How Representative are Estimates of Fast Melt Ascent Velocity under Iceland following its Deglaciation?

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Abstract

Partial melting of the asthenospheric mantle generates the magma that supplies volcanic systems. The timescale of melt extraction from the mantle has been hotly debated. Microstructural measurements of the permeability of partially molten rocks typically suggest relatively slow melt extraction (1 m/yr) [e.g. 1]. By contrast, inferences from geochemical measurements of Uranium series and geophysical observations typically point to much faster melt extraction (100 m/yr) [e.g. 2]. The most recent deglaciation of Iceland caused the mantle below to depressurise, triggering additional mantle melting and magma flux at the surface, which has been extensively mapped. The rapid response of magmatic activity to deglaciation has been used to argue for relatively rapid melt extraction [3,4]. Perhaps, however, this unusual period when magma fluxes increased several-fold is not representative of steady-state melt velocities under Iceland, let alone the mid-ocean ridge system more generally. We develop a one-dimensional, but time-dependent and fully nonlinear, model of the generation and transport of mantle melts force by time-dependent ice unloading. We show that these models are sensitive to the nonlinear nature of the system, namely that the melt velocities are faster during and following a deglaciation event. For a given nonlinear model, we show that an equivalent linear estimate of the steady-state melt velocity is too fast. We calculate an overestimation factor as a function of the factor of mantle melting caused by deglaciation. For the most recent, and best mapped, deglaciation, we show that about 30 m/yr is the best estimate of melt velocity. This is a factor of 3 smaller than previously claimed [4], but still relatively fast. Finally, we discuss the applicability of these results to the mid-ocean ridge system by considering the role of spreading rate and the plume-influence on Iceland. [1] Wark, D. et al. (2003). JGR. doi:10.1029/2001JB001575 [2] Stracke, A., Bourdon, B., & McKenzie, D. (2006). EPSL. doi:10.1016/j.epsl.2006.01.057 [3] Maclennan, J. et al. (2002). Geochem. Geophys. Geosyst. doi:10.1029/2001GC000282 [4] Eksinchol I., Rudge J.F., Maclennan J. (2019) Geochem. Geophys. Geosyst. doi:10.1029/2019GC008222

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1. Introduction

- **Deglaciation of Iceland caused a large increase in magmatic activity**
- **Timing and chemical composition of erupted lavas can be used to infer *rapid melt extraction* from the mantle**
- **Generally consistent with geochemistry (U-series disequilibrium) and seismology (low inferred porosities) but not micro-structural estimates assuming diffuse flow**

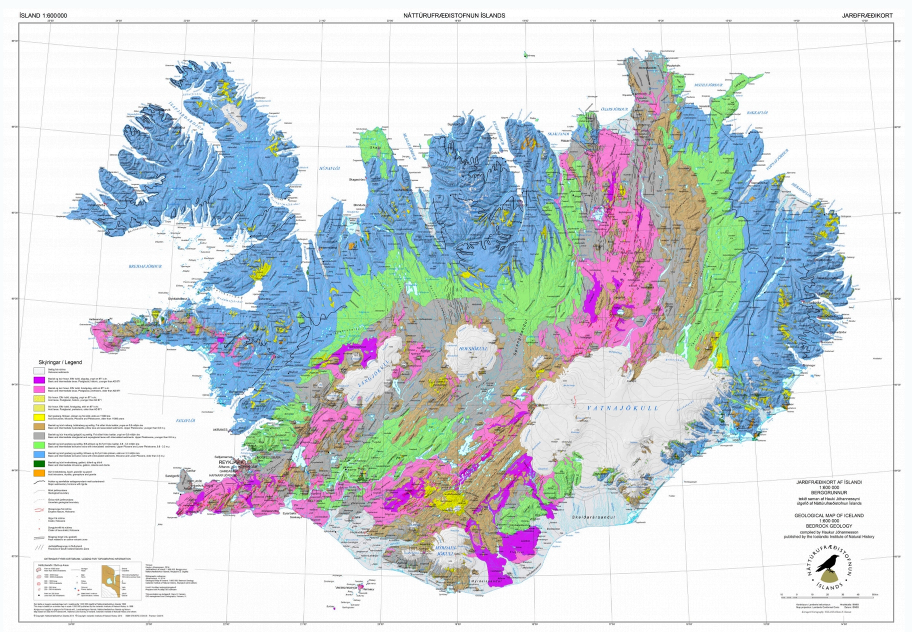

Fig. 1: Geological map of Iceland, including present day icecap and volcanic zones (Haukur Jóhannesson)

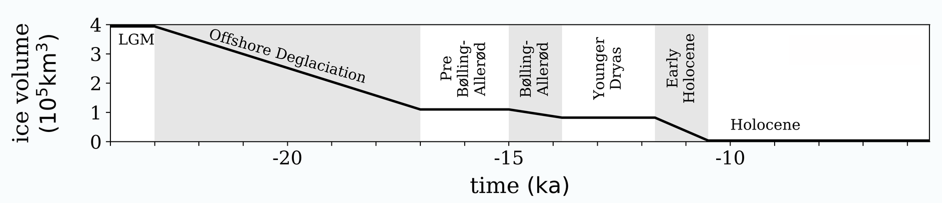

Fig. 2: Simplified history of major deglaciation events. From Eksinchol et al. (2019)

2. Previous estimates

- Jull & McKenzie (1996), Maclennan et al. (2002) and Eksinchol et al. (2019)
- Favour melt velocity around 100 m/yr
- Even faster melt velocity excluded by trace element (La) concentration
- Armitage et al. (2019) used an estimate based on seismology to study CO_2 emissions over 120 ka

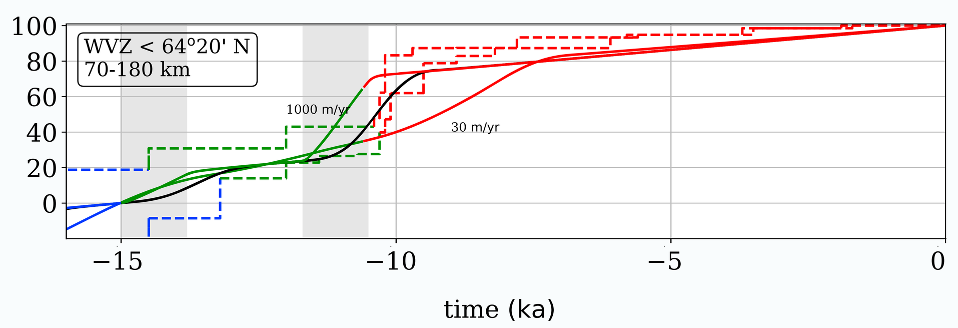

Fig. 3. Observed (dashed) and modelled (curves) cumulative erupted volume in Western Volcanic Zone. Black curve: preferred melt velocity (100 m/yr). From Eksinchol et al. (2019)

3. Methods

3.1 Dynamical model

- 1D continuum model of porous flow with melting
- Mass conservation:

$$\frac{\partial \phi}{\partial t} + \frac{\partial Q}{\partial z} = \Gamma$$

- Porosity: ϕ
- Melt flux from Darcy's Law: $Q = Q_0 \phi^n$, where the prefactor $Q_0 = \Delta\rho g k/\mu$
- Melt velocity: $w = Q/\phi$
- Melt rate: $\Gamma = \Gamma_0 \left[1 + Af(t)\right]$, where steady melt rate Γ_0 depends on maximum degree of melting, mantle upwelling rate and depth of the melting region $\Gamma_0 = F_{\max} W_0 / H$
- Amplification factor A [extra melt from deglaciation], $f(t)$ is a switch (on during deglaciation, else off)

3.2 Steady-state behaviour

- Variation of melt flux and porosity with depth:

$$\overline{Q} = \Gamma_0 z, \quad \overline{\phi} = \left(\Gamma_0 z / Q_0\right)^{1/n}$$

- Maximum melt velocity (at top of melting region):

$$\overline{w}_{\max} = \left(F_{\max} W_0\right)^{\frac{n-1}{n}} Q_0^{\frac{1}{n}} \qquad (\star)$$

3.3 Transient effect of deglaciation

- Calculate scaled extra emissions:

$$\frac{\partial \hat\phi}{\partial \hat t} + \frac{\partial \hat Q}{\partial \hat z} = f(\hat t) = \begin{cases} 1 & (0 \le \hat t \le \lambda) \\ 0 & \text{else} \end{cases}$$

$$\hat Q = 2\hat z^{1/2}\hat\phi + A\hat\phi^2, \quad (n = 2)$$

$$\hat t = \frac{t}{\tau}, \quad \hat z = \frac{z}{H}, \quad \hat Q = \frac{Q - \overline{Q}}{A\overline{Q}_{\max}}, \quad \hat\phi = \frac{\phi - \overline{\phi}}{A\overline{\phi}_{\max}}$$

- Scale time with transport time for a porosity wave $\tau = H/\overline{w}_{\max}$, so deglaciation time is $\lambda = t_d/\tau$

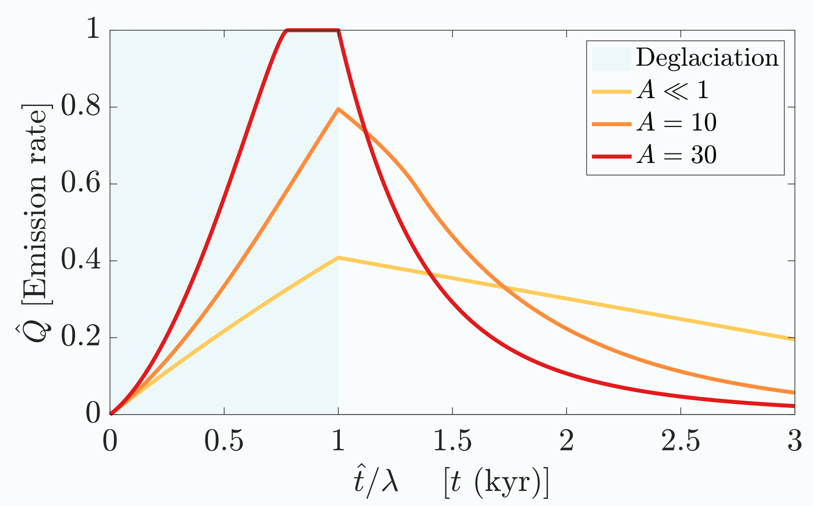

Fig. 4. Calculated extra emissions due to early-holocene deglaciation with different amplification factors for $\lambda = 0.23, w_{\max} = 30\,\mathrm{m/yr}, t_d = 1\,\mathrm{kyr}$

4. Results: deglaciation versus normal Iceland

4.1 Cumulative emissions

- Field observations can be used to estimate history of cumulative emissions (e.g. Fig. 3)
- Emissions rise faster when accounting for *nonlinear feedbacks* due to amplified melting and porosity during deglaciation

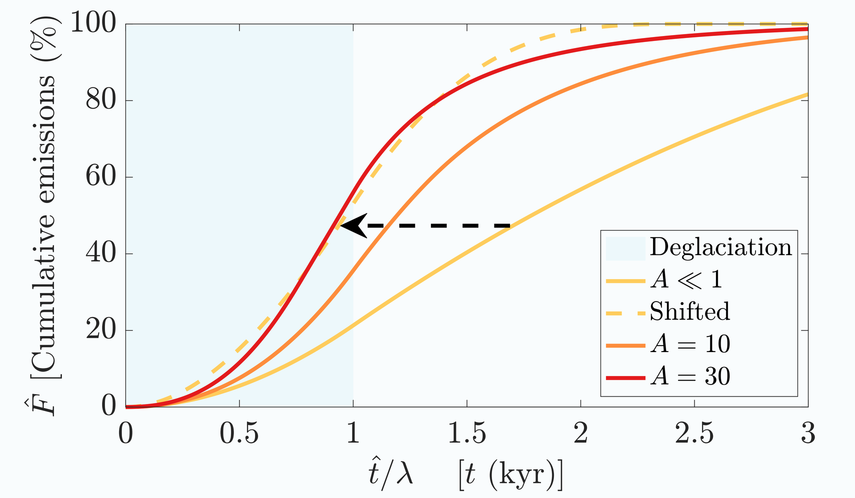

Fig. 5. Cumulative extra emissions from Fig. 4. The dashed black arrow and dashed curve indicate how previous linear models (small amplification factor) can be corrected (shifted) to match a nonlinear model, thus accounting for feedbacks from amplified porosity

4.2 Correction for amplified porosity during deglaciation

- Previous *linear* estimates of melt velocity (100 m/yr) are likely over-estimated by a factor of about 3

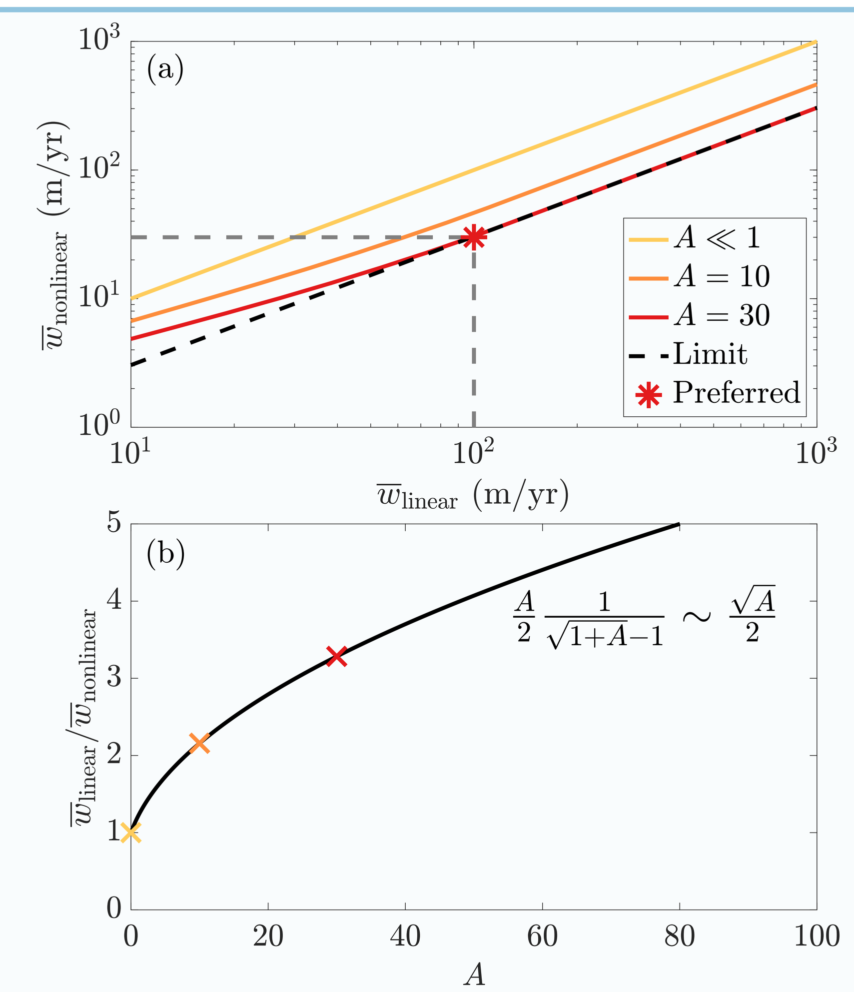

Fig. 6. (a) The true nonlinear velocity required to match observations is smaller than previous linear estimates. (b) The resulting correction factor depends fairly weakly on amplification factor

5. Results: Iceland versus 'normal' ridges

Iceland is different from other mid-ocean ridges:
- Higher degree of melting due to plume
- Slower spreading rate than fast-spreading ridges like the East Pacific Rise (EPR)
- Role of 'active' upwelling due to plume

5.1 Conversion from Icelandic results

- Use equation ($\star$) from Sec. 3.2 for maximum melt velocity and assume Q_0 constant and $n = 2$
- Superscript ^{I} denotes the Icelandic version of a quantity

$$\overline{w}_{\max} = \left(\frac{F_{\max} W_0}{F^I_{\max} W^I_0}\right)^{1/2} \overline{w}^I_{\max}$$

5.2 Role of mantle upwelling

- Two competing effects:
  - (i) For passive mantle upwelling (i.e. driven by plate spreading alone), the slow-spreading rate at Iceland (7 times slower than the EPR) means that faster spreading ridges would have *faster* melt velocity by a factor of about 2.6
  - (ii) If Iceland is influenced by very fast active upwelling (10 times faster than passive), an otherwise equivalent ridge would have *slower* melt velocity by a factor of about 3.2

5.3 Role of degree of melting

- Iceland has a higher degree of melting than elsewhere due to role of plume (e.g. elevated crustal thickness)
- If Iceland has double the degree of melting, an otherwise equivalent ridge would have *slower* melt velocity by a factor of about 1.4

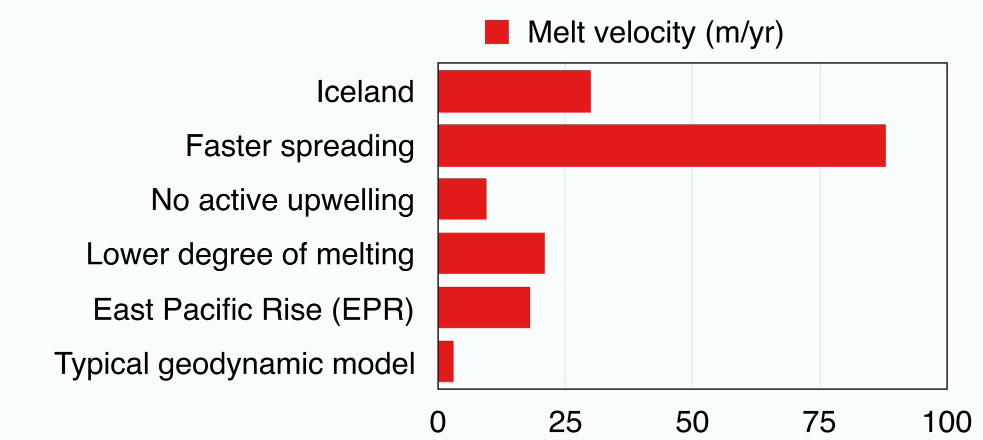

Fig. 7. Possible melt velocity at other ridges accounting for differences relative to Iceland. The EPR value is the product of all the effects considered. Typically, geodynamic models use a much slower melt velocity

Conclusions

- **We account for nonlinear feedbacks due to porosities higher than their steady-state values during deglaciation**
- **Melt velocities have been overestimated by a factor of about 3 because previous studies did not account for this feedback**
- **But melt velocity is still fast (30 m/yr)**
- **Globally, other ridges are still relatively fast (more than 10 m/yr), even accounting for plume influence in Iceland**

6. Discussion

6.1 Two-dimensional effects

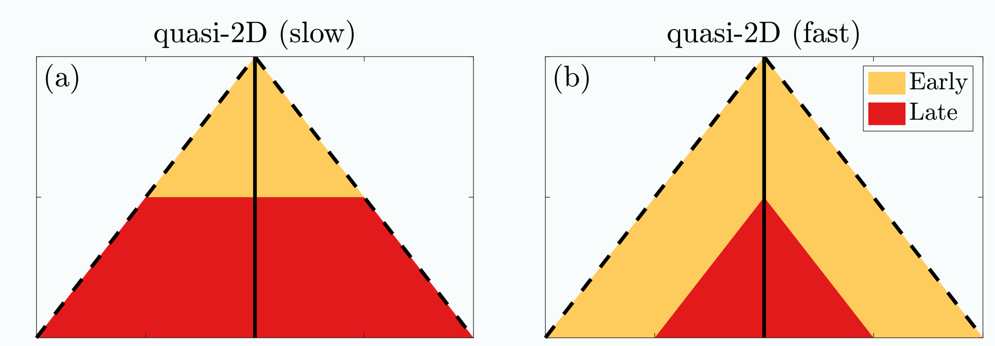

Fig. 8. Geometrical effects in quasi-2D models with different models of melt extraction along a sub-lithospheric channel: (a) slow melt extraction and (b) fast (instant)

- Quasi-2D models can be constructed from a series of 1D column models
- Results depend on assumptions about how fast melt is extracted along sub-lithospheric channel
- 1D model is intermediate
- True 2D/3D models could include channelized flow

6.2 Other effects (partly considered by previous studies)

- Crustal system response to deglaciation (Maclennan et al., 2002, argued that trace element geochemistry shows that signal is not mainly coming from release from crustal magma chambers triggered by deglaciation)
- Elastic response and post-glacial rebound were considered by several studies
- More complex melting behaviour (e.g. the role of volatiles like CO_2) and complex deglaciation history were both considered by Armitage et al. (2019)
- Geographic variations were studied by Eksinchol et al. (2019) using an axisymmetric ice sheet and linear ridge