Lab 3: Volcanism

Volcanism is an important process of most solar system bodies, whether today or in the past, and gives information on the thermal evolution and interior state of the planetary body. Volcanoes transport heat, volatiles, and radioactive materials (which we can date) from the interior to the surface and can have a major influence on a planets climate.

1. Jupiter's moon Io is the most volcanically active body in the solar system. In a later lab, we will explore how these volcanoes occur (i.e. what is their heat source?), but for now, we are going to estimate the size of a dike (vertical magma intrusion).

a) The velocity u of magma traveling upwards through a dike of width w is given by

$$u = \frac{w^2 g \Delta\rho}{\eta}$$

where g is gravity, $\Delta\rho$ is the density contrast between magma and the surrounding rock, and η is the viscosity. Examine the effect of how each variable individually affects the velocity and explain why this equation makes physical sense (in other η, g, or words, if w, $\Delta\rho$, were to increase, what would happen to u and does this make sense?)

b) If the total height through the lithosphere of the dike is d, write down an expression for the time taken for a packet of magma to get from the bottom to the top of the dike.

c) Material cools by conduction according to the equation

$$t = \frac{x^2}{\kappa}$$

where t is time, x is the shortest distance across the cooling object, and κ is the thermal diffusivity (generally ~10^{-6} m^2s^{-1} for rock and ice). By comparing the expressions for the cooling time and the transit time, derive an expression for the minimum width of a dike which will allow magma to ascend all the way to the surface. Check your units to make sure that this equation makes physical sense.

d) Now let's plug in some numbers. Io's lithosphere (the rigid shell atop the mantle) is estimated to be 12-40 km thick, the viscosity of basaltic lava is about 10^3 Pa s, and Io's gravitational acceleration is 1.8 m s^{-2}. Assuming that $\Delta\rho$ = 100 kg m^{-3}, what is the minimum dike width?

e) If the total horizontal length of the dikes on Io is L and they all have a constant width w, write down an expression for the magma discharge rate (in m^3s^{-1}) from these dikes in terms of u, L and w (hint: think about the units).

f) The magmatic resurfacing rate on Io is about 1 cm/yr. If the radius of Io is 1800km, and surface area is given by $4\pi r^2$, what is the corresponding magma discharge rate (in m^3s^{-1})?

g) The number you obtained in part (d) is the **minimum** dike width. Assuming a more typical width is about 1m, use the information given above to determine what the total length of dikes L has to be in order to produce the observed resurfacing rate.

h) Would you expect to see these features from a spacecraft?

2. While passing Io in 2007, the New Horizons spacecraft witnessed the volcano Tvashtar emit a plume of gas 350 km high. The maximum height H, reached by an object on a ballistic trajectory is given by:

$$H = \frac{v^2}{2g}$$

where v is the initial velocity of the material exiting the volcano and g is the acceleration due to gravity. Note that $g = 9.8 \text{ m s}^{-2}$ on Earth, but only 1.81 m s^{-2} on Io.

a) Explain what would happen to H if you were to increase v or g. Does this make physical sense?

b) Determine the initial velocity of the plume material. (For comparison 1000 m s^{-1} is about 2000 miles per hour)

c) Ignoring all other effects, what would be the height of the Tvashtar plume if it had erupted on the Earth? Would such plumes be a hazard to commercial jets (~30,000 feet) or the International Space Station (~400 km)? Why don't plumes on Earth go this high?

d) On Earth, the "Old Faithful" geyser in Yellowstone Park shoots steam about 70 meters high, and the plume from the eruption of Mount St. Helens was about 1000 meters high. Compute the initial velocities of Old Faithful geyser and the Mount St. Helens plume, and compare these values to the initial velocity of Tvashtar.

e) Using the equation provided in Activity 1, estimate the width of the dike that formed Tvashtar.