

The Types of Metamorphism

Burial metamorphism

- Southland Syncline in New Zealand: thick pile (> 10 km) of Mesozoic volcanoclastics
- 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

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°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

Hydrothermal metamorphism

- Hot H₂O-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

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

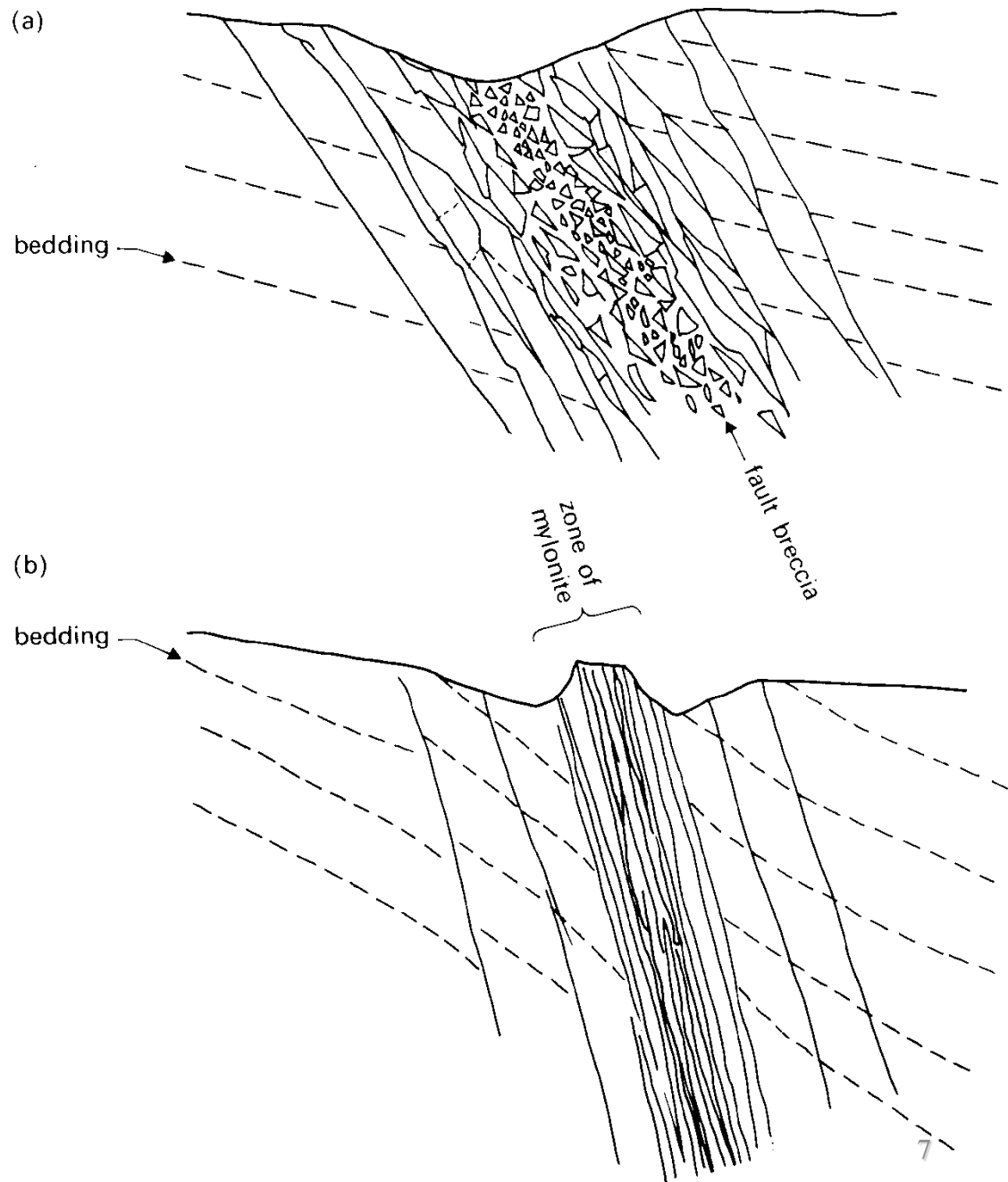


Figure 21.7. Schematic cross section across fault zones. After Mason (1978) *Petrology of the Metamorphic Rocks*. George Allen & Unwin. London.

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

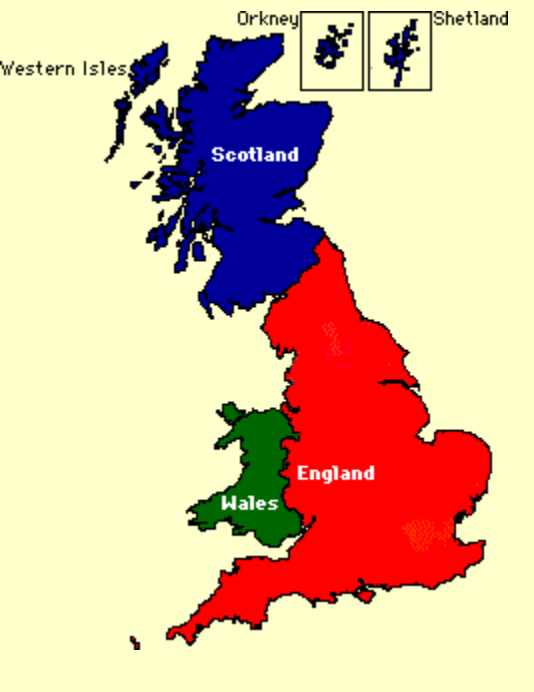
1. **Ultramafic** - very high Mg, Fe, Ni, Cr
2. **Mafic** - high Fe, Mg, and Ca
3. **Shales (pelitic)** - high Al, K, Si
4. **Carbonates** - high Ca, Mg, CO₂
5. **Quartz** - nearly pure SiO₂.
6. **Quartzo-feldspathic** - high Si, Na, K, Al

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

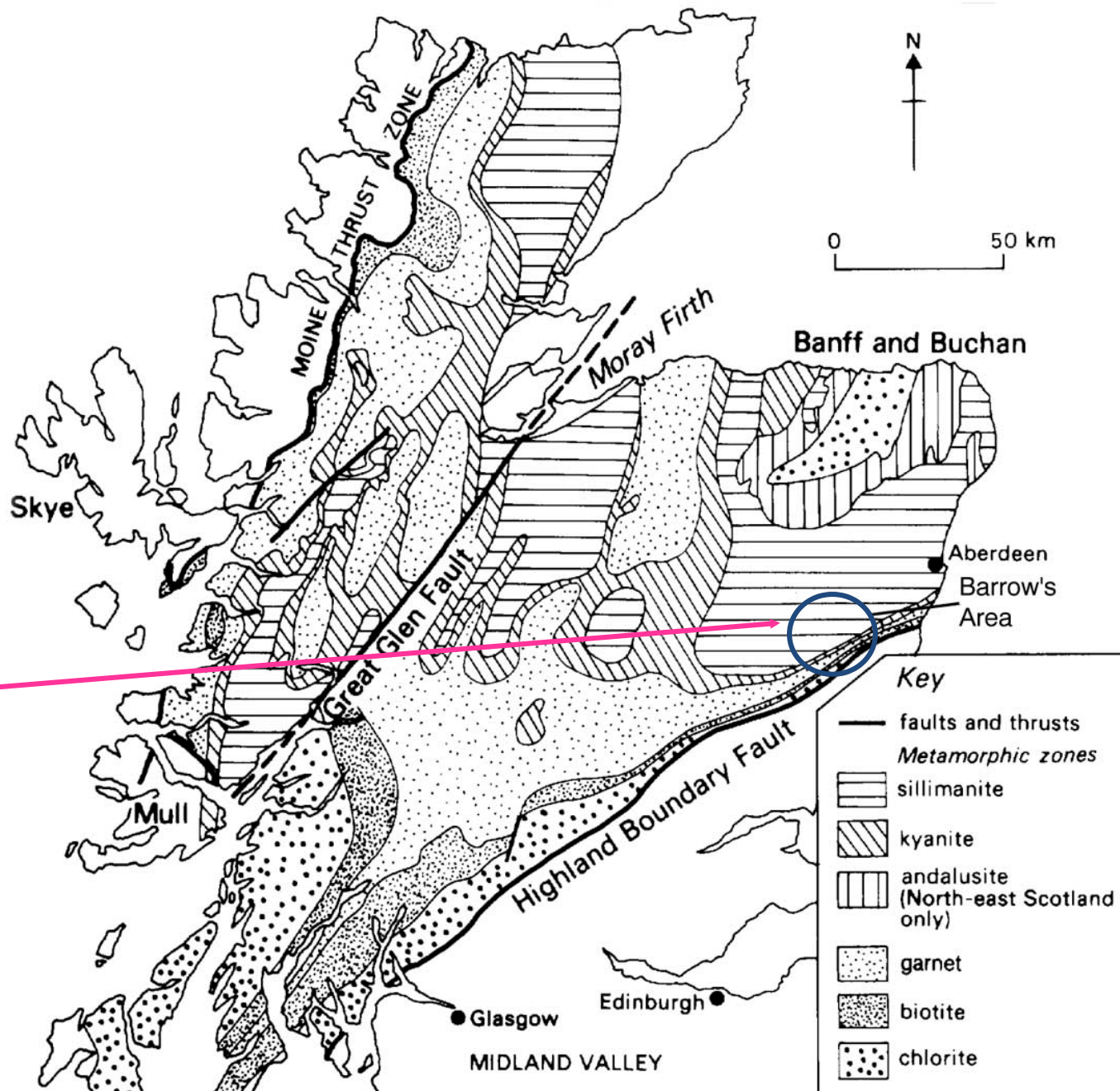


Figure 21.8. Regional metamorphic map of the Scottish Highlands, showing the zones of minerals that develop with increasing metamorphic grade. From Gillen (1982) *Metamorphic Geology. An Introduction to Tectonic and Metamorphic Processes*. George Allen & Unwin, London.

Orogenic Regional Metamorphism of the Scottish Highlands

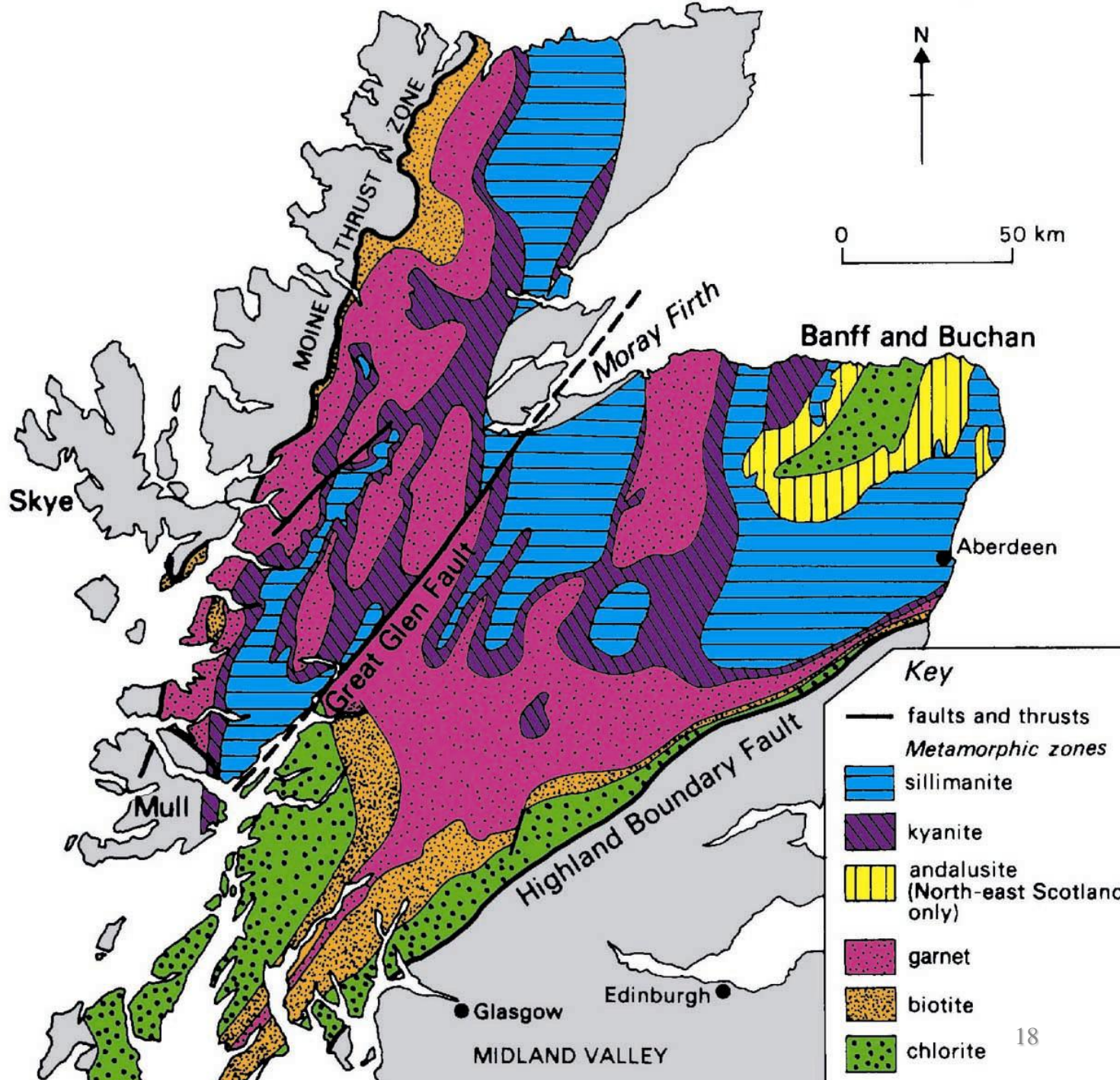
- Barrow studied the **pelitic** rocks
- Could subdivide the area into a series of **metamorphic zones**, each based on the appearance of a new mineral as metamorphic grade increased

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, quartz, 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.



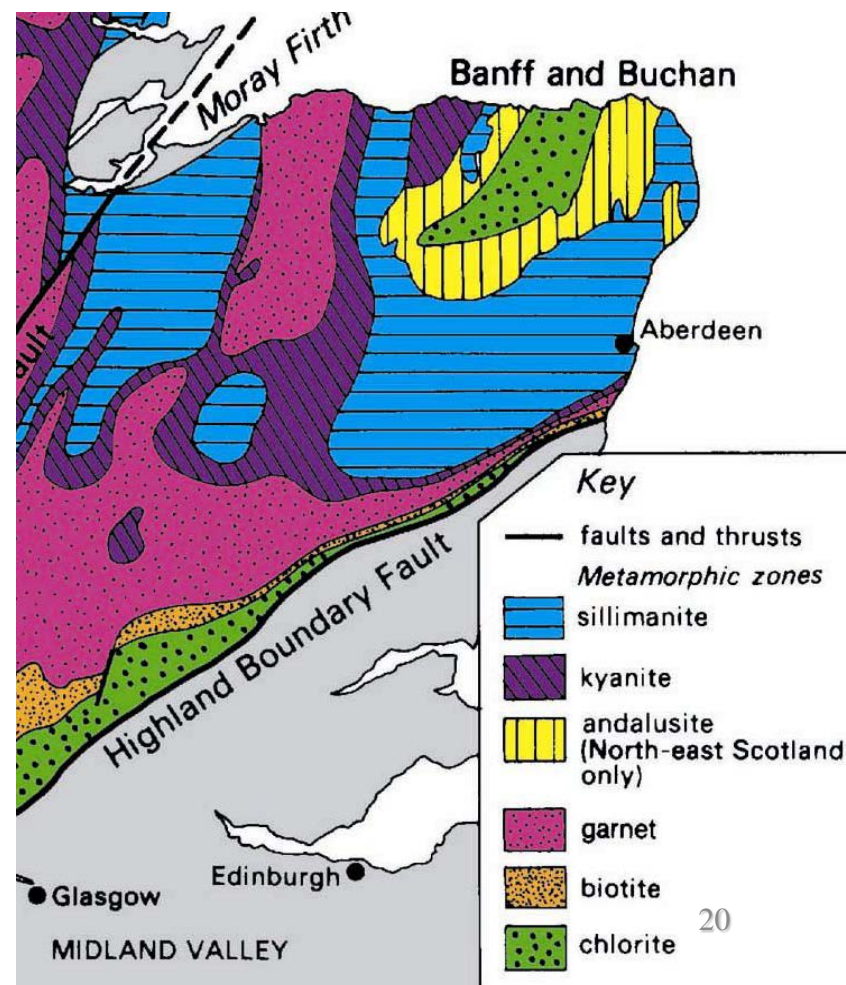
To summarize:

- 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

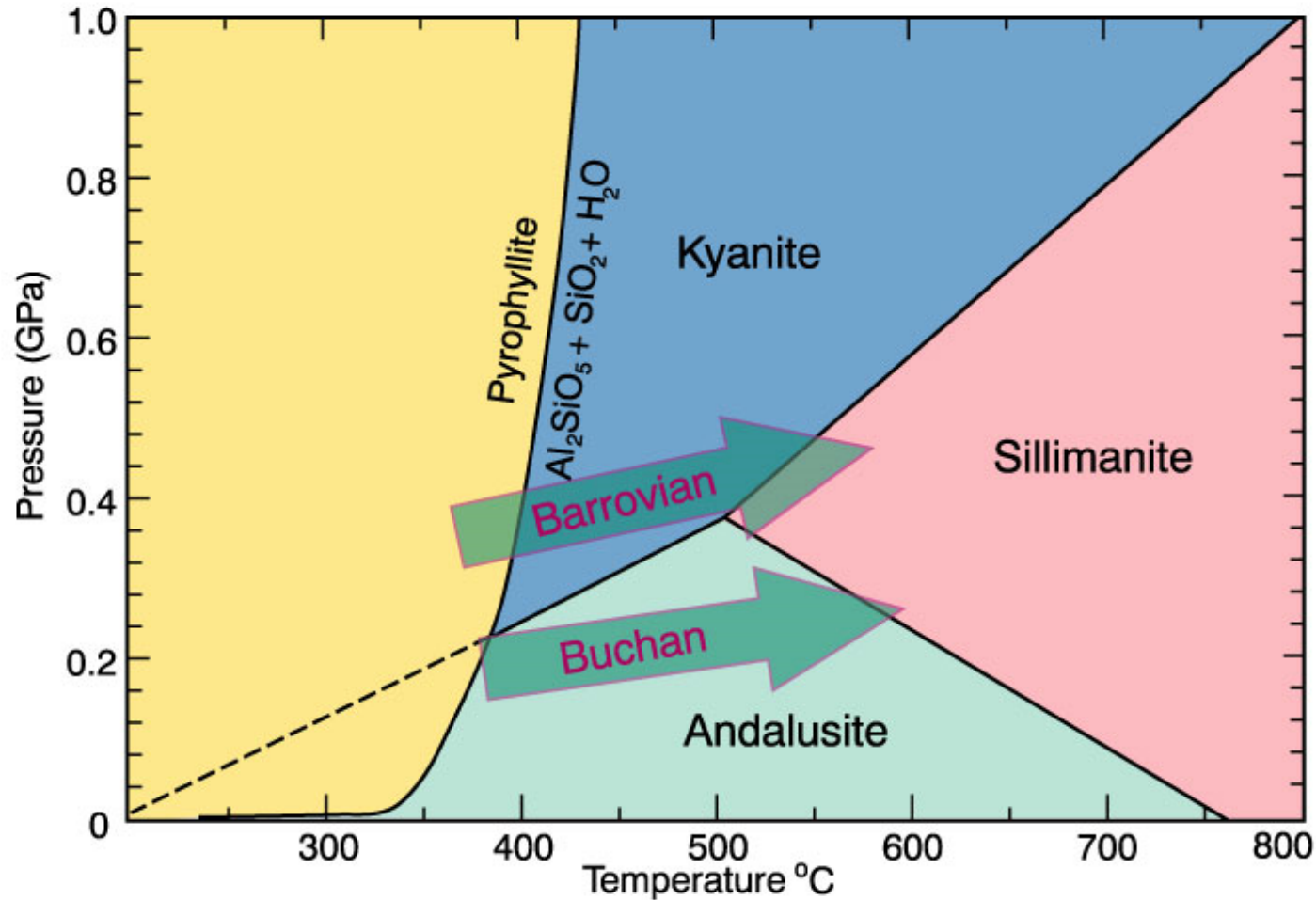


Figure 21.9. The P-T phase diagram for the system Al_2SiO_5 showing the stability fields for the three polymorphs andalusite, kyanite, and sillimanite. Also shown is the hydration of Al_2SiO_5 to pyrophyllite, which limits the occurrence of an Al_2SiO_5 polymorph at low grades in the presence of excess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

Paired Metamorphic Belts of Japan

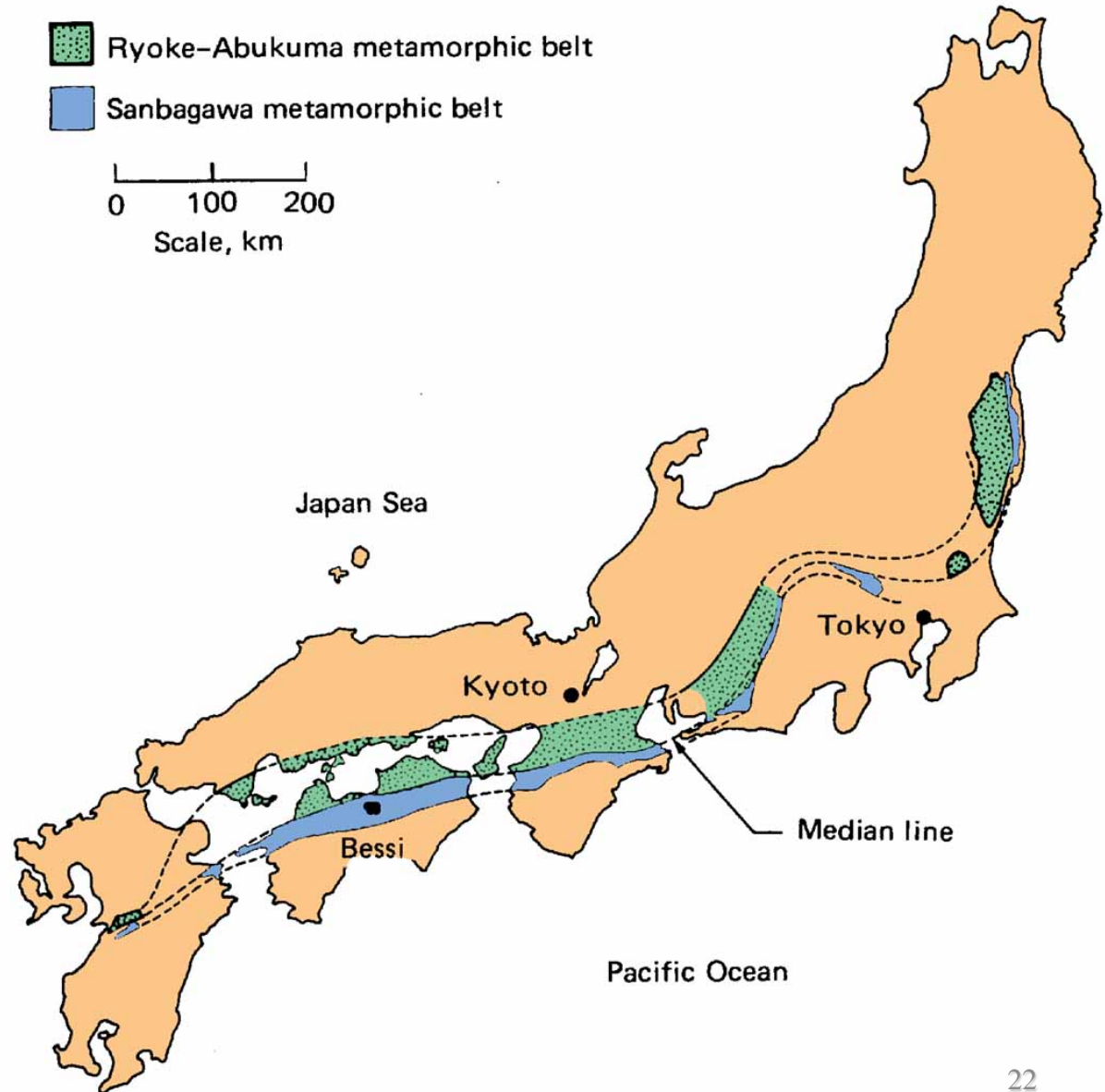
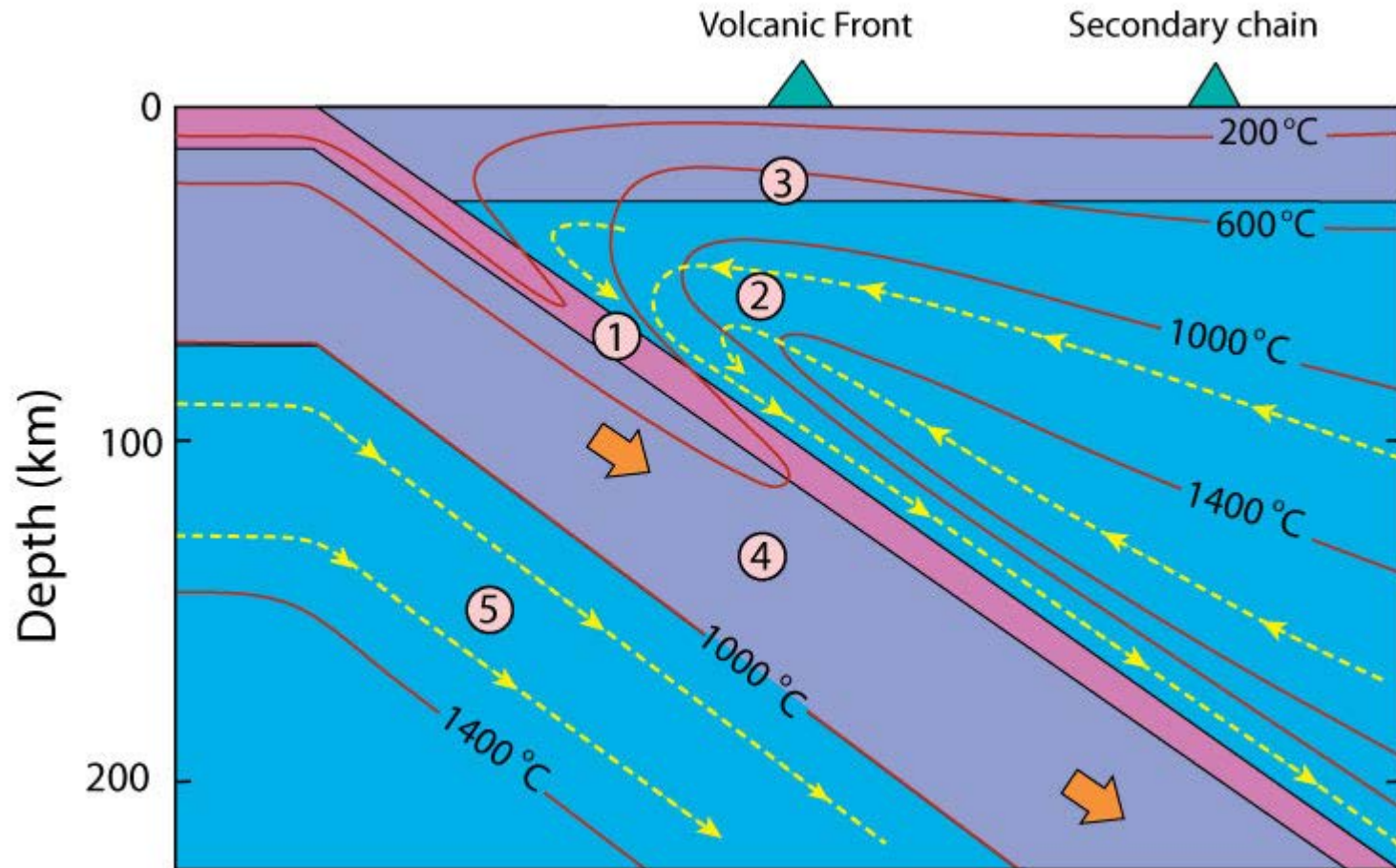


Figure 21.12. The Sanbagawa and Ryoke metamorphic belts of Japan. From Turner (1981) *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill and Miyashiro (1994) *Metamorphic Petrology*. Oxford University Press.

Paired Metamorphic Belts of Japan



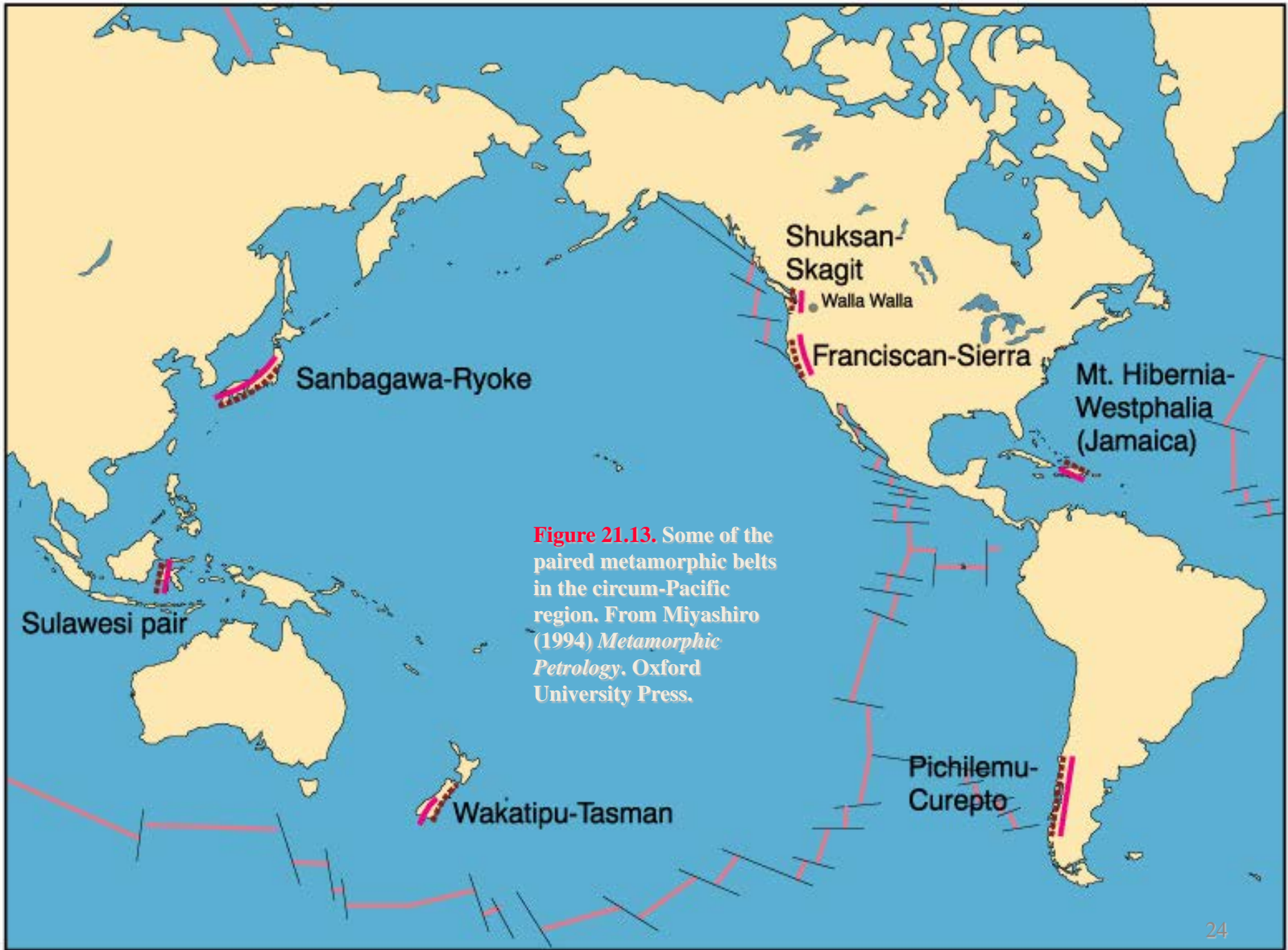


Figure 21.13. Some of the paired metamorphic belts in the circum-Pacific region. From Miyashiro (1994) *Metamorphic Petrology*, Oxford University Press.

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 inequiant 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*. Blackwell 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.

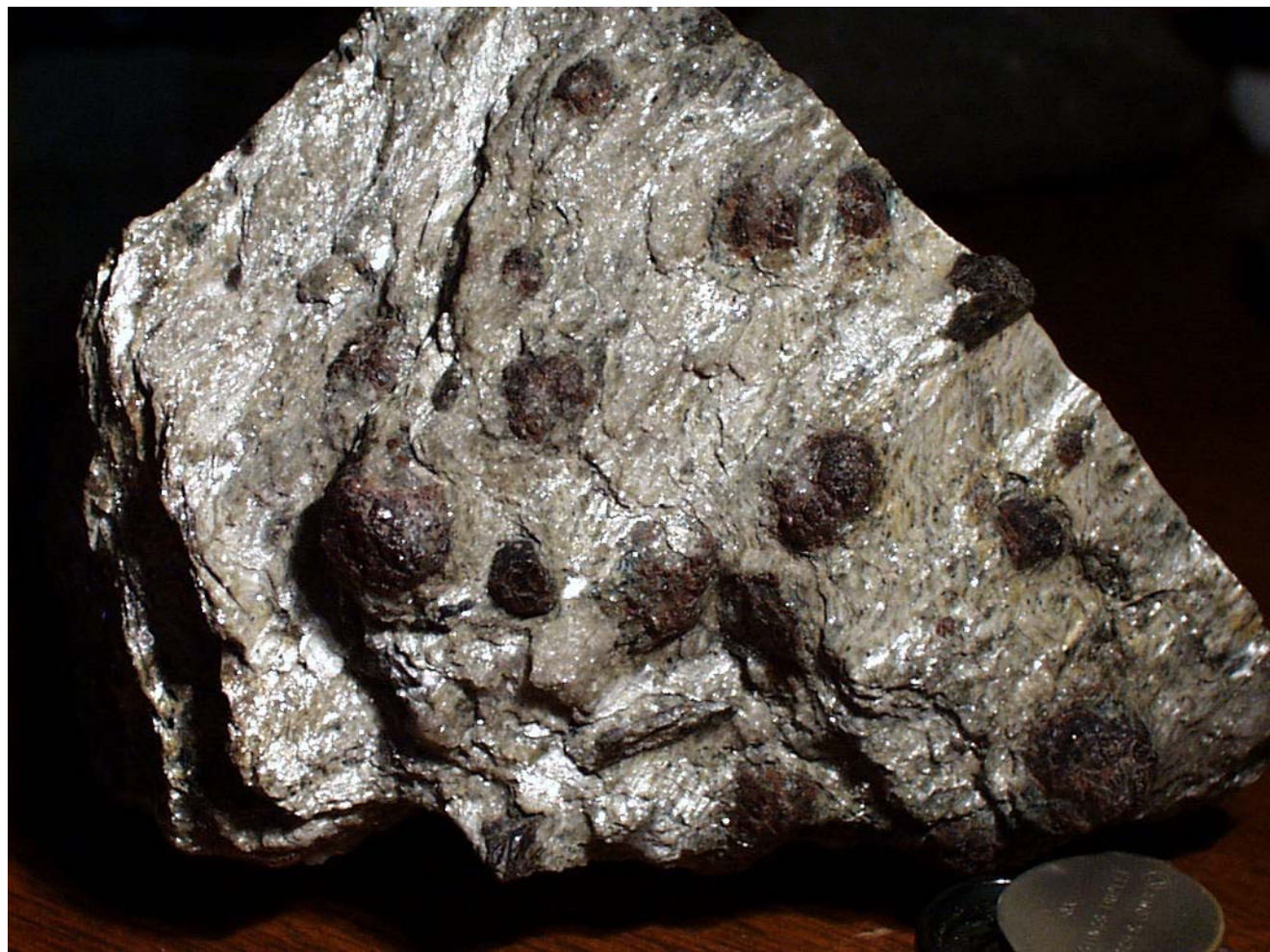


Figure 22.1c. Garnet muscovite schist. Muscovite crystals are visible and silvery, garnets occur as large dark porphyroblasts. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

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 (glauco-phane)**-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

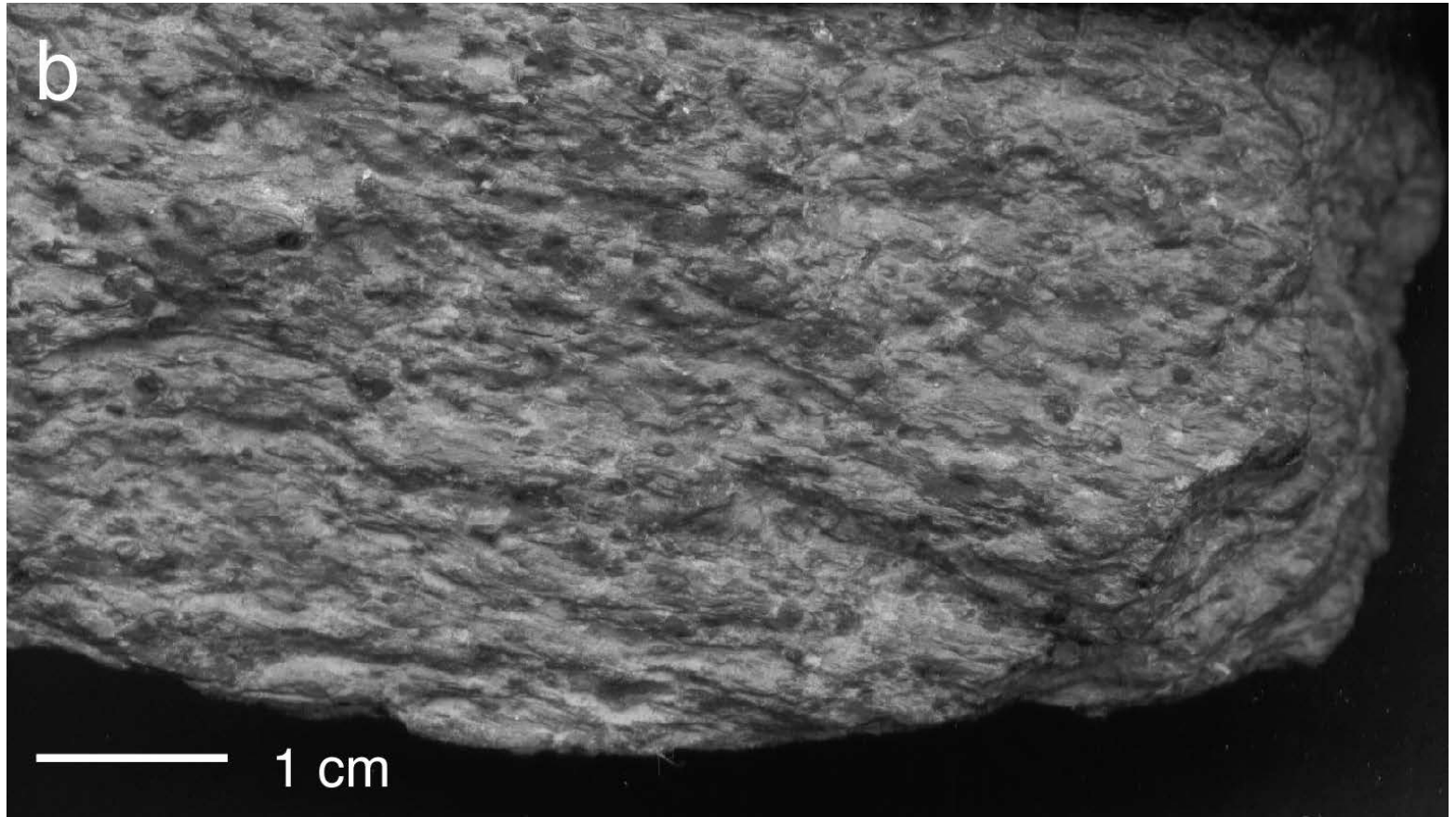


Figure 23.14b. Spotted Phyllite. Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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
50	Fault breccia	Microbreccia	Protomylonite	Blastomylonite (if significantly recrystallized)	Pseudotachylite
70			Mylonite		
90	Fault gouge	Cataclasite	Ultramylonite		

After Higgins (1971)

Chapter 22: High Strain Rocks

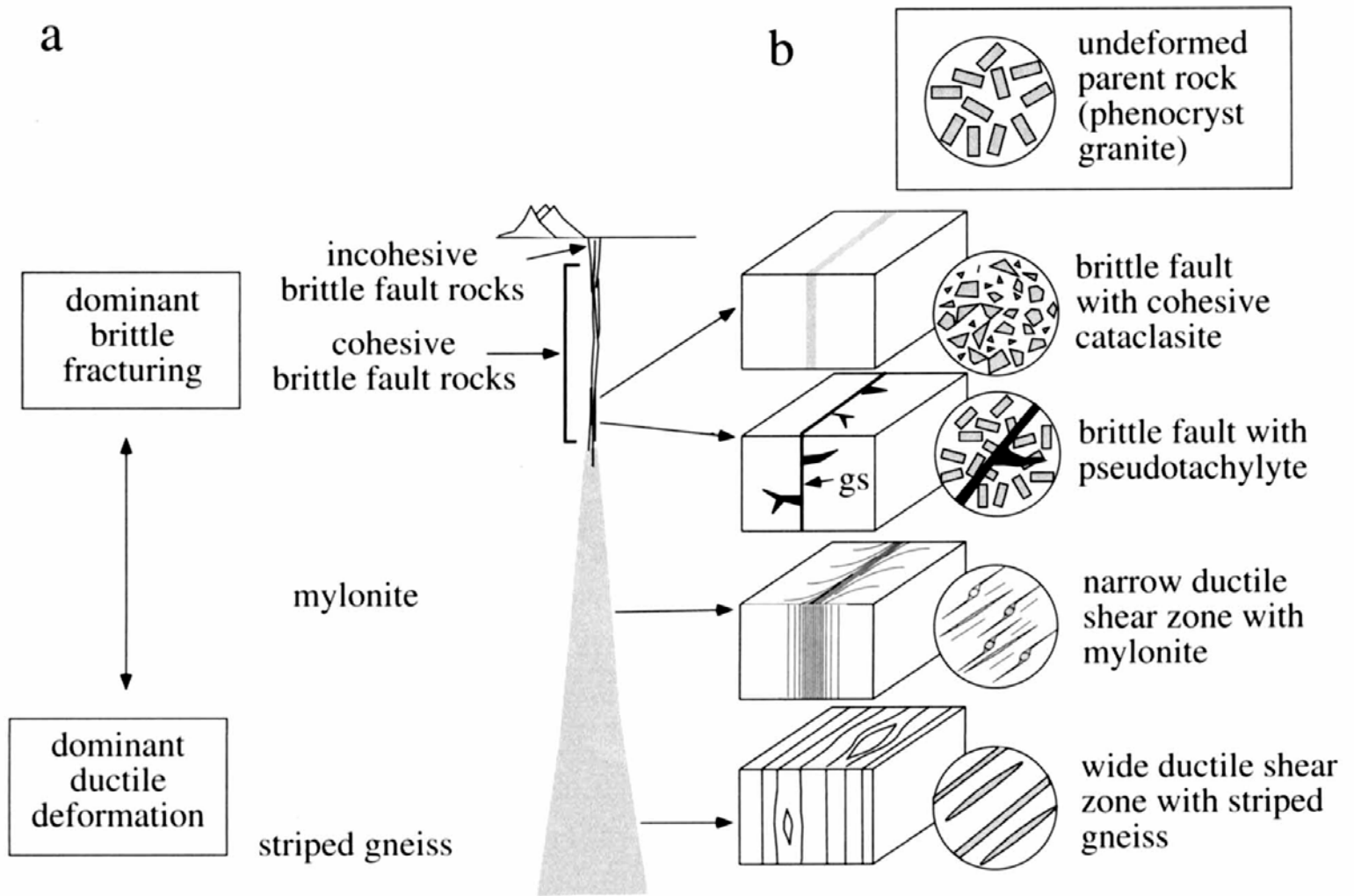


Figure 22.2. Schematic cross section through a shear zone, showing the vertical distribution of fault-related rock types, ranging from non-cohesive gouge and breccia near the surface through progressively more cohesive and foliated rocks. Note that the width of the shear zone increases with depth as 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

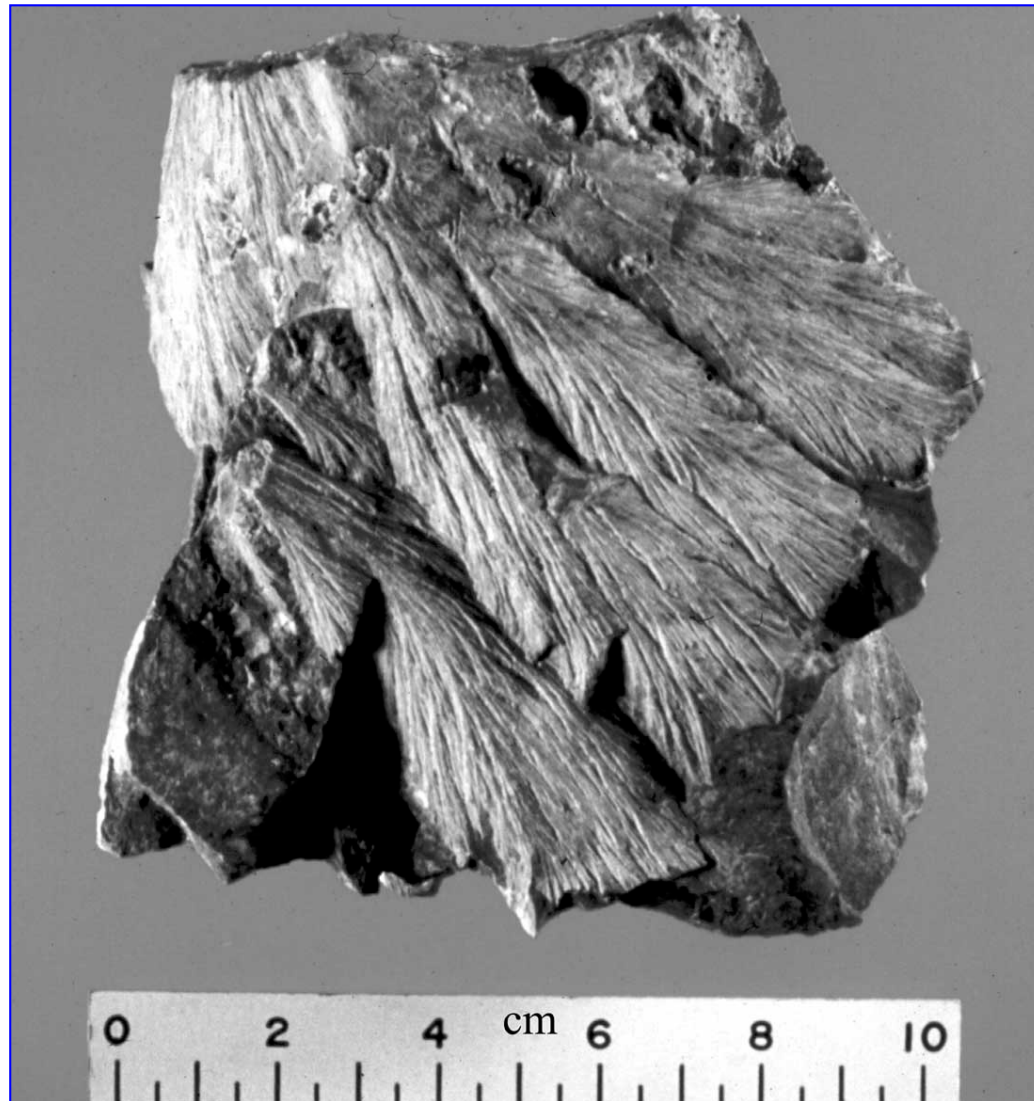


Figure 22.4. Shatter cones in limestone from the Houghton Structure, Northwest Territories. Photograph courtesy Richard Grieve, © Natural Resources Canada.