METAMORPHIC PETROLOGY

METAMORPHISM:

Process of mineralogical and structural (textural) changes of rocks in the solid state in response to physical and chemical conditions which differ from those under which they originated.

1. **Mineral assemblages change.**
2. **Textural Changes (foliations, cleavage, etc).**

- **Physical Conditions = Pressure & Temperature**
- **Chemical Conditions = P_{H2O}, P_{CO2}, fluid solutions w/dissolved solids.**

ALL METAMORPHIC ROCKS WERE ONCE IGNEOUS OR SEDIMENTARY

LOWER AND UPPER LIMITS OF METAMORPHISM:

- **Low grade: diagenesis >> incipient metamorphism: 100^{o}-150^{o}C**
- **High grade: anatexis = formation of partial melt: 750^{o}-850^{o}C**
- **Pressure variations:**

  Top of Crust 1-3 km depth (<1 Kb)

  Base of Crust 20-40 km (>10 Kb)

FACTORS OF METAMORPHISM:

- **Temperature: 100^{o}-850^{o} C**
- **Confining Pressure or "Lithostatic Pressure" (synonymous terms)**
  Equals weight of overlying rock column; Same pressure on all sides.
- **Directed Pressure: Related to deformation**
  Sheering stresses; tectonic over pressure.
- **Fluid compositions: Metamorphic pore fluid H_2O and CO_2 .**

GOALS OF METAMORPHIC PETROLOGY:

- **SETTING: Where did metamorphism occur? What was its structural and tectonic setting?**
- **PROTOLITH: Original nature of the rock before metamorphism.**
- **GRADE of metamorphism: How intense was the metamorphism? What were the physical and chemical conditions of the metamorphism?**
  a. **look for relict structures, fossils**
  b. **look at mineral assemblage and compare to experimental studies in mineral equilibria; estimate temp and pressure.**
  c. **Calculate using mineral compositions, e.g., garnet-biotite geothermometer**

GEOBARIC GRADIENT = Pressure variations within Earth

- **Related to amount of crust or top: approximately 285 bars/km (upper crust)**

20 km = 5700 bars = 5.7 kb   33 km = 10 kb   1 Kb ≈ 3.3 km

Type of Crust	Thickness	Pressure at Base	Example
Normal Continental	35-40 km	10-12 Kb	Canada
Active Margin	60-80 km	18-25 Kb	Sierra Nevada, Andes
Collisional Orogen	80-100 km	24-30 Kb	Himalayas
Oceanic crust	6-10 km	2-3 Kb	Atlantic ocean

Typical Pressure Range For Common Metamorphic Rocks = 2-8 Kb

GEOTHERMAL GRADIENT -- Controls Heat flow at Surface

Two Major Aspects of Geothermal Gradient:

- **Conduction of heat from Mantle >> Limited effect in continents, Controlled by thickness of lithosphere (but note areas with thin lithosphere, e.g., Great Basin)**
- **Radioactive decay of U/Th/K >> important for continental crust**

Type of Crust	Geothermal Gradient	Heat Flow at Surface	Example
Precambrian Shield	15-20^{o}C/km	60 mW/m^2-sec	Canada
Active Margin (Arc)	30^o-35^{o}C/km	100-120 mW/m^2-sec	Sierra Nevada, Andes
Subduction Zone (Accretionary Complex)	10^{o}C/km	40 mW/m^2-sec	Franciscan Complex
Collisional Orogens	25^o-30^{o}C/km	80-110 mW/m^2-sec	Himalayas
Extensional Orogens	40^o-50^{o}C/km	120-150 mW/m^2-sec	Great Basin
Mid-Ocean Ridge	up to 60^{o}C/km	150-200 mW/m^2-sec	Mid-Atlantic Ridge

PLATE TECTONIC CONTROLS ON METAMORPHISM

- **Ocean Floor metamorphism (mid-ocean ridges) = Very high T/low P.**
- **Subduction zone metamorphism = High P/ Low T**
- **Arc basement metamorphism = Low P / High T**
- **Continent-Continent Collision = intermediate P/T**
- **Continental Extension metamorphism = Intermediate P/high T**

DEFINITIONS OF METAMORPHIC ROCKS

Prefixes:	**Ortho-**	**Igneous Protolith**
	Para-	**Sedimentary Protolith**

Examples: **orthogneiss, paragneiss**

Slate, Argillite:	**Low grade metamorphic rocks with partly to well-developed cleavage; almost all are meta shales, metamudstones.**
Phyllonite:	**Higher grade than Slate, with incipient Foliation, shiny surface; almost all are meta shales, metamudstones.**
Schist:	**Higher grade than slate, phyllonite; characterized by distinct metamorphic foliation, abundant platy minerals, some segregation into layers common.**
Garnet-Biotite Schist	**Pelitic schist rich in garnet, biotite, & quartz.**
Gneiss:	**High grade metamorphic rock; varies widely in composition and mineral mode; characterized by distinct compositional banding in most cases.**
Quartzite:	**Metamorphosed quartzite or chert; very fine grained, sugary texture.**
Marble:	**Metamorphosed limestone or dolostone. Typically unfoliated, granular crystalline rocks.**
Migmatite:	**“Mixed Rock”, high grade gneiss in which felsic bands = granitic melt, mafic areas = melting residue, or host into which melts intruded.**
Granulite:	**Very high grade metamorphic rock; typically banded, foliated.**
Granofels:	**Like granulite, but lacking any preferred orientation, platy minerals.**

CLASSIFICATION OF METAMORPHISM BASED OF GEOLOGIC SETTING

1. Local Metamorphism:

a. Contact Metamorphism [Adjacent igneous intrusions]

b. Dynamic = fault zones

2. Regional = Dynamo-thermal metamorphism, effects large regions of Earth.

CONTACT METAMORPHISM

Factors that influence development of aureole

- **Temp of magma**
- **Size of the intrusion (pluton, sill, dike)**
- **Chemical activity of the fluids which migrate out of intrusion: important transfer mechanism of heat, chemicals.**
- **Character of country rocks (chemical reactivity of wall rocks) some respond better to metamorphism pelitic schists, limestones.**
- **Mode of emplacement (forceful emplacement vs magmatic stoping)**
  - **stoping develops static aureole,**
  - **forceful emplacement causes deformation.**

ROCKS IN CONTACT AUREOLES

Hornfels = Massive, fine grained, sugary textured rocks, very tough;

- **textural term**
- **Can have many protoliths (pelitic, felsic volcanic common)**
- **No compositional meaning to hornfels**
- **Can have large Xtls growing within**
- **Not the exclusive rock at contact aureole**

Depends on character of emplacement: Forceful intrusion produces strongly foliated and lineated rocks, results in contact gneisses and schists.

Contact Metamorphism = Generally Isochemical, i.e., same chemical signatures of the protolith

SKARNS: Contact Metasomatism in Limestones

Exception to isochemical contact metamorphism = skarn (tactite)

- **Develop along contact between granite and limestone or dolomite.**
- **Coarse grained rocks**
- **Consist of calc-silicate minerals (SiO_2 added, CO_2 lost)**

Typical calc-silicate minerals:

Diopside	$CaMgSi_2O_6$	**Wollastonite**	$CaSiO_3$
Garnet	$Ca_3Al_2Si_3O_{12}$	**Idocrase**	**Don't Ask**
Actinolite	$Ca_2(MgFe)_5Si_8O_{22}(OH)]$,	**Tremolite**	$Ca_2Mg_5Si_8O_{22}(OH)$
Scheelite	$CaWO_4$	**Quartz**	SiO_2
Calcite	$Ca(CO_2)_3$		

Why do these chemical changes occur? METASOMATISM

- **Two rocks with grossly different compositions.**
- **Chemical gradients set up and extensive chemical migration occurs.**
- **Skarn zone develops at contact, not continuous.**

DYNAMIC METAMORPHISM: Metamorphism associated with fault zones.

Low T, P: **Incohesive rocks; very complex (gouge, breccia).**

High T, P: **Very cohesive w/strong foliations (cataclasite, mylonite).**

Textural Classification of Fault Rocks:

INCOHESIVE Fault Rocks

- **Fault breccias (visible fragments >30% of rock)**
- **Gouge (visible fragments <30% of rock)**

COHESIVE

- **Cataclasite (Brittle): Protocataclasite> cataclasite > ultracataclasite**
- **Mylonite (Ductile): Protomylonite > Mylonite > Ultramylonite**

Brittle-Ductile transition ≈ 250º-350ºC

REGIONAL METAMORPHISM

- **Found in internal parts of orogenic belts**
- **Strong fabrics**
- **May have evidence of multiple deformation, heating events.**
- **Metamorphic history related to Tectonic Evolution of orogen.**

George Barrow (1888) Scottish highlands

- **Documented progressive regional metamorphism.**
- **Dalradion Series = late Precambrian to Cambrian age.**
- **Diverse group of rocks = Active Compressive margin sequence: Impure litharenites (wackes) with mafic-felsic volcanic rocks, pelitic rocks (shales and mudstones); impure carbonates.**
- **Thickness 10-15 km thick (some structural thickening).**
- **Effected by Lower Paleozoic Caledonian Orogeny**

Barrow recognized metamorphism was progressive: rocks progress from low grade mineral assemblages to high grade mineral assemblages as temperature increases.

Barrow Focused in on pelitic rocks and mapped using INDEX MINERALS.

Index minerals for progressive metamorphism in Metapelitic Rocks:

Chlorite	**>> Slate, Phyllite**
Biotite	**>> Phyllite, fine-gr Schist**
Garnet	**>> Schist, Gneiss**
Staurolite	**>> Schist, Gneiss**
Kyanite	**>> Schist, Gneiss**
Sillimanite	**>> Schist, Gneiss**

This is called the "Barrovian Sequence"

C.E. Tilley referred to these lines as ISOGRADS "Same Grade"

ex. biotite isograd = first appearance of biotite in meta-shale.

- **Isograds may cut across structures, bedding**
- **Put tick marks put to the high-Temperature side**
- **Area between Isograds called "Zones", e.g., biotite zone, garnet zone, etc.**

Metamorphic Fabric and Texture

FABRIC:	**Refers to orientation of the crystallographic lattices of the minerals**
TEXTURE:	**Refers to mineral distributions or orientations within the rock, overall structure of the rock.**
Cleavage	**Planar Fabric of Preferred Fracture, sub-parallel orientation, non-penetrative.**
Foliation:	**Any *Penetrative* set of more or less parallel SURFACES.**
Lineation:	**Any *Penetrative* set of more or less parallel LINES.**
Penetrative:	**Caused by re-orientation of the crystalline fabric of the minerals.**

Granoblastic:	**Mosaic texture of equidimensional, anhedral grains.**
Lepidoblastic:	**Abundant platy minerals (chlorite, biotite, etc) with strong preferred orientation. Causes *Foliation*.**
Nematoblastic:	**Abundant linear minerals (actinolite, hornblende, etc) with strong preferred orientation; Causes *Lineation*.**
Poikiloblastic:	**Large, metamorphic grains that enclose numerous small inclusions; analogous to poikolitic igneous texture.**
Porphyroblastic:	**Large metamorphic crystals in a matrix of smaller grains; analogous to porhyritic igneous texture.**
Porphyroclastic:	**Large relict grains of pre-existing mineral in finer-grained matrix of recrystallized material; associated with shear deformation and ductile flow.**
Mylonitic:	**Very fine-grained or aphanitic, anisotropic texture of produced by intense ductile flow and high strain.**
Flaser texture:	**Mylonitic fabric with ovoid megacrysts of relict crystals in vfg matrix. One type of porphyroclastic texture.**

DETERMINATION OF PROTOLITH

Six Common Types:

1. **Pelitic (shale, mudstone)**
2. **Quartzo-feldspathic (sandstone, rhyolite, granite, chert)**
3. **Calcareous (limestone, dolomite, marls)**
4. **Basic (basalt, andesite, gabbro, diorite)**
5. **Magnesian (peridotite, serpentine)**
6. **Ferruginous (ironstone, umbers)**

1. Pelitic Protoliths = Rocks enriched in clay minerals

- **High Al_2O_3, K_2O, lesser amounts Ca**
- **Micas favored because of Al content**
- **Also aluminosilicates: Al_2SiO_5 - sillimanite, andalusite, kyanite.**

Kyanite: Highest density (smallest volume) forms at higher pressures.
Andalusite: Lowest density, largest volume, forms at low pressures.
Sillimanite: Intermediate density, volume; forms at moderate T, P.

Alumino-silicate triple point = 5.5 kb at 600^{o}C

Wet granite solidus: Shows where anatexis occurs in sillimanite zone.

Staurolite ($2*Al_2O_5*Fe(OH)_2$) = Common metamorphic mineral
Need an Al and Fe-rich protolith -- This restricts occurrence

2. Quartzo-feldspathic Protoliths: High SiO_2, low Fe and Mg

- **"Psammitic"**
- **Quartz-rich sandstones with varying % feldspars ("arkose")**
- **Felsic igneous rocks (rhyolites, tuffs, granites)**
- **If protolith >50% quartz then probably a sandstone or chert.**
- **Gneiss: Fine-grained at low grade, coarser with increasing grade.**

Felsic tuffs, granite hard to tell from arkose when highly metamorphosed.

3. Calcareous Protoliths: High CaO, CO_2

- **Limestones and dolomite form MARBLES**
- **Impure limestones (with clay, silt) form Calc-silicates:**
  [tremolite, diopside, wollastonite, forsterite, epidote, et cetera]

4. Basic Protoliths: Low SiO_2 moderate CaO, MgO, FeO

- **Basalts, andesites, gabbros - mafic igneous rocks.**
- **Some shale-limestone mixtures.**
- **Minerals depend on grade: chlorite, actinolite, hornblende, plagioclase, epidote, garnet.**

5. Magnesian Protoliths: Very low SiO_2, high MgO

- **Peridotites >> serpentine, magnesite.**
- **Serpentine (low T) >> antigorite (high T serpentine), olivine.**

6. Ferruginous Protoliths: High Fe_2O_3

- **Ironstones = Precambrian iron formations (Fe-rich cherts).**
- **Umbers = Fe-rich cherts, shales associated with MOR.**

METAMORPHIC FACIES

Metamorphic Facies: All the rocks that have reached chemical equilibrium under a particular set of physical conditions.

- **Facies concept developed by Eskola (Norway, 1915) to compare metamorphic rocks from different areas.**
- **Look at several protoliths to determine facies.**
- **Facies represent specific temperature - pressure regimes.**
- **Named for *Equivalent Mafic rock type* at those conditions.**

Facies of regional Metamorphism:

1) Greenschist Facies	**(includes chlorite/biotite zones of Barrow).**
2) Epidote Amphibolite facies	**(garnet zone).**
3) Amphibolite Facies	**(staurolite/kyanite/sillimanite zones)**
4) Granulite facies	**(not found in Scottish highlands)**
5) Eclogite facies	**(not found in Scottish highlands)**

- **Names indicate specific T and P conditions and not textures or minerals ex. Amphibolite Facies includes calcite marbles, biotite schists and amphibolites.**

Granulite: muscovite + quartz ⇔ sillimanite + Kspar "2nd Sillimanite Ispgrad"

Quartz + biotite ⇔ Kspar + hypersthene

Eskola's Facies for Contact Metamorphism:

1) Hornblende hornfels facies
2) Pyroxene hornfels facies

- **Do not have to be hornfels -- could be a schist.**
- **Use these facies if clearly associated with a pluton.**
- **Hornblende hornfels similar to amphibolite facies.**
- **Pyroxene hornfels similar to granulite.**

NEW Metamorphic Facies -- Since Eskola

6. Zeolite Facies: Incipient metamorphism at low T and P

- **Zeolites = Hydrated feldspars (mostly calcic).**
- **Temperatures 100-200^{o}C.**
- **Index minerals = Laumonite, thompsonite, other zeolites, calcite, interlayered smectite/chlorite.**
- **Metabasalts: Veins and amygdule fillings**
- **Sandstones: Veins, interstitial pore space fillings.**

7. Prehnite-Pumpellyite Facies (Sub-greenschist, low T, P)

- **Index minerals = Prehnite, pumpellyite, calcite, chlorite, albite**
- **Temperatures = 150-250^{o}C**
- **Metabasalts: Veins, amygdules, replacement of primary plagioclase, olivine, glass.**
- **Sandstones: Veins, replacement of clastic feldspars.**

8. Blueschist Facies: High P at low Temperatures

- **Index minerals = Glaucophane, albite, jadeite, lawsonite, aragonite.**
- **Temperatures = 250-350^{o}C.**
- **Pressures > 6-8 kb.**
- **Metabasalts: Glaucophane, albite, lawsonite, sphene**
- **Sandstones, shales: Jadeite, albite, quartz, lawsonite, aragonite, paragonite (Na white mica)**

FACIES – PROTOLITH—MINERAL ASSEMBLAGE TABLE:

Facies	Shale, Sandstone	Limestone	Basalt, Andesite
Zeolite **100-200° C**	**interlayered smectite/chlorite calcite**	**calcite**	**Laumonite, thompsonite, calcite, interlayered smectite/chlorite**
Prehnite-Pumpellyite **150-300° C**	**Prehnite, pumpellyite, calcite, chlorite, albite**	**calcite**	**Prehnite, pumpellyite, calcite, chlorite, albite**
Greenschist **300-450° C**	**muscovite, chlorite, quartz, albite, biotite, garnet**	**calcite, dolomite, quartz, epidote, tremolite**	**albite, chlorite, quartz, epidote, actinolite, sphene**
Epidote Amphibolite **450-550° C**	**muscovite, biotite, garnet, albite, quartz**	**calcite, quartz, tremolite, epidote,diopside**	**albite, epidote, hornblende, quartz**
Amphibolite **500-700° C**	**garnet, biotite, muscovite, quartz, plagioclase, staurolite, kyanite or sillimanite**	**calcite, diopside quartz, wollastonite**	**hornblende, plagioclase, garnet, quartz, sphene, biotite**
Granulite **700-900° C**	**garnet, Kspar, sillimanite or kyanite, quartz, plagioclase, hypersthene**	**calcite, quartz, plagioclase, diopside, hypersthene**	**plagioclase, augite, hypersthene, hornblende, garnet, olivine**
Blueschist **150-350° C** **P > 5-8 Kb**	**Jadeite, albite, quartz, lawsonite, aragonite, paragonite**	**aragonite, white mica**	**Glaucophane, albite, lawsonite, sphene, ± garnet**
Eclogite **350-750° C** **P > 8-10 Kb**	**coesite, Kspar, sillimanite, plagioclase**	**aragonite, quartz, plagioclase, diopside, hypersthene**	**omphacite (px), pyrope garnet**

METAMORPHIC FACIES SERIES

Regional metamorphism: temperature/pressure vary along distinct P-T paths (geothermal gradients) depending on tectonic setting and local variations in heatflow.

Three general P/T types: Low, Intermediate, High

1. Low P/T facies series (ex. Ryoke Belt of Japan)
- **"Regional contact metamorphism"**
- **Greenschist, Amphibolite, Granulite, Hornfels Facies**
- **Characterized by andalusite ± sillimanite - Do not find kyanite**

2. Intermediate P/T facies series (ex. Scottish Highlands)
- **Greenschist, Amphibolite, Granulite, Med-T Eclogite Facies**
- **Same as normal "Barrovian" metamorphism**
- **Sillimanite/kyanite common in pelitic rocks, andalusite rare**

3. High P/T facies series (ex. Franciscan complex in California)
- **Zeolite, Prehnite-Pump, Blueschist, Low-T Eclogite Facies**
- **Characterized by jadeite+lawsonite or glaucophane+lawsonite ±aragonite (blueshist)**
- **Characterized by omphacite+garnet ± kyanite (eclogite)**
- **Do not find andalusite at any grade.**

Glaucophane (amphibole) has wide stability field
Lawsonite and jadeite are more typical for defining this facies:

A) Lawsonite ($CaAl_2Si_2O_7 (OH_2) H_2O$) - Albite Subfacies
- **Intermediate Na,Ca-plag + H2O >> Lawsonite (Ca) + Albite (Na)**
- **Lower blueschist facies**

B) Lawsonite - Jadeite Subfacies
- **Albite goes to jadeite (pyroxene) + silica**
- **$NaAlSi_3O_8$ >> $NaAlSi_2O_6$+SiO_2**
- **Anorthite component >> Lawsonite**
- **Upper blueschist facies, next go to eclogite facies**