SCIENTIFIC DRILLING OF THE MUTNOVSKY MAGMA-HYDROTHERMAL SYSTEM (KAMCHATKA, RUSSIA): TESTING THE MAGMA-HYDROTHERMAL CONNECTION

A workshop proposal to ICDP

A. Kiryukhin, Institute of Volcanology and Seismology, Petropavlovsk-Kamchatksky, Russia

J. Eichelberger and P. Izbekov, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA

Proponents (in addition to above):

J.Eichelberger (GI, Fairbanks,USA), A.Kiryukhin (IVS FEB RAS, Russia), P. Izbekov (GI, Fairbanks,USA), V.Luzin (SC Geotherm, Russia), I.Chernev (SC Geotherm, Russia), O.Selyangin (NIGTC, FEB RAS, Russia), K.Yasukawa (AIST, Japan), N.Tsuchiya (Tohoku Univ., Japan), K.Pruess LBNL, USA), E.Gordeev (IVS FEB RAS, Russia)

Contact person:

John Eichelberger, 1-907-474-5530, eich@gi.alaska.edu

Abstract

Understanding the magmatic contribution to hydrothermal systems is essential to full exploitation of geothermal energy. Conversely, hydrothermal systems control the thermal evolution and hence the volcanic life, chemical evolution, and in at least some cases the eruptive behavior of magma systems.

We propose to investigate the connection between a well-explored hydrothermal system and an adjacent highly active volcano. The site is selected because of its relative simplicity: A single fault is the geothermal production zone and appears to connect directly with the active magma column, which feeds 700^{o}C fumaroles.

Our concept, which is to be the subject of an international workshop, is to directionally drill into the fracture zone at a point intermediate between the active vent and the production field, in order to test the relationship between the two systems. The test will be conducted by comparing the chemical relationship of borehole fluid samples to the fumarolic and geothermal fluids, and by monitoring pressure and temperature in the borehole during excursions from steady state in the geothermal and volcanic systems.

Scientific Objectives

Our hypothesis is that a quasi-stable, actively degassing magma column within Mutnovsky IV Volcano supplies fluid and heat to a fault zone which in turns forms a direct feeder to the geothermal production field. This can be readily tested by penetrating the fault zone at a point intermediate to the geothermal plant and the active crater and measuring parameters indicative of magmatic and meteoric sources, such as temperature, chemistry, isotopic composition, secondary mineral distribution. In addition, the connectivity of the system can be assessed by monitoring pressure and temperature and comparing these records to changes induced in the geothermal field by production and to excursions in conditions in the crater due to eruptive activity. In addition, perturbations in fluid chemistry and pressure can be induced within the borehole and monitored for in the active crater and geothermal field. Any detected linkage will provide quantitative information on mass and thermal fluxes within the system.

These data will help to answer two important questions:

1. By drilling closer to active andesitic volcanic centers of subduction zone arcs, can we expect to encounter higher energy hydrothermal systems?
2. By increasing the rate of energy extraction from magma-driven hydrothermal systems to a rate comparable to the magmatic thermal input, can we expect to extend repose time and diminish the likelihood of hazardous eruption?

Background

Three considerations suggest that the time is ripe for a project to directly address the magma-hydrothermal connection:

1. With the rise of oil prices to the $40-50 barrel range, geothermal energy has moved from a strategy useful in a few remote areas and requiring government subsidies to one broadly applicable to the oil-poor, volcano-rich Pacific Rim.
2. Increasing sophistication and application of geophysical techniques to eruption monitoring and forecasting demand a better understanding on what signals are fundamentally magmatic and what are derived from associated hydrothermal fluids. We also need to understand the system in its totality, because the hydrothermal portion may well control the cooling and even eruptive behavior of the magmatic system.
3. Advances in drilling technology, most spectacularly demonstrated at Unzen Volcano, Japan (USDP), show that directional drilling in volcanic terranes can achieve unprecedented scientific objectives. An obvious next step is to move to a volcano with a shorter repose interval in order to achieve higher temperatures.

General considerations

The far North Pacific, comprising the Russian Far East and Alaska, is an under developed area of great international significance. It contains one of the world's richest fisheries and is the great circle trade route between eastern Asia and North America. It contains the world's most volcanically explosive and seismically tsunamigenic subduction zones, posing significant hazards particularly to jet aircraft and to coastal communities. It is also home to the rich and ancient Aleut culture. The region will gain further importance as global warming opens trans-Arctic shipping routes between the Pacific and Atlantic within the next few decades: a massive reorientation of international commerce at least as dramatic as the opening of the Panama Canal. At present the major challenge to development of viable North Pacific communities is the availability of cheap electrical and thermal energy. Power generation has mostly relied on oil, but even in oil-rich Russia and Alaska the transport of oil to the communities, none of which are connected to national grids, is very expensive. Because of the abundance of volcanoes and associated hydrothermal systems, geothermal energy is an obvious solution. The region occupies and analogous geographic position and holds much the same promise, but has received less attention and heretofore less economic success, as Iceland.

Here we focus on the Kamchatka Peninsula and its major city, Petropavlovsk-Kamchatksky, Russia's northern-most ice-free Pacific port. This region has advanced the farthest in using geothermal energy and also possesses robust geophysical expertise in its research and educational institutions, notably the Institute of Volcanology and Seismology, Kamchatka Experimental and Methodological Seismology Department of the Russian Academy of Sciences, and Kamchatka State Pedagogical University.

Petropavlovsk-Kamchatsky's energy needs are 180 MWe and 500 MWt. After the Mutnovsky (Dachny) Geothermal Powerplant started in 2002, the total installed capacity in Kamchatka reached 66 MWe. This ended the full dependence of Kamchatka's economy from imported oil, which was previously the only energy source. In addition to this is heat production from low temperature geothermal fields (Paratunsky fields, 200 MWt) and planned introduction of binary cycle technology (Mutnovsky, 20 MWe plus, Bolshe-Banny field, 50 MWe (or 200 MWt). Geothermal development thus supports Kamchatka's industry, primarily fish processing, and improves the standard of living for residents with lower energy prices (1.5-2.0 rubles/kW-hr, 200-300 rubles per GCal) compared to high rates from oil PP's (4 rubles/kW-hr, 1200-1500 rubles per GCal). By ending total dependence on imported fuel, geothermal energy has eliminated winter-time energy blackouts that were life-threatening for the elderly and ill.

History of development of the Mutnovsky field

The Dachny fumarole field was discovered in 1962 by E.A.Vakin and I.T. Kirsanov. Exploration works began in 1978, including delineation of surface manifestations, temperatures, soil gas surveys, resistivity surveys, T-gradient drilling, and drilling of the exploration wells. Eighty nine exploration wells were drilled by 1991 (G.M. Assaulov, V.M. Sugrobov et al). Flow tests from production wells were conducted during 1983-

1987 time period, which confirmed the possibility of the 50 MWe production based on a sum of the single well flow rate values. A Mutnovsky 50 MWe powerplant feasibility study performed by WestJec (1996-1997) was based on TOUGH2-modeling of different exploitation scenarios (A.V. Kiryukhin, 1996) and basically confirmed 50 MWe potential of Dachny site. In 1999, a US$100,000,000 loan from EBRD moved the Mutnovsky (Dachny) 50 MWe powerplant project to the construction stage, and since 2002 the powerplant has been in operation (Figs.1,2). All recent developments of the Mutnovsky project were implemented by SC Geotherm (V.E. Luzin).

Results from drilling and production.

The current conceptual model of the Dachny site is based on mapping of active fracture zones, circulation losses and production zones distribution data, gas and fluid chemistry data, and secondary minerals distributions. Recent results of drilling and application of data from analogous systems reveal the “single fault” nature of reservoir. The main production zone in Dachny site strikes north-north-east and dips east-east-south at an angle of 60^o.

Mutnovsky as a “simple” magma/hydrothermal system

1.Conceptual hydrogeological model.

A conceptual hydrogeological model of the Dachny site of the Mutnovsky geothermal field shown in Figs.3 and 4. The main production zone occurs within the North-Mutnovsky volcano-tectonic zone. The zone strikes north-north-east with east-east-south dip 60^o, has an average vertical thickness 240 m, and is penetrated by 9 wells (Fig.4). The strike of the production zone is subparallel to the system of active faults (V.L. Leonov, 1986) (Fig. 5). Host rocks of the production zone are: diorites, Miocene-Pliocene sandstones, and rhyolite and andesite tuffs and lavas. Nevertheless, there is no explicit lithologic control of the production zone. The roof of the production zone is identified by circulation losses during drilling along the plane of main production zone, and the connectivity of the zone has been confirmed by tracer tests. The plane of the main production zone intersects the active magma feeding chamber of Mutnovsky volcano at elevations of +250 - +1250 m at a distance of 8 km from production site (Fig.3).

The Mutnovsky volcano crater glacier apparently acts as a meteoric water recharge area for the fluids producing by exploitation wells in the Dachny. Meteoric recharge is accelerated by melting of the glacier due to high heat flows in the crater (Bottom Field, Fig.3). Thermal input to the production zone may also come from other magmatic bodies accumulated in the North Mutnovsky volcano-tectonic zone. It is not clear whether or not such bodies are directly connected to magmatic system of the active Mutnovsky volcano, or just isolated remains of magma intruded into the plane of hydro-/magma-fracturing created by Mutnovsky volcano. Upflow of high temperature fluids occurs in the south-east part of the Main production zone, where conditions are liquid-dominated at 300°C occurs (Fig. 4). Ascending fluids transform to two-phase conditions in the shallow parts of the production zone (above 0 m.a.s.l.), where production coincides with the wairakite-chlorite secondary minerals association. The main production zone is also characterized by Cl/SO4>1 ratios, and high T values from the Na-K geothermometer. Four additional wells (A1-A4), recently drilled (2001-2003) outside of the main production zone were found to be non-productive. A steam explosion in June 2003, 300 m east from well O45 (Fig.4) and triggered by geothermal exploitation, appears to be an indicator for the upflow root. The following are details of some specific points of the conceptual model above.

1.1. Fluids

Gas and fluid chemistry variations response to exploitation are valuable for reservoir state and boundary conditions assessment. It was observed ~~(Table 2)~~ that the N_2 fraction increases and H_2S decreases with time (wells O16, O29W and 26) since production began, which may reflect meteoric water inflows into reservoir. This coincides with a Na/K geothermometer decline (20°C in well 4E, 4.5°C for well O29W).

Exploitation wells (O29W, 1, 24, 4E, O14, O49N) H and O isotope values are correspond to meteoric water recharge from +1500 to +1600 m.a.s.l., where Mutnovsky volcano's glacier is melting on the hot crater flow (Bottom Field, Fig.1). Light H and O isotope values of steam wells 016 and 26 result from isotope fractionation under shallow two-phase reservoir conditions.

1.2. Secondary Mineralization

The following secondary minerals associations were detected in the Dachny site: (1) Quartz-epidote-chlorite association characterized by Na-Cl fluids circulation at temperatures of 220-300^oC, (2) Wairakite-prehnite-quartz association with two-phase conditions at 150-240^oC (pressures 5-35 bars), (3) Illite-chlorite-calcite zone, corresponding to condensate downflows of SO_4-Cl-HCO_3 composition at 150-220^oC. Rock samples ejected from recently drilled wells A2-A4 during events of the Main production zone penetration shows wairakite-chlorite as a dominant secondary minerals association, while there was no wairakite found outside of the production zone.

1.3. Geothermal Analogs

A similar "single fault" type geothermal field has been developed in Japan (Ogiri) where 30 MWe is produced from single fault of 20 m thickness with a 232^oC liquid phase that circulates in andesite host rock. Other analogous examples are Okuaizu (Japan) and Dixie Valley and Brady (USA).

2.Numerical Model of the Mutnovsky Geothermal Field (Dachny)

2.1 Grid Generation

The geothermal reservoir is represented as a combination of two reservoirs: A-reservoir and B-reservoir. A-reservoir numerical grid corresponds to the Main production zone with averaged vertical thickness 240 m (actual thickness 120 m), each element of which is located at the specified elevation corresponding to the main production zone (Figs.4,5,6). The B-reservoir numerical grid includes three elements corresponding to wells 2E, 5E and O12 in the diorite intrusion contact permeability zone (Fig.6). In total, 24 existing wells, 39 additional interior elements (F-elements and D-element) and 12 boundary (inactive) elements (B-elements) are specified in the model.

2.2 Natural State Modeling

Natural state modeling is targeted to temperature, pressure and phase condition match in the key elements to improve model sources and sink parameters, and permeability distribution. Based on above, total upflow rate estimated in the model is 54 kg/s with enthalpies specified as 1390 кJ/кg (water T=307^{o}C). Permeability in the reservoir is estimated to average 100 mD. Upflows are directed from the south-east part to north-north-east part (liquid discharge) and west part (steam discharge) of the production zone.

2.3 Modeling of the Exploitation

Model calibration is based mainly on the data received from initial production tests of wells 016, 26, 029W, 4Э, A2 and 5E, and data of the total steam and total separate production from the Mutnovsky Powerplant separator. The total steam production (at 7 bars abs) of the above mentioned wells declined from 64.9 kg/s to 59.4 kg/s (8.5%), the total separate production declined from 117.5 kg/s to 107.5 kg/s (8.5%) during one year of the exploitation period. The compressibility coefficients that were found necessary to be implemented in the model were 5.0 10^{-7} Pa^{-1} in the steam-dominated domain and 5.0 10^{-8} Pa^{-1} elsewhere.

To represent well-reservoir interaction, the TOUGH2V2.0 coupled wellbore flow option was used. Exploitation wells are assigned under wellhead pressure conditions.
Modeling results show the steam production at 7 bars from the existing production wells of the Dachny site in the Mutnovsky geothermal field (016, 26, E4, 029W, E5) is limited to 60-70 kg/s with the possibility of decline down to 33 kg/s after 10 years of the exploitation. A significant exploitation load in central part of the Dachny site may have a negative effect for steam productivity. Additional drilling of the seven directional exploitation wells targeted to south-east portion of the main production zone may achieve sustainable production of 85.7-95.1 kg/s steam to maintain a 50 MWe PP supply. Thus, understanding the southeastern extension of the hydrothermal zone is key to the future of power production as well as to a scientific understanding of the relationship of the hydrothermal system to the volcano.

3. Conceptual model of the Mutnovsky Volcano magma system

The volcanic geology, structure, and eruptive history has been described in detail by Selyangin (2000). The volcano has gone through four stages spanning late Pleistocene through Holocene time. Each stage probably reflects the evolution of a small shallow magma reservoir, and the transition from one stage to the next has involved a shift of the eruptive center by as much as 1 km. All stages except for the current incompletely developed stage have produced magmas ranging from basalt to dacite. Mutnovsky IV is characterized by basaltic andesites. Although Mutnovsky grew contemporaneously with nearby Gorely Volcano, there is little or no evidence of interaction between the two magma systems.

Mutnovsky III ended its eruptive cycle with Holocene eruption of dacitic pyroclastic flows and emplacement of a dacite dome within its crater. This crater has been enlarged by explosion, collapse, and/or erosion and is now occupied by a crater glacier, the main recharge source of the hydrothermal system. The crater is the scene of intense fumarolic activity, modestly superheated and arranged in a ring, apparently defining the conduit margin of the late dacite dome. A powerful phreatic explosion in 2000 at the edge of the Mutnovsky III "caldera" and adjacent to Mutnovsky IV reopened a large pre-existing crater that had been covered by the crater glacier. The resulting lake was still hot in 2003 but was ice-covered in 2004.

Mutnovsky IV crater has fumaroles as hot as 700^{o}C and emits a continuous SO2-rich plume. Clearly, the magma column is very close to the surface and/or maintains a vigorous upward gas flux from degassing sustained by magma convection within the conduit. Fumarolic chemistry has been described in detail by Zelensky (2005). Clearly, this is a very hot and dynamic system, with major changes occurring on an annual to decadal time scale.

Tentative drilling plan

Multiple directionally drilled core holes or sidetracks from single site located between current production field and active crater.

Potential sources of drilling funds

Geothermal industry

Russian Academy of Sciences

ICDP

Plan for meeting

We propose to hold an international workshop with ICDP sponsorship, the purpose of which will be to develop a project to explore the relationship between Mutnovsky Volcano and the associated Mutnovsky hydrothermal system. The following questions will be posed:

(1) What is the nature of the fracture network connecting geothermal field and active volcano? What is the relationship between fracture development and magmatism? What can we learn about this relationship from coring the fracture system at depth?

(2) How can we identify magmatic components in the hydrothermal system? What does this mean about the thermal and chemical budget of the magma column beneath the active crater?

(3) What relationships exist between transient parameters of the hydrothermal system and the adjacent active volcano? What does this say about connectivity and mass and heat fluxes within the total system? What parameters should we be monitoring in the hydrothermal system, the volcano, and the scientific hole(s).

(4) Can we manage volcano activity through manipulation of the production load in the adjacent hydrothermal system? What data already exists pertinent to this problem and what new observations can we make through drilling at Mutnovsky?

Transportation between North America and Kamchatka is via a weekly non-stop flight between Anchorage and Petropavlovsk. Therefore it is logical to plan the workshop to span most of a week. Although this is leisurely compared to many workshops, it has the benefit of allowing more time for discussion and writing, as well as seeing the truly remarkable features of active volcanism, tectonism, and hydrothermal circulation near Petropavlovsk. Access to Petropavlovsk from Europe is through Moscow, with more frequent flights. A general plan is as follows:

Venue: Institute of Volcanology and Seismology and Hotel Edelweiss

Day 0: evening icebreaker

Day 1:

Welcomes (Director of IVS, Governor of Kamchatka Oblast, Rector of Kamchatka State Pedagogical University, conveners)

Briefing on current state of knowledge

- Tectonic and geologic setting (E. Gordeev, Director, IVS)
- Volcanic activity in Kamchatka (O. Girina, IVS/KVERT)/ volcano video
- Hydrothermal systems in Kamchatka (A. Kiryukhin, IVS)
- Mutnovsky Volcano (O. Selyangin, NIGTC)
- Mutnovsky hydrothermal system (M. Zelensky, IVS)
- Mutnovsky geothermal field (V. Luzin, SC Geotherm)

Discussion: Completeness of data set; interpretation of data set.

Day 2:

Field trip to Mutnovsky Volcano, hydrothermal field, and power plant (all day).

Day 3:

Scientific and engineering presentations related to Mutnovsky and analogous systems by workshop participants.

Discuss and reach consensus on primary objectives and techniques of the project.

Day 4:

Visit to hot springs in Petropavlovsk vicinity and to Karymskya Geophysical Station (Russia-Japan).

Day 5:

Discuss and agree on outline of proposal and disciplinary teams. Teams meet separately and then return for reports in plenary meeting and summary.

Farewell dinner.

Day 6:
Writing by identified writing team. Optional trips/tours for other participants awaiting flights.

Products of workshop

The workshop will produce a scientific proposal and draft drilling plan for consideration by ICDP, the Russian Academy of Sciences, and the geothermal industry. We will also publish a report of the workshop in Eos and other internationally distributed geoscience periodicals as appropriate.

Budget

10 Scientists/engineers from outside Russia at $3500/person	$35k
10 Russian scientists/engineers from outside Kamchatka at $1000/person	10
Meeting support: drivers, translators, secretaries, abstract volume	5
Total (US$)	50k

Tentative list of invitees (examples)

Hydrothermal fluids/ magmatic gases: A. Kiryukhin (Russia), M. Shinohara (Japan), M. Zelensky (Russia), W. Elders (USA), T. Churikova (Russia), C. Oppenheimer (UK), P. Wallace (USA)

Drilling: H. Sakuma (Japan), D. Nielson (USA), ICDP rep, SC Geotherm rep, Kamchatksburgeotermia State Enterprise rep

Volcanology: O. Selyangin (Russia),V. Kirianov (Russia), S. Nakada (Japan), D. Melknikov (Russia), J. Eichelberger (USA)

Volcano geophysics: S. Senyukov (Russia), D. Saltykov (Russia), J. Neuberg (UK), M. West (USA), J. Freymueller (USA)

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A.V. Kiryukhin, T. Xu, K. Pruess, J. Apps, I. Slovtsov Thermal-Hydrodynamic-Chemical (THC) Modeling Based on Geothermal Field Data//Geothermics, v.33, No.3, 2004, 349-381p.

V.L. Leonov Structural Conditions of Localization of high temperature hydrotherms, Moscow, Nauka publ., 1989, 104 p. (in Russian).

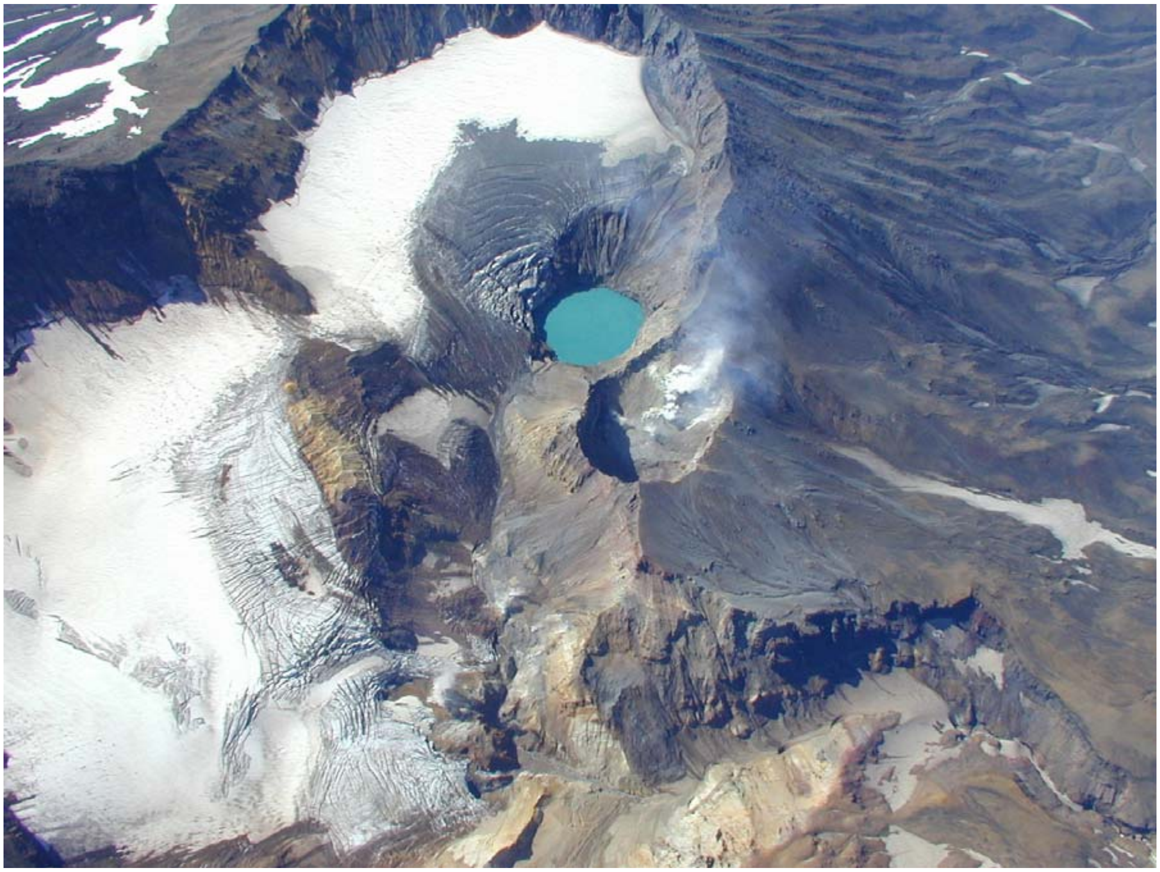
K. Pruess (1991) TOUGH2 - a general purpouse numerical simulator for multiphase fluid and heat flow, Lawerence Berkeley Lab. Report, LBL-29400, Berkeley, California, 102 p.

I.B. Slovtsov Rock alteration in the Mutnovsky Hydrothermal System, Kamchatka, Russia// Proceed. Of Water-Rock Interaction X, 10-15 July 2001, Villasimius, Italy p. 915-918

M.E. Zelensky Transport of the Elements and Minerals Formation in the High Temperature Fumaroles of the Mutnovsky Volcano (Kamchatka) PhD Thesis, Novosibirsk, 2003, 20 p.

Figures:

Fig.1 Mutnovsky geothermal 50 MWe PP (Dachny), photo by A.V. Kiryukhin, 2003. View from NE.



#2 Fig. Picture of the Mutnovsky crater, photo by N.I. Seleverstov, 2002. View from NW.

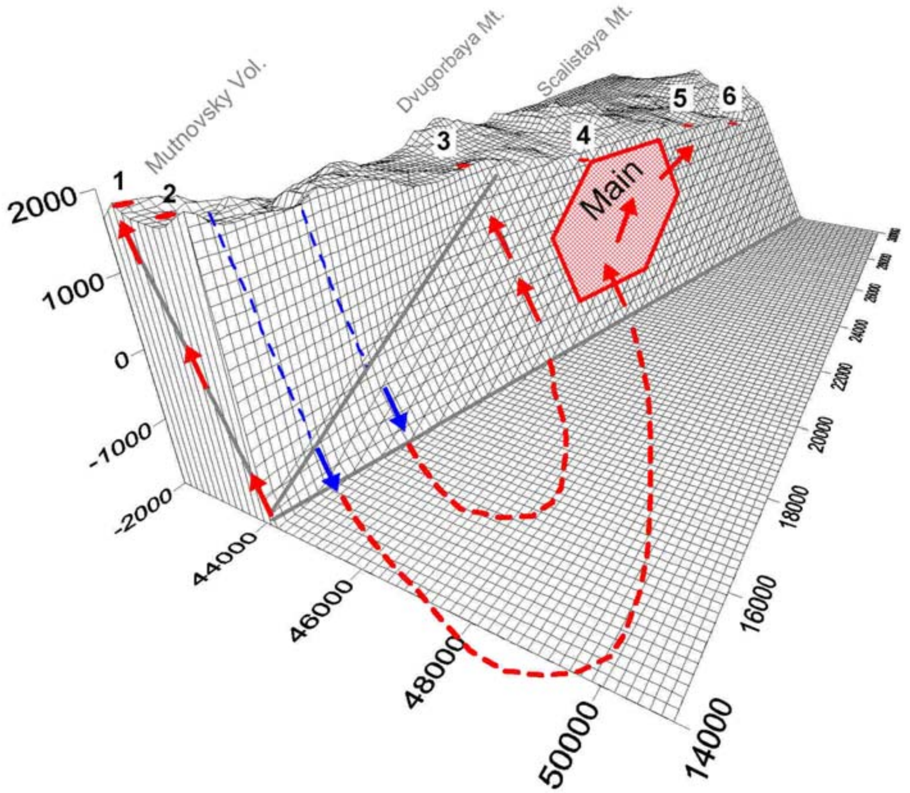


Fig.3 Fault/production plane. Block-diagram of the North-Mutnovsky volcano-tectonic zone included the Main production zone plane. Possible streamlines of fluids from Mutnovsky volcano recharge area to Dachny and Verkhne-Zhirovskoy discharge areas through deeper part of zone, where heat and mass magmatic component exchange took place – are shown by arrows and dashed lines. Main production reservoir shown as polygon area. Steam discharge areas: 1 – Active crater of Mutnovsky volcano, 2 – Bottom Field of Mutnovsky volcano, 3 – North Mutnovsky (West), 4 – Dachny; Hot water discharge areas: 5 – Piratovsky, 6 – Verkhne-Zhirovsky.

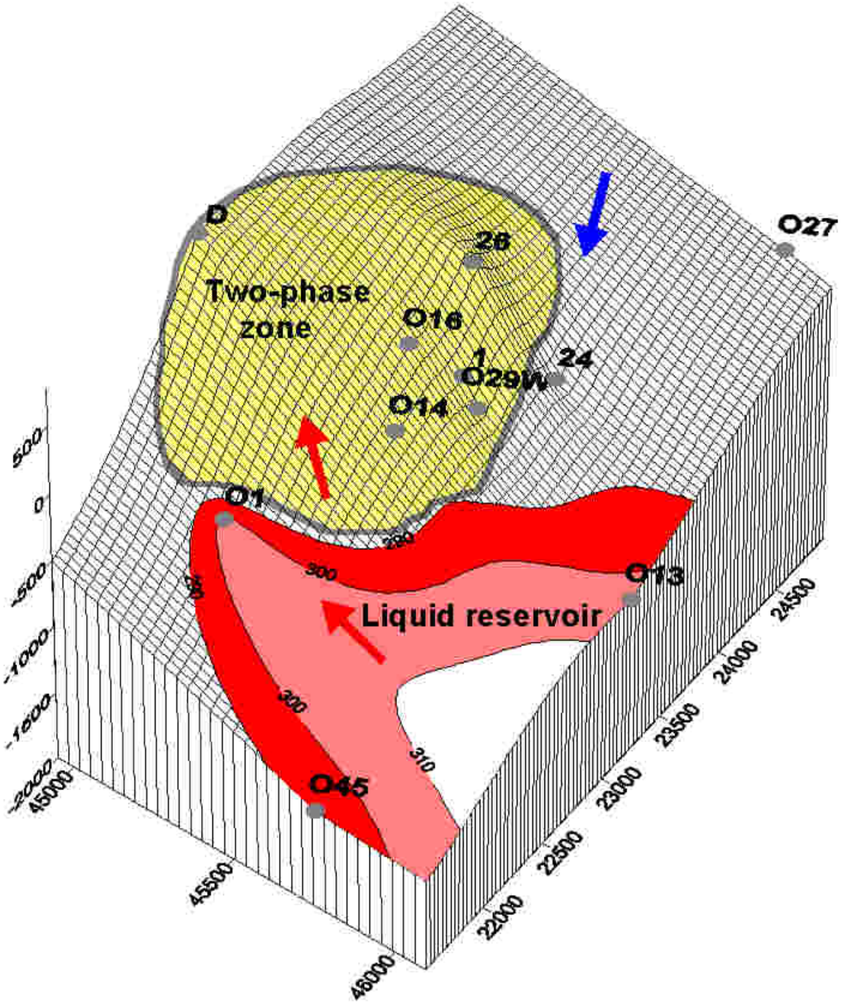


Fig.4 Fault/production plane. Main production zone plane with temperature, phase distributions and production zones locations with corresponding well numbers.

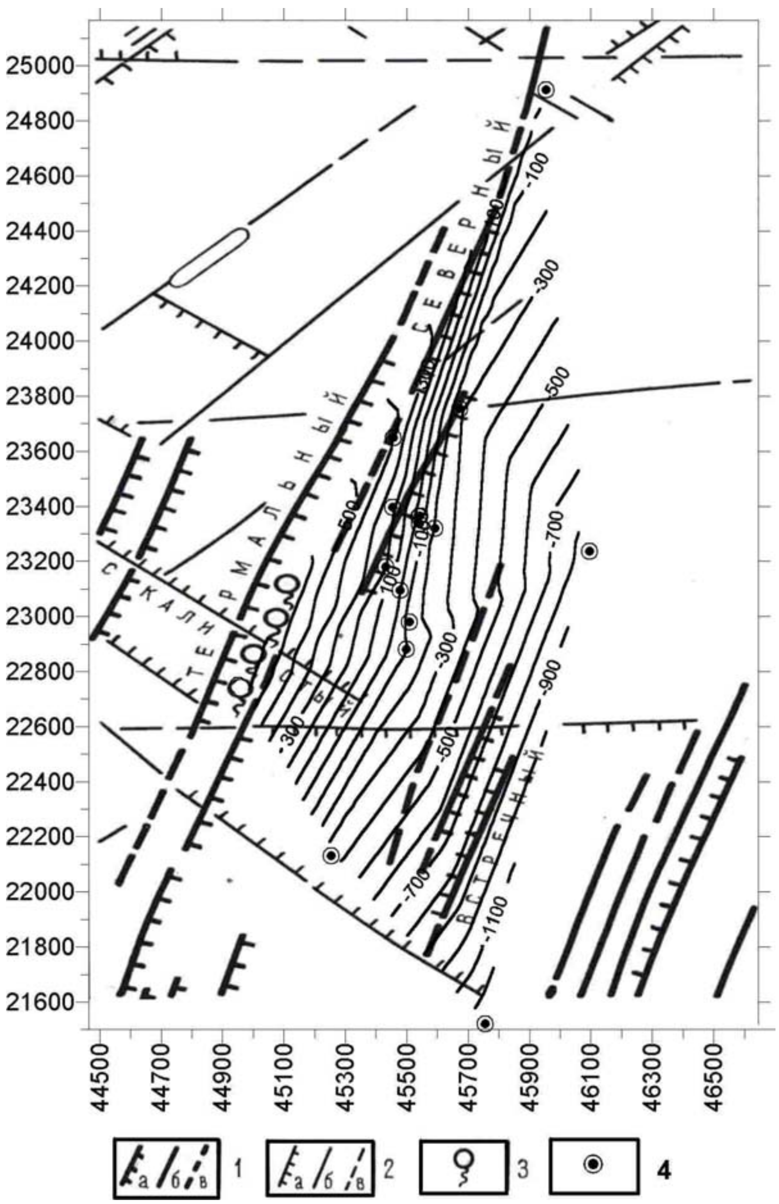


Fig. 5 Fault/production plane. Structural map of the Dachny site (V.L.Leonov, 1986) and top surface of the Main production zone (isolines): 1 – active fractures (north-north-east strike): a – with vertical displacements, б – without vertical displacements, в - assumed; 2- fractures of other strike: a – with vertical displacements, б – without vertical displacements, в - assumed; 3 – thermal manifestations, 4 – points of the production zone intersected by wells (Fig.4).

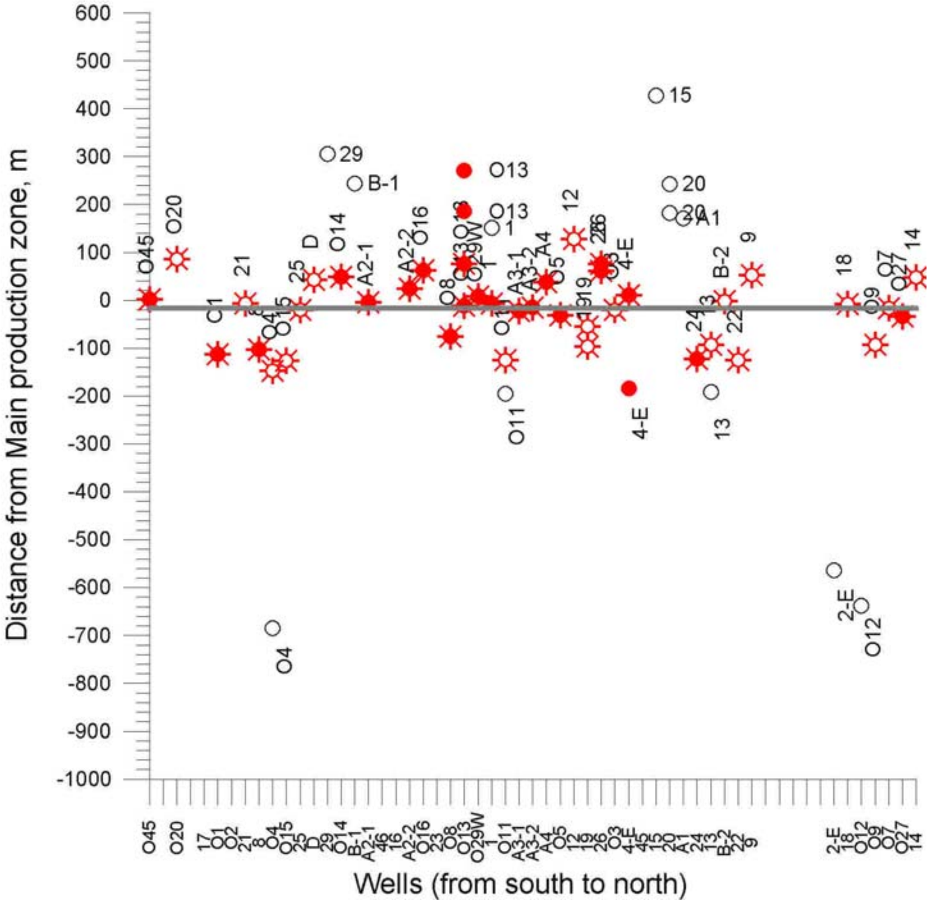
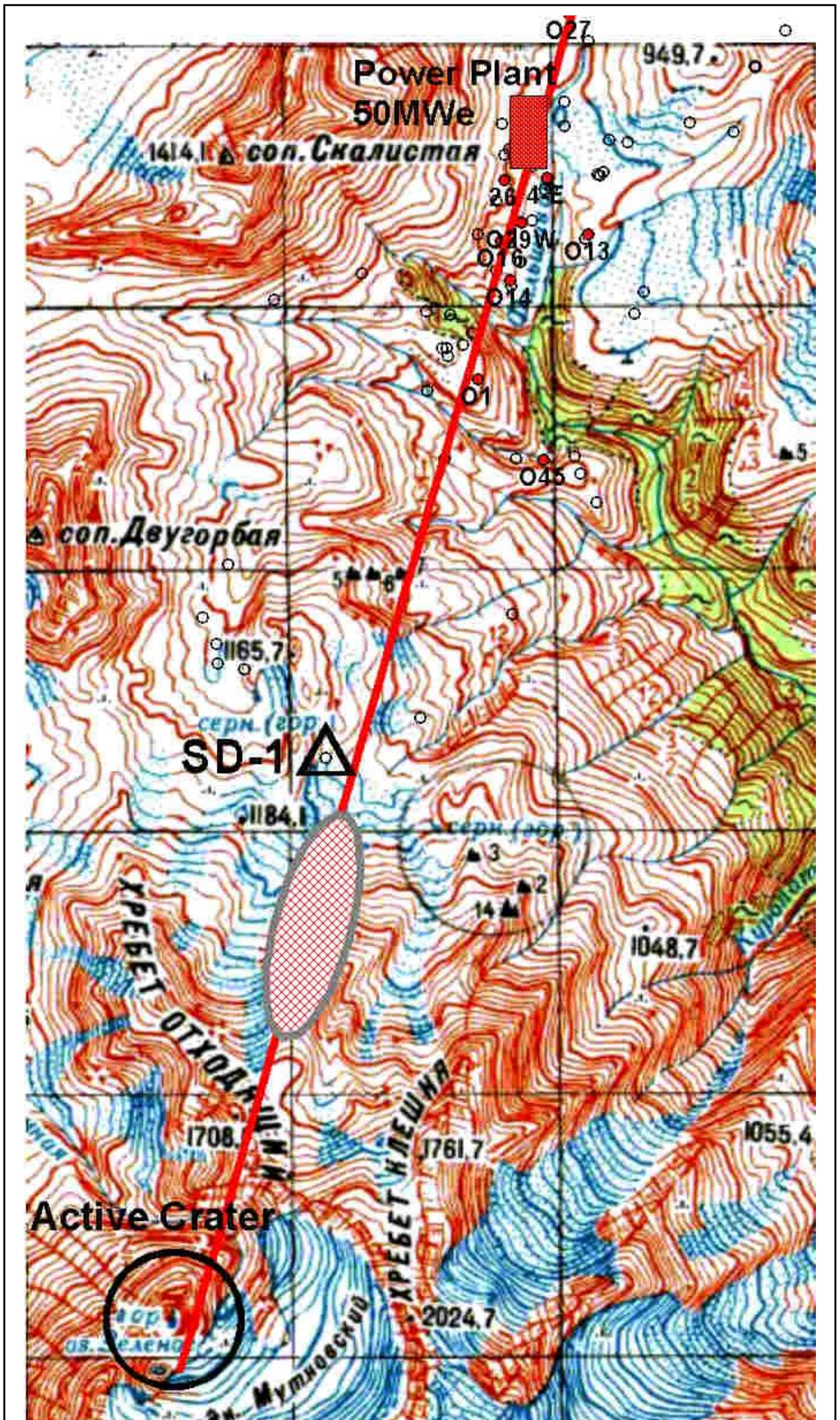


Fig.6 Fault/production plane. Deviation from Main production zone plane ($dz*\cos(60.4^o)$): $Z = -1.691076246561*X +0.48880109651512*Y +65583.1$ to the points of the production (☼✷) and full circulation loss (○●) zones. Filled symbols correspond to production wells.


O27
949,7
Power Plant
50MWe
1414,1 соп. Скалистая
26
4E
O29W
O13
O16
O14
O1
5
O45
соп. Двугорбая
5
6
1165,7
серн. (гор.)
SD-1
1184,1
серн. (гор.)
3
2
14
1048,7
ХРЕБЕТ ОТХОДЯЩИЙ
ХРЕБЕТ КЛЕШНЯ
1708
1761,7
1055,4
Active Crater
гор
оз. Зелено
2024,7
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соп. Мутновская 2322,8
2046,3

Fig. 7 Preliminary drilling plan (2 km size grid used). Existing wells – circles, production wells of the Dachny site - filled circles with numbers, red line – calculated projection of the Main production zone plane at 0 m.a.s.l. (see formulae on Fig.6). Technically possible drilling rig position for scientific drillhole (SD-1) – triangle, drilling targets at elevation 0 m.a.s.l. – filled ellipse.

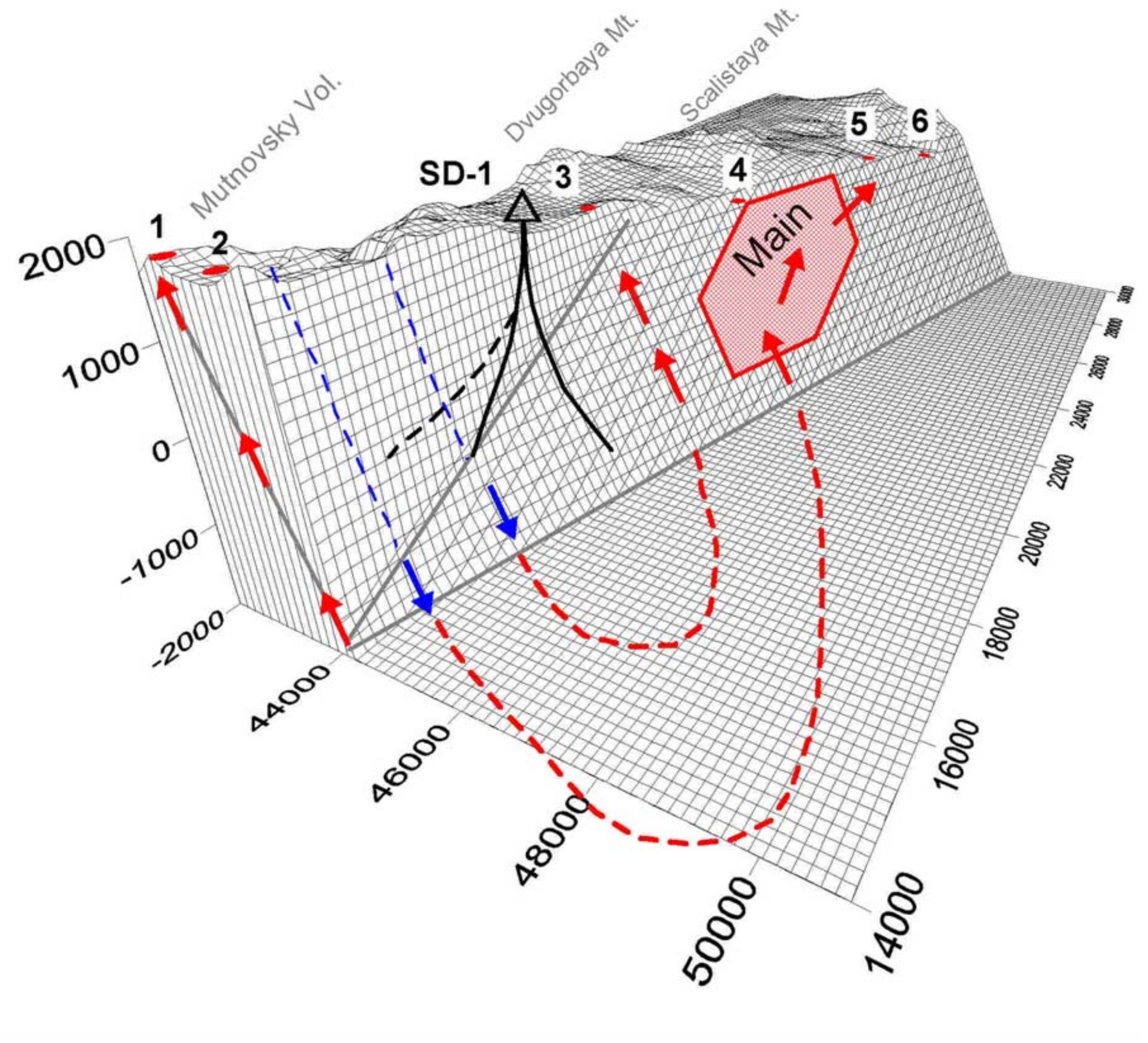

Fig.8 Fault/production plane. Block-diagram of the North-Mutnovsky volcano-tectonic zone included the Main production zone plane and position of scientific drillhole (SD-1) targeted to the plane of hydro-magma-fracturing created by Mutnovsky volcano. Other legend correspond to Fig.1.