MAGMA AND EXTREME GEOTHERMAL: ВЕНЕРА НА ЗЕМЈЕ

John C. Eichelberger[1], A.V. Kiryukhin[2], Charles R. Carrigan[3], Yan Lavallee[4], Randy Normann[5], Jefferson William Tester[6], Pavel Izbekov[1]

[1]U. of Alaska Fairbanks (USA); [2]Institute of Volcanology and Seismology FEB RAS, (Russia); [3]Lawrence Livermore National Laboratory (USA); [4]U. of Liverpool (UK); [5]Perma Works (USA); [6]Cornell U. (USA)

Relatively little attention has been paid to the relationship between hydrothermal reservoirs and active magma bodies. Perhaps a broad ductile and therefore conductive regime exists between them. If the conductive path is long the characteristic diffusion time is large, and over a short timeframe magma and hydrothermal reservoirs can be treated as decoupled. Several lines of evidence now indicate that magma and hydrothermal reservoirs can be closely coupled and need to be considered as a single system: 1) Geothermal drilling has encountered active magma within tens of meters of hydrothermal systems[1]. 2) Laboratory experiments show that thermal fracturing can begin within a hundred degrees of the solidus[2]. 3) Both petrologic observation of recovered magma samples and theoretical considerations suggest magma underlying the hydrothermal system is convecting. The short distance from magma to hydrothermal means perturbations in one regime affects the other on a scale of years or less. Extraction of magma-sourced geothermal energy may even speed up magma convection, making the energy truly renewable. It may also be possible to monitor magma beneath volcanoes directly, vastly improving the capability of predicting eruptions. Excellent examples of closely coupled magma and hydrothermal regimes are provided by Krafla Caldera, Iceland and Mutnovsky Volcano, Kamchatka. Magma has been intersected by drilling at Krafla. Mutnovsky has been considered for magma drilling since the Soviet Union's Super Deep Drilling Program.

Krafla caldera

Krafla Caldera is an ~ 100 ka bimodal system, the northernmost caldera centered in Iceland's northern rift zone, the actively spreading boundary between the North American and Eurasian plates. Boreholes of the Krafla geothermal field within the caldera yield 60 MWe. Several have encountered rhyolite magma or near-magma over an area of about 3 km^2 (Fig. 1). Most studied is Iceland Deep Drilling Program's IDDP-1[3], which returned fragments of liquidus rhyolite and partially melted microgranite roof rock when the drill bit became stuck at 2096 m. A sustained flow test tapping superheated fluid just above the magma yielded 100 MWt, which because of the high temperature (450^{o}C) could produce 35 MWe from just this single well.

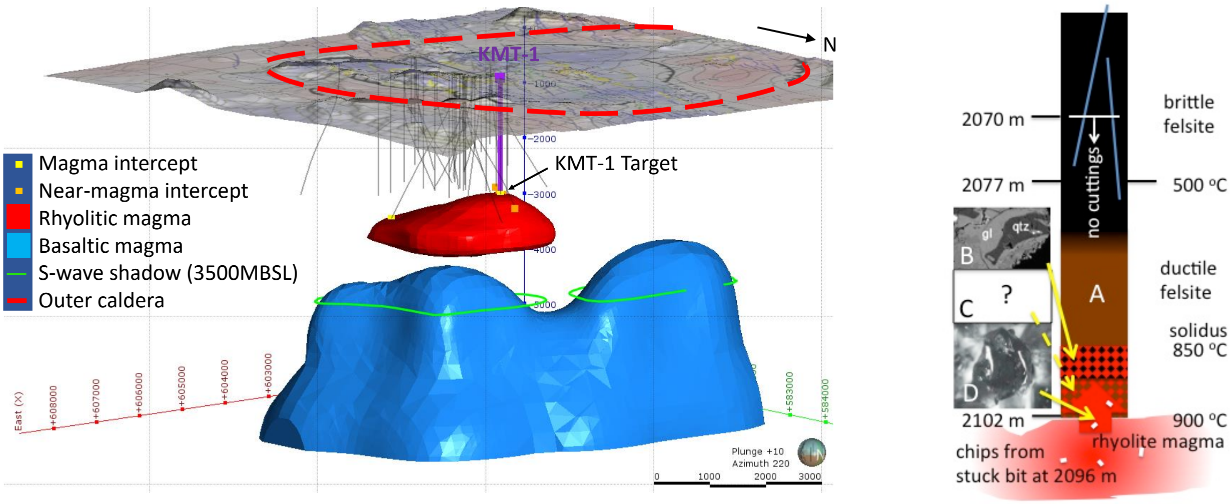

Fig. 1 (l) 3-D view of Krafla rhyolite magma (red, basaltic magma chamber (blue), and existing wells (gray; James Cagley, Reykjavik U.). Green line is S-wave anomaly at 4-km depth. (r) Section from IDDP-1 from hydrothermal system to liquidus rhyolite[4]. KMT-1 (discussed later in text) will be drilled to magma near IDDP-1, with coring through the interval shown.

The estimated temperature gradient above the magma of >20^{o}C/m implies a heat flux of >30 W/m^2, which if supplied by latent heat of crystallization is equivalent to forming a crystalline layer at ~ 1 m/a. This should have produced a layer 30-m thick since the most recent time the intrusion could have arrived undetected by surface deformation. Our preferred explanation is that the magma is convecting vigorously so that cooled magma is replaced by fresh, hot magma before crystals can be painted on the ceiling of the chamber[5,6]. Rather the being a small recent intrusion, the rhyolite may be a long-lived body, similar to what is present under Askja Caldera to the south. Askja vented 0.3 km^3 of similar rhyolite magma in 1875 despite no previous appearance of rhyolite in the Holocene[7].

Mutnovsky volcano

The Mutnovsky geothermal area is part of the Eastern Kamchatka Volcano Belt[8]. Mutnovsky, an 80-ka old and complex of 4 stratocones, acts as a magma- and water-injector into the 25-km-long North Mutnovsky extension zone (Fig. 2). This zone is currently producing 48 MWe from wells that intersect a near-vertical plane, bisecting the Mutnovsky vent system 4 to 10 km to their southwest. The vent complex contains fumaroles >600°C and is located some 1000 m above wellheads from which 300°C fluid is reached at about 2000 m depth. The linear structure leading from the volcano conduit, the near-magmatic temperatures above the conduit, the fact that geothermal production "turned on" frequent phreatomagmatic explosions in the active vent, and that isotope data identifies the crater glacier as the major source of fluid in the hydrothermal reservoir, establishes the intimate connection between the magmatic and hydrothermal regimes, even though no boreholes have yet encountered magma. Extreme fumaroles and the

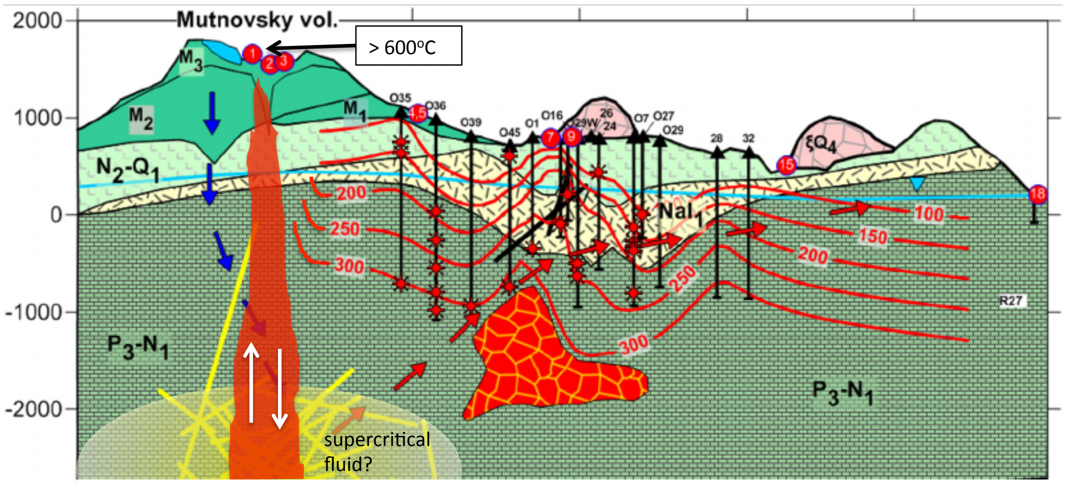

Fig. 2: Cross section of Mutnovsky Volcano and hydrothermal system, adapted from ref. 8.

expectation of isentropic cooling during decompression of fumarolic steam require a convecting magma column reaching within one kilometer of the surface. Using a maximum observed temperature of ~900°C and estimated discharge rate of H_2O of 10^2 kg/s (ref. 9) implies a thermal power output of 400 MWt. Neighboring Gorely Volcano exhibited a long-lived "natural borehole" discharging steam at 900°C and 10^2 kg/s (ref. 10), also 400 MWt. These thermal power outputs and mass discharge rates could be supplied by latent heat from 10 wt% crystallization and release of 1 wt% H_2O from 4 m^3/s of convecting magma.

Unlike Krafla, Mutnovsky has no intervening silicic magma body (there was >10 ka ago) between the hydrothermal system and the ultimate energy source, mafic magma, and the magma-hydrothermal connection is horizontal rather than vertical because of differences in structure and surface topography.

Transport of heat in a magma-hydrothermal system and geothermal energy

Although magma has a heat capacity similar to rock of a hydrothermal reservoir there are two important differences: magma contains latent heat of crystallization and it convects. Indeed, it is likely that most superheated and supercritical fluids at accessible levels in the crust are closely associated with magma[11]. Adding convection (Fig. 3), because crystallization and cooling makes the magma denser causing it to be replaced at the top of the magma chamber or conduit by uncooled magma essentially makes the heat contained in the entire magma reservoir accessible.

It is useful to think in terms of energy density in the system, because that indicates what volume of the heat source must be accessed to yield a give power output of a given amount of time. Magma, because of latent heat and high physical density, and supercritical fluid (SCF) have the highest energy density. However, SCF occupies only a small fraction of its reservoir while the remainder is rock, which has a very low energy density. Magma occupies the entirety of its reservoir. Thus, a convecting magma body is the ultimate geothermal resource.

Krafla Magma Testbed (KMT)

We now know with certainty where magma resides beneath Krafla caldera and that it can be drilled and controlled with existing geothermal techniques. As a result, the first *magma observatory,* Krafla Magma Testbed (KMT) is being planned as an international, open access, scientific platform to advance ductile zone to magma research. This frontier undertaking will enable direct, *in situ* sampling, manipulation, and monitoring of magma and its interface with solid rock, vastly advancing models of high-temperature crustal processes.

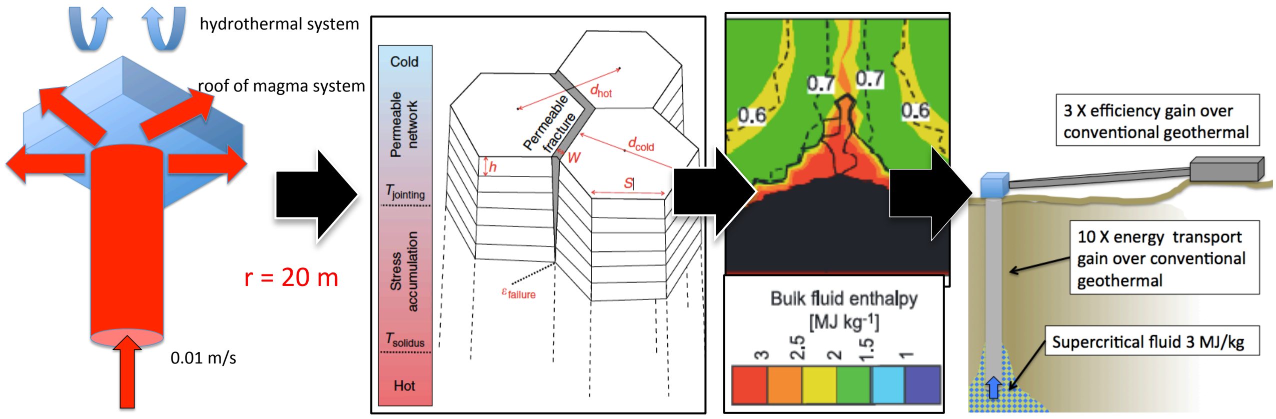

Fig. 3: Concept of how a closely coupled magma-hydrothermal system can be a game-changer in providing more productive and efficient geothermal energy. (l to r) Convective magma plume[5,6] rising at 0.01 m/s supplies chamber roof or top of conduit with 1 GWt if 10% latent heat of crystallization is released. Thermal fracturing allows access of fluid to within meters of magma[2]. Supercritical fluid plume rises from magma roof zone[11]. Tapping supercritical fluid provides 10X gain in heat transport and 3.5X gain in efficiency of conversion to electricity[11] over conventional geothermal[12].

KMT will be a long-term infrastructure (>25 years) for the conduct of interdisciplinary scientific, engineering, technological, and educational activities. Krafla volcano has a long history of geological study, volcano monitoring, and drilling as well as supporting surface facilities, combining to produce the most efficient first base from which to explore Earth beyond the solidus. Five phases of development are planned. In Phase I, we will core the critical interval from solid rock to magma that was missed by IDDP-1 (Fig. 1). A string of thermocouples will provide the first measurements of heat flux from magma to a hydrothermal zone. Subsequent phases will advance drilling engineering and extreme sensor technology, and experiment with one-, two-, and three-borehole techniques for extracting magma-sourced geothermal energy. Temperature, pressure, and chemistry monitoring will be a game-changer in eruption forecasting.

Challenges

Given that the highest temperature measurements made in geothermal boreholes are ~500°C; few, if any, superhot boreholes have survived without damage due to thermal expansion or contraction; and the near-magma environment is acidic and corrosive, there is understandable skepticism that the above objectives can be achieved. However, consider that *in situ* rock and vapor analyses, imagery, and many other measurements were made under acidic geothermal conditions (9 MPa, 457°C; Fig. 4) repeatedly on Venus almost 4 decades ago. We should be able to overcome similar challenges 2 km beneath our feet, with rewards of clean energy and public safety in addition to planetary science. Engineering and technology developments will be required, but that is to be expected in probing a new frontier, in this case molten Earth.

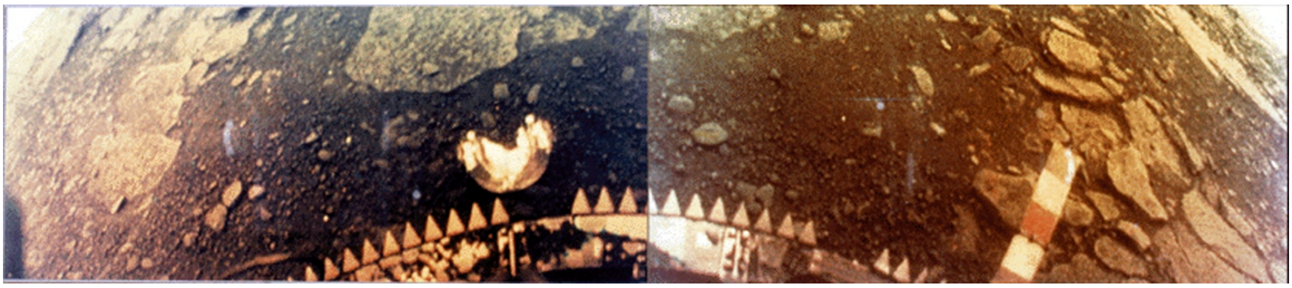

Fig. 4: The surface of Venus viewed from USSR's Venera 13 on 1 March 1982. (Image acquired from NASA archive.)

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