates water level change sensitivity to magma fracking events of Koryaksky volcano 2008-2009. Thus, Ketkinsky geothermal field appears to be the product of magma and water injection from the Koryaksky volcano.

1. INTRODUCTION

The Avachinsko-Koryaksky volcanogenic basin with an area of 2530 km2 includes 5 quaternary volcanoes (2 of which Avachinsky (2750 m abs) and Koryaksky (3456 m abs) are active), sub-basins of volcanogenic-sedimentary Neogene-Quaternary deposits up to 1.4 km thick (Fig. 1 and 2). The basin is located in a depression formed in the upper part of the basement of pre-Cretaceous age, characterized by a low temperature gradient of 24°/km. The basin foundation is composed of metamorphic rocks with low porosity and permeability in general, but local fractured zones are present, from which well tests yielded water inflows of up to 6 kg/s in the 1438-1490 m depth interval (well E1) (Posdeev, 2003). The average thermal conductivity of Cretaceous-age rocks is 2.8 W/m/°C. The Neogene-Lower Quaternary aquifer complex is composed of pyroclastic and volcanogenic-sedimentary formations. The porosity values are rather high: 0.36÷0.48, specific well flow rates are up to 0.01 l/(s-m) (wells GK-1, Pinachevskaya). The aquifer complex of the Pinachevo extrusive massif Q_{1-2} is composed of andesite and rhyolite extrusions and includes vent formations of andesites, dacites and rhyolites (thickness >200-500 m). According to laboratory studies, the porosity is 0.12, permeability 24 mD. Nested artesian-volcanogenic basin (AVB) includes water-bearing complex of water-glacial formations: Holocene alluvial deposits, Upper Pleistocene-Holocene marine and alluvial-marine horizons, Upper Pleistocene glacial and water-glacial complex, water-bearing Holocene proluvial and deluvial-proluvial complex. According to the well testing data of the Bystrinsky groundwater deposit, the permeability range is from 10 to 3000 mD. Koryaksky and Avachinsky volcanoes (Q_{3-4}) composed of andesibasalts and basalts form the groundwater supply area of the volcanogenic basin (Kiryukhin, Kiryukhin and Manukhin, 2010).

In terms of the gas composition, the basement fluids of the volcanic basement (except for the northern slope of Koryaksky volcano) are characterized by the ubiquitous distribution of methane (about 70 vol.%) found in the wells of the Ketkinsky geothermal field, along the south-eastern periphery of the Pinachevo extrusive massif (well GK1, Pinachevo springs), south-west of the Koryaksky volcano (well E1), and wells in the Radyginskaya area (well R3).

Natural groundwater discharges with elevated water salinity in the area of the Ketkinsky geothermal field - Zelenovskoye lakes south-west of Koryaksky volcano were known (Maltseva et al., 2011). Geo-electrical survey carried out (Netesov, 1984) have been revealed one of the isolated high conductivity 13 to 20 Ohm-m column-shaped geophysical anomalies in the Zelenovsky Lakes area was completed by drilling in 1986. Well 23, 341 m deep, brought thermal waters to the surface (self-discharging flow rate of 9.3 l/s, water temperature at the wellhead of 57°C, overpressure of 0.73 ati.

2. MAGMA REACKING SYSTEMS IN SW SECTOR OF KORYAKSKY VOLCANO

Most of injections of magma beneath of the Koryaksky volcano occurred at depths of -3.0 ÷ -5.5 km abs near its south-western foot within a distance less than 1.5-4.0 km from the summit (July 2008-January 2009). Additional Frac-Digger analysis of MEQ's data (KB GS RAS data) from 01.2000 to 10.2019 with the search parameters ($\delta t \leq 30$ days, $\delta R \leq 6$ km, $\delta Z \leq 0.2$ km, $N \geq 6$) revealed a set of magma injections shapes (fig. 1 and 2, Table 1). This set includes eleven flat dikes/sills with dip angles less than 26 degrees at the depths from -6.0 to -3.2 km abs. (time of their injection August 2008 - August 2009). The apparent length in the vertical cross-section is up to 4 km (sill #49). The dip azimuth some of these sills is oriented in the NE direction, which means that permeable thermally conductive faults may form on their continuation towards the Ketkinsky productive geothermal reservoir, provided that the magmatic activity of the Koryaksky volcano is carried out for a long geological time (hundreds to thousands of years) in a similar geomechanical regime.

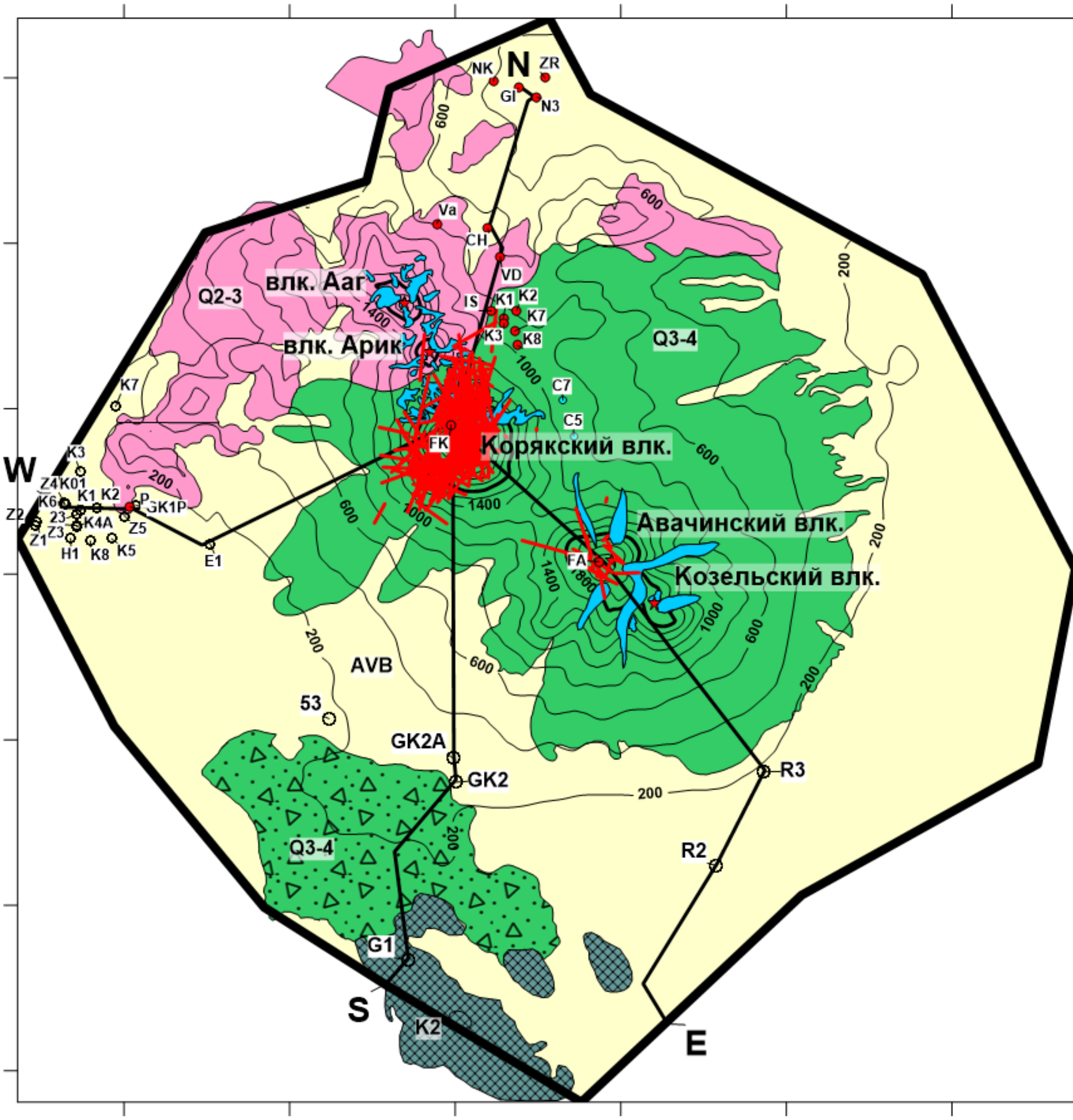

Figure 1. Schematic geological map of the Koryaksky-Avachinsky volcanogenic basin (Kiryukhin, 2020). Geological divisions: K2 - basement rocks of Cretaceous age, N-Q1 - volcanogenic-sedimentary Neogene-Quaternary deposits, $Q_{2\text{-}3}$ - sub-basin of Pinachevsky extrusions, AVB - artesian-volcanic basin, $Q_{3\text{-}4}$ - Avachnsky, Koryaksky, Kozelsky volcanoes and volcanic eruption products near Petropavlovsk-Kamchatsky. Traces of injections of dikes in the period from 2008 to 2019 at an altitude of -3500 m are shown by red lines. Thermal mineral springs (shown by shaded circles): K1, K2, K3, K7, K8 - Koryaksky Narzans, IS - Izotovsky, VD - Vodopadny, CN, CH - Chistinsky, Va - Vakinsky, N3 - Nalychevsky (Luzha-3), GI - Ivanov Griffon, NK - Nalychevsky Boiler, ZR - Zheltorechensky, P - Pinachevsky. Cold springs: C5 and C7. Wells are shown uncolored circles with corresponding numbers. WE and SN are geological section lines. The axis markings are 10 km.

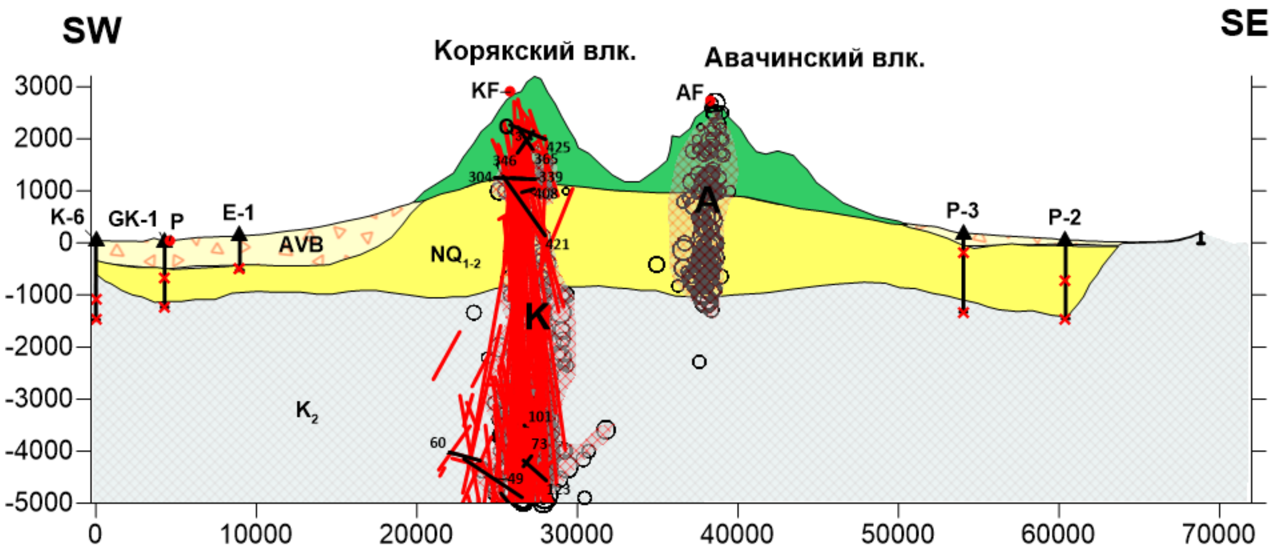

Figure 2. Geological section of the Avachinsky-Koryaksky volcanogenic basin along a southwestern to southeastern line (SW-SE, section position shown in Fig. 1) (Kiryukhin, 2020). The section shows wells with zones of methane water inflow, and the geometry of the magmatic feeding systems of volcanoes (reservoirs K and A) is shown by crosshatching. Circles - hypocenters of local earthquakes in 2009. (KB GS RAS). Additionally, red lines show injections of dikes and sills in the period from 2008 to 2019 in the vertical section of well Z1 - FK (see Fig. 1). Dykes/sills with dip angles up to 30° are shown in black and marked by numbers. Sills #60 and #49 may be involved in the formation of thermally feeding faults for the Ketkinsky geothermal field, given that the water recharge area is elevated parts of the Koryaksky and Avachinsky volcanoes (This figure from Kiryukhin, 2020).

Table 1. Calculated (Frac-Digger) low angle magmatic injections (sills/dykes) in SW sector of Koryaksky volcano.

##	Dip angle (°)	Dip Azimuth (°)	Depth, masl	DATE	ML	## of MEQ's
49	12.9	103.7	-4517	11.08.2008	1.8	12
60	17	2.7	-3352	30.09.2008	1.8	25
73	22.9	274.7	-4829	27.10.2008	1.45	7
76	15.1	147.1	-6000	31.10.2008	1.95	6
80	23.9	21.1	-3590	13.11.2008	1.9	20
85	22.9	51.1	-4300	27.11.2008	2.4	8
101	25.8	92	-3263	30.01.2009	1.45	9
123	19.6	36.4	-4084	22.03.2009	1.6	17
147	8.7	271.8	-5243	30.04.2009	1.65	15
159	19.6	142.2	-3295	24.05.2009	1.45	12
192	18.7	178.4	-3244	26.08.2009	1.55	8

3. PRODUCTION FAULTS SYSTEM OF KETKINSKY RESERVOIR

To identify productive faults, the program Frac-Digger2 (RU reg. ## 2017618050) is used, which allows identifying plane-oriented clusters of productive zones of wells. The following criteria are used to sample elements of plane-oriented clusters: 1) Proximity in horizontal plane δR; 2) Proximity to plane orientation δZ (distance between sample element and plane); and 3) Minimum number of elements in a plane-oriented cluster N. In the FRAC-Digger2 program, sampling from the set of points in the 3D spatio-temporal domain is performed randomly (using the Monte Carlo method). This allows to avoid dependence of the solution on the ordering of the initial set of points by time, which is extremely important for 3D analysis of productive zones distribution and identification of productive faults. When searching for K elements from a list consisting of N elements, the maximum number of unique generations C_K^N is limited by the iteration time, so several program runs are performed to confirm the validity of the identified productive faults.

During calculations of productive zones of Ketkinsky geothermal field the following calculation parameters were accepted: δR=4 km, δZ=100 m (50 m), N=6. Depths of productive zones roof penetrations were used as initial data (according to Ketkinsky geothermal field well catalog, taking into account deviation of wells 4A and 8), 87 zones in total. As a result, three production faults were identified; their characteristics are given in Table 2.

Table 2. Calculated (FRAC-Digger2) characteristics of production faults of Ketkinsky geothermal field (δR=4 km, δZ=100 m, N=6, run 20).

##	Dip angle (°)	Dip Azimuth (°)	Depth, masl	## of prod.	Area,	Total rate, kg/s
1	76	38.1	-641	39	1.76	60.5
2	77	109.8	-553	19	0.49	43.3
3	24.3	139.1	-680	10	3.95	17.9

4. KETKINSKY RESERVOIR – KORYAKSKY MAGMA FRACKING SYSTEM CONNECTION

Now we can combine information on magma fracking system beneath Koryaksky volcano with production fault system of Ketkinsky geothermal reservoir into a single 3D view, where we can see a link between magma and hydrothermal systems, if production fault #3 plane (Table 2) will be extended deep in NE direction to meet magma fracking sill #49 (Table 1) (Fig. 3).

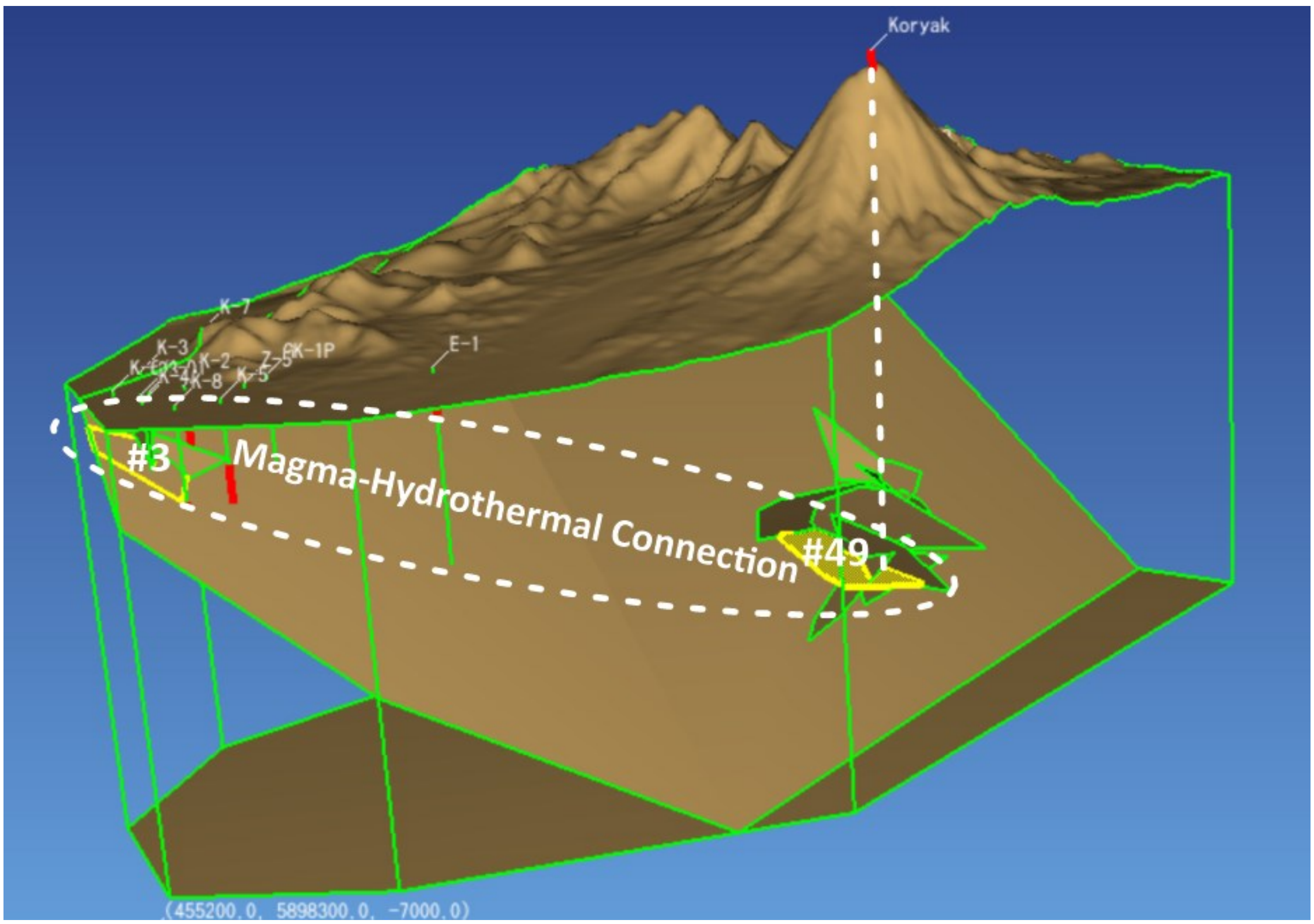

Figure 3. 3D representation of magma fracking system (low angle sills/dykes are shown only) beneath Koryaksky volcano (Table 1) and production faults in Ketkinsky geothermal reservoir (Table 2). There is a rather good geometrical consistency of the two fracture systems mentioned above, in spite they are from 20 to 25 km apart. Thus, a magma-hydrothermal connection of the production reservoirs between those systems are possible.

5. WELL E-1 SENSITIVITY TO MAGMA FRACKING EVENTS

Well E1 was drilled in 1984 to 3003 m depth and after conducting geophysical and hydrogeochemical tests is used for regime observations to search for hydrogeodynamic earthquake precursors. Well E1 is located at a distance of 17 km from the top of Koryaksky volcano above magma-hydrothermal connection zone shown in a Fig. 3. Drilling data in the interval of 0-570 m revealed the Quaternary gravel-pebble deposits, in the interval of 570-665 m - tuffs of Alanei series of Neogene (Nal). In the zone of low water inflow at 625-

647 m, the casing was perforated and an artificial bottom hole was made at 665 m. Casing of the wellbore was made with metal casing with diameter of 219 mm. The water level in the well was established at a depth of about 28 m.

Groundwater in the interval of 625-647 m belongs to the hydrodynamic zone of complicated water exchange due to the structural position of the Alnei volcanic sequence. Gas-hydrochemical parameters of groundwater also indicate relatively stagnant conditions of their formation. During drilling the well in the area of tuffs of the Alneiskaya series at a depth of 570-1060 m, chemical analysis of dissolved gas in water was carried out: N_2 - 60 vol. %, CH_4 - 29 vol. %, O_2 - 10 vol. %, Ar - 0.6 vol. %, CO_2 - 0.3 vol. %, H_2 - 0.2 vol. %, heavy hydrocarbons (from C_2H_4 to C_6H_{14}) - 0.02 vol. %, He - 0.006 vol. % (data of the Central Chemical Laboratory of the Institute of Volcanology of the FEB RAS). The obtained composition of dissolved gas is characterized by excessive concentrations of methane and other hydrocarbon gases compared to the gas dissolved in water and in equilibrium with atmospheric air. This indicates that there is generation or transportation of nitrogen-hydrocarbon composition gas in the area of the borehole in the Alanei volcanics.

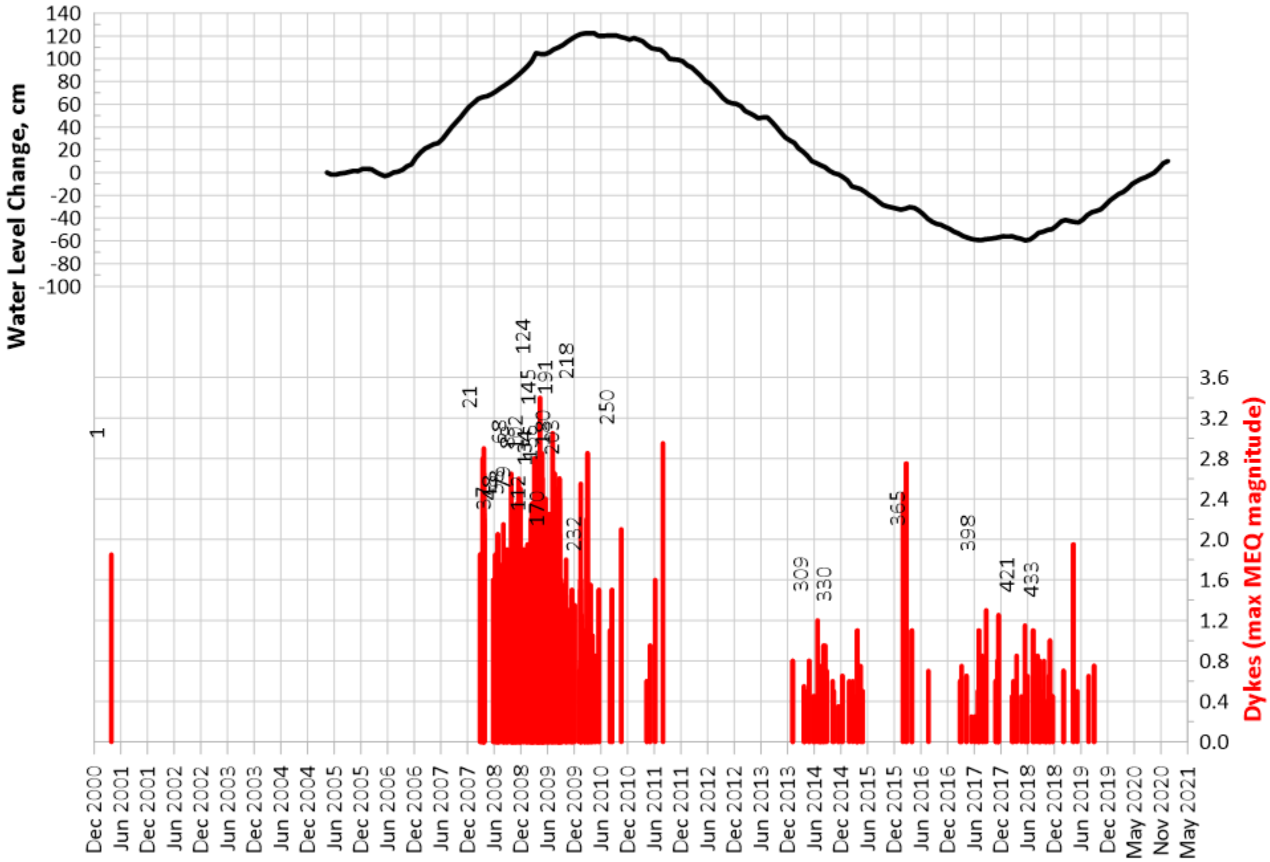

Figure 4. Water level change in well E1 (in cm, barometric compensated) (Kopylova, Boldina, 2012, Voronin, Kopylova 2020) vs of magma injection events beneath Koryaksky volcano http://www.gsras.ru/new/infres.

Water level in well E1 seems to be closely synchronized with magma injection rate beneath of Koryaksky volcano (Fig. 4). Time of Koryaksky vocano activation in 2008-2009 was associated with 1.2 m water level rise in the well E1. In order to assess the possible contribution of the gas lift effect to the observed changes in the level of well E-1, TOUGH2-EWASG isothermal (10°C) simulation was performed. 1D model geometry used: the wellbore from the wellhead to the bottom at the depth of 100 m is represented by a vertical column consisting of 100 high permeability and large porosity elements (1e-8 m^2, 0.99). At the top of the model a constant pressure 1 bar discharge conditions was assigned (0.5 m depth well on deliverability with PI=1e-8 m^3 and P=1 bar). At the bottom of the model gas and water inflow was assigned (constant (0.1 kg/s/m^2 of gas and 0.00133 kg/s/m^2 of water) for gravity equilibrium runs, and 2-year cycling (from 0.02 to 0.18 kg/s/m^2 of gas and from 2.66e-4 to 2.39e-3 kg/s/m^2 of water) for transient run. Gravity equilibrium with water level -28 m was obtained in the model before running transient conditions for 20 years. Modeling results shows 2 m of water level annual cycling response to cyclic input of CH_4 rate at the well bottom. For monitoring well E1 conditions that means that additional 2.5 g/s (3.5 l/s) bottom hole inflow of CH_4 yields 1 m of water level rise. Thus, well E1 may be sensitive to magma fracking events of Koryaksky volcano in terms of water level rise to magma degassing and pressurizing of adjacent geofluid reservoirs.

6. DISCUSSION/CONCLUSIONS

1. While in the range of drilling by wells to a depth of 2.4 km the axis of thermo-anomaly dips in the SSE direction, the gradients of fluid pressure and gas content CH_4 (thermogenic origin) are directed to the NEE. Thus, Ketkinsky geothermal field appears to be the product of magma and water injection from the Koryaksky volcano.

2. Thermal supply may be from magma injections in the form of sills in the depth range from -6 to -3 km abs. in the SW sector of the Koryaksky volcano and heat mining from host rocks too. Water recharge according to the isotopic composition of water is mixed: it is meteoric waters from elevated parts of the Koryaksky volcano and magmatic component water observed too.

3. Koryaksky-Ketkinsky magma-hydrothermal connectivity is also confirmed by: (1) The system of the identified productive faults is geometrically conjugated with some of the magma fracking shapes; (2) Well E1 located above magma-hydrothermal connection zone shows sensitivity to the magma fracking events beneath Koryaksky volcano.

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