Quaternary Science Advances 1 (2020) 100004

Contents lists available at ScienceDirect

Quaternary Science Advances

journal homepage: www.journals.elsevier.com/quaternary-science-advances

Is there a climatic control on Icelandic volcanism?

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ARTICLE INFO

Keywords:
Unloading effect
Isostasy
Deglaciation
Crustal loading
Volcanism

ABSTRACT

The evidence for periods of increased volcanic activity following deglaciation, such as following ice sheet retreat after the Last Glacial Maximum, has been examined in several formerly glaciated areas, including Iceland, Alaska, and the Andean Southern Volcanic Zone. Here we present new evidence supporting the theory that during episodes of cooling in the Holocene, Icelandic volcanic activity decreased. By examining proximal and distal tephra records from Iceland spanning the last 12,500 years, we link two observed tephra minima to documented periods of climatic cooling and glacial advance, at 8.3 to 8 and 5.2 to 4.9 cal kyr BP. We simulate these periods in atmosphere-ocean and ice sheet models to assess the potential validity of the postglacial 'unloading effect' on Icelandic volcanic systems. We conclude that an increase in glacial cover may have decreased shallow magma ascent rates, thus limiting eruption potential and producing apparent quiescent periods in proximal and distal tephra records. However, several major uncertainties remain regarding the theory, including geographical and temporal preservation biases and the importance of any unloading effects against other factors, and these will require more prolonged investigation in future research.

1. Introduction

The effect of reducing sub-aerial loads on crustal strain and lithostatic pressure, often referred to as the 'unloading effect', has been intermittently modelled and explored in a number of settings for the past few decades (Jull and McKenzie, 1996; Maclennan et al., 2002; Carrivick et al., 2009; Sigmundsson et al., 2010; Swindles et al., 2018a). In particular, many studies have emphasised the implications for seismic and volcanological hazards (Pagli and Sigmundsson, 2008; Manconi et al., 2009). However, the difficulties and uncertainties involved in modelling deep-crust and shallow-mantle systems have hindered the development of many forward models, resulting in significant ambiguity surrounding the theory, particularly regarding volcanic systems. Here, we present new evidence exploring a possible relationship between periods of glacial advance and reductions in volcanic activity from the Younger Dryas (around 12 ka) to the present day, as seen through several climate proxies and tephrochronological records. However, it must be noted that such the existence of such a link between climate, glacial systems, and volcanoes remains highly controversial, most plainly evidenced in the dialogue between Swindles et al. (2018a), Harning et al. (2018b), and Swindles et al. (2018b). This manuscript aims to present an objective analysis of the theory, emulating the methods of Swindles et al. (2018a) while also providing a critical discussion of the current methodical shortfalls.

Tephrochronology refers to the use of ash particles deposited in discrete layers during volcanic ashfall events to construct a chronological framework for stratigraphy. Distal deposits of volcanic ash from individual events provide useful isochrons across wide areas. Many previous studies have documented individual tephra layers across much of western Europe, and comprehensive databases of Icelandic tephra have been compiled spanning the last 7000 years (Newton et al., 2007; Swindles et al., 2011, 2017). However, tephra layers in the geological record become increasingly sparse with age (Swindles et al., 2011). As a result, studies detailing ash records from the early Holocene and Late Glacial period (12.5–6.5 ka) are less common, and typically less successful in identifying the provenance of unknown tephra layers (Watson et al., 2017). Here we present the first complete tephrostratigraphy of Europe spanning the period 12.5 ka to the present day.

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https://doi.org/10.1016/j.qsa.2020.100004
Received 12 November 2019; Received in revised form 16 March 2020; Accepted 18 March 2020
Available online 7 May 2020
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Our study aims to examine the proposed ‘unloading effect’ of glacial retreat on volcanic systems in Iceland within the Holocene period. The current trends of global climatic change and the rapid retreat and disappearance of Icelandic ice (Björnsson et al., 2013) make this a pertinent topic of conversation for the modern day, as the impacts of Icelandic eruptions in recent years have had significant implications for European and international aviation (Ulfarsson and Unger, 2011; Budd et al., 2011) and caused subsequent short-term but nonetheless noteworthy economic effects in Europe (O'Regan, 2011).

In order to constrain the variability of glacial loading during the identified climate events, our data are coupled with a thermomechanical model of Icelandic ice coverage and a reconstruction of Icelandic palaeoclimate obtained from climate model simulations spanning the period. We show what appears to be a positive connection between periods of glacial advance and greater ice thicknesses and periods of volcanic quiescence, following a variable lag of between <100 and 600 years. We also discuss the shortfalls and uncertainties surrounding this theory and the methods used to support it.

2. Methods

2.1. Tephra

The distal tephra records in this study were compiled from verified sources largely detailed in Swindles et al. (2017), in addition to further references (Óladóttir et al., 2011; Gudmundsdóttir et al., 2012, 2016; Harning et al., 2018a). The full database of tephra used in this study is included as supplementary material. Tephra ages may have been derived from historical correlations, directly radiocarbon dated, interpolated from age-depth models, wiggle-match radiocarbon dated, or dated through association with another tephra layer. All tephra layers used in this study were verified to have originated at Icelandic sources. While concerns have been raised regarding the reliability and preservation of tephra in geological time, particularly regarding the disparity between rhyolitic and basaltic glasses (detailed more thoroughly in Swindles et al., 2011; Watson et al., 2017), we have endeavoured to be as thorough as possible in collating documented tephra layers, and believe that the comparison of proximal and distal records is sufficient to eliminate the potential effects of preservation bias.

2.2. Atmospheric-ocean general circulation model

The climate model used in this study is the UK Met Office's HadCM3 coupled atmosphere-ocean-vegetation general circulation model (Valdes et al., 2017). For 26 to 21 ka and 21 to 0 ka, model boundary conditions were updated every 1000 and 500 years (respectively) in accordance with the PMIP4 last deglaciation protocol (Ivanovic et al., 2016) using the ICE-6G_C reconstruction of ice sheets and palaeogeography (Argus et al., 2014). Differences with the PMIP4 protocol are pragmatic: the CO_2 curves follow Lüthi et al. (2008) because the protocol had not been finalised at the point of running the simulations, and the simulations are of equilibrium-type rather than being transient (i.e. the boundary conditions were held constant for each 1000/500-year segment) enabling them to be run in parallel. The ocean is not explicitly forced with ice sheet meltwater in these simulations, and water is conserved by forcing global mean ocean salinity to match the ice sheet history, interpolating smoothly between the 1000/500-year timesteps of ICE-6G_C (*melt-uniform* in the PMIP4 protocol).

The climate means used here are calculated from the last 50 years of each simulation period. Ocean areas were masked out and land data was back-filled using a Poisson equation solver with overrelaxation. The native model grid was then interpolated to a higher resolution ($0.5 \times 0.5^{\circ}$) using a bi-cubic spline. Bias correction was performed against New et al. (2000). See Morris et al., 2018 for more information on the model setup, downscaling and bias correction.

2.3. Ice sheet reconstruction

This simulation is a three-dimensional, finite-difference model utilising a 2 km resolution described in detail in Hubbard (2006). The effects of temperature and precipitation change on ice sheet mass balance are simulated using a degree-day algorithm, chosen for its stability over a long-time scale and the simplicity of its parameterisation. The model acts under the assumptions that climate forcing may be applied uniformly across Iceland, and that the relationships between precipitation and temperature may be considered constant over time. The degree-day coefficient was calibrated against glacial measurements from Norway, Greenland, and the Vatnajökull and Hofsjökull ice sheets in Iceland. Spatial gradients are introduced to simulate reduced atmospheric moisture during cooling. Ice thickness and flow velocity are coupled to the thermal evolution of the ice sheet via the calculation of absolute temperature and the initiation of basal sliding. Sea level is viewed as an external forcing variable.

Additionally, the model takes into account isostatic bed response to ice loading. This factor is coupled to ice sheet evolution using an elastic lithosphere, which is loaded using the integrated contribution of local and remote loads within a radius of ~100 km (Hubbard, 2006). The unloaded equilibrium topography is estimated through comparison to present-day subglacial topography. The topographic grid is derived from the terrestrial GTOPO30 (<1 km) and ETOPO2 (<4 km) global data sets, merged onto an Albers equal-area conic projection, and incorporating known subglacial topography from Vatnajökull, Mýrdalsjökull and Hofsjökull. The combined DEM was then adjusted assuming steady-state equilibrium.

The boundary conditions of the model reference mean annual temperature and precipitation values taken between 1961 and 1990 by the Icelandic Meteorological Office, interpolated across the model domain. Likewise, geothermal heat flux was derived from Icelandic borehole measurements (Flóvenz and Saemundsson, 1993), and interpolated across the model using a kriging algorithm.

3. Results

3.1. A correlation between cooling events and lulls in volcanic activity?

It is possible to evaluate the trends of past volcanic activity in Iceland by examining both proximal and distal records of volcanic ash deposits. By combining tephra records retrieved from a range of distances from the volcanic source, we eliminate the bias created by reworking and ‘overwriting’ of deposits by more recent activity (Swindles et al., 2018a), producing a more accurate representation of quiescent and active periods on the island.

The Northern Europe Volcanic Ash database (NEVA) was first published by Swindles et al., (2011), and has since undergone many updates and revisions (Swindles et al., 2017; Watson et al., 2017). This study utilises the newest iteration of the database, in addition to supplemental data spanning a further 5000 years to a maximum age of 12,500 cal kyr BP, as presented in the supplemental material. Additionally, we complement the NEVA distal record with proximal records of Icelandic activity compiled from a number of sources (Óladóttir et al., 2011; Gudmundsdóttir et al., 2012, 2016; Harning et al., 2018a), including terrestrial and marine shelf data.

In Fig. 1, we identify three periods in which volcanic activity appears to decline, ending in three tephra minima at 8.3 to 8 cal ka, 5.2 to 4.9 ka, and 3.7 to 3.4 ka. In each instance, the number (n) of tephra layers found in western Europe decreases by between 50 and 60% from previous levels. These declines correlate strongly with periods of rapid temperature decrease, as inferred from variations in ^{18}O isotopes from the GISP2 Greenland cores (Andersen, 2004). In addition this manuscript utilises combined Icelandic sediment accumulation rates and lacustrine C:N ratios (Geirsdóttir et al., 2013). There is an apparent lag period between the onset of cooling and the point of minimum volcanic activity of ~100–600

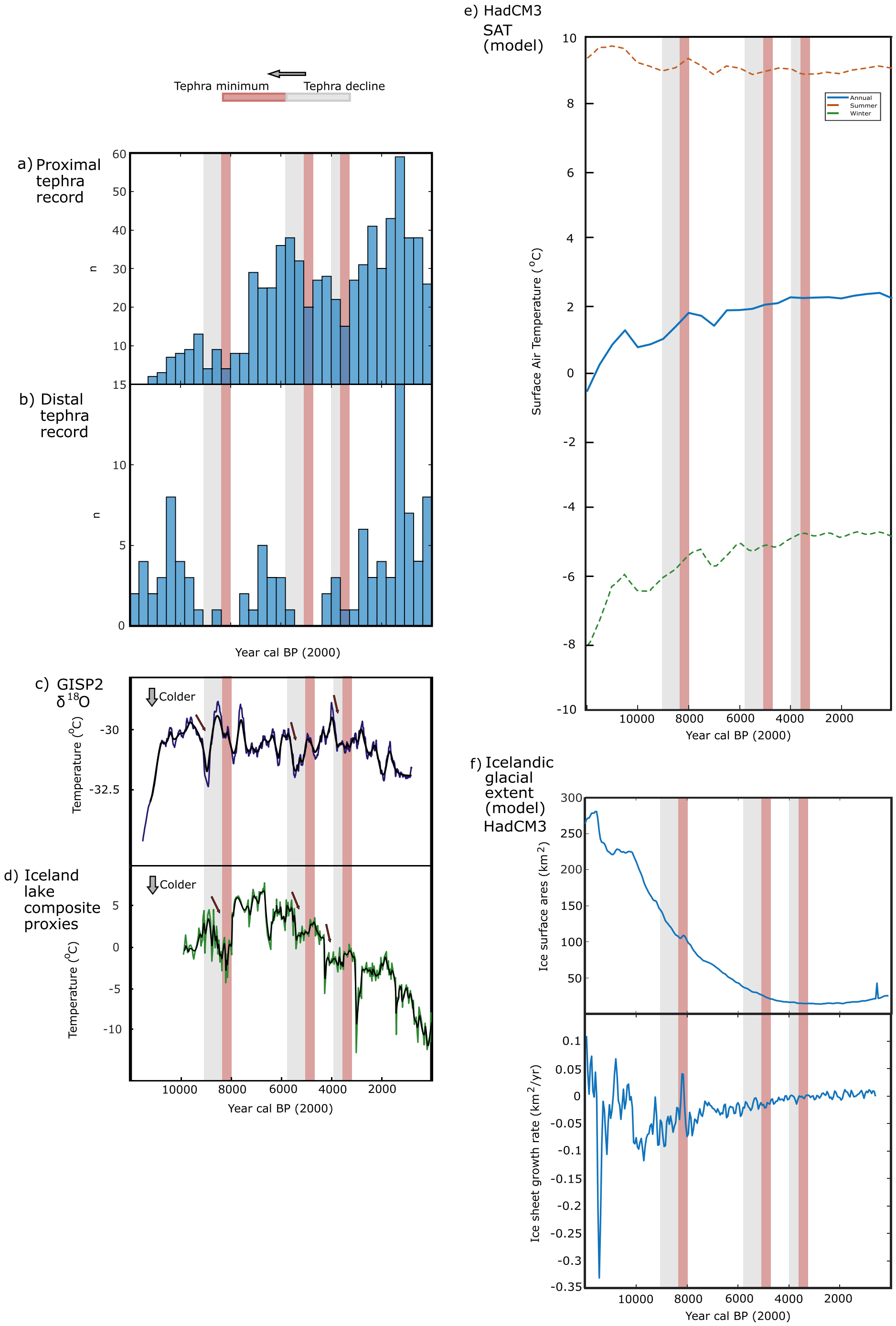

Fig. 1. a) Number (n) of Icelandic proximal tephra in 350 year bins (Óladóttir et al., 2011; Gudmundsdóttir et al., 2012, 2016; Harning et al., 2018a); b) Number of Icelandic distal tephra in 350 year bins; c) Northern Hemisphere mean temperature derived from Gaussian smoothed GISP2 $\delta^{18}O$ concentrations (Andersen et al., 2004); d) Icelandic mean temperature derived from lake composite record (Geirsdóttir et al., 2013); e) Icelandic surface air temperature (SAT) seasonal averages at 500-year resolution from HadCM3 model; f) Modelled ice sheet surface area and growth rate.

years, though the onset of volcanic quiescence typically appears to take <300 years. An apparent sharp increase in *n* that seems to be associated with cooler conditions and increased ice volume within the most recent ~1500 years is attributable to improved preservation and reduced secondary tephra transportation of within this time frame (Swindles et al., 2011, 2017; Watson et al., 2017).

The three cooling events which appear to correlate with declines in volcanic activity in Iceland are well-documented and easily observed in climate proxy records. The 8.2 ka event can be seen in climate records across the Northern Hemisphere, and has been linked to widespread influxes of freshwater melt from the Agassiz and Ojibway proglacial lakes (Alley et al., 1997; Wiersma and Renssen, 2006), although accelerated melting of the Laurentide ice sheet may provide a more plausible alternative explanation (Matero et al., 2017). This event is notable for its relatively short duration and well-constrained boundaries (Weirsma & Renssen, 2006), with the most rapid cooling occurring between ~8.3 and 8.0 ka (Quillmann et al., 2012), though many palaeoecological indicators place the initial onset of cooling at around 8.5 to 8.4 ka (Alley et al., 1997; Matero et al., 2017). Likewise, evidence for the 5.2 ka global climate event typically has distinct boundaries, and is generally recognised to be part of a larger trend of climate change spanning from 6 to 5 ka (Roland et al., 2015). While the data concerning a climatic event around 4.3 to 3.4 ka is less coherent, multiple sources suggesting abrupt shifts to globally drier, cooler conditions within that period (such as low-latitude drought conditions (Hoerling & Kumar, 2003), changes to Northern Hemisphere ocean-atmospheric circulation regimes (Bond et al., 2001; Booth et al., 2005; Roland et al., 2014), and lake-level changes around the Mediterranean (Magny et al., 2009)) are often collected under the banner of the 4.2 ka event. These signals are generally recognised to reflect a spatially complex but overall consistent pattern of cooling in Europe.

Efforts to determine the underlying factors controlling volcanic and rifting activity in Iceland are often complicated due to uncertainties regarding sporadic rifting rates and mantle plume activity (Larsen et al., 1998; Jones et al., 2002). While periodic variations in magma supply have previously been linked to localised changes to volcanic activity, typically affecting volcanic systems within specific areas (for example, synchronous decreases in activity at several volcanic centres beneath Vatnajökull attributed to a decrease in local magma generation (Óladóttir et al., 2011)), such a widespread and spatially uniform response across multiple volcanic systems suggests the influence of large-scale external forcing.

3.2. *Analysing the glacial loading effect in Iceland*

The principle behind the so-called 'unloading effect' relies on isostatic adjustment following glacial growth or retreat, with subsequent impacts on subsurface geothermal and mechanical regimes (Jull and McKenzie, 1996; Schmidt et al., 2013) (see Fig. 2). Under this hypothesis, a reduction in glacial loading would reduce the vertical pressure on both deep and shallow magma storage, resulting in greater quantities of melt (Jull and McKenzie, 1996; Schmidt et al., 2013), potentially increasing the connectivity of the magma 'plumbing' system at depth (Eksinchol, 2019), thereby increasing the depth of volatile exsolution leading to explosive eruptions (Swindles et al., 2018a). It therefore follows that the reverse scenario may hold true – that an increase in glacial loading would cause compression, and that this could effectively reduce the likelihood of an explosive eruption.

In order to test this reciprocal hypothesis against the observed tephrochronological results, we model Holocene and Late Glacial Icelandic ice sheet coverage and palaeoclimate. The model of ice extent is a three-dimensional, thermomechanically coupled simulation adapted from Hubbard (2006), relying on sub-glacial topography, bathymetry, geothermal heat flux and surface temperature (Hubbard, 2006; Hubbard et al., 2006). Palaeoclimate is derived from HadCM3 equilibrium-type climate simulations performed at 1 ka intervals 26 to 21 ka and 500-year intervals 21 to 0 ka, broadly following the PMIP4 last deglaciation protocol (Ivanovic et al., 2016). See 'Methods' for further information.

From the climate simulations, we infer a decrease in mean Icelandic summer surface air temperatures (SAT) of between 0.2 and 0.5 °C approximately concurrently with two of the indicated periods, in agreement with previously published works (Geirsdóttir et al., 2009; Morris et al., 2018). In the case of the tephra minimum observed between 8.3 and 8.0 ka, the model suggests an initial onset of cooling between 10 and 9.5 ka, with a temperature minimum between 9.5 and 9.0 ka. A

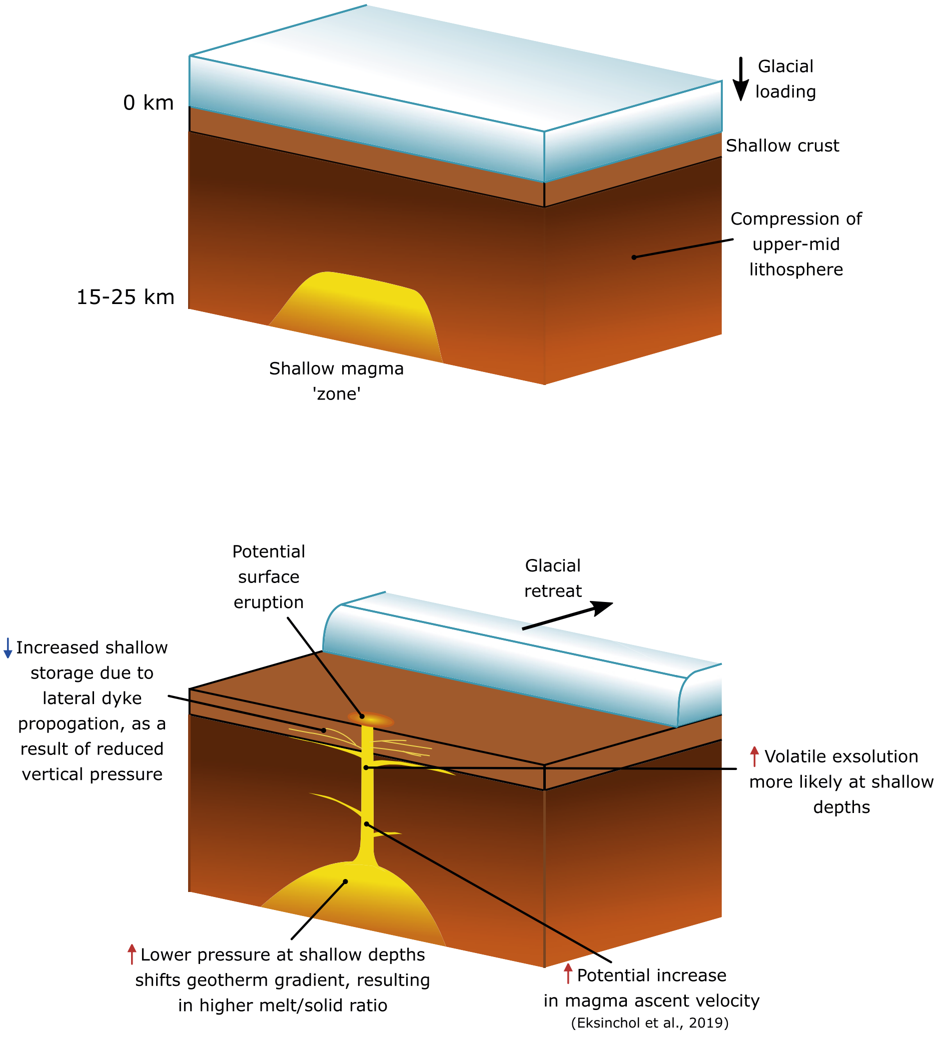

Fig. 2. Conceptual model of ice sheet unloading on a volcanic system. In a subglacial system, the overlying weight causes compression of the upper crust, which is subsequently released when the ice sheet (or glacier) retreats. Peripheral volcanic systems then undergo decompression and a potential rapid increase in melt production, significantly increasing the potential for surface eruptions.

decrease in recorded distal tephra layers is apparent from approximately 10 ka to the 8.0 ka minimum. However, as the proximal record becomes inherently less reliable towards the early Holocene (Swindles et al., 2011; Watson et al., 2017), this trend is difficult to corroborate. The temporal resolution of the climate simulations does not resolve abrupt climate fluctuations such as the 8.2 climatic event in Iceland (Geirsdóttir et al., 2013), which suggests that the observed decline in volcanic activity may be related to a longer-term trend of cooling and ice sheet advance in the early Holocene (Geirsdóttir et al., 2009; Morris et al., 2018). However, the higher-resolution glacial model records a sharp increase in ice sheet growth rate from a trend of slow retreat to an expansion at the rate of ~0.05 km^2/yr coinciding with the tephra minimum at 8.2 ka, indicating an abrupt cooling event which may have precipitated a near-immediate (on the order of a century or less) quiescent response from the volcanic systems.

Further decreases in average summer and winter temperatures are recorded between 6.0 and 5.5 ka, where the climate model indicates an average normalised temperature decrease of ~0.3 °C in both summer and winter seasons (see Fig. 1). The lacustrine and isotope proxy records for this time show a period of cooling of a slightly lower magnitude compared to the 8.2 ka event (~0.3–2.0 °C compared with ~0.7–3.0 °C) over a more sustained period – approximately 500 years compared to 100–200 years. This lengthened timescale of cooling may account for the apparent ‘lag time’ observed between the onset of cooling and the identified tephra minimum. Previous studies have suggested a delay of 500–600 years (Swindles et al., 2018a) between climatic cooling and volcanic response for this event, which is consistent with our results.

Conversely, the climate model records no significant temperature fluctuation associated with the suggested tephra minimum between 3.7 and 3.3 ka. Likewise, the climate proxies for this period provide significantly less convincing evidence for a coherent pattern of substantial cooling. Therefore, while an apparent decline in volcanic activity is evident in the proximal and distal tephra record for this period, this signal may have instead been caused by non-climatic or non-isostatic factors, such as changes to the regional tectonic or magmatic regimes (Jones et al., 2002; Pagli and Sigmundsson, 2008). Additionally, the climate model indicates an abrupt cooling period at around 7 ka. However, there is little physical evidence to support this in the documented proxies (Óladóttir et al., 2011; Gudmundsdóttir et al., 2012, 2016; Harning et al., 2018a). This period in fact coincides with current estimates for the Holocene Thermal Maximum in Iceland (Caseldine et al., 2006; Knudsen et al., 2008), suggesting that this data point may be a result of the local climatic conditions are not well represented in the model at this time and may therefore be discounted.

4. Discussion and conclusions

Our results indicate that a glacial control on volcanic activity in Iceland remains theoretically possible, and may be present in the European stratigraphic and palaeoclimate record. Furthermore, we suggest that the magnitude and rapidity of any climate cooling and subsequent glacial loading event would be a strong factor in determining the response time of underlying volcanic systems regarding the onset of quiescence. It follows that the importance of this factor would be as high for a suggested relative increase in volcanic eruption frequency following warming and glacial retreat (Jull and McKenzie, 1996; Licciardi et al., 2007; Sigmundsson et al., 2010; Swindles et al., 2018a). Regional studies focusing on volcanic systems following the last deglaciation (21–12.5 ka) indicate increases in productivity that range from a decadal scale subsequent to local ice retreat (Maclennan et al., 2002; Praetorius et al., 2016) to a multi-centennial scale across regional volcanic systems (Huybers and Langmuir, 2009; Watt et al., 2013). Fig. 3 shows a simplified model of shallow melt ascent, wherein, following a fifty-year offset period after the onset of warming to allow for glacial response, an initial subglacial melt ascent rate of 30 m/yr

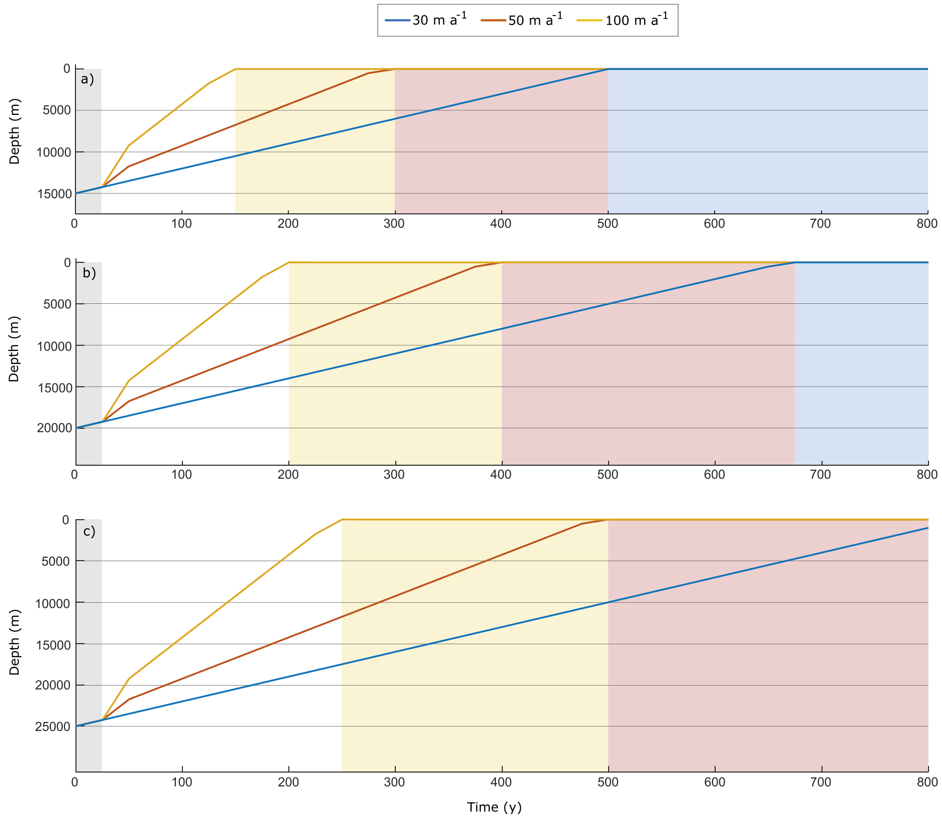

Fig. 3. Depth-time models of magma ascent for shallow bodies at a) 15 km, b) 20 km, and c) 25 km depth. Allowing for a steady state of glaciation (grey) for 50 yrs following climate perturbation, the melt ascent velocity is then increased to 50 m a-1 (red) or 100 m a-1 (yellow), or remains constant at 30 m a-1. The corresponding colour screens indicate the period in which each condition would allow melt to be transported to the surface, i.e. the ‘lag time’ of melt transport.

(Eksinchol et al., 2019) is increased to 50 m/yr and 100 m/yr, according to current estimates of melt ascent rate (Eksinchol et al., 2019). These 'melt ascent' figures may be viewed as an amalgamation of dyke and conduit transport, shallow melt production within sill storage regions, and influx of magma from depth (Schmidt et al., 2013; Eksinchol et al., 2019). These estimates support a centuries-scale response time of existing magma bodies between 15 and 25 km depth. This suggests that the more immediate (<100 year) response observed to more rapid, higher-magnitude cooling events (Maclennan et al., 2002; Praetorius et al., 2016) such as the 8.2 ka event in this study may either represent a much more significant mobilisation of magma, either through increased upwelling due to decompression (Eksinchol et al., 2019) and/or enhanced melt production (Jull and McKenzie, 1996; Schmidt et al., 2013), or represent a rapid utilisation of very shallow (>15 km) pooled magma stored in the crust during glaciation (Maclennan et al., 2002; Watt et al., 2013).

However, there are a number of factors which still cast doubt on the validity of this theory. While the combination of proximal and distal tephra records may represent the most accurate reconstruction of Icelandic volcanism currently possible (Swindles et al., 2018a) it has been noted that the preservation of prehistoric eruption material decreases dramatically with even short distances from the volcanic source (Thordarson and Höskuldsson, 2008). The unreliable preservation of ashfall material in glaciated Northern Hemisphere regions has previously been highlighted in Cooper et al. (2019), introducing significant uncertainty into the reconstruction of age-distribution patterns of volcanic events. Atmospheric perturbations, ground conditions, and erosion/deposition regimes during various climate periods may all affect the completeness of the tephra record, influencing the accuracy of any frequency reconstruction based on these data. Therefore, while the current compilation of sedimentary records may show variation in favour of the unloading theory, it is possible that the inclusion of events which were not preserved (either due to eruption parameters not favouring tephra production or due to failure to incorporate into local sedimentary records) would change the current understanding of the distribution of Icelandic volcanism through time.

Additionally, there are many instances where it is clear that rapid-onset or high-magnitude cooling events do not coincide with decreases in volcanic activity. One pertinent example is the Little Ice Age (1300–1890 AD), which is known to have caused significant glacial advance in Iceland, particularly in the late eighteenth to early nineteenth century (Chenet et al., 2010), but which is not reflected in the tephra records. Multiple other cooling periods during the Holocene, for example at 7, 4.2, and 3 ka (Geirsdóttir et al., 2013) show a similar lack of response by the Icelandic volcanic systems, indicating that, if a climatic control on volcanic activity does exist in this region, it is not often the dominant controlling factor in suppressing volcanism.

In conclusion, while there may be evidence to continue to support the existence of the unloading theory in Iceland, the current degree of uncertainty regarding the timings and magnitude of fluctuating volcanic activity in this region means that caution must be exercised before firm conclusions may be drawn.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

C.L. Cooper acknowledges a Leeds Anniversary Research Scholarship in addition to a Climate Research Bursary awarded by the University of Leeds held during the course of this study. The contribution from R.F. Ivanovic was partly supported by a Natural Environment Research Council (United Kingdom) Independent Research Fellowship (NE/K008536/1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.qsa.2020.100004.

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