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Key Points:

- Economic, political, and environmental pressures may make volcano geoengineering more common in the future
- Safety and ethical concerns include uncertainty, philosophical approaches, justice and inequality, military uses, and cultural values
- Effective governance protocols will be crucial for ensuring the safe and ethical use of volcano geoengineering in the future

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The Ethics of Volcano Geoengineering

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

Plain Language Summary This paper explores the possibility of volcano geoengineering, which involves altering volcanic systems or their eruptions to exploit them or minimize their large potential risk to human society. Volcano geoengineering is a complex issue with many potential safety and ethical concerns which are discussed. There have been past examples of volcano geoengineering, some purposeful and some accidental, and we suggest that economical, political, and environmental pressures may make volcano geoengineering more common in the future. While there may be technical feasibility for reaching volcano plumbing systems or altering atmospheric processes following eruptions, there are many safety and ethical concerns that must be addressed before any large-scale interventions can be considered. A clear ethical distinction should be made between conducting geoengineering and researching its efficacy and safety. While we do not advocate for conducting volcano geoengineering in the short term, we do layout a moral case for research in this field to investigate whether it could ever be safe and effective. Clear governance protocols are mapped out in this study and will be crucial for ensuring the safe and ethical use of volcano geoengineering in the future.

1. Introduction

The term "geoengineering" is commonly associated with climate change mitigation as "the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change" (Shepherd et al., 2009). This broad term has previously included proposals around carbon removal to solar radiation management. Here, we introduce the less developed concept of volcano geoengineering, which conjures up feelings of unease among scientists and the public alike; however, there have been numerous such interventions in recent history. These have ranged from drilling crater walls to drain volcanic crater lakes, channeling and bombing lava flows, siphoning off carbon dioxide and methane-rich volcanic lakes, and cooling lava flow fronts with seawater with mixed success (Figure 1). In addition, due to the persistent threat from potentially catastrophic impacts to society, that include large potential losses of life and damage to critical infrastructure, there have been a small number of proposals put forward for potential volcano geoengineering projects in the future (Arciuolo & Faezipour, 2022; Denkenberger & Blair, 2018; Fuglestvedt et al., 2014; Fujii et al., 2017, 2018; Schuiling, 2008; Wilcox et al., 2017). In the

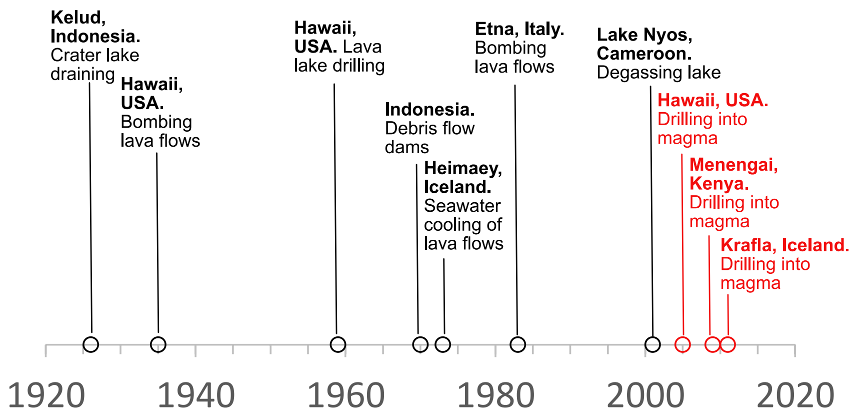

Figure 1. A timeline of some notable instances of volcano geoengineering. Black circles indicate purposeful interventions, whereas the red circles indicate inadvertent volcano intervention.

coming century, geopolitical, economical, and environmental pressures in the pursuit of geothermal energy, mineral resources, carbon sequestration, and climate change mitigation, mean that inadvertent volcano intervention may be an inevitable consequence. This has been evidenced in the last two decades, where geothermal exploration of high-temperature wells has inadvertently pierced magma chambers multiple times in Puna in Hawaii, Krafla in Iceland, and Menengai in Kenya (Eichelberger, 2019). While not causing anything more damaging than loss of drill bits or forcing use of alternative holes, this demonstrates that humans are increasingly able to reach the intimate parts of volcanic systems. Because humanity possesses some of technological and engineering potential to perturb volcanic systems, we reflect that the social, ethical, legal, and political difficulties may be the biggest obstacle to the successful use of volcano geoengineering in the future. Indeed, ethical issues frequently arise in response to other geological activities, such as mining and exploration drilling, where the morality of damaging the environment is in conflict often with the social and economic needs of local human populations and financial growth of nations (Peppoloni & Di Capua, 2022), and the thorny issues of attribution of blame when damaging incidents occur and the causes and responsibilities of such are ambiguous for example, Lusi mud volcano, L'qualia earthquake (Abbott & Nosengo, 2014; Davies & Manga, 2017).

More broadly, direct manipulation of environmental hazards to mitigate their risk is commonplace. Avalanches, forest fires, floods, and landslides are managed and/or altered to mitigate their larger potential risk. At an even larger scale, a recent space mission from NASA (DART) has successfully tested technologies to shift the trajectory of an asteroid in order to test our defences against potentially catastrophic asteroid impacts (Li et al., 2023). Further examples perturbing the natural system include cloud seeding to alter rainfall patterns, and damming of water ways for irrigation, hydroelectricity, and industrial applications. Many of these occur despite the large risks, for instance, the subsidence of the Mekong delta (SE Asia) (home to 17 million people) from groundwater extraction and damming sediment upstream, could mean 40% of its land could be covered by the South China Sea in the coming decades (e.g., Dunn & Minderhoud, 2022). Anthropogenic climate change (an inadvertent human perturbation to the environment), is fueling plans for increased environmental intervention to mitigate the global warming impacts. Some of these projects are already occurring, for example, carbon capture and sequestration, with more ambitious plans such as solar radiation management, ocean fertilization, reforestation, and enhanced weathering, which come with considerable risks (e.g., Haywood et al., 2013; Henderson et al., 2018; Tang & Kemp, 2021). All of the environmental perturbations explored above have large potential benefits, yet also may pose significant risk if not understood or managed properly. Despite this, many of these schemes take place without wider conversations about their potential safety and ethics; this contribution aims to start to address these issues for volcano geoengineering.

Volcanology is a smaller, more nascent field compared with meteorology, biology, or climate research, and as such has not yet given much attention to how humans may potentially perturb volcanic systems. However, given the potentially long-term future of humanity, and the persistent threat from volcanic eruptions and near-term exploitation, it seems inevitable that the question of volcano geoengineering will keep arising. Here, we support a proactive approach to discussions on volcano geoengineering with research and informed debate. The alternative is a reactive response, such as in the lead up to, or during a large magnitude eruption, where humanity may rush to try to directly influence the volcanic system, with little diligence, research, and governance protocols.

In this paper, we introduce the concept of volcano geoengineering and how it has been used previously. We highlight the safety and ethical considerations involved with geoengineering and research of such practices. If humanity decides to go down the route of purposefully intervening with volcanic systems, we propose some ways to ensure this is done safely and ethically in the future.

2. The Successes and Failures of Previous Volcano Geoengineering Interventions

The first significant and recorded perturbation of volcanoes by humans occurred in Indonesia 100 years ago, following the deadly eruption of Mt Kelud in 1919. The volcano erupted through a voluminous crater lake, sending devastating lahars (volcanic mudflows) downslope and killing over 5,000 people. To minimize this future hazard, the volume of the water in the crater lake was reduced by drilling tunnels through the crater to drain the lake, which was completed in 1926 (Suryo & Clarke, 1985). By the next eruption in 1951, the lake volume was 90% less, and the lahars as a consequence were less voluminous and did not travel as far, likely preventing significant loss of life. However, during the eruption, the drainage tunnels became blocked and the eruption excavated the bottom of the crater, allowing a sizable lake to accumulate again. By the time the next eruption occurred in 1966, the lahars caused severe damage and killed 300 people. Despite the initial geoengineering success, it highlights the issues around the need to sustain intervention practices over long periods of time.

Lava flow deflection attempts either by channeling (e.g., Etna, Italy), bombing (Hawaii, USA), or seawater cooling (Heimaey, Iceland) (Figures 1 and 2) had mixed success. In some instances, such as in Etna and Heimaey, this prevented damage to buildings, ports, and bought time for evacuations (Carpenter, 2007; Williams, 1997). However, cooling parts of a lava flow front can lead to pressure build up, this inadvertently led to lava breakouts from other parts of the flow, as in Heimaey, Iceland in 1973. Other downsides include legal ramifications too, actions to divert lava from an industrial site, might instead lead to lava flow inundation into housing or agricultural land. There is limited evidence of the merits of bombing lava flows, yet there are clear risks such as in Hawaii where bombing almost endangered water reserves in Hilo. Some contend that modern bombing methods to manage lava flow hazards might be effective to protect large populations on Hawaii (Lockwood & Torgerson, 1980).

Construction of debris flow dams (e.g., Sabo dams) within valleys around volcanic edifices has arguably been the most effective in mitigating the risks from volcanic hazards such as lahars, pyroclastic flows, and landslides. Whilst not stopping the flows entirely, they break the energy of such flows by capturing some of the denser, basal portions of the flow (Lube et al., 2011). Early dams are recorded in Indonesia in the 1970s, but it is possible earlier dams were constructed particularly in volcano-dense and economically developed countries such as Japan, where they are now commonplace.

Accidental volcano intervention, such as drilling into magma reservoirs has increased in recent years (Figure 1), as geothermal energy exploration has expanded. This has included multiple sites where drilling has intersected magma in Iceland, Hawaii, and Kenya (Eichelberger, 2019). In these incidents, damage to borehole and drilling equipment was recorded (see Figure 2), but they did not trigger volcanic eruptions. We can take away several points from these, that it may be very difficult to detect small magmatic bodies with current geophysical methods, and that in five incidences volcanic eruptions were not triggered by direct interaction with magma, though these are likely far from representative of magmatic systems in general. The incidental drilling has been capitalized by scientists, who now plan to use the opportunity to explore magma in-situ within the crust. The project known as the Krafla Magma Testbed (KMT)—a borehole observatory may help to advance volcanology research. The research was also the motivation of Hawaii scientists to drill into freshly erupted lava accumulations in Hawaii first in the 1950s (Helz, 1993). Molten core was recovered from drilling of several historic lava lakes (1959 Kīlauea Iki, 1963 Alae, and 1965 Makaopuhi), and provided key advances to the field (Hardee, 1980; Helz & Thornber, 1987).

Many of the incidences of intended volcano geoengineering have focussed on mitigating or minimizing volcanic hazards; however, there are also examples where efforts have focussed on prevention of the hazard (limnic eruptions) in the first place, this is introduced below.

3. Prevention of Limnic Eruptions—A Volcano Geoengineering Success Story

Regarding the possibility of volcano geoengineering, the volcanology community seems to adopt a precautionary approach, where deontological constraints to do no harm are weighed more heavily over any potential benefits.

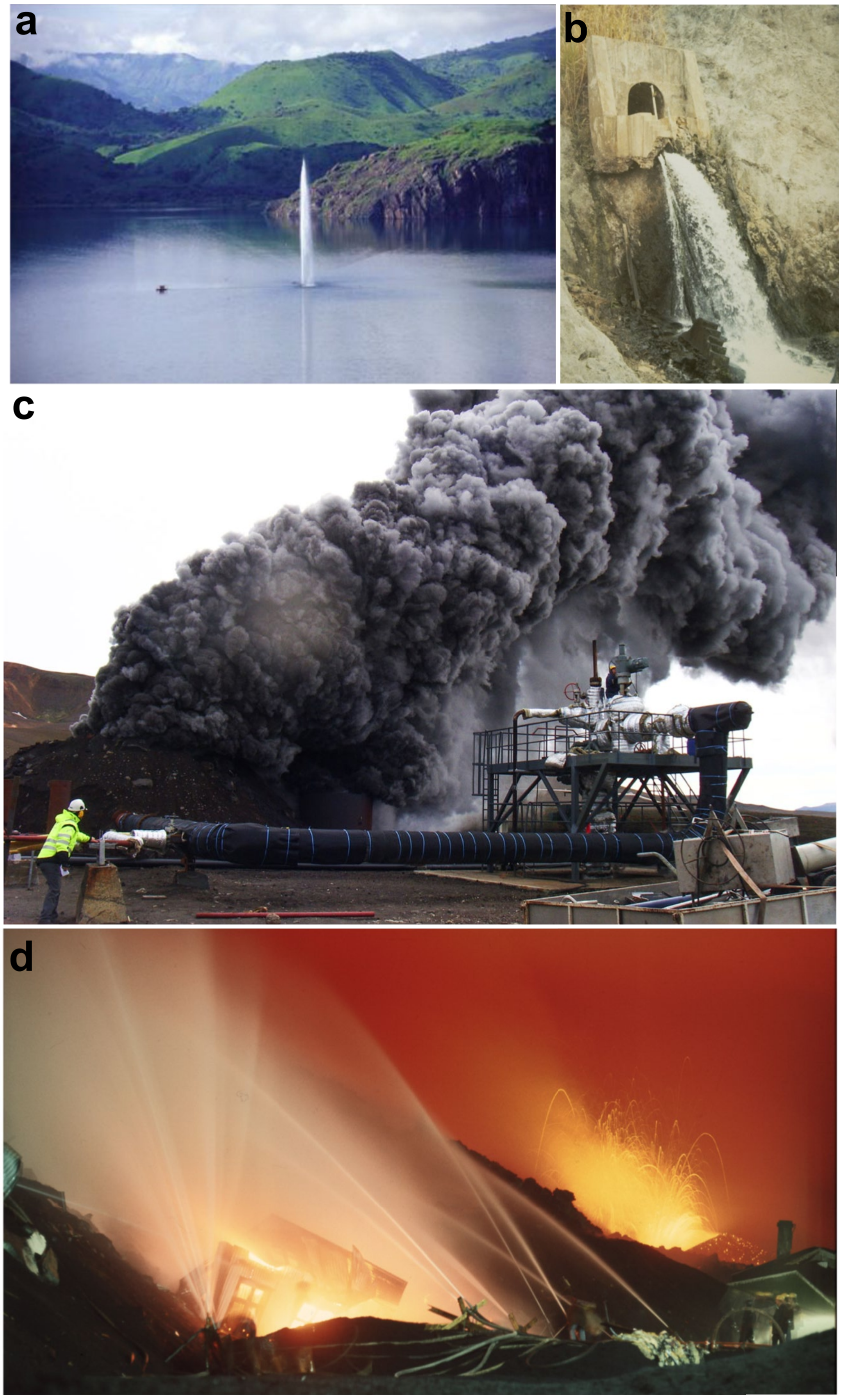

Figure 2. (a) Degassing of carbon dioxide from Lake Nyos, Cameroon from Halbwachs et al. (2020). (b) Drainage tunnel in the crater wall of Kelud Volcano, Indonesia (Global Volcanism Program, Image GVP-01120). (c) Incidental drilling of a magma pocket at Krafla, Iceland in 2009 (image from G.O. Friðleifsson/IDDP). (d) Cooling of lava flows by pumped seawater at Heimaey in Iceland in 1973 by Tristinn H. Benediktsson.

However, there is precedent for a more consequentialist approach to volcano geoengineering, one that weighs potential positive and negative consequences equally (i.e., cost-benefit). Adoption of the latter philosophy led to the successful prevention of hazardous "limnic" eruptions from gas-rich volcanic lakes. Limnic eruptions occur when volcanic gases (e.g., methane, carbon dioxide) stored in the bottom volcanic lakes in concentrated layers, become disturbed. Lake overturning can bring these dense gases to the surface, where they exsolve and move downslope under gravity causing asphyxiation to those who encounter them. We first learned of this phenomena in 1986 after the disaster of Lake Nyos, Cameroon in 1986, which killed 1,700 people and 3,000 livestock by CO_2 suffocation (Baxter et al., 1989). Struck by the scale of the disaster, scientists began to look for methods to mitigate or even prevent these eruptions. The following year Sabroux et al. (1987), presented an idea to degas the bottom of the lake using pipes at a UNESCO meeting in Cameroon (Sigvaldason, 1989). Following this, the plan was presented to physicist and engineer Halbwach. Three years later, Halbwach and colleagues first demonstrated the self-siphon process at Lakes Nyos and Monoun (Cameroon), using a garden hose (Halbwachs et al., 2020). This was scaled up slowly in the following years with more pipes and with wider diameters funded by the United Nations Development Program, until in 2018 when both volcanic lakes were fully degassed (Halbwachs et al., 2020; Jones, 2010). Despite the huge success of this endeavor, there were also significant risks about how safe or feasible this operation could be (Anazawa et al., 2019). For instance, the siphoning-off of gas in an uncontrolled manner, could have potentially triggered whole-scale convection of the lake and lead to a limnic eruption itself. This risk was considered low since attempts to extract methane from Lake Kivu (Rwanda) in the 1960's demonstrated the self-degassing principle without leading to limnic eruption. This situation has parallels with the incidental magma drilling that has already occurred, which did not trigger magmatic eruptions.

Current geoengineering projects at Lake Kivu (which lies at the border between Democratic Republic of the Congo and Rwanda) continue to tap methane from the bottom of the lake, but the motivation is not solely risk reduction; harvesting of the natural gas resources could be worth US$42 billion over 50 years (Jones, 2021). There are worries however with the way deeper water is reinjected back into the lake, which may add toxins to the shallow waters killing ecosystems, and even cause disturbance of the layers and triggering mass gas release (Jones, 2021). Despite some degree of debate and uncertainty, these concerns are being monitored frequently and the operations continue successfully.

For the moment, limnic eruption prevention has been a great success in hindsight, but much like future volcano geoengineering there was some degree of uncertainty about the potential for disastrous consequences. This risk was only allayed by the fact it had been done before with minimal consequences, much like incidental magma drilling. Despite the potential risks, these were weighed up against the larger benefits discussed formally by various experts in the community. Decision making was conducted under the governance of an international body (UNESCO), and a private company was commissioned to gradually scale up operations in a safe and monitored way over the course of three decades. If humanity does decide to conduct further volcano geoengineering, the prevention of limnic eruptions has proven to be a successful model.

4. State of Play Today

Purposeful volcano geoengineering attempts seem to have become more risk-averse over time, for instance projects considered in 1920s, such as drilling into walls of crater, bombing lava flows would be unlikely to happen today. This is probably due to increased chance of litigation, greater awareness of cultural importance, greater knowledge and accountability of potential risks to general public (global communications), and perhaps greater regional exposure to potential hazards due to population growth. The typical public response from geology professionals about volcano geoengineering today is dismissal and reassurances that drilling will not cause any eruption (USGS, 2023), for example:

> "Can we drill into Yellowstone to stop it from erupting?
> In some cases, limited scientific drilling for research can help us understand magmatic and hydrothermal (hot water) systems; however, drilling to mitigate a volcanic threat is a much different subject with unknown consequences, high costs, and severe environmental impacts. In addition to the enormous expense and technological difficulties in drilling through hot, mushy rock, drilling is unlikely to have much effect on whatever magma is stored beneath Yellowstone. At near-magmatic temperatures and pressures, any hole would rapidly become sealed by minerals crystallizing from the natural fluids that are present at those depths."

At the same time, the dismissal of the possibility is often combined with less reassuring arguments based on risk:

> "Even if there were significant "eruptable" [SIC] magma beneath Yellowstone, drilling into it in an attempt to release pressure would have a devastating effect. Scientific research has proven again and again that depressurization is one of the factors that drives magma toward the surface to erupt. So attempts at cooling

and depressurizing magma systems would have many unintended, negative consequences, including making an eruption more likely.
A program of large-scale magma quenching will not be undertaken at Yellowstone or elsewhere in the foreseeable future."

Despite these public messages, this has not dissuaded enthusiasts, engineers, and curious people from considering the possibility (e.g., Denkenberger & Blair, 2018; Fuglestvedt et al., 2014; Fujii et al., 2017; Wilcox et al., 2017). This paper does not plan to review all the different types of volcano geoengineering projects proposed, but we will introduce two potential concepts to illustrate what volcano geoengineering could realistically look like for the sake of later ethical discussions.

1. Preventative geoengineering: whereby drilling, rock fracturing and/or water cooling of the magma or rock around the magma reservoir would aim to promote outgassing and thus diminish the explosivity before an eruption or prevent it entirely (KMT Krafla-MODERATE ERC project; Wilcox et al., 2017).
2. Post-eruption mitigation geoengineering: This would take place after or during a large explosive eruption and could include, for example, a high-altitude aircraft adding non-toxic substances that bind with sulfate aerosols to accelerate the coalescence or coagulation enhancing their removal from the atmosphere (Cassidy & Mani, 2022; Fuglestvedt et al., 2014; Muri et al., 2014; Parker et al., 2018).

5. What Could the Future Hold?

As the world attempts to adopt zero carbon emission goals this century, there is an increasing demand for more renewable energy sources, which can provide baseload (continuous) energy supply to smooth diurnal and seasonal fluctuations that come with other renewables such as solar and wind. Geothermal energy already undertaken in volcanic regions around the world, generates baseload heating and electricity, and compared to solar or wind it requires less areal space, without the need for mass energy storage (e.g., Li-ion batteries). Electricity generation from geothermal sources is increasing 2% each year, with much of the recent growth driven by Turkey, Indonesia, and Kenya (IEA, 2021) but its global energy production will need to increase at a faster rate to meet climate goals.

Currently, conventional geothermal energy is not as cost-competitive per Watt of electricity as other renewables, but recently scientists have started exploring the concept of high enthalpy or "supercritical" geothermal energy. This provides an order of magnitude higher power efficiency (Elders et al., 2014; Reinsch et al., 2017), thus requiring less well drilling. Supercritical geothermal harnesses the high-temperature fluids liberated from magmatic bodies in volcanic-hosted hydrothermal systems (>374°C, >22 MPa) and while it is being investigated in multiple locations around the world, it has yet to be realised. In search of supercritical geothermal energy, engineers will need to drill much closer to magmatic bodies or much deeper (>15 km; Linden, 2022), and thus run the risk of further incidental drilling into magmas.

In the coming century, there is a huge requirement for critical or "technology" metals, for solar, wind, batteries, and electric cars. By 2050, lithium demand is set to increase by 965%, cobalt by 585%, copper by 7%, and silver by 60% compared with current production levels (Arrobas et al., 2017), and yet existing mining operations are extracting ever lower-grade ores and new reserves are harder to find (Hogg & Blundy, 2022). One idea put forward, which avoids the harmful environmental effects and energy intensive nature of mining, is to extract the minerals directly from the geothermal fluids (known as brines) from around magma bodies (Blundy et al., 2021). If this were to go ahead, this would mean further potential to directly interact with volcanic plumbing systems.

Pressures to avert catastrophic climate change may lead to global-scale carbon sequestration, which is built into current International Panel on Climate Change. This would involve drilling thousands of >1 km deep boreholes to inject CO_2 gas (The Royal Society, 2022), or pumping CO_2 into volcanic rocks such as basalt to chemically react with CO_2 to form solid carbonate minerals (Matter et al., 2009). Such wide-scale drilling may potentially interact with volcanic plumbing systems. Climate change concerns have also fueled the discussion and research of stratospheric atmospheric injection to cool the climate (Irvine et al., 2019). As a result, our understanding of the stratosphere and the technology used to manipulate it, is likely to increase. Humanity may also want the option of being able to reverse any stratospheric injection (Parker et al., 2018), if added by rogue actors or nations, or from miscalculations of their impacts. Possessing this knowledge to remove stratospheric particles may make the concept of post-eruption mitigation geoengineering more enticing.

The future therefore would seem to include lots of instances of drilling and intervention in and around volcanic systems, mostly for energy and mineral resource and economic reasons. Currently, there are no plans to attempt to alleviate their direct volcanic hazards. However, this is a possibility that recurs in many discussions: it would be very surprising if it was not investigated in the future.

6. What Could Go Wrong?

Environmental geoengineering projects are not without their risks, and volcano geoengineering is no exception, where the stakes can be high from unintended consequences. To assess the potential for bad consequences from preventative geoengineering, one must be able to answer the question of whether drilling into magma or the surrounding rocks can trigger an eruption itself. Empirical evidence, noting the five incidences of magma drilling without eruption, would suggest that drilling would not trigger an eruption. Perhaps the closest instance is dacite magma traveling 8 m up the well during incidental drilling in Hawaii in 2005 (Teplow et al., 2009). However, how likely an eruption is triggered drilling may depend on the state of the magma when tapped. For instance, if a magma reservoir is primed for an eruption before drilling (significant melt fraction and high overpressures), then potentially small perturbations may destabilize the system, much like has been suggested for earthquake-driven eruptions (e.g., Seropian et al., 2021). However, initial thermo-mechanical modeling suggests inducing an eruption from drilling is unlikely, especially at a more silicic magma reservoir (Dempsey, 2020), though rapid cooling of a system via extensive geothermal energy production as suggested by some authors (e.g., Wilcox et al., 2017) may trigger eruptions via volatile exsolution (Dempsey et al., 2018).

An expert elicitation study by Ilić (2020) investigating the safety of re-drilling into the Krafla magma body as part of the KMT drilling project, identified several potential risk factors which included upwelling of rhyolitic magma into the borehole, eruption of magmas, phreatic eruptions (steam), earthquakes, cooling of the hydrothermal system, and emission of harmful gases into the air and groundwater. Despite the uncertainty of these risks, experts from drilling, volcanology, and other fields rated them as acceptable risks, given some of the higher-rated risks were effectively prevented or mitigated. For instance, gas release and phreatic eruptions were considered to be the highest of the risks, but mitigation by continuous air quality, seismic and deformation monitoring linked to robust emergency response and evacuation plans, allowed these to be deemed acceptable risks. Given how little is known about the potential for bad consequences, further theoretical and experimental work is needed in this area to test these hypotheses, such as that proposed at the magma observatory in the KMT, Iceland.

Another problem associated with any future volcano geoengineering, is the issue of false attribution. This is already an issue with some geothermal operations today, when eruptions have occurred during periods of nearby geothermal drilling, even if the two are causally unrelated, it may be challenging to prove either way (e.g., Lusi mud volcano, Davies & Manga, 2017). Such allegations have occurred in the past with geothermal operations and volcanic eruptions (e.g., Canaloan in 2009 and Pinatubo in 1991, Philippines) and may cause high tensions and false attribution of blame to authorities. Due to the frequent nature of eruptions and increasing exploration of geothermal energy at volcanic regions, coincidences such as these will become more common.

The potential negative consequences of post-eruption mitigation geoengineering, for instance via accelerated stratospheric sulfate removal, appear to be more straightforward, and have been discussed in the context of solar radiation management (Visioni et al., 2020). Some hazards could include abrupt climate changes (akin to termination shocks proposed by solar geoengineering), this may have uneven impacts in certain regions of the world, who may not have been otherwise affected by volcanic winter impacts or climate change. Enhanced stratospheric sulfate fallout, may also lead to localized areas of acid rain, it may exacerbate air pollution, alter the pH of soils, corrode pipelines, bridges and have consequences for water reservoirs and delicate ecosystems (Tracy et al., 2022; Visioni et al., 2020). It should be noted though that sulfate deposition after a large eruption would happen regardless, however perturbation of this process may further concentrate or intensify some of these effects. Climatic and environmental modeling to quantify the impact of these post-eruption mitigation geoengineering scenarios are important for assessing the risk trade-off in the event of a large sulfate-bearing eruption.

7. Ethical Considerations of Volcano Geoengineering

Geoethics, the ethics of Earth Sciences, aims at research and reflection on the values upon which to base appropriate behavior and practice where human activities intersect the geosphere (Peppoloni & Di Capua, 2022).

There are some papers covering the ethics of different aspects of volcano science, including, decision making for public safety (e.g., Dolce & Di Bucci, 2014; Toulkeridis et al., 2018), policy and governance (Donovan & Oppenheimer, 2014), volcano research and communication (Kelman, 2005; Neuberg, 2014). However, ethical considerations about volcano geoengineering have yet to be studied. Ethical issues of volcano geoengineering may arise at different stages in time, for instance, during preliminary discussions, during research and development, choosing to conduct geoengineering, and even issues which may arise after geoengineering has been implemented. Here, we will discuss some applied ethics principles of relevance to issues of volcano geoengineering in their entirety.

From an ethical perspective volcano geoengineering is a form of environmental engineering, subject to many of the same issues as less dramatic projects such as dams and wildfire mitigation. It occurs on a local scale, unlike atmospheric geoengineering which is intended to have global consequences, but often on a far larger scale than standard environmental engineering projects, and involves potentially more destructive phenomena.

While energy and material extraction are likely to be practical motivators for volcano geoengineering, from an ethical perspective risk reduction is particularly salient. Preventing harm to people, ecosystems and the world has moral priority. Given the magnitude of some harms this might be a very strong motivation. A large-magnitude volcanic eruption would threaten the lives of billions affecting local communities, but also even those in distal regions, through climate effects and continent-scale damage (Cassidy & Mani, 2022; Newhall et al., 2018; Papale & Marzocchi, 2019; Self, 2006; Sparks et al., 2005). Even expressed just as a monetary loss it would easily run into tens of trillions of dollars (Mahalingam et al., 2018), and if recurrence times of Tambora-sized eruptions are on the order of 17,000 years (Lin et al., 2022; Rougier et al., 2018) it would make expenditures on the order of several billions of dollars per year a good investment (Cassidy & Mani, 2022). Smaller eruptions still pose noticeable risks to the world system, not just in terms of costs but in terms of potential destabilization of infrastructure, transport and trade that people and countries are dependent on (Mani et al., 2021). An added motivator for expenditure of risk reduction for large magnitude eruptions is the trickle-down effect this would have, with resilience built toward these rarer large magnitude eruptions also building resilience to smaller magnitude, more frequent eruptions too. Together these considerations suggest that it is both rational and prima facie moral to try to reduce the impact of eruptions through volcano geoengineering.

The most obvious issue is safety: does this activity threaten people (or other sources of value, such as a nature reserve)? This can sometimes be a balancing act: a risky action may be undertaken in order to protect people who would otherwise be harmed. While a consequentialist framework may allow harm to come to fewer people who would otherwise not have been harmed than to a larger at-risk group, often people follow a more deontological intuition that it is wrong to impose risk on innocents or people who have not agreed to it. It is sometimes codified as "first, do no harm" principles where the action should always serve to reduce the expected harm, never to add to it.

The precautionary principle can be interpreted to urge investigating if there is risk even if something appears safe (Kriebel et al., 2001). The stronger interpretation that one should not undertake novel interventions until their risks are understood is self-paralyzing: an investigation may require actions on volcanoes that are themselves risky, preventing investigation and resolution of whether there is any risk. Recognizing that imperfect risk information can still allow rational actions (including searching for better information) allows for cautious investigation.

Uncertainty plays a major role here. Were volcanoes deterministic, fully understood systems with predictable consequences, interventions could be compared and the best one selected. However, even in that ideal case uncertainty or disagreement about normative theory would make the decision fraught. In reality, we also do not fully understand the dynamics of volcanoes in general, we cannot easily get complete data about particular ones (with many remaining dangerously understudied), and many physical processes are essentially random. We do not currently know which volcanoes are capable of large magnitude eruptions (Papale, 2021). We do not know how to forecast the magnitude of the eruption showing unrest (Wilson et al., 2021). We do not know what style of unrest (or its duration), prior to a large magnitude eruption (as we have never witnessed one with modern technology/or even historical observations) (Lowenstern et al., 2006). We do not know the global societal consequences of a large-magnitude eruption (Cassidy & Mani, 2022). If we try to prevent an eruption, how will we know it will be successful? How effective could the interventions be?

Such uncertainty may appear paralyzing; however, we regularly act under high uncertainty in business, ethics, and policy. Clark et al. (2018) argue that any significant change and innovation involves a degree of risk, especially one involving a novel field such as drilling into magma reservoirs, since there is no existing solid base for which to secure a decision. One can still try to find the best expected cost-benefit ratio of action, or try to prevent or minimize worst case downsides. Demanding perfect information before acting is unrealistic (as demonstrated by the climate change debate and the Covid-19 pandemic response). Instead, aiming at having enough decision-relevant information to make actions likely to be beneficial and be able to change course if new relevant information arrives is likely to allow adaptive governance. Given the obvious large stakes in some situations the value of information is also high, giving a strong motivation to find relevant information.

Another ethical principle of relevance is acts-omission asymmetry. Typically harmful consequences from a deliberate act are viewed as more blameworthy than from a lack of action (Spector, 2016). Whether this asymmetry is justified is strongly debated in ethics, but it is a clear fact that people psychologically and often legally assume it. This is embodied in the "first, do no harm" principle. This matters for perspectives on pre- versus post-mitigation: attempting to mitigate a risk but failing may be judged more harshly than letting it happen and then attempting to reduce the consequences. Lava flow diversion may cause harm to some while avoiding harm to others. While "do no harm" may be a reasonable action guiding principle in many cases, clearly it cannot always be applied since most actions are at least somewhat risky, and allowing harms to be random can be worse than predictable harm. Rather, there needs to be a balance of reasons in favor of the action, and a general understanding that it is performed under uncertainty.

Stakeholders are a key consideration in the debate of who is responsible for conducting volcano geoengineering and for what motivations. First, this poses unique challenges in regions where volcanoes may straddle borders, resulting in differential preferences for risk mitigation, and in particular the sharing of accountability if things go wrong, particularly where the actions of one country may affect the populations of another (Donovan & Oppenheimer, 2019). This is also particularly salient for discussions of who takes responsibility for risk reduction for volcanoes that have the potential for large magnitude eruptions that can affect the global population—should this solely be the responsibility of the country that "owns" the volcano, rather than a global coordinated approach? Certainly, technologies developed for the purpose of intervening with volcanoes would likely be expensive to develop and run. This could pose the conundrum of how to prioritize which volcanoes we seek to intervene with whilst ensuring equitable access for regions that are significantly resource constrained.

The communication of the risks posed by volcano geoengineering may pose a unique challenge. Public perceptions of geoengineering can often be viewed as "messing with nature" (Corner et al., 2013), and strong public opinion can alter the discourse around engineering interventions. A drilling project for geological exploration around the Campi Flegrei volcanic field in Italy (The Campi Flegrei Deep Drilling Project [CFDDP]) sparked vigorous public debate on whether drilling into the volcano could cause an eruption (Carlino, 2019). Amplified by sensationalism and misinformation in the media, volcanologists faced NIBYism (the attitude of "Not In My Back Yard") from communities around the drilling site, opposed to the drilling program. Even after public consultation meetings and reassurance from the scientific community presenting data to discount the risks, significant objections remained with the local authority applying the precautionary principle, and withdrawing licenses for the drilling program. Examples like the CFDDP demonstrate the importance of careful risk communication with local populations, and inclusion of their voices within the development and design of geoengineering projects to counter NIBYism before it takes hold, successful attempts include the Unzen drilling project (Nakada et al., 2005) and Kralfa magma testbed (Ilić, 2020).

While volcanoes are usually not seen as moral patients, they sometimes hold important cultural value. In Hawaii, profound belief in Pele—a Hawaiian deity and goddess of volcanoes, was thought to have influenced the acceptance of certain lava flow intervention methods (levees over bomb) (Gregg et al., 2008). Similar tensions between indigenous cultural heritage and risk mitigation are also found in other volcanic regions, including New Zealand and Indonesia, amongst others. At the minimum, local stakeholders may have beliefs worth respecting and their values and input should be fed into any proposed mitigation strategies. That may still not overrule interventions: even pluralistic democratic societies sometimes overrule religious preferences or even prohibitions in order to save lives if necessary. However, it does suggest that if experimentation into volcano geoengineering is conducted, it would be best done on uninhabited and non-culturally sensitive volcanic islands, for example, the South Sandwich arc or the Kuril Islands, which has the added value of reducing risk to neighbors. But these islands often host rich biodiversity too: there is a trade of the knowledge gained for risk to a local ecosystem.

7.1. Expectation Management

As geologists are often in pain to explain, there is little to nothing we can do to prevent volcanic eruptions at present (Sparks et al., 2005). Although this paper assumes this inability can change in the future there is no reason to assume it will be a quick and risk-free process. Volcano geoengineering, if it ever emerges as a discipline, will have to manage expectations accurately or it will either oversell risky, expensive or ineffective solutions—or leave stakeholders unaware of the existence of potential solutions to life-threatening problems. This is not merely a matter of "PR" if volcano geoengineering can save or risk lives: ensuring good decision making about such technology carries ethical weight.

Time horizons may potentially be very long. In many forms of environmental risk management, the relevant time horizon is on a human generation timescale (<100 years). Reducing volcano risk may require longer planning horizons, ranging from centuries to many millennia (comparable to considerations of nuclear waste storage). This makes the ethics of future generations highly relevant. We may have duties to prevent harm to future people, much like the geological storage of radioactive waste. These occur because of our privileged early position in time and because some interventions like bleeding off magma chamber heat takes a long time (Wilcox et al., 2017). At the same time, uncertainty about future technology and vulnerability may make us want to delay interventions to a later time when we have more information and resources. Costly early interventions are mainly motivated when the overall benefit to future generations outweigh the opportunity cost of doing other interventions helping current disadvantaged or threatened people. Projects may also need to take long-term maintenance into account, as demonstrated by the Kelud crater lake drainage program (Suryo & Clarke, 1985).

Justice and inequality matters because typically less-resourced people are more vulnerable, and the economic and technical wherewithal of different countries to undertake volcano geoengineering is unequal. Monitoring (a prerequisite for any volcano geoengineering) is very unequally distributed. Safety-enhancing volcano geoengineering may have greater beneficial effects for vulnerable populations, but on its own may be less likely to happen since they are likely to live in less-resourced countries. While international help can improve the situation there is also a risk of "parachute engineering" where external help does not engage with the locals or help building a community that can further maintain the intervention. This is also relevant for the maintainability issue: interventions need to be locally supportable.

7.2. Military Uses

During WWII Harold O. Whitnall, a professor of Geology at Colgate University, wrote an article in *Popular Science* (Whitnall, 1944) where he suggested bombing of Japan should focus on volcanoes, including Mount Fuji, to trigger eruptions. The idea was that bombing might unplug a volcano, causing a pressure relief that would trigger the eruption. It was similar to a 1942 proposal to "convince the mass of Japanese that their gods were angry with them, by dropping bombs down the craters and starting some nice little local eruptions," which reached President Roosevelt at the time "but it was not considered seriously" (Janssens, 1995). Whitnall was also not alone in having the idea: there were rumors in Italy in 1943–1944 that the Allied forces were planning to bomb Vesuvius with the aim of triggering an eruption—an idea promoted by Reginald Purbrick in the UK Parliament (Purbrick, 1943a, 1943b). Nothing came of the ideas, but it would also likely have fallen afoul of international humanitarian law, although it seems some bombs were dropped on Vesuvius by accident in the first raid on Naples in 1940 (Purbrick, 1943b). Already the 1923 Hague Rules of Air Warfare (Article 25) protects objects and places of cultural and religious importance, and Mount Fuji would certainly have counted.

Since then, other treaties and conventions have strengthened the protection. The 1977 Environmental Modification Convention (ENMOD) prohibits the military or other hostile use of environmental modification techniques having widespread, long-lasting or severe effects. This would cover most military use of volcano geoengineering to gain a military advantage or to damage the enemy. There are also regulations against attacks on works and installations containing dangerous forces and against military objectives located in their vicinity (Article 56 of the 1977 Additional Protocol I to the Geneva Conventions), which would definitely cover volcanoes. Further, article 35(3) of the 1977 Additional Protocol I states: "It is prohibited to employ methods or means of warfare which are intended, or may be expected, to cause widespread, long-term and severe damage to the natural environment." Similar rules are in the 1980 Convention on Certain Conventional Weapons and article 8(2)(b)(iv) of the 1998 ICC Statute.

Finally, volcanic warfare is likely to run afoul of many of the principles of proportionality, indiscriminate attacks, affecting medical personnel, and so on. It is by its nature, an indiscriminate weapon and its use would be a war crime under modern rules.

Still, indirect military use of volcano geoengineering, such as energy and mineral production, may be lawfully acceptable. Reducing the environmental impact of an eruption or other activity may also be argued to be within ENMOD and the other regulations since it does not have long-lasting effects and is not indiscriminately harming people, even if it was performed to achieve a military advantage.

8. Governance

Governance in this sense concerns the act or process of overseeing the control and direction of volcano geoengineering. The geo-ethics community suggests governance in this discipline needs to be transparent, authoritative and independent, encouraging the exchange of knowledge and experience between nations and providing decision-making support to governments (Peppoloni & Di Capua, 2021). Furthermore, governing bodies should integrate each country's decisions referring to local contexts into the globalized human system (Di Capua & Peppoloni, 2020; Peppoloni & Di Capua, 2022). Given the nature of the potential risks posed by volcanic eruptions, which can be both regional and potentially global, governance of decision making should incorporate both national and international bodies.

Regional governance is most important when the risks posed by volcano geoengineering are local in scale without crossing international borders, which may be most applicable for preventative geoengineering, such as drilling into or around magma bodies. An example of such is the KMT research project in Iceland. A social science study identified potential risks associated with drilling, and used a risk assessment matrix to categorize risk factors such as gas release, seismicity, or eruptions (Ilić, 2020). The assessment solicited the opinion of 58 experts in various fields of geoscience, engineering and drilling, who rated the likelihood and potential impact severity, both to the environment or health and safety of people. Based on the expert elicitation risk matrix, acceptable risk scores were defined (minor and moderate risk), of which all of the identified risk factors fell within, though some of the risk factors required potential preventative and/or mitigating measures in place (e.g., seismic, water, and gas monitoring). Such risk assessments from independent experts are necessary for exchanging knowledge to decision makers such as local or national governmental representatives.

Global governance is more applicable for post-eruptive mitigation engineering (e.g., removal of ash and or sulfur from the atmosphere), which may pose risks that cross international borders. This is inherently more difficult, both for geopolitical reasons, but also because there is currently no formalized global operations system for volcanic hazard warnings and response, despite its clear necessity (Andredakis & De Groeve, 2016; Tupper & Bear-Crozier, 2022). The closest operations to this are volcanic ash forecasts given by the Volcanic Ash Advisory Centers, which map out ash clouds and forecast their atmospheric movements for purposes of safe aircraft transport, but they do not communicate with ground-based hazard warning and mitigation operations. Global governance of international volcanic risk and global-scale geoengineering requires coalitions and agreements between volcano bodies such as international association of volcanologists and researchers known as IAVCEI, but also with other agencies such as World Meteorological Organization, UNESCO, and United Nations Disaster Risk Reduction (Tupper & Bear-Crozier, 2022), or Global Disaster Alert and Coordination System—a joint UN and European commission operation (Andredakis & De Groeve, 2016). These organizations not only have legal mandates, but the political capabilities to undertake governance on these potentially difficult issues. There is precedent for international governance too, where UNESCO oversaw the decision making to conduct volcano geoengineering at Lake Nyos in 1987 (Halbwachs et al., 2020; Sabroux et al., 1987; Sigvaldason, 1989).

One problem with governance is the speed at which such organizations take to set up, which is at odds with technological and economic interests which often move at a faster pace. In this instance, there could be a potential for a moratorium of volcano geoengineering until such governance organizations exist and can function effectively.

9. An Interim Solution: Geoengineering Principles?

Given these ethical and governance issues (Figure 3), are there reasonable principles that could be adopted for helping frame ethical volcano geoengineering?

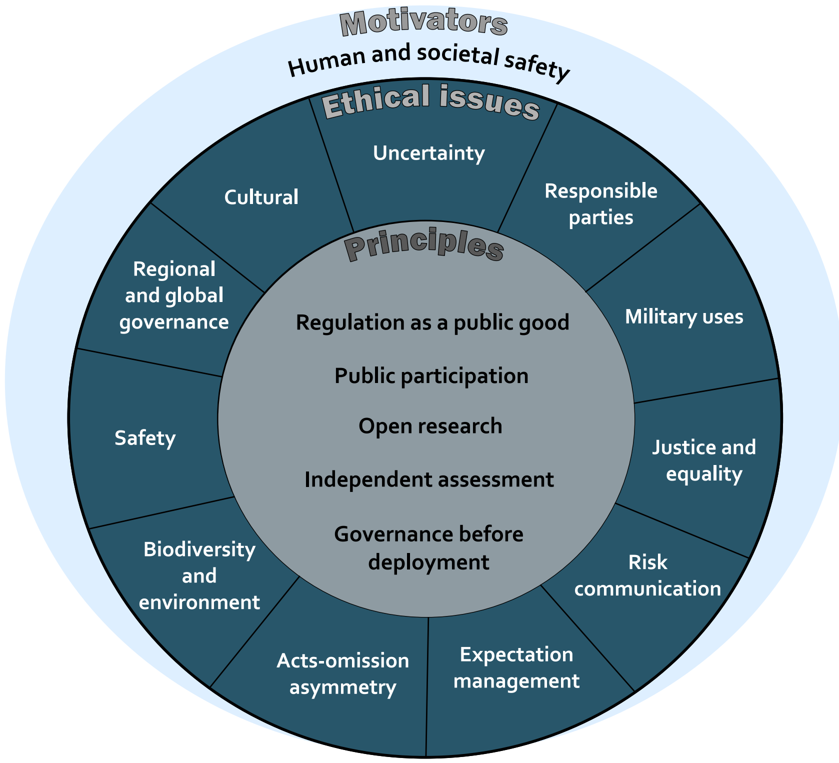

Figure 3. Summary schematic of the motivators, ethical considerations, and principles involved with volcano geoengineering.

The Oxford Principles for geoengineering were designed to guide modification of the atmosphere to affect climate (Rayner et al., 2013), but may with minor changes be updated for the literal geoengineering of volcanoes.

1. Volcano geoengineering is to be regulated as a public good.
2. Public participation in volcano geoengineering decision-making.
3. Disclosure of volcano geoengineering research and open publication of results.
4. Independent assessment of impacts.
5. Governance before deployment.

The motivations are essentially identical: all of humanity has a common interest in the good of a stable geosphere, and hence it should be regulated jointly for the benefit of all and future generations. Unlike the climate, some volcano geoengineering is local enough that this public is not necessarily all of humanity, but for the more cataclysmic risks this is a global public good. Critiques of the Oxford principles have challenged the notion of "the global public good," as this marginalizes the ethical and distributional concerns (Gardiner, 2013). We emphasize here that the localization of volcano hazards makes it relevant to consider both who might benefit and who may be subjected to extra risk during the development of volcano geoengineering.

There may well develop vested interests in volcano geoengineering: it can provide valuable energy or minerals, or act as a necessary protection of key regions. This may give holders of "volcano power" significant influence regionally or globally, which may need balancing by public participation and governance to be in the common interest. This also serves to insure legitimacy. Similarly, independent assessment is necessary to provide impartial and unbiased information for decision-making, reducing the risk that incumbents downplay risks (or overplay safety enhancements).

Unlike solar geoengineering and biotechnology, dual-use concerns (the potential mal-use of technology) about disclosure of research appears weak: most interventions are visible and expensive, not limited by information availability. However, it is important to establish trust with local and international communities, which can be achieved by public consultation of those materially affected and consideration of their self-declared interests and values, as well as openness and disclosure of research plans and results and decision-making (Gardiner & Fragnière, 2018).

These principles can be regarded as a draft of a draft (Figure 3): we are still far from having a proper understanding and consensus of volcano geoengineering ethics, and still far away from any large-scale implementation or governance. But as the historical examples show, volcano geoengineering has already been attempted, and it may behove us to formulate useful principles early.

10. To Research or Not Research

Although there are significant potential benefits of volcano geoengineering, the uncertainties and risks are far too large, and governance structures absent, to justify its deployment in the short-term. Thus, it is important to make a clear ethical distinction between conducting geoengineering versus research to investigate its efficacy and safety. The question this section poses is, whether large-scale research programmes are justified to reduce uncertainties and clarify the risks. This is an active conversation in the climate-field as debates ensue over whether or not to conduct solar geoengineering research (National Academies of Sciences, Engineering, and Medicine, 2021; Parson, 2021; Preston, 2013). Unlike solar geoengineering, however, the potential negative impacts occur mostly on a smaller, regional scale and thus opposition may be more confined than climate perturbations which impact on the global scale.

The concerns of conducting research into volcano geoengineering, whilst a very nascent field, may fall on similar lines as the solar geoengineering debate: (a) the so called "moral hazard," that is, that research into volcano geoengineering might deter investment and research into other ways of reducing volcanic risk such as locating volcanic risk, monitoring and preparedness, with implications for over-reliance in this technology, (b) moral corruption, that is, that the technology or insights could be misused for mal-purposes by parties with vested interests, so called, dual-use technology (e.g., mining/geothermal companies, political reasons), (c) increased realisation/path dependency, that is, that increased research in volcano geoengineering will make its operation more inevitable, despite its risks. These are all sensible and valid concerns. However, the case for researching volcano geoengineering is outlined in the points below and counters some of these potential concerns.

First, the potential for volcano geoengineering to be a moral hazard is purely hypothetical at this stage. For instance, it could be equally likely that the opposite is true, so called reverse moral hazard, where if policy makers and the public see the desperate measures scientists may take to reduce volcanic risk, they may become motivated to invest more money and effort into volcano monitoring and preparedness.

Without research into this area, we may sway on the side of being either under-confident or overconfident in the safety and efficacy of volcano geoengineering, both are nonideal. Under-confidence may reject an activity based on hypothetical or unexplored harms, especially since the action of not researching might lead to harms itself. For instance, not researching engineering solutions to prevent limnic eruptions in Lake Nyos, would have been exercising extreme caution and may have put many lives at risk from future limnic eruptions. In contrast, without thorough research about how to deploy geoengineering safely, or indeed at all, there may be over-confidence in the effectiveness and risk of various methods. This frame of thinking may put populations at more risk if governments/or other parties wish to deploy these techniques in emergencies, without knowing the probabilities of negative outcomes. This also highlights that suppression of research may not decide whether volcano geoengineering gets deployed or not.

The inequality of global volcanic risk and economies means that the benefits versus risks of conducting research may be far higher in some countries compared to others, yet if they are situated in resource-limited nations, they may not have the ability to research volcano geoengineering methods. Decisions of whether to conduct research at all may therefore unjustly rely on developed nations, where the risk calculation in their own nations (benefits vs. risk) may be lower than less developed nations.

As with any research and development programs, there may be serendipitous gains for other fields, this may include better informed research to mitigate asteroid and nuclear winters, or countervailing unintended human-derived solar engineering (Parker et al., 2018). The concern over "dual-use" seems to be limited in this capacity.

One aspect that may be difficult to disentangle here, is what actions delineate between research of geoengineering and volcano geoengineering itself. These two concepts may be thought of very differently in terms of ethics, but their actions may not be too dissimilar. For instance, exploratory drilling of boreholes near magmas (and sometimes into magmas) may be a necessary step of this research, and has been conducted at multiple volcanoes with sometimes little ethical opposition (e.g., Unzen drilling in Japan, soon to be drilled Krafla, Iceland), though sometimes with more (Campi Flegrei) and yet direct, purposeful interventions will need to meet a higher ethical threshold. The blurry lines between such practices further supports the notion that governance, regulation and clear decision making are important for the research stage of volcano geoengineering.

11. Conclusions and Ways Forward

The subject of volcano geoengineering has received very little interest from the academic community to date, though scientists are often dismissive of the subject. Nevertheless, due to technological and economic incentives to drill into Earth's crust and ongoing discussions into solar geoengineering and solar radiation management, discussions on whether to conduct volcano geoengineering will be inevitable. In light of the ethical considerations outlined in this paper and building on aspects from solar geoengineering debate (e.g., Nicholson et al., 2018; Rayner et al., Oxford principles) should society to go further down the route of volcano geoengineering, we suggest the following: that rigorous governance and regulation of any volcano geoengineering is required to guard against the risks, to enable potentially valuable and publicly available research (e.g., quantification of efficacy and safety), to ensure that any future policy must be co-created through community engagement and that volcano geoengineering must only be considered as part of wider mitigation practises. Research and exploration should be phased up gradually and isolated locations chosen that minimize threat to humans, animals, and the environment and mindful of sites of cultural importance. Volcano geoengineering has substantial potential benefits, and some practices may be technically feasible today, but the hazards and uncertainties are too great to warrant its use in the near term. We suggest however there is a strong ethical case to support research into the efficacy and safety of volcano geoengineering, even if we do not decide to conduct it.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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