Constitution of Magmas

Magmas

Best, Ch. 8

• 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 CO₂

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

Role of H₂O

- 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% H₂O
- Natural granite melts have about 4% H₂O

Water Undersaturation

- Common granite mineral assemblage
  - Biotite, K-spar, Fe-Ti oxide
  \[ \frac{1}{2} \text{O}_2 + \text{biotite} = \text{K-spar} + \text{Fe}_3\text{O}_4 + \text{H}_2\text{O} \]
- 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% H₂O
- 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
**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**

- 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

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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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
  \[ P_m = \rho \, g \, z \]
- 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 $\sigma_1$ 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