Chapter 21: Metamorphism

Fresh basalt and weathered basalt

Why Study Metamorphism?

- 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

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

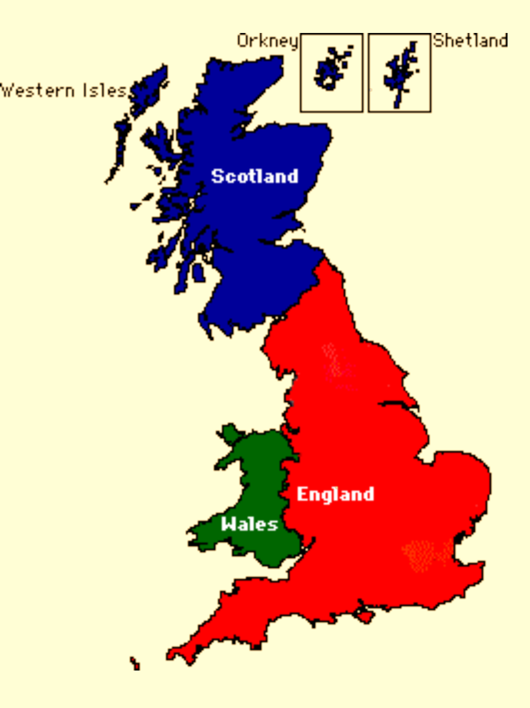
Types of Protolith

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

Orogenic Regional Metamorphism of the Scottish Highlands

- George Barrow (1893, 1912)
- SE Highlands of Scotland - Caledonian Orogeny ~ 500 Ma
- Nappes
- Granites



Barrow's Area

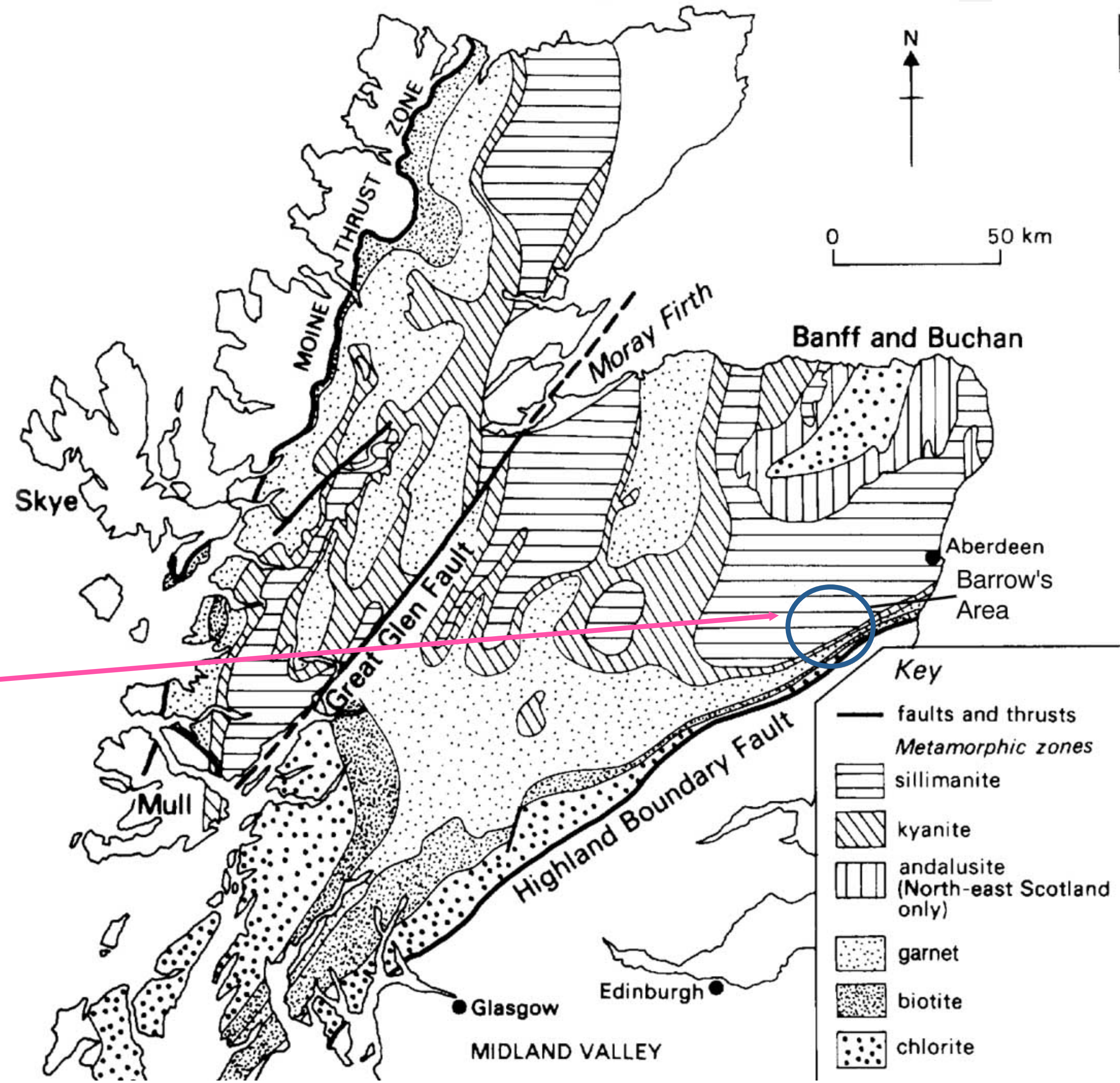


Figure 21.8. Regional metamorphic map of the Scottish Highlands, showing the zones of minerals that develop with increasing metamorphic grade. From Gillen (1982) *Metamorphic Geology. An Introduction to Tectonic and Metamorphic Processes*. George Allen & Unwin. London.

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)

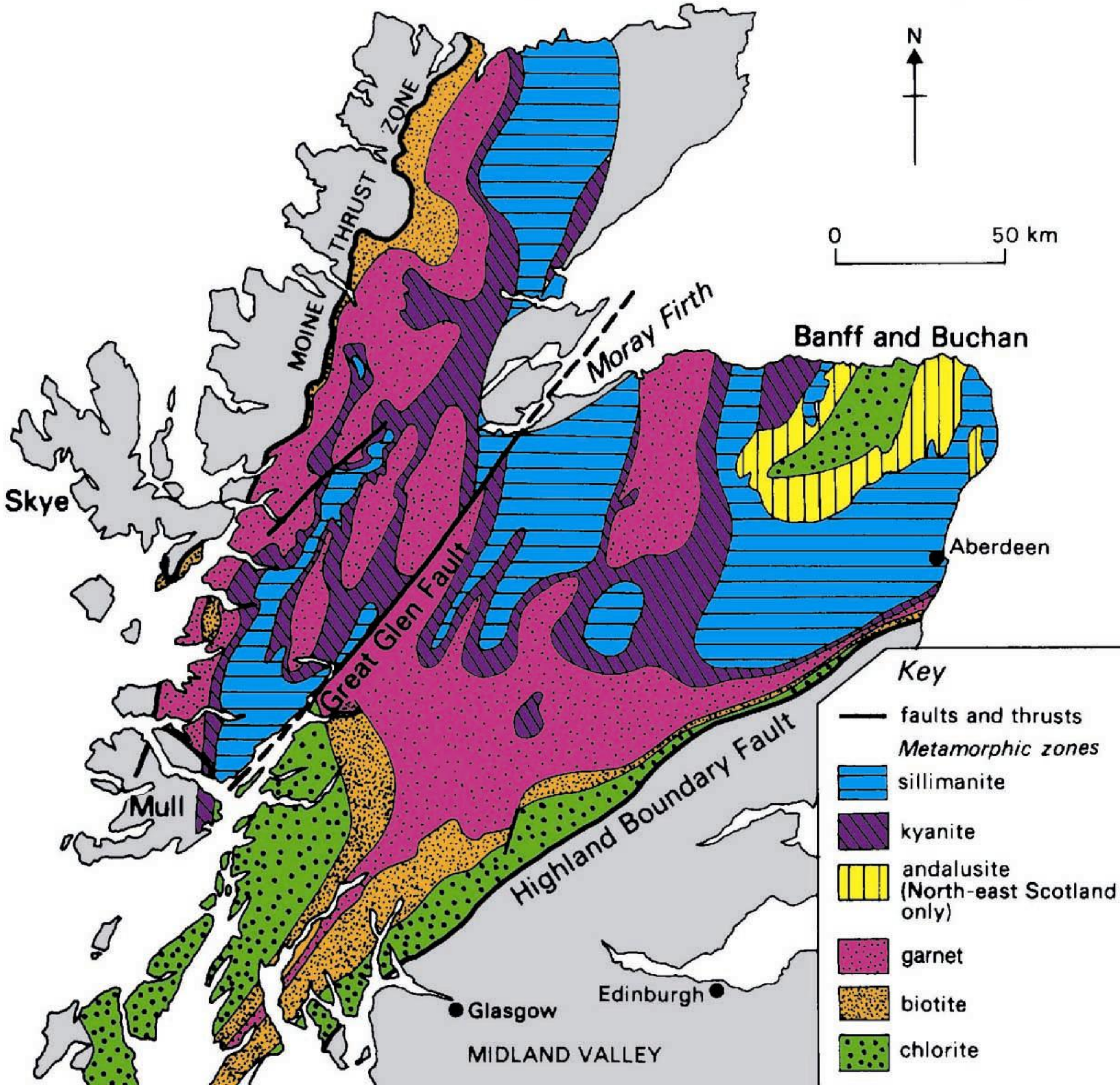


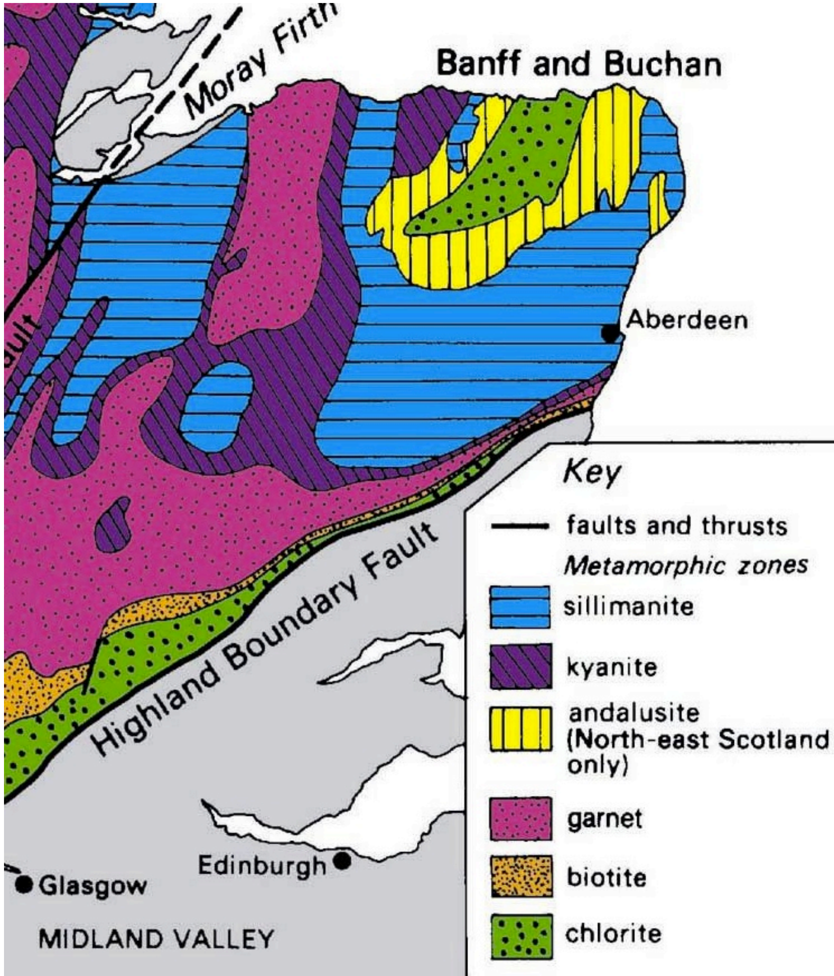
Figure 21.8. Regional metamorphic map of the Scottish Highlands, showing the zones of minerals that develop with increasing metamorphic grade. From Gillen (1982) *Metamorphic Geology. An Introduction to Tectonic and Metamorphic Processes*. George Allen & Unwin. London.

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

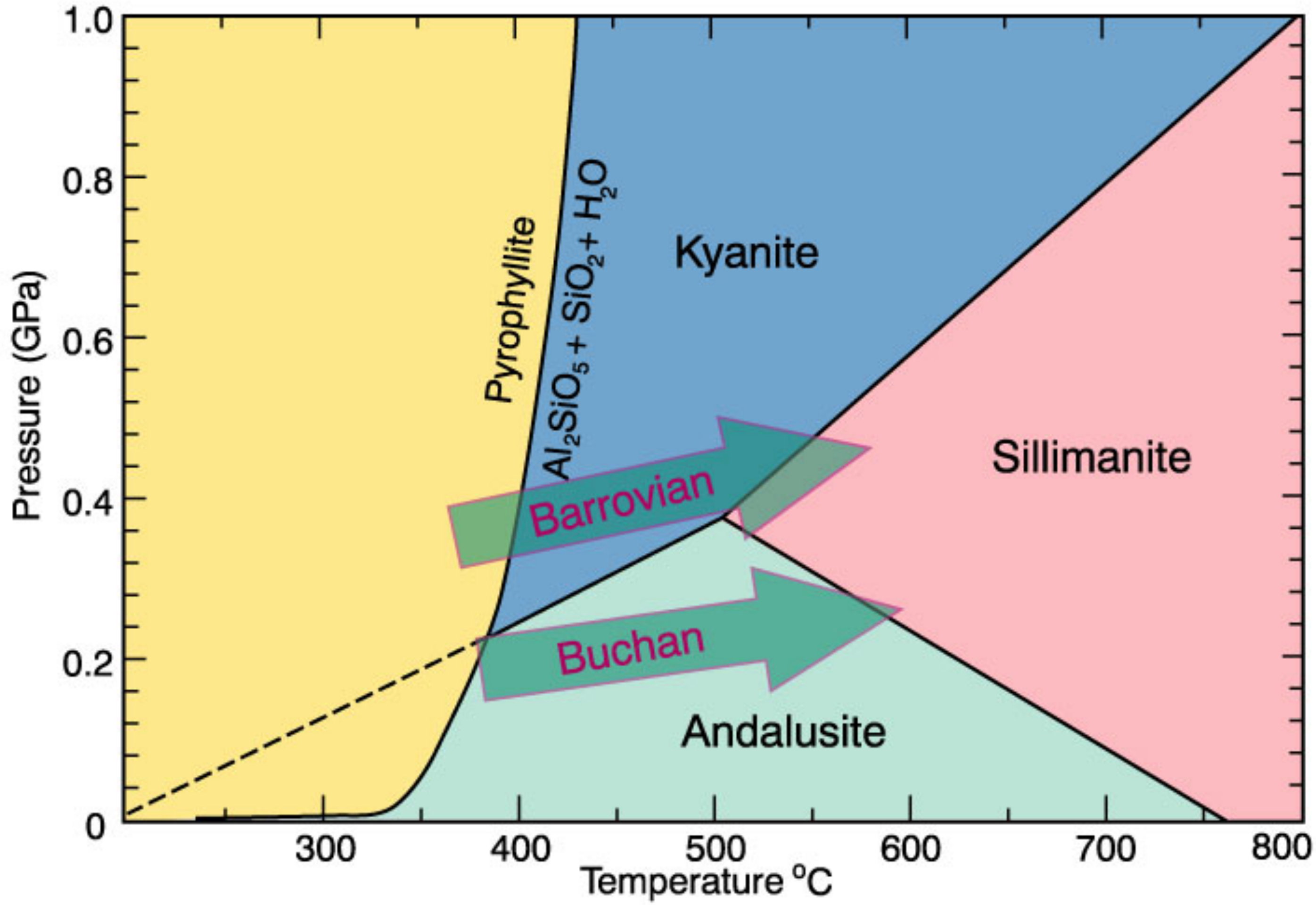


Figure 21.9. The P-T phase diagram for the system Al_2SiO_5 showing the stability fields for the three polymorphs andalusite, kyanite, and sillimanite. Also shown is the hydration of Al_2SiO_5 to pyrophyllite, which limits the occurrence of an Al_2SiO_5 polymorph at low grades in the presence of excess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

Regional Burial Metamorphism Otago, New Zealand

- Jurassic graywackes, tuffs, and volcanics in a deep trough metamorphosed in the Cretaceous
- Fine grain size and immature material is highly susceptible to alteration (even at low grades)

Regional Burial Metamorphism
Otago, New Zealand

Section X-Y shows more detail

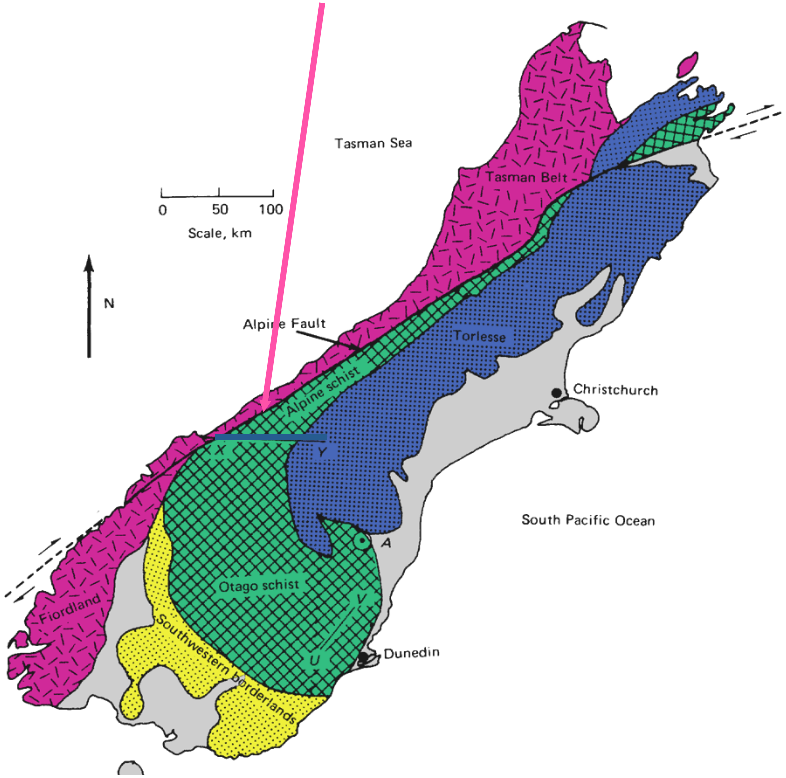
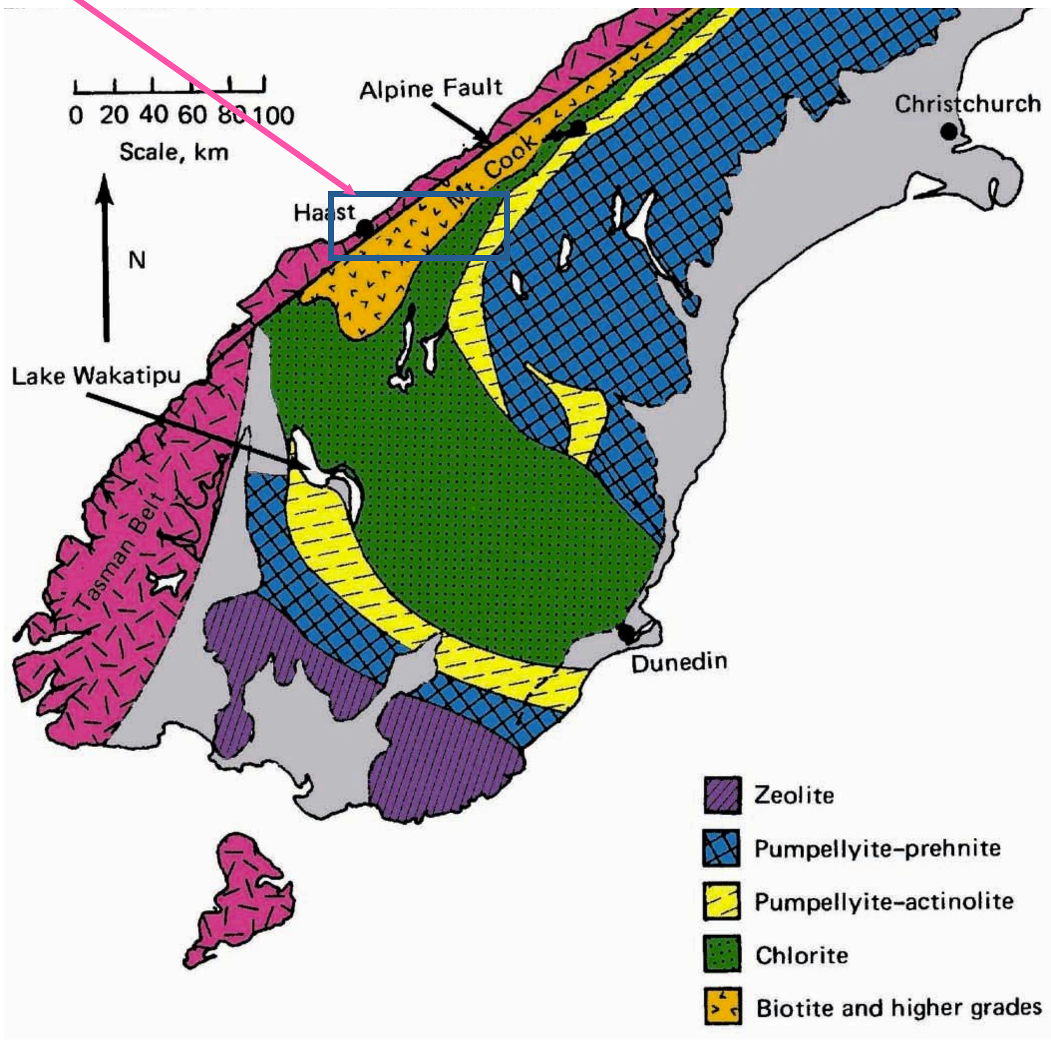


Figure 21.10. Geologic sketch map of the South Island of New Zealand showing the Mesozoic metamorphic rocks east of the older Tasman Belt and the Alpine Fault. The Torlese Group is metamorphosed predominantly in the prehnite-pumpellyite zone, and the Otago Schist in higher grade zones. X-Y is the Haast River Section of Figure 21-11. From Turner (1981) *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill.



Regional Burial Metamorphism
Otago, New Zealand

Isograds mapped at the lower grades:

1) Zeolite
2) Prehnite-Pumpellyite
3) Pumpellyite (-actinolite)
4) Chlorite (-clinozoisite)
5) Biotite
6) Almandine (garnet)
7) Oligoclase (albite at lower grades is replaced by a more calcic plagioclase)

Regional Burial Metamorphism

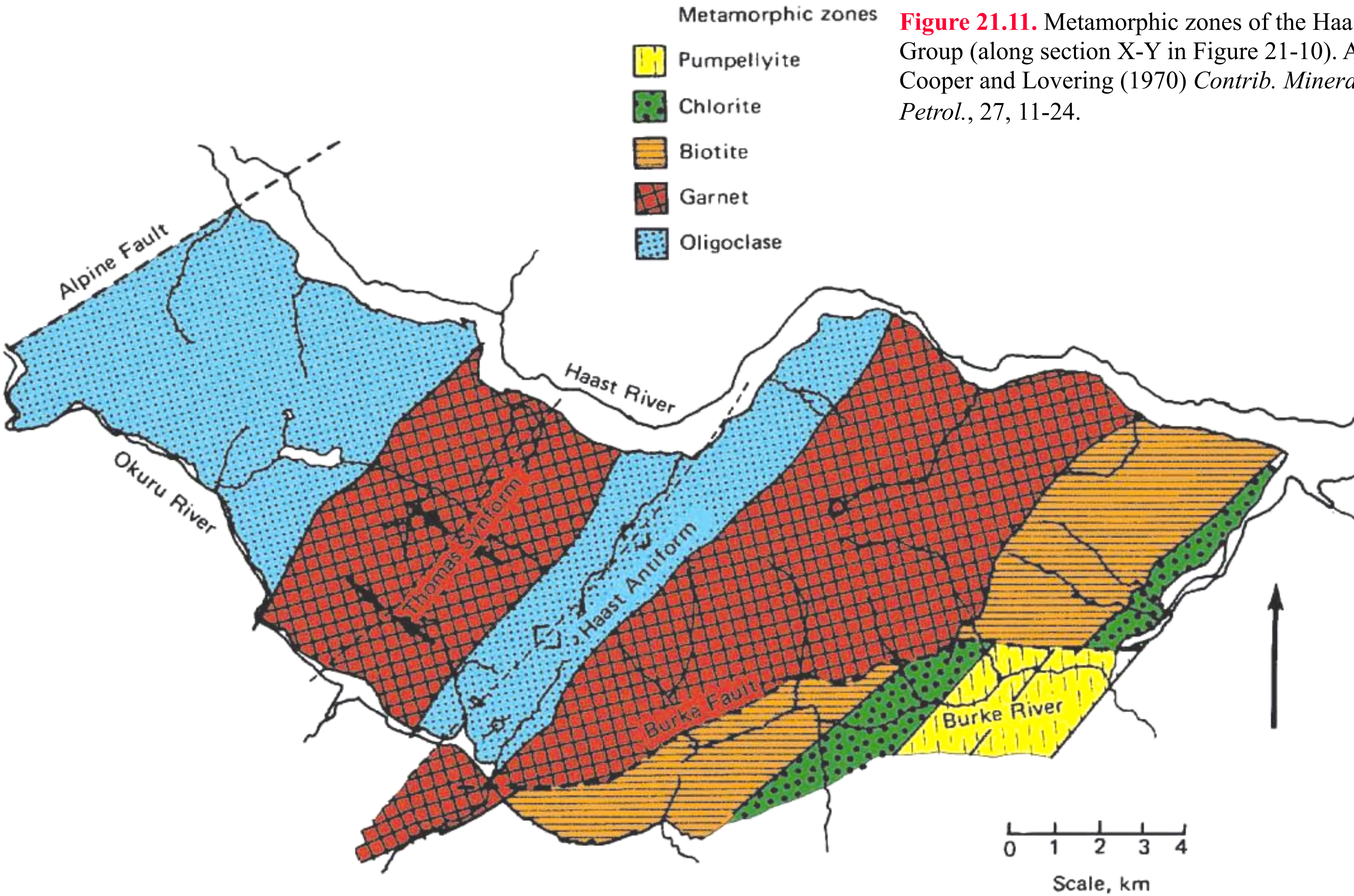


Figure 21.11. Metamorphic zones of the Haast Group (along section X-Y in Figure 21-10). After Cooper and Lovering (1970) *Contrib. Mineral. Petrol.*, 27, 11-24.

Paired Metamorphic Belts of Japan

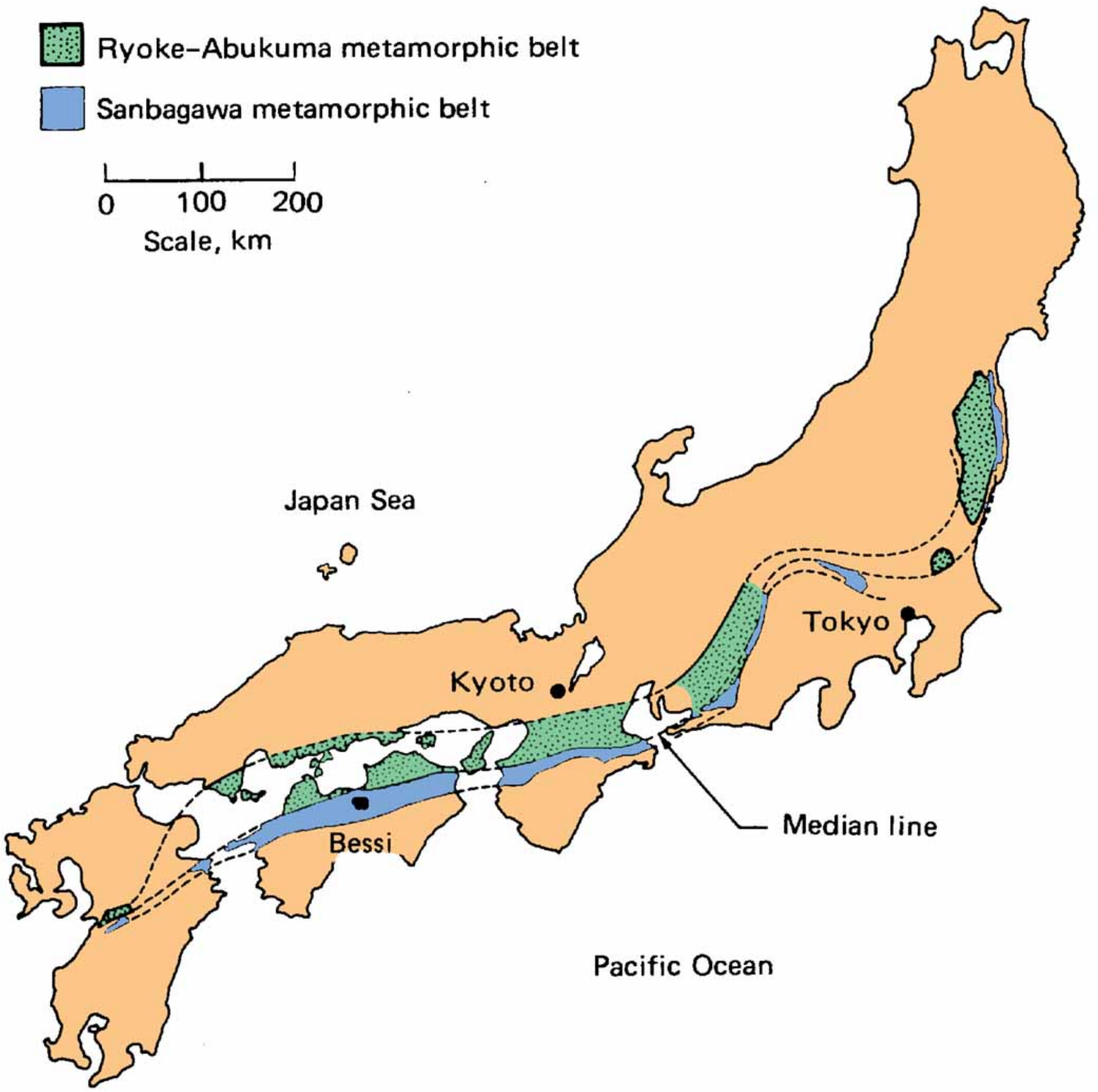
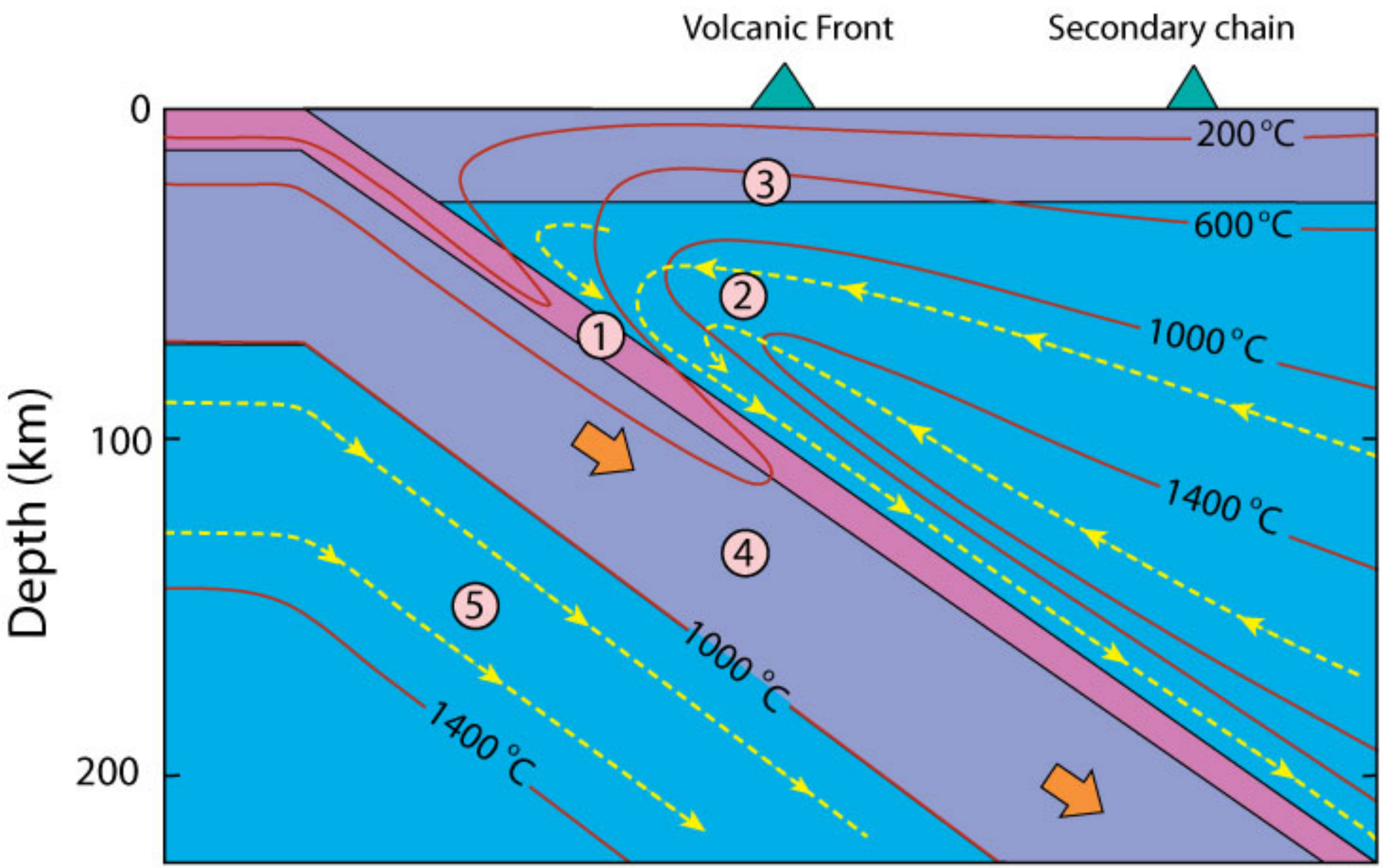


Figure 21.12. The Sanbagawa and Ryoke metamorphic belts of Japan. From Turner (1981) *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill and Miyashiro (1994) *Metamorphic Petrology*. Oxford University Press.

Paired Metamorphic Belts of Japan



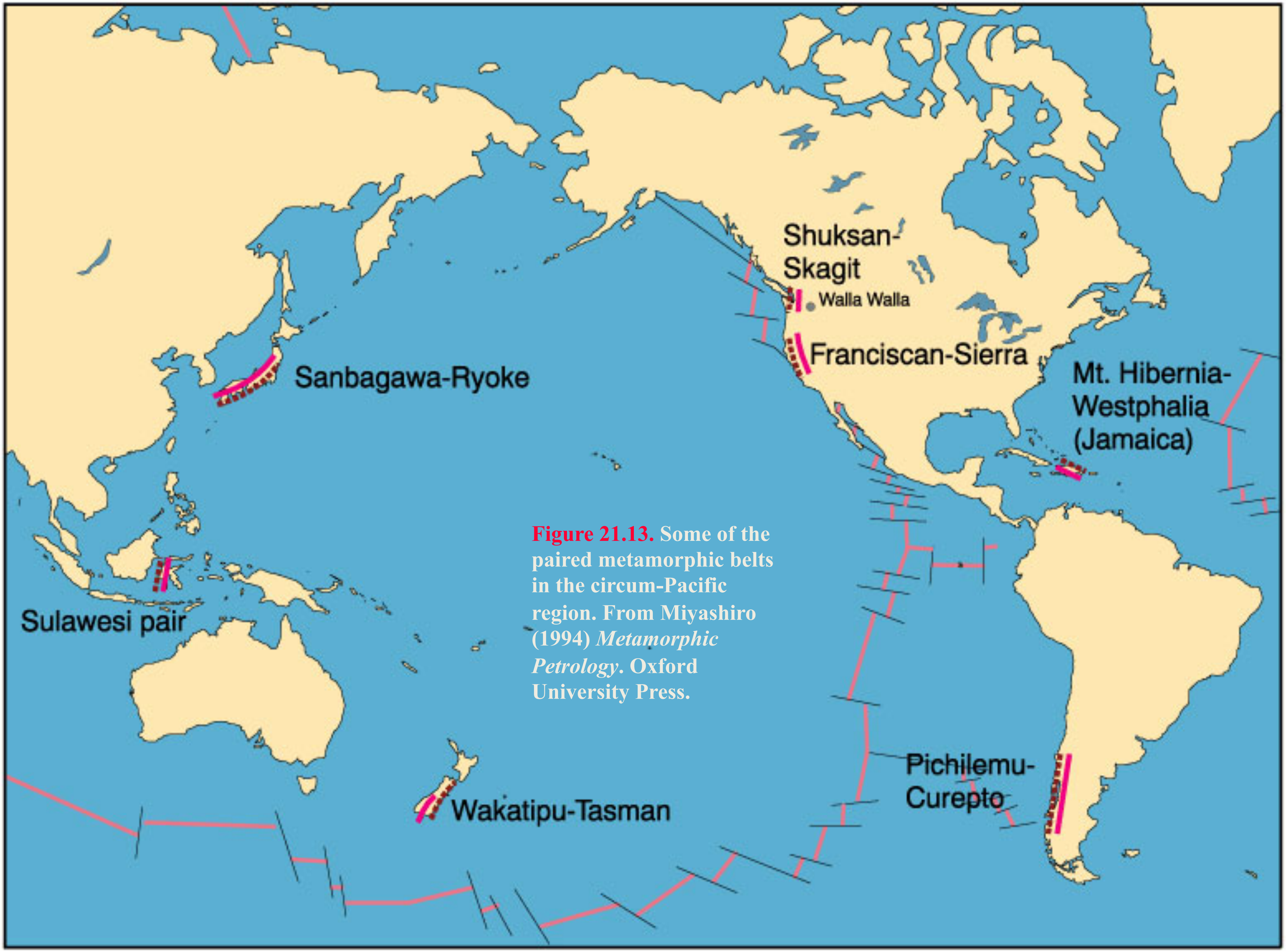


Figure 21.13. Some of the paired metamorphic belts in the circum-Pacific region. From Miyashiro (1994) *Metamorphic Petrology*. Oxford University Press.

Contact Metamorphism of Pelitic Rocks in the Skiddaw Aureole, UK

- Ordovician Skiddaw Slates (English Lake District) intruded by several granitic bodies
- Intrusions are shallow
- Contact effects overprinted on an earlier low-grade regional orogenic metamorphism

Contact Metamorphism of Pelitic Rocks in the Skiddaw Aureole, UK

- The aureole around the Skiddaw granite was sub-divided into three zones, principally on the basis of textures:

Increasing Metamorphic Grade ↓

- Unaltered slates
- Outer zone of spotted slates
- Middle zone of andalusite slates
- Inner zone of hornfels

--- Contact ---

- Skiddaw granite

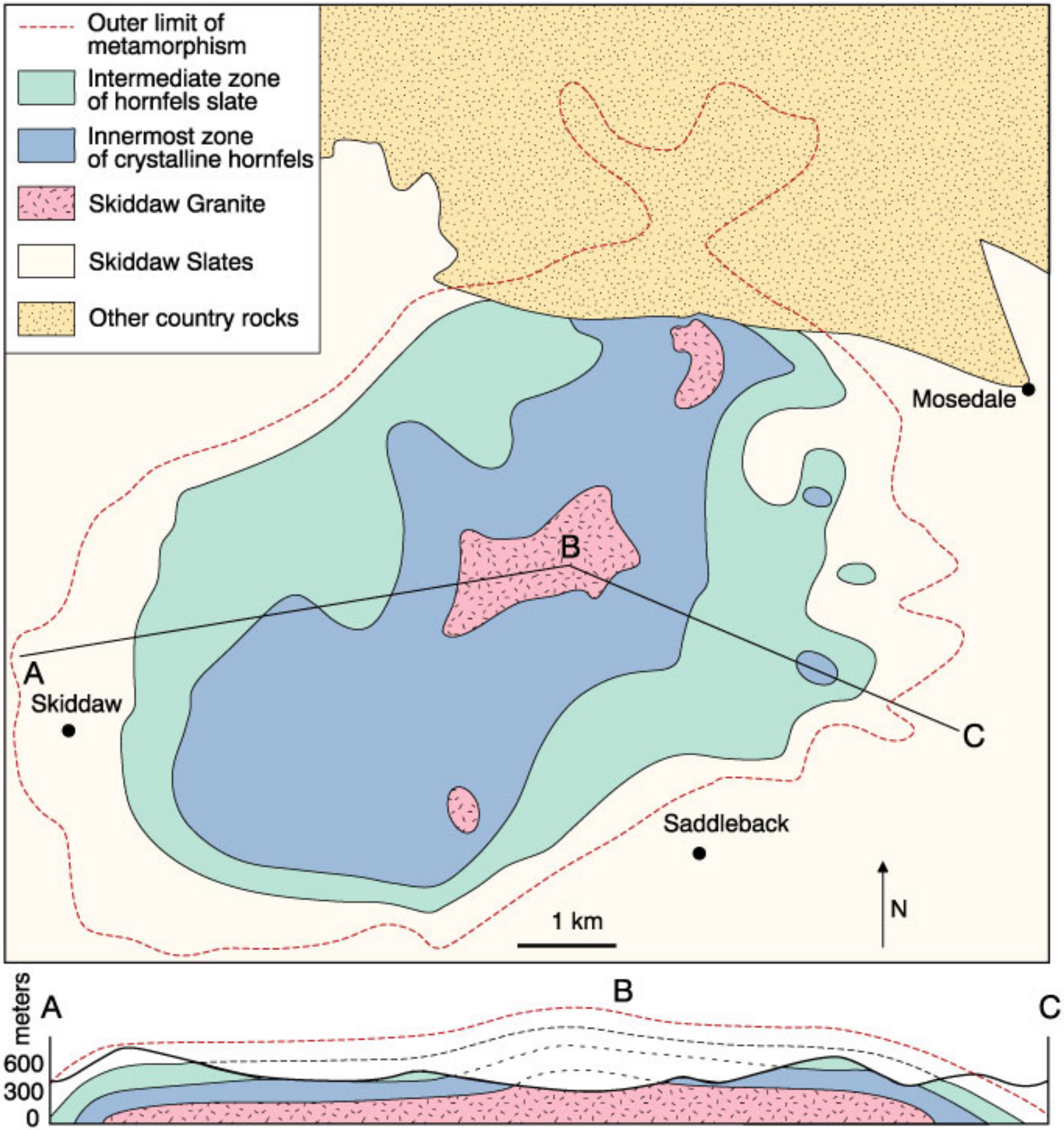


Figure 21.14. Geologic Map and cross-section of the area around the Skiddaw granite, Lake District, UK. After Eastwood et al (1968). *Geology of the Country around Cockermouth and Caldbeck*. Explanation accompanying the 1-inch Geological Sheet 23, New Series. Institute of Geological Sciences. London.

Contact Metamorphism of Pelitic Rocks in the Skiddaw Aureole, UK

- Middle zone: slates more thoroughly recrystallized, contain biotite + muscovite + cordierite + andalusite + quartz

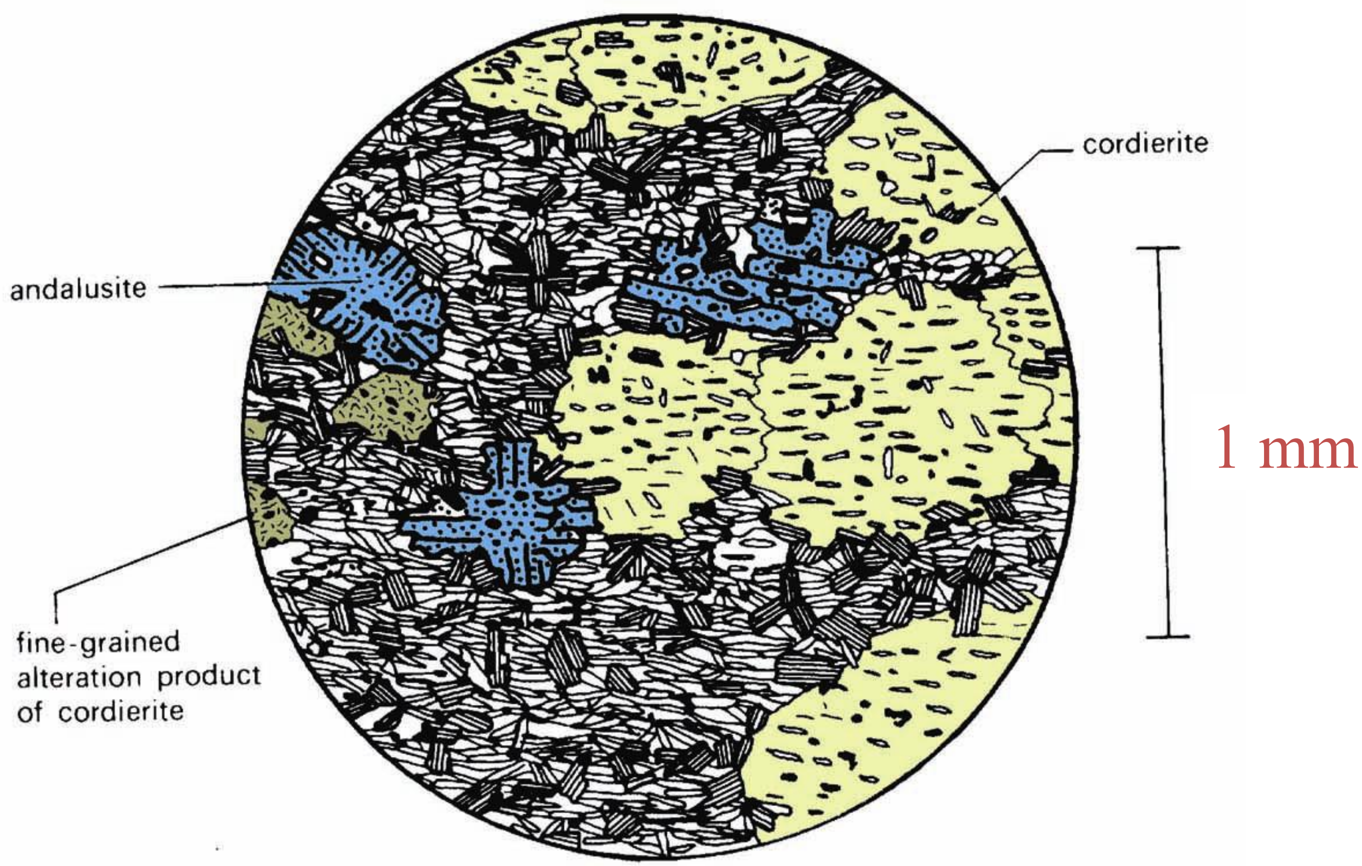
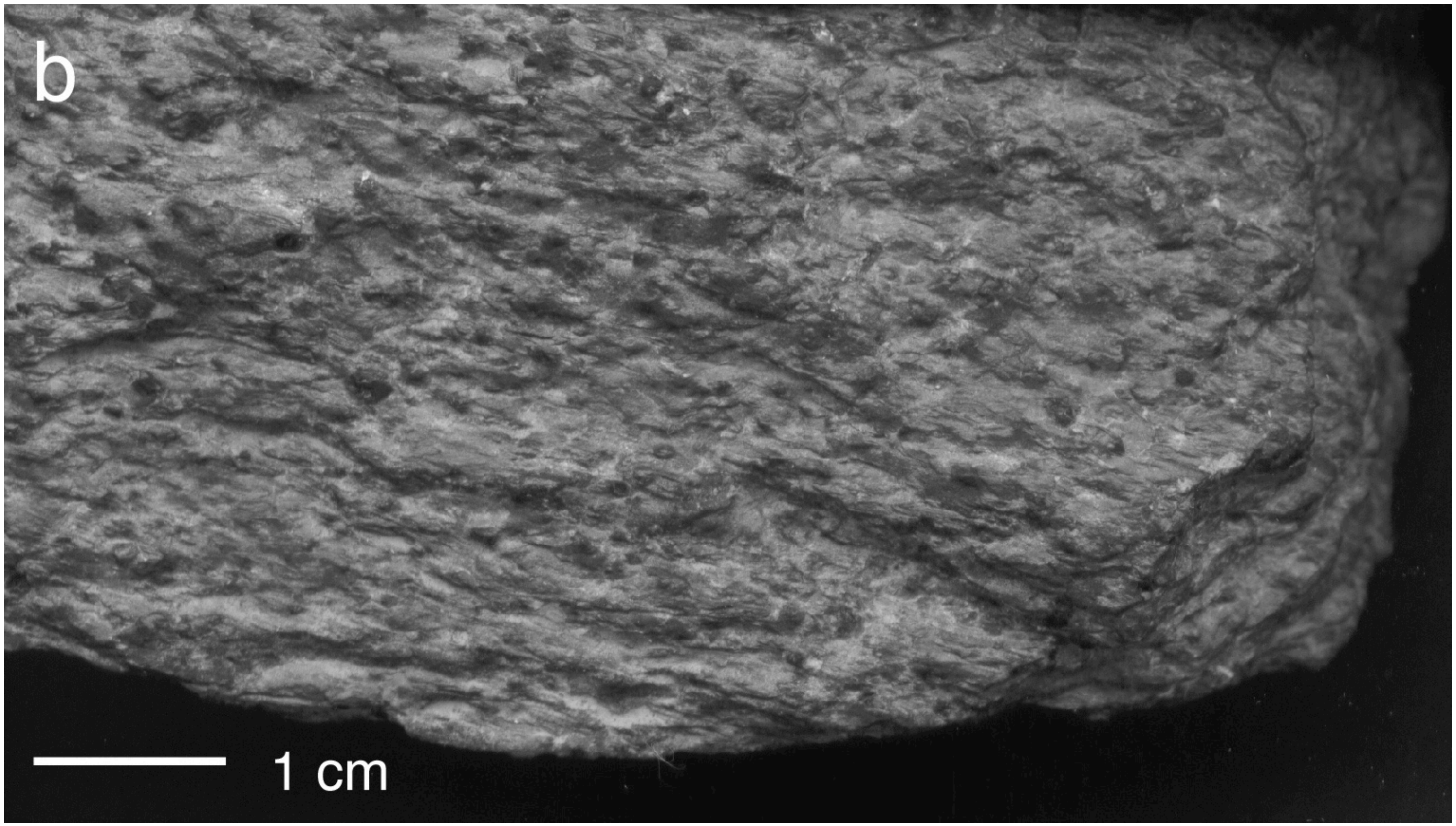
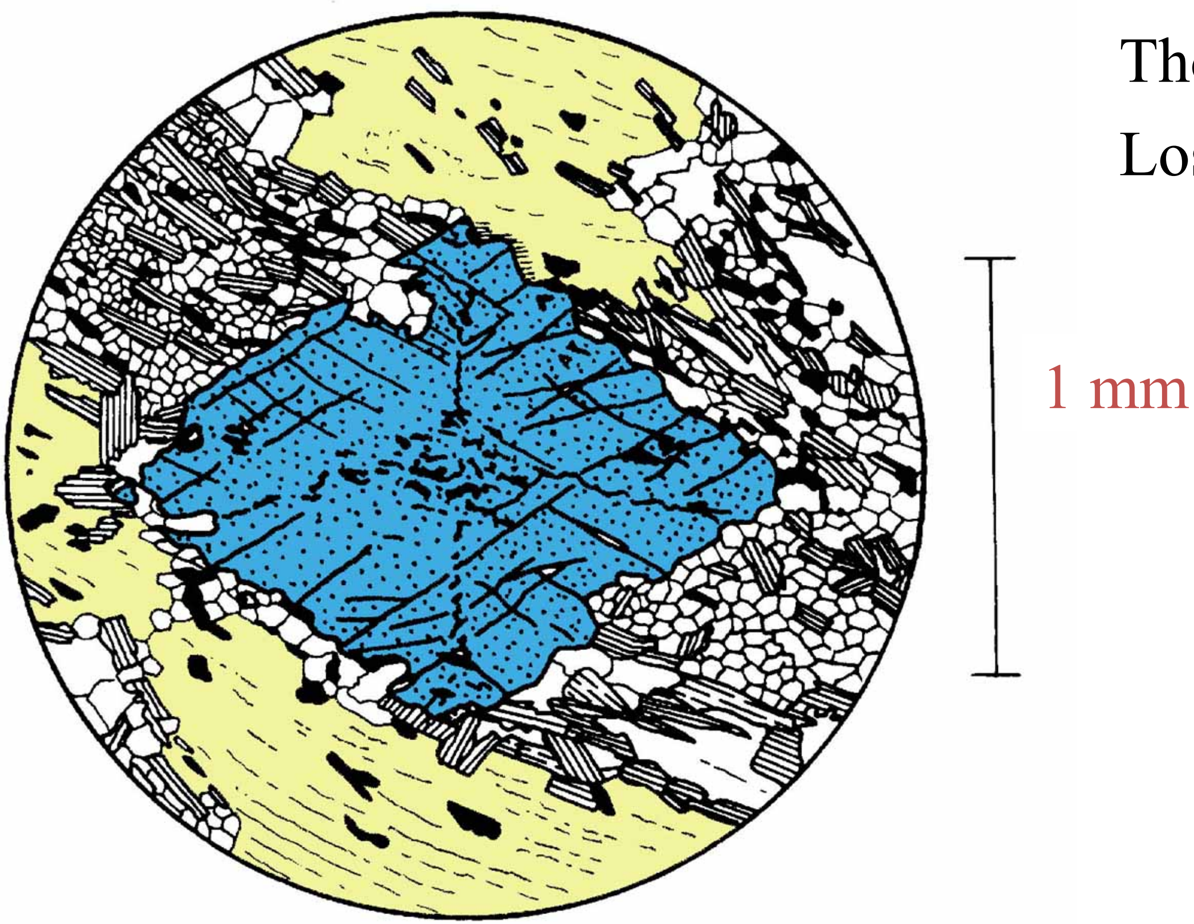


Figure 21.15. Cordierite-andalusite slate from the middle zone of the Skiddaw aureole. From Mason (1978) *Petrology of the Metamorphic Rocks*. George Allen & Unwin. London.


b
1 cm

Contact Metamorphism of Pelitic Rocks in the Skiddaw Aureole, UK



Inner zone:

Thoroughly recrystallized

Lose foliation

Figure 21.16. Andalusite-cordierite schist from the inner zone of the Skiddaw aureole. Note the chiastolite cross in andalusite (see also Figure 22-49). From Mason (1978) *Petrology of the Metamorphic Rocks*. George Allen & Unwin. London.

Contact Metamorphism of Pelitic Rocks in the Skiddaw Aureole, UK

- The zones determined on a textural basis
- Prefer to use the sequential appearance of minerals and isograds to define zones
- But low-P isograds converge in P-T
- Skiddaw sequence of mineral development with grade is difficult to determine accurately

Contact Metamorphism and Skarn Formation at Crestmore, CA, USA

- Crestmore quarry in the Los Angeles basin
- Quartz monzonite porphry intrudes Mg-bearing carbonates (either late Paleozoic or Triassic)
- Burnham (1959) mapped the following zones and the mineral assemblages in each (listed in order of increasing grade):

- Forsterite Zone:
  - calcite + brucite + clinohumite + spinel
  - calcite + clinohumite + forsterite + spinel
  - calcite + forsterite + spinel + clintonite
- Monticellite Zone:
  - calcite + forsterite + monticellite + clintonite
  - calcite + monticellite + melilite + clintonite
  - calcite + monticellite + spurrite (or tilleyite) + clintonite
  - monticellite + spurrite + merwinite + melilite
- Vesuvianite Zone:
  - vesuvianite + monticellite + spurrite + merwinite + melilite
  - vesuvianite + monticellite + diopside + wollastonite
- Garnet Zone:
  - grossular + diopside + wollastonite

Contact Metamorphism and Skarn Formation at Crestmore, CA, USA

An idealized cross-section through the aureole

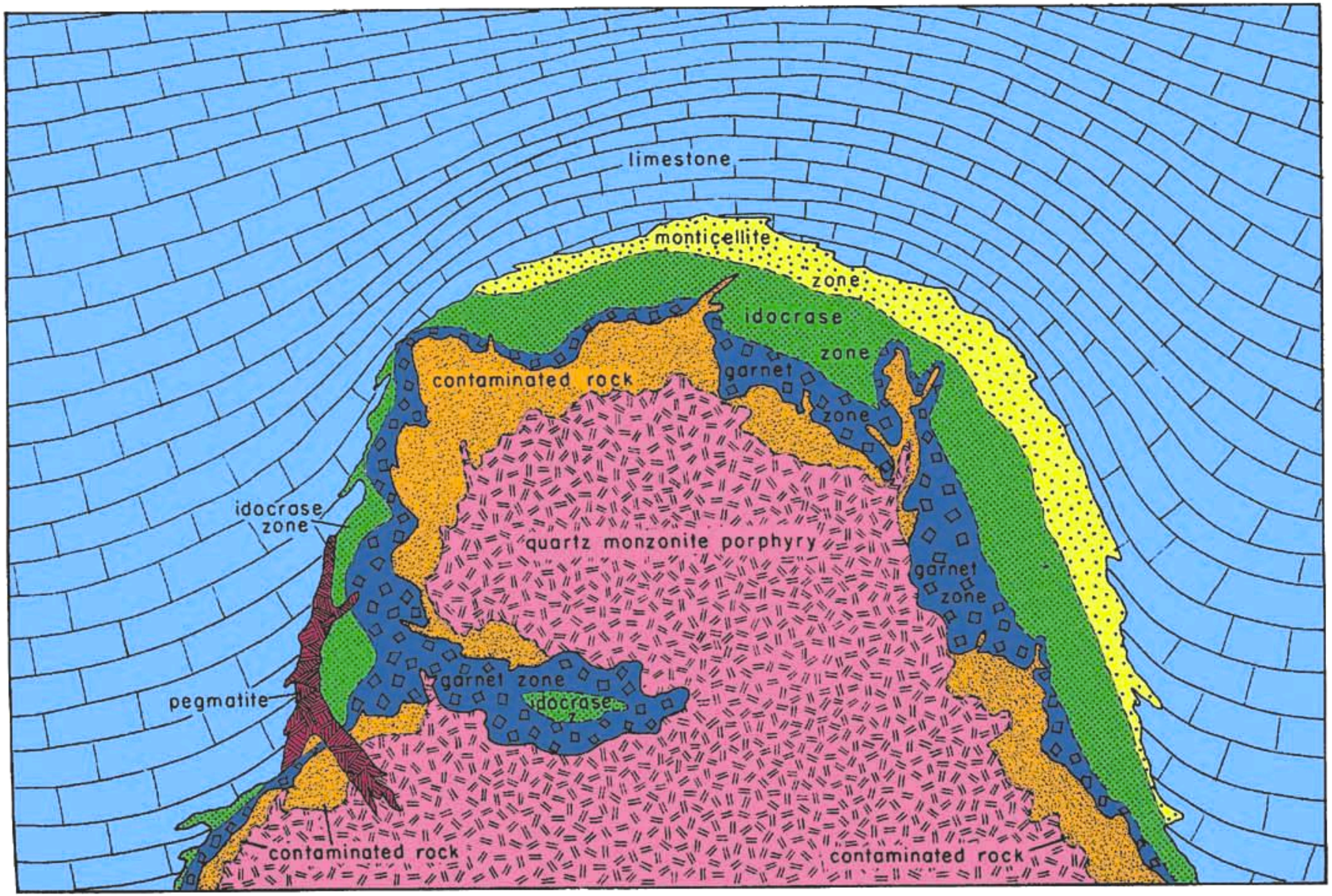


Figure 21.17. Idealized N-S cross section (not to scale) through the quartz monzonite and the aureole at Crestmore, CA. From Burnham (1959) *Geol. Soc. Amer. Bull.*, 70, 879-920.

Contact Metamorphism and Skarn Formation at Crestmore, CA, USA

1. The mineral associations in successive zones (in all metamorphic terranes) vary by the formation of new minerals as grade increases

This can only occur by a chemical reaction in which some minerals are consumed and others produced

Contact Metamorphism and Skarn Formation at Crestmore, CA, USA

a) Calcite + brucite + clinohumite + spinel zone to the Calcite + clinohumite + forsterite + spinel sub-zone involves the reaction:

$$2\ \text{Clinohumite} + SiO_2 \rightarrow 9\ \text{Forsterite} + 2\ H_2O$$

b) Formation of the vesuvianite zone involves the reaction:

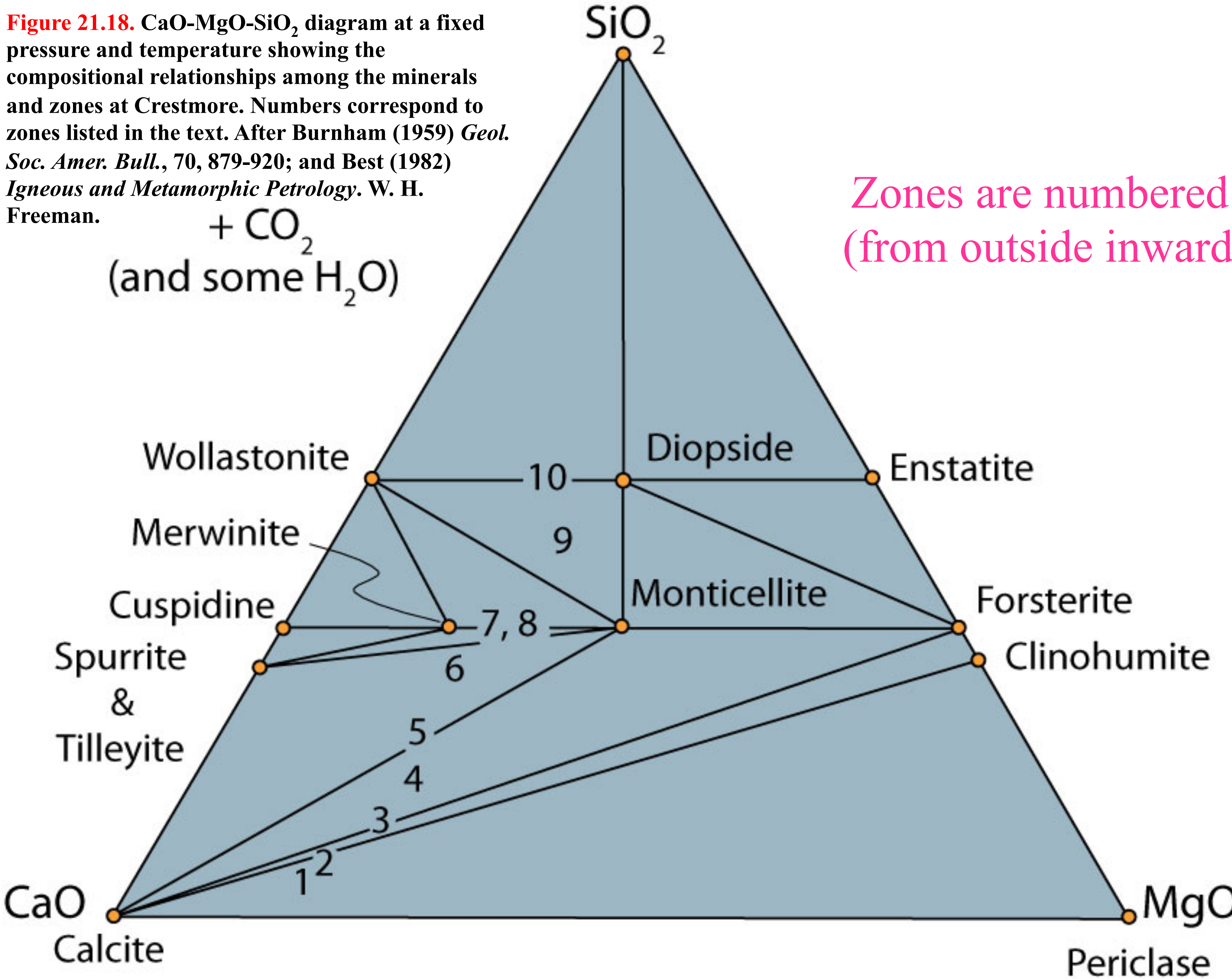
$$\text{Monticellite} + 2\ \text{Spurrite} + 3\ \text{Merwinite} + 4\ \text{Melilite} + 15\ SiO_2 + 12\ H_2O \rightarrow 6\ \text{Vesuvianite} + 2\ CO_2$$

Contact Metamorphism and Skarn Formation at Crestmore, CA, USA

2) Find a way to display data in simple, yet useful ways

If we think of the aureole as a chemical system, we note that most of the minerals consist of the components CaO-MgO-SiO_2-CO_2-H_2O (with minor Al_2O_3)

Figure 21.18. CaO-MgO-SiO_2 diagram at a fixed pressure and temperature showing the compositional relationships among the minerals and zones at Crestmore. Numbers correspond to zones listed in the text. After Burnham (1959) *Geol. Soc. Amer. Bull.*, 70, 879-920; and Best (1982) *Igneous and Metamorphic Petrology*. W. H. Freeman.



Zones are numbered (from outside inward)

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: and 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 inequant 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.**

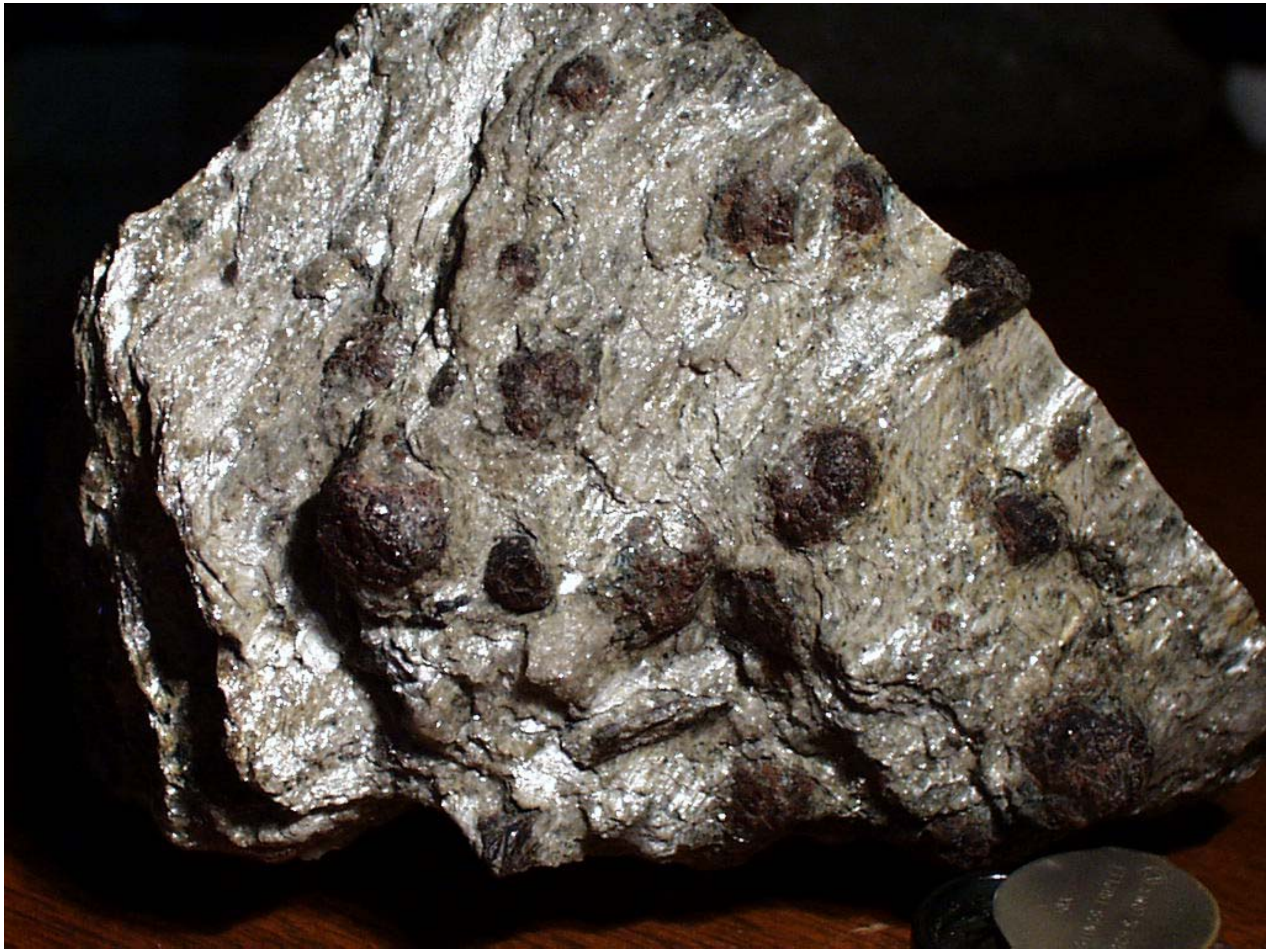


Figure 22.1c. Garnet muscovite schist. Muscovite crystals are visible and silvery, garnets occur as large dark porphyroblasts. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

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. Some confusion may result from the use of this term in sedimentary petrology for a pure quartz 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 + 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-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

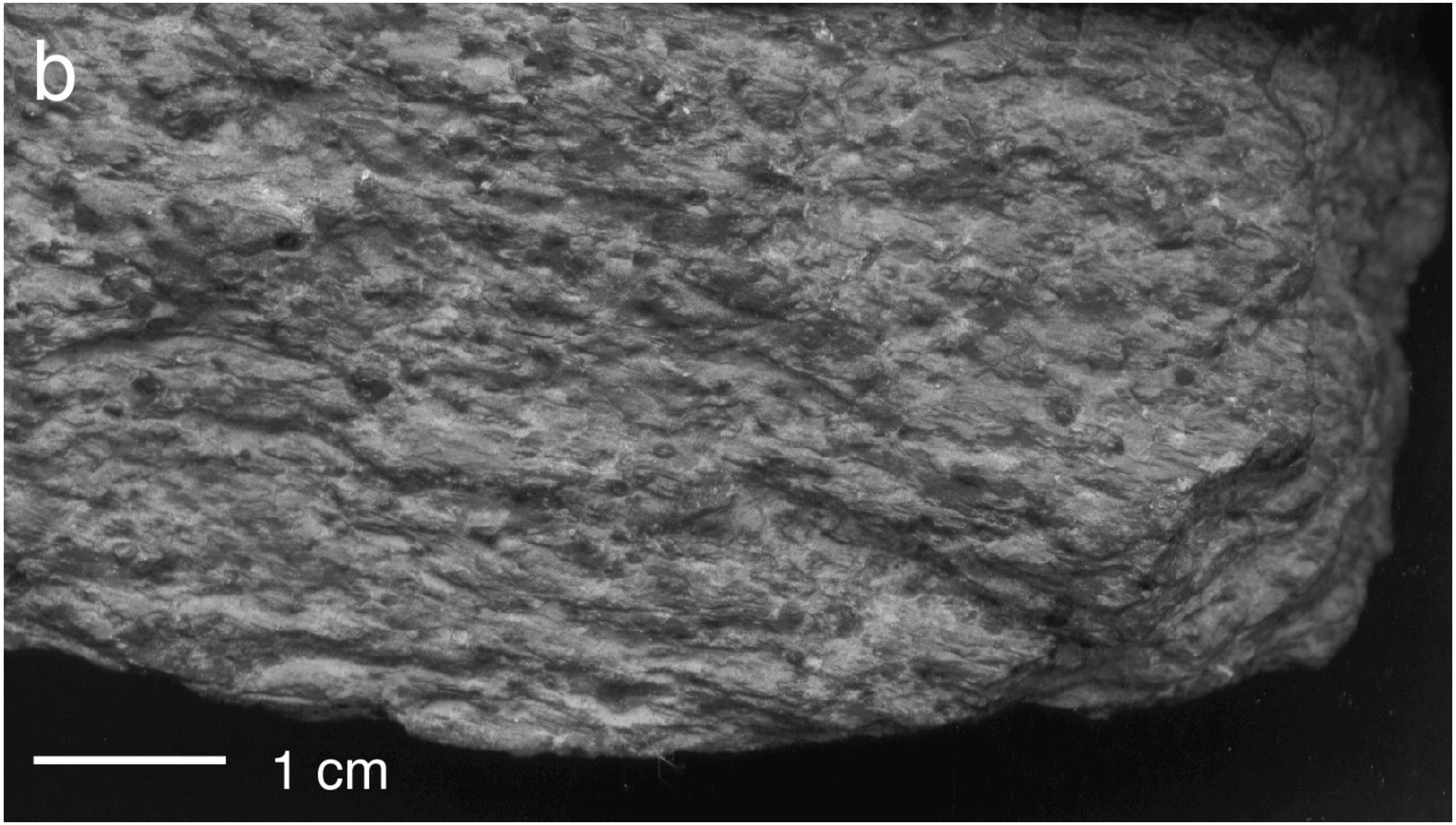


Figure 23.14b. **Spotted Phyllite. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.**

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 Section 23.1). 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 (Fig. 23-18).

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

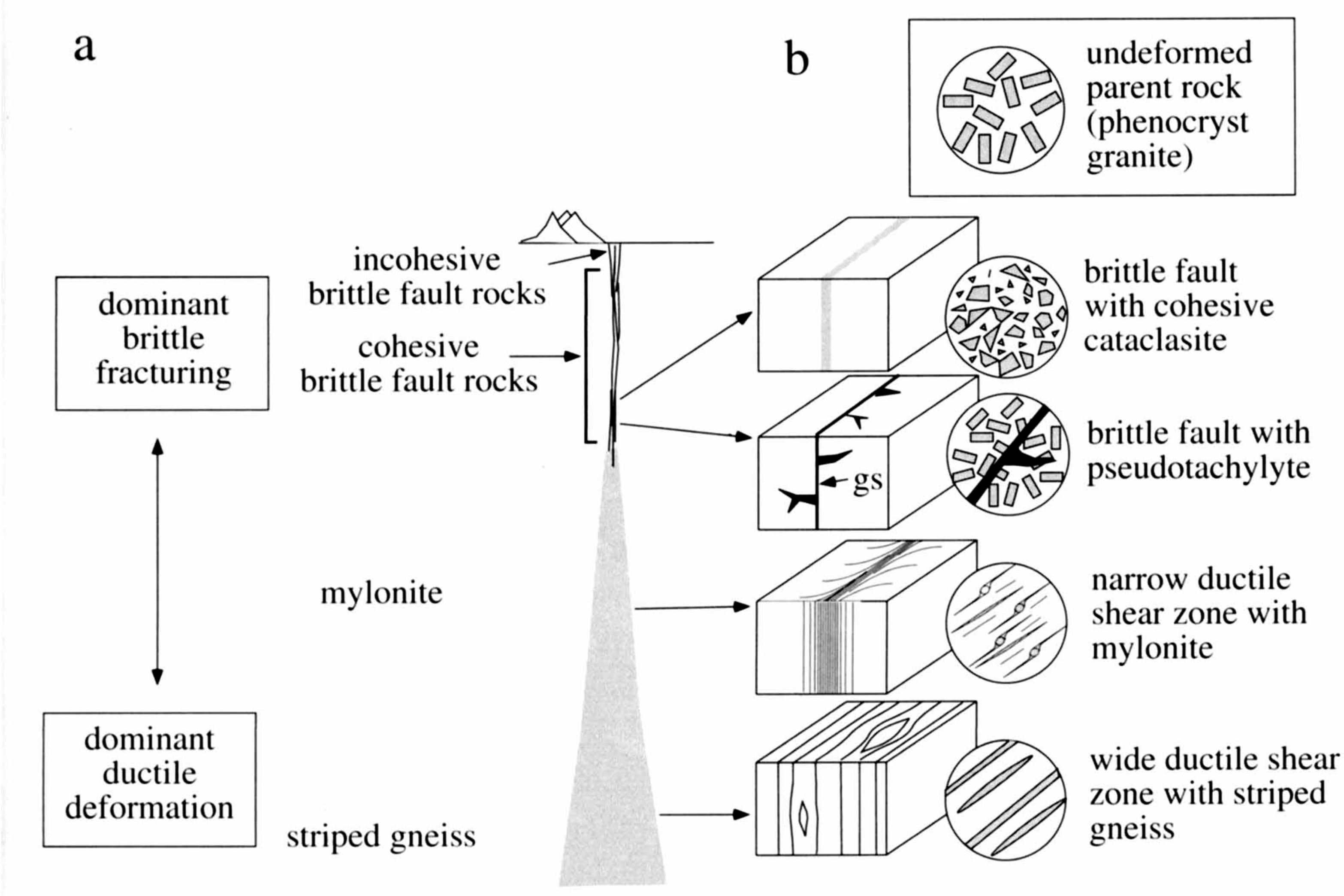


Figure 22.2. Schematic cross section through a shear zone, showing the vertical distribution of fault-related rock types, ranging from non-cohesive gouge and breccia near the surface through progressively more cohesive and foliated rocks. Note that the width of the shear zone increases with depth as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

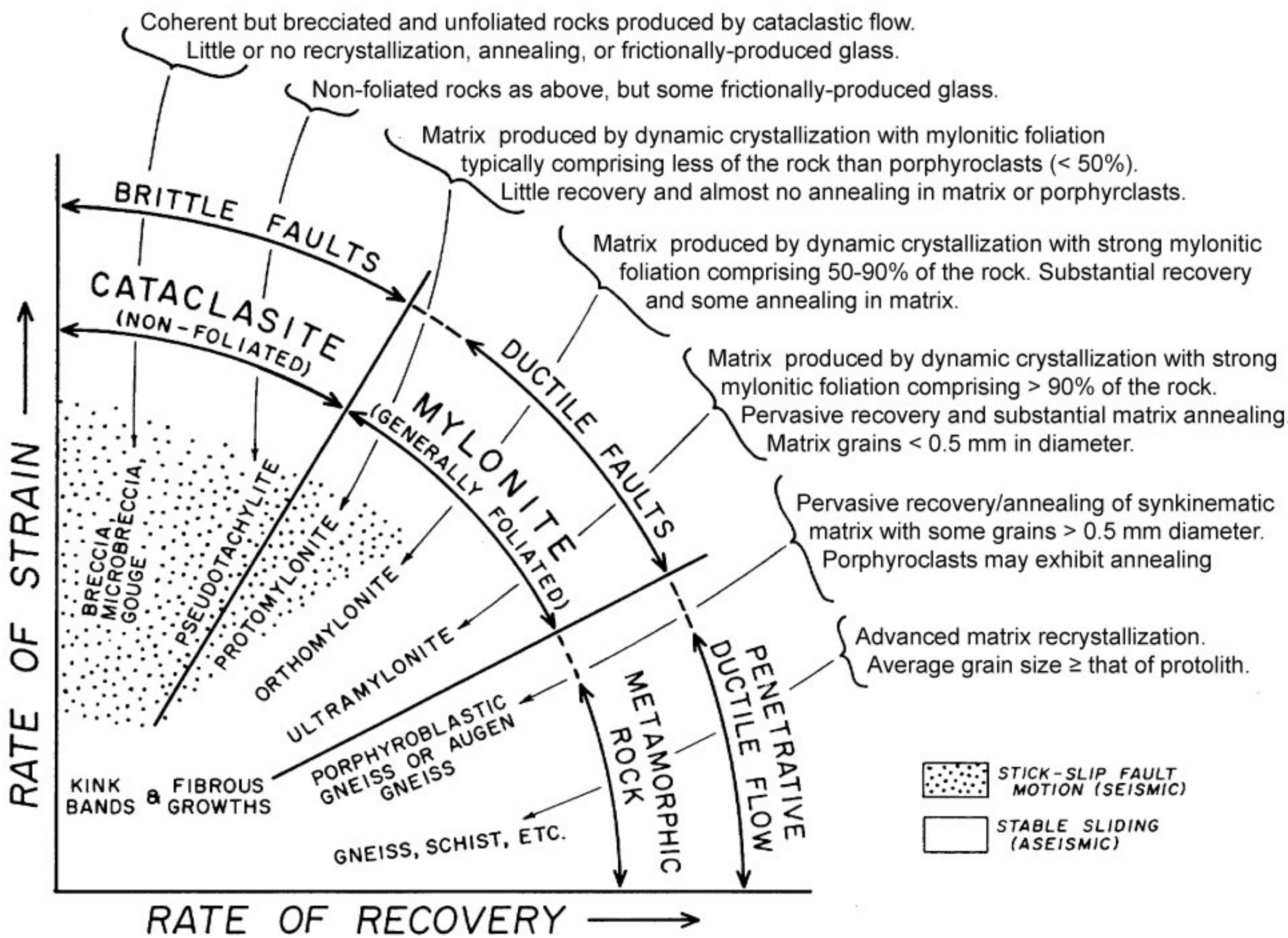


Figure 22.3. Terminology for high-strain shear-zone related rocks proposed by Wise *et al*. (1984) Fault-related rocks: Suggestions for terminology. *Geology*, 12, 391-394.

Chapter 22: High Strain Rocks

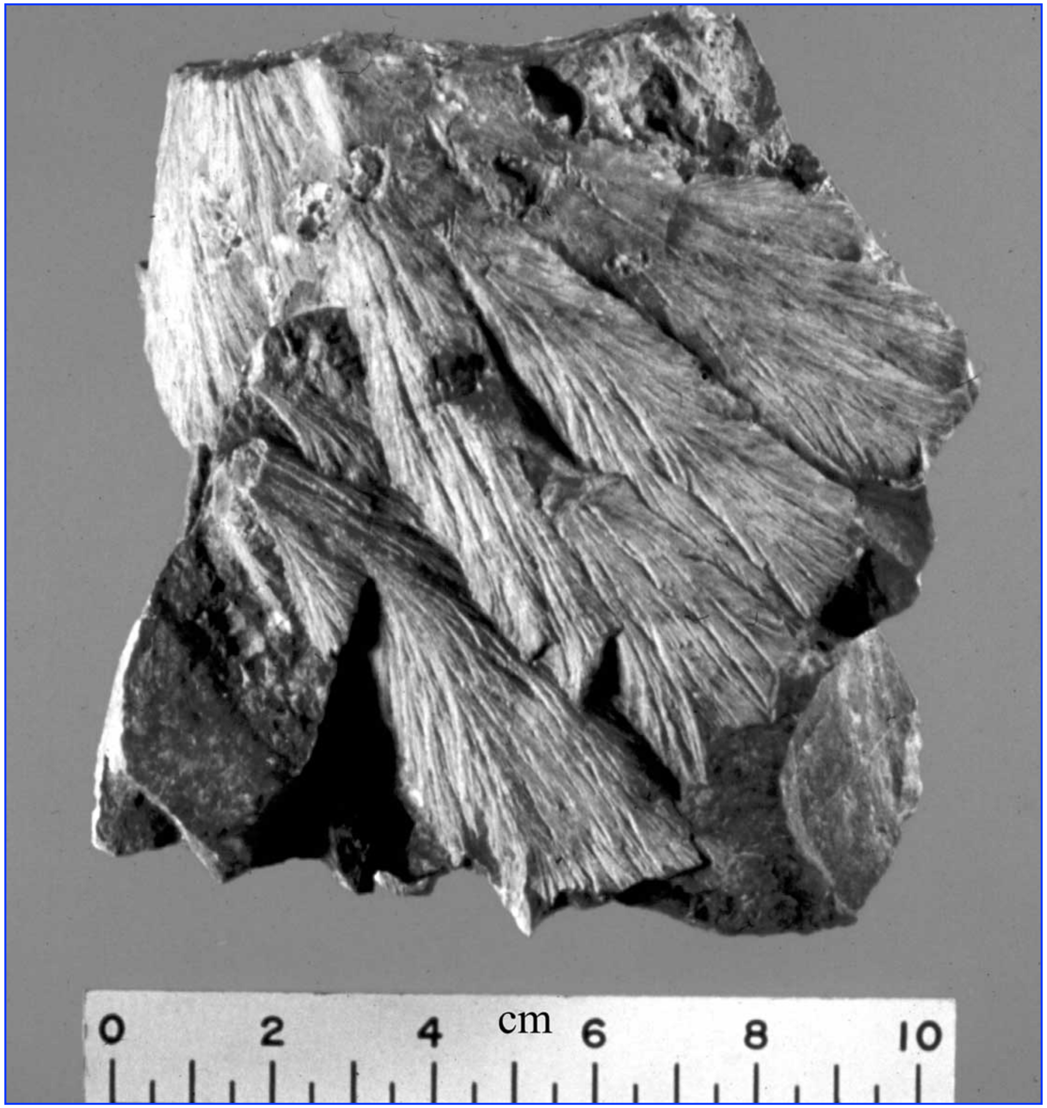


Figure 22.4. Shatter cones in limestone from the Haughton Structure, Northwest Territories. Photograph courtesy Richard Grieve, © Natural Resources Canada.