Magmas

Best, Ch. 8

Constitution of Magmas

- Hot molten rock
- T = 700 - 1200 degrees C
- Composed of ions or complexes
- Phase
  - Homogeneous
  - Separable part of the system
  - With an interface

Composition

- Most components
  - Low vapor pressure
  - Designated by mole fraction (X_i)
- Volatile components
  - Mainly exist as a gas
  - Designated by vapor pressure (p_i)
- Fluid pressure = sum of partial pressures

Gas Law

$$PV = nRT$$

Atomic Structure of Magma

- Quenched to form a glass
- Si & Al are polymerized with O
- Forming networks of Si-O chains
- Short-range structural order

Structural Model

- Network formers
  - Si, Al
- Network modifiers
  - Ca, Mg, etc
- Dissolved water has a strong effect

$$H_2O + O^{-2} = 2(OH)^-$$

Magma Generation

- Magmas form at perturbations in P,T,X
- Convergent plates
- Divergent plates
- Peridotite mantle source

Source Regions

- **Must originate in the mantle or crust**
- **At Hawaii 60 km deep**
- **Only 1 to 3% melt in peridotite**

Melting

- **Heat of fusion**
  - **About 300 times the rock's specific heat**
  - **Melting of rock consumes much heat**
- **Mechanisms for melting**
  - **Temperature increase by mass transfer**
  - **Decompression**
  - **Changes in composition reducing melting point**

Temperature Increase

- **Mechanical deformation**
  - **Friction generates heat**
- **Mass transfer of rock**
  - **Descending oceanic lithosphere**
  - **Basaltic underplating of continental crust**

Decompression

- **Upwelling mantle**
  - **Beneath oceanic or continental rift**
- **Adiabatic system**
  - **Pressure causes all temperature change**

Changes in Composition

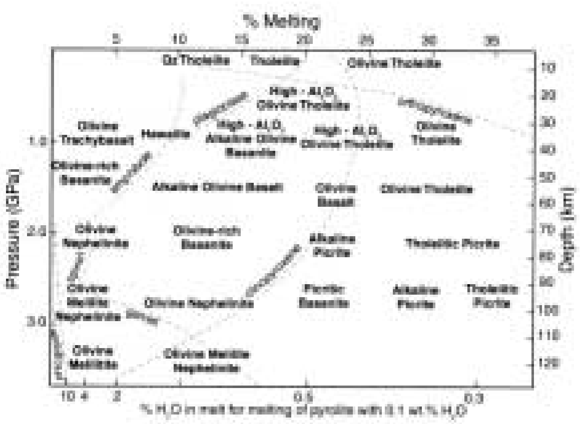
- **Increase in water pressure**
- **Lowers the solidus**
- **Subduction zones**
  - **Peridotite wedge**
  - **Over subducting oceanic crust**

Magma From Solid Rock

- Basalt & peridotite systems
- Granite systems

Basalt & Peridotite

- **Equilibrium fusion**
  - **Solid and liquid remain in equilibrium**
  - **Continuous but limited composition range**
- **Fractional fusion**
  - **Liquid is immediately removed from host rock**
  - **Melts are both oversaturated & undersaturated with respect to Si**



Influence of Pressure

- Pressure strongly influences the cotectic
- Partial melts of mantle peridotite are basalts
- At higher pressures partial melts are more silica deficient

Role of CO_2

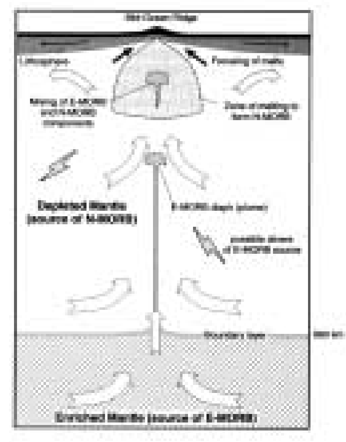
- **Polymerizes melt**
- **Contracts olivine field**
- **Favors silica-poor alkali melts**
- **Repeated melting episodes favors incompatible element enrichment**

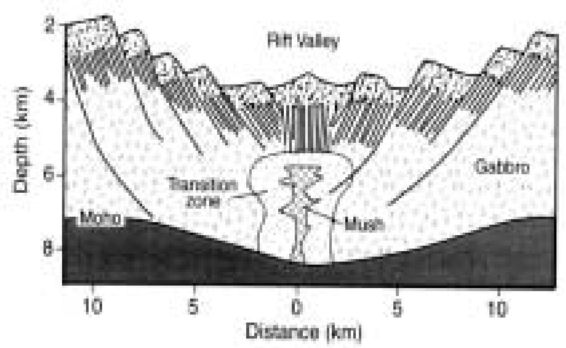
Role of H_2O

- **Depolymerizes melt & stabilizes olivine**
- **Partial melts more silica rich**
- **Favors tholeiitic basalts**

Mantle-derived Primary Melts

- Wide range of melt compositions possible
- Fractional crystallization vs. Partial melting
- Primary melt
  - Segregated from peridotite source rock
  - First crystallized minerals similar to mantle source zone
- Derivative melt
  - Modified after leaving the source region





Volcanic Rocks of Island Arcs

- Complex tectonic situation and broad spectrum
- High proportion of basaltic andesite and andesite
  - Most andesites occur in subduction zone settings

Major Elements and Magma Series

- Tholeiitic (MORB, OIT)
- Alkaline (OIA)
- Calc-Alkaline (~ restricted to SZ)

Granitic (Rhyolitic) Systems

- Impossible to generate granites by partial melting of mantle peridotite or subducted oceanic floor basalt
- Their origin is related to older sialic crust
- Granites concentrated along old subduction zones

Water Saturation

- Saturated granite melts have 10 to 15% H_2O
- Natural granite melts have about 4% H_2O

Water Undersaturation

- Common granite mineral assemblage
  - Biotite, K-spar, Fe-Ti oxide

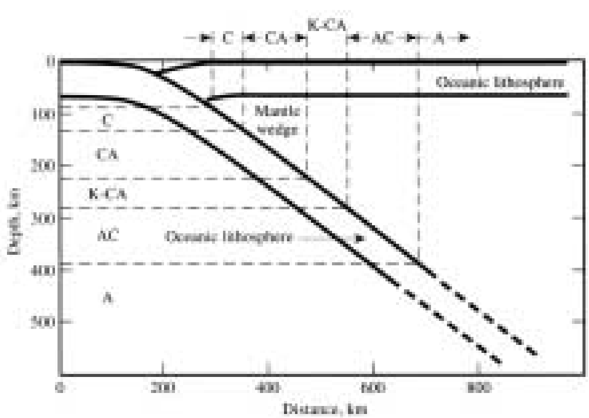
  ½ O_2 + biotite = K-spar + Fe_3O_4 + H_2O
- Excess water drives this reaction to the left
- Hence, most granites are not water saturated

Origin of Granites

- Partial Melting of lower crust
- Source in mica-amphibolites
- Contain 1-2% H_2O
- Lowest T melts are K-rich granite
- Higher T, deeper melts are Ca-rich granodiorite

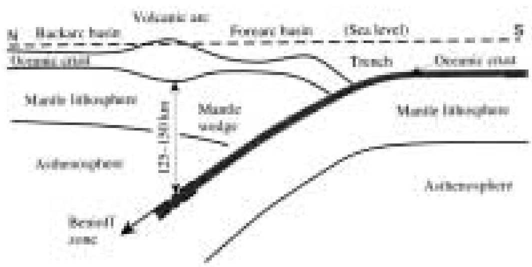
Subduction Zone Magma

- Subducted slab
  - Mafic primary melts
- Peridotite mantle wedge
  - Mafic primary melts

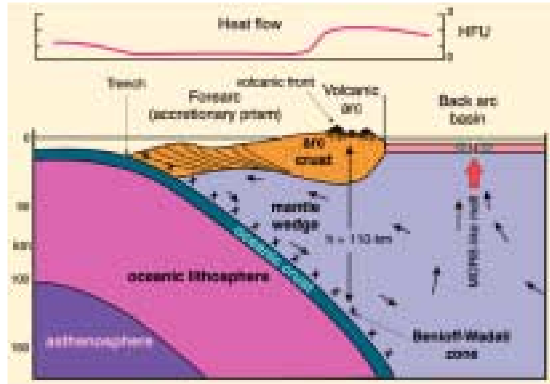


Dehydration Beneath Orogen

- Large amount of water in oceanic slab
  - Water in pore space
  - Water in alteration minerals
- Heating dehydrates the slab
- Liberated water promotes partial melting of peridotite
- Composition is Si-saturated tholeiite



Structure of an Island Arc

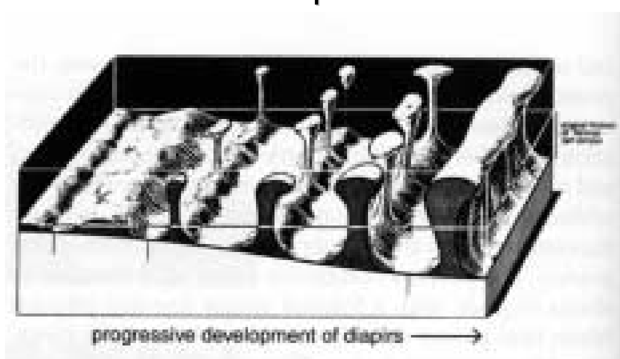


Schematic cross section through a typical island arc after Gill (1981)

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

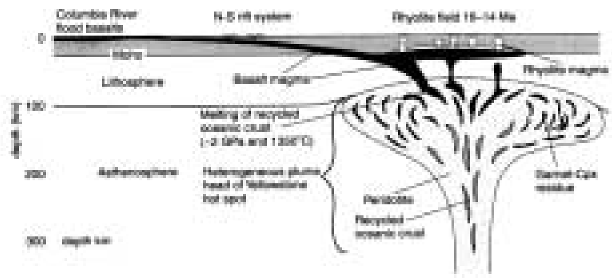


Diapir Ascent

- 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

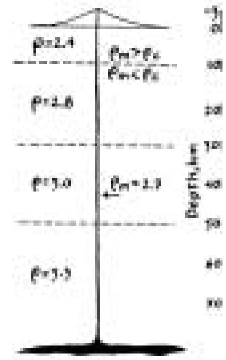
Neutral Buoyancy

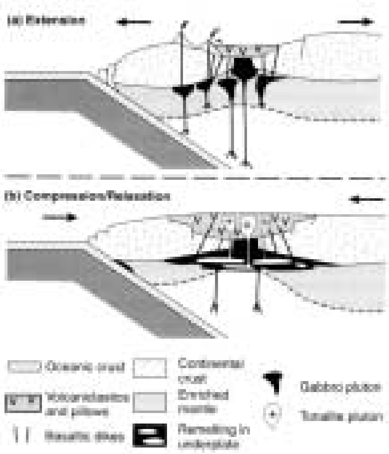
- **Positively buoyant**
  - **Melt less dense than surrounding rocks**
  - **Primary basalt magma surrounded by mantle peridotite**
- **Negatively buoyant**
  - **Melt more dense than surrounding rocks**
  - **Olivine basalt intruded into continental crust**



Density Filter

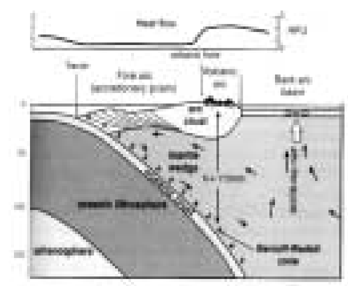
- Crustal rocks block the ascent of denser magmas
- Heat from these magmas melt the lower crust
- Residual melts may rise
- Exsolved volatiles also facilitate rise





Emplacement Process

- Stoping
- Brecciation
- Doming
- Ballooning
- Void zones



Gill, 1981

Magma Diversification

- **Magmatic differentiation**
- **Gravitational settling**
- **Liquid immiscibility**

Crystal-liquid Fractionation

- **Regular pattern of compositional variation**
- **Variation of MgO is a good measure of olivine fractionation**
- **Computer mixing programs can be used**

Magma Mixing

- Two different magmas may blend to produce a hybrid
- Common with calc-alkali magma
- Blended magmas should have linear composition with the parents

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Magma Ascent and Emplacement

Best

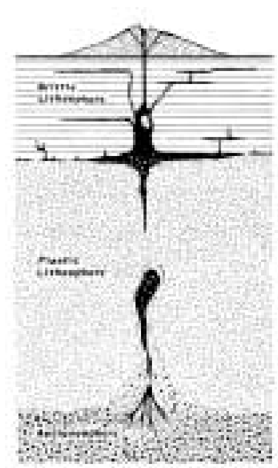
Chapter 9

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

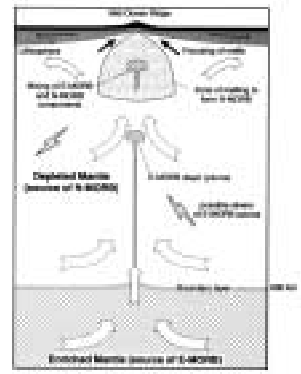


Magma Rise

- **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**



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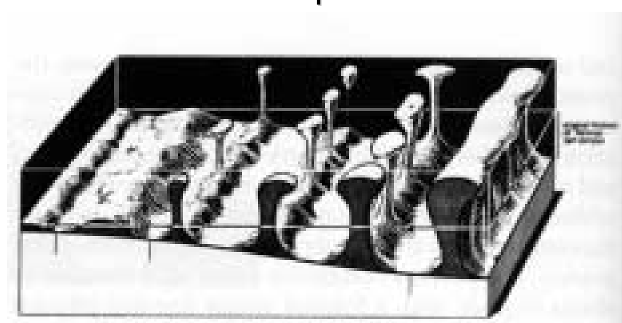

progressive development of diapirs ⟶

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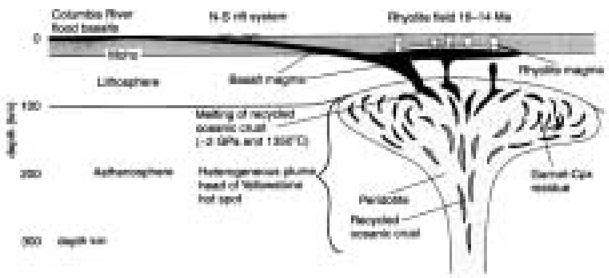

Density Filter

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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

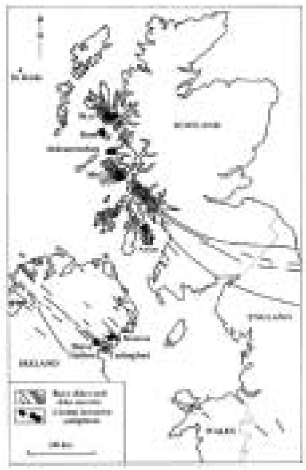
- **Dikes**
  - **Sub-vertical cracks in brittle rock**
- **Diapirs**
  - **Bodies of buoyant magma**
  - **They squeeze through ductile material**

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



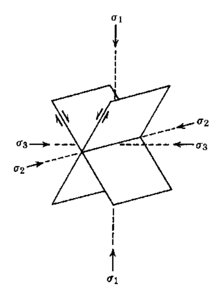
Intrusion into Dikes

- 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

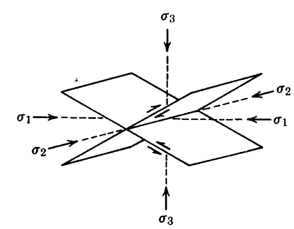
Stress for Dikes

- 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

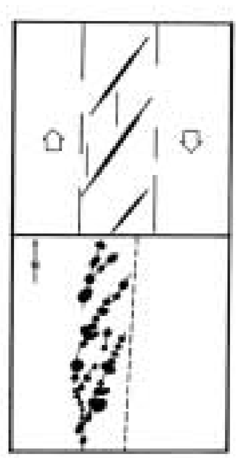


σ_3 vertical



Orientation

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

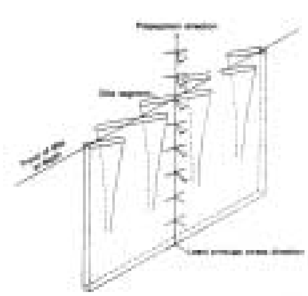


En Echelon Dikes

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**

Spanish Peaks, Colorado

Spanish Peaks, Colorado