Magma Ascent and Emplacement

Reading: Encyclopedia of Volcanoes:
- Physical Properties of Magmas (pp. 171-190)
- Magma Chambers (pp. 191-206)
- Plumbing Systems (pp. 219-236)
- Magma ascent at shallow levels (pp. 237-249)

Topics
- How does magma ascend?
- How do dikes form?
- How is magma emplaced?

Magma Generation
- Partial melting
  - Upper mantle
  - Deep crust
- Magma density
- Less than surroundings

Magma Rise
- Buoyancy
  - Driving force is density difference
  - Resisting force is the magma viscosity
- Silicic magma
  - High viscosity requires large volume
- Mafic magma
  - Low viscosity allows small volumes to rise

Energy Sources
- Thermal energy
  - Melting caused by decompression or volatile flux
- Gravitational energy
  - Driven by density differential

Instabilities
- A layer of less dense material overlain by a denser material is unstable
- The upper layer develops undulations and bulges (Rayleigh-Taylor instabilities)
- The spacing of the bulges depends on the thickness of the light layer and its density contrast with the heavy layer
**Diapirs**

Diapir Ascent

- Velocity of ascent depends on diapir size and shape
- A sphere is the most efficient shape
- Surface area ~ frictional resistance
- Volume ~ buoyant driving force
- Rise velocity proportional to area squared

**Neutral Buoyancy**

- Positively buoyant
  - Melt that is less dense than surrounding rocks
  - Primary basalt magma surrounded by mantle peridotite
- Negatively buoyant
  - Melt that is more dens than surrounding rocks
  - Olivine basalt intruded into continental crust

**Density Filter**

- Crustal rocks block the ascent of denser magmas
- Heat from these magmas melt the lower crust
- Residual melts may rise
- Exsolved volatiles also facilitate rise

**How Can Dense Magma Rise?**

- Volumetric expansion on melting?
- Exsolution of bubbles?
- There must be another cause.
### Magma Overpressure

- For a magma lens, pressure is equal to the lithostatic load
  \[ P_m = \rho_r \cdot g \cdot z \]
- The pressure can be greater in a conduit connecting a deeper pocket to the surface
- This overpressure can be great enough to bring denser magma to the surface

### Magma Ascent

- **Dikes**
  - Sub-vertical cracks in brittle rock
- **Diapirs**
  - Bodies of buoyant magma
  - They squeeze through ductile material

### Dikes

- Intrusions with very small aspect ratio
- Aspect: width/length = $10^{-2}$ to $10^{-4}$
- Near vertical orientation
- Generally 1 - 2 meters thick

### Dike Swarms

- Hundreds of contemporaneous dikes
- May be radial
- Large radial swarms associated with mantle plumes

### Intrusion into Dikes

- Stress perpendicular to the fracture is less than magma pressure
- Pressure must overcome resistance to viscous flow
- Magma can hydrofracture to rock and propagate itself

### Stress for Dikes

- Dikes are hydraulic tensile fractures
- They lie in the plane of $\sigma_1$ and $\sigma_2$
- They open in the direction of $\sigma_3$
- They are good paleostress indicators
Orientation

- Near-vertical dikes imply horizontal $\sigma_3$
- Typical in areas of tectonic extension
- Can be used to interpret past stress fields

En Echelon Dikes

- Dikes commonly form fingers upwards
- Sub-parallel overlapping alignments
- Suggest a rotation of $\sigma_3$ in the horizontal

Radial Dikes

- Stress orientation around a central intrusion
- $\sigma_1$ is perpendicular to the contact (radial)
- $\sigma_3$ is horizontal and tangential to contact
- Radial dikes are radial from intrusion
- Far dikes assume the regional trend

Cone Sheets

- Stress orientation above an intrusion
- Planes containing $\sigma_1$ and $\sigma_3$ are cones
- Magma intruded along these form cone sheets
**Ring Dikes**

- If magma pressure diminished
- The roof of the chamber may subside
- This forms a caldera
- The bounding fault is a ring fault
- If magma intrudes, this is a ring dike

**Tectonic Regime**

- Extensional regime
  - Basalts common
- Compressional regime
  - Andesites common

**Extensional Regime**

- $\sigma_1$ is vertical
- $\sigma_2$ and $\sigma_3$ are are horizontal
- $P_m > \sigma_3$
- Vertical basaltic dikes rise to surface

**Compressional Regime**

- $\sigma_3$ is vertical
- $\sigma_1$ and $\sigma_2$ are are horizontal
- $P_m < \sigma_2$
- Basalt rise limited by neutral buoyancy

**Room Problem**

How to accommodate for the volume of the batholith?

**How to Accommodate Plutons in the Crust?**

A huge volume is involved in batholithic intrusions

**Processes:**
1. Thicken the crust by displacing the Moho downward
2. Lifting the surface of the Earth
3. Exchange positions of magma from lower crust to upper crust
Granite Plutons
- Generally inhomogeneous in composition
- Composite intrusions
  - Emplacement of two different magmas
- Zoned intrusions
  - Concentric gradations

Composite Intrusions
- Compositionally or texturally different
- Chilled, fine-grained inner contact
- Variable time intervals (and cooling histories) between intrusions

Zoned Intrusions
- Concentric parts
- Successively less mafic inward
- Gradational contacts
- Assimilation of country rock?

Batholiths
- An example: the Sierra Nevada Batholith, CA
- A group or groups of separately intruded plutons with a composite volume of $10^6$ km$^3$
- Age extends through the Mesozoic (>130 my)
- Average pluton volume is ~ 30 km$^3$

Emplacement Process
- Stoping
- Brecciation
- Doming
- Ballooning
- Void zones

Gill, 1981
**Stoping**

- Concentration of water near top of magma causes hydrofracturing
- Thermal stress and pressure fractures rock
- Fractured rocks engulfed by magma
- Incorporated blocks sink in the magma
- Magma moves upward occupying space
- Isotropic fabric

**Xenoliths**

- These features are evidence for stoping
- Blocks may become schlieren
- They also could assimilate in magma

**Ring Fracture Stoping**

- Failure of the roof of a chamber
- Dikes form a ring around the sinking slab
- Magma also intrudes above the sinking block

**Breccia Pipes**

- Slender vertical pipe-like bodies of breccia
- Elliptical or circular cross sections

**Dikes vs. Pipes**

- Dikes grow by extensional fracturing
- Their conduit is the route of greatest magma volume for the existing pressure
- A dike requires the least work on the wall rocks to accommodate the volume of magma
- So why do we have pipes?

**Diatremes**

- Perhaps drilling is the answer?
- Diatremes formed by volatile (H₂O, CO₂) rich intrusions
- Crammed with xenoliths of country rock
**Doming**
- Over-pressured magma may make a roof for itself
- This may form a laccolith
- Begin as sills and then inflate toward the surface

**Tectonic Room**
- Dilatant faults zones
- Bends in a fault zone
- Hinge zones of folds
- Domains of extension in a compressive regime

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**The Intrusion**
- Contacts
  - Record length and type of effects
- Border zone
  - May be permeated with changes due to thermal, chemical, and deformational effects

**Contacts**
- Rapid cooling gives a sharp contact
- Strong thermal gradient produces weak contact effects
- Grain size may decrease toward the contact indicating rapid cooling
- Sharp with no change in grain size could indicate flowage past a chilled margin

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**Border Zone**
- Large plutons commonly have a wide border zone
- Invasion of host by dike systems
- Evidence of stoping
- Partial melting of host
- Contact metamorphism

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