MUTNOVSKY SCIENTIFIC DRILLING PROJECT (MSDP): MAGMA-HYDROTHERMAL CONNECTION STUDY

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Abstract

At Mutnovsky Volcano, Kamchatka, Russia, geothermal production is from a single fracture plane that strikes towards the volcano's crater and taps fluid containing a component whose isotopically appropriate source is the Crater Glacier. Mutnovsky's thermal output (>1000 MWt with temperatures above 600°C) and gas emissions (>1000 T/d SO_2) imply shallow magma degassing at a rate on the order of 10 m^3/s. This is exceptional for a volcano in repose, and suggests robust magma convection within Mutnovsky's conduit. With a system geometry characterized by transition from magmatic vapor to dilute hydrothermal fluid at <2 km depth, Mutnovsky is an attractive drilling target for understanding magma-hydrothermal interactions. The Mutnovsky Scientific Drilling Project (MSDP) proposes a comprehensive hydrogeological research program, with stages wherein drilling will play an increasingly important role. Based on results from this first phase, MSDP will drill a more proximal portion of the system that is hotter and more enriched in magmatic components than subsurface fluids previously sampled. Tracer and hydraulic tests will be used to assess overall connectivity of the system, from crater to production zone. Natural events, the numerous strong regional earthquakes and occasional eruptions, will also provide pressure perturbation tests. Finally, if feasibility can be demonstrated, the project will attempt to penetrate Mutnovsky's active conduit.

INTRODUCTION

Geothermal energy use in Kamchatka

The total number of thermal springs in Kamchatka estimated to be 236 (G.F. Pilipenko, 2004, pers. com.). High temperature thermal manifestations occur adjacent to active volcanoes,with the total number of active volcanoes estimated to be 30. Most of the geothermal reservoirs are in Quaternary volcanogenic rocks (layer-type, fractured reservoirs) and in Neogene volcanogenic and sedimentary rocks (vein-type fractured reservoirs). A few geothermal reservoirs are found in metamorphic Cretaceous and Paleozoic rocks.

Conventional geothermal energy use includes high temperature geothermal fields Mutnovsky and Pauzhetsky, and low temperature geothermal fields: Paratunsky, Essovsky, Anavgaisky and Malkinsky. The Mutnovsky geothermal field capacity comprises Verkhne-Mutnovsky power plant (12 MWe installed in 1999) and Mutnovsky itself (50 MWe installed in 2002). The Pauzhetsky power plant started exploitation in 1966 with 5 MWe installed capacity and at this time 8.5 MWe total capacity installed. A 2.5 MWe binary PP feasibility study is on-going.

Other attractive possibilities of high temperature geothermal reservoirs use are Bolshe-Banny, where a 30-40 MWe binary powerplant may be installed, Kireunskaya, where a 10-20 MWe binary power plant may be installed, and Nizhne-Koshelevsky, where a 50 MWe appears to be feasible. Paratunsky geothermal field is operated mostly under free discharge conditions of hot 85-95 °C water with flow rates 220-230 kg/s used for swimming pools, district heating, greenhouses and fish farming. Essovsky and Anavgaisky geothermal fields produce 190 kg/s at 70-80 °C with similar use. Malkinsky geothermal field operated with pumps deliver 20-30 kg/s at 80-90 °C. Future Verkhne-Paratunsky geothermal field use with 280 kg/s of 80°C confirmed capacity is a very promising heat supply of Elisovo city (30,000 population), 50 km away.

The total potential of Kamchatka high temperature geothermal fields for electricity generation is estimated by volumetric method as 1130 MWe x 100 years (excluding the national park-located Semyachik, Uzon and Geyserny geothermal fields), and the total potential of Kamchatka low temperature geothermal fields (less than 150°C) for direct heat use is estimated as 1345 MWh x 100 years (V.M. Sugrobov et al, 1976, 2004).

History of development of the Mutnovsky geothermal field

The Dachny fumarole field was discovered in 1960 by I.T. Kirsanov, and described in details by E.A. Vakin (1976). Exploration work 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 et al,1987, V.M. Sugrobov et al, 1986). Flow tests from production wells conducted during the 1983-1987 time period confirmed the possibility of 50 MWe production based on a sum of the single well flow rate values. A Mutnovsky 50 MWe power plant feasibility study performed by WestJec (1996-1997) was based on TOUGH2-modeling of different exploitation scenarios (A.V. Kiryukhin, 1996) confirmed 50 MWe potential of Mutnovsky geothermal field. Hence, in 1999 a pilot 12 MWe power plant, Verkhne-Mutnovsky, and in 2002 the Mutnovsky 50 MWe powerplant were put into operation. Recent developments of the Mutnovsky project were implemented by SC Geoterm. Fig.1 shows principal features of the Mutnovsky geothermal field and Mutnovsky volcanic area.

Conceptual model of the Mutnovsky magma-hydrothermal system

There are two strong arguments for a direct connection between geothermal production and active magma beneath the volcano. First, there is a single production zone in the Mutnovsky field, a plane of high permeability that if projected towards the volcano intersects the active conduit at shallow depth. Second, there is a component of the producing fluid, defined in terms of O and H isotopic composition, for which the only known equivalent is the crater glacier. The Mutnovsky volcano crater glacier apparently acts as the main source of meteoric water recharge area for the fluids producing by exploitation wells. Meteoric recharge is accelerated by melting of the glacier due to high heat flows in the crater (Bottom Field).

Thermal input to the production zone may also come from other magmatic bodies accumulated in the North Mutnovsky volcanotectonic zone. Some of the wells bottom in diorite intrusives that could represent a local heat source. It is not clear at present whether or not such bodies are directly connected to the magmatic system of the active Mutnovsky volcano, or isolated remains of magma intruded into the plane of hydro-magma-fracturing created by Mutnovsky volcano, or, as some have argued, much older intrusions related to a predecessor magmatic system unrelated to the current volcanic activity. Figure 2 is an interpretive cross section that shows such multiple heat sources.

Upflow of high temperature fluids occurs in the south-west part of the Main production zone, where conditions are liquid dominated at 300oC. Upflow rates estimated based on numerical models are 50-60 kg/s with enthalpies 1270-1390 kJ/kg. 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.

Geology of Mutnovsky volcano

The volcanic geology, structure, and eruptive history has been described in detail by O.B. Selyangin (1993). 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, probably the main recharge source of the hydrothermal system. Enlargement of the crater has exposed a magnificient dike swarm (Fig. 3). If dikes are continuing to intrude the system, either as feeders from depth or as “magma-fracs” off the central conduit, this would provide another means by which heat could be transported beyond the edifice to the zone of geothermal production.

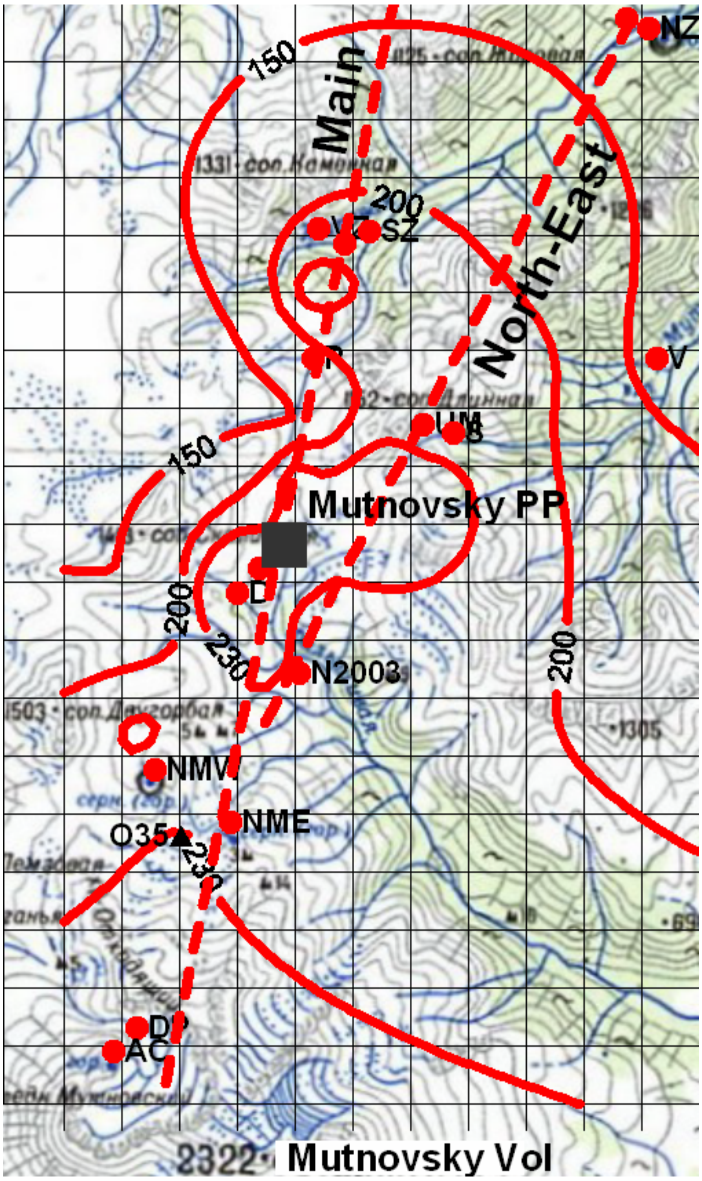

Fig.1 Hot springs and fumarole fields of the Mutnovsky area (filled circles). Counters are temperature distributions at -250 masl. Dashed lines are high permeability plane zones projections, included

production zones of geothermal field and surface thermal manifestations. High permeability plane zones: «Main» (trace at -250 masl) and «North-East » (Kiryukhin et al., 1998, 2005). Triangle- well 035, closest to the Mutnovsky crater well. Grid size is 1 km.

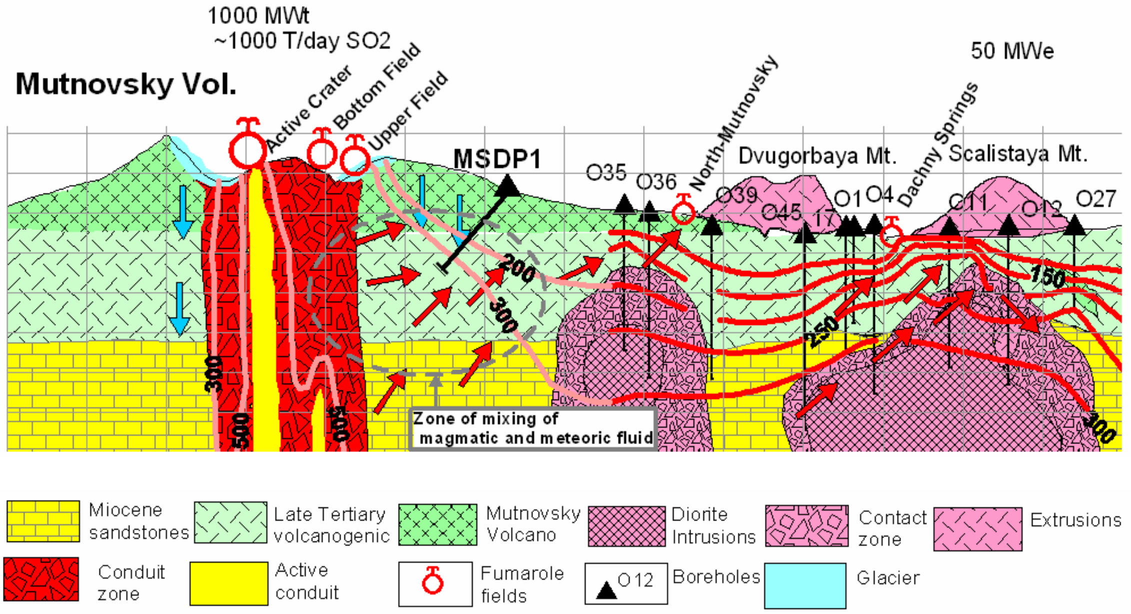

Figure 2: Sub-meridional cross-section and conceptual geothermal/hydrogeological model of the Mutnovsky volcano – Mutnovsky geothermal field system. MSDP1, MSDP2 – potential drilling sites for the Mutnovsky Scientific Drilling Program.

The crater of Mutnovsky III 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. This event appears to have been caused by a dike propagating upward and intersecting the hydrothermal system centered beneath Mutnovsky III, as a crack system opened over a length of a few kilometers, transecting the Mutnovsky III and IV craters and the west flank of Mutnovsky IV.

Mutnovsky's active crater (Mutnovsky IV) has fumaroles as hot as 620oC and emits a continuous SO2-rich plume. Total heat output estimated as 1700 MW (B.G. Polyak, 1988,Y.P. Trukhin, 2003), discharging fumaroles fluids include steam (92.8 wt%), CO2 (3.3 wt %), SO2 (2.9 wt %), H2S (0.6 wt%), HCl (0.3 wt%), HF (0.1 wt%) and H2 (Y.P. Trukhin, 2003, M. Zelensky, 2003). Clearly, the magma column is very close to the surface and must maintain the vigorous upward gas flux by sustained magma convection within the conduit.

Rough estimations of the natural steam upflow rate based on assumed heat output (B.G. Polyak, 1988, Y.P. Trukhin, 2003)) yield to 566 kg/s steam rate with the enthalpy of 3000 kJ/kg. That is equivalent of 480 MWe geothermal Power Plant (if 1.17 kg/s per MWe conversion rate applied to steam at 230-260 bars and 500 oC, O. Fridleifsson, pers. com., 2005). Based on analysis of the 37 geothermal fields case history sustainable exploitation rate is 5.3 times greater than natural upflow rate (S. Sanyal, 2005). This implies the mean possibility of 2544 MWe sustainable production from Mutnovsky volcano conduit zone.

Mutnovsky volcano magma chambers modeling studies performed recently by S.A.Fedotov (2005), I.S. Utkin et al (2005) show the following estimations of the shallow Mutnovsky IV magma chamber parameters: elevation -1.7 km, radius 1.5 km, temperature 900-1250 oC. Heat content of the chamber and adjacent host rocks is estimated to be 3 x 10^{19} J.

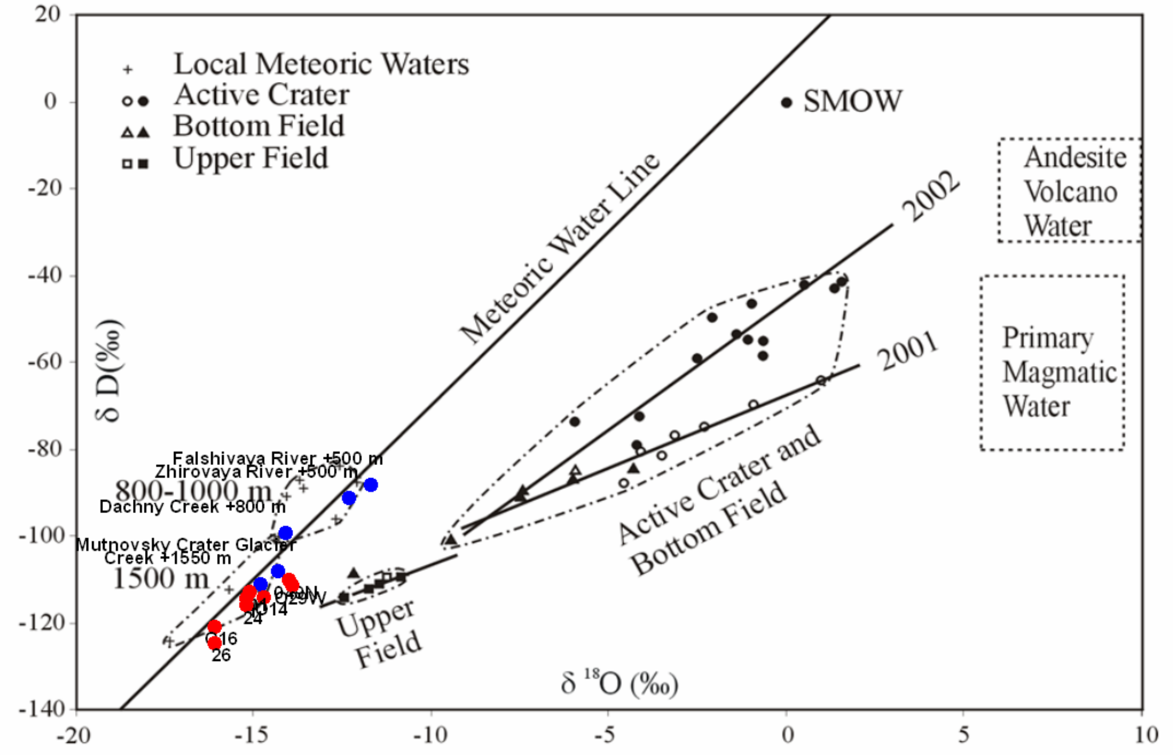

Figure 3: Summarized hydro isotope data on Mutnovsky volcano (after M. Zelensky (2006)) and adjacent geothermal field (after A.Kiryukhin (1998, 2002)).

Fumaroles of Mutnovsky Volcano

Fumaroles of the volcano are localized within three fields: Upper Field, Bottom Field. and Active Crater, hereafter UF, BF and AC. UF and BF are situated 200 m from each other inside Mutnovsky III crater. The active crater of Mutnovsky IV is situated 600 m southwestward, with a variety of hghi-temperature and powerful fumaroles on its floor and western wall. The maximum temperature of gases was 520°C during sampling (620°C in 2005).

In 2001-2002, M. Zelensky obtained 32 samples of volcanic gases. On a δD-$\delta^{18}O$ plot, all sampling points are close to a classic mixing line between magmatic water and local meteoric waters (Fig. 3). However, correlations between isotopic and chemical compositions divide all fumaroles into two groups. Samples from AC and BF fumaroles contain significant amounts of S, HF, HCl and HBr, which are well correlated (R2=0.9-0.96) with isotopic composition, especially with $\delta^{18}O$. All trends on a δD - $\delta^{18}O$ plot almost converge to a point with a value of $\delta^{18}O = -8{,}6 \pm 1$ at zero concentrations of acid gases. Gases from UF contain very low and uncorrelated concentrations of acid gases. This very different behavior may be evidence of two separate hydrothermal systems inside a single volcanic edifice.

The main and the most powerful hydrothermal system discharges at the Active Crater (IV) and the Bottom Field (more than 80% of total discharge). Gases of this system originate from mixing of magmatic 800°C fluid with low temperature (100-150°C) hydrothermal steam. The source of the steam, according to its isotopic composition, may be meteoric waters from above 900m elevation.

Another powerful hydrothermal system discharges as the upper fumarolic field (UF). Fumarolic gases here have a distinct peculiarity: rather high temperature along with a very low content of acids. The hot endmember of this system is meteoric steam at 300°C. The steam mixes with cold meteoric water from 1500m elevation, possibly from the Crater Glacier.

Complementary to the fumarole volatiles and isotopic geochemistry study has been investigation of trace metals in the fumaroles. The solutions in the boilers have compositions that appear to be unique in the world. Their characteristic features are extremely high contents of Cl-ion, Cr, Ni, Co, Ti, V, and B. These elements are extracted from magma and wallrocks by acid magmatic gases and then concentrated in zones of secondary boiling. Thus, there exists a modern ore-forming zone in the region of brine formation.

PROPOSED INVESTIGATIONS

We wish to test the hypothesis that the volcano and the geothermal field are a single magma-hydrothermal system. If the hypothesis is supported by surface observations and by observations and add-on experiments in existing and planned geothermal wells, then we wish to explore the magma-hydrothermal connection directly through dedicated scientific drilling. The project can thus be divided into an initial surface investigation and holes of opportunity phase, and a subsequent deep drilling phase.

SURFACE INVESTIGATIONS

There are a number of surface investigations that will contribute to a test of the single system hypothesis and help to guide and complement later dedicated scientific drilling. From the surface we can see whether the volcano and geothermal system have a single geophysical signature or separate signatures, and whether geophysical events in one part correspond in time with events in the other.

3-D MT imaging of the Mutnovsky volcano and adjacent geothermal field

Thermal horizons, both magmatic and acqueous, have very low electrical resistivity in comparison with host rocks. This gives grounds to use surface electromagnetic methods for their spatial definition. Electromagnetic fields (in particular, those induced in the earth by natural sources located in the ionosphere - magnetotelluric (MT) fields) are widely used to study geothermal and volcanic zones due to their deep penetration into the earth and ability to resolve the parameters of complex geological media, often in cases when other methods do not give adequate results. Geoelectrical models of volcanoes can therefore not only indicate the location of magma chambers but also serve as a reliable basis for assessment of the hydraulic connectedness of the volcanic and associated geothermal systems.

Geological structure of the geothermal areas and volcanoes is often very complicated because of hydrothermal circulation and alteration. 3-D modeling, imaging and inversion tools available now enable adequately high-resolution imaging of the geoelectrical structures of geothermal areas as well as volcanoes (Spichak., 1999).

Foregoing magnetolluric sounding of the Mutnovsky volcano will provide mapping of its magmatic system, determining the fault parameters and guide the best location for subsequent drilling. To this end MT survey will be carried out at the Mutnovsky caldera followed by MT data processing, modeling and interpretation taking into account the geology of the area and MT data measured in the adjacent geothermal field.

Magnetotelluric sounding is probably the best way of attacking the problem of the total heat budget of the volcanic and geothermal system. In order to compare the heat potentials of the Mutnovsky magmatic system and of the adjacent geothermal field the MT sounding of the studied area will be accompanied by reconstruction of corresponding 3-D temperature models. To this end, a new method of the temperature estimation in Earth's interior, called “indirect electromagnetic geothermometer”, will be applied. This is based on using MT data collected on the ground and on the temperature logs available from the drilled wells. Knowledge of both the electrical conductivity and the temperature distribution in the studied area will make it possible to draw important conclusions on the heat balance between the magmatic and geothermal systems, that, in turn, contribute to understanding the volcano-hydrothermal connection.

Knowledge of 3-D geoelectrical structure of the Mutnovsky volcano and its surroundings could be used for scientifically justified monitoring crucial macro-parameters of the magmatic system aimed at probabilistic assessment of the risk of the volcanic activity (Spichak, 2001). In this connection it is important to use the methodology, which will closely link the monitoring results with the internal structure at the moment of the last measurements, in other words, will enable, on the one hand, to update 3-D geoelectric model of the studied area in accordance with the new data collected at the surface or in the drilled borehole and, on the other hand, to take into account the modern 3-D geoelectrical structure of the target when interpreting the monitoring results.

The resistivity data that will come in situ from the drillhole will be used for permanent calibration of MT sounding results, on the one hand, and for monitoring the variations of the fault macro-parameters connecting the volcanic magma system and geothermal field, on the other hand.

Self-potential survey

Self-potential (SP) anomalies are directly related to subsurface heat and fluid movements. Yasukawa et al, 2003 shows the effectiveness of a numerical study on combined resistivity and self-potential modeling to investigate the structure of a volcanic body. This paper shows that a large negative SP anomaly at medium altitude of a volcano, generally interpreted as a surface recharge zone, is not necessarily related to surface recharge but possibly to a high permeability column within the body of the volcano. This column encourages lateral flow, which results in a mixture of meteoric water and hot fluid flowing laterally to the geothermal reservoir. More recent study also shows the effectiveness of SP mapping: In most cases, the streaming potential associated with thermally driven upflow was believed to be the primary cause of the positive anomalies observed around volcanic craters or vents associated with fumarole activity. However, numerical simulations of electro-kinetic potentials recently carried out by Ishido (2004) show that this mechanism is secondary especially for volcanoes having thick unsaturated zone. Instead, in a new quantitative model, the primary cause of the "W"-shaped SP distribution is a combination of the electrokinetic drag current associated with the downward liquid flow in the unsaturated and underlying saturated layers and the presence of a shallow conductor near the volcano summit.

Thus, SP mapping and modeling is a strong tool to investigate the structure of a volcanic body and geothermal reservoir. In studying the Mutnovsky geothermal field, an SP mapping survey should be conducted widely in and around the Mutnovsky volcano. Since theoretically the minimum area of SP mapping should be three times bigger in length than the drilling target depth for an appropriate numerical modeling, the survey area should have a diameter of 6 km or greater for drilling to 2 km. However, in the case of the Mutnovsky geothermal field, SP survey covering the whole Mutnovsky volcano is recommended to understand the total system.

Local networks for seismic and geodetic monitoring

The Kamchatkan regional seismic network was organized in 1962 and now it consists of 41 stations. On-line monitoring of Kamchatka seismicity is based on radio-telemetric seismic stations. Currently, the Kamchatka Branch of the Geophysical Service (KBGS) operates 31 radio-telemetric seismic stations located throughout the Kamchatka Peninsula and on Kamchaka volcanoes. Seismic information is transmitted by radio channel in the UHF band in real–time to operational/receiving centers located in Petropavlovsk-Kamchatsky for data processing (V. Chebrov et al, 2006).

Kamchatka’s regional GPS network (KAMNET) was organized in 1997 and now consists of 18 permanent stations and more than 10 mobile station. GPS station PETS (Petropavlovsk-Kamchatsky) is an IGS station.

In the area of Mutnovsky volcano and Mutnovsky hydrothermal field there no seismic stations. The nearest one is near Gorely volcano at the distance about 12 km to the North. In this situation, it is impossible to define seismic activity of Mutnovsky volcano on satisfactory level. Nevertheless, we can register some local earthquakes, although the determination of hypocenters is not reliable enough. In the Mutnovsky hydrothermal field, the first earthquakes from exploited area were recorded by the Kamchatka regional seismic network during production tests. Intensive exploitation has caused changes in reservoir pressure and other parameters of internal conditions of the upper crust, and this is the likely reason for the induced seismicity. Thus we propose that some seismic processes in this region may be connected with intensive human-caused perturbation of the environment. One of the main tasks for future investigation in this area is acquisition of sufficient local seismic and geodetic observations in order to differentiate between human-caused and natural events and to assess the connectedness of the volcano and geothermal system.

Existing seismic data contains at least a suggestion of continuity along the volcano-geothermal trend, although the low accuracy of hypocenter locations should be kept in mind. Geodetic data will provide a powerful addition to assessing the connectedness. Given the active exploitation of the geothermal system with declining reservoir pressure, the existence of a measurable geodetic signal seems assured. But will there be coupled deflation or perhaps independent inflation of the volcano? If so, what depths of pressure sources are involved? What rates of mass transfer are implied? And how are deformation patterns related to the seismicity? To answer these questions, a local array of seismic and GPS stations is proposed. There should be 5 seismic stations based on Ref Tek equipment. It is logical to combine every seismic station with GPS station for the simultaneous installation and technical servicing.

Microgravity monitoring (H. Rymer, pers. com. 2006)

We propose to establish and monitor a micro-gravity network and a continuous gravity network at Mutnovsky. Both networks will require GPS elevation control. The aim of the micro-gravity and ground deformation network is to quantify any sub-surface mass movements occurring as a result of magma movements, degassing episodes, hydrothermal activity and geothermal exploitation. The spatial resolution of the micro-gravity network will be dictated by the distribution of the gravity stations, but the limiting factor always on the rate of processes that can be detected in these types of surveys is the temporal resolution, dictated by the frequency of field campaigns. As this is likely to be no better than annual at Mutnovsky, we propose to establish an array of 3 or more continuously recording gravity meters. Although the spatial resolution of the data from these instruments will be less good than that of the micro-gravity network, the temporal resolution will allow aliasing by the sampling period of the micro-gravity network to be eliminated. The data provided by these techniques will complement data collected from the boreholes where ‘ground truth’ data on the physical properties of the sub-surface rocks will be obtained. The gravity surveys will provide spatial and temporal control on processes measured independently down the borehole.

We hope to be able to address project objectives suggested as follows:
(i) Monitoring physical parameters to assess the hydraulic connectedness of the volcanic and geothermal systems. Here we will investigate temporal and spatial variations in the density contrast within the hydrothermal system with a view to identifying the steam and water pathways and the magma and volatile conduits.
(ii) In-situ measurement of the response of the magma-hydrothermal system to earthquakes and eruptions, including precursory changes. Here we will use the combination of micro-gravity to investigate the spatial effect and continuous gravity to investigate the temporal effect of variations within the magma-

hydrothermal system as it responds to tectonic and volcanic triggering signals.
(iii) Comparing the conduit environment of a short-repose period volcano with that of long-repose period volcaneso. Here we will use the repeated micro-gravity signals to estimate the rate of change of sub-surface processes at Mutnovsky. This will enable us to compare these with a range of other volcanoes which we are also studying using gravimetry, ranging from persistently active systems at Poás (Costa Rica), Masaya (Nicaragua) and Etna (Italy) to calderas in a state of unrest Krafla and Askja (Iceland), Las Canadas (Tenerife, Spain) and the Campi Flegrei (Italy).
(iv) Determining the overall volatile and thermal budget of the volcano by assessing subsurface hydrothermal advection as well as emission to atmosphere. We would anticipate also being able to contribute to this objective by providing mass estimates for variations within the hydrothermal system.

Fumarole and well fluid geochemistry and microbiology (S.Bortnikova, 2006, pers. com).

Investigation of aqueous geochemistry of the system will be expanded so that analysis of surface and borehole fluids from the north flank of Mutnovsky and the production field span the same range of elements and isotopes as the thoroughly studied crater fumarole fields. These data will permit a much better assessment of Mutnovsky Volcano’s contribution to the geothermal system than is possible now.

High-resolution multilocus sequence analysis of 130 *Sulfolobus islandicus* strains cultured from geothermal regions in North America, the Kamchatka peninsula and Iceland revealed that *S. islandicus* is the dominant cultivable *Sulfolobus* species in the Northern Hemisphere and that there are at least five endemic populations of *Sulfolobus* that are isolated from one another by geographic distance. Due to the nature of their geographic isolation, evolutionary events are likely to have occurred in each of five geothermal communities independently, and therefore may be correlated with the unique geologic history of their individual locale. Based on nucleotide divergence between populations, we estimate that Yellowstone and Lassen populations have been isolated for about 700,000 years, whereas the North American and Kamchatkan populations have been isolated for about 2,000,000 years. These time scales seem to overlap with the geochronology of these different geothermal regions. We have the opportunity to study the genome evolution that has occurred within these populations since they have been isolated from one another. Evolutionary questions about horizontal gene flow and local adaptation using signatures in genome analysis can be answered. The relationship between geologic and evolutionary change in hot spring microbial communities can be used as a metric for calibrating geologic and evolutionary time scales.

In extending microbiological observations to depth in boreholes, there is the possibility of making important observations of thermophiles at pressure that have thus far only been made in a marine environment.

Pressure and temperature monitoring

At this time we have just one well #30 at V-Mutnovsky site, where pressure monitoring with capillary tubing system conducted since 1995 until Sept 2006 (Kiryukhin et al, 2000, 2002, 2006). Tubing was extracted from the well #30 for well valve repair work, and we will need technical assistance from a well service company to reinstall it. The value of such monitoring is soon by the intriguing results depicted in Figure 4. The hydrothermal system appears to function as a sensitive strain meter, and in the case illustrated appears to record strain precursor to a regional earthquake. The utility of pressure sensors in multiple boreholes in assessing connectivity of the system is obvious, and we will attempt to extend such measurements to selected fumaroles within the crater.

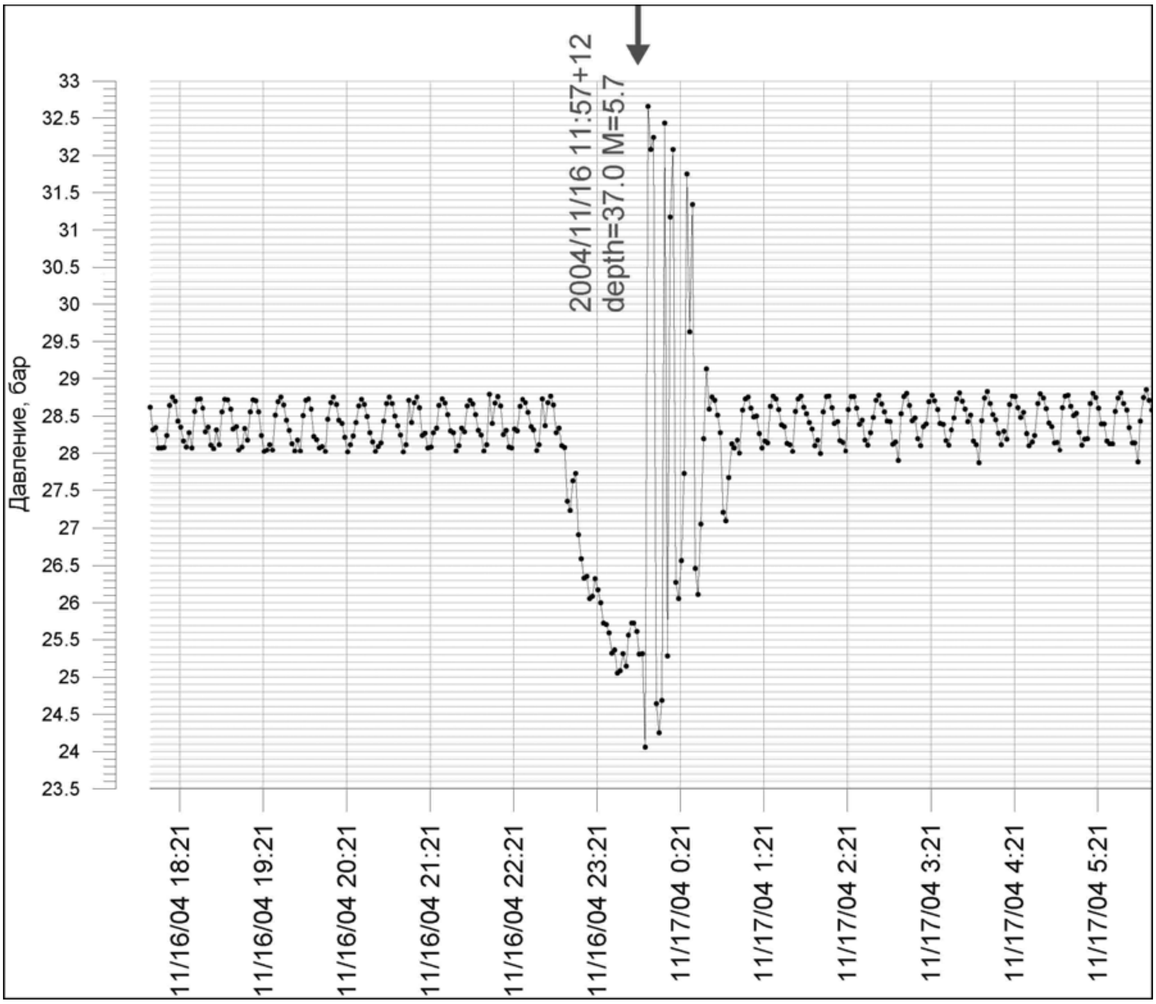

Fig. 4: Pressure in well 30, Mutnovsky geothermal field, with capillary tubing system installed at 950 m depth, in an active fracture zone at 250°C, spanning the time of a regional earthquake. Pressure data is collected every 2 minutes. Pressure usually cycles in well with a frequency 72-180 days^{-1}. Five clear co-seismic (M=4.1-5.9) pressure anomalies were observed during observation period since 1996: pressure drops 0.1- 4.5 bars a few hours before earthquake, and high amplitude pressure cycling after earthquake.

Heat output from fumaroles fields

Mutnovsky's thermal output (>1000 MWt with temperatures above 600°C) and gas emissions (>1000 T/d SO_2) imply shallow magma degassing at a rate on the order of 10 m^3/s. This is exceptional for a volcano in repose, and suggests robust magma convection within Mutnovsky's conduit. Nevertheless re-estimation of the thermal output of Mutnovsky crater (AC, BF, UF), North-Mutnovsky, Dachny, Upper-Mutnovsky fumaroles fields and recently created as a result of steam explosion New-2003 fumarole field using modern infra-red survey and T-loggers observations – strongly required.

Since Mutnovsky geothermal field exploitation started in 1999 seismic and explosion activity in the North-Mutnovsky zone increased: four steam explosions took place, one of them in June 2003 created boiling pits in South-Dachny site, last explosion on April 17, 2007 created a large pit of 30 m depth and

150 m diameter in the Active Crater of Mutnovsky (G. Gavrilenko, D. Melnikov 2007, pers. com.). Satellite images (ASTER) clearly show IR-anomalies of Mutnovsky and Gorely volcanoes craters (“F” and “G” correspondingly) and four IR-anomalies in Mutnovsky geothermal field area (“A”, “B”, “C”, “D”), which may host explosion activity too (Fig. 5).

In summer 2007 helicopter’s MI-8 infra-red survey was done using FLIR camera S40 to identify surface temperature distribution and points of the prominent steam discharges of the Mutnovsky crater floor and adjacent geothermal field areas. Based on IR-survey performed F-anomaly include known thermal anomalies of the Active Crater (AC), Bottom Field (BF) and upper field (UF), and a new thermal anomaly 300 m west to Bottom Field (BF) was detected too (Fig. 6). Besides of this a new thermal spot was found in AC. Radial fracture type thermal anomaly detected inside of phreatic explosion-2000 lake, lake itself disappeared, while water still trapped in the fractures of the lake bottom. Lake water recharge into hot subsurface of the crater floor may trigger new steam explosions.

“B” and “C” ASTER anomalies really correspond to fumaroles fields known with the names Dachny, Utrennee, Utinoe, Medvejie and sites of the PP waste hot water disposal at the earth surface. “A” thermal anomaly corresponds to recently (June 2003) created by steam explosion boiling pits at the South-Dachny site. “D” thermal anomaly corresponds to Verkhne-Mutnovsky waste hot water disposal at the slope below.

The surface temperature distributions of the fumaroles fields integrated with ground based temperature-loggers transient data suggested to be used to renew thermal output estimations above mentioned. For this purposes inverse numerical modeling (iTOUGH2) will apply.

Its may be useful too to do correlation analysis of fluid withdrawal in geothermal field versus seismic and steam explosions activity.

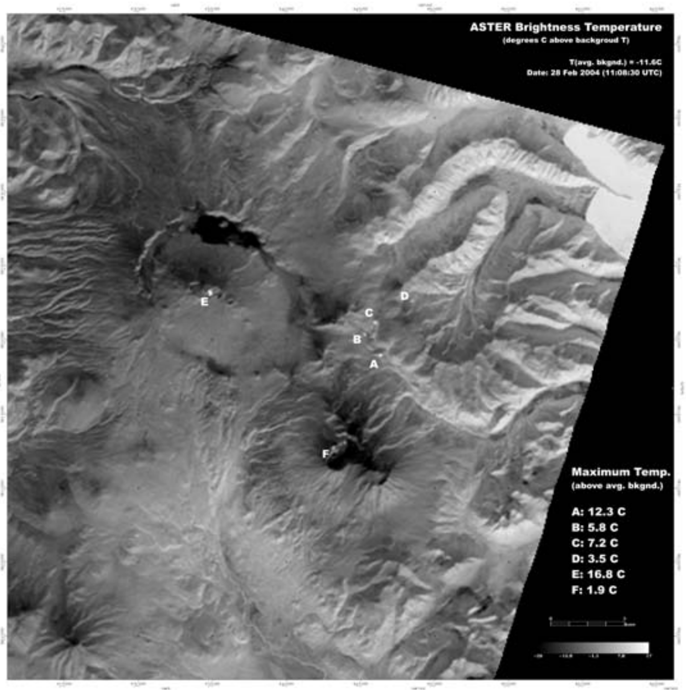

Figure 5. Heat anomalies, detected in Mutnovsky area using ASTER images (data from M. Ramsey, pers. com. 2007). F – Mutnovsky volcano crater, E – Gorely volcano crater, A- New-2003, B – Dachny, C - Mutnovsky PP, D – Verkhne-Mutnovsky PP.

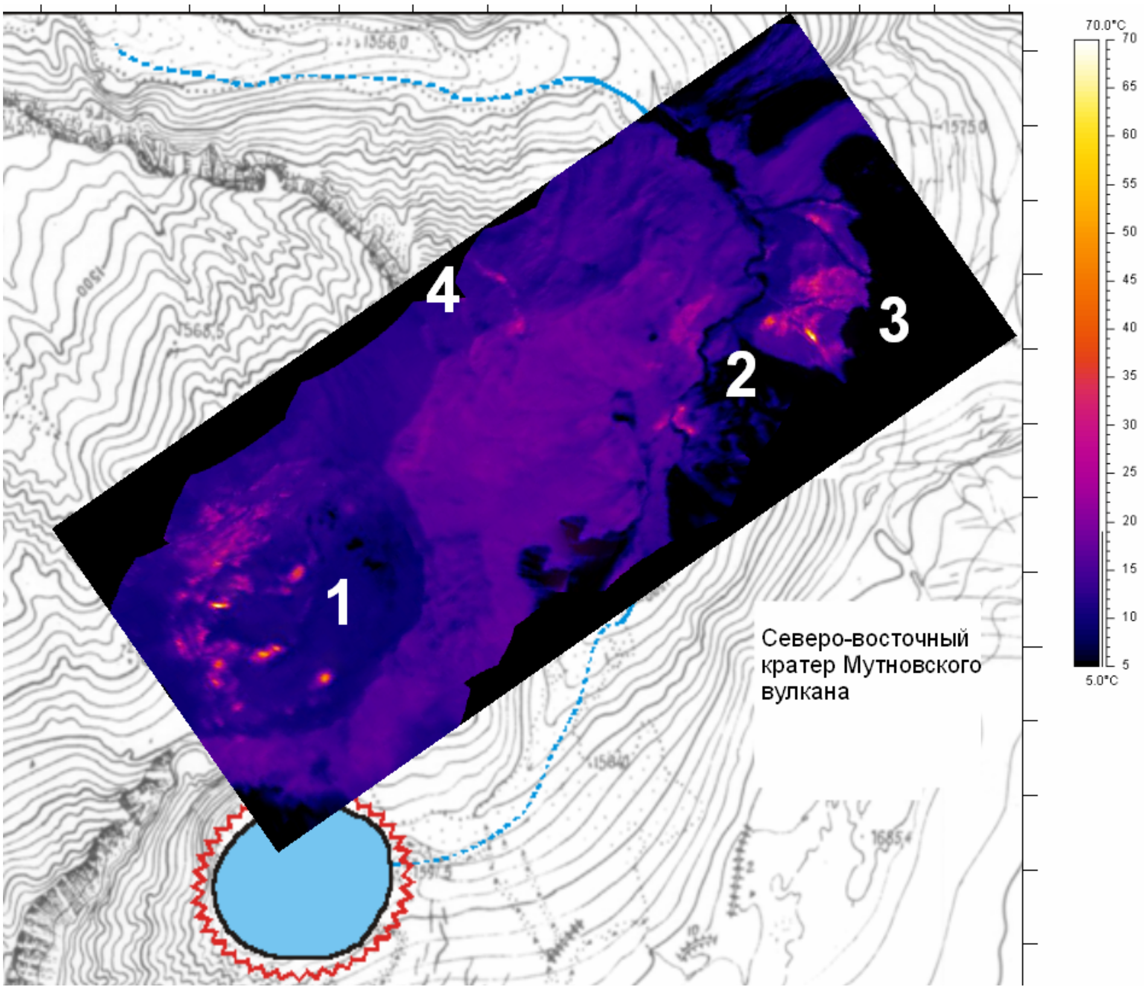

Figure 6. Heat anomalies in Mutnovsky volcano crater detected by helicopter IR-survey (A. Kiryukhin, S. Rose, 2007). Heat anomalies: 1- Active Crater (AC), 2 – Bottom Field (BF), 3 – Upper Field (UF), 4 – New thermal anomaly. Note this area correspond to point “F” in the Figure 5. IR-survey resolution is 1.6 m, grid 100 m.

ANALYSIS OF CORE SAMPLES

A considerable amount of core has already been acquired in the course of exploration and development of the Mutnovsky geothermal field. Thus, some analytical work can be initiated now. Coring will be a priority in future scientific boreholes, which will be continuously cored where possible.

Physical parameters

The following parameters are planned to be measured - density, porosity, gas permeability, pore space structure, microfracture network, sonic velocities, geomechanical characteristics (compression and tensile strength, elastic modulus), thermal and magnetic properties, and then interpreted according to the rocks petrography.

The world experience of geothermal systems has shown very high variety in magnitude of rocks alteration and properties; the alterations can be sharp. The advantage of the proposed complex analysis is to avoid mistakes connected with heterogeneity of rocks. In combination with petrologic and chemical core analysis this will help with the interpretation of geophysical logging and can be used as a basis for reservoir numerical modeling and for modeling the dynamics of volcano deformation in response to changes in hydrothermal and magma pressurization. Another result will be additional information about the evolution of Mutnovsky volcano.

Whole rock composition

The project will reveal the internal geochemical stratigraphy of Mutnovsky volcano. This work will involve flow by flow, high quality geochemical analyses of drill core recovered by the project. Additionally, surface samples will analyzed, in order to integrate this work with what is known of the surface geology and geochemistry of the volcano. The analyses of major and trace elements will be by X-Ray Fluorescence Spectroscopy (XRF) employing the same techniques that were used for the successful Hawaii Scientific Drilling Project (Rhodes and Vollinger, 2005) and for the Tatara - San Pedro Project in Chile (Dungan et al., 2001). The data will be used to construct a geochemical stratigraphy of the volcano, identify major magma types, the magmatic processes that have modified them, and elucidate the long-term magmatic history of the volcano. It will also serve to identify hydrothermal alteration processes, and the extent of alteration of the original magmas.

Hydrothermal petrology (G. Bignall, pers. com, 2006)

A goal of this analysis is to understand the permeability controls and chemical evolution of high-temperature, magmatically-driven hydrothermal systems, mechanisms for focussing ore-formation, and energy use of Mutnovsky-type geothermal resources. By understanding the physical-chemical processes within the active hydrothermal system, hydrology and interaction between hydrothermal and magmatic environments, we aim to develop predictive models for ore formation and deep geothermal resource viability in comparable geological settings (e.g. in New Zealand, Japan, Indonesia etc).

We will use a combination of petrography, SEM-CL imaging, microthermometry and chemical analysis of fluids trapped in minerals (as “fluid inclusions”) to resolve the magmatic, lithologic and hydrothermal control on brine composition in the Mutnovsky magmatic-hydrothermal system. This will lead to an understanding of the hydrology, temporal and spatial evolution of fluids in the magmatic-hydrothermal environment, and conditions for *focusing* ore mineralization, with predictive value for mineral exploration. Will changes in temperature and/or fluid composition be recognized from secondary mineralogy and composition of the trapped fluids? We are convinced project goals to resolve Mutnovsky magma evolution, fluid exsolution (H_2O, CO_2, SO_2 and HCl), and transfer of chemical components between the magma and hydrothermal fluid will prove fundamental to better understanding magmatic-hydrothermal ore deposit formation.

Complementary to understanding the controls on permeability and fluid flow in the active magmatic-hydrothermal system, is research concerning the hydrology and chemical structure of Enhanced Geothermal Systems (EGS). In several countries, deep (>5km) drilling has the potential to expand the exploitable volume of a geothermal reservoir by tapping fluids at greater (even supercritical) temperatures and pressures, and/or artificially stimulating regions of low permeability. If EGS energy resources are to be successfully developed worldwide (including in Kamchatka), it will be essential to understand the nature of interconnected fracture networks, mineral (vein) deposition, formation-related permeability and how fluid pathways and heat exchange surfaces are maintained through the evolution of the magmatic-hydrothermal system. Deep drilling at Mutnovsky is the ideal opportunity to research these issues.

Magmatic intrusions provide the heat source for many long-lived, high-temperature geothermal systems, and can produce a large volume of pseudo-plastic rock at relatively shallow depths, at temperatures and pressures similar to brittle-plastic transition conditions in the Earth's crust. The nature of non (or short-lived) brittle rock behavior is an important consideration for future development of high temperature EGS systems, as the onset of plastic conditions closes interconnected pore spaces and restricts hydrostatic fluid circulation (effectively controlling the depth of deep hydrothermal circulation). It is suggested that the Mutnovsky ICDP drilling will transect the active geothermal system and potential ore-forming environment. The region of interaction between the active magmatic and hydrothermal systems will thus provide a unique opportunity to test our understanding of vein-hydrothermal mineral formation and chemical evolution of high temperature, magmatic-hydrothermal system.

We propose three-stage involvement in the Mutnovsky MSDP drilling programme:

1. Based on experience in New Zealand, Indonesia, Japan and elsewhere, we can provide expert geothermal advice to Geotherm during their proposed ("make-up") drilling programme at Mutnovsky. This will provide invaluable information for future siting the MS DP well.

2. Fluid inclusion characterisation, temperature and salinity measurements during MSDP well drilling. This would provide "real-time" temperature, fluid chemistry information, as the MSDP well penetrates the Mutnovsky geothermal system, and magmatic environment beneath Mutnovsky volcano.

3. Post-drilling fluid inclusion, SEM-CL imaging and petrographic examination of core and cuttings from the ICDP well, to fingerprint the mineral-depositing system, and characterize fluid flow and permeability controls within the high-temperature magmatic-hydrothermal system.

   Fluid inclusion thermometry and chemical analysis of the trapped fluids using Laser Ablation ICP-MS will provide important new insight into magma-fluid-rock interaction processes, and physical-chemical evolutionary trends of fluids in the Mutnovsky magmatic-hydrothermal system. Indeed, fluid inclusion studies are essential for establishing the role of brine chemistry, and will test hypotheses about depositional processes (such as fluid mixing, phase separation, etc) in the formation of mineral (ore) deposits.

   SEM-CL imaging will reveal chronological and physical relationships of precipitated quartz (i.e. microtextural features, such as cryptic alteration, recrystallisation and fracturing) in the Mutnovsky system, and differentiate possible hydrothermal mineral depositing events

Source term for magmatic volatiles (A. Simon, pers. com., 2007)

The gas and heat output of the volcano can be viewed as providing a measure of the amount of magma undergoing decompression and cooling, respectively, per unit time. Taking the rough estimate of Mutnovsky's fumarolic SO2 output of 1000 Tons/day and applying a value of solubility of S in basaltic andesite of 400 ppm yields a result that about 1 m^3/s of magma must be decompressed to maintain this discharge rate. This is not insignificant, being equivalent to the current rate of extrusion of dome lava at Mount St Helens volcano. Yet, Mutnovsky is not erupting. The only obvious explanation for this behavior is that magma is vigorously convecting within the conduit, that is it is undergoing decompression but the degassed magma is flowing back down the conduit rather than erupting. An ascent rate of 1 cm/s, equivalent to that commonly inferred for lava eruptions, over a cross sectional conduit area of 100 m^2, would supply the observed SO2 discharge.

Lavas and tephra erupted at Mutnovsky are the surface expression of a magma plumbing system which originates at the slab-mantle wedge interface. Magma is generated at this interface as the direct result of slab dehydration which provides the chemical components (H_2O, F, Cl, B, P, *inter alia*) necessary to flux melt the mantle wedge. The ascending magma (melt + crystals ± exsolved volatiles) thus contains chemical inputs from the ocean slab, mélange sediments, mantle wedge and, most likely, material ingested and assimilated during ascent. The role of volatiles is not only important in controlling the extent of partial melting in the mantle wedge, but also the eruptive potential of the magma once it ponds near Earth's surface. Thus, there is a critical need to quantify the physico-chemical controls on melt volatile solubilities over the PT range encompassing the entire plumbing system in order to understand better their role in the evolution of the magmatic system and, ultimately, in driving eruptions. Most important is the need to quantify the pre-eruptive volatile content of melt and understand how changes in PT and the bulk melt composition affect volatile solubilities, hence degassing.

Melt composition appears to play the dominant role in controlling the style of eruption (i.e., explosive vs. quiescent) owing to the relationship between composition and viscosity and the importance of the latter in controlling the ability of exsolved volatiles to coalesce and develop the overpressure required to drive eruptions. It is well recognized that catastrophic eruptions are more closely related to high-silica magma systems suggesting that the evolution of an initially mafic melt towards a more SiO_2-rich composition, owing to crystal fractionation, has important implications for future eruptions. Super-eruptions may occur because volatile saturation in high-silica melts is reached early, or during extended periods of repose, and the volatiles are able to coalesce within, but not escape, the magma chamber until the gas pressure exceeds the lithostatic pressure and the excess pressure of the gas phase exceeds the plastic strength of the magma. A comprehensive understanding of the relationship between volatiles and melt composition can best be achieved by identifying a single volcanic complex which offers the ability to quantify the relationship between these two parameters. Mutnovsky volcano is such a natural laboratory as it has produced lavas spanning the range from basalt to rhyolite erupted in a narrow space-time window from what may be a single feeder zone sourced from (potentially) a single, evolving magma chamber which is periodically recharged by more mafic magma. In addition to the accessibility to compositionally-variable lavas, Mutnovsky is actively degassing and the composition of the fumaroles may provide information bearing on the eruptive potential of Mutnovsky. Fumarolic discharge of volatiles at temperatures up to 700°C, with magmatic isotope signatures (Serafimova, 1966; Taran, 1992), indicates that the melt phase is currently degassing, but the composition of the melt is unknown. One significant outcome of the proposed study is to use the composition of the fumaroles to constrain the composition of the currently degassing, but not yet erupted, melt. This information will prove invaluable to the volcanic hazard prediction both at Mutnovsky and volcanic centers worldwide.

Melt and aqueous fluid inclusions hosted in phenocrysts in the lavas at Mutnovsky will be used to constrain: 1) the pre-eruptive volatile contents of the melt phase; 2) the composition of the exsolved volatile phase; 3) the effect of melt composition on volatile solubilities; 4) the relationship between melt composition and fumarolic discharge; and 5) the source of volatiles (i.e., mantle, slab, crust). Silicate melt inclusions are small volumes (up to several 100 µm diameter) of silicate melt which is trapped in crystals during growth of the latter. Aqueous (H_2O-CO_2-NaCl-KCl-$FeCl_2$-$MgCl_2$-etc) fluid inclusions are likewise small volumes of an exsolved volatile phase trapped either during crystal growth, in fractures which occur and seal at the magmatic stage and/or in fractures which occur and seal post-magmatically. Melt and aqueous fluid inclusions can provide information on the composition of the magmatic phase assemblage over the entire duration of magmatic activity, provided that suitable samples are available. The major, minor and trace element composition of melt inclusions can be quantified using electron probe microanalysis (EPMA), laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) and Fourier transform infrared spectroscopy (FTIR). The H_2O and CO_2 concentrations, determined using

FTIR, of melt inclusions can be used to calculated the depth of entrapment. LA-ICPMS and SIMS can be used to determine ratios of important isotopes which provide information on the source of volatiles and melt at Mutnovsky. For this project, lavas from all phases of eruption at Mutnovsky will be collected. The hand samples will be crushed to allow petrographic examination of large, single crystals of olivine, pyroxene and plagioclase all of which will be handpicked based on the presence of visibly recognizable fluid and melt inclusion assemblages.

Data from isolated melt inclusions usually provide more questions than answers; thus, only FIAs and MIAs, populations of contemporaneously entrapped fluid and melt inclusions will be pursued. Melt-inclusion-bearing phenocrysts will be studied optically in the appropriate immersion oil to verify that inclusions remained a closed system after entrapment; i.e., no cracks or capillaries are present. Open-system melt inclusions yield no data on pre-eruptive volatile concentrations. Melt inclusions will be polished to the surface and analyzed first by EPMA. Inclusions from a given MIA will then be analyzed by LA-ICPMS to determine their trace element composition. EPMA data will be used as the internal standard to reduce LA-ICPMS data. Fluid inclusions will be studied in doubly-polished thin sections. Microthermometrically-determined Na concentrations will be used as the internal standard to reduce LA-ICPMS data. The melt inclusion data will constrain the compositional evolution of the magmatic system over time and provide insight into rejuvenation of the magma by periodic input of hotter, less evolved magma. The detailed study of FIAs and MIAs will constrain the effect(s) of melt composition on the exsolved gas composition. By comparing the volatile composition of melt and fluid inclusions with fumarole emissions, a comprehensive model will be built which allows one to predict the composition of the melt phase at depth during repose.

DRILLING

Once we have established through surface observations that our hypothesis of a direct magma-hydrothermal connection at Mutnovsky is correct, then our objective will become to penetrate and sample the transition zone. Such a borehole will become a key observation midpoint in a ~10-km-long fracture-hosted system with active magma at one end and geothermal production at the other. The magmatic end will be monitored at the surface within Mutnovsky III and IV craters and the geothermal end will be monitored at depth through production wells. This concept is shown schematically in Figure 5. In addition to obtaining direct information on the current chemical and physical state of the system at this intermediate point, it will be possible to use time-dependent behavior to determine the hydraulic characteristics of the entire system. Perturbations from the steady state arise from production at the geothermal end, eruptive events at the magmatic end (with obvious fluctuations short of eruption), stress changes induced by regional earthquakes, and pressure tests of the scientific borehole itself.

The plan for drilling will be developed in parallel with progress in the surface investigations. However, some aspects can be explored now. It seems clear that we will want to penetrate as far beneath the Mutnovsky edifice and as close to the active conduit as possible. The borehole will therefore need to be directionally drilled. Its path should take it across the projection of the plane of geothermal production.

We will continue discussions concerning the extent to which geothermal and scientific objectives can be combined and hence costs shared. For example, whether this could be a geothermal well that will be deepened for the scientific objectives. An important question is how close the well or wells can be sited to the volcano. This will be a tradeoff between road-building and water supply problems and the length of the borehole. The depth at which deviation of the trajectory begins must be carefully planned to prepared for blowout protection but at the same time allow for maximum core recovery within the zone of fluid flow. To this end we propose a mini-workshop in Potsdam to explore and plan the scientific possibilities in drilling the transition zone.

If drilling conditions are favorable and data indicate that the active conduit is within reach, we will propose a subsequent stage of the project aimed at intersecting, quenching at depth, and sampling magma. This is an objective embraced by the decadal white paper of ICDP, and would provide an unprecedented "ground truth" in volcanology, both in terms of the internal structure and conditions of volcanoes and the state and composition of unerupted magma.

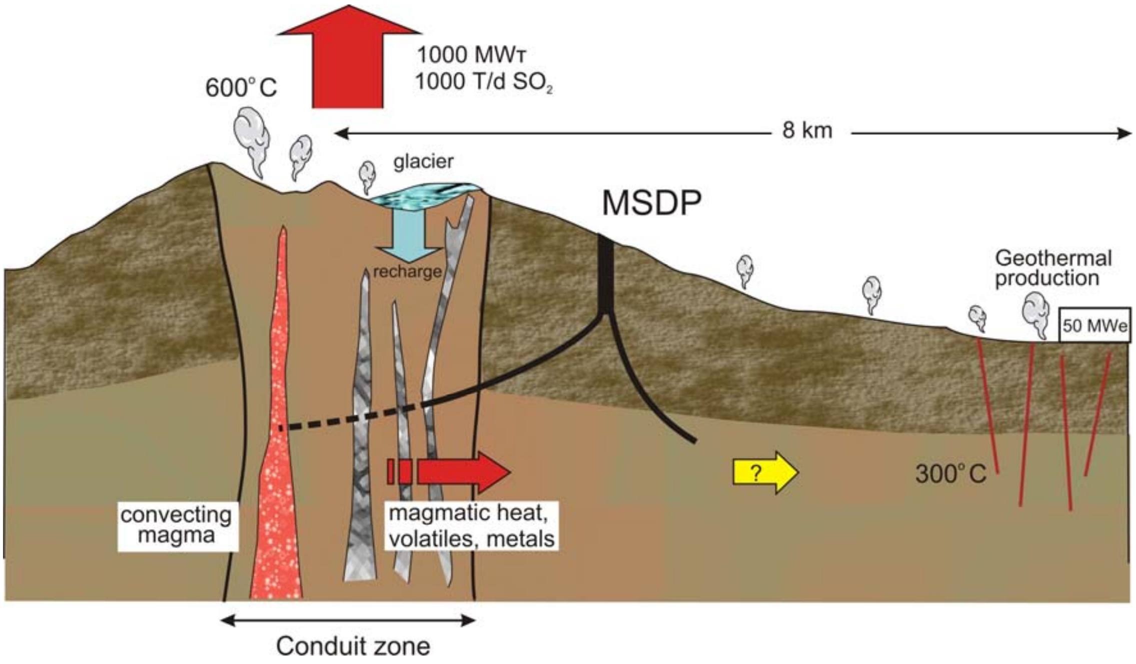

Fig. 5: MSDP drilling will penetrate the connection between the geothermal system and the geothermal production regime and the active volcanic conduit, where the high rate of magma degassing implies the existence of a convecting magma column (by J. Eichelberger, 2007).

Conclusions

1. At Mutnovsky Volcano, Kamchatka, Russia, geothermal production is from a single fracture plane that strikes towards the volcano's crater and taps fluid containing a component whose isotopically appropriate source is the Crater Glacier. Mutnovsky's thermal output (>1000 MWt with temperatures above 600°C) and gas emissions (>1000 T/d SO_2) imply shallow magma degassing at a rate on the order of 10 m^3/s. This is exceptional for a volcano in repose, and suggests robust magma convection within Mutnovsky's conduit. With a system geometry characterized by transition from magmatic vapor to dilute hydrothermal fluid at <2 km depth, Mutnovsky is an attractive drilling target for understanding magma-hydrothermal interactions.

2. The Mutnovsky Scientific Drilling Project (MSDP) proposes a comprehensive hydrogeological research program, with stages wherein drilling will play an increasingly important role. Based on results from this first phase, MSDP will drill a more proximal portion of the system that is hotter and more enriched in magmatic components than subsurface fluids previously sampled. Tracer and hydraulic tests will be used to assess overall connectivity of the system, from crater to production zone. Natural events, the numerous strong regional earthquakes and occasional eruptions, will also provide pressure perturbation tests.

3. Finally, if feasibility can be demonstrated, the project will attempt to penetrate Mutnovsky's active conduit.

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