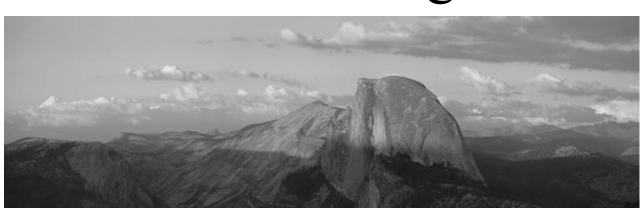
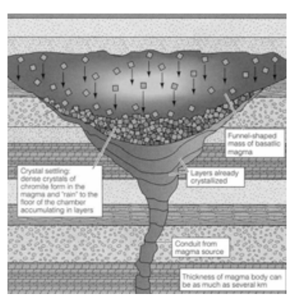
Lecture 20 Magmatic Diversity

Friday, April 1st, 2005

Chapter 11: Diversification of Magmas





Magmatic Differentiation

- Any process by which a magma is able to diversify and produce a magma or rock of different composition

Examples include:-
1. Crystal fractionation
2. Thermo-gravitational diffusion
3. Liquid Immiscibility
4. Magma Mixing
5. Mixed Processes

Magmatic Differentiation

- Two essential processes
  1. Creates a compositional difference in one or more phases
  2. Preserves the chemical difference by segregating (or fractionating) the chemically distinct portions

Crystal Fractionation

- Dominant mechanism by which most magmas, once formed, differentiate?

• Championed by Bowen as the primary way in which igneous rocks are formed from parental basaltic magma
• But can crystal fractionation yield the vast volumes of silicic magmas in granitic batholiths?

Gravity settling

- The differential motion of crystals and liquid under the influence of gravity due to their differences in density

Gravity settling

- Cool point a → olivine layer at base of pluton if first olivine sinks
- Next get ol+cpx layer
- finally get ol+cpx+plag

Cumulate texture:
Mutually touching phenocrysts with interstitial crystallized residual melt

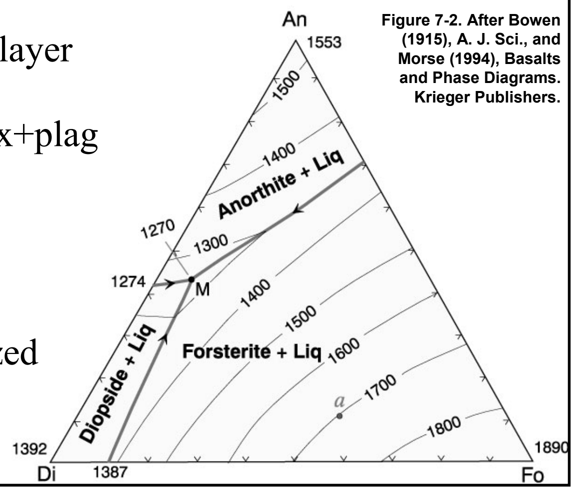


Figure 7-2. After Bowen (1915), A. J. Sci., and Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.

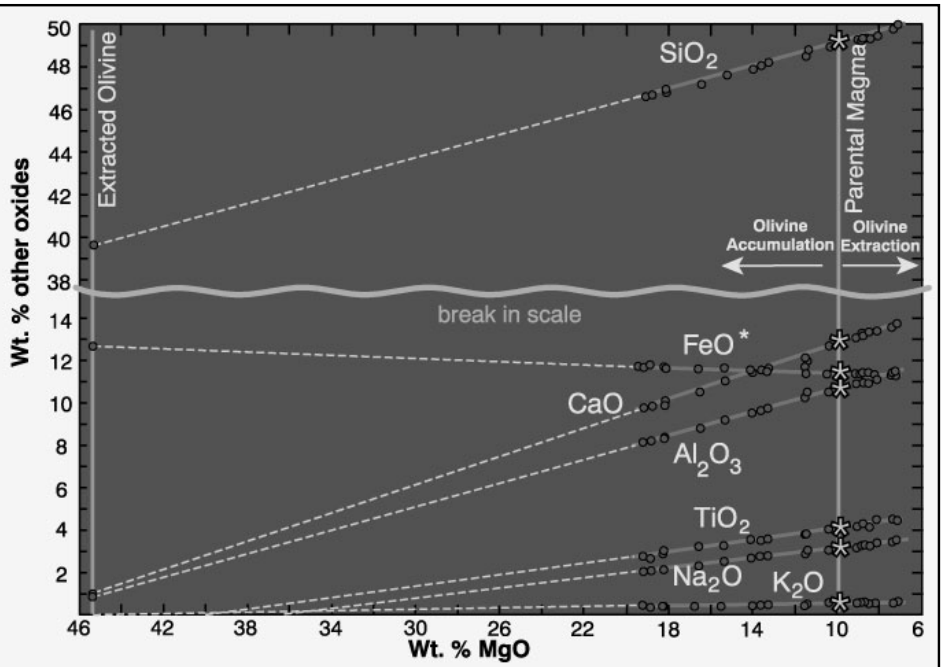


Figure 11-2 Variation diagram using MgO as the abscissa for lavas associated with the 1959 Kilauea eruption in Hawaii. After Murata and Richter, 1966 (as modified by Best, 1982)

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_1 = the density of the liquid (g/cm^3)

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

(Applies to a Newtonian fluid ony)

Olivine in basalt

- Olivine (ρ_s = 3.3 g/cm^3, r = 0.1 cm)
- Basaltic liquid (ρ_1 = 2.65 g/cm^3, η = 1000 poise)
- V = 2 · 980 · 0.1^2 (3.3-2.65)/9 · 1000 = 0.0013 cm/sec

Roughly 4.7 cm/hr or over a meter/day
During the five year study of the Makaopuhi lava lake, olivine had the potential to sink over 2 km!

If layered intrusions take between 10,000 and a million years to solidify, then crystal settling is a real possibility

Rhyolitic melt

- $\eta = 10^7$ poise and $\rho_l = 2.3$ g/cm^3
- hornblende crystal ($\rho_s = 3.2$ g/cm^3, r = 0.1 cm)
  - V = 2 x 10^{-7} cm/sec, or 6 cm/year
- feldspars ($\rho_l = 2.7$ g/cm^3)
  - V = 2 cm/year
  - = 200 m in the 10^4 years that a granitic 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

Note that feldpar might float in dense Fe-rich basaltic magmas ($\rho_l > 2.7$ g/cm^3)

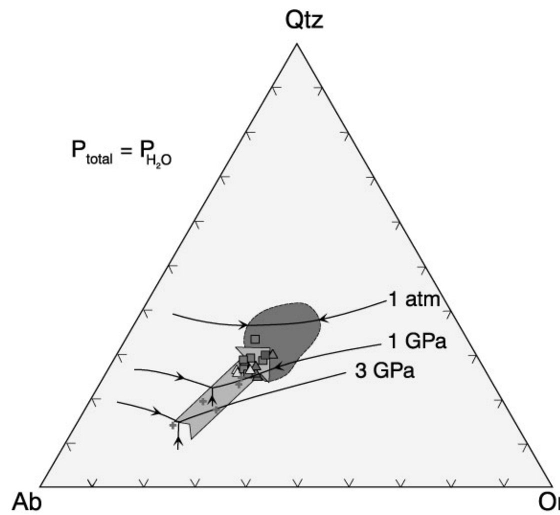
Stokes' Law is overly simplified

1. Crystals are not spherical
2. Only basaltic magmas very near their liquidus temperatures behave as Newtonian fluids

So, what about silicic magmas?

Many silicic magmas approach the ternary eutectic
Either fractional crystallization does take place or they are minimum (eutectic) melts

Figure 11-3 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) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall



Thermogravitational diffusion

Stable and persistent stagnant boundary layers have been shown to occur near the top and sides of magma chambers

Model

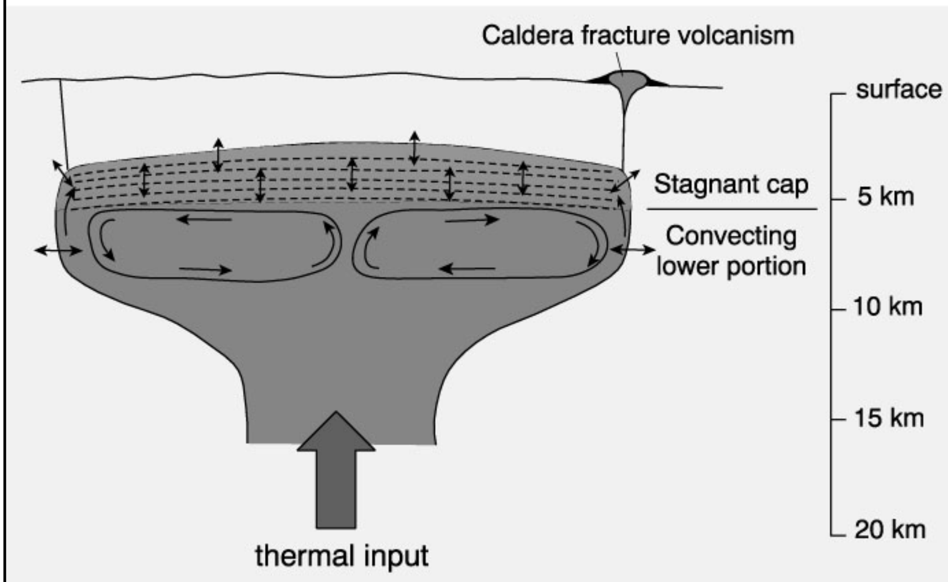


Figure 11-11. Schematic section through a rhyolitic magma chamber undergoing convection-aided *in-situ* differentiation. After Hildreth (1979). Geol. Soc. Amer. Special Paper, 180, 43-75.

Hildreth (1979) 0.7 Ma Bishop Tuff at Long Valley, California

- Vertical compositional variation in the stratified tuff
- Thermal gradient in chamber
- Compositional variation in tuff equivalent to about 40% fractionation of feldspar and quartz
- How could these minerals sink in a highly viscous silicic magma?

The Soret Effect and Thermogravitational Diffusion

- Thermal diffusion, or the Soret effect
- Heavy elements/molecules migrate toward the colder end and lighter ones to the hotter end of the gradient

Walker and DeLong (1982) subjected two basalts to thermal gradients of nearly $50^oC/mm$ (!)

Found that:

- Samples reached a steady state in a few days
- Heavier elements → cooler end and the lighter → hot end
- The chemical concentration is similar to that expected from fractional crystallization

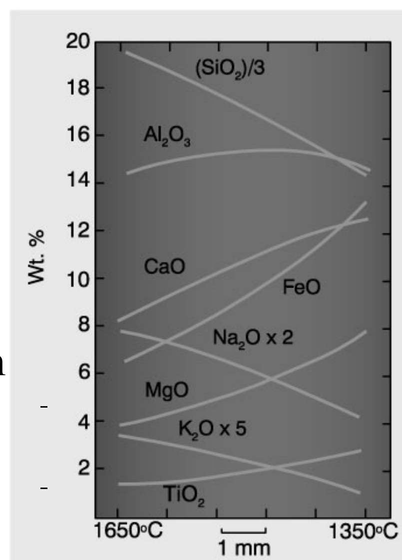


Figure 7-4. After Walker, D. C. and S. E. DeLong (1982). Contrib. Mineral. Petrol., 79, 231-240.

BOUNDARY LAYER CRYSTALLIZATION

Thermal gradient at wall and cap → variation in % crystallized

- Compositional convection → evolved magmas from boundary layer to cap (or mix into interior)

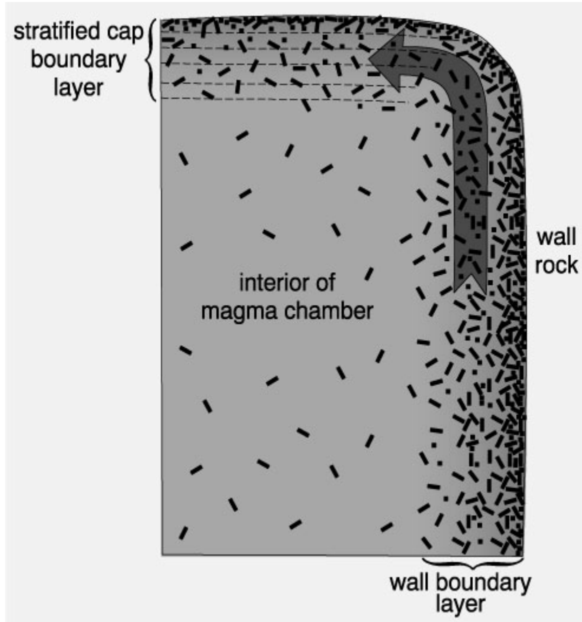


Figure 11-12 Formation of boundary layers along the walls and top of a magma chamber. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall

Liquid Immiscibility

- Liquid immiscibility in the Fo-SiO_2 system

Could liquid immiscibility give rise to coexisting silicic and basaltic magmas?

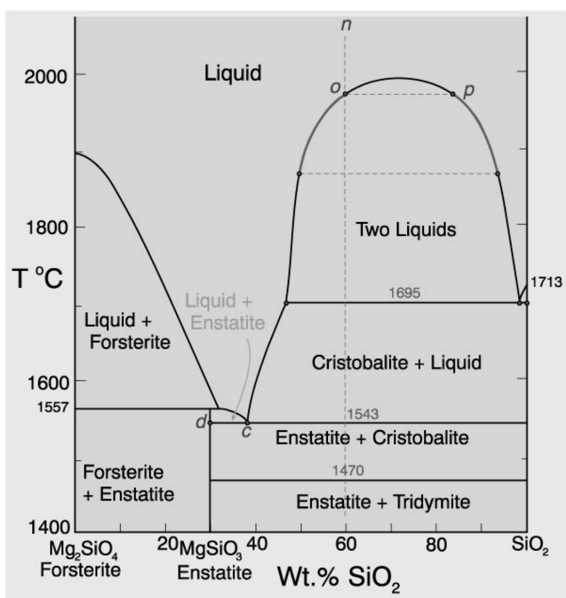


Figure 6-12. Isobaric T-X phase diagram of the system Fo-Silica at 0.1 MPa. After Bowen and Anderson (1914) and Grieg (1927). Amer. J. Sci.

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

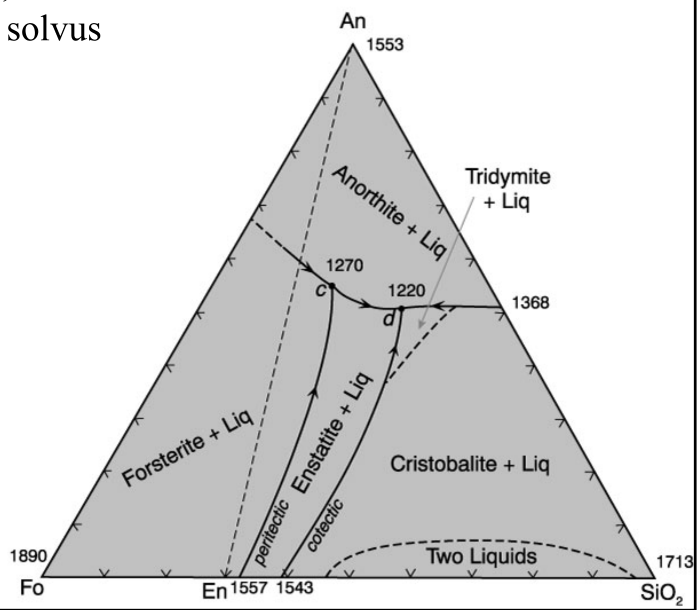


Figure 7-4. Isobaric diagram illustrating the cotectic and peritectic curves in the system forsterite-anorthite-silica at 0.1 MPa. After Anderson (1915) A. J. Sci., and Irvine (1975) CIW Yearb. 74.

- Renewed interest when Roedder (1951) discovered a second immiscibility gap in the iron-rich Fa-Lc-SiO_2 system

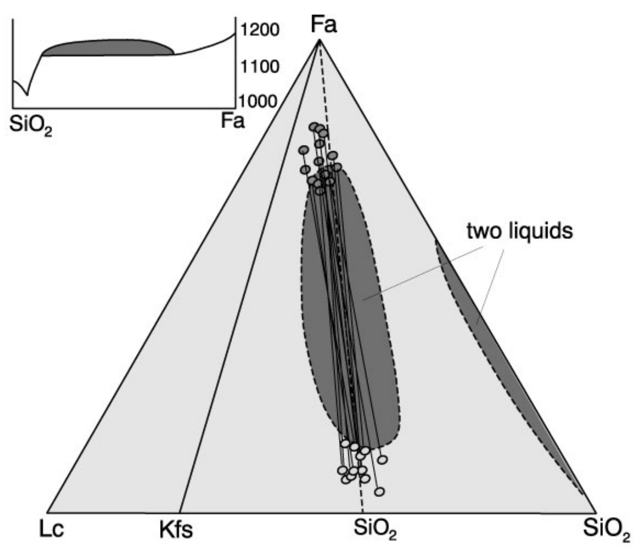


Figure 11-7. Two immiscibility gaps in the system fayalite-leucite-silica (after Roedder, 1979). Yoder (ed.), The Evolution of the Igneous Rocks. Princeton University Press. pp. 15-58. Projected into the simplified system are the compositions of natural immiscible silicate pair droplets from interstitial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

Some Examples

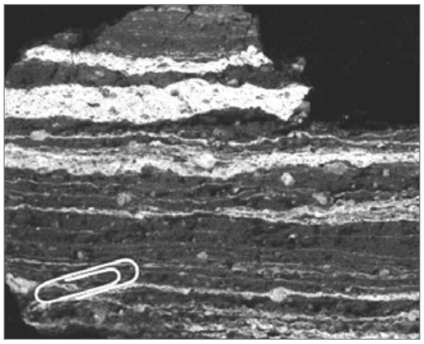
- Late silica-rich immiscible droplets in Fe-rich tholeiitic basalts (almost ubiquitous in lunar basalts and some MORB)
- Sulfide-silicate immiscibility (massive sulfide deposits)
- Carbonatite-nephelinite systems

More of a petrological curiosity
Unlikely process for major magmatic bodies

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

First proposed by Bunsen (1851) to explain bimodal rhyolite and basalt in Iceland with lesser volumes of intermediate lavas

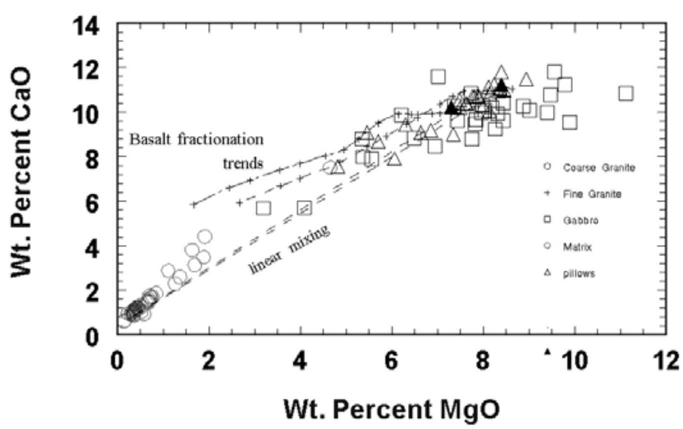


Comingled basalt-Rhyolite
Mt. McLoughlin, Oregon

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

Vinalhaven



Example of limited mixing between granite and basalt magmas

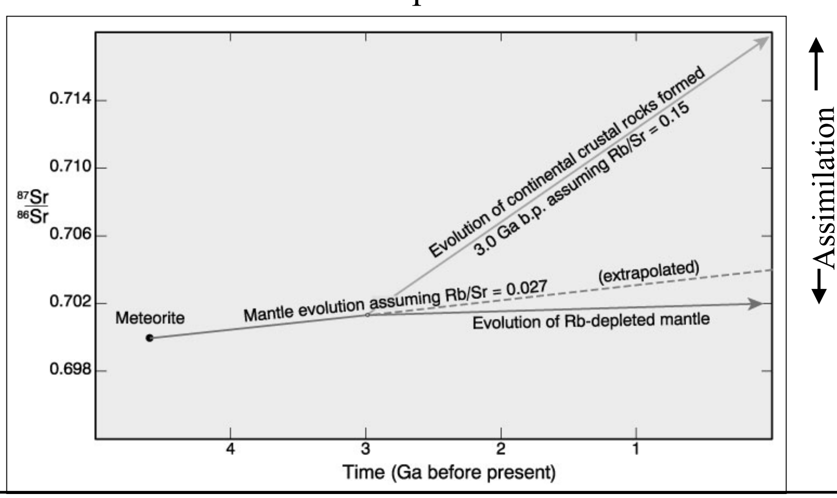
Assimilation

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

Detecting and assessing assimilation

Isotopes are generally the best

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



Mixed Processes

- May be more than coincidence: two processes may operate in conjunction (cooperation?)
  - AFC: FX supplies the necessary heat for assimilation
  - Fractional crystallization + recharge of more primitive magma