PROCEEDINGS, Thirty-Second Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 2007
SGP-TR-183

OUTPUT OF THERMAL ENERGY FROM MUTNOVSKY VOLCANO (KAMCHATKA) AND THERMAL FEEDING OF MUTNOVSKY HYDROTHERMAL SYSTEM

O.B. Vereina

Geological Institute of the Russian Academy of Sciences
Pyzhevskii per. 7,
Moscow, 119017, Russia
e-mail: o_vereina@ginras.ru, vega-iris@mail.ru

ABSTRACT

Correlation of volcanic and hydrothermal activity is discussed in connection with exploitation of Mutnovsky hydrogeothermal system in Kamchatka. The geothermal field is situated near Mutnovsky volcano that is in the state of intense fumarolic activity. As a result of this activity, thermal energy evacuates permanently to atmosphere with the intensity of ~1100 MW_t. Energy potential of the volcano and parameters of thermal feeding of hydrothermal reservoirs (flow rate of ascending heat-carrier and its enthalpy) are discussed. The calculations are based on numerical modeling of the natural state of the system. Using this approach it is not necessary to determine the geometry and state of feeding magmatic bodies.

INTRODUCTION

Analysis of heat output through powerful high-temperature hydrothermal systems shows that their heating cannot be provided only due to accumulation of regional (background) conductive heat flow by meteoric infiltration waters. Systems should have additional sources for thermal feeding. Such sources can be local thermal foci appearing in the interior due to intrusions of magmatic melts.

Identification of heat sources in hydrothermal systems is one of the keys to construct its conceptual model. In order to reveal local heat sources in concrete hydrothermal systems the following parameters are necessary to estimate: 1) the magnitude, Q_1, of heat output at natural discharge of the system (according temperatures and flow rates of hydrothermal fluids discharged on the earth surface within the system boundaries), and 2) the scales, Q_2, of thermal feeding of the system by background conductive heat flow on the whole area of its water recharge. If $Q_1 > Q_2$, the presence of additional heat sources within the systems proves unambiguously. However, this presence cannot be excluded if $Q_1 < Q_2$ because Q_2 corresponds to theoretical maximum unachievable in real situations. Indirect signs of presence of additional heat sources within the systems are high values of abyssal (“base”) temperatures of hydrothermal fluids calculated by means of hydrochemical geothermometers.

The consideration of hydrogeological conditions and heat budget of high-temperature hydrothermal systems of Iceland, USA, New Zealand, Kamchatka and other areas [White, 1957; Bödvarsson, 1961; Averiev, 1964, Polyak, 1966; Sugrobov, 1979; Kononov, 1983; etc.] show that their heating cannot be provided by regional conductive heat flow only. Heat output through these long-lived systems can be provided only by additional heat sources.

In physical respect, such sources represent positive anomalies in geotemperature field. Their geological nature is, however, debatable topic. Some researchers following to [Averiev, 1964], suppose that source of additional heat in geothermal reservoirs of volcanic areas is supercritical fluid (“endogenous steam”) segregated on the crust-mantle boundary. But the coupled study of isotopic compositions of He in hydrothermal gases and Sr in young volcanics spread in areas of hydrothermal activity showed close correlation between $^3He/^4He$ и $^{87}Sr/^{86}Sr$ values [Polyak et al., 1979]. This correlation indicates the coupled transfer of volatile He and lithophile Sr from the mantle into the crust by the same agent representing silicate substance. Therefore, it is possible to suppose that hydrothermal process is a consequence of existing magmatic foci arising in upper horizons of the crust due to intrusions of melt. This melt exhales some quantity of volatiles and is cooled giving thermal energy to surrounding underground fluids.

According to geophysical data, in Kamchatka magmatic foci are supposed on relatively shallow depth within Pauzhetka, Koshelev, Mutnovsky systems, under Avachinsky Volcano and some other active volcanoes [Kiryukhin & Sugrobov, 1987].

ENERGY POTENTIAL OF MUTNOVSKY VOLCANO

Mutnovsky Volcano is located in 80 km to the south from Petropavlovsk City that is the largest one from Kamchatka’s cities. This volcano is one of the most studied eruptive centers in Kamchatka [Marenina, 1956; Kirsanov, 1964; Vakin et al., 1976; Melekestsev et al., 1987; Ovsyannikov & Zubin, 1991; Taran et al., 1992; Zelensky et al., 2002; etc.]. Near its foothills, the powerful Mutnovsky hydrothermal system is situated. Geothermal resources of the system are partially used by two GeoPP put into operation in 1999 and 2002. In future, their capacity is supposed to be increased.

The volcano began to act in the Later Pleistocene. It is formed by four joined cones, composed mostly of high-Al basalts of Ca-Na series; andesites are subordinated. In the upper part of the edifice, there are two merged craters – NE (Lower) and SW (Upper) – each of 1,5-2 km in diameter, and so-called Active Vent (Fig. 1). During the Holocene, the volcano eruptions were mainly of phreatic type. In XIX-XX, there were at least 15 explosions.

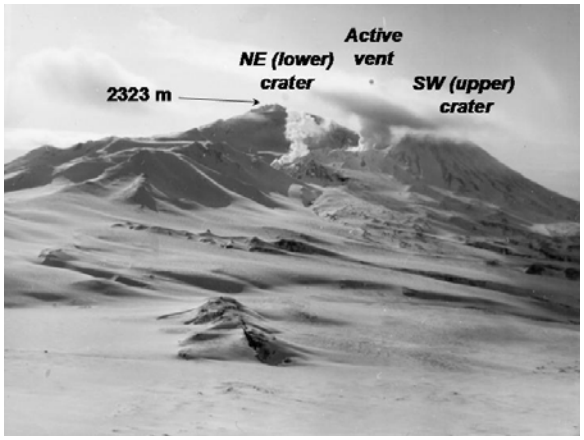

Figure 1. Mutnovsky Volcano, view from NW (photo I.T. Kirsanov, 1963)

The volcano is distinguished by very intensive fumarolic activity concentrated on two (Bottom and Upper) fumarolic field of the NE Crater and on the walls of the Active Vent. Energy effect of this activity was estimated by special investigations [Polyak, 1965; Muraviev et al., 1983; Polyak et al., 1985].

In 1963, 1980 and 1981, the total heat output in NE Crater was estimated including conductive heat losses through heated ground, heat output by individual steam jets, dispersed steaming, and Vulkannaya River issued from the crater (Table 1).

Table 1. Heat output (MW_t) from NE crater of Mutnovsky Volcano (Polyak, 1965; Muraviev, Polyak et al., 1983)

Field	**Upper field**			**Bottom field**		
Year	**1963**	**1980**	**1981**	**1963**	**1980**	**1981**
Q_{cond}	**1.28**	**~1.25**	**~1.25**	**0.28**	**0.46**	**0.42**
Steam jets	**280**	**272**	**n.d.**	**40**	**44**	**42**
Dispersed steaming	**17**	**8.4**	**n.d.**	**4.2**	**1.7**	**n.d.**
Springs	**not detected**			**n.d.**	**13.7**	**14.1**
River	**not detected**			**32**	**34**	**44**
Total	**300**	**280**	**n.d.**	**>76**	**93**	**100**

E.A. Vakin with co-authors reported on the total output of thermal energy in NE Crater in 1974 that was estimated as 394 MW_t without differentiation of components [Vakin et al., 1976]. Summing up these data, one can conclude that energy effect of fumarolic activity in NE Crater during 1963-1981 was rather stable and close to 400 MW_t. This stability is supported by the similarity of ground temperatures on Bottom field of NE Crater in 1963 and 1980 (Figs. 2, 3).

The total heat losses through volcanic apparatus were higher, because fumarolic activity took place on the walls of the Active Vent, too. Its energy effect was calculated with the help of IR-survey of heat radiation from the vent walls in 1982 [Polyak et al., 1985]. As a result, the total heat losses through Mutnovsky Volcano during interparoxismal stage of its activity could be approximated as ~1100 MW_t. [Polyak et al., 2004].

The same quantity of thermal energy could be evacuated from the interior by lava flow with flow rate of 2.10^7 ton/yr. It is 10-15 times more real productivity of Mutnovsky Volcano in the Holocene [Melekestsev et al., 1987] and only 3 times less than that typical for Klyuchevsky Volcano [ibid.] These estimations allow us to suppose that above-mentioned data on heat output by fumarolic activity of Mutnovsky Volcano characterize its energy potential quite adequately.

There are other hydrothermal manifestations in the vicinities of the volcano (Fig. 4). They are steam-gas jets and hot springs with temperatures of >90°C and total heat output >160 MW_t (Table 2). The existence of these manifestations makes the perspective of geothermal development of the Mutnovsky region still more promising.

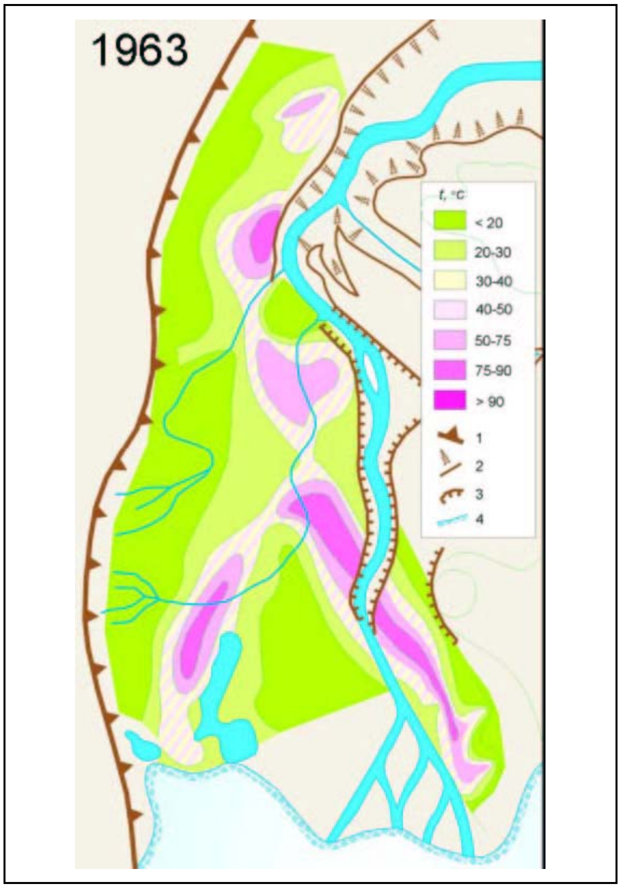

Figure 2. Mutnovsky Volcano, NE crater, bottom fumarolic field, ground temperature at 0.15 m depth in 1963 (Polyak, 1965)

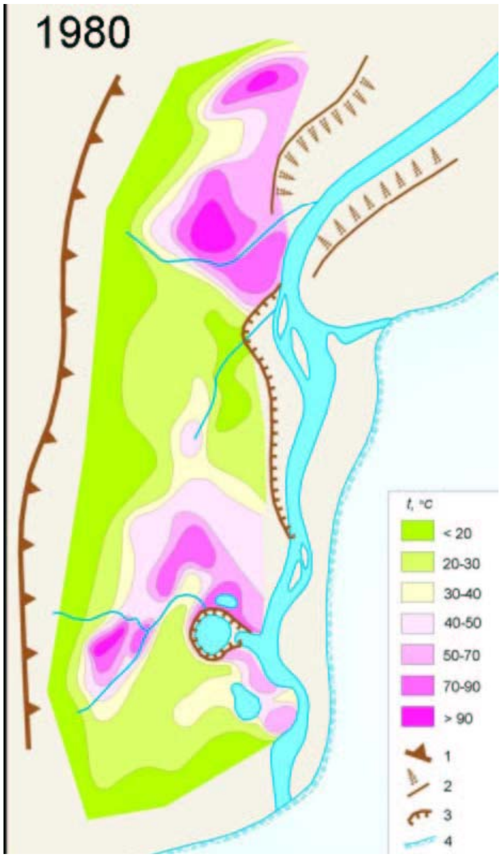

Figure 3. Mutnovsky Volcano, NE crater, bottom fumarolic field, ground temperature at 0.15 m depth in 1980 (Muraviev et al., 1983)

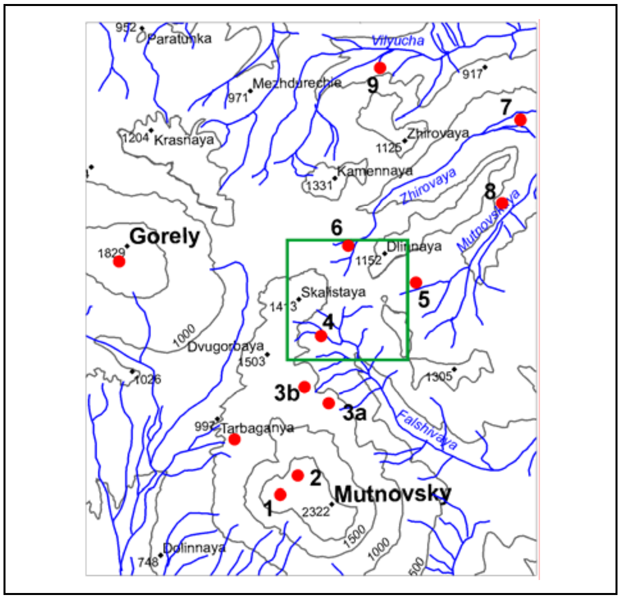

Figure 4. Mutnovsky geothermal region: red dots denote fumaroles and hot springs (see ## in Table 2), green outline denotes field area.

Table 2. Geothermal discharge in the Mutnovsky Volcano area, according to (Vakin et al., 1986)

##	Site	$T_{surf.}$, ^oC	MW_t
1	Mutnovsky Vol., active vent	> 700	700
2	Mutnovsky Vol., NE crater	305	400
3a	North Mutnovsky Spr., east group	98	19
3b	North Mutnovsky Spr., west group	110	9
4	Dacha Spr.	98	73
5	Pereval Spr.	96	9
6	Upper Zhirovskie Spr.	96	18
7	Lower Zhirovskie Spr.	115 (kcal/kg)	16
8	Voinovskie Spr.	93	8
9	Vilyucha Spr.	90	12

MODELING OF THERMAL FEEDING OF THE MUTNOVSKY HYDROTHERMAL SYSTEM

Numerical modeling has proved to be an effective tool for estimation of parameters of hypothetic additional heat sources in hydrothermal system. By now the follows models for Mutnovsky system were developed.

Model I

One of the first models of this kind [Kiryukhin & Sugrobov, 1987] used CONVEC code and described heat transfer in hydrothermal system caused by cooling of two magmatic bodies with initial temperatures assumed to be 700 ^{o}C and total volume 275 km^3. According to geological and geophysical data, centers of the bodies were assumed at depth of 7.4 and 9 km. The bodies were supposed to intrude into water-saturated reservoir of 15 km length and 5 km width 35,000 years ago. Infiltration (with 5 kg/(s*km^2) average flow rate) was simulated in the left part of the model, and discharge was in the right part.

In given conditions thermal anomaly similar to real temperature distribution within the field is formed. Heat output of hydrothermal system was estimated at 168 MW$_t$.

Model II

The improved model of Mutnovsky field including Dachny and Verkhne-Mutnovsky sectors was considered in [Kiryukhin, 1996, 2002]; modeling area is shown in Fig. 5. TOUGH2 simulator [Pruess et al., 1999] and 3D rectangular numerical grid containing five layers in depth range 750 m.a.s.l. - 1250 m.b.s.l. were used. Model did not include magmatic bodies as internal heat sources; external heat sources reflecting the conductive heat flow through the basement of reservoir and abyssal heat-carrier inflow were assumed. Natural state modeling represents solving the inverse problem on estimation of these external sources; real values of temperature and pressure in reservoir were used as convergence criterion.

Calculation of mass and heat balance produced the same inlet and outlet estimations equal to 54.1 kg/s and 74.9 MW$_t$; heat-carrier enthalpy was estimated at 1270 kJ/kg for Verkhne-Mutnovsky sector and 1390 kJ/kg for Mutnovsky sector.

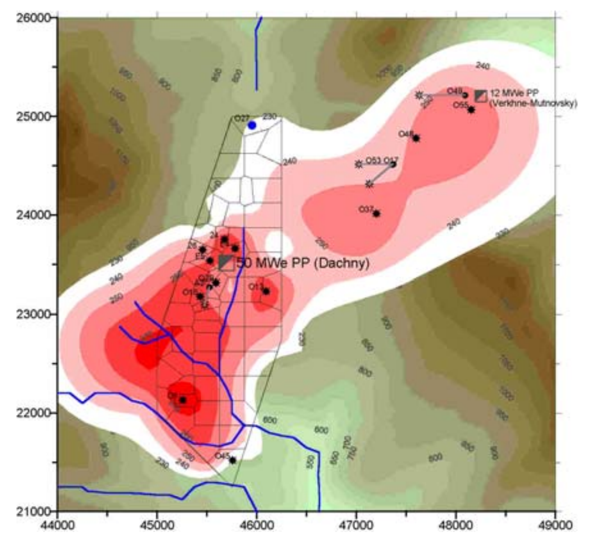

Figure 5. Mutnovsky geothermal field within modeling area (Kiryukhin, 1996); grid corresponding to reservoir of "Main" productive zone (Kiryukhin, 2004, 2005; Kiryukhin & Vereina, 2005), temperature distribution at 250 m.b.s.l., topography features and GeoPP locations are shown. Productive wells and feed zones projections are designated with filled circles and stars, respectively.

Model III

Natural state model of Mutnovsky system in [Vereina, 2003, 2005] included the studied field and adjacent areas. TOUGH2 code and 5-layer numerical grid (constructed by A-Mesh preprocessor [Haukwa, 1998]) in depth range 250 m.a.s.l. - 1750 m.b.s.l. were used. Heat and mass sources were assumed in the layer of average depth 1250 m.b.s.l.

Three variants of modeling were considered: with one, two and three heat and mass sources. In the last case the best fit for simulated and real data (for two-phase state in the Dachny site and pressure distribution within the field area) was observed.

Estimations for flow rate and enthalpy of heat-carrier inflow into reservoir amounted at 55 kg/s and 1650 kJ/kg, respectively. Calculated temperature distribution and two-phase zone at 250 m.b.s.l. are shown in Fig. 6.

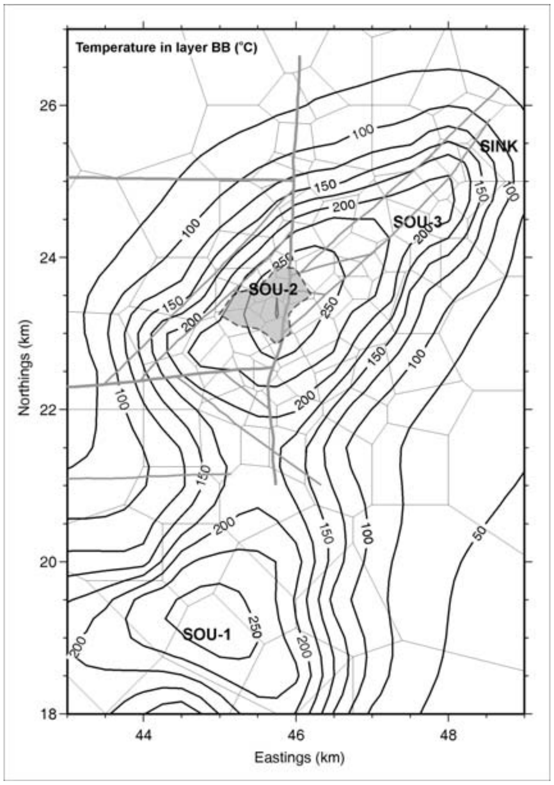

Figure 6. Results of natural state modeling Mutnovsky geothermal field [Vereina, 2003, 2005]: temperature distribution at 250 m.b.s.l. when three heat and mass sources (SOU1, SOU2, SOU3) are assumed. Painted area denotes two-phase zone.

Although this model was not completed because of lack of more comprehensive data about productive zone, it was an attempt to construct a common model including both geothermal field and active volcano.

Model IV

After recognizing the geometry of "Main" productive zone at the Dachny sector the refined reservoir model was developed [Kiryukhin, 2004; Kiryukhin & Vereina, 2005]. It describes productive zone of NNE strike and SSE dip of average angle 60^o. Numerical grid (Fig. 7) was generated by A-Mesh preprocessor with some additions; its outline is shown in Fig. 5. The improved estimations for flow rate and enthalpy of abyssal heat-carrier inflow into reservoir amounted at 54 kg/s and 1390 kJ/kg, respectively.

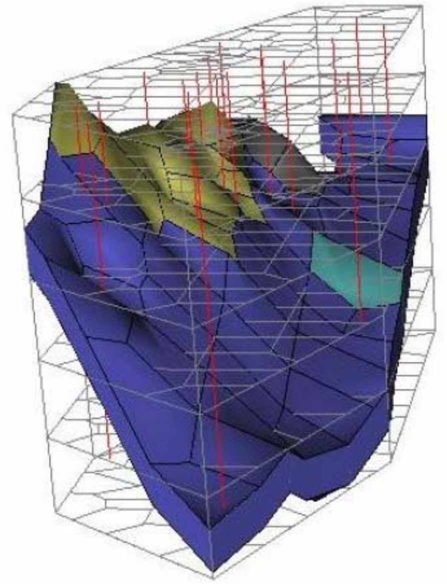

Figure 7. Geometry of the 3-D numerical model of the "Main" production zone of the Dachny sector, Mutnovsky geothermal field [Kiryukhin & Vereina, 2005]

CONCLUSIONS

The main heat sources in high-temperature hydrothermal systems are local magmatic foci appearing in the interior due to melt intrusions. Convective heat-mass transfer is main mechanism of heat exchange in such systems. Circulation of thermal waters from their recharge areas to areas of discharge is controlled by pressure drop and fluid density variations and permeability of host rocks.

Numerical modeling of geothermal reservoirs enabled us to estimate parameters of sources of their thermal feeding (flow rate of ascending heat-carrier and its enthalpy) based on simulation of their natural state. It represents a solving the inverse problem on providing convergence of simulated and real temperature and pressure in reservoir. Using this approach it is not necessary to determine the geometry and state of feeding magmatic systems.

At the same time, conditions of co-existence of active volcanoes and hydrothermal systems are not quite understandable. Mutnovsky geothermal field and crater fumaroles of Mutnovsky volcano are 8 km apart only; they are probably related to one and the same of fissure zone of enhanced permeability that serves as a common channel for transport magma and thermal fluids. The further investigation is necessary to reveal a possibility to increase the intensity of thermal feeding of the field due to energy potential of the volcano and to use this possibility to affect on the volcano activity. This problem could be solved in the frame of the planned International Mutnovsky Scientific Drilling Project (MSDP).

ACKNOWLEDGEMENTS

This work has been supported by Russian Foundation for Basic Research (grant 05-05-64021).

REFERENCES

Averiev V.V. (1964) “On relation between hydrothermal and volcanic activity”, *Proceed. **II** All-Union Volcanological Workshop*, Kamchatka, USSR, 3-17 September 1964, 251-253 (in Russian).

Bödvarsson G. (1961) “Physical characteristics of natural heat resource in Iceland”, *UN Conference on New Sources of Energy, Rome*, 1961, 1-19.

Haukwa, C.: (1998) “AMESH, a mesh creating program for the integral finite difference method: A User’s Manual”. Lawrence Berkeley National Laboratory, *report LBNL-45284*, 53 p.

Kirsanov I.T. (1964) “ The state of active volcanoes in Middle and Souyhern Kamchatka in 1961-1962”, *Bull. Volcanol. Stations*, #**36**, 48-60 (in Russian).

Kiryukhin A.V., and Sugrobov V.M. (1987) “*Models of heat transfer in hydrothermal systems of Kamchatka”*, Moscow: Nauka Publ., 150 p. (in Russian).

Kiryukhin A.V. (1996) “Modelling Studies: Dachny Geothermal Reservoir, Kamchatka, Russia”, *Geothermics*, **26**, #1 ,1996, 63-90.

Kiryukhin A.V. (2002) “*Modeling of geothermal exploitation”*. Vladivostok: Dalnauka Publ., 216 p. (in Russian).

Kiryukhin A.V. (2004) “Modelling study of the Mutnovsky geothermal field (Dachny) in connection with the problem of steam supply for 50 MWe PP”, *Proceedings, **29**-th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 26-28,* 8 p.

Kiryukhin A.V. (2005) “Modelling of the Dachny Site Mutnovsky Geothermal Field (Kamchatka, Russia) in Connection with the Problem of Steam Supply for 50 MW_e Power Plant”, *Proceedings World Geothermal Congress 2005*, 12 p.

Kiryukhin A.V., and Vereina O.B. (2005) “Modelling of the fault type geothermal reservoir (Dachny site, Mutnovsky geothermal field)”, *Proceedings 30-th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 31–February 2,* 8 p.

Kononov V.I. (1983) “*Geochemistry of thermal waters in area of recent volcanism*”, Moscow: Nauka Publ., 215 p. (in Russian).

Marenina T.Yu. (1956) “Geologo- petrograhichy outline of Mutnovsky Volcano”, *Proceed. Lab. Volcanol. of the USSR Acad. Sc.*, **12** (in Russian).

Melekestsev I.V., Braytseva O.K., and Ponomareva V.V. (1987) “Dynamics of Activity of Mutnovsky and Gorely volcanoes in Holocene and potential hazard for adjacent regions”, *Volcanology & Seismology*, #**3**, 3-18 (in Russian).

Muraviev A.V., Polyak B.G., Turkov V.P., and Kozlovtseva S.V. (1983) “New estimation of heat output with fumarolic activity from Mutnovsky volcano (Kamchatka)”, *Volcanology & Seismology*, 1983, #**5**, 51-63 (in Russian).

Ovsyannikov A.A., and Zubin M.I. (1991) “Mutnovsky Volcano”, *Active volcanoes of Kamchatka*, vol. **2,** Moscow: Nauka Publ., 316-337 (in Russian).

Polyak B.G. (1965) “Heat output of Mutnovsky volcano during interparoxismal stage of activity”, *Reports of Academy of Sciences USSR*, **162**, #**3**, 643-646 (in Russian).

Polyak B.G. (1966) “*Geothermal features of the area of recent volcanism (Kamchatka)”,* Moscow: Nauka Publ., 180 p. (in Russian).

Polyak B.G., Prasolov E.M., Buachidze G.I. et al. (1979) “He and Ar isotopic composition in thermal fluids from Alpine-Apennines region and its relation to volcanism”, *Reports of Academy of Sciences USSR*, **247**, 1220-1225 (in Russian).

Polyak B.G., Bezukh B.A., Kaftan V.I. et al (1985), “An experience of landing IR-survey for estimations of temperatures and heat radiation of Mutnovsky Volcano(Kamchatka)”, *Volcanology & Seismology*, #3, 54-63 (in Russian).

Polyak B.G. Melekestsev I.V., and Kirsanova T.P. (2004) “Energetic regime of Mutnovskiy volcano (Eastern Kamchatka)”, *Int. Geothermal Workshop “Heat & Light from the Heart of the Earth”, Kamchatka, Russia, 9-14 August 2004,* 28.

Pruess, K., Oldenburg, C., and Moridis, G.: (1999) *“TOUGH2, user’s guide version 2.0*”. Lawrence Berkeley National Laboratory, 197 p.

Sugrobov V.M. (1979) “Geothermal resources of Kamchatka, classification and assessment”, *Geothermal study and use in volcanic areas*, Moscow: Nauka Publ., 26-35 (in Russian).

Taran Yu.A., Pilipenko V.P., Rozhkov A.M., and Vakin E.A. (1992) “A geochemical model for fumaroles of Mutnovsky Volcano, Kamchatka, USSR”, *J. Volcanol. Geotherm. Res*., **49**, 269-283.

Vakin E.A., Kirsanov I.T., and Kirsanova T.P. (1976) “Thermal grounds and hot springs of the Mutnovsky volcanic region”, *Hydrothermal systems and thermal fields of Kamchatka*. Vladivostok city, 85-114 (in Russian).

Vakin E.A., Pilipenko G.F., and Sugrobov V.M. (1986) “General description of Mutnovsky field and the resource assessment”, *Geothermal and geochemical studies of high-temperature hydrothermal systems*, Moscow: Nauka Publ., 6-40 (in Russian).

Vereina O.B. (2003) “Natural state modeling of the Mutnovsky geothermal field, Kamchatka, Russia”, *Geothermal training in Iceland 2003* (*Reports of the UNU GTP)*, Reykjavik, 505-526.

Vereina O.B. (2005) “Numerical Modelling of the Natural State of the Mutnovsky Geothermal Reservoir (Kamchatka, Russia)”, *Proceedings World Geothermal Congress 2005*, 8 p.

Vereina O.B., Kiryukhin A.V., and Kononov V.I. (2005) “Heat feeding of Mutnovsky geothermal system (Kamchatka)”, *VII International Conference “New Ideas in the Earth Sciences*”, Moscow, Russia, April 2005.

White D.E. (1957) “Thermal waters of volcanic origin”, *Bull. Geol. Soc. of Amer*., **68**, #**12**, 1637-1657.

Zelensky M.E., Ovsyannikov A.A., Gavrilenko G.M., and Senyukov S.L. (2002), “Eruption of Mutnovsky volcano (Kamchatka) 17 March 2000“, *Volcanology & Seismology*, #**6**, 25-28 (in Russian).