Mutnovsky Scientific Drilling Project Workshop:
The Magma-Hydrothermal Connection

What is the relationship between volcanoes that ring the Pacific plate and hydrothermal systems? A typical geometry is a stratovolcano or dome complex with fumaroles at the summit and hydrothermal manifestations on its flank. Analogous subsurface mineralization is porphyry copper deposits flanked by shallow Cu-As-Au acid-sulfate deposits and base metal veins. Possible reasons for this association are: (1) flow of magmatic gas and heat from the volcano's conduit, mixing with meteoric water; (2) dikes extending from or feeding towards the volcano that extend well beyond the surface edifice; or (3) peripheral hot intrusions that are remnants of previous volcanic episodes and unrelated to current volcanism.

At Mutnovsky Volcano, Kamchatka, Russia, evidence for scenario 1 is that 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^{o}C) and gas emissions (>1000 T/d SO_2) imply shallow magma degassing at a rate on the order of 10 m^3/s, ten times the current magma discharge rate of Mount St Helens. This is exceptional for a volcano in repose, and suggests robust magma convection within Mutnovsky's conduit. Moreover, the magmatic contribution is an underestimate if the hydrothermal system is "scrubbing" gas output, an important issue in volcano monitoring.

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. Few sites can boast infrastructure, access, and expertise for drilling so close to an active crater. Mutnovsky's geothermal power plant provides one third of Petropavlovsk's electric power, and plant operators have an ambitious drilling program to sustain and expand production.

Introductory talks
Thirty-nine presenting scientists from six countries, as well as many additional participants for a total of perhaps 70, met in Petropavlovsk-Kamchatsky during the last week of September to consider scientific drilling at Mutnovsky. For Americans who think of the United States as a big country, the 9-hour, 9-time zone flight from Moscow to Petropavlovsk was enlightening, and about the same length as their trip from the US to Russia. Indeed, the loss of direct airline connections between the US and Russian Far East meant that some participants had to circle the globe to attend.

In the opening session, we were welcomed by Alexander Orlov, Deputy Director, Kamchatka Government Natural Resources Use and Environmental Protection Department, and Evgenii Gordeev, Director, Institute for Volcanology and Seismology (IVS), Academy of Science of the Russian Far East, where the meeting was held. The project concept, as introduced at the start of the meeting, was to drill and sample the magma-hydrothermal system at a point intermediate between the active crater and the

geothermal production field, and to conduct hydraulic and chemical tests to assess their connectivity. The concept evolved considerably over the next few days, with spirited discussions about the connection and the scientific objectives. In meeting in Russia, we recalled that the impetus for an international scientific drilling program on the continents can be traced to the ambitious nation-wide deep drilling program of the Soviet Union during the 70s and 80s.

The group included a number of veterans of past and current scientific drilling projects. Setsuya Nakada (U Tokyo) gave a view based on Unzen results of a broad "conduit zone" of becciation intruded by dike swarms that extend in the subsurface far beyond the edifice itself, a conclusion strongly supported by magnificent exposures at Mutnovsky. Wilfred Elders (UC Riverside) discussed his experiences in deepening commercially drilled geothermal wells for scientific purposes, first in Salton Sea, California as the start of the US continental drilling program, and now in Iceland in quest of the supercritical fluid regime. In this connection, the "best video clip" award goes to Noriyoshi Tsuchiya of Tohoku University (Japan), who showed the subcritical/supercritical transition in his laboratory experiments. John Eichelberger of the UAF Geophysical Institute (UAFGI) traced research drilling of volcanoes from Kilauea Iki lava lake, Hawaii in the 1970s and 1980, through Inyo Domes and Long Valley Caldera, California during the 1980s and 1990s, to Unzen Volcano, Kyushu, Japan during the present decade. The important, though in some ways disappointing, result at Unzen of low conduit temperatures makes a hot conduit an attractive next target.

A Mutnovsky primer

Alexey Kiryukhin (IVS) introduced Mutnovsky. Wells have been drilled to depths exceeding 2000 m and to temperatures exceeding 300^{o}C. A large body of data already exists concerning fluid composition and conditions in the geothermal and volcanic systems through the efforts of Russian scientists and the local development company, Geoterm JSC. There are some interesting pressure excursions associated with regional earthquakes, presented by Andrey Polyakov (IVS) and Veniamin Romantsev of St. Petersburg Electrotechnical University, suggesting that the entire system may be a sensitive strainmeter.

Michael Zelensky of the Institute of Experimental Mineralogy RAS (Moscow) and Svetlana Bortnikova of the Institute of Geology and Mineralogy RAS (Novosibirsk) defined three fumarole fields within the crater related through dilution of magmatic gas by meteoric water. We later encountered M. Zelensky at work in the crater, where he showed us a fumarole depositing pyrite. S. Bortnikova explained the remarkable chemistry of the fumaroles, for example, the highest fumarolic Cr concentrations ever recorded. Victor Okrugin (IVS) observed that this is an epithermal ore-depositing system in action. He termed Mutnovsky's Crater "a unique natural chemical reactor" where 35 previously unknown hydrothermal minerals have been discovered. Another life-long investigator of Mutnovsky's mysteries who spoke was Yury Trukhin, Director of the Geotechnical Research Center (Petropavlovsk). An object of extensive international research is the diverse microbiological population of extremophiles. In counterpoint, Ivan

Meleketsov (IVS) viewed the volcano as a “parasitic chimney” of a more powerful and older Mutnovsky hydrothermal system.

Geophysical investigations
Geophysical investigations are needed in prelude to dedicated scientific holes. Vyacheslav Spichak of the Institute of Physics of the Earth (Moscow) showed imaging by deep-penetrating 3-D magnetotelluric (MT) soundings in magma-hydrothermal systems. Andrew Newman (Georgia Institute of Technology) urged ground deformation measurements and the improved interpretation that would come in turn from drilling results on near-source rheology, properties that Julia Frolova’s (Moscow State University) petrophysical analysis program is well-posed to measure. Victor Chebrov and Julia Kugaenko (both of the Geophysical Survey, Kamchatka Branch) and A. Newman likewise stressed the importance of seismic studies in illuminating structure and defining zones of hydrothermal and magmatic activity. Such observations have been initiated by Geoterm, but we would like to broaden them to encompass the volcano. Anatoly Kargopoltsev of South Kamchatka Natural Park gave a heartening view of the importance of scientific research in the park wherein Mutnovsky is located. Finally, Oleg Povarov of the Geothermal Energy Association (Moscow) and Sergey Fedotov of IVS argued for exploratory drilling at Avachinsky Volcano near Petropavlovsk, where a volumetrically large annulus of hot dry rock may surround a shallow magma chamber.

The workshop moved for two days of tours and discussions at the Mutnovsky Power Plant and Hotel, where last season’s snow still lingered as the new winter season began. For those who made a 25-km hike, the highlight of the meeting was the visit to Mutnovsky’s Crater, where “gas….jets whistle, sing, and hiss” (V. Okrugin) amid bright “colors (of) native sulfur and sulfates in great volume” and glacier ice draped with fresh white snow, an excellent place to recall Robert Frost’s poem, “Fire and Ice”.

Results of discussions
We plan a comprehensive geophysical and geochemical research program, with stages wherein drilling will play an increasingly important role. Immediate priorities are MT, seismic, geodetic, and gravity surveys to define the extent and behavior of the magma - hydrothermal system. Geoterm has plans for three new 2000-m wells (Ivan Chernev, Geoterm), and is open to siting these for maximum scientific gain. Next we 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. The goal of reaching magma in the coming decade is one endorsed by the forthcoming International Continental Drilling Prorgam (ICDP) White Paper.

For now, we focus on the magma-hydrothermal connection. The question of what hydrothermal systems do to magma is as important to volcanologists as the question of what magma does to hydrothermal systems is to economic and geothermal geologists.

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