جامعة جنوب الوادي

كلية العلوم بقنا

قسم الجيولوجيا

مقرر الصخور المتحولة [كود المقرر 318 ج]

لطلاب الفرقة الثالثة علوم جيولوجيا

جميع الشعب

الفصل الدراسي الثاني

2023-2022

Geology Department

Metamorphic Rocks Course [ii]

for

for 3rd Year Students

by

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Contents

Learning Objectives

After this course, students will be able to:

- **Definite of Metamorphism.**
- **Differentiate between the main types of Metamorphism**
- **What factors controlling Metamorphism?**
- **Definite the types of Protolith**
- **Definite the metamorphic processes**
- **Name and define each process that forms metamorphic rock**
- **Describe each process that forms various types of metamorphic rock.**
- **Describe the grade of metamorphism.**
- **Classified the metamorphic rocks based on texture/ structures**

Materials

- Metamorphic rock samples.
- Geological maps.
- Thin sections.
- Photos.

First Lecture

- ## Introduction:
  - ***What is metamorphism?***

- ## Definitions

➢ Meta means ‘change’, Morph means ‘form’

➢ A change in form of pre-existing rocks of all types. Sedimentary, igneous and metamorphic

  - Metamorphism begins in the range of 100-150^{o}C for the more unstable types of Protolith.
  - Some zeolites are considered diagenetic.

➢ "Metamorphism is the mineralogical and/or textural changes that take place in a rock in response to changes in its physicochemical environment."

- **Metamorphism**

Metamorphism is the change of minerals or texture (distinct arrangement of minerals) in pre-existing rocks (Protoliths), without the protolith melting into liquid magma (a solid-state change).

- **Metamorphism**

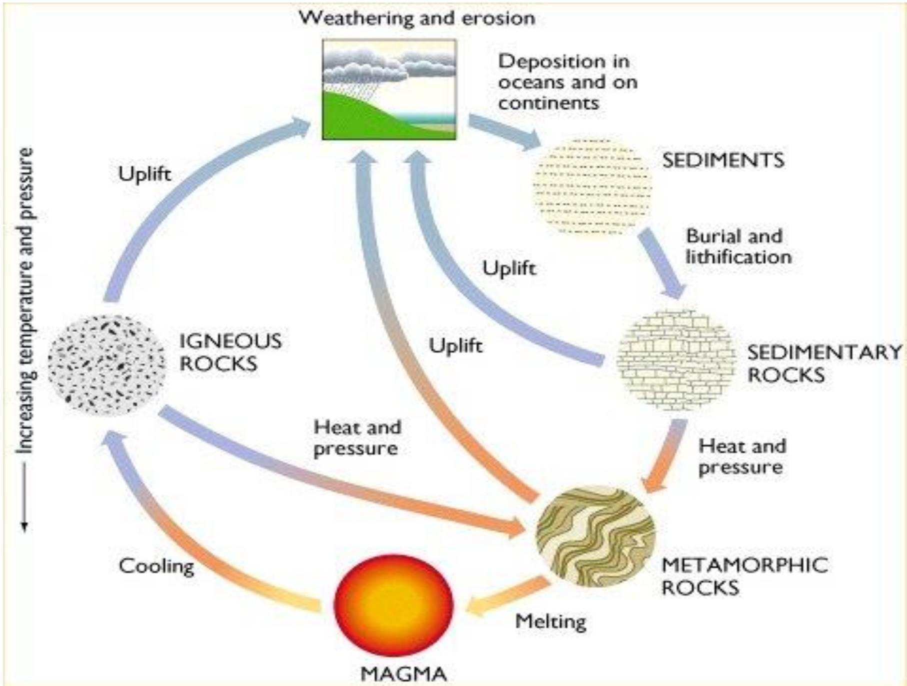
"Metamorphism is a sub-solidus process leading to changes in mineralogy and/or texture (for example grain size) and often in chemical composition in a rock. These changes are due to physical and/or chemical conditions that differ from those normally occurring at the surface of planets and in zones of cementation and diagenesis below this surface. They may coexist with partial melting."

- ***Why do we study metamorphic rocks?***

II- Range of Metamorphism:

The temperature "boundaries" between metamorphism and diagenesis on one hand and metamorphism and igneous activity on the other are not clear cut, or well defined, but will depend on many factors. Nevertheless, the range of metamorphism can be set at >150-200°C and <700-800°C.

- **THE ROCK CYCLE**



- **Agents of Metamorphism**

  ✓ **Temperature:**

  Typically the most important factor in metamorphism.

  Increasing temperature has several effects:

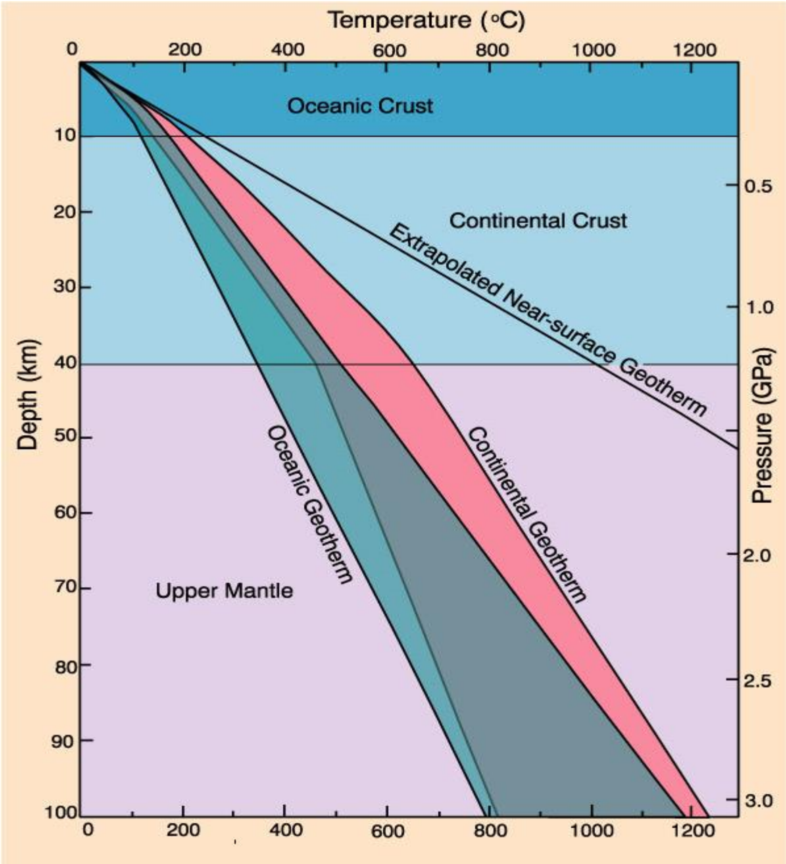
1) **Promotes recrystallization → increased grain size:**

- **Larger surface/volume ratio of a mineral → lower stability.**
- **Increasing temperature eventually overcomes kinetic barriers to recrystallization, and fine aggregates coalesce to larger grains.**

2) **Drive reactions that consume unstable mineral(s) and produces new minerals that are stable under the new conditions.**
3) **Overcomes kinetic barriers that might otherwise preclude the attainment of equilibrium.**

- **Pressure**
  - **“Normal” gradients may be perturbed in several ways, typically:**
  - **High T/P geo-themes in areas of plutonic activity or rifting.**
  - **Low T/P geo-themes in subduction zones.**
  - **Stress is an applied force acting on a rock (over a particular cross-sectional area)**
  - **Strain is the response of the rock to an applied stress (= yielding or deformation)**
  - **Stress affects the textures and structures, but not the equilibrium mineral assemblage**
  - **Strain energy may overcome kinetic barriers to reactions**

- **Fluids**
  - **Evidence for the existence of a metamorphic fluid:**
  - **Fluid inclusions**
  - **Fluids are required for hydrous or carbonate phases**
  - **Volatile-involving reactions occur at temperatures and pressures that require finite fluid pressures**



Second Lecture

- **Types of Metamorphism**
  - **Contact Metamorphism "Thermal Metamorphism".**
  - **Regional Metamorphism**
  - **Orogenic Metamorphism**
  - **Burial Metamorphism**
  - **Ocean Floor Metamorphism**
  - **Cataclastic Metamorphism.**
  - **Fault-Zone Metamorphism.**
  - **Hydrothermal Metamorphism.**
  - **Impact or Shock Metamorphism.**

- ## Summary of main Types of Metamorphism

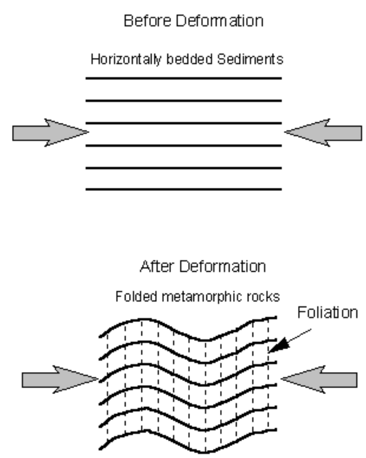
Type	Textures	Main factors	P-T conditions	Environment
Cataclastic	cataclastic	mostly P	med P, low T	Fault zone
Contact	Hornfelsic granoblastic	T ± fluids	High T, variable P	Near igneous intrusions
Regional	usually foliated	P, T ± fluids	variable P and T	Orogenic belts, areas of regional deformation
Burial	Non foliated, relict	P and T	Low P and T	Deep sedimentary basins with volcanic and sedimentary sequences
Ocean floor	Variable; non-foliated, foliated and relict	T, fluids ± P	Low to med P, med. to high T.	Ocean floor, close to spreading centers.
Impact	Shock textures; tektites	P and T	very high P and T	Sites of meteoritic impact.

- ## Three major types of Metamorphism

- **Regional metamorphism** occurs when large areas of the crust are subjected to high temperatures and/or pressures.

Conditions

- ✓ Metamorphism occur covering larger area, which is subjected to intense deformation under direct or differential stress.
- ✓ Rocks formed under such environment are usually strongly foliated, such as slates, schists, and gneisses.
- ✓ The differential stresses result from tectonic forces, e.g. when two continental masses collide with one another resulting into mountain building activity. Compressive stresses result in folding of the rock.



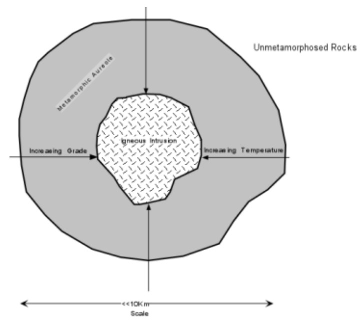
- ## Thermal "Contact" metamorphism:

- This type of metamorphism occurs locally adjacent to the igneous intrusion; with high temperature and low Pressure.
- Low to moderate pressure (P) Pressures are generally less than 4 kilo bars (Kb); low to high temperature (T) Temperatures of metamorphism vary widely from 400-1000 Celsius (C).

- There is little change in bulk composition of the rock.
- Area surrounding the intrusion (Batholith) is heated by the magma; metamorphism is restricted to a zone surrounding the intrusion, this zone is known as

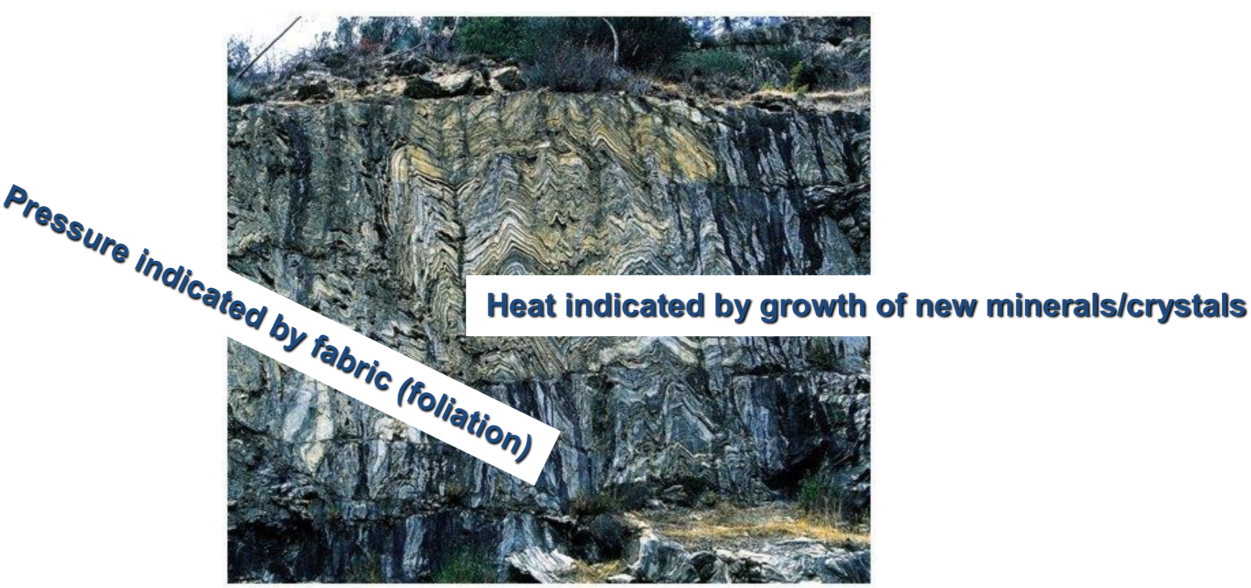
METAMORPHIC AUREOLE

- The rocks formed are non-foliated fine-grained rocks called as <u>HORNFELS</u>.



- **Dynamic metamorphism** Dynamic metamorphism is associated with zones of high to moderate strain such as fault zones. Cataclastic, crushing and grinding of rocks into angular fragments, occurs in dynamic metamorphic zones, giving cataclastic texture.

- **Factors Controlling Metamorphism**



- **Types of Protolith**
  - Protoliths:

- **The protolith of a metamorphic rock is its original rock before metamorphism. Because metamorphism is predominantly isocheimal, chemical analysis of a metamorphic rock yields clues as to its protolith. A good metamorphic petrologist can therefore guess the protolith of the metamorphic rock from its mineralogy. Texture may also be useful in some cases, as some metamorphic rocks preserve textures inherited from their Protoliths.**

1. **Pelitic / mud rocks - high Al, K, Si**
2. **Quartz-feldspathic - high Si, Na, K, Al**
3. **Calcareous- high Ca, Mg, CO2**
4. **Mafic- high Ca, Mg, Fe**
5. **Ultramafic- very high Mg, Fe, low Si, Al**

- WHY IS CHEMICAL COMPOSITION OF PROTOLITH IMPORTANT?

- **Metamorphism of Pelitic Sediments**
  Mudstones and Shales: very fine grained mature clastic sediments derived from continental crust; grade into coarser greywackes and sandy sediments toward the continental source.
- Metapelites represent a distinguished family of metamorphic rocks, because the clays are very sensitive to variations in temperature and pressure, undergoing extensive changes in mineralogy during progressive metamorphism.
- The mineralogy of pelitic sediments is dominated by fine Al-K-rich phyllosilicates, such as clays (kaolinite, or smectite), fine white micas (sericite, paragonite, or phengite) and chlorite, all of which may occur as detrital.

- The phyllosilicates may compose more than 50% of the original sediment.
- Fine quartz constitutes another 10-30%.
- Other common constituents include feldspars (albite and K-feldspar), iron oxides and hydroxides, zeolites, carbonates, sulphides, and organic matter.
- Distinguishing chemical characteristics: high Al2O3 and K2O, and low CaO.
- Reflect the high clay and mica content of the original sediment and lead to the dominance of muscovite and quartz throughout most of the range of metamorphism.
- High proportion of micas & common development of foliated rocks, such as slates, phyllites, and mica schists.
- The chemical composition of pelites can be represented by the system K2O-FeO-MgO-Al2O3-SiO2-H2O ("KFMASH")
- If we treat H2O as mobile, the petrogenesis of pelites is represented well in AKF and A(K)FM diagrams

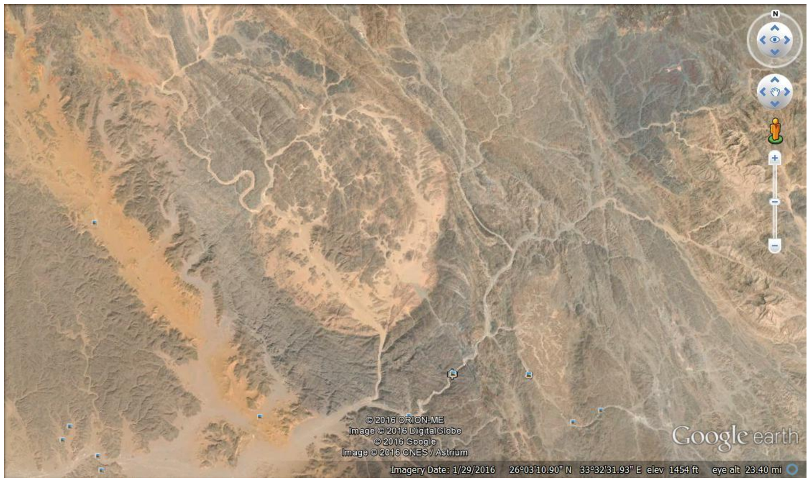
Table 28-1. Chemical Compositions* of Shales and Metapelites

	1	2	3	4	5
SiO_2	64.7	64.0	61.5	65.9	56.3
TiO_2	0.80	0.81	0.87	0.92	1.05
Al_2O_3	17.0	18.1	18.6	19.1	20.2
MgO	2.82	2.85	3.81	2.30	3.23
FeO	5.69	7.03	10.0	6.86	8.38
MnO	0.25	0.10			0.18
CaO	3.50	1.54	0.81	0.17	1.59
Na_2O	1.13	1.64	1.46	0.85	1.86
K_2O	3.96	3.86	3.02	3.88	4.15
P_2O_5	0.15	0.15			
Total	100.00	100.08	100.07	99.98	96.94

* Reported on a volatile-free basis (normalized to 100%) to aid comparis

1. "North American Shale Composite". Gromet *et al.* (1984). **2.** Average of ~100 published shale and slate analyses (Ague, 1991). **3.** Ave. pelite-pelagic clay (Carmichael, 1989). **4.** Ave. of low-grade pelitic rocks, Littleton Fm, N.H. (Shaw, 1956). **5.** Ave. of

- **Example of contact metamorphism; Um Had metamorphic AUREOLE**

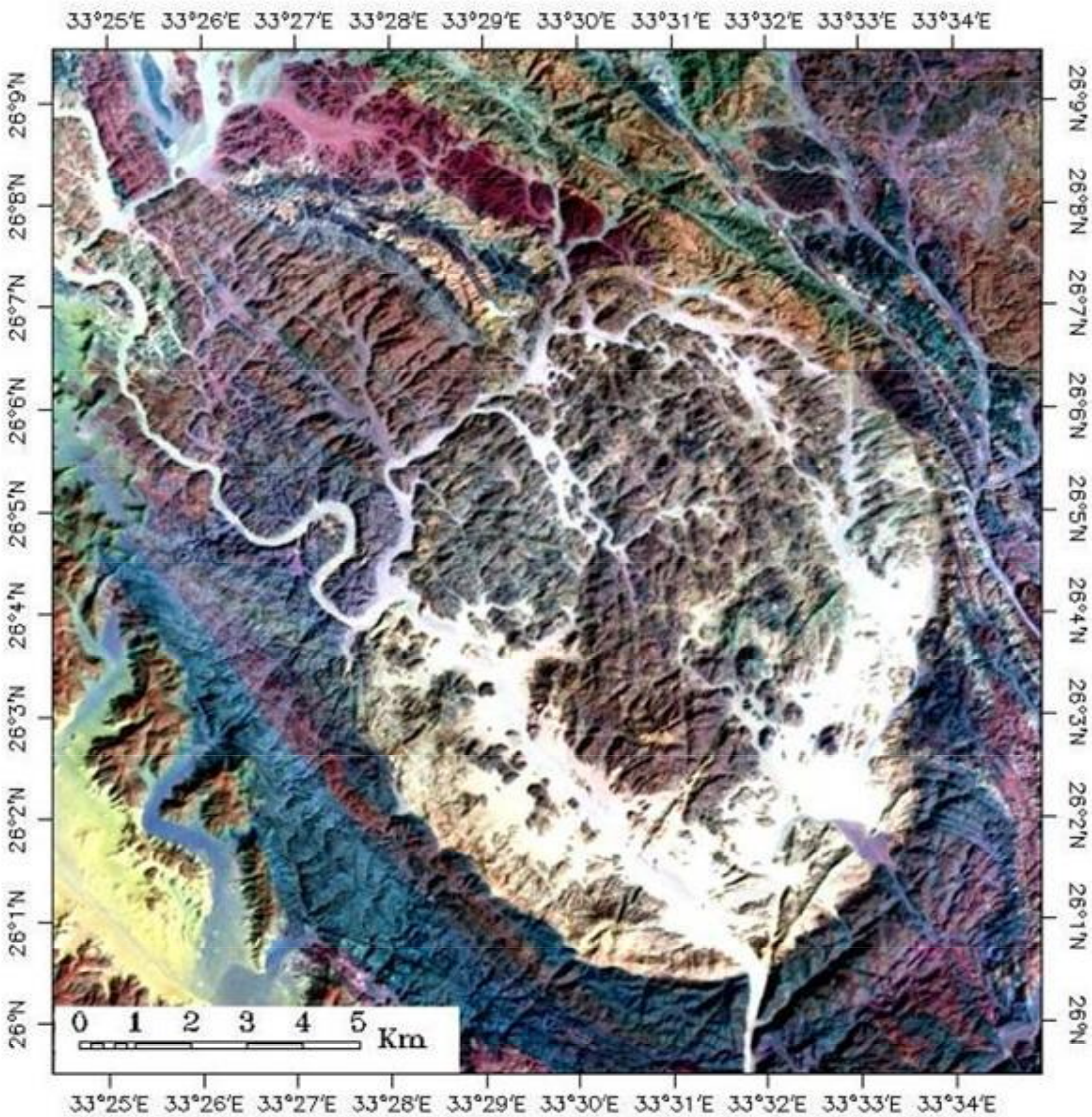


Um Had area is occupied mainly by ophiolitic mélange assemblage represented by serpentinites, metagabbro, and metabasalt. The ophiolitic mélange rocks are intruded by granitic rocks, and overlain by Hammamat sediments (next map). The ophiolitic mélange rocks are composed mainly of serpentinites, metagabbros and metabasalts. The ophiolitic mélange assemblage is intruded by post-emplacement younger granites and later basic to acidic dykes that cut all of the ophiolite units. The Um Had area contains a large elliptical structure trending northwest outlining a core of medium- to high-grade partly gneissic rocks enclosed by a domed thick mylonitic shear zone (e.g., Fowler, 2001). The core is up-heaved by the Um Had granitoid intrusion. The latter and its equivalents scattered throughout the Egyptian Eastern Desert was emplaced during Pan-African orogeny.

These granitoids are referred to as late- to post-orogenic calc-alkaline to transitional A-type granitoids.

These granitoids are characterised by unfoliated, small, nearly circular to elongate epizonal plutons with sharp intrusive contacts. The southern, SW and SE contacts of this intrusion dip generally at moderate angles outwards, whereas, the western and eastern contacts are steep and associated with syn-intrusion faulting. On the other hand, the northern edge is defined by the northernmost significant dykes cropping out along Wadi Shegila. To the west and south of Um Had intrusion, the Dokhan volcanics and Hammamat sediments crop out.

- **Um Had metamorphic map**



The northern part; the mineral assemblages:

1. Epidote, chlorite, andalusite, muscovite, quartz, k-feldspar, and albite.
2. Sillimanite, plagioclase, cordierite, muscovite, quartz and k-feldspar.
3. Sillimanite, plagioclase, cordierite, quartz, and k- feldspar.

Third Lecture

▪ Metamorphic zones:

- **Chlorite zone**: Pelitic rocks are changed to hornfels typically contain chlorite, muscovite, quartz and albite.

- **Biotite zone:** Pelitic rocks are changed hornfels, with biotite, chlorite, muscovite, quartz, and albite.
-
- **Garnet zone:** Pelitic rocks are changed to hornfels with conspicuous red almandine garnet, usually with biotite, chlorite, muscovite, quartz, and albite or oligoclase.
-
- **Staurolite zone:** Pelitic rocks are changed to hornfels with staurolite, biotite, muscovite, quartz, garnet, and plagioclase. Some chlorite may persist.
- **Sillimanite zone:** Pelitic rocks are changed to hornfels with Sillimanite, biotite, muscovite, quartz, plagioclase, garnet, and perhaps staurolite.

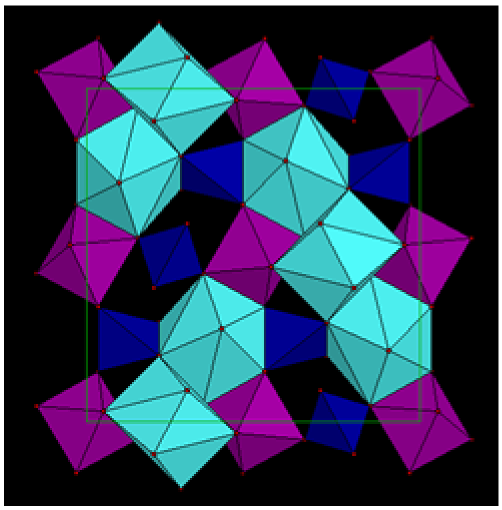
▪ Metamorphic processes

- **Chlorite + muscovite === staurolite + biotite + quartz + H_2O (dehydration).**
- **Staurolite + muscovite + quartz === Sillimanite + biotite + H_2O (higher T & low P).**
- **Calcite + quartz === wollastonite + CO_2 (decarbonation).**
- **Chlorite + quartz = staurolite + garnet**
- **Chlorite + muscovite = staurolite + biotite + quartz + water.**

Fourth Lecture

- Metamorphic Minerals

Garnets



Garnet: $A^{2+}_3 B^{3+}_2 [SiO_4]_3$

"Pyralspites" - B = Al

- Pyrope: $Mg_3 Al_2 [SiO_4]_3$
- Almandine: Fe3 Al2 [SiO4]3
- Spessartine: Mn3 Al2 [SiO4]3

"Ugrandites" - A = Ca

- Uvarovite: Ca3 Cr2 [SiO4]3
- Grossularite: Ca3 Al2 [SiO4]3
- Andradite: Ca3 Fe2 [SiO4]3

Garnet (001) view blue = Si purple = A turquoise = B

- Carbonates **are changed to amphibolies as follows:**

- **Reactions that involve the evolution or consumption of CO2.**
- **$CaCO_3 + SiO_2 = CaSiO_3 + CO_2$**

  Calcite + quartz = wollastonite + CO_2

- Metamorphic processes

- **Recrystallization**

  During recrystallization, the grains making up the protolith change shape and size. The identity of the mineral does not change during this process, only the texture. Recrystallization occurs due to heating of the protolith. The temperature at which this occurs can vary depending on the minerals present. Recrystallization generally begins when temperatures reach above half the melting point of the mineral on the Kelvin scale.

  Solid-solid phase transformation:

- Polymorphic reaction → a mineral reacts to form a polymorph of that mineral
- No transfer of matter, only a re-arrangement of the mineral structure
- Example:
  - Andalusite → Sillimanite

Al_2SiO_5 Al_2SiO_5

- Solid-solid net-transfer:

- Involve solids only
- Differ from polymorphic transformations: involve solids of differing composition, and thus material must diffuse from one site to another for the reaction to proceed
- Examples:
- $NaAlSi_2O_6 + SiO_2 = NaAlSi_3O_8$
  Jd Qtz Ab
- $MgSiO_3 + CaAl_2Si_2O_8 = CaMgSi_2O_6 + Al_2SiO_5$
  En An Di And

- Solid-Solid Net-Transfer II:

- If minerals contain volatiles, the volatiles must be conserved in the reaction so that no fluid phase is generated or consumed
- For example, the reaction:

  Mg3Si4O10(OH)2 + 4 MgSiO3 = Mg7Si8O22(OH)2

  Talc Enstatite Anthophyllite

  involves hydrous phases, but conserves H2O

  It may therefore be treated as a solid-solid net-transfer reaction

- Hydration/ Dehydration Reactions:

- Metamorphic reactions involving the expulsion or incorporation of water (H2O)
- Example:
  - Al2Si4O10(OH)2 <=> Al2SiO5 + 3SiO2 + H2O

  Pyrophyllite And/Ky Quartz water

- Carbonation / Decarbonation Reactions

- Reactions that involve the evolution or consumption of CO2
- $CaCO_3 + SiO_2 = CaSiO_3 + CO_2$

calcite quartz wollastonite

Reactions involving gas phases are also known as volatilization or devoltilization reactions.

These reactions can also occur with other gases such as CH_4 (methane), H_2, H_2S, O_2, NH_4+ (ammonia) – but they are not as common.

- **Phase change**

Phase change metamorphism is the creating of new minerals with the same chemical formula as the protolith. This involves a rearrangement of the atoms in the crystals.

- **Neocrystallization**

Neocrystallization involves the creation of new mineral crystals different from the protolith. Chemical reactions digest the minerals of the protolith which yields new minerals. This is a very slow process as it can also involve the diffusion of atoms through solid crystals.

- **Pressure solution**

Pressure solution is a metamorphic process that requires a rock to be under strong pressure from one direction and in the presence of hot water. During this process mineral of the protolith partially dissolve, diffuse through the water and precipitate elsewhere.

- **Plastic deformation**

In plastic deformation pressure is applied to the protolith, which causes it to shear or bend, but not break. In order for this to happen temperatures must be high enough that brittle fractures do not occur, but not so high that diffusion of crystals takes place.

Fifth Lecture

Regional Metamorphism

- **Regional metamorphism** occurs due to changes in pressure and temperature over a large region of the crust.

- **Oogenesis** (**mountain building**) due to the collision of continents or island arcs on closure of ocean basins is associated with the most significant areas of regional metamorphism in which thickening of the crust and tectonic forces lead to increased temperature and pressure.
- **Orogeny-** **long-term mountain-building**; **Orogeny,** may comprise several tectonic events; **Orogeny,** may have several deformational phases; **Orogeny,** may have an accompanying metamorphic cycles with one or more reaction events.

Example:

The term 'Pan-African Orogeny ' was coined by WQ Kennedy in 1964 on the basis of an assessment of available Rb-Sr and K-Ar ages in Africa. The Pan-African was interpreted as a tectono-thermal event, some 500 Ma ago, during which a number of mobile belts formed, surrounding older cartons.

The concept was then extended to the Gondwana continents although regional names were proposed such as Brasiliano for South America, Adelaidean for Australia, and Beardmore for Antarctica. This thermal event was later recognized to constitute the final Part of an orogenic cycle, leading to orogenic belts which are currently interpreted to have resulted from the amalgamation of continental domains during the period -870 to -550 Ma.

The term Pan-African is now used to describe tectonic, magmatic, and metamorphic activity of Neoproterozoic to earliest Palaeozoic age, especially for crust that was once Part of Gondwana.

- **Regional metamorphism** also occurs at subduction zones, in the sub-ducting plate, in the overlying accretionary mélange, and in overlying continental crust.
- **Foliations** are typically formed in regionally metamorphic rocks; due to **directed stress**.

- **The most common regionally metamorphic rocks** are **slate, phyllites, schists; gneiss and granulite** are typical of regional metamorphism.
- **A wide range of metamorphic rocks** are produced by regional metamorphism, depending on the prevalent pressure and temperature conditions, the nature of the protolith rocks, and the pressure and temperature path followed during metamorphism.

▪ Textures of Regional Metamorphism

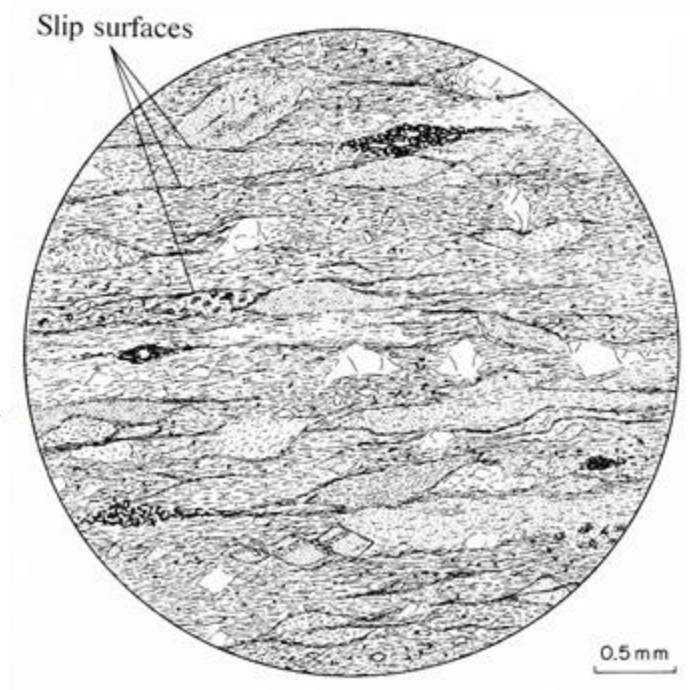
- **Texture** is used to describe the size, shape, and arrangement of grains within a rock.
- Dynamo-thermal (crystallization under dynamic conditions).

• Definitions:

- **Tectonites**- a deformed rock with a texture that records the deformation.
- **Fabric-** the complete geometric configuration of textural elements.
- **Foliation-** planar textural element
- **Lineation**- linear textural element
- Lattice Preferred Orientation (LPO)
- Dimensional Preferred Orientation (DPO)

Rock Name		Texture	Grain Size	Comments	Original Parent Rock
Slate	Increasing Metamorphism ↓	Foliated	Very fine	Excellent rock cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite		Foliated	Fine	Breaks along wavy surfaces, glossy sheen	Shale, mudstone, or siltstone
Schist		Foliated	Medium to Coarse	Micaceous minerals dominate, scaly foliation	Shale, mudstone, or siltstone
Gneiss		Foliated	Medium to Coarse	Compositional banding due to segregation of minerals	Shale, granite, or volcanic rocks
Migmatite		Foliated	Medium to Coarse	Banded rock with zones of light-colored crystalline minerals	Shale, granite, or volcanic rocks
Mylonite		Weakly Foliated	Fine	When very fine-grained, resembles chert, often breaks into slabs	Any rock type
Metaconglomerate		Weakly Foliated	Coarse-grained	Stretched pebbles with preferred orientation	Quartz-rich conglomerate
Marble		Nonfoliated	Medium to coarse	Interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite		Nonfoliated	Medium to coarse	Fused quartz grains, massive, very hard	Quartz sandstone
Hornfels		Nonfoliated	Fine	Usually, dark massive rock with dull luster	Any rock type
Anthracite		Nonfoliated	Fine	Shiny black rock that may exhibit conchoidal fracture	Bituminous coal
Fault breccia		Nonfoliated	Medium to very coarse	Broken fragments in a haphazard arrangement	Any rock type

Progressive syntectonic metamorphism of a volcanic graywacke, New Zealand.
From Best (1982). *Igneous and Metamorphic Petrology*. W. H. Freeman. San Francisco.



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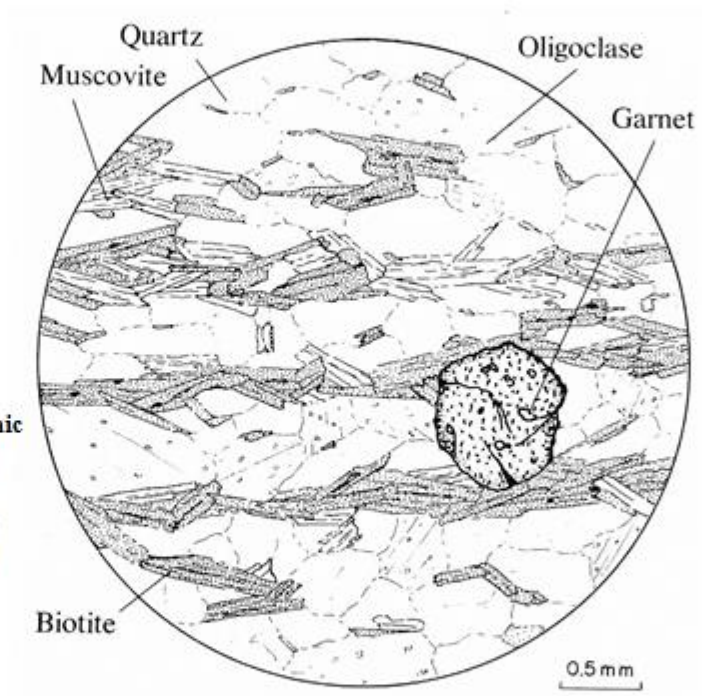
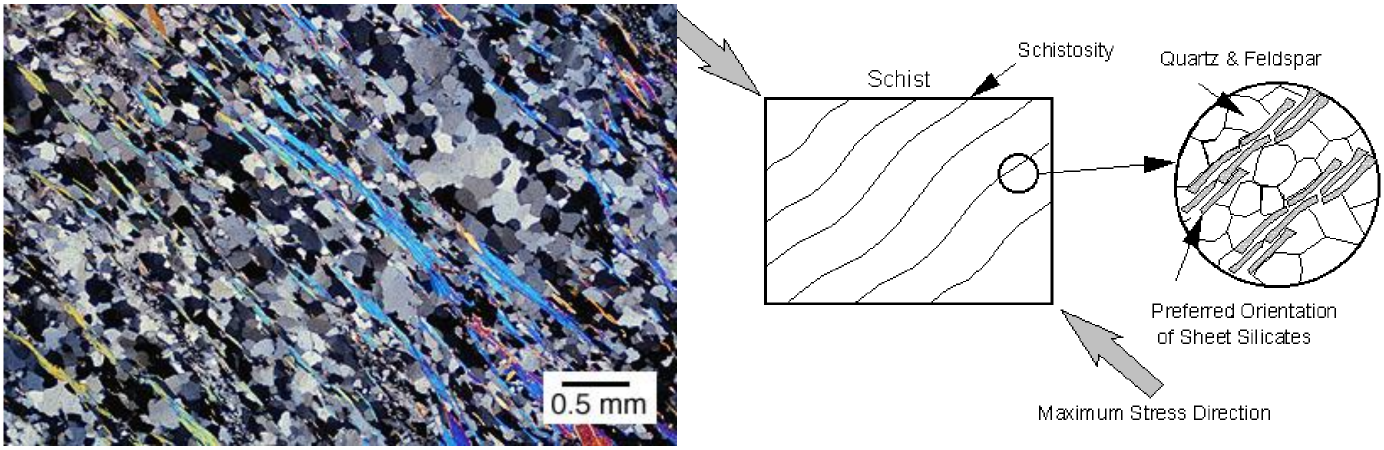


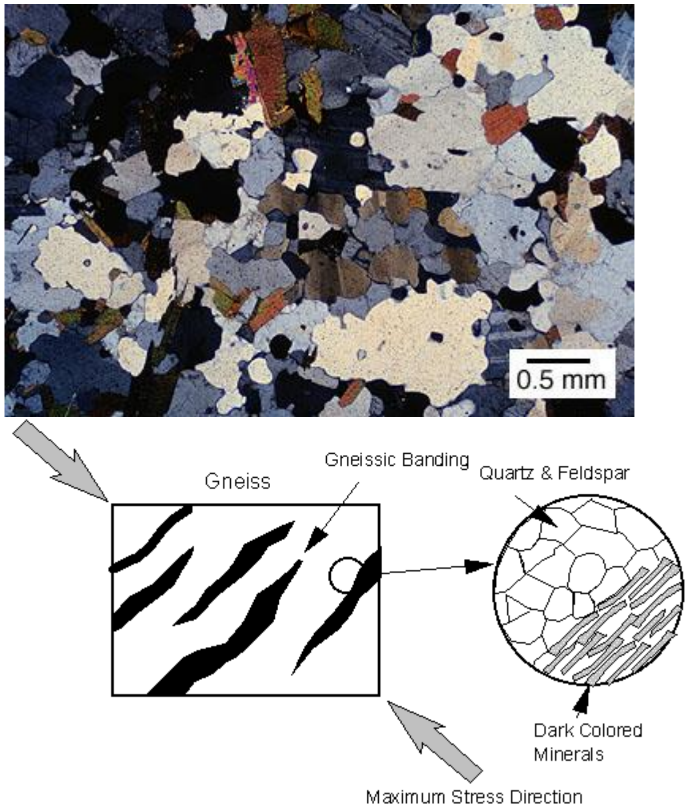
- **SCHISTOSE STRUCTURE “Schistosity”**



- Usually formed during intermediate and high grade metamorphism.
- Grain size increases and can be seen by naked eye; grains tends to enlarge with increasing grade of metamorphism; the coarse grained sheet-structure minerals show preferred orientation
- grain size is the main difference between the slaty structure and schistose structure.

Platy minerals visible

- **GNEISSIC STRUCTURE “Gneissic banding”**
  - Minerals segregated into bands
  - Usually associated with high-grade regional metamorphism (where differential stress prevails I.e. tectonic forces).
  - Where the sheet silicates and other minerals like quartz/feldspars/hornblende/pyroxene are segregated in distinct bands in the rocks- known as ***gneissic banding.***



Sixth Lecture

- **Classification of Metamorphic rocks based on texture/structures**

- **SLATE**

-strongly cleaved rock

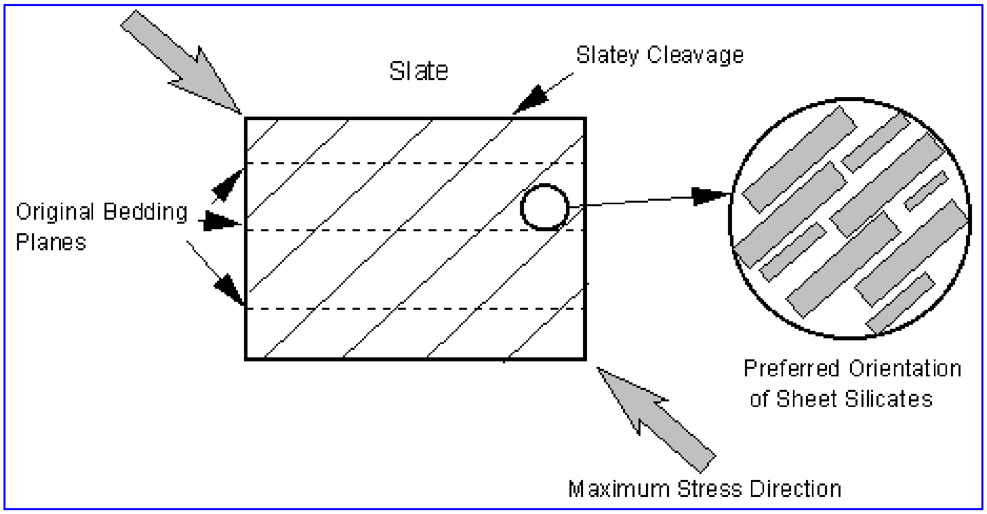
-cleavage planes are developed due to orientation of fine phyllosilcate grains; e.g. Muscovite, biotite, chlorite etc.

-individual grains too fine to be visible with naked eye

SLATY CLEAVAGE

- Usually formed during the early stage of Low-grade Metamorphism due to lithostatic stress.

- A new sheet-structure mineral tends to be parallel to the bedding planes during metamorphism.



- **PHYLLITE**

-similar to slate, but slightly coarser phyllosilicate grains

-grains can be seen in hand specimen, giving silk appearance to cleavage surfaces

-often cleavage planes less perfectly planar than slates

• Meatiq Dome

The Meatiq basement dome is located approximately 80 km west of Quseir, immediately north of the Quseir-Qift road in the CED. **The structurally lowest parts comprise the Um Ba'anib gneiss which locally hosts amphibolite lenses**. In contrast to the gneiss, some of the amphibolites are partially migmatized. The basal gneiss is overlain by a dominant metasedimentary succession of quartz rich schists which are locally intercalated with metapelitic schists. Garnet- and biotite-bearing metapelites, which are up to several hundred meters thick, form the upper section of the metamorphic core complex. Lenses of amphibolites and metagabbros occur within the metasedimentary succession, locally discordant to the main foliation. Marble bands associated with amphibolite lenses in the upper sections of the metapelites.

▪ METAMORPHIC EVOLUTION

The metamorphic evolution of the Meatiq metamorphic core complex is summarized as follows; **three distinct metamorphic events are identified** in the basement, whereas only the last one, **M3**, is recognized in the **ophiolite and island-arc volcanic rocks**. Therefore, a distinct metamorphic break between the basement and the cover nappes is evident.

The migmatization of some of the amphibolite lenses in the Um Ba'anib gneiss represents the only record of the M1 metamorphic event. The minimum metamorphic temperatures are estimated to be **> 750** ° C for the M 1 event based on published experimental results of melt reactions of metabasites.

The basement was subsequently metamorphosed in a high temperature, medium pressure **M_2** metamorphic event. The high temperature conditions of M_2 are indicated by:

i) **the breakdown reaction of muscovite to alkali feldspar** and **sillimanite in the presence of quartz**; ii) chemically uniform cores of garnets, which formed due to diffusional equilibration of the garnet composition at high temperature; and iii) the breakdown of Fe-staurolite to the peak assemblage of garnet and sillimanite.

Peak M_2 conditions are also constrained by garnet- biotite and garnet-staurolite thermometers and the GASP, GRIPS and GRAIL barometers to be at least 620°C to 690°C and 6 to 8.5 kbar. Assuming peak M 2 pressures of 6 to 8 kbar and water saturated conditions, the muscovite out reaction would indicate temperatures of at least 650°C (Spear, 1993) for the peak of the M 2 event.

The intensity of the a 3 metamorphic event increases towards the contact of the basement and the ophiolite and island-arc volcanic nappes in the south. Peak M 3 metamorphic conditions in the basement are calculated to be <550°C and <4 kbar (stability of andalusite). Peak M3 temperatures in the ophiolite and island-arc volcanic rocks are limited to <540°C by the mineral assemblage antigorite+talc in the serpentinites.

CONCLUSIONS

The amphibolite enclaves in the Um Ba'anib gneiss record the oldest tectonic history in the Meatiq basement. The chemical variation indicates that different tectonic settings have been recorded in these amphibolites, ranging from within-plate basalts to N-type MORB settings. The geological history may include the formation of oceanic crust to within-plate magmatism either in an oceanic or continental setting, although the exact timing between the different amphibolite lenses is not established.

▪ Seventh lecture

▪ Prograde and retrograde metamorphism

• Prograde metamorphism

Metamorphism is further divided into prograde and retrograde metamorphism. Prograde metamorphism involves the change of mineral assemblages (paragenesis) with increasing temperature and (usually) pressure conditions. These are solid state dehydration reactions, and involve the loss of volatiles such as water or carbon dioxide. Prograde metamorphism results in rock characteristic of the maximum pressure and temperature experienced. Metamorphic rocks usually do not undergo further change when they are brought back to the surface.

Normally progress through series of mineral assemblages, for example:

4. Epidote, chlorite, andalusite, muscovite, quartz, k-spar, and albite.
5. Sillimanite, plagioclase, cordierite, muscovite, quartz and k-feldspar.
6. Sillimanite, plagioclase, cordierite, quartz, and k-spar.

Common Prograde Sequence

Index minerals make zones:

- ✓ **Chlorite zone**. Pelitic rocks are slates or phyllites and typically contain chlorite, muscovite, quartz and albite.

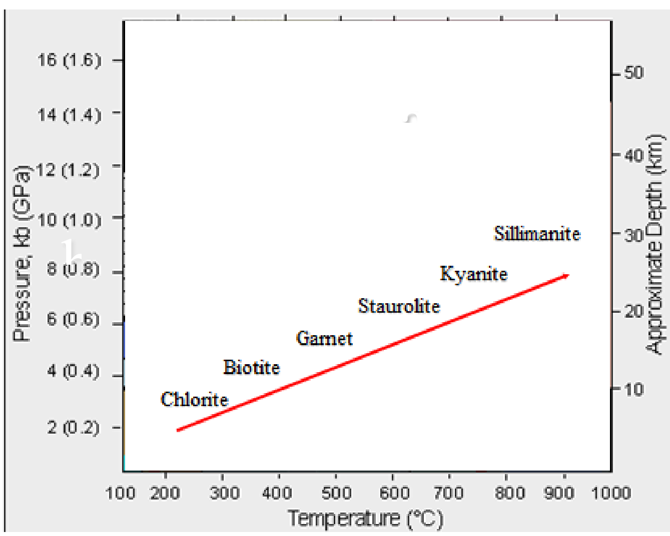
- ✓ **Biotite zone**. Slates give way to phyllites and schists, with biotite, chlorite, muscovite, quartz, and albite.

- ✓ **Garnet zone**. Schists with conspicuous red almandine garnet, usually with biotite, chlorite, muscovite, quartz, and albite or oligoclase.

- ✓ **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 Al2SiO5).

Sequence of indicator minerals



- Pelite protolith: Foliated Metamorphic Rocks-- low grade

- Pelite protolith: Foliated Metamorphic Rocks --middle grade.

- Pelite protolith: Foliated Metamorphic Rocks
  -- high grade.

Retrograde metamorphism involves the reconstitution of a rock via revolatisation under decreasing temperatures (and usually pressures), allowing the mineral assemblages formed in prograde metamorphism to revert to those more stable at less extreme conditions. This is a relatively uncommon process, because volatiles must be present.

The eighth lecture

- ## Metamorphic Grade

Refers to maximum T or P of metamorphism.

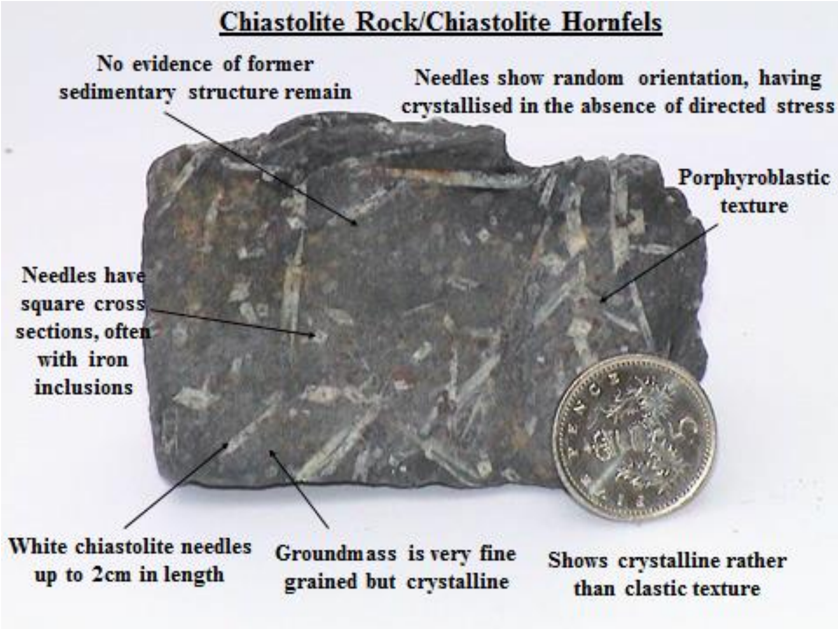
What grades have we talked about?

The idea of grade is general. We can better express the maximum P, T constraints using the concepts of metamorphic **zone** and **facies**.

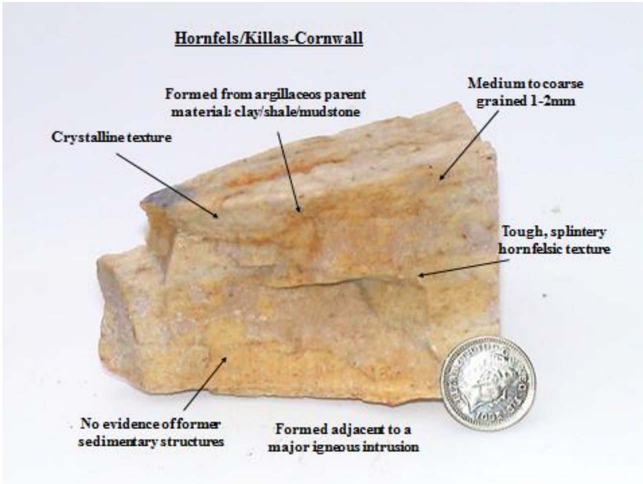
- ## Low Grade
  - ✓ **Increased temperature to 300 – 400 degrees centigrade.**
  - ✓ **Partial recrystallization occurs.**
  - ✓ **New minerals occur as oval spots 2 – 5 mm in diameter.**
  - ✓ **Cordierite or iron oxides are formed.**
  - ✓ **Spots show sieve or poikiloblastic texture Spots have** overgrown and included grains of the original argillaceous rock.
  - ✓ **Relic structures such as bedding / lamination and fossils may be evident.**

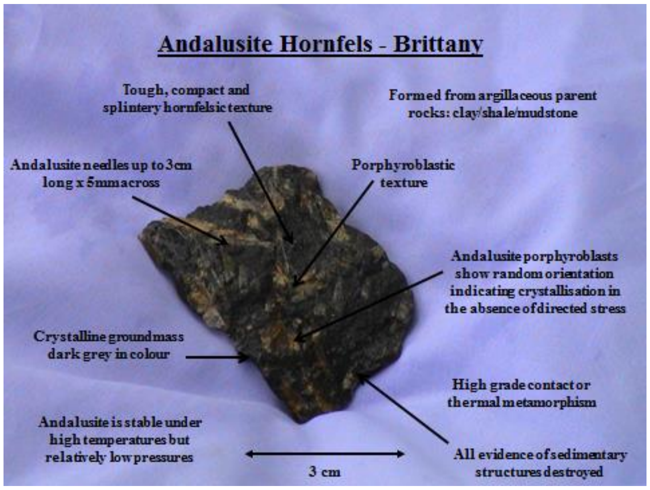
- ## Medium Grade
  - ✓ **Increase in temperature to 400 – 500 degrees centigrade, results in coarser grained rock.**
  - ✓ **Extensive recrystallization occurs.**
  - ✓ **Needles of chiastolite develop and show porphyroblastic.**

- ✓ texture. Up to 2 cm long, 3 mm in diameter, square cross section often with iron inclusions. Groundmass is mainly micas
- ✓ Needles show random orientation, having crystallized in the absence of pressure
- ✓ No relic structures are evident



- **High Grade**
  - ✓ Increase in temperature 500–600 degrees centigrade, results in grain size >2 mm.
  - ✓ Hornfels shows hornfelsic texture-a tough, fibrous and splintery-looking rock with a crystalline texture
  - ✓ Andalusite often occurs as porphyroblasts.
  - ✓ No evidence of any relic structures



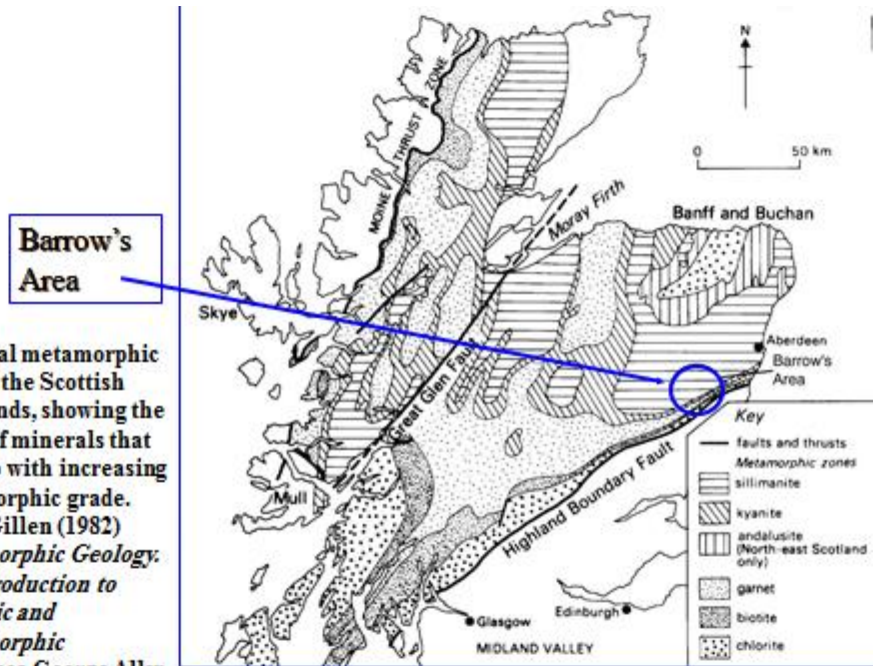


The ninth lecture

- **Metamorphic Zones**
  - **Progressive Metamorphism**
    - **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.**

➢ Example: The Scottish Highlands



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.

- **George Barrow (1893, 1912); studied the pelitic rocks in SE Highlands of Scotland. Barrow subdivides the area into a series of metamorphic zones, each based on the appearance of a new mineral as metamorphic grade increased. These zones named Barrovian Zones.**

▪ 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, quart, 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 Al2SiO5)**

- **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**

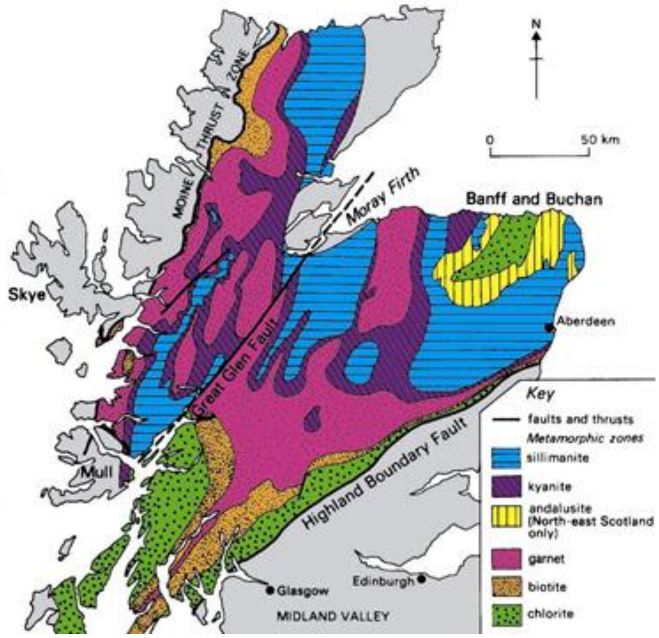
✓ **Isograd = line that separates the zones (a line in the field of constant metamorphic grade).**

- **Buchan zones**

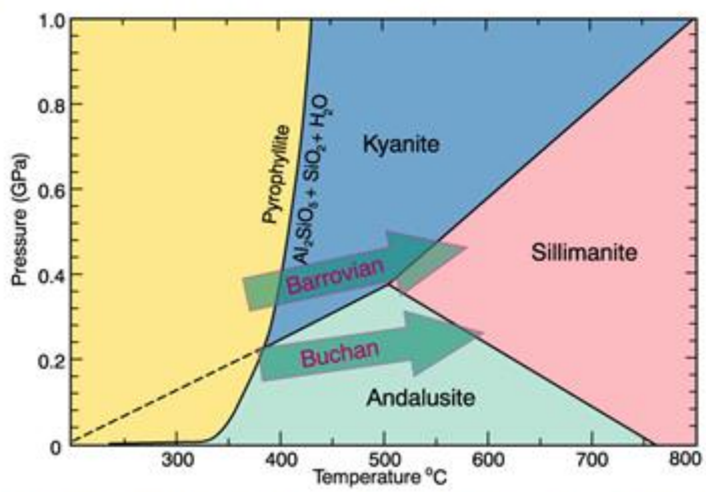
The pelitic compositions are similar, but the sequence of isograds is:

  - chlorite
  - biotite
  - cordierite
  - andalusite
  - sillimanite

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.



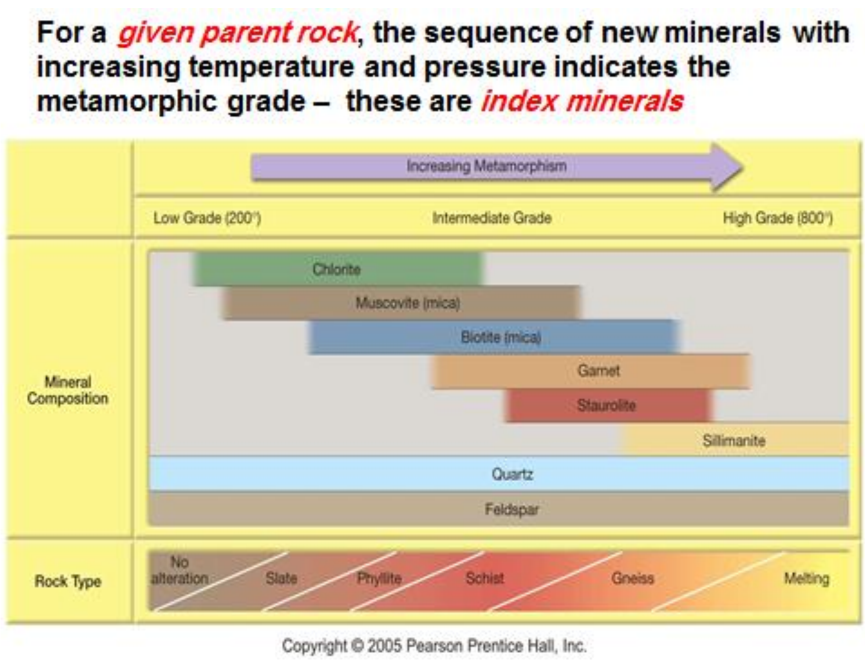
The stability field of andalusite occurs at pressures less than 0.37 GPa (~ 10 km), while kyanite → sillimanite at the sillimanite isograd only above this pressure

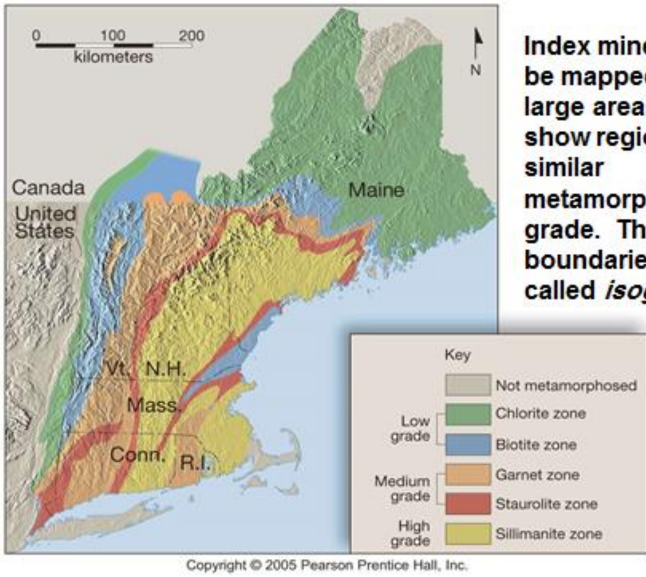


The P-T phase diagram for the system Al_2SiO_5 showing the stability fields for the three polymorphs andalusite, kyanite, and sillimanite. Also shown is the hydration of Al_2SiO_5 to pyrophyllite, which limits the occurrence of an Al_2SiO_5 polymorph at low grades in the presence of excess silica and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

- **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.**

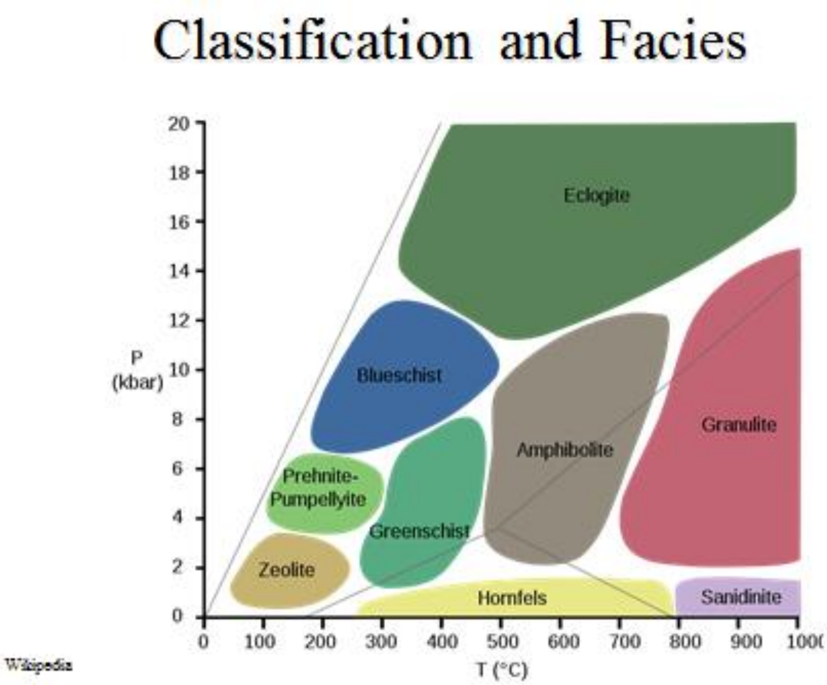




Index minerals can be mapped over large areas, to show regions of similar metamorphic grade. The boundaries are called *isograds.*

Tenth lecture

- **Metamorphic Facies**



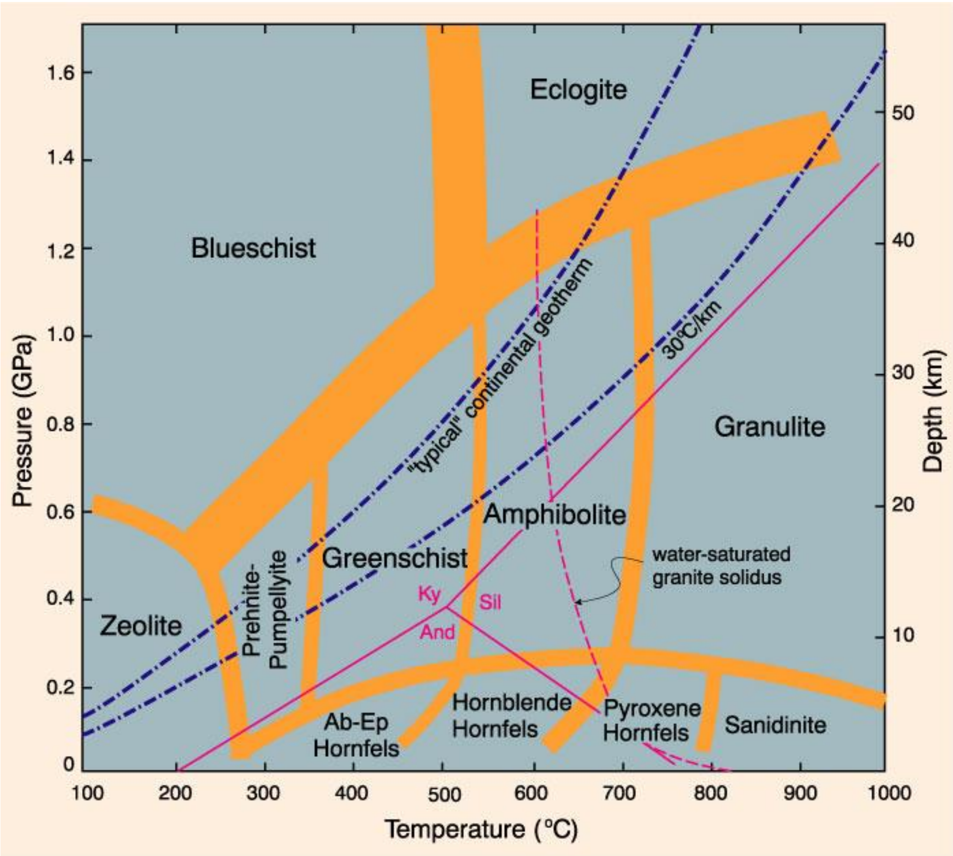
- **Eskola (1915) developed the concept of metamorphic facies:**

- **What is a metamorphic facies?**

Eskola (1920) proposed 5 original facies:

1. **Greenschist**
2. **Amphibolite**
3. **Hornfels**
4. **Sanidinite**
5. **Eclogite**

- **Easily defined on the basis of mineral assemblages that develop in mafic rocks.**
- **More facies have been added since original designations.**



Temperature-pressure diagram showing the generally accepted limits of the various facies used in this text. Boundaries are approximate and gradational. The "typical" or average continental geotherm is from Brown and Mussett (1993). Winter (2001) An Introduction to Igneous and Metamorphic Petrology.

Metamorphic Facies defined for mafic protolith

- **The definitive mineral assemblages that characterize each facies (for mafic rocks).**

Table 25-1. Definitive Mineral Assemblages of Metamorphic Facies

Facies	Definitive Mineral Assemblage in Mafic Rocks
Zeolite	zeolites: especially laumontite, wairakite, analcime
Prehnite-Pumpellyite	prehnite + pumpellyite (+ chlorite + albite)
Greenschist	chlorite + albite + epidote (or zoisite) + quartz ± actinolite
Amphibolite	hornblende + plagioclase (oligoclase-andesine) ± garnet
Granulite	orthopyroxene (+ clinopyrixene + plagioclase ± garnet ± hornblende)
Blueschist	glaucophane + lawsonite or epidote (+albite ± chlorite)
Eclogite	pyrope garnet + omphacitic pyroxene (± kyanite)
Contact Facies	Mineral assemblages in mafic rocks of the facies of contact metamorphism do not differ substantially from that of the corresponding regional facies at higher pressure.

After Spear (1993)

▪ Eleventh lecture

▪ Barrovian & Buchan metamorphism

The map and inset to the right shows that Scotland is subdivided into 5 distinct domains with characteristic stratigraphic, igneous and tectono-thermal evolutions and separated by major NE-SW-trending faults.

From north to south the domains are: the Foreland zone, the Northern Highlands, the Grampian Highlands, the Midland Valley and the Southern Uplands. The faults are: the Moine Thrust, the Great Glen Fault, the Highland Boundary Fault and the Southern Uplands Fault. In general, the age of the rocks increases from south to north.

We will be looking in detail at the Grampian and Northern Highlands and the oldest rocks in the UK, the Lewisian rocks of the Foreland zone.

Barrovian metamorphism

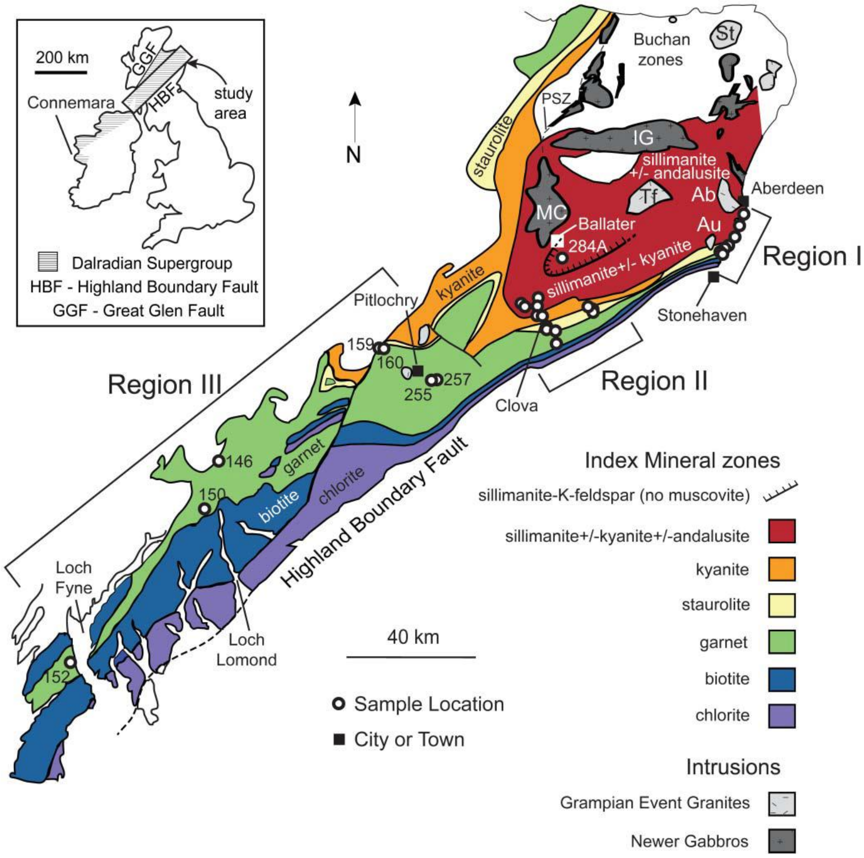
The map and inset on the right shows the distribution of regional metamorphic zones in Scotland.

The majority of Scotland enjoyed Barrovian metamorphism that reflects a ‘normal’ crustal geotherm (moderate dP/dT), characterised by the kyanite to sillimanite transition in metapelitic rocks.

In his classic studies of the Scottish Highlands, Barrow (1893, 1912) concluded that pelitic rocks undergoing progressive regional metamorphism would exhibit systematically changing mineral assemblages as a function of metamorphic grade. The Barrovian type locality in the Scottish Highlands has been the focus of extensive investigation for over a century, yet questions remain regarding the peak pressures (P) and temperatures (T) of metamorphism, as well as regional P–T paths. It is clear from the mineralogy as well as available thermobarometric studies that different areas, from the northeastern coast near Aberdeen to the southwestern coast, were subject to different peak metamorphic P–T conditions.

Metamorphism in the Buchan area in the NE was at lower P, and is characterised by the andalusite to sillimanite transition in metapelitic rocks.

We will be examining these classic metamorphic areas, principally looking at mineral assemblage development but also at variations in protolith composition, sedimentology and structure.



▪ Scottish Regional Metamorphism - Barrovian

The Dalradian Supergroup of the Grampian Highlands is a thick sequence of deformed and metamorphosed sediments (mainly marine) and volcanics deposited between approximately 800 Ma and 500 Ma. The Dalradian block is structurally bounded to the north by the Great Glen Fault and to the south by the Highland Boundary Fault (Fig. 1). The rocks were affected by the complex Grampian Orogeny, the result of the early stages of closure of the Iapetus Ocean during the early to mid- Ordovician.

George Barrow (1853 - 1932) was a British geologist and is one of the all-time superstars of metamorphic geology. In one of the most important metamorphic studies in history (published in 1893), he was the first to map a metamorphic field gradient by determining a sequence of metamorphic zones in the Scottish Highlands (see Fig. 2). Every first appearance of an index mineral was taken by Barrow as the beginning of a new metamorphic zone. The lines connecting the first appearance of a mineral and separating the zones are isograds. The age of peak metamorphism is now constrained to 465-470 Ma (i.e., Ordovician).

The underlying principles of metamorphic zones were later clarified by the Finnish geologist Pentti Eskola, who introduced the concept of the metamorphic facies. The zones as mapped by Barrow with increasing grade:

Zone of digested clastic mica (now the **Chlorite Zone**)

quartz-chlorite-muscovite-plagioclase

Biotite Zone

quartz-chlorite-biotite-muscovite-plagioclase

Garnet Zone

quartz-muscovite-biotite-garnet-plagioclase

Staurolite Zone

quartz-muscovite-biotite-garnet-staurolite-plagioclase

Kyanite Zone

quartz-biotite-muscovite-garnet-kyanite-plagioclase

Sillimanite Zone

quartz-biotite-muscovite-garnet-sillimanite-plagioclase

Barrow believed the zones resulted from the heat from the small granitic intrusions found in the high-grade zones.

Another geologist, C.E. Tilley, working on the same rocks in a different area suggested that the temperature of each zone was largely determined by the depth of burial. Tilley (1924) suggested that the isograds mark rocks originating under closely similar *P*-*T* conditions, essentially what we believe today.

We will spend a day retracing the steps of Barrow and examining the different textural and mineral assemblage evolution of the zones.

- **Scotish Metamorphism – Buchan Type**

The Buchan Facies Series of regional metamorphism is characterized by the widespread development of andalusite and cordierite in metapelitic rocks, indicating that the conditions of metamorphism were at lower *P*than those of the Barrovian Facies Series. Once again, the type locality of Buchan metamorphism is the Dalradian of Scotland.

- **The Buchan is characterised by the following metamorphic zones:**
  - **Biotite Zone (Greenschist Facies)**
  - **Cordierite Zone (Amphibolite Facies)**
  - **Andalusite Zone (Amphibolite Facies)**
  - **Sillimanite Zone (Amphibolite to Granulite Facies)**

We will be spending 3 days looking in detail at these classic rocks, examining the classic low-*P* metamorphic zones and associated assemblages developed in metapelitic and calc-silicate rocks. We will see partially melted rocks (migmatites), meta-gabbros and associated contact metamorphic rocks, amphibolite-facies shear-zones, sedimentary structures and much else.

Perhaps the word’s best-exposed regional isograds occur within the coastal section around Banff.

المحاضرة الثانية عشر

Migmatization processes

- **migmatization processes could form as a result of :**

A- closed system (no gains or loses during migmatization)

1- Aanatexis (partial melting) at higher temperature

2- Metamorphic differentiations at higher temperature

B- Open system

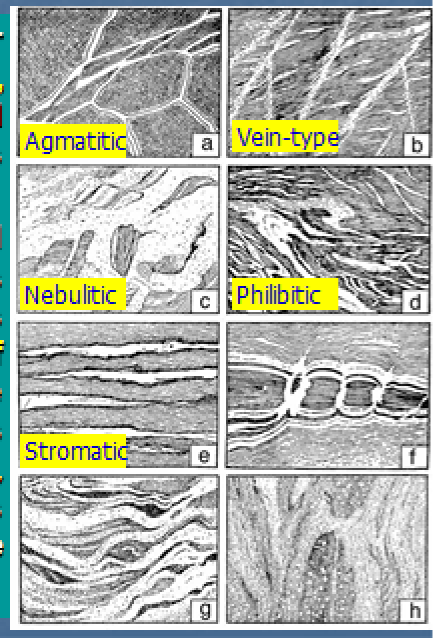
3- K-Na rich external fluid metasomatism

4- Injection of granitic materials to the schistose rocks

In the closed system migmatites three mineral zones develop:

4- High temperature metapelites

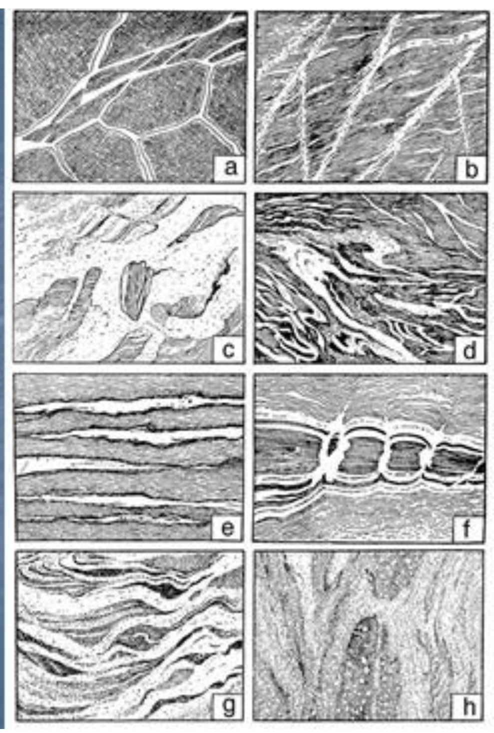
- At high-temperatures, above or coeval to sillimanite zone, metapelites undergo partial melting, and the yielded rock is known as Migmatites.
- The Migmatites are mixed rocks predominantly schists but with pads, veins or layers of leucocratic material of granitic composition. The leucocratic (granitic) materials are well known as leucosomes, while the metamorphic parts are known as mesosome (resistite) and melansomes.



Migmatites

a. Breccia structure in agmatite.
b. Net-like structure.
c. Raft-like structure.
d. Vein structure.
e. Stromatic, or layered, structure.
f. Dilation structure in a boudinaged layer.
g. Schleiren structure.
h. Nebulitic structure.

From Mehnert (1968) *Migmatites and the Origin of Granitic Rocks*. Elsevier.



2- Cordierite-garnet-K-feldspar zone

- At higher grade, pelitic rocks develop assemblages with: Cordierite + garnet + K-feldspar + sillimanite + muscovite + Qtz
- This mineral assemblage is typical for the high grade pelitic migmatites, and is often taken to mark the beginning of the granulite facies
- The assemblages result from continuous reaction such as:

biotite + sillimanite + quartz ➔ K-feldspar + cordierite garnet + melt

IV- Sillimanite zone zone

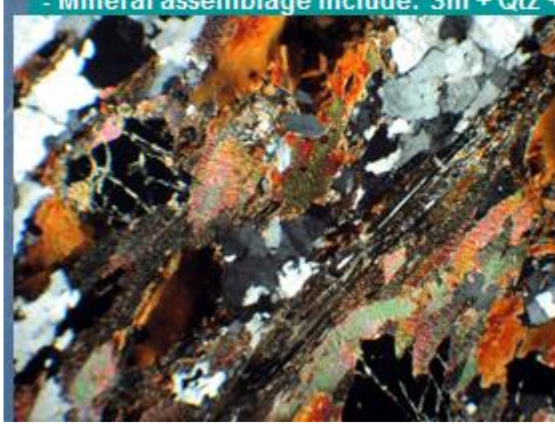
Sillimanite in this zone can occur due to the occurrence of the polymorphic solid-solid reaction:

andalusite ➔ sillimanite

but as with regional metamorphism the occurrence of muscovite + cordierite + quartz in this zone suggests that a separate reaction may occur:

chlorite + muscovite + quartz ➔ cordierite + sillimanite + biotite + H_2O

- Mineral assemblage include: Sill + Qtz + Bt + Pl ± Grt ± St ± Crd



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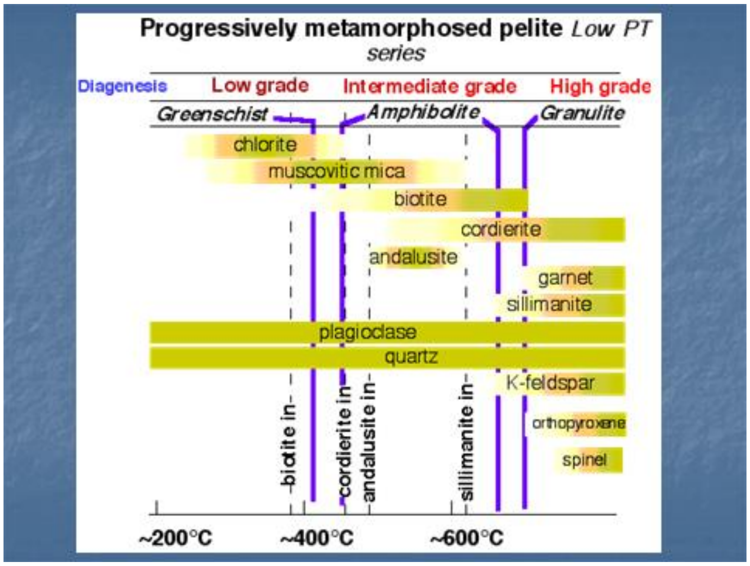

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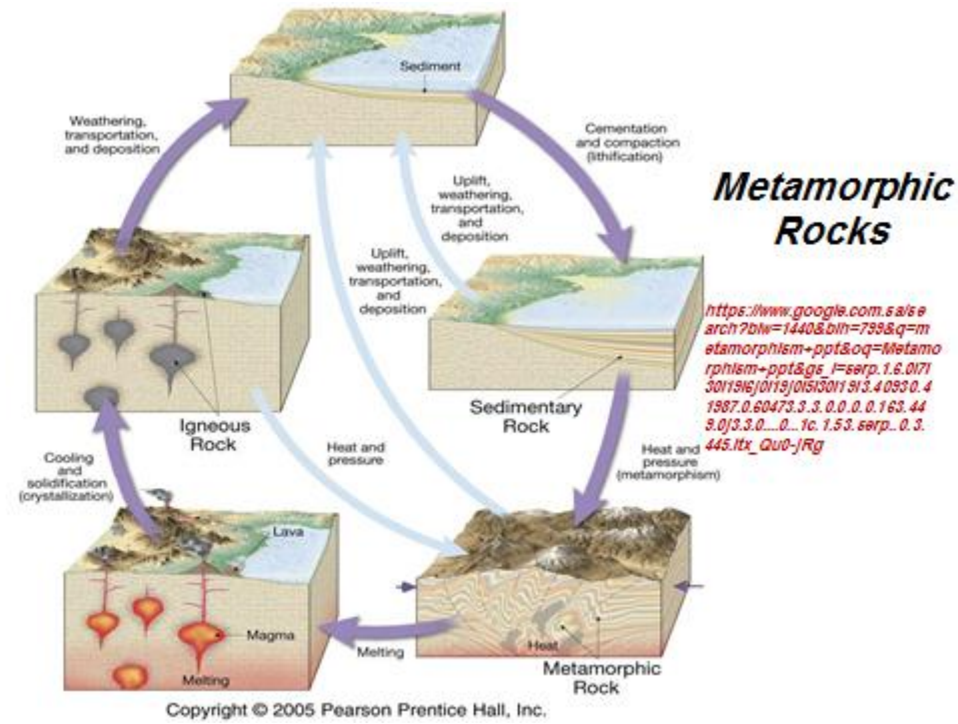
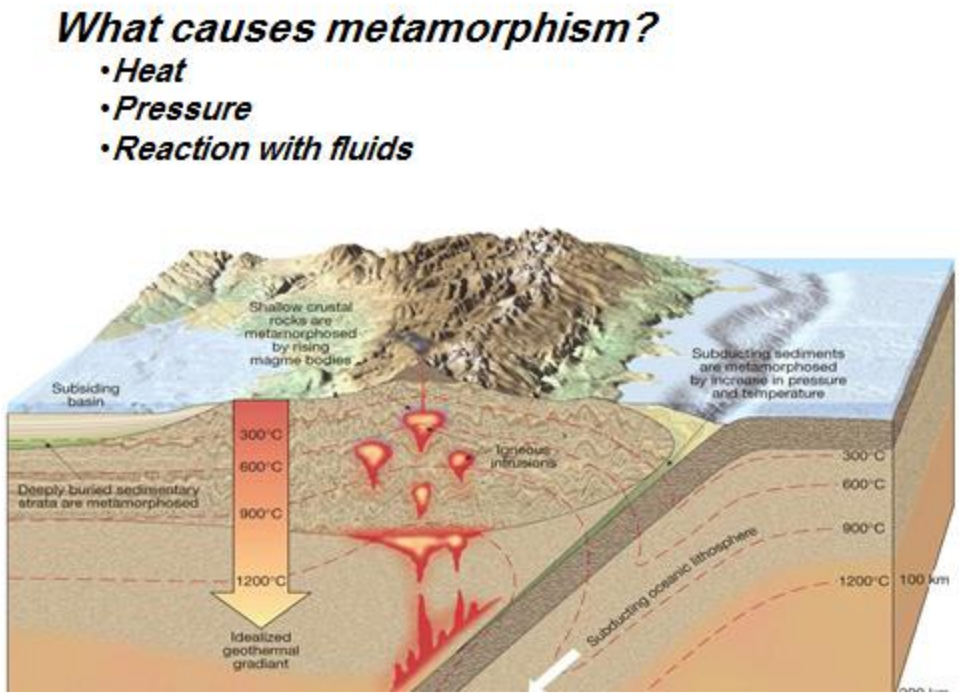
مراجعة وتطبيقات

Further Reading





What changes during metamorphism?

- ***Mineralogy changes***
  - **New minerals form that are stable under the new metamorphic conditions**
    - **Polymorphic transformations**
    - **Mineral reactions**
  - ***Rock texture changes***
  - **Foliation can develop in response to stress**
  - **Minerals recrystallize**

- **Polymorphic transformations**

Kyanite === sillimanite

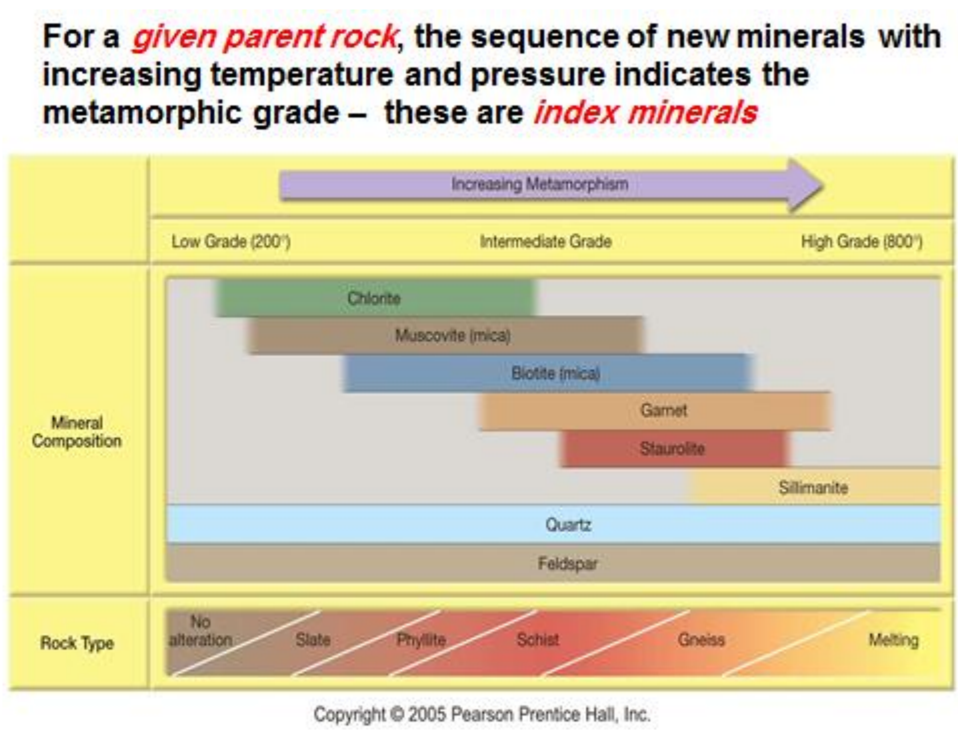
Calcite === Aragonite

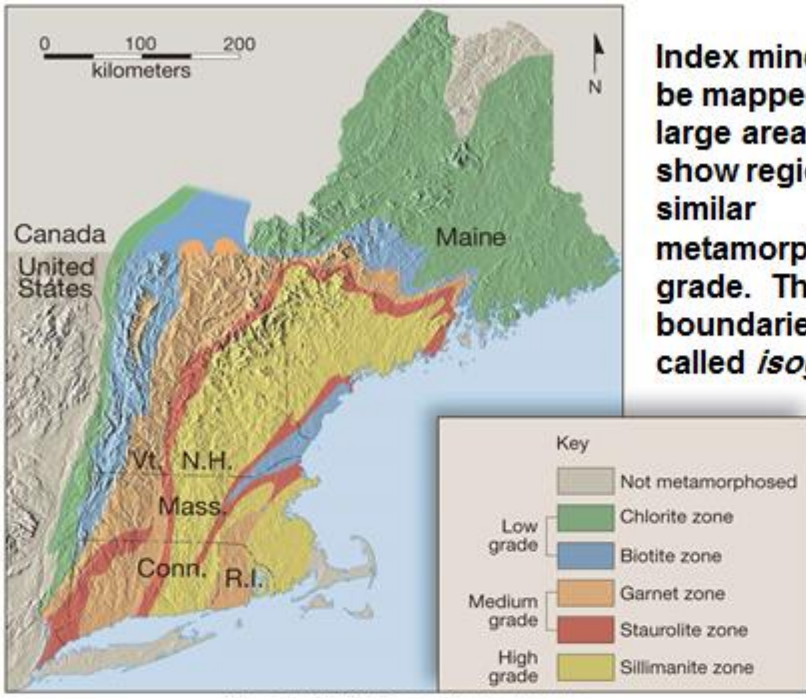
- **Mineral reactions**

Chlorite + muscovite === staurolite + biotite + quartz + H_2O (dehydration)

Staurolite + muscovite + quartz === sillimanite + biotite + H_2O (higher T & P)

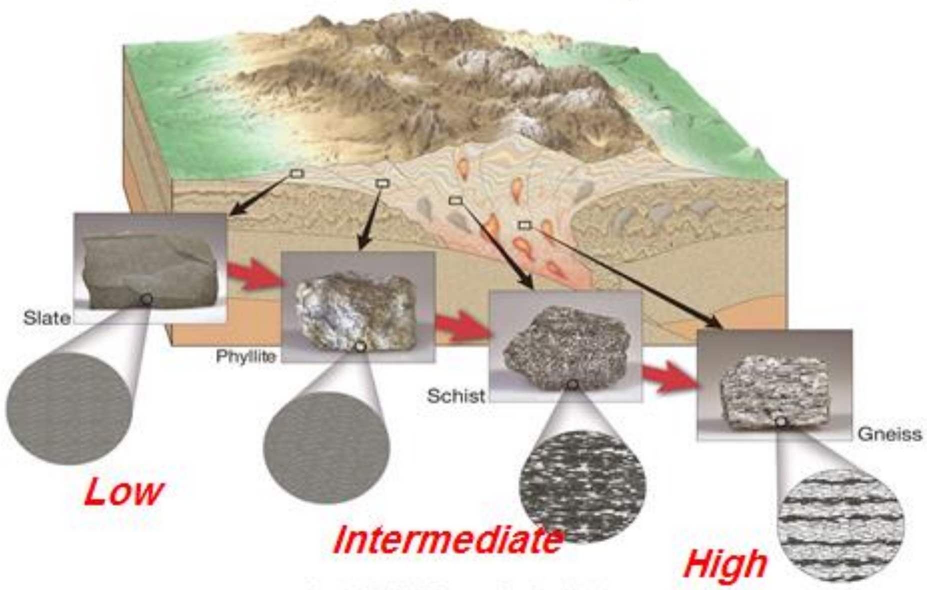
Calcite + quartz === wollastonite + CO_2 (decarbonation)

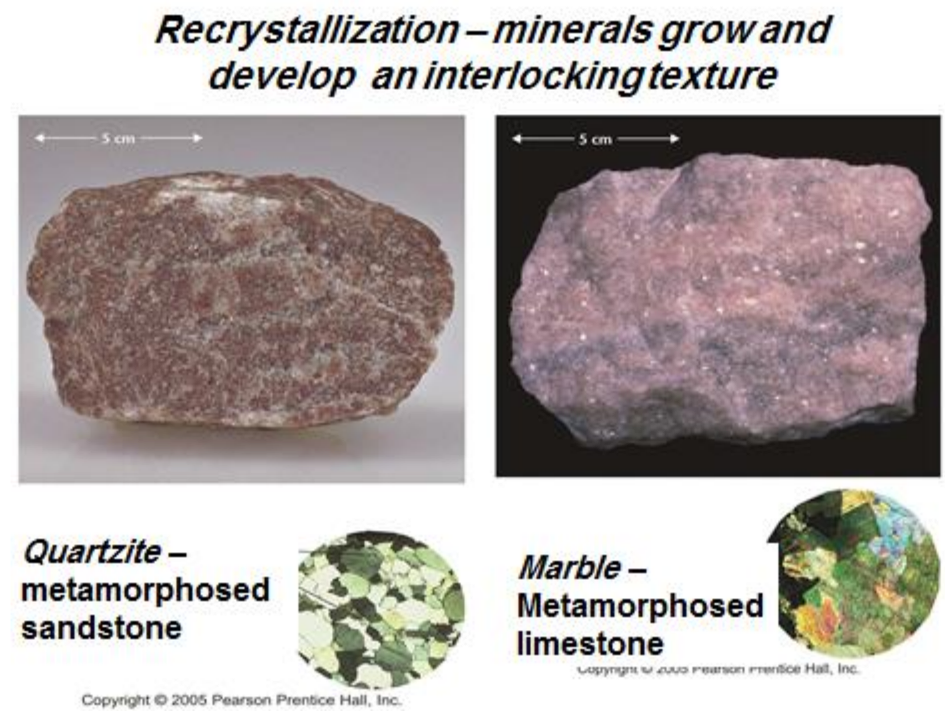




Index minerals can be mapped over large areas, to show regions of similar metamorphic grade. The boundaries are called *isograds*.

Metamorphic Grade
= intensity of metamorphism





Metamorphic rocks are classified by:

Parent rock

Temperature and pressure conditions

Parent rocks (protoliths) control the elements that are available to form minerals:

- Pelitic (shales and siltstones, Al rich)
- Mafic (basalts, greywackes, Mg and Fe rich)
- Carbonate or calc-silicate (limestones, Ca and Mg rich)

Table 11.9 Typical Mineral Zones in Pelitic Rocks[a]

Grade	Index Mineral	Mineral Zone	Common Mineral Assemblage
Very low	Chlorite	Chlorite	Chlorite, muscovite, albite, quartz
Low	Biotite	Biotite	Biotite, muscovite, plagioclase, quartz, ± chloritoid, chlorite
	Garnet	Garnet	Biotite, muscovite, garnet, plagioclase, quartz, ± cordierite, garnet
Medium	Staurolite	Staurolite	Biotite, muscovite, staurolite, plagioclase, quartz, ± cordierite, garnet
	Andalusite or kyanite	Andalusite/ kyanite	Biotite, muscovite, andalusite or kyanite, plagioclase, quartz, ± cordierite, garnet
	Sillimanite	Sillimanite	Biotite, muscovite sillimanite, plagioclase, quartz, ± garnet
High	K-feldspar	K-feldspar-sillimanite	Biotite, K-feldspar, sillimanite, plagioclase, quartz

[a] The mineral assemblage may vary depending on the bulk composition of the rocks involved.

Table 11.10 Mineralogy of Mafic Rocks in Selected Facies

Facies	Mineralogy
Greenschist facies	Chlorite, albite, epidote/zoisite ± actinolite
Epidote-amphibolite facies	Plagioclase, hornblende, epidote ± garnet
Amphibolite facies	Plagioclase, hornblende, ± garnet
Granulite facies	Orthopyroxene, plagioclase ± Ca-clinopyroxene, hornblende, garnet

Table 11.11 Mineralogy of Blueschist and Related Rocks in Selected Facies

Facies	Characteristic Minerals
Zeolite	Zeolites, usually laumontite, wairakite, or analcime
Prehnite-pumpellyite	Prehnite, pumpellyite
Blueschist	Glaucophane, lawsonite, epidote

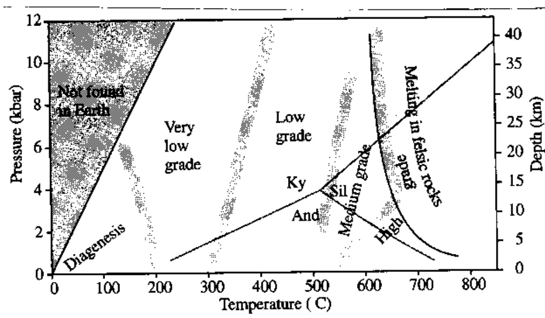


Figure 11.9 Metamorphic grade boundaries. Adapted from Winkler (1976). Stability fields of the aluminum silicates [$AlAlOSiO_4$: andalusite (And), sillimanite (Sil), and kyanite (Ky)] are shown.

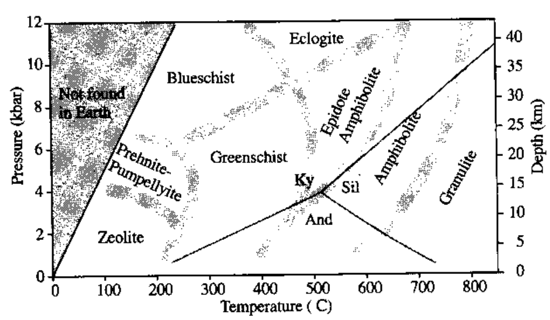


Figure 11.10 Approximate temperature–pressure fields of the eight principal metamorphic facies. Adapted from Spear (1993).

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