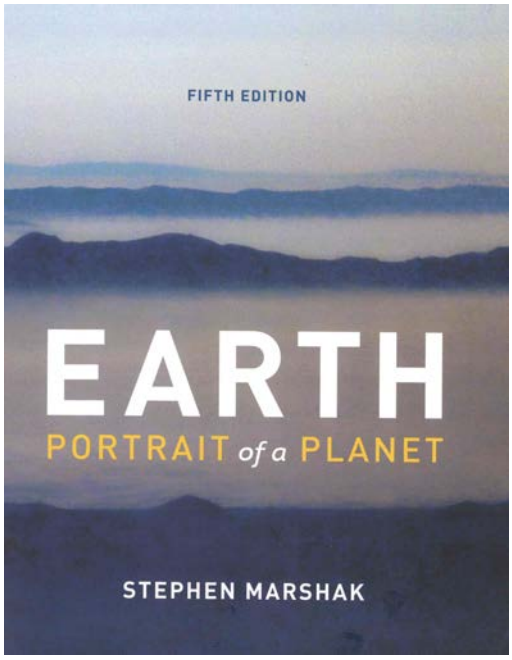
Metamorphism: A Process of Change



Earth

Portrait of a Planet
Fifth Edition

Chapter 8

Metamorphism

Metamorphic rock forms from a pre-existing rock or ***protolith***.

During ***metamorphism***, new minerals grow at the expense of old minerals, and/or the shape, size, and arrangement of grains in the rock may change. Changes occur in the solid state because melting doesn't occur.

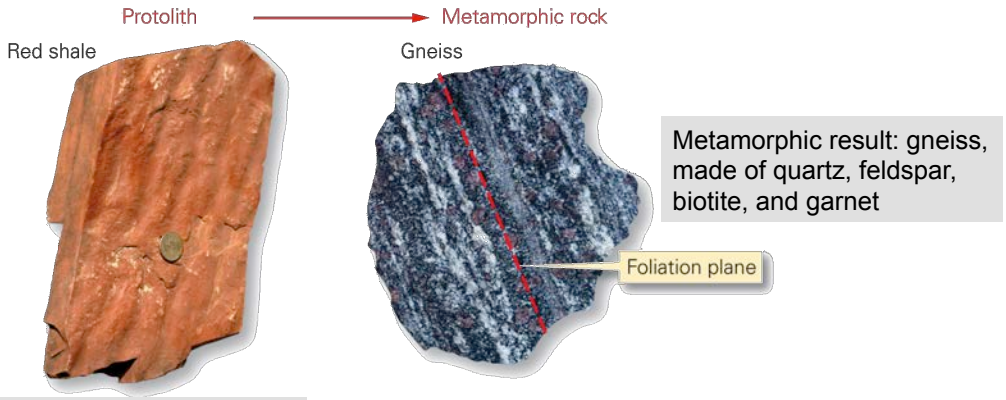
Changes induced by heat, pressure, differential stress, and/or hydrothermal fluids.

Metamorphism occurs between diagenesis and melting.

Protoliths

Protoliths undergo changes in texture and mineralogy. These changes are due to variations in temperature, pressure, tectonic stress, and the amount of reactive water. Metamorphic changes occur slowly in the solid state, without melting and without becoming sediment.

Metamorphism can change the mineralogy of the rock.



Metamorphic result: gneiss, made of quartz, feldspar, biotite, and garnet

Protolith: red shale, made of quartz, clay, and iron oxide

Metamorphism

How to tell if a rock is "metamorphic"?

1. **Metamorphic texture**: minerals have grown in situ and interlock.
2. **Metamorphic minerals**: distinct minerals that only grow under metamorphism (may have a metamorphic mineral assemblage).
3. **Metamorphic foliation**: defined by parallel alignment of platy minerals and/or the presence of light and dark colored bands.

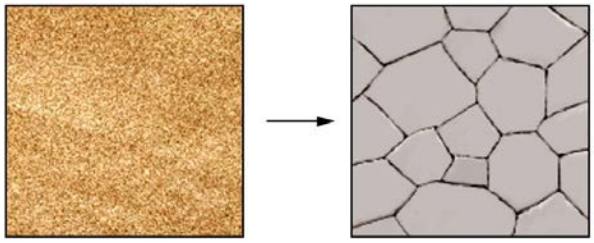
Changes can destroy all evidence of the protolith.

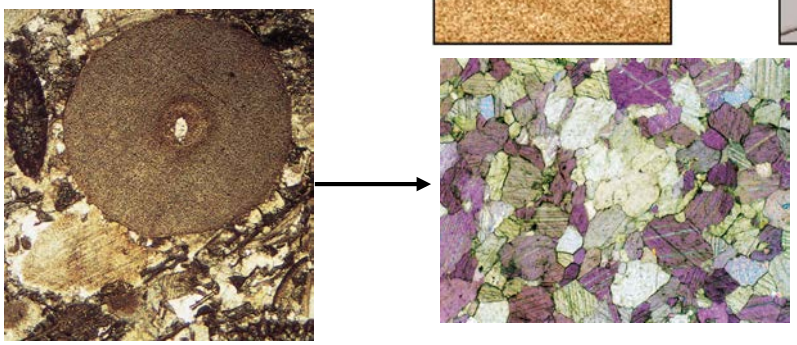
Metamorphic Textures & Minerals

Several processes involved in forming metamorphic textures & minerals.

Recrystallization: changes shape and size of a mineral grain without changing the mineral.

Protolith of siltstone recrystallizes to form Quartzite - made of larger quartz crystals.





Limestone protolith

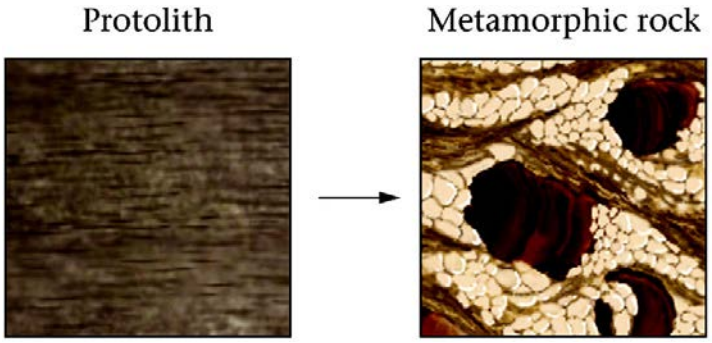
Marble

Calcite has recrystallized to form an interlocking texture.

Metamorphic Textures & Minerals

Phase Change: polymorphic transformation (crystal structure change).

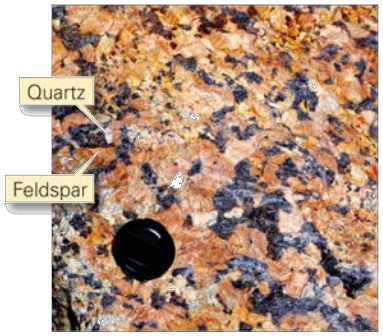
Metamorphic Reaction (Neocrystallization): Growth of new minerals. Old minerals (reactants) decompose to form new ones (products). This requires atoms to migrate or diffuse through solid crystals = slow. Fluids can speed up this process.

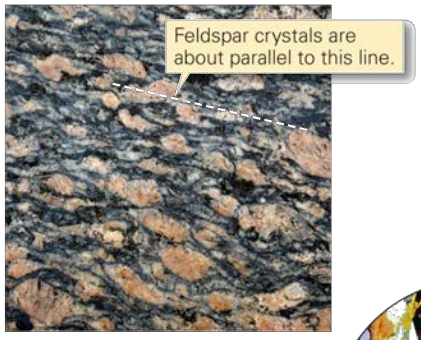


Neocrystallization in a protolith of silty shale forms a rock of quartz, mica, large garnets, etc.

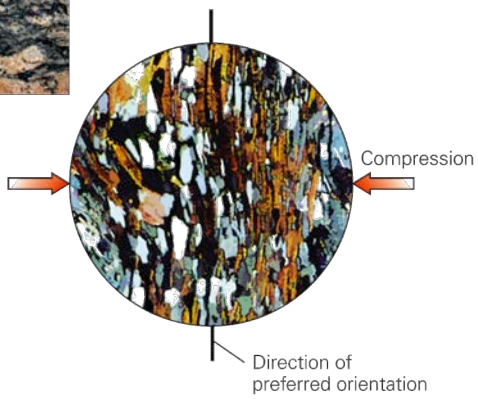
Metamorphic Textures & Minerals

Foliation: defined by alignment of platy minerals (i.e., micas), or creation of alternating light/dark bands.
Differential stress and/or shear.



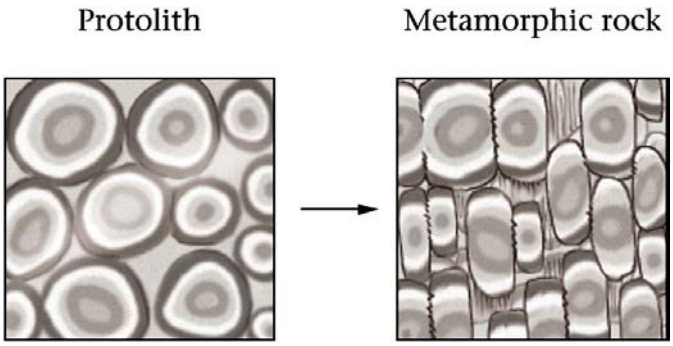


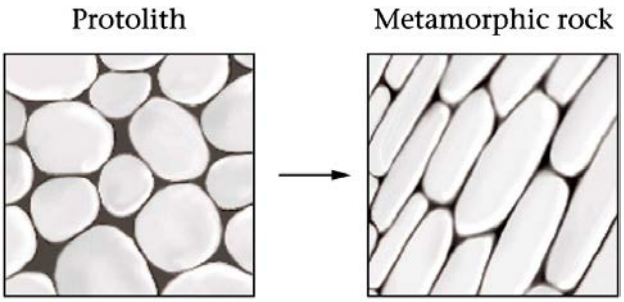
Metamorphism often imparts a foliation upon the new rock. Foliation is a planar fabric that cuts through the rock.



Metamorphic Textures & Minerals

Pressure Solution:
directional stress is needed in the presence of H_2O. High pressure areas of grains dissolve and recrystallize in low pressure area.

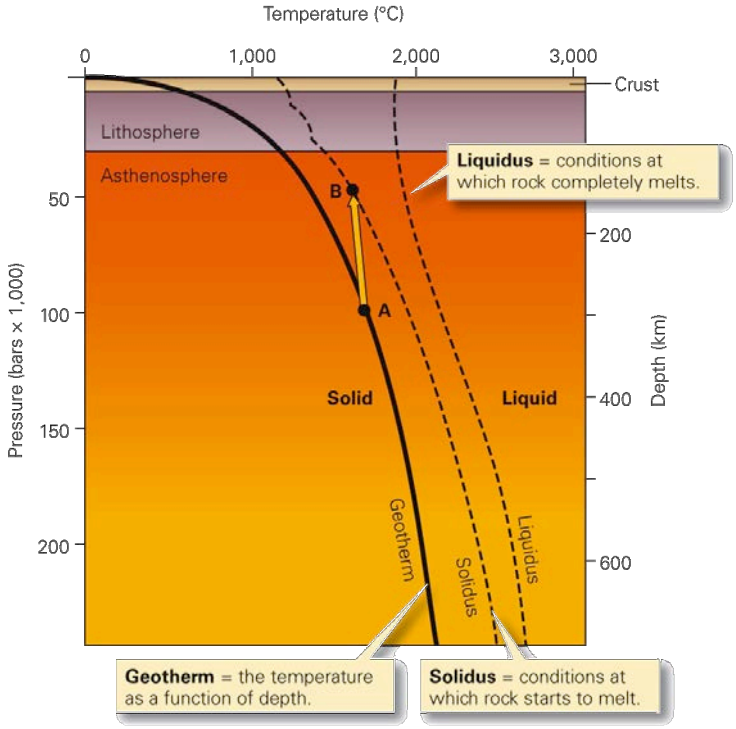




Plastic Deformation: happens at elevated temperatures - minerals are plastic.

Causes of Metamorphism

Metamorphism occurs between 250˚C and 850˚C and the depth to this temperature varies with tectonic setting.



Causes of Metamorphism

Temperature

Increasing energy can cause bonds to break - recrystallization and neocrystallization can occur. Often called ***contact metamorphism*** as this occurs around igneous intrusions.

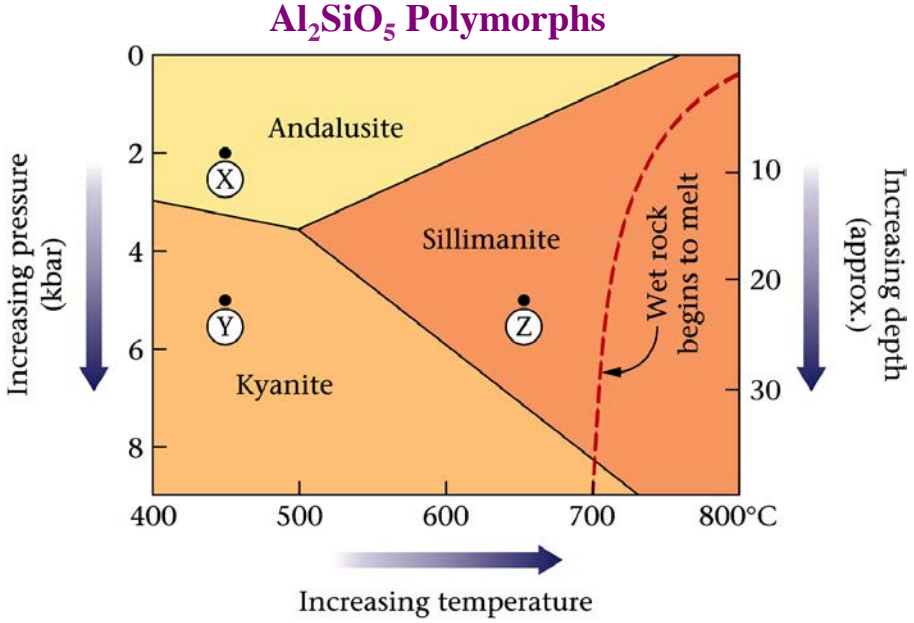
Pressure

Under extreme pressure, existing minerals breakdown to denser ones (e.g., basalt --> eclogite during subduction. This involves phase transformations and/or neocrystallization.

Ultra high pressure phases found at the Earth's surface (meta-stable) - coesite is a high pressure form of quartz. Also diamond.

Causes of Metamorphism

Pressure & Temperature

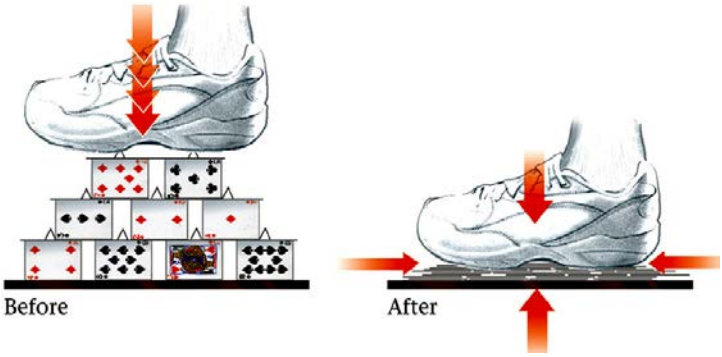


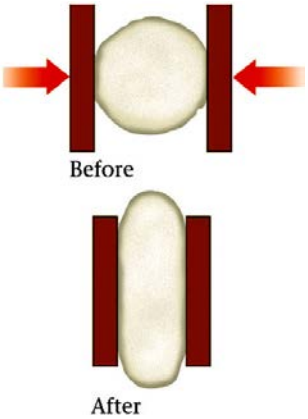
X = Andalusite; Y = Kyanite; Z = Sillimanite

Causes of Metamorphism

Differential Stress

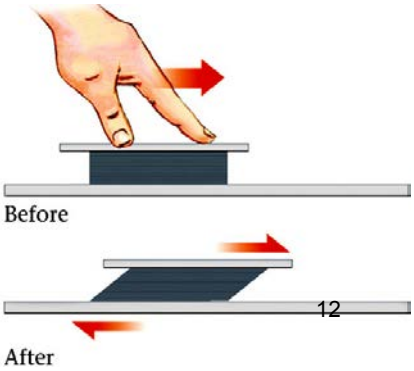
Stress in one direction differs in magnitude from that in another direction.





Normal Stress: tension or compression is perpendicular to a surface.

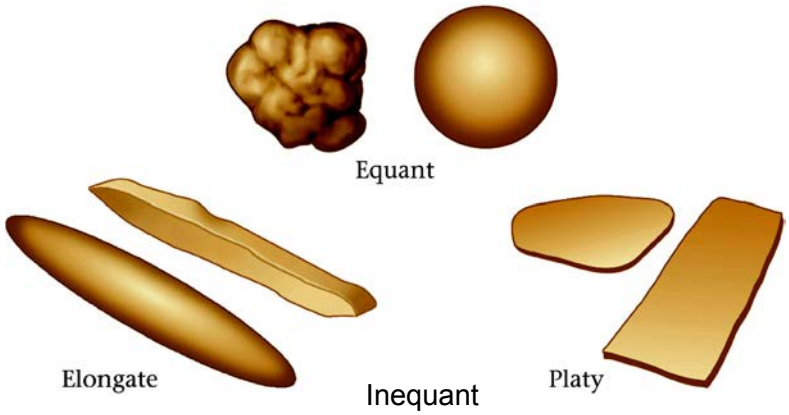
Shear Stress: Shearing moves one part of a material sideways relative to another.



Causes of Metamorphism

Differential Stress

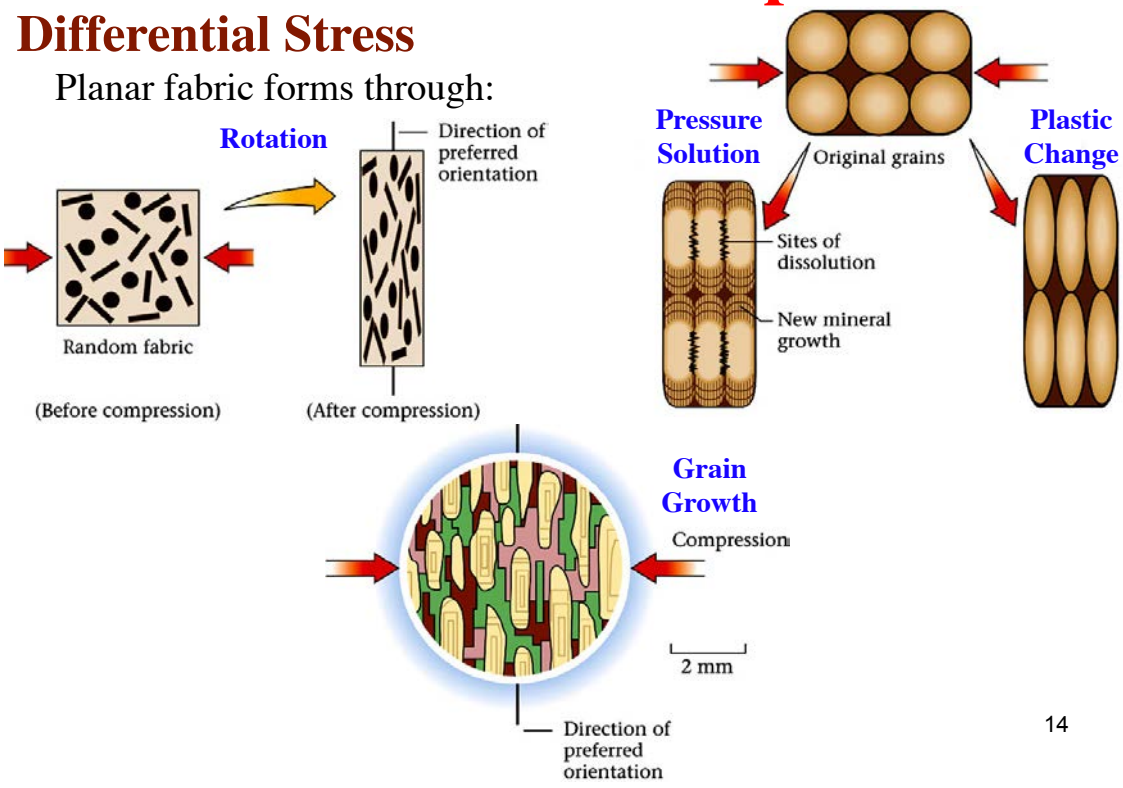
Rocks put under differential stress at high temperature deform plastically - produces preferred mineral orientation (platy and elongate minerals - termed ***inequant***; equant = equidimensional). Preferred orientation of inequant grains gives the rock a ***planar fabric***.



Causes of Metamorphism

Differential Stress

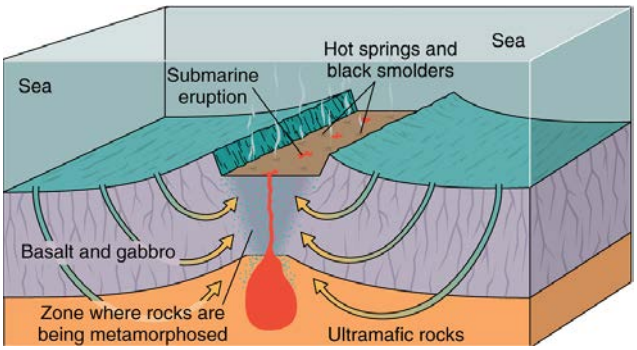
Planar fabric forms through:



Role of Hydrothermal Fluids

Supercritical fluids - contain water and steam.

Chemically active - can react with the rocks.



Prograde metamorphic reactions liberate fluid:

$$KAl_3Si_3O_{10}(OH)_2 + SiO_2 \rightarrow KAlSi_3O_8 + Al_2SiO_5 + H_2O$$

Muscovite Quartz K-feldspar Sillimanite Water

Fluids: accelerate metamorphic reactions (facilitate movement of atoms); move atoms around (changing rock composition) - this is ***metasomatism***.

SCsmoker2.mov

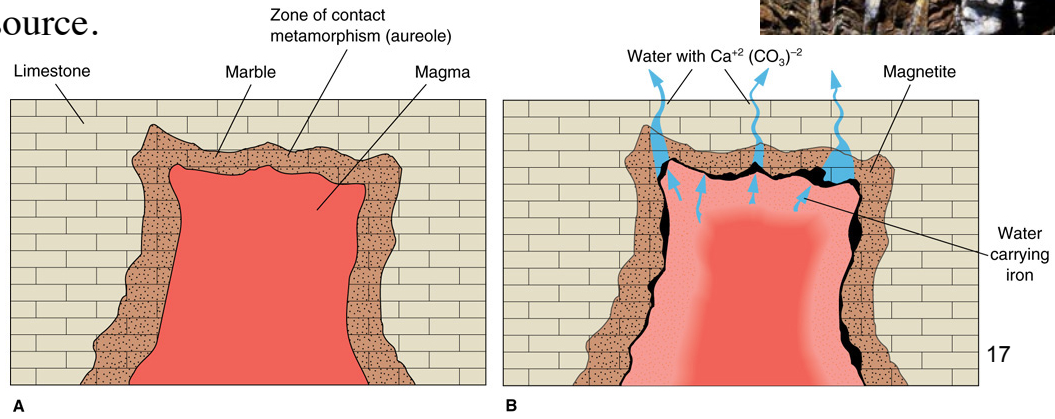
Role of Hydrothermal Fluids

Hydrothermal Processes Role of Water	Name of Process or Product
Water transports ions between grains in a rock. Some water may be incorporated into crystal structures.	Metamorphism
Water brings ions from outside the rock, and they are added to the rock during metamorphism. Other ions may be dissolved and removed.	Metasomatism
Water passes through cracks or pore spaces in rock and precipitates minerals on the walls of cracks and within pore spaces.	Hydrothermal rocks

Role of Hydrothermal Fluids

Fluids can produce veins in metamorphic terranes.

Metasomatism: addition of ions from external source.



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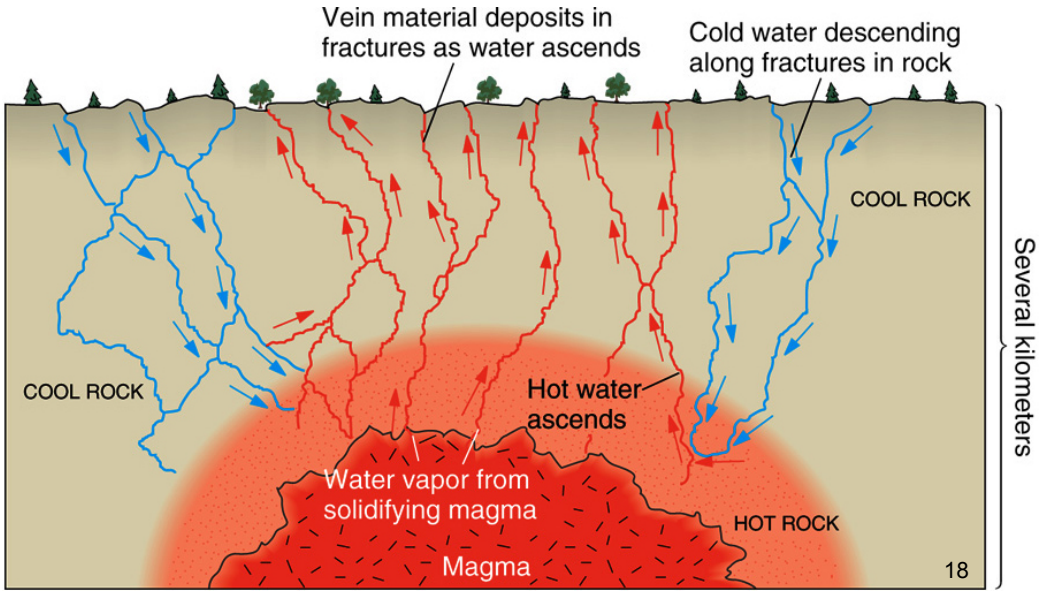
Role of Hydrothermal Fluids

Metamorphic ***aureole*** is greater around granitic plutons than around gabbroic plutons, even though the magma temperature is lower (Bowen's Reaction Series).



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Classification

Mineralogical and textural if foliated:

"garnet-mica schist"

"quartz-feldspar gneiss"

If non-foliated, named on compositional basis (and often color):

"(white) quartzite" or "(pink) marble"

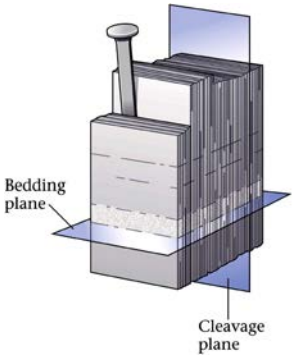
Exception: "Blueschist"

Metamorphic Rocks

Two broad types: **Foliated** and **non-foliated**

Sequence of prograde metamorphic changes from shale/mudstone:
Slate --> Phyllite --> Schist --> Gneiss --> Migmatite

Slate: oriented clay minerals allows the rock to be easily cleaved.



Has distinctive
slaty cleavage

Metamorphic Rocks

Phyllite: growth of microscopic micas to give strong foliation – rock is "shiny" (***phyllitic luster***).

PHYLLITE: growth of microscopic micas to give strong foliation – rock is "shiny".

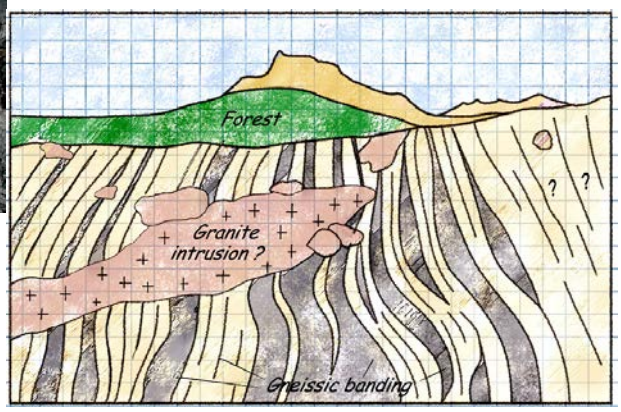
Metamorphic Rocks

Schist: strongly foliated with visible micas and feldspars. Foliation is termed ***schistosity***.

Prophyroblasts = metamorphic phenocrysts

Metamorphic Rocks

Gneiss: strongly banded rock with dark bands of micas, amphiboles, & pyroxenes, light bands of feldspars & quartz.

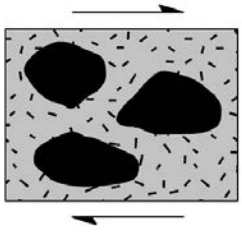


Metamorphic Rocks

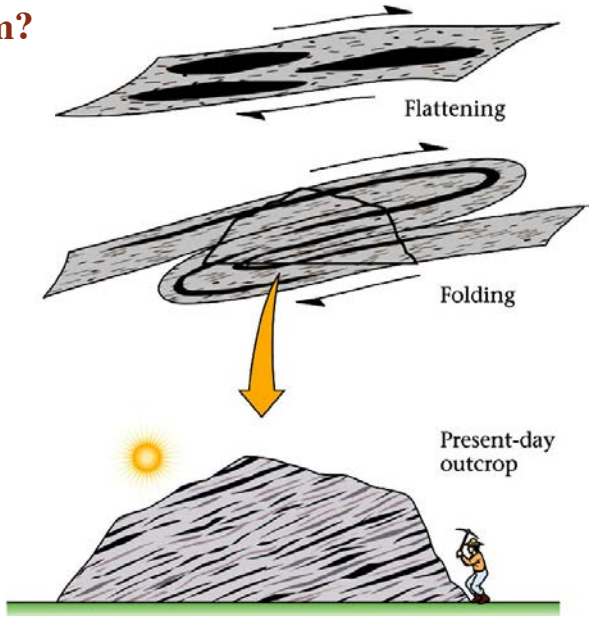
How does gneissose banding form?

Relict original bedding.

Extreme Shearing (plastic flow).



Metamorphic differentiation: metamorphic reactions separate different minerals into different layers.

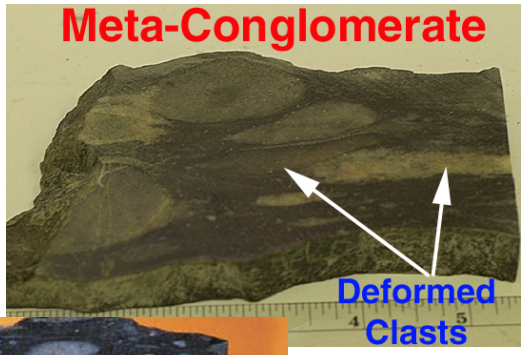


Metamorphic Rocks

Migmatite: strongly veined rock as it has partially melted. This rock type is at the transition between metamorphic and igneous petrology.

Metamorphic Rocks

Stretched/Flattened-Clast Conglomerate: flattening occurs through combination of plastic deformation and pressure solution.

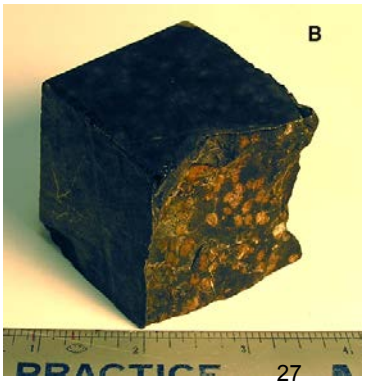


Metamorphic Rocks

Nonfoliated

Can form under differential stress. Commonly found in contact metamorphism.

Hornfels: rock produced by heating of the protolith in the absence of pressure. Specific mineral assemblage depends upon the protolith. New minerals may form "spots" (new mineral = Cordierite).



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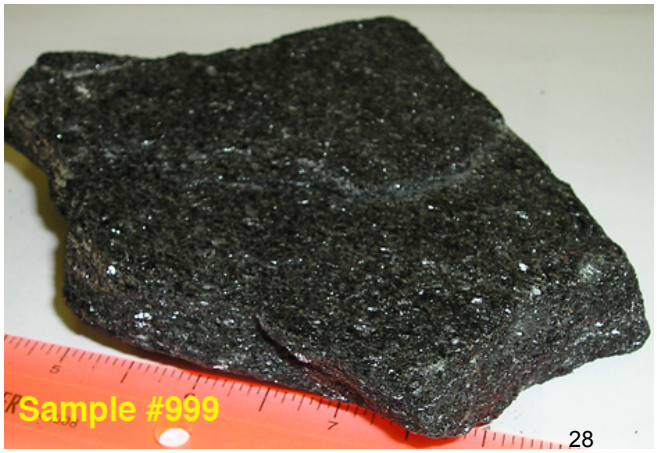
Metamorphic Rocks

Amphibolite: metamorphosed mafic rocks - contain hornblende and plagioclase +/- biotite. As the rock contains little mica, foliation is poorly developed.



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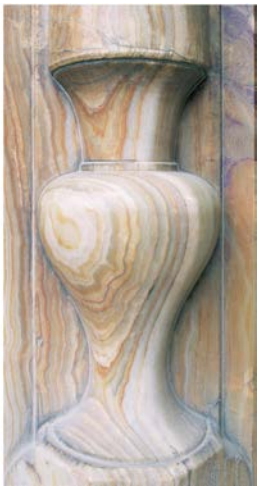
Metamorphic Rocks

Quartzite: metamorphosed sandstone. Quartzite fractures through grains; sandstone fractures around grains. No compositional layering. Occasionaly quartz grains can be flattened to give a poor foliation.

Marble: Metamorphosed limestone. Recrystallization of calcite to give interlocking fabric.

Destroys relict features. Impurities give color.

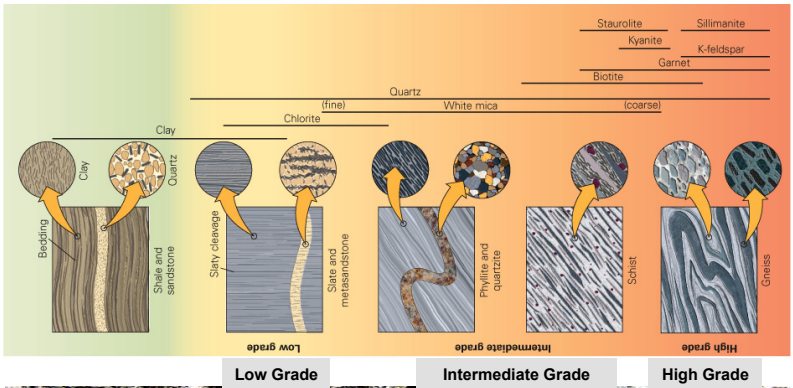
Calcite is relatively weak and easily recrystallizes - makes marble good for sculpting (WHY?).



Metamorphic Rocks

The protolith is the major control on the resulting metamorphic rock.

This chart portrays the metamorphic rocks that result from alteration of a pelitic (clay-rich) protolith.



Metamorphic Rocks

Four terms for metamorphic rocks:

Pelitic: aluminium-rich sedimentary rocks (e.g., shales). Produce abundant micas and garnet;

Basic (mafic): low SiO_2, high Fe, Mg - lots of amphibole and biotite;

Calcareous: Ca-rich sedimentary rocks - marble.

Quartzo-Feldspathic: felsic protoliths - lots of quartz and feldspar. Q + F are stable under metamorphic conditions.

Typical Metamorphic Minerals

Chlorite:	**Hydrous Fe-Mg-Al silicate**
***Talc*:**	**Hydrous Mg-silicate**
Serpentine:	**Hydrous Mg silicate**
***Graphite*:**	**Carbon**
Garnet:	**Ca-Mg-Fe-Al silicate**
Staurolite:	**Fe-Al silicate**

Also:
Quartz, muscovite, biotite, feldspar, amphibole, calcite.

Metamorphic Facies:

Rocks having broadly similar mineral assemblages = same metamorphic facies – analogous to climatic zones.

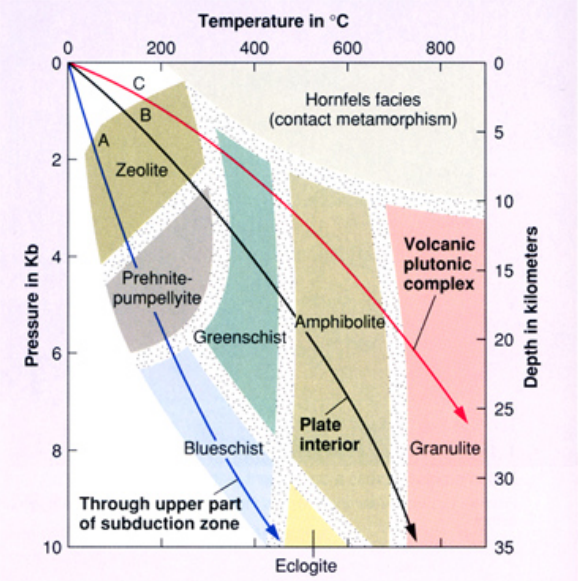
The metamorphic facies is determined by the specific mineral assemblage present.

The facies is defined as a mineral assemblage that may only occur over a relatively narrow range of P-T conditions.

Formed under broadly similar P-T conditions.

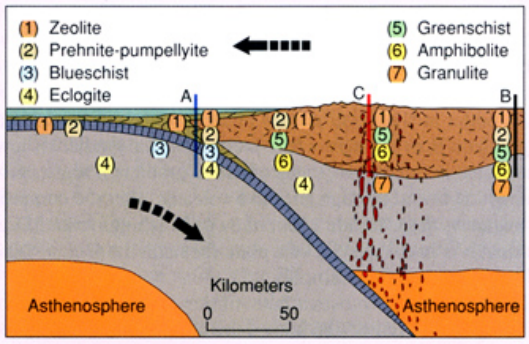
Mineralogy dependent upon protolith composition.

Metamorphic Facies:



Box 7.4 — FIGURE 1

The metamorphic facies. Facies are named after minerals (prehnite, zeolite, pumpellyite) or rock types (e.g., blueschist, granulite). Boundaries between facies are approximate. The arrows represent increases in temperature with depth for the three lines labeled *A, B, C* in figure 2 and in figure 7.16.



Box 7.4 — FIGURE 2

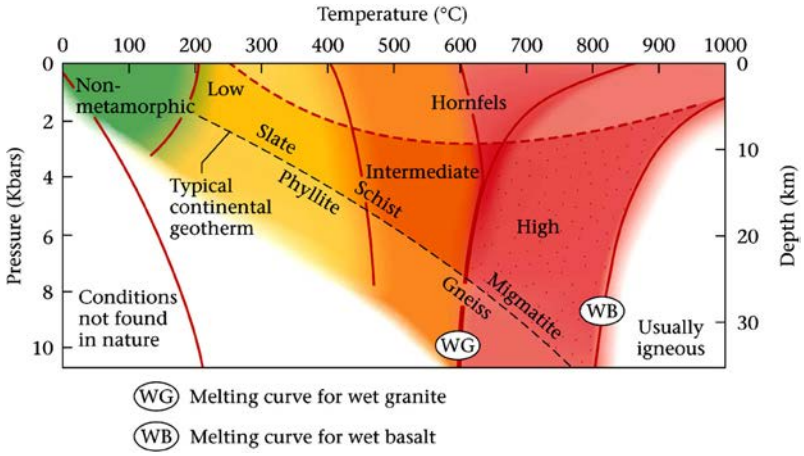
Schematic representation of the distribution of facies across a convergent plate boundary.

A set of metamorphic mineral assemblages indicative of a certain P-T range.
Each specific assemblage in a facies reflects a specific protolith composition

Metamorphic Grade

Degree of parent rock alteration, mostly dependent on increasing temperature for increasing grade.

Prograde: slate-phyllite-schist-gneiss-migmatite (melting).

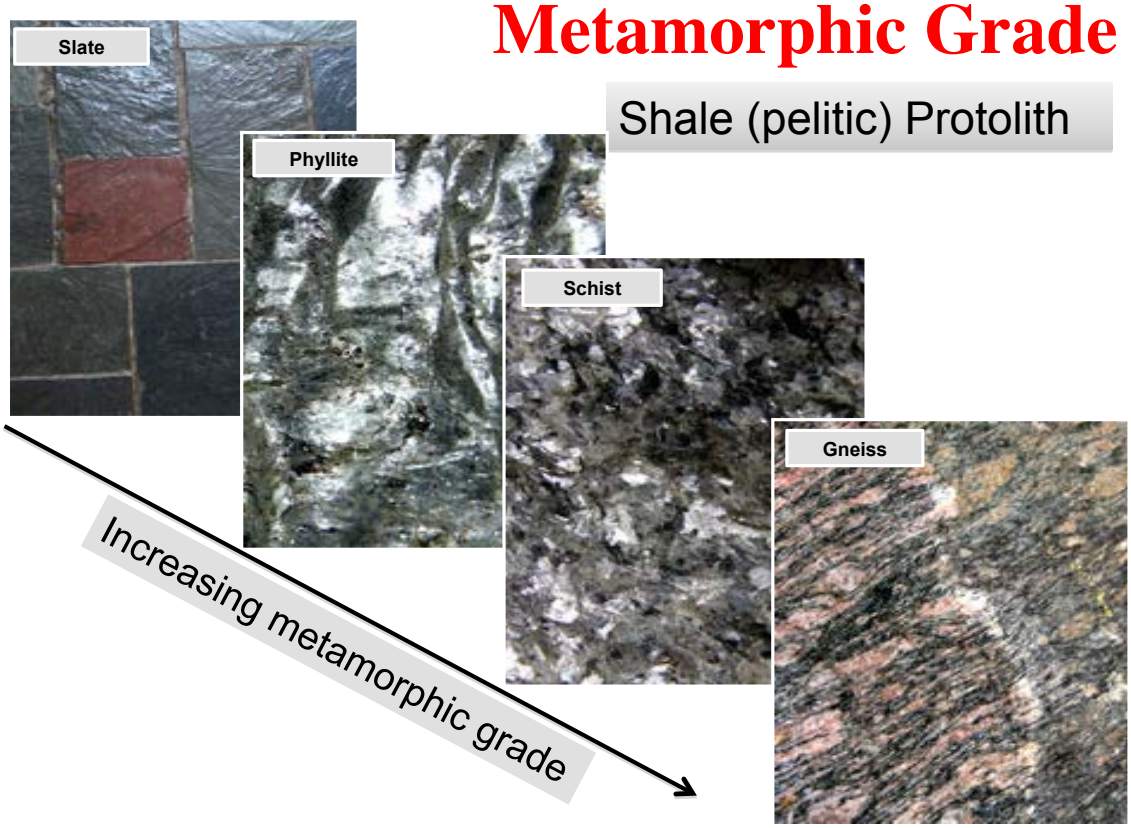


Prograde metamorphic Reaction (liberates fluid):

$CaCO_3$	+	SiO_2	→	$CaSiO_3$	+	CO_2
Calcite		Quartz		Wollastonite		Fluid

Metamorphic Grade

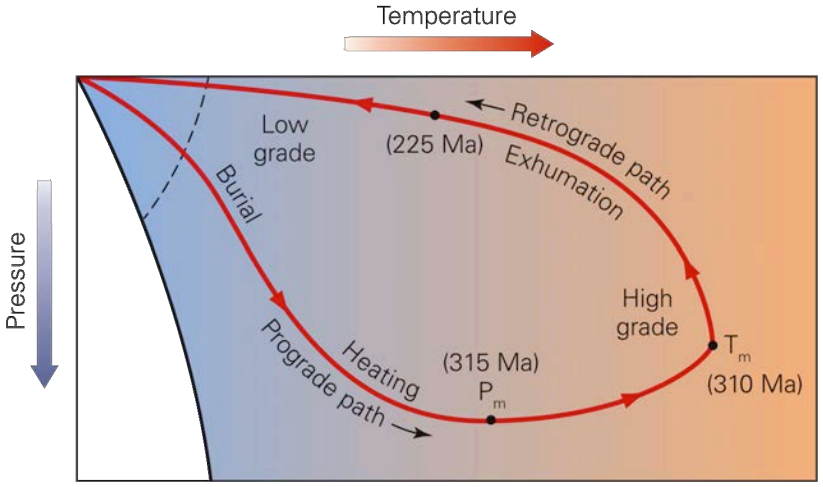
Shale (pelitic) Protolith



Metamorphic Grade

PROTOLITH Basalt (mafic)	LOW Greenschist	INTERMEDIATE Amphibolite	HIGH Mafic granulite	PARTIAL MELTING
	Zeolite Chlorite No Al	Epidote Amphibole	Al Garnet Pyroxene	
Shale (pelitic)	Slate Phyllite	Schist	Gneiss	Migmatite
Clay	Chlorite	Quartz/Feldspar Muscovite Biorite Garnet Staurolite Kyanite	Sillimanite	

Prograde & Retrograde Metamorphism

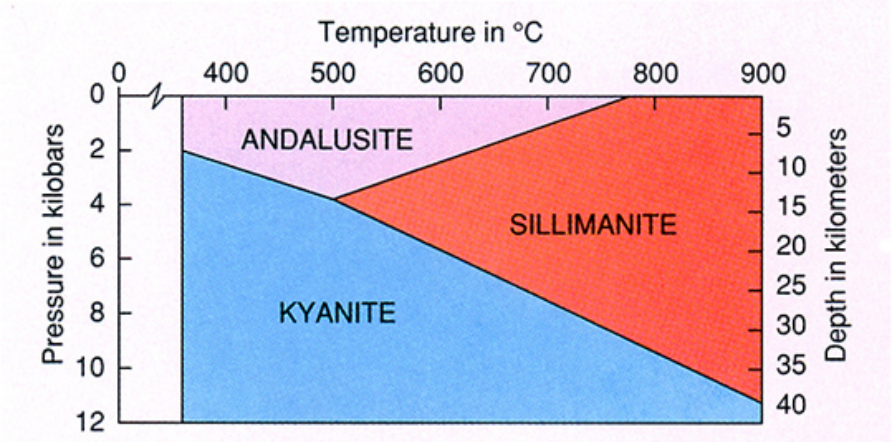


Prograde metamorphism occurs when a rock is buried deeply in an orogenic belt. Deeply buried rocks are brought back to the surface via erosion. Retrograde metamorphism occurs to deep-seated rocks that are brought back to the surface. Retrograde reactions are only possible if hydrothermal fluids add water. Without added water, prograde metamorphic rocks will remain unaltered.

Index Minerals

Form over a restricted range of pressure & temperatures (determined in the laboratory).

When found in rocks, the P-T of formation can be reasonably estimated.



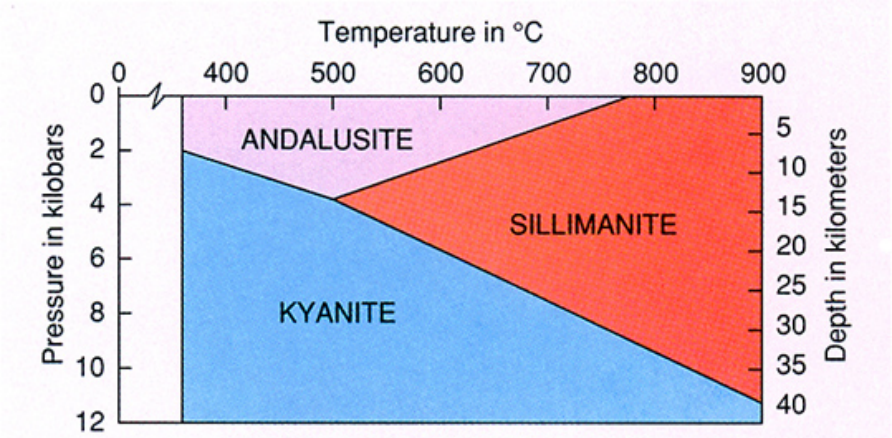
BOX 7.3 — FIGURE 1

Phase diagram showing the stability relationships for the Al_2SiO_5 minerals.

Index Minerals

Kyanite, Andalusite, Sillimanite: all Al_2SiO_5, different crystal structures - *polymorphs*.

Andalusite - low P & T; Kyanite - high P;
Sillimanite - high T.



BOX 7.3 — FIGURE 1

Phase diagram showing the stability relationships for the Al_2SiO_5 minerals.

METAMORPHIC ZONES

Mappable part of the metamorphic body of rocks of same grade. Adjacent zones are separated by **ISOGRADS** – defined by the appearance of critical **INDEX** mineral.

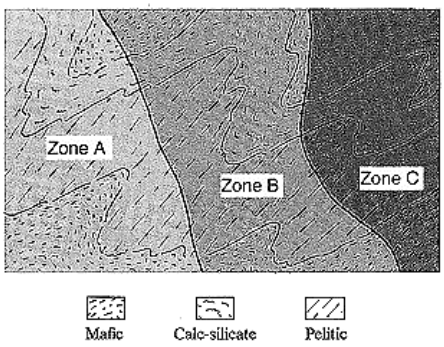
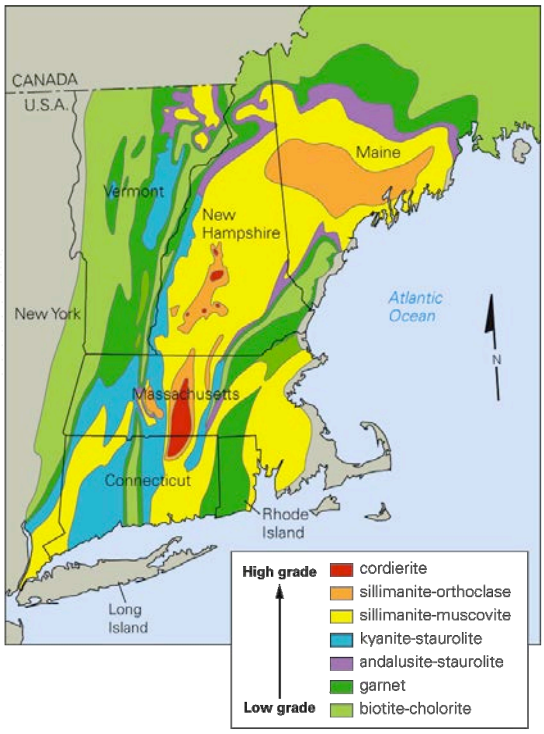


Figure 10-24 Metamorphic isograds (heavy lines) and metamorphic zones (different shades) can be independent of stratigraphic or depositional contacts, as in this schematic sequence of different rock types.



METAMORPHIC ZONES

Pelitic rocks are sensitive to changes in metamorphic conditions – good indicators of metamorphic grade and metamorphic zones.

Zones/isograds reflect conditions of metamorphism (e.g., Barrovian Zones, Scotland; New England).

Metamorphic zones also defined on the basis of imposed metamorphic fabric rather than mineral assemblages (e.g., textural sub-zones in mineralogically uniform rocks).

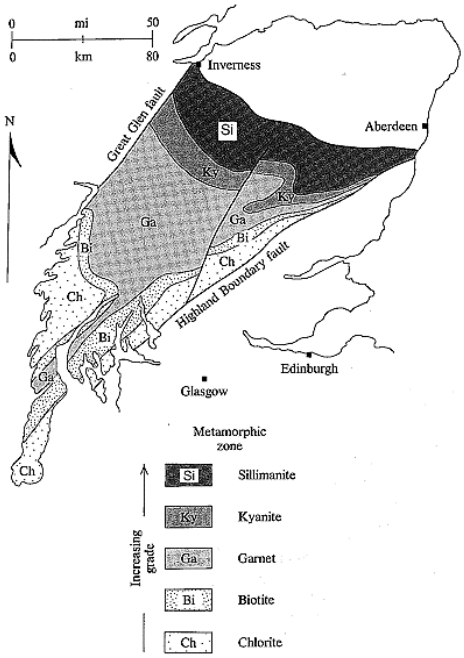


Figure 10-25 Regional Barrovian metamorphic zones in the Scottish Highlands.

Types of Metamorphism: Contact

Thermal, local, around intrusions. Size of aureole depends on:

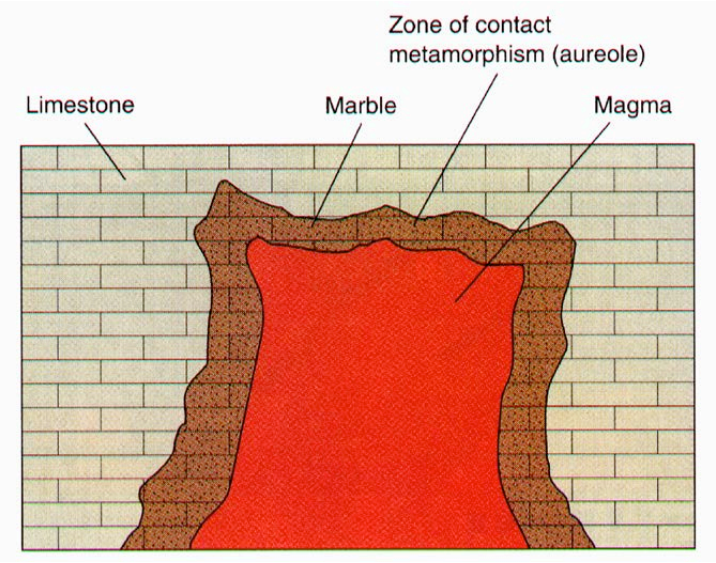
Size of intrusion

Heat (composition)

Fluid content of magma

Fluid content of country rock

Country rock type



Types of Metamorphism: Contact

Produces non-foliated, ***granoblastic*** rocks:

Hornfels (if clastic - shale)

Quartzite (if sandstone)

Marble (if carbonate)

Types of Metamorphism: Regional

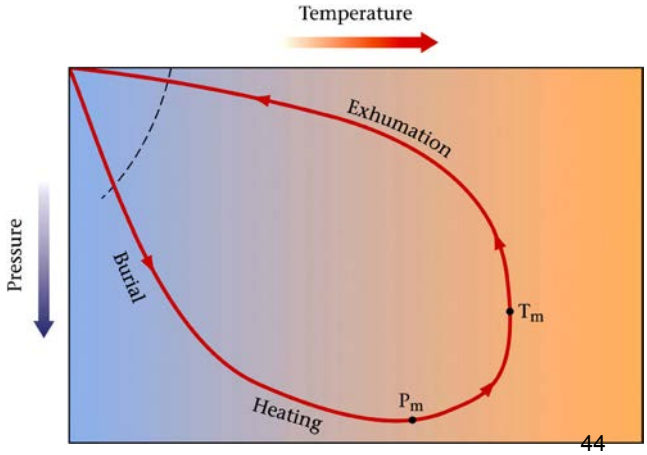
Also known as ***dynamothermal*** - produces both foliated and non-foliated metamorphic rocks.

Associated with mountain belts - affects very large areas.

Heat & directed pressure on rocks buried deep within the Earth - ***Prograde*** or ***Retrograde***.

Prograde metamorphic reactions liberate a fluid.

Retrograde is difficult – pore spaces decrease during prograde so getting fluid back in is not easy.



Types of Metamorphism: Regional

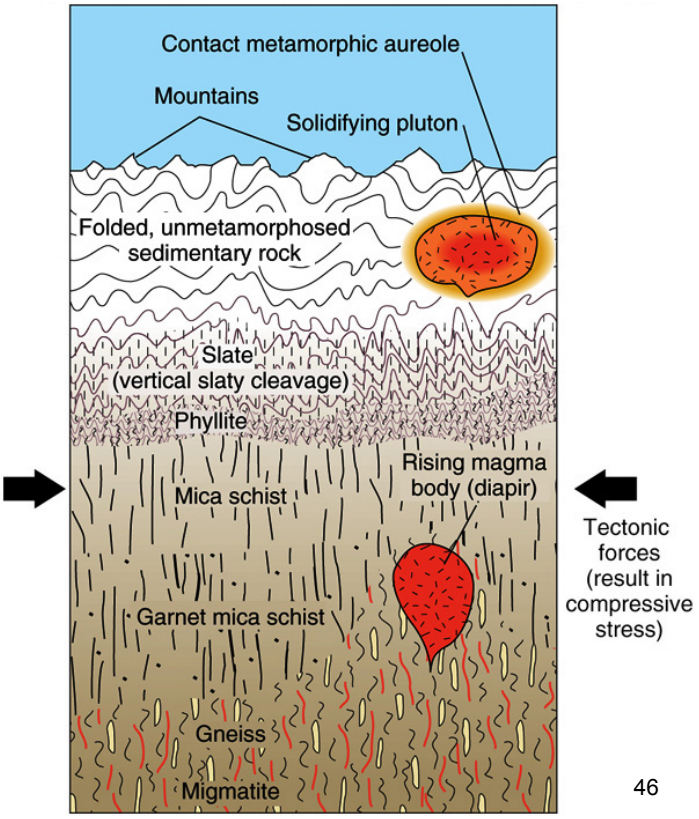
Temperature highly variable. For example -
Basalt = *greenschist* (chlorite, actinolite, Na-plag) –-> *amphibole schist* –-> *amphibolite* (hornblende, plagioclase ± garnet).

Shale	➔	Mica Schist
Quartz Sandstone	➔	Quartzite
Limestone	➔	Marble
Peridotite	➔	Talc or Serpentinite Schist

Regional Metamorphic Rocks that Form under Approximately Similar Pressure and Temperature Conditions

Parent Rock	Rock Name	Predominant Minerals
Basalt	Amphibole schist (amphibolite)	Hornblende, plagioclase, garnet
Shale	Mica schist	Biotite, muscovite, quartz, garnet
Quartz sandstone	Quartzite	Quartz
Limestone or dolomite	Marble	Calcite or dolomite

Regional Metamorphism

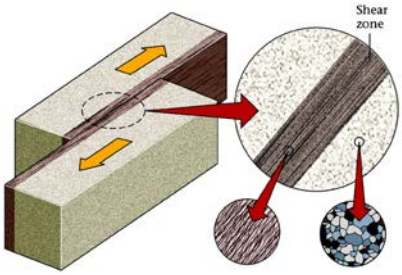


Types of Metamorphism: Burial

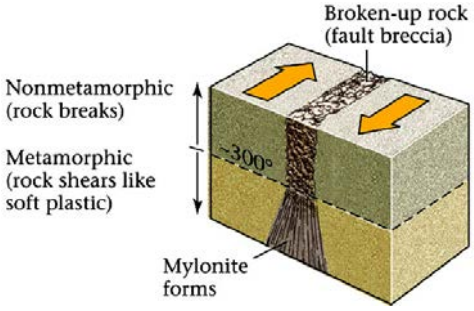
Burial of sediments 8-15 km deep can produce metamorphic reactions, dependent upon the local geothermal gradient and the type of sediment buried (shale vs. sandstone).

Produces low grade non-foliated rocks.
These temperatures break up oil molecules - once the depth where metamorphic reactions begin is reached, oil companies stop drilling.

Types of Metamorphism: Dynamic



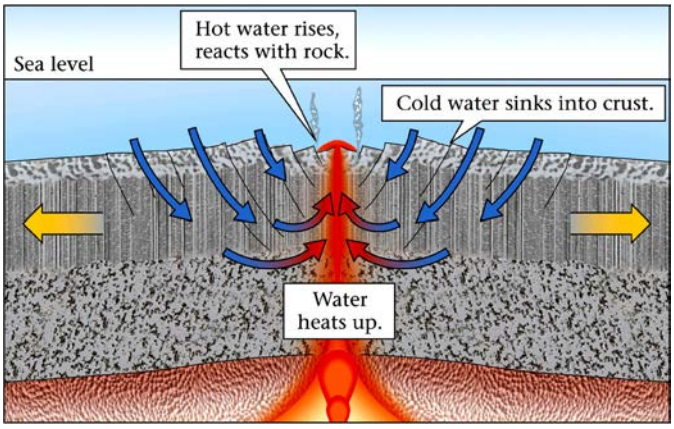
Mechanical grinding of rock along a brittle fault plane produces fault gouge.



At greater depths (warmer) rock recrystallizes to produce mylonite. This has a foliation parallel to that of the fault.
Mylonites can be found at all plate boundaries.

Types of Metamorphism: Hydrothermal

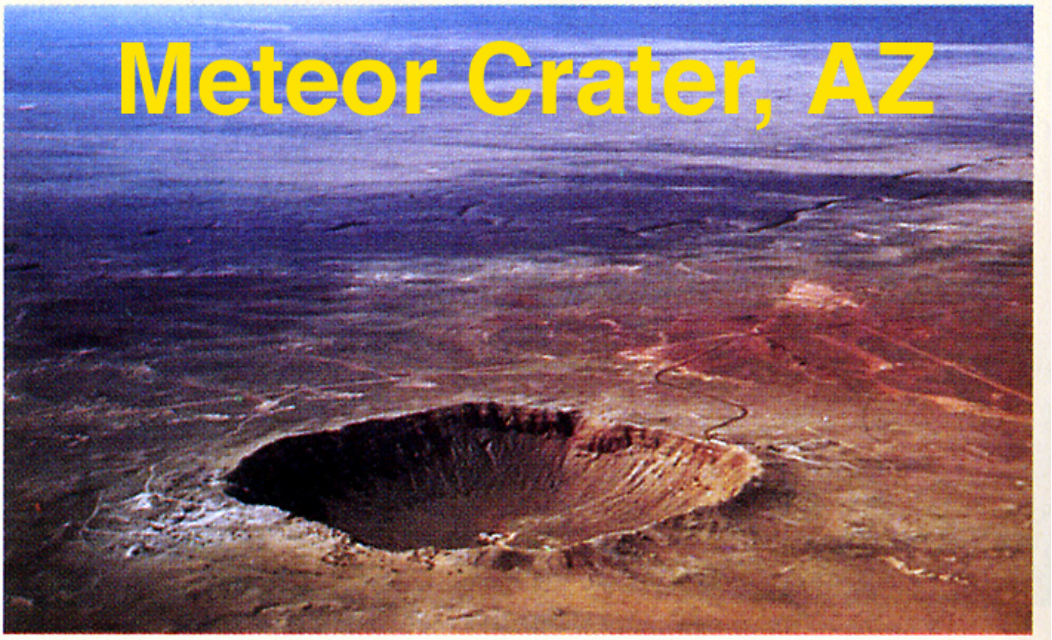
Provides transport mechanism and can promote reactions.
Hydrothermal metamorphism: hot water streams add/ remove ions. May promote ore formation.



Interaction of hot fluids with the mafic rocks produces chlorite and gives the rock a greenish hue = Greenschist Facies Metamorphism.

Types of Metamorphism: Shock

Meteorite impact – sudden and intense deformation.



See **www.meteorcrater.com**

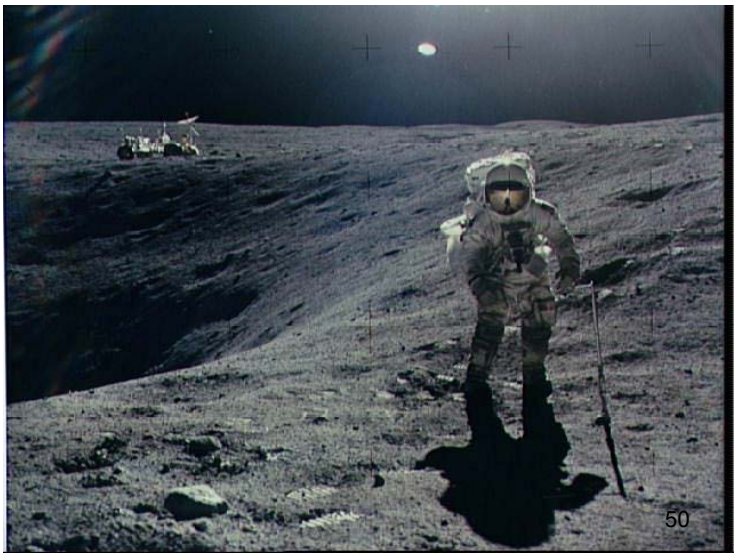
Types of Metamorphism: Shock

High-pressure polymorph of quartz – ***coesite & stishovite*** – can form.

Impact melt can form.

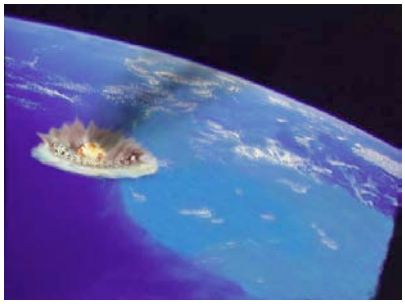
Lots of rock fragmentation & mineral deformation.

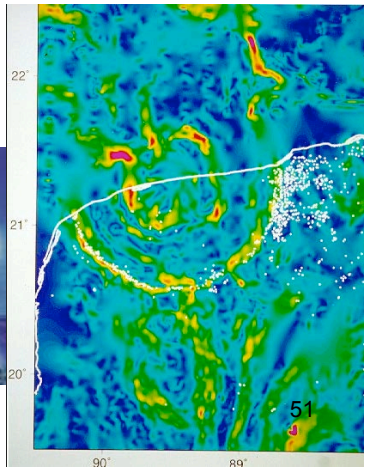
Moon – no atmosphere so lots of meteorite impacts (micro and macro!). Produces regolith, rock flour, impact melt, breccias.



Types of Metamorphism: Shock

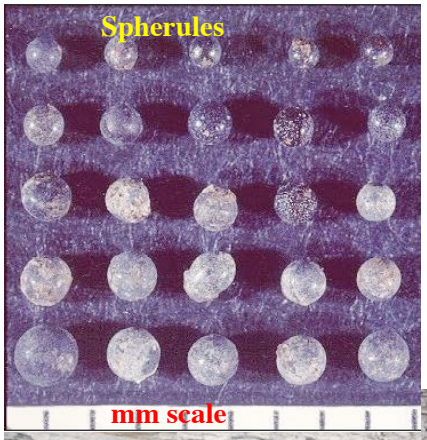
Chicxulub.

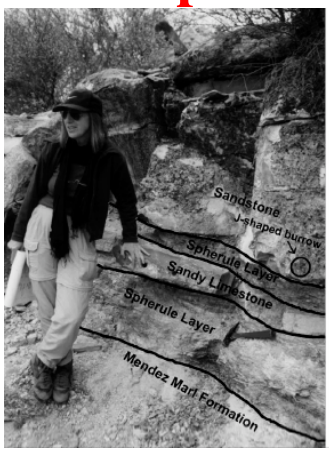


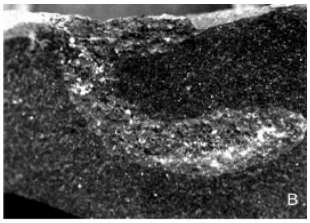


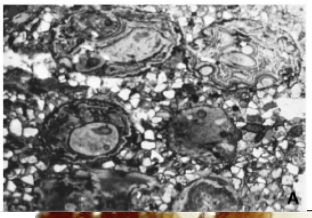
Types of Metamorphism: Shock

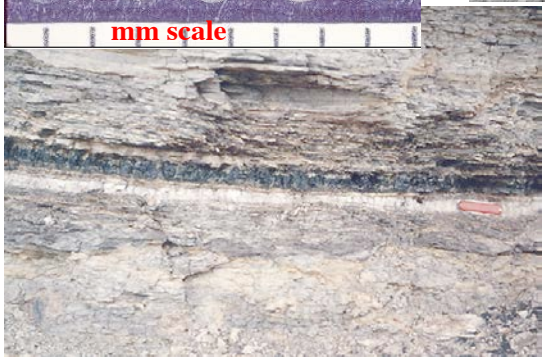
Chicxulub.



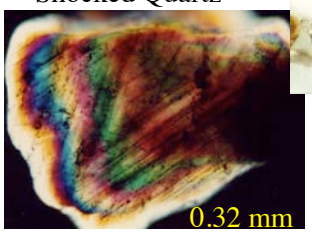








Shocked Quartz



Impact Glass

The Real Reason the Dinosaurs Became Extinct

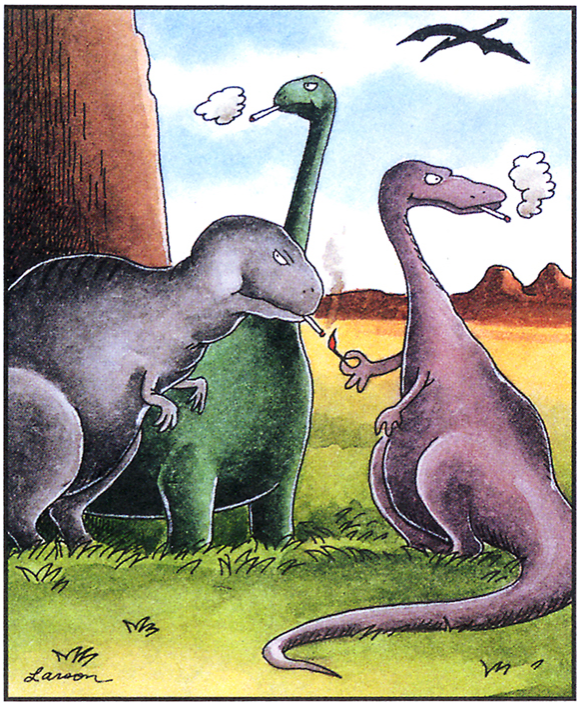


Plate Tectonics and Metamorphism

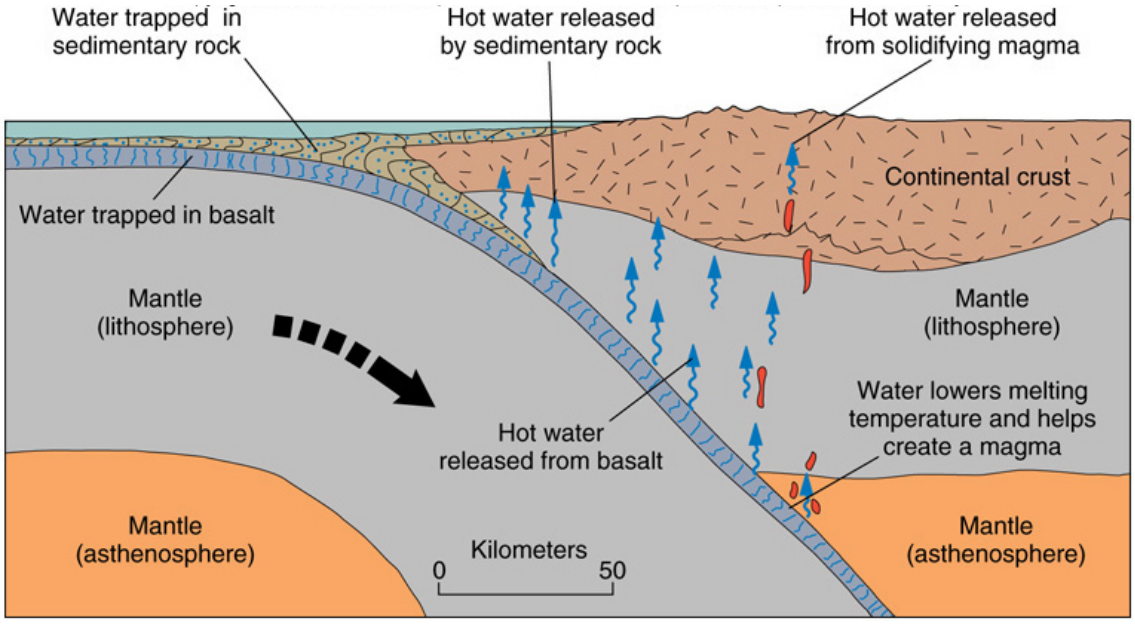


Plate Tectonics and Metamorphism

Gravitational collapse & spreading – central part of mountain becomes too high & collapses. Rock forced downward.

Foliation developed parallel to collapse & spreading.

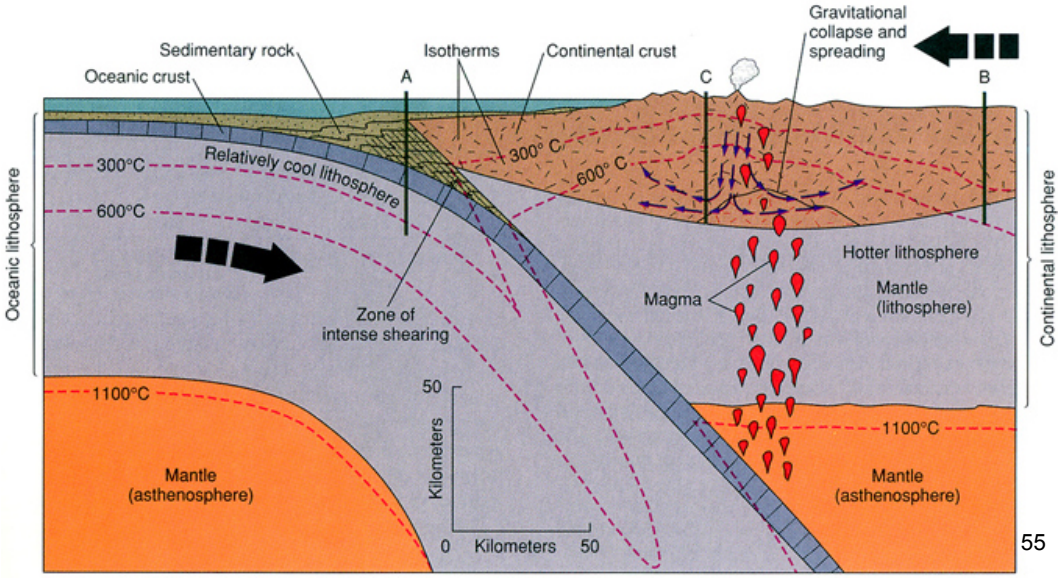


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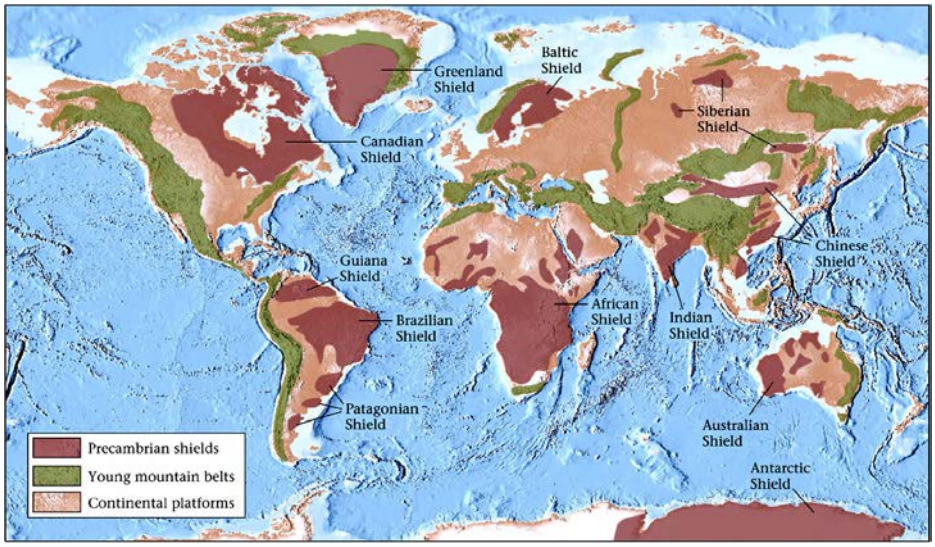
Plate Tectonics and Metamorphism

Oldest rocks on earth = "Precambrian" - invariably metamorphosed. These are found in the oldest part of continents or "shields".



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Summary

Metamorphism: Texture, Minerals, Foliation, Protolith.

Metamorphic Textures: Recrystallization, Phase Change, Neocrystallization, Pressure Solution, Plastic Deformation.

Causes of Metamorphism: Temperature, Pressure, Differential Stress.

Hydrothermal Fluids: Metasomatism, Veins, Size of Contact Metamorphic Aureoles.

Metamorphic Rocks: Foliated, Nonfoliated.

Metamorphic Facies.

Metamorphic Grade.

Index Minerals.

Metamorphic Zones.

Types of Metamorphism: Contact, Regional (Dynamothermal), Burial, Dynamic, Hydrothermal.