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Accessing Magma: A Necessary Revolution in Earth Sciences and Renewable Energy

YAN LAVALLÉE*, JACKIE E. KENDRICK*, JOHN C. EICHELBERGER**, PAOLO PAPALE†, FREYSTEINN SIGMUNDSSON†† & DONALD B. DINGWELL*

*Earth and Environmental Sciences, Ludwig-Maximilians-Universität München (LMU-Munich), Theresienstrasse 41/III, 80333 Munich, Germany.
Email: yan.lavallee@lmu.de
**International Arctic Research Center, University of Alaska Fairbanks, USA
†Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, via della Faggiola 32, 56126 Pisa, Italy
††Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, 101 Reykjavík, Iceland

Earth System Science stands as the future operating framework to monitor the pulse of the Earth, and to diagnose and address the challenges of global change. Magmatism and volcanism are primary processes connecting the solid Earth to the atmosphere, hydrosphere, and biosphere. In addition to regulating the Earth system, they are both an unavoidable source of hazards and a tremendous resource of energy and raw materials. Accessing magma is the necessary next step in the exploration of our planet. It will enable us to develop next-generation geothermal energy (magma energy), to transform volcano monitoring strategies, and perhaps even to alleviate volcanic activity. Recent exploratory geothermal drilling activities around the world have serendipitously encountered shallow magma bodies in the Earth. Following these remarkable magma drilling occurrences, the Krafla Magma Testbed (KMT) has been established in Iceland in order to create the first magma observatory – a world-class international in situ magma laboratory with access to the magma-rock-hydrothermal boundary through wells suitable for advanced studies and experiments. Here we review the importance of magma in the Earth system, present the multifaceted need for magma observatories and introduce the benefits of KMT as we enter a new generation of energy demands and resilience strategies.

The Earth System and the Role of Magmatism

During its evolution, the Earth has physically and chemically differentiated, as the densest elements were drawn into the core and the lightest ones buoyantly rose to the surface, establishing the geosphere, blanketed by the hydrosphere and atmosphere. Biochemical reactions at the intersection of these spheres spurred the development of the biosphere. Most recently, the population surge at the end of the second millennium fostered the creation of the technosphere (UNESCO 2018). With this rapid growth, the Earth's resources have been extensively exploited, and the connectivity between the spheres has been disturbed, prompting climate change and a population increasingly at risk of natural hazards (Small and Naumann 2001). As geoscientists in the third millennium, it is our duty to quantitatively describe the Earth system and find solutions to maximize resource utilization, minimize our impact, and so, increase our adaptability and resilience towards a sustainable existence (Deutsche Akademie der Naturforscher Leopoldina 2022).

Since the establishment of the theory of plate tectonics, which may be regarded as the last major revolution in Earth sciences, we have obtained a quantitative process-based understanding of the Earth's dynamics (Cloetingh *et al*. 2023). Magmatism and volcanism are primary agents in the Earth system; they are responsible for the transfer of mass and heat through the lithosphere and into the outer spheres. The shallow transport of magma is powered by the presence of volatiles, which greatly contribute to the buoyancy of magma. As magma ascends through the Earth, the solubility of volatiles in magma decreases, causing vesiculation (i.e., formation of gas bubbles), which impacts the properties of magma (including its buoyancy and viscosity) and so its mobility and eruptibility. Thus, volcanic eruptions are the expressions of magma surging to the Earth surface due to excess gas. It has been estimated that about 10% of magmas erupt, whilst 90% stall at depth to form plutonic rocks, constructing the Earth's crust (Schmincke 2004). Such ratios vary depending on the tectonic setting, yet methods to accurately probe and quantify magma transport and storage have been beyond our grasp. With the advent of satellite-borne remote sensing observations, volcanoes have been the subject of extensive scrutiny, which has provided us with much improved quantitative budgets of volcanic emissions worldwide (e.g., Werner *et al*. 2019). The principal outputs are volcanic ash and gas; primarily H_2O (>650 Tg/yr, although with high uncertainty due to its abundance in the atmosphere; Fischer *et al.* 2019), followed by CO_2 (~300 Tg/yr; Werner *et al*. 2019), sulphur compounds (~20 Tg/yr; Carn *et al.* 2017), and smaller concentrations of halogens (bromine, chlorine etc.) and other molecules, which can react to form aerosols (Aubry *et al.* 2021; Roberts *et al.* 2018) upon transport in the atmosphere, impacting the Earth's outer spheres (Figure 1). Ninety-nine percent of carbon on Earth is stored in the subsurface; it is commonly incorporated into and/or remobilized by magmatic activity, which can release it into the atmosphere and hydrosphere. Volcanic eruptions have been advocated as culprits for both the cooling and warming of the Earth's atmosphere (Robock 2000; Toon 1980). They thus disrupt the climate, ecosystems and civilization; sometimes

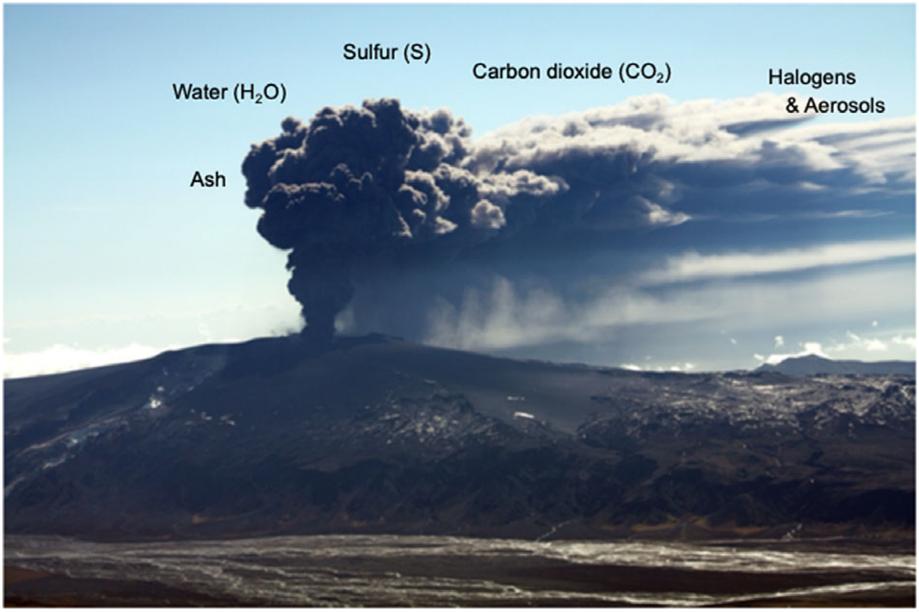

Figure 1. Photograph of a volcanic plume during the 2010 Eyjafjallajökull eruption (Iceland), indicating some of the primary outputs of volcanic emissions. Credit: Photo from Magnus T. Gudmundsson (University of Iceland).

positively – via increased fertility of soil (Fiantis *et al*. 2019), blooming of fisheries (e.g., Parsons and Whitney 2012), or increased artistic productivity (Chester 2005) – but most commonly negatively, depending on the scale of events, which may range from mild disruption to infrastructure and daily activities, to the obliteration of civilization (Grattan and Torrence 2016; Self 2006).

Volcanic Hazard Assessment and Risk Mitigation

Magmatic unrest and volcanic activity may generate a wide spectrum of volcanic hazards, ranging from toxic gas emissions to volcanic ash plumes that can circle the globe, to searing pyroclastic density currents, mud flows and mass movements (landslides, rock falls, sector collapses) of volcanic edifices that can travel several tens to hundreds of kilometres in a few hours and cause distal tsunamis (Sigurdsson *et al*. 1999). These hazards pose a potential threat to approximately 15% of the Earth's population (Freire *et al*. 2019). At present, nearly one billion people live within 100 km of volcanoes active during the last 10,000 years – a number which has nearly doubled in the last two decades (Loughlin *et al*. 2015; Witham 2005). The most common aftermaths of volcanic activity include loss of human life, respiratory illness, death of crops and livestock, and economic losses due to damage or destruction of infrastructure. Since AD 1500, we know of 278,368 fatalities (Brown *et al*. 2017), and in the twentieth century volcanic events have killed approximately

98,000 people while affecting about 5.6 million people worldwide (Witham 2005). In terms of economic impact, the consequences vary widely; the recent disruption caused by the 2010 eruption of Eyjafjallajökull volcano in Iceland forced the cancellation of over 100,000 flights, with financial repercussions estimated at approximately €3.3 billion (Mazzocchi *et al*. 2010). So, even in the case of modestly sized eruptions we must consider that their impact is set to increase as the Earth's population spreads towards active volcanoes. Yet, the geologic record indicates that the scale and reach of these hazards extends far beyond what we have historically witnessed. For instance, a large event (e.g., >100 km^3 of erupted volume) has ~4% chance of occurrence in this century (Papale 2018; Papale and Marzocchi 2019), and it has been argued that we are not adequately prepared for the occurrence of a super-eruption, which would cause global climatic disturbance (Cassidy and Mani 2022). The largest ash dispersal event since the last ice age, the 1815 eruption of Tambora (Indonesia), caused widespread crop failures and famine after global average temperatures dropped by ~1°C (Stothers 1984). Given that world food reserves total an estimated 74 days (FAO *et al*. 2012), such global disruption of temperature could be catastrophic.

In the last four decades, volcanology has undergone a revolution in quantitative observations of volcanic processes, thanks to sophisticated monitoring methods and advances in computational power as well as intelligent, machine-learning algorithms. Perhaps unsurprisingly, the most common question asked to a volcanologist is: *can we predict volcanic eruptions?* The short answer is *no, but we can sometimes forecast the onset of eruptions* (Bell *et al.* 2018; Voight *et al.* 1999) *or transitions in eruptive behaviour* (De la Cruz-Reyna and Reyes-Davila 2001; Lavallée *et al.* 2008), depending on the character of precursory signals (Poland and Anderson 2020). Although to date our forecasting efforts are frequently undertaken with hindsight, better monitoring network cover and faster data processing capabilities are improving this situation. Importantly, the acquisition and analysis of long-term datasets have already provided us with a view of the recurrence rate of volcanic activities at particular volcanoes (e.g., Carter *et al.* 2020) in a range of settings (Marzocchi *et al.* 2021; Papale *et al.* 2022), and integrated analysis of multi-parametric systems has given us increasing detail of shallow magma transport and precursory signals leading to volcanic eruptions (Sigmundsson *et al*. 2020). Yet, at this stage, we do not have the ability to answer *where?*, *how?* and *for how long?* an eruption is likely to occur. These are key questions that need to be addressed to improve volcanic hazard assessments and, in turn, adequately mitigate the risks. But to answer these questions, the community requires continuous, multi-parametric monitoring at a greater number and broader diversity of active volcanoes worldwide. It must validate processing methods and ground-truth observations. Ultimately, it must constrain and quantify the state of magma – an environment for which we, to date, possess only indirect knowledge. Direct knowledge of the state, distribution and properties of magma will enable the development of robust, quantitative, predictive tools that comprehensively integrate magma generation, transport and eruptions in the Earth system.

Our models of magma genesis, storage and transport rely in large part on somewhat indirect evidence exposed in the geologic record – both from eroded batholiths (magma bodies crystallized in the subsurface) and eruptive products – and from laboratory measurements which have helped constrain the properties (chemistry, petrology, density, diffusivity, viscosity, etc.) of magma and igneous rocks at natural conditions (Dingwell 2006; Ghiorso and Gualda 2015; Giordano *et al.* 2008; Lavallée and Kendrick 2021). Examination of these rocks has highlighted that magma reservoirs organize in different configurations depending on the production rate of magmatism and the level of interaction with the surrounding rocks. Magma bodies range in size and can be fully molten, or a complex amalgamation of partially crystallized magma mushes (Cashman *et al.* 2017). Despite decades of efforts in volcano geophysics, we cannot confidently detect, locate nor image magmatic bodies in the subsurface. Whilst some studies have inferred the presence of magma in the Earth's crust, the location and size of magma reservoirs remain speculative, as our models have never been ground-truthed; hence, models remain models. Common methods employ passive and active seismicity, ground deformation, gravity, ground resistivity and magneto telluric surveys, and they sometimes provide estimates concurrent with petrological estimates of magma storage conditions during the studies of eruptive products. Yet, such constraints are somewhat biased towards larger storage bodies and thus only coarsely accurate (in the range of ±~1–2 km) due to many unknowns. The ability to test our models on a system with known (directly monitored) rock and magma properties would drastically change this situation.

Probing the Subsurface and the Roof of Magma Bodies

Coring and drilling can radically improve knowledge of the subsurface by supplementing geophysical datasets with direct observations and in situ measurements; this costly practice is primarily undertaken by the industry (oil and gas, geothermal, etc.), is comparatively rare in active volcanic areas, and even scarcer in the service of monitoring volcanoes. Nevertheless, drilling in volcanic provinces, such as Iceland, Italy, New Zealand and Mexico, has exposed the diversity of reservoir rocks, showing extensive variations in rock types, in degree of alteration, fracture networks, and in geothermal gradients; dictated by tectonic setting and the circulation and action of hydrothermal fluids (e.g., Mortensen *et al.* 2014). The circulation of hydrothermal fluids is driven by the thermal gradient, imparted by heat production in the Earth's interior and heat loss at the surface (e.g., Lister 1980). Earth's heat loss has been estimated at 46 ± 3 TW (Jaupart *et al.* 2015). Heat is heterogeneously lost depending on the composition and thickness of the crust and the occurrence of magmatism. On continents, non-volcanic provinces exhibit a mean heat flow of about 80 mW/m^2 (Pollack *et al.* 1993), leading to a geothermal gradient commonly estimated at ~25°C/km in the shallow parts of the Earth. But in volcanic terrains where magma may rest in the crust at temperatures of up to ~1300°C, heat flow can locally exceed 30 W/m^2 and the geotherm may be a thousand times higher (see below, and Eichelberger *et al.* 2021). Considering the heat capacity of magma, one can estimate that cooling 1 litre of magma from 1000°C to 20°C in 1 second, would generate approximately 1 MW; scaled up, a 1 km^3 magma body could generate 1 GW$_t$ for about 30 years (Eichelberger *et al.* 2021). So, even small magmatic intrusions create considerable thermal anomalies (Burchardt *et al*. 2022). Yet, magma reservoirs can be hundreds and even thousands of cubic kilometres in volume, so the energy potential of magma is immense. Moreover, the rock surrounding magmatic bodies tends to be 'wet', hosting large-capacity hydrothermal systems which make harnessing fluids relatively simple, in comparison to tight, 'dry' rocks which require more extensive stimulation (i.e., enhanced geothermal systems, EGS). The hydrous nature of magma-geothermal systems provides a net advantage to the extraction of energy.

Heat retained in the Earth's interior has long been exploited by humans and animals alike (Arriaga 2005; Fraser *et al*. 2014). Utilized where readily available in active magmatic provinces for space heating since early civilization, efforts have most recently expanded to include the production of electricity by adapting technology from hydropower plants. As of 2022, geothermal energy accounts for ~0.5% of our energy portfolio (IRENA and International Geothermal Association 2023). Largely this is due to the high production costs (compared with other energy sources) and heterogeneous worldwide distribution. Yet, in volcanic provinces, it can be the backbone of an energy supply and a strong economy. It has been estimated that 39 countries could produce 100% of their electricity with geothermal energy (Dauncey and Mazza 2001). In Iceland, geothermal energy is readily accessible and has been rooted in the lifestyle since Iceland's early settlement, fostering its economic growth. In 2022, the country produced about 6 TWh of geothermal energy (i.e., 30% of its annual production) and over 90% of houses and many industries (aluminium smelting, cosmetics, geothermal spas) were powered by this renewable resource (Statistica 2021). This volcanic island hosts eight geothermal power plants and several hundred geothermal wells (commonly reaching ~1–2 km in the Earth's crust), generating an average of 5 MWh. In search of solutions to enhance the economics of geothermal resources by increasing energy output at a lower cost, a consortium between three Icelandic geothermal companies and academic experts was created in the year 2000 to establish the Iceland Deep Drilling Project (IDDP); their goal, to drill deeper in geothermal systems to reach hydrothermal fluids with higher enthalpy (i.e., energy density extant at supercritical conditions) to increase energy output. The first well (IDDP-1) was drilled in 2009 at Krafla volcano, which hosts a geothermal powerplant (with a capacity of 60 MW$_e$) operated by Landsvirkjun National Power Company of Iceland since 1978 (LV-2015-040). This site was chosen for the first borehole as extensive studies since the 1975–1984 Krafla Fires eruption had inferred the presence of a large magma reservoir at ~5 km depth; hence IDDP-1 aimed to reach 4.5 km depth (Friðleifsson *et al.* 2014). But to the astonishment of all, drilling had to cease at a mere 2.1 km, where they serendipitously encountered magma at a location not anticipated from geophysical surveys. This prompted operations to shift laterally, whereby magma was intersected a further two times. Hence, the consortium opted to perform flow tests which extracted fluids at a temperature of 450°C (Axelsson *et al.* 2014); the hottest fluids ever recorded at a geothermal power plant. Although these fluids were corrosive and generated infrastructural challenges, the flow tests indicated that this magma well could potentially produce 36 MW_e (Axelsson *et al.* 2014) that is, 5–10 times the average energy output of conventional wells in Iceland. Thus, in the right environment, a power station could rely on fewer wells to meet demand, significantly reducing operation and maintenance costs.

Lessons Learnt from Magma Encounters

Crucial lessons have been learnt from encountering magma at Krafla, and elsewhere. Here we review six of these, which must be studied and reflected upon as we plan future efforts.

(1) We Know for the First Time where Magma Resides Below a Volcano

Since the encounter at Krafla, magma has also been intersected at Puna (Hawaii, USA; Teplow *et al*. 2009) and Menengai (Kenya; Mibei *et al*. 2016). Interestingly, all three bodies are chemically evolved and stored at similar depths despite chemically contrasting country rocks (Eichelberger *et al*. 2018). The primary benefit of knowing the exact location of magma is that it has allowed us to revisit geophysical datasets and improve our methodologies to (re)assess if magma can be detected and delineated. As anticipated, knowing the solution meant that the signals which had previously not provided evidence for a shallow magma body, could be more rigorously analysed, giving hints of its presence (Schuler *et al*. 2015, 2016) and providing improved strategies for interpreting data that could be applied in other locations (Kim *et al*. 2020). These findings point to the necessity of validating our methods and ground-truthing our models to support volcano monitoring efforts and plan geothermal drilling in active volcanic provinces.

(2) We Know the Properties and Conditions of Magma in the Crust for the First Time

Although in Iceland about 90 vol.% of rocks are mafic and primitive (i.e., they almost directly derive from the Earth's mantle with little differentiation during transport to the Earth's surface), a highly differentiated, granitic melt was encountered at Krafla (Elders *et al*. 2011). The magma contains very few crystals and is capped by similar granitic rock (fully crystallized) in a way that challenges even our newest models of magmatic systems, raising questions about the origin of the magma. Has primitive magma differentiated to such evolved compositions via crystallization? Or is magma the result of partial melting of the geothermal reservoir rock? An answer to these questions in a setting such as Iceland will inform us about the formation of continental crust.

In addition, the glass chips (which represent in situ quenching of magma) returned to the surface in the drilling muds have allowed us to quantify the concentration of volatiles dissolved in magma and, in turn, estimate the pressure and temperature conditions extant in the magma body (Elders *et al*. 2011), assuming magma reaction to drilling may have been minimal if we consider the rapid quenching rate experienced by the recovered glass chips (e.g., Wadsworth *et al*., 2024). Interestingly, this magma stored at 900°C appears to experience a pressure of 30–50 MPa (Zierenberg *et al*. 2013). This finding was unexpected as lithostatic pressure estimates by conventional methods predict pressures of 60 MPa at 2.1 km, a discrepancy which may argue for the rapid response of magma to drilling.

(3) Magma was not Prone to Erupt

Would drilling into magma trigger an eruption? The removal of rocks during drilling generates a potential pathway for magma transport and induces decompression that provokes magma vesiculation (akin to uncorking a bottle of Champagne), which influences its mobility and eruptibility. But the fluids utilized for drilling induce cooling, which suppresses vesiculation and reduces fluidity. So, what is the response of magma to drilling? Does magma experience decompression before being quenched to glass? Could we learn to regulate the gas content of magma in order to regulate its buoyancy and eruptibility?

The preconceived notion that drilling into magma would trigger an eruption was rapidly challenged following the events of IDDP-1. The rhyolitic magma did not erupt to the surface when drilled into; yet, magma did ascend 10 m up the well before solidifying against cooler rocks (see below). Similarly, the dacitic magma encountered at Puna in Hawaii (notably, a chemistry never erupted at Kilauea), flowed a mere 8 m up the well-bore. This may however not always be the case: Construction of the power plants at Krafla coincided with the early stages of a 9-year basaltic fissure eruption (Larsen *et al*. 1979), and on 8 September 1977, 30 tons of low-viscosity magma ascended through a pre-existing 1138 m well, causing a brief, 20-minute eruption. Thus, not all magmas are primed to erupt, for example, if their resistance to flow is high (i.e., they have high viscosity) and if they are not a priori oversaturated in volatiles that prompt extensive vesiculation. Furthermore, these contrasting fates beg the question of whether we could regulate volatile loss to control magma buoyancy and ascent, as we do when carefully uncorking a bottle of champagne to prevent violent foaming. A borehole into magma could provide the opportunity to moderate outgassing, which, perhaps, could one day be used to lessen the explosivity of an imminent eruption or even prevent one. So, did magma and volatiles respond to drilling during IDDP-1?

The glass fragments recovered from the drilling mud hints at a potential response of magma during drilling; in particular, there is evidence of slight occurrences of vesiculation (< 11%) due to decompression, and oxidation due to chemical interaction with the fluids (Saubin *et al*. 2021). Yet, the magnitude of observed changes may be argued as relatively trivial, having insignificantly impacted the buoyancy of the magma, which only flowed up the well by 10 m. Thus, overall, the drilling conditions selected during IDDP-1 may be deemed appropriate for magma drilling in environments akin to Krafla; nonetheless, the systems' response must be accurately modelled (the EU projects IMPROVE and MODERATE target these challenges) to optimize these conditions in the future, and to raise the possibility of regulating outgassing by controlling the pressure and temperature of magma.

(4) The Geothermal Gradient above Magma is 1000 Times Higher than Typical Geotherms

Perhaps the most remarkable findings made by magma encounters is how steep the thermal gradient leading to magma is. At Krafla, the reservoir rock at 2070 m depth reaches (and possibly exceeds) a temperature of 450°C, whilst at 2100 m magma is at ~900°C (Axelsson *et al*. 2014; Elders *et al*. 2011). Thus, the thermal gradient is approximately 16°C/m. At Puna and Menengai, the gradients reach 5°C/m and 17°C/m, respectively. These magnitudes are 1000 times higher than typical geotherms. Importantly, such gradients cannot be explained by conductive cooling and cannot be sustained for long durations if fluid circulation contributes to cooling, thus indicating that heat is likely continuously replenished in magmatic systems due to convection and the latent heat of crystallization (Eichelberger 2020), which can buffer heat loss by releasing ~2°C per percent of crystals formed (e.g., Blundy *et al*. 2006).

(5) The Rocks Above Magma were Unexpectedly Highly Permeable to Fluids

In the geothermal sector, there is a common presumption that hot rocks are ductile and deform plastically, and so cannot fracture; therefore, it is assumed that fluid circulation cannot be efficient due to the lack of fracture pathways in near-magma environments. Yet during IDDP-1, drilling operations were disturbed at depths below 2000 m as the rocks became increasingly permeable, resulting in complete loss of the drilling fluids (15–45 L/s) to the surrounding rock (Mortensen *et al*. 2014).

Thermal stimulation is commonly practised to enhance fluid circulation in geothermal reservoirs (Grant *et al*. 2013) where thermal contraction by cooling can be sufficient to fracture rocks (Timoshenko and Goodier 1970). In natural cases, thermal jointing is commonly observed in rocks crystallized from magmatic intrusions, causing columnar joints (Figure 2(A)). Novel laboratory experiments on Icelandic lava showed that 150°C of cooling from the solidus (temperature below which material is fully crystalline) is sufficient to induce fractures (Lamur *et al*. 2018). When cooling by fluids is efficient and rapid, magma can also vitrify (Dingwell and Webb 1990); thus, by thermally stimulating a magma reservoir it can thermally joint at higher temperatures and over greater volumes (Figure 2(B)). Because cooling-

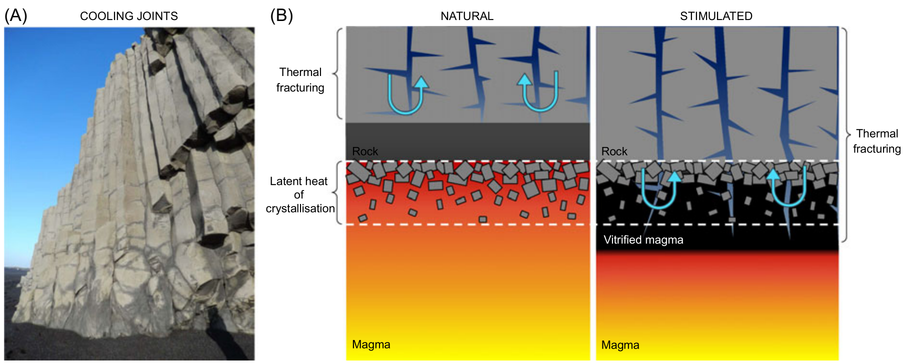

Figure 2. Thermal fracturing in magmatic environments. (A) Columnar jointed basalt near Vík, Iceland, showing the geometrical fracture patterns that develop due to cooling contraction of magma and lava bodies. (B) Sketch of fracture arrangement during natural (left) and anthropogenically stimulated (right) cooling of magma. The sketch shows that fractures can penetrate magma if cooling is sufficient, for example enhanced by drilling fluids. These fractures allow fluid circulation, which transfers mass and heat into the hydrothermal system.

induced contraction acts to widen the generated fractures (Lamur *et al.* 2018), cooling from greater temperatures can more drastically enhance fluid flow (e.g., Lavallée *et al.* 2019), allowing magma wells to produce up to 10 times more energy than conventional geothermal wells (Figure 3). Thus, magma and its superhot surroundings are the ideal environments to perform thermal stimulation and extract energy.

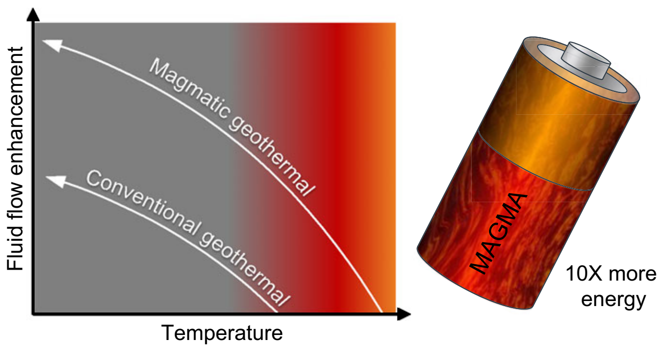

Figure 3. Extent of fluid flow enhancement due to cooling joint propagation during thermal stimulation of conventional geothermal systems versus magmatic systems, which can yield up to 10× more energy.

(6) Magma Wells may be Challenging to Operate

Engineering challenges were associated with magma drilling and operations in such extreme environments (Ingason *et al.* 2014; Thorbjornsson *et al.* 2020). In particular, the drill string got stuck in magma and was liberated by injecting more drilling fluids to quench and thermally contract the magma. When drilling operations and the injection of fluids ceased, thermal relaxation of the rocks caused extensive thermal expansion of the casing, which caused damage – a challenge that has prompted the industry to develop flexible coupling technology to avoid such an outcome in the future. Flow tests, although extremely energetic, caused the corrosion of the casing, which can challenge structural instability through time (Ingason *et al*. 2014). Thus, these challenges need to be carefully considered in future (near-)magma drilling projects and new materials and technologies must be developed and rigorously tested (Karlsdottir *et al*. 2015; Thorbjornsson *et al*. 2015; and as targeted by the EU-funded projects DEEPEGS and GeoWell).

Diverse in their nature, these crucial lessons are potential game-changers which are paving the way for future efforts. They beg for our return to magma, with an increased level of preparedness, and have inspired the community to establish the first magma observatory.

Creating the First International Magma Observatory

Arguably, safe access to magma will transform our understanding of magmatic systems and volcanic hazards and propel us into the next generation of geothermal energy, which we name: magma energy.

Innovative requirements must be met to safely access magma. We need a robust plan, informed by carefully integrating scientific knowledge, cutting-edge technologies and the latest engineering practices, in order to develop innovative magma engineering practices to successfully achieve this ambitious goal. Our knowledge is ripe for this vision.

The quest to access magma has been extensive. In addition to the above examples of unintentional magma drilling at Krafla, Puna and Menengai, we have a wealth of knowledge from pioneering coring into lava lakes in Hawaii by the US Geological Survey in the 1960s, which can be considered a prototype of future magma drilling. Most notable among these is Kilauea Iki lava lake (see Helz 2009; Helz and Thornber 1987), which filled a crater by more than 100 m during the 1959 eruption of Kilauea. Kilauea Iki was cored multiple times over a period of more than two decades (achieving nearly 100% recovery), yielding a rich dataset including the liquid line of descent (i.e., tracking the evolution of mineral phases in time, space, and temperature), as well as constraints on heat transfer mechanisms (Hardee 1980) and processes of melt-crystal segregation. The knowledge obtained from these detailed studies forms the basis for all geoscience study programmes worldwide. In the late 1970s and early 1980s, the USGS was joined by Sandia National Laboratories as part of the US Department of Energy's Magma Energy Project to test the feasibility of extracting energy directly from magma (see Colp 1982), and included placing a heat exchanger directly into the molten lens below the surface of the solidifying lava lake. The project was judged to have demonstrated the feasibility of extracting energy directly from magma (Dunn *et al*. 1987), and has since paved the way for the future creation of the first magma observatory.

The creation of a magma observatory stands to transform current knowledge and provide new strategies for interpreting and utilizing the Earth as we enter the third millennium. To ensure applicability to other magmatic systems worldwide, a series of objectives need to be achieved. The activities should:

(1) Enable sampling, instrumentation and experimental manipulation of magma;
(2) Characterize the state and evolution of the magma-rock-hydrothermal transition zone to an unprecedented level;
(3) Develop new monitoring methods and approaches capable of identifying, locating, and characterizing magma bodies;
(4) Develop and test new designs to construct stable wells for sampling and continuous long-term monitoring of magma bodies;
(5) Test new materials and instruments resilient to extreme conditions;
(6) Develop and test new energy harnessing technologies;
(7) Evaluate the response of magma and fluids to geothermal exploration and utilization.
(8) Develop guidelines to assess magma response to drilling to inform operations in real-time; and
(9) Improve reliability of warnings of impending volcanic eruptions worldwide through a ground-truthed understanding of subsurface volcanic processes and how to monitor and interpret them.

Such fundamental goals must be at the core of a magma observatory. With these in mind, and equipped with the knowledge that previous drilling efforts in lava lakes and magmas have provided unparalleled insights into magma dynamics, an international initiative was created between academics and the industry to establish the first magma observatory, under the auspices of the Krafla Magma Testbed (KMT; www.kmt.is). The vision of KMT is to become a world-class international in situ magma laboratory with access to the magma-rock-hydrothermal boundary through wells, available for advanced studies and experiments. Endorsed by the government of Iceland and supported by the International Continental Scientific Drilling Program (ICDP) the project has gained momentum since its inception in September 2014 and meticulous interdisciplinary planning resulted in the creation of a non-profit organization in autumn 2023.

The KMT infrastructure will include a multi-hole facility and an education centre to foster scientific exchange and knowledge transfer to the next generations, the public, stakeholders, and authorities. A range of innovative activities have been planned for the next few decades. In the first instance, two wells will be produced, whilst monitoring the system using surface, downhole and space-borne instruments (Figure 4).

- *Well 1 will enable sampling across the rock–magma interface to characterize the state of this transition and the properties and conditions of magma*. Subsequently, well 1 will be instrumented with thermocouples, fibre-optic cables, and strain gauges, to monitor the temperature, pressure, and deformation of the rock and magma. Once completed, the system will be allowed to thermally relax (to reach

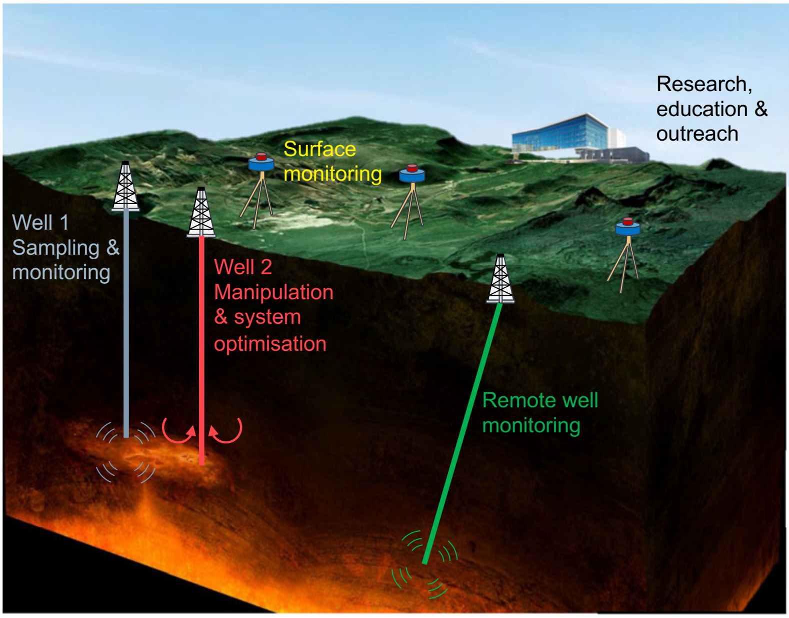

Figure 4. Illustration of the implementation plan of the Krafla Magma Testbed. More information can be found at www.kmt.is.

its 'background' conditions following the disturbance prompted by drilling and fluid injection), thus enabling constraints on the extent of disturbance by drilling and on the ambient condition of the magma-hydrothermal system. Experiments will be undertaken to quantify signal propagation in the rocks and magma, to refine models that interpret the subsurface.

- *Well 2 will enable experimentation.* Well 2 will be drilled ~1 year later, following complete relaxation of the system imparted by the operations in well 1. Close monitoring via instruments in well 1 will allow for a direct assessment of the response of magma to drilling well 2. Magma will be sampled to assess how the system evolved during that period. Following completion of the well, a range of experiments will be undertaken, including magma manipulation to assess the response of magma, thermo-mechanical stimulation followed by flow tests to assess the energy offered by magmatic fluids and to optimize future geothermal energy harnessing practices, and, finally, to test the resilience of new materials, sensors and instruments to extreme environments such as magma bodies, or near-magmatic environments extant in black smokers (increasingly considered for geothermal energy production), on other planets (e.g., Venus), and in certain industries (e.g., nuclear power plants, metallurgy, glass manufacturers).

Following the success of these two wells, further wells are planned for energy and complementary observations of the system.

A magma observatory is needed to bolster large-scale international scientific infrastructure (e.g., hadron collider, arctic station, international space station, etc.)

and enhance the completeness of Earth system observations; to date, we have higher resolution images of the Sun's surface than of our own planetary interior. The opportunity to obtain direct access to magma will transform the geosciences and our ability to engineer the Earth. One could even speculate that, in the future, in volcanology and geothermal science, we will refer to the time as *before KMT* and *after KMT*.

The vision of KMT is commendable and the prospect of accessing magma has recently gathered significant attention from the media, the public, and industry. In recent years, an increasing number of start-ups have developed their service strategy around the opportunity offered by magma energy. The world needs to hear about this prospect, to maximize the future use of this resource globally and improve our sustainability on Earth.

Empowering Cities on Magma

Active volcanoes are found in many settings around the globe (Figure 5). Many major cities and megalopolises are built on volcanic landscapes (Tokyo, Mexico City, Naples, Auckland, to name but a few). Reiterating that ~10% of the Earth's population live within 100 km of an active volcano, it is crucial that we begin exploring and utilizing the magmatic environment immediately. The potential global impact of accessing magma – both for volcanic hazards and magma energy – is vast (Figure 5), especially when considering that the majority of countries eligible to receive official development assistance (ODA) by the intergovernmental Organization for Economic Co-operation and Development, are volcanically and so magmatically active. Accessing magma could radically transform the economic landscape. In Europe alone, the economic potential offered by magma exploration is tremendous, as several countries are volcanically active (i.e., having had an eruption in the past 10,000 years; e.g., France, Iceland, Italy, Spain, Portugal, Greece) or have experienced relatively recent volcanic eruptions (Germany, Luxembourg), or are associated with volcanically active colonies and/or territories (e.g., Montserrat, Guadeloupe, Reunion Island, etc.). We must learn to access this resource safely to harness its tremendous power. Magma energy offers higher energy output at a reduced cost, which could radically revolutionize the performance of geothermal energy in the world energy landscape. Similarly, we stand to gain a wealth of information on volcanic unrest. Just as we all heavily rely on weather forecasting tools to go about our daily activities, it is now time for the volcanological community to modernize its approaches and ground-truth observations to develop a comprehensive quantitative model capable of predicting the lifecycle of magma (from its genesis to its differentiation, storage, transport, and eruption), to constrain the global impact of volcanic emissions to the atmosphere, the hydrosphere, the biosphere, and climate. Accessing magma, next-generation geothermal energy, and modernization of volcanology are direly needed for communities, stakeholders, policymakers and the industry to improve sustainability, increase our preparedness, and build a more resilient future.

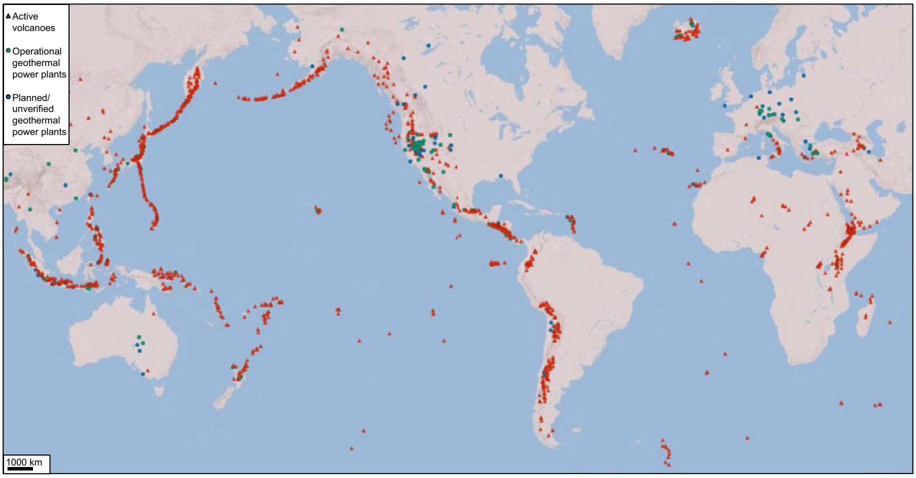

Figure 5. Global distribution and coexistence of active volcanoes and geothermal power plants. Active volcanoes shown were compiled by the Smithsonian Institution © [https://volcano.si.edu/projects/vaac-data/] and are defined as those exhibiting activity in the last 10,000 years (Global Volcanism Program, 2023). Powerplants are defined as operational or planned/unverified (Coro and Trumpy 2020). The map was constructed in MATLAB using a basemap provided by Esri (2009).

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Competing Interest Statement

We declare that all authors have no conflicts of, or competing, interests related to this article.

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About the Authors

Yan Lavallée received his BSc (2001) in Earth and Planetary Sciences from McGill University, Canada; his MSc (2003) in Space Studies from the University of North Dakota, USA; and his Dr.rer.nat. (2008) in Mineralogy from the Ludwig-Maximilians-Universität München, LMU-Munich, Germany. Between 2012 and 2022 he was Chair of Volcanology and Magmatic Processes at the University of Liverpool, UK, and in 2022 he returned to the LMU-Munich where he was appointed Chair of Magmatic Petrology and Volcanology. Lavallée's principal research interest is in understanding the behaviour of magmas and rocks, and their impact on volcanic, geothermal, and planetary systems. He is amongst the world-leaders in experimental volcanology, and in (geo)material testing at extreme conditions. He is co-founder and Chair of the Science and Technology Board of the Krafla Magma Testbed (KMT) – an initiative aiming to establish the first international magma observatory. He has been bestowed with the Macelwane medal of the American Geophysical Union and the Wager Medal of the International Association of Volcanology and Chemistry of the Earth's Interior. He is a Fellow of the American Geophysical Union, Founder of the Young Academy of Europe Charity Organization, and a Member of Academia Europaea.

Jackie Kendrick is an experimental volcanologist and rock physicist with a bachelor and masters in Geology from University College London, UK. She completed a PhD in Mineralogy at Ludwig Maximilian University (LMU-Munich, Germany) in 2013, which was followed by research positions at the University of Liverpool and the University of Edinburgh, including a prestigious Early Career Fellowship of the Leverhulme Trust. Since 2022 she is a senior academic (*Akademischer Oberrätin*) at LMU-Munich, commissioning state-of-the-art laboratories for geomaterial testing. Her accolades include the 2016 Outstanding Young Scientist Award of the European Geosciences Union (EGU), Geochemistry-Mineralogy-Petrology-Volcanology (GMPV) division, and since 2017 she has been an elected Fellow of the Young Academy of Europe. From 2017–2019 she served on the GMPV division Scientific Advisory Committee of EGU, and in 2019 she represented the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) on the International Union for Geodesy and Geophysics (IUGG) council. She has been Principal and Co-Investigator and partner on numerous national and international grants, is editor of several specialist journals in volcanology, geology and geothermal research and has served as a member of evaluation panels for funding agencies in Portugal and the UK.

John Eichelberger has a career that spans a half century in volcanology, scientific drilling, geothermal energy, natural hazards, and international Arctic education. Educated at MIT and Stanford, he was on the research staff at Los Alamos and Sandia National Laboratories from 1974 to 1979, and 1979 to 1991 (participating in the Magma Energy Project), respectively. In 1991 he became Professor at the University of Alaska Fairbanks (UAF) where he led the expansion of the Alaska Volcano Observatory and pioneered collaborative volcano monitoring, science, and education programmes with Kamchatka, Russia and Hokkaido, Japan. He left UAF to serve as Program Coordinator for the Volcano Hazards at the US Geological Survey in 2007, but returned in 2012 to be Graduate School Dean and Vice President Academic of UArctic. He received the European Geosciences Union's (EGU) Soloviev Medal in Natural Hazards in 2015, and the Geological Society of America (GSA) designated him Distinguished Lecturer for Continental Scientific Drilling in 2020. He is known for original insights into magma mixing and porous-flow degassing of ascending magmas, as well as leadership or participation in several volcano-related drilling projects. Eichelberger co-founded the Krafla Magma Testbed (KMT), Iceland, to be the world's first borehole observatory to study magma. He is also working to core to near-magma at Augustine Volcano, Alaska, complementary to conventional geothermal development there. Eichelberger believes that superhot magmatic energy is the best green, firm power option for the future and that acquiring direct data from magma is a volcano hazard community obligation. He is a Fellow of the GSA and a member of American Geophysical Union, EGU, Geothermal Rising, International Association of Volcanology and Chemistry of Earth's Interior, and the Society of Petroleum Engineers.

Paolo Papale was born in 1964 and started his academic career in 1990 at the University of Pisa, then moved to the National Institute of Geophysics and Volcanology (INGV) of Italy where he has been Director of Research since 2003. At INGV he coordinated the National Projects in Volcanic Hazards (2005–2010) before becoming the first Director of the newly born Volcanoes Division (2013–2016) and the funder of the Center for Volcanic Hazards (2016). In 2005 he started serving the European Geosciences Union (EGU) where he was first Secretary for Volcanology (2005–2011), then President of the GMPV – Geochemistry, Mineralogy, Petrology and Volcanology Division – and EGU Council Member (2007–2011). He was a member of the Commission of the United Nations for the Lake Kivu crisis in 2002, and advisor for volcanic crises and emergency planning operations by the National Civil Protection Department of Italy. From 2011 he has been a member of the Academia Europaea, for which he has chaired the Earth and Cosmic Sciences Section (2017–2021), then the Class on Exact Sciences from 2021, when he became a member of the Board of Trustees of the Academia. He is a co-founder of KMT – Krafla Magma Testbed, a large initiative which aims at creating an international facility represented by the first magma observatory in the world, for advanced scientific and industrial research. He is fellow of the International Union of Geodesy and Geophysics. He has been Coordinator, Principal Investigator, WP leader and key person for several projects of the European Union; founder and co-chair of the Volcano Observatory Best Practice (VOBP) workshop series; Editor of scientific journals and specialized books, and founding Editor of *EGU-Solid Earth*; and evaluator or member of the evaluation panels for EU, NSF, NERC, and other national science funding agencies.

Freysteinn Sigmundsson is an Icelandic geophysicist doing research on volcanism, magmatic and tectonic processes, plate spreading, and earthquakes. He also studies present-day movements of the solid Earth caused by glacier retreat due to climate change and how that affects volcanoes. He studied geophysics at the University of Iceland (BSc and MSc) and at the University of Colorado in Boulder, USA, where he finished a PhD degree in 1992. He is a researcher at the Nordic Volcanological Center, Institute of Earth Sciences at the University of Iceland. His research focuses on using measurements and modelling of ground deformation, interpreted together with evidence from other fields, to improve understanding of volcano processes. He has made pioneering applications of Global Navigation and Satellite System (GNSS) geodesy and interferometric analysis of satellite synthetic aperture radar images (InSAR) to map deformation and study geological processes, using opportunities provided by the Iceland natural laboratory. He is a fellow of the American Geophysical Union and a member of the International Association of Volcanology and Chemistry of the Earth's Interior and Academia Europaea. He has had long-term interest and involvement in the plans for drilling into magma at Krafla volcano, Iceland.

Donald B. Dingwell received his BSc (1980) in Geology/Geophysics from the Memorial University of Newfoundland, and his PhD in Geology at the University of Alberta (1984). After two years as a Carnegie Research Fellow at the Geophysical Laboratory of the Carnegie Institution of Washington and one on the Faculty of the University of Toronto. He was recruited to Germany to the newly-founded Bavarian Geo-institute. There he obtained his Venia Legendi in Geochemistry in 1992. Between 2000 and 2024 he held the Chair in Mineralogy and Petrology at the Ludwig-Maximilian-University of Munich. Dingwell's principal research interest is the physico-chemical description of molten rocks and their impact on volcanic systems. His research work has been supported by grants from the ERC, Carnegie Institution, NSERC, German Research Society (DFG), Alexander-von-Humboldt-Stiftung, European Commission, NATO, and several other research agencies as well as selected industries. The fruits of that research (>550 articles with over 35,000 citations) have been recognized by scientific awards and fellowships of the German Mineralogical Society (DMG), the German Research Society (DFG) the Mineralogical Society of America (MSA), the American Geophysical Union (AGU), the European Geosciences Union (EGU) and the Institute of Scientific Information (Highly Cited researcher). He is an elected member and Vice President of the Academia Europaea and a member of several international scientific societies. He served as the President of the European Geoscience Union and Secretary General of the European Research Council.