

Progressive Metamorphism

Reading:

Winter, Chapter 21

Progressive 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

Progressive 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

P-T-t Path

- The preserved zonal distribution of metamorphic rocks suggests that each rock preserves the conditions of the maximum metamorphic grade (temperature)
- All rocks that we now find must also have cooled to surface conditions
- At what point on its cyclic P-T-t path did its present mineral assemblage last equilibrate?

Prograde Reactions

- Retrograde metamorphism is of only 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

The common types of sedimentary and igneous rocks fall into six chemically based-groups

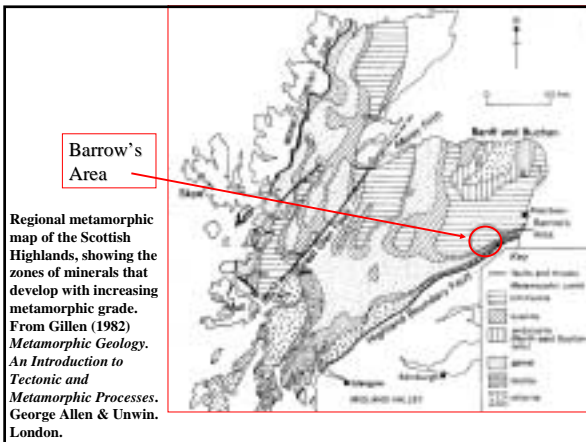
1. Ultramafic - very high Mg, Fe, Ni, Cr
2. Mafic - high Fe, Mg, and Ca
3. Shales (pelitic) - high Al, K, Si
4. Carbonates - high Ca, Mg, CO₂
5. Quartz - nearly pure SiO₂.
6. Quartz-feldspathic - high Si, Na, K, Al

Examples of Metamorphism

- Interpretation of the conditions and evolution of metamorphic bodies, mountain belts, and ultimately the 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
- Granites



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

Low Grade Barrovian Zones

- 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

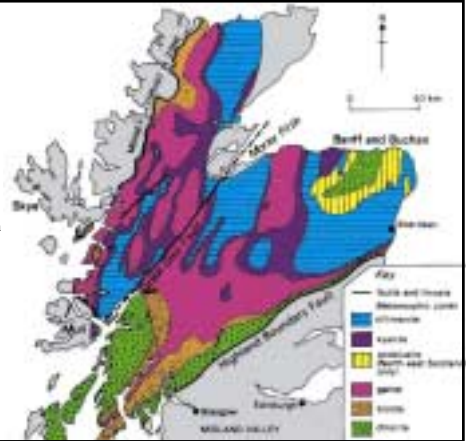
High Grade Barrovian Zones

- 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)

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)

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.



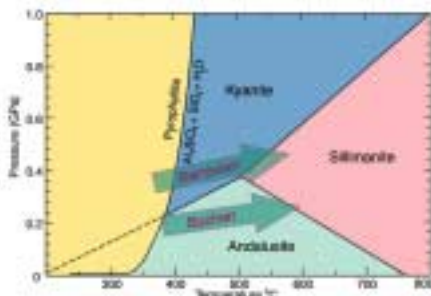
Summary

- An isograd (in this classical sense) 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
- Since 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

Banff and Buchan Districts

- The 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



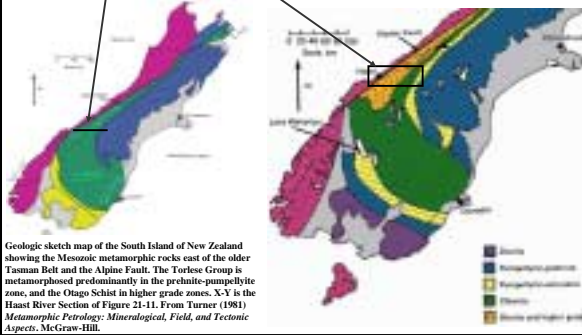
The P-T phase diagram for the system Al_2SiO_5 , showing the stability fields for the three polymorphs andalusite, kyanite, and sillimanite. Also shown is the hydration of Al_2SiO_5 to pyrophyllite, which limits the occurrence of an Al_2SiO_5 polymorph at low grades in the presence of excess silica and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

Regional Burial Metamorphism

- Otago, New Zealand example
- Jurassic graywackes, tuffs, and volcanics in a deep trough metamorphosed in the Cretaceous
- The fine grain size and immature nature of the material is highly susceptible to alteration, even at low grades

Otago, New Zealand

Section X-Y shows more detail

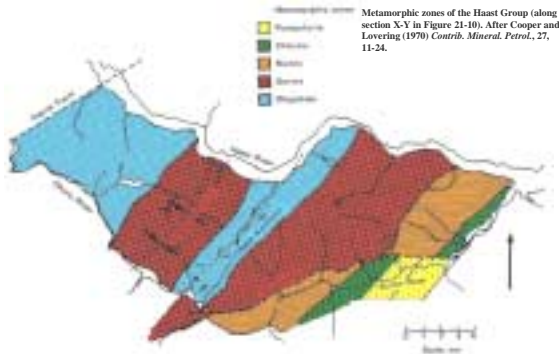


Otago, New Zealand

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



Otago, New Zealand

- Orogenic belts typically proceed directly from diagenesis to chlorite or biotite zones
- The development of low-grade zones in New Zealand may reflect the highly unstable nature of the tuffs and graywackes, and the availability of hot water
- Whereas pelitic sediments may not react until higher grades

Paired Metamorphic Belts of Japan

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

- The NW belt ("inner" belt, inward, or away from the trench) is the Ryoke (or Abukuma) Belt
 - Low P/T Buchan-type of regional orogenic metamorphism
 - Dominant meta-pelitic sediments, and isograds up to the sillimanite zone have been mapped
 - A high-temperature-low-pressure belt, and granitic plutons are common

Paired Metamorphic Belts of Japan

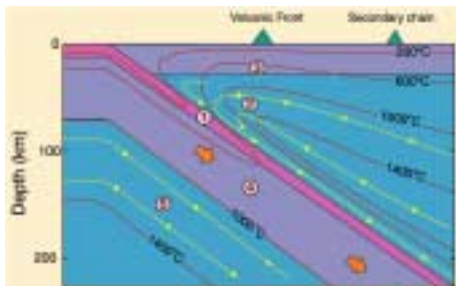
- Outer belt, called the Sanbagawa Belt
- It is of a high-pressure-low-temperature nature
 - Only reaches the garnet zone in the pelitic rocks
 - Basic rocks are more common than in the Ryoke belt, however, and in these glaucophane is developed (giving way to hornblende at higher grades)
 - Rocks are commonly called blueschists

Paired Metamorphic Belts of Japan

- Two belts are in contact along their whole length across a major fault zone (the Median Line)
- Ryoke-Abukuma lithologies are similar to seds derived from a relatively mature volcanic arc
- Sanbagawa lithologies more akin to the oceanward accretionary wedge where distal arc-derived sediments and volcanics mix with oceanic crust and marine sediment

Paired Metamorphic Belts of Japan

The 600°C isotherm could be as deep as 100 km in the trench-subduction zone area, and as shallow as 20 km beneath the volcanic arc



Miyashiro (1961, 1973) suggested that the occurrence of coeval metamorphic belts, an outer, high-P/T belt, and an inner, lower-P/T belt ought to be a common occurrence in a number of subduction zones, either modern or ancient



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

Contact Metamorphism of Pelitic Rocks

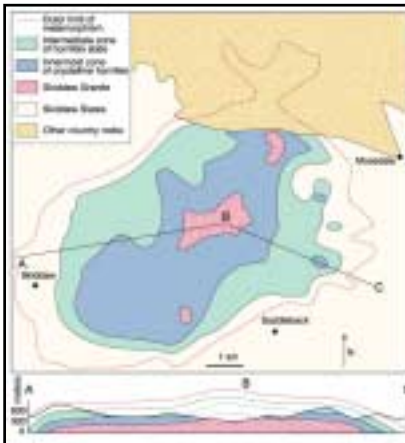
- Ordovician Skiddaw Slates (English Lake District) intruded by several granitic bodies
- Intrusions are shallow, and contact effects overprinted on an earlier low-grade regional orogenic metamorphism

Skiddaw Aureole, UK

- The aureole around the Skiddaw granite was subdivided into three zones, principally on the basis of textures:
 - Unaltered slates
 - Outer zone of spotted slates
 - Middle zone of andalusite slates
 - Inner zone of hornfels
 - Skiddaw granite

Increasing
Metamorphic
Grade



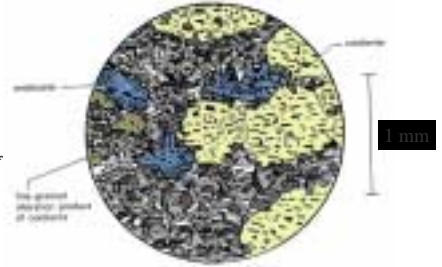


Geologic Map and cross-section of the area around the Skiddaw granite, Lake District, UK. After Eastwood et al (1968). *Geology of the Country around Cockermouth and Caldbeck*.

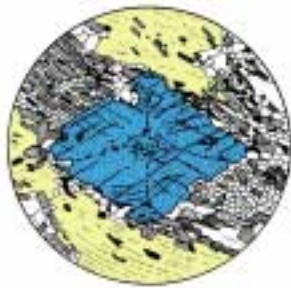
The Skiddaw Aureole, UK

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

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



The Skiddaw Aureole, UK



Inner zone:
Thoroughly recrystallized
Lose foliation

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

The Skiddaw Aureole, UK

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

Contact Metamorphism of Pelitic Rocks

- Inner aureole at Comrie (a diorite intruded into the Dalradian schists back up north in Scotland), the intrusion was hotter and the rocks were metamorphosed to higher grades than at Skiddaw
- Tilley describes coarse-grained non-foliated granofels containing very high-temperature minerals such as orthopyroxene and K-feldspar that have formed due to the dehydration of biotite and muscovite in the country rocks

Skarn Formation at Crestmore, CA, USA

- Crestmore quarry in the Los Angeles basin
- Quartz monzonite porphyry of unknown age intrudes Mg-bearing carbonates (either late Paleozoic or Triassic)
- Brunham (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:

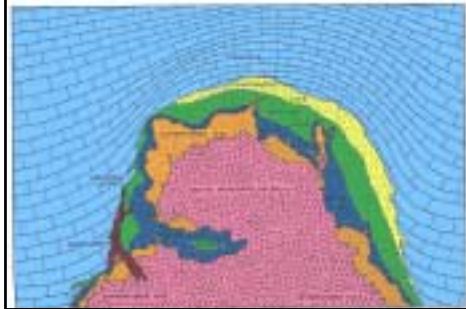
- vesuvianite + monticellite + spurrite + merwinite + melilite
- vesuvianite + monticellite + diopside + wollastonite

– Garnet Zone:

- grossular + diopside + wollastonite

Skarn Formation at Crestmore, CA, USA

An idealized cross-section through the aureole



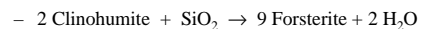
Idealized N-S cross section (not to scale) through the quartz monzonite and the aureole at Crestmore, CA. From Burnham (1959) *Geol. Soc. Amer. Bull.*, 70, 879-920.

Skarn Formation at Crestmore, CA, USA

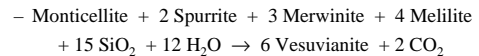
1. The mineral associations in successive zones (in all metamorphic terranes) vary by the formation of new minerals as grade increases
2. This can only occur by a chemical reaction in which some minerals are consumed and others produced

Skarn Formation at Crestmore, CA, USA

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



- b) Formation of the vesuvianite zone involves the reaction:



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-SiO₂-CO₂-H₂O (with minor Al₂O₃)

