Author(s)/Höf.:

Freysteinn Sigmundsson, Michelle Parks, Halldór Geirsson, Fabien Albino, Peter Schmidt, Siqi Li, Finnur Pálsson, Benedikt G. Ófeigsson, Vincent Drouin, Guðfinna Aðalgeirsdóttir, Eyjólfur Magnússon, Andy Hooper, Sigrún Hreinsdóttir, John Maclennan, Erik Sturkell, Elisa Trasatti

Title/Titill:

Influence of climate change on magmatic processes: What does geodesy and modelling of geodetic data tell us?

Year/Útgáfuár: 2024

Version/Útgáfa: Pre-print, samþykkt ritrýnt handrit

Please cite the original version:
Vinsamlega vísið til útgefnu greinarinnar:

Sigmundsson, F., Parks, M., Geirsson, H., Albino, F., Schmidt, P., Li, S., Pálsson, F., Ófeigsson, B. G., Drouin, V., Aðalgeirsdóttir, G., Magnússon, E., Hooper, A., Hreinsdóttir, S., Maclennan, J., Sturkell, E., & Trasatti, E. (2024). Influence of climate change on magmatic processes: What does geodesy and modeling of geodetic data tell us? Í *GNSS Monitoring of the Terrestrial Environment: Earthquakes, Volcanoes and Climate Change* (bls. 287-299). Elsevier. https://doi.org/10.1016/b978-0-323-95507-2.00013-x

Influence of climate change on magmatic processes: What does geodesy and modelling of geodetic data tell us?

Freysteinn Sigmundsson[1], Michelle Parks[2], Halldór Geirsson[1], Fabien Albino[3], Peter Schmidt[4], Siqi Li[1,*], Finnur Pálsson[1], Benedikt G. Ófeigsson[2], Vincent Drouin[2], Guðfinna Aðalgeirsdóttir[1], Eyjólfur Magnússon[1], Andy Hooper[5], Sigrún Hreinsdóttir[6], John Maclennan[7], Erik Sturkell[8], Elisa Trasatti[9]

1. Institute of Earth Sciences, Science Institute, University of Iceland
2. Icelandic Meteorological Office
3. ISTerre, France
4. University of Uppsala, Sweden
5. COMET, University of Leeds, UK
6. GNS Science, New Zealand
7. University of Cambridge, UK
8. University of Gothenburg, Sweden
9. INGV, Istituto Nazionale di Geofisica e Vulcanologia, Italy

* Now at: Institute of Geophysics, China Earthquake Administration, China

Abstract

Anthropogenic global climate change is causing ice mass loss in all glacierized regions in the world. Iceland provides conditions that make it an efficient laboratory to study the effects of retreating glaciers on magmatic activity, as retreating glaciers currently cover approximately 10% of Iceland and 50% of its active volcanoes. Retreat of glaciers results in unloading and glacial isostatic adjustment as observed well in Iceland by extensive GNSS (Global Navigation and Satellite System) and Interferometric Synthetic Aperture Radar (InSAR) geodetic measurements. The unloading results in more magma being generated in the mantle through decompression melting. It also induces stress changes in the crust that may affect magma migration and the stability of existing magma bodies. Large uncertainties are involved in evaluating the effects, as they depend on many factors such as the detailed structure of magmatic systems and the rheology of host rock and magma.

1. Introduction

Glacier mass loss due to due to anthropogenic climate change is now occurring in all glacierized regions in the world (e.g., Fox-Kemper et al., 2021, IPCC, 2021; Hugonnet et al., 2021; Zemp et al., 2019; Björnsson et al., 2013, Aðalgeirsdóttir et al., 2020). The ice mass loss affects not only volcanoes covered by retreating glaciers, but also volcanoes up to considerable distances away from retreating glaciers. A one metre reduction of ice, with a density of 910 kg/m^3, corresponds to a normal stress change on the surface of the Earth of (910 kg/m^3) × (9.8 m/s^2) × (1 m) = 9 kPa. This pressure change effect decays with depth in the crust and mantle, dependent on the width of the surface load involved. Pressure change also occurs outside the extent of the unloading involved. At depth where magma is generated and stored, the effect may be on the order ~1 kPa/yr. If ice retreat continues over decades and begins to correspond to load change of tens of meters or more over considerable areas, then influence on subsurface magmatic processes may be anticipated. We here evaluate how GNSS measurements contribute to the improved understanding of the effect of ice unloading. We use Iceland as a laboratory as glaciers cover ~10% of Iceland and have generally been retreating since ~1890 (Björnsson et al., 2013; Aðalgeirsdóttir et al., 2020).

There is considerable evidence for variations in loads on the surface of the Earth affecting magmatic activity. On a global scale, periodicities in glaciations, according to Milankovitch cycles, have also been identified in tephra records and phase shifts between the glacial and volcanic records suggest a peak in volcanism during deglaciation. However, these records are noisy and the correlation coefficients identified are generally too low for precise constraints on the relative timing (Kutterolf et al., 2019). Global sea level change has also been suggested to influence magmatic activity (McGuire et al., 1997; Crowley et al., 2015). On a more local scale, an anti-correlation has been found between volcanism and glaciations in California for the last 800,0000 years, indicating volcanism has been modulated by changes in climate (Glazner et al., 1999). A further study of correlation of timing of volcanic activity and growth and retreat of glaciers in California found a statistically significant cross correlation between changes in eruption frequency and the first derivative of the glacial time series, implying that the temporal pattern of volcanism is influenced by the rate of change in ice volume (Jellinek et al., 2004). Variations in recent surface load variation on Earth have also been suggested to modulate magmatic activity, such as the observation that the 2011-2016 uplift (mapped with GNSS geodesy) of the Long Valley caldera during a period of drought was much faster than drought-induced rebound of surrounding terrain, suggesting that the removed load may have caused decompression and magmatic inflation in the Long Valley Caldera magmatic system (Hammond et al., 2019).

One of the strongest pieces of evidence for glacial retreat influencing magmatic processes comes from studies of environmental conditions and eruption activity at the end of the last glaciation in Iceland. During the Weichselian glaciation (~70 kyr BP to ~12 kyr BP), Iceland was covered by a >300 km wide ice sheet that was depressing the surface and causing downward flexure (Sigmundsson, 1991). By the end of the Pleistocene, widespread deglaciation reversed this process causing the Earth's surface to rebound in response to ice loss. As a result, a major increase in volcanic activity occurred in Iceland (e.g. Slater et al., 1998), with a 30-50 fold increase in eruption rates and change in chemical signature of extruded lavas (e.g., Sigvaldason et al., 1992; Maclennan et al., 2002). Jull and McKenzie (1996) could fit this observation with a model of the effect of deglaciation on magma generation.

There are over 30 active central volcanoes in Iceland, half of which lie beneath glaciers (Fig. 1). Volcanism results from the interaction of the plate spreading and a hotspot (hotspot-ridge interaction). In Iceland, the N-American and Eurasian plates diverge at ~19 mm/yr. Excessive mantle upwelling occurs in a mantle plume beneath Iceland. The interaction of a spreading ridge and upwelling of anomalously hot material within the mantle has formed Iceland. As Icelandic glaciers are retreating fast (Aðalgeirsdóttir et al. 2020; Belart et al. 2020), it may thus only be a matter of time when deglaciation again affects eruptive activity here – with the potential for more frequent or larger eruptions. Furthermore, modulation of the crustal stress in response to the changing surface load may affect seismicity with implications for changes in the long-term seismic hazard. This needs to be understood in the overall context of volcanism and glaciations, that are responsible for shaping Iceland (e.g., Sigmundsson et al., 2020).

Present day retreat of the glaciers in Iceland is causing the Earth's surface to rebound in response to unloading of the ice, by the process of glacial isostatic adjustment (GIA), on timescales ranging from seasonal to centurial. GIA is here taken to include both the viscoelastic response of the Earth, as well as the instantaneous elastic response to load changes. GIA in Iceland is well observed by GNSS (Global Navigation and Satellite System) and Interferometric Synthetic Aperture Radar (InSAR) geodetic measurements; the central part of Iceland is uplifting at rates of >30 mm/year as a result of ongoing GIA (e.g. Árnadottir et al., 2009; Compton et al., 2015; Drouin and Sigmundsson, 2019).

The glacier mass loss modifies the stress field in the crust and upper mantle and may alter volcanic activity in three ways (Fig. 2) (Sigmundsson et al., 2010; 2013): i) Increases melt generation at depth due to decompression (Jull and McKenzie, 1996; Pagli and Sigmundsson, 2008, Schmidt et al., 2013). ii) Influences magma migration (e.g. Hooper et al., 2011). iii) Affects the stability of magma bodies – bringing a volcano either closer to, or further from failure (Albino et al., 2010). In the latter case, larger volumes of melt need to accumulate before an eruption is triggered, which can increase the hazards of an eruption.

A recent review of these and other effects of climate change on volcanoes is given by Aubry et al. (2022). Here, we consider the role of geodetic measurements, in particular GNSS observations, for providing an estimate of the effects on magma plumbing systems.

2. Ongoing glacier load changes at volcanoes

The subsurface climate change effect on volcanoes is due to load changes taking place at retreating ice caps. To estimate the effects, an estimate of load changes is needed. A global study by Hugonnet et al. (2021) spanning 2000-2019 has revealed accelerated retreat of glaciers in many regions of the Earth, and that in general thinning rates of glaciers outside ice sheet peripheries doubled over the study period. However, there are contrasting glacier fluctuations in different parts of the world. Areas of major glacier retreat in volcanic regions include Iceland, Alaska and the Southern Andes (Fig. 3).

In Iceland, global warming due to anthropogenic climate change has resulted in mass loss of the glaciers in Iceland since ~1890. The loss of 540±130 gigatonnes (Gt) or 16±4% of the 1890 volume has been estimated for all glaciers in Iceland for the period ~1890-2019 (Fig. 3) and half of this mass loss occurred in 1995-2019 (Aðalgeirsdóttir et al., 2020). The largest ice cap, Vatnajökull, has lost most ice. Projections for the other main ice caps of Iceland, Hofsjökull and Langjökull indicate that they will likely disappear within the next 150 to 200 years (Björnsson & Pálsson, 2008; Aðalgeirsdóttir et al., 2006). Simulations for Vatnajökull indicate that it may lose up to 80-90% of its volume by 2300, depending on climate scenarios (Schmidt et al., 2019).

The rate of reduction in surface loading due to climate change in Iceland has varied with time in the period since 1890, including a time period when the retreat temporarily halted (Fig. 3). Temperature records, glacier mass balance observations (both in-situ and geodetic), GNSS observations of ice elevation change, and modelling indicate significant glacier fluctuations in the last century, with increased mass loss in the 1930s-1950s, near zero or positive balance in 1960s-1980s and increased mass loss again after mid-1990s, as well as large inter-annual variability (e.g. Björnsson et al., 2013; Belart et al., 2020; Aðalgeirsdóttir et al., 2020).

The assumption of constant deglaciation rates for the whole 20th century has been found to yield a reasonable fit to the observed long term, nation-wide, GIA signal in Iceland in earlier studies (e.g., Árnadóttir et al., 2009). However, studies of more recent GIA deformation with increasing spatial and temporal resolution display notable variations in

GIA deformation rates (e.g. Compton et al., 2015), and indicate the assumption of constant rate of ice mass reduction is insufficient and in need of updating (e.g. Drouin and Sigmundsson, 2019). It is important to better understand these variations and analyse further if the immediate elastic response to load changes is larger than previously considered.

3. Uplift and deformation of volcanoes due to climate change and magma movements

Extensive continuous GNSS observations (cGNSS) in Iceland and InSAR observations have revealed the ongoing rise of Iceland (Fig. 4). Vertical velocities have been interpreted in a series of GIA models. However, an updated model considering the newest set of observations is though needed. A few examples of the vertical component of deformation at continuous GNSS (cGNSS) stations is shown in Fig 5. A station at Jökulheimar (JOKU) has uplifted about 70 cm in the last three decades. The station is within the volcanic zone of Iceland, but far from central volcanoes. The inferred uplift is due to GIA. The initial observed uplift rate in the 1990s was significantly lower than for the later period. The temporal pattern can though not be described as a steady acceleration until present, rather there are some fluctuations in the uplift rate. The slow initial rate occurs in a time period when there was a pause in the ice loss of the nearby Vatnajökull ice cap.

Although the vertical displacement of station JOKU is dominated by GIA, the horizontal displacement is not. The station is within the plate boundary deformation zone at the boundary of the North American and Eurasian plates. The difference in east component of the displacement at this site and the Höfn (HOFN) site in SE-Iceland shows mostly the effect of plate spreading (Fig. 6). When interpreting regional deformation fields, it is thus evident one has to consider both GIA and plate movements.

An example of a station where volcano deformation is superimposed on GIA and plate movement is shown in Fig. 7, at the Grímsvötn volcano. Such superposition of displacement components originating from different sources provides challenges for interpretation.

4. Modelling the effects

4.1 Decomposing observed deformation fields to infer GIA and volcano processes

The observed ground displacement field in a volcanic region influenced by glacial retreat is influenced by at least three processes, that can influence to a varying degree: (i) GIA, (ii) plate movements, (iii) magmatic processes. If the respective velocities at a GNSS site are v_{GIA}, v_{PS}, and v_{volcano}, then the observed velocity, v_{observed}, can be expressed as:

$$v_{\mathrm{observed}} = v_{\mathrm{GIA}} + v_{\mathrm{PS}} + v_{\mathrm{volcano}} + v_{\mathrm{noise}} \quad (1)$$

where the last term represents the noise. Here, v_{volcano} can include for example the deformation caused by magma movements and viscoelastic response due to previous volcanic processes. The velocity due to plate movemeents, v_{PS}, may be constant over a study area if it is an intraplate volcano, but varies a across a study area if it is within a plate boundary deformation zone. v_{noise} is the noise in the observation data as well as unmodeled deformation. In order to evaluate volcano deformation, there is the need to decompose observed deformation into these components. Therefore, as GIA may play an increasing role as glacial retreat continues, then climate change has an influence on how to model volcano processes from GNSS data. Most GIA models are of global nature and do not consider well contributions from retreating ice caps covering volcanoes. Iceland is an exception. Due to low asthenospheric viscosity, the main GIA signal is due to present-day retreat of the Icelandic ice caps, that has been mapped. However, experience shows that GIA signals may rapidly change with time, and one has to consider the possibility that observed deformation in a particular time window is not well described by a previously existing GIA model. A preferred approach is to evaluate a GIA model which is most up to date for the time period considered, but this may not be feasible. Another approach, less favourable, is to scale a previously existing GIA model to reproduce better observations (e.g., Geirsson et al., 2012). Long time series of GNSS observations are then particularly valuable for the decomposition of observed deformation fields. An example of this procedure is shown in Fig. 8, from a study by Li et al. (2021). In this study, GIA was corrected using a scaled model from Auriac (2014) and the plate spreading correction uses a model by Drouin and Sigmundsson (2019), before analysing the local volcano deformation.

When modelling the effects of load changes on magmatic systems, there is the need to initially map the crustal deformation field in the area. Once data has been analysed and time series of change are available, one should consider how plate movements contribute to these time series. Then here is the need to consider a GIA model that in essence captures the role of load changes in producing ground displacement, over a wide area surrounding the volcanic region of interest, so the associated subsurface stress changes can be realistically modelled. Thereafter, one can proceed to model local volcano deformation sources. The selection of appropriate rheology to include is important to derive realistic information on what is happening in volcano interiors; the assumption of elastic behaviour may only be appropriate when modelling deformation on short time scales. The shape, depth and size of magma bodies in volcano roots will have an effect on how ice retreat influences magmatic systems. Determining these is extra challenging in volcanic regions affected by GIA. If GIA signals are not accounted for, this can lead to issues for derived volcano models, for example on the determination of volume change related to magma inflow. When a new period of inflation begins at a volcano undergoing GIA it is important to have an estimate of the GIA signal, so the signals due to magmatic processes at depth can be properly determined.

4.2 Influence on magma generation

Modeling has demonstrated that both the increase in magma volume and the chemical signature of the lavas can be explained by decompressional melting, due to the stress changes in the mantle resulting from the reduction in surface loads (Jull and McKenzie, 1996; Maclennan et al., 2002; Eksinchol et al., 2019), but uncertainties remain (Cooper et al., 2020).

To evaluate the effect of pressure release on magma generation, one has to consider how mantle melting takes place under volcanoes in general. A large volume of magma within the Earth is generated by decompression melting, when hot mantle material upwells. The upwelling leads to pressure decrease, and if the mantle is warm enough then magma is generated. For each volcanic region on Earth, there is the need to couple a model of a pressure change inferred from a GIA model, with a mantle melting model. The total melting rate in a mantle undergoing both upwelling as well as GIA response can be written as the material derivate of *F*, the melt fraction by weight:

$$\frac{DF}{Dt} = \left(\frac{\partial F}{\partial P}\right)_S \left(\frac{\partial P}{\partial t} + \overline{\mathbf{V}} \cdot \nabla P\right) \tag{2}$$

Here *P* is pressure, *T* temperature, ∂P/∂t is the in situ pressure change due to GIA decompression, and the last term is the pressure change due to upwelling, with **V** being the velocity vector of the solid matrix. $(\partial F/\partial P)_S$ is the partial derivative of the degree of melting with respect to pressure at a constant entropy. This equation needs to be evaluated within a melting regime in the mantle (Fig. 9). Schmidt et al. (2013) expanded on the work of Pagli and Sigmundsson (2008) and Árnadóttir et al. (2009), by combining the subsurface stress-field from a revised 3D GIA model with a model of mantle melting in the Icelandic mantle. Their study showed that glacially induced pressure changes in the mantle increase melt production rates by 100–135%, or an additional 0.21–0.23 km^3 of magma per year beneath Iceland.

There is, however, a large uncertainty in if, how and when this magma reaches the surface, because it has to travel from the melting region, spanning the depth from the base of the lithosphere and potentially down to 250 km, all the way up through the lithosphere. The bulk of volatile-free melting under Iceland takes place between about 120 km depth and the base of the crust (Matthews et al., 2016), and the arrival of the generated melt to the surface will be delayed. Studies of Icelandic basalts have indicated melt ascent velocities ranging from 30 m/yr to more than 1 km/yr (e.g. Maclennan et al., 2002; Eksinchol et al., 2019) where the upper range implies additional magma generated by ongoing GIA would constitute an increasingly significant contribution to melt supply of magmatic systems in Iceland at present (Fig. 9). However, alternate views have been presented, suggesting a time scale of hundreds of years between perturbations in climate and volcanic activity (Swindles et al., 2018).

4.3 Influence on magma emplacement

In addition to increased magma generation, stress changes associated with ice retreat can also alter the capacity for storing magma within the crust. A magma intrusion in 2007-2008 at Upptyppingar to the north of the Vatnajökull ice cap, aligned almost perpendicular to the zone of plate spreading, and was inferred to be under the influence of ice unloading (Hooper et al., 2011). Using numerical modelling, Hooper et al. (2011) estimated the direction of maximum extensional stress acting on the dike. They also modelled the effect of the of ice load decrease since 1890 on the stress field. They concluded that the direction of maximum extensional stress had been rotated by ice mass change from the direction expected from plate spreading alone, leading to enhanced capture of magma within the crust.

While the effect of ice retreat for this off-rift dike was to increase capacity for magma storage, Hooper et al (2011) also calculated the effect it would have for dikes intruded perpendicular to the direction of plate spreading, such as the latter part of the dike that propagated from Bárðarbunga in 2014. They found that for dikes with this orientation, the capacity for storage is decreased. As dikes intruded in the rift zones are usually oriented in this manner, the overall effect of ice retreat on the capacity for magma storage in the crust is likely to be a decrease, leading to an increase in erupted volumes.

4.4 Influence of ice retreat on stability of shallow magma bodies

Numerical models, e.g. using the Finite Element Method, are needed to quantify the stress changes caused by the modulation of ice cap loading and to evaluate its effect on the stability of the shallow magma reservoirs (Albino et al., 2010). The aim of such models is to evaluate how external processes modify host rock stresses and consequent effects on the stability of magma bodies, by enhancing or preventing the initiation of an intrusion emanating from a magma body. The model results will also depend on the failure criterion used.

Initially, one can consider an axi-symmetrical geometry: the magma body in the crust is modelled as an ellipsoidal cavity with a given overpressure (ΔP_m) and the glacier changes are modelled as an unloading disk applied at the surface (ΔP_s). One thus needs an estimate of the glacial retreat, as well as an indication of shape, size and depth of the magma body (Figure 10). To undertake modelling of such processes, there is the need to furthermore assume a rheology for the model domain (the host rock), as well as a failure criteria. Simplest models assume the host rock medium is elastic and homogeneous. Numerical models of this type show that a surface unloading causes: i) a decrease of the overpressure within a magma body, with the amplitude depending on the shape of the reservoir and the compressibility of the magma; and ii) a change (increase or decrease) of the failure pressure (ΔP_f), the pressure required to initiate an intrusion; the sign of the change depends on the shape of the reservoir as well as the spatial distribution of the unload.

A model as described above has been applied to the subglacial Katla volcano, located under the Mýrdalsjökull ice cap in S-Iceland. The most recent confirmed eruption at Katla breaking the ice cover, with explosive activity and tephra fall, occurred in 1918. An ice unloading model for the area, spanning a 5-years period between 1999 and 2004, has both a seasonal surface snow load change between summer and winter with a maximum amplitude up to 6 meters at the center of the Mýrdalsjökull ice cap superposed on a long-term thinning of -4 meters along the edges of the ice cap during the period 1999 to 2004 (Pinel et al., 2007).

These surface pressure changes correspond to stress changes of 40-60 kPa that is the same order of magnitude as static stress changes observed for earthquake triggering (King et al., 1994).

In addition to the ice loading model, a model for the magmatic system is required. For a shallow magma body under Katla, Albino et al. (2010) model a radially symmetric molten magma body of oblate sill-shaped geometry (half-width= 2.5 km and half-height=0.5 km) with the center located at 3 km below the surface based on the results of 2D seismic surveys (Gudmundsson et al., 1994). Using model set up like this, Albino et al. (2010) found that the seasonal unloading at Mýrdalsjökull between winter and summer induces a decrease in magma pressure ΔP_{m} of 30 kPa (considering a magma bulk modulus of 10 GPa) and a decrease in failure pressure ΔP_{f} of 45 kPa. Because $|\Delta P_{m}|<|\Delta P_{f}|$, the magma body moves closer to failure conditions by an amount of 15 kPa during unloading periods (spring-summer). If the failure criteria for onset of magma movements relates, *e.g.*, to tensile strength of 1-10 MPa (Haimson and Rummel F, 1982), then such modulation of stress can provide an explanation for preferred eruptions of Katla during the months from May to October when the seasonal load is reducing (from the load maximum in early summer to load minimum in late fall), as observed in historical records (Eliasson et al., 2006). Thus, provided that the volcano is already very close to failure conditions, the stress modulation resulting from seasonal unloading may become significant in terms of eruption triggering.

For the long-term thinning of the Mýrdalsjökull ice cap, the models of Albino et al. (2010) show a decrease in magma pressure ΔP_{m} of 2.4 kPa/yr and a decrease in failure pressure ΔP_{f} <1 kPa. In that scenario in which $|\Delta P_{m}|>|\Delta P_{f}|$, the reservoir moves away from failure by an amount of 1.4 kPa/yr. Thus, for this particular example, the influence of long-term thinning appears limited. However, the host rock medium does not behave purely elastic beneath Iceland due to the presence of the hot spot and the associated intense volcanism activity. If a Maxwell viscoelastic layer below 10 km depth is assumed (Fig. 2), the results are very different. Modeling presented by Sigmundsson et al. (2013) show that in such a case the magma body is moving away from failure by an amount of 8.3 kPa/yr which corresponds to about ~1 MPa over 120 years (Sigmundsson et al., 2013). This result shows that the visco-elastic response has a large influence on the long-term evolution of volcanic systems even for shallow reservoirs located in the brittle upper crust. Although the conditions to initiate an intrusion will be more difficult through time, it implies that more magma can accumulate in the reservoir prior to an eruption resulting potentially in large erupted volumes.

5. Discussion

The knowledge of the state of stress surrounding magmatic systems and more importantly its evolution is key information to better understanding the influence of climate change on subsurface magmatic processes and triggering mechanism of an eruption. Commonly, an increase of magma pressure is the driving mechanism to initiate and propagate magma intrusions towards the surface from a shallow magma body. Magma intrusions initiate when magma overpressure exceeds a mechanical threshold. The conditions of failure of magma bodies depend on the state of stress surrounding the reservoir and the tensile strength of the host rocks. As a result, external processes that modify the host rock stresses potentially modify the stability of magma reservoirs by enhancing or preventing the initiation of an intrusion. In Iceland, many of the active volcanoes are covered by glaciers, therefore the interactions between glaciers and volcanism are frequent and they have been extensively studied (e.g., Pagli & Sigmundsson, 2008; Sigmundsson et al., 2010; Hooper et al., 2011). Lessons learned in Iceland can provide guidance for evaluation of the effects of climate change on magmatic processes in other parts of the world.

6. Conclusions

GNSS observations are critical to measure GIA signals in volcanic regions and for the development of GIA models. Based on GIA models, stress and pressure changes in the crust and the mantle resulting from changes in ice loading due to climate change can be estimated. These form the basis for evaluation of increased melt generation due to climate change, as well as for estimates of eventual changes in conditions of subsurface magma emplacement and triggering effects on magmatic systems. Uncertainties in the estimates are large, and a detailed model of a magmatic system needs to be incorporated when evaluating the effects. Stress changes within and surrounding a shallow magma body, as a result of ice retreat due to climate change, may bring a magma body either closer or further from failure depending on the compressibility of the magma and the shape, size and location of it.

Acknowledgments

This work was supported by the ISVOLC project funded by the Icelandic Science Fund (project number 239615-051)..

References

Aðalgeirsdóttir G., T. Jóhannesson, H. Björnsson, F. Pálsson, O. Sigurðsson, 2006. The response of Hofsjökull and southern Vatnajökull, Iceland, to climate change. *J. Geophys. Res*., 111, F03001, doi:10.1029/2005JF000388.

Aðalgeirsdóttir, G., Magnússon, E., Pálsson, F., Thorsteinsson, T., Belart, J., Jóhannesson, T., et al., 2020. Glacier changes in Iceland from ∼1890 to 2019. *Frontiers in Earth Science, 8,* 520.

Albino, F., Pinel, V., Sigmundsson, F., 2010. Influence of surface load variations on eruption likelihood: Application to two Icelandic subglacial volcanoes, *Geophys. J. Int*, 181, 1510-1524, doi: 10.1111/j.1365-246X.2010.04603.x.

Árnadóttir, T., Lund, B., Jiang, W., Geirsson, H., Björnsson, H., Einarsson, P., Sigurdsson, T., 2009. Glacial rebound and plate spreading: results from the first countrywide GPS observations in Iceland. *Geophysical Journal International*, *177*(2), 691-716.

Aubry, T. J., Farquharson, J.I, Rowell, C. R., Watt, S. F. L., Pinel, V., Beckett, F., Fasullo, J., Hopcroft, P. O., Pyle, D. M., Schmidt, A., Staunton Sykes, J., 2022. Impact of climate change on volcanic processes: current understanding and future challenges, *Bull. Volc*., 84: 58.

Auriac, A., 2014. Solid Earth response to ice retreat and glacial surges in Iceland inferred from satellite radar interferometry and finite element modelling, Ph.D. thesis. Faculty of Earth Sciences, University of Iceland.

Belart, J., Magnússon, E., Berthier, E., Gunnlaugsson, Á. Þ., Pálsson, F., Aðalgeirsdóttir, G., Jóhannesson, T., Thorsteinsson, T., Björnsson, H., 2020. Mass balance of 14 Icelandic glaciers, 1945–2017: spatial variations and links with climate. *Frontiers in Earth Science*, *8*, 163.

Björnsson, H., & Pálsson, F. (2008). Icelandic glaciers. *Jökull*, *58*, 365-386.

Björnsson, H., Palsson, F., Gudmundsson, S., Magnusson, E., Adalgeirsdottir, G., Johanneson, T., Berthier, E., Sigurdsson, E., Thorsteinsson, T., 2013. Contribution of Icelandic ice caps to sea level rise: Trends and variability since the Little Ice Age. *Geophysical Research Letters, 40*, 1546-1550, doi: 10.1002/grl.50278.

Compton, K., Bennett, R. A., Hreinsdóttir, S., 2015. Climate-driven vertical acceleration of Icelandic crust measured by continuous GPS geodesy. *Geophysical Research Letters*, *42*(3), 743-750.

Cooper, C. L., Savov, I. P., Patton, H., Hubbard, A., Ivanovic, R. F., Carrivick, J. L., Swindles, G. T., 2020. Is there a climatic control on Icelandic volcanism?. *Quaternary Science Advances*, *1*, 100004.

Crowley, J. W., Katz, R. F,1. Huybers, P., Langmuir, C. H., Park, S-H., 2015. Glacial cycles drive variations in the production of oceanic crust, *Science*, 347, 1237-1240.

Drouin, V., Sigmundsson, F., 2019. Countrywide observations of plate spreading and glacial isostatic adjustment in Iceland inferred by sentinel-1 radar interferometry, 2015–2018. *Geophysical Research Letters*, *46,* 8046–8055. https://doi.org/10.1029/2019GL082629

Eksinchol, I., Rudge, J.F., Maclennan, J., 2019. Rate of melt ascent beneath Iceland from the magmatic response to deglaciation. *Geochemestry. Geophysics. Geosystems.*, doi 10.1029/2019GC008222.

Eliasson, J., Larsen, G., Tumi Gudmundsson, M., Sigmundsson, F., 2006. Probabilistic model for eruptions and associated flood events in the Katla caldera, Iceland. *Computational Geosciences*, *10*, 179-200.

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, et al., 2021. Ocean, Cryosphere and Sea Level Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi:10.1017/9781009157896.011

Glazner, A. F., Manley, C. R., Marron, J. S., Rojstaczer, S., 1999. Fire or ice: Anticorrelation of volcanism and glaciation in California over the past 800,000 years. *Geophys. Res. Lett.*, 26, 1759-1762.

Geirsson, H., LaFemina, P., Arnadottir, T., Sturkell, E., Sigmundsson, F., Travis, M., et al., 2012. Volcano deformation at active plate boundaries: Deep magma accumulation at Hekla volcano and plate boundary deformation in south Iceland. *Journal of Geophysical Research: Solid Earth*, *117*(B11).

Gudmundsson, O., Brandsdóttir, B., Menke, W., Sigvaldason, G. E., 1994. The crustal magma chamber of the Katla volcano in south Iceland revealed by 2-D seismic undershooting. *Geophysical Journal International*, *119*(1), 277-296.

Hammond, W. C., Kreemer, C., Zaliapin, I., Blewitt, G., 2019. Drought-triggered magmatic inflation, crustal strain, and seismicity near the Long Valley Caldera, Central Walker Lane. *Journal of Geophysical Research: Solid Earth*, 124, 6072–6091. https://doi. org/10.1029/2019JB017354

Haimson, B., Rummel F., 1982. Hydrofracturing stress measurements in the Iceland Research Drilling Project drill hole at Reydarfjordur, Iceland. *J. Geophys. Res*., 87, 6631-6649

Hooper, A., Ófeigsson, B., Sigmundsson, F., Lund, B., Einarsson, P., Geirsson, H., Sturkell, E., 2011. Increased capture of magma in the crust promoted by ice-cap retreat in Iceland. *Nature Geoscience*, *4*(11), 783-786.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L. et al., 2021. Accelerated global glacier mass loss in the early twenty-first century. *Nature*, *592*(7856), 726-731.

IPCC, 2021. Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, et al. (eds) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jellinek, A. M., Manga, M., Saar, M. O., 2004. Did melting glaciers cause volcanic eruptions in eastern California? Probing the mechanics of dike formation, *J. Geophys. Res*., 109, B09206, doi:10.1029/2004JB002978.

Jull, M., McKenzie, D., 1996. The effect of deglaciation on mantle melting beneath Iceland. *Journal of Geophysical Research: Solid Earth*, *101*(B10), 21815-21828.

King, G. C., Stein, R. S., Lin, J., 1994. Static stress changes and the triggering of earthquakes. *Bulletin of the Seismological Society of America*, *84*(3), 935-953.

Kutterolf, S., Schindlbeck, J. C., Jegen, M., Freundt, A., Straub, S. M., 2019. Milankovitch frequencies in tephra records at volcanic arcs: The relation of kyr-scale cyclic variations in volcanism to global climate changes, *Quaternary Science Reviews*, 204, 1-16

Li, S., Sigmundsson, F., Drouin, V., Parks, M. M., Ofeigsson, B. G., Jónsdóttir, K., et al., 2021. Ground deformation after a caldera collapse: Contributions of magma inflow and viscoelastic response to the 2015–2018 deformation field around Bárðarbunga, Iceland. *J. Geophys. Res. Solid Earth*, 126, e2020JB020157. https://doi.org/10.1029/2020JB020157.

Maclennan, J., Jull, M., McKenzie, D., Slater, L., Grönvold, K., 2002. The link between volcanism and deglaciation in Iceland. *Geochemistry, Geophysics, Geosystems*, *3*(11), 1-25.

McGuire, W., Howarth, R., Firth, C. *et al.* (1997) Correlation between rate of sea-level change and frequency of explosive volcanism in the Mediterranean. *Nature*, 389, 473–476.

Matthews, S., Shorttle, O., Maclennan, J., 2016. The temperature of the Icelandic mantle from olivine-spinel aluminum exchange thermometry. *Geochemistry, Geophysics, Geosystems*, *17*(11), 4725-4752.

Pagli, C., Sigmundsson, F., 2008. Will present day glacier retreat increase volcanic activity? Stress induced by recent glacier retreat and its effect on magmatism at the Vatnajökull ice cap, Iceland. *Geophys. Res. Letters*, *35*(9).

Pinel, V., Sigmundsson, F., Sturkell, E., Geirsson, H., Einarsson, P., Gudmundsson, M. T., Högnadóttir, T., 2007. Discriminating volcano deformation due to magma movements and variable surface loads: application to Katla subglacial volcano, Iceland. *Geophysical Journal International*, *169*(1), 325-338.

Schmidt L.S., Aðalgeirsdóttir, G., Pálsson, F., Langen, P. L., Guðmundsson, S., Björnsson, H., 2019. Dynamic simulations of Vatnajökull ice cap from 1980 to 2300. *Journal of Glaciology*, 66(255), 97–112.

Schmidt, P., Lund, B., Hieronymus, C., Maclennan, J., Árnadóttir, T., Pagli, C., 2013. Effects of present-day deglaciation in Iceland on mantle melt production rates. *Journal of Geophysical Research: Solid Earth*, *118*(7), 3366-3379.

Sigmundsson, F.,1991. Post-glacial rebound and asthenosphere viscosity in Iceland. *Geophysical Research Letters*, *18*(6), 1131-1134.

Sigmundsson, F., Pinel, V., Lund, B., Albino, F., Pagli, C., Geirsson, H., Sturkell, E. 2010. Climate effects on volcanism: Influence on magmatic systems of loading and unloading from ice mass variations with examples from Iceland, Special issue on climate forcing of geological and geomorphological hazards. *Phil. Trans. Roy. Soc. A*, 368, 1-16.

Sigmundsson, F., Albino, F., Schmidt, P., Lund, B., Pinel, V., Hooper, A., Pagli, C., 2013. Multiple effects of ice load changes and associated stress change on magmatic systems, In: *Climate Forcing of Geological Hazards*, Eds. Bill McGuire and Mark A. Maslin, Wiley-Blackwell, pp. 108-123.

Sigmundsson, F., Einarsson, P., Hjartardóttir, Á. R., Drouin, V., Jónsdóttir, K., Árnadóttir, T., Geirsson, H., Hreinsdóttir, S., Li., S, Ófeigsson, B. G., 2020. Geodynamics of Iceland and the signatures of plate spreading, *Journal of Volcanology and Geothermal Research*, *391*, 106436.

Sigvaldason, G.E., Annertz, K., Nilsson, M., 1992. Effect of glacier loading/deloading on volcanism: postglacial volcanic production rate of the Dyngjufjöll area, central Iceland. *Bull Volcanol* **54**, 385–392.

Slater, L., Jull, M., McKenzie, D., Gronvöld, K., 1998. Deglaciation effects on mantle melting under Iceland: results from the northern volcanic zone. *Earth and Planetary Science Letters*, *164*(1), 151-164.

Swindles, G. T., Watson, E. J., Savov, I. P., Lawson, I. T., Schmidt, A., Hooper, A., et al., 2018. Climatic control on Icelandic volcanic activity during the mid-Holocene. *Geology*, *46*(1), 47-50.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., et al., 2019. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, *568*(7752), 382.

Figures

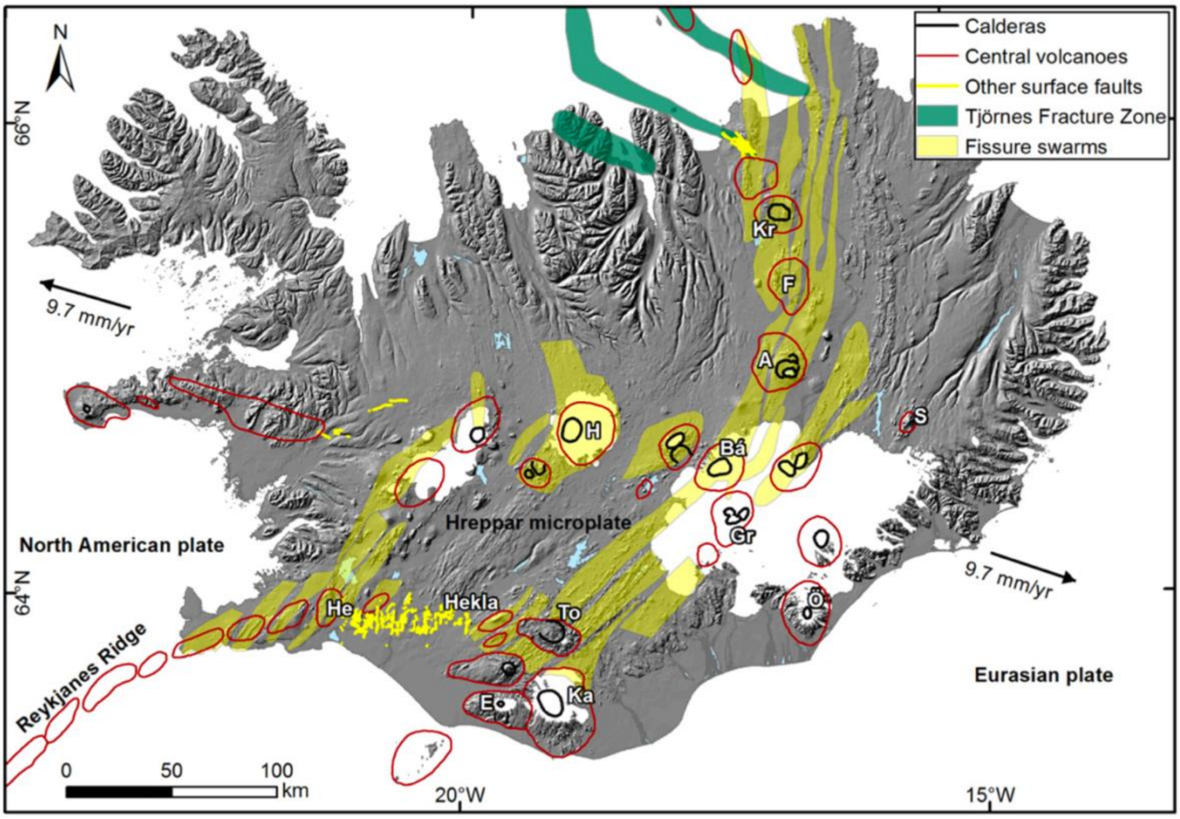

Fig. 1. Volcanic systems of Iceland, with their central volcanoes, calderas and fissure swarms. Names of selected systems are indicated: Kr = Krafla, F = Fremri Námar, A = Askja, S = Snæfell, Ö = Öræfajökull, Bá = Bárðarbunga, Gr = Grímsvötn, E = Eyjafjallajökull, Ka = Katla, He = Hengill, To = Torfajökull, H = Hofsjökull, and Hekla. Also shown are active faults and fractures in the South Iceland Seismic zone (yellow), and the three main strands of the Tjörnes Fracture Zone (TFZ) offshore Northern Iceland (green). Glaciers in white. Reproduced from Sigmundsson *et al*. (2020).

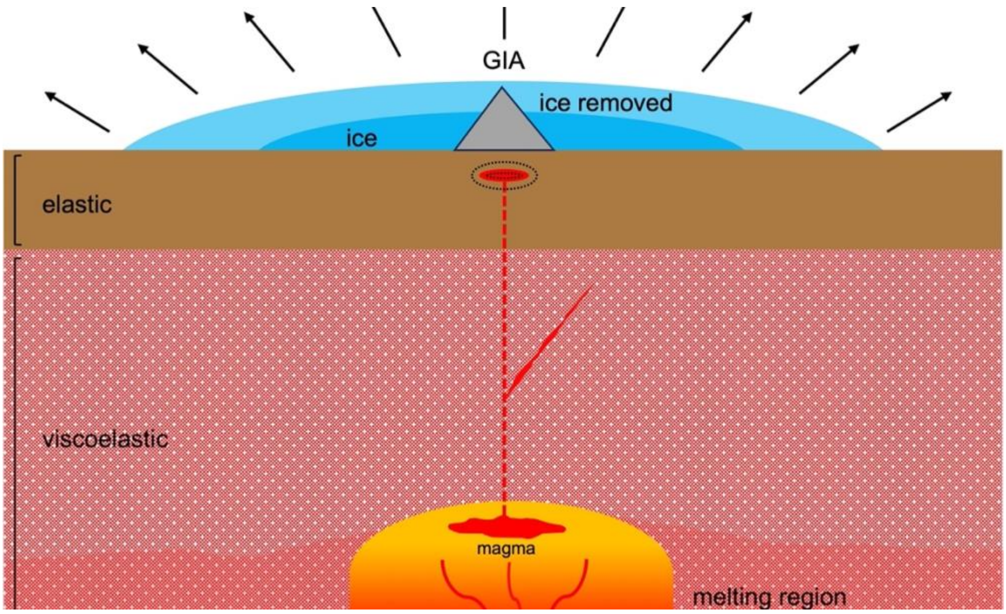

Fig. 2. A schematic view of the processes involved at subglacial volcanoes as a result of deglaciation, indicating the melting region, and magma accumulation in viscoelastic and elastic surroundings. Magma generation due to pressure release under a retreating ice cap may increase, new pathways of magma may form, and the stability of magmatic bodies at shallow depth may decrease or increase, depending on their geometry and rheology.

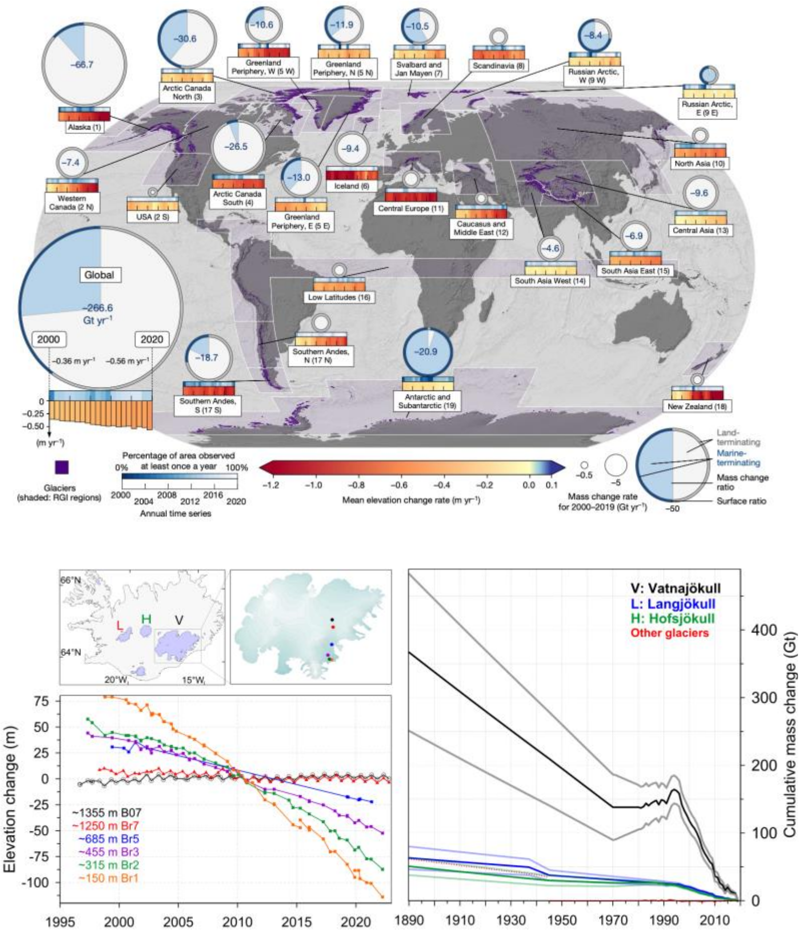

Fig. 3. Glacier retreat, globally and in Iceland. Upper: World-wide regional glacier mass changes and their temporal evolution from 2000 to 2019 as estimated by Hugonnet et al. (2021). Regional and global mass change rates with time series of mean surface elevation change rates for glaciers (indigo) of 19 regions (white-delimited indigo polygons; region numbers indicated in parentheses), shown on top of a world hillshade. Regions 2, 5, 9, 17 are further divided (N, S, E and W indicating north, south, east and west, respectively) to illustrate contrasting temporal patterns. Mass change rates are represented by the area of the disk delimiting the inside wedge, which separates the mass change contribution of land-terminating (light grey) and marine-terminating (light blue) glaciers. Mass change rates larger than 4 Gt/yr are printed in blue inside the disk (in units of Gt/yr). The outside ring discerns between land (grey) and marine-terminating (blue) glacier area. Annual time series of mean elevation change (in m/yr) and regional data coverage are displayed on time friezes at the bottom of the disks. Lower panel reproduced from Hugonnet et al. (2021) with permission from Springer Nature.

Lower left: Surface elevation change at mass balance survey sites on Breiðamerkurjökull outlet of Vatnajökull ice cap as measured with biannual GNSS observations by the Institute of Earth Sciences, University of Iceland. Elevation in 2010 is used as reference for all sites. Iceland map shows glaciers (main ice caps: V = Vatnajökull, L = Langjökull, H = Hofsjökull). Coloured dots on Vatnajökull show location of the GNSS observations sites.

Lower right: Cumulative mass change (Gt) of three main ice caps in Iceland and the sum of other glaciers in Iceland as inferred by Aðalgeirsdóttir et al. (2020).

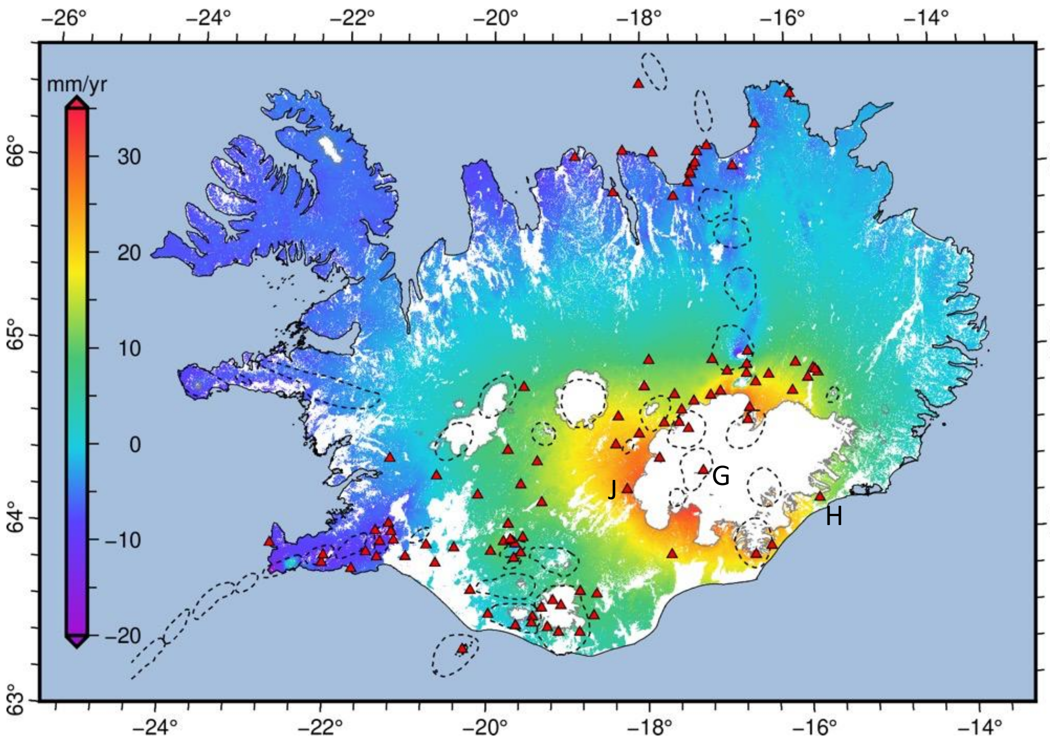

Fig. 4. Map of location of continuous GNSS stations (cGNSS) (red triangles) and InSAR map of uplift. Estimated average vertical velocities induced by GIA between summer 2015 and summer 2020 in Iceland, derived from Sentinel-1 interferometry, using the procedure described by Drouin and Sigmundsson (2019). Outlines of central volcanoes indicated. Letters indicate cGNSS stations mentioned in text. H = HOFN, J = JOKU, G = GFUM

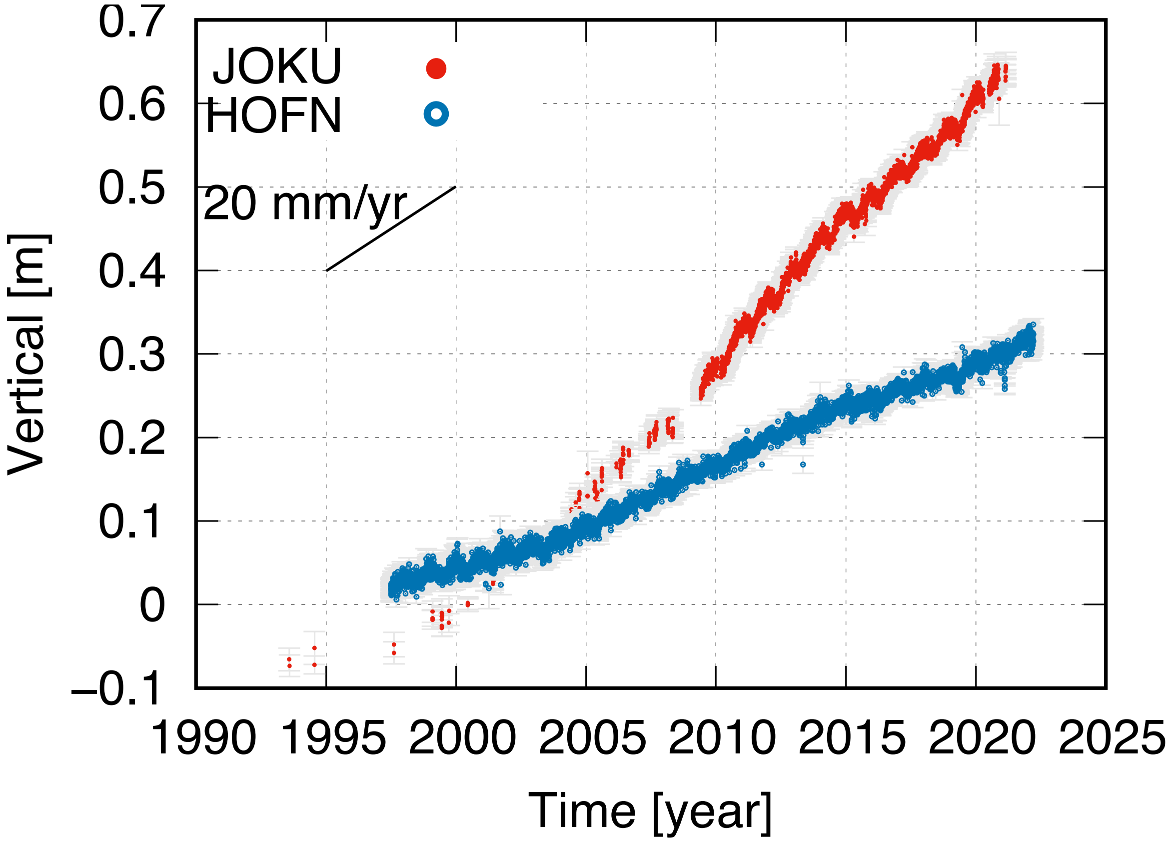

Fig. 5. Time series of vertical displacement at cGNSS sites JOKU (Jökulheimar) and HOFN (Höfn). See Fig. 4 for location of stations.

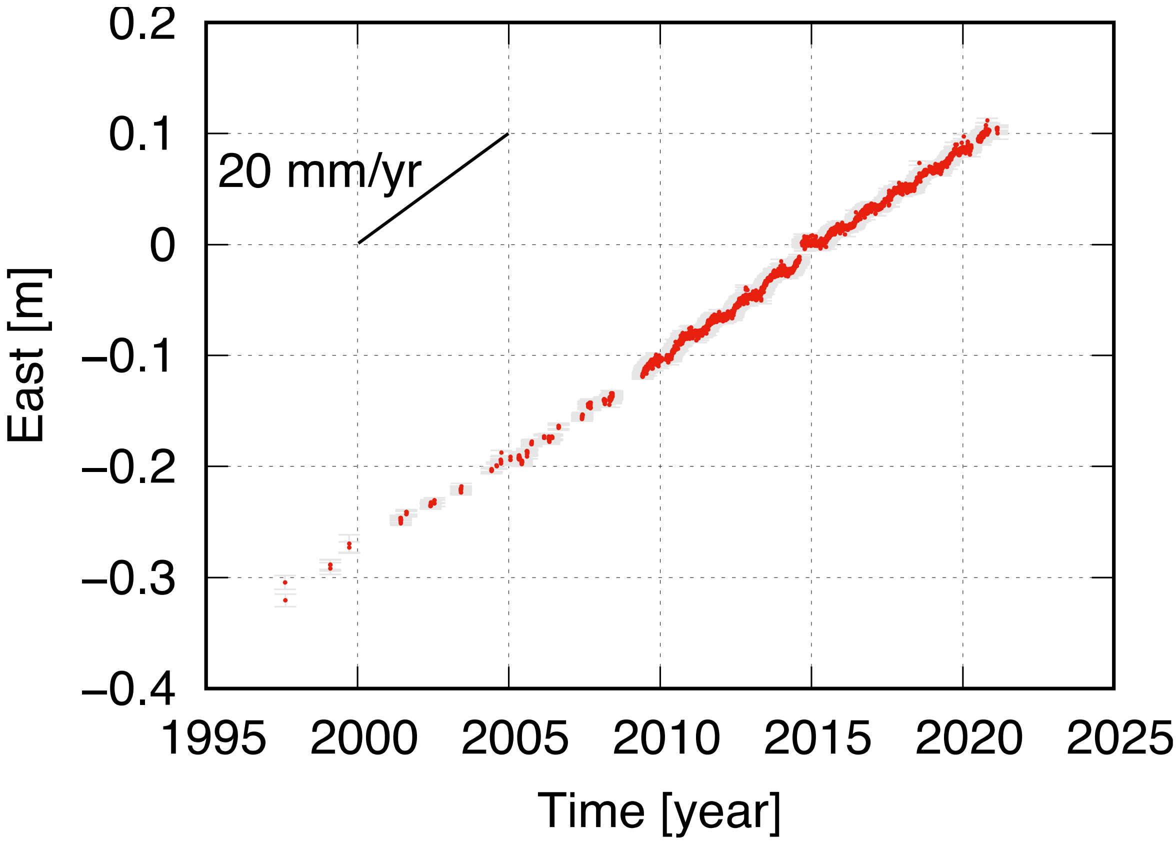

Fig. 6. Time series of the difference in east component of displacement of cGNSS stations JOKU and HOFN. See Fig. 4 for location of stations. See Fig. 5 for vertical displacement of the sites.

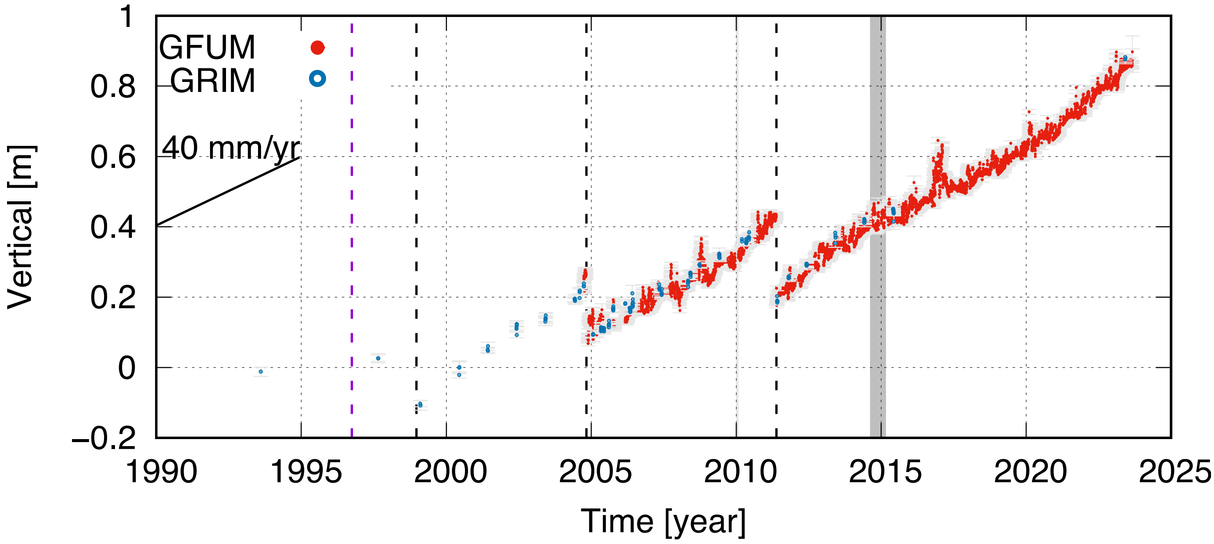

Fig. 7. Time series of vertical displacement at cGNSS site GFUM, and nearby campaign site GRIM, at Grímsvötn volcano. See Fig. 4 for location of GFUM. Vertical hatches lines represent eruptions at Grímsvötn (and in 1996 at the nearby Gjálp eruption site). The shaded time period in late 2014 and 2015 marks the timing of the Bárðarbunga eruption. The uplift is a combination of GIA and local volcano signal relating to pressure changes in the magmatic system.

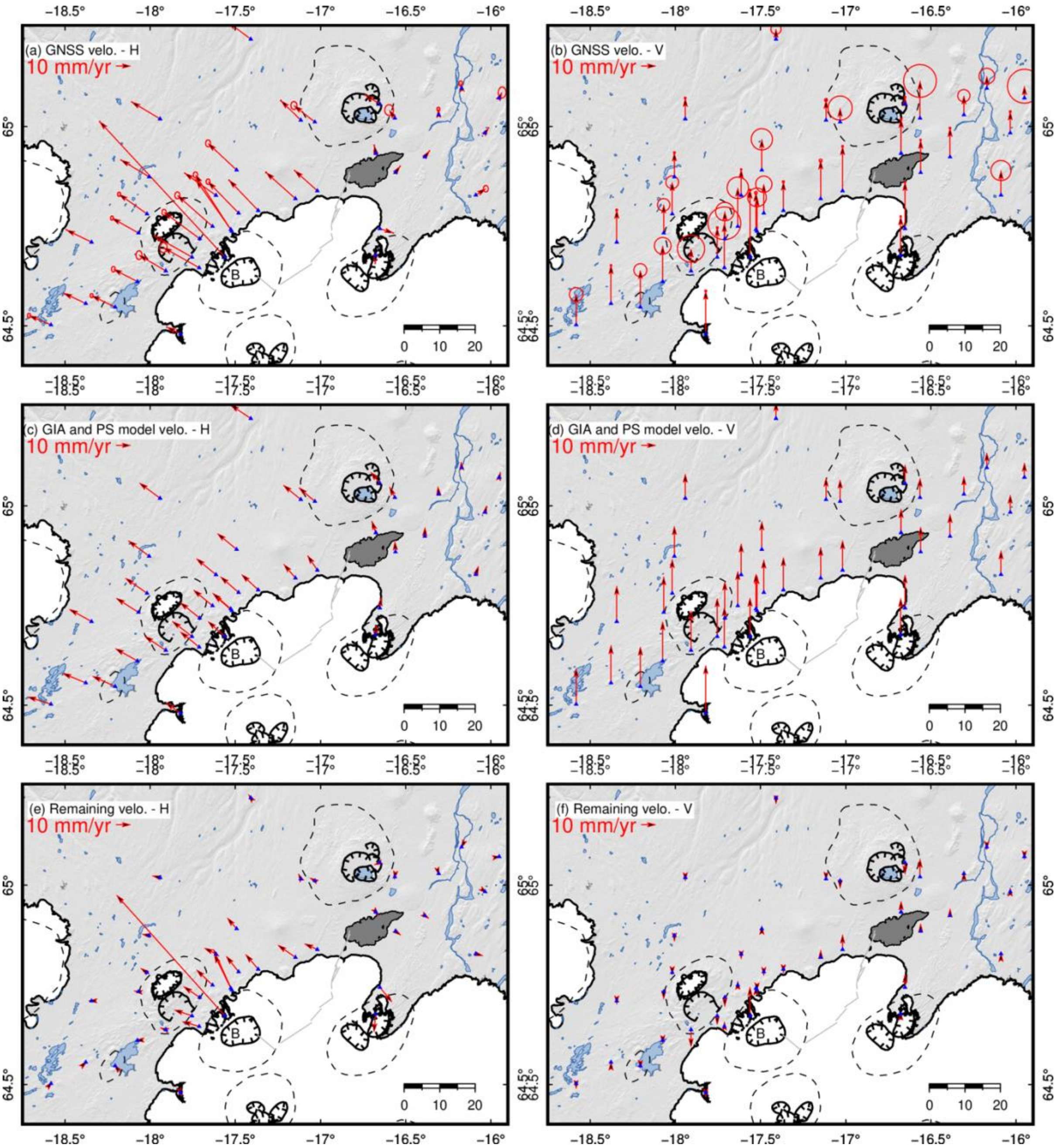

Fig. 8. Horizontal (left) and vertical deformation fields in central Iceland, near Bárðarbunga volcano (caldera marked with B). Average velocity field from GNSS measurements covering the period 2015–2018, following an eruption and dike injection in 2014-2015. Panels (a) and (b) show inferred average velocity relative to a stable Eurasian plate, with ellipses at the end of the arrows indicating 95% confidence intervals. Panel (c) shows model horizontal velocity field of combined contributions of scaled GIA model by Auriac (2014) and plate spreading, and (d) is the average vertical GIA velocity. Bottom panels show residual velocities after subtracting velocities shown in middle panels from observed velocities, that can be used for modelling magmatic processes. Data from Li *et al*. (2021), who interpreted the data with a series of models, including a model considering viscoelastic response from both magma withdrawal and associated caldera collapse.

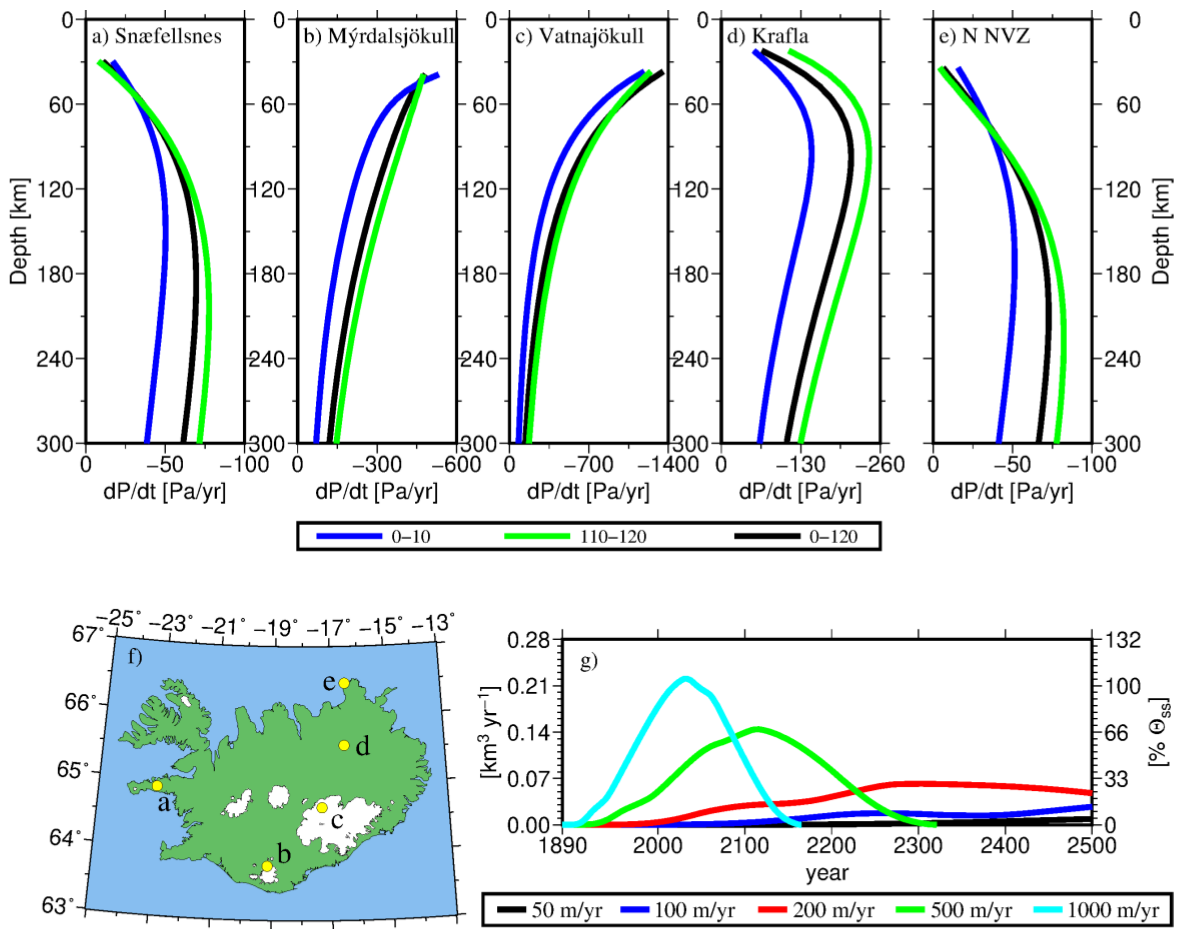

Fig. 9. (a–e) Predicted glacially induced pressure changes (d*P*/d*t*) in the mantle as a function of depth and time at selected locations across Iceland. (a–e) The dP/dt as a function of depth averaged over the time periods (model years) 0–10 (blue), 110–120 (green), and 0–120 (black). (f) Map showing the locations of the depth profiles a–e. (g) Increase in melt supply rate, ΔMSR, at the base of the elastic lithosphere due to deglaciation of Iceland between 1890 and 2010, assuming a mantle potential temperature of 1500°C, a bulk water content of 125 ppm, and melt ascent velocities of 50 m/yr (black), 100 m/yr (blue), 200 m/yr (red), 500 m/yr (green), and 1000 m/yr (cyan). Left vertical scale gives the ΔMSR in units of km^3/yr; the scale on the right, [% ,Θ_{ss}], gives it as a percentage of 0.21 km^3/yr, the estimated steady state melt production rate under Iceland. Note that all curves are based on a time-varying decompression rate between 1890 and 2010, rather than the mean over the period. Figure reproduced from Schmidt *et al*. (2013).

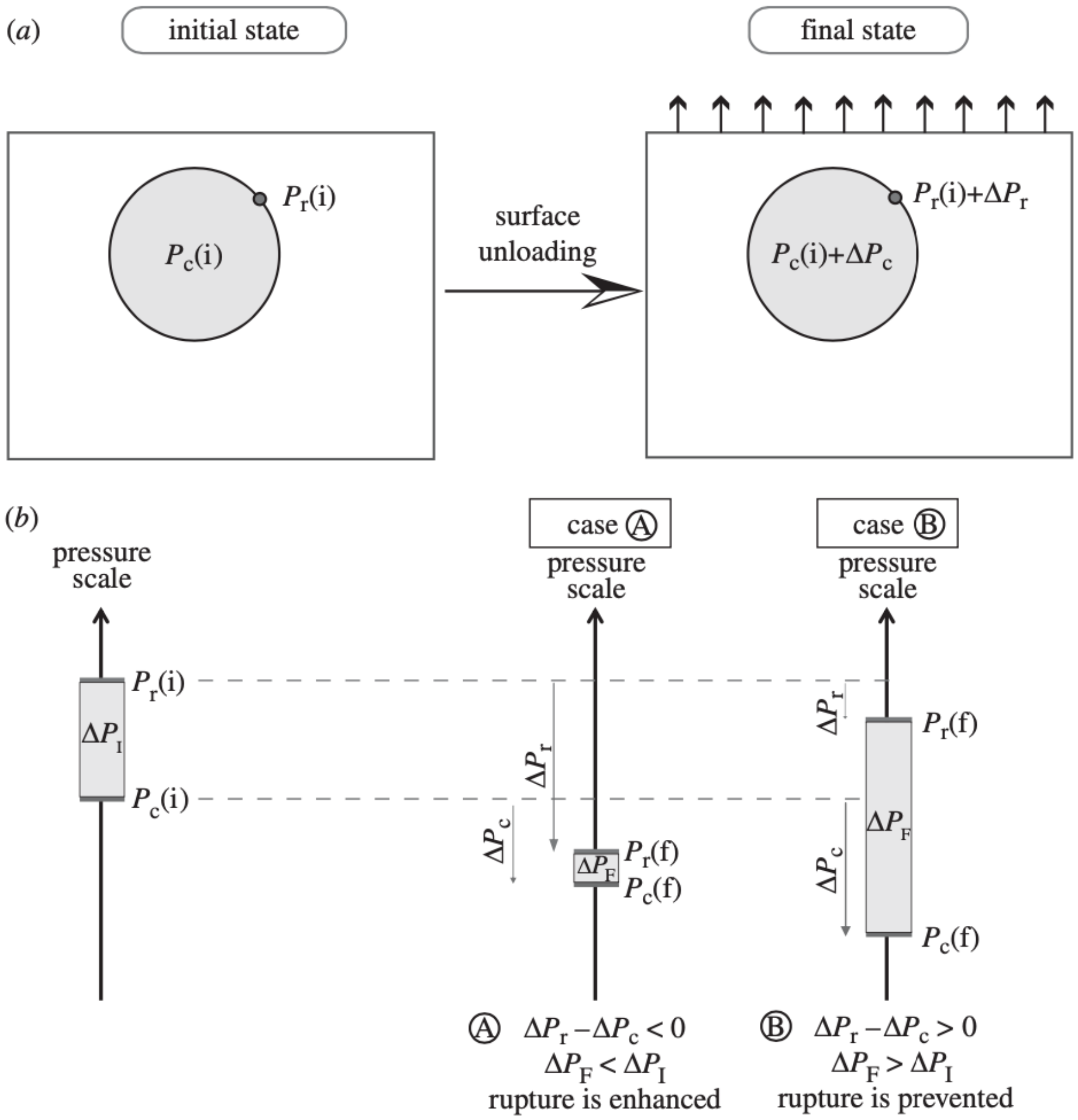

Fig. 10. (a) Evolution of magma pressure, P_c, and threshold pressure for failure, P_r, during an unloading event. (b) Evolution of the ability of the system to erupt. ΔP_I and ΔP_F represent, respectively, the difference between magma pressure and threshold pressure for failure before and after an unloading event. The final state depends on the initial state and the change in P_c and P_r : $\Delta P_F = \Delta P_I + (\Delta P_r - \Delta P_c)$. In the case $\Delta P_F < \Delta P_I$ (case A), rupture likelihood is enhanced and may occur or not depending on the initial state. In the case $\Delta P_F > \Delta P_I$ (case B) no eruption will occur. Figure reproduced from Sigmundsson *et al*. (2010).