Arc Magmatism

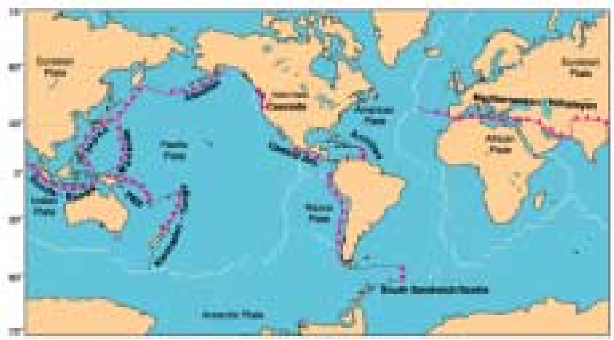
Reading:
Winter, Chapter 16

Island Arc Magmatism

- Activity along arcuate volcanic island chains along subduction zones
- Distinctly different from the mainly basaltic provinces
  - Composition more diverse and silicic
  - Basalt generally occurs in subordinate quantities
  - More explosive than the quiescent basalts
  - Strato-volcanoes are the most common volcanic landform

- Igneous activity is related to convergent plate situations that result in the subduction of one plate beneath another
- The initial petrologic model:
  - Oceanic crust is partially melted
  - Melts rise through the overriding plate to form volcanoes just behind the leading plate edge
  - Unlimited supply of oceanic crust to melt

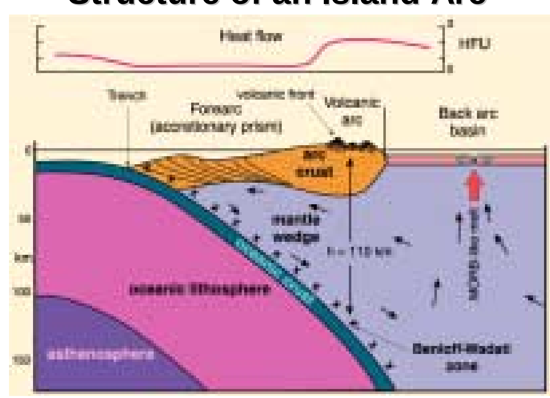
Ocean-ocean → Island Arc (IA)
Ocean-continent → Continental Arc or Active Continental Margin (ACM)



Subduction Products

- Characteristic igneous associations
- Distinctive patterns of metamorphism
- Orogeny and mountain belts

Structure of an Island Arc



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

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

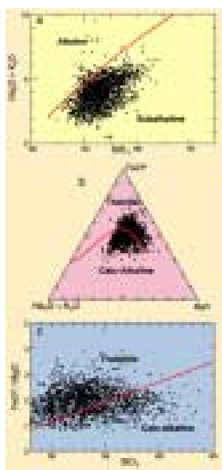
- Tholeiitic (MORB, OIT)
- Alkaline (OIA)
- Calc-Alkaline (~ restricted to SZ)

Major Elements and Magma Series

a. Alkali vs. silica
b. AFM
c. FeO*/MgO vs. silica

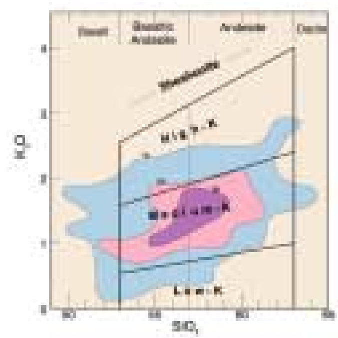
Diagrams for 1946 analyses from ~ 30 island and continental arcs with emphasis on the more primitive volcanics

Data compiled by Plank and Langmuir (1988)

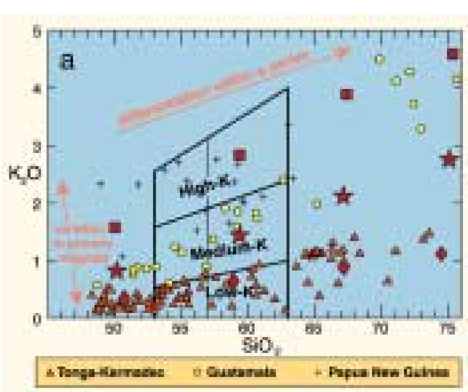


Sub-series of Calc-Alkaline

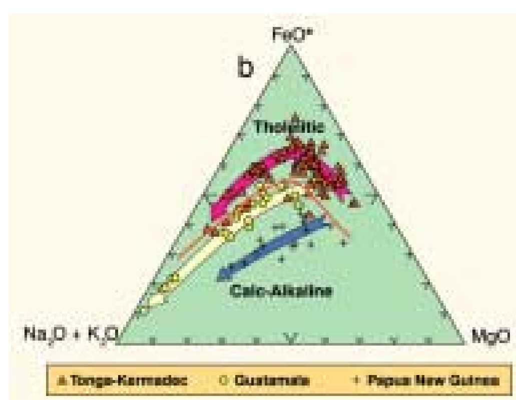
- K_2O is an important discriminator $\rightarrow$ 3 sub-series



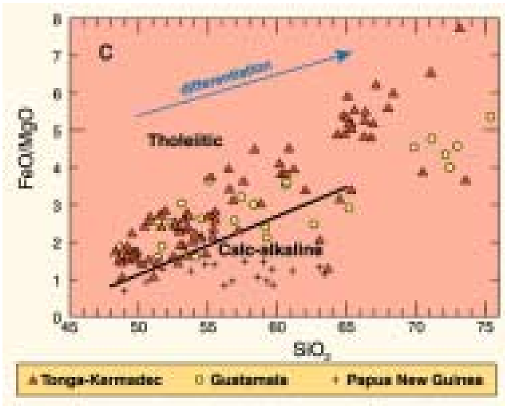
The three andesite series of Gill (1981) Contours represent the concentration of 2500 analyses of andesites stored in the large data file RKOC76 (Carnegie Institute of Washington).



K_2O-SiO_2 diagram distinguishing high-K, medium-K and low-K series. Differentiation within a series dominated by fractional crystallization. Primary magmas are distinguished by variations in K_2O at low SiO_2. After Gill, 1981

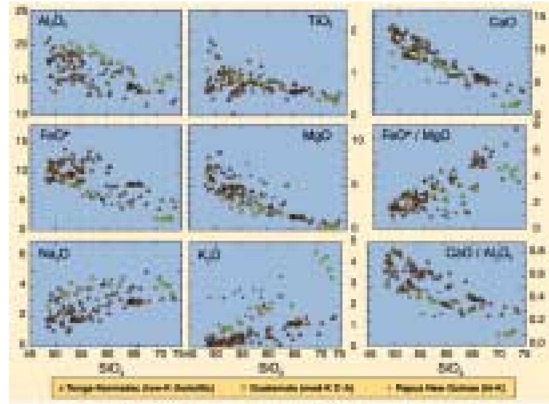


AFM diagram distinguishing tholeiitic and calc-alkaline series. Arrows represent differentiation trends within a series.



FeO*/MgO vs. SiO_2 diagram distinguishing tholeiitic and calc-alkaline series.

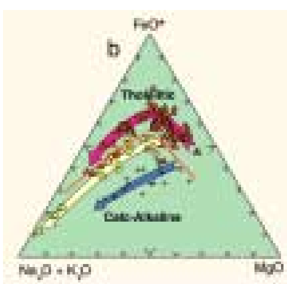
Tholeiitic vs. Calc-alkaline



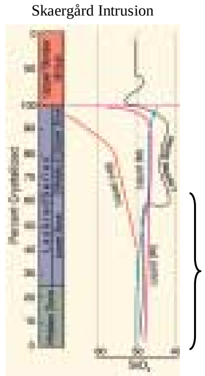
From Winter (2001)

Tholeiitic vs. Calc-alkaline

C-A shows continually increasing SiO_2 and lacks dramatic Fe enrichment



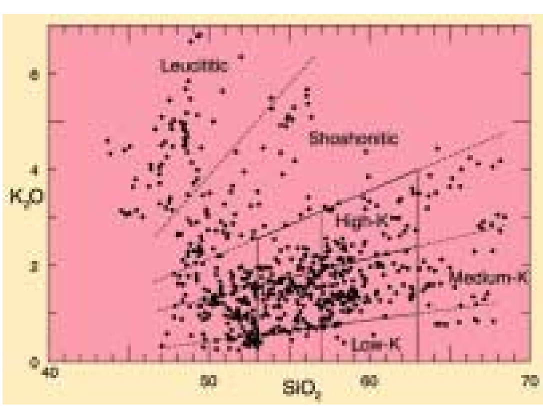
Tholeiitic silica in the Skaergård Intrusion



No change

Calc-alkaline differentiation

- Early crystallization of an Fe-Ti oxide phase
  - Probably related to the high water content of calc-alkaline magmas in arcs, dissolves → high f_{O2}
- High water pressure also depresses the plagioclase liquidus and → more An-rich
- As hydrous magma rises, ΔP → plagioclase liquidus moves to higher T → crystallization of considerable An-rich-SiO_2-poor plagioclase
- The crystallization of anorthitic plagioclase and low-silica, high-Fe hornblende is an alternative mechanism for the observed calc-alkaline differentiation trend



K_2O-SiO_2 diagram of nearly 700 analyses for Quaternary island arc volcanics from the Sunda-Banda arc. From Wheller et al. (1987) J. Volcan. Geotherm. Res., 32, 137-160.

Petrogenesis of Island Arc Magmas

- Why is subduction zone magmatism a paradox?

The main variables that can affect the isotherms in subduction zone systems are:

1) the rate of subduction
2) the age of the subduction zone
3) the age of the subducting slab
4) the extent to which the subducting slab induces flow in the mantle wedge

Other factors, such as:

– dip of the slab
– frictional heating
– endothermic metamorphic reactions
– metamorphic fluid flow

are now thought to play only a minor role

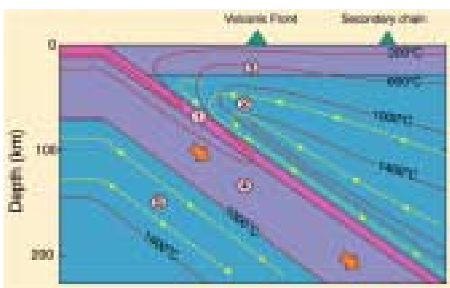
Main Variables Affecting Isotherms in Subduction Zones

- The rate of subduction
- The age of the subduction zone
- The age of the subducting slab
- The extent to which the subducting slab induces flow in the mantle wedge

Typical thermal model for a subduction zone

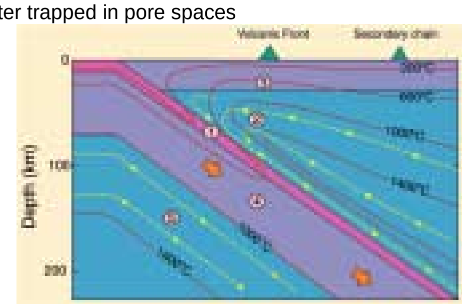
- Isotherms will be higher (i.e. the system will be hotter) if
  - a) the convergence rate is slower
  - b) the subducted slab is young and near the ridge (warmer)
  - c) the arc is young (<50-100 Ma according to Peacock, 1991)

Cross section of a subduction zone showing isotherms (Furukawa, 1993) and mantle flow lines (Tatsumi and Eggins, 1995)



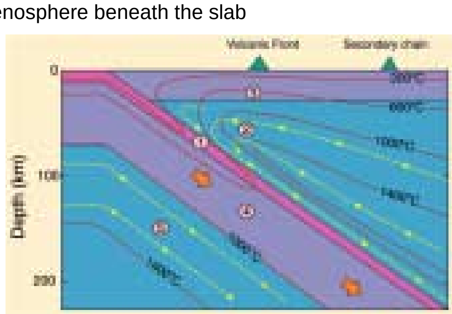
The principal source components → IA magmas

1. The crustal portion of the subducted slab
   - 1a Altered oceanic crust (hydrated by circulating seawater, and metamorphosed in large part to greenschist facies)
   - 1b Subducted oceanic and forearc sediments
   - 1c Seawater trapped in pore spaces



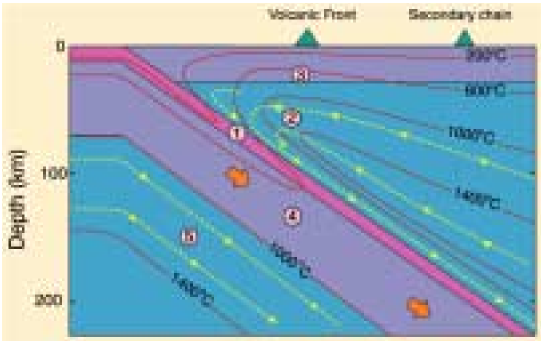
The principal source components → IA magmas

2. The mantle wedge between the slab and the arc crust
3. The arc crust
4. The lithospheric mantle of the subducting plate
5. The asthenosphere beneath the slab



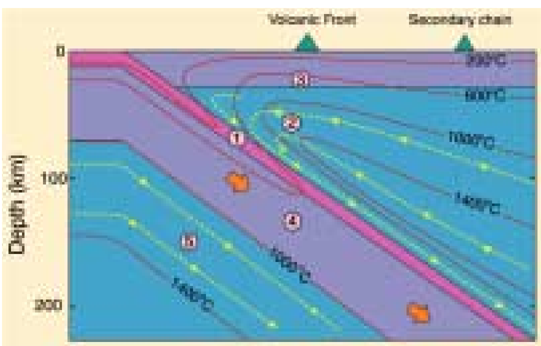
- Left with the subducted crust and mantle wedge
- The trace element and isotopic data suggest that both contribute to arc magmatism. How, and to what extent?
  – Dry peridotite solidus too high for melting of anhydrous mantle to occur anywhere in the thermal regime shown
  – LIL/HFS ratios of arc magmas → water plays a significant role in arc magmatism

- The sequence of pressures and temperatures that a rock is subjected to during an interval such as burial, subduction, metamorphism, uplift, etc. is called a pressure-temperature-time or P-T-t path



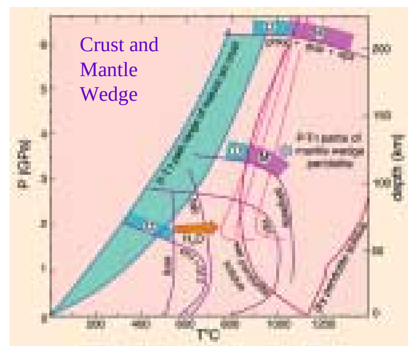
- The LIL/HFS trace element data underscore the importance of slab-derived water and a MORB-like mantle wedge source
- The flat HREE pattern argues against a garnet-bearing (eclogite) source
- Thus modern opinion has swung toward the non-melted slab for most cases

Mantle Wedge P-T-t Paths



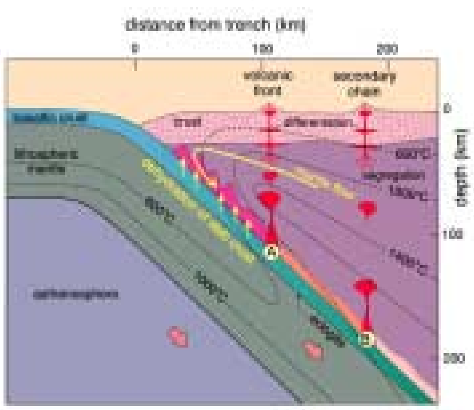
- Amphibole-bearing hydrated peridotite should melt at ~ 120 km
- Phlogopite-bearing hydrated peridotite should melt at ~ 200 km
  → Is there a second arc behind first?

Some calculated P-T-t paths for peridotite in the mantle wedge. The subducted crust dehydrates, and water is transferred to the wedge (arrow). After Peacock (1991), Tatsumi and Eggins (1995). Winter (2001).



Island Arc Petrogenesis

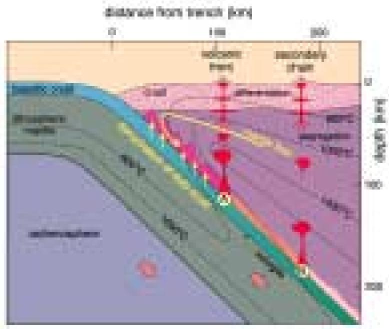
A model for subduction zone magmatism with reference to island arcs. Dehydration of slab crust causes hydration of the mantle, which undergoes partial melting as amphibole (A) and phlogopite (B) dehydrate. From Tatsumi (1989) and Tatsumi and Eggins (1995).



Multi-stage, Multi-source Process

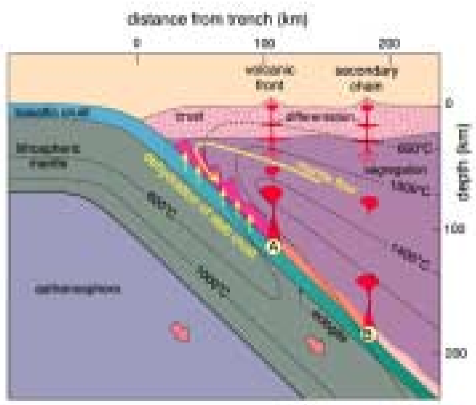
- Dehydration of the slab provides the LIL enrichments + enriched Nd, Sr, and Pb isotopic signatures
  - These components, plus other dissolved silicate materials, are transferred to the wedge in a fluid phase (or melt?)
- The mantle wedge provides the HFS and other depleted and compatible element characteristics

- Phlogopite is stable in ultramafic rocks beyond the conditions at which amphibole breaks down
- P-T-t paths for the wedge reach the phlogopite-2-pyroxene dehydration reaction at about 200 km depth



- The parent magma for the calc-alkaline series is a high alumina basalt, a type of basalt that is largely restricted to the subduction zone environment, and the origin of which is controversial
- Some high-Mg (>8wt% MgO) high alumina basalts may be primary, as may some andesites, but most surface lavas have compositions too evolved to be primary
- Perhaps the more common low-Mg (< 6 wt. % MgO), high-Al (>17wt% Al_2O_3) types are the result of somewhat deeper fractionation of the primary tholeiitic magma which ponds at a density equilibrium position at the base of the arc crust in more mature arcs

Fractional crystallization occurs at various levels



Continental Arcs

Reading:
Winter Chapter 17

Continental Arc Magmatism

Potential differences with respect to Island Arcs:

- Thick sialic crust contrasts greatly with mantle-derived partial melts may → more pronounced effects of contamination
- Low density of crust may retard ascent → stagnation of magmas and more potential for differentiation
- Low melting point of crust allows for partial melting and crustally-derived melts

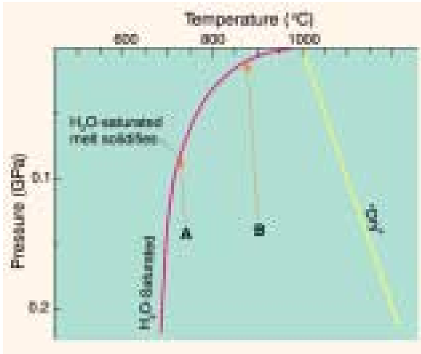
North American Batholiths

Major plutons of the North American Cordillera, a principal segment of a continuous Mesozoic-Tertiary belt from the Aleutians to Antarctica.

Figure after Anderson (1990.

The Sr 0.706 line in N. America is after Kistler (1990), Miller and Barton (1990) and Armstrong (1988).

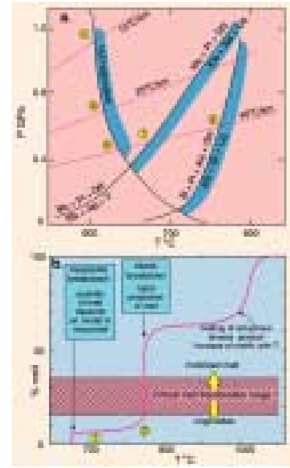
- Pressure-temperature phase diagram showing solidus curves for H_2O-saturated and dry granite.
- An H_2O-saturated granitoid just above the solidus at A will quickly intersect the solidus as it rises and will therefore solidify.
- A hotter, H_2O-undersaturated granitoid at B will rise further before solidifying.



Crustal Melting

a. Simplified P-T phase diagram
b. Quantity of melt generated during the melting of muscovite-biotite-bearing crustal source rocks, after Clarke (1992) and Vielzeuf and Holloway (1988).
c. Shaded areas in (a) indicate zones of melt generation.

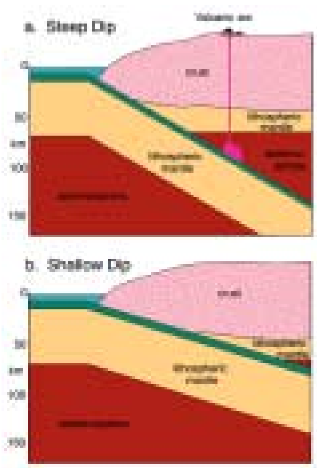
Figures from Winter (2001)



Subduction Section

Schematic diagram to illustrate how a shallow dip of the subducting slab can pinch out the asthenosphere from the overlying mantle wedge.

Winter (2001)

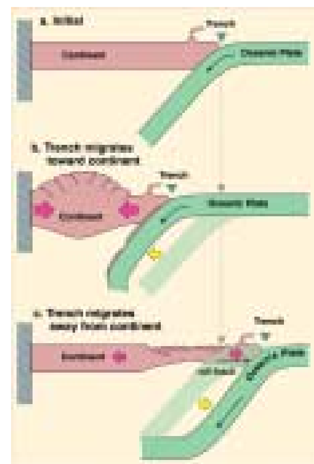


Thick Crust Model

Schematic cross sections of a volcanic arc showing an initial state (a) followed by trench migration toward the continent (b), resulting in a destructive boundary and subduction erosion of the overlying crust.

Alternatively, trench migration away from the continent (c) results in extension and a constructive boundary. In this case the extension in (c) is accomplished by "roll-back" of the subducting plate.

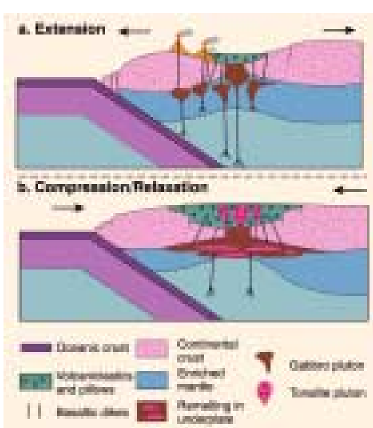
Winter (2001) .

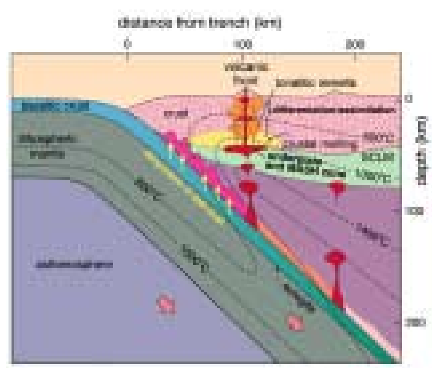


Continental Underplating

Schematic diagram illustrating (a) the formation of a gabbroic crustal underplate at an continental arc and (b) the remelting of the underplate to generate tonalitic plutons.

After Cobbing and Pitcher (1983)





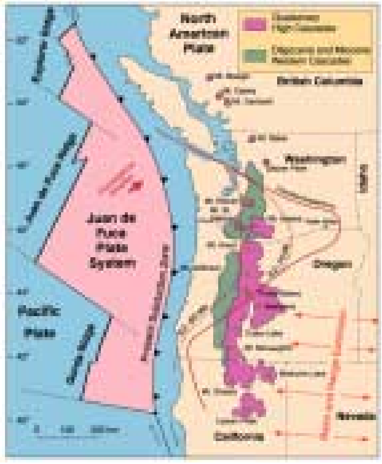
Schematic cross section of an active continental margin subduction zone, showing the dehydration of the subducting slab, hydration and melting of a heterogeneous mantle wedge, crustal underplating of mantle-derived melts where MASH processes may occur, as well as crystallization of the underplates. Winter (2001)

Cascade Arc System

Map of the Juan de Fuca plate

After McBirney and White (1982) and Hughes (1990).

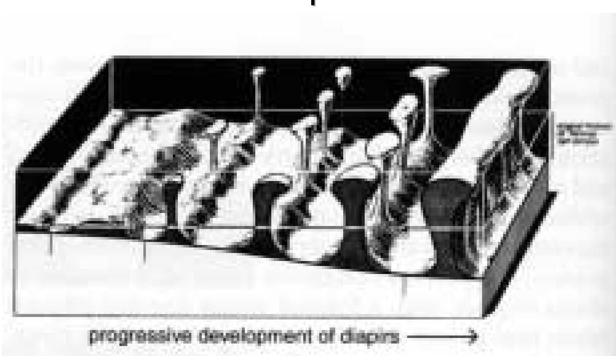
Winter (2001)



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

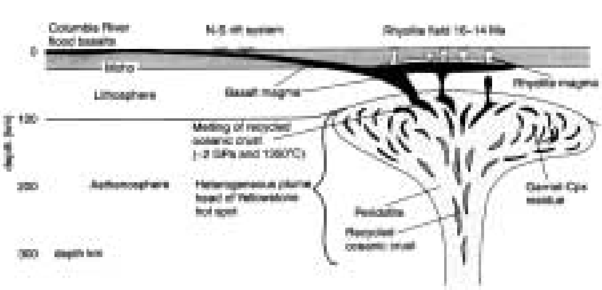


Diapir Ascent

- 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

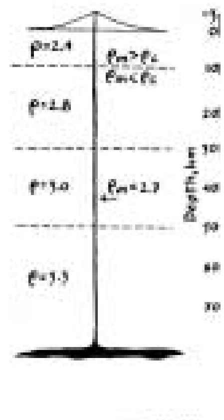
Neutral Buoyancy

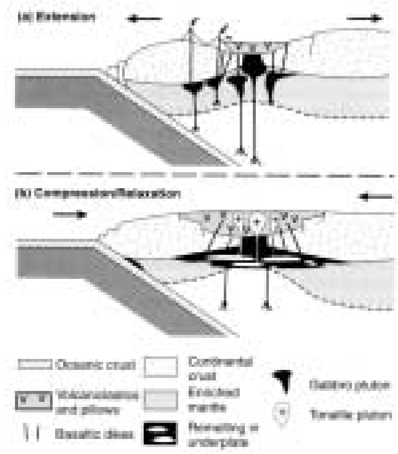
- Positively buoyant
  - Melt less dense than surrounding rocks
  - Primary basalt magma surrounded by mantle peridotite
- Negatively buoyant
  - Melt more dense than surrounding rocks
  - Olivine basalt intruded into continental crust



Density Filter

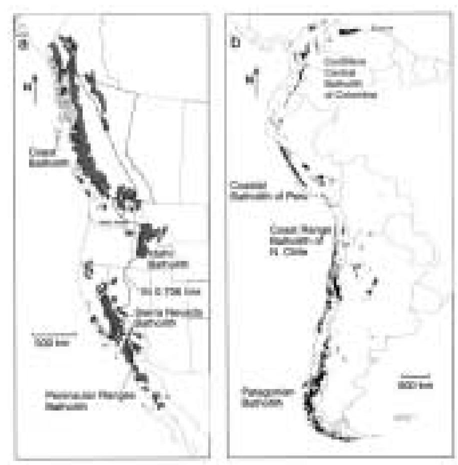
- Crustal rocks block the ascent of denser magmas
- Heat from these magmas melt the lower crust
- Residual melts may rise
- Exsolved volatiles also facilitate rise





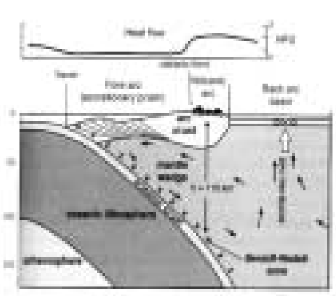
Batholiths

- An example: Sierra Nevada Batholith, CA
- A group or groups of separately intruded plutons with a composite volume of 10^6 km^3
- Age extends through the entire Mesozoic era (>130 my)
- Average pluton volume is ~ 30 km^3



Emplacement Process

- Stoping
- Brecciation
- Doming
- Ballooning
- Void zones



Gill, 1981