Volcanic Explosions: Classification and Physics

Introduction

- Volcanic explosions result from the catastrophic expansion of a gas phase.
- Direct observations are difficult (except from afar) and limited - for obvious reasons.
- Underlying physics of volcanic explosions must therefore be deduced from:
  - Geologic observations - results of past explosions
  - First principles - laws of physics
Lacroix’s (1908) Classification of Explosive Eruptions

- Hawaiian
  - Continuous lava fountaining
- Strombolian
  - Pulsed bursts
- Vulcanian
  - Intermittent explosions
- Plinian
  - Large, continuous explosion with large plume

Hawaiian

- Hawaiian “Explosions”
  - Perhaps not an explosion, but does involve an eruption driven by rapid expansion of volcanic gas.
- “Hawaiian” eruption refers to fountaining, where magma is propelled above the surface by expanding gas

Pu‘u O‘o, 1983
Hawaiian Style Eruptions

- Fountains may reach 500 m, but 10-100m is more typical.
- High fountaining commonly announces a new eruption or eruptive phase in Hawaii, when comparatively undegassed magma arrives at the surface.
  - Subsequent phases show much smaller fountains or none at all.
- Gas disrupts magma into "clots"
  - Ratio of clot:gas was 1:70 in Pu‘u Oʻo
- Typically produces Scoria Cones
- Unsolidified clots may coalesce to form flows.

Hawaiian Fountaining of Etna
Stromboli, Eolian Islands, Italy

Strombolian Eruption Style
**Strombolian Eruptions**

- Strombolian style refers to discontinuous individual explosions repeated at intervals of a few per minute to a few per hour.
- Gas:clot ratio $10^5:1$
- $10^{-2}$ m$^3$ to $10^2$ m$^3$ erupted/explosion
- Muzzle velocities <100 m/s
- Results from single large bubble reaching the surface and bursting

**Strombolian Eruption of Etna**
Vulcano, Eolian Islands, Italy

Vulcanian Eruption Style
Vulcanian Eruptions

- Discrete, very violent explosions
- Capable of ejecting enormous blocks and generating atmospheric shock waves
  - Muzzle velocities ≤ 400 m/s (supersonic)
  - Speeds suggest 100x overpressure
- May produce ash clouds and pyroclastic flows
- High proportion of non-juvenile material in ejecta.

Sakura-jima, Japan

Vulcanian Explosions

- Vulcanian Explosions are thought to occur when debris blocks a vent a gas exsolved from the magma builds up beneath the blockage.
- When the strength of the block is exceeded, it is ejected.
- Consequent drop in pressure on the magma results in further exsolution and expanding gas propels magma out of the vent.

Plinian Style Eruptions

- Plinian Eruptions are the largest and most energetic eruptions, producing clouds of ash that reach the stratosphere
  - Used for large range of eruptions.
  - Therefore, sometimes broken down into
    - subplinian (<0.1 km$^3$)
    - plinian
    - ultraplinian (>10 km$^3$)
- Typically produce both large ash falls and pyroclastic flows

1944 Plinian Eruption of Vesuvius
Vesuvius Above Pompeii

- Named for the description given by Pliny the Younger of the 79 AD eruption of Vesuvius

Plinian Explosions

- Plinian explosions occur when bubbles of exsolving magmatic gas completely disrupt the magma
  - i.e., a transformation from a bubbly liquid to a gas containing fragments of liquid.
  - Restricted to gas-rich silicic magmas.
Physics of Volcanic Explosions

- The traditionally qualitative and observation-oriented field of volcanology began a transformation into quantitative science in about the 1970’s when modern volcanologists began asking why and how and applying physics to find the answers.
- Understanding volcanic eruptions involves both application of physical laws and geologic observations.

Role of Gas Exsolution and Bubbles

- Gas acts as the propellant in all volcanic explosions.
  - This gas generally originates as water and CO$_2$ dissolved in the magma.
  - (However, other sources of water, e.g., ground water can be important - particularly in vulcanian explosions).
  - Consequently, understanding its dissolution and subsequent growth of bubbles is key to understanding explosions.
**Bubble Nucleation**

- Exsolution of gas from magma results in formation of new phase (bubbles) and consequently, the formation of an interface between this phase and the existing liquid phase. This interface has an *interfacial* or *surface free energy*, $\sigma$, associated with it, which must be be overcome in order for a bubble to grow.
- Overcoming this surface free energy requires a degree of supersaturation.

**Energetics of Bubble Nucleation**

$$\Delta G_{tot} = 4\pi r^2 \sigma + \frac{4}{3} \pi r^3 \frac{\Delta G}{V}$$

[Diagram showing the energetics of bubble nucleation with $\Delta G_{tot}$, $r_{crit}$, $\Delta P1$, $\Delta P2$, and $\Delta P3$]
Bubble Nucleation & Growth Rates

- Surface free energy between gas and silicate magma is fairly large, requiring significant degree of supersaturation.
  - This will result in rapid bubble formation once the necessary $\Delta G$, is attained
- Surface free energy correlates with viscosity, so nucleation will be more difficult in rhyolite than in basalt.
- Crystals provide a potential site of bubble nucleation where surface free energy is lower
  - Because finite surface free energy already exists between the crystal and liquid.

- Once it begins, nucleation will occur at rate:
  $$J \propto D \exp\left(-\frac{16\pi\sigma^3}{3RT \Delta P^2}\right)$$
  - Leads to strong exponential dependence on supersaturation
- Growth & nucleation rates also proportional to diffusion coefficient, $D$, and hence can be limited by diffusion of gas to bubble surface
  - Diffusion rates related to viscosity, so bubble growth is more likely to be diffusion limited in silicic lavas than in basic ones.
**Effect of Bubbles**

- Formation of bubbles reduces the density of the magma, increasing it buoyancy and the force exerted on overlying rock.
  - The effect is to drive the magma upward, increasing chances of eruption.
  - Rising magma experiences decreasing pressure, leading to more exsolution, etc.
- Key factors for eruptive style:
  - Can bubbles rise through the magma?
    - Leads to non-Plinian eruptions if yes.
  - Can bubbles coalesce?
    - Leads to Strombolian eruptions if yes.
  - Depends on magma viscosity

**Rise of Bubbles**

- Stokes Law:
  \[
  v = \left[ \frac{(\rho_i - \rho_g)g}{18\mu} \right] d^2 \approx \frac{\rho_i g d^2}{18\mu}
  \]
  - \(v\) is velocity, \(d\) is bubble diameter (\(\mu\) is dynamic viscosity)
  - For basaltic liquid, 1mm bubble rises at 0.5 m/h (1 km in 3 months), 1cm bubble at 50 m/hr
  - For wet granitic liquid, 1 mm bubble rises at 0.4 m/yr, 1 km in 2500 yrs.
Conduit Flow Regimes

- Bubbly mix
- Slug
- Annular
- Dispersed

Effusion  Strombolian  Fire Fountains (Hawaiian)

Model of Vergniolle & Jaupart

- Accumulation of Foam in Magma Reservoir
- Collapse of Foam into large gas pockets
- Gas pockets erupt in annular flow
Role of Viscosity & Yield Strength

- Yield strength and viscosity key factors in eruptive style
  - Low viscosity, yield strength favor collapse of foam, and also annular flow.
  - Higher viscosity inhibits foam collapse
    - When collapse occurs, slug rise favored over annular flow.