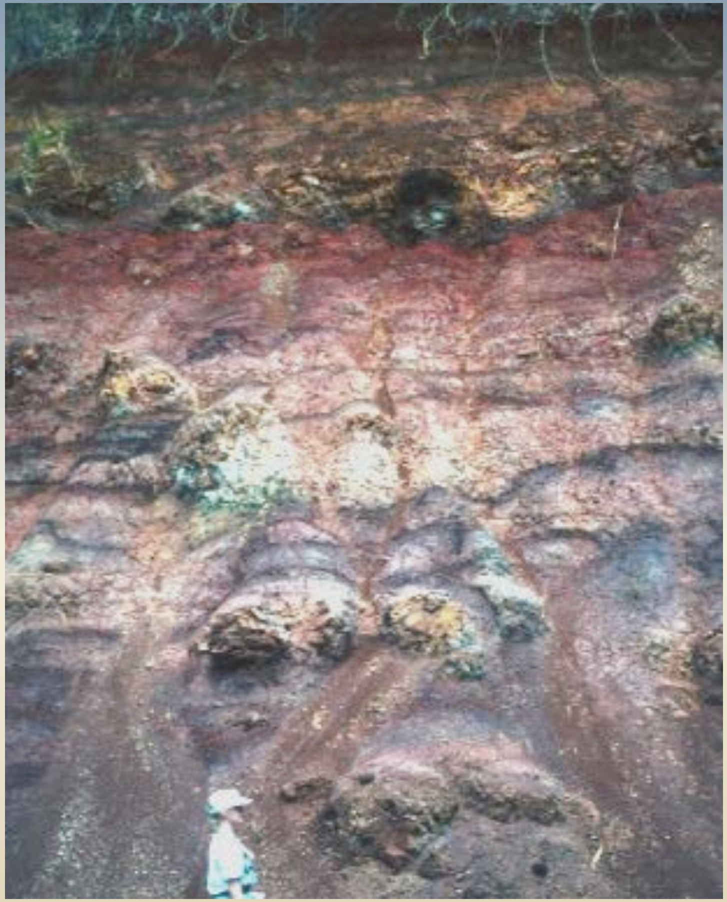
Chapter 21: Metamorphism



Fresh basalt and weathered basalt

Chapter 21: Metamorphism

The IUGS-SCMR proposed this definition:

"Metamorphism is a subsolidus process leading to changes in mineralogy and/or texture (for example grain size) and often in chemical composition in a rock. These changes are due to physical and/or chemical conditions that differ from those normally occurring at the surface of planets and in zones of cementation and diagenesis below this surface. They may coexist with partial melting."

The Limits of Metamorphism

Low-temperature limit grades into diagenesis

- Processes are indistinguishable
- Metamorphism begins in the range of 100-150^{o}C for the more unstable types of protolith
- Some zeolites are considered diagenetic and others metamorphic – pretty arbitrary

The Limits of Metamorphism

- High-temperature limit grades into melting
- Over the melting range solids and liquids coexist
- Xenoliths, restites, and other enclaves?
- Migmatites ("mixed rocks") are gradational

The Limits of Metamorphism

Metamorphic Agents and Changes

- Temperature: typically the most important factor in metamorphism

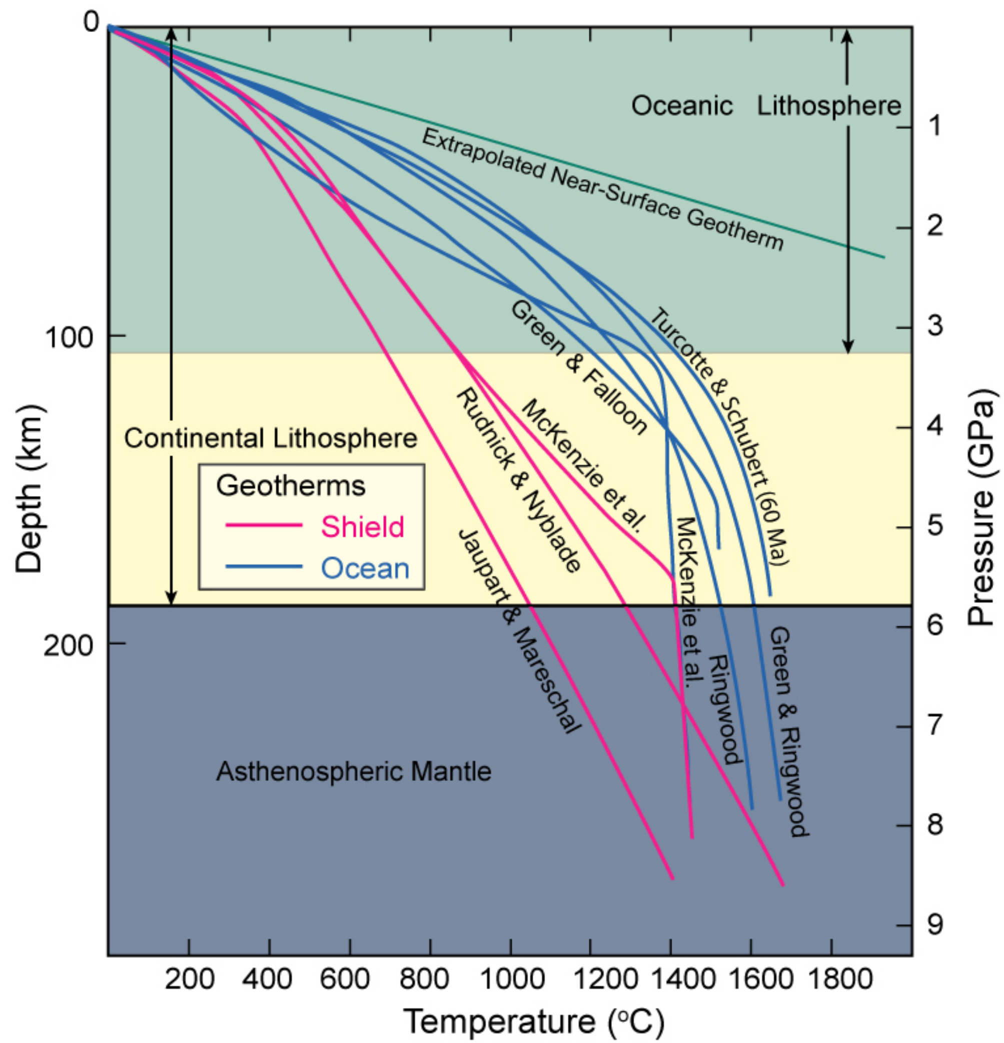


Figure 1.9. Estimated ranges of oceanic and continental steady-state geotherms to a depth of 100 km using upper and lower limits based on heat flows measured near the surface. After Sclater *et al*. (1980), Earth. Rev. Geophys. Space Sci., 18, 269-311.

Metamorphic Agents and Changes

Increasing temperature has several effects

1) Promotes recrystallization → increased grain size
2) Drive reactions (endothermic)
3) Overcomes kinetic barriers → equilibrium

Metamorphic Agents and Changes

Pressure

- “Normal” gradients perturbed in several ways, most commonly:
  - High T/P geotherms in areas of plutonic activity or rifting
  - Low T/P geotherms in subduction zones

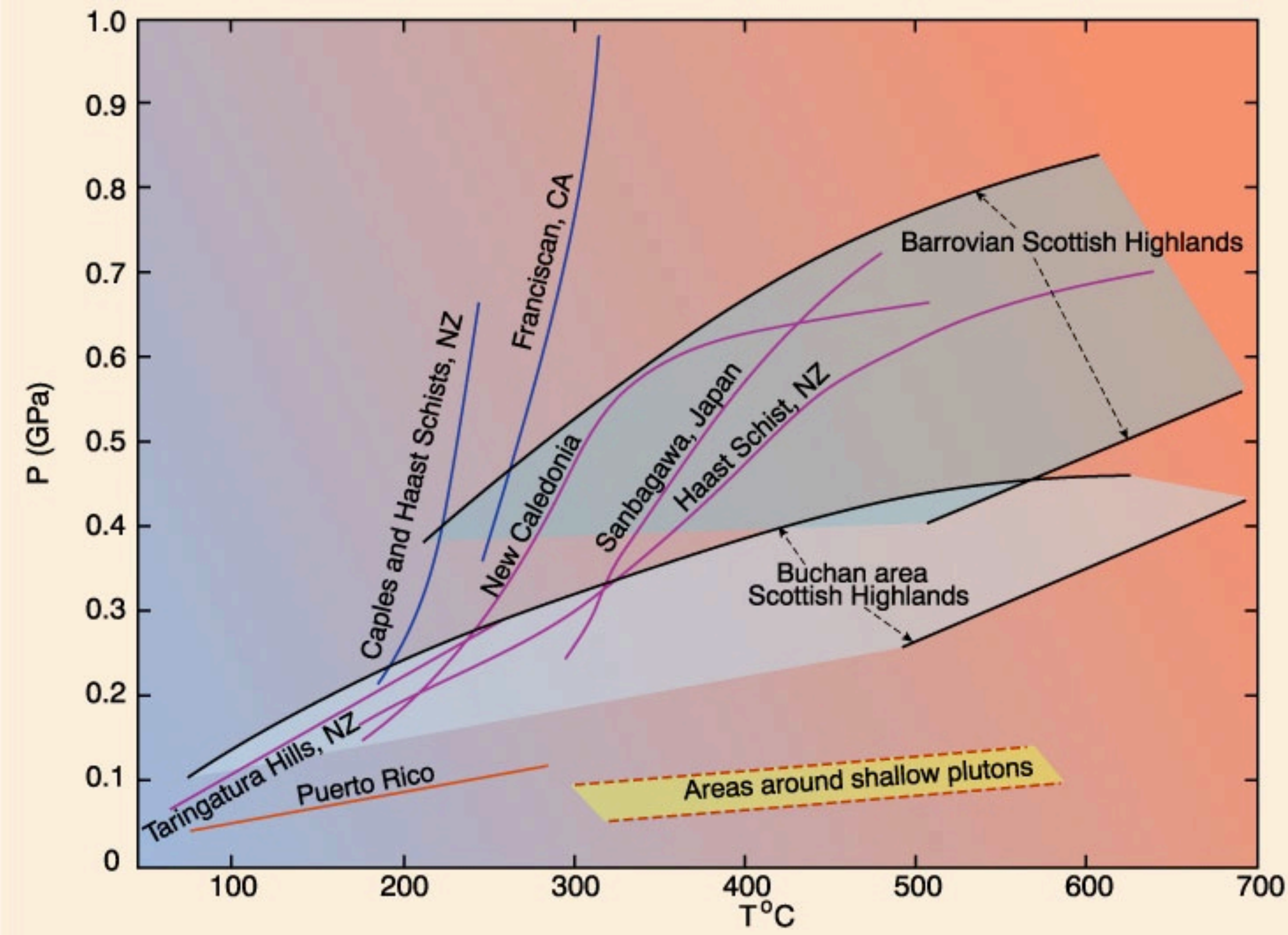
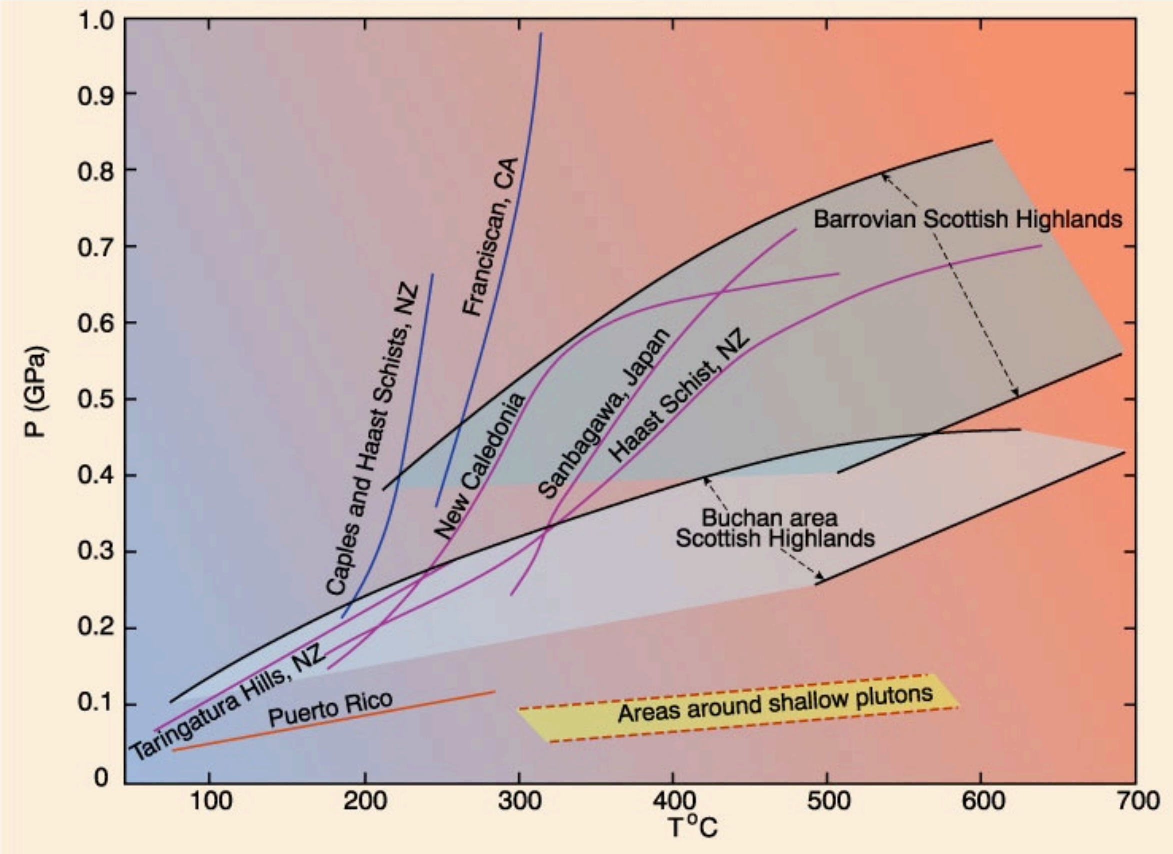


Figure 21.1. Metamorphic field gradients (estimated P-T conditions along surface traverses directly up metamorphic grade) for several metamorphic areas. After Turner (1981). *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill.

Metamorphic Agents and Changes

- Metamorphic grade: a general increase in degree of metamorphism without specifying the exact relationship between temperature and pressure

- Expect denser minerals for low T/P paths



Metamorphic Agents and Changes

- Lithostatic pressure - uniform stress (hydrostatic)
- Deviatoric stress = pressure unequal in different directions
- Resolved into three mutually perpendicular stress (σ) components:

  σ_1 is the maximum principal stress

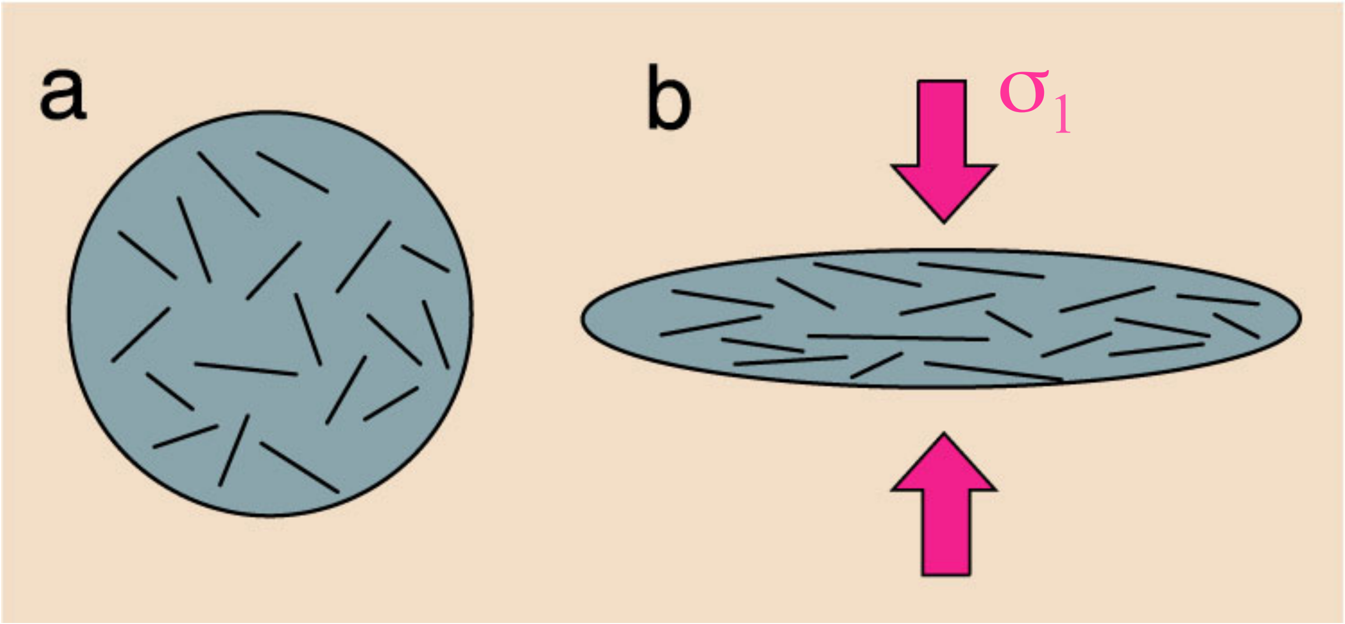
  σ_2 is an intermediate principal stress

  σ_3 is the minimum principal stress
- In hydrostatic situations all three are equal

Metamorphic Agents and Changes

- Stress
- Strain → deformation
- Deviatoric stress affects the textures and structures, but not the equilibrium mineral assemblage
- Strain energy may overcome kinetic barriers to reactions

- Foliation is a common result, which allows us to estimate the orientation of σ_1



Strain ellipsoid

- $\sigma_1 > \sigma_2 = \sigma_3 \rightarrow$ foliation and no lineation
- $\sigma_1 = \sigma_2 > \sigma_3 \rightarrow$ lineation and no foliation
- $\sigma_1 > \sigma_2 > \sigma_3 \rightarrow$ both foliation and lineation

Figure 21.3. Flattening of a ductile homogeneous sphere (a) containing randomly oriented flat disks or flakes. In (b), the matrix flows with progressive flattening, and the flakes are rotated toward parallelism normal to the predominant stress. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Metamorphic Agents and Changes

Shear motion occurs along planes at an angle to σ_1

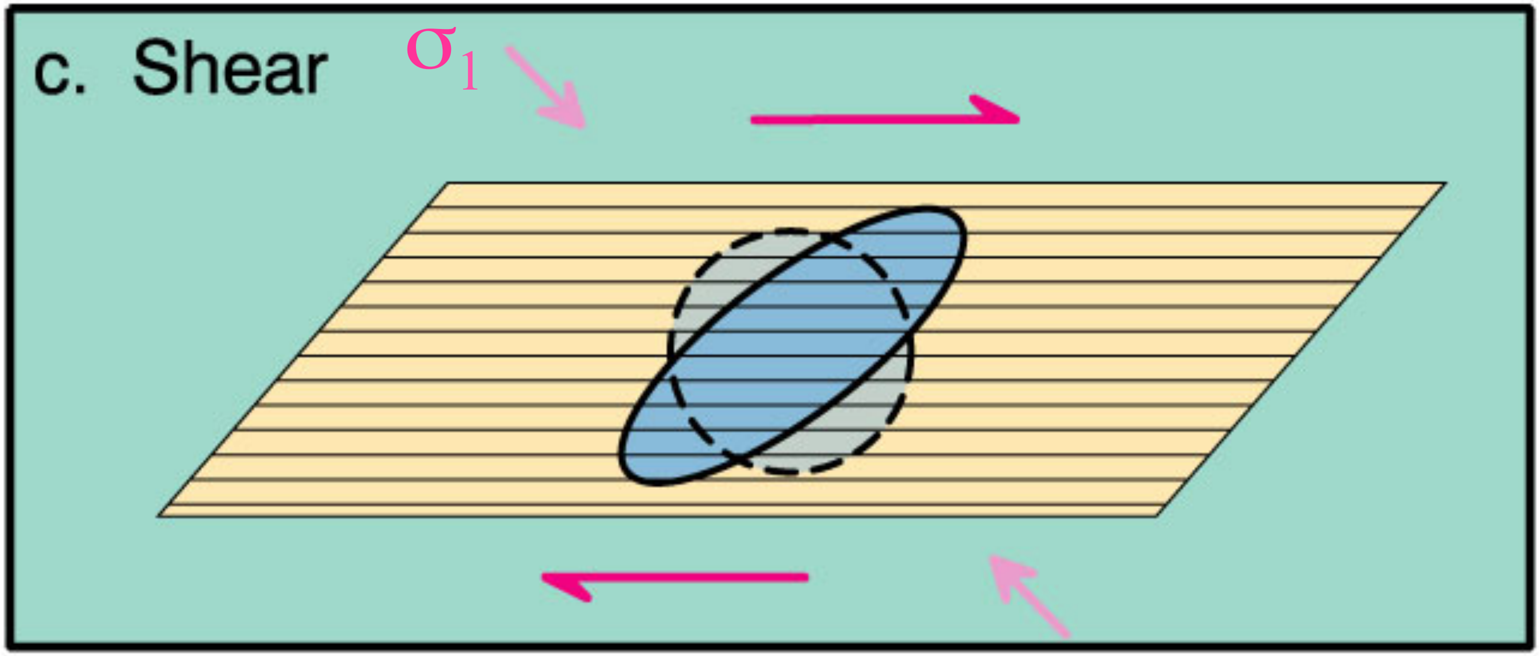


Figure 21.2. **The three main types of deviatoric stress with an example of possible resulting structures. b. Shear, causing slip along parallel planes and rotation. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.**

Metamorphic Agents and Changes

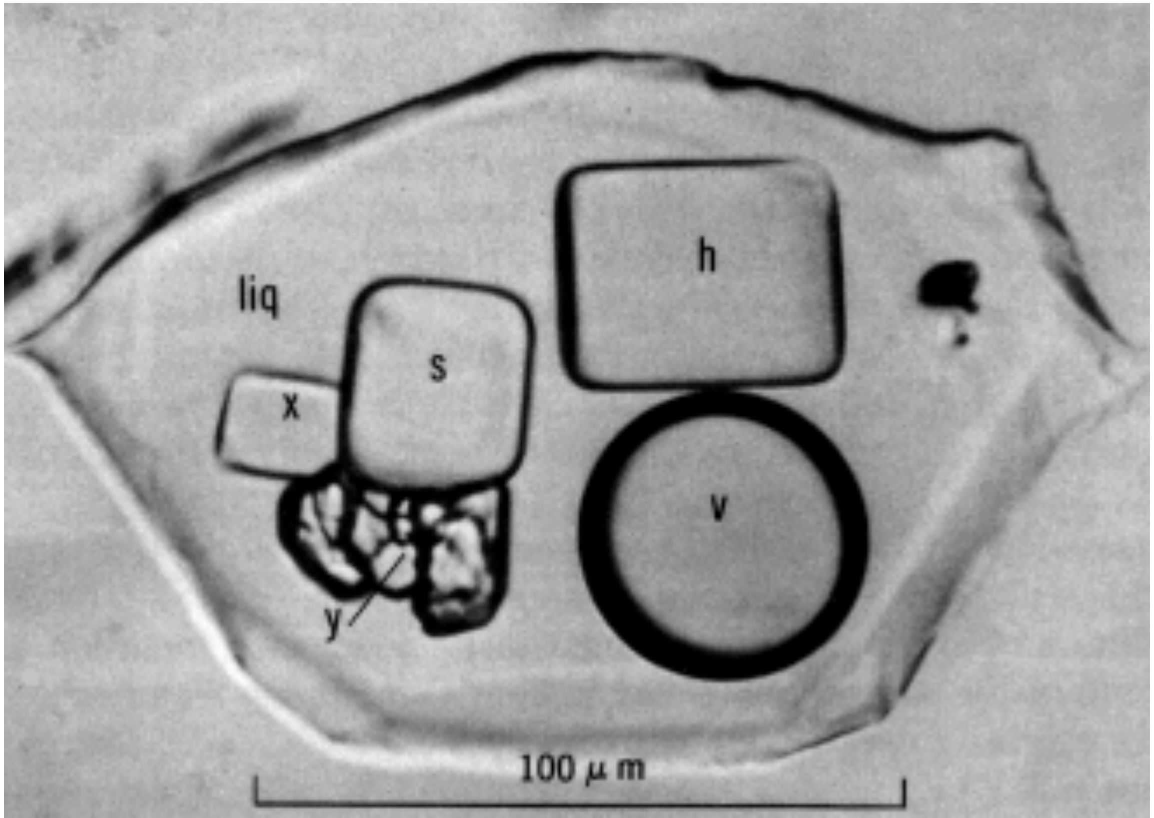
Fluids

Evidence for the existence of a metamorphic fluid:

- Fluid inclusions
- Fluids are required for hydrous or carbonate phases
- Volatile-involving reactions occur at temperatures and pressures that require finite fluid pressures

Metamorphic Agents and Changes

Fluids



Metamorphic Agents and Changes

- P_{fluid} = Σ partial pressures of each component ($P_{fluid} = p_{H_2O} + p_{CO_2} + \ldots$)
- Mole fractions of components must sum to 1.0 ($X_{H_2O} + X_{CO_2} + \ldots = 1.0$)
- $p_{H_2O} = X_{H_2O} \times P_{fluid}$
- Gradients in T, P, X_{fluid}
- → Zonation in mineral assemblages

The Types of Metamorphism

Different approaches to classification

1. Based on principal process or agent
   - Dynamic Metamorphism
     (deviatoric stress dominant → deformation, recrystallization)
   - Thermal Metamorphism
   - Dynamo-thermal Metamorphism

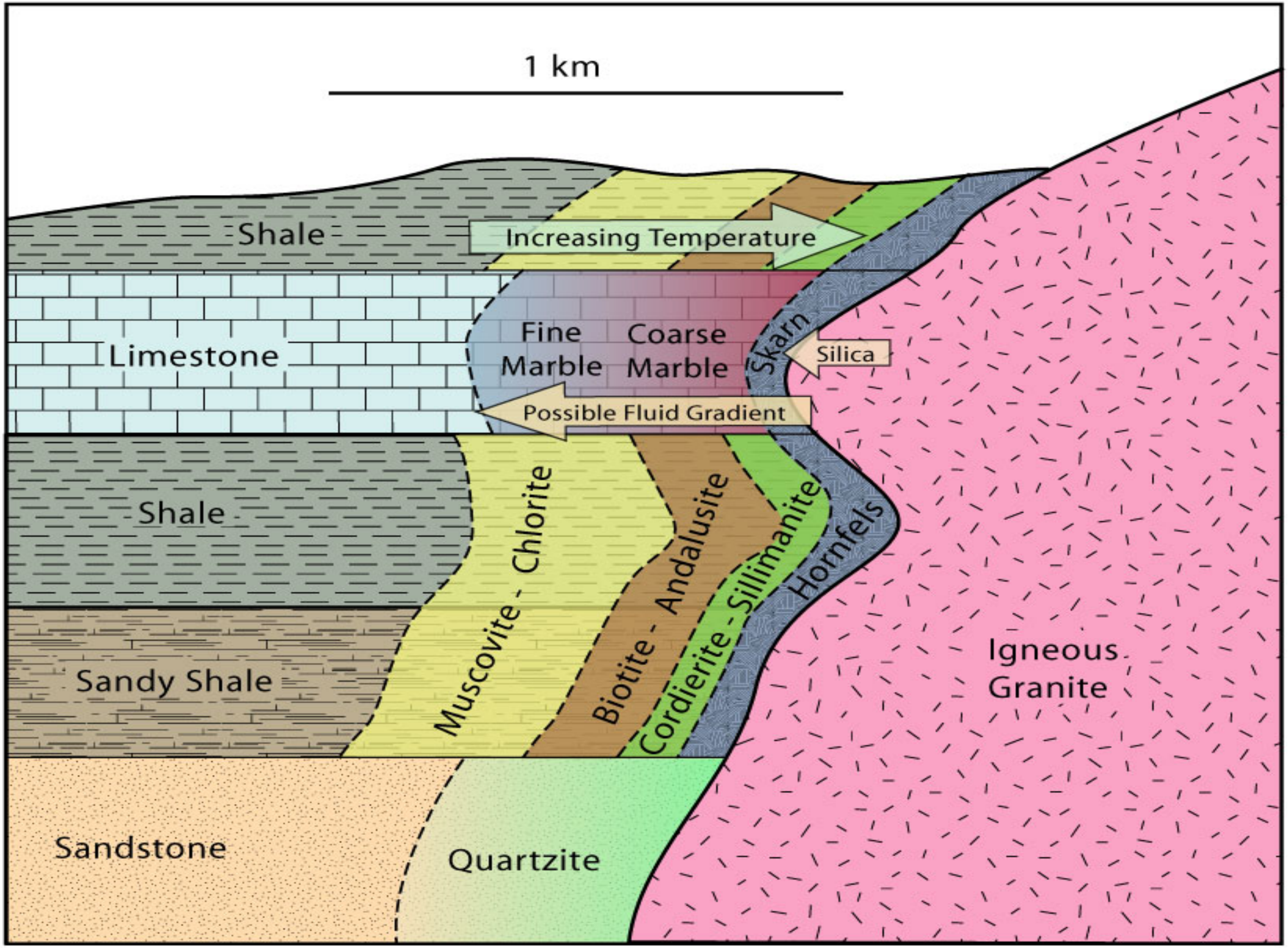
The Types of Metamorphism

Different approaches to classification

2. Based on setting
   - Contact Metamorphism
     - Pyrometamorphism
   - Regional Metamorphism
     - Orogenic Metamorphism
     - Burial Metamorphism
     - Ocean Floor Metamorphism
   - Hydrothermal Metamorphism
   - Fault-Zone Metamorphism
   - Impact or Shock Metamorphism

Contact Metamorphism

- Adjacent to igneous intrusions
- Thermal (± metasomatic) effects of hot magma intruding cooler shallow rocks
- Occurs over a wide range of pressures, including very low
- Contact aureole


1 km
Shale
Increasing Temperature
Limestone
Fine Marble
Coarse Marble
Skarn
Silica
Possible Fluid Gradient
Shale
Muscovite - Chlorite
Biotite - Andalusite
Cordierite - Sillimanite
Hornfels
Sandy Shale
Igneous Granite
Sandstone
Quartzite

The Types of Metamorphism

Contact Metamorphism

The size and shape of an aureole is controlled by:

- The nature of the pluton
  - Size
  - Shape
  - Orientation
  - Temperature
  - Composition
- The nature of the country rocks
  - Composition
  - Depth and metamorphic grade prior to intrusion
  - Permeability

The Types of Metamorphism

Contact Metamorphism

Most easily recognized where a pluton is introduced into shallow rocks in a static environment

→ Hornfelses (granofelses) commonly with relict textures and structures

The Types of Metamorphism

Contact Metamorphism

Polymetamorphic rocks are common, usually representing an orogenic event followed by a contact one

The Types of Metamorphism

Pyrometamorphism

Very high temperatures at low pressures, generated by a volcanic or sub-volcanic body

Also developed in xenoliths

The Types of Metamorphism

Regional Metamorphism : metamorphism that affects a large body of rock, and thus covers a great lateral extent

Three principal types:

- Orogenic metamorphism
- Burial metamorphism
- Ocean-floor metamorphism

The Types of Metamorphism

Orogenic Metamorphism is the type of metamorphism associated with convergent plate margins

- Dynamo-thermal: one or more episodes of orogeny with combined elevated geothermal gradients and deformation (deviatoric stress)
- Foliated rocks are a characteristic product

The Types of Metamorphism

Orogenic Metamorphism

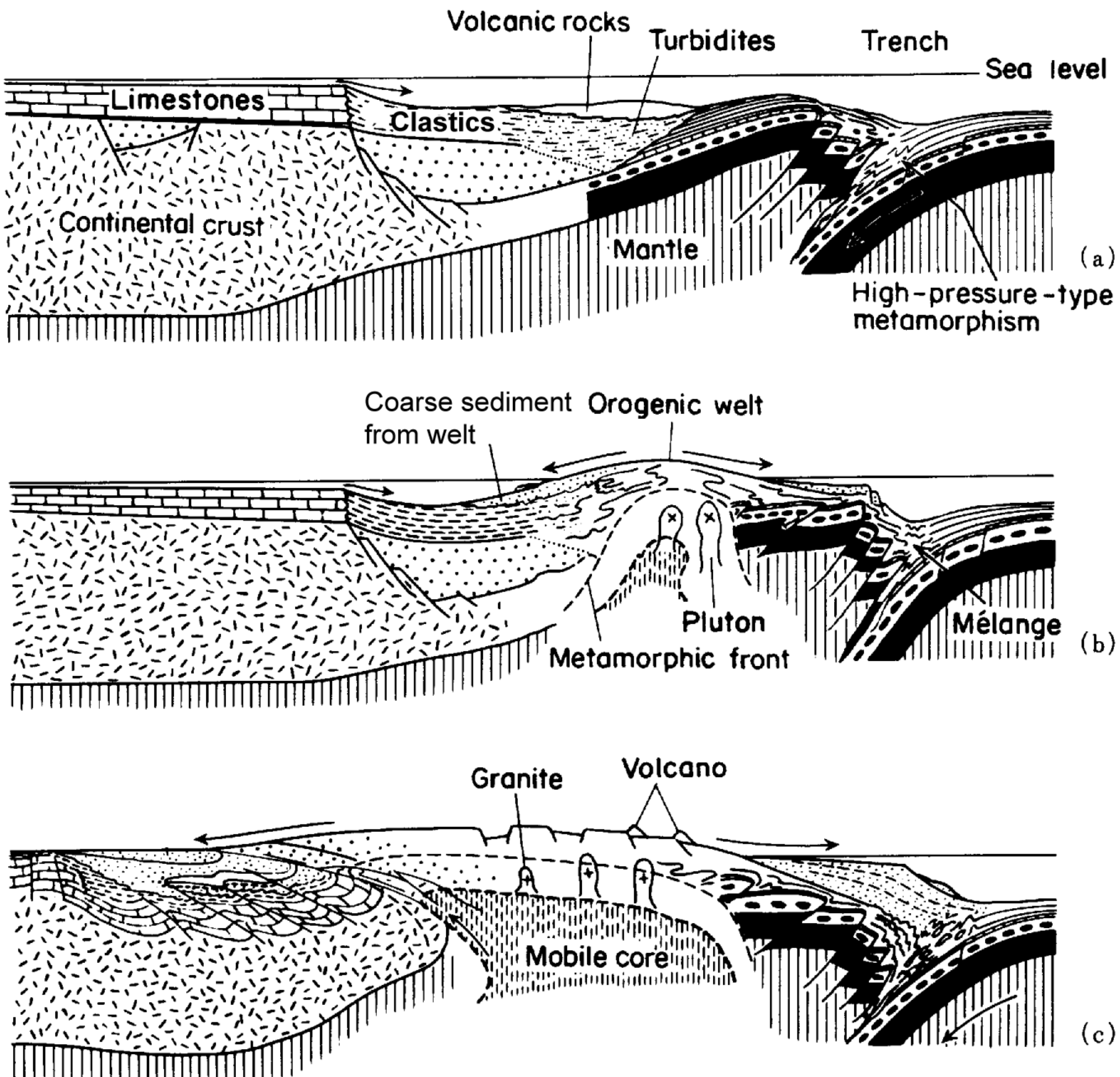
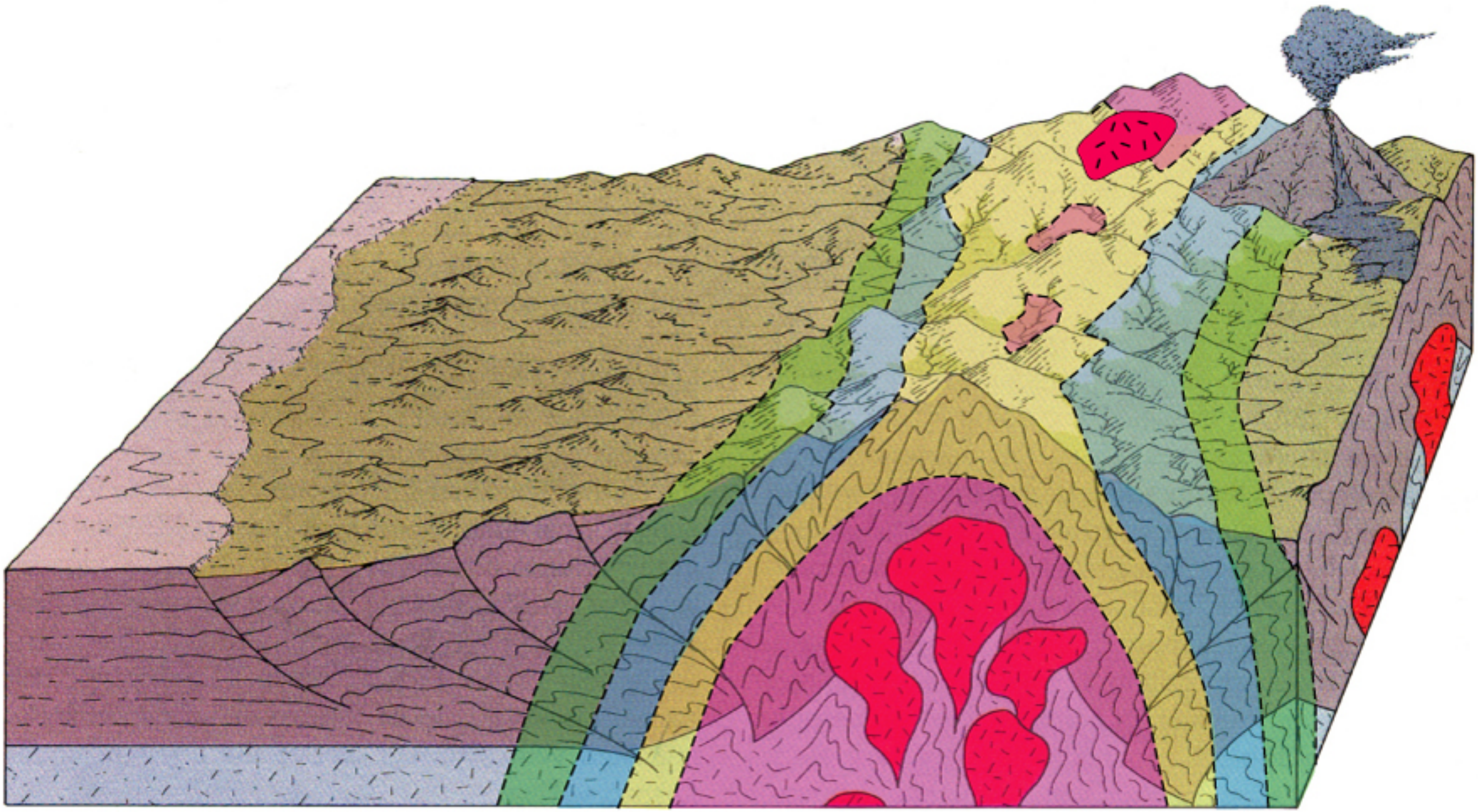


Figure 21.6. **Schematic model for the sequential (a → c) development of a "Cordilleran-type" or active continental margin orogen. The dashed and black layers on the right represent the basaltic and gabbroic layers of the oceanic crust. From Dewey and Bird (1970) *J. Geophys. Res.*, 75, 2625-2647; and Miyashiro *et al.* (1979) *Orogeny*. John Wiley & Sons.**

The Types of Metamorphism

Orogenic Metamorphism

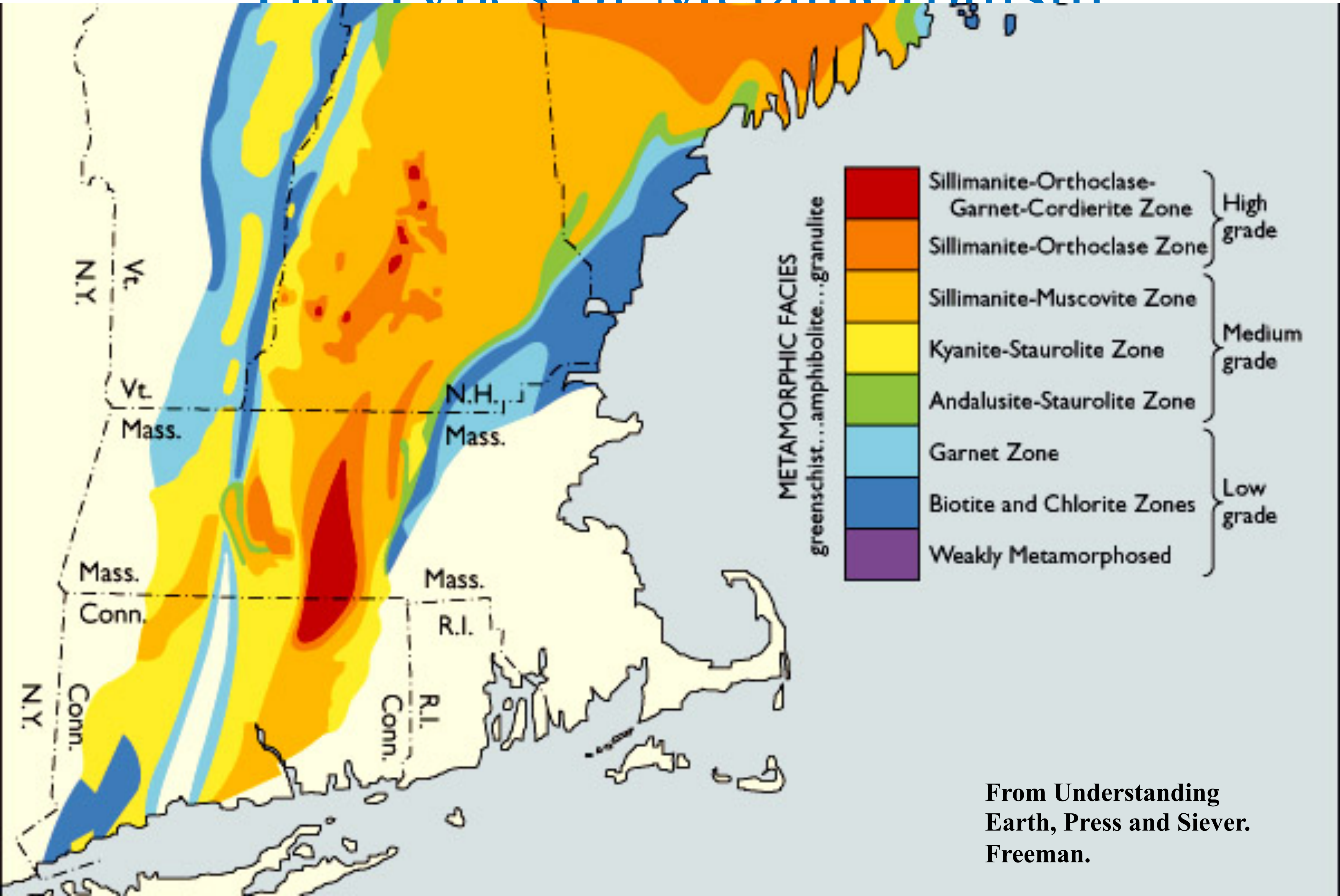


The Types of Metamorphism

Orogenic Metamorphism

- Uplift and erosion
- Metamorphism often continues after major deformation ceases
  - Metamorphic pattern is simpler than the structural one
- Pattern of increasing metamorphic grade from both directions toward the core area

The Types of Metamorphism



From Understanding Earth, Press and Siever. Freeman.

The Types of Metamorphism

Orogenic Metamorphism

- Polymetamorphic patterns
- Continental collision
- Batholiths are usually present in the highest grade areas
- If plentiful and closely spaced, may be called regional contact metamorphism

The Types of Metamorphism

Burial metamorphism

- Southland Syncline in New Zealand: thick pile (> 10 km) of Mesozoic volcaniclastics
- Mild deformation, no igneous intrusions discovered
- Fine-grained, high-temperature phases, glassy ash: very susceptible to metamorphic alteration
- Metamorphic effects attributed to increased temperature and pressure due to burial
- Diagenesis grades into the formation of zeolites, prehnite, pumpellyite, laumontite, etc.

The Types of Metamorphism

Hydrothermal metamorphism

- Hot H_2O-rich fluids
- Usually involves metasomatism
- Difficult type to constrain: hydrothermal effects often play some role in most of the other types of metamorphism

The Types of Metamorphism

Burial metamorphism occurs in areas that have not experienced significant deformation or orogeny

- Restricted to large, relatively undisturbed sedimentary piles away from active plate margins
  - The Gulf of Mexico?
  - Bengal Fan?

The Types of Metamorphism

Burial metamorphism occurs in areas that have not experienced significant deformation or orogeny

- Bengal Fan → sedimentary pile > 22 km
- Extrap. → 250-300°C at the base (P ~ 0.6 GPa)

- Passive margins often become active

- Areas of burial metamorphism may thus become areas of orogenic metamorphism

The Types of Metamorphism

Ocean-Floor Metamorphism affects the oceanic crust at ocean ridge spreading centers

- Considerable metasomatic alteration, notably loss of Ca and Si and gain of Mg and Na
- Highly altered chlorite-quartz rocks- distinctive high-Mg, low-Ca composition
- Exchange between basalt and hot seawater
- Another example of hydrothermal metamorphism

The Types of Metamorphism

Fault-Zone and Impact Metamorphism

- High rates of deformation and strain with only minor recrystallization
- Impact metamorphism at meteorite (or other bolide) impact craters
- Both correlate with dynamic metamorphism, based on process

(a) Shallow fault zone with fault breccia

(b) Slightly deeper fault zone (exposed by erosion) with some ductile flow and fault mylonite

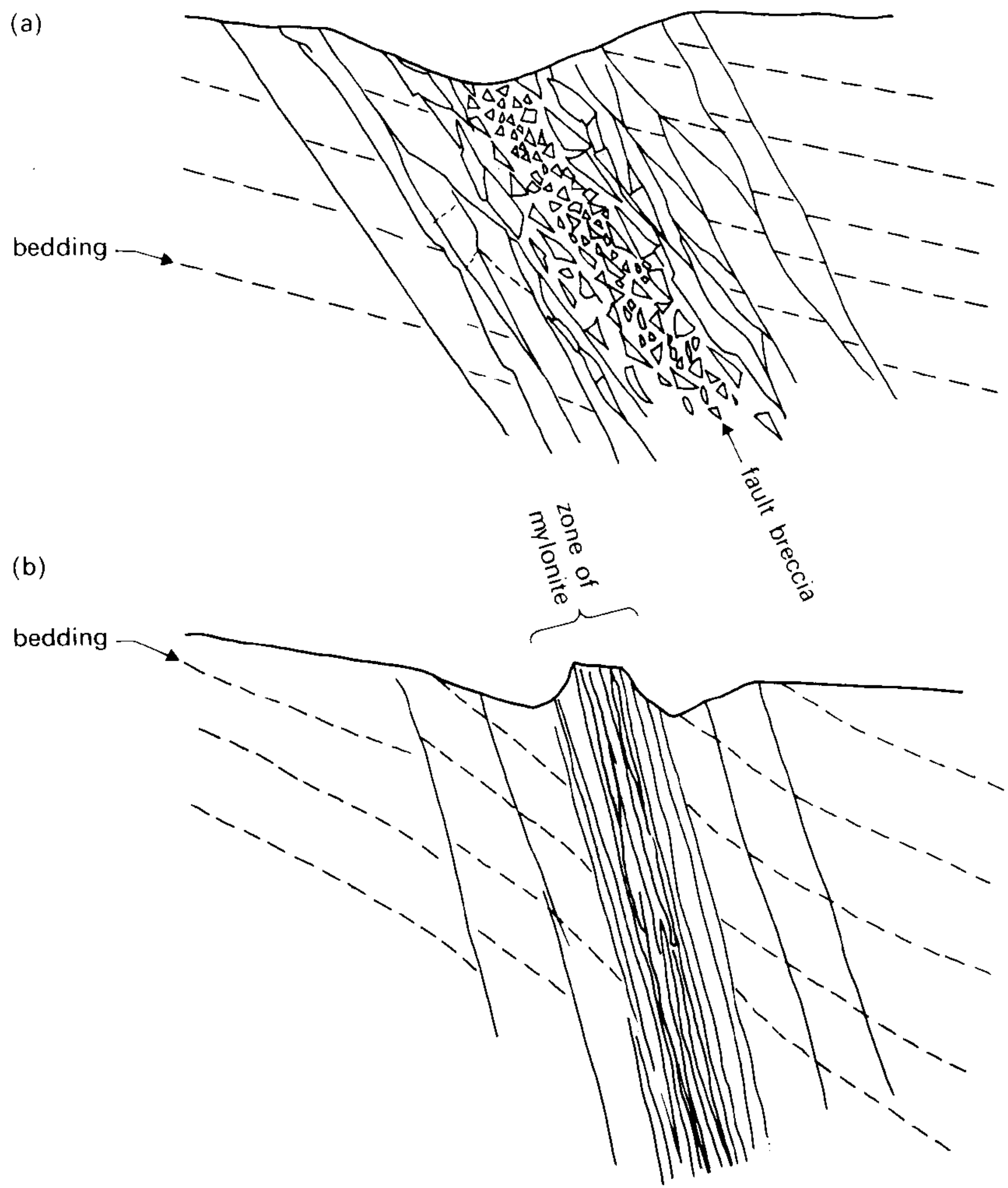


Figure 21.7. **Schematic cross section across fault zones. After Mason (1978) *Petrology of the Metamorphic Rocks*. George Allen & Unwin. London.**