Deglaciation and Volcanism

Part III Magma Dynamics: Practical 3

The aim of this practical is to give you an idea of the appropriate magnitudes of the effects of deglaciation on volcanism. Two situations are considered: First, the effects directly beneath the glaciers, as exemplified by Icelandic volcanism. Second, the effects on the global mid-ocean ridge system due to the overall sea level changes. You may assume the following numerical values:

Quantity	Symbol	Value
Density of ice/water	ρ_w	1,000 kg m^{-3}
Density of mantle	ρ_m	3,300 kg m^{-3}
Density of oceanic crust	ρ_c	2,900 kg m^{-3}
Young's modulus of rock	E	70 GPa
Poisson's ratio of rock	ν	0.25

Iceland

1. Observations of post-glacial uplift in Iceland suggest that rebound takes place with a time constant of $\tau = 300$ years for removal of an ice sheet of horizontal wavelength $\lambda = 800$ km covering the whole island. Use the expression for the rebound constant

$$\tau = \frac{4\pi\eta}{\rho_\mathrm{m} g \lambda}$$

   to estimate the mantle viscosity η beneath Iceland. Similar calculations for removal of the Fennoscandian ice sheet yield estimates of $\eta = 10^{21}$ Pa s. Why is your estimate for Iceland different?

2. Mantle material upwells beneath Iceland at around 10 mm yr^{-1}. What is the corresponding decompression rate in Pa yr^{-1} of the upwelling mantle material?

3. Suppose an ice sheet of thickness $h = 2$ km melts over a period of 1,000 years. What is the pressure change in the mantle as a result of the unloading, and what is the corresponding decompression rate in Pa yr^{-1} during the period of unloading? For simplicity, assume a uniform layer of ice for your calculations.

4. Assuming a uniform melt productivity with pressure during isentropic melting, estimate the corresponding increase in melt production during glacial unloading.

5. Suppose an ice sheet of thickness h now instantly loads the mantle after having been in an ice-unloaded state for a long period of time. For how long will the loading by this ice sheet suppress melting, given that mantle material upwells at 10 mm yr^{-1}?

Global ridge system

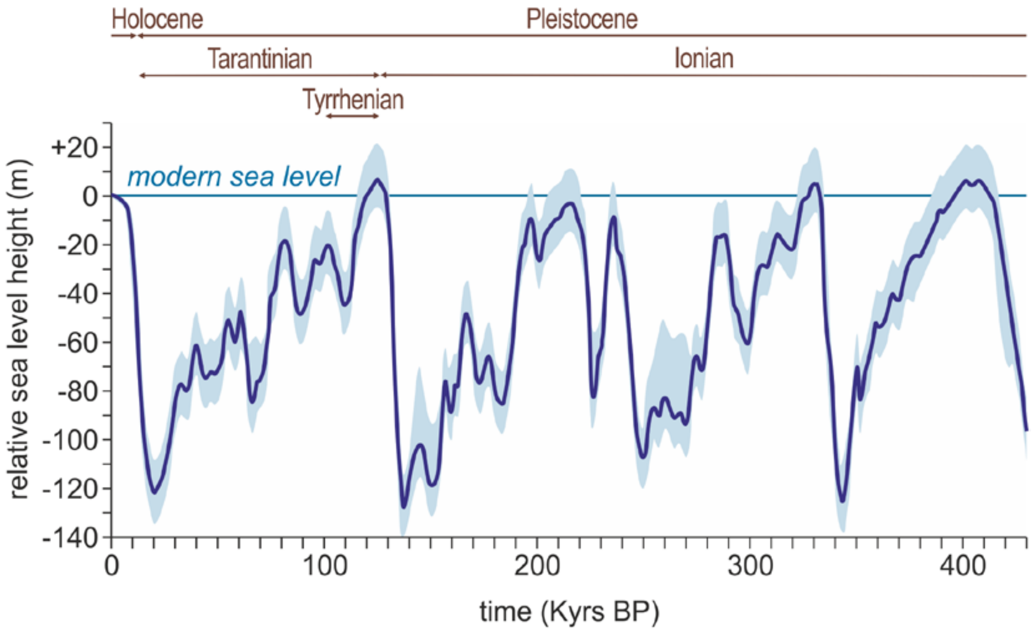

Figure 1: Eustatic sea-level curve (bold black line), with associated confidence intervals for the late Quaternary

6. The average rate of upwelling beneath the global mid-ocean ridge system is around 30 mm yr^{-1}. What is the corresponding decompression rate in Pa yr^{-1}?

7. Using Figure 1, estimate the rate of change of sea-level during the last major deglaciation (between 19,000 and 8,000 years ago). Hence calculate the rate of decompression associated with this change in sea level.

8. Using your answers to the previous parts, estimate the magnitude of crustal thickness variations associated with sea level changes. What assumptions underlie your estimate?

9. Assuming Airy isostasy, estimate the variations in bathymetry associated with the variations in crustal thickness.

10. Figure 1 shows evidence for Milankovitch cycles with dominant periods of 23,000 years, 41,000 years and 100,000 years. What horizontal wavelengths would these correspond to in the ocean floor for a spreading rate of 30 mm yr^{-1}?

11. The natural horizontal wavelength associated with flexure is

$$\lambda_{\text{flex}} = 3.4 \left(\frac{E T_e^3}{(1-\nu^2)(\rho_{\text{m}} - \rho_{\text{w}})} \right)^{1/4},$$

where topography is expected to be largely isostatically supported for wavelengths of loading greater than λ_{flex}, and largely supported by elastic stresses in the plate for wavelengths shorter than this. Spreading ridges have $T_e \approx 3$ km. Estimate λ_{flex} and comment on whether the isostatic approximation you used in question 9 is appropriate.

References

This practical is closely based on the following articles, which I thoroughly recommend you read:

Jull M. and McKenzie D. (1996) The effect of deglaciation on mantle melting beneath Iceland. *J. Geophys. Res.* **101** 21,815-21,828 doi:10.1029/96JB01308

Crowley J.W., Katz R.F., Huybers P., Langmuir C.H., Park S.-H. (2015) Glacial cycles drive variations in the production of oceanic crust. *Science* **347** 1237-1240 doi:10.1126/science.1261508

Olive J.-A., Behn M.D., Ito G., Buck W.R., Escartin J., Howell S. (2015) Sensitivity of seafloor bathmetry to climate-driven fluctuations in mid-ocean ridge magma supply. *Science* **350** 310-313 doi:10.1126/science.aad0715

Answers

Iceland

1. $\eta = \dfrac{\rho_m g \lambda \tau}{4\pi} = 2 \times 10^{19}$ Pa s. The mantle beneath Iceland is hotter and in part partially molten, so this would be expected to reduce the viscosity from what is seen beneath Fennoscandia.

2. 330 Pa yr^{-1}.

3. $\Delta P = \rho_w g h = 20$ MPa. $dP/dt = \Delta P/t = 20,000$ Pa yr^{-1}.

4. The rate of melt production increases by a factor of 20,000/330 = 60. More detailed calculations of this effect take account of the finite lateral extent of the ice sheet, and the effects of post-glacial rebound (see Jull and McKenzie (1996) for further details).

5. $t_{\text{supressed}} = \dfrac{\rho_w h}{\rho_m v} = 60,000$ years.

Global ridge system

6. 1,000 Pa yr^{-1}.

7. about 100 m in 10,000 years $\implies$ 10 mm yr^{-1} sea level rise and 100 Pa yr^{-1} decompression.

8. Typical oceanic crust is 7 km thick. The decompression rate changes by $\pm 10\%$ from the above, and hence the crustal thickness would be expected to change by the same amount, i.e. ± 700 m. An assumption has been made here that melt is transported instantly to the surface – if melt transport speeds are slow, the magnitude of the variations in crustal thickness could be significantly reduced.

9. Isostatic balance yields bathymetric variations $d = \dfrac{\rho_m - \rho_c}{\rho_m - \rho_w} e = \pm 120$ m.

10. 0.7 km, 1.2 km, and 3 km.

11. $\lambda_{\text{flex}} = 100$ km, much greater than the wavelengths above, so the use of Airy isostasy is not appropriate. (This is one of Olive's criticisms of the Crowley paper.)