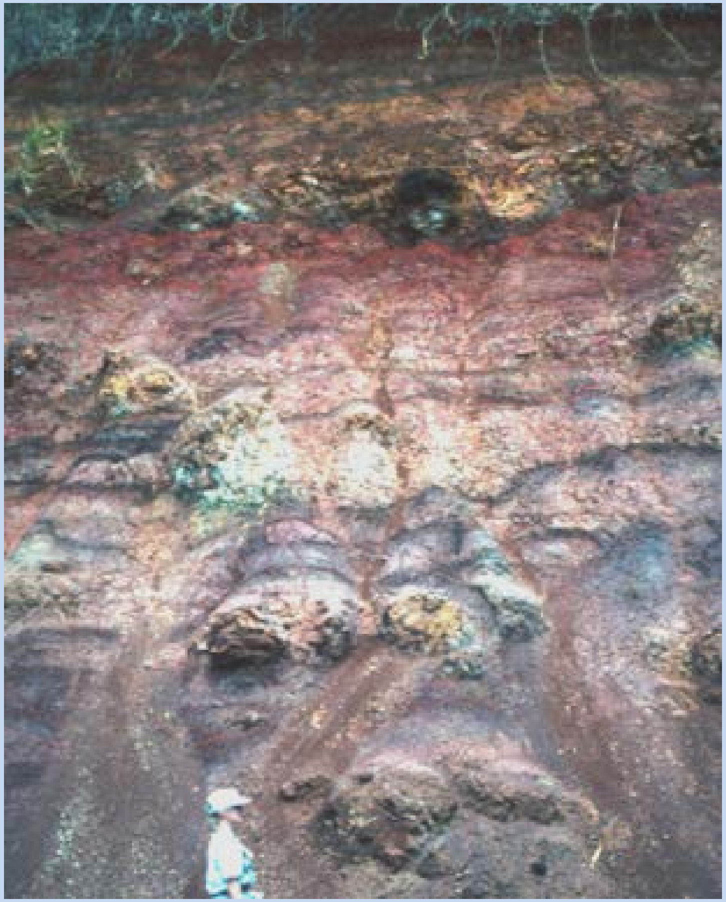
Chapter 21: Metamorphism



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

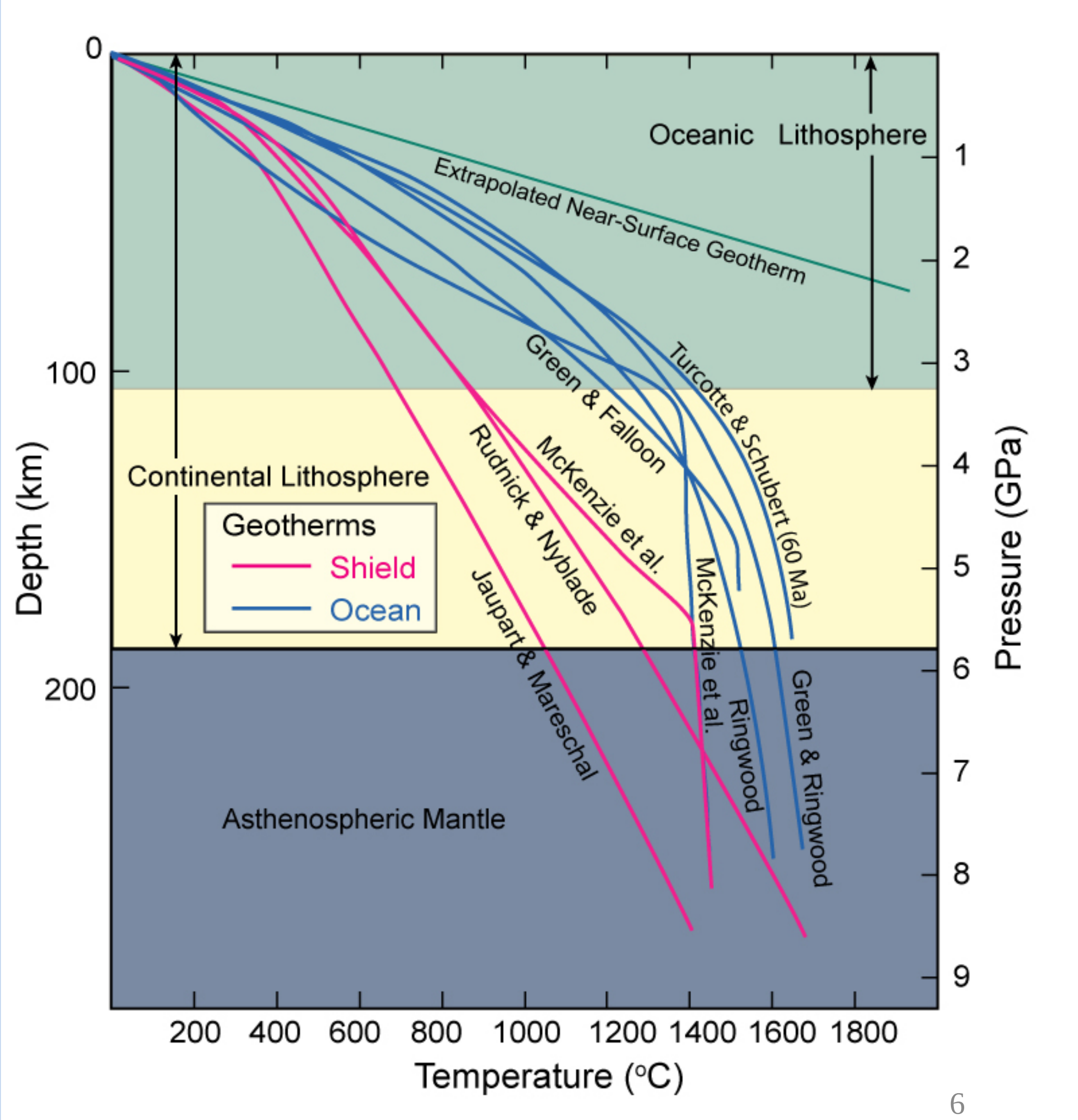


Figure 1.9. Estimated ranges of oceanic and continental steady-state geotherms to a depth of 100 km using upper and lower limits based on heat flows measured near the surface. After Sclater *et al.* (1980), Earth. Rev. Geophys. Space Sci., 18, 269-311.

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

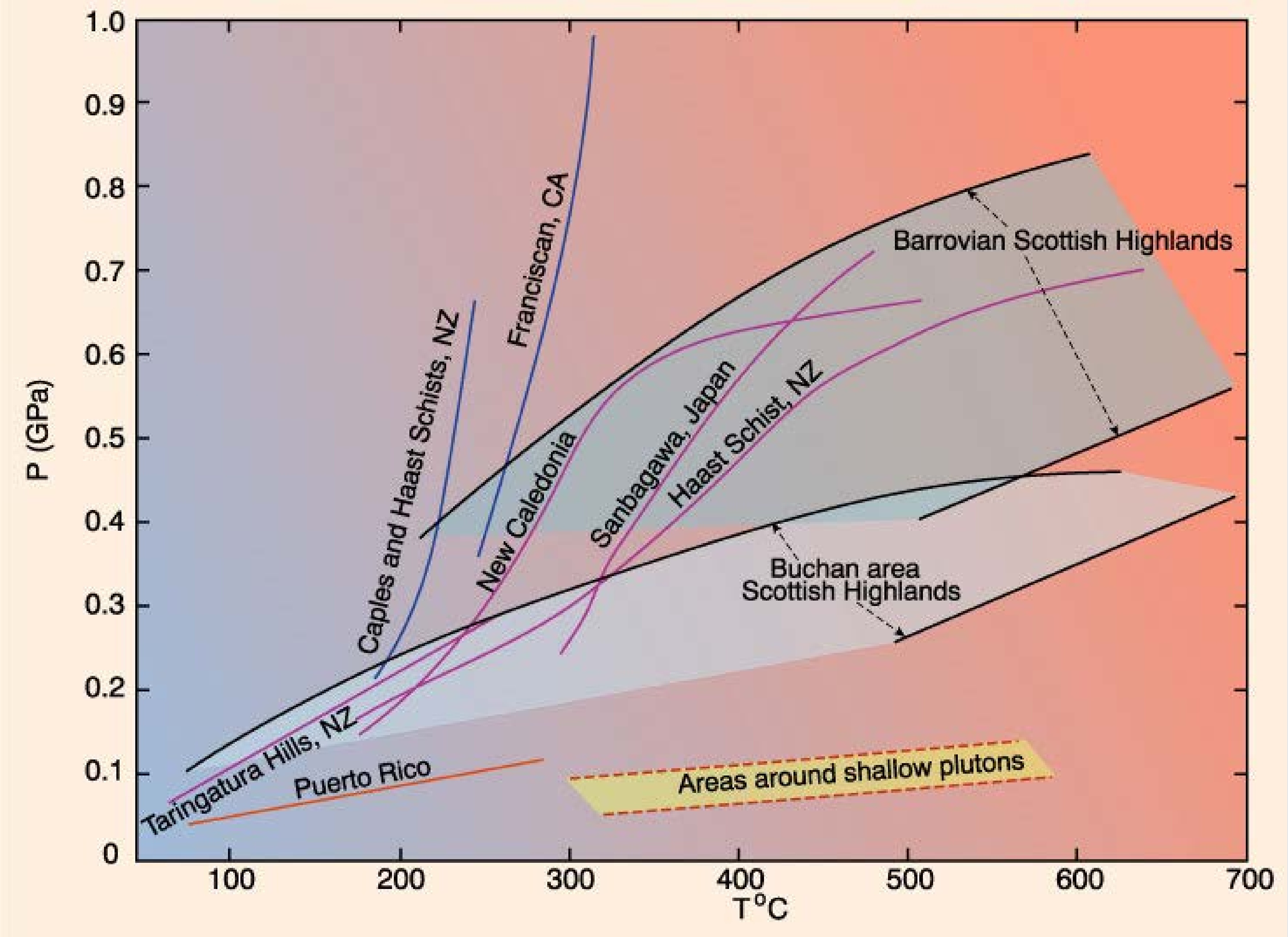
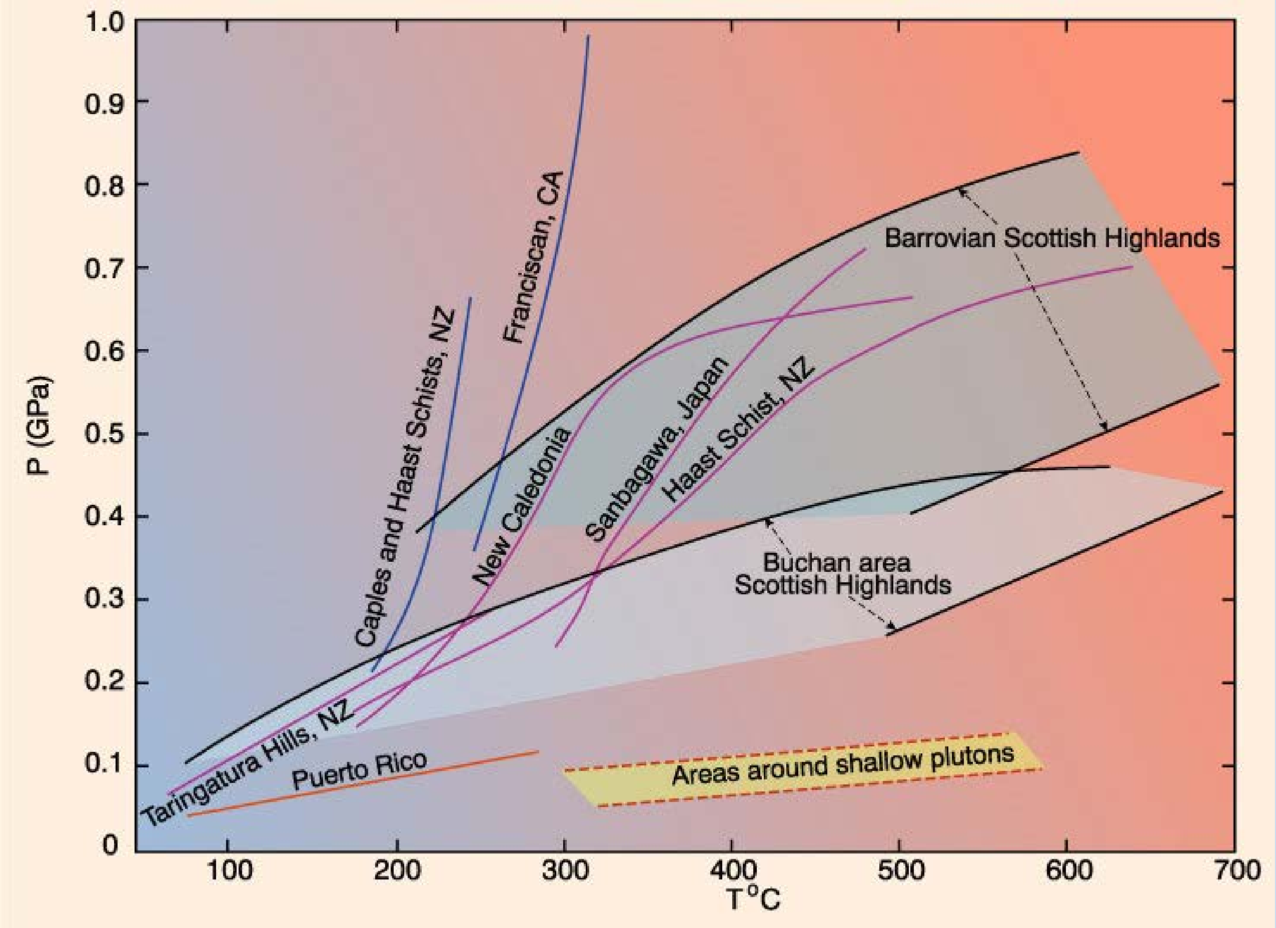


Figure 21.1. **Metamorphic field gradients** **(estimated P-T conditions along surface traverses directly up metamorphic grade) for several metamorphic areas. After Turner (1981).** ***Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*****. McGraw-Hill.**

Metamorphic Agents and Changes

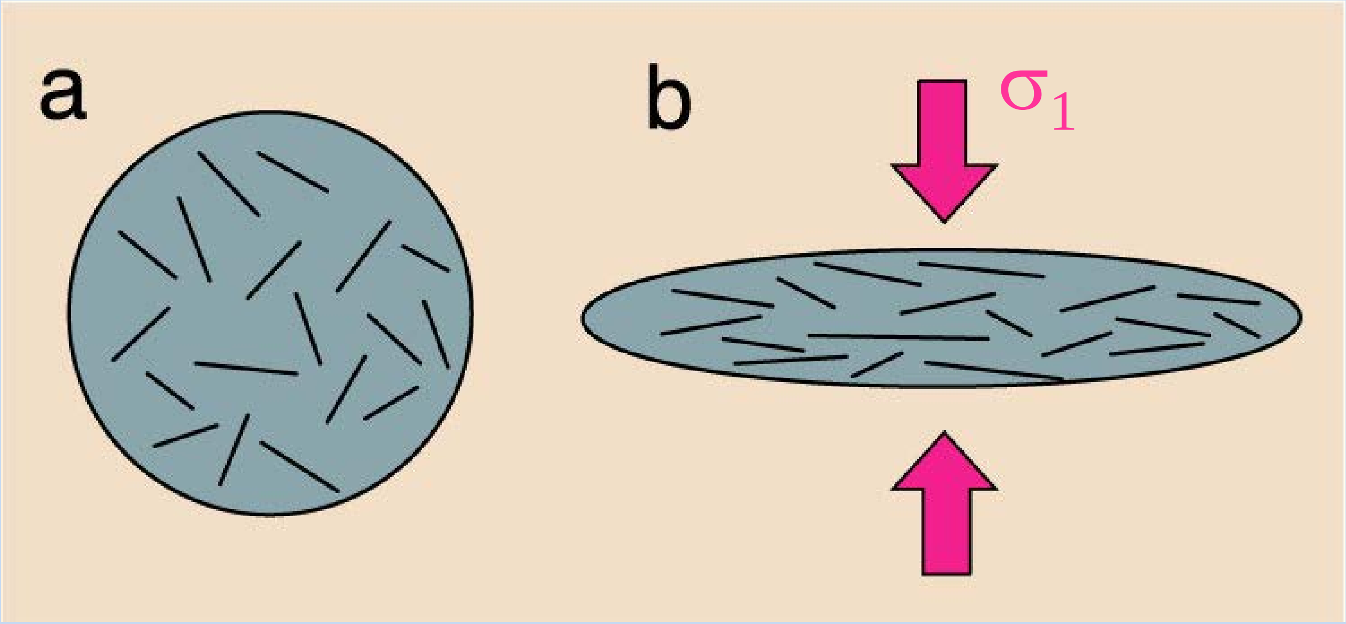
- Metamorphic grade: a general increase in degree of metamorphism without specifying the exact relationship between temperature and pressure



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

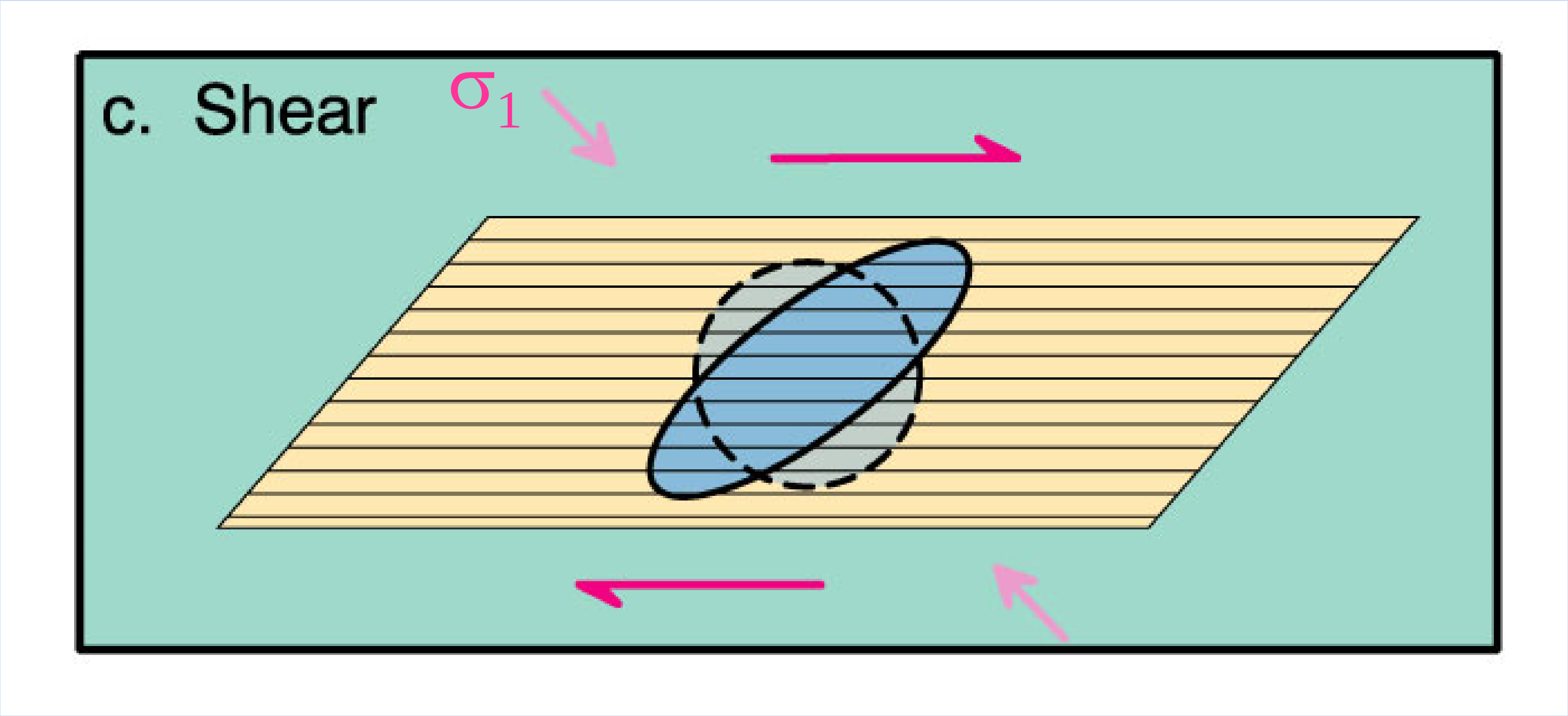


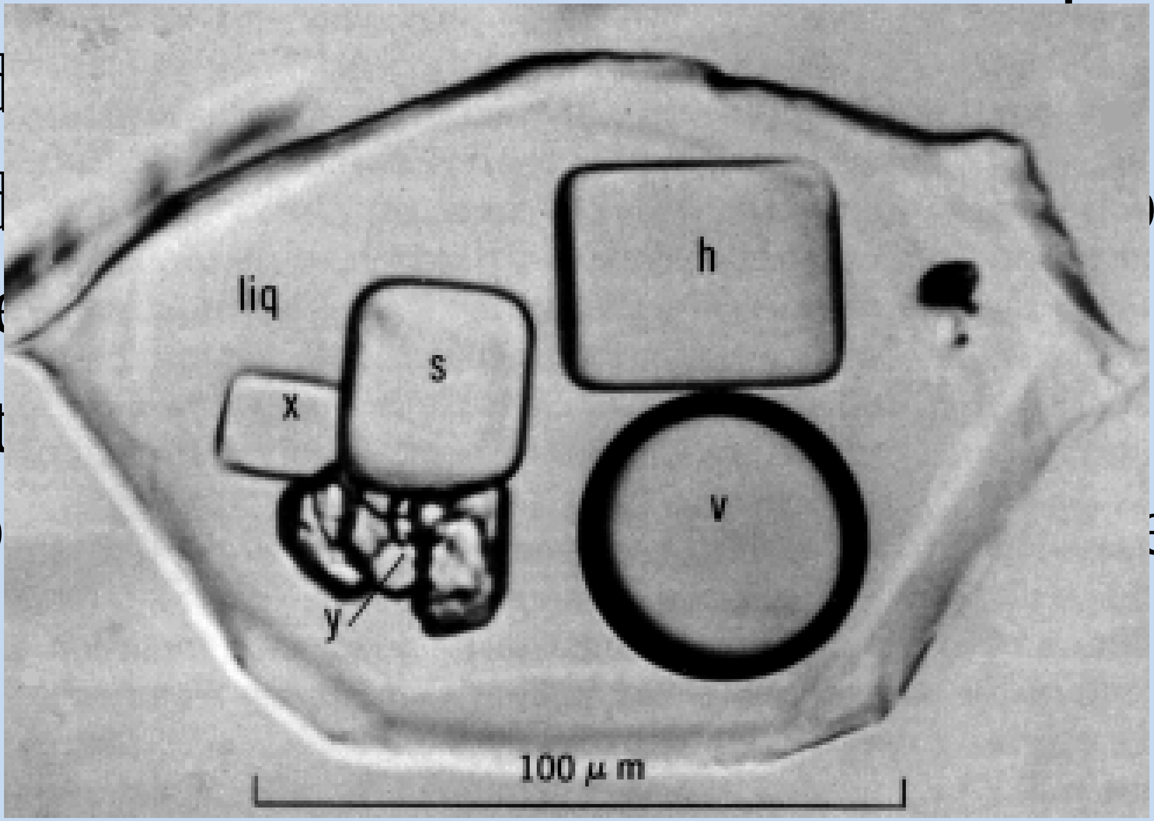
Figure 21.2. The three main types of deviatoric stress with an example of possible resulting structures. b. Shear, causing slip along parallel planes and rotation. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Metamorphic Agents and Changes

Fluids

Evidence for the existence of a metamorphic fluid:

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

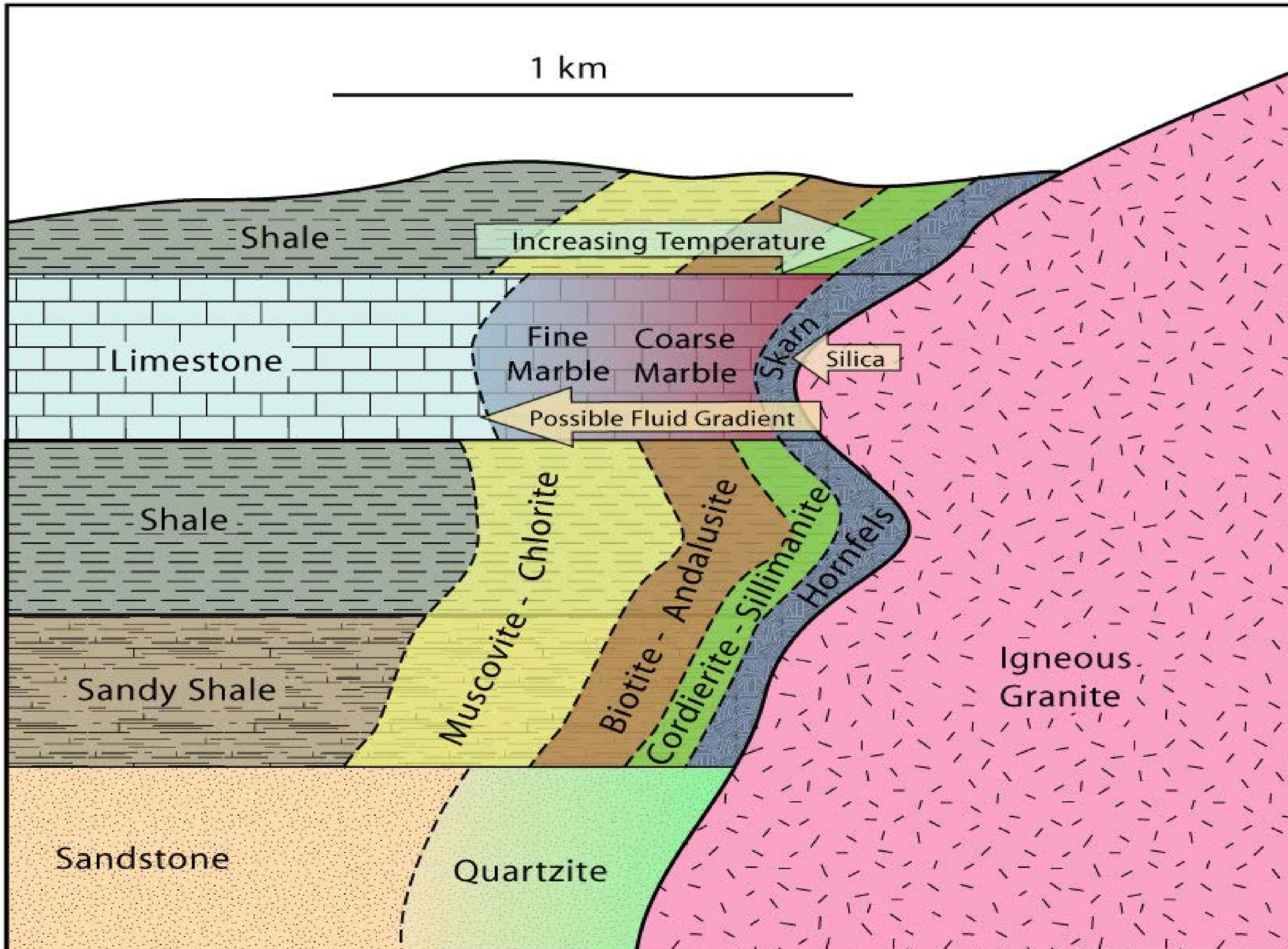
- **Contact** Metamorphism
  - Pyrometamorphism
- **Regional** Metamorphism
  - Orogenic Metamorphism
  - Burial Metamorphism
  - Ocean Floor Metamorphism
- **Hydrothermal** Metamorphism
- **Fault-Zone** Metamorphism
- **Impact** or **Shock** Metamorphism

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

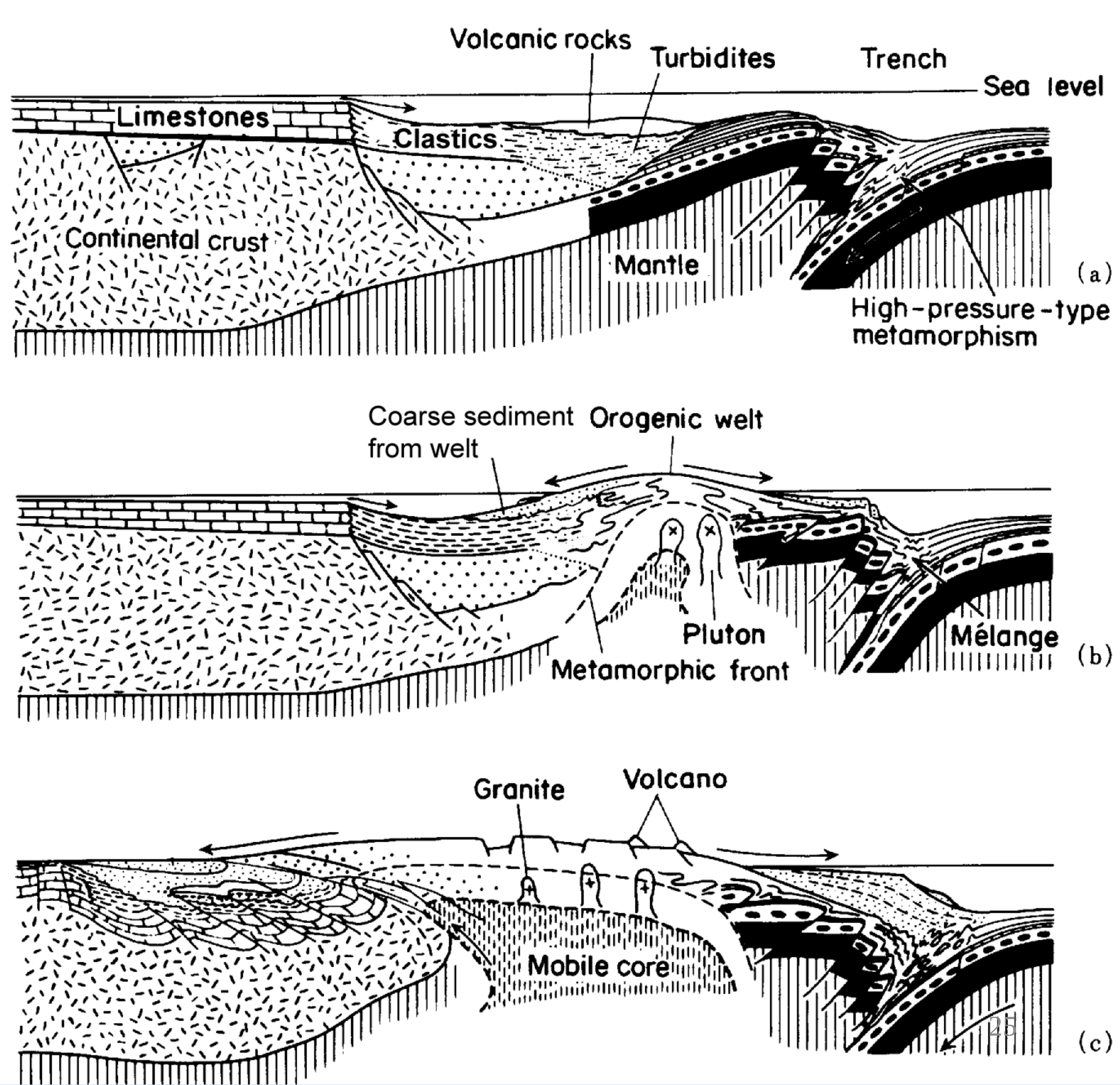
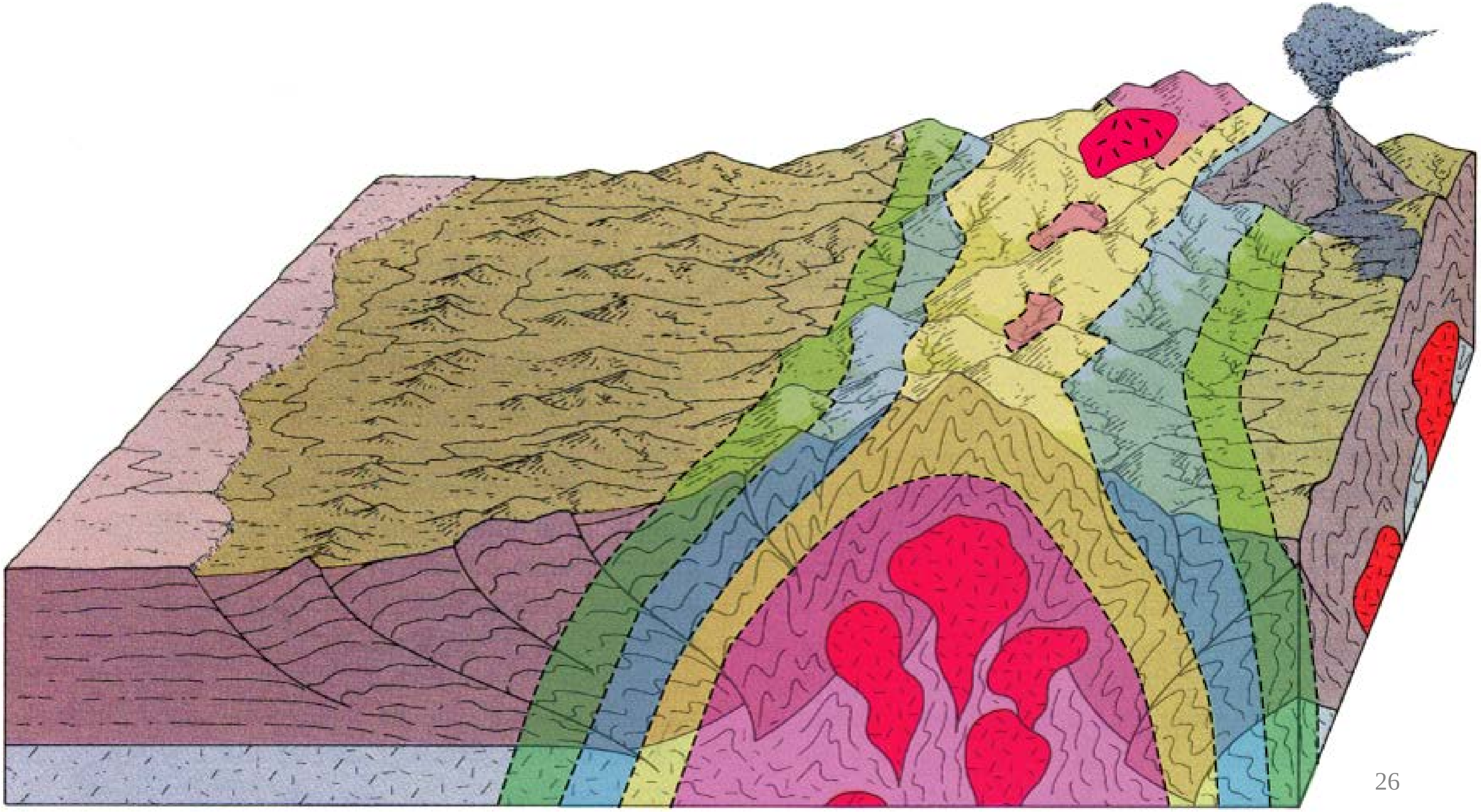


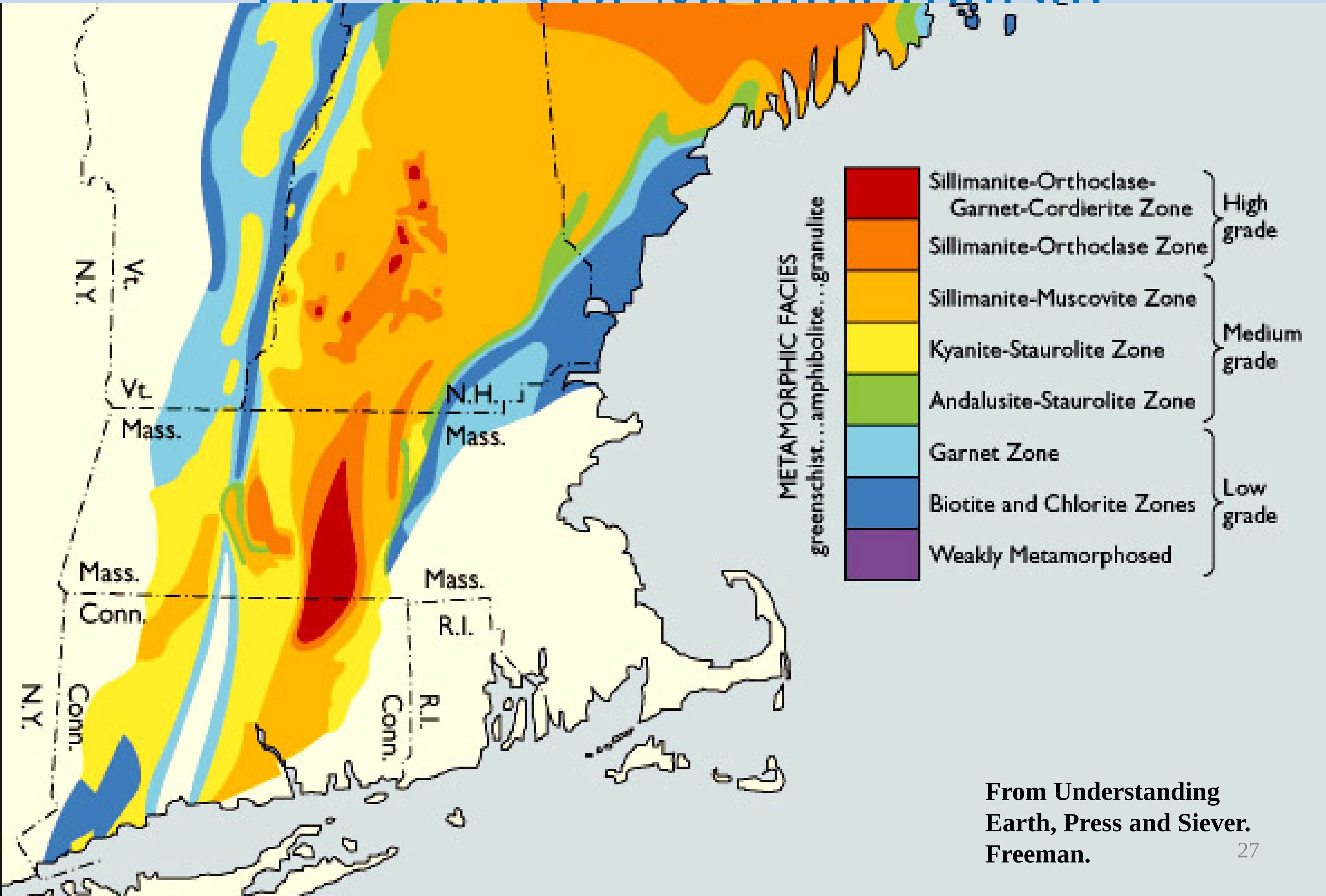
Figure 21.6. Schematic model for the sequential (a → c) development of a "Cordilleran-type" or active continental margin orogen. The dashed and black layers on the right represent the basaltic and gabbroic layers of the oceanic crust. From Dewey and Bird (1970) *J. Geophys. Res.*, 75, 2625-2647; and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

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
- Extrapolate → 250-300^{o}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

(a) Shallow fault zone with fault breccia

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

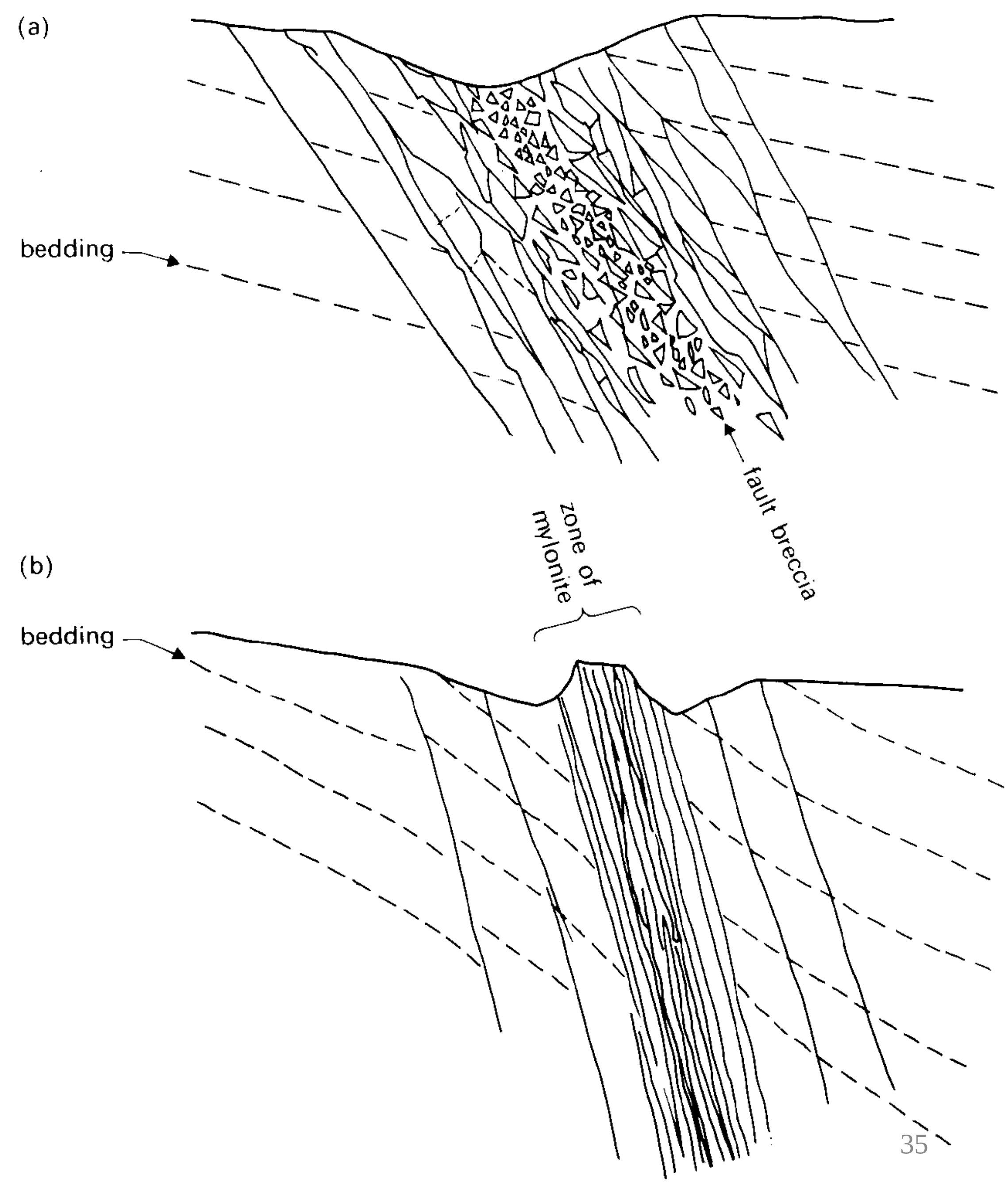


Figure 21.7. Schematic cross section across fault zones. After Mason (1978) *Petrology of the Metamorphic Rocks*. George Allen & Unwin. London.

Prograde Metamorphism

- Prograde: increase in metamorphic grade with time as a rock is subjected to gradually more severe conditions
  - Prograde metamorphism: changes in a rock that accompany increasing metamorphic grade
- Retrograde: decreasing grade as rock cools and recovers from a metamorphic or igneous event
  - Retrograde metamorphism: any accompanying changes

The Progressive Nature of Metamorphism

A rock at a high metamorphic grade probably progressed through a sequence of mineral assemblages rather than hopping directly from an unmetamorphosed rock to the metamorphic rock that we find today

The Progressive Nature of Metamorphism

Retrograde metamorphism typically of minor significance

- Prograde reactions are endothermic and easily driven by increasing T
- Devolatilization reactions are easier than reintroducing the volatiles
- Geothermometry indicates that the mineral compositions commonly preserve the maximum temperature

Types of Protolith

Lump the common types of sedimentary and igneous rocks into six chemically based-groups

1. Ultramafic - very high Mg, Fe, Ni, Cr
2. Mafic - high Fe, Mg, and Ca
3. Shales (pelitic) - high Al, K, Si
4. Carbonates - high Ca, Mg, CO_2
5. Quartz - nearly pure SiO_2.
6. Quartzo-feldspathic - high Si, Na, K, Al

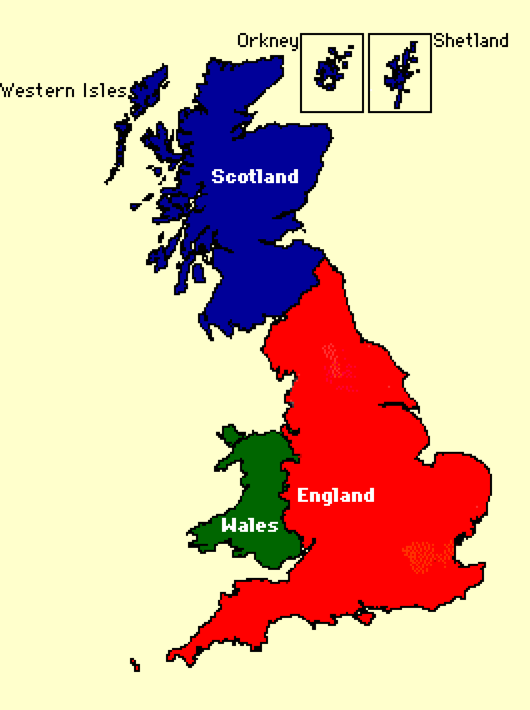
Some Examples of Metamorphism

- Why study metamorphic regions/areas?

- Interpretation of the conditions and evolution of metamorphic bodies, mountain belts, and ultimately the state and evolution of the Earth's crust
- Metamorphic rocks may retain enough inherited information from their protolith to allow us to interpret much of the pre-metamorphic history as well

Orogenic Regional Metamorphism of the Scottish Highlands

- George Barrow (1893, 1912)
- SE Highlands of Scotland - Caledonian Orogeny
  ~ 500 Ma
- Nappes – series of intensely folded rocks
- Granites



Barrow's Area

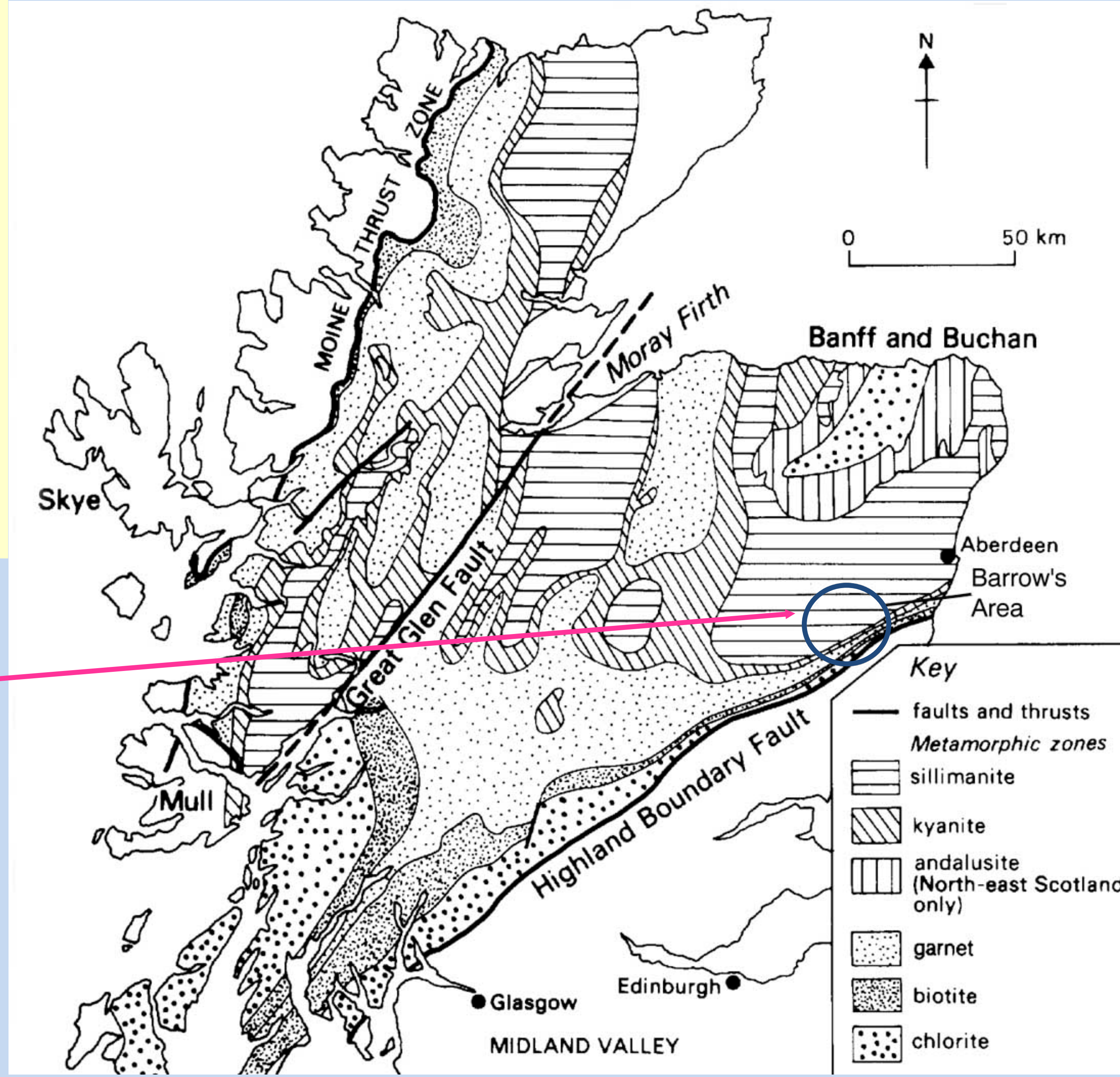


Figure 21.8. Regional metamorphic map of the Scottish Highlands, showing the zones of minerals that develop with increasing metamorphic grade. From Gillen (1982) *Metamorphic Geology. An Introduction to Tectonic and Metamorphic Processes*. George Allen & Unwin. London.

Orogenic Regional Metamorphism of the Scottish Highlands

- Barrow studied the pelitic rocks
- Could subdivide the area into a series of metamorphic zones, each based on the appearance of a new mineral as metamorphic grade increased

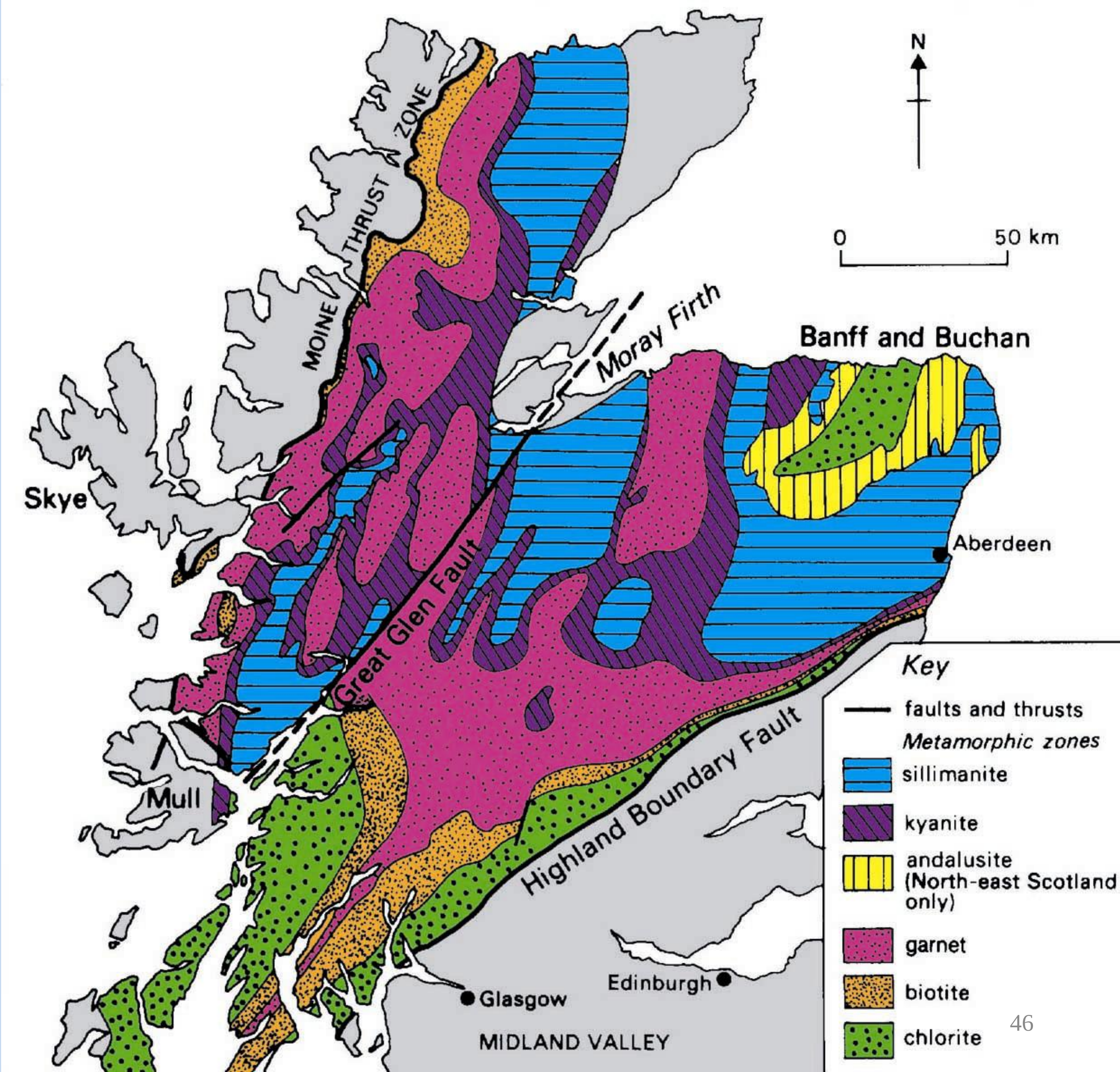
- New mineral that characterizes a zone is termed an Index Mineral

The sequence of zones now recognized, and the typical metamorphic mineral assemblage in each, are:

- Chlorite zone. Pelitic rocks are slates or phyllites and typically contain chlorite, muscovite, quartz and albite
- Biotite zone. Slates give way to phyllites and schists, with biotite, chlorite, muscovite, quartz, and albite
- Garnet zone. Schists with conspicuous red almandine garnet, usually with biotite, chlorite, muscovite, quartz, and albite or oligoclase
- Staurolite zone. Schists with staurolite, biotite, muscovite, quartz, garnet, and plagioclase. Some chlorite may persist
- Kyanite zone. Schists with kyanite, biotite, muscovite, quartz, plagioclase, and usually garnet and staurolite
- Sillimanite zone. Schists and gneisses with sillimanite, biotite, muscovite, uartz, plagioclase, garnet, and perhaps staurolite. Some kyanite may also be present (although kyanite and sillimanite are both polymorphs of Al_2SiO_5)

- Sequence = "Barrovian zones"
- The P-T conditions referred to as "Barrovian-type" metamorphism (fairly typical of many belts)
- Now extended to a much larger area of the Highlands
- Isograd = line that separates the zones (a line in the field of constant metamorphic grade)

Figure 21.8. Regional metamorphic map of the Scottish Highlands, showing the zones of minerals that develop with increasing metamorphic grade. From Gillen (1982) *Metamorphic Geology. An Introduction to Tectonic and Metamorphic Processes*. George Allen & Unwin. London.

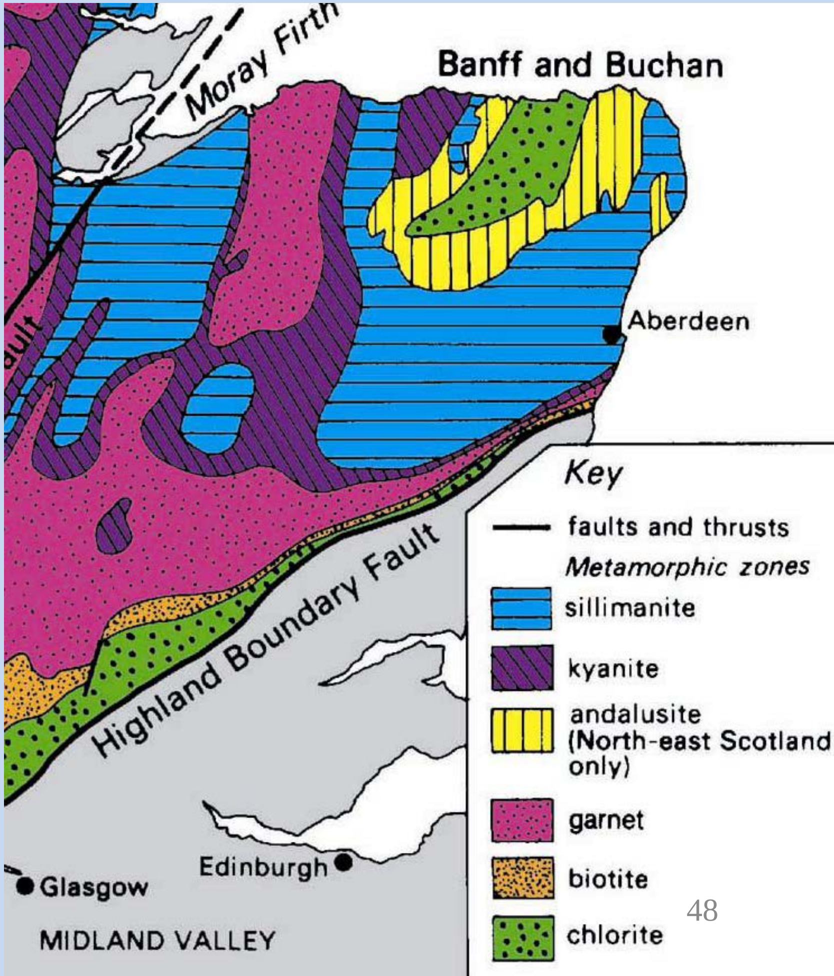


To summarize:

- An isograd represents the first appearance of a particular metamorphic index mineral in the field as one progresses up metamorphic grade
- When one crosses an isograd, such as the biotite isograd, one enters the biotite zone
- Zones thus have the same name as the isograd that forms the low-grade boundary of that zone
- Because classic isograds are based on the first appearance of a mineral, and not its disappearance, an index mineral may still be stable in higher grade zones

A variation occurs in the area just to the north of Barrow's, in the Banff and Buchan district

- Pelitic compositions are similar, but the sequence of isograds is:
  - chlorite
  - biotite
  - cordierite
  - andalusite
  - sillimanite



The stability field of andalusite occurs at pressures less than 0.37 GPa (~ 10 km), while kyanite → sillimanite at the sillimanite isograd only above this pressure

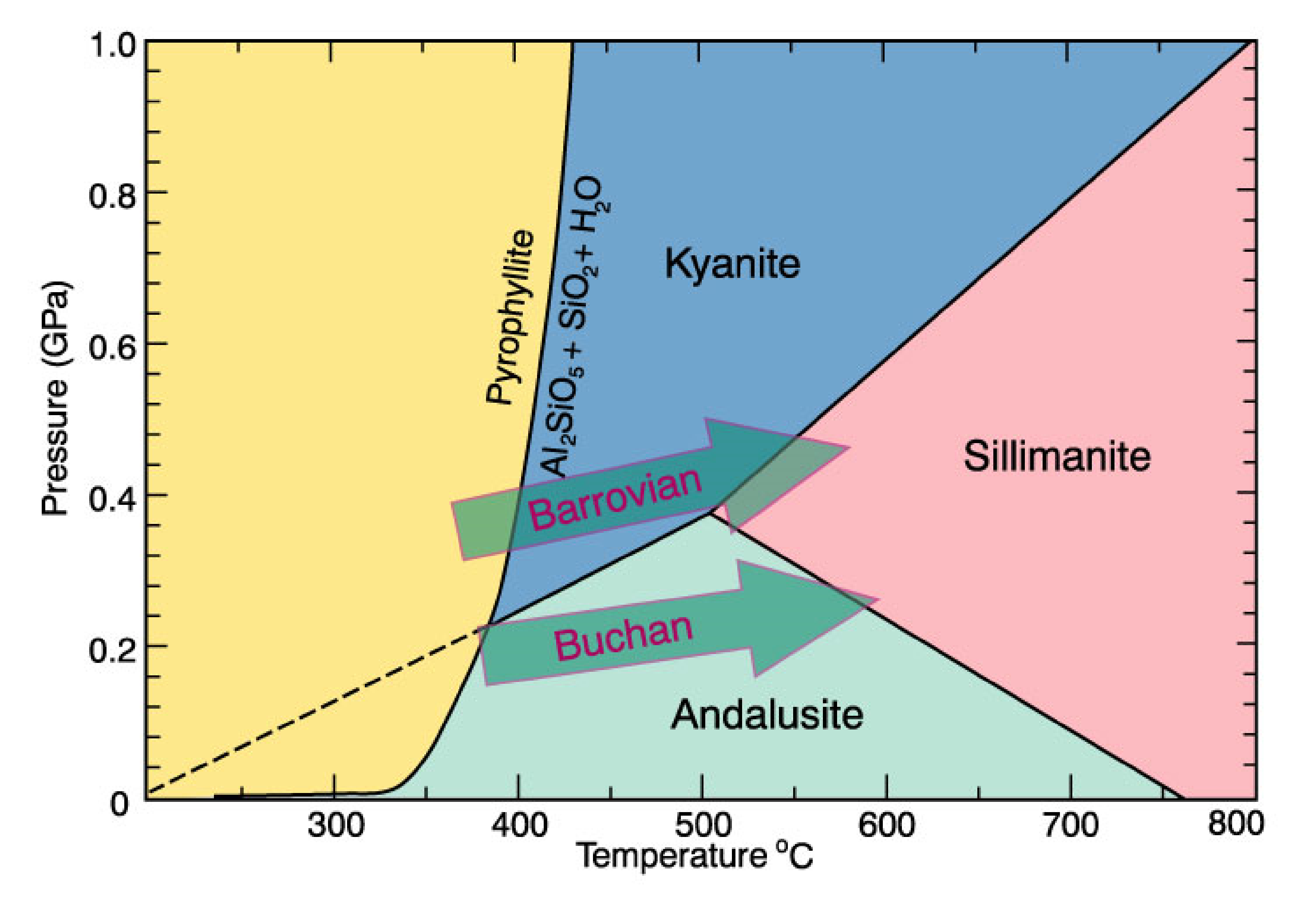


Figure 21.9. The P-T phase diagram for the system Al_2SiO_5 showing the stability fields for the three polymorphs andalusite, kyanite, and sillimanite. Also shown is the hydration of Al_2SiO_5 to pyrophyllite, which limits the occurrence of an Al_2SiO_5 polymorph at low grades in the presence of excess silica and water. The diagram was calculated using the program TWQ (Berman, 1988, 1990, 1991).

Paired Metamorphic Belts of Japan

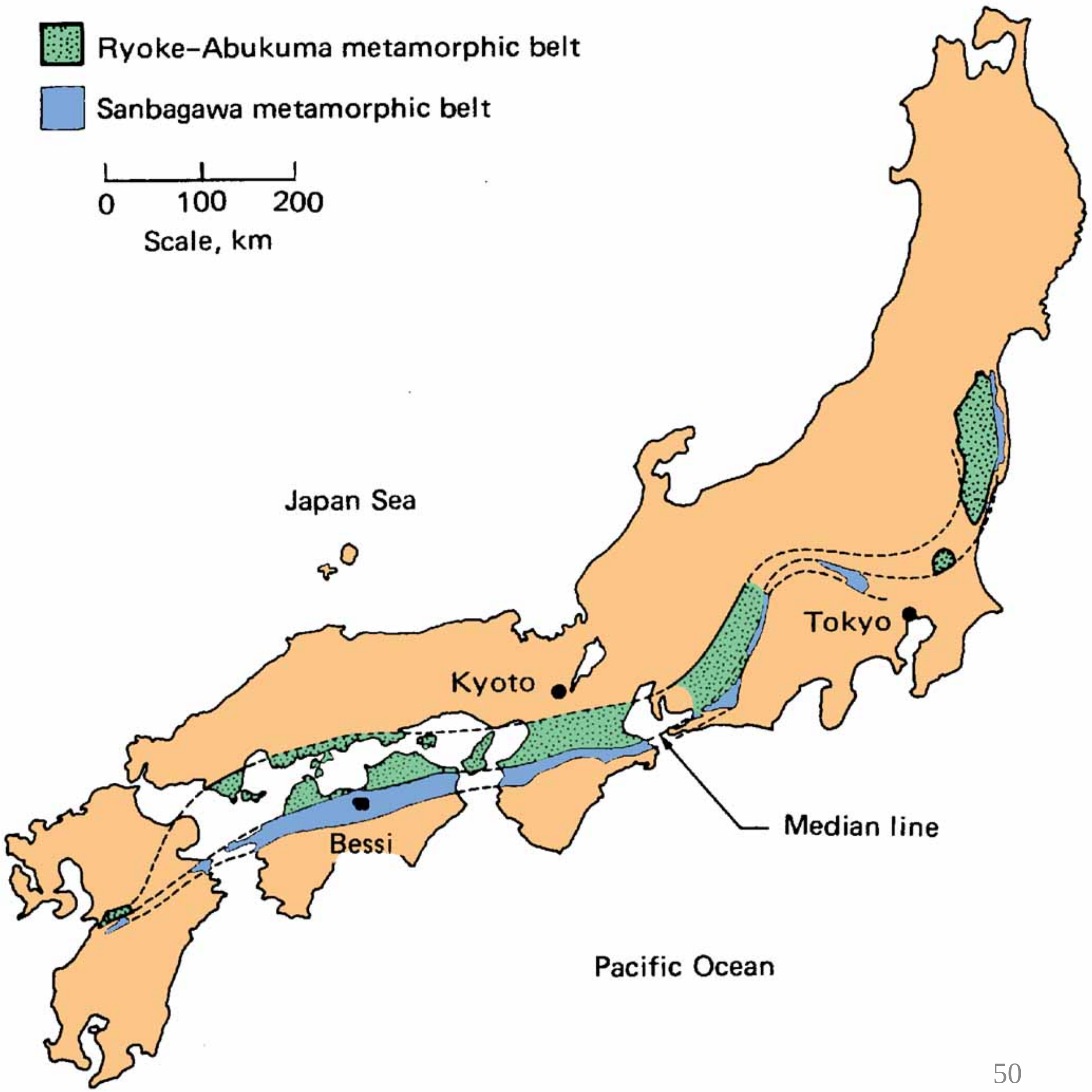
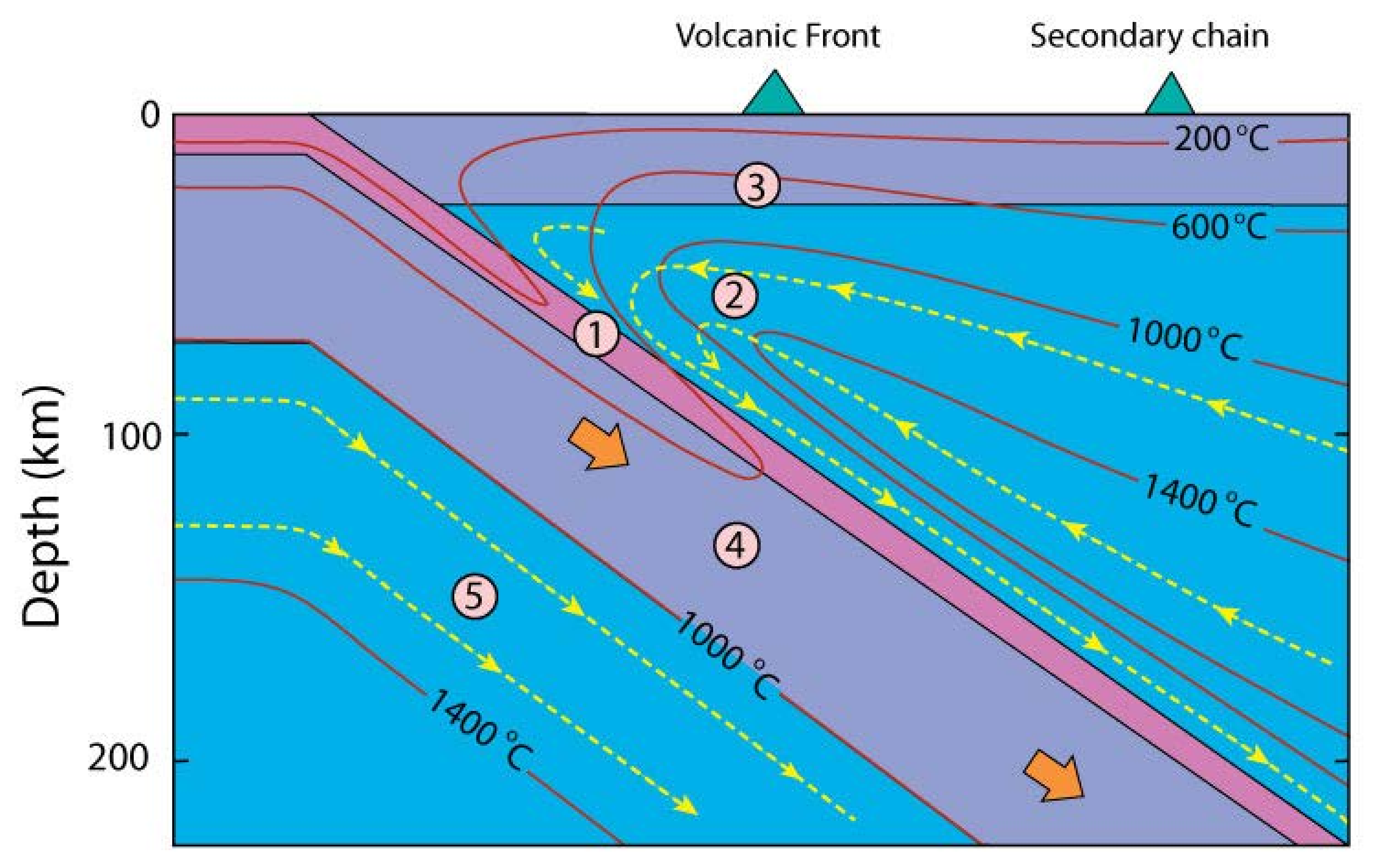


Figure 21.12. The Sanbagawa and Ryoke metamorphic belts of Japan. From Turner (1981) *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill and Miyashiro (1994) *Metamorphic Petrology*. Oxford University Press.

Paired Metamorphic Belts of Japan



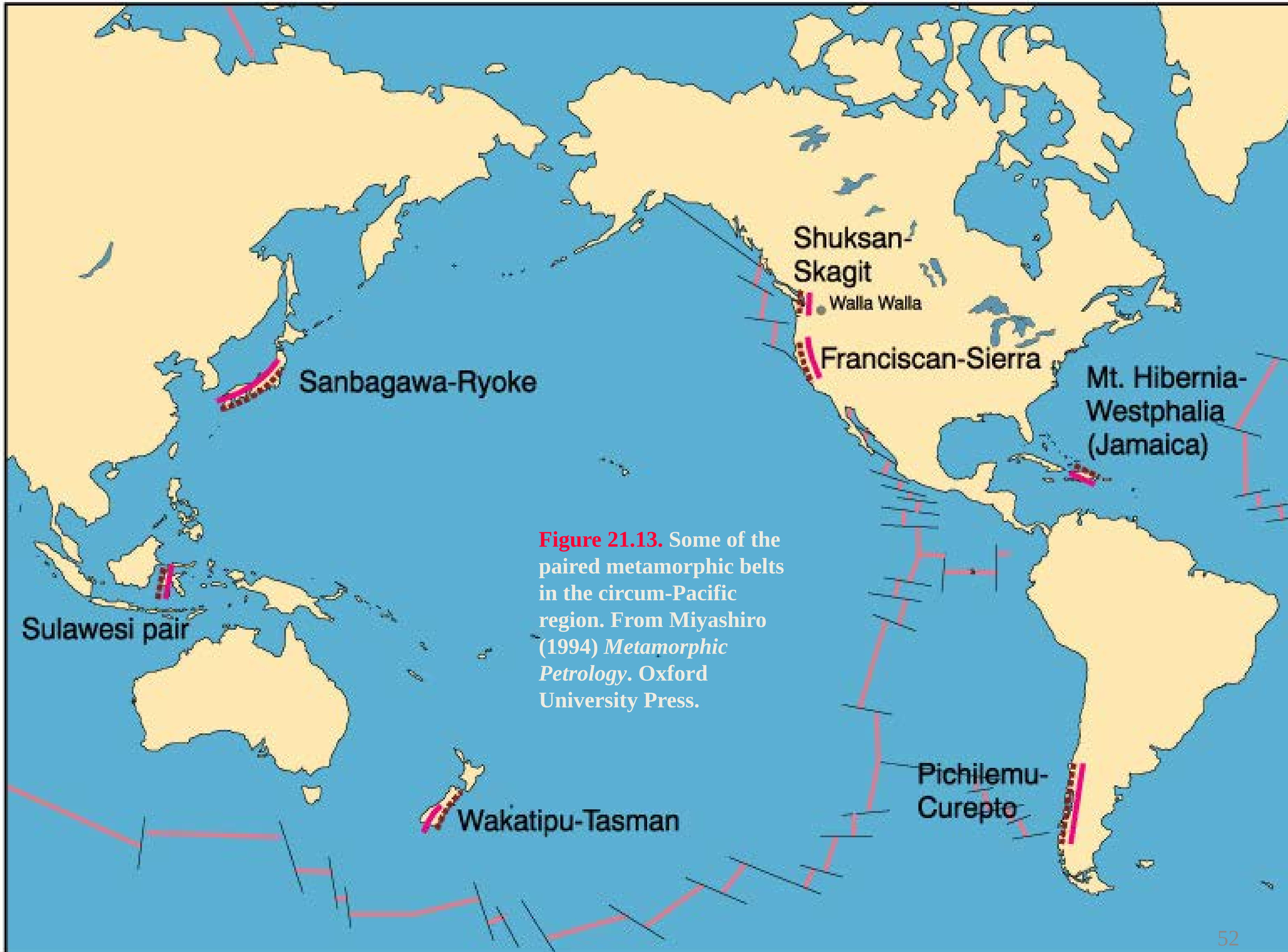


Figure 21.13. Some of the paired metamorphic belts in the circum-Pacific region. From Miyashiro (1994) *Metamorphic Petrology*. Oxford University Press.