Magma Diversification

Reading:
Winter, Chapter 11

Magmatic Differentiation

- Any process by which a magma is able to diversify and produce a magma or rock of different composition
- Creates a compositional difference in one or more phases
- Preserves the chemical difference by segregating (or fractionating) the chemically distinct portions

Eutectic Systems

- First melt always has eutectic composition
- Major element composition of eutectic melt is constant until one of the source mineral phases is consumed (trace elements differ)
- Once a phase is consumed, the next increment of melt will be different X and T

Fractionation

- Separation of a partially melted liquid from the solid residue requires a critical melt %
- Sufficient melt must be produced for it to
  - Form a continuous, interconnected film
  - Have enough interior volume that it is not all of it is adsorbed to the crystal surfaces

The ability to form an interconnected film is dependent upon the dihedral angle (θ) a property of the melt

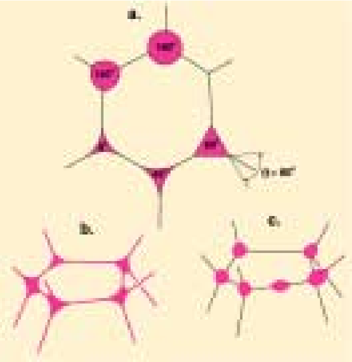


Illustration of the dihedral angle (θ) of melt droplets that typically form at multiple grain junctions. After Hunter (1987) In I. Parsons (ed.), Origins of Igneous Layering. Reidel, Dordrecht, pp. 473-504.

Gravity settling

- Cooling to point a produces an olivine layer at the base of the pluton if first olivine sinks
- Next forms ol+cpx layer
- finally forms ol+cpx+plag

Cumulate texture:
Mutually touching phenocrysts with interstitial crystallized residual melt

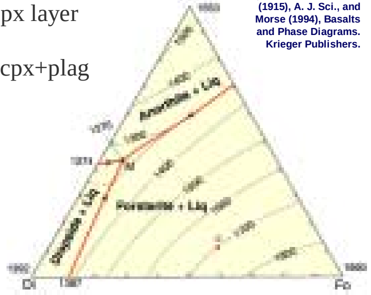
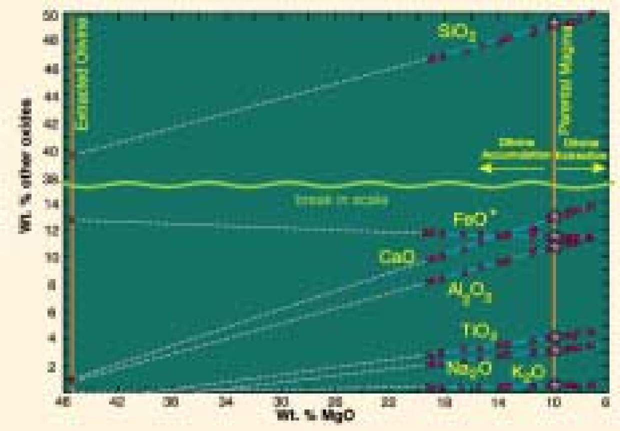


Figure 7-2. After Bowen (1915), A. J. Sci., and Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.



Variation diagram using MgO as the abscissa for lavas associated with the 1959 Kilauea eruption in Hawaii. After Murata and Richter, 1966 (as modified by Best, 1982)

Stoke's Law

$$V = \frac{2gr^2(\rho_s - \rho_l)}{9\eta}$$

V = the settling velocity (cm/sec)

g = the acceleration due to gravity (980 cm/sec^2)

r = the *radius* of a spherical particle (cm)

ρ_s = the density of the solid spherical particle (g/cm^3)

ρ_l = the density of the liquid (g/cm^3)

η = the viscosity of the liquid (1 c/cm sec = 1 poise)

Olivine in Basalt

- Olivine (ρ_s = 3.3 g/cm^3, r = 0.1 cm)
- Basaltic liquid (ρ_l = 2.65 g/cm^3, η = 1000 poise)
- V = $2\cdot980\cdot0.1^2\,(3.3-2.65)/9\cdot1000 = 0.0013$ cm/sec

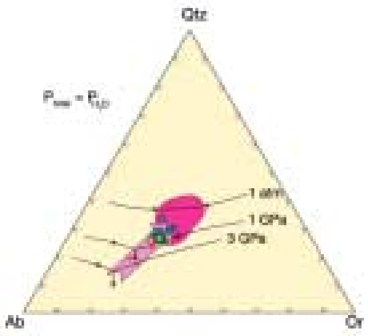
Rhyolitic Melt

$\eta = 10^7$ poise and ρ_l = 2.3 g/cm^3

- hornblende crystal (ρ_s = 3.2 g/cm^3, r = 0.1 cm)
  - V = 2 x 10^{-7} cm/sec, or 6 cm/year
- feldspars (ρ_l = 2.7 g/cm^3)
  - V = 2 cm/year
  - = 200 m in the 10^4 years that a stock might cool
  - If 0.5 cm in radius (1 cm diameter) settle at 0.65 meters/year, or 6.5 km in 10^4 year cooling of stock

Silicic magmas approach the ternary eutectic

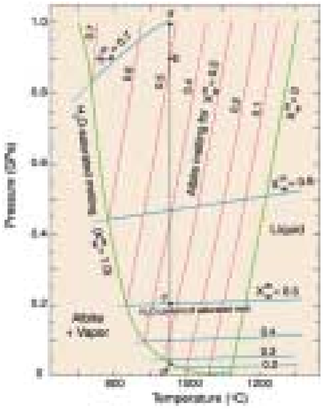
Either fractional crystallization takes place or;
They are minimum (eutectic) melts



Position of the H2O-saturated ternary eutectic in the albite-orthoclase-silica system at various pressures. The shaded portion represents the composition of most granites. Included are the compositions of the Tuolumne Intrusive Series (Figure 4-32), with the arrow showing the direction of the trend from early to late magma batches. Experimental data from Wyllie *et al*. (1976). From Winter (2001)

Volatile Transport

As a volatile-bearing (but undersaturated) magma rises and pressure is reduced, the magma may eventually become saturated in the vapor, and a free vapor phase will be released



From Burnham and Davis (1974). A J Sci., 274, 902-940.

Late-stage Fractional Crystallization

- Fractional crystallization enriches late melt in incompatible, LIL, and non-lithophile elements
- Many concentrate further in the vapor
- Particularly enriched with resurgent boiling (melt already evolved when vapor phase released)
- Get a silicate-saturated vapor + a vapor-saturated late derivative silicate liquid

Volatile Release

- Raises liquidus temperature and promotes porphyritic texture
- May increase P causing fracture the roof rocks
- Vapor and melt escape along fractures as dikes
  - Silicate melt precipitates quartz and feldspar in small dikes of aplite
  - Vapor phase produces dikes or pods of pegmatite

- Concentrate incompatible elements
- Complex: varied mineralogy
  - May display concentric zonation

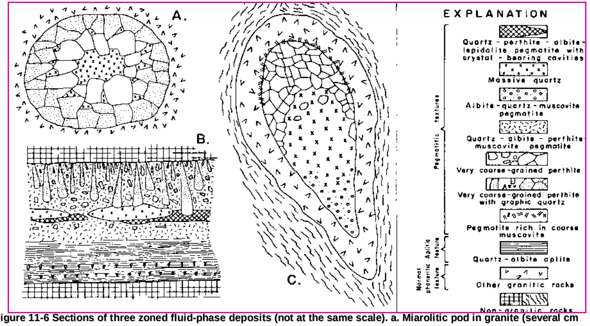
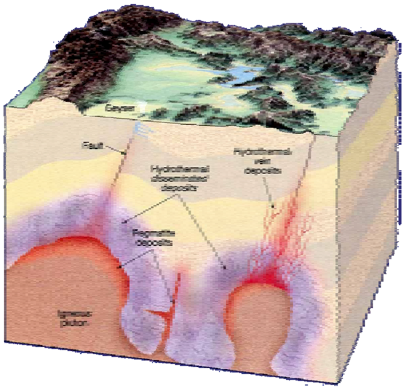


Figure 11-6 Sections of three zoned fluid-phase deposits (not at the same scale). a. Miarolitic pod in granite (several cm across). b. Asymmetric zoned pegmatite dike with aplitic base (several tens of cm across). c. Asymmetric zoned pegmatite with granitoid outer portion (several meters across). From Jahns and Burnham (1969). *Econ. Geol.*, 64, 843-864.



8 cm tourmaline crystals from pegmatite

5 mm gold from a hydrothermal deposit

Liquid Immiscibility

Liquid immiscibility in the Fo-SiO_2 system

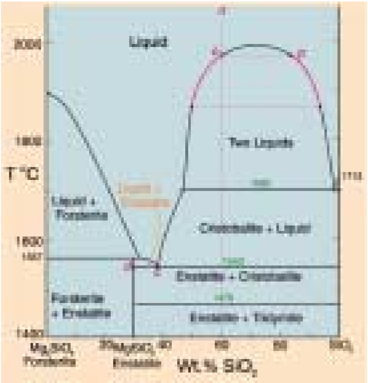
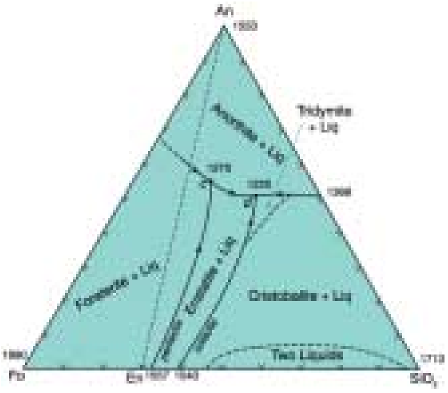


Figure 6-12. Isobaric T-X phase diagram of the system Fo-Silica at 0.1 MPa. After Bowen and Anderson (1914) and Grieg (1927). Amer. J. Sci.

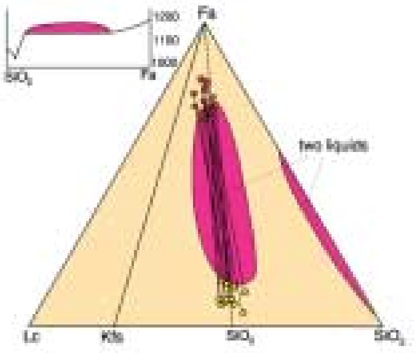
The effect of adding alkalis, alumina, etc. is to eliminate the solvus completely

Figure 7-4. Isobaric diagram illustrating the cotectic and peritectic curves in the system forsterite-anorthite-silica at 0.1 MPa. After Anderson (1915) A. J. Sci., and Irvine (1975) CIW Yearb. 74.



Immiscibility Gap

Figure 11-7. Two immiscibility gaps in the system fayalite-leucite-silica (after Roedder, 1979). Yoder (ed.), The Evolution of the Igneous Rocks. Princeton University Press. pp. 15-58. Projected into the simplified system are the compositions of natural immiscible silicate pair droplets from interstitial Fe-rich tholeiitic glasses (Philpotts, 1982). Contrib. Mineral. Petrol., 80, 201-218.



Some Examples

- Late silica-rich immiscible droplets in Fe-rich tholeiitic basalts (see Roedder)
- Sulfide-silicate immiscibility (massive sulfide deposits)
- Carbonatite-nephelinite systems of African Rift

Tests for Immiscible Origin

- The magmas must be immiscible when heated experimentally, or they must plot on the boundaries of a known immiscibility gap
- Immiscible liquids are in equilibrium with each other, and thus they must be in equilibrium with the same minerals

Compositional Convection and *In Situ* Differentiation

- *In-situ*: crystals don’t sink/move
- Typically involves
  - Diffusion
  - Convective separation of liquid and crystals

Thermogravitational diffusion

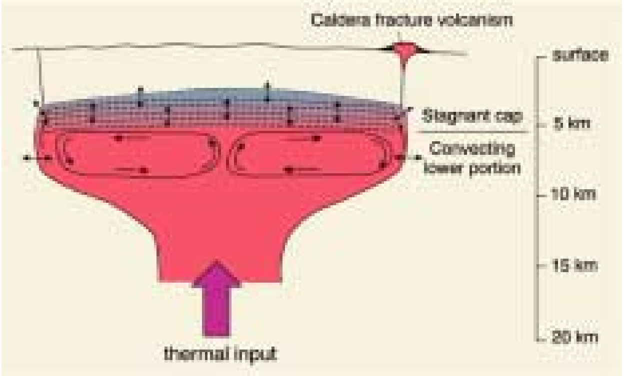


Figure 11-11. Schematic section through a rhyolitic magma chamber undergoing convection-aided *in-situ* differentiation. After Hildreth (1979). Geol. Soc. Amer. Special Paper, 180, 43-75.

Langmuir Model

- Thermal gradient at wall and cap gives variation in % crystallized
- Compositional convection yields evolved magmas from boundary layer to cap (or mix into interior)

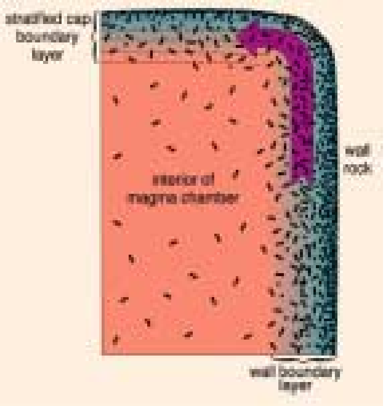
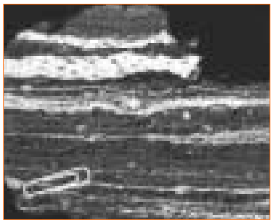


Figure 11-12 Formation of boundary layers along the walls and top of a magma chamber. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall

Magma Mixing

- End member mixing for a suite of rocks
- Variation on Harker-type diagrams should lie on a straight line between the two most extreme compositions



Comingled basalt-Rhyolite
Mt. McLoughlin, Oregon

Figure 11-8 From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall

Basalt pillows accumulating at the bottom of a granitic magma chamber, Vinalhaven Island, Maine

Assimilation

- Incorporation of wall rocks (diffusion, xenoliths)
- Assimilation by melting is limited by the heat available in the magma

Zone Melting

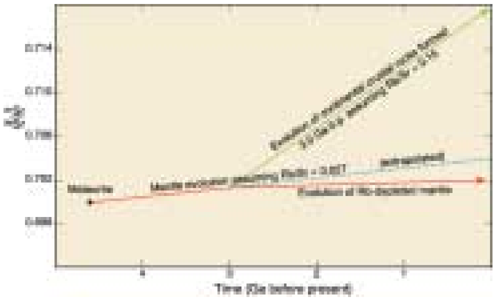
- Crystallizing igneous material at the base equivalent to the amount melted at the top
- Heat transfer by convection

Detecting and Assessing Assimilation

Isotopes are generally the best

- Continental crust becomes progressively enriched in $^{87}Sr/^{86}Sr$ and depleted in $^{143}Nd/^{144}Nd$

Estimated Rb and Sr isotopic evolution of the Earth's upper mantle, assuming a large-scale melting event producing granitic-type continental rocks at 3.0 Ga b.p After Wilson (1989).



Tectonic-Igneous Associations

- Associations on a larger scale than the petrogenetic provinces
- An attempt to address global patterns of igneous activity by grouping provinces based upon similarities in occurrence and genesis

Mixed Processes

- May be more than coincidence: two processes may operate in conjunction
- Assimilation-Fractional Crystallization
  - FX supplies the necessary heat for assimilation
  - Fractional crystallization + recharge of more primitive magma

Tectonic-Igneous Associations

- Mid-ocean ridge volcanism
- Ocean intra-plate (island) volcanism
- Continental plateau basalts

Subduction-Related

- Island arcs
- Continental arcs
- Granites (not a true T-I association)
- Mostly alkaline igneous processes of stable craton interiors
- Anorthosite massifs