



BOOK OF ABSTRACTS

KMT Symposium
10-12 April 2024
Munich, Germany



Government of Iceland





Preface

It is with great enthusiasm that we present the Book of Abstracts for the Krafla Magma Testbed (KMT) Symposium, held under the theme "Together, toward a greener and safer future." This symposium brought together leading experts, researchers, and professionals from the fields of geosciences and deep-drilling engineering to share their insights, research, and innovations related to the Krafla volcanic and geothermal systems and analogous environments.

The KMT Symposium aimed to foster a vibrant and collaborative community of experts dedicated to advancing our understanding of volcanic and geothermal systems. The abstracts contained within this volume reflect the diverse and cutting-edge research that was presented at the symposium. From geology, geophysics, and petrology to rheology, geochemistry, and geoengineering, these contributions represent the forefront of scientific inquiry and technological advancement.

The symposium provided a unique platform for interdisciplinary dialogue, enabling participants to exchange ideas, discuss challenges, and explore new frontiers in sustainable energy solutions. The discussions and connections made during the event are vital for driving forward the innovative research that will help address some of the most pressing issues facing our planet today.

We extend our deepest gratitude to all the contributors, reviewers, sponsors, and organizers whose dedication and hard work made the KMT Symposium a resounding success.

As you explore the abstracts in this book, we hope you will be inspired by the breadth and depth of research showcased here. The Krafla Magma Testbed initiative continues to gain momentum, and the collaborative spirit of this symposium will undoubtedly propel us toward a greener and safer future.

Thank you for your participation and for contributing to the growing body of knowledge that supports the KMT vision.

Sincerely,

KMT Symposium Team



Organizing Committee

The success of the Krafla Magma Testbed (KMT) Symposium is a result of the dedicated efforts of our Organizing Committee. Their hard work and commitment have been instrumental in bringing this event to fruition.

Local organizing committee

- **Yan Lavallée (Chair)**, Chair of Magmatic Petrology and Volcanology
Ludwig-Maximilians-Universität München
- **LMU Volcanology Lab Team**
Ludwig-Maximilians-Universität München

KMT Project Office

- **Amel Barich**, Science Officer - Krafla Magma Testbed (KMT)
- **Eva Laufey Eggertsdóttir**, Communications Officer - Krafla Magma Testbed (KMT)

Scientific Committee

We extend our heartfelt appreciation to the members of the Scientific Committee for their invaluable contributions in shaping the academic and research focus of the symposium. Their expertise and guidance have ensured a high standard of scientific excellence.

- **Anette Mortensen**, Geothermal Expert - Landsvirkjun
- **Freysteinn Sigmundsson**, Research Scientist - University of Iceland
- **John Eichelberger**, Professor Emeritus - University of Alaska Fairbanks
- **John Ludden**, Chair of the Board of Directors - Krafla Magma Testbed (KMT)
- **Paolo Papale**, Research Director - Istituto Nazionale di Geofisica e Vulcanologia
- **Yan Lavallée**, Chair of Magmatic Petrology and Volcanology - Ludwig-Maximilians-Universität München

Acknowledgements

We would also like to acknowledge the contributions of all the volunteers, session chairs, and staff who played a crucial role in making the KMT Symposium a successful event. Your dedication and hard work are greatly appreciated.



Plenary Session



Plenary Session 1:

Krafla Magma Testbed: The Initiative | John Ludden – Chair, Board of Directors, KMT

Inception of KMT: A Vision for Advancing Geoscience | John Eichelberger – Professor Emeritus, University of Alaska Fairbanks

Transformative Contributions of KMT to Volcanology: Advancing Understanding and Mitigation of Volcanic Hazards | Paolo Papale – Research Director, Italian Institute of Geophysics and Volcanology

Current Landscape of Geothermal Energy Worldwide and in Iceland: Embracing the Magma Energy Revolution | Vordís Eiríksdóttir – Director, Geothermal Operations, Landsvirkjun

KMT Science Plan | Yan Lavallée – Chair of Magmatic Petrology and Volcanology, Ludwig-Maximillan University

Announcement of the Establishment of the KMT Non-Profit Organisation | Björn Þór Guðmundsson – CEO, KMT

Plenary Session 2:

Geophysical constraints on the structure of Krafla and how it compares with other central volcanoes in Iceland | Magnús Tumi Guðmundsson – Professor, University of Iceland

KMT and EPOS: Horizons of Collaboration in Data Management | Kristín Vogfjörð – Coordinator for Geoscience Research, Iceland Meteorological Office

Engineering challenges of drilling into magma and extracting its energy | Sveinbjörn Holmgeirsson – Geoenergy Consulting

KMT Outreach and Education | Ben Kennedy – Professor, University of Canterbury



Oral Presentations



Session 1 - Geothermal system exploitation

Power generation potential of superhot geothermal wells

Authors: Samuel Scott

Author Affiliation: University of Iceland

Abstract: In this presentation, I describe ongoing work to quantify the power generation potential of wells drilled into superhot conditions. The power generation potential of superhot wells is quantified using two types of models. The first type of model consists of a simplified wellbore model coupled to a power cycle. Derived estimates for power output closely match previous estimates of the power generation capacity of the IDDP-1 well (rated at up to ~36 MWe depending on the utilization scheme). Although the specific enthalpy of superhot fluids is larger than that of supercritical fluids, the estimated power output of wells drilled to superhot conditions is lower than the estimated power output for wells drilled to supercritical conditions (up to 50-60 MWe; Albertsson et al., 2003) due to the lower fluid density at superhot conditions. This study thus shows that the calculated power output from wells in the near-magma environment depends sensitively on reservoir pressure. However, the approach undertaken by this first kind of model has limitations, including the assumption of a given mass flow rate or volumetric inflow rate at the base of the well. The second kind of model performed in this study involves explicitly modeling fluid flow around an intrusion at ~2 km depth, and simulating production from a well drilled across the brittle-ductile transition. In this model, which was calibrated to match the natural state temperature distribution of the Krafla geothermal field, the mass flow rate into production wells depends on the reservoir pressure and permeability structure. While this work is ongoing, initial results suggest that matching the first-order characteristics of the IDDP-1 well, including the steep temperature gradient in the vicinity of the intrusion, discharge enthalpy of ~3200 kJ/kg, and mass flow rate up to ~55 kg/s, require high permeability in the near-magma environment of ~10 millidarcies. The results thus indicate that the high productivity of superhot wells reflects high permeability close to the intrusion, likely as a result of thermal cracking or jointing processes as an intrusion cools and becomes permeable.



Informing deep geothermal reservoir rock mass properties from drilling data - experience from IDDP-1

Authors: Marlene Villeneuve (1), Ben Kennedy (2), Anette Mortensen (3), Elodie Saubin (2), Aliaa Hammoud (1)

Authors Affiliations: Montanuniversität Leoben (1), University of Canterbury (2), Landsvirkjun (3)

Abstract: During geothermal drilling it is important to know the quality of the rock mass for well completion, mud weight selection, interpreting features of interest, to characterise the subsurface in the absence of core. In deep geothermal drilling, tens to hundreds of meters are drilled without cutting retrieval and, therefore, without insight into the rock mass. Wireline logs are commonly used to interpret the subsurface, however, these data are typically collected after drilling an interval, and do not necessarily provide rock mass information. Despite their increasing development, studies using drilling parameters and logging-while-drilling to interpret the rock mass in high-temperature, deep geothermal environments remain rare. Here we present a method where the drilling parameters from drilling of IDDP-1 are used to assess the quality of the rock mass, with particular focus on its effect on drillability. We use the drilling reports and drilling data to develop and test this method based on recent work into relating drilling (Wyerling et al. 2017) and tunnelling boring machine parameters to the rock mass (Gong et al. 2007; Frenzel et al. 2012; Villeneuve 2017) to demonstrate how methods from geotechnical drilling and tunnelling can inform geothermal drilling.

First, we normalize and process the drilling parameters. Penetration rate (PR) and torque (T) are normalized by RPM, whereas weight on bit (WOB) is normalized by drill bit diameter, allowing comparison of values over different intervals of drilling. The drilling parameters are then processed to produce the penetration index (PI), which is the ratio of normalized PR to normalized WOB, and the net advance rate (NAR) which is the drilling speed averaged over 1 m length, including times when PR is 0, but RPM is > 0 . Based on previous work regarding interaction of tunnel boring machines with rock masses, we provide interpretations of the rock masses encountered by the drill bit. Key variations in both normalised (PRs, WOBs, Ts) and processed (PI, NAR) drilling parameters are used to interpret the drillability in different rock masses (e.g. poor drillability, blocky ground).

Major variations highlighted on large-scale drilling logs vs depth are combined with the interpretations from drill cuttings to determine the impact of lithology changes on drillability, as well as other indicators of down-hole conditions, such as circulation loss and feed zones, interpreted from flow rate changes. Of particular interest is the link between areas over which the drilling analysis indicates "blocky ground" with circulation loss and feed zones. We show that the PI and NAR combination, along with torque, can provide insight into the locations of fractured rock masses, as confirmation for feed zones that also show increased loss of circulation. Ongoing work is aimed at validating this method with geological characteristics obtained from cuttings, wireline logs and geological models. The development of logging-while-drilling technologies for high-temperature wells also presents the possibility to combine drilling and wireline log data processing for real-time interpretation during drilling.



IDDP-2 – Drilling into supercritical conditions – What do we know and what remains hidden in the subsurface?

Authors: Tobias Björn Weisenberger

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Abstract: Drilling of RN-15/IDDP-2 in the Reykjanes geothermal field in southwest Iceland was carried out in 2016 and 2017. With a total measured depth of 4650 m the well RN-15/IDDP-2 marks the deepest well drilled in Iceland to date. The high-temperature conditions of the predicted amphibolite facies were confirmed by a temperature and pressure log that was carried out on January 3rd, 2017, yielding a minimum temperature of 426°C at a pressure of 340 bar, reaching supercritical fluid conditions. As the well had not recovered from cooling during drilling, maximum temperatures are significantly higher as indicated by petrological studies (Bali et al., 2020; Zierenberg et al. 2021). The pre-existing production well RN-15 was chosen as Well of Opportunity. It was originally drilled in 2004 to a vertical depth of 2507 m. Drilling of RN-15/IDDP-2 started with a total loss of circulation and fluid return where only recorded while drilling phase 5 from 3000 to about 3200 m measured depth. With nearly 2000 m, this marks one of the longest blind drilled sections in Iceland. Geological information about the subsurface geology therefore relies on spot coring, downhole logging data and information obtained from drilling data. The latter two are only indirect information that are subject to interpretation. For example, post-drilling evaluation of fluid losses and temperature logs show that structure features in the subsurface align well with previous mapped structural features. Spot coring was the only direct information about the subsurface geology. In total, 13 core runs were conducted during drilling of phase 4 and 5. Solely nine core runs retrieved core material with a total core length of 27.31 m and a core recovery of 63%, whereas the three deepest cores improved the core recovery significantly. Core runs 11 to 13 recovered 22.13 m core. In contrast to core runs 1 to 10, core runs 11 to 13 were drilling with a different bit type and core diameter. Therefore, direct core information is only available for about 1% of the drilled subsurface geology below 2507 m. This contribution will give an overview on experiences during drilling of IDDP-2 and aims to stimulate planning of future scientific drilling, such as KMT. Coring equipment for drilling into very-high temperature conditions will need to be tested. In parallel, contingency plans will need to be developed, such as targeted side-wall coring based on downhole logging information.



Increased Structural Integrity of Borehole Casings by using Axial Thermal Expansion- and Annular Pressure Relief- System for use in HT-Thermal Wells

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Abstract: Current lessons learned from drilling and producing high-temperature (HT) geothermal wells and superheated/supercritical deep geothermal wells brings forward the conclusion that the metal casings are a bottleneck for reliable structure and/or a successful project. That is, structural failures in wells that occasionally occur in conventional geothermal wells and are more pronounced in superhot wells, i.e. the Iceland Deep Drilling Wells, IDDP-1 drilled in 2008-2009 and IDDP-2 drilled in 2016. Both previously drilled IDDP wells had detrimental casing failures that in IDDP-1 lead to abandonment and in IDDP-2 lead to shallower inflow into the well at a casing damage rather than the target depth that are at supercritical conditions. In both cases the failures were twofold, i.e. caused by (i) post-yielding because of constrained thermal expansion and (ii) annular pressure buildup due to excess liquid (or water pocket) in cement causing partial or full collapse of the casing. The former (i) can be controlled by using novel Flexible Couplings that allow expansion of each casing joint permitting it to work within the elastic range of the metal without passing the yield point. And the latter (ii) can potentially be mitigated by introducing a pressure-relief element in the production casing removing annular overpressure in a cemented casing-to-casing annulus, this is being investigated in the EU Horizon Europe supported project COMPASS led by ON Power. The patented Flexible Couplings have been developed within ÍSOR from the year 2015 within several research projects (EU Horizon 2020 supported GeoWell and DEEPEGS, and GEOTHERMICA project GeConnect) and the annular pressure relief system is being developed in the EU Horizon Europe project COMPASS that in part serves as a preparation for drilling of IDDP-3 in the Hengill geothermal system operated by ON Power. Synergy exists in well design, between deep superhot geothermal wells and the KMT (Krafla Magma Testbed), where both well structures deal with similar physics and the novel technology could be an enablers for such drilling projects.



Session 2 – Reservoir rock properties and fluid flow

Dynamic cap-rock formation above a silicic magma reservoir, Reyðarártindur pluton, Iceland

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Abstract: The rate of heat and fluid transfer from magma bodies, and hence the development of geothermal reservoirs, are primarily influenced by the properties of the surrounding host rock. However, exploration of geothermal systems related to shallow-crustal magma bodies via geophysical methods and drilling often miss 3D features that exert major controls on the geothermal system. This study uses field mapping, sampling, rock strength testing, and geochemical modelling to detail the dynamic interactions between a fossil granitic magma body and its host rock.

The granitic Reyðarártindur pluton intruded into zeolite facies meta-basalts at approximately 2 km depth. Notably, the geological setting and composition mirrors that of the IDDP-1 and future KMT drilling projects. At Reyðarártindur, exposure to the heat from the pluton caused a 10 m-thick zone of the host rock above the pluton to be altered to a hornfels, which lacks primary basaltic structures, such as cooling joints and auto-breccias. The hornfels is extremely strong and impermeable as a result of recrystallization and sintering that eliminated all porosity in the rock and sealed and healed fractures. Partial melting of the meta-basalt produced rhyolitic magma, now exposed as a thin layer of granite that displays enriched rare earth element concentrations. At a later stage of pluton development, overpressure associated with magma recharge fractured the cap-rock, producing systematic fracture sets that are partly intruded by dykes fed from the pluton.

The hornfels cap-rock acted as a 'lid' to the magma body, restricting the loss of heat and fluids from the magma reservoir. Convective transfer of heat and fluids would have only developed once faults and fractures penetrated the cap-rock. This study highlights the importance of the processes occurring at the magma-host rock interface, in particular the timing and 3D geometry, for the development of the associated magmatic-hydrothermal system.



Subsurface soil and lithology alteration shaping degassing at Krafla caldera, Iceland

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Abstract: Alteration by rock-fluid interaction can significantly impact rock and soil properties influencing fluid flow within hydrothermal aquifers, and shaping surface features and degassing in geothermal settings over time. Hence, the understanding of the spatial distribution of thermal manifestations in correlation with the geological setting and alteration type remains essential for unravelling the processes controlling the transport of fluids from within the hydrothermal aquifers to the surface.

Previous studies focused on the effect of alteration within hydrothermal aquifers on a scale of hundreds of meters. In contrast, limited research has explored the influence of subsurface lithologies – including their intrinsic and altered permeability – and their spatial distribution on degassing activity. This study examines subsoil portions across the active geothermal fields of Krafla caldera in Iceland, to explore the relationship between various soils/lithologies and primary degassing areas. In particular, we investigate how hydrothermal alteration influences the petrophysical characteristics of these lithologies, thereby modulating surface-level fluid circulation.

In two field campaigns carried out in 2022 and 2023, we assessed the in situ petrophysical properties of over 200 samples across 22 sites in the Viti and Hveragil regions. Moreover, we conducted subsoil diffuse CO₂ flux measurements for specific profiles. Field permeability ranged from 10⁻¹¹ to 10⁻¹⁶ m², with CO₂ fluxes varying between 1.25 to 2628.33 g/m² day. Additionally, we examined the grain size distribution and the componentry of selected subsoil layers.

Our findings delineate the presence of both active (thermal) and inactive (non-thermal) regions, depicting the variable impact of hydrothermal alteration on the subsoil properties. In active geothermal sites, the dominance of mineral dissolution/replacement facilitates the formation of preferential pathways for fluid flow. Within inactive areas, mineral cementation of pores and fractures appears to act as barriers to fluid movement. These outcomes offer crucial insights for comprehending and quantifying the effect of hydrothermal alteration on fluid dynamics, shedding light on the progression of surficial manifestations and degassing patterns within active geothermal areas.



Mechanical behaviour of geothermal reservoir rocks at Krafla

Authors: Jackie E. Kendrick (1), Guðjón H. Eggertsson (2), Anthony Lamur (1), Josh Weaver (3), Paul A. Wallace (1), and Yan Lavallée (1)

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Abstract: In order to predict reservoirs' production potential and assess the engineering challenges that may arise during exploitation, knowledge of rock properties are vital. Stimulation practices employed to optimise production must be tailored to the geological setting and rock properties. With the geothermal sector shifting its target towards reservoirs with higher temperatures and pressures in order to source supercritical fluids (e.g., the Iceland Deep Drilling Project, IDDP), knowledge of the behaviour of rocks under increasingly extreme conditions is required.

When the first well of IDDP was drilled in 2009 within the Krafla caldera, the drilling was terminated at 2.1 km as the drill penetrated magma that could not be bypassed. The region, however, showed great potential for exploitation. To better constrain the mechanical properties and thermal response of the Krafla reservoir rocks to cold water injection (during drilling and stimulation), six different rock types were sampled, based on knowledge off the main lithologies. These included 3 basalts, hyaloclastite, obsidian, ignimbrite, felsite and micro-gabbro with porosities ranging from 10 to 60 %.

We performed a suite of uniaxial compressive strength, triaxial and indirect tensile strength tests. Across the spectrum of materials tested we show that the rock strength is primarily controlled, and inversely proportional to the porosity. The highly variable microstructures of the different samples (from large, rounded vesicles to highly-connected hairline fractures) cause large variabilities in mechanical response to stressing, including differences in UCS:UTS ratio, contrasting Young's Modulus and significant differences to the nature of failure, particularly under confined conditions. In particular, rocks with higher porosities (>15% vol. pores) displayed pore collapse at relatively low effective pressures (potentially extant in the Krafla geothermal reservoir).

Thermal stimulation procedures are also common in high temperature reservoirs, as the introduction of cold fluids can induce a rapid volumetric contraction that builds stress that can be sufficient to fracture rocks; a method considered relatively easy and cost-effective. Here, we performed a set of thermal expansivity measurements showing the intricacies of volumetric expansion during controlled heating. Such measurements provide us with a constraint of the degree of cooling required to induce cooling-fractures in each lithology. To further test the effects of thermal stimulation on fluid flow, samples of basalt and felsite were thermally stressed by heating to 450 °C and cooling at different rates (in air, in water and at a controlled rate of <5 °C·min⁻¹). The results suggest that the permeability of originally highly fractured rocks is relatively unaffected by thermal stressing, but that originally unfractured rocks show a nonlinear increase in permeability with each thermal stressing cycle, especially when a significant thermal shock is imposed by quenching in water. These results demonstrate that the mechanical properties and the impact of thermal stimulation are highly dependent upon lithology, calling for a detailed understanding of the lithologies' subsurface distribution. For Krafla, the insights into the mechanical and thermal properties of the reservoir rocks ultimately facilitate implementation of better and safer exploitation strategies.



The impact of fracture generation on fluid flow in the Krafla geothermal reservoir

Authors: Anthony Lamur (1), Guðjón H. Eggertsson (2), Jackie E. Kendrick (1), Sigurður H. Markússon (3), Yan Lavallée (1)

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Abstract: The magmatic-hydrothermal system at Krafla Volcano, North-East Iceland, has been exploited by Landsvirkjun National Power since 1977 to generate electricity. The presence of fractures in hydrothermal systems influence the storage capacity and efficiency of fluid flow necessary for successful and sustained exploitation for geothermal energy production. Here, to gain insight on the permeability of the reservoir rock, we present results of laboratory experiments conducted to evaluate the effect of multiple fractures on the permeability and porosity of the various lithologies found within Krafla caldera (including dense and porous basalts, obsidian, felsite, ignimbrite, gabbro and hyaloclastite). The samples were cored to 2:1 aspect ratio (diameter:length) disks and the permeability was measured at confining pressures between 1-100 MPa in a hydrostatic pressure vessel during loading and unloading. The permeability and porosity are generally correlated, and for a given porosity the variations in permeability reflect the connectivity and tortuosity of the permeable pathways. During increasing confinement, pre-existing cracks and pores close, causing a net permeability reduction. During unloading, samples fail to recover to pre-loading permeabilities as cracks do not necessarily fully reopen. To further examine the hysteresis imposed by crack closure and reopening, we cyclically loaded/unloaded a felsite sample ten times by varying pore pressure and show an additional nonlinear reduction in permeability with each pressurisation cycle; thus an understanding of the pressurisation path may be a requirement to constrain fluid flow variations in geothermal systems (1).

We then investigate the influence of macro-fractures on fluid flow (2). We used the Brazilian tensile testing method to impart a single through-going fracture in each sample, and measured the permeability evolution with increasing confinement. We then introduced a second fracture perpendicular to the first one, before re-measuring the permeability evolution at the same confinement conditions. We model the predicted permeability using a combination of the Kozeny-Carman relationship and arithmetic mean of the permeability. Our results show that the generation of the first macro-fracture induced the most significant permeability changes, and that the permeability increase due to the presence of a macro-fracture is highest for samples with a porosity <15%. The generation of a second fracture had little additional effect on permeability across the range of porosities tested. The findings show that the effective pressure is a key control on the efficacy of fluid flow in intact and especially, fractured rocks (1-3). The results also indicate that although stimulation practices may initially significantly enhance fluid flow, sustaining that flow may require fracture offset or propping, or volumetric changes induced by, for example, thermal contraction.



IDDP-1 in context: Insights from Krafla's past rhyolitic eruptions, and the link between the 1724 and 2009 CE magmas

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Abstract: The 2009 encounter with rhyolitic magma in the IDDP-1 well marks the latest chapter in a long history of rhyolitic magmatism at Krafla, including at least eight eruptions between ~190 ka and 1724 CE. We studied the petrochemistry of these older rhyolites to explore the origin of silicic magmas at Krafla and offer context for understanding the modern system. Mineral zoning patterns in each of the past rhyolites reveal diverse histories among grains, implying mixing of crystal cores from multiple evolved melt bodies and/or assimilated felsic intrusions ("felsite") before final rim growth. Evidence for mafic recharge is absent in most crystals, implying that rhyolite storage and fractionation occurred in isolation from the underlying mafic system. Comparison of glass compositions with published experimental work casts doubt on previous models for rhyolite generation by melting of altered basalts. Fractional crystallization and assimilation-fractional crystallization (AFC) models instead predict compositions similar to Krafla rhyolites after 60–70 vol% crystallization of a quartz tholeiite melt, representative of the evolved crystal-poor basalts that typically erupt within Krafla caldera. We suggest that stalling and crystallization of these evolved basalts at shallow depth forms crystal mushes from which evolved melts are extracted: these melts ascend and mix with other similar melt bodies and/or assimilate earlier felsic intrusive material, before either erupting as crystal-poor rhyolites or solidifying as felsite. Rhyolite erupted in 1724 CE from Viti crater is compositionally indistinguishable from the 2009 IDDP-1 rhyolite with respect to both major and trace elements, and likely represents the same magma body which has thus been resident for at least ~300 years. Petrologic evidence implies extremely rapid mobilization of this rhyolite by basaltic diking during the 1724 event.



IDDP3 and beyond – what's next?

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Abstract: The interest in superhot geothermal has grown substantially in recent years. There are a few ongoing projects focused on opening these resources for utilization, such as the New Zealand Geothermal Next Generation Project, the Japan Beyond Brittle Project, and the Iceland Deep Drilling Project (IDDP). The IDDP was launched in the early 2000's. The three biggest power companies in Iceland; Landsvirkjun, HS Orka and Orkuveitan – Reykjavik Energy, formed a consortium with domestic and international partners to work towards the goal of drilling supercritical production wells. Each of the abovementioned power companies committed itself to drill a superhot ~4.5 km deep well in its production field. The first well of the project, IDDP-1, was drilled in Krafla, N-Iceland. That well was drilled into magma at a depth of 2.1 km. It was possible to do flow tests in that well and it yielded superhot steam. The data gathered in those flow tests were very interesting. It was, however, difficult to handle the fluid due to corrosion and scaling. Moreover, the casing failed and the well had to be abandoned. The second well of the project, IDDP-2, was drilled in Reykjanes, SW-Iceland. That well reached a depth of 4.6 km and core samples were collected from that depth. The casing, however, failed during recovery and the production part of the well is not accessible. However, supercritical conditions were measured in the well before casing failure. The next well of the project, IDDP-3, is now being planned by Reykjavik Energy in the Hengill area in SW-Iceland. The main lesson learned from previous IDDP wells is that there are a number of technical and geoscientific challenges that must be solved before drilling a deep production well. The biggest issue is well integrity, and it is evident that a new well design is needed for successfully drilling and operating such a well. Reykjavik Energy is currently pursuing two options for deep geothermal utilization. Firstly, deep production will be pursued along with the IDDP consortium. Reykjavik Energy and the consortium have revised the goal of the IDDP project. The goal is now to reach "superhot" conditions instead of supercritical conditions; i.e. the goal is to drill into a formation where the enthalpy of the fluid is greater than 3000 kJ/kg. In addition, alternative casing materials and flexible couplings will be used in the superhot production well to minimize the risk of casing failure this time around. Another avenue of interest that is being pursued by Reykjavik Energy is deep injection. This concept has been called hybrid superhot EGS and the goal is to reach for the resources below the conventional resources. Injection into superhot formations below the reach of production wells of conventional high enthalpy geothermal field is believed to create and stimulate permeability there. The injected water will then carry the heat from the deeper superhot formation towards the production wells and support the already existing production. The main advantage of the superhot hybrid EGS concept is that it can be achieved using existing well technology. When successful, this method will prolong the lifetime of conventional high enthalpy geothermal projects by enlarging the reservoir downwards and decrease the need for make-up drilling. Moreover, superhot hybrid EGS is an important milestone in developing superhot EGS. This paper will present the deep utilization journey of Reykjavik Energy and partners with a focus on future plans, technical challenges and the work ahead.



Session 3 – Magmatic conditions at Krafla

Distinct but linked magma storage zones fed the 1975-1984 Krafla Fires eruptions

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Abstract: The 1975-1984 Krafla Fires event in northeast Iceland was the first plate-boundary rifting episode to be tracked using seismic and geodetic monitoring. Geophysical observations from this episode have driven the development of conceptual models of magma transport during plate spreading. For instance, the lateral flow model of melt supply from shallow magma chambers to fissure eruptions was inspired in part by these observations. Complementary petrological data could provide an important test of these models but has not been available to date. In order to address this knowledge gap, we studied the petrology and geochemistry of all nine Krafla Fires basaltic eruptions. Our large dataset of new whole-rock, matrix glass and mineral analyses from samples collected during or shortly after each eruption reveal a clear compositional bimodality that persisted across the episode, with evolved quartz tholeiite (MgO = 5.7–6.4 wt.%) erupted inside Krafla caldera, and more primitive olivine tholeiite (MgO = 6.4–8.7 wt.%) erupted north of the caldera margin. Barometric calculations indicate tapping of these magmas from distinct reservoirs: a primitive lower-crustal reservoir at a most probable depth of ~14 – 19 km, and a more evolved, shallower reservoir at a most probable depth of ~7-9 km beneath the caldera. These reservoirs were often tapped simultaneously, at times without any mixing of the two magmas. Diffusion modelling indicates that primitive magma erupted in 1984, in the final and largest eruption, rose from lower-crustal depths over timescales of a few months at most – well within the duration of the decade-long rifting event. These observations are not consistent with the widely held view that the eruptions were entirely fed by lateral magma outflow from the shallow reservoir. They instead require some decoupling of the flow paths of the two magma types: the primitive magma either bypassed the sub-caldera reservoir laterally or ascended vertically from beneath the northern vents. Gradual inflation of the caldera between rifting events may indicate continuous flow of deep-sourced melt into the shallow storage zone. Comparison of the Krafla Fires with other rifting events and eruptions highlights key differences between events and sets out the requirements for any generalized models of rift-zone magmatism. Integration of petrologic, geochemical and geophysical data is required to provide a holistic view of future rifting events in Iceland and at other spreading centres.



Storage conditions of rhyolitic magma at Krafla, Iceland: an experimental Investigations of IDDP-1 glass samples

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Abstract: The 2009 encounter of rhyolitic magma at 2.1 km depth during IDDP-1 offers a novel opportunity to explore magmatic conditions in the shallow crust. In order to support the development of safe practices as part of the Krafla Magma Testbed, a comprehensive understanding of magma state at storage conditions and response to drilling, powerplant, and research activities is crucial. Natural glass fragments quenched and retrieved during drilling can be used to constrain magma properties and storage conditions. We conducted experiments using these rhyolitic fragments at temperatures of 880 to 920°C and pressures of 35 and 45 MPa (estimated by dissolved H₂O-CO₂ concentrations (1)) for durations between 6 and 48 h, to assess the storage conditions and the response to perturbations of conditions caused by drilling. Experiments were conducted in a cold-seal pressure vessel under water-saturated conditions and varied oxygen fugacities (NNO+1 (more oxidised) or QFM (more reduced)). The rhyolitic fragments selected for the experiments range from light brown to black, varying vesicularity ($\leq 1\%$) and are microlite free, but contain dispersed phenocrysts of plagioclase, pyroxene, Ti-magnetite, and apatite.

Experiments conducted at NNO+1 generated darker brown glass colours, recorded no dissolution of the original crystal grains, but induced overgrowth in some pyroxene crystals in all charges. At 45 MPa and 900°C, there was a temporal change in vesicularity, with shorter experiments (6 h) exhibiting a higher percentage of vesicles (4.9%) compared to longer experiments (22 h – 2.5%). Reducing the temperature to 880°C led to an increase in microlite content and vesicularity of 3.9% (19 h). At a lower pressure of 35 MPa we observed the appearance of quartz as a newly crystallised phase. When the temperature was reduced from 900°C to 880°C, there was an increase in microlite content and an increase in vesicularity from 2.7% (900 °C) to 14.8% (880 °C). Under QFM conditions, glass colour changed notably to light brown and quartz crystallised in all experiments. Additionally, we observed a significant reduction in microlite content compared to NNO+1. At 45 MPa and 900°C, vesicularity ranged from 5.4% at 6 hours to 10.9% at 24 hours, then decreased to 7.0% at 48 hours, while the microlite abundance showed a reduction over time. At 35 MPa and 900°C, there was no significant difference in vesicularity between 6 and 48 h runs (3.4% and 4.3%, respectively), even by increasing the temperature to 920°C (3.9%). Our experiments constrain magma storage conditions at 900-920 °C, 45 MPa, and relatively oxidised conditions. The findings further demonstrate that at the implied shallow conditions, magma is highly sensitive to small P-T-X changes, over short periods, analogous to those imposed by geothermal drilling, potentially resulting in changes in the crystalline phase (e.g., pyroxene overgrowth, quartz crystallisation) and vesicularity that impact magma properties. Comprehensive models of magma storage and response to drilling, powerplant and/or research activities ought to incorporate the petrological constraints provided herein to guide safe practices and implementation strategies when accessing magma.



Numerical simulation of the formation of the IDDP-1 rhyolitic melt (Krafla volcano, Iceland)

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Abstract: We simulate the formation of rhyolitic magma sampled during drilling by the IDDP-1 at Krafla volcano, Iceland (1). Our thermochemical model simulates heat transfer, melting and deformation resulting from a convecting magma layer intruded into host felsic rocks, hence reproducing hot rhyolite magma. The thermochemical model is based on the resolution of the Navier-Stokes equations for incompressible fluids, with temperature and crystal content dependent viscosities in the Boussinesq approximation, so that it accounts for both compositional and thermal convection and for the release of crystallization latent heat. The two distinct magmas are simulated with a numerical scheme based on the VOF method implemented in the opensource platform OpenFoam. The solver was adapted from a previous one ("MultiMeltInterFoam", Louis-Napoléon et al., 2020, 2024).

The setup involves three layers: an upper and lower felsic crust separated by an intermediate, hot basaltic magma. Phase diagrams for the Krafla basalt and the Viti granophyre are produced with the Rhyolite-MELTS.

We assume immediate injection of a basaltic sill of thickness 100 m and temperature 1150°C into a cold (400°C) felsic crust. Initially, a layer of solidified basalt is formed on both top and bottom compositional interfaces, that prevents convective heat transfer towards the host crust. As the host rock temperature increases, the melting front starts to propagate upwards and convection develops in the molten part of the rhyolite. At the bottom, melting is inefficient due to the accumulation of solidified basalt. After 45 years, approximately 20 m of molten rhyolite has formed at the top of basaltic sill. Vigorous convection keeps the temperature nearly constant in both layers.

A simplified 1D model from (1) was tuned based on the results of the 2D simulations. Only one fitting parameter manages to reproduce the whole thermal evolution of the system with reliable accuracy and significantly smaller CPU time.



Experimental investigation of kinetics of basaltic melt-felsic crust interaction: Implications for the Icelandic rhyolite genesis and the felsic crust delamination

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Abstract: Magma-rock and/or melt-rock interactions are open-system processes involving reactions of the rock partial melting, mineral dissolution in melt, and magma hybridization. In this work, we have experimentally investigated mechanisms of reaction between anhydrous basaltic melt and felsic granophyre rock at 1250°C and 0.2 GPa at oxygen fugacity of QFM (quartz-fayalite magnetite mineral buffer) to model the consequences of the felsic crust interaction with basaltic melt in the shallow crustal settings, with a goal to explain the origin of low- δ 18O rhyolite that was encountered by drilling in Krafla volcano (IDDP-1). It is not currently known if IDDP-1 melt is produced by partial melting of low- δ 18O felsic crust due to reaction with basaltic magma or by differentiation of the hybridized magma. We performed experimental reactions between Icelandic felsic crustal rock (granophyre or felsite) from Krafla volcano with Icelandic Fe-Ti tholeiite basalt to constrain the mechanism and rate of the hybridization reaction. In the kinetic 10 min-duration runs, the granophyre rock partially melts; and SiO₂ contents in the interface silicic melts (up to 75 wt% SiO₂) formed due to dissolution of quartz mineral diffuses to basaltic melt with characteristic rate of D ($6.67 \pm 1.15 \times 10^{-11}$ m²/s), which is comparable to the effective binary diffusion coefficients of silica in anhydrous basaltic melts. Comparison of major element chemistry of the natural IDDP-1 rhyolite glasses demonstrates poor similarity to those of the partial and interface melts produced in the kinetic experiments. Our data imply that the IDDP-1 felsic melts can be produced due to partial melting and dissolution of quartz-(plagioclase and alkali feldspar)-rich granophyre rocks associated with limited diffusion-driven hybridization with the basaltic magma. If dissolution of a felsic granophyre rock in basaltic magma is uniquely diffusion-controlled and the process only includes interaction along the interface, very slow hybridization of the interface silicic melt with basaltic melt would happen. Instead, we suggest that in order to produce the IDDP-1 rhyolite at shallow crust, the parental granophyre rock was not or very shortly intercalated with the super-liquidus basaltic magma in the Krafla caldera setting, and the felsic granophyre rock interacted with progressively cooling and crystallizing basaltic magma at temperatures from 1150 to 900 °C (Borisova et al., 2023). Further understanding of the magma-fluid-rock interaction processes will be obtained through the KMT drilling project.



Convective Melting and Water Behavior around Magmatic-Hydrothermal Transition: Stable Isotopes and Numerical Modeling with Application to Krafla Volcano, Iceland

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Abstract: Water is an essential component of rhyolitic magmas and nearly universally, silicic magmatism in the upper crust includes a transition from magma to water-saturated roof rocks. Magmatic-hydrothermal transitions where water is abundant and isotopically distinct (low- $\delta^{18}\text{O}$, δ^{D}) a situation characteristic for Iceland and Krafla. We present new stable isotopic measurements of rocks around Krafla (1,2) and in the IDDP melt and Viti crater xenoliths (2,3). We find these to be lower than the δ^{D} (-118‰) in the mantle-derived magmas or hydrothermal system. The formation of a fluid with such a low δ^{D} can be provided by the addition of low- δ^{D} water from OH-bearing minerals in hydrothermally altered roof rock or direct addition to glass below glass transition (4). This may happen during dehydration of epidote from the altered roof rocks, and, alternatively, may also proceed by the mechanism of thermal diffusion (the Soret effect) through the partially molten/hydrothermal transition zone controlled by fluid fugacity. The high-temperature gradient in the contact zone between magma and the geothermal system of about 15–17°/m with conditions at the cold end close to the critical point for the aqueous fluid further decreases the expected δ^{D} value at the hot end of the contact zone to less than -110‰ (3). We also present results of numerical simulation (3,5) of crust melting by either a hot rhyolitic or basaltic melt using a hypothesis that 2009 IDDP rhyolitic melt was produced during 1974–1984 Krafla Fires basaltic eruptions, or alternatively during 1724 Myvatn Fires. Zircons in rhyolitic domes in Krafla range in age from 20 to 80 ka (1), but IDDP melt has 0 ± 2 ka U-Th age zircons (5) conforming possibility to be produced by either of these two events. Thermal model is able to maintain a nearly liquidus rhyolite at 2 km depth if the sill is 100 m thick. We consider that rhyolitic melt could be preserved with a sharp $\Delta T = 500^\circ\text{C}$ upper boundary to its hydrothermal halo if it were convecting (3, 6). We modeled in detail (1–2 cm resolution) convective behavior using the effect of the addition of water to a water undersaturated rhyolitic sill from the hydrothermal system on top contained within the porous felsitic roof rocks. Less than 1 wt% water uptake in the melt proceeds via its thermodynamically estimated saturation with a partial melt, corresponding to the fugacity of hydrothermal water in the melt-fluid zone at particular T–P– XH_2O conditions and affects rates of melting and convection. In two series of numerical experiments run at pressures of 200 and 50 MPa, the interaction of water-filled porous felsite with near liquidus rhyolite magma resulted in water absorption, induced partial melting creating a narrow several meters wide mushy zone, and sluggish convection below that distributed water across the intruded sill. At P=200 MPa, the addition of about 1.5 wt% water results in stronger volume convection, causing the melting rate to increase to 20 m/year. However, the addition of <0.22 wt% water induced no melting on the magma/contact mush interface, and the intruded sill crystallizes without convection. With the parameters observed in 2009, including the water concentrations in the melt (1.8 wt%) and felsite (0.92 wt%) and the high temperature of the intruded magma (945°C–980°C), we obtained slow melting of the preheated felsite roof at a rate of about 1 m/year. This seems reasonable if the 2009 magma was intruded during the 1975–1984 Krafla Fires eruption.



Lithium Behavior in the Krafla Volcanic Zone: A Comparative Analysis between Surface Rhyolites and Felsic Cuttings from the Iceland Deep Drilling Project -1 (IDDP-1)

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Abstract: The unexpected discovery of felsic magma by the Iceland Deep Drilling Project - 1 (IDDP-1) in the Krafla volcanic system (KVS) presents a unique opportunity to investigate pre-eruptive lithium (Li) dynamics and establish a more direct connection between magma reservoirs and volcanic deposits. Our study provides new insights into Li abundances and isotope compositions in bulk rock, minerals, and groundmass glass from rhyolitic lavas at KVZ, encompassing various stages of groundmass crystallisation. Additionally, we examined felsic cuttings retrieved from the IDDP-1 well, comprising crystal-poor obsidian and crystal-bearing to -rich "felsite" particles. No evidence of Li loss through secondary hydration is found in glasses from surface lavas. Lithium inventories in groundmass glasses and minerals within lavas exhibit variations consistent with the cooling history of the deposit, resembling patterns seen in Snake River Plain ignimbrites. Lithium contents of glassy rhyolitic lavas, whether bulk-rock (average $27.2 \pm 3.1 \mu\text{g g}^{-1}$) or groundmass glass (average $28.4 \pm 4.7 \mu\text{g g}^{-1}$), and their bulk isotopic compositions (average $\delta^7\text{Li} = 4.4 \pm 0.2 \text{‰}$) overlap with those observed in IDDP-1 obsidian cuts (average $24.9 \mu\text{g g}^{-1}$ Li in bulk, $28.6 \pm 1.5 \mu\text{g g}^{-1}$ in groundmass glass, and $\delta^7\text{Li} = 4.5 \pm 0.2 \text{‰}$). Glassy lavas lacking spherulites may potentially preserve pristine magmatic Li element and isotope compositions, while areas with extensive groundmass crystallization reveal Li enrichments in phenocrysts. Plagioclases in slowly cooled parts of the deposit record a two-fold increase in Li contents compared to plagioclase found in glassy counterparts, along with evidence of open-system degassing marked by heavier bulk Li isotope compositions and lower bulk Li contents of the crystallized lava portions (average, $\delta^7\text{Li} = +7.2 \pm 0.1 \text{‰}$ and $7 \pm 0.8 \mu\text{g g}^{-1}$ Li) relative to bulk glassy lithologies (average, $\delta^7\text{Li} = +4.1 \pm 0.1 \text{‰}$ and $28 \pm 2 \mu\text{g g}^{-1}$ Li). Partition coefficients derived from IDDP-1 cuts successfully predict Li inventories in vitrophyres of rhyolites on the surface of the KVS. Li isotope compositions of the crystal-rich IDDP-1 cuts are significantly heavier (average, $\delta^7\text{Li} = +7.2 \pm 0.2 \text{‰}$) than lavas and IDDP-1 obsidian cuts, casting doubt on the notion that the IDDP-1 rhyolitic magma could result from the melting of felsite lenses in the KVS. Li contents in groundmass glasses within IDDP-1 crystal-rich cuts show higher Li contents (average $55.1\text{--}60.7 \mu\text{g g}^{-1}$), correlating with the higher crystal content and an increase in other incompatible elements (average $250 \mu\text{g g}^{-1}$ Rb) relative to obsidian cuttings (average $75 \mu\text{g g}^{-1}$ Rb).



Session 4 – Magma response to drilling and engineering practices

The ethics of volcano geoengineering

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Abstract: Volcano geoengineering is the practice of altering the state of volcanic systems and/or volcanic eruptions to exploit them or mitigate their risk. Although many in the field insist there is little that can be done to mitigate the hazard, past examples of both intentional and inadvertent volcano interventions demonstrate that it is technically feasible to reach volcano plumbing systems or alter atmospheric processes following eruptions. Furthermore, we suggest that economic, political and environmental pressures may make such interventions more common in the future. If volcano geoengineering ever becomes a discipline, it will need to overcome many safety and ethical concerns, including dealing with uncertainty, deciding on philosophical approaches such as a consequentialism or precautionary principle, justice and inequality, military uses, cultural values and communication. We highlight that while volcano geoengineering has significant potential benefits, the risks and uncertainties are too great to justify its use in the short term. Despite this, because of the potential large benefits to society, we believe there is a strong ethical case to support research into the efficacy and safety of volcano geoengineering for its potential future use. We propose that rigorous governance and regulation of any volcano geoengineering is required to protect against potential risks, to enable potentially valuable and publicly available research (e.g., quantification of efficacy and safety), to ensure that any future policy must be co-created through community engagement, and that volcano geoengineering should only be considered as part of larger mitigation practises.

The Krafla Magma Testbed provides an exciting opportunity to begin research on volcano geoengineering, this talk will focus more specifically about the ethical considerations of drilling into magma intentionally.



Insights into the krafla magma body from fossil intrusions and drilling returns

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Abstract: The way a shallow rhyolitic intrusion may respond to magma drilling is governed by the physical properties of the magma and the host rocks it intrudes. Here, firstly, we characterize rock properties at the margins of shallow rhyolite intrusions, by investigating the rock strength, permeability, and fracture density of the margins of four fossil rhyolite intrusions in Iceland. Secondly, we analyse the texture and geochemistry of magmatic glass and host felsite drilling chips from a time-series at IDDP-1 well to better understand magma response to drilling, and shallow storage conditions.

The field results reveal that the impact of shallow rhyolite intrusions on surrounding host rocks is dependent on the initial host rock properties, which in turn influence the style of magma propagation. Initially weak, porous and highly-permeable conglomerate and hyaloclastite respond by pore occlusion, with permeability decreasing accordingly. Their ductile compaction accommodates magma propagation, allowing irregular intrusive geometries to form. In contrast, initially strong, low-permeability basaltic lava and welded ignimbrite respond by brittle deformation, with intense fracturing associated with weakening. Rhyolitic intrusions in Iceland have variably sized and fractured chilled margins, with a maximum possible thickness of ~7 m. The aureole width in host rocks increases with increasing intrusion size, but aureole formation around < 10 m wide intrusions requires more rapid heat transfer than provided by conduction alone. For these small intrusions, intense fracture development in chilled margins could allow fluid advection and convection to significantly boost the heat transfer.

At Krafla, isotopic compositions suggest that the rhyolite magma formed by partial melting of felsite promoted by hydrothermal circulation and input of fresh rhyolite magma pulses from deeper. We suggest the presence of lenses of distinct magma composition and texture does not support intense magma convection. The main brown melt generated by high degree felsite partial melting is overlain by a clear melt formed by low-degree partial melting, and which is richer in silica, crystals, and vesicles. As the drill bit approached the magma, it encountered a ~14.5 m thick weak zone, where permeability has been enhanced by thermal cracking of hot rocks in contact with cold drilling fluids. Below this, a stronger ~8 m thick lithology, possibly damaged by the intrusion, separated the magma from the overlying hydrothermal system. Magma then responded to the encounters by limited bubble growth, deformation and nucleation, and caused systematic and consistent reaction of the drilling parameters, it was approached nine times over three drilling attempts. The trend revealed by the field data implies that knowledge of the aureole extent can inform the thickness of the intrusive shallow rhyolite body impacting the host rock. Based on our interpretation of lithologies around the active intrusion at Krafla, the most likely range of aureole size (8-22 m) implies a 700-1100 m thick magma body. This large dimension suggests that the rhyolite may be older than the last eruptive activity (Krafla Fires, 1975-1984).



Magma vesiculation and upwelling in cylindrical boreholes: outgassing and buoyancy

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Abstract: Magmas evolve in response to changes in temperature, pressures, and chemistry. As magmas progress to the surface, this can result in the exsolution of volatiles vapor bubbles that increases the buoyancy and eruptibility of magma. Ascent occurs at a rate controlled by the magma buoyancy and rheology, which are themselves dependent on the bubble cargo, and the geometry of the ascent pathway. At high ascent rates (or decompression rates), the exsolved vapor phase has little time to escape from the melt and promotes high shear rates in the melt phase which can result in fragmentation and explosive eruptions. Conversely, when gas is permitted to escape at low ascent velocities, the gas pressure and buoyancy reduce, which favors effusive eruptions or even magma stalling at depth.

We investigate the deformation and outgassing behavior of vesiculating rhyolites flowing in cylindrical conduits with implications for magma upwelling in both volcanic conduits and boreholes. We perform experiments using an aphyric rhyolitic obsidian from Hrafninnuhryggur ridge at Krafla volcano and produce vesiculation up to 80% by volume through heating and volatile exsolution at atmospheric pressure. Cylinders of the obsidian are placed into cylindrical tubes that assert varying degrees of "confinement" to the vesiculating samples. The vesiculation of the samples promotes isotropic expansion in unconfined samples and anisotropic flow in samples confined to a cylindrical geometry.

We demonstrate that anisotropic expansion against the conduit wall results in bubble deformation, which allows for enhanced coalescence and bubble connectivity, particularly at the conduit margins. This results in an increase in gas permeability, even at relatively low total gas fraction (as low as ~20 vol.%) when compared to unconfined experiments that require a higher vesicularity before percolation is achieved (>60 vol.%). We begin with centimeter-scale samples and explore progressively larger samples approaching the size of a borehole inner diameter (~16 cm) to understand the competing length and time scales of diffusive outgassing, bubble deformation, porosity and permeability evolution, and viscous flow. We make use of finite element method models to apply observations of micro-scale textural development to sample-scale flow dynamics to inform predictions of the rates of magma outgassing and flow at the field scale. The empirically-validated model can be used to simulate magma upwelling in boreholes such as during IDDP-1, and will be invaluable to define safe engineering practices as well as downhole research activities associated with the Krafla Magma Testbed.



Vesiculation and outgassing from rhyolitic magma at Krafla volcano: implications for drilling and research strategies

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Abstract: Accessing magma presents itself as a new frontier in geosciences and a key question in everyone's mind is, how does magma respond? Magma properties are heavily influenced by volatiles (primarily H₂O at shallow depth). In particular, volatile exsolution into bubbles (i.e., vesiculation) and outgassing determine the porosity, buoyancy, and rheological evolution of magmas, which in turn dictates their eruptibility. Exsolution is commonly triggered by decompression, heating, and/or crystallisation, whilst pressurisation, cooling, and/or melting can cause volatile resorption (i.e., hydration). So, upon drilling—which induces decompression from rock removal and cooling from drilling fluid—we anticipate the occurrence of vesiculation and fragmentation (or brecciation), producing variably vesicular and buoyant fragments which can invade the bottom of a well. Likewise, when fluid injection ceases, thermal relaxation may prompt further exsolution/ resorption depending on the pressure-temperature path.

Here we provide a framework to constrain vesiculation and diffusive outgassing from rhyolitic magma parcel of different volumes and validate it via experiments on Krafla rhyolite (using 1–12 mm diameter cores of surficial obsidian (1) and IDDP-1 glass chips (unpublished)). Bubbles grow readily at our experimental temperatures of 900–1000 °C. We find that vesicularity is progressively counteracted by fragment size-dependent, diffusive outgassing (When the volatile partial pressure is lower in the ambient gas than in the melt-hosted bubbles). This volatile loss produces a bubble-free dehydrated rind, which thickens proportional to the diffusion lengthscale of the volatile species. We show that more efficient outgassing is possible from small fragments with higher surface area to volume ratios, and therefore, pyroclasts with a smaller initial radius develop a higher proportion of dehydrated rind, densify faster, and attain more subdued vesicularities. We find that this diffusive outgassing process can produce fully dense, non-vesicular pyroclasts, effectively erasing the textural evidence of the vesiculation event altogether. Thus, the competition between vesiculation and diffusive outgassing controls the buoyancy of magma fragments. Using an analytical approach to the evolving clast geometry, we show that current closed system bubble growth models and diffusion models can be combined to estimate vesicularity in a magma parcel (of a given volume) surrounded by a free gas of relatively low partial pressure of H₂O. Considering the pressure, temperature, and chemical composition extant in the Krafla reservoir (as constrained by IDDP-1 studies), our analyses highlight that Krafla magma would rapidly vesiculate and likely fragment, if decompression preceded quenching by interaction with drilling fluid. In a fragmental state (before quenching or upon reheating when fluid injection ends), our analysis further indicates that the vesicularity and density would evolve rapidly as a function of fragments/parcel geometry, so both dense and vesicular regions may coexist at the bottom of the well. Such a dynamic control needs to be incorporated in simulations to plan drilling and research activities in projects such as KMT.



Session 4 – Geophysical properties of the volcano-geothermal system

3D crustal density distribution of the Krafla Volcanic System

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Abstract: The Krafla Volcanic System (KVS) in Iceland's Northern Volcanic Zone (NVZ) features a 10 km wide caldera and an array of scoria cones spread across 5-9 km wide fissure swarm. The last eruption event in the KVS, The Krafla Fires, occurred between 1975 and 1984, when an extensive network of basaltic sills and dikes were intruded in the central part of the caldera at depths of 3-7 km. In 2009, the Icelandic Deep Drilling Project (IDDP) unexpectedly encountered a rhyolitic magma body at 2.1 km depth, underscoring the importance of understanding the system's shallow crustal magmatic architecture.

Gravity measurements provide insights into the distribution of subsurface mass densities, revealing the structural configuration of magma and hydrothermal systems in volcanic areas. While previous gravity studies have contributed valuable insights into the geological structures and subsurface dynamics in Krafla, they have been limited in scope. These studies primarily focused on interpreting gravity data within the confines of the Krafla caldera, overlooking the broader subsurface context. A consequence of this was the non-detection of a shallow magmatic body discovered during the IDDP-1 drilling project. Additionally, the interpretation of gravity data has traditionally been constrained to a two-dimensional framework, lacking the depth and detail provided by three-dimensional gravity inversion techniques. Leveraging a comprehensive dataset comprising previous studies and 76 new gravity measurements within the Krafla Volcanic System (KVS), we have calculated the local Bouguer anomaly, providing a robust foundation for investigating the subsurface dynamics of the region through 3D inversion modelling.

Models from 3D inversion of the data exhibit a coherent, persistent, and robust pattern of bodies of anomalous densities. Horizontal sections through the 3D model, ranging from 0 to 15 km depth below sea level, reveal that the main low- and high-density anomalies are in the first 7 km of the crust, losing resolution with depth. The most prominent feature is a ring-like high-density anomaly associated with the surface outline of the Krafla caldera rim. This positive density anomaly surrounds a low-density anomaly that extends down to 5 km depth and lateral thickness variation located between Ytri-Bjarghóll and Sandabotnaskarð. This bowl-shaped low-density structure gets stronger with depth and extends north to reach the IDDP-1 area at 3 km bsl. Separate low-density features surround the Krafla caldera flanks. They are divided into shallow rooted (<2.5 km depth) structures in the western part of the Krafla caldera, and deep-rooted in the east, Hágöng area. These negative units correlate at surface with rhyolitic domes and welded tuff formed during the eruptive phase of the KVS. The distribution of these anomalies along the KVS displays a high structural complexity that is not only limited to the insides of the caldera.



Multi-scale seismic imaging and related seismicity patterns of Krafla volcano and its geothermal system

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Abstract: Within the interdisciplinary approach of the MSCA-ITN IMPROVE to better understand Krafla volcano, geophysical imaging can be a tool to link the results of various geoscientific disciplines.

To image the first 3-4 km of the subsurface, we are using multi-scale and multi-physics techniques, including passive seismics on differently scaled arrays and the electromagnetic methods MT and ERT, all overlapping and in the area of the future KMT site.

For now, the focus was mainly on analysing the seismic datasets.

The large scale dataset was provided by Landsvirkjun and ISOR, and consists of 10 years of data from the local seismic network with 12 permanent broadband stations, which have been continuously recording seismic data since 2013. We supplemented this network in June 2022 with a dense, small scale network of 98 nodes. This resulted in two arrays, operating in parallel, which makes it possible to compare the ability of both networks on how well they resolve velocity structures with different wave types but also their ability to localise the seismicity reliably with a given velocity model.

Here we present multi-scale 3-D velocity models for P-, S- and surface waves, independently

derived for both networks through local earthquake and ambient noise tomographies. These models offer a glimpse into the subsurface structures of the volcanic system by utilizing various types of waves that are responsive to distinct rock/fluid properties and depths. The relocated and clustered seismic activity, documented by both permanent and temporary networks, underscores active structures pinpointed through tomography.

Both the seismicity and strong velocity anomalies are located at similar depths as the magma batch that was drilled into with the IDDP1.

With the velocity models and the relocated seismicity offering better constraints on the magma batch, we hope to strengthen the understanding of the connected volcanic and geothermal systems.



Reflection imaging at Krafla volcano using local earthquakes: challenges and possible solutions

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Abstract: Krafla is a volcano caldera in the north-east of Iceland which gained a lot of attention following the unexpected encounter of magma at 2.1km depth during geothermal drilling at the IDDP1 borehole in 2009. Despite numerous geophysical studies, the magma body remained undetected prior to drilling. The Krafla case highlights a common challenge in imaging the subsurface geology: typically applied methods like seismic tomography are effective in resolving large-to-moderate-scale structures within Earth, but often smooth out small-scale objects due to limited ray coverage (which depends on the distribution of earthquakes and seismic stations on the surface). However, reflections of seismic waves at interfaces in the subsurface can provide valuable information about small-scale geological features. These reflections occur and create detectable signals in seismograms if there is a significant contrast in impedance (product of rock density and seismic velocity) between two geological materials. In the summer of 2022, we deployed ~100 short-period seismic stations at Krafla as part of the IMPROVE project. Our goal is to detect reflections of seismic waves from the magma body at the IDDP1 borehole and subsequently determine its dimensions. We analyse ~300 local earthquakes (magnitudes < 1.5) and high-frequency industrial noise from the power plant at Krafla and find that seismic wavefields are dominated by extensive scattering and reverberations within the uppermost ~90m of the subsurface. The complexity of these 'site effects', attributed to geological features like lava caves and flows, complicates the identification of reflections from the magma pocket. However, we notice that wavefields are less complex when studying different earthquakes recorded by a fixed station, thereby ensuring that seismograms share the same site effect. Using this, we develop methods based on auto-correlation techniques to reduce the influence of site effects in the data, in order to facilitate seismic imaging in volcanic environments. We detect wave arrivals that are potentially associated with reflections stemming from the magma-rock interface below the IDDP1 borehole. To validate these observations and potentially determine the dimensions of the magma body, various imaging techniques will be applied. Our objective is to contribute to a better understanding of subsurface structures and processes and ultimately improve the efficiency and sustainability of geothermal energy extraction at Krafla and similar volcanic environments.



Using magnetotelluric data for determining the 4D evolution of active magmatic systems via both campaign and continuous data streams

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Abstract: Detection of geophysical signatures associated with volcanic eruptions, is key to understanding the underlying physical processes preceding these events and for accurate hazard assessment. Magma reservoirs are the main storage regions for eruptible magma and characterizing their temporal evolution requires the ability to detect and interpret changes in the magmatic system from surface measurements. Traditionally, monitoring of active magmatic systems has been carried out with seismic and geodetic approaches, both of which require dynamic 'active' changes within the magmatic system. Seismic monitoring relies on the number and location of earthquakes, to indicate magma migration. And geodetic measurements rely on identifying ground inflation events which have traditionally been interpreted to represent recharge of magma from a deep parental source into shallower crustal reservoirs. Magnetotellurics which measures subsurface electrical properties has an increased sensitivity to the physical properties or temperature of the magma stored within a reservoir, making it a promising additional monitoring technique able to detect 'static' phase changes within the evolving magma and the thermal structure of the magma reservoir. Thus, magnetotellurics is sensitive to both 'magma on the move' and the changes in the physical properties of magma that occur within the magma reservoir. Mount St Helens (MSH) was the site of a detailed magnetotelluric survey completed during the most recent dome building eruptive phase 2005-06 and is now in a period of quiescence. We use MSH as a case study and compare the original measurements from 2005-06 to repeated measurements at the same locations in 2022-23 to develop a temporal analysis approach and test the use of magnetotelluric measurements for monitoring applications. In addition to the repeat campaign, we have deployed 4 long-term monitoring stations with continuous data streaming. Finally, we intend to compare the continuous MSH time series with a similar long-term continuous magnetotelluric station network at Stromboli volcano, a system in a persistent state of eruptive activity. The data collected for these volcanoes will allow us to compare the dynamics of magma reservoirs, and the induced magnetotelluric signal, in active and quiescent volcanic systems.



Geodetic signature of thermal modulation of magma

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Abstract: Loss of ~ 0.04 km³ of cooling water over a period of 5 months after the accidental and unexpected drilling into an upper-crustal high-silica magma body at Krafla caldera (Iceland) points towards volumetric contraction and fracture formation in the reservoir upon rapid undercooling (hereafter referred to as thermal modulation).

Here, we present 2D plane strain numerical models to investigate the geodetic (ground displacements and gravity changes) signature of thermal modulation of an ephemeral and shallow-seated (at 2 km depth) rhyolitic magma body hosted within a basaltic crust. We simulate different temperature-time paths from background crustal temperature (according to a local geothermal gradient) to liquidus magmatic temperature (~ 1140 K) followed by rapid (-150 K/month) wholesale cooling to background (geotherm) temperatures. Thermal modulation of either a horizontal (sill-like) or a vertical (dyke-like) magma body follows after different magma residence times of 1, 4 and 10 years in the simulations. The magma body is represented by a thin sheet with a cross-sectional area of 31400 m², that is below the resolution limit of conventional geophysical imaging. The reservoir has a temperature-dependent density with a contrast of -400 kg/m³ with the surrounding medium (2800 kg/m³) at the start of each simulation. Physical properties of the crust and reservoir are temperature-dependent in all models, which solve for the influence of upper-crustal thermal perturbation on thermal strains and density changes prior, during and after thermal modulation.

Predicted ground displacements and gravity changes are detectable by conventional modern geodetic instrumentation with magnitudes of up to 0.15 m of ground subsidence and tens of μ Gals of gravity changes. Prior to thermal modulation, the maximum magnitudes of both observables correlate with magma residence time at liquidus temperatures. However, the modulation causes the largest magnitude of ground subsidence for the shortest residence time. For the longest residence time, subsidence upon thermal modulations is significantly less (by >50 %). Reservoir orientation plays a role in controlling the magnitude of thermal contraction with up to 15% more contraction caused by a sill compared to a dyke. Residual gravity changes (after correcting for the free-air effect) are greatest (~ 50 μ Gal/yr) for residence times of 1 and 4 years with statistically insignificant variations between the two sets of results. The effect of reservoir orientation is significant for both residence periods with a sill leading to ~ 25 % larger maximum gravity increases upon modulation. The smallest maximum increase (~ 20 μ Gal/yr) in gravity is predicted for the thermal modulation of a dyke after a 10-year liquidus residence time. For a sill-like reservoir the predicted maximum increase in gravity is 75% higher. The differences in predicted surface displacements and gravity changes upon thermal modulation are due to the protracted dissipation of a larger amount of heat stored within host rocks for longer magma residence times compared to shorter times. This leads to delayed responses of crustal strains and bulk density changes upon thermal modulation.

Our results contribute to the quantification of the amount of thermally modulated magma upon exploitation of high-enthalpy reservoirs using conventional and readily available volcano-monitoring instrumentation.



Session 6- Hydrothermal fluids and associated hazards

The fluid chemistry of the superhot IDDP-wells in Krafla, Reykjanes and Hengill, Iceland

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Abstract: The Iceland Deep Drilling Project (IDDP) aims to drill into supercritical geothermal systems and examine their economic potential. Within the project, two wells have already been drilled into superhot or supercritical conditions; IDDP-1 in Krafla and IDDP-2 in Reykjanes. The third well, IDDP-3, is expected to be drilled into superhot formations in the Hengill volcano in the near future.

This contribution will briefly discuss the chemistry of discharged fluids from IDDP-1 and IDDP-2. The insight gained from the first two IDDP-wells and superhot wells already drilled in the Hengill area will then be used to predict the chemistry of the fluids intended to be tapped by IDDP-3. The first well, IDDP-1, was drilled into magma at 2.1 km depth in the Krafla geothermal field in 2009 and yielded superheated vapour-like fluid at up to 142 bar-g and 452°C with enthalpy > 3000 kJ/kg. The fluid contained gaseous HF and HCl which formed strong acids when the fluid condensed, leading to severe corrosion of the casing and surface installations. Along with mechanical failure of the casing after the well was quenched with water, this led to the cementing and abandonment of the well (Friðleifsson et al., 2021). The second well, IDDP-2, was drilled to a depth of about 4.5 km in the Reykjanes geothermal field in 2016. Due to a damaged casing near the shallowest feed point at 2.3 km depth, the well has not been logged to the bottom since 2017, but earlier temperature logs revealed a temperature of at least 426°C and the bottom-hole temperature has been estimated 535°C (Friðleifsson et al., 2021). For the same reason, the fluid discharged is dominated by the conventional Reykjanes brine, but some indications of hotter fluids are observed (Jónsson and Galeczka, 2022). The preferred target formations for well IDDP-3 are at a depth of 2-3.5 km, where the expected temperature and pressure are 400-550°C and 150-250 bar. The fluid will be superhot (but not supercritical) with enthalpy in excess of 2800 kJ/kg, and is expected to be vapour-like at reservoir conditions. Cl is assumed to be present in the form of gaseous HCl and therefore condensation of the superhot fluid will result in the formation of a highly acidic liquid phase. SiO₂ is also predicted to be dissolved in concentrations ranging from 25 to 300 mg/kg, so depressurisation of the fluid will result in the formation of amorphous silica dust that can cause erosion inside the casing and in surface installations.

Acknowledgements

The IDDP-1 and IDDP-2 drilling and testing were funded by Landsvirkjun, Alcoa, HS orka, Statoil (Equinor), Orkuveita Reykjavíkur, and Orkustofnun.

The drilling of IDDP-2 was partly funded through the DEEPEGS project, which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 690771.

This work was carried out within the COMPASS project, which has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101084623.



Supercritical fluids around magmatic intrusions

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Abstract: Supercritical fluids have been encountered around magmatic intrusions at shallow depths (~2-5 km) in active hydrothermal systems worldwide. These fluids may originate from the surrounding groundwater, along with magma gases. The vapor-like fluid is neither a hydrogen-bonded fluid like liquid water nor a gas, but it is comprised of aggregates of water molecules held together by hydrogen bonding, with the cluster sizes and geometries defined by temperature and pressure. Generally, the size of the water clusters increases with increasing pressure, and so does the solubility of various elements in aqueous supercritical fluid. Applying thermodynamic modeling based on recent experiments and developed thermodynamic equations reveals that aqueous supercritical fluids are characterized by low concentrations of non-volatile elements (such as Si, Na, K, Ca, Mg, Al), which are controlled by salt, oxide, and aluminum silicate solubility. Meanwhile, volatile element abundances (such as C, S, Cl) are predicted to be similar to those in the surrounding groundwaters. In contrast, volcanic gas input signatures are very different and are depicted by a sharp increase in C, S, and Cl abundances in the hydrothermal fluids.



Soil CO₂ emission and stable isotopes ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) of CO₂ and calcites reveal the fluid origin and thermal energy in the supercritical geothermal system of Krafla, Iceland

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Abstract: The Krafla geothermal system extends over a fissure swarm that periodically erupts basaltic lavas and has recently attracted an economic interest due to supercritical fluids forming near a shallow magma intrusion (~ 2 km depth). Here, we discuss new soil CO₂ flux and stable isotope data of the CO₂ efflux ($\delta^{13}\text{C}$) and hydrothermal calcites ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) of drill cuttings, to estimate both the current magmatic outgassing from soils and the thermal flows in the geothermal system. Soil CO₂ emission is controlled by tectonics, following the NNE-SSW fissure swarm direction and a WSW-ENE trend, and accounts for ~ 62.5 t d⁻¹. While the $\delta^{18}\text{O}$ of the H₂O in equilibrium with deep calcites is predominantly meteoric, both the $\delta^{13}\text{C}$ of the soil CO₂ efflux and of the fluids from which calcite precipitated have a clear magmatic origin, overlapping the $\delta^{13}\text{C}$ estimated for the Icelandic mantle ($-2.5 \pm 1.1\text{‰}$). Estimates based on the soil CO₂ emission from the southern part of the system show that these fluxes might be sustained by the ascent and depressurization of supercritical fluids with a thermal energy of ~800 MW. Such significant amount of energy might reach 1.5 GW, if supercritical conditions extended below the whole investigated area. Pairing the soil CO₂ emission with stable isotopes of the efflux and calcite samples has important implications for both volcano monitoring and geothermal exploration, as it can help us to track magmatic fluid upflows and the associated thermal energy.



Insights into pre-eruptive conditions priming steam-driven eruptions in geothermal areas: Lessons from Viti crater at Krafla volcano

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Abstract: KMT is a visionary endeavor that aims to provide in-situ access to a shallow magma storage paving the road to tackle a plethora of exciting science, engineering and energy challenges. One of the core goals of KMT is to explore “extreme geothermal energy” from supercritical fluids to melts or magmas themselves. Such new opportunities need to be assessed and mitigated for risks, as for instance uncontrolled blowouts of steam, host-rock or magma in similarity to steam-driven eruptions volcanic and/or hydrothermally active areas to safeguard new technologies.

Here we provide insights into the pre-eruptive conditions priming steam-driven eruptions in geothermal areas on the example of the Viti crater at Krafla central volcano in Iceland. Viti crater formed by a steam-driven eruption associated with the Mývatn Fires (1724-1729). A magmatic intrusion has been inferred as the trigger perturbing the geothermal field hosting Viti, but the cause of the explosive response remain uncertain.

We conducted a detailed stratigraphic reconstruction of the breccia erupted from Viti crater, and characterized the lithologies involved in the explosion in order to reconstruct the pre-eruptive setting, fingerprint the eruption trigger and reveal the eruption mechanisms.

Based on our results, the Viti eruption can be classified as a magmatic-hydrothermal type and was a complex event with three eruption phases. The injection of rhyolite below a pre-existing convecting hydrothermal system likely triggered the Viti eruption. Heating and pressurization of shallow geothermal fluids initiated disruption of a capping layer formed by a scoria cone via an initial series of small explosions. This onset phase was superseded by larger, broader, dominantly shallow explosions (~200 m depth) driven by decompression of hydrothermal fluids within highly porous, poorly compacted tuffaceous hyaloclastite units. At the same time, deep-rooted explosions (~1 km depth) began to feed the eruption with large inputs of fragmented juvenile and host rock from a deeper zone. Shallow explosions enlarging the crater dominated the final phase.

Stratigraphic boundaries, along with variable degrees of alteration affecting porosity, permeability, and likely host rock strength played a key role in eruption dynamics. The presence of a pre-existing altered and weak zone led to the first narrow/localized series of explosions, initially breaking and ejecting only shallow sub-surficial material.

Our results indicate that at Krafla, as in similar geological settings, shallow and thin hyaloclastite sequences hosting hot geothermal fluids and capped by low-permeability lithologies are susceptible to explosive failure, e.g. in the case of shallow magmatic intrusion(s). Implications to perturbation of the hydrothermal system by drilling activity, as the disruption of a capping layer, the connection between altered weak zones, or the interaction with shallow magma bodies yet need to be scrutinized.



Posters



Well logging data analysis using unsupervised machine learning for crystalline rock unit prediction in Krafla geothermal field in Iceland - IDDP-1 case study

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Abstract:

Objectives:

Understanding subsurface geology is pivotal for safe exploration and efficient exploitation of supercritical geothermal resources, especially in active volcanic areas like Iceland. The IDDP-1 well in the Krafla geothermal field aimed for 4-5 km depth to tap into supercritical conditions. However, drilling ceased at 2.1 km due to an unexpected magma encounter. Despite high productivity and bottom-hole temperature, the intended target depth was not reached. Missing cuttings hindered understanding of the encountered formations, rock-magma interface, and limited the completeness of the lithology log.

Procedure:

Unsupervised machine learning algorithms play a crucial role in clustering large data sets into groups of similar characteristics. Gamma Ray, Resistivity, Neutron and Calliper log data from IDDP-1 were used to form clusters based on similar data features using Gaussian Mixture Model (GMM). Subsequently statistical data analysis was performed using python scripts. Finally, the results were validated by comparing them with the available lithological descriptions.

Results and Conclusion:

Well log data was effectively clustered into broad classes of igneous rock types, including mafic, intermediate and felsic. The statistical analysis and correlation with lithological description proved instrumental in attributing intervals with missing cuttings to these generalized rock mass classifications, thereby enhancing the prediction of the lithological nature of these intervals. This process enabled the regeneration of composite logs, allowing the division of the entire borehole stratigraphy into intervals with similar properties. Moreover, the algorithm is believed to have accurately identified the transition zone from rock to magma, as it has been clustered independently. The results obtained will provide valuable support for the next drilling stage by offering insight into the depth and nature of encountered rock masses, lithological boundaries, and the rock-magma interface. This will be possible to achieve without waiting for the cuttings to emerge to the surface, utilizing real-time logging data.



The (non-)influence of caldera ring faults on heat transfer from a cooling intrusion

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Abstract: Heat transfer from cooling igneous intrusions into a hydrothermal system occurs via (1) conduction within impermeable hot rock surrounding the intrusion and (2) convective fluid flow in permeable host rock. The transport and distribution of hot fluids via convective flow is mainly controlled by host rock permeability and structures such as faults, which can form preferential fluid flow pathways due to locally enhanced permeability. Here, we explore how heat transport evolves spatially and temporally in a conceptual caldera setting including a high-permeability ring fault.

We conduct three-dimensional numerical simulations of hydrothermal fluid flow in the vicinity of a cooling magma chamber emplaced at 3 km depth. A cone-shaped, inwardly dipping, high-permeability zone is located above the intrusion representing a caldera ring fault. We systematically vary the permeability within the host rock, the ring fault, and the crystallised intrusion, as well as the temperature at which rocks start to deform ductile and become impermeable (i.e., T_{BDT} = brittle-ductile-transition temperature) to explore their first-order controls on heat transfer and regional fluid flow above a magma chamber.

In simulations without a ring fault, a convective hydrothermal system develops in the permeable host rock above the intrusion. High T_{BDT} (460 °C) combined with moderate permeability (1E-15 m²) at lower temperatures for both the crystallised parts of the intrusion and the host rock leads to efficient heat mining from the intrusion, resulting in high fluid enthalpies and extensive boiling zones. Adding a high-permeability ring fault does not significantly enhance intrusion cooling, but it transiently modifies the system's thermal structure. Early-stage, fault-dominated fluid up-flow quickly transports heat from impermeable, conduction-dominated areas near the intrusion to shallow levels. Later, a larger hydrothermal plume develops, i.e., convective heat transport shifts from fault-restricted to broad convection in the caldera infill and the fluid flux and temperatures within the ring fault are decreasing. Importantly, simulations with ring fault produce smaller boiling zones and hydrothermal plume temperatures are reduced by up to 50 °C at 500 m depth compared to systems without a ring fault. Preliminary results further suggest that the presence of a ring fault reduces the thickness of the impermeable rim (460–800 °C) surrounding the intrusion.

The three-dimensionality of our simulations further allows us to explore intra-fault fluid flow. We observe intra-fault convection in settings where the permeability contrast between the ring fault and the host rock is at least two orders of magnitude and fault permeability is $\geq 1\text{E-}14$ m². Here, localised high-temperature up-flow zones result in boiling near the surface during the early-stage, fault-dominated fluid flow phase. In contrast, where no intra-fault convection is observed, flat to slightly undulating high-temperature fronts migrate upwards along the ring fault. In these scenarios, no meteoric recharge via the fault plane is observed.

Our simulations reveal the effect of ring faults on heat transport in caldera settings. By exploring fault- and caldera-dominated fluid flow phases in these highly transient systems, our findings can help to improve assessing the geothermal potential of reservoirs in shallow-level volcanic complexes.



21st Century science education potential at the Krafla Magma Testbed.

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Abstract: Science education is at a critical junction globally. Politically and economically fueled misinformation is causing the public to lose trust in conventional education and scientific systems. The Krafla Magma Testbed (KMT) is an opportunity to provide a lasting tangible physical and virtual centre for re-imagining science education and reinstalling trust in science. The drilling endeavor combines engineering, sustainability, and physical sciences, and addresses fundamental questions that relate to the nature of science providing a springboard to excite and empower the next generation to use science and engineering to find solutions for our planet. It addresses the UN sustainability goals 4 (Quality Education), 3 (Good Health and Well-Being), 7 (Affordable clean energy), 9 (Industry, Innovation and Infrastructure), and 11 (Sustainable Cities and Communities). However, a targeted educational program is essential to the KMT project to clearly communicate the science potential and the breakthroughs as they emerge to non-specialist audiences. Thereby showcasing the benefits of big science collaborations to promote a safer sustainable society.

At KMT educational resources will take many forms, (1) online virtual resources for teachers and students, (2) onsite and online research and field training, and (3) physical displays, tours and demonstrations at a visitor centre. Many online and physical resources have already been co-developed with teachers, communities and cultural experts simultaneously providing resources for the classroom and pushing the boundaries of education research. All our educational resources are developed with universal design for learning principles, with particular focus on collaborative and interactive learning.

We will focus our presentation on (a) The role-playing interactive drilling game "Magma Drillers Save Planet Earth" targeting ages 13-20; (b) Massive open online course and virtual fieldtrip (Watson et al., 2023) "Exploring volcanoes and their hazards- Iceland and New Zealand."; (c) Learnz natural hazards virtual field trip to Iceland; (d) 5-minute volcano card game targeting ages 8+, (e) opportunities of computer games in volcano science. Huge opportunities exist with game-based learning of science and for science communication. Volcanoes provide the ideal visual backdrop and explosive processes for computer gaming, and several volcano themed games have been developed as educational tools to teach hazard preparedness, nature of science, volcano chemistry, and cultural awareness already. We will present how these were co-developed with communities and teachers as game-based learning and research tools. We will show the importance of integration into curriculum, and into teaching communities. We discuss the benefits of coordination with national education organizations as well as research grant opportunities. The concept of the project has already produced award winning education resources. The resources have been effective at teaching school age children, but have also been successfully used in other settings. The potential for a visitor and research centre will provide opportunities to engage and inspire local and international visitors and scientists to push the boundaries of science to achieve scientific leaps that will have lasting impacts to global society and sustainability.



A short history of the long quest for magma

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Abstract: A paper by Dallas Peck, Thomas Lloyd Wright, and Robert Decker of the US Geological Survey (USGS), published in *Scientific American* in 1979, recounts the justification of drilling lava lakes: to use a lava lake as the best available proxy to study processes of a magma chamber. What is not documented is the audacity required for James Moore and Donald Richter to stand on Kilauea Iki (KI) lava lake, only a few months old, and use a hand-held drill powered by a chain saw motor and cooled with water from a coffee can to sample the molten lava beneath them. Many wells were drilled with increasingly sophisticated equipment to provide a time series spanning three decades. This tracking of changes over time, with temperature profiles, matching petrologic analysis, coeval surface geophysics, and even viscosity measurements and heat exchanger tests is a prototype for what we envision for the Krafla Magma Testbed with actual, unerupted magma. At the time, the practical justification for the quest for magma was energy. The driver was a perceived coming shortage of fossil fuels, whereas now the quest is driven by a need to reduce use of fossil fuels. Authors of the 1979 paper estimated that the energy of magma within the United State (not including Alaska) was 40 ZJ (zettajoules or a billion terajoules). This reflected the conventional wisdom of the time that volcanoes, particularly rhyolite calderas, were the surface expression of giant, chemically stratified melt-rich magma balloons. The predecessor agencies of the US Department of Energy and its Sandia National Laboratories joined USGS in a feasibility study for magma energy. Work by Harry Hardee and James Dunn and colleagues at Sandia described the thermal budget of KI and conducted large-scale laboratory experiments. They concluded that energy extraction from magma was feasible. The next step was to find a real magma chamber, not degassed lava self-encrusted on the surface. Long Valley Caldera in California, one of three giant rhyolite calderas in the US, was chosen as having all the geophysical indications of a large magma body. But an exploratory borehole drilled 3 km into the center of the inflating caldera was remarkably cool. The difficulty of sophisticated geophysics to find the hypothesized vast accumulations of magma led to a paradigm shift in both geophysics and igneous petrology. Instead of giant magma balloons, volcanologists changed their concept to mush pillows, incapable of erupting but capable of producing ephemeral melt-rich bodies that are quickly erupted. Unlike in the oil and gas industry, magma geophysics had not been subjected to the ground truth of presence or absence of magma except for the negative result at Long Valley. It remained for geothermal engineers in pushing for higher temperatures to accidentally discover melt-rich magma at Puna, Hawaii; Krafla, Iceland; and Menengai, Kenya, at depths much shallower than anyone imagined. Now the door is opened for a magma testbed that will take us far beyond the untested hypotheses of today and change the mindset of how we study magma.



The solidification of obsidian glass during drilling of the IDDP-1 drill hole

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Abstract: Understanding the thermal fate of magmatic rocks during scientific high temperature drilling represents a contribution to their interpretation in terms of magmatic state and their mechanical response to the drilling process.

Chips of black crystal-poor unfoamed calc-alkaline rhyolitic obsidian have been obtained from a depth of 2100m in the IDDP-1 borehole. Five samples (20-40 mg) have been subjected to scanning calorimetry to evaluate the glass transition temperature, viscosity and cooling history of these obsidians that are believed to have been quenched by the drilling process. In addition to scanning runs on the raw glasses, their controlled cooling/heating cycle behavior has been determined at 5, 10 and 25K/min.

The glass transition temperatures of the raw samples lie in the range of 500-525°C. The glass transition temperature shifts with controlled cooling/heating rates yields an activation energy of 335 kJ/mol. The absolute value of the glass transition temperature has been compared with the Hess and Dingwell (1996) viscosity model for calc-alkaline rhyolite. The comparison allows the inference that the obsidian contains water contents consistent with those reported in literature. Furthermore, the activation energies obtained from the T_g peak shift with cooling/heating rate are entirely consistent with those water contents. The cooling rate estimated for the raw samples are higher than 25K/min. A relatively high cooling rate for a "natural" obsidian.

These glasses have been interpreted to have been quenched from temperatures of 940-760°C (based on water content). From the present glass transition analysis it would appear that the first 200-400K of cooling of these magmas occurred above the glass transition in a plastic state, followed by ca. 500K of solid-state (glassy) cooling.

These results demonstrate that it is possible to use glassy materials derived from the drilling-induced quenching of magma to evaluate the physical state and thermal conditions attendant on deep scientific drilling of these systems.



Fluid flow and temperature-dependent permeability in fractured magmatic aureole

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Abstract: Magmatic intrusions cool through diffusive heat loss to the surrounding host rocks. From a mechanistic viewpoint, cooling/heating induces contraction/expansion which may prompt fracturing at various scales. These fractures in turn control fluid circulation and heat transfer between the hotter, cooling intrusion and the colder, heating host rock. The cooling of magmatic bodies commonly results in the generation of columnar joints that include: one or two regions (termed colonnades) of well-defined columns with transversal striae that represents the relatively slow, inward progression of the cooling front; and, internally, a region of irregular fracture sets with high density and tortuosity (termed entablature) that represents the relatively rapid cooling of the body's interior due to extensive cooling by fluid ingress. The latter scenario is anticipated to similarly arise when drilling fluids are injected into a (near-)magmatic environment, as during the serendipitous magma encounter by IDDP-1 at Krafla volcano in 2009.

At Krafla, the rhyolitic magmatic body at 2.1 km depth is capped by a crystallised felsite. Here, we address whether the development of columnar joints in the felsite can account for the fluid loss observed during drilling? We explore the temperature dependence of fracture width and efficacy of fluid circulation associated with fluid injection during IDDP-1. To do so, we consider fluid flow in the 30 m above the magma where temperatures rise rapidly from 400 to 900 °C. In particular, we consider 2 geometrically contrasting scenarios in which fluid pressure is lost from the borehole: 1) lateral fluid flow through a columnar-jointed volume (i.e., through a colonnade); and 2) fluid flow through an entablature-like volume adjacent to the borehole and into the colonnade. We combine existing permeability models [1; 2] and consider the temperature dependence of mechanical properties in order to resolve fracture opening/closing and its impact on fluid flow. We then assess which scenario best accounts for the extent of fluid loss during IDDP-1 drilling.



Mechanical Compaction and Thermal Liability of Hyaloclastite from Krafla

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Abstract: Geothermal fields are prone to temperature fluctuations from natural hydrothermal activity, anthropogenic drilling practices, and magmatic intrusions. These fluctuations may elicit a response from the rocks in terms of their mineralogical, physical (i.e., porosity and permeability), and mechanical properties. Hyaloclastites are a highly variable volcanoclastic rock predominantly formed of glass clasts produced during non-explosive, quench-induced fragmentation, in both subaqueous and subglacial eruptive environments. In geothermal fields hyaloclastites are common as both weak, highly permeable reservoir rocks and as compacted impervious cap rocks.

At Krafla the caldera infill is dominated by hyaloclastite and basaltic intrusions to a depth of 1300 m, forming a reservoir rock hosting hydrothermal fluids harnessed for heating and energy production. Given their important role in the Krafla system, here we explore the thermal liability and mechanical characteristics of hyaloclastites from the surface and subsurface. Subsurface samples were retrieved during the coring of boreholes KH-4 (70 m) and KH-6 (556 m and 732 m) by Landsvirkjun. In hyaloclastites basaltic glass is readily altered through interaction with water, forming a palagonite-rich matrix that can clog pores and limit permeability. Contrary to this, the abundant hydrous phyllosilicate minerals within the palagonite can dehydrate at elevated temperatures. Using a range of petrographic, mineralogical, and mechanical analyses, we show that dehydration events at 130, 185, and 600°C result in progressive mass loss. This evolution results in a positive correlation between treatment temperature, porosity gain, and permeability increase [1]. We further investigated the response of the hyaloclastite to confinement during burial. Upon loading in a hydrostatic cell, the porosity and permeability of the surficial samples decreased linearly with mean effective stress, as pores and cracks closed due to recoverable elastic compaction up to ~23 MPa (equivalent to ~1.3 km depth). Beyond this, permanent inelastic compaction ensued, during which porosity and permeability reduction accelerated. In comparison, the porosity and permeability of the subsurface samples were lower throughout, and were less sensitive to mean effective stress, decreasing linearly with confinement throughout. Using a triaxial cell we determined the brittle-ductile transition of the surface samples at an effective mean stress of ~10.5 MPa. We induced progressive shifting of the brittle-ductile transition to higher values by destructive compaction, yet we could not recreate the significantly higher values of the brittle-ductile transition of subsurface samples (i.e., 37.5 MPa for 70 m sample, >75 MPa for 556 m, and 68.5 MPa for 732 m). This observation suggests that compaction upon burial alone is insufficient to explain the physical and mechanical properties of the subsurface hyaloclastites present in the reservoir at Krafla volcano [2]. Mineralogical alteration in unison with mechanical compaction must therefore be invoked to explain the reduction of porosity and increase in strength of the hyaloclastite in the active geothermal system at Krafla. The observed thermally and mechanically induced changes to the hyaloclastites would significantly impact fluid flow in hydrothermal reservoirs and we must thus consider the potential implications for hyaloclastite-hosted geothermal systems, especially those undergoing active manipulation.



Bubble growth in Krafla obsidian: Insights from 4D Synchrotron experiments

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Abstract: The kinetics of bubble growth in silicic melts influence the evolution of magma properties such as viscosity and density, and hence the competition between magma storage in the crust and transport to the surface. Bubble growth can be triggered by magma decompression, crystallization and heating during ascent, or usually as a combination of these. Here, we aim to shed light into the dynamics of bubble growth in rhyolitic magma at Krafla volcano (Iceland) by conducting foaming experiments at atmospheric pressure on water-bearing obsidians. Obsidian cylinders (3 mm in diameter and height) were heated and continuously scanned via X-ray micro-tomography during foaming at the Swiss Light Source Synchrotron, revealing the 4D textural evolution of the bubble network. We quantify changes in bubble content, shape, number density and size distribution and associated nucleation and growth rates. We compare our results with other types of phenocryst-free and -bearing rhyolitic obsidians from Lipari and Laguna del Maule volcanoes respectively. Finally, we combine our in-situ measurements with predicted evolution of porosity and bubble size from the bubble growth model of Coumans et al (2020) for a crystal-free rhyolitic magma. We generalize our findings to discuss the influence of heterogeneous nucleation, phenocryst content, water content and shearing on vesiculation kinetics in rhyolitic magma and potential consequences for the Krafla system.



Controlling permeability evolution of fragmental, hydrous magma in boreholes.

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Abstract: Understanding the evolution of porosity and permeability is essential to constrain the development of magma buoyancy and so, its eruptibility. In 2009 the IDDP-1 drilling well unexpectedly intersected a magmatic body at 2.1km, which provided us with glass chips (i.e., quenched magma fragments) to study the response of magma to drilling operations. In particular, drilling is anticipated to prompt magma decompression which can trigger vesiculation and cooling which induces vitrification; thus, we anticipate fragmentation (or brecciation) at the bottom of the borehole. Subsequently, once fluid injection ceases, thermal re-equilibration of the system would allow viscous relaxation and so, physio-chemical evolution of the magma fragments; that is, fragments may vesiculate (causing volumetric expansion and dehydration), diffusively outgas (causing contraction and further dehydration) and sinter, thus increasingly sealing the system [1]. This serves to progressively clog the borehole as the fragments acquire coherence [1-3]. The competition between these three processes, which act on different timescales (depending on factors such as grain size, viscosity, temperature, and water concentration), is a key control on the evolution of porosity, permeability and buoyancy of such transient fragmental systems. Can we utilize this knowledge to manipulate the system and control outgassing and buoyancy at the bottom of a borehole? [4]

Here we present the results of controlled laboratory experiments, supported by an integrated numerical model (including vesiculation dynamics, water solubility, magma viscosity, diffusive outgassing, and sintering), to constrain the evolution of porosity and permeability of fragmental magma with variable grain size distributions; the performance of the model—developed and validated for monodispersed systems [3]—is tested against novel experiments on polydisperse systems.

In monodispersed systems, the grain size impacts the porosity-permeability evolution of the system; in particular, larger clasts can achieve higher vesicularities than fine ash (as diffusive outgassing is less dominant). This causes greater porosity and permeability fluctuations (decrease, increase, and decrease) in coarser systems, whereas finer fragmental systems tend to degas and sinter swiftly (causing progressive reductions of porosity and permeability). In polydisperse systems, sintering is more effective due to increased grain-grain contacts. In addition, coarse fragments dominate the porosity and permeability evolution. We show that the contrasting timescales for vesiculation, diffusive outgassing, and sintering are the primary control on the densification of fragmental magma in boreholes. We explore how careful manipulation of the imparted conditions could control densification and so, regulate magma outgassing, buoyancy and the ability to flow up the borehole.



Obtaining structural data from three-dimensional digital outcrops constructed using unmanned aerial vehicles

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Abstract: One of the main problems when carrying out geological fieldwork is the difficulty or lack of access in remote areas, mainly in active volcanic zones. Although there are many ways in which quality geological information can be accessed, in general, this information has high costs (Cawood et al., 2017). Despite this, and due to the accelerated development of new technologies, it is possible to acquire unmanned aerial vehicles equipped with high-resolution cameras at relatively low prices (no more than USD 1,500). Through these vehicles, it is possible to access even at distances of tens of kilometers from the point of observation to obtain high-resolution images. If the taking of images is carried out with certain considerations, it is possible to build three-dimensional digital models of the outcrops from which quality geological data can be obtained as orientations and thickness of fractures and dikes.

This work presents a methodology from which three-dimensional models of inaccessible sectors can be developed, allowing the acquisition of structural data at different scales (from cm to m). To validate this methodology, a comparison is also presented between the data obtained from the different three-dimensional digital outcrops and the data obtained through field geology (using a compass). The three-dimensional models were created using Agisoft Photoscan software, while the digital mapping was done using MOVE (Petroleum Experts) software. The data used corresponds to structural data obtained in the basement of the Nevados de Chillán Volcanic Complex (NChVC, 36.8°S). The NChVC is currently active and ranks fourth in the hazard ranking by the National Geology and Mining Service of Chile SERNAGEOMIN (Lara et al., 2021). Despite the impossibility of accessing it, its study is of prime importance, which is why it is necessary to look for new alternatives to access quality information and improve our understanding of its evolution and eruptive processes.



The role of retarders on the thermo-mechanical degradation of hardened well cement casings: a case of the Icelandic Deep Drilling Project

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Abstract: The mineralogical assemblage of cement is thermally sensitive. In geothermal drilling practices, silica flour can be added to Portland cement mixtures to increase the thermal resilience of the hardened hydrated cement. This study assesses the thermo-mechanical properties of two hardened silica-bearing Portland cements (cast with and without retarder) used in the construction of geothermal wells for the Icelandic Deep Drilling Project (IDDP).

We detail the nature and timing of the reactions of both cement types during controlled thermal stressing experiments. We show that thermal stressing of these hardened well cements induces evaporation of free-standing water within an open system. Moreover, with increasing temperature thermal stressing induces devolatilisation of calcium silicate hydrate (C-S-H), portlandite and, in the cements containing retarders, CaCO₃ polymorphs (e.g., aragonite). In our experiments the dehydration of portlandite occurs at a temperature range ~50 °C higher than in conventional Portland cement, demonstrating the enhanced thermal resilience of well cement with added silica flour. Together, these devolatilisation reactions cause progressive contraction of the hardened well cement (i.e., negative thermal expansivity), with a mass loss of ca. 10 wt.% between ~80-200 °C; and an additional ~5 wt.% mass loss between 425-500 °C, which serves to increase the porosity and permeability. The consequence of this devolatilisation is a reduction of the tensile strength, compressive strength, and Young's modulus.

We compare the results from cements thermally stressed in the laboratory with the thermo-mechanical properties of hardened well cement samples retrieved from the casing of IDDP-1. Thermo-mechanical properties are highly comparable, and thermal and mineralogical evidence suggest shallow casing of IDDP-1 may have reached temperatures as high as 500 °C. In addition to the mineralogical assemblage of the thermally-stressed laboratory samples, the IDDP-1 casings contain xonotlite, a secondary mineral phase produced during exposure of water-bearing Portland cement with silica flour to high temperature. This difference could indicate that thermal stressing at the laboratory scale (and at atmospheric pressure conditions) promotes an open system which allows for dehydration (prior to any potential xonotlite formation), whereas, the IDDP well cement may remain water saturated in the borehole (favouring xonotlite formation). This suggests that in addition to thermal stressing, fluid interaction imparts further mineralogical, mechanical and physical properties of cement used in geothermal boreholes, highlighting the necessity of detailed stability investigations of all components of well casings to extreme environments.



Insights into the caldera cycle of the Torfajökull central volcano, South Iceland

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Abstract: The Torfajökull volcanic system in South Iceland with its inferred caldera is the largest silicic system in Iceland and furthermore hosts the biggest high-temperature geothermal area in the country (Sæmundsson & Friðleifsson 2001). While posing immense volcanic hazards, caldera-forming volcanoes also harbor potential georesources. Understanding their evolutionary patterns and activity cycles is crucial for hazard mitigation and resource exploration. Previous studies suggest a cyclical progression involving incubation, maturation, and fermentation, leading to caldera-forming eruptions, followed by either system death or rejuvenation (Bouvet de Maisonneuve et al. 2021). Testing how this cycle applies to different volcanic systems, understanding what causes the death or recovery of the system, and finding ways to verify the current stage of a caldera-forming volcano is an important challenge in volcanology. This study tackles these challenges by examining the magmatic storage environment of Torfajökull, spanning from pre-caldera to post-caldera eruptions. We use U-Th disequilibrium dating on zircon crystals to determine the ages of the units and the crystallization history of the magma, while the chemical composition of the volcanic glass and minerals yield information required to reconstruct and estimate the magma chamber evolution and conditions preceding the eruptions. The oldest samples dated and studied here are from the so-called ring fracture rhyolites (Laufafell: 56.4 ± 4.3 ka, Raudufossfjöll: 63.3 ± 7.5 ka). They contain homogeneous anorthoclase feldspars, magnesium-poor clinopyroxenes, and fayalitic olivines. Based on zircon crystallization age distribution, which hint at the efficient evacuation of the magma reservoir during the Thórs mörk ignimbrite eruption, we confirm that this eruption is indeed associated with the caldera-forming event of Torfajökull (Moles et al. 2019), which we date at 38.0 ± 4.4 ka. This ignimbrite exhibits similar feldspar chemistry to the ring fracture rhyolites but with distinctly lower Mg# clinopyroxenes, indicating more evolved conditions. Over the past 10,000 years, post-glacial volcanism has produced multiple small rhyolitic units. Geochemically, these units record slightly less evolved magmatic conditions and their mineral chemistry is less homogenous than the pre-caldera units, with the youngest three lavas incorporating significant recharge crystals, likely through the influence of the neighboring Veidivötn fissure swarm intersecting Torfajökull from the north. Our findings provide valuable insights into evolution of Torfajökull, from a pre- to post-caldera stage. Further research on an expanded sample collection aims at determining the water-saturated or undersaturated state of the magma chambers and at providing more insights into the state of magma differentiation along the life-cycle of Torfajökull.



From storage to the surface: the rheology of rhyolite magma from Krafla, with implications for geothermal drilling

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Abstract: Changes in rhyolite melt viscosity during magma decompression and degassing exert a first order control on ascent through the crust and volcanic eruption style. These changes have, as yet, unknown hazard implications for geothermal drilling in pursuit of high-enthalpy fluids close to magma storage regions. Here, we exploit the situation at Krafla volcano in which rhyolite has been sampled at both the Earth's surface and at shallow storage depths via the drilling of the 2009 IDDP-1 borehole and the 2008 KJ-39 borehole. We use differential scanning calorimetry to constrain that the IDDP-1 magma quenched to glass at ~ 793 K, by cooling at a rate of approximately ~ 25 K.min⁻¹. We measure the equilibrium viscosity of the IDDP-1 rhyolite at temperatures close to the glass transition interval and our results show that the rhyolite viscosity is consistent with models assuming a dissolved H₂O concentration of 2.10 ± 0.23 wt.% (which compares well with 1.47-2.09 wt.% published previously). We couple these results with micro-penetration and Couette rheometry over a range of potential magma storage temperatures, to constrain the response of surficial Krafla rhyolites to stress. The surficial rhyolites at Krafla match the same viscosity model assuming a lower dissolved H₂O concentration of 0.14 ± 0.03 wt.% (which compares well with the 0.1-0.2 wt.% published previously). In both cases – the rhyolite melt extracted from storage depths, and the surficial rhyolites – the H₂O concentrations inferred from rheometry are consistent with direct determinations by Fourier transform infrared spectroscopy and a modified Dumas method. Taken together, we constrain the relaxation and viscosity of these magmas from source-to-surface. Finally, we use relatively high-stress compression tests to determine the onset of unrelaxed behavior and viscoelastic melt rupture pertinent to understanding the melt response to rapid pressure changes that may be associated with further (near-) magma exploration at Krafla.



2D numerical simulation of the shallow magmatic body at Krafla

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Abstract: In 2009, the IDDP-1 drilling inside the Krafla caldera aiming to 4 km depth in search of supercritical hydrothermal fluids got stuck at 2.1 km, retrieving quenched glass cuttings. It was then understood that an unexpected and undetected rhyolitic magma body had been drilled. This body stood without apparent signs of crystallisation at the rooftop, opposing the most common belief that magmatic bodies at shallow depths should present a mushy region adjacent to the body's walls.

We aim to simulate the dynamics of this magma. We perform 2D numerical simulations of the magma thermo-fluid dynamics, assuming thermodynamic equilibrium in a sill-like, disk-shaped body 1200 metres wide and 260 metres thick.

In order to simulate the magma dynamics we use the software GALES (Garg and Papale, *Frontiers in Earth Sciences* 2022), which solves the 4D dynamics of multi-component fluids in geometrically complex domains, using a one-velocity model approach. The properties density, heat capacities, single-phase and multiphase non-Newtonian viscosity, thermal conductivity, and compressibility, are locally computed as a function of pressure, temperature, phase distribution, and phase composition. Early results show a strong influence of the exsolved volatile phase on the bulk properties, especially density. This translates in the development of small, rising plumes from the bottom part of the magmatic chamber, composed of crystals and exsolved gas. Crystallization is however too slow, requiring the addition of a sink term so that the gas phase can escape the magma body, transporting heat, rising the magma liquidus surface, and triggering further crystallization.

We are currently implementing the code with the addition of such a sink term. The results will allow a first evaluation of the conditions under which a crystal mush can form and be stable close to the roof and margins of a shallow magmatic intrusion, and an estimation of the lifespan of a cooling magmatic body of these characteristics.



Heat loss from shallow dyke intrusions to the atmosphere during the 1975-84 volcano-tectonic episode in Krafla

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Abstract: The 1975-84 volcano-tectonic episode strongly impacted the heat budget of the Krafla geothermal system, as the fracturing increased the fluid permeability, and the injected magmatic intrusions provided additional heat input to the system. Previous research estimated the volumes and positions of the magmatic intrusions using ground deformation and seismic data. When a dyke solidifies and cools, it releases latent and sensible heat to the surrounding permeable rock. Part of this heat is released to the atmosphere by convection and evaporation of the groundwater and with the rise of steam in fissures. The heat transfer to the atmosphere by steaming is therefore related to the heat transfer from the dyke to the surrounding rock. A power law function (Hochstein & Bromley, 2001) estimates the heat loss by the geothermal system to the atmosphere through fumaroles. The thermal power of the fumaroles is a function of their area, as seen in vertical air photos. We analyzed air photos taken either during the eruptive activity or in the months following each of the nine eruptions of the Krafla fires to determine the position and area of fumarole clouds. They indicate that steam clouds and new surface alteration signals mainly occur by the eruptive fissure. This study aims to estimate (1) the heat input to the Krafla geothermal system during the Krafla fires from magmatic intrusions and (2) which fraction of this heat is lost to the atmosphere, mainly through steaming, over this same period. Such heat budget analyses provide significant constraints on the link between magma and geothermal activity in a young igneous system and the sustainability of such systems.



Surface roughness analysis of volcanic rocks as a new approach to characterize vesicle textures – A study on Krafla magmatic products

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Abstract: Optical and microscopical analyses of surficial and internal textures are key elements of volcanic rock characterization. Yet conventional methods for textural analyses often pose challenges and difficulties in terms of sample preparation and/or time and resources consumption.

We explore Confocal Scanning Laser Microscopy (CSLM) and surface roughness analysis as a time- and resource-efficient approach to characterize different vesicle textures. Therefore, we analyzed explosive and effusive rocks from Krafla volcano and their experimental analogs. The results were compared to detailed Scanning Electron Microscopy (SEM) investigations and 2D to 3D conversion by image analysis software FOAMS. Monodisperse samples with homogeneous vesicle texture as e.g., Krafla lava flows or Hveragil pumice show remarkable similarities in vesicle size and volume distribution, when compared directly with CSLM and SEM. For experimental and natural samples with high heterogeneity and vesicle interactions analysis with FOAMS becomes necessary as manual de-coalescence of images becomes inevitable to avoid errors in quantification. However, the latter method is extremely time consuming and prone to human errors.

Combining our textural data with numerical modeling, we present a universal scaling model to link surface roughness with vesicle number density, porosity, and polydispersity. Our results indicate that CSLM can be a powerful tool to investigate vesicle structures from the millimetric to micrometric scale. The resulting data is both quantitatively and qualitatively equivalent to SEM-derived data for a variety of volcanic rock types. This, combined with the simple sample preparation and handling make CSLM a valid alternative to SEM investigations to characterize vesicles, particles, and any sort of rock property that reflects on topography. Surface roughness analysis via CSLM is also a promising method to quantify variable degrees of hydrothermal alteration, as also abundant in the Krafla volcanic system.



Physical properties of reservoir rocks in high-enthalpy geothermal settings

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Abstract: Magmatic intrusions in active volcanic regions create high-temperature environments where geothermal systems can reach supercritical conditions with fluid temperatures and pressures exceeding 400 °C and 22 MPa, respectively. With the growing demand for renewable energy, such geothermal reservoirs are attracting considerable scientific and economic interest, potentially offering up to 10 times the output of conventional systems. However, there are still significant uncertainties and economic risks associated with their discovery and development.

The decision on exactly which areas to target for drilling in the subsurface often has to be based on geophysical methods, i.e. seismic and geoelectrical surveys. However, their interpretation is hindered by the diminishing knowledge of the physical properties of fluid-bearing rocks as exploration depth and temperature increase. Presently, the interpretation of geophysical exploration data is often based on physical formation properties that are either measured at depths that can be reached by drilling or determined in the laboratory - often neglecting in-situ conditions - and then interpolated to higher temperatures. To date, only limited petrophysical data have been collected under simulated reservoir conditions with temperatures above 200 °C, which is mainly due to the high complexity of the measurement setups required to control the pore fluid pressure at high temperatures and corrosive test conditions. To address this gap, we developed and operate two high-temperature/ high pressure flow-through set-ups to study both the electrical properties of formation fluids and the electrical and hydraulic properties of rocks in reactive flow experiments up to temperatures of 500 °C and pressures between 25 – 35 MPa. Various lithologies (including volcanic rocks and limestones) and fluid compositions have been tested.

Since ions tend to recombine and precipitate from aqueous solutions under near- and supercritical conditions, thereby reducing the conductivity of the formation fluid [1, 2], geoelectric sounding methods are considered predestined for identifying supercritical geothermal reservoirs by significant conductivity contrasts [3, 4]. However, our study shows that reactive mass transport has the potential to mask the postulated conductivity contrasts, as the simultaneous introduction of new charge carriers may mask the conductivity contrast. The detectability of supercritical reservoirs therefore depends mainly on the intensity of fluid-rock interactions, the extent of which is a function of pressure, temperature, mineral composition, exposure time and specific surface area. Microstructural analyses indicate that rock alteration is most effective where fresh fluid flows continuously along grain boundaries, whereas stagnant fluids in low permeability samples led to less pervasive alteration of the rock. In this case, mineral dissolution appears to slow down considerably or even come to a standstill. Based on these experiments and the resulting new questions we are currently working on experimental concepts to improve our understanding both on the transient character of permeability and the influence of the fluid-solid-interface on the electrical rock properties.



Low overpressure in a magma domain prior to rifting predicted by a modified dike sequence model for the 1975–1984 Krafla rifting episode

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Abstract: Repeated dike intrusions at extensional plate boundaries release cumulated stress and accommodate plate spreading. Study of the behavior of such dike sequences can improve the understanding of volcanic systems and volcano-tectonic activity. During 1975–1984, about twenty dikes were injected into the Krafla fissure swarm in North Iceland. Each dike opened a section of the plate boundary. Several dikes propagated in the same direction with decreasing length of the opened sections and their distances away from the Krafla caldera center. Buck et al. (2006) proposed a simple model that predicts dike opening pattern by linking tectonic stress and magma overpressure (compared to the lithostatic pressure). The predicted areas of dike opening are broadly consistent with observations.

To better interpret the dike sequence model, we propose a modified version of the Buck et al. (2006) model, by coupling together dikes and magma domain (consisting liquid magma, partial melt, magma mush and hot solid rock), using the formulation of Rivalta (2010). Cracks are assumed to preexist, with tectonic stress and local topography providing together effective tensile stress stimulating magma flow. Magma flows into cracks when effective tensile stress and magma chamber overpressure (sum as net driving pressure) exceed the host rock tensile strength. A dike stops propagating further when net driving pressure ahead of dike tip drops below a threshold and opens part of the crack. The modified model is set up based on material properties in published research (Sigmundsson et al., 2020; Jónsson, 2012), where the density, shear modulus, Poisson's ratio and tensile strength are assumed to be 2400 kg/m³, 12 GPa, 0.25 and 6 MPa, respectively. The conditions of dike formation are adjusted to obtain a similar pattern of observed surface opening. Under the assumption of spherical magma domain, its inferred radius is ~3.5 km to support dike length >20 km. The tectonic stress, if uniform along the rift, is inferred to be ~10 MPa, decreasing to zero in both ends of the rift. The tensile strength for initializing the first diking needs to be ~2.3 times larger than the set-up value to drive long-distance dike migration. The stopping pressure threshold is set to be the same as the tensile strength. This modified model shows that a host rock tensile strength 40% lower than used by Buck et al. (2006) can generate a comparable pattern of dike opening. The magma domain pressure may have been only 4 MPa higher than the lithostatic pressure at the onset of the first diking in Krafla rifting episode. The second and third dikes occur in the model even if the pressure of the magma domain is 4 MPa lower than the lithostatic pressure. This modified model indicates that the effects of tectonic stress, despite low overpressure in a magma source, can cause major dike emplacement in the crust. Dimensions of a feeding magma domain and its properties play an important role in dike propagation.



The sources of metals and noble gases in volcano-hosted geothermal systems; Þeistareykir, Krafla and Bjarnarflag

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Abstract: Geothermal fluids carry heat and elements, notably metals. Hot fluids are capable of mobilising and transporting elements through complexation and as particulates. The sources, transportation, and localized deposition of such metals are of interest to a wide area of research fields, not limited to ore formation. Trace elements can be used to understand the circulation of fluids and detect precipitation of phases.

Metals in volcanic-hydrothermal systems are derived from interactions with the surrounding rocks as well as from degassing of magma. At Krafla and Þeistareykir, specific metal concentrations in well fluids, the volatile metals (e.g. Tl, Pb, Bi) in particular, correlate with noble gases (Saby et al., 2022). Since the noble gases are derived directly from magma, this suggests that these metals are also sourced from magma and offers another way to learn about the magmatic gas flux across the field. This interpretation is supported by the compositional fingerprint of deep reservoir fluids, which match the relative abundance predicted for a magmatic volatile phase as derived from emanation coefficients.

Other elements, e.g. the base metals, are derived primarily from the surrounding rocks through alteration reactions and leaching. Their concentrations and elemental fingerprint do not match that of a magmatic volatile phase, but are consistent with the elemental flux calculated for water-rock interaction from progressively altered basalt from the geothermal reservoir recovered as cuttings. The metal exchange vectors during water-rock interaction are being further investigated using a comprehensive analytical approach applied to mineral phases and fluid inclusions. However, the crucial interface between magma and host rock is unavailable. This transition is characterised by steep gradients in temperature and redox state and can result in sharp changes in the nature and composition of the magmatic volatile phase as it transits the boundary and interacts with other fluids.

Our analyses show that well fluids sampled at the surface do not reflect the composition of the reservoir fluids at depth as a result of boiling and associated selective metal deposition (Saby et al, in review). To explore the mobilisation of metals at the magmatic-hydrothermal transition further, we are designing a deep fluid sampler with in-situ sensor capabilities to capture a sample of the reservoir fluid down-well at temperatures of up to 350°C.

Melt inclusions, fluid inclusion and volcanic surface emissions all testify to the enrichment of metals in the magmatic volatile phase, and hence to the potential of this phase as a significant contributor of metals to deep crustal fluids. The magmatic-hydrothermal interface marks the transition from magma to host rocks and the associated changes at this interface lead to redistribution of metals between rocks and fluids, and major changes to the magmatic volatile phase. Accessing this region in the KMT will provide new insights into the fates of metals across this boundary, and ultimately on the how elements are transferred from magma to geothermal reservoirs.



Implications from volatiles in glass from magma drilling

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Abstract: Drilling into molten magma offers a unique opportunity to sample and quench magma in-situ to learn more about magma properties and volatile budgets at shallow depths. Here, we present results from three different boreholes that intercepted magma: IDDP-1 and KJ-39 in the Krafla geothermal system in Iceland, and KS-13 in the Puna geothermal system on Hawaii. We used electron microprobe analysis (EMPA) to measure major elements and other volatile data (S, Cl, F) and micro-Fourier-transform infrared spectroscopy to measure water and carbon dioxide concentration and speciation data in the glass samples recovered.

Our results from a time sequence of glass chips returned at IDDP-1 at Krafla broadly support the previous work of Zierenberg et al. (2013). The glass cuttings increased in proportion of brown to clear glass over time. The two types of glass have similar major element compositions (average SiO₂ contents for clear and brown glass 77.37 and 76.31 wt%, respectively). H₂O contents extend to higher values in the brown glass (1.40–1.54 wt% for clear glass, 1.44–2.15 wt% for brown glass) with CO₂ generally higher in the clear glass (89–191 ppm) than in the brown glass (58–115 ppm, most chips <90 ppm). Over time total H₂O content did not change systematically, however, OH/molecular H₂O (0.97 to 2.53) and CO₂ in the brown glass increase. This could be explained by an increase in temperature as hotter magma from deeper in the system rose into the borehole and quenched to form brown glass. The estimated H₂O–CO₂ saturation pressures are similar to those of Zierenberg et al. (2013), falling between lithostatic (50 MPa) and hydrostatic pressures (16 MPa), and are not related to time of collection.

Glass chips from KJ-39, also at Krafla and only 2.5 km south of IDDP-1, show a large compositional and textural range: from andesite (58.21 wt% SiO₂) to rhyolite (74.51 wt% SiO₂). H₂O contents range from 0.64–3.02 wt% and CO₂ 5–40 ppm. S contents range from below detection to 1373 ppm and show a strong negative correlation with SiO₂, as does F (548–1869 ppm), while Cl (474–851 ppm) shows a positive correlation with SiO₂. We suggest that the rhyolitic compositions form by partial melting of a hydrated basalt, consistent with Mortensen et al. (2010), while the andesitic and dacitic glass compositions suggest partial melting of another source, an andesite. The wide range of glass compositions in the KJ-39 chips compared to IDDP-1 suggests that the two melts are not derived from the same source; however, the proximity of the two wells indicates that melting could have been driven by the same heat source.

Measurements of the volatile and major element chemistry of glass recovered when borehole KS-13 intersected a melt body in the Puna geothermal system on Hawaii are currently being undertaken. These results will be compared to those from Krafla to investigate further shallow magma bodies and whether volatile saturation pressures are useful in estimating their depth.



Oxide nanolites formation in the Krafla shallow silicic magma: Insights from high-pressure, high-temperature experiments

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Abstract: In 2009 rhyolitic magma was intersected by a geothermal well at the Krafla volcanic area in Iceland. Recent experiments on rhyolitic magma relevant for the 2009 magma showed that oxide nanolites enhance the degassing dynamics and increase the magma viscosity. Yet, whether or not oxide nanolites form in the low-pressure Krafla rhyolitic magmatic system remains unknown. In this study, we explore the pressure and temperature conditions in which nanocrystals may form in the subvolcanic Krafla system. We conducted high-pressure and high-temperature experiments in externally heated rapid-quench cold-seal pressure vessels using natural rhyolite from the most recent silicic eruption at Krafla, Hrafninnuhryggur ridge, as well as synthesized compositions that mimic a range of iron contents actually found in the 2009 rhyolitic magma. The experiments revealed oxide nanocrystal formation in the iron-rich rhyolitic magmas, which represent the maximum Fe-content of the 2009 composition. Temperature appears to play an important, but secondary role in controlling the formation of oxide nanocrystals. The results show that the bulk iron content in the melt is the main factor controlling nanocrystal formation and, thus, iron limits the ability for the rhyolitic magma currently stagnant at Krafla to form oxide nanocrystals. Due to the potential that oxide nanocrystals hold for enhancing degassing processes and increasing magma viscosity, we suggest that the rhyolitic magma beneath Krafla volcano may hold the potential to erupt explosively in case nanocrystals form prior or during magma ascent towards the surface.



2D Numerical Simulation of Thermo-Fluid Dynamics in a Magma-Borehole System

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Abstract: The "Krafla Magma Testing" project is dedicated to enhancing our understanding of magmatic systems and developing high-enthalpy geothermal energy solutions. Our research focuses on studying the processes associated with drilling into magma chambers employing a sophisticated numerical modeling approach. We aim to simulate heat transfer dynamics within a two-dimensional geometry representing a magma-borehole system, assuming that the circulating fluid is liquid water at 40° C, whose properties are calculated with the Steam Tables (based on IAPWS Industrial Formulation 1997). We adopt a rhyolitic chemical composition for the magma and a temperature of 900°C. Its physical properties are modeled as a function of local pressure, temperature, and composition in the space-time domain, with embedded constitutive equations for melt-gas mixtures (e.g., SOLWCAD). Further, magma rheology is considered independent of strain rate.

In the first step, the code solves equations for mass, momentum, and energy, observing variations in pressure, velocity, and temperature. It was observed that, in the well, the flow velocity and pressure reached a quasi-steady state in just the first 30 seconds. In the subsequent step to accelerate the simulation, only the energy equation is solved with the flow conditions obtained in the first step. For both steps, we don't consider the heat loss through rocks. Through several simulations, with systematically varying mass flow rates and well sizes, we observed the dynamic interplay of heat transfer between the well fluid (i.e. 40°C) and the surface of the magmatic body (i.e. 900°C). The preliminary simulation results reveal no significant variations within the range of flow rates and well sizes adopted. Currently, we are running the simulations for the second step to obtain the temporal evolution of the magma body.



Is the felsite above the shallow rhyolitic magma evidence of a crystallising mush at Krafla?

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Abstract: The 2009 encounter of magma during IDDP-1 indicates that a rhyolitic magma is overlaid by a melt-bearing crystal-rich felsite. This architecture is somewhat enigmatic. First, the presence of rhyolite in a predominantly basaltic environment raises questions as to the origin of this evolved magma. Second, the near aphyric nature of the rhyolitic melt raises questions as to what heat source allows it to remain crystal-poor over prolonged periods, considering that the overlying geotherm is very steep (~17 K/m). Third, the presence of disequilibrium textures in the felsite has been used to postulate that it is melting, which would provide the source for the rhyolitic magma, however, this does not explain why such evolved compositions have been generated in the first place.

Here, we present preliminary results of a Raman study of cuttings retrieved during IDDP-1, scrutinising the textures of nanocrystals present in crystal-poor glass (brown and clear glass material), as well as in crystal-rich felsite. We found the presence in low-amounts of nanolites in all materials, being oxides common in obsidian materials and mainly plagioclase in the felsite. These minerals are also present as large phenocrysts in these samples. We view the presence of nanolites as an indicator of crystallisation conditions and so, we posit that the felsite may be a crystallising counterpart of the rhyolitic magma, perhaps representing a marginal mush zone. We look forward to discussing with the community about how this new petrological evidence aligns with the latest chemical and petrological analysis.



What is the confining pressure on a magma body?

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Abstract: Although it has become the custom petrologists and geophysicists alike to assume that magma pressure is simply the overburden or lithostatic load, density \times g \times depth, there is far from consensus on this point. Credible arguments have been made for pressures ranging from the least principal stress in the rock container to excess pressure, perhaps by crystallization with second boiling in a constant volume container. Various models consider the buoyancy of magma relative to solid rock or the potentially much greater effect of exsolved vapor bubbles, or the deviatoric stress imposed by tectonics or the volcanic edifice, or none of the above. The problem was elevated beyond theoretical speculation by the provocative finding from IDDP-1 that melt quenched in situ at 2.1 km depth by drilling recorded a vapor pressure of 40 MPa rather than ~60 MPa as might be the expected lithostatic stress (Zierenberg et al, 2012). It is unprecedented to be able to measure H₂O + CO₂ concentration in melt quenched at depth, and precisely known depth. A universally used method is to measure these volatiles in melt inclusions (MI) in phenocrysts, which presumably protect the MI from volatile loss due to decompression. There are workarounds for the unexpected low vapor pressure recorded by IDDP-1 drilling chips, but they are less arduous than the assumptions and corrections required for MIs. Therefore, it is reasonable to pursue the consequences of 40 MPa being the containment pressure of IDDP-1 magma. The Krafla rhyolite magma body (of much debated size and age) lies at the center of the North American – Eurasian rift, which is extending at 2 cm/yr, punctuated in the near field by rifting events that perturb the stress, but with a caldera formed by magma-induced stresses that could decouple it from the regional field. What evidence supports or permits an apparent magma pressure now of 40 MPa? (1) A standpipe pressure kick of 19 MPa occurred when the drill bit encountered magma. If this was the pressure required to clear magma from the nozzles, then one can add 21 MPa from the cold hydrostat in the drill stem for 40 MPa magma pressure (B. Wagner, pers. comm., 2023). (2) A reasonable hypothesis is that magma pressure is simply the average of the three principal stresses in the rock envelope, the fluid body balancing forces acting upon it. Measurements of least principal stress as deep as 4 km in extensional geothermal systems of Taupo, NZ (ref); Fenton Hill, NM, USA (ref); and Nevada, USA (ref), all extensional like at Krafla, record least principal stresses of 0.5 to 0.7 lithostatic at depths to 4 km. A mean would fall close to 40 MPa. (3) YL calculated a magma confinement pressure of 40 MPa using a modified geomechanical model of Esor., 19., and obtained a confinement pressure of 40 MPa for intensely fractured, water-saturated basaltic upper crust. In the future, we must interrogate magmas about what they “feel” and correct or reject our models accordingly.



Evidence for the formation of silicic lava by sintering recorded in situ in the Hrafninnuhryggur feeder dyke, Krafla

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Abstract: Understanding of the physical nature of naturally ascending silicic magma must precede and underpin any attempt to open an artificial pathway between such magma and the surface. Recent observations of rhyolitic eruptions in Chile have revealed many details of silicic conduit dynamics¹, involving sustained, simultaneous explosive and effusive behaviour from the same vent, and inspired the proposal that silicic lavas are produced by the sintering of subsurface pyroclasts² prior to advection from the vent. Here, we provide the first unambiguous evidence for the sintering origin of silicic lava³, from textures and dissolved magmatic volatiles in the glacially dissected rhyolitic volcanic conduit at Hrafninnuhryggur, Krafla volcano, Iceland^{4,5}, whose composition closely matches that of the IDDP-1 rhyolite⁶.

We show that (1) a vesicular pyroclastic deposit adjacent to country rock at the conduit margins grades continuously into dense conduit-filling obsidian; (2) this conduit-filling obsidian records direct microtextural evidence for a sintered origin including cusped relict clast boundaries and the presence of country rock lithic fragments throughout; (3) high resolution total H₂O concentration transects across the conduit show that the magma was degassed to different degrees laterally across the conduit with systematic spatial variation that is consistent with progressive conduit clogging and final gas pressurisation; and (4) textures in overlying near-surface lava bodies record the variably sheared and brecciated remnant of the same in-conduit sintering inferred beneath.

This exceptional record of a silicic conduit system connected to upper eruptive deposits provides support for the 'cryptic fragmentation model' for effusive silicic volcanism² and illustrates how subsurface mobility and intrusion of Icelandic rhyolite may occur in a fragmental state that is then typically erased during magma deformation, cooling, and crystallisation.



Field experience of fiber optic sensing in high-temperature geothermal wells in Iceland

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Abstract: Drilling a well in a superhot or near-magma environment is a challenging endeavor and requires robust equipment and technology. Fiber optic sensing technology allows well bore monitoring and reservoir characterization under very harsh conditions. In this contribution, we want to present outcomes of fiber-optic field works of the past years, that were acquired in high-temperature geothermal wells in Iceland. We show how distributed temperature sensing (DTS) and distributed acoustic sensing (DAS) allow to assess the well completion and the operation of the well. We present data from a reverse cementing operation of the production casing in the Iceland Deep Drilling Project 2 and subsequent well operations (fluid injection, shut-in, well stimulation). Next to the fiber optic downhole infrastructure, we suggest an additional surface network of fiber optic cables to enable sophisticated methods for reservoir monitoring e.g. detecting micro seismicity and changes of the subsurface poro-elastic properties. With the experience from past and ongoing projects, we aim to evaluate the challenges of present magma and to design a tailor-made monitoring strategy for the extreme thermo-mechanical conditions expected in the KMT project.



Prograde & retrograde fracture-hosted fluid-rock reactions under 'superhot' conditions: An example from Mexico

Authors: Chris Rochelle, Alicja Lacinska

Authors Affiliation: British Geological Survey

Abstract: Fractures within the deep cores of hydrothermal systems represent major flow pathways facilitating the onset of natural convection and subsequent maintenance of fluid flow. Understanding the processes occurring along such fractures and how they impact the transfer of mass and heat to overlying hydrothermal systems is important as they ultimately impact the productivity of hot fluids during geothermal exploitation. This is especially important where fluid movement crosses contrasting rock types, resulting in a range of fluid-rock reactions, mineral dissolution and precipitation, and changes in fracture permeability. In this study we investigated the reactivity of Ca- and Mg-rich host rock minerals with a granite-derived, Si-rich supercritical fluid. Although the host rocks and their minerals are different to those at Krafla (metamorphosed carbonates versus lavas), some of the reaction processes bear comparison, and we suggest that some of the mineral characterisation approaches could be usefully employed within studies for the KMT.



Gas monitoring within caldera settings: Mexico and Iceland

Authors: Chris Rochelle, Helen Taylor-Curran

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Abstract: The monitoring of geothermal gases within, or just above, the soil can be used to provide useful information on baseline environmental conditions, the surface location of permeable structures (e.g. faults) and geochemical processes within the deep subsurface. Although improvements in equipment have allowed more and faster analyses whilst in the field, it remains a challenge to monitor large areas with high resolution within reasonable timescales – be that for environmental monitoring or exploration surveys. This challenge is also shared by other areas of geoscience, such as: monitoring above underground stores of carbon dioxide, methane or hydrogen; monitoring pipeline routes or abandoned infrastructure such as boreholes; exploring for natural methane, hydrogen, or helium. It is therefore useful to share knowledge about the range of techniques used in different geological settings, in order to facilitate cross-fertilisation of ideas. On this poster we will present information on some of the approaches we have used or trialled for gas monitoring, with examples taken mainly from work at Los Humeros, Mexico, but also some at Krafla.



Understanding magmas through melt volatiles

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Abstract: Volatile elements in magma play a critical role in the chemical and physical properties of melts. As volatiles exsolve into magmatic gas, they promote magma buoyancy, accelerating ascent, and modulating eruptive dynamics. For instance, an increase in pre-eruptive volatile content leads to a corresponding increase in eruption intensity. Direct measurements of magmatic gases are challenging due to their inaccessibility. Consequently, limited data exist on the natural composition of magmatic gases. Nonetheless, gases collected at the surface provide valuable insights into magma sources, cooling, decompression and crystallization processes, and interactions with surrounding rocks and groundwater systems. Here, we will explore the various state-of-the-art techniques used for direct measurements of magmatic gases. These include for example open-path Fourier Transform Infrared spectroscopy (OP-FTIR), multisensor gas devices (MultiGas) used on the ground along with airborne devices (drones, planes), as well as gas sampling and laboratory analysis. Examples of such measurements are provided, illustrating how they can be used to understand and quantify magma behavior, including phenomena such as lava fountaining and subsurface cavities, and the progressive cooling and crystallization of melts.



High-Resolution Seismic Methods for Geothermal Exploration and Monitoring across the Hengill volcanic area

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Abstract: Hengill volcano and its associated geothermal fields represent Iceland's most productive harnessed high-temperature geothermal fields, where energy is provided by cooling magmatic intrusions connected to three volcanic systems. The crustal structure in this area is highly heterogeneous and shaped by the intricate interplay between tectonic forces and magmatic/hydrothermal activities, making detailed subsurface characterization challenging. In the Northern part of the Hengill geothermal field, super-hot geothermal resources have been spotted that are currently considered for geothermal exploration.

Over the past years, we have studied the site in great detail, and acquired high-quality datasets from a 40+ broadband seismic station array, a dense 500+ station nodal array and distributed acoustic sensing data from a fibre line crossing the area. We compare the results that we obtained from various seismic imaging methods e.g., earthquake tomography, ambient noise methods and discuss their potential and limitation to enable high-resolution seismic methods for exploration and monitoring of geothermal plays in such complex volcanic environments.



Experimental compaction of fragmental hyaloclastite at Krafla, Iceland

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Abstract: Unconsolidated lithologies hold the potential to localise fluid flow and can accommodate large strains in response to stress changes, including fluid extraction. Thus, understanding their compaction behaviour is key to characterising the prolonged transfer of fluids in geothermal/hydrothermal systems. At Krafla volcano, large areas are covered by young volcanoclastic materials (hyaloclastite) with inherently high porosities, making them susceptible to compaction and grain comminution. Here, we present unsaturated compaction experiments using Krafla hyaloclastite in two grain size populations (lapilli; 2-4 mm and ash; 0.5-2 mm) to quantify the compaction behaviour. Samples were confined in a rigid metal cylinder (42 mm diameter, 43 mm fill height) which was then loaded between two pistons (40 mm diameter). We performed (1) dynamic tests with a set stressing rate of 0.1 MPa/min until a target stress of 2, 5, 10 or 20 MPa before unloading, and (2) quasi-static (creep) tests which used the same loading rate and target stresses, but for which the stress was held for 6 hours. All experiments investigate increasing overburden, which is simulating burial or fluid extraction (which cause an increase in effective mean stress).

During dynamic tests compaction rates were highest at the onset of stressing, where grain rearrangement is effective at reducing intra-granular voids. Compaction rates then decreased with stress as the fragmental samples became increasingly interlocked. Acoustic emissions (AEs) increase with compaction, presumably due to comminution and friction between grains. Sieving shows that comminution is most prevalent within the first 5 MPa of stressing, suggesting that AEs during later compaction are likely associated with grain rearrangement. The lapilli samples, which have initially higher porosities (due to the lower packing efficiency of larger grains), experience more significant compaction. Under constant stress compaction rates rapidly decline after reaching the target stress, then reach quasi-stable rates dependent on the stress state. AEs are comparatively low under constant stress, as comminution is most significant during the loading phase. This suggests that hyaloclastite may respond rapidly to changes in stress, but equilibrate quickly to the new stress state with minor continuous compaction and comminution.

Inelastic compaction has been invoked as a mechanism for porosity-permeability reduction of hyaloclastite in the Krafla geothermal reservoir during progressive burial or extraction of fluids, both of which serve to increase effective pressure [1]. Compared to indurated (coherent) hyaloclastite that comprises the upper 1300 m of the geothermal site, the fragmental material tested here inelastically compacts at much lower effective mean stresses. As a result of the higher porosity due to intergranular space, the porosity reduction is also much higher in the granular samples. Such permeable, porous rocks may be key to maintaining fluid circulation in active geothermal sites, and thus an understanding of how hyaloclastites with different degrees of lithification (granular or solid) may variably respond to changes in effective mean stress in geothermal/hydrothermal systems is vital to optimise system exploitation.



Testing the resilience of self-healing environmental barrier coatings (EBCs) for borehole metal casing

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Abstract: One major threat to the structural stability of borehole casing in geothermal wells is the impact of corrosive hydrothermal fluids due to thermo-physico-chemical actions of aggressive chemical agents. Such extreme environments are commonly encountered in other engineering systems / applications, for which environmental barrier coatings (EBCs) can be utilised to protect and minimise, or even counteract, degradation. Yet we envisage that during installation of metal casing in a well, mechanical loading and friction may damage EBCs (i.e., scratch, chip, fracture, etc.), representing potential corrosion foci. We advance that to counter this impact, reactive or self-healing coatings (which improve their performance during interaction with hydrothermal fluids) should be considered and tested. Here, we present initial work and material preparation to investigate the adequacy and performance of such intelligent coatings, considering the occurrence of solvothermal reactions involving chlorine- and sulfur-bearing reactive fluids (Bendix et al., 2008, Müller & Heuss-Aßbichler, 2016) at high pressure and temperature conditions extant in the Krafla geothermal system (Ármansson et al., 2014, Hauksson et al., 2014). We advance that KMT represents an optimal testing facility to develop and validate the adequacy and performance of intelligent, self-healing, environment barrier coatings to increase the longevity and structural stability of borehole casing in superhot geothermal and magmatic systems.