Plinian Eruptions III: The Umbrella Region, Column Collapse, and Pyroclastic Flows

EAS 458 Volcanology

- Plinian eruptions occur in gas-rich viscous magma systems.
- Plinian eruptions can be viewed as occurring in a series of steps:
  - Gas exsolution and bubble formation, which we discussed last time.
  - Fragmentation of the magma.
  - Gas thrust: gas & magma accelerated out of vent.
  - Convection; gas/ash/air mixture rises buoyantly.
  - Umbrella region; mixture rises only because of momentum and spreads.
- Plinian eruptions may fail to produce stable convective columns, or convective columns may collapse, producing pyroclastic flows.
The Umbrella Region

- At some point, convective column reaches neutral buoyancy
  - In other words, density of gas-ash mix equals density of surrounding atmosphere; higher temperature of plume balances extra density of solids.
  - When this occurs the column ceases to rise convectively and spreads.
  - Some rise continues, however, due solely to remaining momentum.

Height of the Umbrella Region

- Sparks, R. S. J., (Bull. Volcanol., 48, 3-15, 1986.) concluded the umbrella height could be calculated as:

\[ H_T = 1.32(h_0 + H_B) \]

- Where \( h_0 \) is depth of the virtual source
  - \( h_0 = 8r \)
  - e.g., for \( r = 60 \) m, \( h_0 = 480 \) m
  - For most cases, \( h_0 < H_B \), so the umbrella region will be about 1/3 the height of convective region.
Velocities in the Column

- Velocities in the column are primarily a function of initial velocity.
- Vertical velocities remain substantial in the umbrella region.
- Horizontal velocities in the umbrella region are in the range of 10-100 m/s - driven by mass conservation.

Column Collapse & Pyroclastic Flows

Mayon, Philippines, 1984
Pyroclastic Flows

- “Pyroclastic Flow” - as the roots “pyro” and “clast” suggest, refers to the flow of hot material.

- This term is extremely broad and is applied to a wide range of phenomena that have a variety of causes, but all are ultimately due to volcanic eruptions.

- Related (generally more specific) terms:
  - Ignimbrite
  - Pumice flow
  - Block and ash flow
  - Nuee Ardente (glowing cloud)

- One cause of pyroclastic flows is eruptive column collapse

+40 seconds


+60 seconds

Deposit of the August 7, 1980 Pyroclastic Flow
Deposit of the October 22, 1980 Pyroclastic Flow

Pinatubo Ignimbrite
Eruptive Column Stability

- What conditions lead to convection, and what conditions to collapse?
- Condition necessary for convection:
  - $\rho_{\text{column}} < \rho_{\text{atmosphere}}$
  - Since ash is more dense than the atmosphere, the above requires that the gas in the column be less dense than surrounding atmosphere
- Requires:
  - Low gas density
  - Heat
  - Low ash density

Gas Densities & Stability

- Ash Density
  - $\sim 2.3 \text{ g/cc}$
  - 2300 g/l
- Gas Densities
  - 1 mole occupies 22.4 l at STP
  - Mean molecular weight of air: $\sim 28.8; 1.29 \text{ g/l}$
  - Molecular weight of CO$_2$: 44; 1.96 g/l
  - Molecular weight of water: 18; 0.8 g/l
- In general, a pure CO$_2$ plume will be too dense to ever become convective.
- Convective stability becomes more difficult as CO$_2$/H$_2$O ratio increases.
- Large clasts will tend to fall out early, diluting the ash.
**Air entrainment**

- Achieving convective conditions requires that air be entrained to dilute the ash.
  - At the vent, even a cloud produced by magma with 10% H₂O will be 5 times more dense than the atmosphere.
  - In the gas thrust region, a volume of column can entrain up to 4 times its volume in air.
- Entrainment is enhanced by turbulence (indeed, requires turbulence).
  - Turbulence is promoted by high velocity
- Therefore, higher velocities lead to greater entrainment.
- Entrainment occurs only at the sides
  - Therefore, the wide columns (wide vents) entrain proportionally less air than narrow columns (narrow vents)

**Effect of Vent Radius**

- Entrainment occurs at the interface between column and surrounding air
  - This is proportional to the circumference of the column (and ultimately the vent), so it increases linearly with radius
- Mass flux (specifically of particles) is proportional to the area of the vent
  - Mass flux increases with square of vent radius (for a fixed velocity)
- Therefore, at large r, increasing r works against convective stability
Heat

- Entrained air must be heated and expanded to overcome density of ash.
- Because the heat capacity of gas is low, heat comes primarily from ash
  - Both from cooling and solidifying
- Heating efficiency is proportional to mass flux.
- Heating efficiency is also related to grain size: small grains give up heat more rapidly than large ones.

Key Factors Controlling Stability

- Gas content
- Ejection velocity
  - Depends on gas content
- Mass Flux
  - Depends on velocity, but also vent radius
  - (recall that velocity deep in system depends on square of radius because of viscous effects)
  \[ u = \frac{g(\rho_0 - \rho_f)r^2}{8\eta} \]
  - Mass flux therefore depends on 4th power of radius
- Vent Radius
  - Positive effect on mass flux, negative on entrainment
Two Scenarios for Collapse

- **Scenario 1:**
  - Vent widens by erosion to the point where column becomes unstable (can’t entrain enough air)

- **Scenario 2:**
  - Water content of magma drops, decreasing eruption velocity at constant radius

---

Case History of Eruptive Column Collapse: Vesuvius, 79 AD

- **Sources:**
  - Pliny the Younger’s Letter to the historian Tacitus
  - Geological field work & archeological excavation
Vesuvius had been dormant for centuries
- not recognized as a volcano by the Romans (although Etna was)
- Strabo has noticed similarities of rocks to Etna
- Large, damaging earthquake in 62 AD
  - Occasional subsequent shocks over next 16 years.

POMPEI
24 agosto 79 d.C.
Pliny's Account

- Pliny, in Misenum, observes large cloud over Vesuvius on the afternoon of August 24.
- Pliny the Elder, an admiral, organizes rescue effort; can land no nearer than Stabiae.
- Ash and fumes at Stabiae that night, Pliny the Elder dies (heart attack?) trying to escape.

- Morning of August 25, ash blocks out Sun in Misenum (as dark as a sealed room); continual tremors.
- Pliny the Younger and his mother flee northward, but are overcome by clouds of ash.
- Hours later, the ash clears. Paroxysmal phase lasts 20 hours.
- Pliny observes that smooth cone of Vesuvius replaced by stump and the entire region is covered in gray.
**The Geologic Record**

**Geologic Record: Lower Units**

- **EU 1: basal unit**
  - Surge deposit produced by phreatomagmatic explosion (due to presence of crater lake?)

- **EU 2 White Pumice**
  - Thick sequence of well-bedded pumice corresponding to Plinian phase of the eruption.
  - Found mainly to the East (indicating westerly wind)
  - 1.5 m thick at Pompeii
  - Accumulated at 10-15 cm/hour
  - Discharge rates of $8 \times 10^7$ kg/s - decreases near end
  - Column height: 26 km
Geologic Record: Lower Units

- EU 3 Grey Pumice
  - Begins with increase in eruption rate to $1.5 \times 10^8$ Kg/s
  - Color change corresponds to compositional change
  - Column height of 32 km; decreases to 17 km over next 9 hours
  - EU 2 and EU 3 interrupted by at least 5 pyroclastic flows produced by column collapse

The Geologic Record: Upper Units

- Provide evidence of phreatomagmatic events
  - Pyroclastic flow and surge deposits interbedded with thin fall deposits
  - Rich in lithic fragments, including deep-seated limestone, marbles, skarns
  - Probably result from interaction of magma with regional aquifer
Eruption of Zoned Magma Chamber

- Correlation between mass discharge rate and composition:
  - Higher discharge rates scoured deeper into magma body.

Pyroclastic Flows
The Epilogue

- Pompeii and Herculaneum destroyed by pyroclastic flows; death told unknown (about 20,000 residents at the time).
  - 4 m in Pompeii
  - 23 m in Herculaneum
- Ash cover lead Romans to abandon the area
- Pompeii and Herculaneum eventually forgotten
- Rediscovered in 1595
  - Some plundering of art over the next several centuries
- Excavation begins in 1748
- Vesuvius has subsequently erupted more than 50 times.