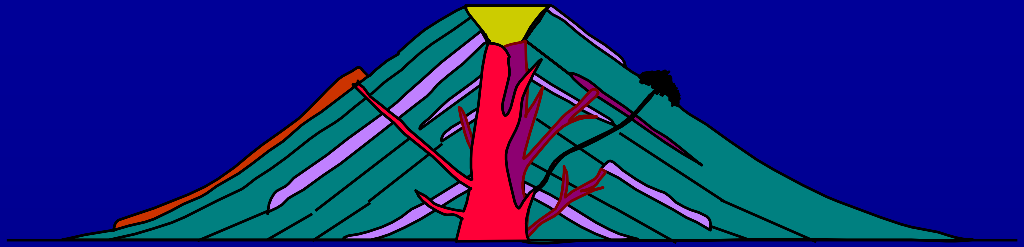


Igneous Petrology

The Earth’s Interior

Crust:

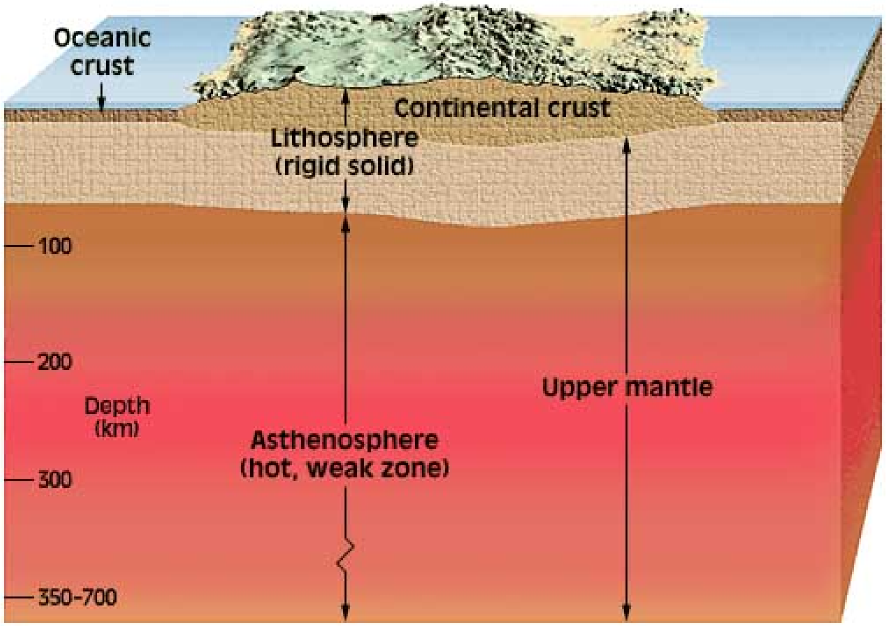
Oceanic crust

Thin: 10 km

Relatively uniform stratigraphy

= ophiolite suite:

- sediments
- pillow basalt
- sheeted dikes
- more massive gabbro
- ultramafic (mantle)



Continental Crust

Thicker: 20-90 km average ~35 km

Highly variable composition

- Average ~ granodiorite

The Earth' s Interior

Mantle:

Peridotite (ultramafic)

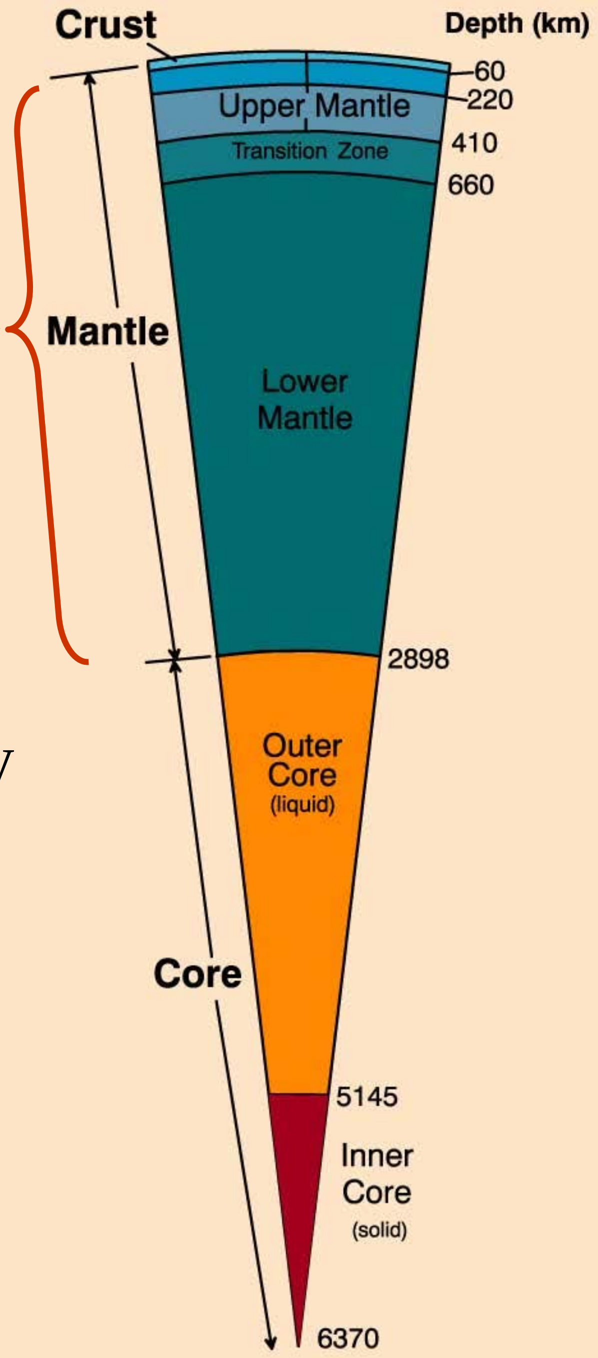
Upper to 410 km (olivine → spinel)

- Low Velocity Layer 60-220 km

Transition Zone as velocity increases ~ rapidly

- 660 spinel → perovskite-type
  - $\mathrm{Si}^{IV} \rightarrow \mathrm{Si}^{VI}$

Lower Mantle has more gradual velocity increase



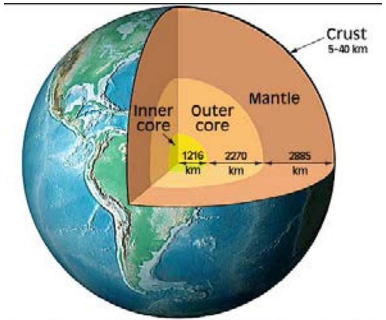


Figure 1.2 Major subdivisions of the Earth. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

The Earth's Interior

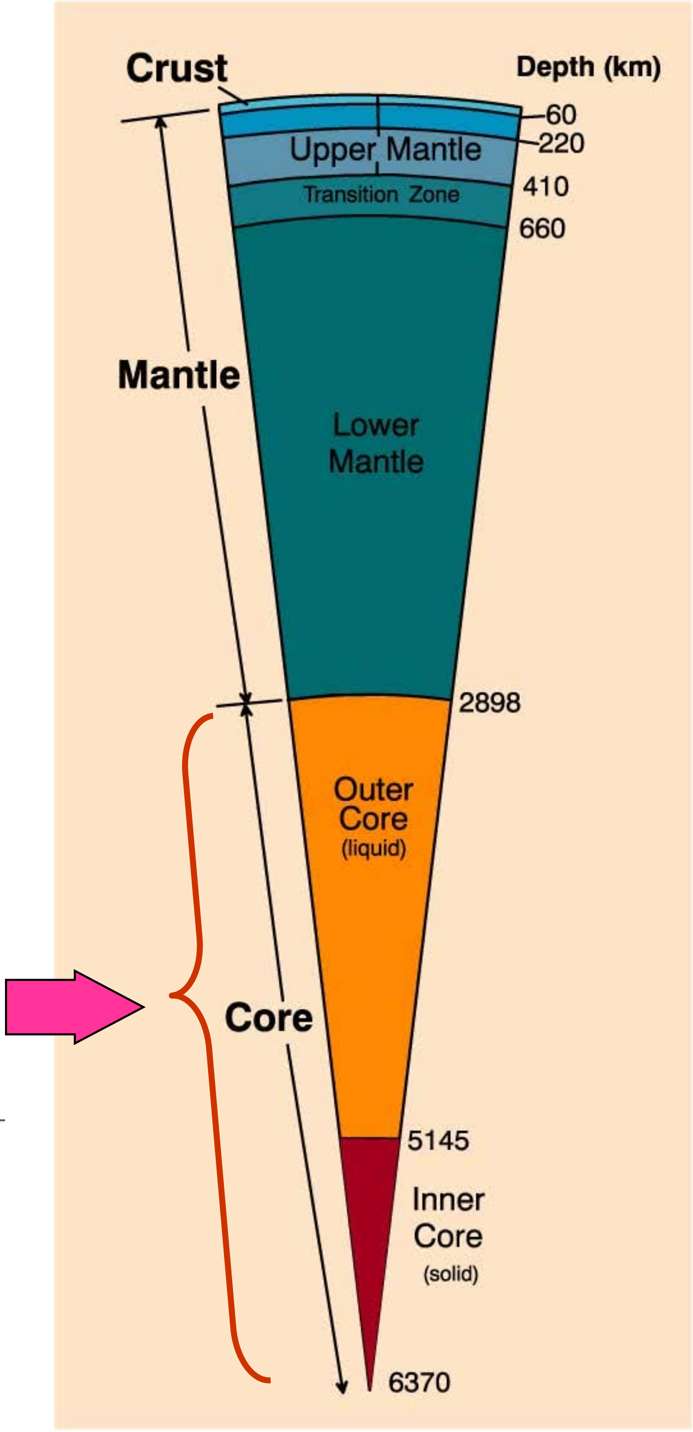
Core:

Fe-Ni metallic alloy

Outer Core is liquid

- No S-waves

Inner Core is solid



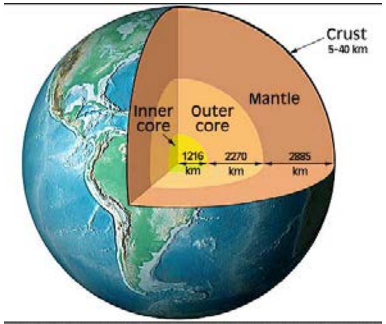


Figure 1.2 Major subdivisions of the Earth. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

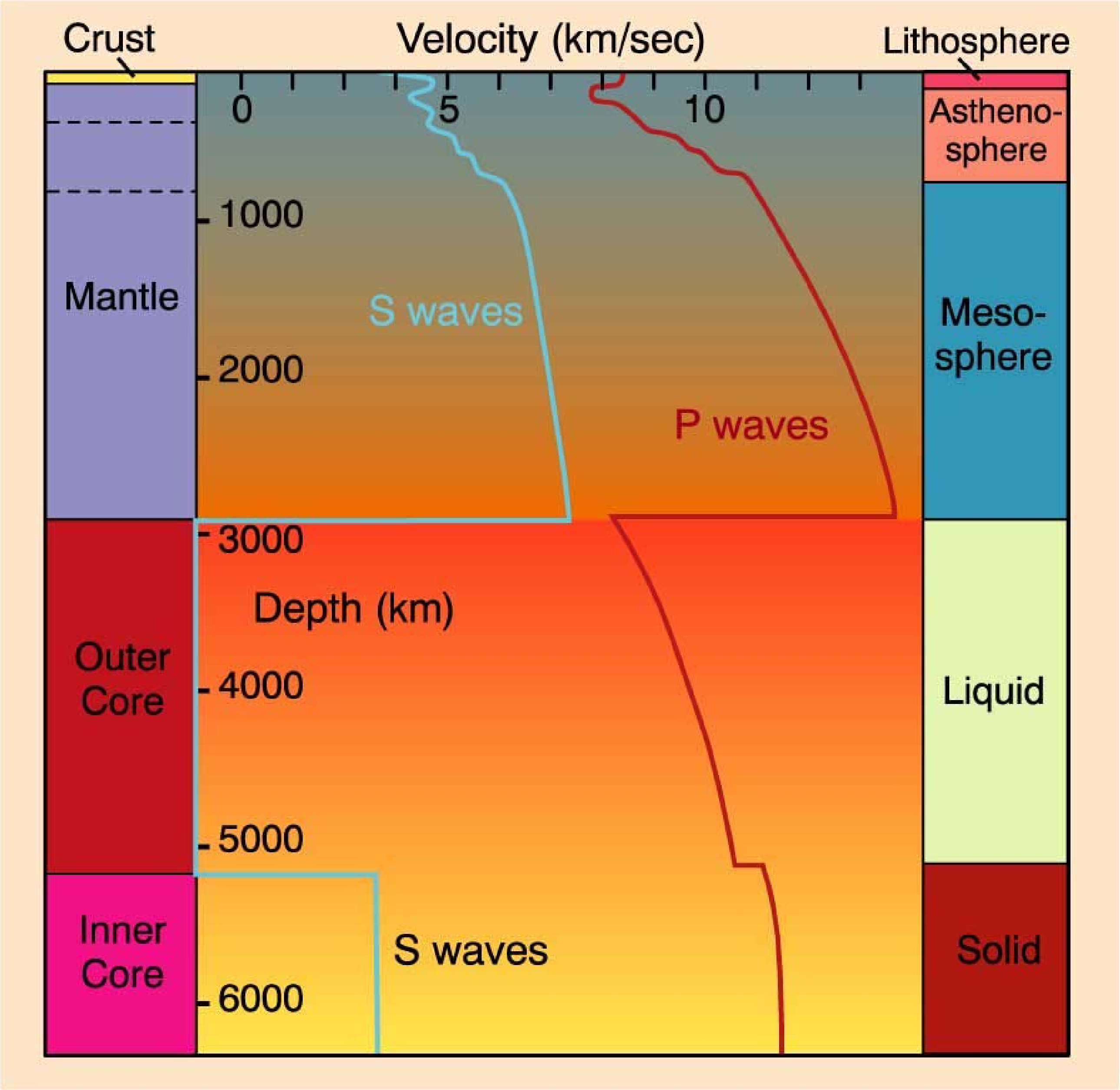


Figure 1.3 Variation in P and S wave velocities with depth. Compositional subdivisions of the Earth are on the left, rheological subdivisions on the right. After Kearey and Vine (1990), *Global Tectonics*. © Blackwell Scientific. Oxford.

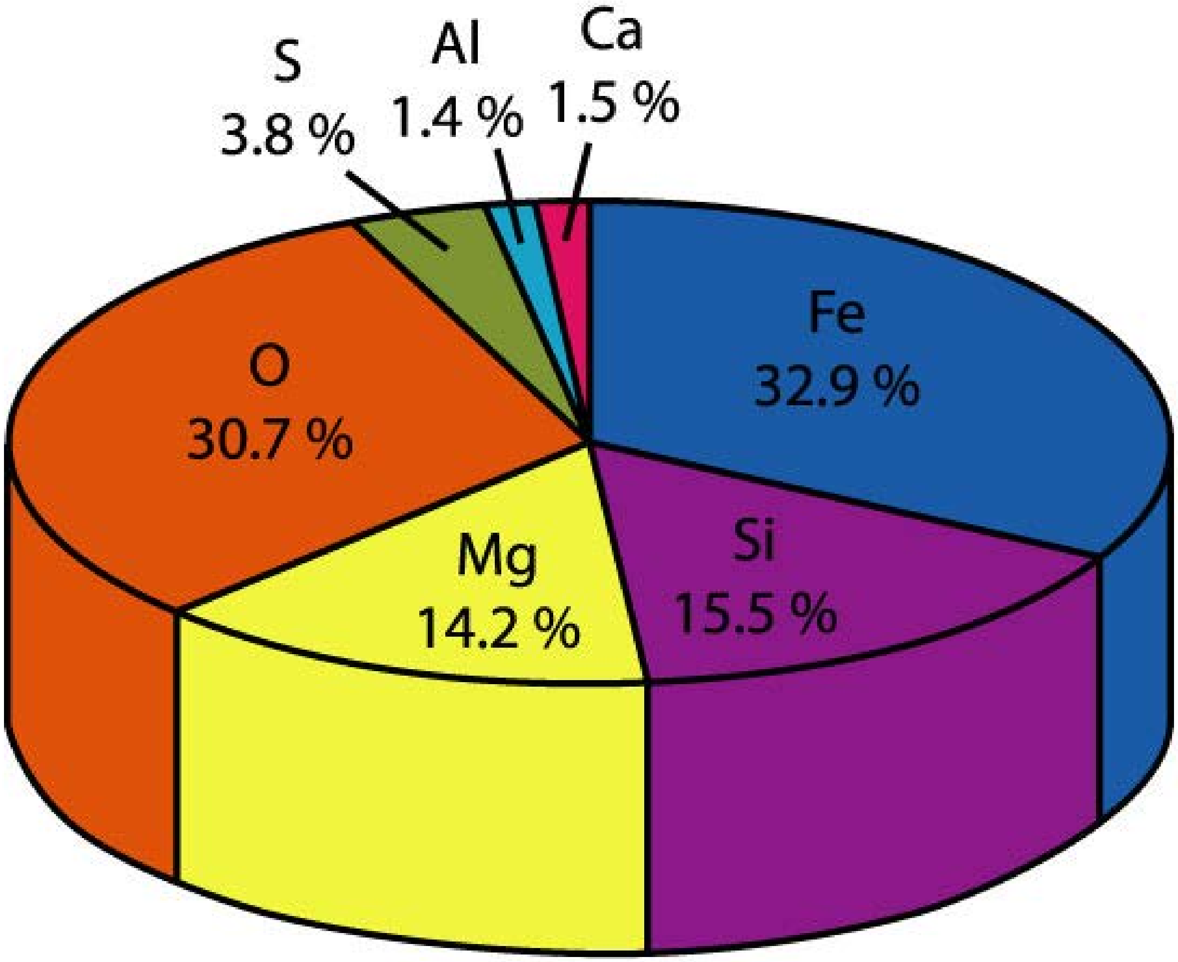
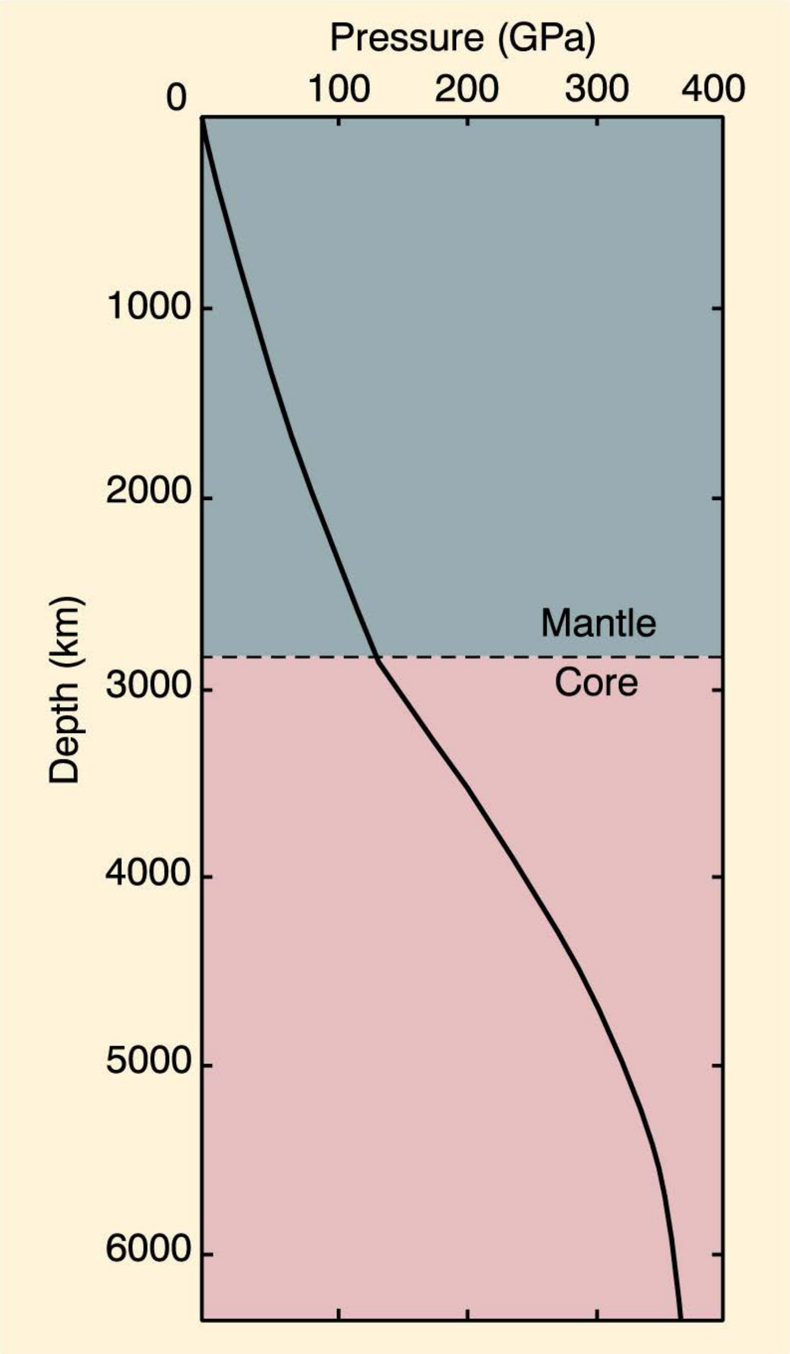


Figure 1.5 Relative atomic abundances of the seven most common elements that comprise 97% of the Earth's mass. An Introduction to Igneous and Metamorphic Petrology, by John Winter , Prentice Hall.

The Pressure Gradient

- P increases = ρgh
- Nearly linear through mantle
  - ~ 30 MPa/km
  - ≈ 1 GPa at base of ave crust
- Core: ρ incr. more rapidly since alloy more dense

Figure 1.8 Pressure variation with depth. From Dziewonski and Anderson (1981). Phys. Earth Planet. Int., **25**, 297-356. © Elsevier Science.



Heat Sources in the Earth

1. Heat from the early accretion and differentiation of the Earth
   - still slowly reaching surface

Heat Sources in the Earth

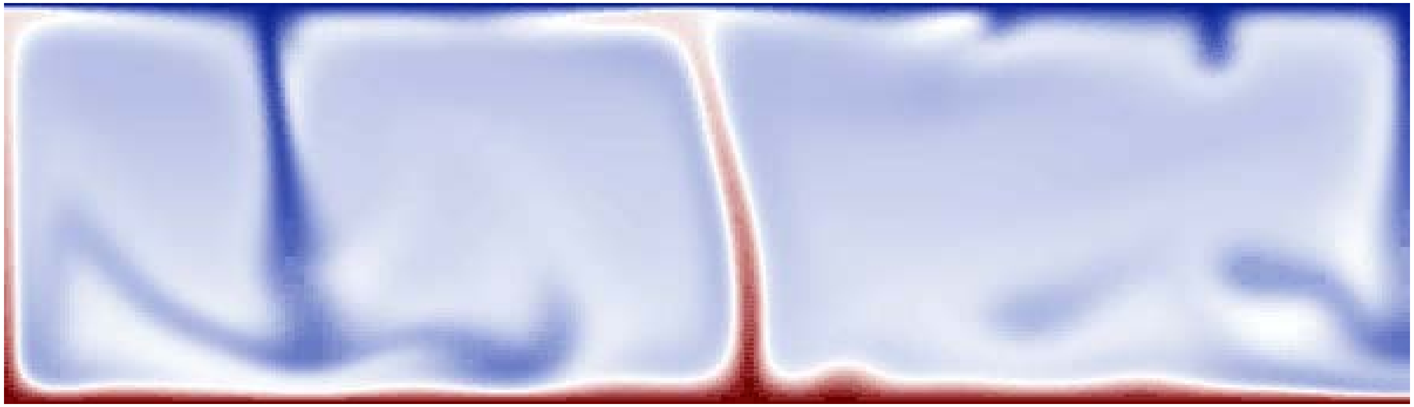
1. Heat from the early accretion and differentiation of the Earth
    - still slowly reaching surface
2. Heat released by the radioactive breakdown of unstable nuclides

Heat Transfer

1. Radiation
2. Conduction

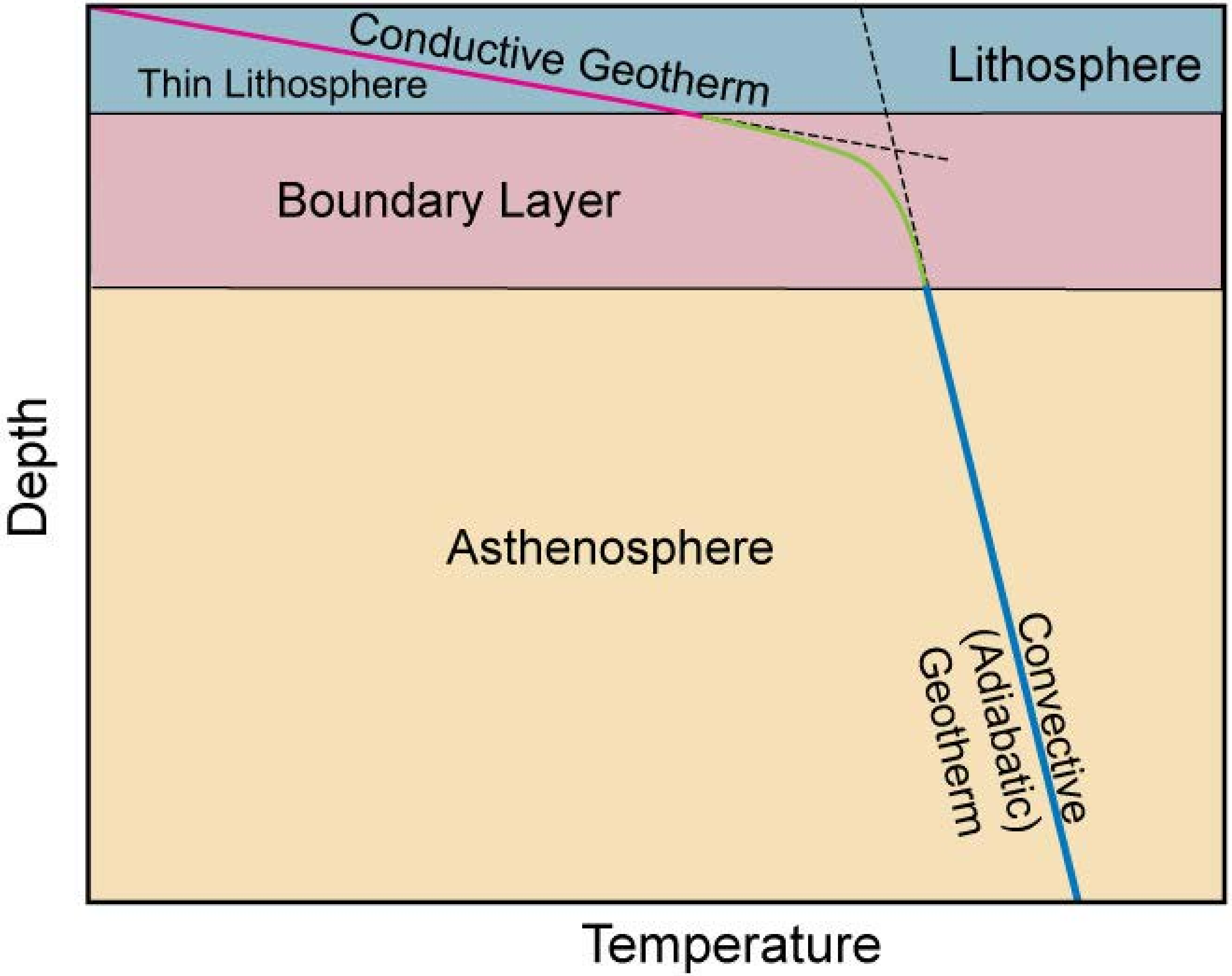
Heat Transfer

1. Radiation
2. Conduction
3. Convection



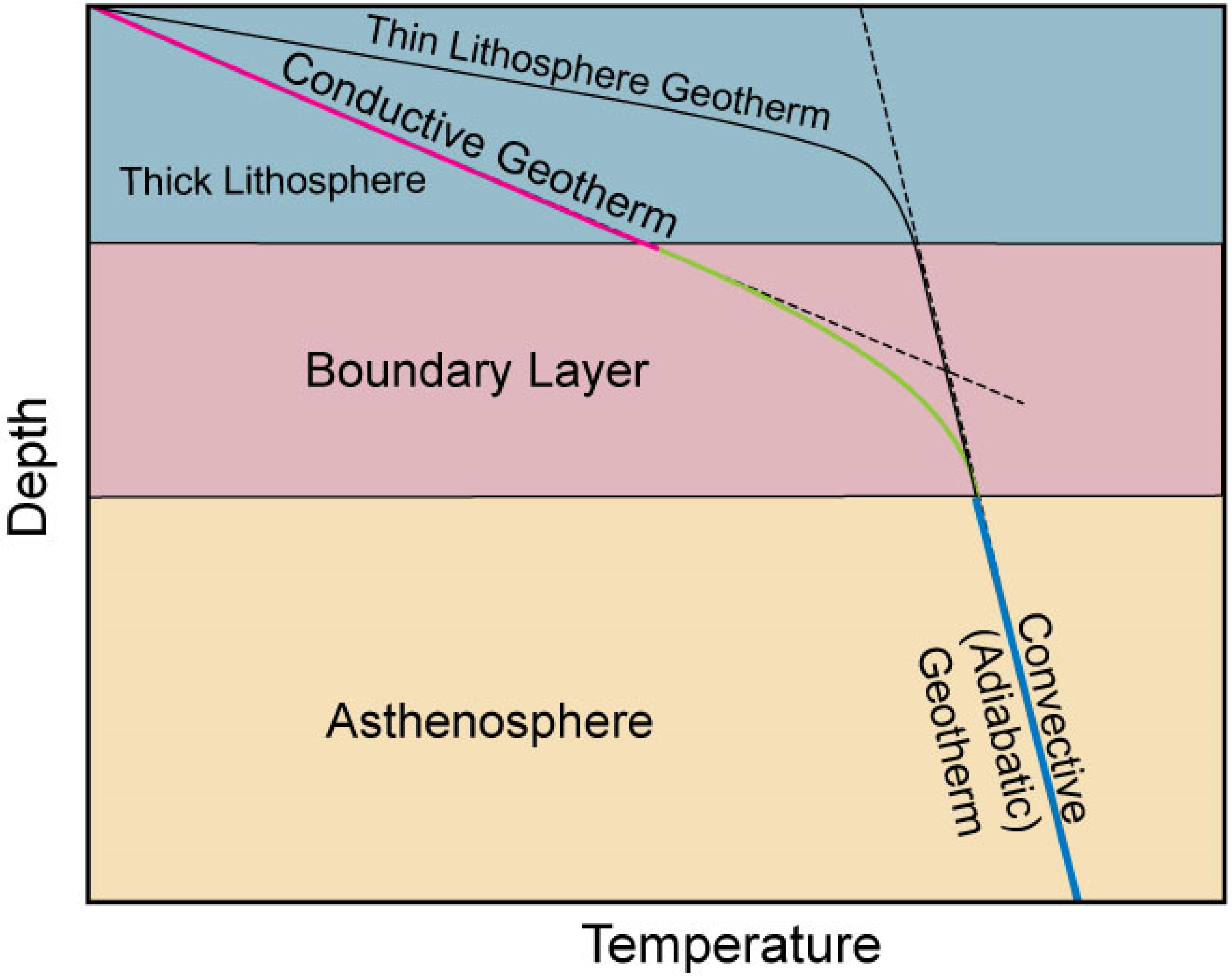
The Geothermal Gradient

Figure 1.9 Diagrammatic cross-section through the upper 200-300 km of the Earth showing geothermal gradients reflecting more efficient adiabatic (constant heat content) convection of heat in the mobile asthenosphere (steeper gradient in blue)) and less efficient conductive heat transfer through the more rigid lithosphere (shallower gradient in red). The boundary layer is a zone across which the transition in rheology and heat transfer mechanism occurs (in green). The thickness of the boundary layer is exaggerated here for clarity: it is probably less than half the thickness of the lithosphere.



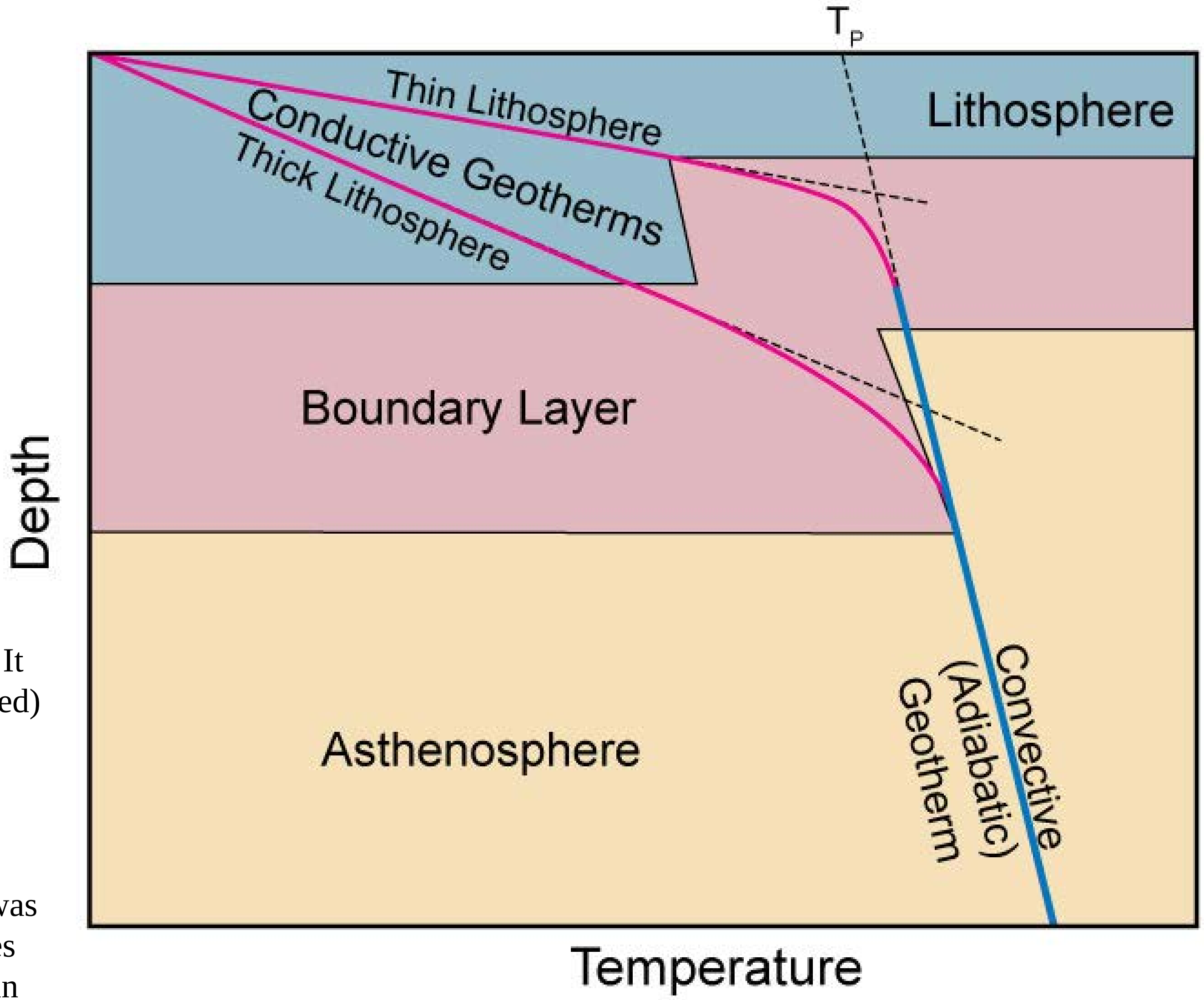
The Geothermal Gradient

Figure 1.9 A similar example for **thick** (continental) lithosphere.



The Geothermal Gradient

Figure 1.9 Notice that thinner lithosphere allows convective heat transfer to shallower depths, resulting in a **higher** geothermal gradient across the boundary layer and lithosphere.



T_P is the potential temperature. It permits comparison of (estimated) temperatures at depth from one locality to another. Because temperature varies with depth, one must select some reference depth. In this case the surface was chosen. One simply extrapolates adiabatically from the T and P in question to the surface.

The Geothermal Gradient

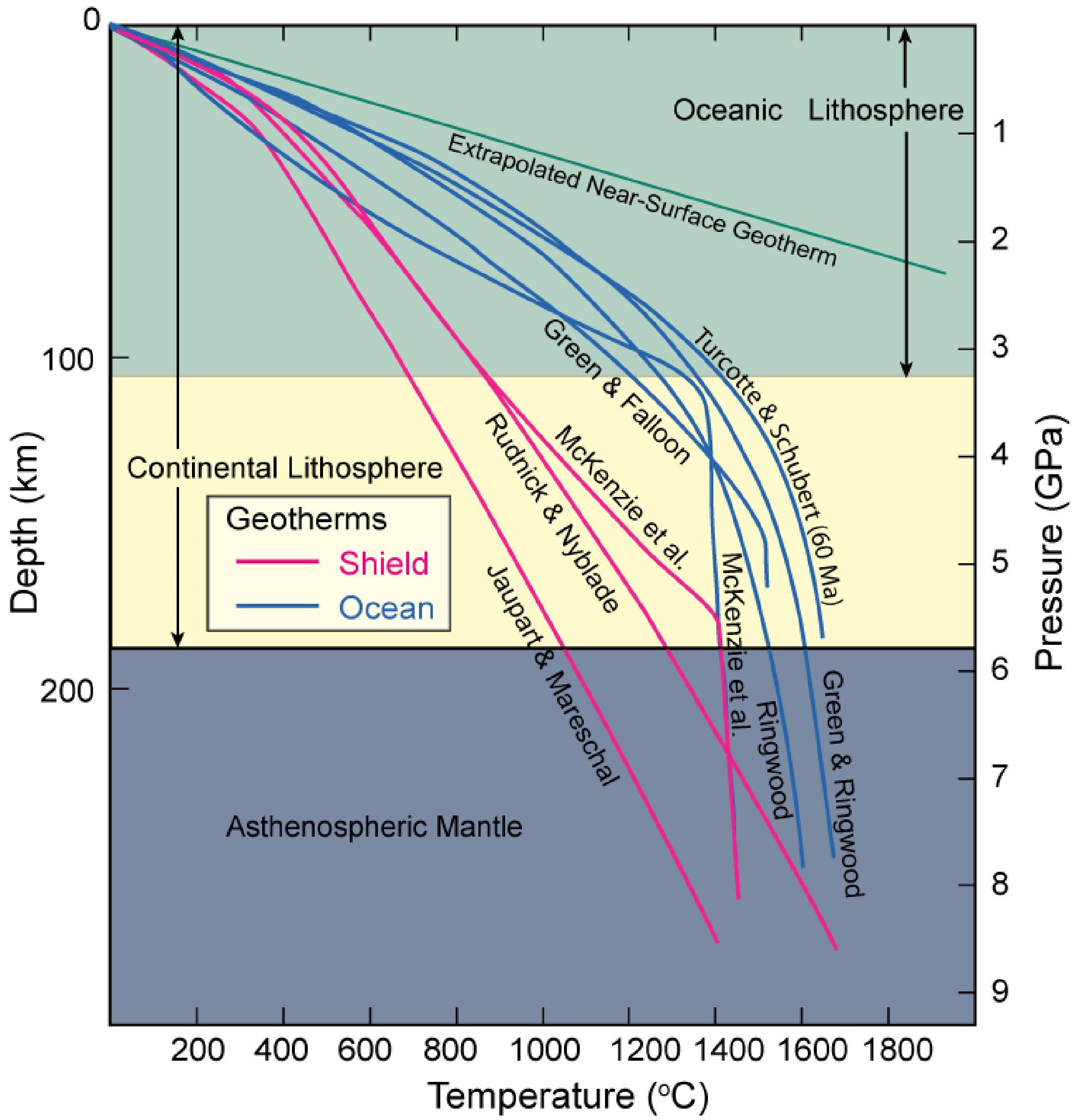


Figure 1.11 Estimates of oceanic (blue curves) and continental shield (red curves) geotherms to a depth of 300 km. The thickness of mature (> 100Ma) oceanic lithosphere is hatched and that of continental shield lithosphere is yellow. Data from Green and Falloon ((1998), Green & Ringwood (1963), Jaupart and Mareschal (1999), McKenzie *et al*. (2005 and personal communication), Ringwood (1966), Rudnick and Nyblade (1999), Turcotte and Schubert (2002).

The Geothermal Gradient

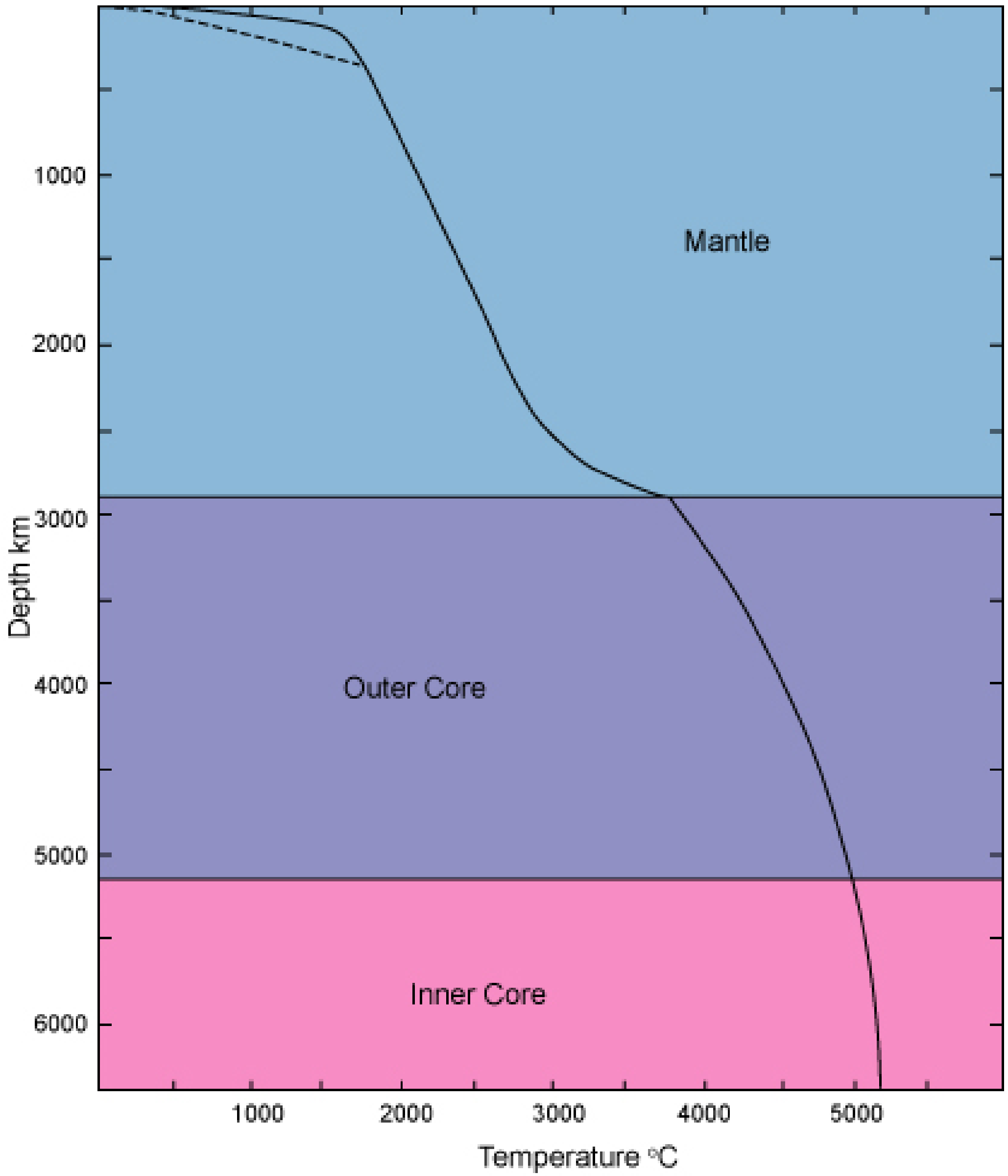


Figure 1.12 Estimate of the geothermal gradient to the center of the Earth (after Stacey, 1992). The shallow solid portion is very close to the Green & Ringwood (1963) oceanic geotherm in Fig. 1–11 and the dashed geotherm is the Jaupart & Mareschal (1999) continental geotherm.

The Geothermal Gradient

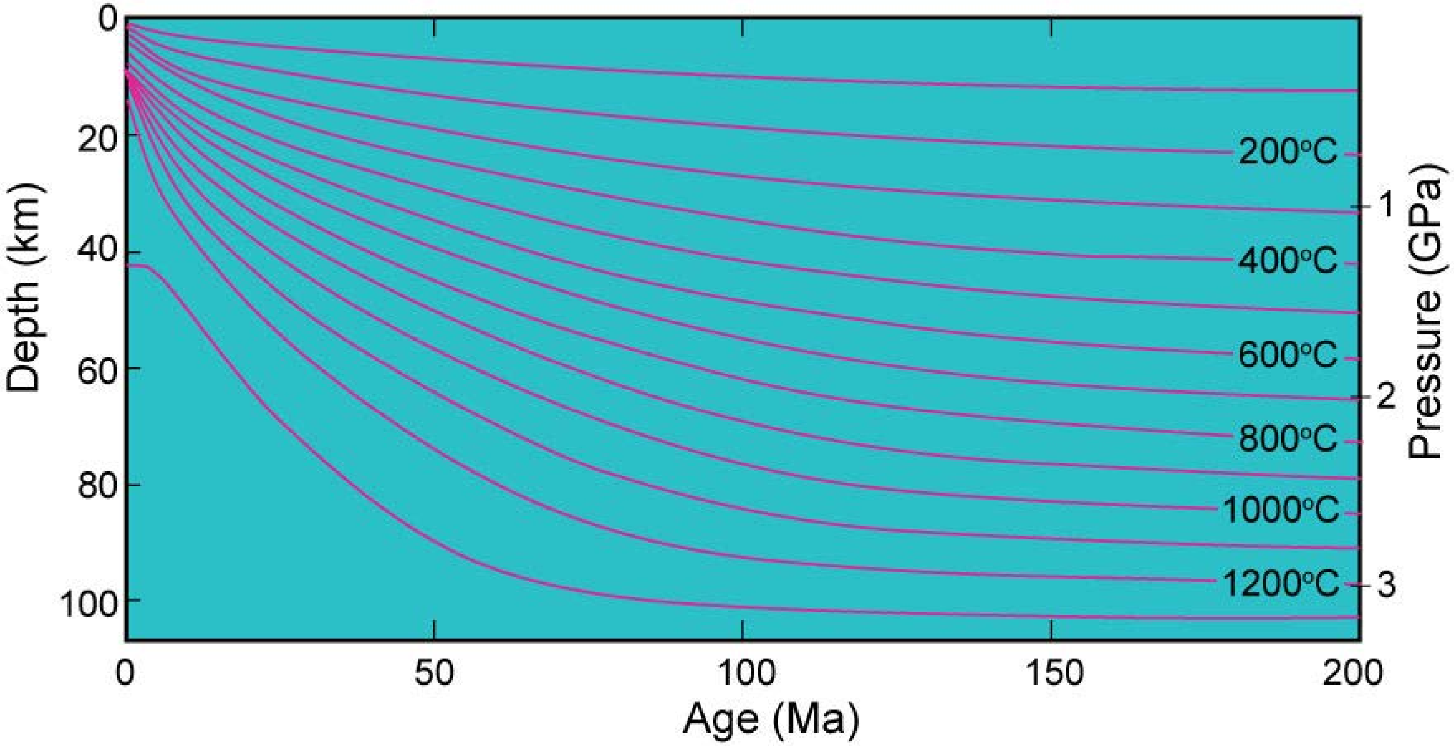


Figure 1.10 Temperature contours calculated for an oceanic plate generated at a mid-ocean ridge (age 0) and thickening as it cools. The 1300°C isotherm is a reasonable approximation for the base of the oceanic lithosphere. The plate thickens rapidly from zero to 50 Ma and is essentially constant beyond 100 Ma. From McKenzie *et al*. (2005).

The Geothermal Gradient

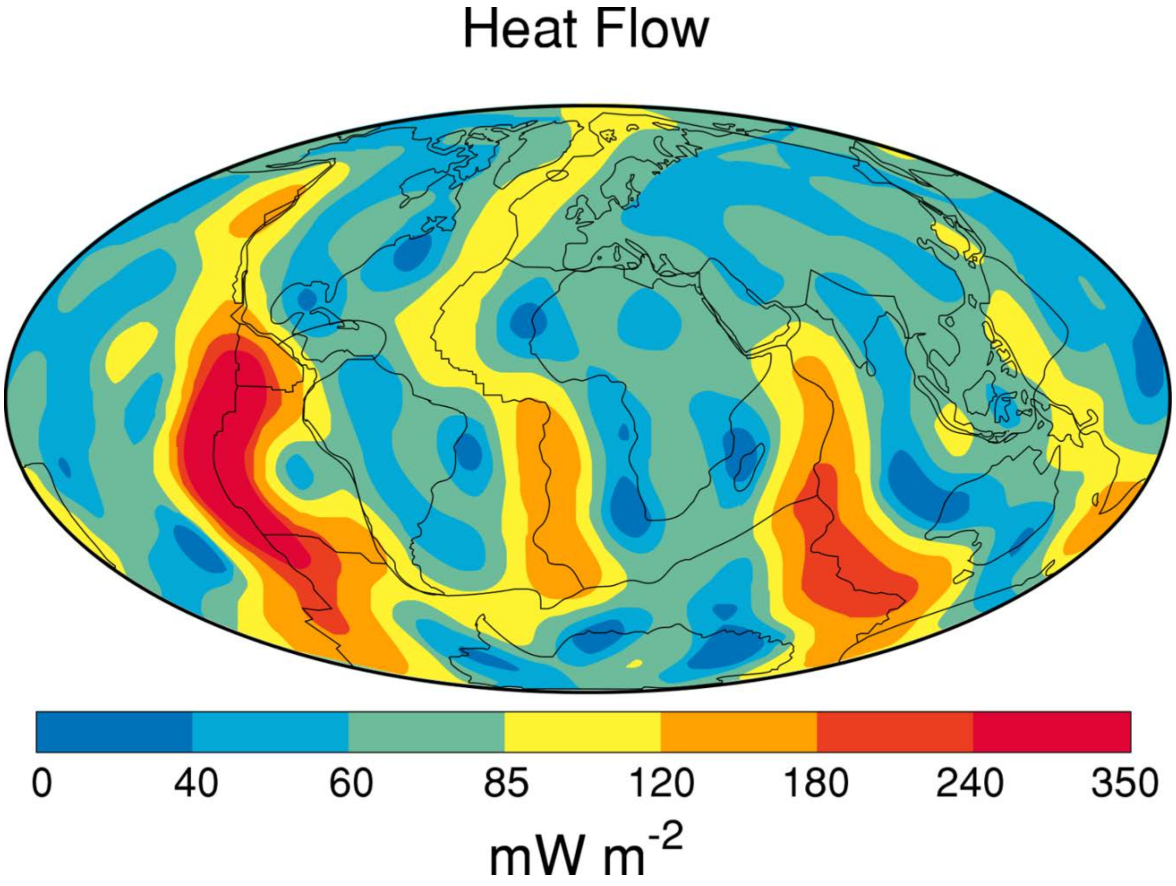
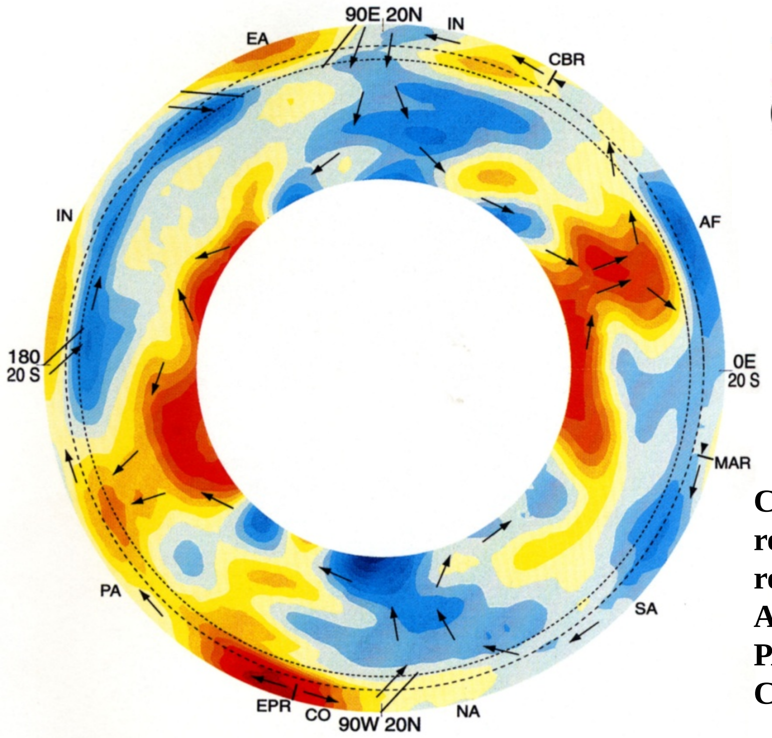
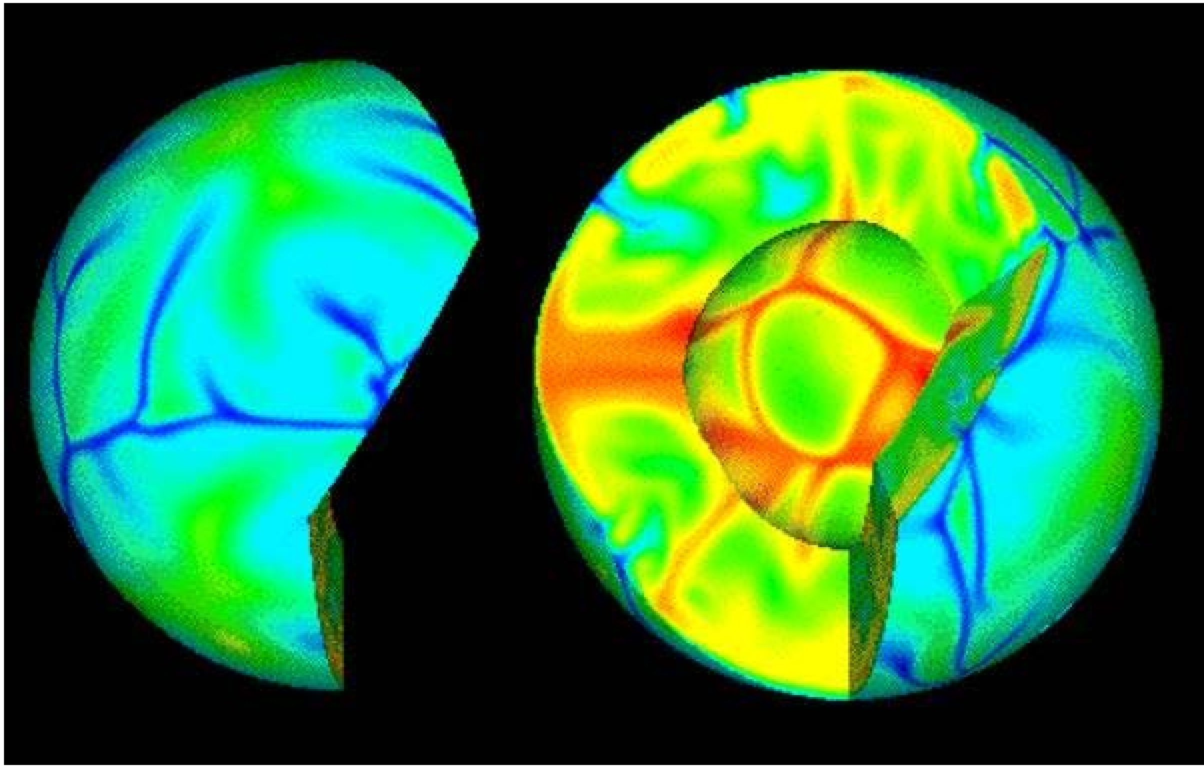


Fig 1.13. **Pattern of global heat flux variations compiled from observations at over 20,000 sites and modeled on a spherical harmonic expansion to degree 12. From Pollack, Hurter and Johnson. (1993) Rev. Geophys. 31, 267-280.**



Cross-section of the mantle based on a seismic tomography model. Arrows represent plate motions and large-scale mantle flow and subduction zones represented by dipping line segments. EPR =- East pacific Rise, MAR = Mid-Atlantic Ridge, CBR = Carlsberg Ridge. Plates: EA = Eurasian, IN = Indian, PA = Pacific, NA = North American, SA = South American, AF = African, CO = Cocos. From Li and Romanowicz (1996). J. Geophys. Research, 101, 22,245-72.

The Geothermal Gradient

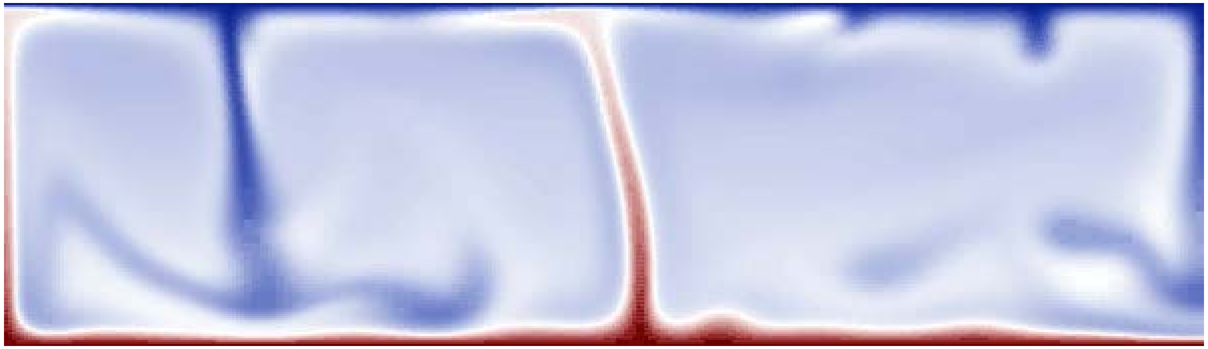


Thermal structure in a 3D spherical mantle convection model (red is hot, blue is cold).
J. H. Davies and H.-Peter Bunge
http://www.ocean.cf.ac.uk/people/huw/AGU99/mantlecirc.html

Plate tectonics

Cooling mechanisms for a hot planet

If the viscosity is low enough, plumes (in blue) will descend from the cooled upper layer: a form of convection.



But the upper mantle is too viscous for this

Figure 12-18. Cold plumes descending from a cooled upper boundary layer in a tank of silicone oil. Photo courtesy Claude Jaupart.

Mantle dynamics

Is the 670 km transition a barrier to whole-mantle convection?

Maybe?

Partly?

No?

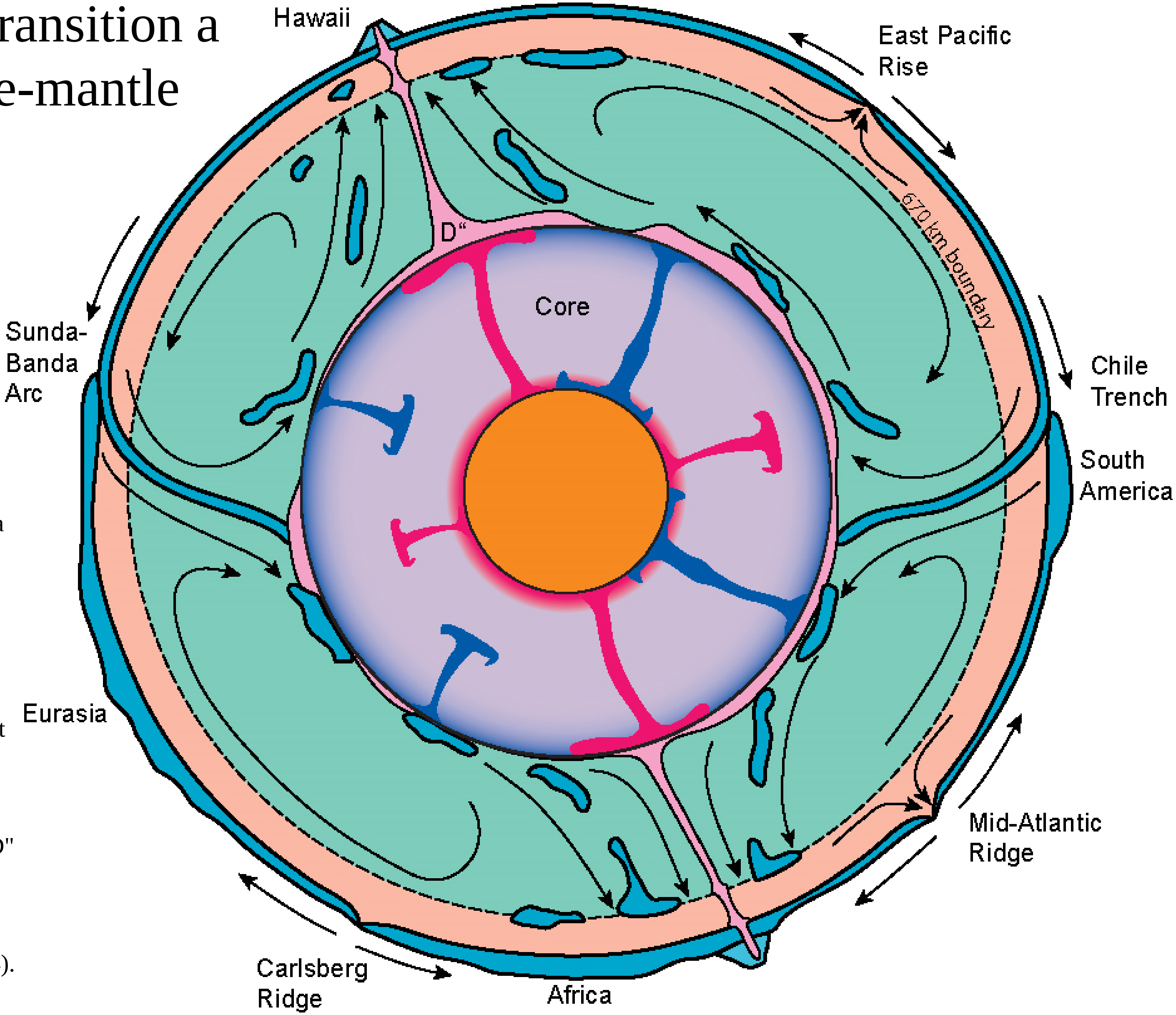
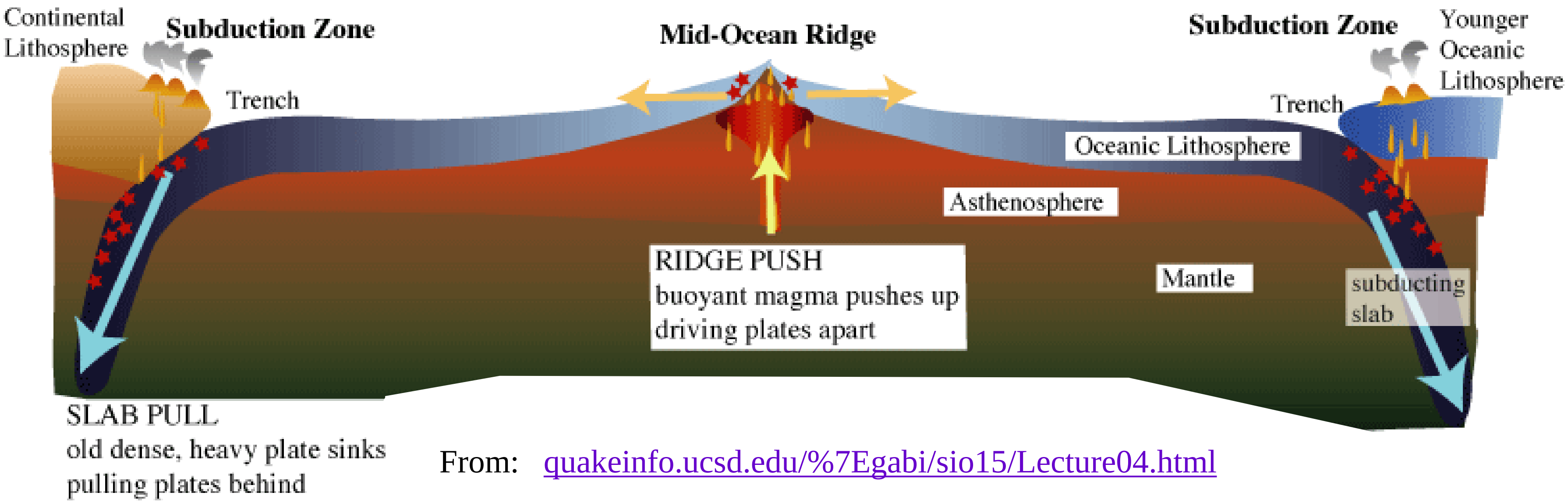


Figure 1.14. Schematic diagram of a 2-layer dynamic mantle model in which the 660 km transition is a sufficient density barrier to separate lower mantle convection (arrows represent flow patterns) from upper mantle flow, largely a response to plate separation. The only significant things that can penetrate this barrier are vigorous rising hotspot plumes and subducted lithosphere (which sink to become incorporated in the D" layer where they be heated by the core and return as plumes). Plumes in core represent relatively vigorous convection (see Chapter 14). After Silver et al. (1988).

Plate tectonics



From: quakeinfo.ucsd.edu/%7Egabi/sio15/Lecture04.html

“Slab Pull” is thus much more effective than “Ridge Push”

But both are poor terms: “slab pull” is really a body force (gravity acting on the entire dense slab….)

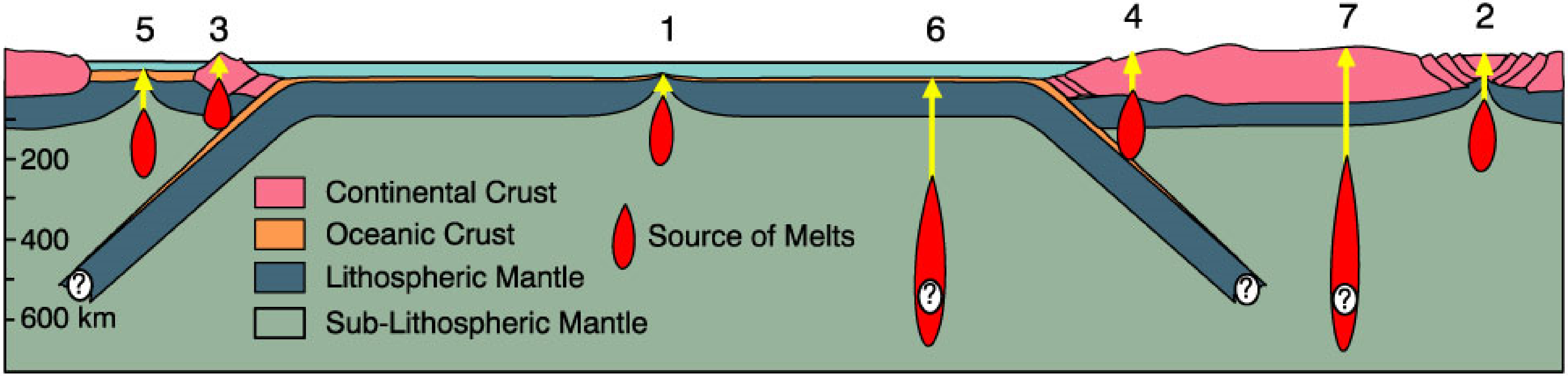
The old question of whether convection drives plate tectonics or not is also moot: plate tectonics ***is*** mantle convection.

The core, however, cools by more vigorous convection which heats the base of the mantle by conduction and initiates plumes (lower viscosity)

Plate Tectonic - Igneous Genesis

1. **Mid-Ocean Ridges**
2. **Intracontinental Rifts**
3. **Island Arcs**
4. **Active Continental Margins**
5. **Back-Arc Basins**
6. **Ocean Island Basalts**
7. **Miscellaneous Intra-Continental Activity**

kimberlites, carbonatites, anorthosites...



Classification of Igneous Rocks

Textures:

- Aphanitic- crystals too small to see by eye
- Phaneritic- can see the constituent minerals
  - Fine grained- < 1 mm diameter
  - Medium grained- 1-5 mm diameter
  - Coarse grained- 5-50 mm diameter
  - Very coarse grained- > 50 mm diameter
- Porphyritic- bimodal grain size distribution
- Glassy- no crystals formed

Classification of Igneous Rocks

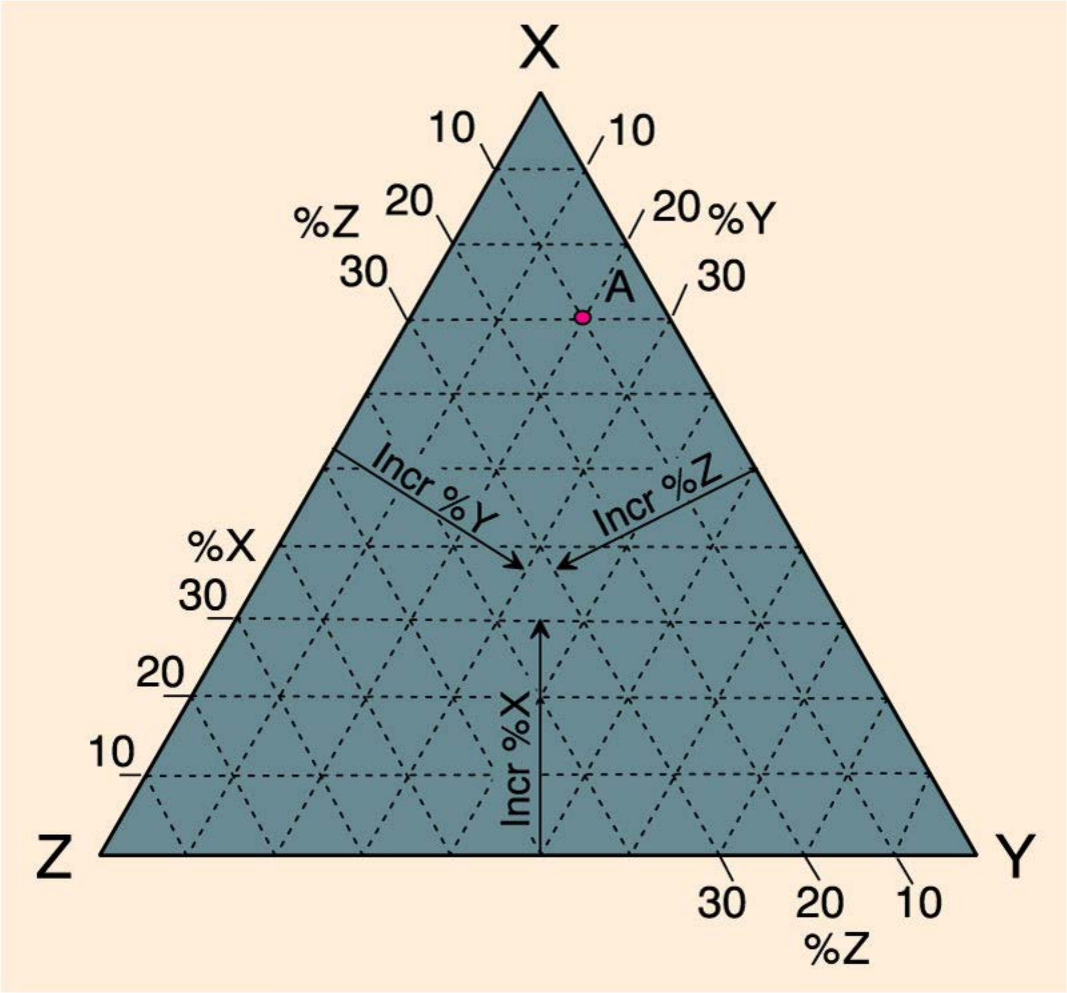


Figure 2.1a. Method #1 for plotting a point with the components: 70% X, 20% Y, and 10% Z on triangular diagrams. An Introduction to Igneous and Metamorphic Petrology, John Winter, Prentice Hall.

Classification of Igneous Rocks

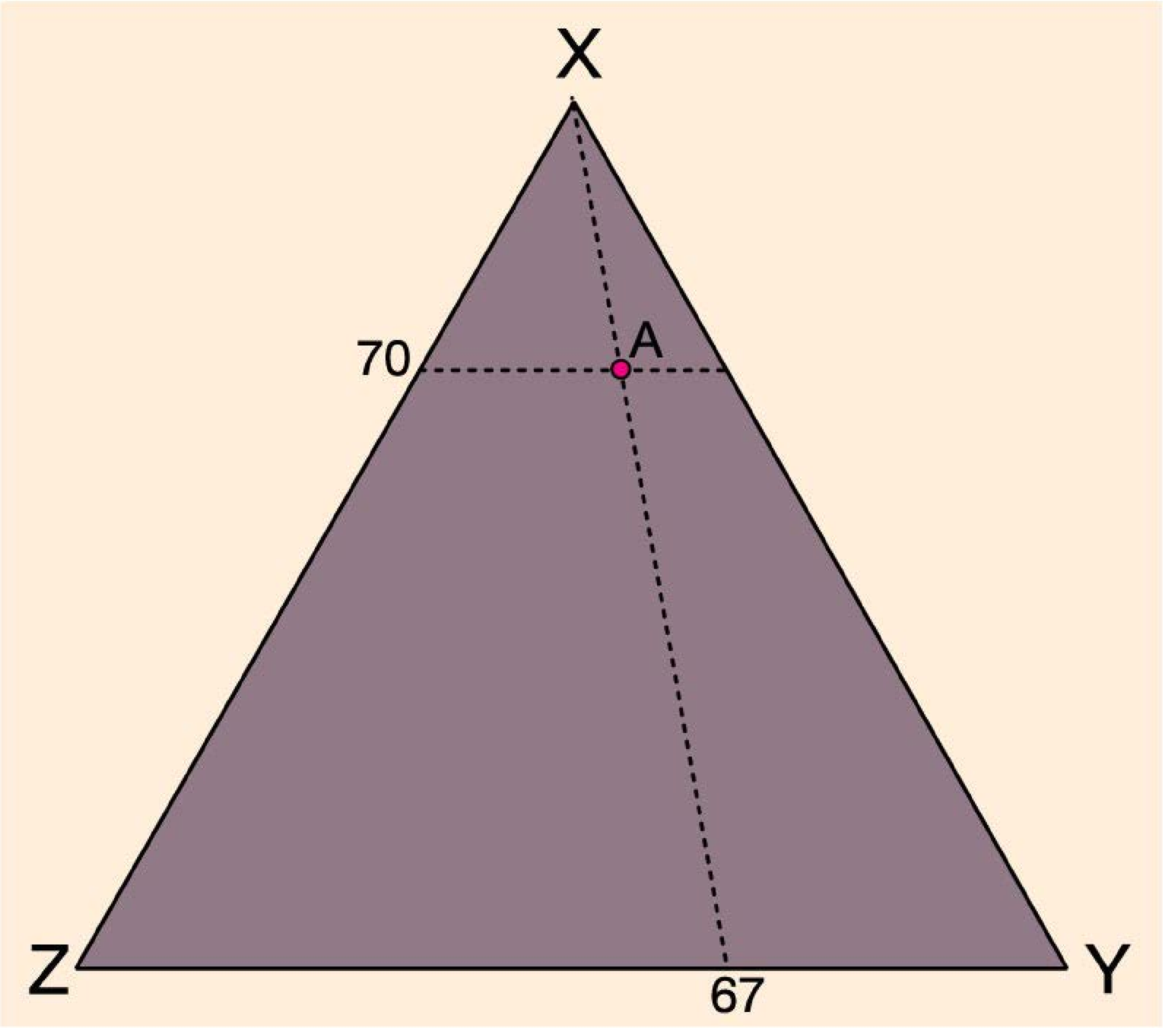
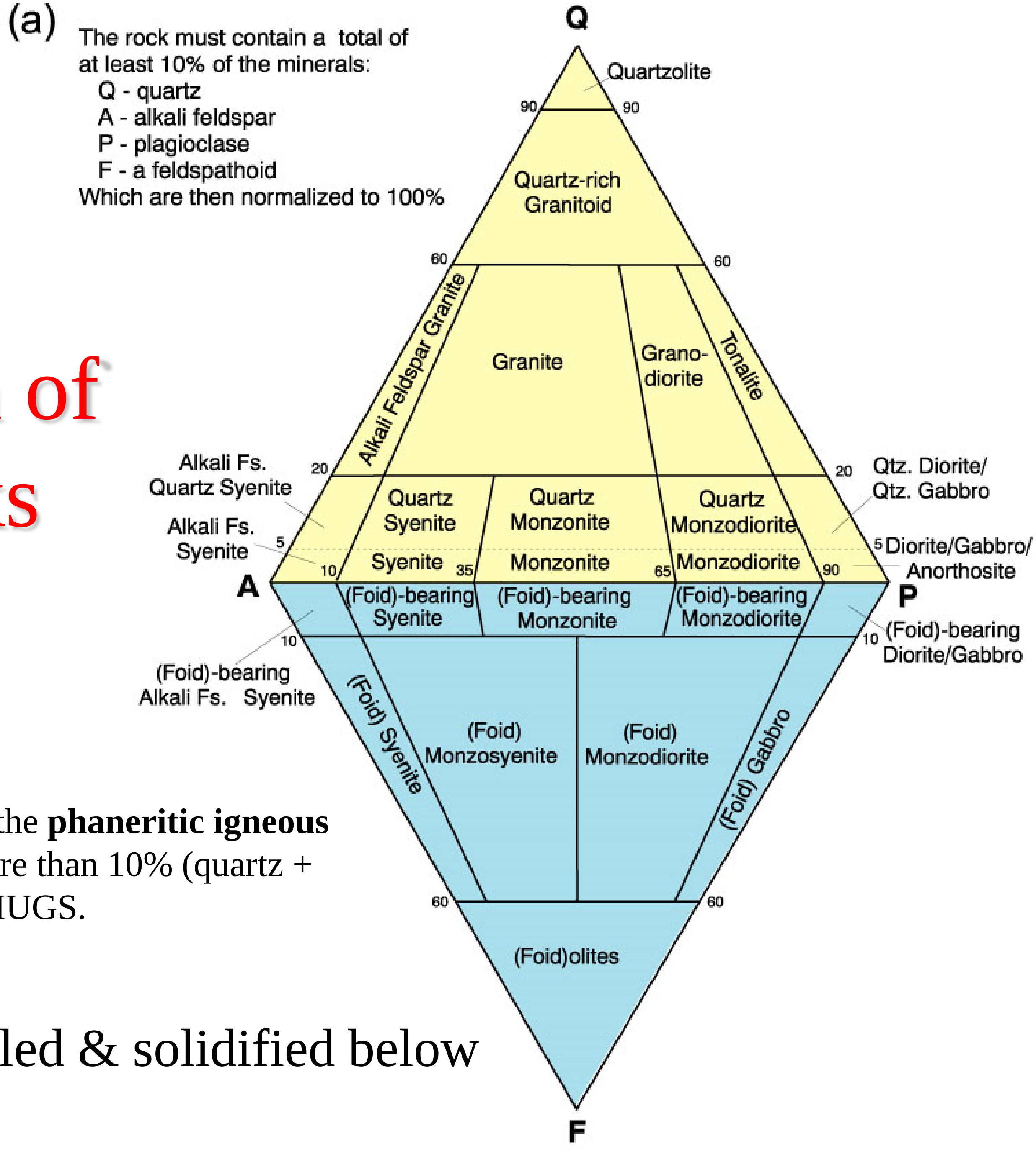


Figure 2.1b. Method #2 for plotting a point with the components: 70% X, 20% Y, and 10% Z on triangular diagrams. An Introduction to Igneous and Metamorphic Petrology, John Winter, Prentice Hall.

Classification of Igneous Rocks


(a)

The rock must contain a total of
at least 10% of the minerals:
Q - quartz
A - alkali feldspar
P - plagioclase
F - a feldspathoid
Which are then normalized to 100%

Figure 2.2a. A classification of the **phaneritic igneous rocks:** Phaneritic rocks with more than 10% (quartz + feldspar + feldspathoids). After IUGS.

Plutonic rocks = cooled & solidified below Earth’s surface

Classification of Igneous Rocks

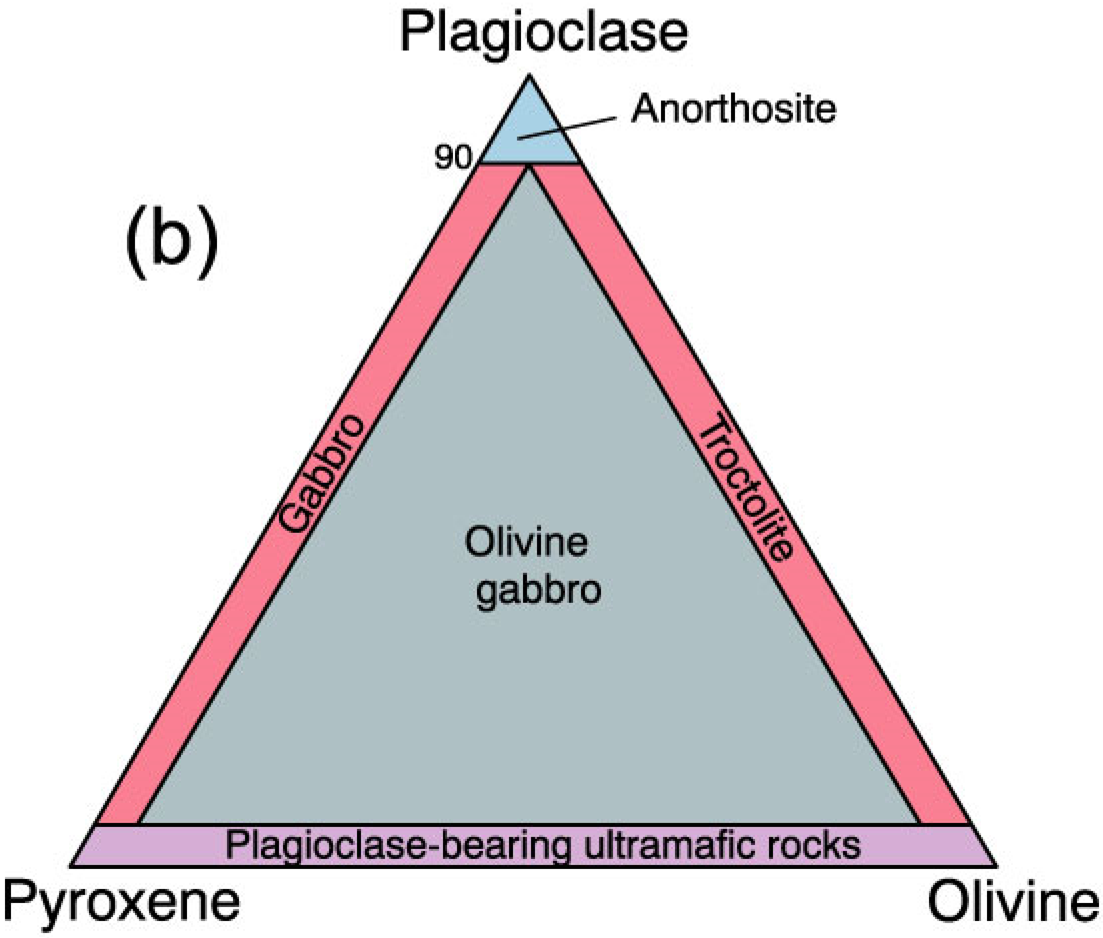


Figure 2.2b. A classification of the phaneritic igneous rocks: **Gabbroic rocks**. After IUGS.

Classification of Igneous Rocks

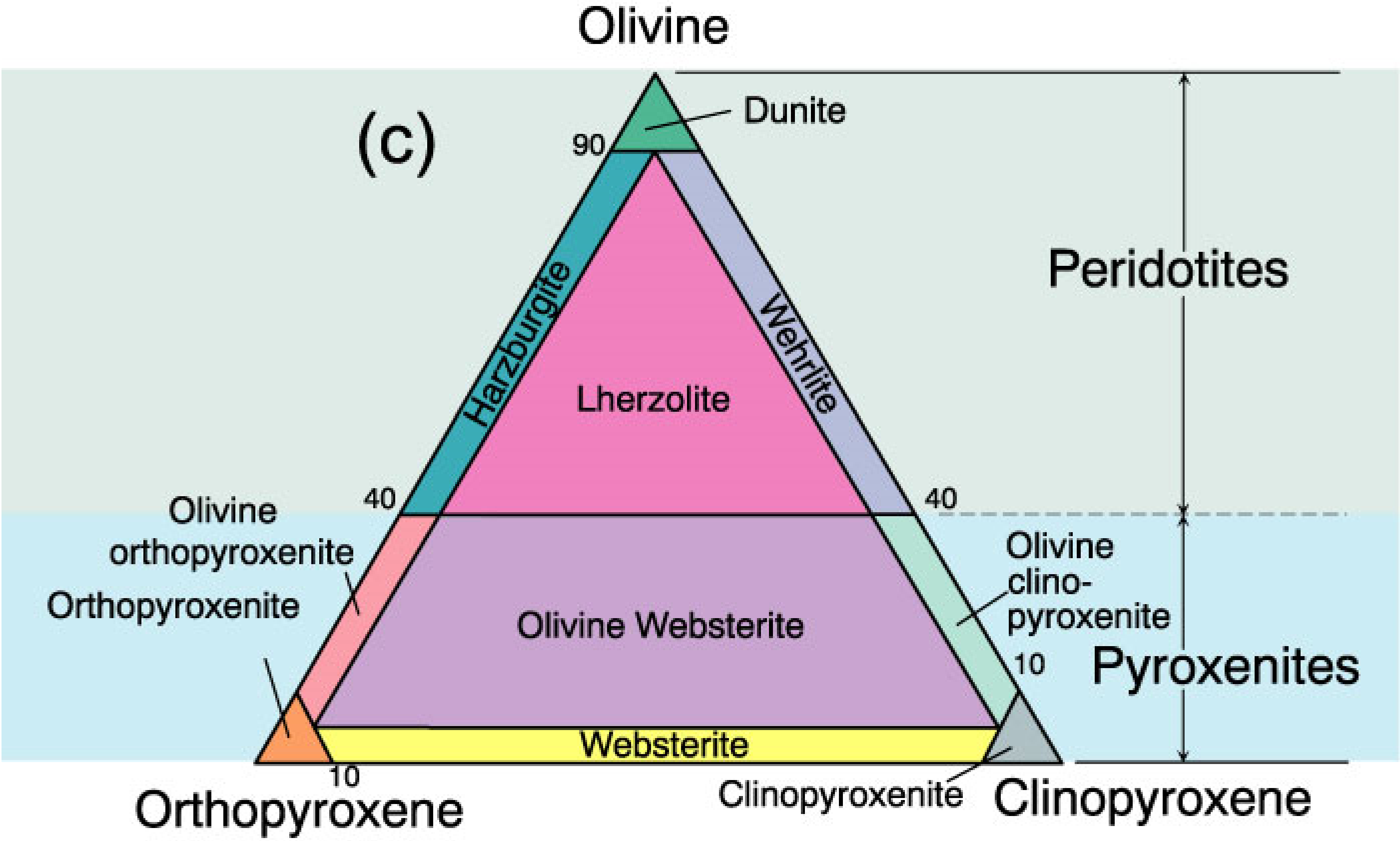


Figure 2.2c. A classification of the phaneritic igneous rocks: **Ultramafic rocks**. After IUGS.

Classification of Igneous Rocks

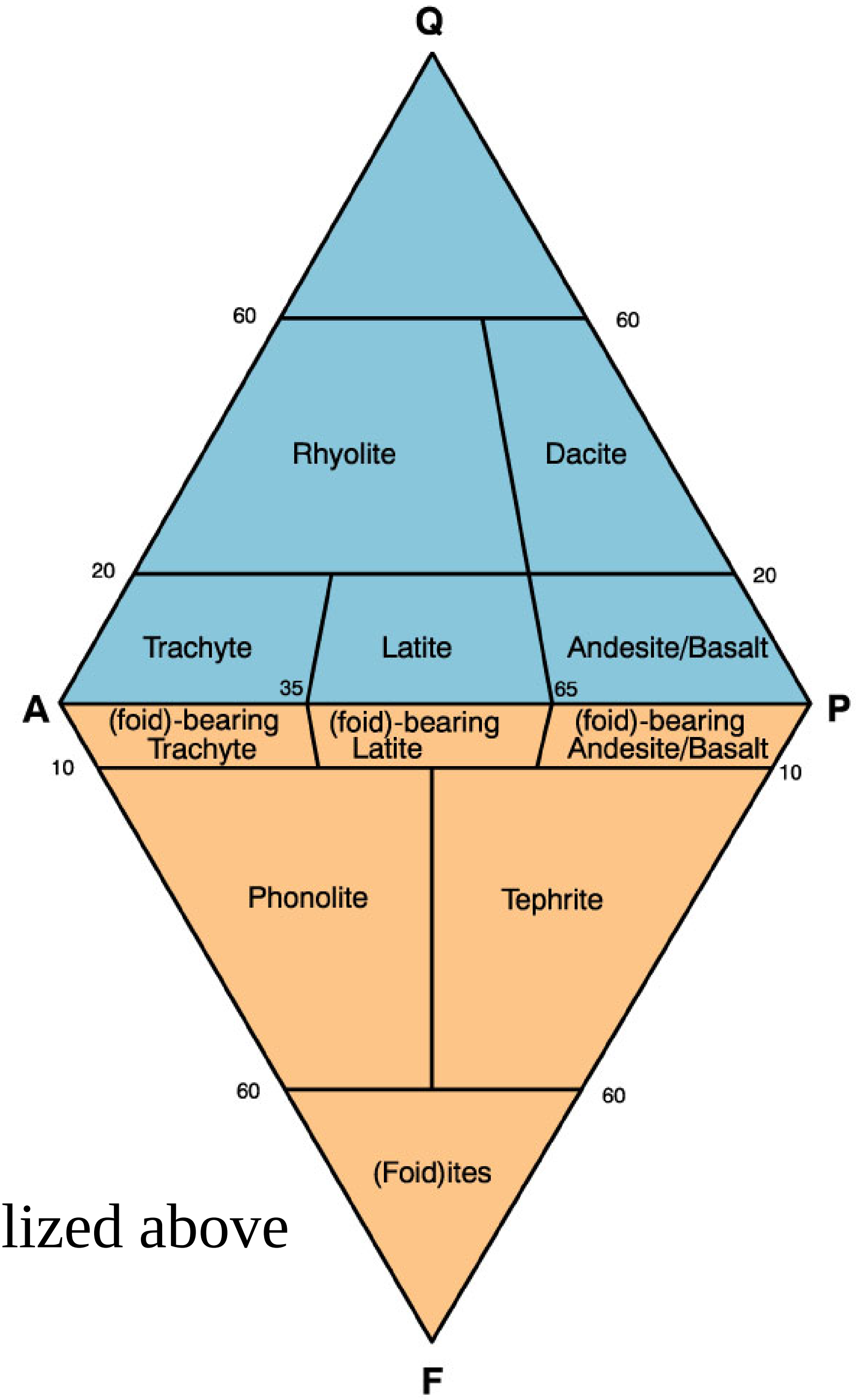
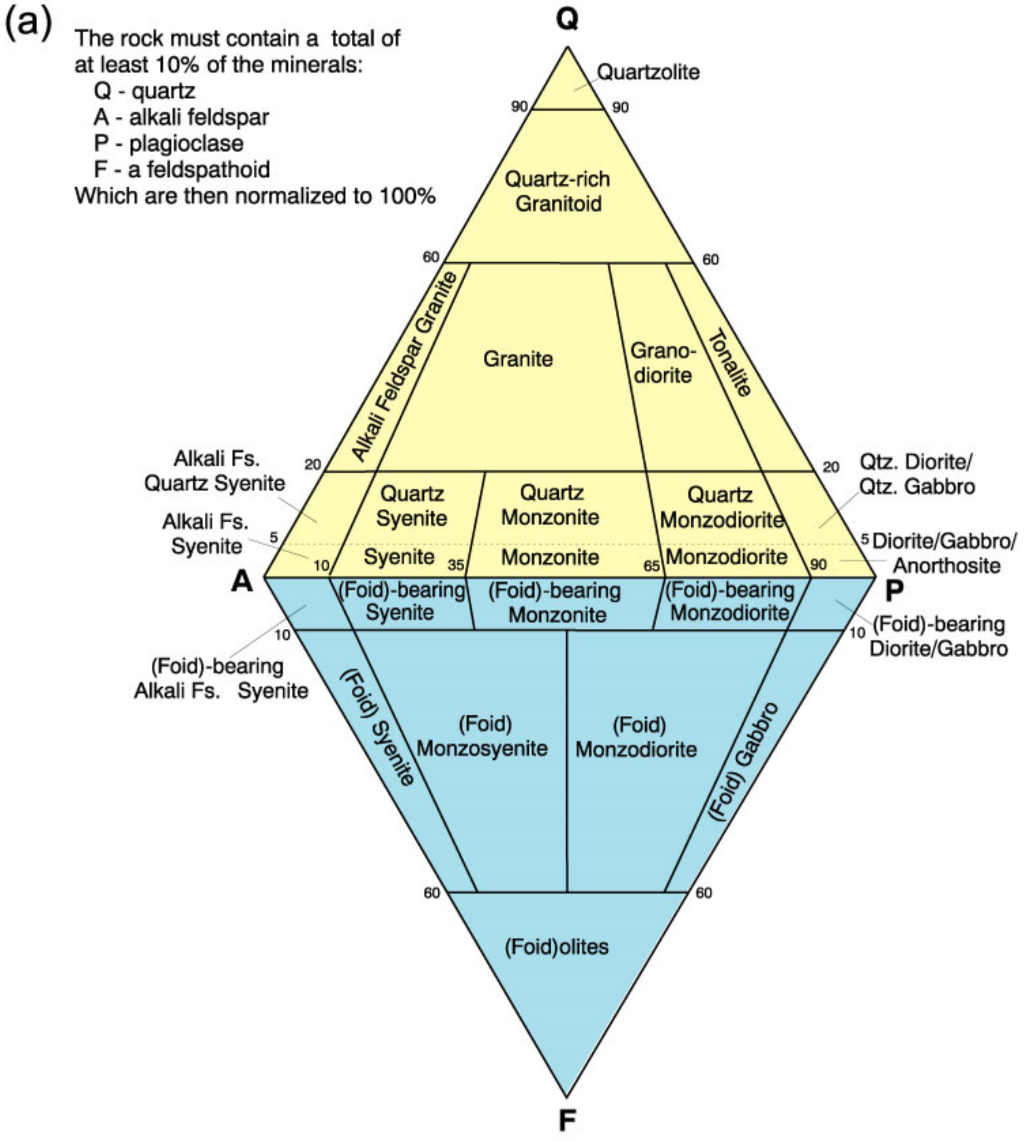
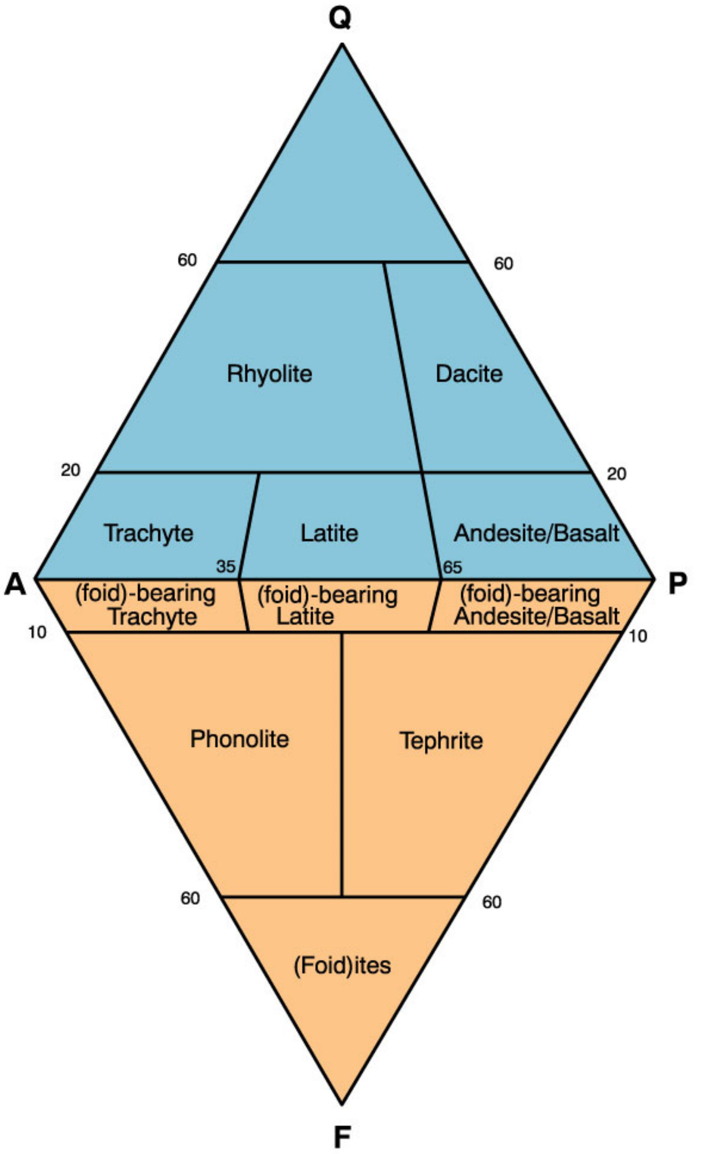


Figure 2.3. A classification and nomenclature of volcanic rocks. After IUGS.

Volcanic rocks = cooled & crystallized above Earth’s surface

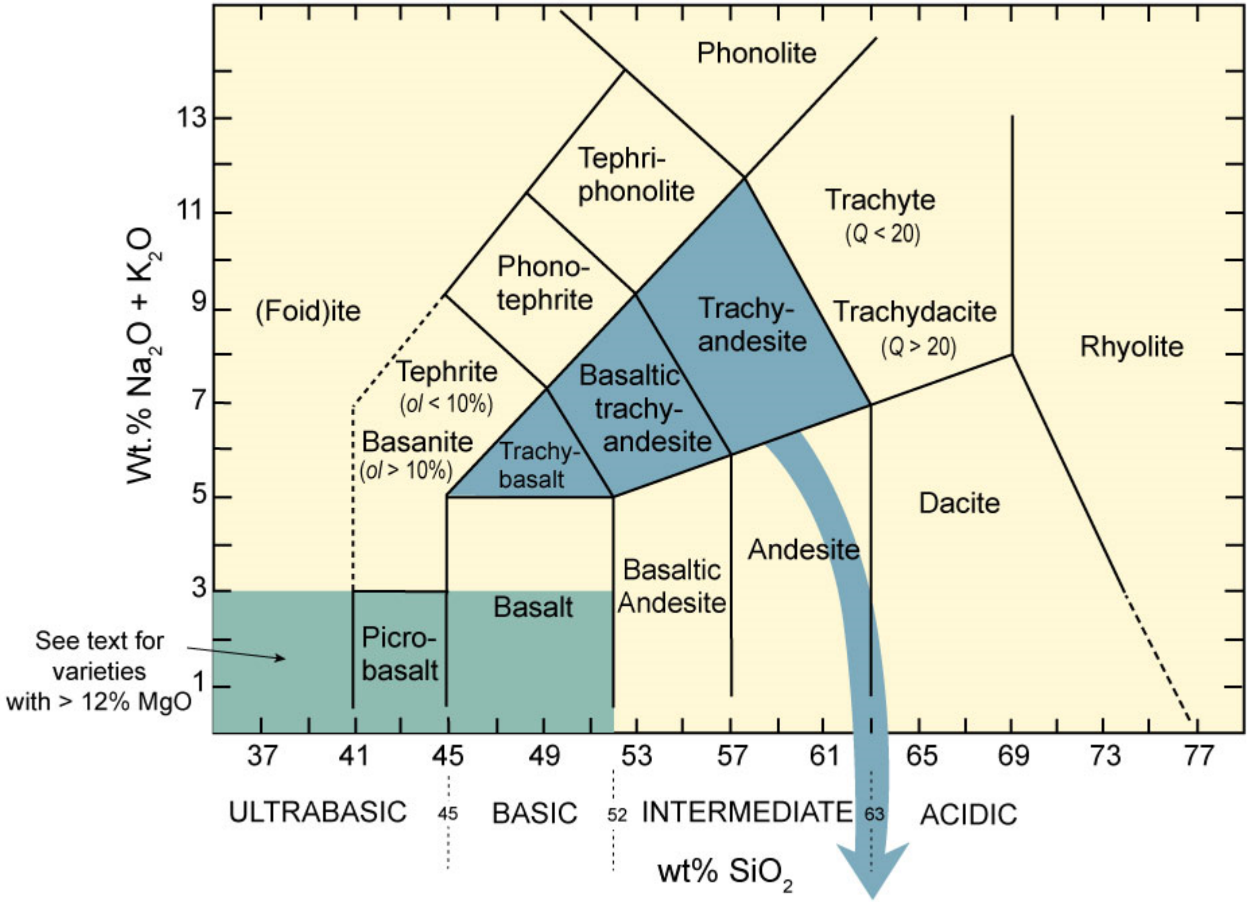

The rock must contain a total of at least 10% of the minerals:
Q - quartz
A - alkali feldspar
P - plagioclase
F - a feldspathoid
Which are then normalized to 100%

Plutonic Rocks



Volcanic Rocks

Classification of Igneous Rocks



Further subdivisions of shaded fields	Trachybasalt	Basaltic Trachyandesite	Trachyandesite
$Na_2O - 2.0 \geq K_2O$	Hawaiite	Mugearite	Benmoreite
$Na_2O - 2.0 < K_2O$	Potassic Trachybasalt	Shoshonite	Latite

Figure 2.4. A chemical classification of **volcanics** based on total alkalis vs. silica. After Le Maitre (2002) . Igneous Rocks: A Classification and Glossary of Terms. Cambridge University Press.

Classification of Igneous Rocks

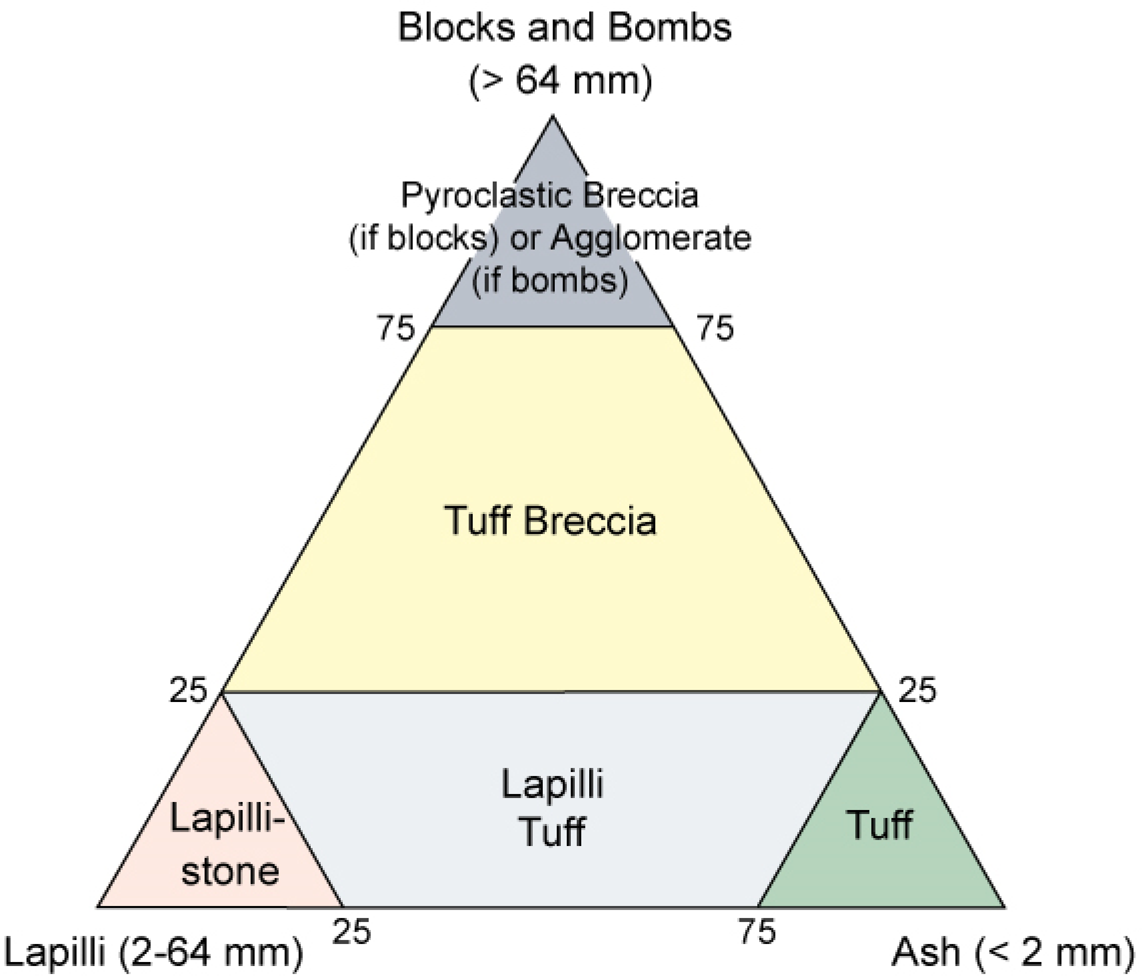


Figure 2.5. Classification of the **pyroclastic rocks**. After Fisher (1966) Earth Sci. Rev., **1**, 287-298.

Chapter 3: Igneous Textures

- **Questions to be considered**?

  - What textures may be produced as magma cools and crystallizes to form igneous rocks?

  - What physical variables control the development of igneous textures, and how they do so?

  - Use knowledge we have and textural information to interpret the developmental history of the rock

Chapter 3: Igneous Textures

The texture of a rock is a result of various *processes* that controlled the rock’s genesis and, along with *mineralogy* and *chemical composition*, provides information that we may use to interpret the rock’s origin and history

Table 3.1 at end of Chapter 3 provides a glossary of common igneous rock textures

Chapter 3: Igneous Textures

- **3.1. PRIMARY TEXTURES (CRYSTAL/MELT INTERACTIONS)**
- Formation and growth of crystals, either from a melt or in a solid medium, involves 3 principal processes:
  - 1- *Initial nucleation* of the crystal
  - 2- Subsequent *crystal growth*
  - 3- *Diffusion of chemical species* (and heat) through the surrounding medium to and from the surface of a growing crystal

Chapter 3: Igneous Textures

- **Nucleation:**
  - Is a critical step in the development of a crystal.
  - Very tiny initial crystals have a **high ratio of surface area to volume**, and thus, a large proportion of ions at the surface
  - However, surface ions have unbalanced charges because lack the complete surrounding lattice
  - Result is a high surface energy for the ‘initial crystal’ and therefore low stability
  - Hence, clustering of compatible ions in a cooling melt will separate, even though conditions are suitable for crystallization

Chapter 3: Igneous Textures

- **Nucleation (cont'd):**
  - Under such conditions, crystallization is possible, but nucleation isn't
  - Crystallization may take place if a "critically sized embryonic cluster" or "crystal nucleus" must form, with a sufficient internal volume of fully bonded ions to overcome the surface-related instability
  - This typically requires some degree of **undercooling** – *cooling of a melt below the true crystallization temperature of a mineral*, or **supersaturation** – *sufficient number of ions to be stable so as to spontaneously cluster together ("homogeneous nucleation").*

Chapter 3: Igneous Textures

- **Nucleation (cont'd):**
  - Experimental studies indicate that crystals with simple structures tend to nucleate more easily than those with more complex structures
    - E.g., Oxides (magnetite, ilmenite) generally nucleate more easily (i.e., less undercooling required) than does olivine, followed by pyroxene, plagioclase, and alkali feldspar, with progressively more complex Si-O polymerization

  - May explain why oxides are typically small and numerous, whereas alkali feldspars are large (regardless of degree of undercooling)

Chapter 3: Igneous Textures

- **Crystal Growth:**
  - Involves the addition of ions onto existing crystals or crystal nuclei
  - For simple structures with high symmetry, faces with a high density of lattice points tend to form more prominent faces (the “Law of Bravais”)
  - Different faces also grow at different rates
  - Simplistic generalization, fast-growing faces tend to be those with smaller interplanar lattice spacings (and higher surface energies)

Chapter 3: Igneous Textures

- **Crystal Growth:**
  - In most instances, composition of surrounding melt differs considerably relative to that of the growing crystal
  - Growth of mineral will deplete the adjacent melt in the chemical constituents that are preferentially incorporated into the mineral
  - Hence, for growth to proceed, new material must ***diffuse*** through the melt, cross the depleted zone, and reach the crystal surface
  - Formation of a crystal from a melt produces heat ("the latent heat of crystallization") – this heat must be removed from growing surface, or else temperature may become too high for crystallization to proceed

Chapter 3: Igneous Textures

- **3.1.1 Rates of nucleation, growth, & diffusion**
  - The **relative rates** of initial *nucleation*, *crystal growth* and *diffusion* will have considerable influence on the ultimate texture of the resulting rock
    - However, whichever rate is the *slowest* will be the overall rate-determining process and exert the most control over crystallization
  - Additional rate to factor-in: **cooling rate**

Chapter 3: Igneous Textures

- If cooling rate is slow, equilibrium is maintained or closely approximated

- If cooling rate is too high, significant **undercooling** may take place – reduces nucleation, growth or diffusion

- Initially, undercooling enhances rates of nucleation, crystal growth and diffusion – however, continued undercooling **decreases kinetics** (diffusion, mobility) and **increases viscosity**, thus inhibiting these rates

Chapter 3: Igneous Textures

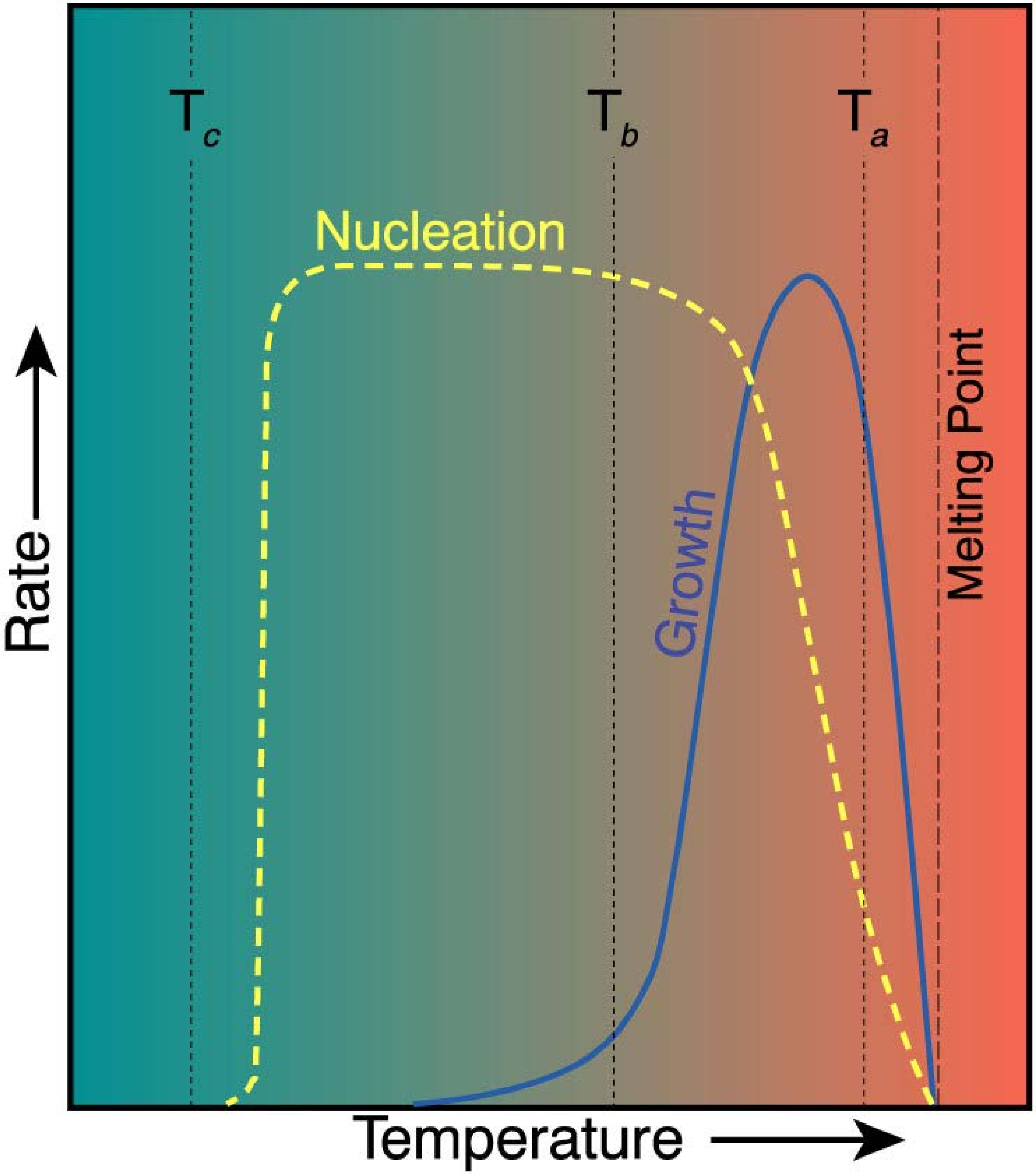


Figure 3.1.