Ascent of magma on Io: Why so hot?

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Background (1)

- Update on some work presented by Laz at LPSC, attempting to reconcile lava temperatures and interior models for Io.
    - Early NIMS/SSI studies suggested lava temperatures ~1600^{o}C.
    - Interior models suggests ~1200^{o}C is all that can be sustained.
    - What happened to the extra 400^{o}C?
- NIMS/SSI data reprocessing of Pele and Tvashtar.
    - Surface temperature reduced by 200-300^{o}C.
    - Now could be as low as 1000^{o}C.
    - Implication: lava temperatures of at least ~1300^{o}C.
    - Now we only have to account for 100-200^{o}C.
- Revised internal modelling.
    - Rapid resurfacing and subsidence => lithospheric compression.
    - Assuming a 30 km thick crust, ascending magma would have to overcome a ~0.5 GPa confining pressure to ascend.
    - 20% melting at this pressure should take place at ~1270°C.
    - Now we only have to account for 30-130^{o}C.
    - Close, but not there yet. Also, note the liberal assumptions so far.

Background (2)

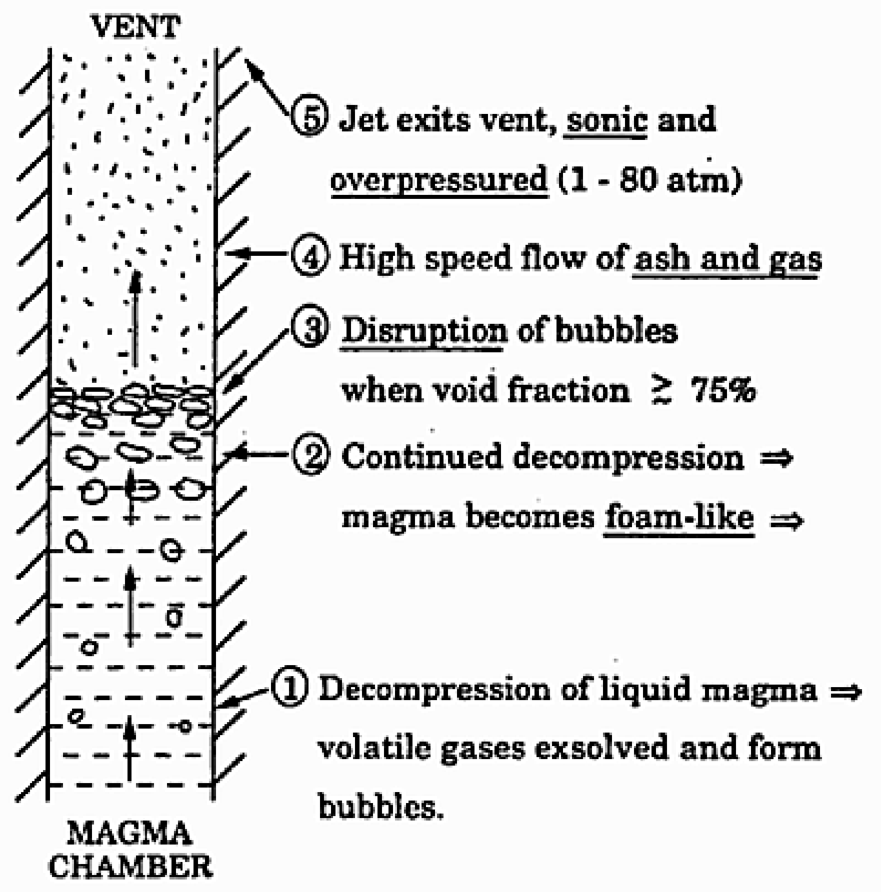
- Previous workers have suggested and usually dismissed a number of possible explanations for conduit superheating.
- Laz suggested the possibility that viscous dissipation played a role, and presented some preliminary results at the LPSC. Derived an expression for viscous dissipation in conduits based on work done against friction:
    - $\mathbf{\Delta T = \Delta P/\rho} \boldsymbol{C}$
- Given the large driving pressures, it is relatively easy to produce temperature changes of the order of 100-200 K.
- Problems:
    - Does not take into account gravity.
    - Does not take into account actual volcano geometries.
    - Does not take into account volatiles.
    - The same should be true on the Earth. Not observed.
    - Can it really be that simple!?
- Re-derive from first principals and explore a wider range of conditions.

Background (3)

Primary interest is thermodynamic, so I'm not going to use a rigorous fluid mechanical model based on full Navier-Stokes equations.

Instead, I use a simple axially-symmetric, subsonic, compressible conduit flow model (*erupt*), which evolved from Lionel Wilson's work in the 70s/80s (*Mitchell*, 2005). This incorporates ideal thermodynamics and relatively basic fluid dynamics, that do not deal with the effects of shocks and waves. It only applies in the subsonic domain.

I conserve mass, energy and momentum, and consider work against friction and gravity. Energy is given by KE + PE + Enthalpy = 0, thus adiabatic -> no heat exchange through conduit walls.



Analysis (1)

Conservation laws

- $\mathrm{d}h + \mathrm{d}(u^2/2) + g\,\mathrm{d}z = 0$ (Energy)
- $\rho\, u\, \mathrm{d}u + \mathrm{d}P + F\,\mathrm{d}z + \rho\, g\,\mathrm{d}z = 0$ (Momentum)
- $(\mathrm{d}\rho / \rho) + (\mathrm{d}v / v) + (\mathrm{d}A / A) = 0$ (Mass)

Other important equations

- $\mathrm{d}h = c\,\mathrm{d}T + (m_m / \rho_m)\,\mathrm{d}P$ (Bulk enthalpy)
- $(1 / c) \sim (m_m / c_{v,m}) + (m_g / c_{p,g})$ (Mixture of specific heats)
- $F = \rho\, u^2 f / 2\, r$ (Definition of F)

Without all the working, from the above equations:

- $\mathrm{d}T/\mathrm{d}z = (1 / c)\,(m_g / \rho_g)\,\mathrm{d}P/\mathrm{d}z + F / \rho\, c$ (Conduit temperature change)

So, temperature decreases as a result of decompression of gas (RHS expr. 1) and increases as a function of work done against friction (RHS expr. 2), as expected.

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Analysis (2)

How does viscous dissipation fit it? Implicitly, as a result of viscosity and friction under the adiabatic assumption. This contrasts with *Mastin*'s (2005) explicit treatment, which should produce similar results.

The coefficient of friction is given by

- $f = 16/Re + f_0$ (circular) OR $f = 24/Re + f_0$ (fissure)

where $f0$ is a constant, dependent on wallrock roughness, given by previous authors as $f0 \sim 0.005$ (Mastin, 1995) or 0.01 (e.g. Wilson and Head, 1981), and the Reynolds Number, *Re*, is given by:

- $Re = 2 \rho u r / \eta$ (circular) OR $Re = 4 \rho u r / \eta$ (fissure)

where η is the bulk viscosity.

Note that, in the definition of f, the $\boldsymbol{f_0}$ **expression dominates in the turbulent** case, and the $24/Re$ (or $16/Re$) dominates in the laminar case. From my experiments with *erupt*, I've found that there is a feedback in most circumstances on Io that causes conduit flow (for basaltic compositions) to remain predominantly turbulent.

Analysis (3)

If we assume that volatiles do not play a role, our equation for temperature change becomes:

- $\mathrm{d}T/\mathrm{d}z = (u^2 f / 2 r c)$

Given that the flow is turbulent, f is a poorly constrained quantity, $f_0 \sim 0.005$ to 0.01.

Also, as density and area are constant, velocity must be constant (from conservation of mass). This allows a simplification of conservation of momentum to:

- $u^2 = (2 r / \rho f)(-\mathrm{d}P/\mathrm{d}z - \rho g)$,

which, when substituted back into our incompressible form of $\mathrm{d}T/\mathrm{d}z$ gives:

- $\mathrm{d}T/\mathrm{d}z = (2 r / \rho f)(-\mathrm{d}P/\mathrm{d}z - \rho g)(f / 2 r c)$,

which, when simplified, becomes:

- $\mathrm{d}T/\mathrm{d}z = -(\mathrm{d}P/\mathrm{d}z / (\rho c)) - (g / c)$.

which is independent of radius, velocity and (surprisingly) friction.

Analysis (3)

From previously:

- $\mathrm{d}T/\mathrm{d}z = -(\mathrm{d}P/\mathrm{d}z / (\rho\ c)) - (g / c)$.

Multiplying through by dz and solving for the entire conduit gives:

- $\Delta T = -(\Delta P / \rho\ c) - (g\ \Delta z / c)$

cf. Keszthelyi et al. (2005) who derived

- $\Delta T = -(\Delta P / \rho\ c)$.

Expression 2 is the result of work done against gravity (g is +ve in this scheme).

Assuming 0.5 GPa driving pressure at 25 km depth, and basaltic composition (c ~ 840 J kg^{-1} K^{-1}; P ~ 2700 Pa; g ~ 1.8 m s^{-1}), gives a temperature change of 220 - 54 = 166 K. [On Earth, I tried similar, based on lithostatic pressures and a few km depth, and generally got temperature changes of the order of 1s to 10s of K.]

This implies flow of ~33 m s^{-1} (>300 m high fire fountain) through a 1 m radius conduit (fully turbulent for viscosities < ~100 Pa s), and ~106 m s^{-1} (>3 km high fire fountain) through a 10 m conduit (fully turbulent even for andesites).

Changing the co-efficient of friction changes the velocity profile.

Caveats

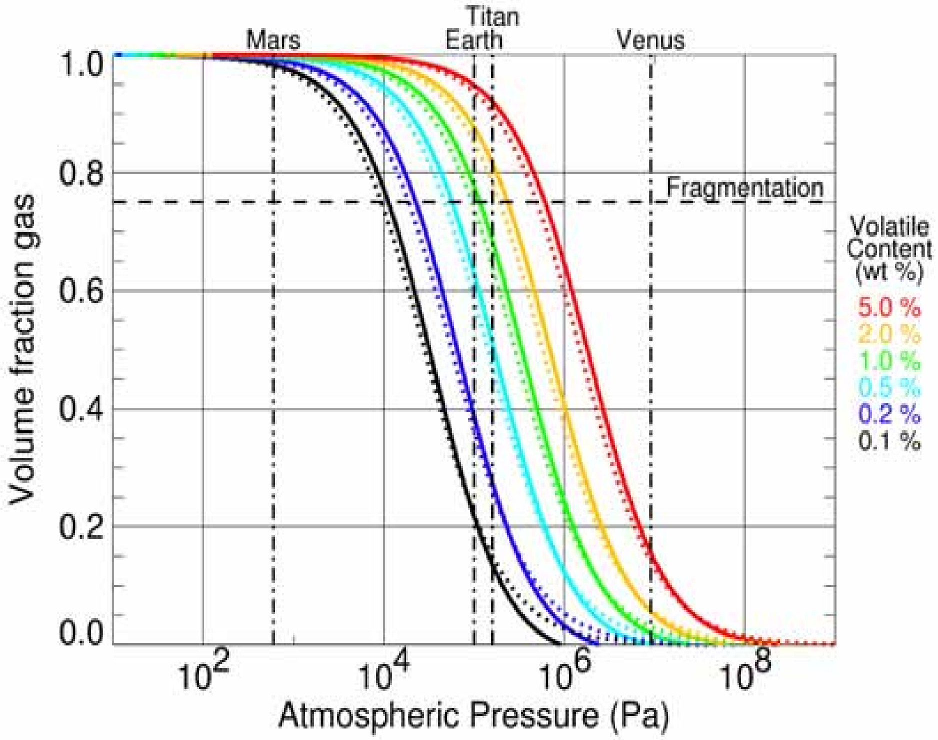
No loss of heat from magma in the conduit.

Processes are assumed to be quasi-steady.

The conduit is parallel sided (unstable and thermally inefficient). Likely evolution to Laval nozzle over time.

Volatiles are not considered in any way. From before:

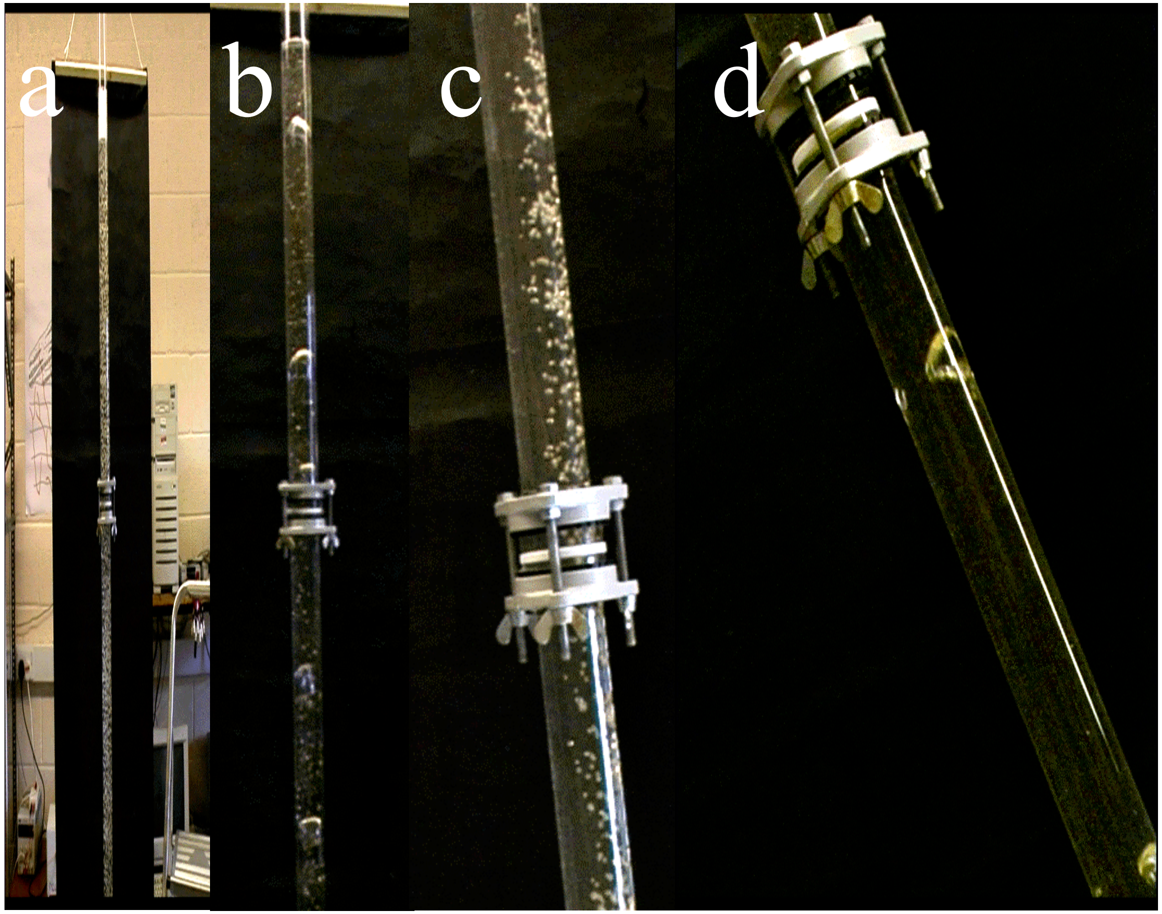
- $dT/dz = (1 / c)\,(m_g / \rho_g)\,dP/dz + u^2 f / 2\,r\,c$



The first expression on the RHS describes cooling due to expansion of a volatile gas component of the eruptants. Decompressing an ideal gas from 0.5 GPa to near vacuum should theoretically produce a massive temperature drop.

In reality, volatiles should mostly de-couple thermally from the magma near fragmentation, usually at substantial depth and much higher pressure, but the net effect during ascent can still be great even for very low (less that Kilauea) sulphur contents – of the order of 10s to 100s of K.

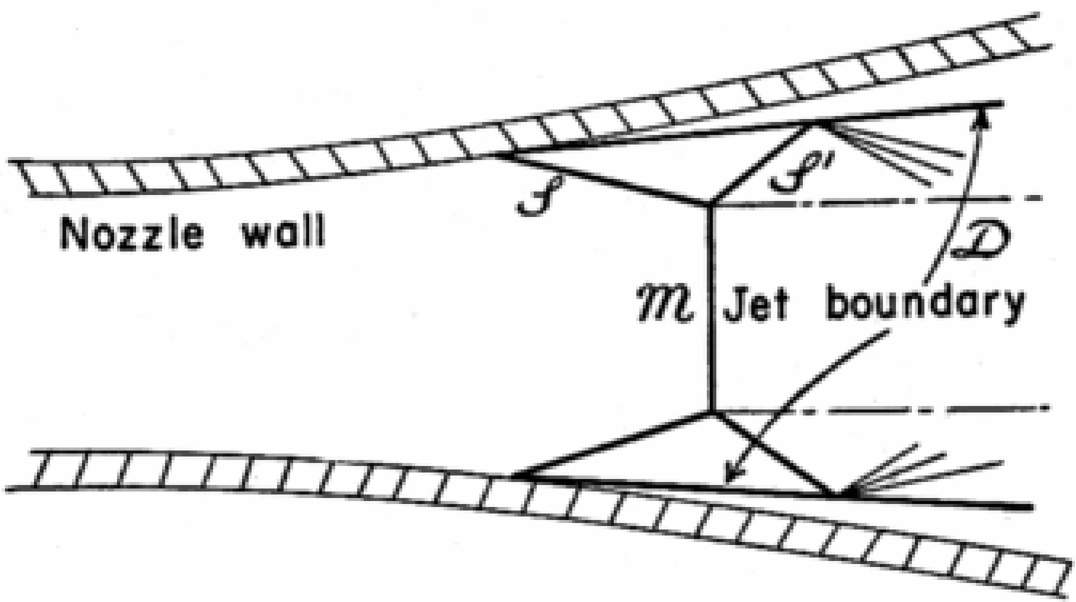
Gas-volatile decoupling



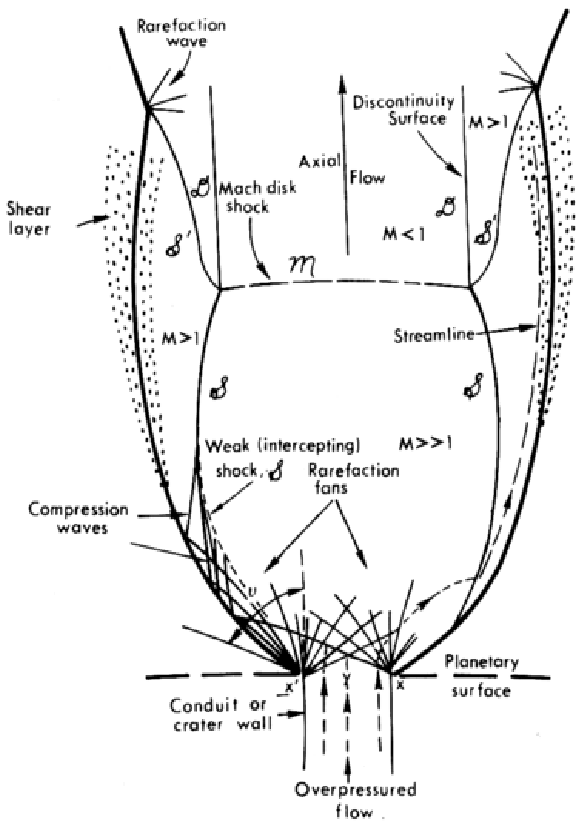
Volatiles can also de-couple due to conduit inclination. From sugar-solution analogue experiments at Lancaster Univ. (source: S. Lane). From left to right: (a) vertical bubbly flow, (b) vertical slug flow, (c) bubbles show tendency to rise at 6^{o}, (d) bubbles accumulate at 29^{o}.

High-speed compressible flow (1)

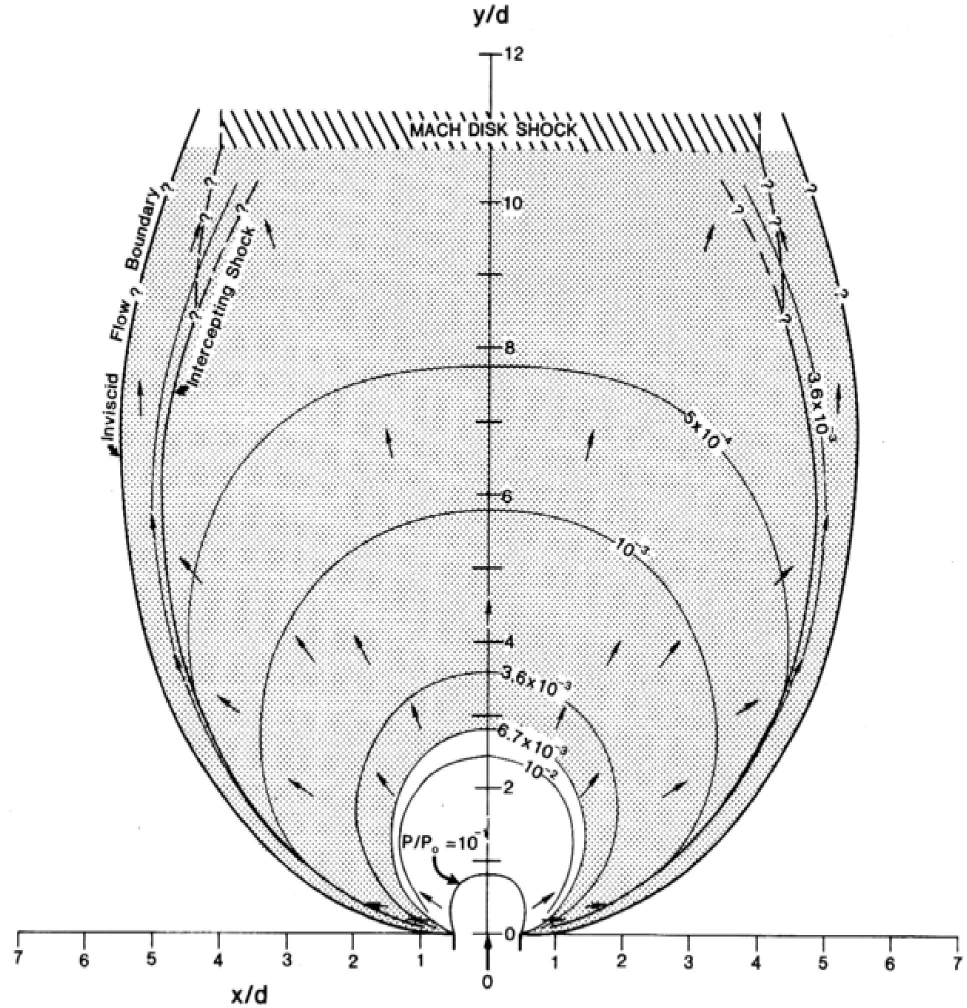
- Beyond fragmentation, shocks and rarefaction waves are established where Mach > 1.
  - Prandtl-Meyer expansion. Flow is refracted inward.
  - Extremely difficult to solve or simplify.
  - Multiple Prandtl-Meyer cells.
  - Applies both above and below the surface.
  - Non-isentropic, therefore likely net loss of KE to enthalpy.



High-speed compressible flow (2)



(a)



(b)

High-speed compressible flow (3)

Conclusions

• Viscous dissipation has the potential to cause large increases in temperature during conduit ascent. This effect is significant on Io due to lithospheric pressures which far exceed lithostatic.

• This may at least partially explain high temperatures modelled at some volcanic sites on Io. It is certainly capable of explaining the 100-200 K temperature deficit based on re-analysis on NIMS/SSI data (*Keszthelyi et al*., 2005).

• However, the temperature increases due to viscous dissipation may be offset by adiabatic cooling due to volatile expansion in cases where the magma contains, and is thermally coupled with, volatiles such as S_2 and SO_2.

• Higher eruption temperatures = fast, gas free eruptions from great depths?

• In further work we will seek to characterise the relative roles of viscous dissipation and adiabatic cooling over a range of likely eruption conditions on Io.