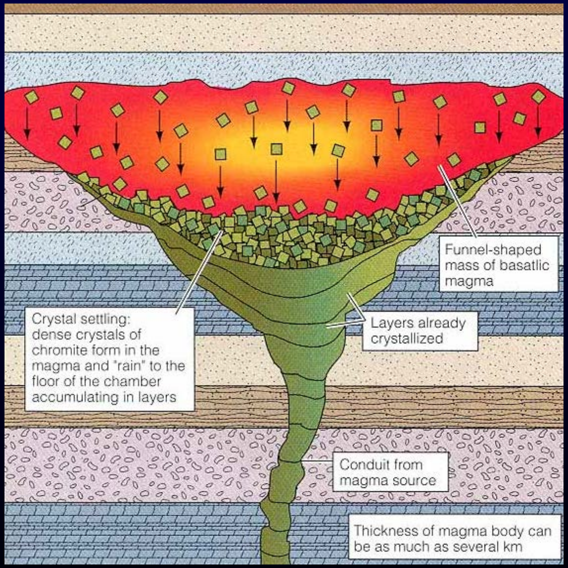
Chapter 11: Diversification of Magmas



Magmatic Differentiation

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

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

Partial Melting

Separation of a partially melted liquid from the solid residue

Effects of removing liquid at various stages of melting

- Eutectic systems
  - ☞ First melt always = 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

- 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

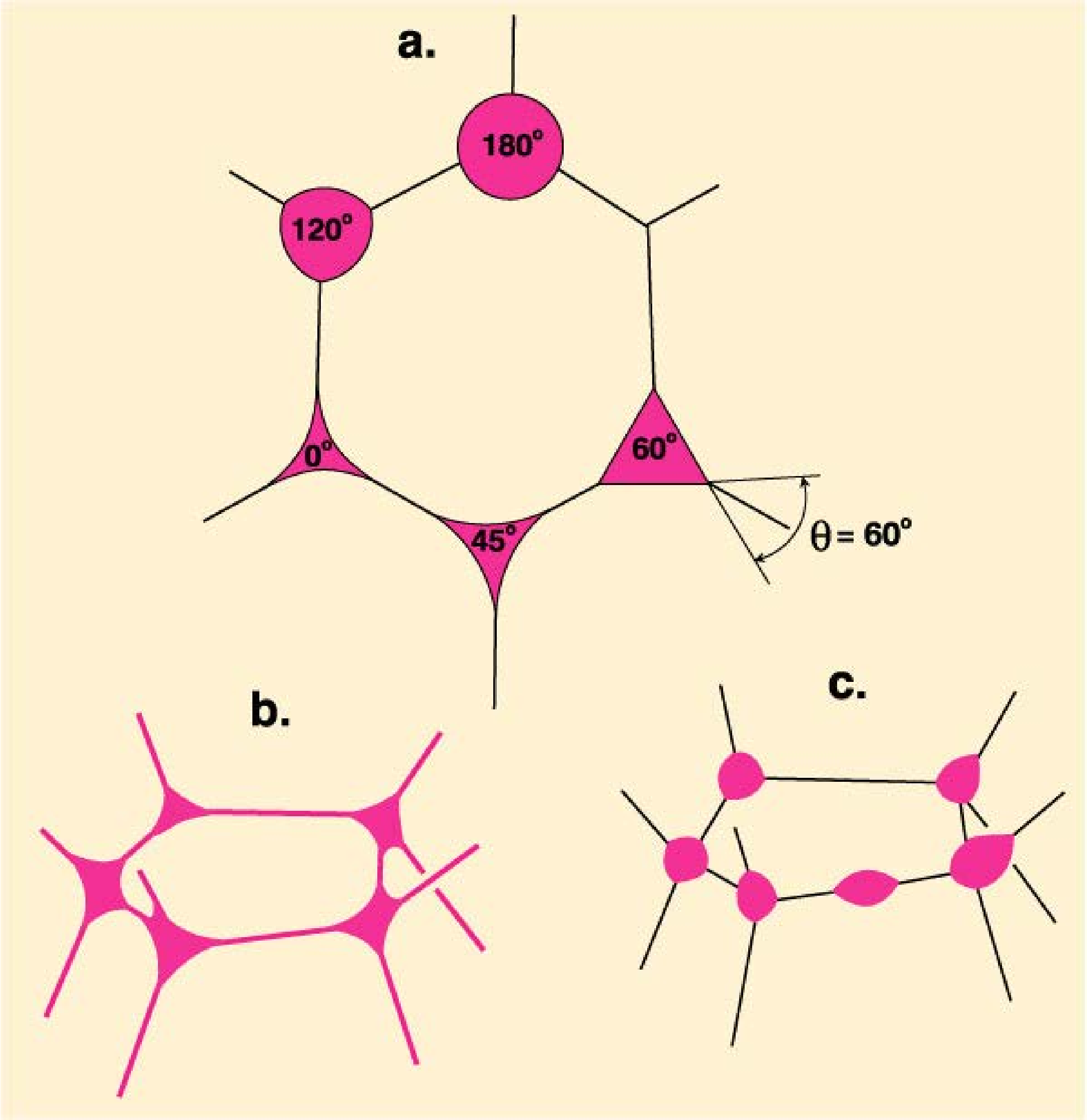


Figure 11.1 Illustration of the dihedral angle (θ) of melt droplets that typically form at multiple grain junctions. After Hunter (1987) In I. Parsons (ed.), Origins of Igneous Layering. Reidel, Dordrecht, pp. 473-504.

- Gravitational effects (buoyant liquid)
- Filter pressing, or compaction, of crystal mush
- Shear - the RCMP drops considerably
- RCMP varies with
  - T
  - viscosity
  - X

Crystal Fractionation

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

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+pla

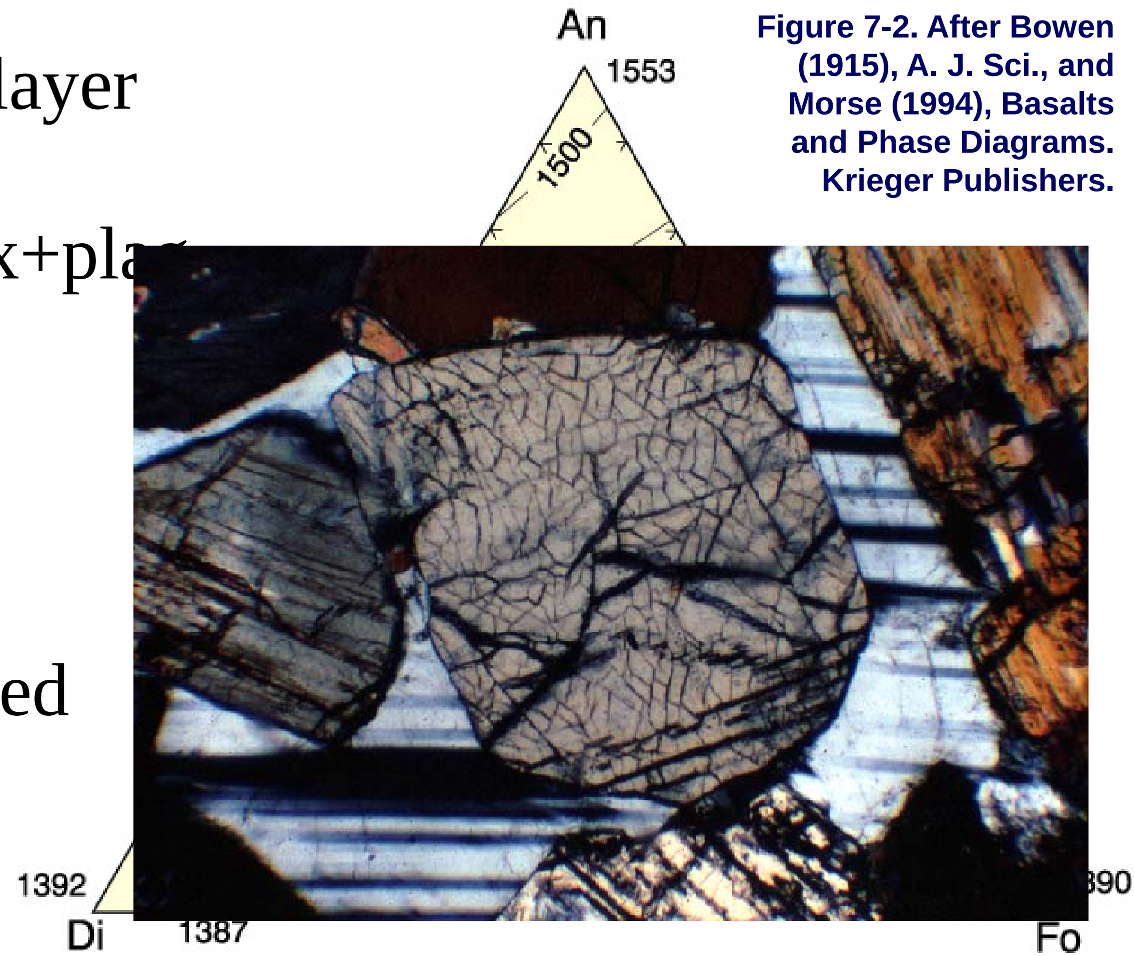


Figure 7-2. After Bowen (1915), A. J. Sci., and Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.

Cumulate texture:

Mutually touching phenocrysts with interstitial crystallized residual melt

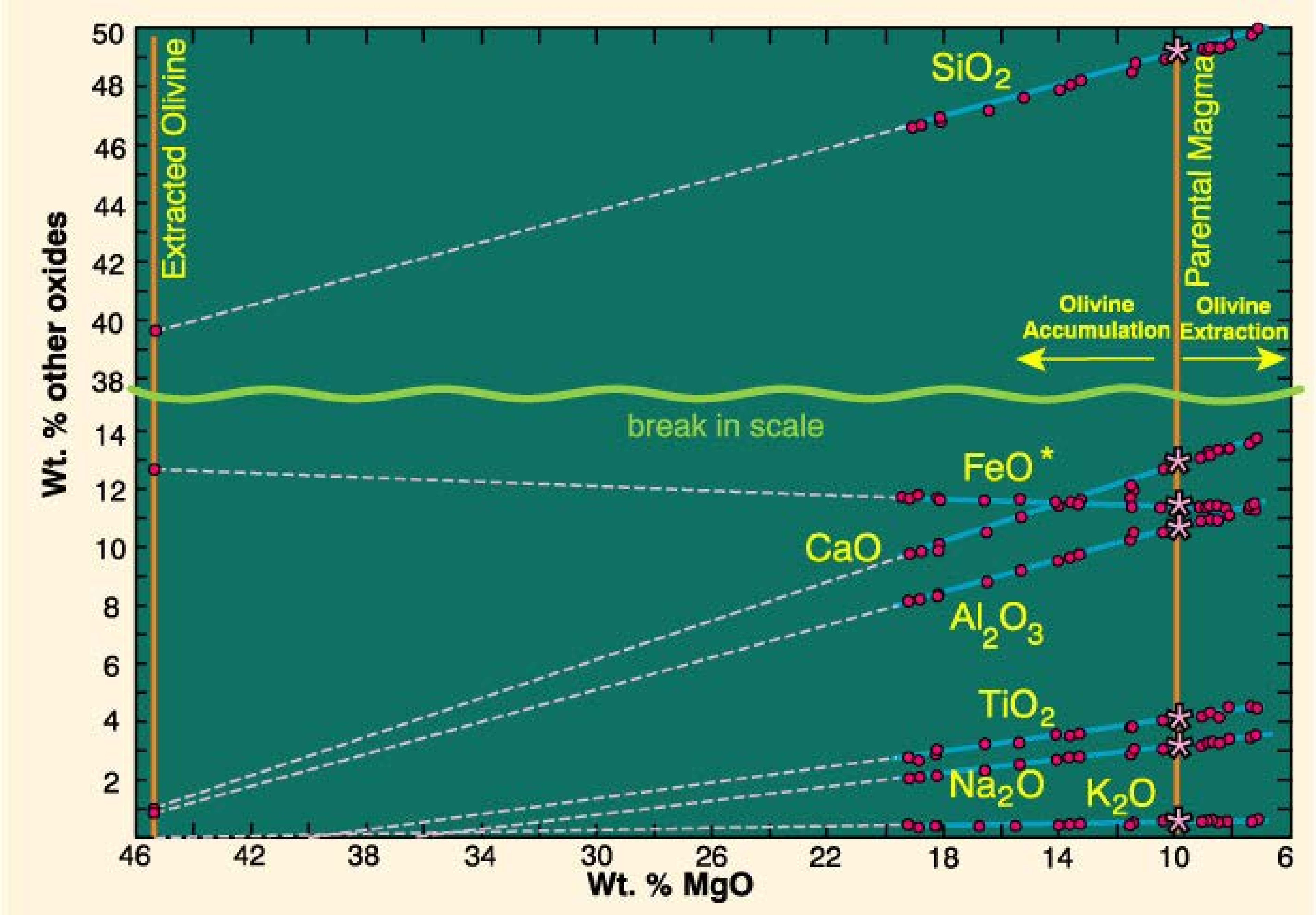


Figure 11.2 Variation diagram using MgO as the abscissa for lavas associated with the 1959 Kilauea eruption in Hawaii. After Murata and Richter, 1966 (as modified by Best, 1982)

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

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

**Assume presence of Newtonian fluid (no yield stress)

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)
- $V = 2 \cdot 980 \cdot 0.1^2 (3.3-2.65)/9 \cdot 1000 = 0.0013$ cm/sec
- 4.7 cm/hr, or >1 meter/day
- In 5 years, olivines could have settled over a distance of 2 km!
- Magmas can solidify over time periods of 10^4 to 10^6 years, permitting considerable gravitational settling

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)
  - $V = 2 \times 10^{-7}$ 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 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

Stokes' Law is overly simplified

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

Many silicic magmas approach the ternary eutectic

Either fractional crystallization does take place or they are minimum (eutectic) melts

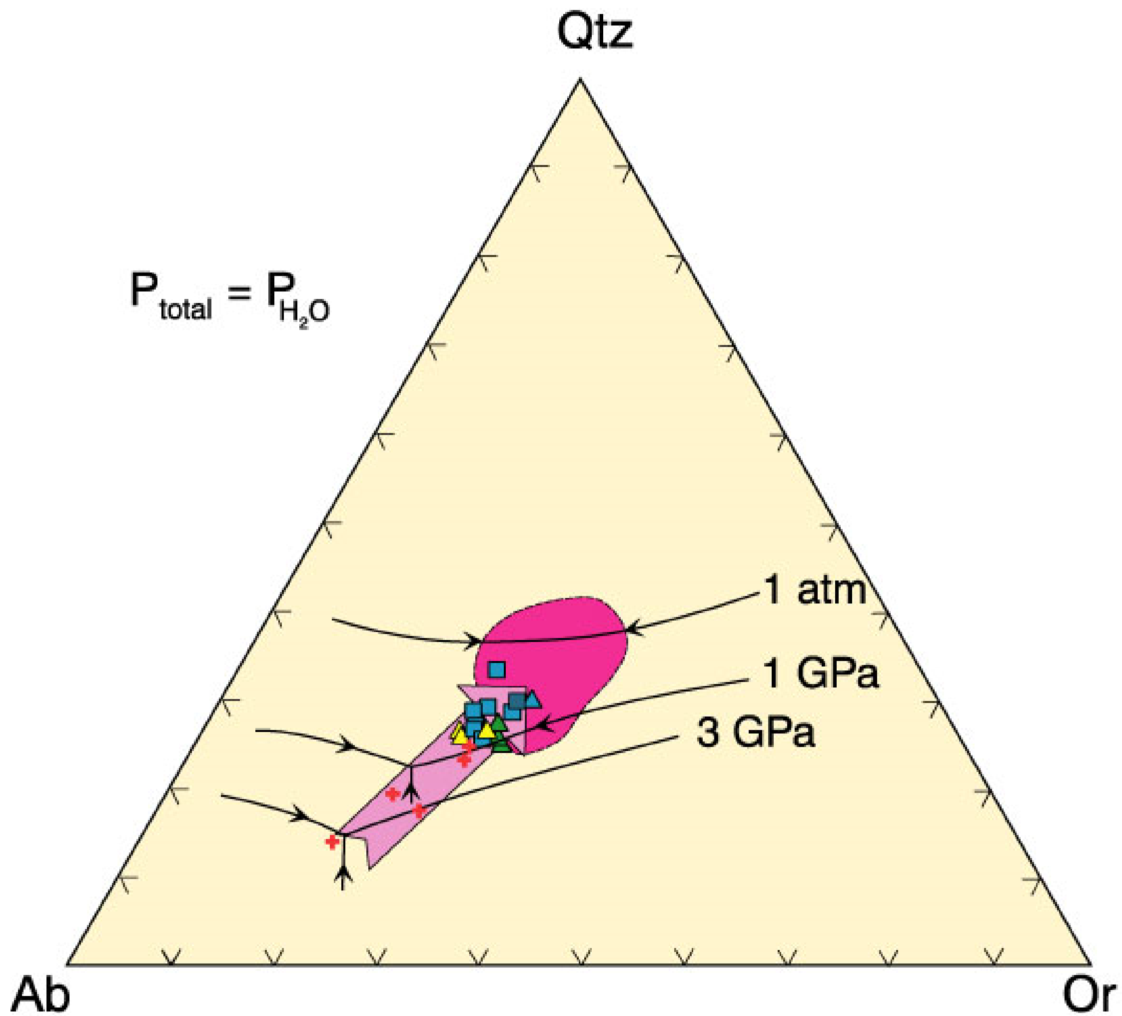


Figure 11.3 Position of the H2O-saturated ternary eutectic in the albite-orthoclase-silica system at various pressures. The shaded portion represents the composition of most granites. Included are the compositions of the Tuolumne Intrusive Series (Figure 4-32), with the arrow showing the direction of 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

Polybaric Fractional Crystallization

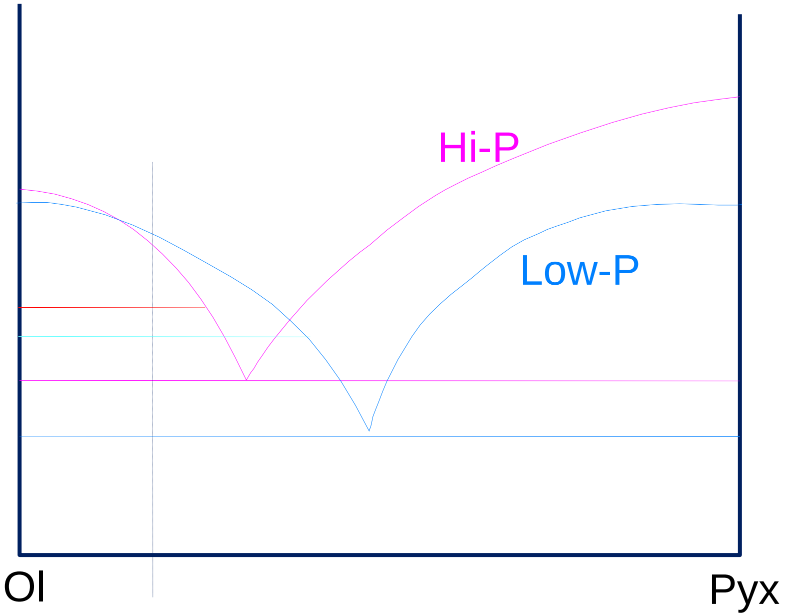
1. Stability of phases will change (hi-P garnet)

Polybaric Fractional Crystallization

1. Stability of phases changes (hi-P garnet...)
2. Shift of the eutectic point with pressure will cause the quantity of the liquidus phases to vary

High-P (purple tie-line) has liq > ol

Low-P (blue tie-line) has ol > liquid



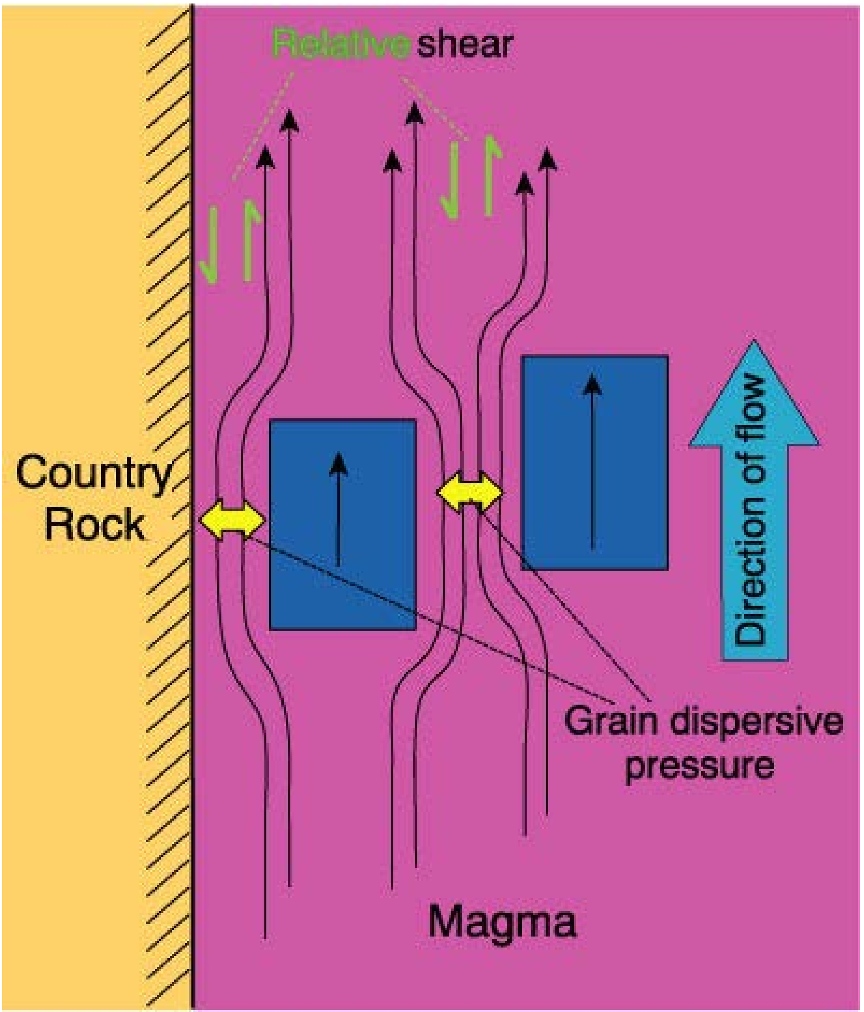
Expansion of olivine field at low pressure causes an increase in the quantity of crystallized olivine

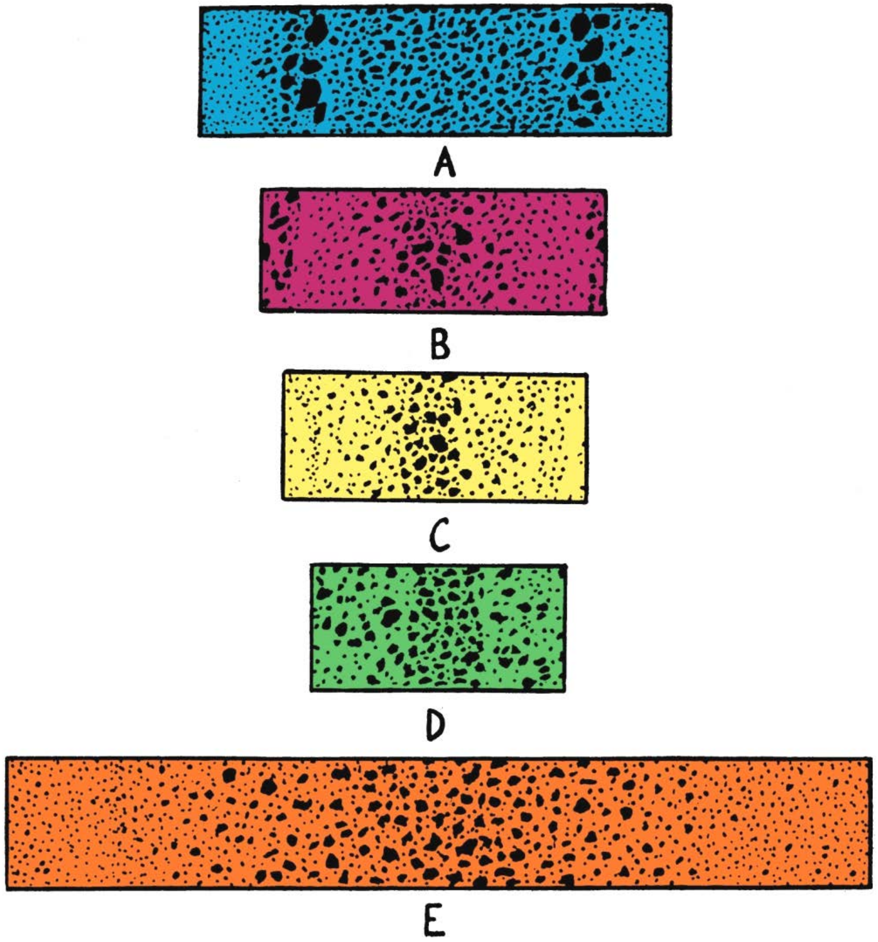
Two other mechanisms that facilitate the separation of crystals and liquid

1. Compaction

Two other mechanisms that facilitate the separation of crystals and liquid

2. Flow segregation





Figures 11.4 and 11.5 Drever and Johnston (1958). Royal Soc. Edinburgh Trans., 63, 459-499.

Volatile Transport

1. Vapor released by heating of hydrated or carbonated wall rocks

Volatile Transport

2. 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

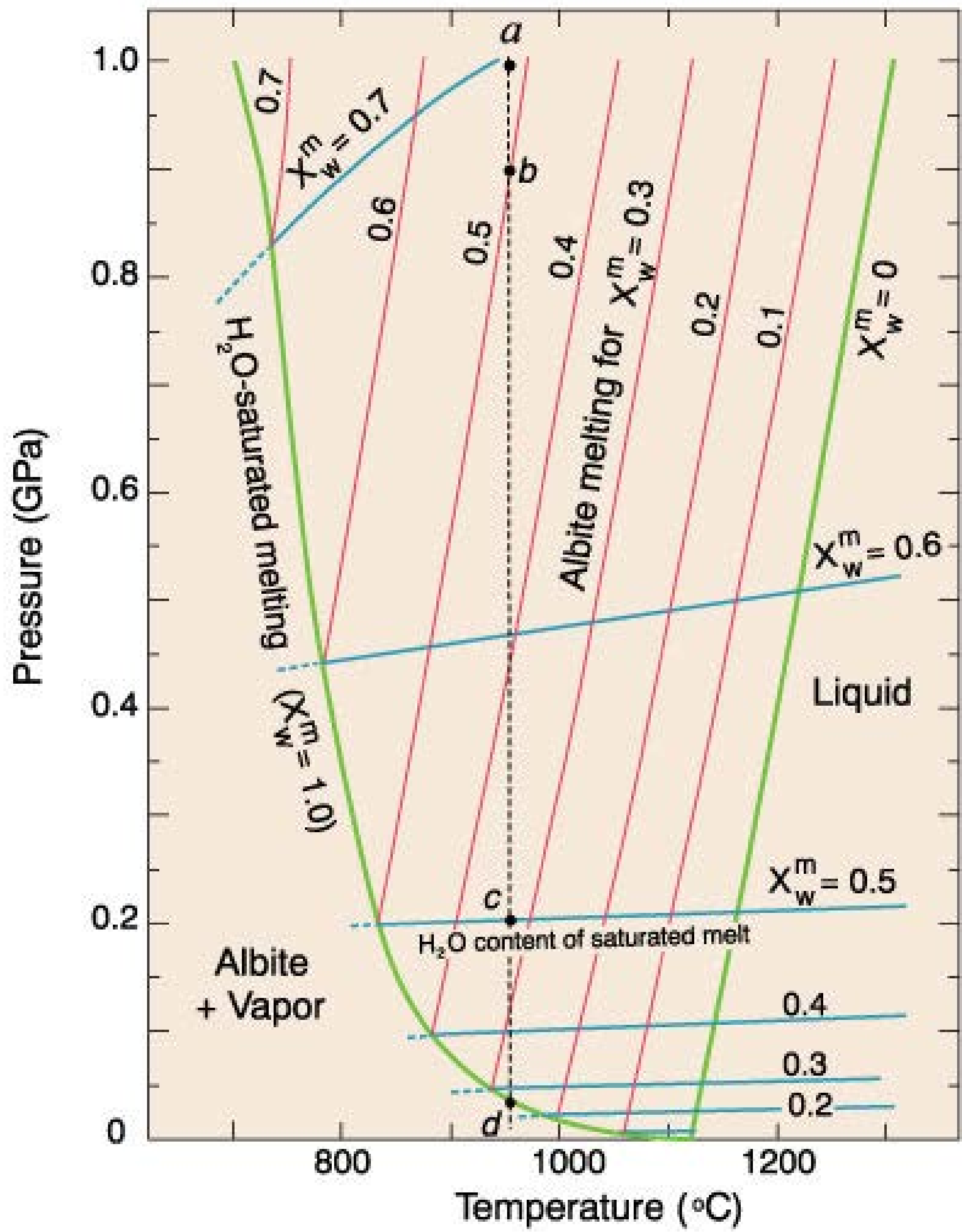
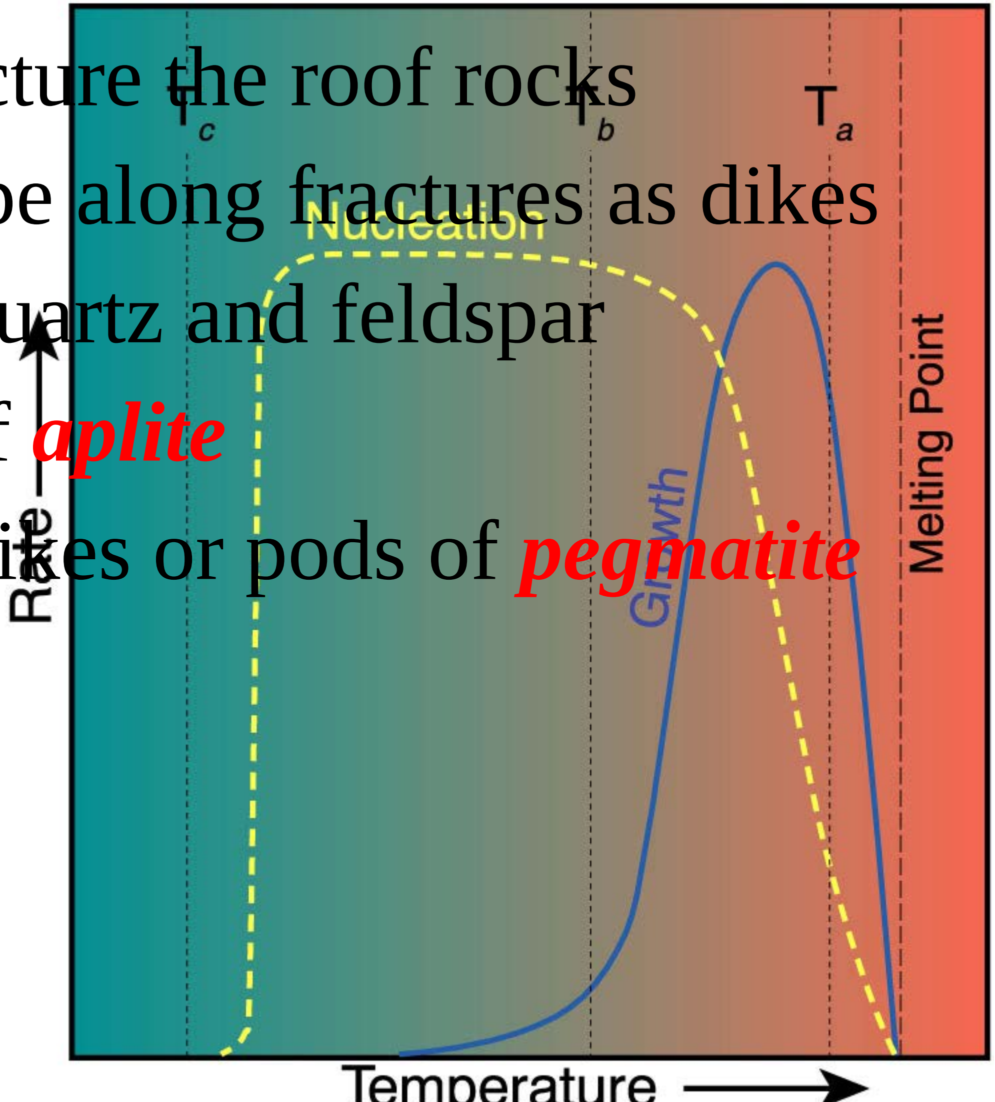


Figure 7.22. From Burnham and Davis (1974). A J Sci., 274, 902-940.

3. 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 → ***porphyritic texture***
- May increase P - fracture the roof rocks
- Vapor and melt escape along fractures as dikes
    - ☞ ***Silicate melt*** → quartz and feldspar → small dikes of ***aplite***
    - ☞ ***Vapor phase*** → dikes or pods of ***pegmatite***



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

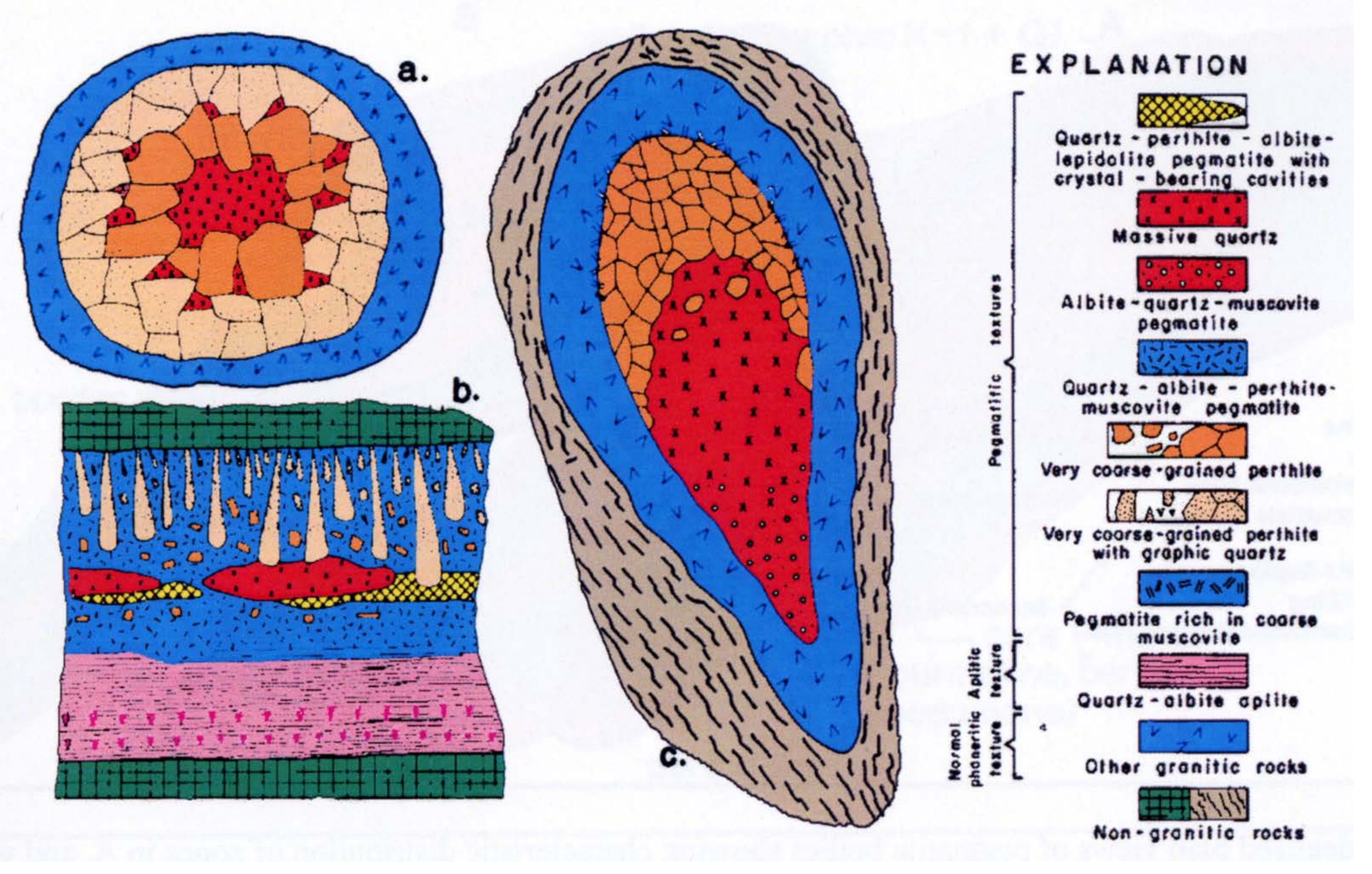
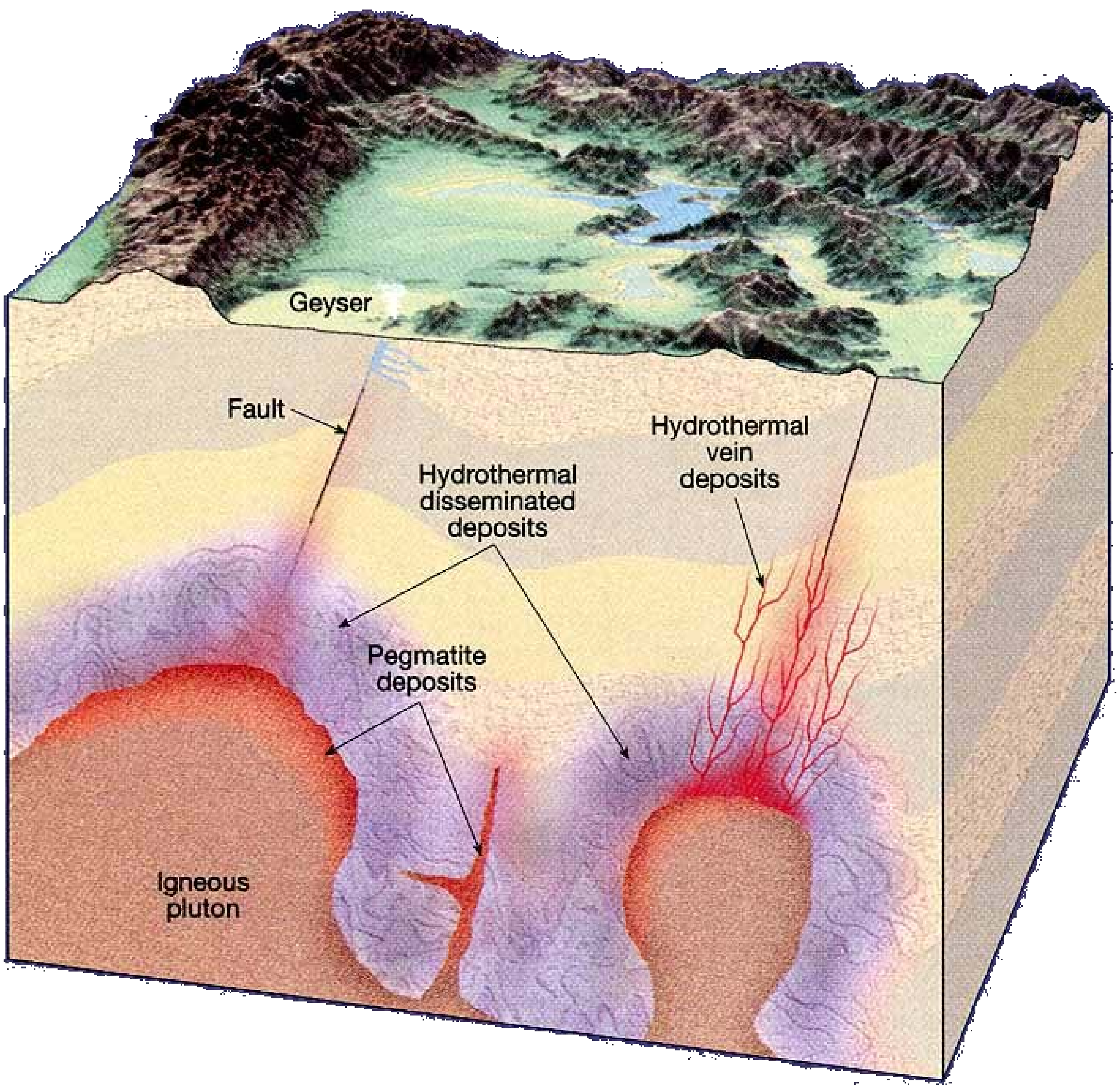


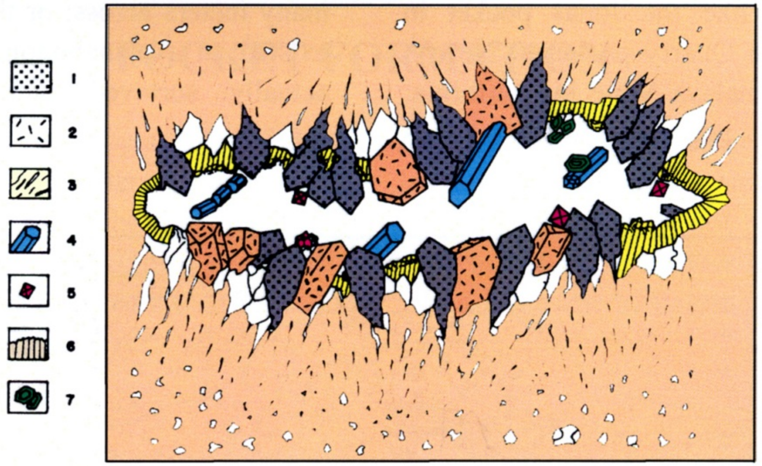
Figure 11.6 Sections of three zoned fluid-phase deposits (not at the same scale). **a.** Miarolitic pod in granite (several cm across). **b.** Asymmetric zoned pegmatite dike with aplitic base (several tens of cm across). **c.** Asymmetric zoned pegmatite with granitoid outer portion (several meters across). From Jahns and Burnham (1969). *Econ. Geol.*, 64, 843-864.

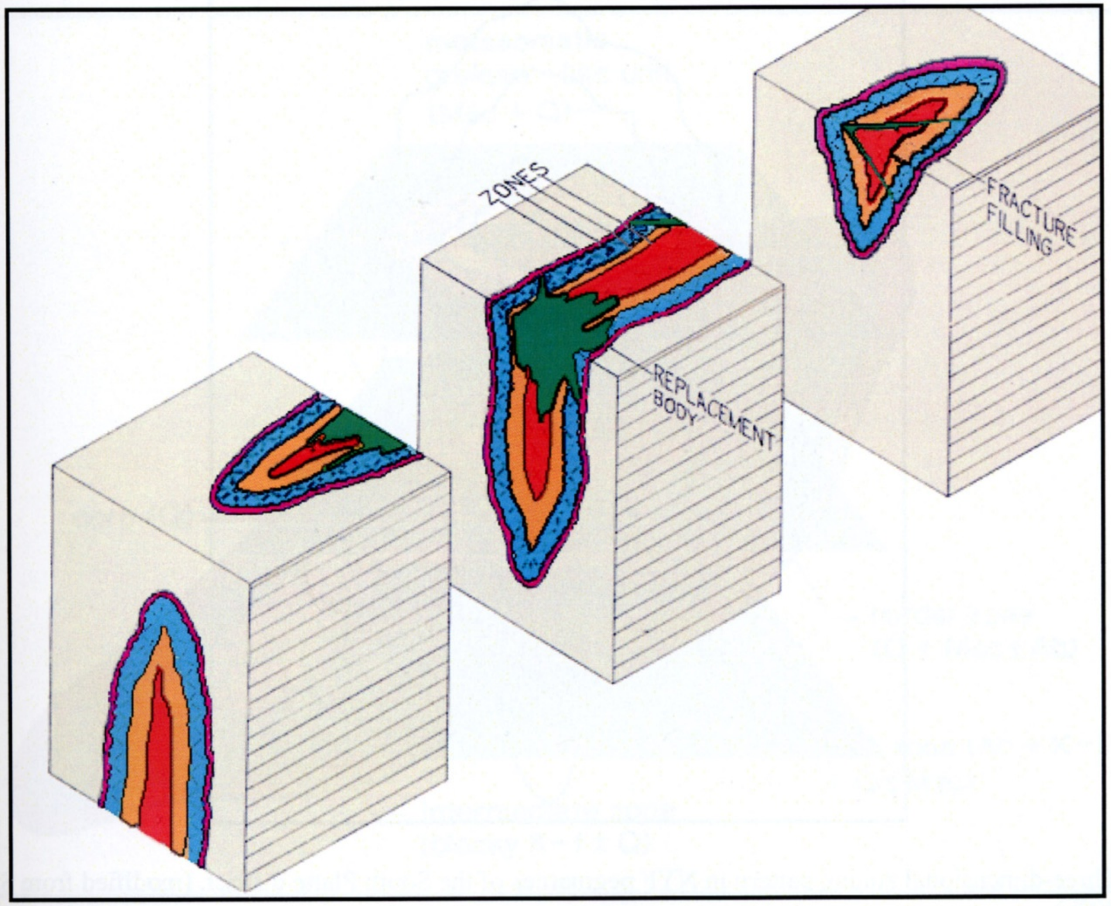


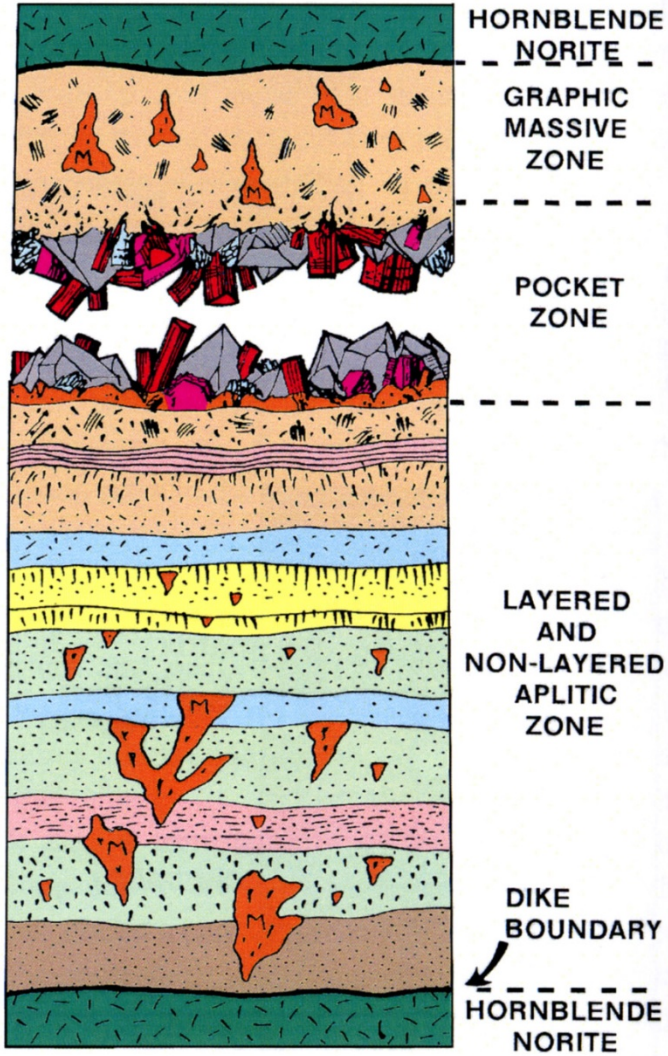
8 cm tourmaline crystals from pegmatite

5 mm gold from a hydrothermal deposit

Pegmatites







Scale: 1 cm on the figure equals about 8 cm. M = microcline

Aplite dikes

Compositional Convection and *In Situ* Differentiation Processes

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

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^{o}C/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

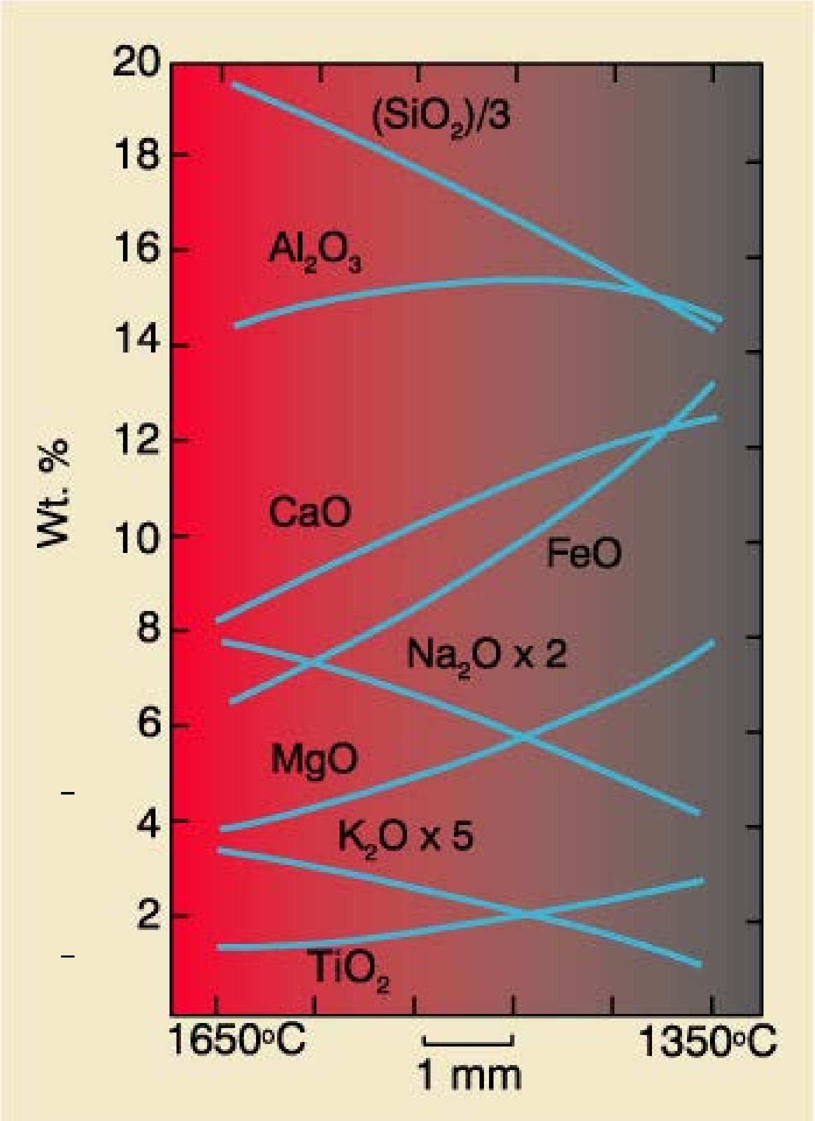


Figure 7.4. After Walker, D. C. and S. E. DeLong (1982). Contrib. Mineral. Petrol., 79, 231-240.

Thermogravitational diffusion

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

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

- Vertical compositional variation in the stratified tuff
- Thermal gradient in chamber

Model

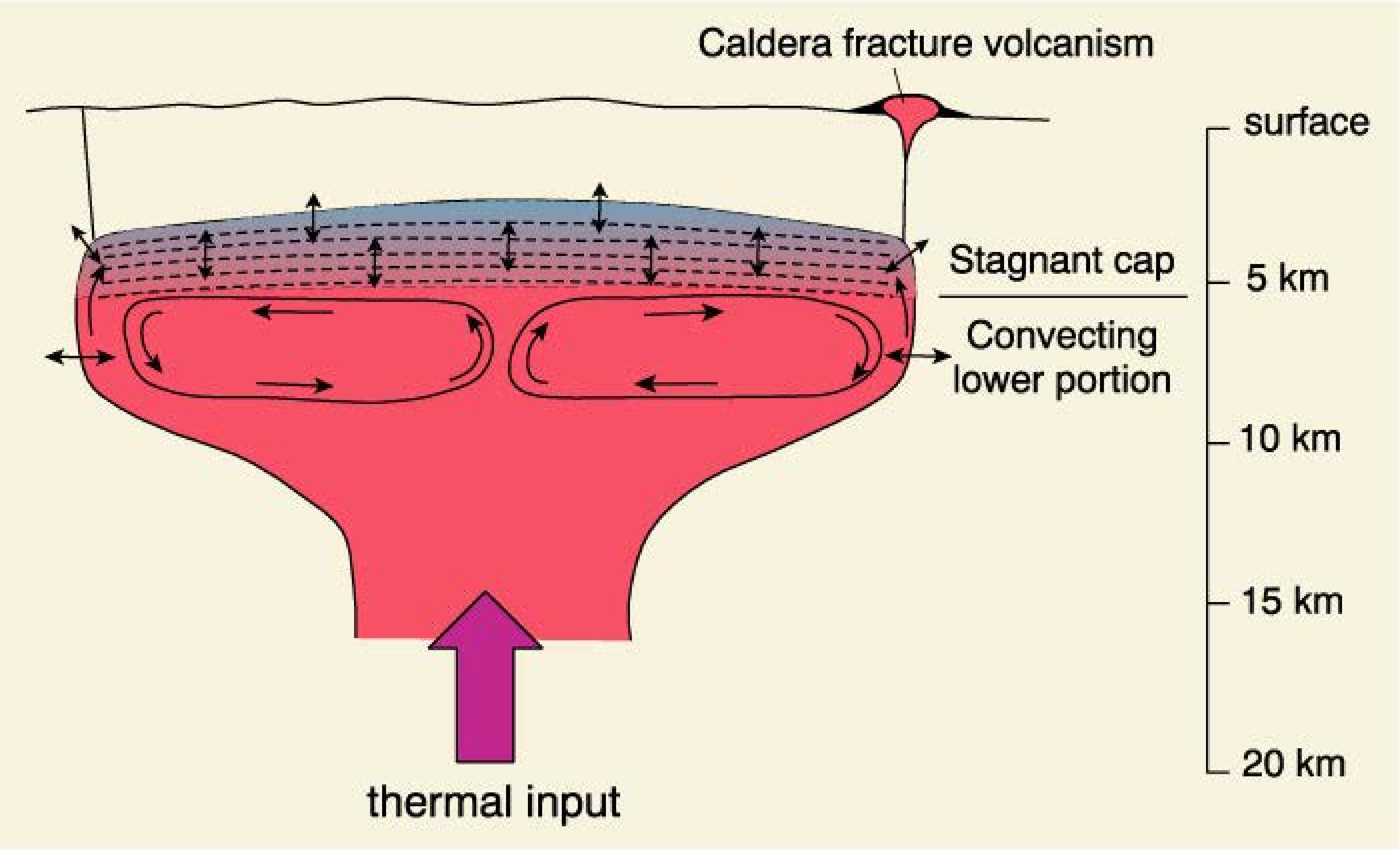


Figure 11-11. Schematic section through a rhyolitic magma chamber undergoing convection-aided *in-situ* differentiation. After Hildreth (1979). Geol. Soc. Amer. Special Paper, 180, 43-75.

Langmuir Model

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

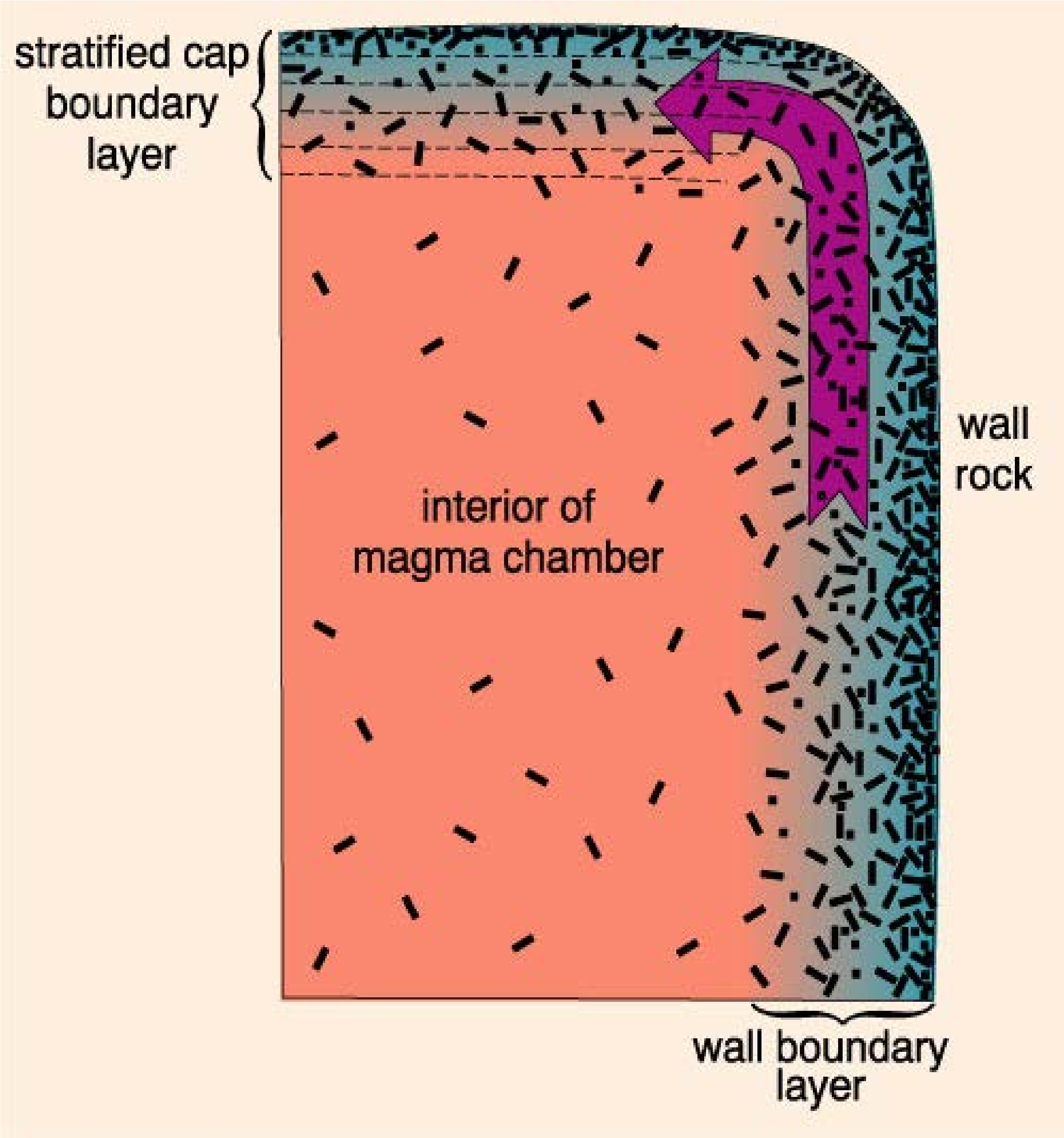
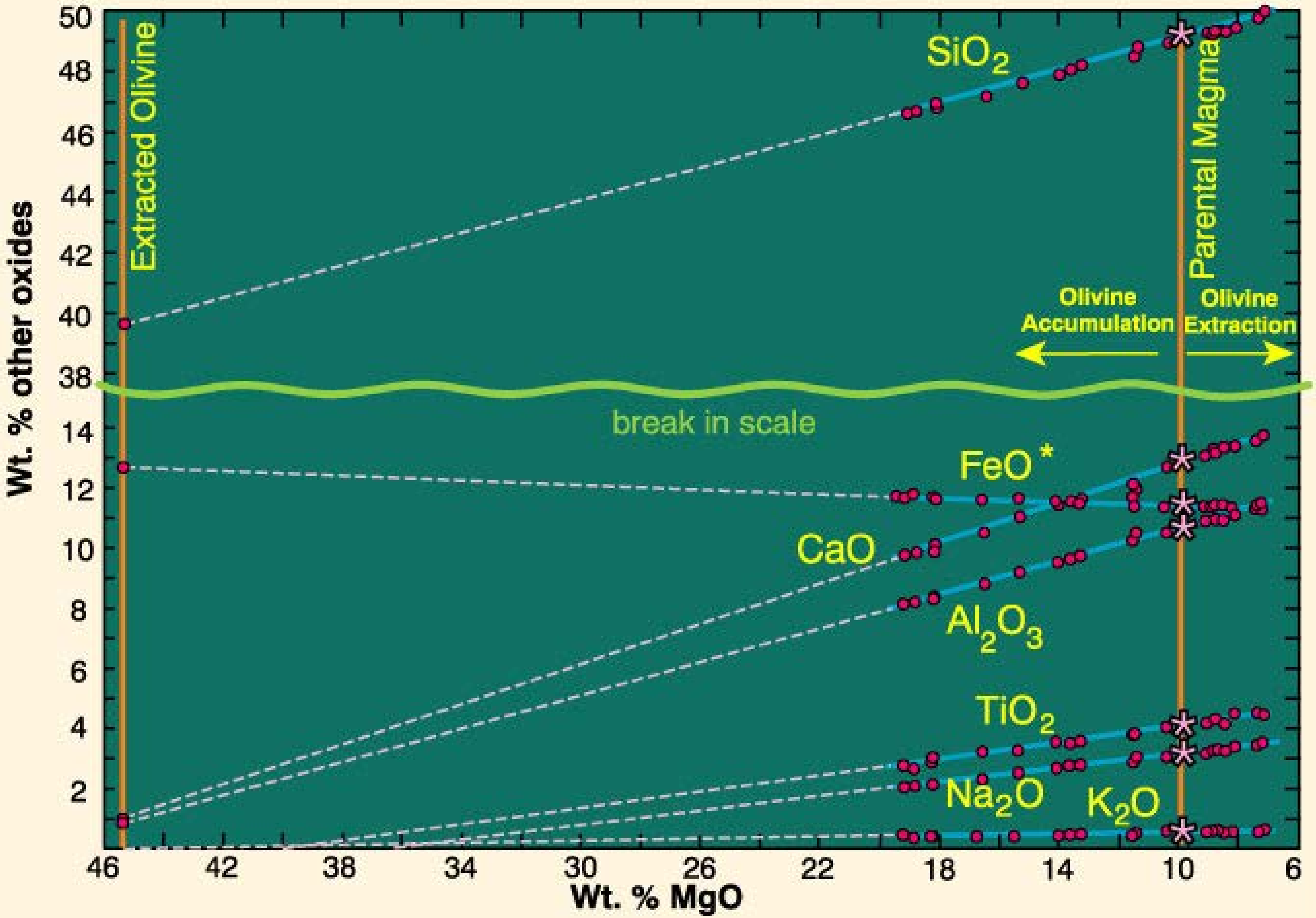


Figure 11.12 Formation of boundary layers along the walls and top of a magma chamber. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall

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



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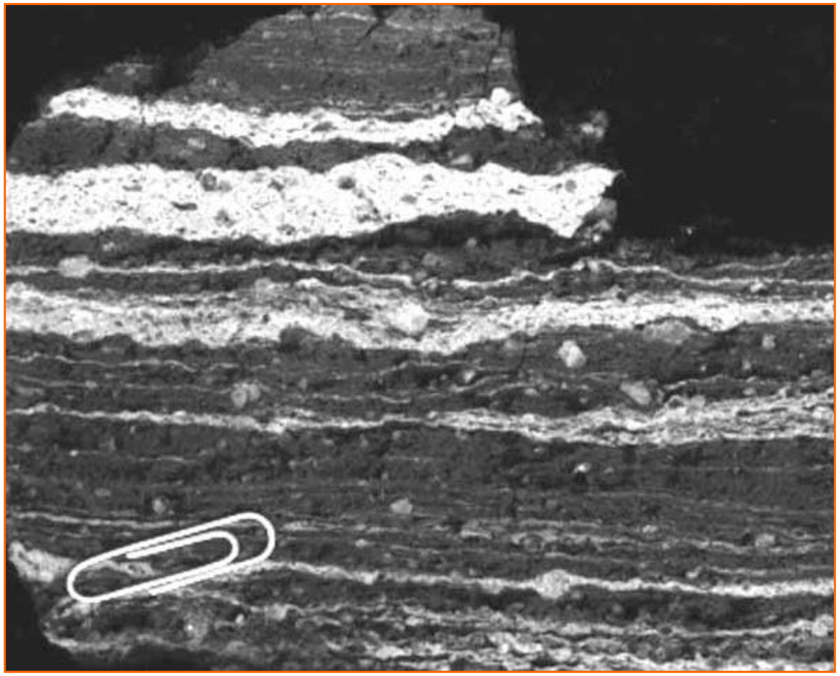


Comingled basalt-Rhyolite
Mt. McLoughlin, Oregon

Figure 11.8 From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall

Basalt pillows accumulating at the bottom of a in 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

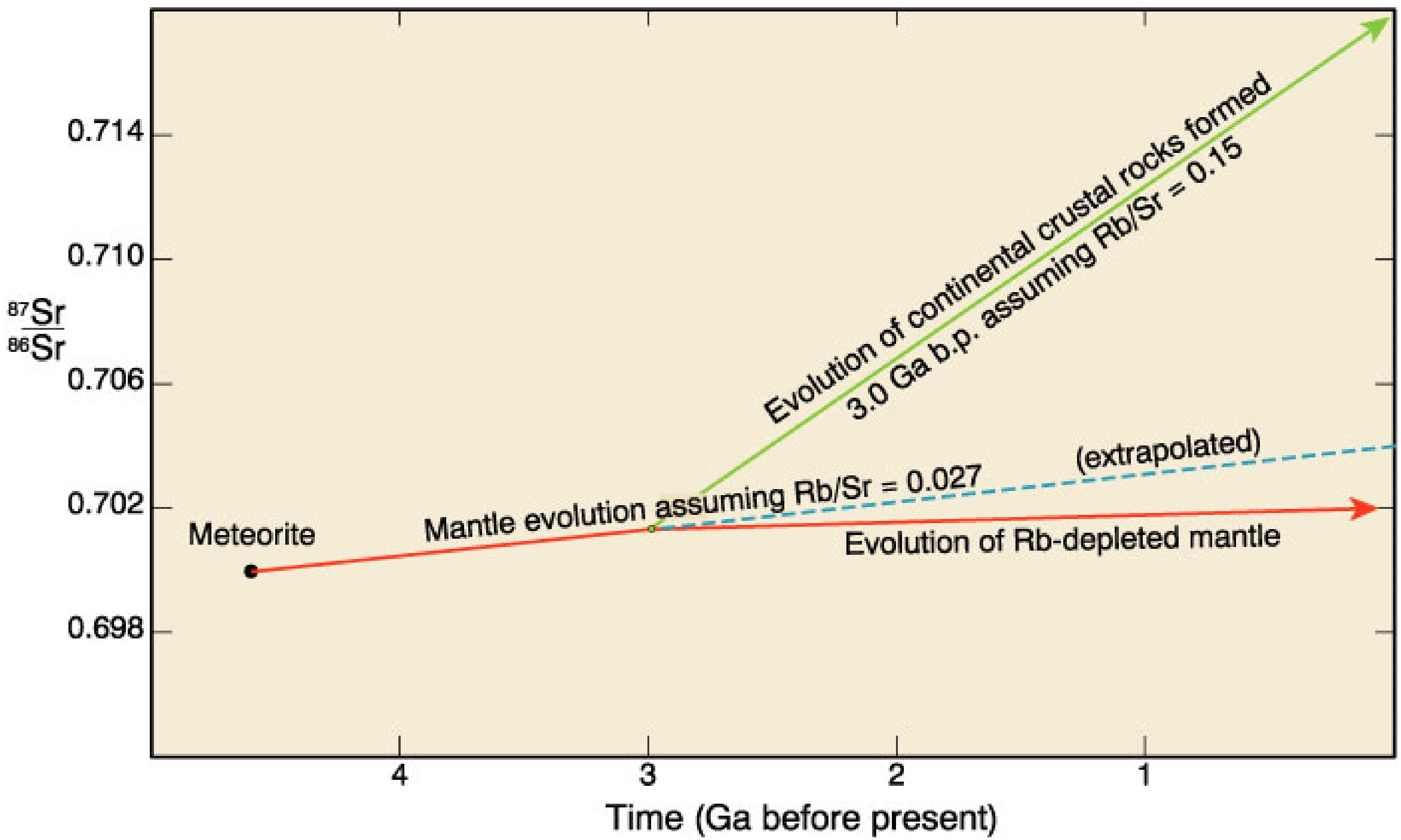
- Zone melting
  - ☞ Crystallizing igneous material at the base equivalent to the amount melted at the top
  - ☞ Transfer heat by convection

Detecting and assessing assimilation

Isotopes are generally the best

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

Figure 9-13. 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). Igneous Petrogenesis. Unwin Hyman/Kluwer.



Detecting and assessing assimilation

9-21	$^{238}U \rightarrow {}^{234}U \rightarrow {}^{206}Pb$	$(\lambda = 1.5512 \times 10^{-10}\ a^{-1})$
9-22	$^{235}U \rightarrow {}^{207}Pb$	$(\lambda = 9.8485 \times 10^{-10}\ a^{-1})$
9-23	$^{232}Th \rightarrow {}^{208}Pb$	$(\lambda = 4.9475 \times 10^{-11}\ a^{-1})$

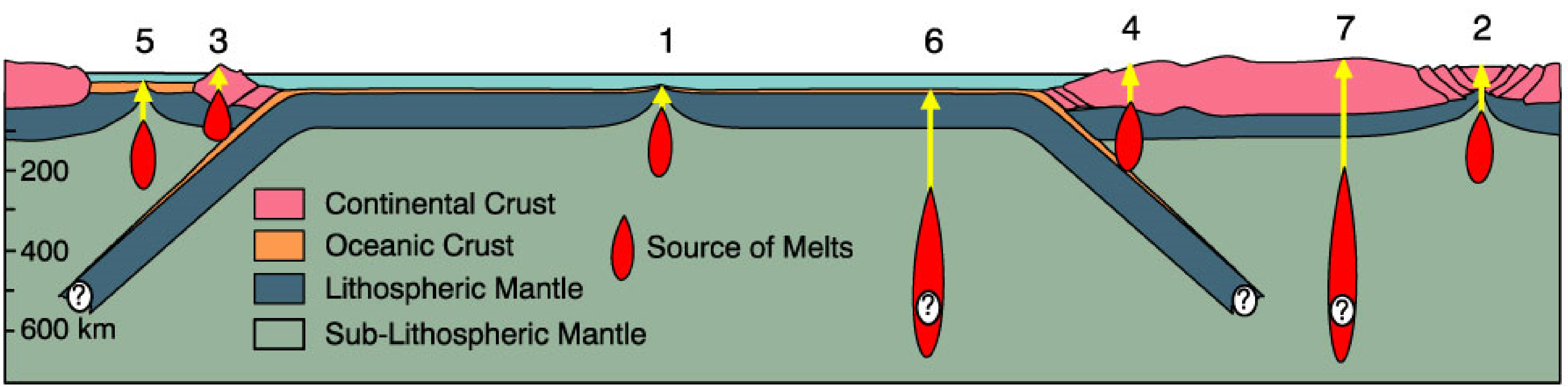
- U-Th-Pb system as an indicator of continental contamination is particularly useful
- All are incompatible LIL elements, so they concentrate strongly into the continental crust

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

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



Tectonic-Igneous Associations

- Mid-Ocean Ridge Volcanism
- Ocean Intra-plate (Island) volcanism
- Continental Plateau Basalts
- Subduction-related volcanism and plutonism
  - Island Arcs
  - Continental Arcs
- Granites (not a true T-I Association)
- Mostly alkaline igneous processes of stable craton interiors
- Anorthosite Massifs