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Origin of Water in the Mutnovsky Geothermal Field: An Oxygen (^{18}O) and Hydrogen (D) Study

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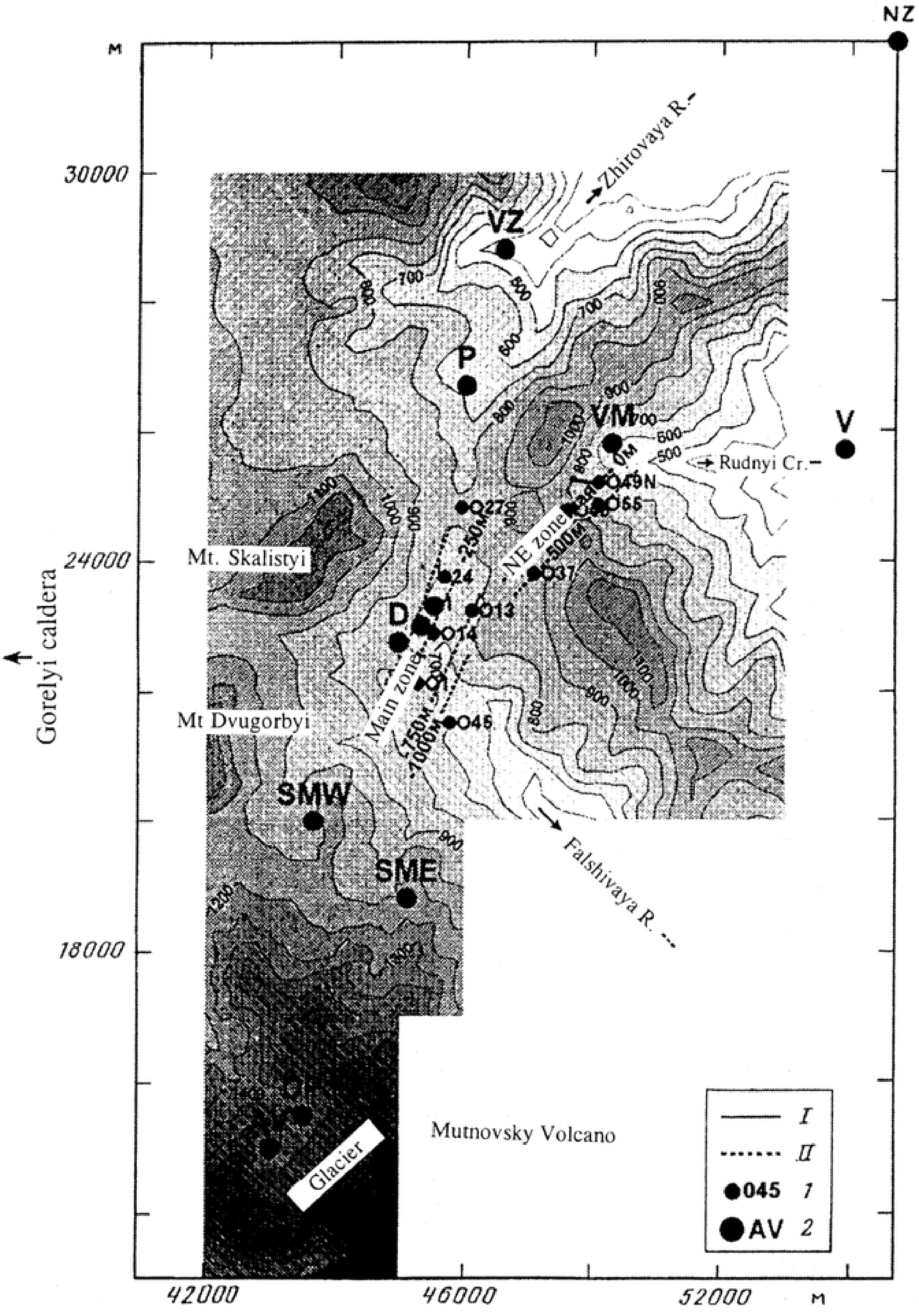
Isotopic analyses of fluids from the wells drilled in the Mutnovsky geothermal field revealed that the water of a melting glacier in the crater of Mutnovsky Volcano might be a source of water supply to the Dachnyi and Verkhne-Mutnovsky reservoirs of the geothermal field.

INTRODUCTION

The production developments of the Mutnovsky geothermal field (12 MW in 1997, 80 MW in future) are intended to be carried out simultaneously with the isotope monitoring, D, T, and ^{18}O, to monitor changes of water replenishment and the effects of pumping the used water back into the reservoir in order to optimize the production.

For this purpose, samples were collected from the wells, cold springs, and meteoric water in the Dachnyi reservoir area during production tests in 1986–1990 [2], [5], [6], [8], and recently in 1995–1996 in the Dachnyi (Well 014) and Verkhne-Mutnovsky areas of the Mutnovsky geothermal field, where new production wells had been drilled (048, 049N, and 055) in connection with the construction of a pilot power plant (12 MW) (Fig. 1).

The results of the isotopic study of these samples are used here to describe the initial hydroisotopic states of the reservoirs.


NZ
M
30000
24000
18000
42000
46000
52000
M
Gorelyi caldera
Zhirovaya R.
VZ
P
VM
V
Rudnyi Cr.
Mt. Skalistyi
Mt Dvugorbyi
D
027
24
1
013
014
037
049N
065
045
NE zone
Main zone
-250M
-500M
-750M
-1000M
SMW
SME
Falshivaya R.
Glacier
Mutnovsky Volcano
700
800
900
1000
600
500
1200
I
II
045 1
AV 2

METHODS OF STUDY

Samples for isotopic and chemical analyses were collected from Well 049N during a long production test (November 11, 1995, to May 7, 1996) with a discharge of 13 kg/s and enthalpy of 1260 kJ/kg, from Well 014 drilled into the Dachnyi reservoir (which had been producing since 1988 with a discharge of 8 kg/s), and from Well 048 during short production tests (Tables 1 and 2).

Table 1 includes the results of chemical analyses for some other wells of the Mutnovsky geothermal field. All samples of hot water from the wells were collected from the liquid portion of a liquid–vapor mixture, separated using a James separator under atmospheric conditions.

Table 3 lists isotopic data for the samples of fresh snow and cold springs that we collected in 1996 and 1998.

The chemical and isotopic analyses of the samples were made in the Department of Geothermal Research, Geological Survey of Japan. Chemical analyses were also made in the Institute of Volcanology, Petropavlovsk-Kamchatsky. In addition to these results, we used many data on D, ^{18}O, and T available in the literature [1], [2], [6], [8] (Table 4).

RESULTS

Following Arnason [3], we used the following correction for isotope fractionation (steam loss):

$$\delta_0{}^{18}\mathrm{O} = \delta_L{}^{18}\mathrm{O} - 0.975(t_0/100 - 1), \tag{1}$$

$$\delta_0 \mathrm{D} = \delta_L \mathrm{D} - 4.63(t_0/100 - 1), \tag{2}$$

Figure 1 Map of Mutnovsky geothermal field: *I* – ground surface contour lines, m (abs.); *II* – contour lines (−750, −250, and +250 m, abs.) of the surfaces of the productive zones penetrated by wells in the Dachnyi area (Wells 045, 01, 014, 016, 1, 029W, 013, and 24 – Main productive zone [5]), and a contour line (0 m abs.) of the surfaces of the productive zones in the Verkhne-Mutnovsky reservoir (Wells 037, 048, 055 and Perevalnye hot springs – NE productive zone [5]); *1* – wells, *2* – hot springs: AV – active hydrothermal site in Mutnovsky crater, DP – Donnoe site in Mutnovsky crater, SMW – North Mutnovsky (Western) hot springs, SME – North Mutnovsky (Eastern) springs, D – Dachnyi springs, VM – Verkhne-Mutnovsky springs, P – Pirate springs, V – Voinovsky springs, VZ – Verkhne-Zhirovaya springs, NZ – Nizhne-Zhirovaya springs.

Table 1 Chemical compositions (mg/l) of fluids from wells in Mutnovsky geothermal field (after separation under atmospheric conditions) and calculated temperatures, °C.

Date	Well no.	Enthalpy, kJ/kg	SiO_2	Na^+	K^+	SO_4^{2-}	Cl^-	TDS*	T_{SiO_2}	$T_{Na\text{-}K}$	Cl/SO_4
11.1991	045**	2320	890	320	70.0	90	435	1805	311	291	4.83
08.1988	01	1500	1340	230	54.0	100	306	2030	304	303	3.06
09.1988	014	2050	666	247	46.0	182	238	1379	280	266	1.31
09.1995	014	-	-	226	39.1	120	242	-	-	255	2.00
09.1988	1	1450	1050	247	49.0	192	240	1778	279	276	1.25
09.1988	24	1400	1002	247	49.0	235	218	1751	274	276	0.93
07.1993	037	1665	742	243	41.3	134	244	1406	291	253	1.82
07.1996	048	1506	-	259	49.4	129	261	-	-	270	2.04
07.1993	049H	-	965	250	42.5	154	237	1659	270	253	1.54
12.1995-05.1996***	049H	1260	-	256	49.5	129	260	-	-	270	2.01

Note. Analyses of 1988–1993 were made in the Central Chemical Laboratory of Institute of Volcanology, analyst V. K. Marynova. Analyses of 1995–1996 were made in the Geological Survey of Japan, analyst M. Takahashi. Samples of 1986–1996 (except from Well 045**) were collected by A. V. Kiryukhin, samples of 1995–1996, by A. V. Kiryukhin, A. Yu. Polyakov, and M. D. Lesnykh.

* TDS – total salinity.

** after N. P. Asaulova, *Report on Exploration after Back Pumping in Mutnovsky Geothermal Field (1988–1993)* (Termalnyi Village: Kamchatgeolkom Files, 1994).

*** Average of 11 samples collected from December 1995 to May 1996.

Table 2 Isotopic compositions of fluids from wells in Mutnovsky geothermal field (after separation under atmospheric conditions).

Sample no.	Date	Well no.	δD, ‰	δ^{18}O, ‰	Enthalpy, kJ/kg	δD, ‰ (formula (4))	δ^{18}O, ‰ (formula (3))
MK96-1	13.12.1995	049-H	−100,9	−11,91	1260	−109,3	−13,68
MK96–1	13.12.1995	049-H	−101,5	–	1260	−109,9	–
MK96-2	20.12.1995	049-H	−102,1	−12,28	1260	−110,5	−14,05
MK96-2	20.12.1995	049-H	−101,9	–	1260	−110,3	–
MK96-3	27.12.1995	049-H	−101,5	−12,19	1260	−109,9	−13,96
MK96-5	14.02.1996	049-H	−101,3	−12,23	1260	−109,6	−14,00
MK96-7	22.02.1996	049-H	−102,0	−12,34	1260	−110,2	−14,11
MK96-9	28.02.1996	049-H	−101,9	−12,31	1260	−110,3	−14,08
MK96-11	10.03.1996	049-H	−101,1	−12,37	1260	−109,5	−14,14
MK96-12	18.04.1996	049-H	−101,5	−12,16	1260	−109,9	−13,93
MK96-13	24.04.1996	049-H	−101,5	−12,27	1260	−109,9	−14,04
MK96-16	1.05.1996	049-H	−101,7	−12,31	1260	−110,1	−14,08
MK96-17	7.05.1996	049-H	−101,2	−12,35	1260	−109,6	−14,12
MK96-21	28.07.1996	048	−101,3	−12,25	1500	−112,2	−14,51
MK96-22	10.08.1995	014	−98,4	−11,34	2050	−114,7	−14,77
MK96-23	1.09.1995	014	−96,8	−11,17	2050	−113,1	−14,60
MK88-51	2.08.1988	01	−102,0	−12,8	1500	−112,8	−15,07
MK88-86	2.07.1988	1	−104,0	−13,0	1450	−114,3	−15.17
MK88-129	9.09.1988	24	−106,0	−13,0	1400	−115,8	−15.06

Note. Samples were collected by A. V. Kiryukhin, A. Yu. Polyakov, and M. D. Lesnykh (Institute of Volcanology). Specimens MK96-1 to MK96-23 were analyzed by M. Takahashi (Geological Survey of Japan). Specimens of Sample MK88 were analyzed by V. A. Polyakov and V. Bobkov (VSEGINGEO, Moscow).

where $\delta_0{}^{18}$O and δ_0D are the initial values of D and ^{18}O; $\delta_L{}^{18}$O and δ_LD are the D and ^{18}O values obtained after a single-act separation under atmospheric conditions; t_0 is the initial fluid temperature.

In the case of boiling, taking into account heat transfer between the fissures and blocks, which resulted in the additional heating of the fluid, formulas (1) and (2) were modified:

$$\delta_0{}^{18}\mathrm{O} = \delta_L{}^{18}\mathrm{O} - 0.2105 \cdot 10^{-2}(h_0 - 419.4), \tag{3}$$

$$\delta_0 \mathrm{D} = \delta_L \mathrm{D} - 0.9996 \cdot 10^{-2}(h_0 - 419.4), \tag{4}$$

where h_0 is the enthalpy of the operating well, from which a given sample had been collected. To avoid D and ^{18}O overestimation, we used the modified formulas (3) and (4).

Table 2 lists the isotopic compositions of fluids from the wells corrected for steam loss. Tables 3 and 4 give the isotopic compositions of meteoric waters from the Mutnovsky area. Figure 2 summarizes the data presented in Tables 2, 3, and 4. All samples of high-temperature fluids from the wells fall in the ranges of $-13.6‰ < \delta^{18}$O $< -15.2‰$ and $109.3‰ < \delta$D $< -115.8‰$ in the D$-^{18}$O diagram.

Table 3 Isotopic compositions of meteoric waters in Mutnovsky geothermal field.

Sample no.	Date	Sample site	δD, ‰	$\delta^{18}O$, ‰
MK96-4	10.02.1996	Dachnyi area (snow)	–105,0	–15,04
MK96-6	19.02.1996	»	–163,4	–21,91
MK96-8	26.02.1996	»	–76,8	–13,55
MK96-10	4.03.1996	»	–146,8	–19,46
MK96-14	24.04.1996	»	–72,6	–10,68
MK96-19	29.05.1996	»	–100,3	–13,84
MK96-20	31.05.1996	Verkhne-Mutnovsky (snow)	–100,3	–12,07
MK96-24	17.08.1996	Verkhne-Mutnovsky Creek	–87,6	–12,10
MK88-157	08.1988	Dachnyi Creek	–99,0	–14,1

Note. Samples were collected by A. V. Kiryukhin, A. Yu. Polyakov, and M. D. Lesnykh (Institute of Volcanology). Specimens of Samples MK96 were analyzed by M. Takahashi (Geological Survey of Japan), Sample MK88, by V. A. Polyakov and V. Bobkov (VSEGINGEO, Moscow).

Table 4 Isotopic composition of meteoric water in Mutnovsky geothermal field [8].

Sample no.	Дi Date од)	Sample site	δD, ‰	$\delta^{18}O$, ‰
T1	08.1983	Falshivaya R.	–89	–13,6
T2	08.1983	Well T39	–100	–14,3
T3	08.1983	Creek in Northwestern geothermal field	–84	–12,6
T4	08.1983	Vulkannaya R.	–91	–14,1
T5	08.1983	Creek in Falshivaya R. canyon	–87	–13,7
T6	04.1983	Well V-8	–96	–12,7
T7	08.1983	Creek in Mutnovsky crater	–101	–14,4
T8		Gorelyi Volcano (snow)	–76	–12,1
T9	04.1983	Dachnyi Area (snow)	–83	–12,9
T10	08.1983	Dachnyi Area (rain)	–82	–11,0
T11	07.1982	Creek from Mutnovsky glacier	–124	–17,4

The initial meteoric waters that control the water replenishment of the hydrothermal system and defined as the intersection of the meteoric water and hot fluid lines have the following isotopic composition:

$$\delta\,^{18}O,\delta D) = (-15.7\text{‰}, -115\text{‰}).$$

The fluids of the Verkhne-Mutnovsky reservoir (Wells 048 and 049N) showed a positive shift ($\sim 1.5\text{‰}\ \delta^{18}O$) compared to the fluids from the Dachnyi reservoir (Wells 01, 1, and 24). This may indicate that the Verkhne-Mutnovsky fluids were stored in the geothermal reservoir for a longer time compared to the fluids of the Dachnyi reservoir. The meteoric water samples showed a significant meteoric water line scatter which is particularly high for the samples of rain and snow water:

$$(\delta\,^{18}O,\delta D) \subset (-21.77 \ldots -10.61\text{‰}),\ (-163.4 \ldots -62\text{‰}).$$

(A possible explanation of this might be a transfer by very strong winds that blow in the area of the Mutnovsky geothermal field.)

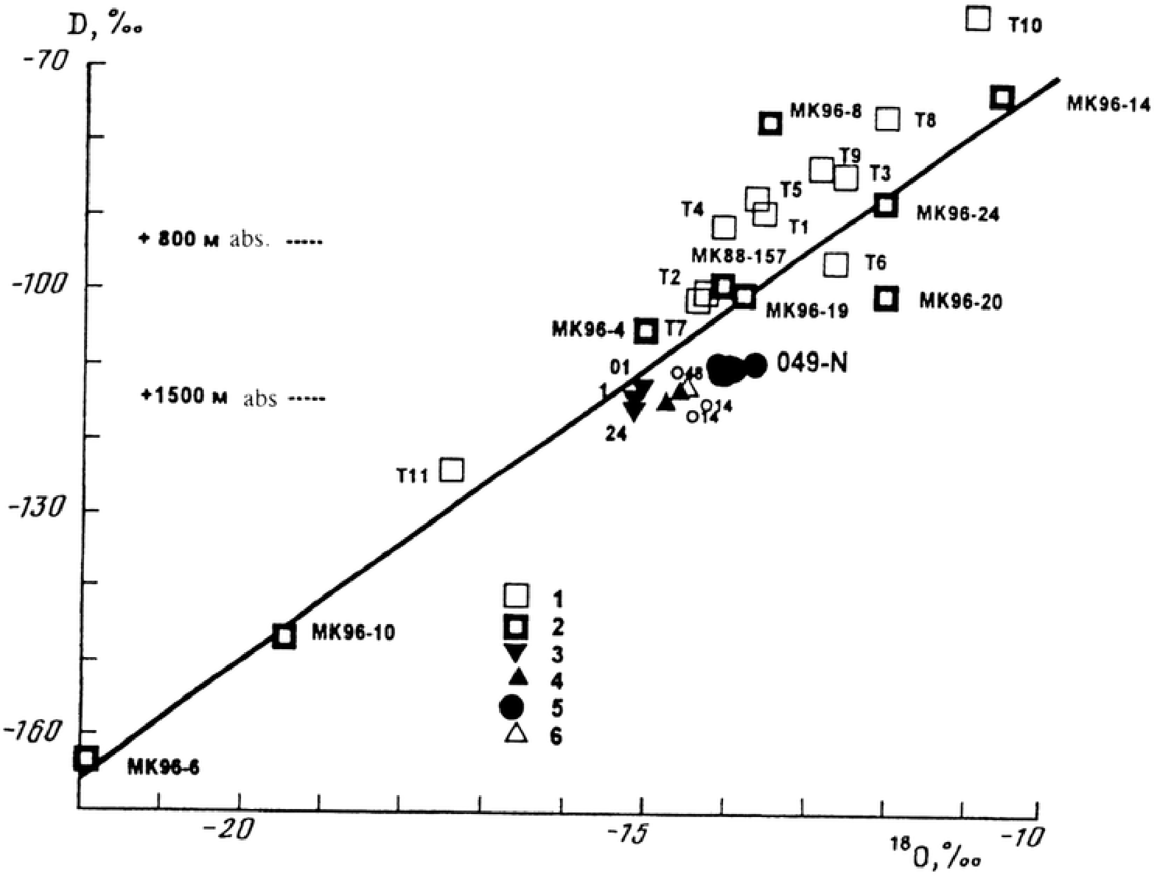


Figure 2 Distribution of D and ^{18}O in waters of the Mutnovsky geothermal field: 1 - meteoric water [8], 2 - meteoric water, 3 - Wells 01, 1, and 24 in Dachnyi area [6], 4 - Well 014, Dachnyi area [6], 5 - Well 048, Verkhne-Mutnovsky area, 6 - Well 049-N, Verkhne-Mutnovsky area.

Scatter is considerably lower for meteoric water from cold springs and creeks, which gave the following averaged snow–rain distribution:

$$(\delta\,^{18}O, \delta D) \subset (-17.4 \ldots -12.0‰), \; (-124 \ldots -84‰).$$

Our analysis of the chemical and isotopic (δD, $\delta^{18}O$) variations of fluid that flowed from Well 049N during a production test of December 1995–May 1996 (Table 1) did not reveal any perceptible regular variations during the observation period (Fig. 3).

DISCUSSION OF RESULTS

The fact that the isotopic compositions of meteoric waters in the Dachnyi and Verkhne-Mutnovsky areas were found to vary in the range of $\delta^{18}O$, $\delta D \subset (-14.3 \ldots 12.0‰)$,

(−100 ... −87‰), with the average values being $\delta^{18}O = -13.5‰$ and $\delta D = 93.5‰$, suggested them to be more heavy than the fluid from the wells. This means that the region of the water source of the geothermal fluid has an absolute height exceeding +800 ... +900 m. B. Arnason [3] reported a D decline of 3‰ with a 100-meter rise for the hydrothermal systems of Iceland. If this relation is valid for Kamchatka, the potential source of water supply to a geothermal reservoir must be at a height of +1500 m above sea level to be compatible with the observed data.

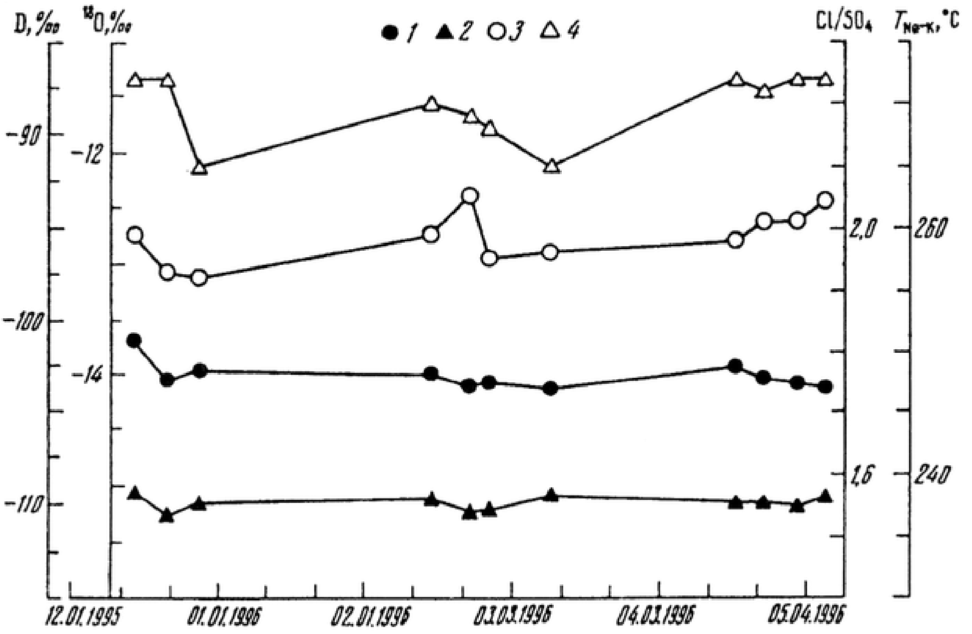


Figure 3 Variation of D, ^{18}O, Cl/SO_4, and T_{Na-K} in Well 049-N (*1, 2, 3,* and *4*, respectively).

Another necessary restriction for the source of water supply is a low tritium concentration. The deep wells of the Mutnovsky geothermal field show averagely 2.7 TU, even though the average value for meteoric water is 15.1 (1986–1988) [5]. The rather high actual flow rates in the geothermal reservoir (16–28 m/day [5]) indicate that even with a path of 15–20 km for the fluid flow from the source region to a geothermal reservoir, the fluid stay in the system must not be larger than 3.5 years, and the initial tritium concentration must not change substantially, tritium half-life being 12.33 years. In this context, a possible water source may be a glacier in the crater of Mutnovsky Volcano, the melting portion of which ranges between +1500 and +1600 m above sea level and can serve as a potential source of comparatively low-tritium water. Although the Vulkannaya River flowing from this crater was not found to be 100% "sterile" in terms of tritium content (a sample collected in 1986 yielded 12 TU, analyst V. V. Romanov, Institute of Water Management, USSR Academy of Sciences), it should be taken into account that this water is the product of glacier melting, diluted by precipitation water.

Thanks to a significant heat flow, a substantial portion of which is the conductive heat emission from the hot ground surface in the crater, the melting volume is large enough to feed the Vulkannaya River with a flow rate of 150–1500 kg/s and account for the 55-kg/s flow rate of the total ascending hot water flow (estimated by modeling for the reservoirs concerned [7]).

Another volcanic massif of the area is Gorelyi Volcano having a height of 1812 m. Although its roughly 8-km^2 area is situated at a height of +1500 m, the peripheral area of the caldera floor has a height of c. +1000 m and is tilted southward, where it is drained by the Mutnaya River. There are powerful cold springs where the Osvistannaya River flows from the Mutnaya. These springs are known as Kubovye and discharge a few cubic meters of cold water per second containing 17 TU (a sample collected in 1986 and analyzed by V. V. Romanov from the institute mentioned above). This suggests that the Gorelyi caldera does not contain any significant potential water sources with a low tritium concentration (there are no large glaciers in it).

The highest of the other mountains in the area, Mount Skalistaya and Mount Dvugorbaya, have absolute heights below +1500 m, do not have glaciers on them, and cannot be potential water sources for the Mutnovsky Geothermal field.

In theoretical terms of the origin of hydrothermal systems, we still have to find an answer to the question: What are the regions of water supply to these systems? Are they slopes of volcanic cones measuring tens of square kilometers in area, or local zones where magmatic–hydrothermal systems crop out (volcanic craters)? Actually, it is possible to pump 55 kg/s of water into a geothermal reservoir through a well with a diameter of 168 mm (0.022 m^2). A "hole" of this cross-sectional area can well be visualized under the melting glacier in the Mutnovsky crater.

CONCLUSIONS

1. The results of this isotopic study (δD, δ^{18}O, T) revealed that the region of water supply to the Dachnyi and Verkhne-Mutnovsky reservoirs of the Mutnovsky geothermal field must be located at an absolute elevation of c. +1500 m and that the water must be low in tritium. These conditions are satisfied by the melting glacier in the crater of Mutnovsky Volcano. Less suitable is the caldera of Gorelyi Volcano.

2. The isotopical (δD and δ^{18}O) and chemical (Cl/SO_4 and T_{Na-k}) data obtained during a Well 049N production test (December 1995–May 1996) did not show any substantial seasonal variations in the Mutnovsky hydrothermal system during that observation period.

3. The utmost understanding of a water source for the Mutnovsky geothermal field calls for more isotopic (D, T, ^{18}O) monitoring.

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