

Geological Risk Associated with Drilling into Magma at Krafla Caldera, Iceland: Preliminary Evaluation

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ABSTRACT

Magma has been encountered unexpectedly when drilling in several volcanic regions in the world, one being in Iceland. In 2009, drilling of Iceland Deep Drilling Project's IDDP-1, intended to reach supercritical conditions at a depth of 4 – 5 km beneath Krafla caldera, ended abruptly when ~900°C rhyolitic magma was intersected at a depth of 2.1 km. The aim of Krafla Magma Testbed (KMT) is to drill into shallow magma at Krafla to advance our understanding of magmatic systems and their coupling to hydrothermal reservoirs. It is unprecedented to purposefully drill into magma at these depths and this unusual objective raises the question of associated risks. Here we aim to identify and assess the geological risks and discuss mitigating measures. The active Krafla volcanic system, with its fissure swarm and caldera volcano had a volcano-tectonic episode in 1975-84 featuring nine eruptions. It is also a geothermal energy production site for the past 40 years. The current evaluation of risks is underpinned by existing geological, volcanological and geophysical knowledge of the Krafla volcanic system, experience from the IDDP-1 project, as well as experiences from drilling into magma in Menengai, Kenya and Puna, Hawaii. Identified risk factors include: i) upwelling of magma into the borehole and other movement of magma within the bedrock, ii) magmatic eruptions of rhyolitic or basaltic origin, iii) increase in seismic activity, iv) changes in the chemical composition of groundwater or hydrothermal fluid, and v) harmful gas emissions. There is also need for assessing how these factors could impact the ongoing energy production at the site. At both IDDP-1 and Puna, it is inferred that magma upwelled about 10 metres up into the borehole. Therefore, risk associated with magma upwelling is of particular concern and needs to be evaluated in detail.

1. INTRODUCTION

Geothermal energy has been utilized since ancient times. In the beginning, geothermal water was used for bathing and washing. Later on, it was used for district heating and cooking as well and, since early last century, it has been used to produce electricity. Constant development within the sector has allowed geothermal power to become a viable option amongst renewable energy sources. In 2018, the world total installed capacity for geothermal power was 13,329 MWe according to data from the International Renewable Energy Agency (IRENA, 2018). However, this represents only ~0.6% of global energy production from renewable energy sources, and despite its advantages of small footprint and baseload power, adoption has lagged behind other clean, renewable energy resources. Increased worldwide demand for energy and the urgent need to reduce consumption of fossil fuels, calls for new ways to utilize geothermal energy so that sustainable production can be maintained. Recent advancements included the ability to drill deeper and to sustain high enthalpy wells at locations with a high thermal gradient. Ideas about drilling deep enough to reach supercritical conditions started surfacing around the turn of the century. One evolved into the Icelandic Deep Drilling Project, IDDP. The first of the project boreholes, IDDP-1, was drilled in Krafla caldera in 2009. The project came to a halt when the drill hit magma at 2100 m depth. IDDP-1 was never completed in the sense that it never reached the designated depth and conditions. However, the well was maintained for the next two years and flow testing revealed that such a well might in fact support much higher production capacity than conventional geothermal wells (Elders et al., 2013). The IDDP-1 project generated new questions as to whether harnessing the energy of magma, the ultimate geothermal source, is possible. It also raised the possibility of directly observing and testing magma at depth for purposes of improving eruption hazard assessment and eruption forecasting. Hence arose a new initiative, the Krafla Magma Testbed, KMT.

Although intentional magma drilling has never been undertaken, there are several instances of drilling encounters with magma. In 2005, during the drilling of injection well KS-13 at the Puna Geothermal Venture wellfield on the Big Island of Hawaii, a melt of dacitic composition was encountered at 2488 m depth (Teplow et al., 2009). In the fall of 2008, geothermal well KJ-39 was drilled to a depth of 2865 m in the Krafla geothermal field in north-eastern Iceland. The drill got stuck in the well and temperatures measured up to 385.6°C. The drilling produced cuttings including silicic glass from the bottom of the well suggesting that the drill had intersected melt (Mortensen et al., 2010). In 2009 the IDDP-1 intersected magma and produced similar glassy cuttings. Two years later, in early 2011, drilling began for a geothermal well field in the Menengai volcano, Kenya. The plan was to drill to 3000 m depth but proximity to a magma body in the shallow crust prevented them from reaching the desired depth in some of the wells. Cuttings from two of the wells, MW-04 and MW-06, yielded glass at depths of ~2100 and ~2200 m respectively (Mbia et al., 2015). From a volcanology standpoint, the opportunity provided by retrieving glass directly quenched from magma at depth, provides us with a mean to constrain magmatic conditions, important for risk assessment.

The Krafla Magma Testbed is a platform for exploring the possibility of intentional magma drilling for research and energy production. Few places in the world, if any, offer greater certainty on the location of a magma body as the Krafla caldera volcano, at the site of the IDDP-1 borehole. It is worthwhile noting that IDDP-1 may not have been the first magma encounter at such depth at Krafla, adding to our confidence in the presence of a shallow magma body at a depth around 2.1-2.5 km. The goals for Krafla Magma Testbed are to i) use direct observations to infer mechanisms and fluxes of mass and heat between magma and the Krafla hydrothermal system, ii) use acquired knowledge of the subsurface to improve surface geophysical and geochemical techniques for locating magma bodies and evaluating their characteristics, iii) record geophysical observations during drilling and fluid injection to understand volcano “unrest” signals, and thus vastly improving the understanding of eruption warning signs, iv) improve observational capabilities in extreme temperature and pressure conditions so that magma bodies can be monitored directly, v) advance drilling and completion technology to offer long-term monitoring and utilization (Eichelberger et al., 2018; Eichelberger, 2019).

2. THE KRAFLA CALDERA

2.1 Geological setting, volcanic history and ground deformation

Krafla is a central volcano in the Northern Volcanic Zone (NVZ) in northern Iceland, a divergent plate boundary between the North American plate and the Eurasian plate (Fig. 1). The central volcano is approximately 20 km in diameter, with an 8 by 10 km wide caldera that was formed in an eruption ~110,000 years ago (Sæmundsson, 2015). The oldest rock formations of Krafla central volcano are approximately 300,000 years old (Sæmundsson, 1991). The associated Krafla Fissure Swarm (KFS) extends about 50 km from the centre of the caldera towards the north, and about 40 km towards the south (Fig. 1). In the centre of the Krafla caldera is the hill Leirhnjúkur and a few kilometres south-east of Leirhnjúkur is Leirbotnar, the main production site for the Krafla geothermal power plant. Bjarnarflag, a high-temperature geothermal area that is utilized as well for geothermal energy extraction, is south of the Krafla caldera.

The Krafla volcanic system appears to be bimodal, where most of the eruptions are basaltic, minor is silicic, and a trace is of intermediate composition (Jónasson, 1994). The Krafla central volcano is mostly comprised of basaltic formations and since the formation of the caldera, it has erupted both basaltic and rhyolitic magmas. Rhyolitic lava and traces of andesitic extrusives are present along the caldera bounding fault zone and in the explosive crater Víti (Fig. 1). Víti was formed at the beginning of the Mývatn Fires (Sæmundsson & Sigmundsson, 2013). The two most recent major volcano-tectonic episodes within the Krafla volcanic system are the so-called Mývatn Fires and Krafla Fires. The Mývatn Fires took place between 1724 and 1729 and the Krafla Fires between 1975 and 1984. In the Krafla Fires, about 20 dike events are identified, of which nine resulted in eruptions (Buck et al., 2006). In the last 2800 years of the Krafla system has produced six volcano-tectonic events (Sæmundsson, 1991). For 5000 years before that, only one such episode is known in the system (Sæmundsson, 2015).

Crustal deformation has been studied in great detail at Krafla over the last 50 years or so. The region is subjected to several sources of deformation: i) Land rise of few millimetres per year due to glacial isostatic adjustment caused by viscoelastic response to retreating icecaps (e.g., Auriac et al., 2013), ii) Plate motion from the diverging plate boundary at a rate of ~17.2-17.7 mm/yr in direction 291.4-292.5° (Drouin et al., 2017a), iii) Viscoelastic response to stress changes in the crust from the last rifting episode, iv) Crustal inflation and deflation caused by magmatic processes and v) Deflation due to geothermal processes and utilization of fluids at Leirbotnar and Bjarnarflag (Fig. 1 and 2).

Modelled deformation sources of potentially magmatic origin are a shallow magma body with an inferred pressure centre near Leirhnjúkur mountain (Sturkell et al., 2008 & Drouin, 2017b), estimated at a depth of 2-4.5 km according to most geodetic models (Tryggvason, 1999; Árnadóttir et al., 1998; Sigmundsson et al., 1997; de Zeeuw-van Dalfsen et al., 2004; Heimisson et al., 2015). An inflation source north of Krafla that could potentially either be a deep-seated magma body at a depth of ~21 km or be a consequence of post-rifting viscoelastic relaxation (Metzger & Jónsson, 2014; Ali et al., 2014). Other known magmatic source in the area is the rhyolite magma body intersected at a depth of 2.1 km by the IDDP-1 drilling.

2.2 Geothermal utilization

In 1969, a 3 MW geothermal power plant was built at Bjarnarflag (Fig. 2a). It was one of the first power plants to utilize steam from a high-temperature geothermal area for power production in Iceland (Landsvirkjun, 2019a). Around the middle of the 20th century, north Iceland was experiencing problems with the power distribution grid, because it did not support the required capacity. As a result, there were frequent blackouts. The electricity deficiency was also affecting economic development in the region. Hence, more energy was needed. The Bjarnarflag power plant had already been commissioned and when plans to increase the production capacity of Laxárvirkjun hydropower plant came to a halt, due to resistance from the local population, further development in geothermal utilization appeared to be the best option. The National Energy Authority (Orkustofnun) had already conducted detailed research in the area between the years 1960-1972 and after a preliminary study, suggested either Bjarnarflag or Krafla as the best location for a new power plant. The Krafla area was thought to have larger reservoir as well as being less likely to cause environmental damage in the Mývatn region. Therefore Krafla was agreed upon as the location of a new power plant (Fig. 2b). The first geothermal wells in the area were drilled in 1975 and that same year construction of the new power station began. A total of 21 wells were drilled in the area until 1985. The first production unit was commissioned in 1978 with a capacity of 10 MW_e (Gunnarsson, 2012). The capacity increased with further construction until 1999, when it reached the power station's current potential of 60 MW_e (Landsvirkjun, 2019b). After the onset of the Krafla Fires in December 1975, the production site was greatly affected by its proximity to the eruption, especially by changes in chemical composition and temperature of the geothermal fluid. However, this activity provided an excellent chance for scientists to study a volcano-tectonic episode (Gunnarsson, 2012).

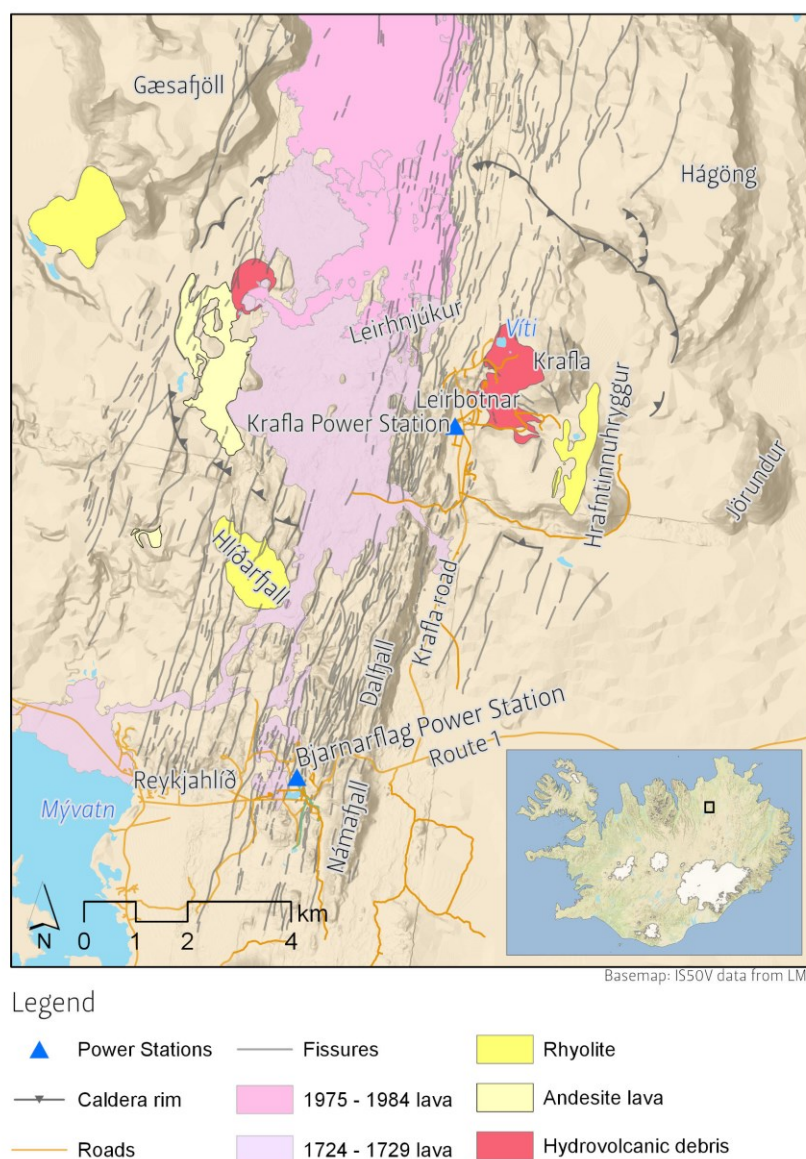


Figure 1: Geological map of part of the Krafla volcanic system in north-east Iceland (see inset), showing the central volcano with its caldera, the Krafla and Bjarnarflag geothermal areas, and power stations. Basemap and infrastructure data from Landmælingar Íslands (National Land Survey of Iceland) and Landsvirkjun (The National Energy Company). Geological feature data from ÍSOR (Iceland Geosurvey).

2.3 Icelandic Deep Drilling Project

In 2009, the IDDP-1 borehole was drilled in the Krafla caldera (Fig. 2b). It was a part of the Iceland Deep Drilling Project and the aim was to drill 4.5 km into supercritical conditions, attempting to establish power output from a supercritical well. A feasibility study indicated that, at the same volumetric flow rate, a supercritical well would have an order of magnitude higher power output than a conventional high-temperature geothermal steam well (Friðleifsson, 2003). The drilling had to be terminated at a depth of 2.1 km, when the drill hit ~900 °C, high-silica (76.5% SiO₂) melt (Elders et al., 2013; Zierenberg et al., 2012).

The location of the IDDP-1 borehole was initially based on TEM and MT resistivity surveys that had been carried out in previous years and micro-seismic data (Árnason et al., 2007), as well as information from nearby geothermal production wells, K-35 and K-36 (Friðleifsson et al., 2014). Based on an interpretation of resistivity data, the depth of the Krafla magma chamber was estimated to be at ~4.5 km. Information from K-36 indicated potentially high permeability in that part of the field as well as production of superheated steam from its lowermost feed zone (Friðleifsson et al., 2014). The drilling of the IDDP-1 well started in June 2008, after 8 years of preparations (Pálsson et al., 2014). A year later, during drilling for a production casing at ~2.1 km depth, the drill bit experienced a sudden rise in torque and a drop in hook load and the drill string got stuck. The lowermost part of the drill string was detached and after a successful sidetrack, a second attempt was made with the same results. In both of these events, no cutting samples were recovered due to loss of circulation of the drilling fluid. After placing a cement plug and making a second successful sidetrack, drilling commenced two weeks later. Like in previous attempts, the drill string nearly got stuck at 2.1 km. When pulling back the drill string, magma flowed into the lowermost 10 metres of the borehole (Elders et al., 2014) reaching the drill string which got stuck as it experienced a sudden rise in torque and a drop in hook load. However, this time, the crew managed to maintain circulation through the drill string and retrieve abundant cuttings of glass, indicating that magma had quenched and fragmented at the base of

the borehole (Pálsson et al., 2014). According to Friðleifsson et al. (2015), further drilling was not considered feasible. However, given this unique opportunity for research in a near-magma environment, a decision was made to prepare the well for production from the contact zone of the magma. The original packer designed for cementing the production casing failed to hold sufficient pressure and started to leak after several hours. Rather than ordering a new casing packer, a reversed cementing procedure was done from surface. After a necessary replacement of a master valve, the well was closed in early July 2009. Cold water was then injected into the well for four weeks before it was eventually shut in for recovery. Discharge tests and pilot production tests were undertaken during 2010 to 2012 (Friðleifsson et al., 2015). During the 2-year-long flow test period, where the well underwent a series of flow tests, it produced superheated steam at wellhead pressure of 140 bar and temperature of 450°C (Markusson & Hauksson, 2015). The condensed superheated steam contained hydrochloric and hydrofluoric acid, making it highly corrosive (Hauksson et al., 2014). By keeping the well head pressure above 80 bar, this could be avoided. Corrosion was not severe when the steam was superheated but repeated shutdown caused the steam to condensate to form acid and thus increasing corrosion. Volatile silica was present in the steam phase and precipitated if the well head pressure fell below 80 bar, resulting in severe erosion of surface equipment. After two years of testing the well had to be closed following a master valve failure (Markusson & Hauksson, 2015).

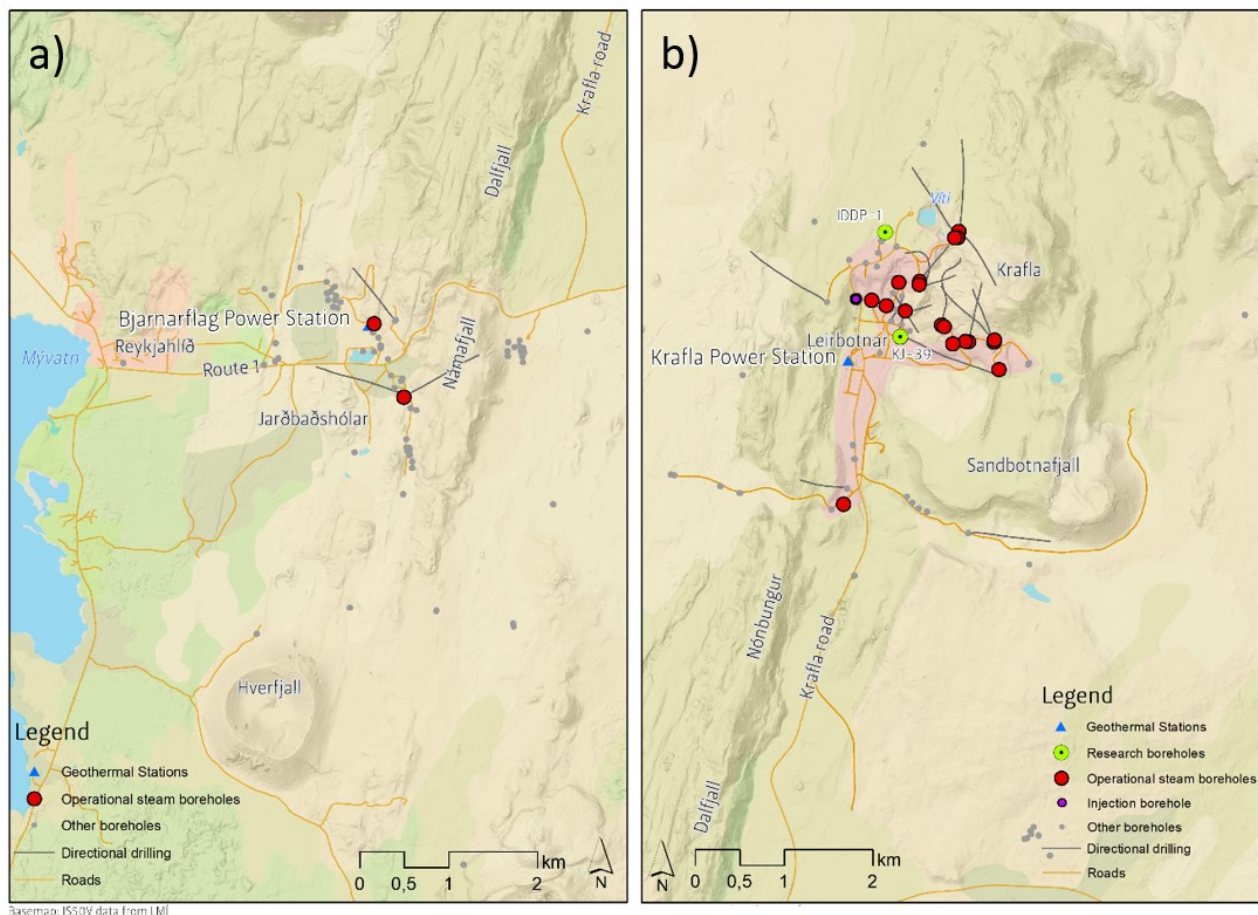


Figure 2: Well sites for the Bjarnarflag and Krafla geothermal power plants. Green dots show the location of the IDDP-1 and KJ-39 wells. See legends for other features . Basemap and infrastructure data same as in Figure 1.

2.4 Eruption from a well in Bjarnarflag

During the 1975-84 Krafla Fires a unique event took place when magma started to erupt from a well head in the Bjarnarflag geothermal area. One of the diking events in the rifting episode began on September 8th, 1977, with seismic activity and subsidence within the Krafla caldera. It was followed by a basaltic fissure eruption at the northern part of the caldera rim. Ground fissures then started opening up in a southward direction. About two hours after the onset of the eruption, it began to decline. However, the seismic activity continued and began propagating further south, out of the caldera and towards the Bjarnarflag geothermal area. The eruption gradually declined until it ceased later that same day (Einarsson, 1991). Later that evening, just before midnight, an orange coloured column of fire was noticed. The column rose tens of metres into the air from the well head of well nr. 4 in Bjarnarflag. The eruption came in bursts and lasted for approximately 30 minutes. Initially it was not clear if the column was from an eruption or not but the following morning a hole could be seen on the well's top piece and pumice had escaped through the hole and settled around the well (Björnsson & Sigurðsson, 1978; Larsen et al., 1979). Ragna Karlsdóttir was an eyewitness to the events in September 1977 (Karlsdóttir, 2016). Seismicity migrated rapidly to the south, away from Leirhnjúkur and the fissure eruption. After hearing reports about flashes and sparks at the geothermal well site in Bjarnarflag, Ragna went to the well site along with a geologist. Once they reached the first well, everything appeared to be as normal. Suddenly, an incandescent column rose as basaltic tephra erupted from the wellhead. Basaltic tephra was erupting up through the well. When returning to the site the following morning, the eruption had already come to an end and tephra had spread out around the wellhead.

3. EVALUATION OF GEOLOGICAL RISK FACTORS

The plan of the KMT project is to drill into the same body of magma as was intersected during drilling of the IDDP-1 borehole. The critical point in the process is when the drill bit comes into contact with the melt. The borehole eventually may act as a conduit for the magma and can subsequently induce pressure change and movement within the magma body. Other possible risk factors include induced earthquakes, emission of hazardous volcanic gasses and changes to the hydrothermal system or groundwater. Each factor is discussed briefly in an attempt to evaluate whether an event is likely to occur or not. It is important to consider possible impact on human health. The nearest population, apart from those few that are working at Krafla power station at any given moment, is in Reykjavíð, Mývatn (Fig. 1), with a population of 208 people at the end of 2018 (Hagstofa Íslands, 2019). It is located approximately 9 km to the south-west of the power station. Other urban areas that might be affected include Húsavík, located approximately 47 km to the north-west of the power station, with a population of 2,307 people, and Akureyri, approximately 60 km to the west of the power station, with a total population of 18,644 people. Other densely populated areas are farther away and habitation in rural areas is limited. Therefore, potential impact of events that might occur, is mostly limited to people working on site as well as infrastructure damage. There are several ways to evaluate risk. Here, we base this initial evaluation on likelihood and severity of consequences.

3.1 Upwelling of magma into borehole

As described in chapter 2.3, magma flowed up into the IDDP-1 borehole when the drill bit came into contact with a rhyolitic magma body. Since KMT-1 would be drilled into the same magma body, the likelihood of magma upwelling and erupting through the well must be considered. Whether or not flow up hole will occur, and the distance, will depend on several factors, such as the viscosity and density of the magma, the pressure within the confined magma body, the diameter of the borehole and ambient fluid pressure in the borehole. As seen in Fig. 3, the viscosity of the magma strongly depends on both temperature and chemical composition including volatile content (Gonnerman, 2015; Hui and Zhang, 2007). Since the magma body in question is of rhyolitic origin and therefore high in SiO₂ content, it has relatively high viscosity and would require stronger pressure difference than a basaltic magma would to upwell to a given height in the borehole. The H₂O content of the quenched rhyolitic magma from IDDP-1 was inferred to be ~1.77 wt% (Schiffman et al., 2014), which is lower than the ~2.8 wt.% expected considering ambient P-T conditions at the base of the borehole (e.g., Liu et al., 2005); this may be due to the resultant vesiculation of magma triggered by drilling. Using the chemical composition of the glass cuttings from IDDP-1 (Zierenberg et al., 2012) as input parameters in the GRD viscosity calculator (Giordano et al., 2008) and the inferred ambient temperature conditions at 2100 m, we estimate the viscosity at 10⁵-10⁶ Pa s (Fig. 4). Magma upwelling and resultant pressure and pressure fluctuations may damage equipment (e.g., drill bits and strings, and monitoring equipment) and jeopardise borehole and casing integrity. The possibility of a borehole eruption will be discussed in sections 3.2 and 3.3.

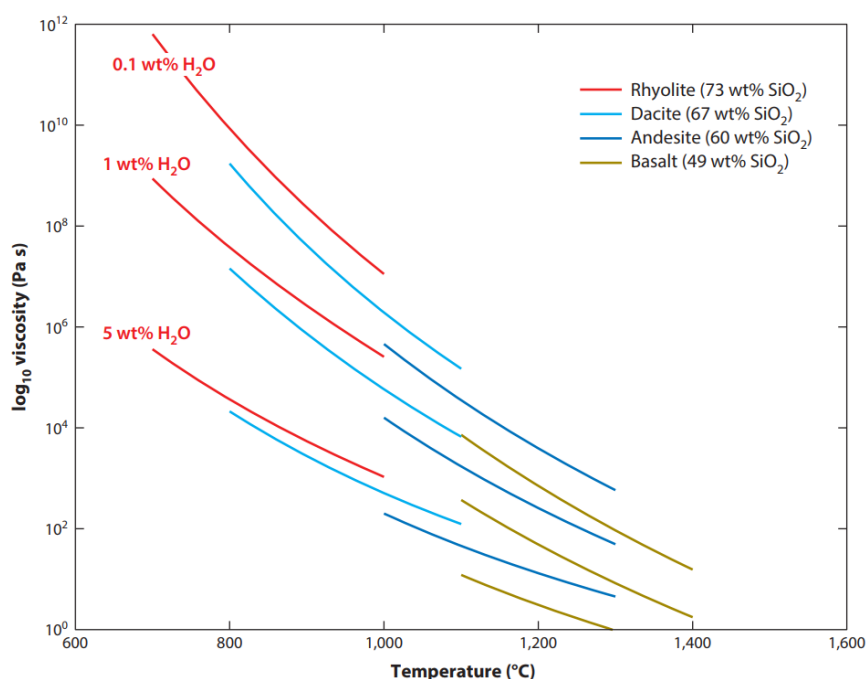


Figure 3: Viscosity as a function of temperature for natural silicate melts (reproduced from Gonnerman, 2015; based on Hui and Zhang, 2007). Each composition is plotted from a range of typical eruptive temperatures. Viscosity decreases with temperature and dissolved water content but increases with SiO₂ content. The dependence of viscosity on dissolved water increases with SiO₂.

There are several steps that might be taken to increase the chances of a successful drilling operation and structurally sound borehole. The diameter of the borehole influences the likelihood of magma upwelling; a small borehole diameter would limit magma upwelling. Also, maintaining a high pressure in the borehole would minimize the resultant pressure gradient experienced by magma, thus reducing the occurrence of vesiculation which increase magma buoyancy and the chance of upwelling into the borehole. Finally, the selection of drilling fluid as well as the flow rate imposed during drilling is important, as it controls cooling efficiency. High cooling rates would enhance quenching of the magma (which results in high viscosity or even solidification as well as prevention of prolonged probable vesiculation) before the drill bit makes contact and therefore lessens the likelihood of upwelling and possible issues with the drill bit getting stuck in melt.

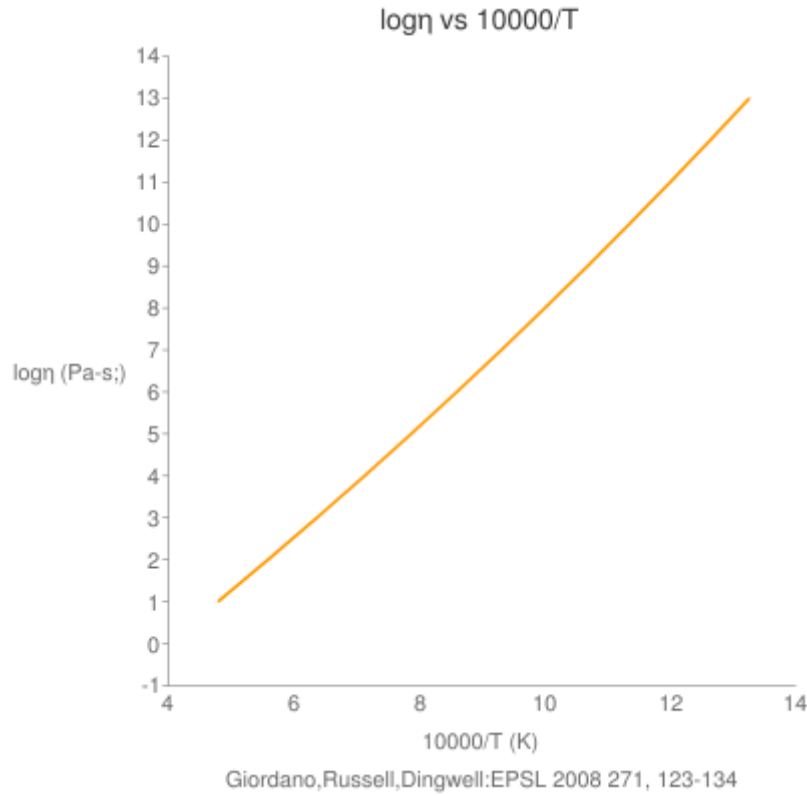


Figure 4: Viscosity as a function of temperature based on the major element composition of glass (wt%) retrieved from the bottom of IDDP-1, determined by electron microprobe (Zierenberg et al., 2012).

3.2 Magma upwelling and eruption – Rhyolite

The magma body targeted in KMT is of silicic composition with temperature $\sim 900^\circ\text{C}$ (Zierenberg et al., 2012). As seen in Fig. 3, silicic magma in general has several orders of magnitude higher viscosity than basaltic magma. Rhyolite within a magma chamber is hydrated which reduces the difference in viscosity from what is plotted in Fig. 3. Here, we consider that the upward flow of magma in a borehole can be described as Hagen-Poiseuille's laminar flow in a pipe; thus there would be an inverse relationship between magma flow rate Q [m^3/s] and viscosity η [$\text{Pa}\cdot\text{s}$], dependent also on pressure differential Δp and the geometry parameter d (length), S and k of the borehole (e.g., De la Cruz-Reyna & Yokoyama, 2011) according to:

$$Q = \frac{S}{k\eta} \left(\frac{\Delta p}{d} \right) \quad (1)$$

The higher the viscosity of a melt, the lower the flow rate. As the viscosity increases, it is also harder for volatiles to escape the magma. This increases the likelihood of fragmentation of rhyolitic magma. Should fragmentation ensue, it could possibly result in an eruption from the borehole. The likelihood of explosive eruptions is intrinsically linked to the volatile content of the magma and time allowed to vesiculate before drilling operation quench it in. The scenario of an event where basaltic magma intrudes into the rhyolitic magma body, triggering an eruption will also need to be considered. Such an event occurred when the explosive crater Viti was formed in 1724, leading to a phreatomagmatic eruption (Sæmundsson & Sigmundsson, 2013). Possible consequences could be severe and endanger people in proximity to the drill site, damage/loss of drilling equipment, temporary termination of power production in Krafla as well as all other possible impact of explosive volcanic eruptions.

Although, from previous experience a large rhyolitic eruption may not be considered a likely event, the consequences of even a small explosive event could be severe. That being the case, the need for preventative measures needs to be established. The measures outlined in section 3.1 would all be relevant in this case as well, in addition to other measures such as detailed numerical modelling for different scenarios before start of drilling. Models could allow for the drilling team to identify signs of magmatic unrest by means of continuous monitoring of ground deformation, seismicity and gas emission, etc. They might also contribute to identifying the scenarios that are most likely to happen. In addition to the preventative measures, a response plan would be necessary to minimize the effects of an eruption. The response plan should include, among other things, an evacuation plan and safety perimeter as well as a response plan for the operation of the power plant.

3.3 Magmatic eruption – Basalt

Basaltic magma has low viscosity compared to rhyolitic magma and thus it tends to ascend and erupt at higher rates than rhyolitic magma. However, KMT-1 targets the rhyolitic magma body previously encountered during IDDP-1, so direct encounter of drilling with basaltic magma is not expected. Furthermore, geological record at Krafla for the last few thousand years has been interpreted to reflect very episodic nature of magmatism, with eruptions confined to distinct volcano-tectonic episodes associated with rifting, separated by quiet intervals (no eruptions).

In the unlikely event of a basaltic eruption taking place it could have similar consequences to those of a rhyolitic eruption. Basaltic magma being more fluidal tend however to erupt primarily effusively. Based on previous research and knowledge of the area, and the limited likelihood of such an event, there is minimum need for preventative measurements such as those mentioned above. However, the same emergency response plan as the one rhyolitic eruption would be applicable in this case as well.

3.4 Other magmatic movement

Magma migration without an eruption, such as intrusions (sills or dikes) or magma transfer from one body to another, within the Krafla volcanic system in response to drilling is another potential unrest scenario. When drilling into a magma body the question arises whether or not the pressure difference created by the drilling procedure could trigger migration. There are two issues that require special consideration. Sufficient pressure increase on the magma body can cause the magma to open up new pathways or pressurized drilling can cause cracking of the bedrock, opening up new pathways. Considering that the fluid pressure during drilling is lower than the pressure of the magma reservoir rock, it is unlikely that magma would migrate anywhere but into the borehole.

Potential consequences include changes in the magmatic system and the hydrothermal system that is being utilized for geothermal energy production and can potentially be affected by relocation of the heat source or contact with magma. There is minimum or no immediate threat to people, but there is potential risk to equipment and/or the KMT-1 project. Changes to the hydrothermal system could possibly also affect the production capacity of the power plant. Therefore, continuous seismic monitoring as well as deformation monitoring would be helpful in identifying possible threats as well as identifying and mapping the development of fractures. A response plan is also needed to outline preventative measure and mitigation.

3.5 Earthquakes

As with all subsurface drilling operations there is a chance that the drilling might induce seismicity (i.e., earthquakes). Due to the nature of the bedrock in the area, which is relatively young and porous it does not have the potential to accumulate the stresses necessary to produce high magnitude earthquakes since the bedrock gives way at low shear stresses. Therefore, larger events are unlikely to happen but intermittent seismicity with occasional low magnitude earthquakes must be considered possible and somewhat likely, especially in the case where the borehole would be drilled under pressure.

Since high-magnitude earthquakes are unlikely to occur they present a minimum threat to people. However, prolonged seismicity and earthquakes of lesser magnitude can cause damage to structures in proximity to the drill site. Since the area is prone to naturally occurring earthquakes, the local population is prepared for such events and the structures are made to withstand seismic effects up to a certain degree. The possibility of increased influx of cold groundwater into the hydrothermal system due to earthquake induced fracturing in the bedrock should also be considered. It is certainly possible, and at best in may enhance fluid exchange for energy production; yet prolonged efficient energy extraction could, in a worst-case scenario, cause cooling of the heat source, affecting the energy production. With the low impact earthquakes that can be expected in the area it is unlikely that the increase would be sufficient to cause rapid or extensive cooling. As with the other factors, continued ground deformation, seismicity, gas emission and temperature monitoring is relevant and very important in this case. Since the consequences are minimal in the most likely scenarios, the need for preventative and/or mitigating measures is limited to a response plan. As for mitigating measures, financial claims due to structural damages or other form of loss caused by induced seismicity could potentially affect the operation and informing external stakeholders would be essential.

3.6 Emission of volcanic gases

Magma carries dissolved gases and as magma decompresses (due to drilling or ascent) it vesiculates and releases gases into the atmosphere. The most common of these gases are water (H₂O) as well as carbon dioxide (CO₂), sulfur dioxide (SO₂) and hydrogen sulfide (H₂S) (USGS, 2017). Carbon dioxide can pool in low-lying area and lower oxygen (O₂) concentration, creating potentially lethal conditions to people in proximity to the drill site. High concentrations of sulfur dioxide can cause irritation to skin and the mucous membranes of the eyes, nose and throat. Hydrogen sulfide is very toxic, causing irritation of the respiratory tract and possibly pulmonary edema after prolonged exposure. More severely, even at low concentration levels it can cause loss of consciousness and death.

If the drill intersects magma, it is possible that it might enhance volcanic gas emissions. Analysis of IDDP-1 dry steam samples from the flow test period revealed low concentrations of CO₂ and a very low CO₂/H₂S ratio (Ármanncsson et al., 2014). Therefore, it is not likely that volcanic gas emissions will pose a threat to people. However, given the potential severity of exposure to these gases, there must be continuous air quality monitoring during drilling, especially of CO₂ and H₂S concentrations. A response plan is necessary, establishing emergency evacuation procedures and safety zones. In case of elevated level of hazardous gases, people should be instructed to keep out of low-lying areas

3.7 Changes in chemical composition of water

Magma can potentially emit halogens like fluorine, chlorine and bromine in the form of hydrogen halides (HF, HCl, HBr). They are acidic, with high solubility and can therefore cause acidification of the hydrothermal fluid and acid rain as well as poisoning drinking water and farm land (USGS, 2017). Acidification of the hydrothermal fluid is likely to cause damage to casings and well heads of the KMT borehole if flow tested (note that in other monitoring phases of the project, the well will be buffered by novel gas); it may also possibly impact other equipment/boreholes used in the power production at Krafla. The long-term effects of acid rain include damage to buildings and other man-made structures by corroding metal and dissolving stone. However, there is no short-term effect. Hydrogen halides can potentially poison drinking water, making it unsafe for drinking. These chemicals are already affecting the hydrothermal system and groundwater in low levels and are not cause for concern. In the unlikely event of an eruption or other magmatic movement towards the hydrothermal system, levels can increase immensely and alter the chemical composition of water bodies in proximity to the eruption site.

Continuous monitoring of air quality as well as water quality in both ground water and hydrothermal fluid would be essential. Monitoring chemical composition of the hydrothermal fluid would also be important. Some preventative measures can be taken, such as careful consideration of the borehole casing to reduce the possibility of cross contamination with ground water. A response plan should be created in the event of contamination, including information about safe chemical values as well as arrangements for back-up water supply and other relevant information.

3.8 Cooling of the hydrothermal system

High temperature contact metamorphic rocks in the lowermost part of the IDDP-1 borehole constitute a conductive boundary layer that allows for heat transport of estimated minimum 23 W/m² from the magma body to the overlying hydrothermal system (Schiffman et al, 2014). Should the volume of the magma body decrease severely, there is a possibility that it might not sustain the current temperature of the hydrothermal system in the long run. As mentioned above, there is also the possibility of increased influx of cold water into the system from fracturing of the bedrock due to drilling operation and rupture events near the borehole, which might also affect the temperature of the hydrothermal system. In both cases, the likelihood of rapid cooling of the system is estimated low and the more likely scenario, if either of the possibilities occur, is that the cooling rate will be low enough to have little or no impact on the power production during the lifetime of the power plant and well beyond. It is worthwhile noting that when IDDP-1 intersected, and in turn quenched magma, large volume of cold water was injected into the well. The injection did not affect the geothermal energy production. A tracer test later revealed a link between IDDP-1 and one of the production wells at Krafla when a small fraction of the tracer appeared in well K-36, indicating that the cooling effect of injection in IDDP-1 was not strong. (Juliussón et al., 2015).

Cooling of the geothermal system is not considered to be a particular concern. There is no direct danger to people or the environment and the consequences of indirect issues, like problems in energy production, are unlikely and of minimum immediate importance. However, continuous monitoring of temperature within the hydrothermal reservoir is advised.

4. CONCLUSIONS

Geological risk factors affecting drilling into magma on purpose in the Krafla caldera have been presented and discussed. Our evaluation is that most of the risk factors have either low likelihood or low severity and should not have a crucial impact on the proposed KMT-1 project. The more likely events may eventually be prevented, and/or their influence mitigated. The same applies to the factors with more severe consequences. The most likely geological risk factor to have influence on drilling into a known magma body is considered to be upwelling of magma into the borehole. It can lead to possible loss of drilling equipment or damage of the borehole. The risk can potentially be reduced by means such as sufficient cooling and maintaining fluid pressure in the well depending on the research practices undertaken in the borehole during different phases of KMT. Modelling is useful to identify possible risk for different scenarios beforehand. Continuous monitoring of seismicity and ground deformation, gas emission, temperature as well as air and water quality and other characteristics, are essential for the construction of emergency response plans should any hazardous event occur. To further evaluate the geological risk and possible impact on the KMT project, a detailed risk assessment is needed, as well as detailed numerical modelling that would provide important information for the risk assessment. The risk factors considered for Krafla volcano in relation to drilling into magma are mostly generic and can be applied to similar projects in other areas as well. It is, however, important to always consider the local and regional geological setting of each geothermal area.

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