Chapter 21: Metamorphism

Fresh basalt and
weathered basalt

Chapter 21: Metamorphism

- *Metamorphism*:
  - Meaning “change of form” in Greek (meta morph)

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

Metamorphic Agents and Changes

- Temperature: typically the most important factor in metamorphism

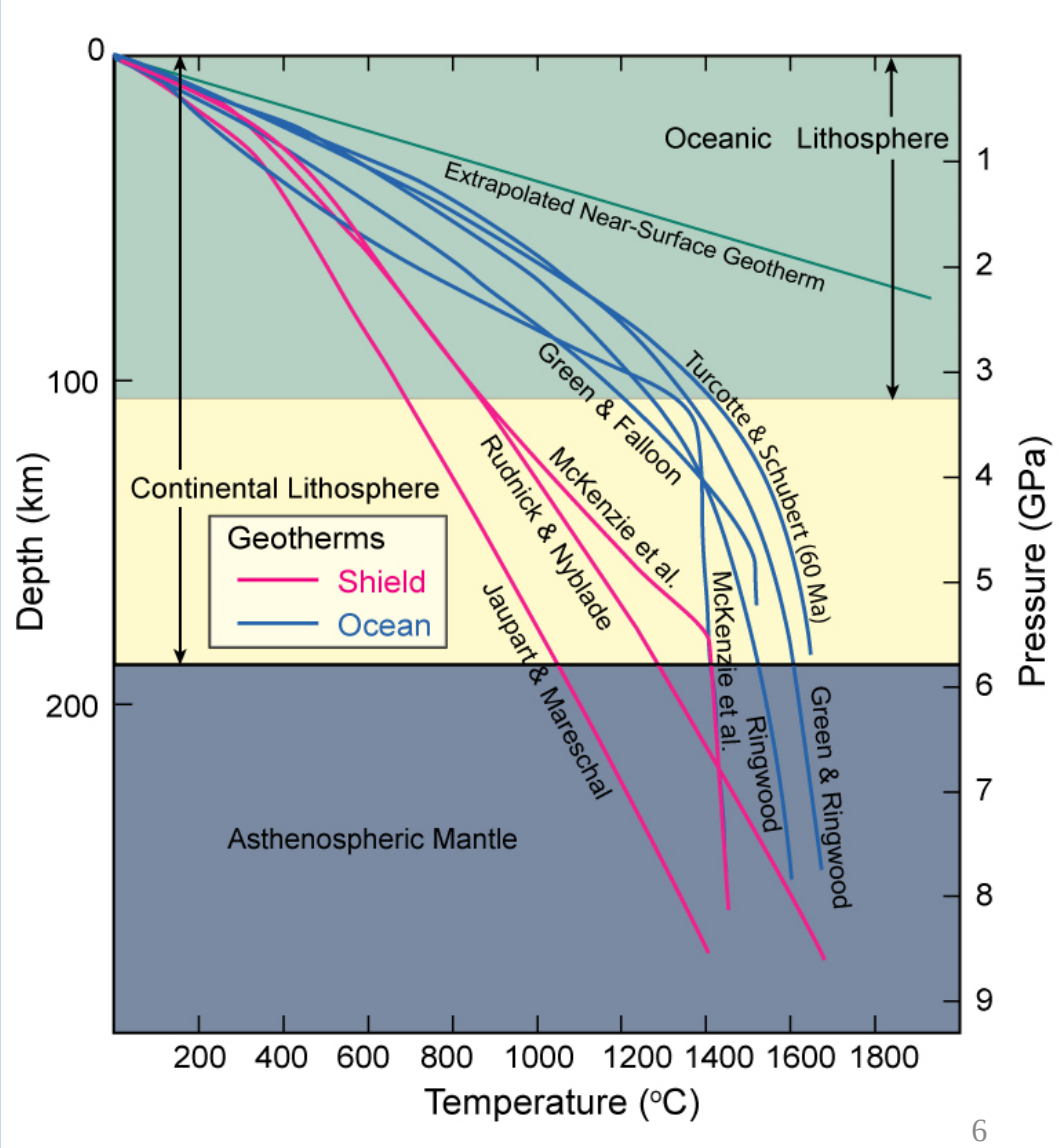


Figure 1.9. Estimated ranges of oceanic and continental steady-state geotherms to a depth of 100 km using upper and lower limits based on heat flows measured near the surface. After Sclater *et al.* (1980), Earth. Rev. Geophys. Space Sci., 18, 269-311.

Metamorphic Agents and Changes

Increasing temperature has several effects

1) Promotes recrystallization → increased grain size
    1) Larger surface/volume ratio – lower stability

2) Drive reactions (endothermic)

- consume unstable minerals that produce stable minerals under new conditions

3) Overcomes kinetic barriers

- promotes attainment of 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

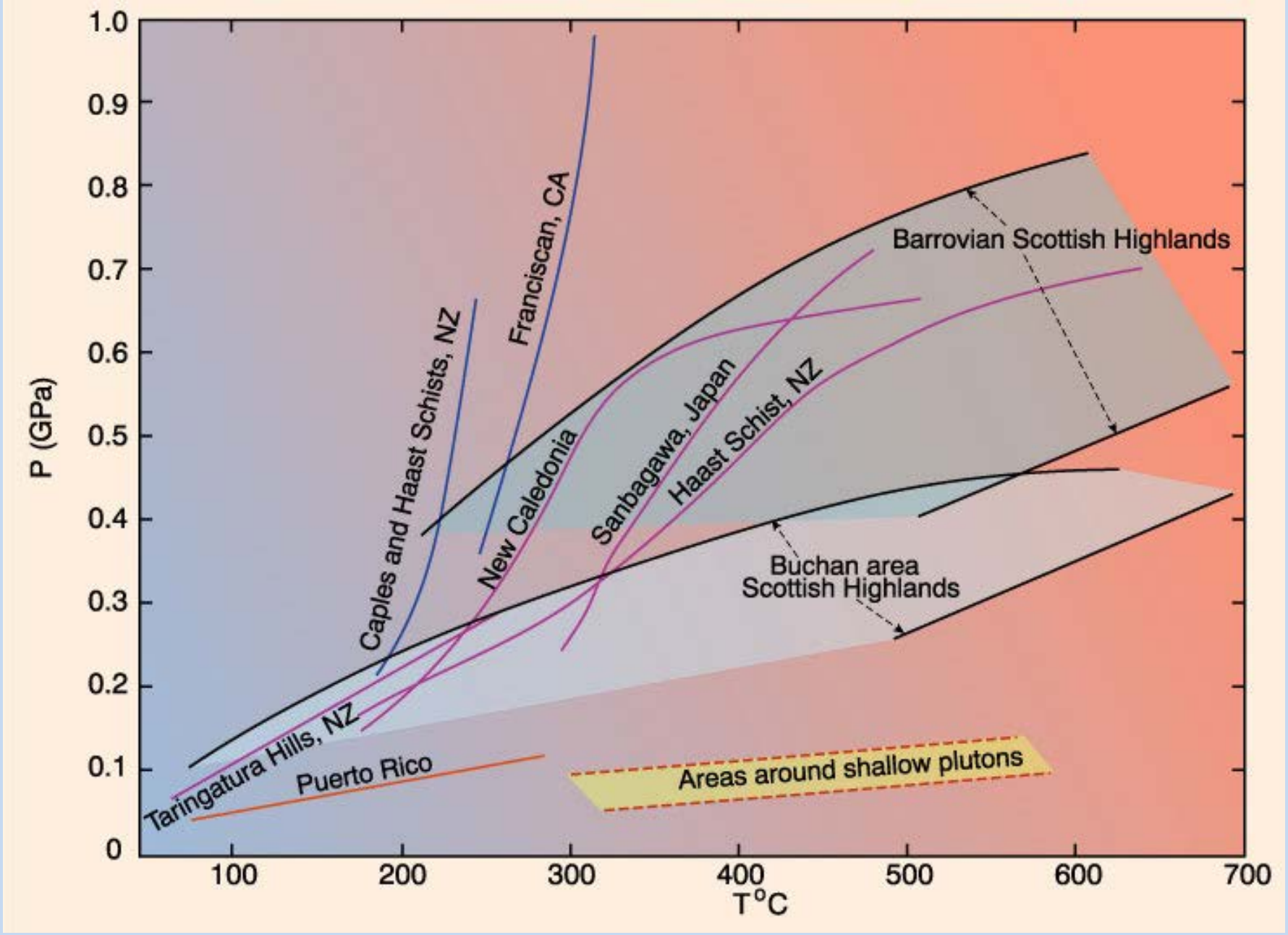
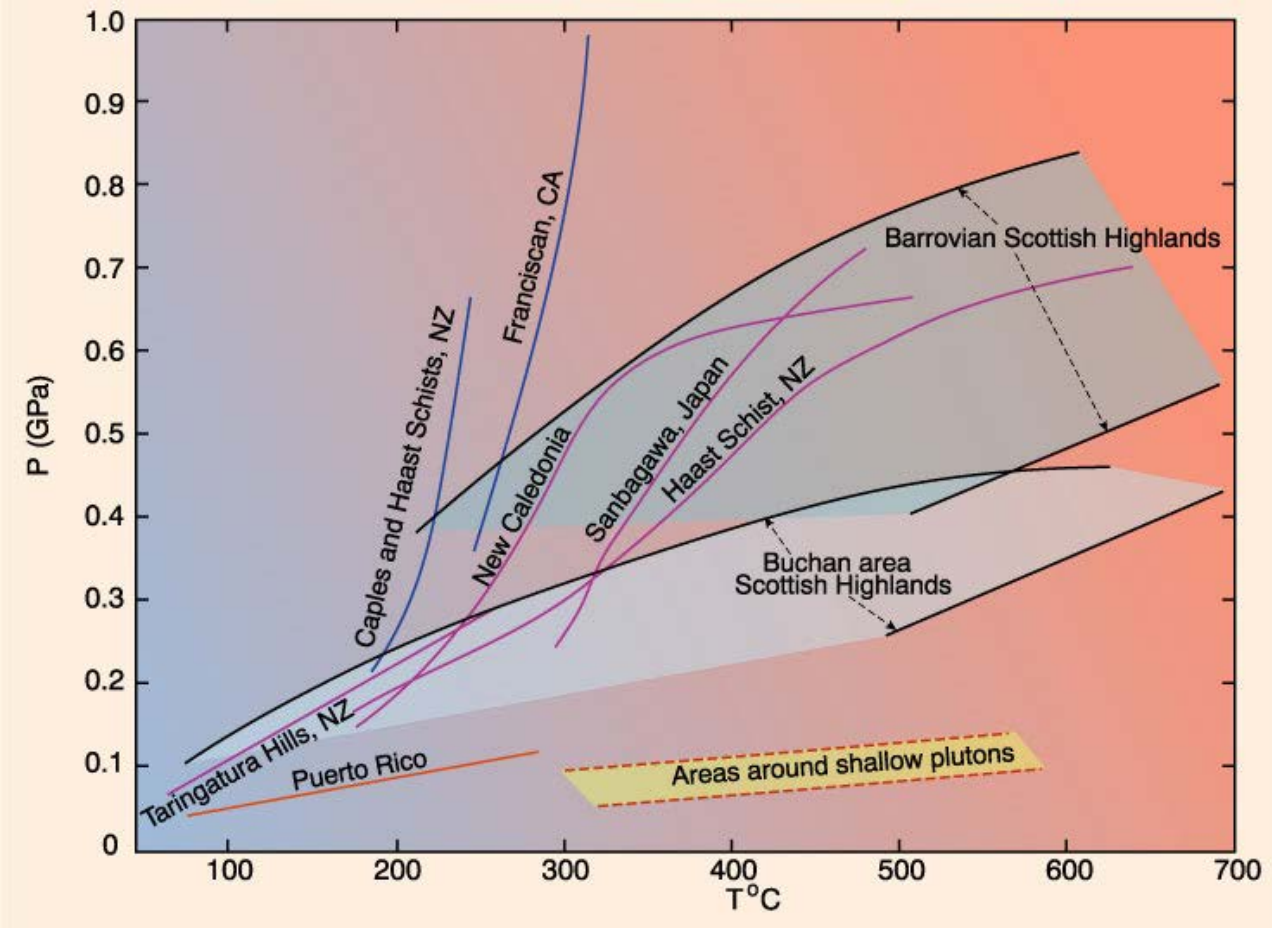


Figure 21.1. Metamorphic field gradients (estimated P-T conditions along surface traverses directly up metamorphic grade) for several metamorphic areas. After Turner (1981). *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill.

Metamorphic Agents and Changes

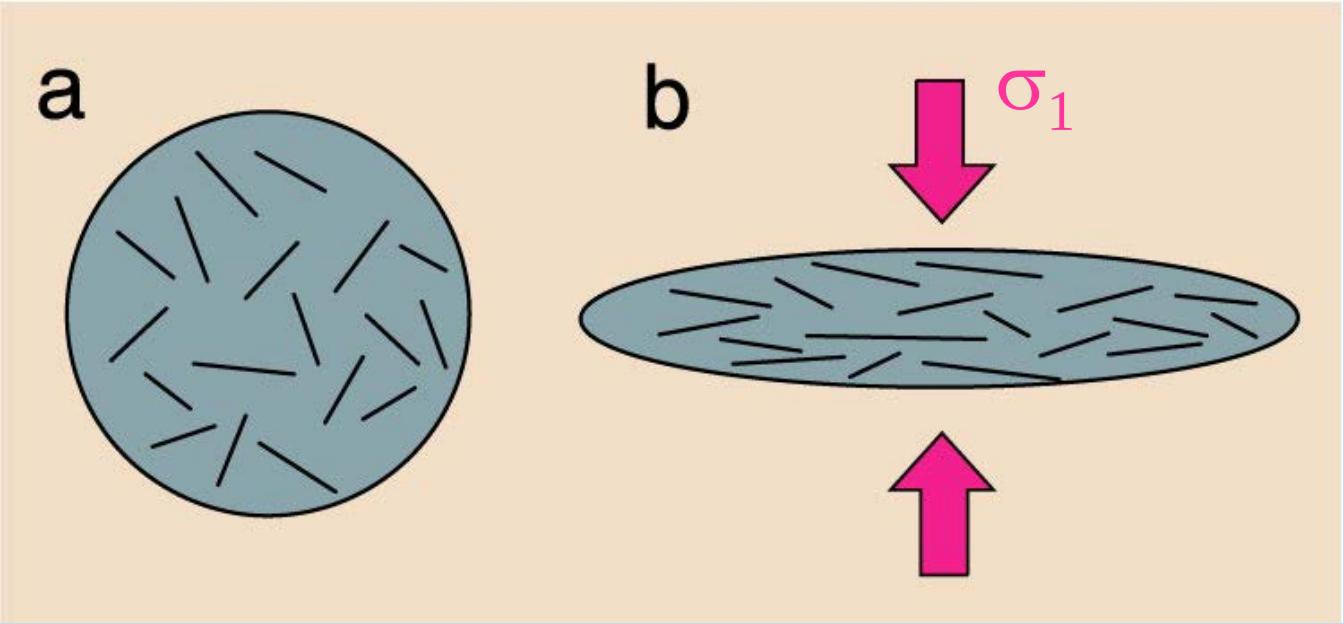
- Metamorphic grade: a general increase in degree of metamorphism without specifying the exact relationship between temperature and pressure



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

- 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

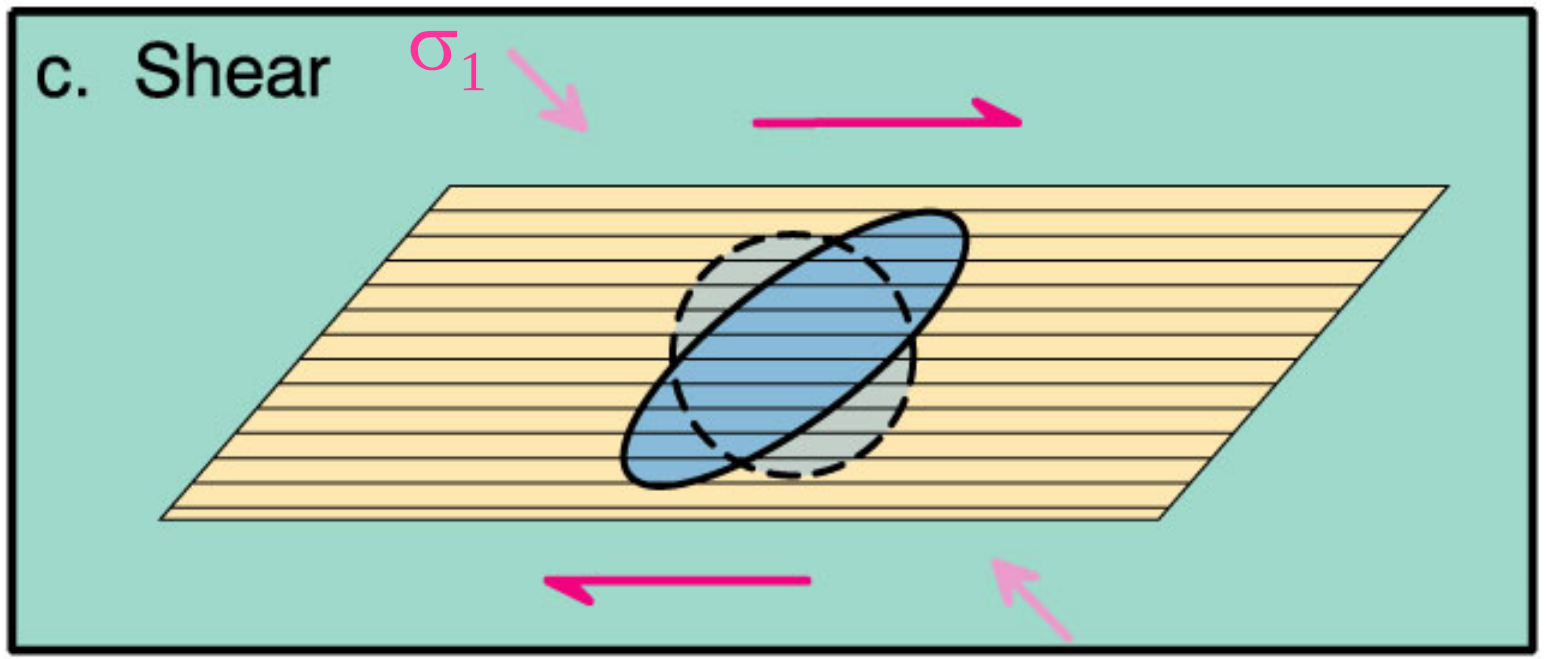


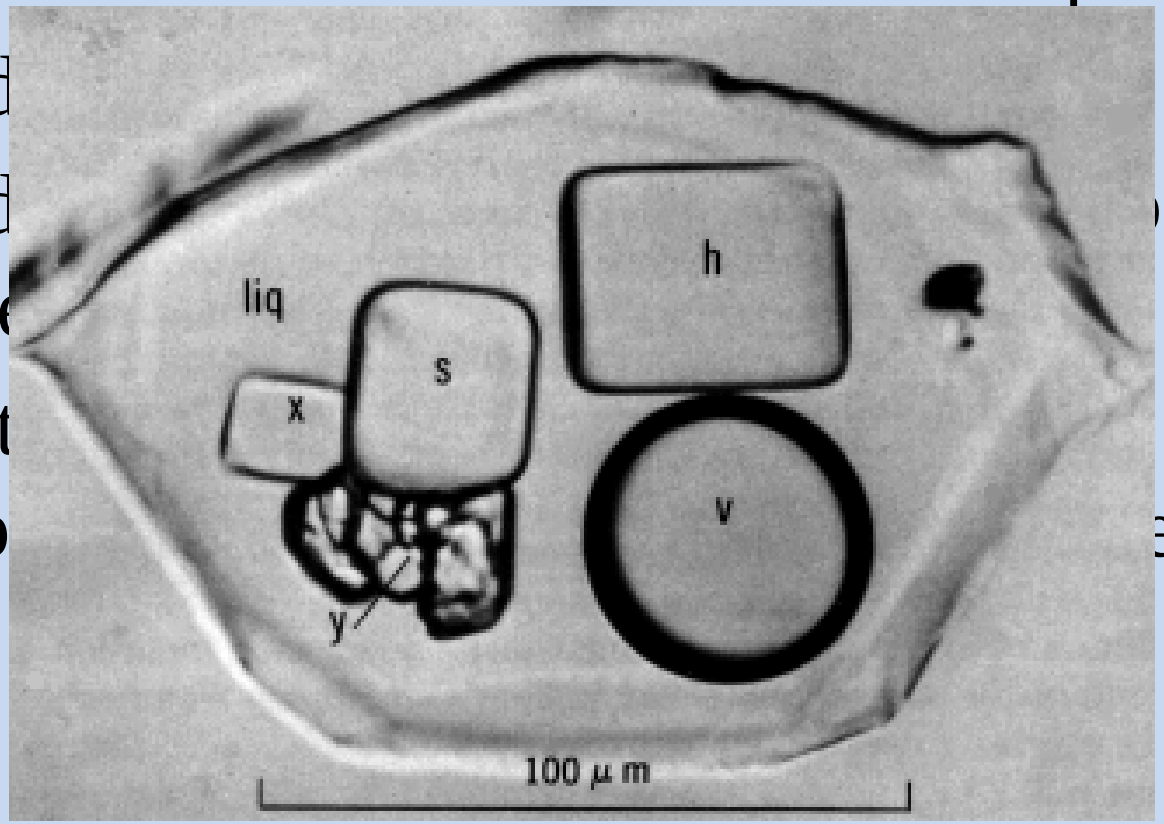
Figure 21.2. **The three main types of deviatoric stress with an example of possible resulting structures. b. Shear, causing slip along parallel planes and rotation. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.**

Metamorphic Agents and Changes

Fluids

Evidence for the existence of a metamorphic fluid:

- Fluid
- Fluid onate phase
- Volat e finite temp fluid



The Types of Metamorphism

Different approaches to classification

1. Based on principal process or agent
   - **Dynamic** Metamorphism
   - **Thermal** Metamorphism
   - **Dynamo-thermal** Metamorphism

The Types of Metamorphism

Different approaches to classification

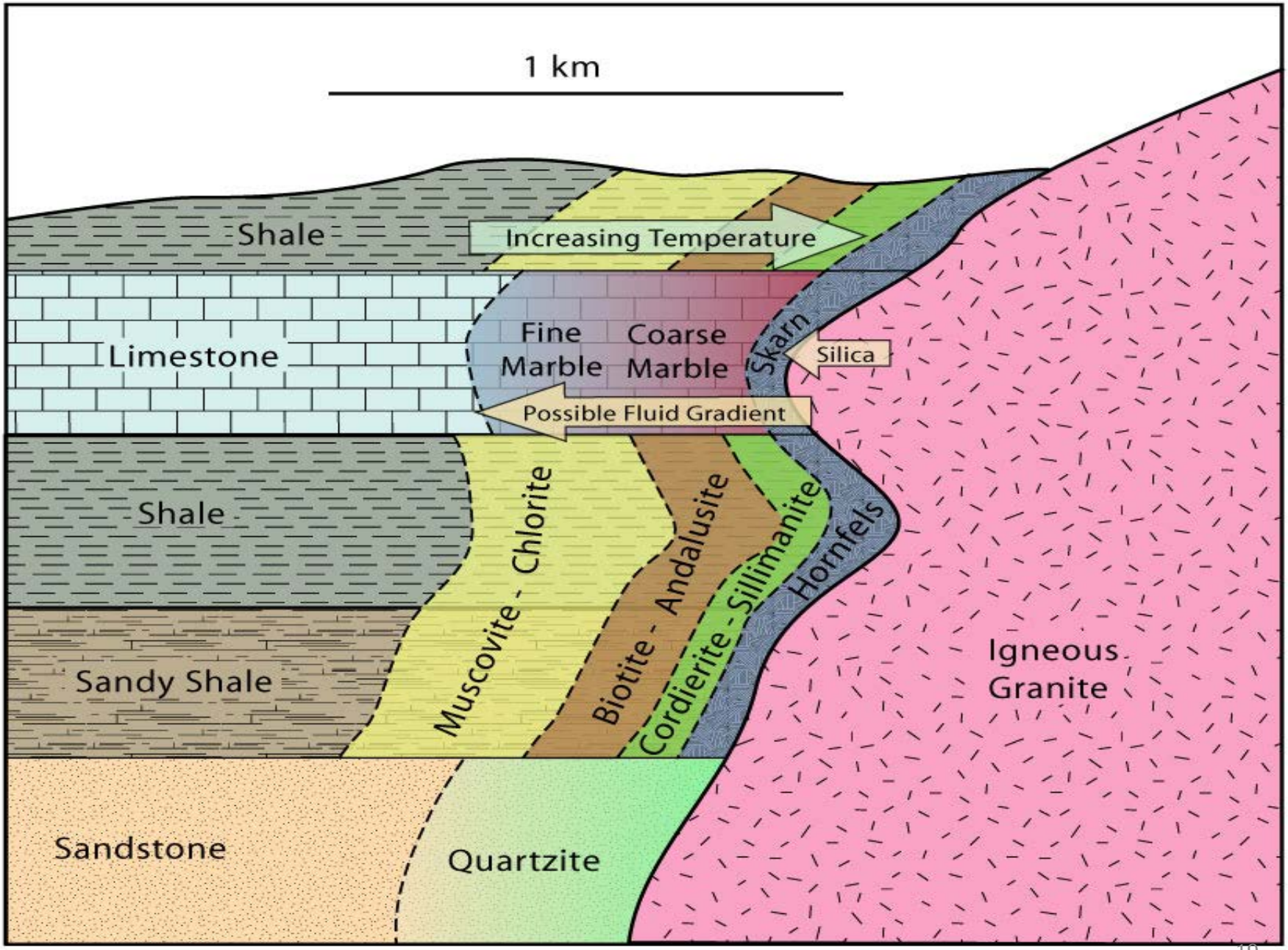
2. Based on ***field setting***
   - **Contact** Metamorphism
     - Pyrometamorphism
   - **Regional** Metamorphism
     - Orogenic Metamorphism
     - Burial Metamorphism
     - Ocean Floor Metamorphism
   - **Hydrothermal** Metamorphism
   - **Fault-Zone** Metamorphism
   - **Impact** or **Shock**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

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


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

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

- Spotted phyllite (or slate)
- Overprint may be due to:
  - Lag time for magma migration
  - A separate phase of post-orogenic collapse magmatism (Chapter 18)

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 *sensu lato*: 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

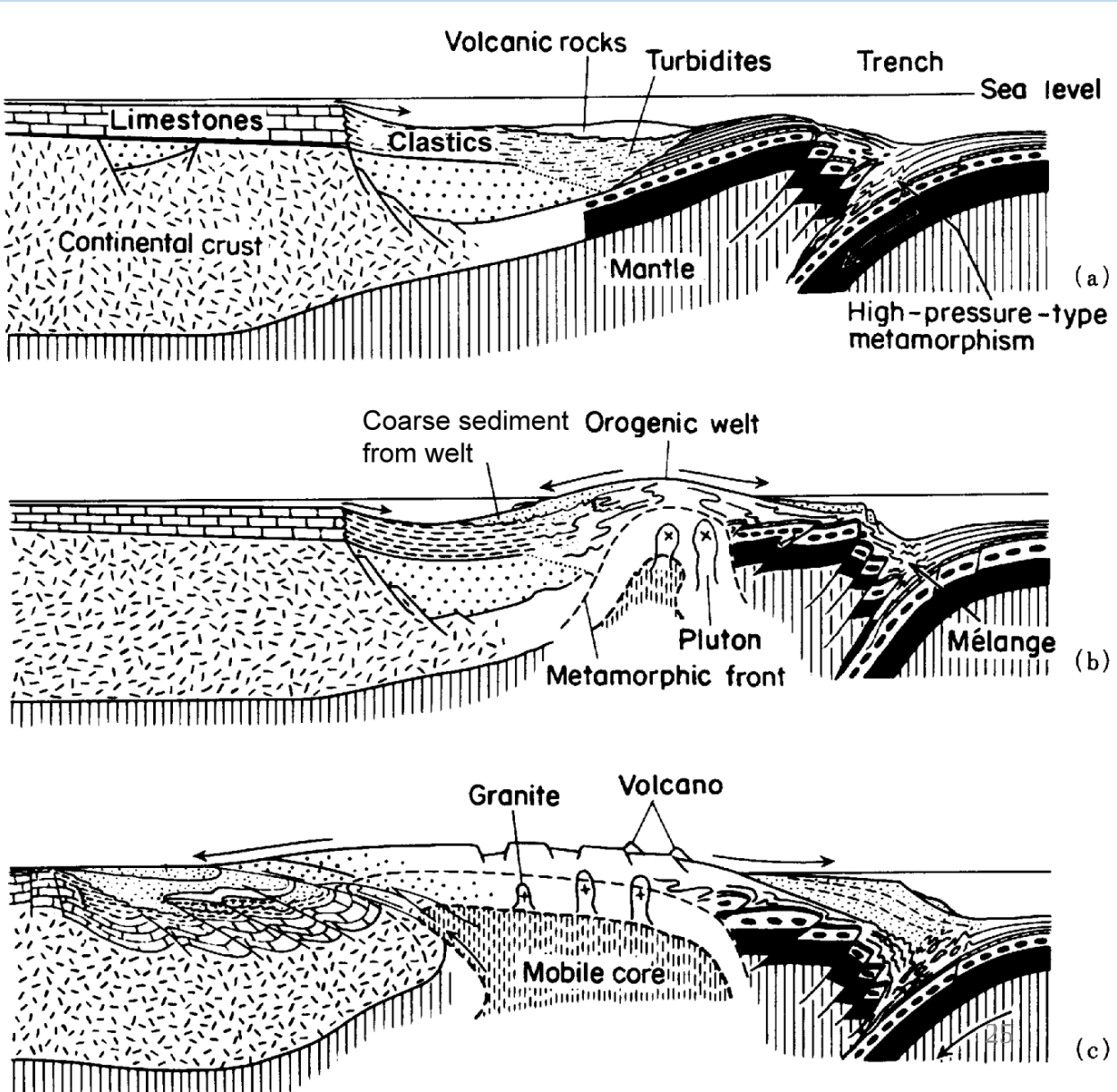
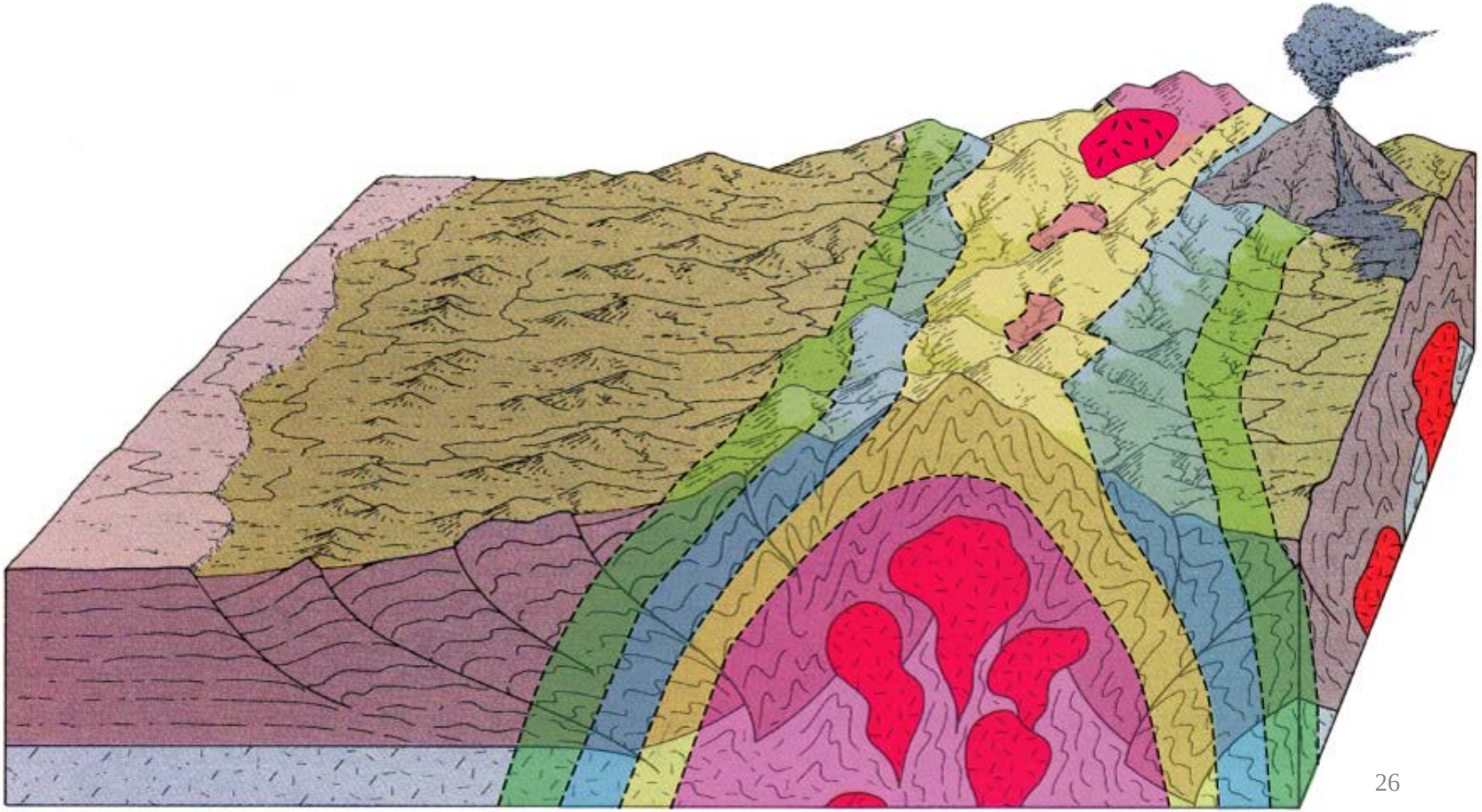


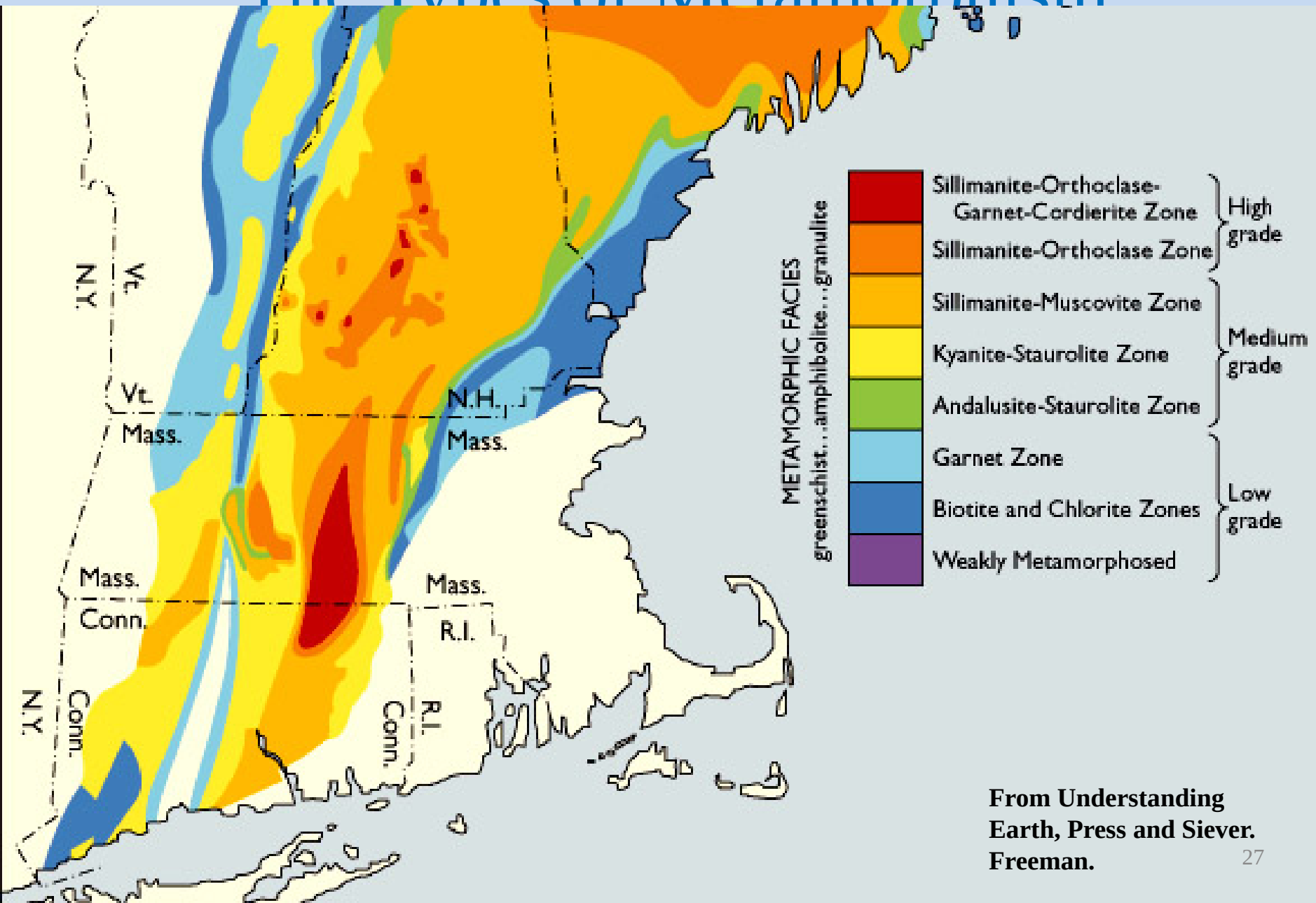
Figure 21.6. **Schematic model for the sequential (a → c) development of a "Cordilleran-type" or active continental margin orogen. The dashed and black layers on the right represent the basaltic and gabbroic layers of the oceanic crust. From Dewey and Bird (1970) *J. Geophys. Res.*, 75, 2625-2647; and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

The Types of Metamorphism

Orogenic Metamorphism



The Types of Metamorphism



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