EPSC 567: VOLCANOES + CLIMATE TERM PAPER

The relationship between eruptions rates and deglaciation in Iceland

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ABSTRACT

Volcanism and glaciation are two processes that rarely occur in tandem and in accessible areas for study. This makes Iceland a model natural laboratory to study both volcanism and glaciation. This paper reviews critical aspects of the relationship between the two geological processes and how they have influenced each other since the last glacial maximum (LGM). A strong deglaciation episode directly following the LGM relieved significant pressure from the solid Earth in that time and induced decompression mantle melting in the upper mantle. This, in turn, supplied greater amounts of melt to the surface for several thousands of years following the end of the last deglaciation $\sim$12 ka. The erupted lavas from this period in time have characteristic geochemical signatures with wider ranges in MgO content as well as lower rare Earth element (REE) concentrations as compared to lavas that erupted prior or following that period in time. A greater volume of eruptions then surely increased further deglaciation and other environmental consequences such as global sea level rise. With current anthropogenic warming in effect, Iceland's glaciers are deglaciating once more at an increased rate since the mid 20th century. If increased eruption rates are to follow this deglaciation, as they did after the end of the last deglaciation, global mean sea level will rise again, with the potential eustatic signal being approximately 9 mm.

INTRODUCTION

Positioned in between 63-66 °N, Iceland is known for its persistent volcanism and glacial features. Iceland is unique in that the island's conception and existence is due to two unique geological features: the spreading of the North American and Eurasian tectonic plates along the Mid-Atlantic ridge as well as a hotspot rising from the mantle. For the sake of the ongoing scientific debate surrounding whether or not this hotspot is indeed a mantle plume, hotspot will be used to define the area of buoyant rising of mantle material that rises to the surface (Street, 2017). With the combination of the spreading plates and the hotspot, magma in Iceland is supplied over a series of rift zones (Figure 1). The active rift zones are positioned more or less over the spreading between the underlying tectonic plates, and this can be seen with the ages of rock formations getting progressively older following the directions of the two spreading tectonic plates (Figure 1). Given the mantle material supply from the hotspot and rift zones, the majority ($\sim$90%) of outcrops on Iceland are basaltic in composition while only $\sim$10 % of outcrops have more rhyolitic compositions (Saemundsson, 1979). Many of these outcrops are influenced by glacial processes occurring over large timescales (i.e. glacial carving). Therefore, the geology of Iceland is somewhat intertwined with its historical glacial profiles (Saemundsson, 1979).

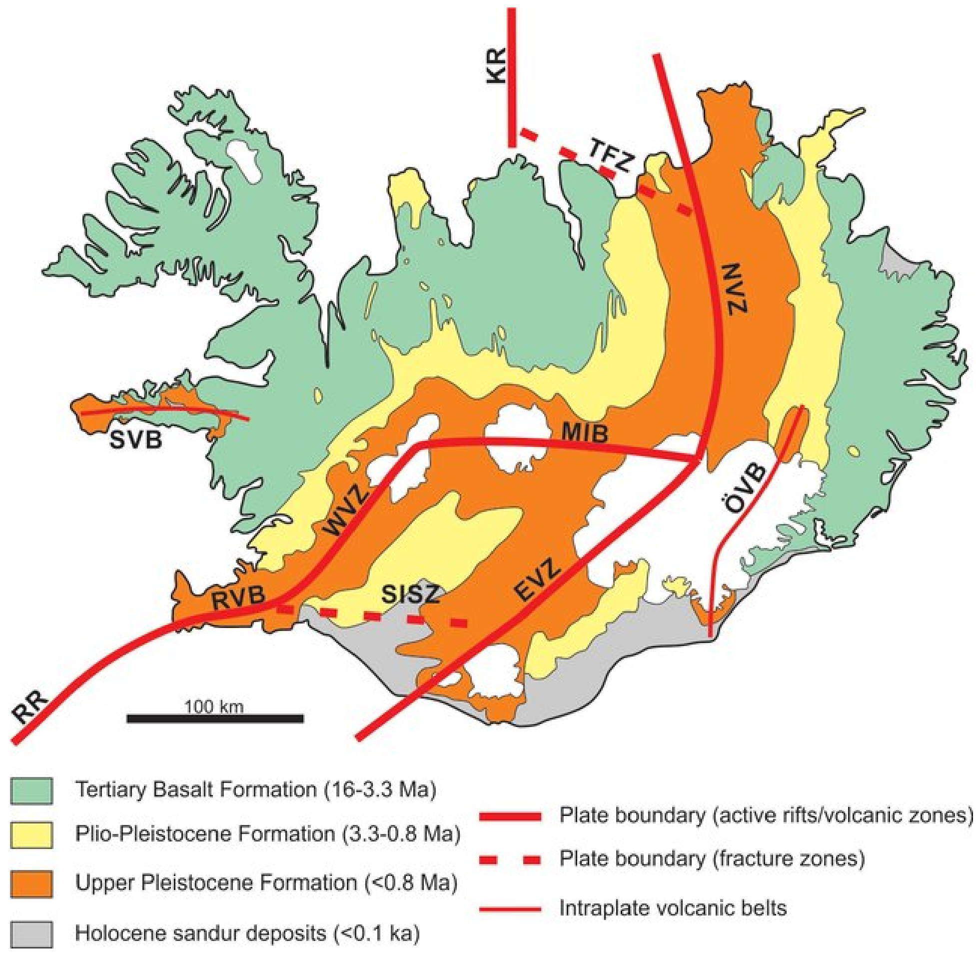

Figure 1: Plate boundary zones and formations across Iceland. Note that the formations get progressively older the further away from the spreading ridge. Figure from *Saemundsson, 1979*.

Glacial cycles are controlled by the Milankovitch cycles, specifically, eccentricity which controls how elliptical Earth's orbit is around the sun, corresponding to 100 ky intervals. Low insolation values, along with natural negative feedbacks on the surface of the Earth, will lower the global mean surface temperatures enough to initiate a glacial phase (glacial inception). These glacial cycles have persisted since the Pleistocene. During a 100 ky cycle, we see a gradual glaciation process where global ice volume increases until a glacial maximum, which can take up $\sim$80 kr of the cycle. Deglaciation, on the other hand, occurs very rapidly ($\sim$20 ky) and that will have corresponding impacts on the solid earth over which the ice lies on. Volcanic activity is thus proposed to be heavily influenced by the stresses imposed by glaciation and further deglaciation. In the 21st century, as we approach 1.5-2 °C warming, it is important to know how eruption rates and deglaciation interplay with each other for the sake of predicting the stability of glacio-volcanoes in Iceland, as well as environmental consequences such as local and far field sea level rise. Therefore, the main goal of this paper will be to explore some of the relationships between deglaciation and eruption rates in Iceland. Due to constraints on certain data as well as a more practical scope of problem, the paper will focus on how these two geological processes of Iceland have potentially interacted since the end of the last deglaciation ∼13-12 ka. Both published geochemical evidence and geophysical models will be used to try and constrain a general mechanism for this relationship. This paper will also attempt to qualitatively describe the environmental impacts of deglaciation in Iceland. In particular, how the solid earth effects from increased eruption rates and deglaciation will distribute global or local sea level rise in a warming climate.

Volcanic Activity in Iceland since the Last Glacial Maximum

Due to the spreading ridge and hotspot located directly beneath Iceland, volcanic activity in Iceland since the last glacial maxuimum (LGM) ∼22-20 ka has been consistent in both frequency and composition. Because the rift zones sample from the upper mantle, the compositions of the volcanic products are mainly basaltic (Sigvaldason et al., 1992). The outcrops produced by the various eruptions since the LGM have been emplaced in the forms of tuyas, pillow basalts, lava shields, etc. (Svigvaldason et al., 1992; Street, 2017). The volumes and compositions of these deposits represent key evidence for knowing whether or not the dissipation of Northern Hemispheric land ice, following the LGM, increased melt production underneath Iceland and thus, eruptions rates. Therefore, these extrusive features need dates and volumetric estimations. Svigvaldason et al. (1992) were pioneers of this task as they provided minimum estimates of the lava shield volumes in central Iceland (MIB zone in Figure 1). What followed was the estimate of the production rate extrapolated from these estimated volumes. Volumes were calculated by first measuring the areal extent of the lava flow and multiplying by the thickness of the deposit. This method however, can only produce minimum estimates as older lava flows are repeatedly covered by younger lavas (Svigvaldason et al., 1992). Accurate dating of these volcanic products are also important. The LGM falls within the accurate dating limit for radiocarbon dating ($\sim$ 40-50 ka), hence why lava flows were dated with Carbon-14 measurements (Svigvaldason et al., 1992). These ages however, are rough at best. Therefore, following the work of 1992, more accurate dating techniques would have been developed and could be potentially applied to their work.

The results of the work produced by Svigvaldason et al. (1992) are shown in **Table 1**. The results clearly show that lava flows dating > 4500 B.P. (interpreted as early post-glacial eruptions) have larger volumes while the younger flows all have lesser volumes and hence lesser production rates (Table 1). This supports the idea that mantle melt production will increase directly following glacial unloading. The production would then expectantly fall gradually once the majority of isostatic rebound is reduced following the initial fast rebound phase (see **Mechanism For Upper Mantle Melting** section for details). While the evidence points in favour to this theory, it is difficult to determine its certainty through the dating of some eruptive products. For one, the data is restricted to one glacial cycle as previous lava flows are erased from the record following glacial carving and glacier formation that occurs over a 100 ky cycle. For another reason, dating techniques are not sufficiently constrained in the context of this study to identify eruptions or lava flows prior to 4500 BC. This date leaves $\sim$6000+ years of ambiguity from the timing of the dissipation of Northern Hemispheric ice sheets (Caron et al. 2018; Svidvaldason et al., 1992; Street 2017). Future studies would then need to date volcanic deposits produced by early post-glacial eruptions (tuyas, pillow basalts, lava shields, etc.) differently. One suggested way to constrain timing of events is through dating of sulfate

Age: > 4500 B.P.	Area (km^2)	Thickness (km)	Volume (km^3)
Askja	39.9	0.1	4.0
Askja lava fan	158.1	0.03	4.7
North-	31.7	0.03	1.0
northeast	3.9	0.02	0.08
lava fans	39.2	0.02	0.8
Northern lava fan	58.5	0.01	0.6
Southern lava fan	207.5	0.03	6.2
Kollóttadyngja (cone)	69.1	0.63	14.5
Svartadyngja (cone)	18.8	0.1	0.6
Svartadyngja (lava)	19.9	0.02	0.4
Age: > 3500 < 4500 B.P.			
Northeast of Dyngjufjöll	26.7	0.01	0.3
Flatadyngja (cone)	24.7	0.11	0.9
Flatadyngja (lava)	85.8	0.02	1.7
Age: > 2900 < 3500–4500 B.P.			
Askja	39.9	0.03	1.2
Askja lava fan	18.4	0.02	0.4
Litladyngja (cone)	15.9	0.06	0.3
Litladyngja (lava)	69.2	0.02	1.4
Age: > AD 1158 < 2900 B.P.			
Northern lava fan	12.2	0.07	0.09
Age: > AD 1362 < AD 1158–2900 B.P.			
Askja	5.0	0.01	0.05
Age: > AD 1477 < 1362–2900 B.P.			
Askja	33.0	0.01	0.3
Askja lava fan	2.7	0.02	0.05
Northern lava fan	3.4	0.007	0.02
Age: > AD 1920 < AD 1477			
Northern lava fan	13.0	0.007	0.02
Age: < AD 1920			
Askja	3.6	0.007	0.03
Askja lava fan	9.0	0.01	0.09
Southern lava fan	25.1	0.01	0.3

Period years BP	Production rate km^3/1000/year
10 000–4500	5.98
(8000–4500	9.39)
4500–2900	3.88
2900–present	0.32

Table 1: Ages and volumes for lava flows located at the Dyngjufjöll volcanic complex (area located in the center of Figure 1). Included also are the estimated production rates from the constrained time periods. Figure retrieved from *Svigvaldason et al., 1992*.

peaks in ice cores both in Greenland and Antarctica (Hammer et al. 1980). As Iceland is in the Northern Hemisphere, Greenland would more likely have an ice core to show sulfate peaks from explosive Icelandic eruptions due to partitioning of atmospheric sulfate (Hammer et al., 1980). However, this would imply that the eruptions would have to be stratospheric and highly explosive (Hammer et al. 1980). This is difficult in Iceland as many volcanoes are subglacial and thus, much of the kinetic energy generated in an eruption will be transferred to the melting of overlying glaciers (basal melting), leaving it rare for an Icelandic eruption to have a plume height that would reach the stratosphere and spread sulfate globally. Therefore, dating techniques are needed for deposits that would have been produced subglacially (Street 2017). Methods that are normally used for dating, such as ^{40}Ar-^{39}Ar and radiocarbon dating, are limited for dating these deposits. The reason being that there is insufficient organic material present in the deposits to date accurately using radiocarbon ages (Street, 2017). Instead, radiocarbon dating can only really be used to date the younger lava flows that intersect with tuyas, for example (Street, 2017). Additionally, ^{40}Ar-^{39}Ar cannot be used because these younger post-glacial lava flows ($\sim$12-10 ka) do not have enough radiogenic ^{40}Ar built up since the flows' conceptions (Street, 2017). While this makes is so new dating techniques must be developed, such as U-Th/He dating (Street, 2017), this does not mean that specific compositional changes though somewhat unconstrained dates cannot provide key information. The next section will explore how geochemical evidence of samples with relatively constrained eruption dates can point to patterns in the eruption history of Iceland.

GEOCHEMICAL EVIDENCE

Within these Icelandic eruptive post-glacial deposits, is there some geochemical variation, as a result of changing glacial cover? A widely accepted model for glacially influenced geochemical changes was proposed by Jull & McKenzie (1996). Their model implied that melts produced from the unloading of ice (see **Mechanism for upper mantle melting** section for details) will vary in rare Earth element (REE) concentrations in comparison to melts produced when there is no ice being unloaded (Jull & McKenzie, 1996). Their findings were later backed up by Macllenan et al. (2002) where 80 basaltic samples from Krafla and Theistareykir (Kr zone in Figure 1) were tested for geochemical variation. A key difference between glacial and early post-glacial samples is the concentration of REE to MgO content. For one, samples from the glacial period have a much narrower MgO content range while post-glacial samples have a more extended one (Figure 2). However, we mainly observe that REE, such as La, are much less abundant in post-glacial samples (Figure 2). The clear difference in REE concentrations between glacial and post-glacial samples indicates that the ice unloading indeed has an effect on the composition of melt being supplied to the surface. As these samples are taken from the Northern Volcanic zone (NVZ in Figure 1), these eruptions sample material from the rift zone (Jull & McKenzie, 1996; Macllenan et al., 2002). Therefore, the material seen is supplied from the shallow mantle, around 60 km depth according to Jull & McKenzie (1996). In that case, it is likely that increased mantle melting is what causes the REE concentration changes as well as increased eruption rates (Macllenan et al., 2002).

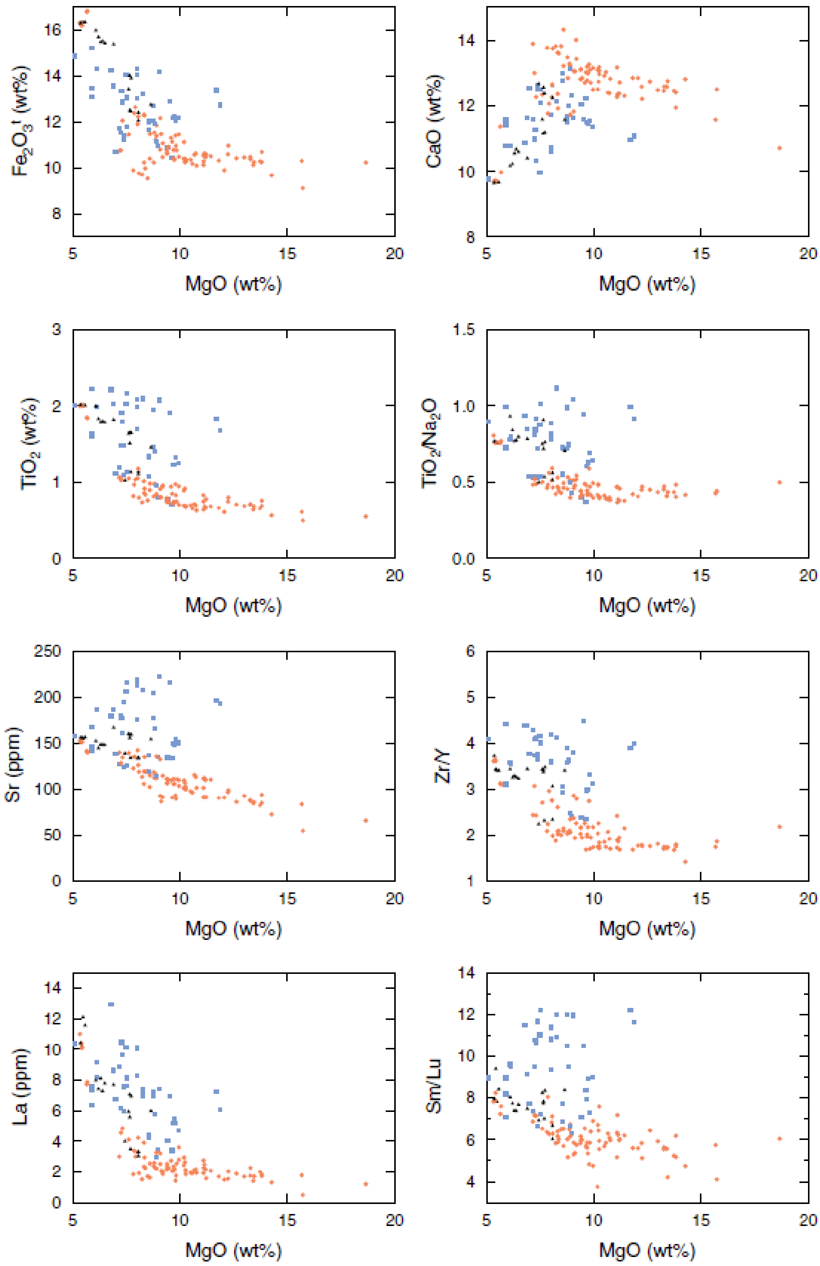

Figure 2: Major and trace element concentrations plotted against MgO content for all 80 basaltic samples taken in *Maclennan et al., 2002*. The samples originate from both Krafla and Theistareykir in the northern volcanic zone of Iceland. Here, blue circles are glacial sample (>12 ka), orange circles are early post-glacial samples (12-7 ka), and black triangles represent samples whos dates are within the last 7 ka. Figure retrieved from *Maclennan et al., 2002.*

The following question to address is then how is it possible for glacial unloading to instigate shallow mantle melting? One possibility could be the supply of meltwater to the mantle. This, in turn would suppress the mantle solidus and generate more melt (Eason et al., 2015: Nichols et al., 2002). However, the following section will describe another mechanism that could cause for the mantle solidus to be suppressed in more detail.

MECHANISM FOR UPPER MANTLE MELTING

Now we can consider how glacial unloading can increase mantle melting rates. By what mechanism is this possible? How great are the melting rates caused from this decompression melting?

Theoretically, melting in the mantle will occur when a parcel of mantle material is brought closer and closer to its solidus temperature. In order for this to happen, there needs to be some sort of change in the system so that the solidus temperature gradient can be steeper than the adiabatic geotherm and induce mantle melting (Schmidt et al., 2013). When ice masses are removed from the lithosphere, the solid Earth is relieved of a tremendous amount of pressure. Due to this literal 'relaxing' of the solid Earth, pressure changes would provide the necessary change in the upper mantle system to steepen the solidus temperature gradient; decompression mantle melting (Jull & McKenzie, 1996; Schmidt et al., 2013). This would explain the change in REE concentrations seen in early post-glacial basalt samples (Figure 2). Large decompression episodes would increase the degree of partial melting in the upper mantle and reduce the concentration of trace elements (Jull & McKenzie, 1996). However, the length of time that great enough pressure changes to induce melting would occur over is uncertain. Solid earth modelling is the only suitable method for attempting to answer this question. That being said, the behaviour of the solid Earth beneath a glacial environment is complex. This response to glacial loading or unloading on a system is more commonly known as glacio-isostatic adjustment (GIA). This is the process where upon a glacial mass being removed from the solid Earth, the solid Earth will rebound due to mantle material flowing under where the mass was placed (Figure 3).

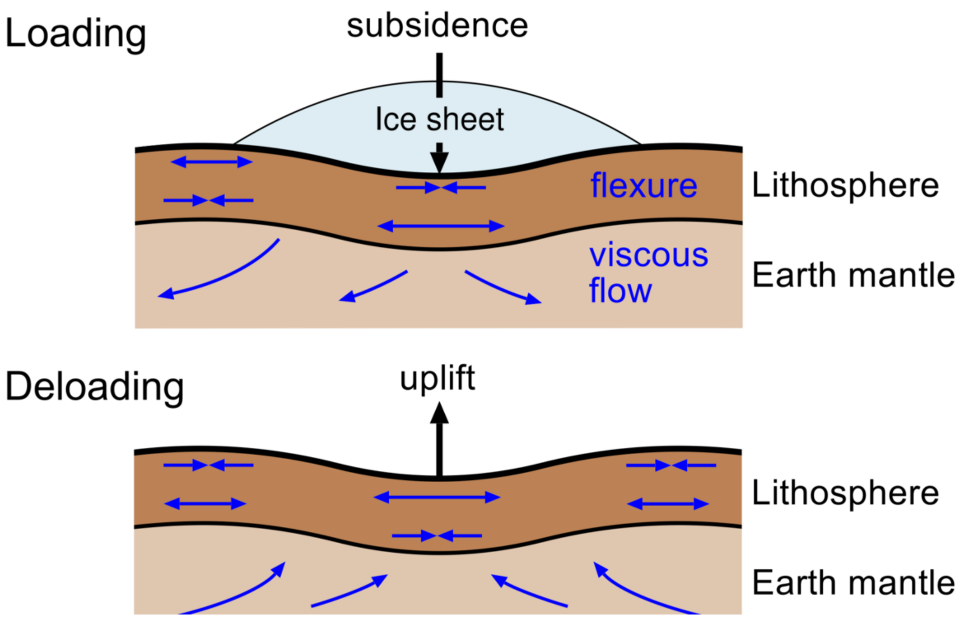

Figure 3: Conceptual model of GIA theory.

Following GIA, Schmidt et al. (2013) performed a relevant study in which they modelled pressure changes of the upper mantle beneath Iceland and estimated melting rates due to these changes in pressure. Their model runs were based on recent 20th and 21st century deglaciation in Iceland and their observed uplift rates (Figure 4). Their results show that decompression rates of change are, as would be expected by constant deglaciation, are greater over long time scales (Figure 4). In addition, locations where there are currently existing glaciers experience large decompression rates at the upper levels of the mantle (Figure 4c). Due to these large decompression rates, regions overlain by large ice caps will experience the most melt production (Schmidt et al., 2013). For example, the region under the Vatnajökull ice cap accounts for 20 % of Iceland's mantle melt production (Schmidt et al., 2013). Under the rift zones, however, there is no clear pattern to quantify the decompression rates (Figure 4d, 4e), even though we would expect greater mantle melt rising due to the buoyant nature of the magma at the spreading ridge (Sigvaldason et al., 1992).

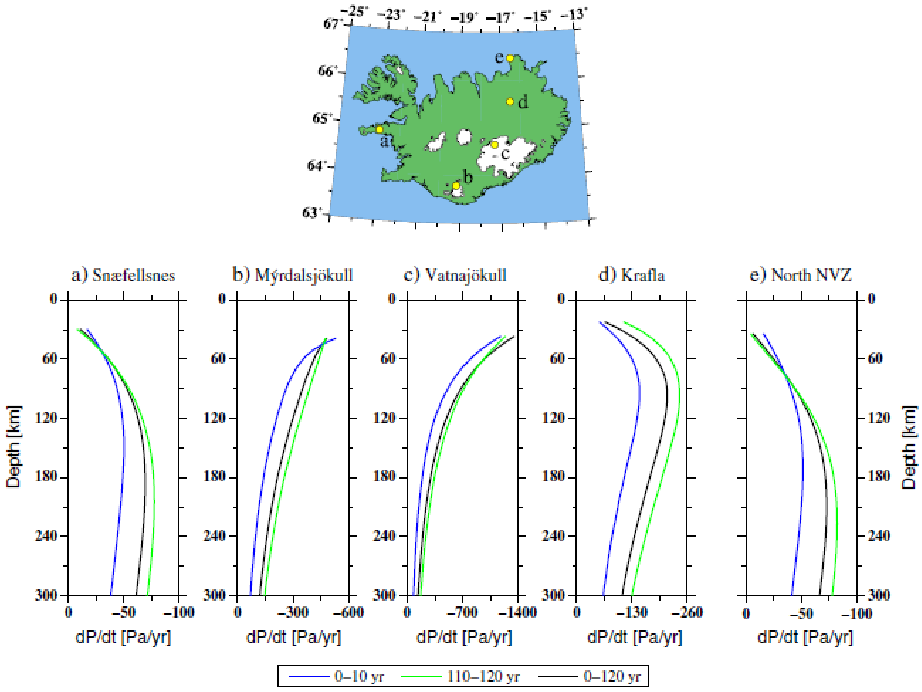

Figure 4: Modelled decompression rates for 5 locations distributed across Iceland. Note that under some location, mantle decompression rates decrease with time and vice versa. Figure adapted from Schmidt et al., 2013.

This example, provided by Schmidt et al., provides us with an analogue for how melting rates in the upper mantle might be affected by glacial unloading at the end of the last glacial cycle ∼12 ka. During that time uplift rates were along the lines of 300 mm/yr (Caron et al., 2018) instead of present rates of ∼ 25-29 mm/yr, so we would expect melt production rates to be significantly higher (Schmidt et al., 2013). That being said, decompression mantle melting rates in the upper mantle are still significant under 20th and 21st century deglaciation, as will their associated eruption rates of 0.21-0.23 km^3/yr (Schmidt et al., 2013). This amount is the equivalent of an eruption that would match one seventh of the size of the 2010 Eyjafjallajökull eruption every year (Schmidt et al., 2013).

FEEDBACKS

Understanding the overall communication between eruption rates and deglaciation is a non-trivial task. Imprecise dates of volcanic deposits over Iceland prevent necessary time constraints that allow us to say whether or not increased eruption rates directly follow periods of mass deglaciation (glacial unloading) for certain. However, taking advantage of climate models allows for general feedbacks of the relationship to take form.

Generally, when a large mass, such as a glacier, is removed, solid earth will respond elastically and then viscoelastically once low viscosity mantle material will force a rebound of the lithosphere to compensate for the mass loss (Jull & McKenzie, 1996). During this load release, mantle melting rates and subsequent production will generally increase due to decompression and the steepening of the solidus temperature gradient (Svidvaldason et al., 1992). If more magma occupies the magma chamber, the chamber can over pressurize, leading to an explosive eruption or magma escaping the chamber by means of dikes, sills or even degassing through fumeroles. The thermal energy radiated from these processes will then increase glacial melting and melt water will redistribute itself into nearby bodies of water. However, the feedback between glaciers and volcanic eruptions becomes more complex if there is an explosive eruption. For example, if there is any ash fall near glaciers, the radiative balance of the glaciers would change due to changes in surface albedo. Normally, this would simply imply that more ice would melt due to an increased absorption of incoming longwave radiation. In addition, there would also be increased meltwater runoff (Muschitiello et al., 2017) However, if there is ashfall, aerosols in the atmosphere would also scatter incoming radiation and cool the surface, allowing for increased ice extent and solidification and decreased runoff (Muschitiello et al., 2017). Increased solidification of ice would also increase the density of ice and force fracturing of said ice. Therefore, when melting would occur, melt water could seep through the cracks and spread basally (under the glacier). This, in turn, would prime the glacier for further melting as basal friction would be reduced by water and be be allowed to flow down slope more easily, triggering further ice loss.

There is also the possibility that 20th and 21st century warming can trigger eruptions simply from melt water production (Sigmundsson et al., 2010). If there is enough seasonal snow accumulation on certain volcanoes in the winter, then the magma chamber can compress. An example would be that of Krafla; 6m of average snow accumulation over the edifice every winter season (Sigmundsson et al., 2010). The mass lifted from the volcano by melt water being produced and leaving the volcano rapdily, perhaps in the form of a jökullhaup (rush of meltwater from a glacier capped volcano), can relieve enough pressure to cause an eruption. For example, a jökullhaup of 0.5 km^3 is though to be the cause of the 2004 eruption of Grímsvötn (Sigmundsson et al., 2010). Therefore, in increasingly high temperature summer months (presumeably caused by anthropogenic warming), eruptions could be more likely in Iceland from increased ice melting, as have been seen from recent Krafla eruptions occurring in the summer months (Sigmundsson et al., 2010).

We can thus consider that deglaciation and eruption rates are part of a negative feedback loop. Deglaciation will induce decompression mantle melting which will then increase eruption rates, further melting glaciers. The next section will discuss what happens with the meltwater produced from this negative feedback loop and the environmental consequences it poses.

SOLID EARTH EFFECTS

In this section, we consider the environmental effects of deglaciation induced by augmented eruption rates. The main direct climatic effect of melting ice masses is undoubtedly sea level rise. In addition, there may be additional effects on climate as a result of melting ice such as reduced albedo that would affect the radiative balance on Iceland's surface, or even local ocean circulation changes due to an increased input of freshwater. That being said, sea level rise is one of the more important product of global warming as upwards of 40% of the world's population lives within 100km of the coast. However, global mean sea level rise is also difficult to properly characterize as its global distribution is non trivial. For one, the solid earth responses to glacial unloading will redistribute where sea level would 'expectantly' rise.

As previously mentioned, GIA is the process where the solid Earth will isostatically compensate for ice mass loss (Figure 3). Therefore, if Iceland's surface is rebounding from GIA, then sea level would fall around Iceland and be distributed elsewhere (Figure 3). For example, sea level would rise 2000 km from the ice sheet where upper mantle material would have flowed out from in direction of the once compressed lithosphere. This area is known as the peripheral bulge (Caron et al., 2018).

This is where tracking 21st century global sea level rise becomes difficult. Due to the fact that there are land ice masses all around the globe, GIA is happening wherever there is glacial loading or unloading. Solid Earth responses are also not equal at every unloading site. Iceland, for instance, will have faster uplifting rates due to its location over a hotspot where upper mantle viscosity values are lower. With lower viscosity, the solid Earth's viscous response will be more rapid because mantle material will not be as strained and can flow more rapidly (Svigvaldason et al., 1992; Caron et al., 2018). Therefore, sea level will be distributed unevenly. This is called sea level fingerprinting (Larour et al., 2017). This process is relevant in determining which coastal areas are more affected by certain glacial melting than others (Figure 5).

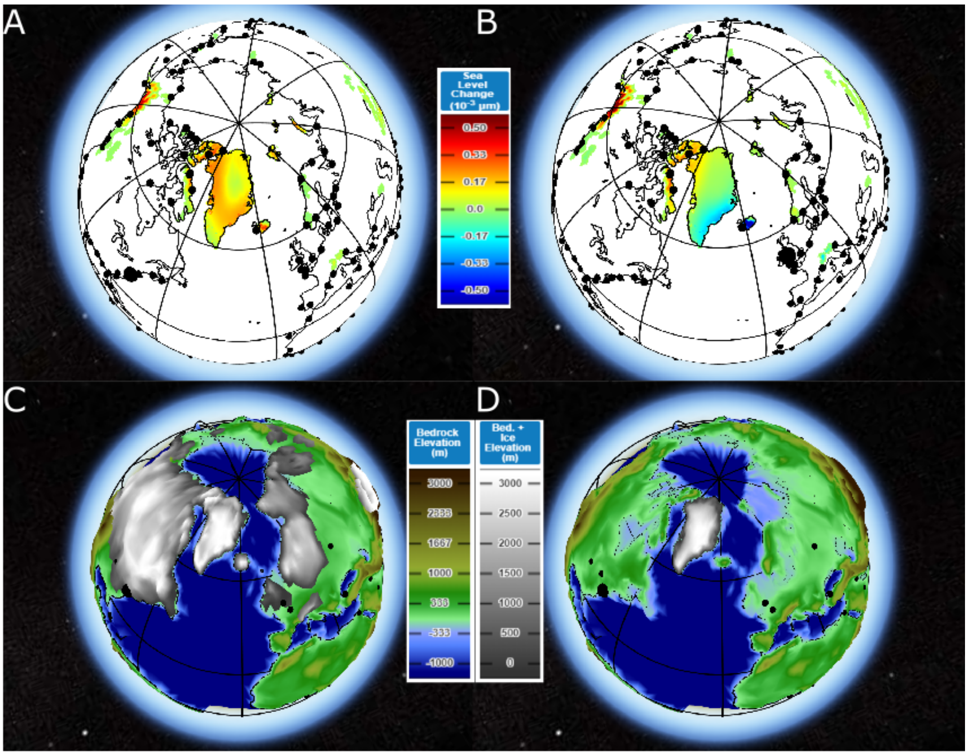

Figure 5: Sea level fingerprints and GIA theory uplift rates. (A) New York City sensitivity to ice mass loss measured as amount of local sea level rise due to ice thickness loss in areas colored (land ice). (B) Dublin sensitivity to ice mass loss by the same metrics as (A). Note that, as indicated by the colorbar, Dublin's sea level change is negative when contributed from Iceland ice loss while, New York City's is positive. (C) & (D) GIA theory bedrock and bedrock+ice elevations at 21 ka (C) and present day (D). Figure adapted from *Larour et al., 2017* and *Caron et al., 2018*.

In that case, let us consider a scenario. In the unlikely event that increased volcanic eruption rates are enough to melt the entirety of Iceland land ice ∼3600 km^3 (Box et al., 2017), then we may consider the entire eustatic sea level contribution. By assuming that Earth is a non-rotating spheroid, 70% of Earth's surface is ocean, no GIA, etc., we can calculate a global eustatic sea level rise of ∼9.28 mm. For reasons previously mentioned, this rise in sea level would not be distributed evenly across the Earth. However, this example provides a basis to understand some of the environmental consequences as there are some coastal cities that would be greatly impacted by a sea level rise of enough meltwater to cover the global oceans with a layer of 9 mm thickness. The current contribution of Iceland land ice mass loss to global mean sea level rise is 2.6% but increased melting, whether volcanogenic or not, would raise this contribution nonetheless (Box et al., 2017).

CONCLUSION

The relationship between eruption rates and deglaciation in Iceland is complex. While many models have sought to explain and further quantify whether eruption rates will more greatly affect deglaciation or the other way around, few have succeeded. This is due to a number of factors. For one, the dating of eruption deposit samples, mostly tuyas, lava shields and pillow basalts is required. However, these samples required dating as far back as the LGM, and even more importantly, the timing of the dissipation of most Northern Hemispheric land ice mass ($\sim$12-10ka). These dates are difficult to assess as the more common dating techniques such as radiocarbon dating are not as effective in dating samples that erupted subglacially. However, estimated dates still provide a means to explore the relationship between deglaciation and eruption rates. A likely mechanism for increased eruption rates is dominated by deglaciation. As enough ice is removed from the crust, the solid earth will rebound isostatically, thereby decompressing the upper mantle and suppressing the solidus; decreasing the mantle melting temperature. With increased upper mantle melting, there will be increased magma supply rates, and hence, increased eruption rates as evidence by higher volume lava flows during the early post-glacial period (the time where most unloading was occurring). Further work is needed to constrain the dates of eruptive materials in the early post-glacial period to concretize these mechanisms. However, in the 21st century where deglaciation is forced anthropogenically, Icelandic glaciers, whether increasingly melted by eruption rates or not, will contribute to global mean sea level rise as well as increased eruption rates of glacio-volcanoes.

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