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

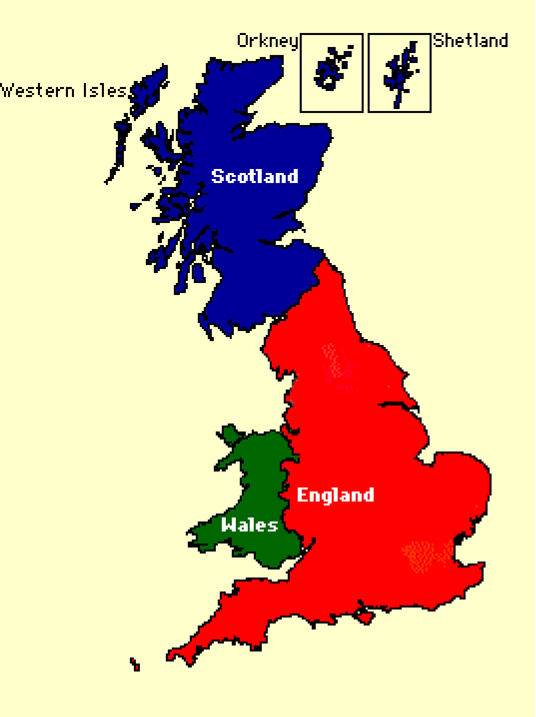
Some Examples of Metamorphism

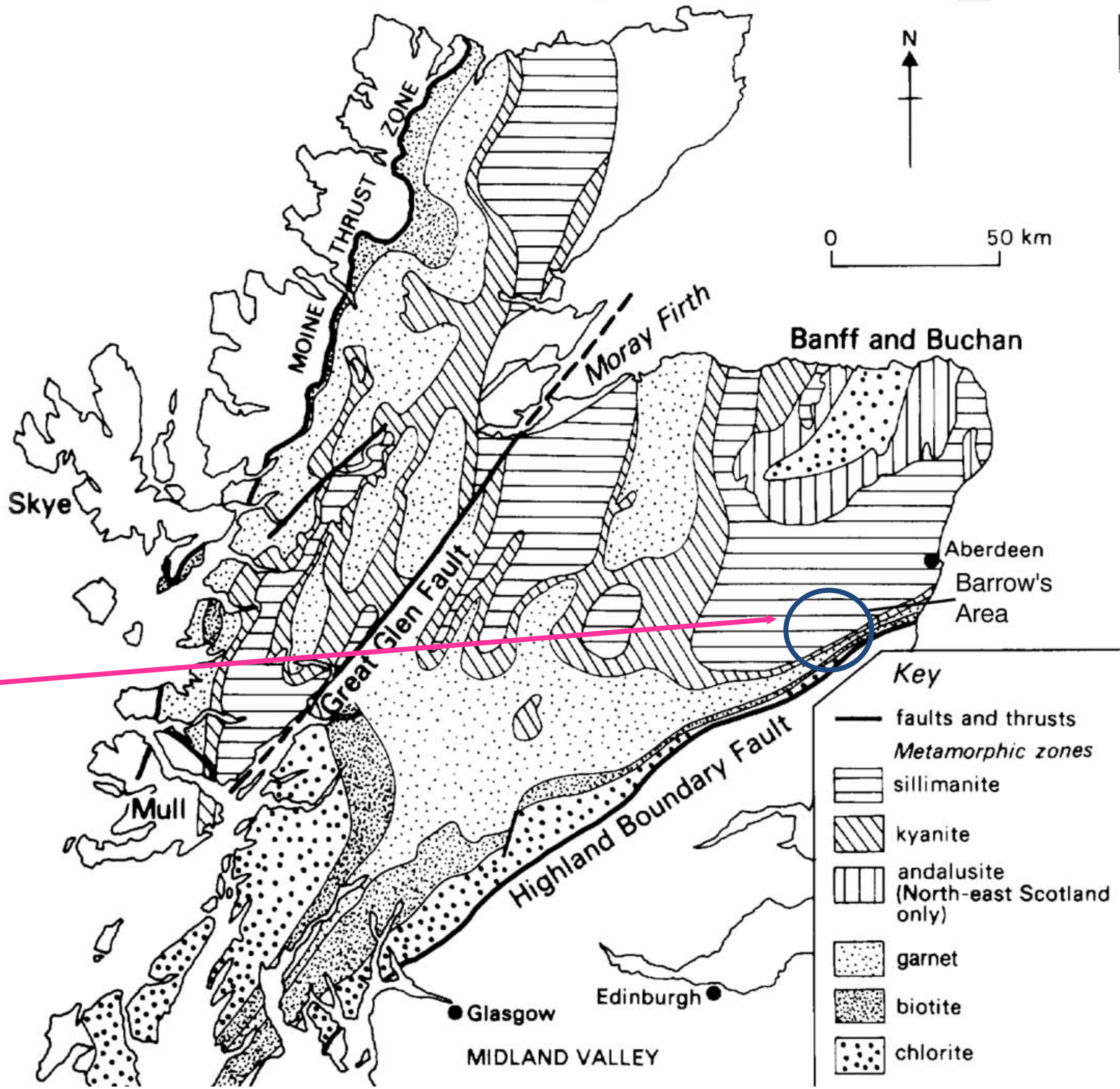
- Why study metamorphic regions/areas?

- 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

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)

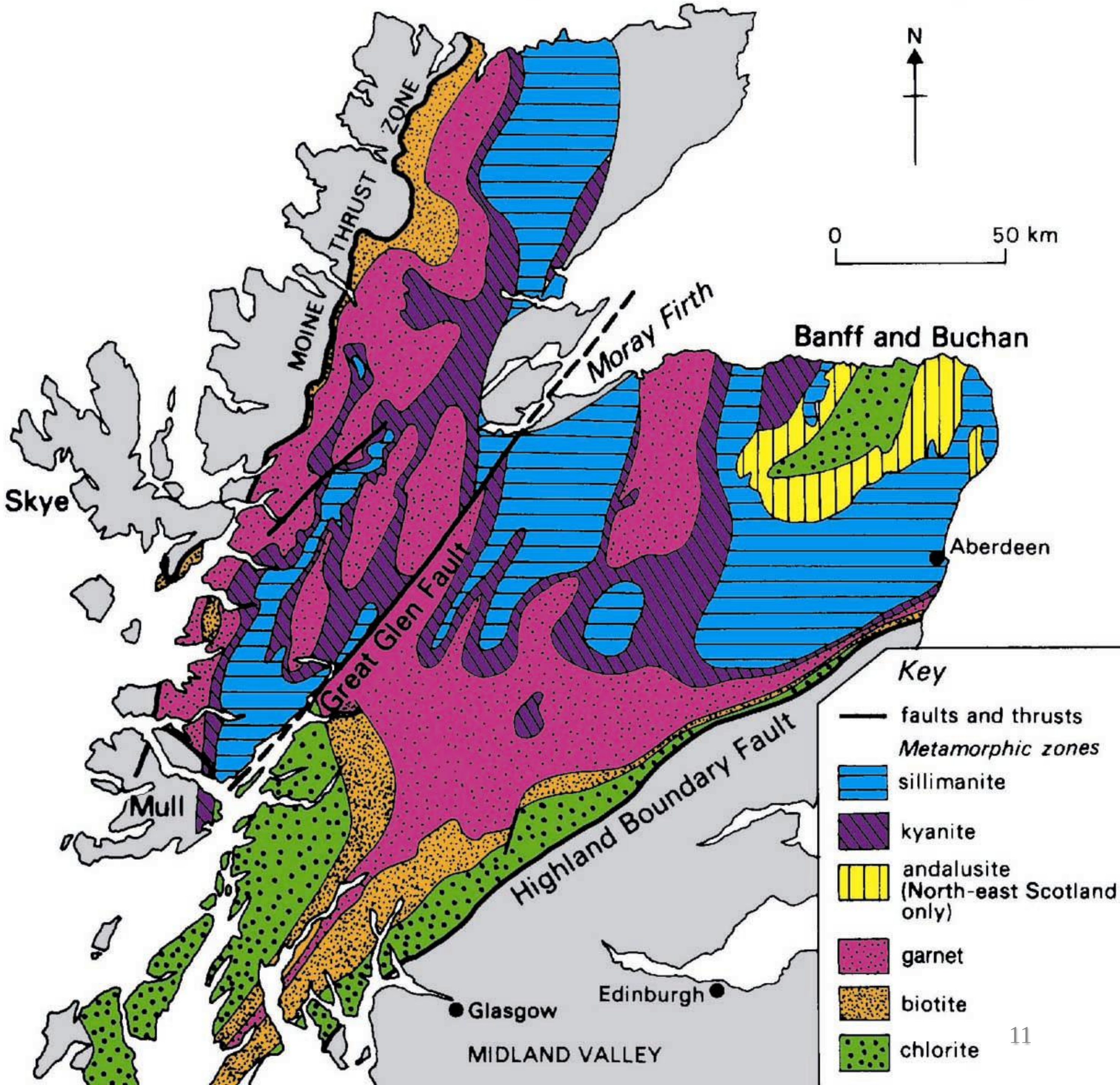


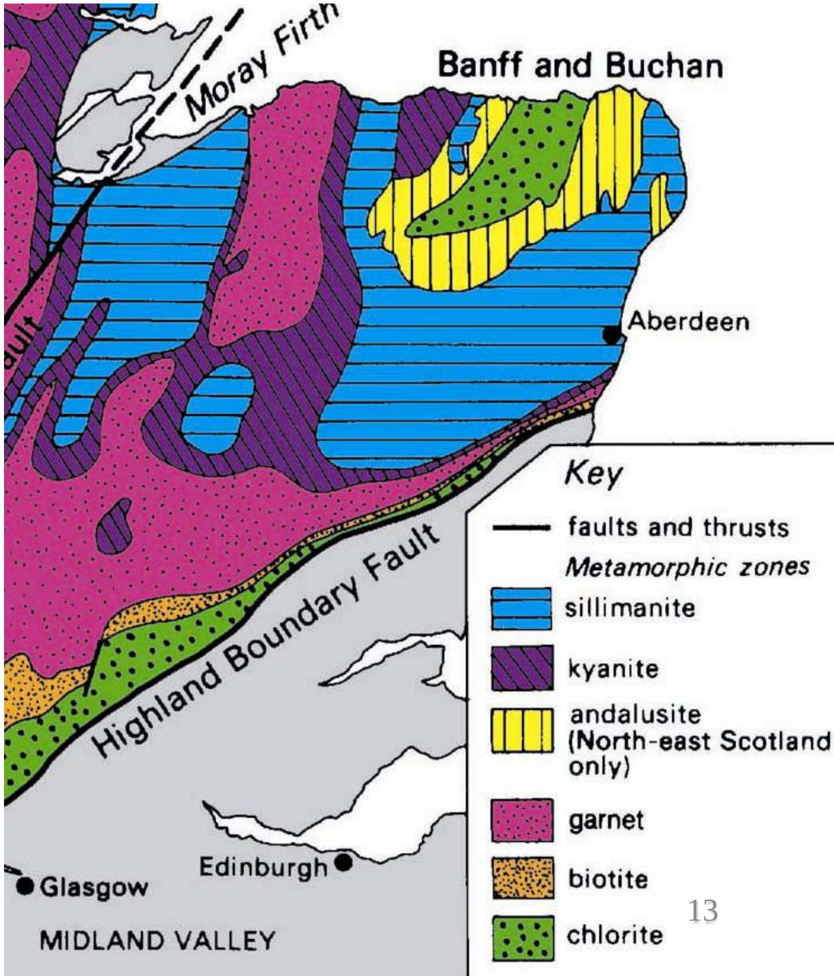
Figure 21.8. Regional metamorphic map of the Scottish Highlands, showing the zones of minerals that develop with increasing metamorphic grade. From Gillen (1982) *Metamorphic Geology. An Introduction to Tectonic and Metamorphic Processes*. George Allen & Unwin. London.

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

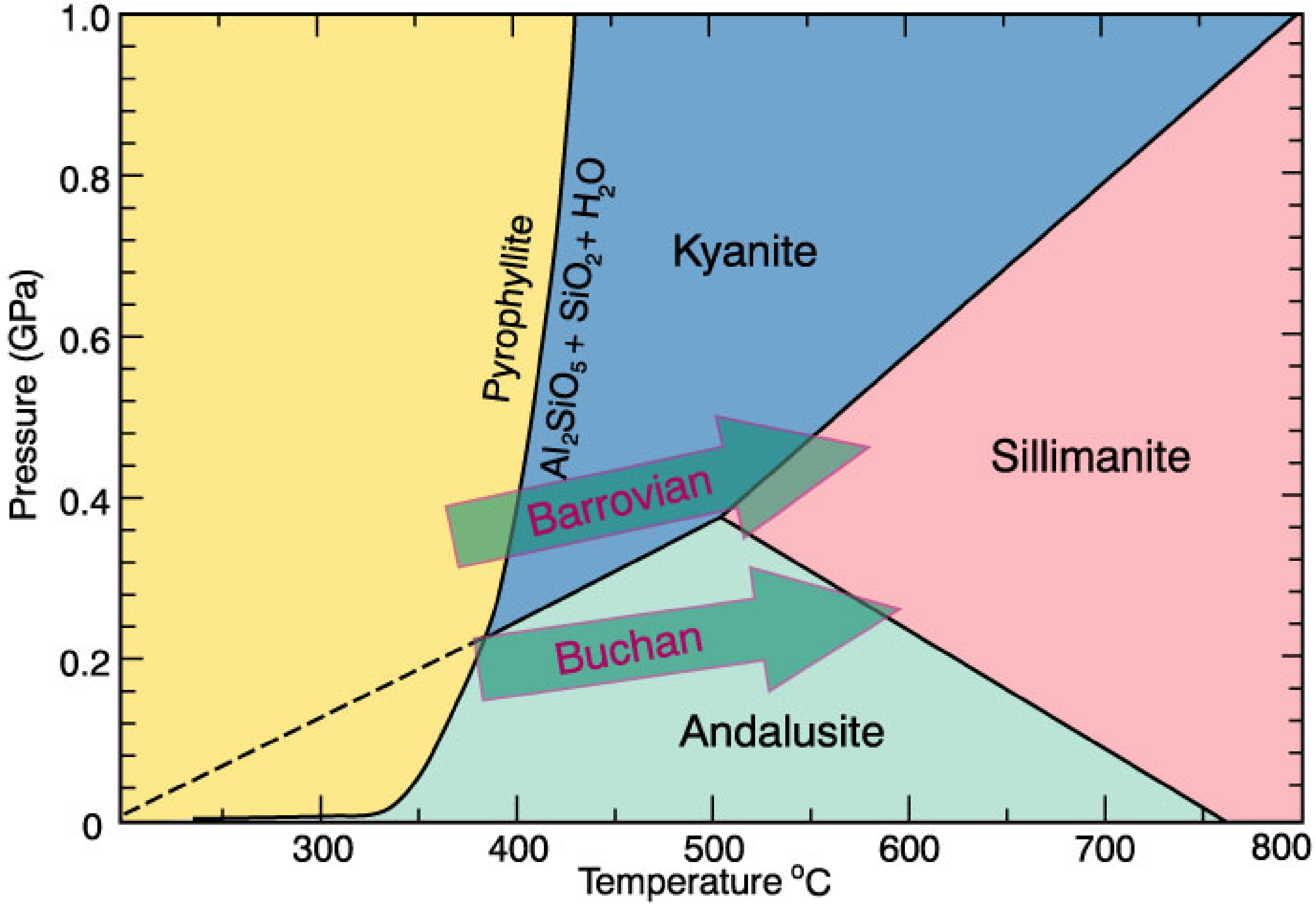


Figure 21.9. The P-T phase diagram for the system Al_2SiO_5 showing the stability fields for the three polymorphs andalusite, kyanite, and sillimanite. Also shown is the hydration of Al_2SiO_5 to pyrophyllite, which limits the occurrence of an Al_2SiO_5 polymorph at low grades in the presence of excess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

Paired Metamorphic Belts of Japan

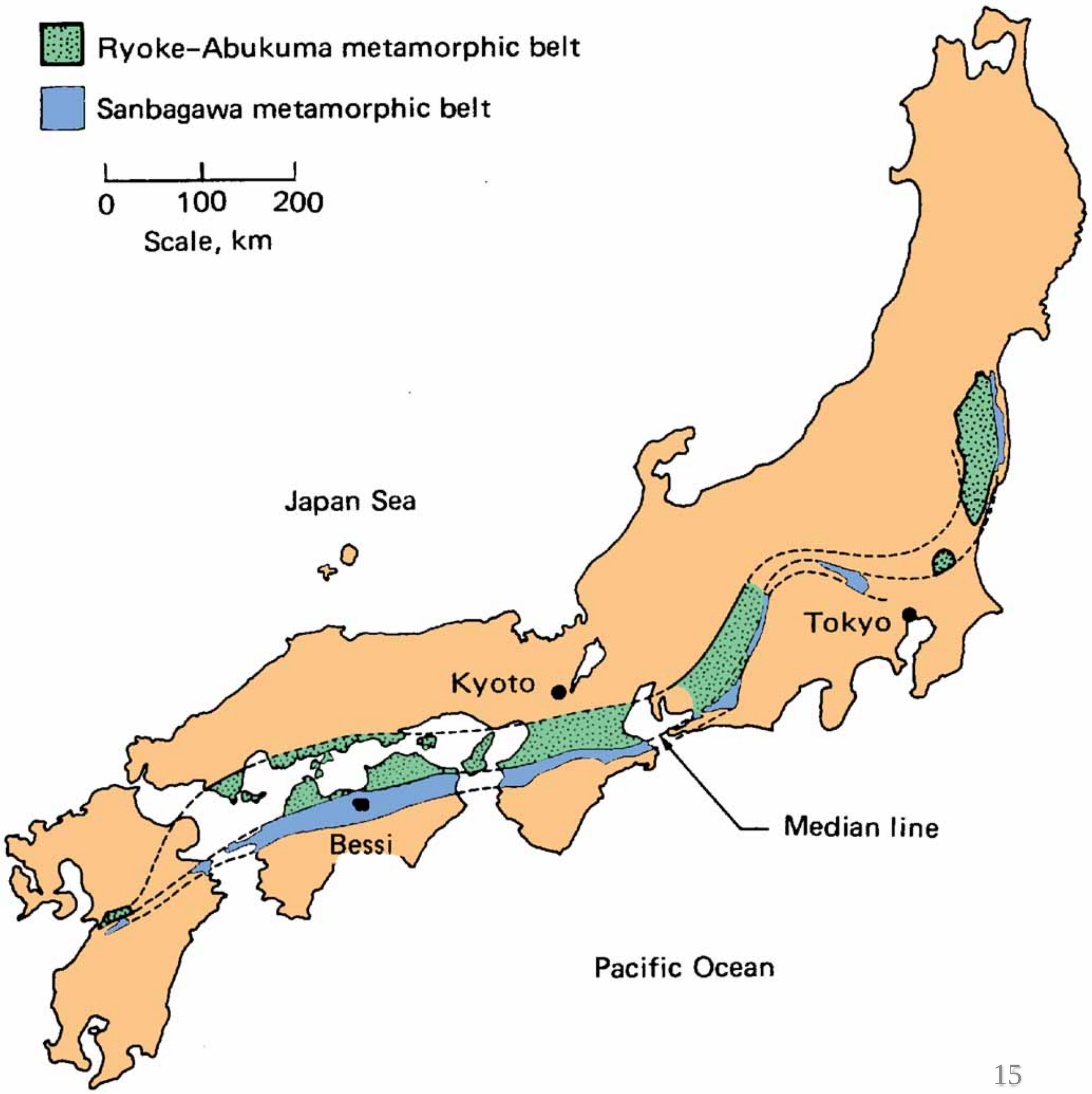
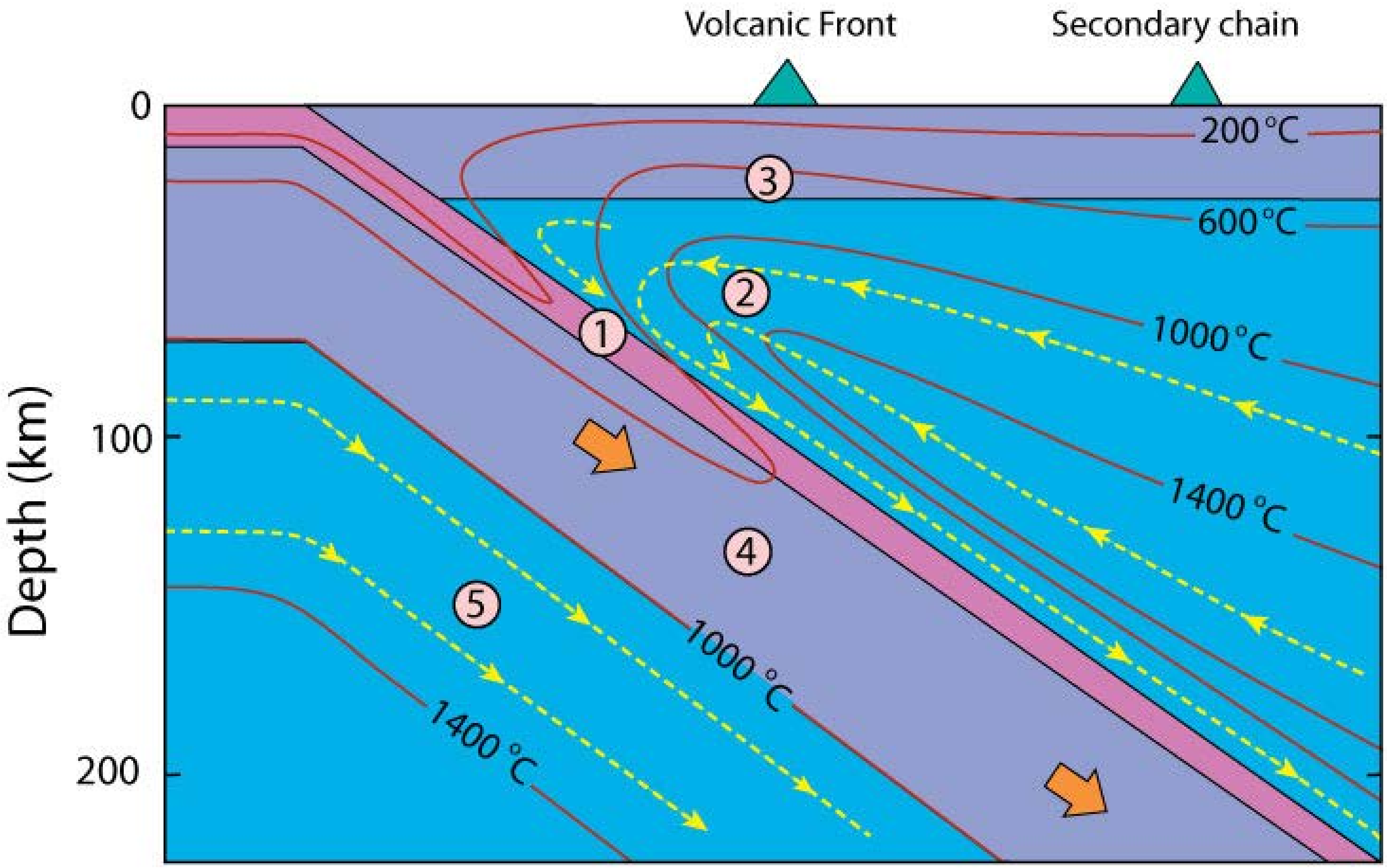


Figure 21.12. The Sanbagawa and Ryoke metamorphic belts of Japan. From Turner (1981) *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill and Miyashiro (1994) *Metamorphic Petrology*. Oxford University Press.

Paired Metamorphic Belts of Japan



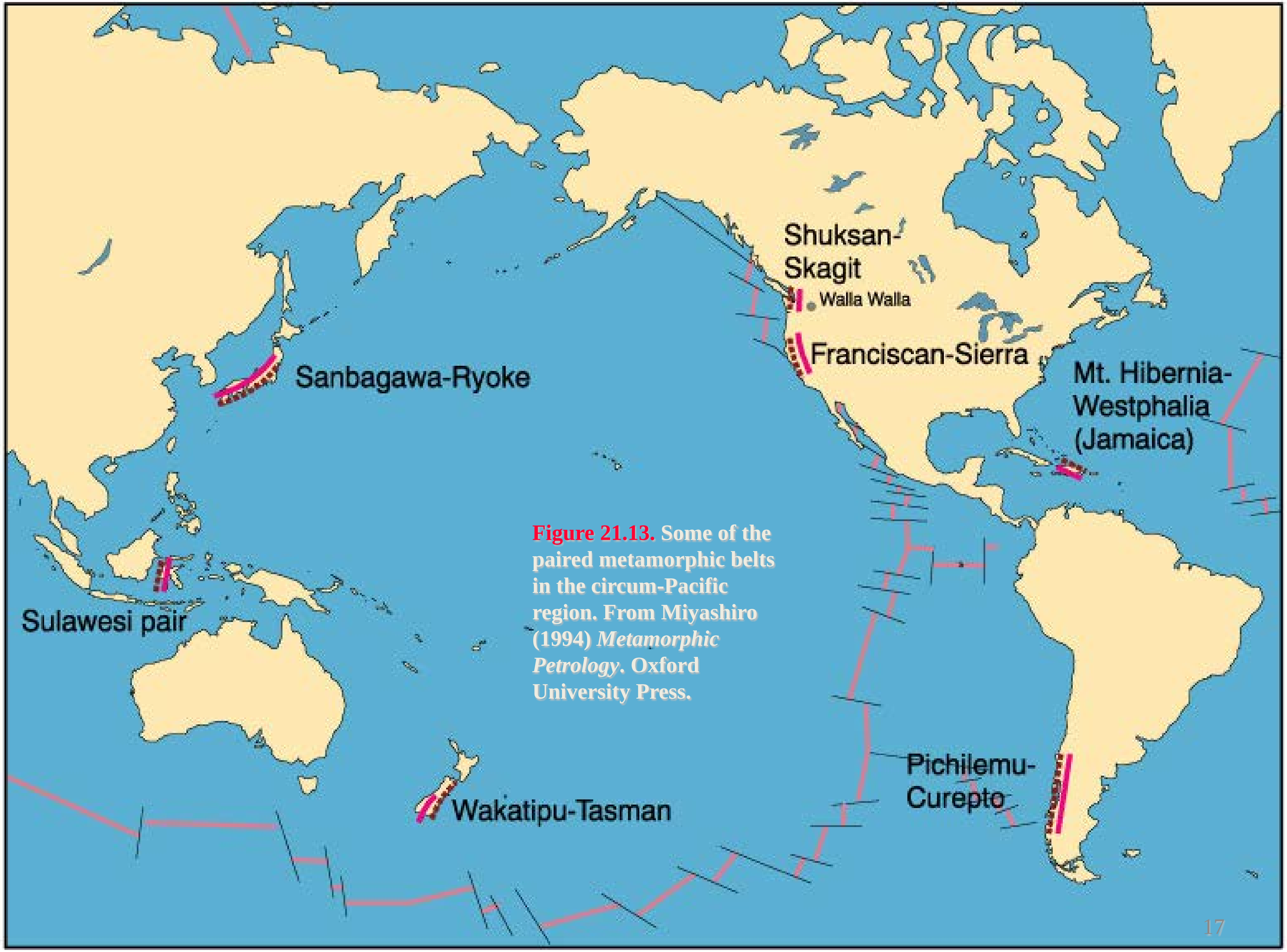


Figure 21.13. Some of the paired metamorphic belts in the circum-Pacific region. From Miyashiro (1994) *Metamorphic Petrology*. Oxford University Press.

Chapter 22: A Classification of Metamorphic Rocks

- Metamorphic rocks are classified on the basis of *texture* and *composition* (either mineralogical or chemical)
- Unlike igneous rocks, which have been plagued by a proliferation of local and specific names, metamorphic rock names are surprisingly simple and flexible
- May choose some prefix-type modifiers to attach to names if care to stress some important or unusual textural or mineralogical aspects

Foliated Metamorphic Rocks

- Foliation: any planar fabric element
- Lineation: any linear fabric elements
  - They have no genetic connotations
  - Some high-strain rocks may be foliated, but they are treated separately

Foliated Metamorphic Rocks

Cleavage

- Traditionally: the property of a rock to split along a regular set of sub-parallel, closely-spaced planes
- A more general concept adopted by some geologists is to consider cleavage to be any type of foliation in which the aligned platy phyllosilicates are too fine grained to see individually with the unaided eye

Foliated Metamorphic Rocks

Schistosity

- A preferred orientation of inequaint mineral grains or grain aggregates produced by metamorphic processes
- Aligned minerals are coarse grained enough to see with the unaided eye
- The orientation is generally planar, but linear orientations are not excluded

Foliated Metamorphic Rocks

Gneissose structure

- Either a poorly-developed schistosity or segregated into layers by metamorphic processes
- Gneissose rocks are generally coarse grained

Foliated Metamorphic Rocks

Slate: **compact, very fine-grained, metamorphic rock with a well-developed cleavage. Freshly cleaved surfaces are dull**

Phyllite: **a rock with a schistosity in which very fine phyllosilicates (sericite/phengite and/or chlorite), although rarely coarse enough to see unaided, impart a silky sheen to the foliation surface. Phyllites with both a foliation and lineation are very common.**

Figure 22.1. Examples of foliated metamorphic rocks. a. Slate. b. Phyllite. Note the difference in reflectance on the foliation surfaces between a and b: phyllite is characterized by a satiny sheen. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Foliated Metamorphic Rocks

Schist: **a metamorphic rock exhibiting a schistosity. By this definition schist is a broad term, and slates and phyllites are also types of schists. In common usage, schists are restricted to those metamorphic rocks in which the foliated minerals are coarse enough to see easily in hand specimen.**

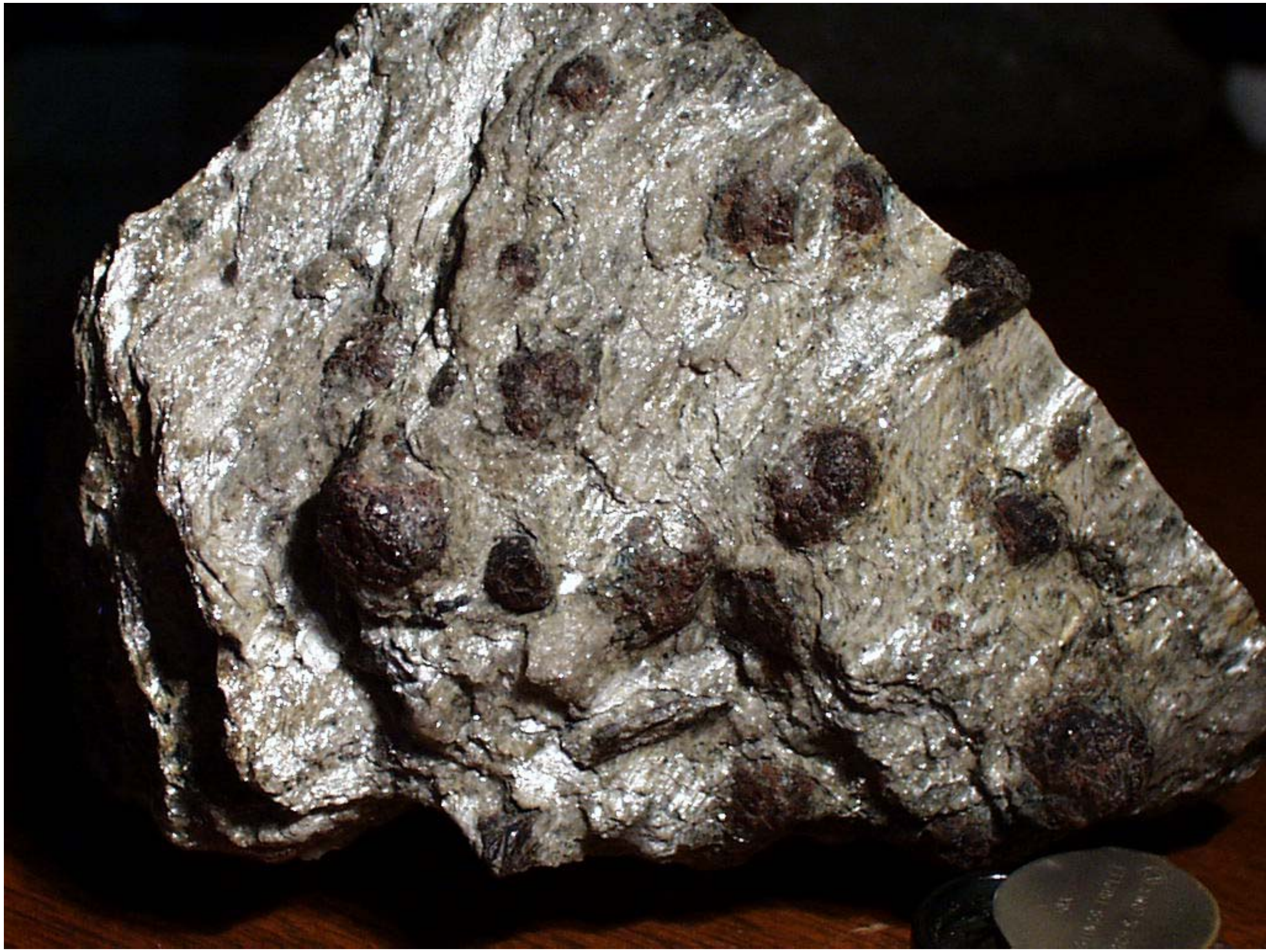


Figure 22.1c. Garnet muscovite schist. Muscovite crystals are visible and silvery, garnets occur as large dark porphyroblasts. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Foliated Metamorphic Rocks

Gneiss: **a metamorphic rock displaying gneissose structure. Gneisses are typically layered (also called banded), generally with alternating felsic and darker mineral layers. Gneisses may also be lineated, but must also show segregations of felsic-mineral-rich and dark-mineral-rich concentrations.**

Figure 22.1d. Quartzo-feldspathic gneiss with obvious layering. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Non-Foliated Metamorphic Rocks

Simpler than for foliated rocks

Again, this discussion and classification applies only to rocks that are not produced by high-strain metamorphism

Granofels: a comprehensive term for any isotropic rock (a rock with no preferred orientation)

Hornfels is a type of granofels that is typically very fine-grained and compact, and occurs in contact aureoles. Hornfelses are tough, and tend to splinter when broken.

Specific Metamorphic Rock Types

Marble: a metamorphic rock composed predominantly of calcite or dolomite. The protolith is typically limestone or dolostone.

Quartzite: a metamorphic rock composed predominantly of quartz. The protolith is typically sandstone.

Specific Metamorphic Rock Types

Greenschist/Greenstone: a low-grade metamorphic rock that typically contains chlorite, actinolite, epidote, and albite. Note that the first three minerals are green, which imparts the color to the rock. Such a rock is called greenschist if foliated, and greenstone if not. The protolith is either a mafic igneous rock or graywacke.

Amphibolite: a metamorphic rock dominated by hornblende (**amphibole**) + plagioclase. Amphibolites may be foliated or non-foliated. The protolith is either a mafic igneous rock or graywacke.

Specific Metamorphic Rock Types

Serpentinite: an ultramafic rock metamorphosed at low grade, so that it contains mostly serpentine.

Blueschist: a **blue amphibole (glaucophane)**-bearing metamorphosed mafic igneous rock or mafic graywacke. This term is so commonly applied to such rocks that it is even applied to non-schistose rocks.

Eclogite: a green and red metamorphic rock that contains clinopyroxene and garnet (omphacite + pyrope). The protolith is typically basaltic.

Specific Metamorphic Rock Types

Skarn: a contact metamorphosed and silica metasomatized carbonate rock containing calc-silicate minerals, such as grossular, epidote, tremolite, vesuvianite, etc. Tactite is a synonym.

Granulite: a high grade rock of pelitic, mafic, or quartzo-feldspathic parentage that is predominantly composed of OH-free minerals. Muscovite is absent and plagioclase and orthopyroxene are common.

Specific Metamorphic Rock Types

Migmatite: a composite silicate rock that is heterogeneous on the 1-10 cm scale, commonly having a dark gneissic matrix (*melanosome*) and lighter felsic portions (*leucosome*). Migmatites may appear layered, or the leucosomes may occur as pods or form a network of cross-cutting veins.

Chapter 22: A Classification of Metamorphic Rocks

Additional Modifying Terms:

Porphyroblastic means that a metamorphic rock has one or more metamorphic minerals that grew much larger than the others. Each individual crystal is a porphyroblast

Some porphyroblasts, particularly in low-grade contact metamorphism, occur as ovoid "spots"

If such spots occur in a hornfels or a phyllite (typically as a contact metamorphic overprint over a regionally developed phyllite), the terms spotted hornfels, or spotted phyllite would be appropriate.

Chapter 22: A Classification of Metamorphic Rocks

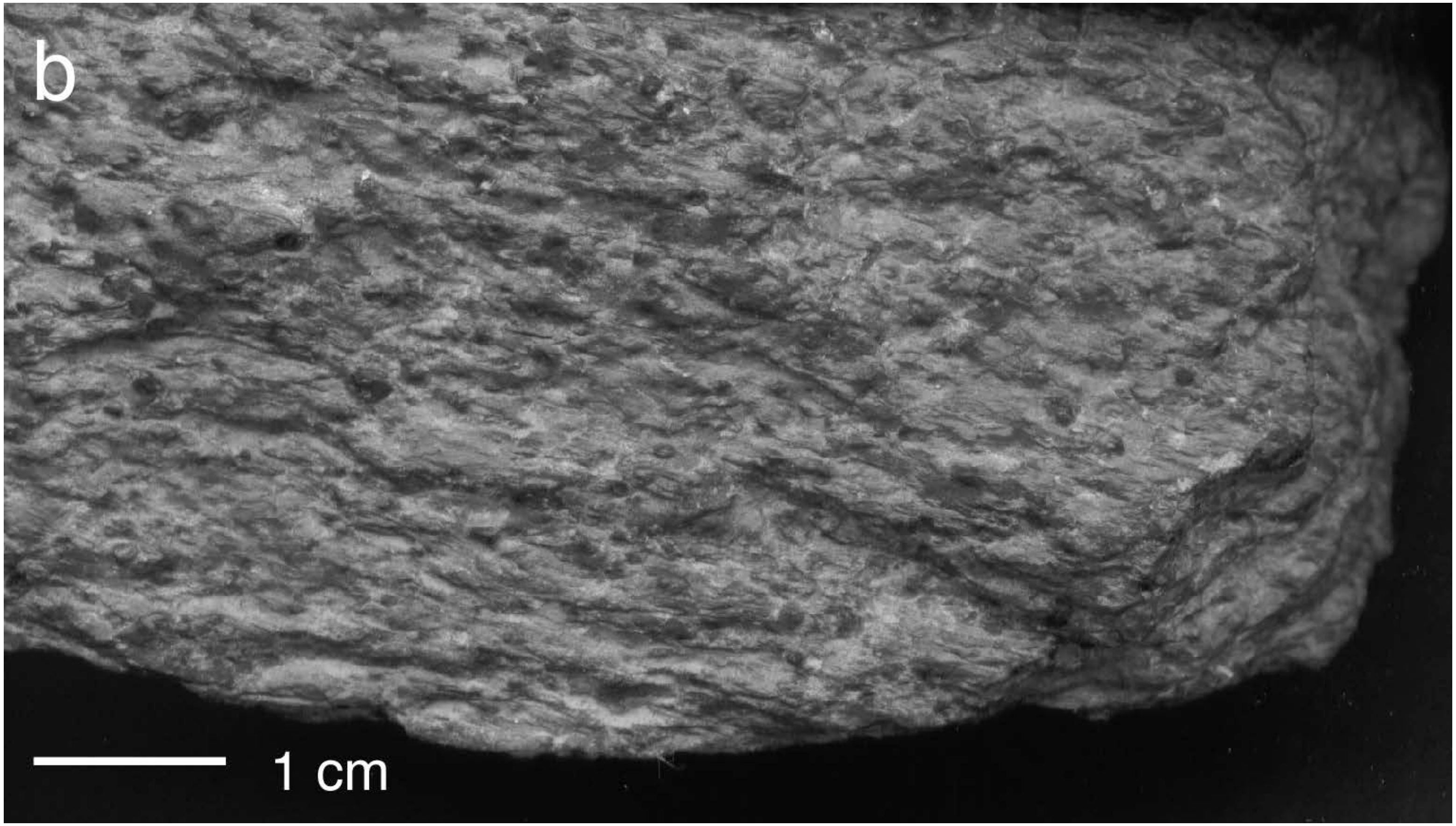


Figure 23.14b. **Spotted Phyllite. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.**

Chapter 22: A Classification of Metamorphic Rocks

Additional Modifying Terms:

Some gneisses have large eye-shaped grains (commonly feldspar) that are derived from pre-existing large crystals by shear (as described in lecture 1). Individual grains of this sort are called auge (German for *eye*), and the (German) plural is augen. An augen gneiss is a gneiss with augen structure (next slide).

Chapter 22: A Classification of Metamorphic Rocks

Figure 23.18. Augen Gneiss. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Chapter 22: A Classification of Metamorphic Rocks

Additional Modifying Terms:

Other modifying terms that we may want to add as a means of emphasizing some aspect of a rock may concern such features as **grain-size**, **color**, **chemical** aspects, (aluminous, calcareous, mafic, felsic, etc.). As a general rule we use these when the aspect is unusual.

Obviously a *calcareous marble* or *mafic greenschist* is redundant, as is a *fine grained slate*.

Chapter 22: A Classification of Metamorphic Rocks

Additional Modifying Terms:

Ortho- a prefix indicating an igneous parent, and

Para- a prefix indicating a sedimentary parent

The terms are used only when they serve to dissipate doubt. For example, many quartzo-feldspathic gneisses could easily be derived from either an impure arkose or a granitoid rock. If some mineralogical, chemical, or field-derived clue permits the distinction, terms such as *orthogneiss*, *paragneiss*, or *orthoamphibolite* may be useful.

Chapter 22: High Strain Rocks

Table 22-1. Classification of High-Strain Fault Zone Rocks

% fine matrix	Rocks without primary cohesion	Rocks with primary cohesion			
		Non-foliated	Foliated		Glass in matrix
	Fault breccia	Microbreccia	Protomylonite	Blastomylonite (if significantly recrystallized)	Pseudotachylite
50			Mylonite		
70	Fault gouge	Cataclasite			
90			Ultramylonite		

After Higgins (1971)

Chapter 22: High Strain Rocks

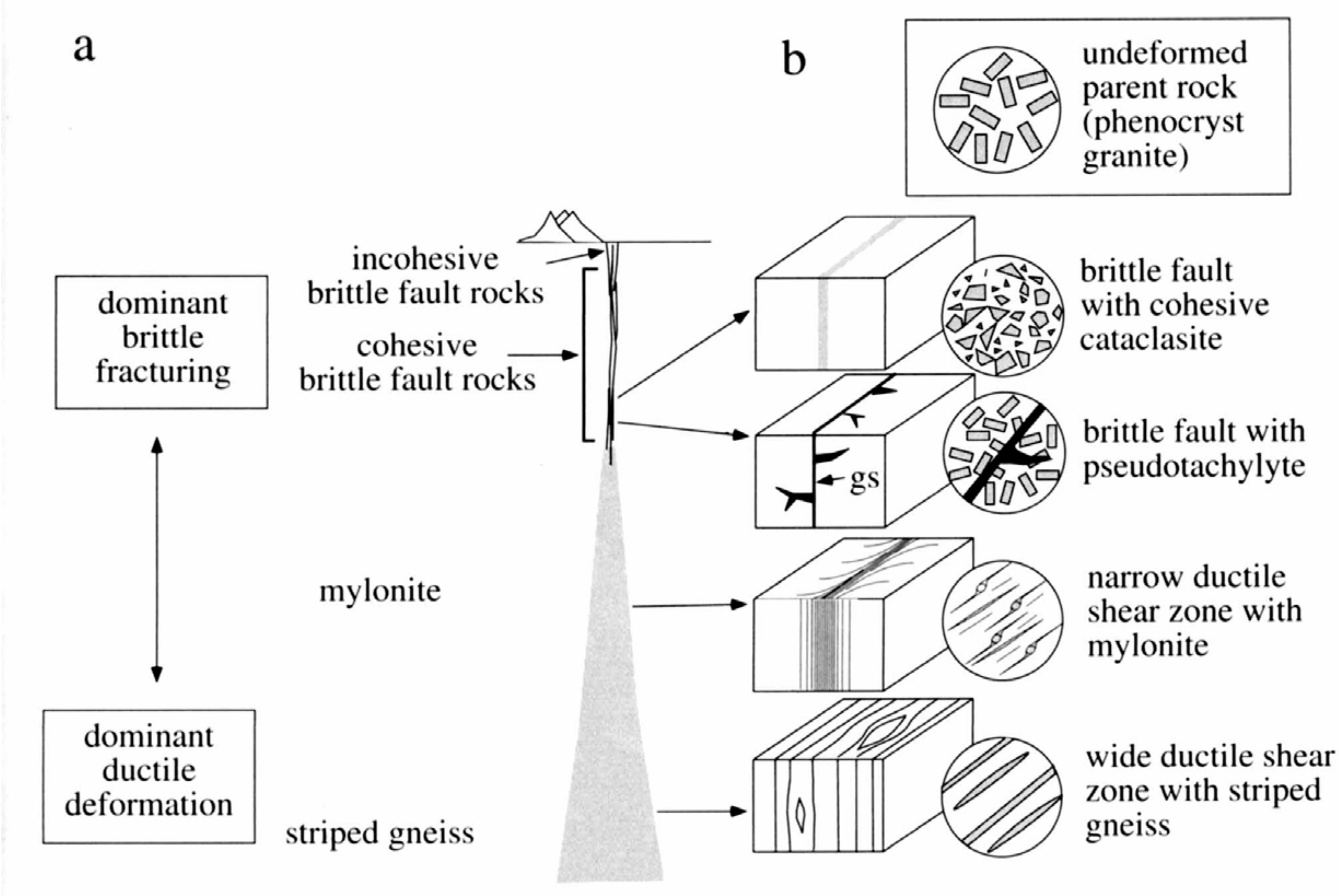


Figure 22.2. Schematic cross section through a shear zone, showing the vertical distribution of fault-related rock types, ranging from non-cohesive gouge and breccia near the surface through progressively more cohesive and foliated rocks. Note that the width of the shear zone increases with depth as the shear is distributed over a larger area and becomes more ductile. Circles on the right represent microscopic views or textures. From Passchier and Trouw (1996) *Microtectonics*. Springer-Verlag. Berlin.

Chapter 22: High Strain Rocks

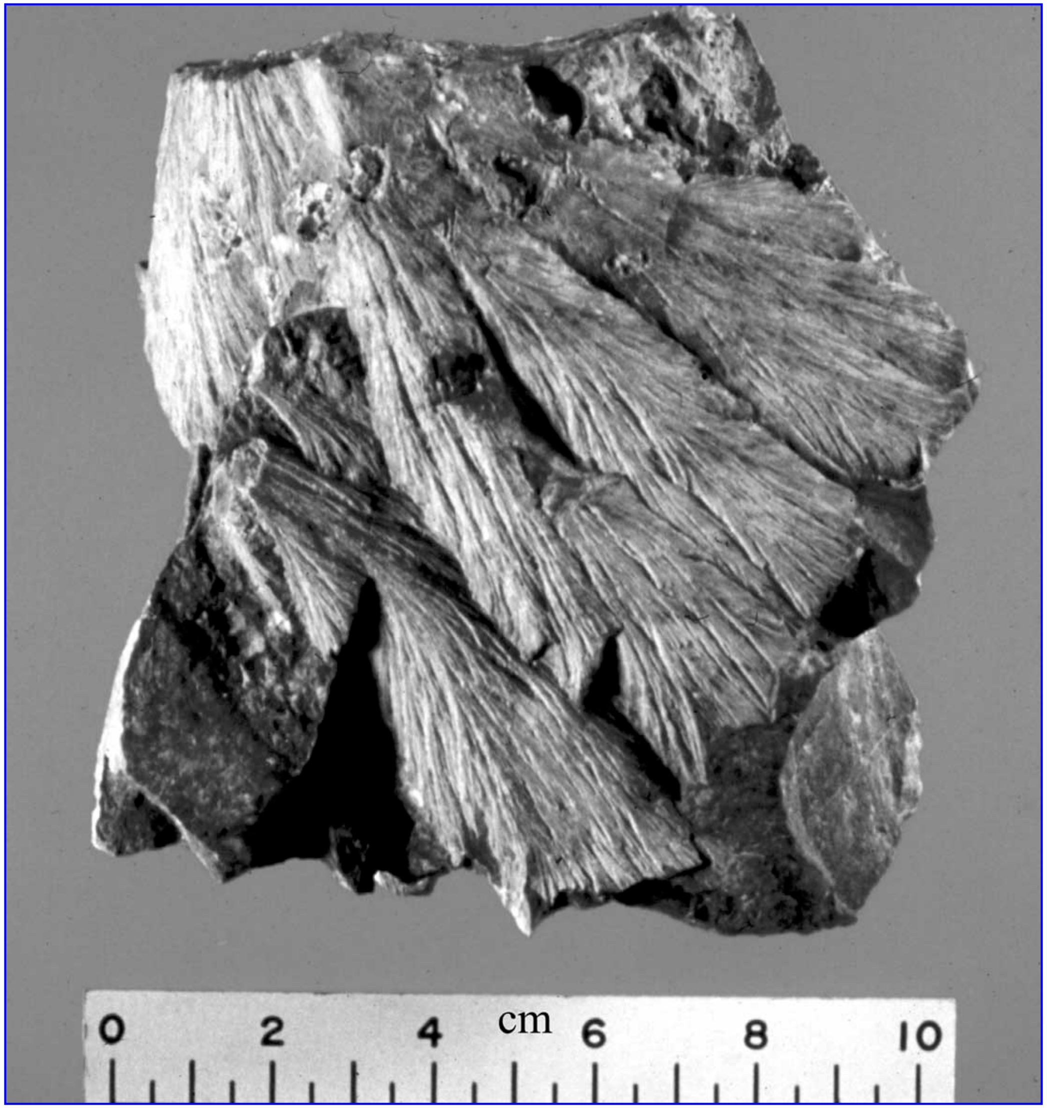
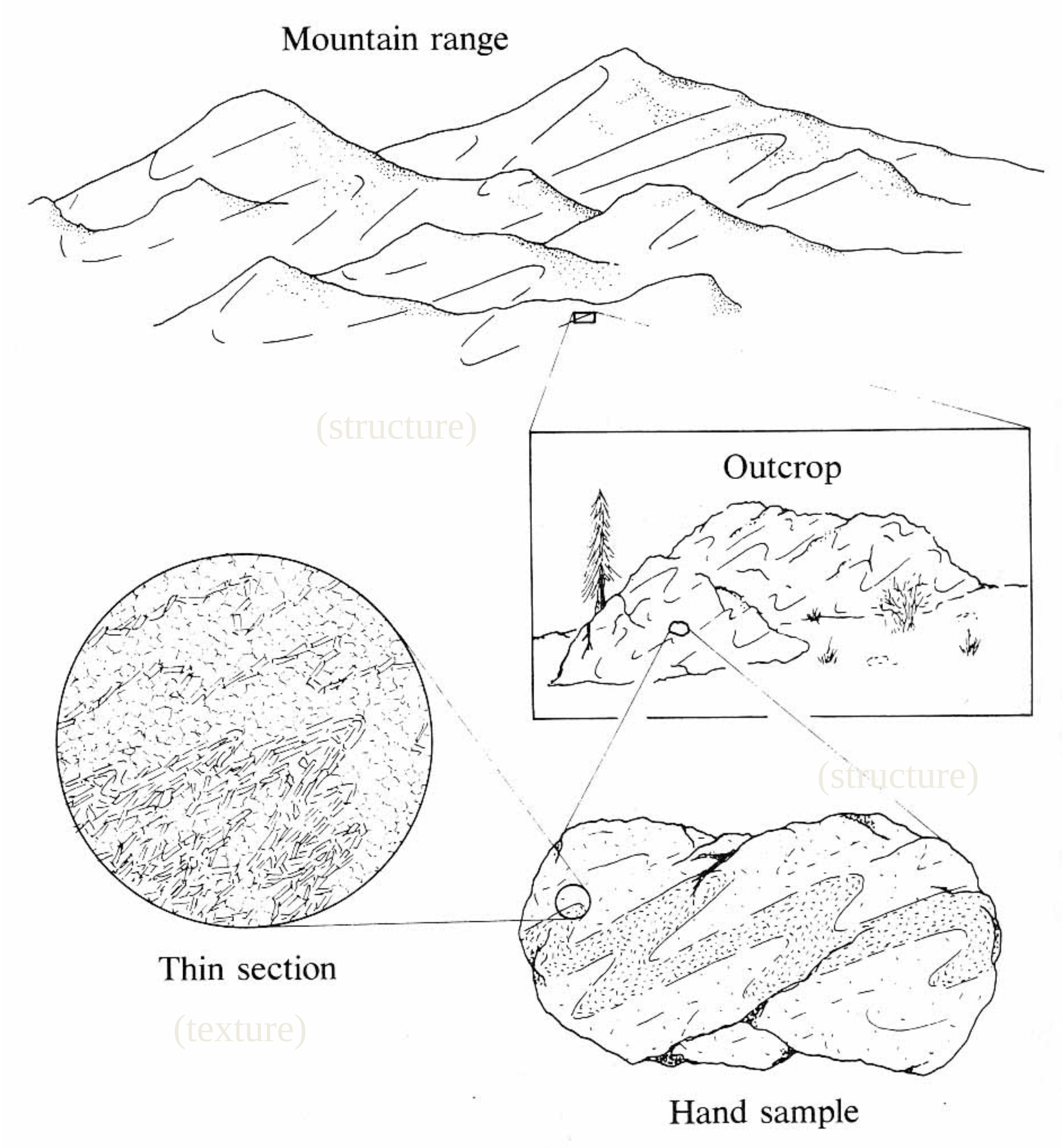


Figure 22.4. Shatter cones in limestone from the Haughton Structure, Northwest Territories. Photograph courtesy Richard Grieve, © Natural Resources Canada.

Chapter 23: Metamorphic Textures



Structures vs. Textures

The fractal nature of geology

Diagram showing that structural and fabric elements are generally consistent in style and orientation at all scales. From Best (1982). *Igneous and Metamorphic Petrology*. W. H. Freeman. San Francisco.

Chapter 23: Metamorphic Textures

Textures are small-scale penetrative features

Relict Textures

- Inherited from original rock
- "Blasto-" = relict
- Any degree of preservation
- Pseudomorphs of minerals or pre-metamorphic textures/structures

Chapter 23: Metamorphic Textures

Metamorphic Textures

The Processes of Deformation, Recovery, and Recrystallization (listed in order of increasing temperature and/or decreasing strain rate) are:

1. **Cataclastic Flow**

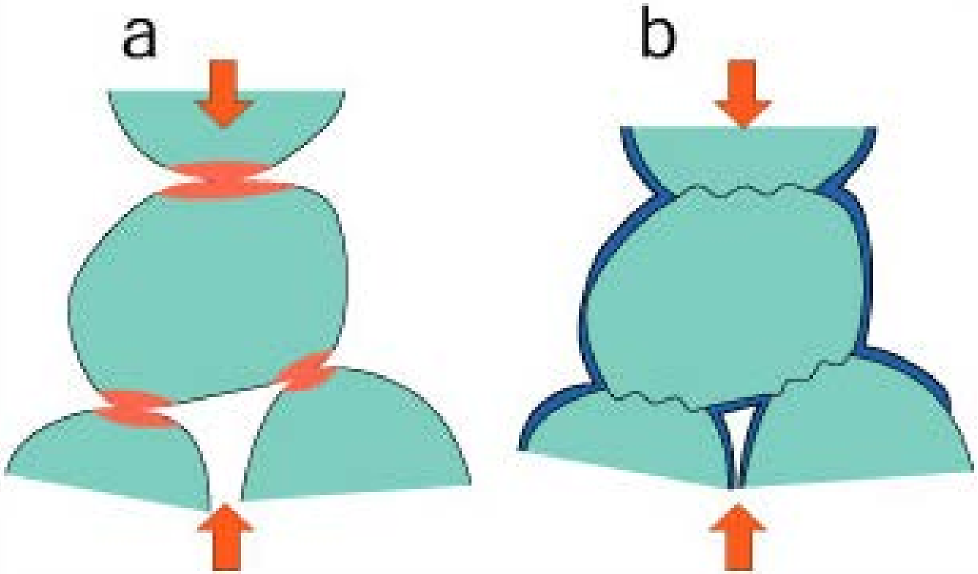
   - Mechanical fragmentation and sliding, rotation of fragments
   - Crush, break, bend, grind, kink, def^{m} twins, undulose extinction, shredding of micas, augen, mortar, etc.

Chapter 23: Metamorphic Textures

Metamorphic Textures

The Processes of Deformation, Recovery, and Recrystallization

2. Pressure Solution



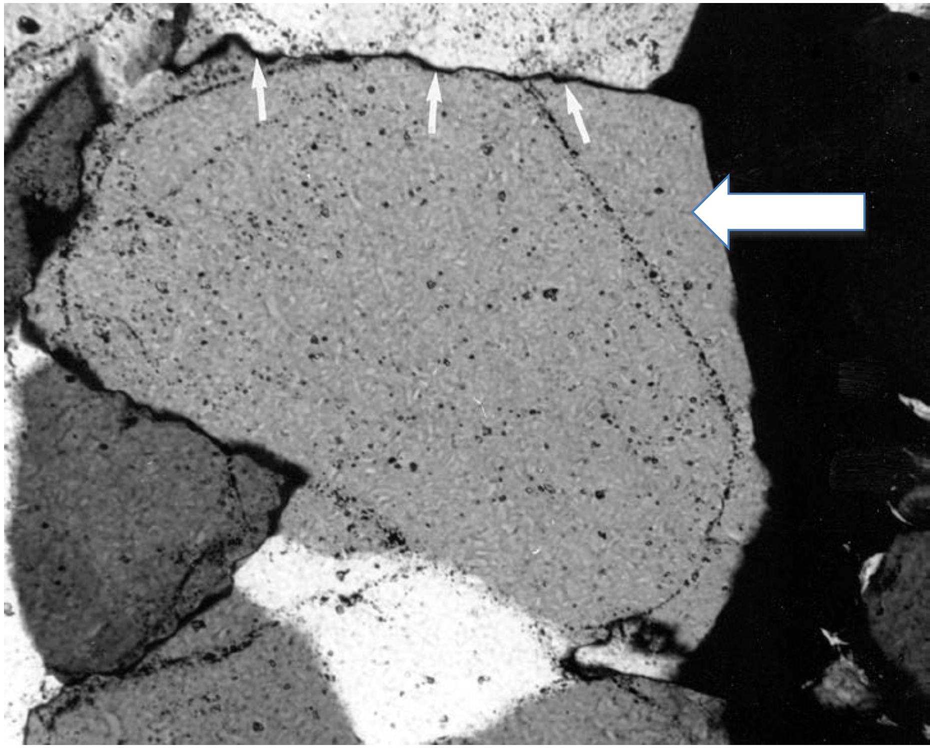


Figure 23.2 a. Highest strain in areas near grain contacts (hatch pattern). b. High-strain areas dissolve and material precipitates in adjacent low-strain areas (shaded). The process is accompanied by vertical shortening. c. Pressure solution of a quartz crystal in a deformed quartzite (σ_1 is vertical). Pressure solution results in a serrated solution surface in high-strain areas (small arrows) and precipitation in low-strain areas (large arrow). ~ 0.5 mm across. The faint line within the grain is a hematite stain along the original clast surface. After Hibbard (1995) *Petrography to Petrogenesis*. Prentice Hall.

Chapter 23: Metamorphic Textures

3. **Plastic Intracrystalline Deformation**

- No loss of cohesion
- Several processes may operate simultaneously
  - Defect migration
  - Slip planes
  - Dislocation glide
  - Deformation twinning

Chapter 23: Metamorphic Textures

4. **Recovery**
   - Loss of stored strain energy by vacancy migration, dislocation migration and annihilation
   - Polygonization- general term for formation of low-strain subgrains

Chapter 23: Metamorphic Textures

5. **Recrystallization**
    - Grain boundary migration
    - Subgrain rotation
    - Solid-state diffusion creep at higher T
    - Crystal plastic deformation (general term)
        - Grain boundary sliding and area reduction

Coalescence- recovery and recrystallization by which large grains form by the addition of smaller strained grains by grain boundary migration

Chapter 23: Metamorphic Textures

Dislocation migration forms two strain-free subgrains

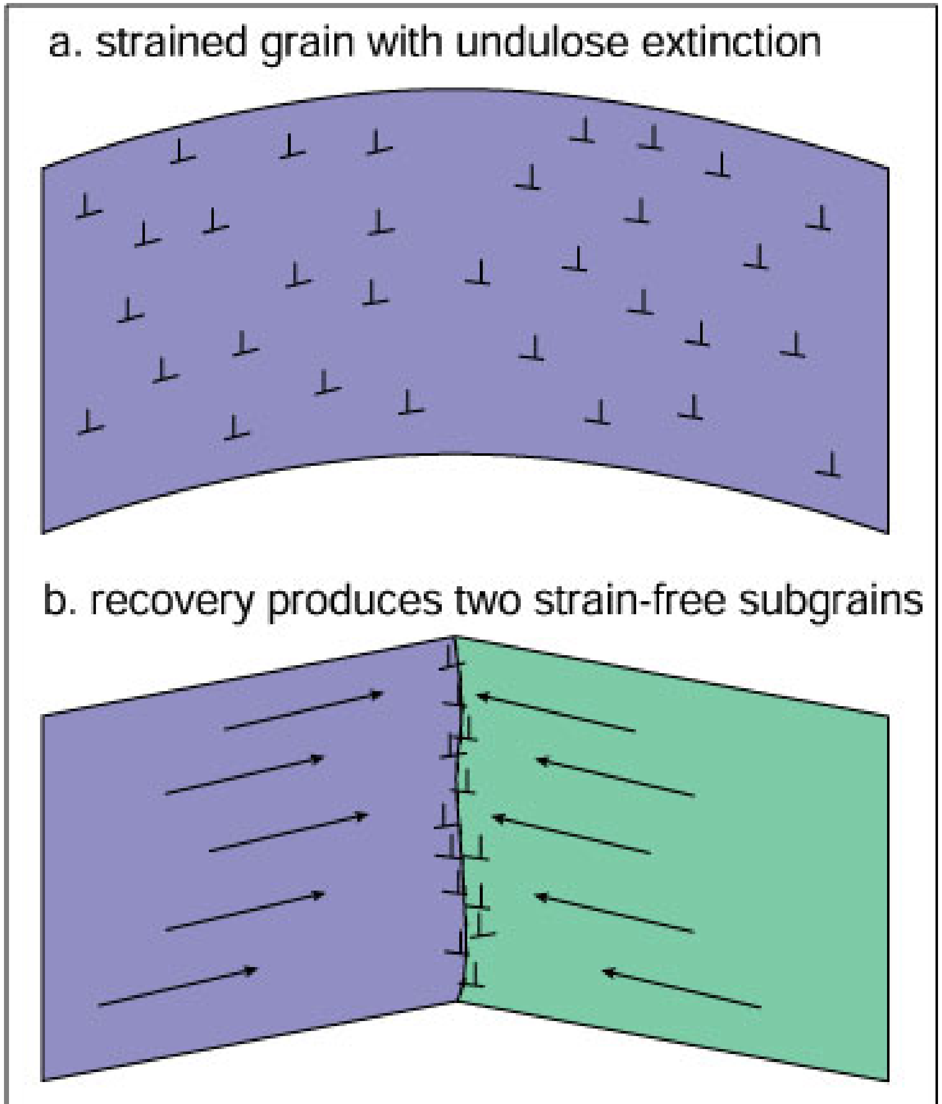


Figure 23.5. Illustration of a recovery process in which dislocations migrate to form a subgrain boundary. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Chapter 23: Metamorphic Textures

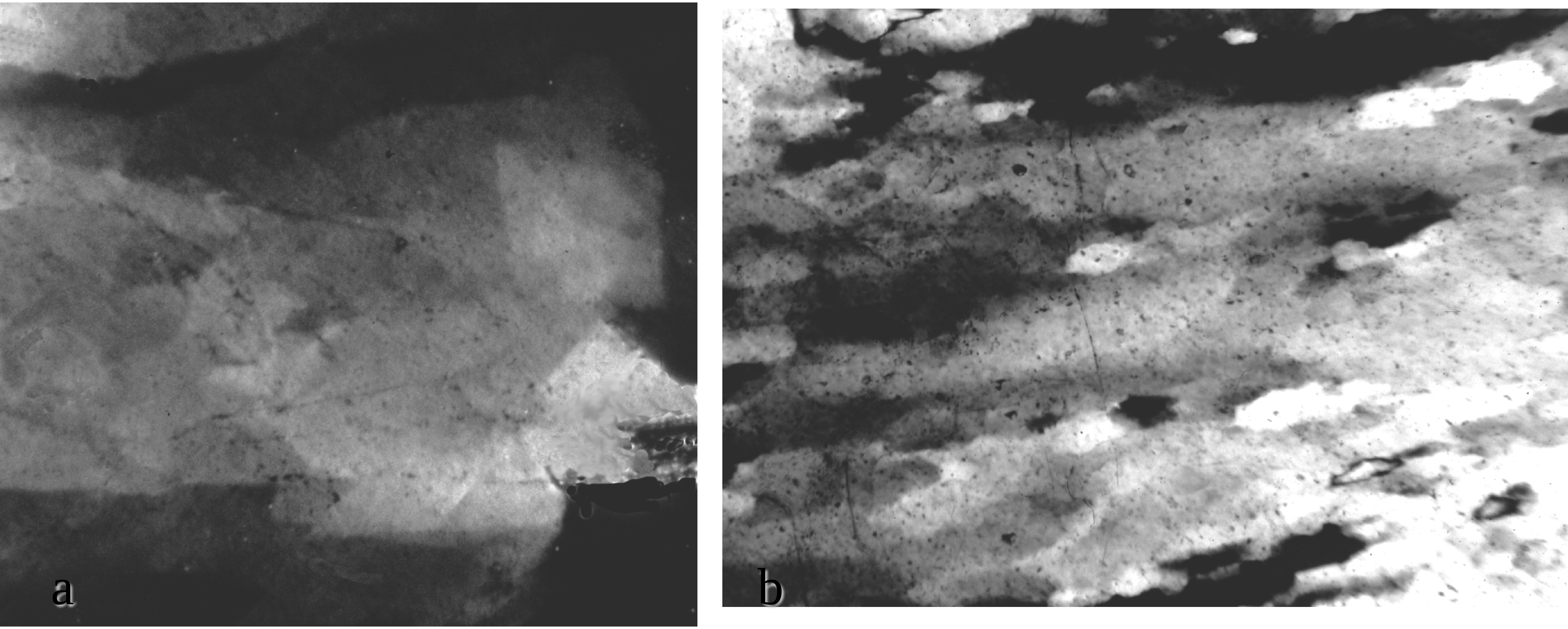


Figure 23.4 a. **Undulose extinction and** (b) **elongate subgrains in quartz due to dislocation formation and migration Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.**

Recrystallization by grain boundary migration and sub-grain rotation

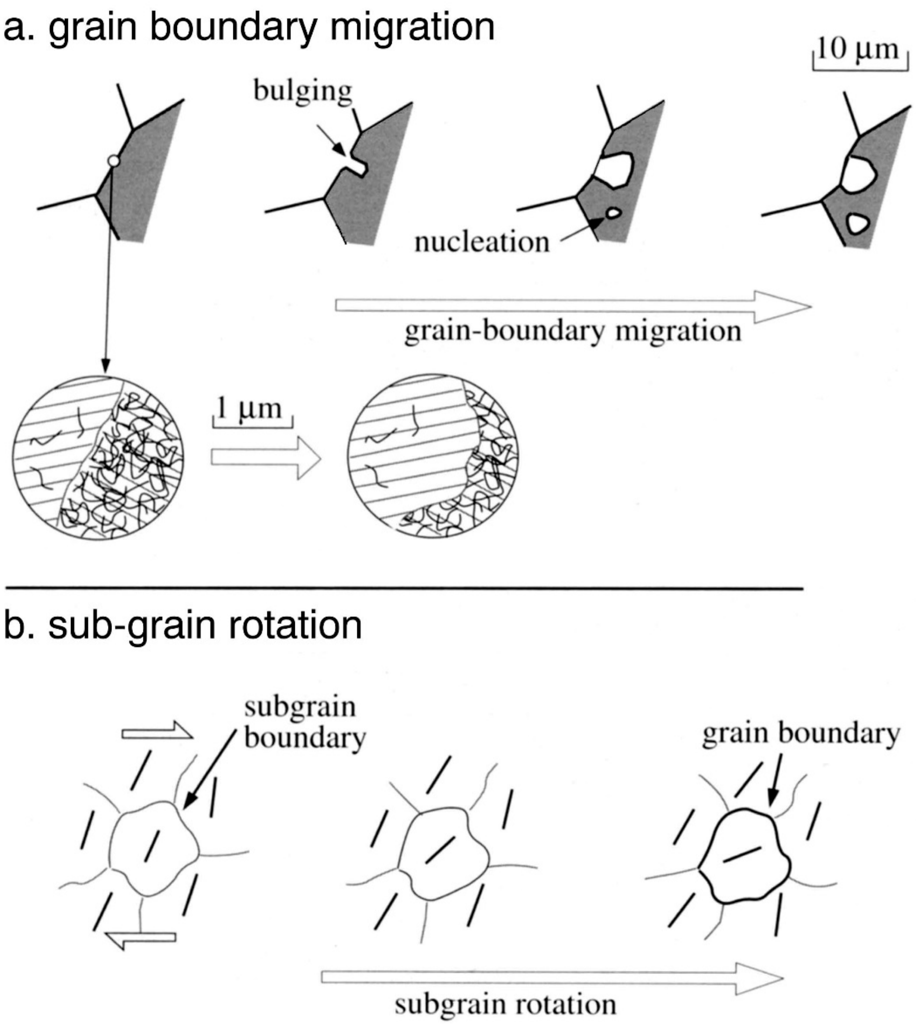


Figure 23.6. Recrystallization by (a) grain-boundary migration (including nucleation) and (b) subgrain rotation. From Passchier and Trouw (1996) *Microtectonics*. Springer-Verlag. Berlin.

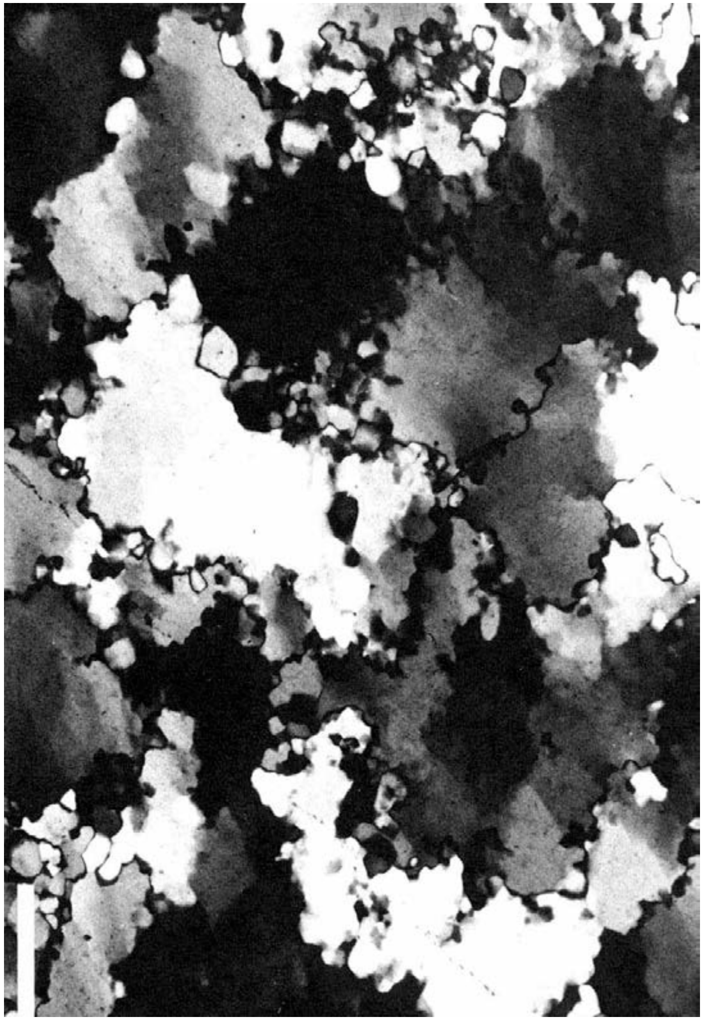


Figure 23.7a. Recrystallized quartz with irregular (sutured) boundaries, formed by grain boundary migration. Width 0.2 mm. From Borradaile *et al.* (1982).