Article Title: ‘It’s like going to the Moon...’ Exploring risk and stakeholder views of Iceland’s Krafla Magma Testbed (KMT)

Abstract: In 2009, the Icelandic Deep Drilling Project (IDDP-1) accidentally drilled into an active magma chamber at Krafla volcano in North-Eastern Iceland, only the third such occurrence in recorded history. Initially regarded as a failure, the event has since been reframed as a unique scientific opportunity, leading to the proposed Krafla Magma Testbed (KMT), a programme of renewed drilling and research to advance understanding of planetary processes and extreme geothermal energy. Drawing on semi-structured interviews with thirteen local stakeholders representing regional development workers, local political actors, a geologist and energy and power plant workers, this study explores how risk is perceived through the framing of the KMT. Findings suggest that risk is shaped not only by local experience, socio-economic conditions, and place-based identities, but also by wider global dynamics including climate politics and notions of planetary responsibility. Viewed through the lenses of the Anthropocene and geoethics, the KMT represents both a scientific and ethical frontier where deliberate human engagement with magma raises complex questions of governance, justice, and accountability. Ultimately, the study highlights that how risk is understood is context-specific and evolving, reflecting how local communities and global scientific ambitions intersect in navigating the challenges of living on a dynamic and volatile Earth.

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Highlights:

- The KMT is exploratory research designed to drill into an active magma chamber
- We explore framings of risk looking at place-specific knowledges
- Doing good for the global community through reducing risk were important
- Framings of volcanic risk is changing as our relationship with the earth changes

1.0 Introduction

In this paper we present the findings of a qualitative scoping study that explores risk framing with stakeholders, including regional development works, local political actors, a geologist and energy and power plant workers, in relation to the Krafla Magma Testbed (KMT). Krafla is a volcano in the North-East of Iceland and is also home to Iceland's oldest geothermal field [1]. During a drilling operation by the Iceland Deep Drilling Project (IDDP) called IDDP-1 in 2009, that aimed to look for supercritical geothermal resources at 4.5 km, a magma chamber was accidentally encountered at 2.1 km and unexpectedly hit ~9000oC rhyolite magma [2]. Whilst the drilling failed to achieve its intended goal, this event at Krafla opened the door to

exploration of the hydrothermal/magma system (see [1] and[1]). This is only the third recorded time in history where magma in-situ has been encountered in this way [3]. What was at the time seen as a failure has now become a site of new scientific opportunity. Through a newly formed scientific research programme called the Krafla Magma Testbed (KMT), the plan is to re-drill into the magma chamber and use it as a test site to better understand volcanic processes, hazard reduction, and energy from magma.

The aim of this paper is to understand how local stakeholders view risk in relation to the KMT and to tentatively frame this within our new and evolving relationship with the Earth. Framings of risk can relate to how different 'publics' including experts, local people, policymakers and other stakeholders, understand risk in relation to particular hazards [4]. In this instance, risk in relation to volcanic activity and intentional drilling into Krafla's volcanic caldera. Volcanic communities for many centuries have had a strong connection to their volcanic landscape. For instance, early civilisations developed the use of fire at the mid-Atlantic rift system [5], have taken advantage of fertile soils for crop growing, utilised hot springs for hot water, health and tourism, and now the geothermal properties of volcanic systems for energy generation. Risk has been explored in the context of volcanic hazards many times [6,7,8] however, the KMT presents an evolution in the relationship between people and volcanic processes, through the purposeful interaction with a volcanic system. Understanding risk in this context will help situate risk framing, and thought around geo-ethics[2], as society moves to a more extreme relationship with

[1] https://www.kmt.is Accessed 04/03/2025

[2] Peppoloni and Di Capua [10 p.15] define geoethics as an awareness that 'the human species has irreversibly modified and is continuing to modify the natural environments and territories in which it lives and operates, not only their physical, chemical and biological characteristics, but also social and cultural traits that connote social–ecological systems today as in the past, which in turn, in a feedback mechanism, influence people's economic

earth processes [9]. Understanding risk in this context is important for both normative and substantive reasons. Normatively, there is an ethical obligation to recognise how local stakeholders who live and work in and around the Krafla region, perceive the KMT project, and to ensure that they have a meaningful voice in decisions about how the project develops [43]. Substantively, incorporating local perspectives not only increases the likelihood that the KMT project will achieve its ambitions at both local and global scales, it also offers a valuable case study of risk in the context of society's more extreme relationship with the earth and contributes to a growing body of work on planetary responsibility [10, 27, 43].

This more extreme relationship is in part a symptom of living on a changing planet. The most recent IPCC report emphasises the extent to which the planet's climate is changing and urges considerable action to be taken [11]. Geoengineering of earth systems has been proposed as a technical fix to mitigate the effects of climate change, such as the use of solar, by increasing reflection of sunlight back to space [12]. Whilst Krafla isn't a geoengineering solution as such, it has become a science and technology fix to mitigate the effects of natural hazards and provide a 'green' solution to large scale energy production. Iceland presents an interesting case in exploring, not just risk in relation to volcanic hazards, but additionally how the production of risk in this context is entwined with a green economy, energy security and national identity. What was only a few generations ago a fairly primitive place, Iceland is now a prosperous country negotiating its position on the world stage. The following sections (2.0-2.2) will describe the Icelandic context in more detail, including the aims of the KMT, followed by an

development, social perspectives and sense-making. It then becomes a responsibility for geoscientists to look beyond their traditional areas of work and each interact proactively with civic communities to promote changes that are needed.'

exploration of risk framing with local stakeholders. This will then lead into the methodology (section 3) and results and discussion (section 4) where risk, global opportunities and societal acceptance will be discussed in detail.

2.0 Iceland in Context

To understand how the possibility of the KMT has emerged, it is necessary to understand Iceland in context, particularly in relation to it's spatial demography, its historical trajectory of economic activity and development, and its distinctive environmental and geological setting.

Iceland is sparsely populated with 390,000 inhabitants, most of which reside in the south-west of the Island, in or around the Iceland's capital. The active volcanic caldera and geothermal field of Krafla is located in the remote North- Eastern region of Myvatn, with a population of approximately 227 living in the nearest village of Reykjahlíð 15km away. Approximately 60 km to the north of Krafla is the town of Húsavík (population, 2400) and situated 120 km to the west of Krafla is Akureyri, the second most populated town in Iceland (20,000 people). Although the population in this region is not large, it has a growing tourist industry based on whale watching and natural amenities provided by its volcanic landscape, including Lake Myvatn and lava field tours in the Myvatn region.

Iceland's wild landscape and particular geological setting has presented both opportunities and challenges for Icelanders in terms of its energy provision. Its rugged and extreme terrain has made it difficult to connect the sparsely distributed communities that are shaped by their geographic setting, on a national scale. Development of technology and national electrification emerged in Iceland just after the Second World-War through investment from America -a

legacy from the war effort given Iceland's strategic positioning and techno-scientific role during that time [13].

Dammed hydro-power has become a key energy provider utilizing the many fjords and glacial river systems. However, these have not gone without political and environmental unrest, linked to the damming of certain valued landscapes [13]. Geothermal power is also a significant contributor to energy provision utilising the volcanic heat of the rocks below. Evidence of this can be seen to be occurring naturally across Iceland, through the various hot springs and groundwater that has been warmed by volcanic heat. The resultant hot water and steam can be used as an energy source, driving turbines that generate electricity on a large-scale. Iceland takes advantage of their particular geological setting and currently generates 99% of their energy from hydro-power and geothermal energy of which Krafla's geothermal field contributes 60 MW of installed capacity [14]. The regional and national scale tell a story of Iceland's own energy transition, from small-scale power plants in the 1930's and 40's and the use of coal and oil, to the introduction of the first steam generated geothermal power plants in 1970's, the first of which happened to be at the Krafla site [14]. Geothermal energy has until recently also been framed more favourably compared to the controversial and often large-scale dammed hydro-power developments Iceland has witnessed since 1970's. At a domestic level there is no current need to increase installed capacity by any significant margin. At present, over 76 % of Iceland's generation goes to industrial activity, with just over 18 % to domestic consumption [15]. The current drive for increase in installed capacity, such as geothermal or hydro-power, comes from development of heavy industry from international business, often in

Iceland's more remote regions. This initiative is in part due to Iceland's policies implemented to help boost the Icelandic economy, particularly after the economic crash of 2008 [1, 13].

Iceland's economic mobilisation and local/national contestation around energy provision is well reflected in the socio-political discourse that has led to the KMT. This is through national policies and global market politics that has seen Iceland have a significant increase in development of international 'heavy industry', such as aluminium and silicon smelting, outsourcing their factories to Iceland. These industries, whilst bringing much needed development to rural areas (eg. Energy access, infrastructure, employment), are not without contestation and there are well organised activist groups in Iceland such as 'Saving Iceland' [16], who protest the development of heavy industry, that can emit both $CO_2$and SO_2. Their aim being to protect the 'pristine wilderness of Iceland's remote subarctic highlands' [13 p.205].

2.1 The Krafla Magma Testbed (KMT)

The KMT is a scientific research project with the ambition of establishing the first-ever research infrastructure able to access a magma chamber on the Krafla caldera. The KMT project proposed that Krafla is the only place we now know with certainty, where magma resides beneath the Earth's surface and that it can be drilled and controlled with existing geothermal techniques [17].

To take advantage of this serendipitous discovery, the Krafla Magma Testbed (KMT) project was formed. The KMT project comprises 38 research institutes and companies across 11 countries who are committed to continuing this research and who are now seeking funding to commence

the first phase of the project, the proof of concept, to drill a research borehole into the boundary between solid and molten rock and monitoring the temperature from that point on [18].

The KMT project proposes to provide a unique opportunity for scientists to investigate magma properties directly in situ. The aims of the project are to vastly advance scientific understanding of magma, increasing the quantity and efficiency of geothermal energy production, and direct sampling and observing the volcanic system. The KMT aims to realise its goals via four project pillars[3]: (i) Volcanic hazards – through sensor networks this pillar aims to establish where and under what conditions magma is stored beneath a volcano, exploring magma behaviour and movement that could lead to an eruption ; (ii) Planetary science – through access to magma samples and direct observations this pillar aims to aid the development and testing of models about how the planet works and observe the real properties of the system; (iii) Geothermal energy – investigating the feasibility of extracting heat directly from magma rather than indirectly from rocks heated by magma. This has the potential to increase the heat energy extractable from a geothermal field by an order of magnitude and efficiency of conversion to electricity by a factor of two or three; and (iv) Technology and Innovation – developing sensor systems and technology that can withstand magmatic environments and temperatures of ~900oC.

Drilling into a magma chamber can be perceived by a lay person as ‘risky business’. Indeed, the image of such an endeavour is something that could easily be the subject of a blockbuster

[3] For more details on the Krafla Magma Testbed see: https://www.kmt.is/ (accessed 04/03/2025)

disaster movie or novel, conjuring images of volcanic eruptions and mass disruption. The risks itself of drilling in this way are largely unknown. Drilling into any volcano will have uncertainty and be subject to the geophysical properties of the volcanic site in question. Understanding how risk is framed is therefore important as we move to a more extreme relationship with the earth. The following section will explore risk framing in more detail before moving into the methodology and empirical findings.

2.2 Risk framing

Risk is multi-faceted and can be framed in a multitude of ways which are explored more in section 2.2. At a simplistic level and for the purposed of this paper, risk could be framed in two ways. Nature derived risks, such as volcanic eruptions, earthquakes, floods, and human derived risks, such as nuclear incidents and chemical spills [19]. However, the type of risk created by the KMT is neither entirely a natural risk nor entirely human induced. There is an interplay between the earth system and our expanding ability to interact with it. The existing literature on risk relating to volcanic hazards mainly relates to hazard management and mitigation. In the absence of conceptual works on risk that relate to this new interplay, the following will explore risk using existing framings of risk related to volcanic landscapes and engineered interventions in the subsurface.

Risk related to active volcanic landscapes and framings of risk and preparedness are a key component of hazard management and mitigation. Different scholars have explored the role of risk perception in particular, in relation to a number of themes such as trust, cultural framings

and connection to place [20, 21]. Volcanic risk traditionally looks at how the potential hazard from a volcanic eruption can be reduced. However, risk to a population is not just determined by a hazard, but by the socio-economic factors and political sphere of that particular, country, region or community. For instance, how populated a volcanic area is (think Naples in Italy) and the reliance on resources associated with the volcano such as geothermal energy. There are situated (place-specific) knowledges and therefore a need to understand how those who live on a volcano perceive the risk through their own lived experiences and tacit knowledge [21]. Social, cultural, economic and environmental factors can all effect how an individual or community perceives risk and often risk perception is based on a combination of all of these [22].

Volcanic risk in Iceland has a particular focus on response to vulnerability and preparedness across different communities and connection to place [20, 22]) and the risk perception of tourists compared to Icelandic nationals [23]. However, these framings of risk have been developed on traditional understandings of risk in relation to volcanic hazards. Iceland now posits a new framing, presented in new ways through technological advancements, a changing earth and in a specific environmental, social and cultural context.

With regards to the latter, Baldwin and Stanley [23] suggest hazard and risk bare an important relationship with the circulation and crises of capital eg. In Iceland the 2009 economic crash instigated a recovery that was partly focus on foreign tourism driven by 'adventure tourism' to see volcanic activity triggered by the Eyjafjallajökull eruptions of 2010 [24] and later, foreign industrial plants such as the aforementioned silicon and aluminium smelters [13]. This would align with the assertion made by Baldwin and Stanley [23] that there is a fusion between

market risk and environmental uncertainty, which suggests how risk shapes the political ecology of the environment. They go on to discuss such risky natures and suggest that this 'opens up questions about risky natures and natures of risk into other aspects of the political' and this might include, amongst others, citizenship, speculation, calculation and concepts linked to the analysis of neoliberalism and the environment [23, p.3].

Volcanic risk and engineered interventions in subsurface systems can occupy an intersection of geophysics, technology, and social meaning. Volcanic risk in Iceland has been explored by Jóhannesdóttir & Gísladóttir [22] who investigated how residents of southern Iceland living under threat from Katla perceive vulnerability, preparedness, and trust in official plans. They found differences between local experience and scientific forecasts, limits in public confidence in evacuation strategies, and the role of cultural narratives in shaping acceptance of risk. When we shift from familiar natural hazards to intentional interactions with a physical system such as deep-drilling, either in this case toward magma bodies, or through enhanced geothermal systems (EGS), then the complexity multiplies. Cousse et al. [25] show that public support for EGS depends strongly on whether people view interventions in the deep underground as "tampering with nature" and how they balance perceived benefits against risks (e.g. uncertainty, leakage, induced seismicity). Spijkerboer et al. [26] further argue that purely technical framings of geothermal innovation miss crucial dimensions including socio-technical imaginaries and local narratives that need to be fully explored if we are to understand contestations and acceptance of subsurface projects. Meanwhile, more recent work on volcanic geoengineering and subsurface interventions by Cassidy et al., [9] suggest that deliberate

interventions in magma systems risk triggering unintended consequences, raise profound governance challenges, and therefore demand greater transparency, consent, and monitoring.

This suggests that volcanic risk in the context of engineered systems is not only a matter of geologic probabilities, it is also a socio-technical gamble. Projects like the Krafla Magma Testbed (KMT) represent a new class of partly anthropogenic and partly natural risk. It poses not only uncertain physical threats (eruption, fracturing, induced seismicity, system failure) but also legitimacy risks, issues of trust and conflicting values. Understanding how different publics including residents and local experts interpret or frame risk in this context is just as important as modelling magma dynamics itself. Only by integrating geoscience, technology, and a range of stakeholder perspectives can we hope to responsibly manage associated risks.

2.3 Risk, the Anthropocene and Geoethics

The Krafla Magma Testbed (KMT) sits squarely at the crossroads of Anthropocene thinking and geoethics as it poses not just questions of what humans can do with geological forces, but what humans *ought* to do. Clark [27] argues that magma is not just raw material or energy resource, but a political and ontological force. Clark [27] suggests that when a magma body was unexpectedly encountered during geothermal drilling at Krafla, it opened up possibilities for in situ study and power generation but also inaugurated a new kind of “geopower,” where human-ambition, capital, and the Earth’s deep materiality are entangled in complex, unpredictable ways. This is framed as part of a ‘political geology’, which demands we see magma as agentic, relational, and a key actor in political ecologies and in the Anthropocene [27].

Geoethics further demands that we consider moral responsibility, governance, and justice in such interventions [10]. The KMT's proposed close manipulation of magma systems raises ethical issues about experimental risk, about consent of affected publics, about potential downstream effects (for example, triggering eruptions or modifying hydrothermal systems), and about attribution of blame should things go wrong. In the Anthropocene, human action has geological consequence and geoethics insists that interventions like KMT be governed by transparent decision-making, participatory governance, rigorous precaution, and acknowledgment of deep temporal and material entanglements. To summarise, Iceland is inherently a volcanically active country, and its people have long lived with the anticipation and reality of eruptions. Over centuries, both residents and visitors have developed a deep familiarity with volcanic risk. Indeed, for some, this very element of danger is part of Iceland's allure [23, 34]. However, the Krafla Magma Testbed (KMT) introduces a fundamentally new kind of volcanic risk, one that is neither wholly natural nor entirely human-made. Advances in deep-drilling technology, motivated by the pursuit of greater geothermal energy and Krafla's unique geological conditions, have created an unprecedented opportunity: to intentionally drill into an active magma chamber. This endeavour carries novel and complex hazards, including the risk of eruption, technological failure, and significant environmental disruption, while also setting a potential precedent for similar experiments elsewhere in the world.

It is therefore important to understand how local stakeholders frame and respond to these risks. The KMT represents a man-made risk that is without precedent in human interaction with volcanic systems, and its success or failure could profoundly shape future approaches to energy, hazard management and fundamental scientific knowledge. The following section

draws on empirical data from interviews with local stakeholders to explore how risk is framed within this particular set of publics. This is not intended as an exhaustive or definitive take on how risk is framed in relation to the KMT, however it is presented as an important contribution in understanding how social and economic perspective might frame risk in this context.

3.0 Methodology and Approach

The empirical data presented in this paper was part of a scoping project that aimed to principally explore the opportunities and challenges that may arise from the proposed deep geothermal drilling at Krafla volcano, in northern Iceland, more recently referred to as the Krafla Magma Testbed (KMT). If the KMT is successful, it has the potential to revolutionize understanding of volcanic hazards and processes, and also provide a significant new source of renewable energy. This involved visiting Krafla and the surrounding area to conduct semi-structured interviews with key stakeholders in the region. Semi-structured interviews were chosen as a method to allow for an open conversational approach and which are commonly used to elicit information in relation to participants knowledge and perspective on pre-determined topic areas (Longhurst, 2016). Ethical approval and risk assessment was approved from the ethics panel of the lead author's institution (Ethics reference: FST17095) and the data collection for the scoping project took place over 1 week in May 2018[4]. Thirteen participants took part in the interviews ranging from regional development workers (3), power plant

[4] At the time of publication the KMT project was still in Phase 0 and drilling had not yet commenced. The main difference since 2018 is that population numbers in the region in which Krafla is located, have increased a small amount due to an increase in tourism to the North of Iceland.

workers (2), energy company consultants (2), geologists (1), local council members (2), local political actors (MP, 1, Mayor, 1), and a member of the local educational centre (1). The energy company consultants (2) and geologists (1) were the only participants with expert knowledge of the KMT ie. Understood the technical details of what the KMT might do and its associated risks from a geophysical perspective, all other participants had heard of the KMT either through their role in the community or through word of mouth. One participant had not heard of the KMT. All participants interviewed lived in the North East[5]region, apart from the energy company consultants who were based in Reykjavík. Participants were recruited via one of the regional development workers in the region and via a contact at Landsvirkjun, the energy company responsible for the Krafla power plant. Given the aims of the scoping project, to understand local stakeholders perspectives on the project, and how they would perceive this project in terms of risk, this study purposefully aimed to interview those who had awareness of the project through their role in the community or as part of the project, although level of awareness varied across participants. The one participant who hadn't heard about the KMT was aware of the drilling that took place in 2009. At the time this research took place, the KMT project had not been formally announced to the wider community due to the immaturity of the project (they were still in the process of trying to co-ordinate funding across international agencies, and at the time of this paper's submission, this was still ongoing). Focusing specifically on stakeholders who have an awareness of the project due to their position (ie. Technical/energy experts, local political actors, regional development workers) provides an

[5] All participants from the NE of Iceland were from communities in and around the Krafla area. These are very small communities and are part of the wider municipality of Þingeyjarsveit which has a population of approximately 900 people and covering an area of 6000 km2 (English | Þingeyjarsveit accessed 04/03/2025)

initial insight into how stakeholders view the concept of the KMT and could potentially be used to develop future place-specific communication strategies. Future work will also focus on wider community views, both locally and nationally.

Interviews were transcribed verbatim and thematically coded using a set of pre-determined themes related to risk, economy, and climate, while also allowing additional themes to be inductively generated from the data. This combined a deductive and inductive analytical approach. [28]. The main additional themes that emerged from the data was 'responsibility' (both locally and globally), discussed further in section 4.0. The two authors independently thematically coded the data, followed by a discussion of common themes and differences to emerge. They use a reflexive approach, acknowledging their own positionality and how this might shape the questions asked, and how the data was subsequently analysed and continually questioned their theoretical approach and assumptions, as suggested by Braun and Clarke [29].

This paper specifically focuses on risk and exploring the overriding theme of responsibility that emerged in relation to the KMT but is also situated within understanding drivers for the local and global economy and the broader global net zero transition. Given the small size of the communities involved it was felt adding participant descriptors to the quotes could make the participants easily identifiable to others in and around the region. In the interest of anonymity, these have been removed however broad descriptors can be found in Table 1.

Sector	Local Industry	Regional development/policy makers	Education
Participant number	Participant 5, Participant 2, Participant 7	Participant 1, Participant 4,	Participant 3

Table 1. Showing participants who are quoted and the broad sectors they come from. Although a small number of participants were from Reykjavík, all participants quoted here are from in and around the Krafla area. Participant 3 had not previously heard of the KMT, all other participants had heard about it in some capacity.

4.0 Results and Discussion

Given the close-knit nature and small population in and around Krafla, all stakeholders interviewed knew of the geothermal drilling event that took place in 2009. Participants were asked about what they understood to have happened during the drilling event and their thoughts on re-drilling into the caldera as part of the KMT.

Section 4.1 looks at how risk was understood at the time of the drilling event in 2009 and how that shapes subsequent framings of risk in relation to the proposed KMT. Section 4.2 looks at global climate politics through carbon targets and the socio-economic context of the region, including the role of local 'responsibility' in terms of living on a volatile and changing earth. In particular, this section highlights how these factors further feed into local stakeholders thoughts on risk in this case.

4.1 Risk in the context of drilling for the KMT.

The risk literature suggests that people's views of risk are dynamic and can flux through states of change. For instance, sometimes this might be about the chance of eruption, other times it could be linked to livelihoods or other issues that may affect the local population [21]. This state of flux could also be related to wider socio-political and socio-economic issues. Such as how and who manages and communicates vulnerability, or the benefits the volcano provides in

terms of economic prospects (eg. Jobs linked to geothermal energy or tourism), or even cultural ties and connection to place [30]. As Beck [19 p. 21] suggests, risk maybe defined as "a systematic way of dealing with hazards and insecurities induced and introduced by modernisation itself" and they are politically reflexive.

In this instance, this state of flux in framings of risk was very apparent with our participants. There was clear concern about the potential risks produced at the time of the accidental drilling in 2009, which are clearly articulated by a number of the participants. This included reflections on the event such as 'completely no control' or, '[guys who worked there] were worried for a while that everything might just blow up' (see Textbox 1).:

The deep drilling project that was here at Krafla and of course, a lot of people [here] were working around it. So just through that I know a little bit about what went on, what happened when they hit the magma...As I understand it, it was mostly confusing to start with because they didn't know what was happening because this was so shallow they didn't expect to hit anything at this depth. So this is second hand so I'm trying to remember what he siad...There was some obstruction or something wasn't going as expected so they just kept drilling to find out if they could get through this, whatever it was...And he described everything was trembling around them and they were afraid that everything was just going to blow out, out of the well and if that would have happened none of them would have survived. But I don't think this is in any of the official documents...But this is what they talked about, the people who were working there.' Participant 1

'So my friends working on the projects, they are not geologists, they are mechanics that work in the power plant and just the drillers. [They] were there for part of the time where this crazy black steam came out of this crazy thirty, forty megawatt borehole, completely no control. Was in 2000 and... [2009]...I don't remember, we drove up there and it was hectic is the word I would use.' Participant 2

Textbox 1: Recounts of the IDDP-1 drilling at Krafla in 2009

These recounts tell of the perceived level of risk encountered during the drilling event and the perceived uncertainly around control and possible eruption. This has similarities with Beck's [19] suggestion that risk is associated with the technical manageability of the hazard. You might expect that given the level of uncertainty and perceived lack of control, that this would have a significant impact on local stakeholders' perception of risk with regards a new attempt to drill into the magma chamber as part of the KMT. However, although there is clear concern about the potential risk that presented itself in 2009, the perception of risk changed after the event.

This change appears to reflect firstly the ability of IDDP- 1 team to 'manage' the crisis, followed by the perceived change in scientific knowledge (of the IDDP-1 team and local drillers) about drilling into the caldera as a consequence of the accidental event. Additionally, change in risk was also influenced by the potential to maximise opportunities that having access to magma in-situ would create for the local community and at a national level. This was linked particularly to the idea of security and learning more about magmatic environments to better predict future eruptions. This is well articulated by Participant 2 and supported by Participant 3, who go on to say (See Textbox 2):

'But they managed it you know and it worked you know. We would never have gotten where we are without taking risks...as long as we don't damage or as long as we don't tap into our volcano enough to change it's behaviour or damage the natural structure of the volcano itself. We are learning and it must be part of the project. I mean our volcano is drilled like a swiss cheese and many of the holes are not even being used.' Participant 2

'No I don't think so [they wouldn't be afraid]...I remember back in '84, '83, '84 when eruptions occured within this area and a lot of people remember that year. A lot fo people living in the Lake Myvatn area remember that and is that something people are afraid of? Of course, I mean it is something really dangerous of course. But still people are, people live there, they want to live there and it's a danger that comes with the territory. But are we willing to learn more about how we can protect ourselves? For sure. And I think poeple would take it that way rather than would produce some kind of histeria in the area.' Participant 3

Textbox 2: On management of risk.

The risk associated with the KMT, therefore appears to be viewed pragmatically. Wachinger et al., [31] suggest that the level of risk perception is linked to trust (or lack of trust) in experts and authorities. Therefore, people may perceive greater risk if their trust in experts is lacking or damaged. However, trust only becomes an issue when an individual is faced with uncertainly around a particular potential hazard event. In this instance, although these stakeholders perceived the 2009 drilling event as risky, they also considered it a learning experience and viewed how the 'failed' event was managed as a positive. This event potentially increased their trust in the experts, as not only did they manage to control the risk of the failed drilling in 2009, but they perceive the KMT group to be also actively making it a new, positive initiative for the community.

Icelanders are well experienced when it comes to volcanic risk and eruptions. Several of the participants commented on this risk as a lived experience: *'we Icelanders, we're used to it [risk of eruption]'* *'most people don't really think about it, the danger [of eruption] because it's*

something they live with'. This supports the literature that suggests direct experiences can also affect an individual's level of risk perception [31]. For instance, someone who has already experienced a volcanic eruption may have a heighted sense of risk, or that the opposite impact can occur. This could be someone who has experienced and survived a hazard event (like an eruption) with little damage, and therefore they develop a reduced sense of risk and believe a future event is less likely to impact them [31].

With the stakeholders we spoke to risk and a sense of security from future eruptions were key concerns. However, this was not in the sense that the risk of re-drilling into the caldera would be too great, more so that the KMT would reduce risk from future eruptions. This was believed to be through the benefits of the scientific knowledge gained through the experiment, adding greater future security. This was not only for themselves in Iceland, but also in other volcanic regions across the globe (see Textbox 3).

'I think people will be generally positive...especially if it's introduced in terms of security...I think most people don't really think about it, the danger [of eruption] because it's something they live with. But they want to be informed, that's really important, that they feel like they are part of the decision making and that they know what's going on.' Participant 4

'It's a little bit of a matter also of security because in Iceland eruption occurs so often that it's important to have as much information as we can in order to predict eruptions.' Participant 5

'Another aspect of the KMT project is that security you know, with volcanic eruptions, being able to hopefully support research that are able to foresee volcanic eruptions and stuff like that, which is very important for the people of Katla...and of course Katla was[n't] the only one that erupted last year...That's definitly one of the most exciting parts of the project...That's why the Italians especially who are very excited...for them it's really because they built their cities on top of volanoes basically...it's really important for them to be able to predict with more security if a volcano was going to erupt, so maybe this is the perfect location to try out becasue we know exactly where lava is, what do you call it when it's underground? [Magma].' Participant 1

Textbox 3: Perceptions of security.

Krafla is Iceland's longest running geothermal power plant and a significant employer in the area. Most people we spoke to knew someone who worked at the powerplant or had a connection to it in some way. It has also become a key tourist site, drawing in tourists that have travelled to the NE of Iceland as a key destination to pass through. This is coupled with tourist activities such as a visitor centre, volcanic tours, and whale watching opportunities at the nearby town of Húsavík. Krafla and its volcanic landscape consequently provide significant economic potential in the area. The KMT isn't seen as a threat to this, rather as a chance to enhance this potential and put Krafla on the world map (as discussed in section 4.2).

Until recent decades, these communities have seen a population decline with many leaving to seek out employment and further opportunities. The rise of the tourist industry and industrial plants (discussed more in the section below) have had a significant impact on raising the population in the region. This is viewed very positively for those who live there but there are still conflicts over preserving the landscape and further development. This all fits with the existing narrative around sustainable livelihoods including maximizing the benefits of the volcanic environment, understanding and managing vulnerability and risk, and managing crisis [32]. The difference being that the sustainable livelihoods approach has been developed for natural eruptions, rather than the man-made risk presented here. What the livelihoods approach does emphasise is the need to understand the local cultural and economic setting. This will be discussed in more detail in the section below.

In summary, the risk at the time of the drilling was perceived as high, however the manageability of the event has increased trust in key stakeholders. This includes the tacit knowledge of the community and the drilling team and how this may feed into how they drill in

the future. Although there is some risk perceived with the KMT, the idea that the risk was ‘worth it’ as the scientific learning from the KMT might lead to greater security across Iceland in the future.

4.2 Global climate politics and a changing planet

The Iceland economy has previously been embedded in local resource industries such as fishing. It has since diversified to include tourism and foreign owned industrial plants such as aluminium and silicon smelters [13]. Iceland has become very appealing to such energy intensive industries as it not only provides them with competitively priced energy in terms of geothermal power, it also helps plants that are thought of as heavily carbon emitting to green their image, through the use of renewable (geothermal) energy. Through this process they are also ‘off-shoring' their carbon emissions, essentially moving their carbon emissions to another country’s budget. This has meant that countries with high carbon emissions such as the USA and parts of Europe, who are the owners of some of the industrial plants in Iceland, get to shift these industrial emissions to Iceland’s carbon budget. This has been seen as having mutual benefit, as it also provides Iceland with new jobs and infrastructure (see Textbox 4).

'Of course you have individuals in the area who are opposed to large projects. They want to keep things the way that they are and they see any kind of construction, any kind of change as a bad thing, some people just want to keep the appearance as they are, so that's something that needs looking into to…especially because they don't want geothermal areas changed or damaged and that's something nobody wants. But at the same time this is mostly a renewable source and that's very valuable, especially in a global perspective.' Participant 1

'If we calculate these examples all the way through [the Aluminum smelters] and if we want to pay our dues to the global community its really easy to make the case that we, yes, despite the fact that you don't want necessarily the Aluminum factory in your backyard, it globally makes incredibly much more sense to have it, may be ten times less CO2 than you have already being emitted in China and elsewhere in the world where you are using coals to keep things running.' Participant 3

Textbox 4. on Global connections

Iceland's geothermal resources therefore play a key role in part of the Global North's climate mitigation strategy through the ability to off-shore and 'green' certain industries. These industries are also producing materials that are needed for a net zero transition. For instance, aluminium is commonly used in wind turbines and solar photovoltaics and silicon for solar panels, energy storage and EV batteries [33]. Iceland's geothermal resources are consequently bound in climate geo-politics and a key tool in Iceland's growing position in the global economy.

Iceland's vast geothermal opportunities have led the country to diversify their economic portfolio even further. Iceland is one of the first countries to gain expertise in deep geothermal drilling, having launched the Icelandic Deep Drilling Project (IDDP) in 2009. Indeed Krafla was its first deep drilling site, known then as IDDP-1. Iceland's aim is to become world leaders in deep geothermal drilling and become a hub for scientific expertise in deep drilling (IDDP, 2022).

Geothermal energy in Iceland is not without its controversies in terms of local and national acceptance [16, 34]. This seems particularly due to many geothermal power plants being an energy source for *foreign* industrial plants such as aluminium and silicon smelters, rather than Iceland using the energy to make their own products of materials to sell on the global market. Notwithstanding these objections, in the rural north where infrastructure is less developed and economic opportunities are fewer, there appears to be some level of acceptance towards such industries.

[the geothermal energy industry] might give some opportunities for entrepreneurship and it will of course, it might affect job opportunities and it might affect, for example, what's it called, the level of education in the area. Participant 1

Nearly all of the participants in this study emphasised the importance of promoting the region for both tourism and for families to settle, acknowledging the population decline of previous decades. Recent tourism has helped provide economic opportunities and, although small, there has been growth in the local population – one participant even commented that now the local school had enough students for a football team! As such the community was looking for further opportunities that might ensure the survival of the local area. This wasn't just thorough tourism and at the time of our interviews in 2018, a new silicon smelting plant had opened in the nearby area of Bakki[6]. Although there did appear to be some reservations from local people with regards the plant, there was also the acknowledgement of the opportunities this presented for the community.

[6] PCC BakkiSilicon near Husvik https://www.pcc.is/ accessed 25/07/2024

I think I can say, at least for me [more industry], this wasn't something that I had wished for the community but we have been trying a lot of things before and something had to be done because the population was decreasing dramatically. So if it wasn't going to be just an extinct area we had to get something and it has really changed. The population is increasing again, houses are selling on higher prices and there are more job opportunities and they are more diverse. So a lot of good things have come out of it, even though it wouldn't have been our first choice. Participant 3

In addition to the advantages for the region, global opportunities and a sense of global responsibility was also discussed. This was in terms of 'off-shoring' carbon emissions to Iceland and the positive benefits of doing so not just locally but also globally. In addition to foreign industry building factories in Iceland, some participants also spoke about the possibility of large-scale data centres being located in the country if interconnectors were put in place to mainland America and Europe (See Textbox 5). These different industries and the possibility of the KMT are hoped to also strengthen the knowledge economy in the North of Iceland.

'Iceland has many kinds of positive things for it, cheap energy, green energy, renewable energy…cold climate, yes, chilly…and that actually saves much more energy because in warmer countries they actually use more energy for cooling than running their computers. So these are all positive things. But actually that has been looked very thoroughly into and our weak part in Iceland for having data centres that is part of it, why these bigger companies have not had more data connection from Iceland to the mainland America and Europe. We need two cables in both directions to be in kind of safe enough for it.' Participant 5

'[In Iceland] we have all of these, shall we say, primary industries, this industry [smelting check], agriculture and the primary energy you know, from energy production. But we sometimes need, shall we say, the next level, the knowledge industry connected to it that has always been evolving in the fisheries and somewhat in the energy sector. But this has mostly been growing around Reykjavik, so we want to add this level to this area…we have an indicator of a scientific community but it needs more…and just this general development of projects that can connect to it. You need people who can plan, you need people that can work on the financial aspect, on the social aspect, this all connects and is, shall we say, has the potential to create a more robust scientific community in north east Iceland.' Participant 1

Textbox 5. Iceland economy, making use of resources, building a knowledge economy.

The sense of global responsibility continued with regards Krafla and the KMT In other words, the potential benefits of the KMT in terms of knowledge production that would help provide future 'security' from eruptions, outweighed the risks associated with drilling back into the magma chamber. This was framed not only as a big opportunity for Iceland in terms of future hazard management, but they also felt responsibility to help those in other volcanically active countries around the globe.

The idea that the KMT could build a new knowledge economy around Krafla was something that was spoken about very favourably. This was in terms of the increased level of tourism to the region through the building of a visitor centre (something the scientist behind the KMT have suggested) but also a deep sense of pride in being world-leading in something that is seen as so beneficial to the global community and having 'their volcano' at the centre of a world leading scientific endeavour.

...it's like going to the moon, it's a huge thing. So I can't wait. And to be the community, in the big picture obviously, the data collection, it will be incredible if we can do it. And this is something that we need to play on. If in future we will be able to predict a volcanic eruption with better accuracy that's thanks to our research. If we, as the community who volunteer our volcano to do this, it will make us make very proud of the Project. Participant 2

The knowledge economy also related to the potential energy benefits the KMT might bring in terms of utilising magmatic heat, one of the proposed 'pillars' of the KMT. It is proposed that the borehole could produce more than 10 times that of a conventional borehole, with borehole lifespan potentially indefinite, therefore significantly boosting Iceland's geothermal energy production. Given Iceland already meets its domestic energy needs, there was much discussion on the export potential of the energy produced, including a proposed undersea cable to places such as the UK. Indeed, when the idea of producing energy from magmatic temperatures was first discussed in the public domain, the then Prime Minister of the UK, David Cameron, commented on the opportunity for an interconnector leading to speculation in the UK national newspapers.

"It's not impossible to imagine that Iceland could send 2GW of energy at a time to the UK, Holland or Denmark via underwater cables – enough to power around 1.5m homes. Perhaps that could happen in the next two decades." Quote taken from the article: *Could British Homes be powered by Icelandic volcano?* The Guardian, 2017.

However, giving away 'raw energy' was not something that was seen as favourable to our participants. On the contrary, embedding the energy in products they felt had the economic

advantage would lend itself more to Icelandic strengths as the following participant on Iceland's history of exporting goods, demonstrates.

It is only like thirty years since we were totally you know, fish was the only thing we were exporting but now of course Aluminium came in and with the IT industry and then the tourism it was like vroom. I mean it's less than a hundred years since Iceland was just a very poor country, very primitive. Participant 7

The implication in the above is that whatever happens to the raw energy will have implications for both the local and national economy, and they draw parallels with the fishing industry that the country was previously so reliant on.

In summary, the actions that led to drilling into the magma chamber at Krafla and the subsequently proposed KMT project are not a symptom of just a regional or national strategy, they are tied up in wider global climate politics and the global economy. The need to shift carbon emissions globally (through off-shoring) has led to foreign industrial developments, which has led to more geothermal energy that drove the IDDP-1 and subsequently the accidental drilling into magma. This in turn has led to the concept of the KMT. This has potential global implications for both low carbon energy production at scale and significantly advancing planetary science.

The implications of these global aspects are framed within the boundaries of a changing planet. Driven in part by the pressing need for carbon reduction and through inhabiting a volatile earth. 'Solutions' to these challenges are complex and bound up in concepts of risk and local and global drivers, as we inhabit the earth in new ways. Our participants felt there was a global

responsibility to use 'their' volcano for the purposes of the KMT. This was linked to the scientific knowledge that would be produced to better understand volcanic hazards in the future. This was discussed in terms of security and appeared to out weigh the risks of re-drilling back into the magma chamber. The benefits to the local economy through the proposed visitors centre, increased tourism and being a 'scientific hub' were favourable. There also appeared to be a sense of pride in this, that it would be their volcano that would be responsible for such a scientific break through. This 'sense of security' and sense of global responsibility are interesting threads to emerge from the data and are themes that should be further researched with wider community members both locally and nationally.

5.0 Broader implications

Local stakeholders framing of risk in relation to Krafla and the KMT are important to understand. This is because risk in this sense isn't linked only to the volcanic hazard itself but to the purposeful interaction between humans and magmatic environments. The mere fact that the KMT is born out of an accident, that by local accounts caused significant misgivings at the time, is testament to the way risk can be shaped in relation to the context of place and past experience.

Rather than being deterred by the drilling accident in 2009, our participants felt lessons could be learned from the experience and this chimed readily with the Icelandic outlook on life (being adaptable and pragmatic). The potential significance of the KMT in terms of its scientific

ambitions was also a key motivator in reducing risk perception and a sense of global responsibility emerged.

The people that live in and around Krafla are not dissimilar to other global volcanic communities, in that they rely on the volcano for local livelihoods. This is predominantly through tourism and geothermal energy (and by extension, industrial power plants such as the aluminium or silicon smelters). However, one might ask the question that if this drilling and testbed were to take place in another country, would local stakeholders still perceive risk in the same way. There are a range of factors that shape understanding of risk in this instance. The country's connection to its volcanic landscape, the socio-economic climate of the country and the region – particularly in terms of regional development, the country's geopolitical connections in terms of carbon off-shoring through foreign industries and importantly, a pragmatic and inquisitive community. Had this happened in a different place, or at a different time, or had the implications of the accidental drilling in 2009 been more significant, local acceptance or risk perceptions might be shaped very differently (see Somma et al. [35] for a comparison of three geographically different deep drilling sites). Although most of the local stakeholders that took part in this study had heard about the KMT, very few of them had any technical knowledge of the project or expertise in volcanic risk, other than their lived experience as being part of a volcanic community. That being said, this scoping study is limited by its pool of participants and to explore risk and risk perceptions more fully, a larger pool of participants in the Krafla region and more widely in Iceland should be explored.

Understanding the vagaries of risk in this context and how this might change in relation to place is important and holds global implications. This is because the KMT in some, or all its parts,

could be replicated at other suitable volcanic sites across the globe. The KMT has received significant global attention with countries such as New Zealand hoping to benefit from and replicate efforts from the KMT, and a number of other countries holding an interest in its progression [17]. If the KMT is successful in its goals to re-drill into the magma chamber and monitor magma in-situ, it has been suggested there maybe a number of other potential sites for magmatic drilling across the globe including Russia, Kenya, Japan, Mexico and the US [17, 36] . Even if the scientific goals are not replicated, the fact that magmatic heat could produce energy at significant yield and with much longer borehole longevity than the conventional, makes drilling into a caldera a potentially appealing option [17, 18].

Local perception and acceptance may well be viewed differently depending on the history of the place, the trust relationship the local community has with risk management stakeholders, their embodied relationship with the landscape (for example, indigenous connections to the earth) and broader socio-economic and political factors. For instance, since the interviews took place for this research another significant global development has taken place. Where once Iceland was able to increase its carbon budget through the Kyoto agreement and benefit economically through industrial off-shoring, there are now calls for Iceland to reduce its carbon emissions since its increase in the last reporting period [37, 38].

At a deeper level, the KMT can be understood through the conceptual lenses of the Anthropocene and geoethics. In this geological epoch, defined by human activity becoming a planetary force, the KMT represents a significant reconfiguration of how society engages with Earth's deep processes. As Zalasiewicz et al. [39] argue, the Anthropocene collapses the boundaries between culture and nature, rendering human and geological systems co-

evolutionary. Furthermore, Clark [27] situates magma as an agentic participant in human history. The decision to intentionally interact with magma, rather than merely observe it, transforms humans into active geological agents. Geoethical perspectives reinforce that new endeavours such as this carry moral weight and lead to complex questions of responsibility, justice, and governance [40, 41]. In this light, the KMT is not only a new 'scientific frontier' but also an ethical frontier, questioning the limits of acceptable intervention in the Earth system.

Recent scholarship in political geology suggests projects like the KMT expose the entanglement of knowledge, power, and matter [42]. The experiment's legitimacy depends not only on its technical safety but also on the fairness of its governance, the transparency of its decision-making, and the inclusivity of its stakeholder engagement. The KMT could therefore exemplify what we might called "geoethical practice in the Anthropocene", creating a balancing act between curiosity and caution, ambition and accountability. In this sense, the volcanic landscape of Krafla becomes a site on which the ethics and politics of a the planetary are performed, and where we learn what it means to live and act as a geological force.

6.0 Conclusion

In conclusion, the global significance of the Krafla Magma Testbed (KMT) appears to have shaped how stakeholders perceive and frame risk, including a willingness to learn from the 2009 accidental drilling event with a sense of pride in the project's potential scientific and societal contributions. While our participants expressed enthusiasm for the opportunities the KMT could bring, ranging from local economic benefits and increased tourism to global advances in volcanic hazard mitigation, fundamental science and energy innovation, it's

important to recognise that their views represent only a small proportion of the wider community and a particular set of 'publics' through their positions within the community. For the KMT to progress responsibly, more research needs to be done on understanding risk and risk perceptions more in both the Krafla region and Iceland more broadly.

The KMT is also the result of an intersection of local and global drivers. The KMT is tentatively linked with global climate politics and the economic incentives of decarbonisation, which have encouraged the expansion of geothermal energy in Iceland and inadvertently led to the initial encounter with magma. This connection situates the KMT not only as a national endeavour but as part of a planetary effort to navigate the challenges of living sustainably on a volatile Earth.

Viewed through the conceptual lenses of the Anthropocene and geoethics, the KMT also marks a profound shift in how humanity engages with the planet's deep processes. In deliberately interacting with magma, humans become active geological agents by being participants in, rather than observers of, Earth's processes. Such engagement carries scientific promise but also raising complex questions about responsibility, justice, and governance. The KMT therefore represents not only a scientific frontier but also an ethical one, requiring a balance between curiosity and caution, ambition and accountability.

Ultimately, perceptions of risk and their associated ethical and political dimensions, are context specific and continually evolving. Projects like the KMT highlight the need for careful reflection on how local communities and global initiatives intersect in shaping our collective relationship with the Earth.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT in order to check the grammar of a small number of paragraphs and to organise referencing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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