Magma Ascent and Emplacement

Reading: Encyclopedia of Volcanoes:

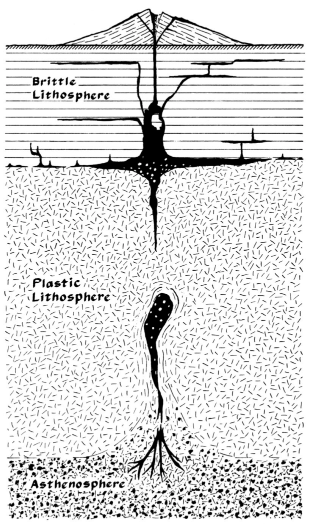
Physical Properties of Magmas (pp. 171-190)
Magma Chambers (pp. 191-206)
Plumbing Systems (pp. 219-236)
Magma ascent at shallow levels (pp.237-249)

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

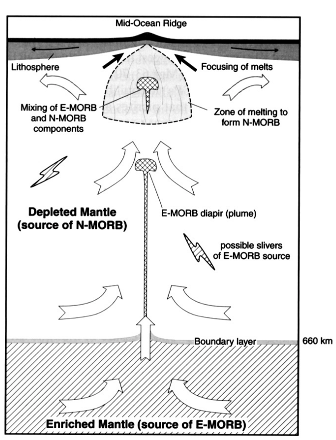


Magma Rise

- 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

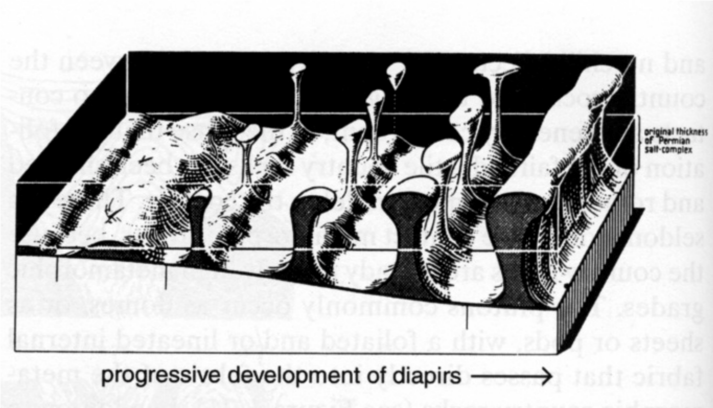
- Thermal energy
  - Melting caused by decompression or volatile flux
- Gravitational energy
  - Driven by density differential



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

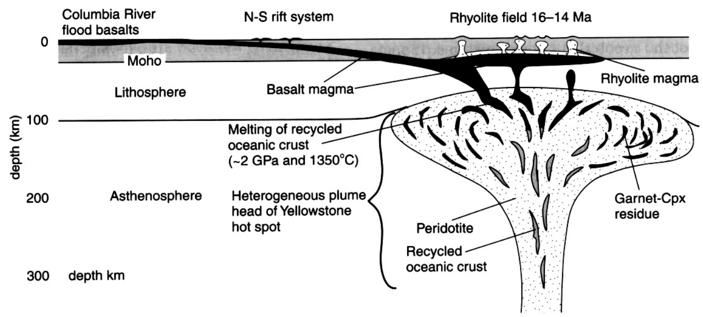


Diapir Ascent

- 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

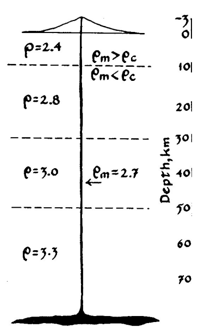
Neutral Buoyancy

- 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

$$P_m = \rho_r g z$$

- 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

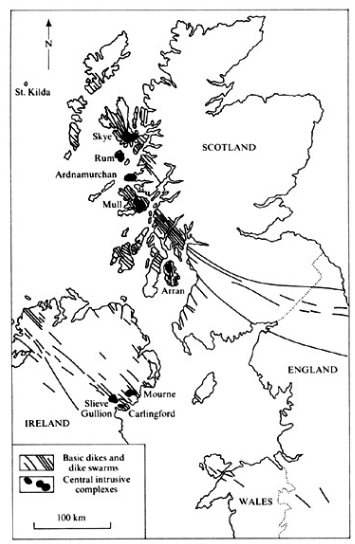
- Dikes
  – Sub-vertical cracks in brittle rock
- Diapirs
  – Bodies of buoyant magma
  – They squeeze through ductile material

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

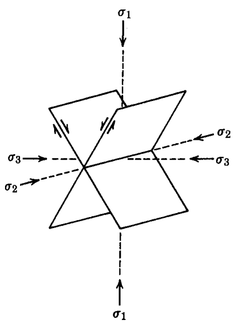
- Stress perpendicular to the fracture is less than magma pressure
- Pressure must overcome resistance to viscous flow
- Magma can hydrofracture to rock and propagate itself

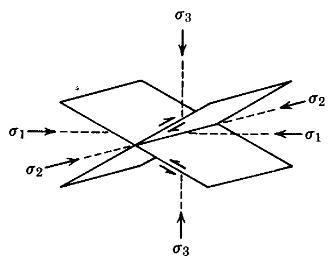
Stress for Dikes

- Dikes are hydraulic tensile fractures
- They lie in the plane of σ_1 and σ_2
- They open in the direction of σ_3
- They are good paleostress indicators

σ_1 vertical

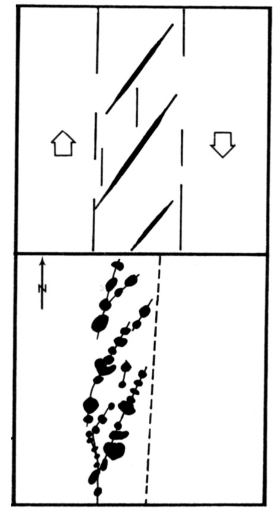
σ_3 vertical





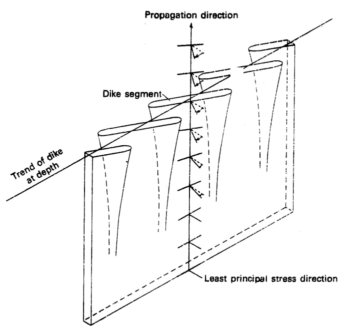
Orientation

- Near-vertical dikes imply horizontal σ_3
- Typical in areas of tectonic extension
- Can be used to interpret past stress fields



En Echelon Dikes

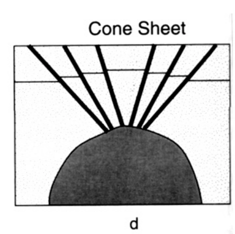
- Dikes commonly form fingers upwards
- Sub-parallel overlapping alignments
- Suggest a rotation of σ_3 in the horizontal



Radial Dikes

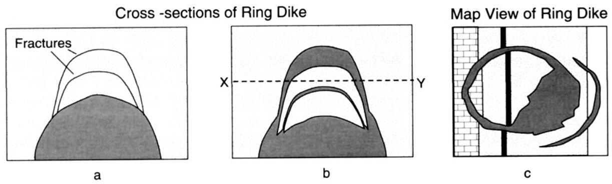
- Stress orientation around a central intrusion
- σ_1 is perpendicular to the contact (radial)
- σ_3 is horizontal and tangential to contact
- Radial dikes are radial from intrusion
- Far dikes assume the regional trend

Cone Sheets



- Stress orientation above an intrusion
- Planes containing σ_1 and σ_2 are cones
- Magma intruded along these form cone sheets

Ring Dikes



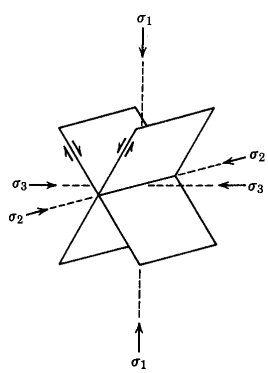
- If magma pressure diminished
- The roof of the chamber may subside
- This forms a caldera
- The bounding fault is a ring fault
- If magma intrudes, this is a ring dike

Tectonic Regime

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

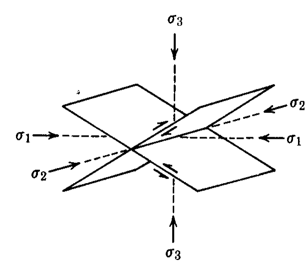
Extensional Regime

- σ_1 is vertical
- σ_2 and σ_3 are are horizontal
- $P_m > \sigma_3$
- Vertical basaltic dikes rise to surface



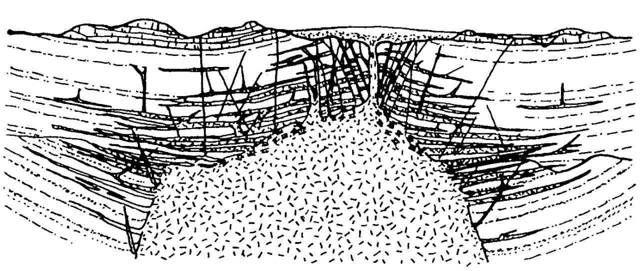
Compressional Regime

- σ_3 is vertical
- σ_1 and σ_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

<u>Processes</u>:

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

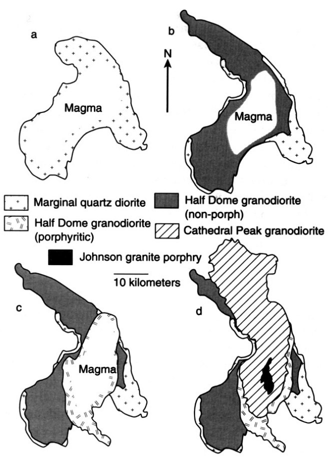
- Generally inhomogeneous in composition
- Composite intrusions
  - Emplacement of two different magmas
- Zoned intrusions
  - Concentric gradations

Composite Intrusions

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

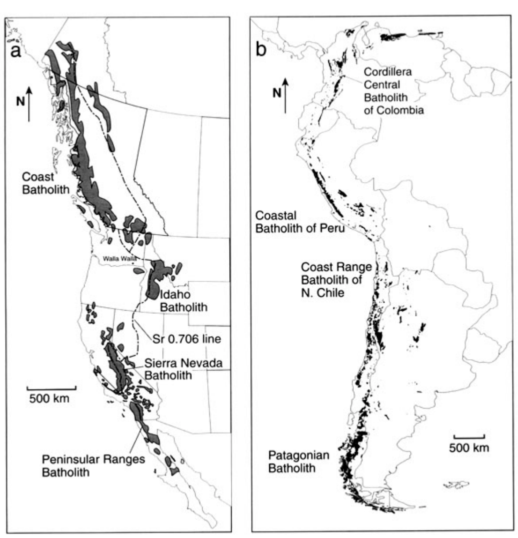
Zoned Intrusions

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



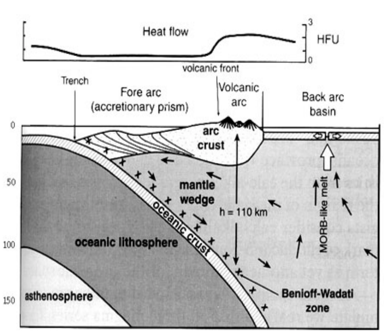
Batholiths

- 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



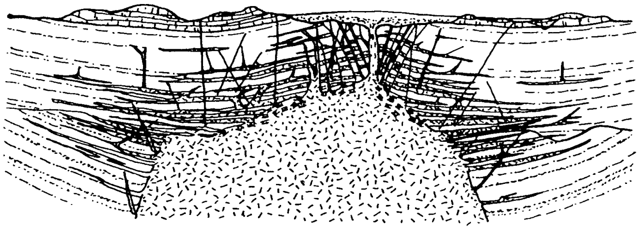
Gill, 1981

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

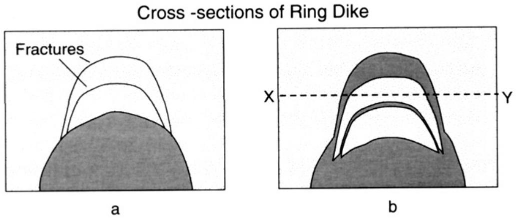
- These features are evidence for stoping
- Blocks may become schlieren
- They also could assimilate in magma



Ring Fracture Stoping

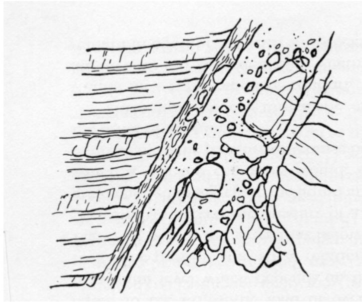
- Failure of the roof of a chamber
- Dikes form a ring around the sinking slab
- Magma also intrudes above the sinking block

Cross -sections of Ring Dike



Breccia Pipes

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

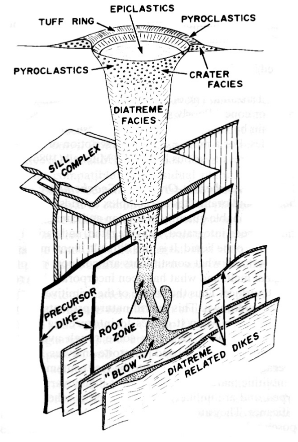


Dikes vs. Pipes

- 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?

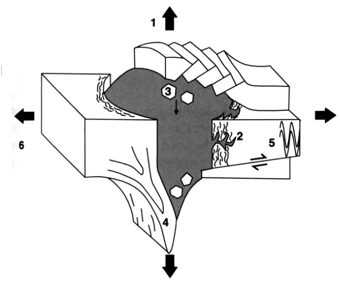
Diatremes

- Perhaps drilling is the answer?
- Diatremes formed by volatile (H_2O, CO_2) rich intrusions
- Crammed with xenoliths of country rock



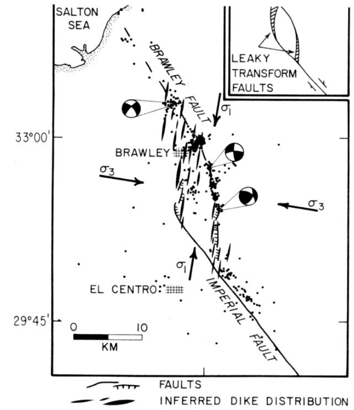
Doming

- 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



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 decreases toward the contact indicating rapid cooling
- Sharp with no change in grain size could indicate flowage past a chilled margin

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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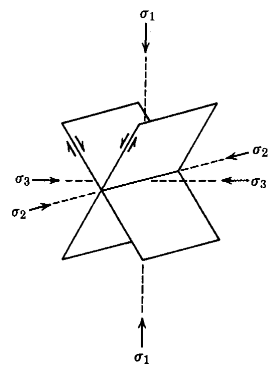

Compressional Regime

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