GRC Transactions, Vol. 42, 2018

Krafla Magma Testbed:

Understanding and Using the Magma-Hydrothermal Connection

John Eichelberger[1], Hjalti Pall Ingolfsson[2], Charles Carrigan[3], Yan Lavallee[4], Jefferson William Tester[5]; Sigurdur H Markusson[6]

[1]International Arctic Research Center, University of Alaska Fairbanks (USA); [2]KMT Project Office, GEORG Geothermal Research Cluster (Iceland); [3]Lawrence Livermore National Laboratory (USA); [4]University of Liverpool (UK); [5]Cornell University (USA); [6]Landsvirkjun National Power Company (Iceland)

Keywords

Geothermal, hydrothermal, volcanology, high-temperature drilling, high enthalpy fluid, magma, convection, quenching, latent heat

ABSTRACT

The Krafla Magma Testbed (KMT), Krafla Caldera, Iceland, is proposed to be the first magma observatory, an international multi-borehole facility where teams will conduct scientific experiments and engineering tests focused on the magma-hydrothermal interface in a superhot geothermal systems (SHGS). Objectives are to: 1) Core and monitor from the roots of the hydrothermal system to the top of the magma body; 2) Provide ground-truth testing of surface-based techniques for locating magma; 3) Perturb the deep system to understand signals interpreted as volcano "unrest"; 4) Advance drilling and completion technology so that superhot and supercritical fluids can be produced from the magma roof zone; and 5) Advance sensor technology so that magma bodies can be monitored directly, vastly improving the eruption warnings important to 10% of Earth's population.

KMT will provide a vanguard view of magma and hydrothermal circulation as the single system that it is. It will integrate the separate communities of practice of geothermal energy, which relies heavily on direct drilling observations; and volcanology, which relies on surface observations and theoretical models. The driving force is that geothermal drilling hit magma in Iceland, Kenya, and Hawaii, revealing how close to the surface magma exists and how closely connected magma is to the hydrothermal system.

KMT is a 3rd path in efforts to expand geothermal use. One path is to go deeper in cooler places, the Enhanced Geothermal System (EGS) concept, relying on advances in drilling and reservoir stimulation for economic viability, e.g. Frontier Observatory for Research in Geothermal Energy (FORGE) of the U.S. Department of Energy. Another, within SHGS, is to drill to conditions where fluids should be supercritical, e.g. IDDP-2 of Iceland Deep Drilling Program (IDDP) at Reykjanes. The 3rd, also SHGS and pursued by KMT, is to access the vicinity of a magma body. This takes advantage of magma's high energy density due to latent heat of crystallization and delivered by convection to sustain high power output. Not only have SHGS wells proximal to magma at Krafla Caldera, Iceland, exhibited high flow rates equivalent to >100 MWt, but the expected efficiency of conversion to electricity is ~30% vs. ~10% for conventional geothermal. When combined with the new efficiencies of High Voltage Direct Current (HVDC) tranmission, the economic balance could shift from low-grade geothermal sources near the consumer to high-grade sources farther from the consumer.

1. Introduction

As we enter an era where CO_2 in the atmosphere and its attendant effects are building to crisis levels, geothermal energy is emerging as a particularly attractive clean option. It is continuous (bed load) and unlike the other continuous clean source, hydroelectric (although hydroelectric is not always continuous in seasonal cycles and decadal droughts), it has negligible ecological impact and a small footprint. Geothermal power plants are sited on their "fuel" source and reinject "waste" on site, therefore requiring no long-distance transport of hazardous, spillable materials. Although the resource is not uniformly distributed – no energy resource is and emerging HVDC technology can extend the economical reach of power generation – geothermal could benefit far more of humanity than the 0.3% of electricity (World Energy Council, 2016) it now produces. A major impediment to greater use of geothermal energy is its inefficiency. Geothermal reservoirs associated with volcanic systems tap mere whiffs of steam at ~250°C from the ~1000°C magmatic furnace below. The low efficiency, of the order of 10%, of converting this wet steam to electricity translates to a requirement of having many supply wells and hence high drilling costs. Often there is continuing need for drilling to make up for decline in steam pressure in the exploited reservoir.

Much could be gained by going to higher pressure and temperature and tapping superheated or supercritical fluid. This could boost energy transport to the surface by 10 X and efficiency of conversion to electricity by 3 X (Tester et al., 2006; Scott et al., 2017). The Iceland Deep Drilling Program (IDDP; Fridleifsson et al., 2017) has successfully reached high pressure and high temperature conditions where fluids are expected to be supercritical. This important achievement may, however, encounter a limitation in common with conventional geothermal and with Enhanced Geothermal Systems (EGS) at conventional temperatures: the source of energy is hot rock and rock is poor at storing and conducting heat because of low heat capacity and low thermal conductivity.

2. Energy From Magma

Although magma has a heat capacity similar to rock there are two important differences: it contains latent heat of crystallization, which can be treated as if magma had 10 times the heat capacity of rock, and it convects. These differences remove the limitation of poor heat storage and slow conduction. Indeed, it is likely that most superheated and supercritical fluids at

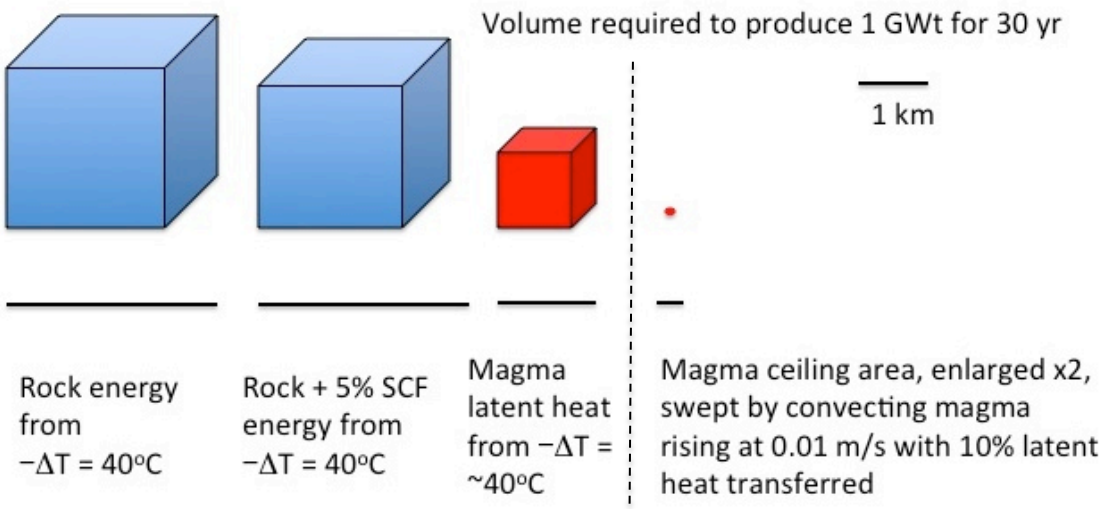


Figure 1: Comparison of reservoir volumes required to yield 10^{18} J (1 GWt for 30 yr). Also shown is area of rising magma column that would deliver 1 GWt for conditions specified. SCF is supercritical fluid.

accessible levels in the crust are closely associated with magma (Scott et al., 2017). Figure 1 depicts the reservoir volumes required to yield 1 GWt over a period of 30 years (10^9 s). Adding convection, because crystallization and cooling make the magma denser causing it to be replaced at the top of the magma chamber by uncooled magma, essentially makes the heat contained in the entire magma reservoir, likely multiple cubic kilometers, available for extraction up to the point where crystallization immobilizes it, thought to be about 50 vol%.

Taking Scott et al.'s (2017) numerical model for superheated and supercritical fluids to be correct, the plume of fluid rising from the magma body could be tapped to yield more than an order of magnitude gain in electric power production per well (Fig. 2). The processes involved in heat transfer from magma to the hydrothermal system are discussed by Lavallee et al. (this volume) and challenges to drilling and maintaining such boreholes by Holmgeirsson et al. (this volume).

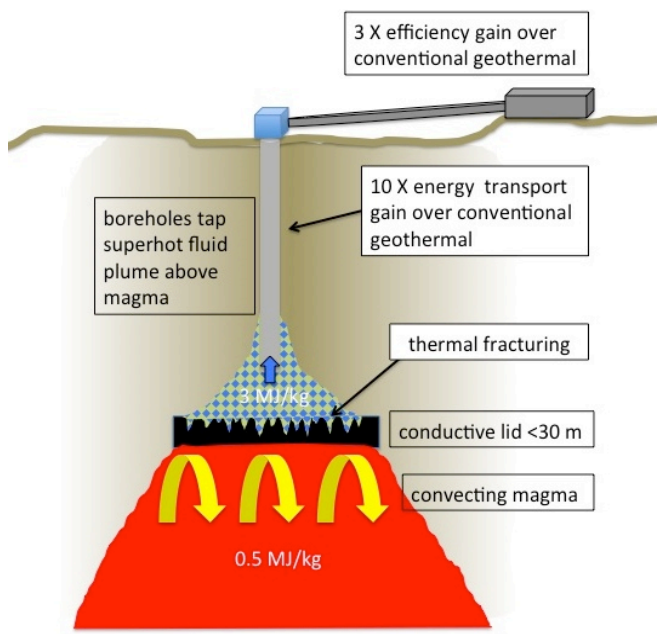


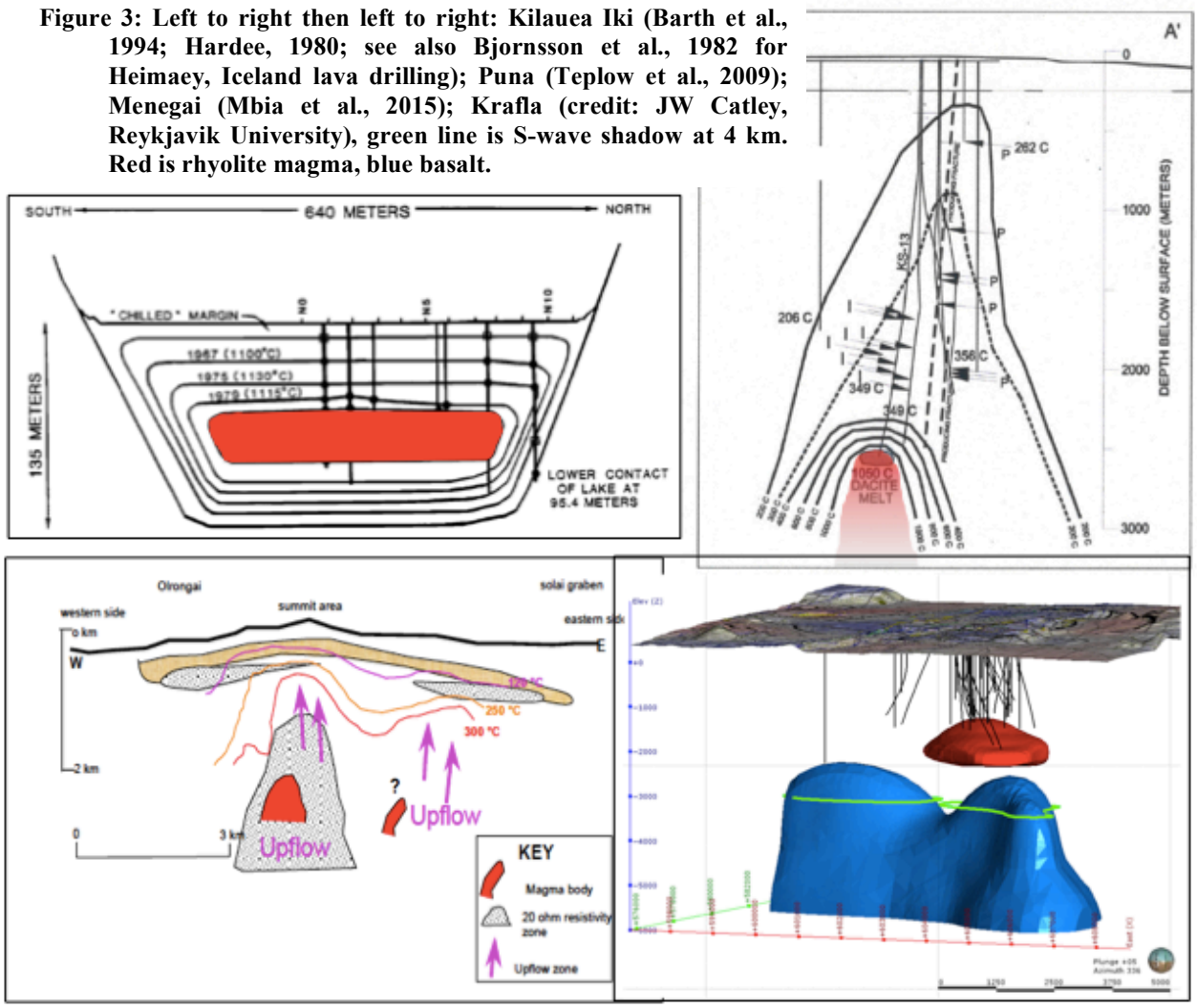
Figure 2: Depiction of power generation from "magma energy". Convecting magma continually delivers uncooled magma to thin conductive "lid" (Carrigan, 1984, 1987). Extreme thermal gradient in the lid aided by thermal fracturing transports magma energy to a superheated or supercritical plume (Scott et al., 2017), which can then be tapped for efficient power production (Tester et al., 2009).

3. Discovering Magma

None of this discussion would be useful were it not for accidental encounters with magma by geothermal drilling over the past decade at Krafla, Iceland; Puna, Hawaii;

and Menengai, Kenya. Impediments to getting direct data from magma *in situ* were the lack of geophysical techniques for accurately locating magma together with economic and safety risks because conditions were unknown. It was also unknown how close magma was beneath exploited geothermal systems, hence it was by serendipitous discoveries that it was found that magma could be drilled and safely controlled using standard geothermal practices. Figure 3 shows visualizations of the drilling encounters that have occurred to date. By far the best documented is IDDP's IDDP-1, which encountered liquidus rhyolite magma at 2102 m depth in

Figure 3: Left to right then left to right: Kilauea Iki (Barth et al., 1994; Hardee, 1980; see also Bjornsson et al., 1982 for Heimaey, Iceland lava drilling); Puna (Teplow et al., 2009); Menegai (Mbia et al., 2015); Krafla (credit: JW Catley, Reykjavik University), green line is S-wave shadow at 4 km. Red is rhyolite magma, blue basalt.



Krafla Caldera. This was not the first well at Krafla to encounter the magma, but with the operator Landsvirkjun National Power Company working with the IDDP team and with funding from the International Continental Scientific Drilling Program (ICDP) and the U.S. National Science Foundation (NSF), a large amount of data and interpretation were published in an open and timely way in a special issue of Geothermics (2014). Although IDDP-1 helped to show the geothermal potential of magma (Elders et al., 2014), the goal of IDDP is to find supercritical fluids. IDDP-1 got too hot too shallow (low pressure). IDDP moved on as planned to the Reykjanes Peninsula. Thus the opportunity to explore magma at Krafla Caldera, first envisioned as using IDDP-1, arose.

The three sites where magma has been drilled offer some "surprises" in common, besides the existence of the magma itself:

1. Magma is encountered at remarkably shallow depth.
2. There is an abrupt discontinuity between roof rock and magma.
3. Magma and the superjacent hydrothermal system are separated by a very thin conductive zone.
4. There is an absence of thermodynamically required crystallizing magma (mush).
5. There are no recent eruption products that match the shallow magma.

Points 1-3 imply very high rates of cooling. Heat fluxes approach 100 W/m^2, which would produce a 1 m/yr layer of crystals by extraction of latent heat of crystallization alone. But this poses a paradox because no such crystallization is recognized (point 4). Postulating that the intrusion just recently arrived or that the mush zone just recently detached seems like special pleading, and appears ruled out for Krafla by the absence detectable inflation since the Krafla Fires of 1975-1984. Kilauea Iki lava lake is the one place where there is a reliable temperature gradient measured just above the melt lens – providing a direct measure of heat flux - and a reliable rate of crystallization also measured, and we observe almost exactly the expected rate of crystallization. Point 5 is a caution to volcanologists: eruptions may not give a reliable sampling of magma present under a volcano.

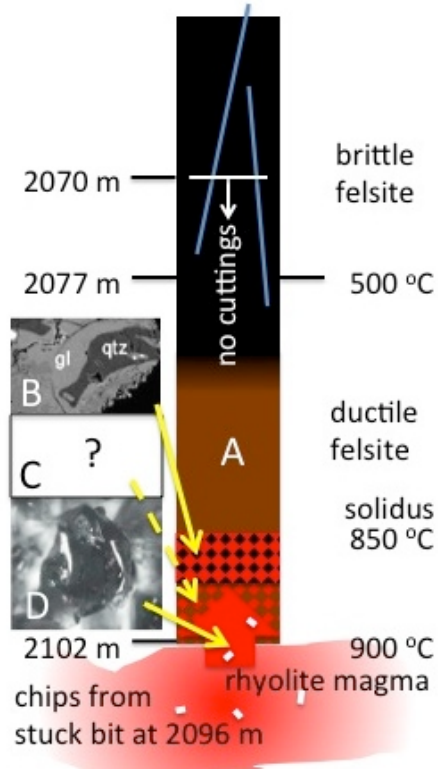


Figure 4: Results from drilling IDDP-1. No cuttings were recovered between 2070 m and hole bottom, but chips that came up after bit became unstuck at 2096 m in magma that had flowed up-hole are of partially melted felsite (B) and liquidus rhyolite (D). Missing is partially crystallized rhyolite (C). Sources: Mortensen et al., 2014; Zierenberg et al., 2012; Schiffman et al., 2014; Further discussion in text.

The margin of a magma body is not expected to be a discontinuity between solid rock and liquidus magma, especially when the bulk compositions are similar. There should be a gradation from solid through a mush zone of increasing melt content to liquid magma. The mush zone might comprise crystallizing magma or melting roof rock with crystallizing magma below it. Latent heat of crystallization is large compared to heat capacity for magma, about 10^9J/m^3 or about five times the heat released by 100°C of cooling without the phase change, so we should expect any melting in the roof to be balanced by crystallization of magma at the ceiling, yet we do not see it. Unfortunately, the record from the lower 30 m of IDDP-1 is incomplete (Fig. 4). Because of lost circulation, itself a surprise because rock at near-magmatic temperatures should be ductile and therefore not support open fractures, no cuttings were recovered. What were recovered were chips of obsidian (volatile-rich magma quenched *in situ,* unlike the degassed magma that volcanoes erupt) and glass-bearing fine-grained granite (interpreted to be the partially melted roof of the magma body) when the drill bit was jerked loose after becoming stuck in magma. If these chips accurately

reflect materials comprising the bottom several meters of the well, then what is missing is crystallizing magma to provide heat needed to melt the roof. The most likely explanation for this is that the magma is convecting so that cooled magma is continually displaced from the roof and does not paint its ceiling with crystals. This makes the connection between the magmatic and hydrothermal portions very close indeed. With thermal fracturing beginning only 100°C below the solidus (Lamur et al., 2018), the characteristic time for thermal diffusion from magma to aqueous fluid will be the order of a year. Thus a perturbation in the hydrothermal system, for example increasing fluid production, will rather quickly affect the magma, for example speeding up convection. The key to this problem is to drill a path near IDDP-1, to core the missing interval from hydrothermal system to magma, and to leave a string of thermocouples in the well, providing the first ever measurement of heat flux across the magma – hydrothermal connection.

4. Forecasting Eruptions

Some 10% of the global human population lives within 100 km of hazardous volcanoes. We cannot expect to make reliable eruption forecasts without knowing more about magma. The current state of volcanology can be compared to trying to forecast weather based on surface observations alone. Nevertheless, considerable progress has been made over the last forty years in understanding what leads up to a volcanic eruption and what signals can usefully be measured at the surface.

Very generally (every volcano is different), an eruption sequence begins with the rise of new hot magma from the lower crust or mantle towards a mid to upper crustal reservoir which is generally cooler, and for the continental and Icelandic cases more silica-rich (Fig. 5). This rise is heralded by increasing microseismicity, surface inflation, and increase in CO_2 emission relative to H_2O. Microseismicity reflects

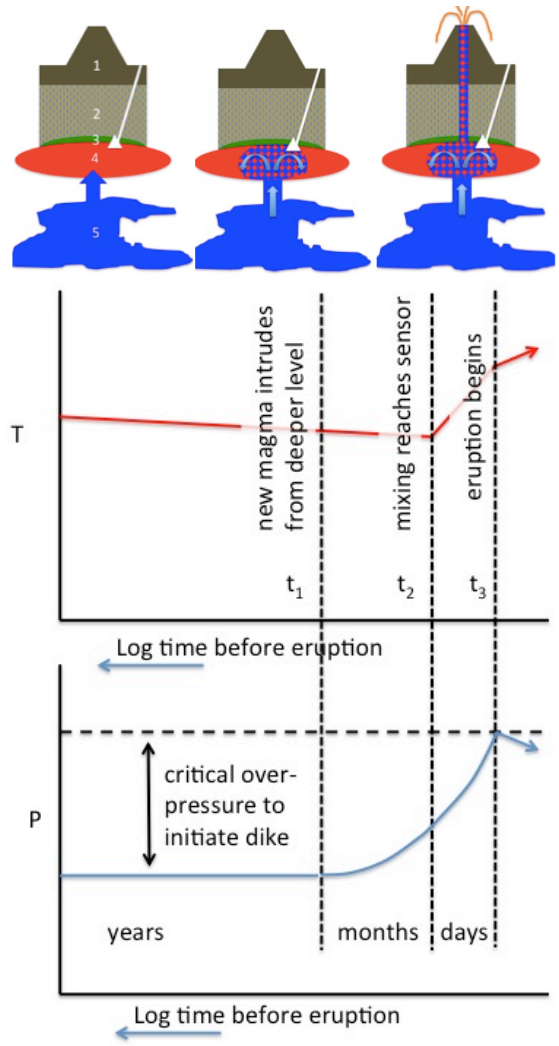


Figure 5: Above, generic eruption sequence (l-r): t_1 basalt begins to intrude shallow silicic chamber. 1=volcano, 2=hydrothermal system, 3=conductive lid, 4=silicic magma, 5=basalt magma, white triangle is T and P sensors; t_2 mixing of magmas reaches sensors; t_3 eruption begins. Below, Hypothetical scenario for record of in situ P, T sensors during basalt-triggered eruption. Episode begins at t_1 causing pressure in shallow chamber to increase but without immediate change in T; b) At t_2, mixing of new magma reaches sensor causing T to begin increasing; rate of P change increases because new magma is vesiculating (Eichelberger, 1980); c) Pressure in shallow chamber exceeds critical overpressure, >10 MPa (Rubin, 1995) dike propagates to surface and eruption begins.

breaking of rock due to flow of magma, inflation reflects transfer of mass upward, and CO_2, much less soluble than H_2O in melt at shallow depth, reflects degassing of new magma during ascent. These anomalies gradually increase in intensity, perhaps over a run-up of a few months (Pallister et al., 1992; Sigmundsson et al., 2010) until an eruption begins. It is common to find both the new and shallowly stored older magma mixed in some or all of the eruption products. Often, evidence is found in crystal zoning that the stored magma was heated 50°C - 100°C within days prior to onset of eruption (e.g., Pallister et al., 1996).

Seismic monitoring involves telemetered networks that can quickly locate microearthquakes. But earthquakes occur in brittle rock and so tell us where magma is not. Fracturing by magmatic gases or hydrothermal fluids are likely causes. Deformation is measured both by surface GPS networks and by satellite Interferometric Synthetic Aperture Radar (InSAR). The former gives time-continuous spot measurements, the latter space-continuous instantaneous measurements, with precision that can be <1 cm. Magma pressure and volume increases can be inferred from these measurements, but are highly model-dependent. We can speculate on what might be observed where sensors are directly monitoring the state of a magma chamber in a generic eruption (Fig. 5). Of course, it will take time and experience at multiple sites to confidently use this new kind of data to warn whole populations, just as using seafloor pressure sensors was not immediately used with surface seismic sensors to quantify tsunamis, thereby contributing to fatally flawed warnings of the Tohoku tsunami of 2011. What KMT will do is solve the problem of obtaining direct data, correlate measurements with what surface instruments record, and begin the process of putting this information into forecasting practice.

5. Development of KMT

The vast opportunities afforded by discovery of a magma body at easily accessible depth, coupled with compelling needs for clean energy and reliable volcanic eruption warnings, mean that more than a single borehole is called for. We are developing a plan for an international infrastructure, much like a particle accelerator or telescope array, where research teams can come to conduct scientific experiments and engineering tests. This will be the world's first magma observatory with a decades-long life over which significant changes in the magma-hydrothermal system are anticipated. The starting point is Landsvirkjun's geothermal field with almost 50 boreholes below the surface and extensive facilities on the surface, together with their public-spirited interest in data-sharing, outreach, education, and regional development. Krafla Caldera has long attracted scientists, so that Krafla is now one of the best studied and monitored volcanoes on Earth. The goals of KMT are to:

1) Advance the science of molten and near-molten Earth.
2) Develop more direct and accurate ways of understanding and monitoring volcanoes.
3) Determine how best to exploit the intense energy of magma.
4) Test new technology and materials that will function in the most extreme conditions in Earth's crust and on other planets.

KMT will proceed in phases as follows:

1st Phase: Proof of Concept (KMT-1a)

Drill a dedicated research borehole near IDDP-1 with the aim of recovering a core from the base of the hydrothermal system to magma, and monitor temperature through that interval; in parallel,

we will collaborate with the sensor community to develop new temperature-resilient technologies to monitor pressure. The borehole will be cased using new innovative, patented, flexible couplings allowing the steel to thermally expand without accumulating enough stress and strain to cause failure of the casing. Following a successful recovery of a core, the borehole will be allowed to heat up, under constant monitoring and supervision, in order to monitor thermal recovery of magma and its roof to deduce thermal properties of the material and determine heat flux out of magma after steady-state conditions are reached.

2nd Phase: Re-coring for time series and flow testing (KMT-1b)

Following a successful Proof of Concept, the team intends to re-enter the first hole and drill a sidetrack to recover another core (for second point in time series) and monitor pressure as well as temperature while the borehole heats up again. When the conditions at the bottom of the well have reached equilibrium with the surrounding environment, we may initiate flow testing of the well if we deem the well and the conditions suitable without jeopardising the future of the well. If strong flow does not result spontaneously, we will try cold-water injection and stimulation of the vicinity of the magma as with IDDP-1. A flow test will put the new flexible couplings and casing to the extreme test of surviving the harsh condition of high temperature and corrosive geothermal fluids. The flow-test will also provide valuable opportunity to sample the chemistry of the geothermal fluid close to magma as well as various opportunities for geothermal engineering testing and experiments. Upon completion of this work, a new thermocouple string with, if possible, pressure sensors, will be installed.

3rd Phase: Recoring and sonde deployment (KMT-Ic). In the 3rd phase, we will sidetrack and core magma again and deploy a dense tethered sonde which will descend into the magma, profiling temperature and pressure through the magma body and return information about its viscosity and density. The sonde will be designed to permit sensing the solid base of the magmatic body, if it can be reached, thus defining the thickness of magma underlying the geothermal system.

4th Phase: Drill second borehole to determine lateral variability of magma and its contact zone and to conduct a two-well (injection and flow) energy extraction experiment (KMT-2)

In the 4th phase the intention is to drill KMT-2 and recover a core in a different part of the magma reservoir, while monitoring P-T in the first hole to test conductivity of the magmatic system. This data and associated stimulation of magma in two places, combined with geophysical observations, will enhance our ability to image the spatial distribution of the magma reservoir. We will attempt energy recovery by injecting on one well and allowing the other to flow, thus forming a circulation loop through chilled and thermally fractured magma or along the magma body's margin.

5th Phase: Directionally drill third, deeper borehole, to determine vertical variability of magma and conduct a third energy extraction experiment (KMT-3).

The geometry of the well will be such that it will test whether the magma body is a sill (a flat sheet) or more bladder-like, as magma chambers are often viewed to be. If a sill (the borehole passes under but does not encountered magma), an interval deep under KMT-1 and/or KMT-2 will be cored to determine its lithology, for example whether it contains basalt and/or rhyolite

feeders to the overlying body. Temperature and pressure will again be measured. As the well will be inclined, it will be possible to determine whether the overlying body is gaining or losing heat from below. Water will be injected to rise and bathe the body while KMT-1 and -2 are allowed to flow, as an additional approach to energy extraction.

If instead the magma margin is encountered, it will be cored to see if the different orientation of buoyancy forces relative to the wall influence magma flow and crystallization behaviour. Coring the magma will further constrain the height and chemical gradients in the body and changes in the boundary zone with depth. Water will be injected into the margin of the magma body to see if this stimulates flow and energy extraction from KMT-1 and KMT-2. Conditions at the bottom of KMT-3 will likely be supercritical, unless flow is dominated by saline fluids.

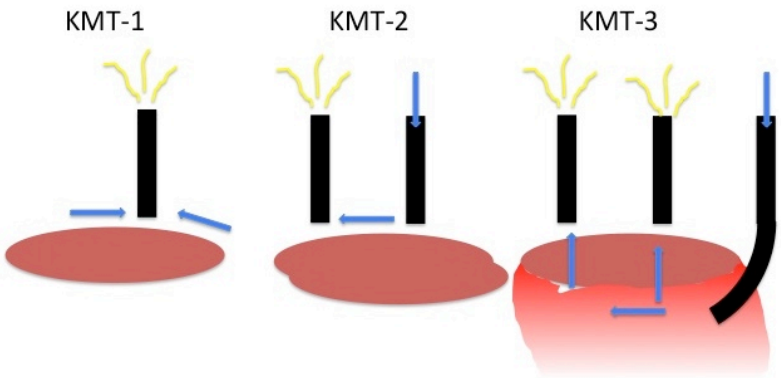


Figure 6: Envisioned stages of experiments for energy extraction from magma. KMT-1 will permit an informed repeat of the IDDP-1 test, KMT-2 a two-well approach, and KMT-3 an injection from below magma or into magma sidewall, under supercritical conditions.

This suite of wells will continue to be available to research teams to test borehole instruments and drilling components under increasingly severe conditions. Research on the core samples will likewise continue. There will now be three ports for monitoring the magma body (or two if the body is a sill). Of particular interest will be whether magma pressure drops as rifting proceeds, and whether cooling of magma can be detected as flow tests withdraw heat from the system. The wells will make possible three modes of energy extraction experiments (Fig. 6).

6. Partners

KMT is an open organization that necessarily comprises institutions of both the private and public sectors. The KMT Project Office (www.kmt.is) is hosted by the Geothermal Research Cluster (GEORG) in Reykjavik. Our primary industrial partner is Landsvirkjun National Power Company, owner and operator of the Krafla geothermal field and power plant. Among the universities represented are Alaska (USA), Canterbury (NZ), Cornell (USA), Iceland (IS), Liverpool (UK), Munich (DE), and Southern Methodist (USA), research institutes Sandia National Laboratories (USA) and GeoForschungsZentrum (DE), and government agencies British Geological Survey, US Geological Survey, and Istituto Nazionale Geofisica e Vulcanologia (IT). Others are welcome, including private sector entities, and anticipated. Information on membership will be available through www.kmt.is.

7. Summary

KMT will open the final frontier of planet Earth and facilitate understanding and future exploration of other planets as well. It represents a new path to high enthalpy geothermal: fluid circulation by thermal fracturing rather than hydrofracturing above a convecting magmatic heat source. It also holds promise for greatly improved forecasting of volcanic eruptions. And it is an overdue partnership between volcanologists and geothermal experts and between scientists and engineers. There are many challenges to be overcome but virtually every part of the effort – drilling to magma, coring at very high temperature, operating sensors at extreme conditions, have been accomplished separately. It remains to put them together in a magma testbed. There are places to remaining explore that are still hidden from us but as close and important as magma.

REFERENCES

Barth, G.A., Kleinrock, M.C., and Helz, R.T., The magma body at Kilauea Iki lava lake: Potential insights into mid-ocean ridge magma chambers, *J. Geophys. Res*., 99: 7199-7217, (1994).

Björnsson, H., Björnsson, S., and Sigurgeirsson, Th.: Penetration of water into hot rock boundaries of magma at Grímsvötn, *Nature,* 295, 580-581, (1982).

Carrigan, C.R., Time and temperature dependent convection models of cooling reservoirs: Application to volcanic sills, *Geophys. Res. Lett.,* 11, 693-696, (1984).

Carrigan, C.R., and Cygan, R.T, Implications of magma chamber dynamics for Soret-related fractionation, *J. Geophys. Res*. 91, 11451-11461, (1986).

Eichelberger, J.C., *Nature* 288, 446-450, (1980).

Elders, W.A., Friðleifsson, G.O., Albertsson, A., Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide, *Geothermics*, 49, 111-118, (2014).

Fridleifsson, G.O. et al., The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the seawater-recharged Reykjanes geothermal field in SW Iceland has successfully reached its supercritical target, *Scientific Drilling* 23, 1-12, (2017).

Hardee, H.C., Solidification in Kilauea Iki Lava Lake, *Journal of Volcanology and Geothermal Research*, 7, 211-223 (1980).

Hólmgeirsson, S. et al., Krafla Magma Testbed: Engineering challenges of drilling into magma and extracting its energy, *GRC Transactions,* this volume, (2018).

Lamur, A. et al., Disclosing the temperature of columnar jointing in lavas, *Nature Comm*., 9p (2018).

Lavallée, Y., Eichelberger, J., Carrigan, C., Ingolfsson, H.P., How is energy transferred from magma to hydrothermal systems? A primary goal of Krafla Magma Testbed, *GRC Transactions,* this volume, (2018).

Mbia, P.K., Mortensen, A.K., Oskarsson, N., Hardarson, B.S., Sub-surface geology, petrology, and hydrothermal alteration, of the Menengai Geothermal Field, Kenya: Case study of Wells

MW-02, MW-04, MW-06, and MW-07, *Proceedings of World Geothermal Congress 2015*, 20p., Melbourne, (2015).

Mortensen, A. K., Egilson, F., Gautason, B., Árnadóttir, S., and Gudmundsson, Á.: Stratigraphy, alteration mineralogy, permeability and temperature conditions of well IDDP-1, Krafla, NE Iceland, Geothermics, 49, 31-41, (2014).

Pallister, J.S., Hoblitt, R.P., Reyes, A.G. A basalt trigger for the 1991 eruptions of Pinatubo Volcano? *Nature* 356, 426-429, (1992).

Pallister, J.S., et al., Magma mixing at Mount Pinatubo: petrographic and chemical evidence from the 1991 deposits, *in* Fire and Mud, USGS Professional Paper, (1996).

Pálsson,B.,Hólmgeirsson,S,.Gumundsson,A.,Bóasson,H.A.Ingason,K.,Sverrisson,H.,Thórhallsn, S., Drilling of the well IDDP-1, *Geothermics* 49, 23-30, (2014).

Rubin, A.M. Propagation of magma filled cracks, *Ann. Rev. Earth Plane.t Sci.* 23, 287-336 (1995).

Schiffman, P., Zierenberg, R. A., Mortensen, A. K., Fridleifsson, G. 6., and Elders, W. A.: High temperature metamorphism in the conductive boundary layer adjacent to a rhyolite intrusion in the Krafla geothermal system, Iceland, *Geothermics*, 49, 42-48, (2014).

Scott, S, Driesner, T, Weis, P, Boiling and condensation of saline geothermal fluids above magmatic intrusions, *Geophys. Res. Lett*. 44, 1696-1705, (2017).

Sigmundsson, F. et al., Intrusion triggering of the 2010 Eyjafjallajokull explosive eruption, *Nature* 468, 426-433, (2010).

Teplow, W., Marsh, B., Hulen, J., Spielman, P., Kaleikini, M., Fitch, D., Rickard, W., Dacite melt at the Geothermal Venture Wellfield, Big Island of Hawaii, *GRC Transactions* 33, 989-1005, (2009).

Tester, J.W. et al., The Future of Geothermal Energy, *MIT and DOE INL/EXT-06-11746*, (2006).

World Energy Council, *World Energy Resources Full Report* 2016.

Zierenberg, R.A., Schiffman, P., Barfod, G.H., Lesher, C.E., Marks, N.E., Lowenstern, J.B., Mortensen, A.K., Pope, E.C., Bird, D.K., Reed, M.H., Fridleifsson, G.O., Elders, W.F., Composition and origin of rhyolite melt intersected by drilling in the Krafla geothermal field, Iceland, *Contributions to Mineralogy and Petrology*, 165, 327-347 (2012).