

## EPSC 201 LECTURE 20 MARCH 29

Glaciers are thick masses of recrystallized ice (minerals have compacted into ice):

- Last all year long (still present in the summer, even when the climate is warmed)
  - Flow via gravity
  - Mountain and continental
- Presently cover ~10% of Earth (of continental land). During ice ages, coverage expands to ~30%.
- The most recent ice age ended ~11 ka. Covered New York, Montreal, London, and Paris. Cycles of ice sheets happen on thousands of years time scale.
- Ice sheets were hundreds to thousands of meters thick.

### Ice: The Water Mineral

- Ice is the solid state of water ( $H_2O$ )
- Forms when water cools below the freezing point
- Natural ice is a mineral; it grows in hexagonal crystals

**Forming a glacier:** need ice to stick around in the summer

- Cold local climate (polar latitudes or high elevation)
- Snow must be abundant and accumulate in winter, more snow must fall than melts in the subsequent summer

### Glacial Deposits

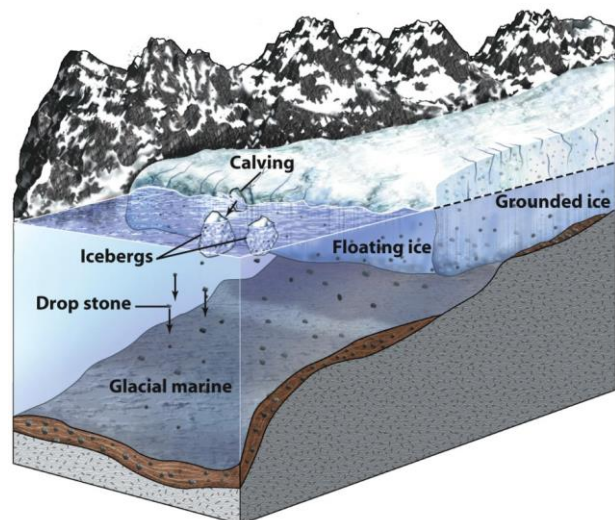
Glacial marine – sediments from an oceanic glacier

-Calving icebergs raft sediments away from the ice

-Melting icebergs drop stones into bottom mud

Glaciers can transport sediments and contribute to the formation of sedimentary rock. Part of the glacier breaks off and becomes an ice berg and drops sediments in the ocean.

Glacial moraine, ice flows along and acts as a conveyor belt... end up with a pile of mixed rocks. That type of deposit is called a glacial moraine. Glaciers are very good at carrying sediments since they can lock sediments in the ice.



Pleistocene Ice ages ~2.5 Ma-11 ka – Glacial maximum where North America was covered by ice. Ice has been growing.

Oxygen isotopes suggest twenty or more glaciations throughout Earth history, wherein high  $^{18}\text{O}/^{16}\text{O}$  = colder, and lower  $^{18}\text{O}/^{16}\text{O}$  = warmer. Today we are in an inter-glacial (between ice ages).

On a short time scale, what causes the start of a glacial state (start of glacial maximum)?  
Complicated question...

### Causes of glaciation

Milankovitch hypothesis: climate variation over 100 to 300 ka predicated by cyclic changes in orbital geometry. These cycles change how much solar radiation is received on Earth which affects the climate.

- The shape of the Earth's orbit varies (~100 000 year cyclicality) – eccentricity of the orbit (circular vs. oval shape)
- Tilt of the Earth's axis varies from  $22.5^\circ$  to  $24.5^\circ$  (~41 000 years)
- Precession – earth's axis wobbles like a top (23 000 years)

### Will there be another glaciation?

We are living in an interglacial (will ice return)?

- very likely! Recent interglacial have lasted ~10 000 years
- but it has been 11 000 years since the last deglaciation
- A cool period (1300-1850) resulted in the Little Ice Age. This is known by looking at paintings from this time period (paintings depicted settings covered in snow)
- We are in a super-inter-glacial (ice is retreating very rapidly) – may be due to human-induced warming
- During the past 150 years, temperatures have risen and most mountain glaciers have dramatically retreated

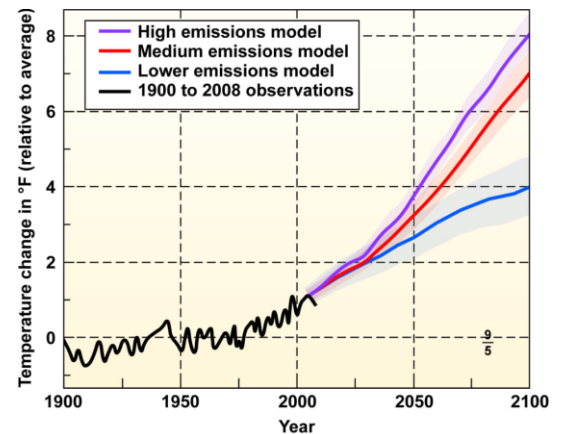
### Human Impact on the Earth System

Consensus now: global warming is a fact

- Surface air temperature have warmed by  $\sim 1^\circ\text{C}$  since 1880 (Note: current average surface temperature is  $14^\circ\text{C}$ )
- Global average temperature is higher today than at any time in the last 2000 years, even warmer than during the medieval warm period
- There is a sharp rise in temperature change in the past few decades which is higher than any change recorded in the past..

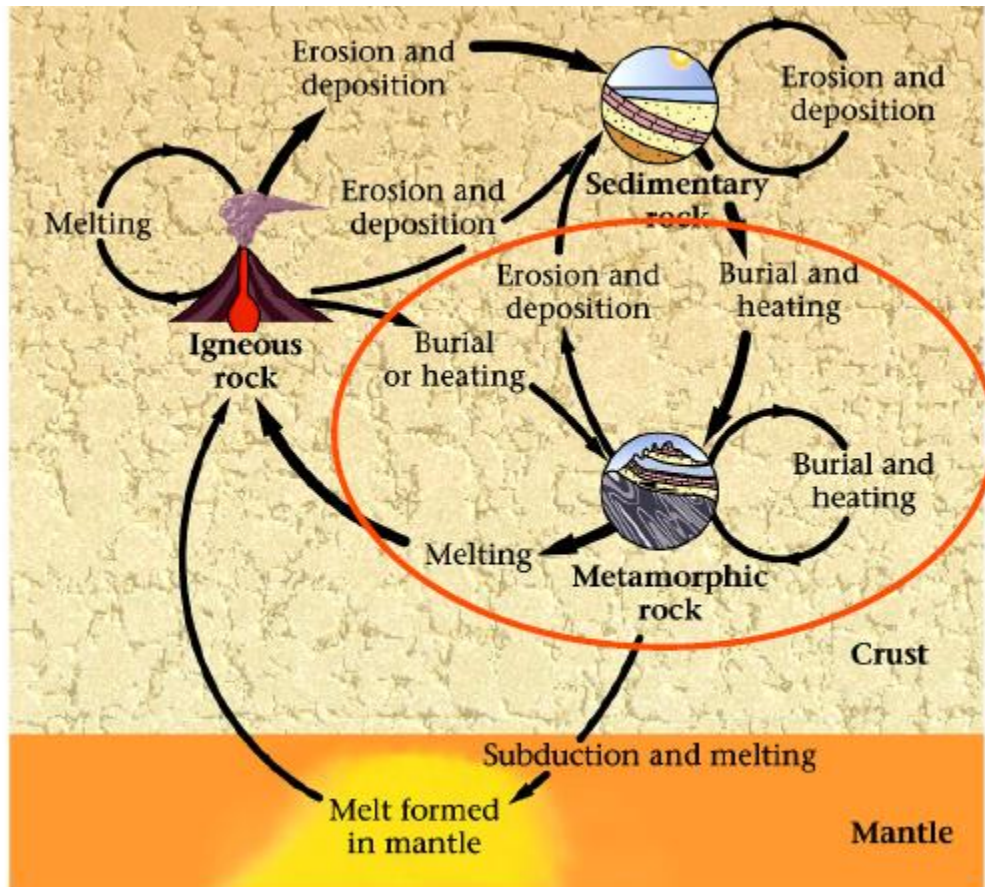
Computer models predict climate changes:

- By 2050, average annual T will increase by  $1.5^\circ\text{C}$  to  $2.0^\circ\text{C}$
- By 2150, global T may be  $5^\circ\text{C}$ - $11^\circ\text{C}$  warmer than present



## CHAPTER 7 METAMORPHISM: A PROCESS OF CHANGE → how one rock becomes another rock

\*\*Read the chapter in the textbook, this lecture is only an overview.



Igneous rock – melt things and then refreeze them

Sedimentary rock – erosion and deposition and then form rocks

All these things are linked together...

\*know how to classify rocks.

### Metamorphic rocks

Rocks that have undergone solid-state alteration of pre-existing rocks. Meta = change. Morphe = form. The pre-existing rocks that are altered through metamorphism are called **protoliths**. Metamorphism can alter any protolith (igneous, sedimentary, or metamorphic). Take a pre-existing rock and alter it **WITHOUT MELTING IT**.

Protolith: pre-existing rock, irrespective of its origin or nature.

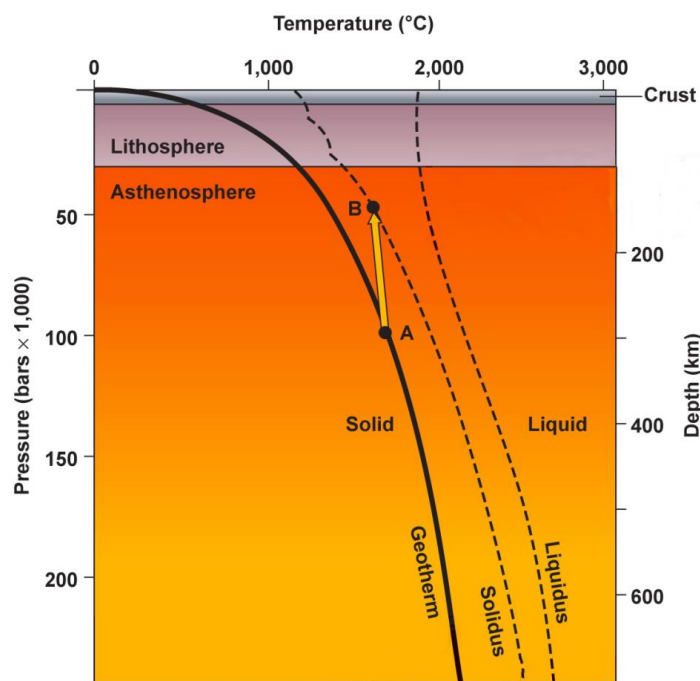
Metamorphic rocks: originate from changes in the mineralogy and/or texture of a rock in response to modifications of its physical or chemical environment. Formation of new minerals at the expense of old ones. Shape, size, and arrangement of grains in the rock may change.

Metamorphic rocks can be categorized by the types of minerals.

Metamorphism occurs when the protolith is subjected without melting to (occur very slowly in the solid state):

- Heat
- Pressure
- Differential stress (push, pull, or shear)
- Bathing in hydrothermal fluids (super-critical water, e.g. in subduction zone)

The agents of metamorphism are heat (T), pressure (P), compression and shear, and hydrothermal (hot water) fluids. Not all agents are required to alter a rock mass, although they often co-occur. Rocks may be overprinted by multiple events.



Metamorphism occurs between 250°C and 850°C and the depth to this temperature varies with tectonic setting. Sources of heat: the geothermal gradient, magmatic intrusions, and tectonic compression.

Pressure changes with depth as well, so pressure can create a metamorphic rock too. Also, if you add water! Water helps for something to deform more easily.

### How to identify a metamorphic rock?

They possess metamorphic minerals, new minerals that grow in place within the solid rock only under metamorphic temperatures and pressures. Metamorphic mineral grains are typically large and interlock with each other rather than being cemented.

Foliation: parallel alignment of platy minerals and/or presence of alternating light- and dark-colored layers.

They have metamorphic texture defined by distinctive arrangements of mineral grains not found in other rock types. The texture results in metamorphic foliation due to the parallel alignment of minerals or the presence of alternating light and dark colored layers.

The most common processes for forming metamorphic rocks include:

- Recrystallization: Changes the shape and size of the grains without changing the identity of the mineral making up the grain
- Phase change: Transforms one mineral to another mineral with the same composition but different crystal structures. (rearrangement of atoms)
- Metamorphic reaction (neocrystallization): Growth of new mineral crystals that differ from those of the protolith. Chemical reactions digest minerals of the protolith to produce new minerals of the metamorphic rock.
- Pressure solution: Happens when a wet rock is squeezed more strongly in one direction than the other. Mineral grains dissolve where their surfaces are pressed against other grains, producing ions that migrate through the water to precipitate elsewhere
- Plastic deformation: happens when a rock is squeezed or sheared at elevated temperatures and pressures. Under these conditions, grains behave like soft plastic and change shape without breaking

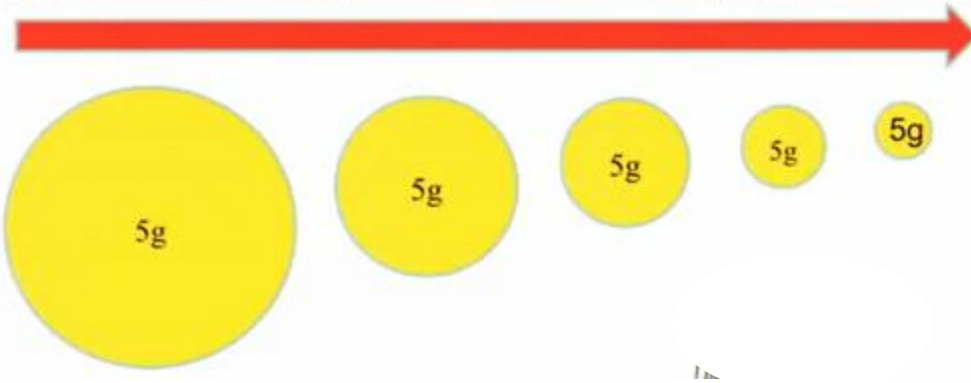
**Metamorphism occurs over thousands to millions of years when the protolith is subjected w/o melting to:**

1. **Heat** causes the atoms to vibrate faster, stretching and bending chemical bonds. If bonds are stretched too far and break, they detach from their original neighbors, move slightly, and form new bonds with other atoms causing recrystallization and neocrystallization. Recrystallization is rearrangement of atoms (breaking of bonds and reforming new bonds) within grains or the migration of atoms into and out of grains. Mineral grains grow larger at the expense of smaller ones until they interlock (go from small clasts to large, new grains). Recrystallization involves the modification of the shape and size of mineral grains without a change in mineralogy. E.g. Limestone can undergo metamorphic change to become marble. We go from small clasts to larger clasts.

Phase change – one mineral changes into another mineral of the same composition – polymorph. Crystal structure changes. E.g. Aragonite → calcite (same chemical composition,  $\text{CaCO}_3$  – looks different but same composition BUT different mineral since the structure is different).

**2. Pressure:** under the effect of pressure, mineral grains will deform depending on how fast and how the pressure is applied. Changing the space for the minerals to grow and fit together which causes metamorphism. As pressure increases, the space between mineral grains is eliminated as grains are pressed together. At higher pressures, grains dissolve where they contact and precipitate in the pore spaces forming larger grains. At even greater pressures, they may undergo a phase change to minerals that have a more compact atomic structure.

As the confining pressure increases, so does the density



The mass remains the same but the volume decreases = confining pressure. The atoms pack more closely together and denser minerals tend to form. Such transformations involve phase changes and/or neocrystallization. The space between different parts of the rock is getting smaller. Pieces of mineral get closer together and touch and some may break apart and recrystallize. When pressure and temperature increase, the original mineral assemblage in a rock becomes unstable, and a new assemblage forms out of minerals that are stable.

Similar in ice sheets – snow fall on ice sheet, the layer gets buried, you end up with firn. The more the ice is buried, the more the ice is compressed, which creates glacial ice. Snow → firn → glacial ice

**3. Differential stress:** Push, pull, or shear. Applying different pressure in different areas than others. Pressure but not applied equally in all directions.

Shear: Acts parallel to surface. Shear stress moves part of a material sideways causing it to be smeared out in opposite directions. It is like sliding out a deck of cards.

Compression (horizontal or vertical): flattens a material and acts downwards. Compression is a common result of tectonic forces. Mountain building creates horizontal compression. Squeezing from both sides. Pulling (tension) is the opposite.

When you apply pressure, the grains will stretch out in a perpendicular direction = **foliation**. If the grains are smushed out in one direction, this is a big sign the rock has been compressed. When rocks are subjected to compression and shear at elevated temperatures and pressures, they can change shape without breaking. As it changes shape, the internal texture of a rock also changes.

Foliations develops because the rocks have been subjected to compression and/or shear and they have a significant component of platy minerals.

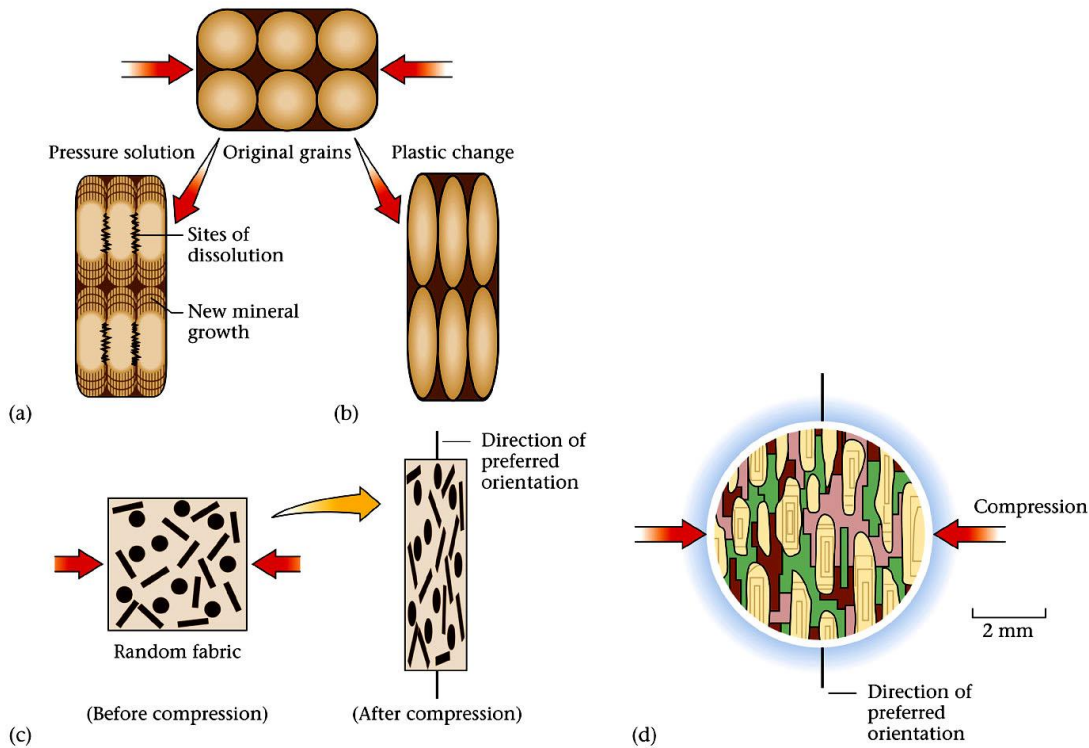
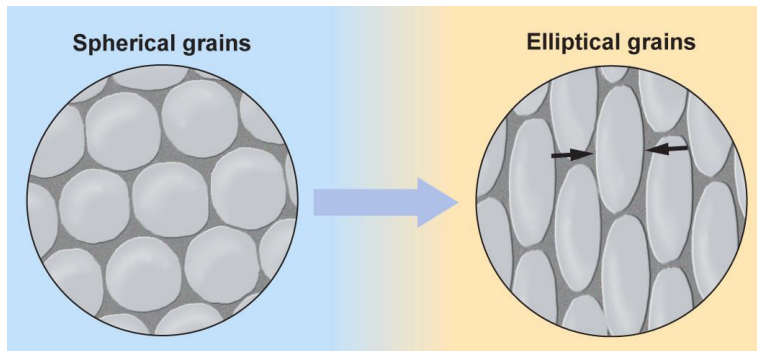


FIGURE 8.6

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Foliation gives metamorphic rocks a striped or streaked appearance and/or the ability to split into thin sheets. Mineral grains soften and deform when rock is squeezed or sheared at elevated temperature and pressure. The minerals change shape without breaking, like plastic. Mineral grains orient themselves with their long axis perpendicular to the stress field.



-Platy (pancaked shape) grains become parallel to one another

-Elongate (cigar shaped) grains align in the same direction

-Both platy and elongate grains are inequant grains, meaning that the dimension of a grain is not the same in all directions; in contrast, equant

grains have roughly the same dimensions in all directions. The alignment of inequant minerals in a rock results in a preferred orientation.

E.g. Metaconglomerate is a metamorphosed conglomerate. Pebble clasts are flattened by pressure solution and plastic deformation. Foliation is defined by the flattened inequant clasts.

What we are doing is basically breaking bonds between atoms and reforming them in different places. Compression and shear combine with elevated T and P to cause minerals and rocks to

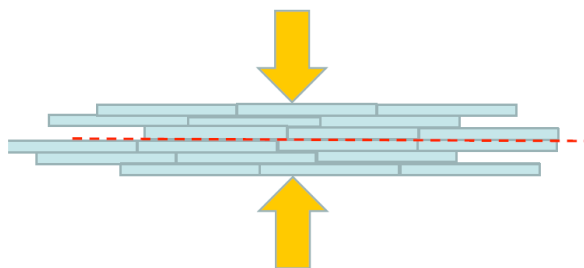
change shape without breaking. Internal textures are changed as minerals rotate or dissolve and recrystallize in preferred orientations.

Foliation → apply pressure to minerals → recrystallization or formation of new minerals in response to pressure → as P and T increase: continued recrystallization and formation of new mineral assemblages.

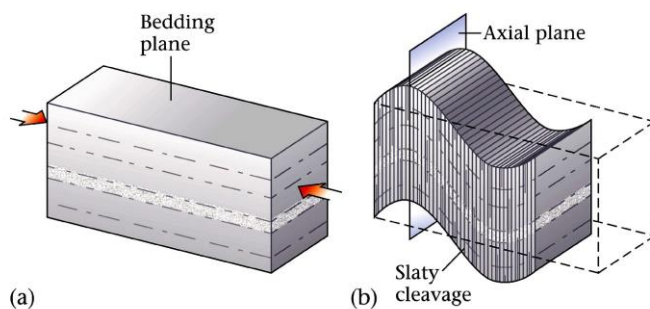
Foliation due to shearing: squeezing or shearing a rock under metamorphic conditions can cause rock to change shape and develop a preferred mineral orientation. This means that inequant mineral grains are aligned. Preferred mineral orientation can develop when existing mineral grains are rotated and stretched. As the rock continues to shear, the grains elongate further and align. A foliation has developed. Under appropriate conditions, new grains of metamorphic minerals grow, these align with the foliation while some old grains disappear. The preferred orientation becomes obvious.

Foliation: parallel alignment of platy minerals and/or the presence of alternating light- and dark-colored layers. Foliated metamorphic rocks can be distinguished from one another according to their composition, their grain size, and the nature of their foliation. The most common types include:

- Slate: forms by metamorphism of shale or mudstone. The finest-grained foliated metamorphic rock, it forms by the transformation/metamorphism of shale. Cleavage develops perpendicular to the direction of compression/stress, irrespective of the original bedding.



If compression is applied perpendicular to the bedding plane, then foliation will happen in the same direction as the original bedding plane. In the diagram, the original protolith bedding plane is parallel to the foliation.



Cleavage develops perpendicular to the direction of compression/stress, irrespective of the original bedding. The shape of the bedding plane can really change depending on where the force is applied.

FIGURE 8.9

Metamorphism and the formation of new minerals – neocrystallization. New minerals form from old. Protolith minerals become unstable and undergo chemical reactions that recycle elements to form a new mineral assemblage. E.g. Clay and quartz  $\rightarrow$  T + P  $\rightarrow$  Quartz, garnet, mica (protolith  $\rightarrow$  metamorphic rock). New minerals form from the same atoms.

E.g. Phyllite forms by metamorphism of slate.

E.g., Phyllite  $\rightarrow$  Schist (medium to coarse grained) i.e., chlorite + muscovite  $\rightarrow$  garnet + biotite + water.

E.g. Gneiss: highest metamorphic grade. Geologists use the term metamorphic grade in a somewhat informal way to indicate the intensity of metamorphism, meaning the amount or degree of metamorphic change. A little bit of T & P = low grade, a lot of T & P = high grade. Muscovite is converted to feldspar and the rock becomes compositionally layered.

- Light layers contain felsic minerals (quartz, feldspar)
- Dark layers contain mafic minerals (biotite, amphibole, pyroxene)

Classification of metamorphic grade depends primarily on temperature, because temperature plays the dominant role in determining the extent of recrystallization and neocrystallization during metamorphism.

- Low grade rocks: form at relatively low temperatures (250-400C)
- High grade rocks form at high temperatures (over 600C)

Two major subdivisions of metamorphic rocks: **foliated and non-foliated**. Not all metamorphic rocks become foliated (we don't always get lines on the mineral). If pressure is applied equally from all directions on a rock, it does not deform but can still undergo recrystallization, phase changes, and reactions. Non-foliated metamorphic rocks have no planar fabric evident because they lack inequant minerals and/or they recrystallized without differential stress.

Non-Foliated metamorphic rocks: Hornfels; Quartzite: forms by metamorphism of pure quartz sandstone; Marble: forms by metamorphism of limestone.

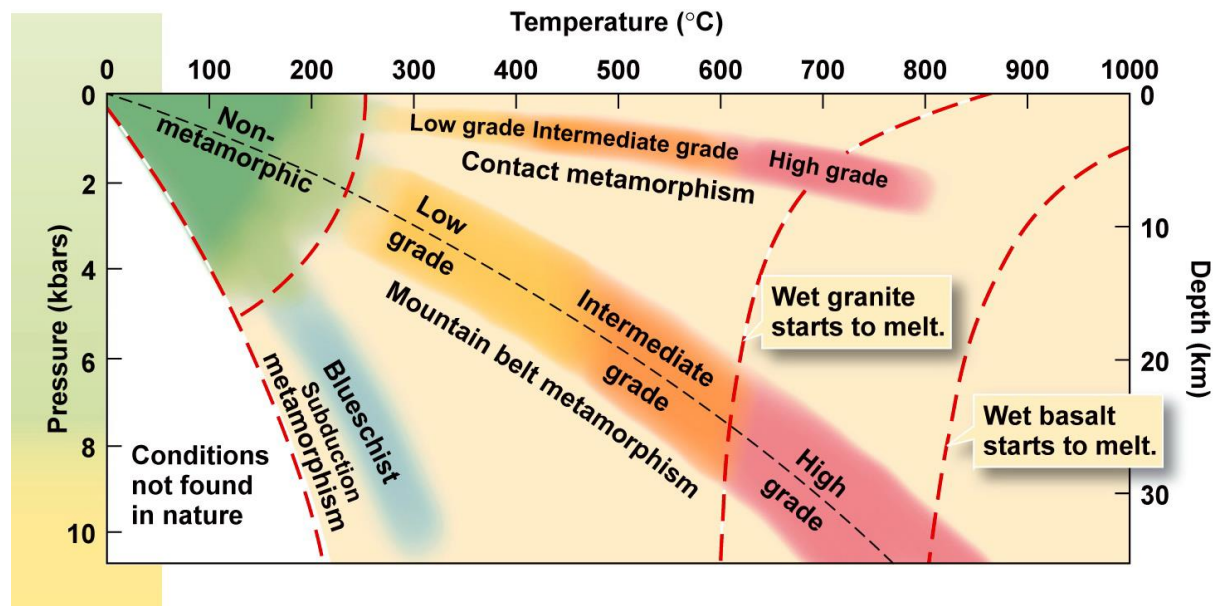
### **Hydrothermal Fluid: changes speed of the reaction**

Hydrothermal fluids (hot water with dissolved ions and volatiles) speed up chemical reactions and add or subtract elements. Hydrothermal fluids chemically react with rock; they accelerate metamorphic reactions, because atoms involved in the reactions can migrate faster through a fluid than they can through a solid. Hydrothermal fluids provide water that can be absorbed by minerals during metamorphic reactions. Finally, fluids passing through a rock may pick up some dissolved ions and drop off others, as a bus picks up and drops off passengers, and thus can change the overall chemical composition of a rock during metamorphism.

The process of changing a rock's chemical composition by reactions with hydrothermal fluids is called **metasomatism**.

**Thermal or contact metamorphism** → development of hornfels (develop near igneous setting, where there is hot magma, thus heating the rocks on the outside. You get a gradient of different types of rock as you move away from the heat source) and metamorphic aureole.

Aureole: The distinct belt of metamorphic rock that forms around an igneous intrusion is called a metamorphic aureole or contact aureole. The width of an aureole depends on the size and shape of the intrusion, and on the amount of hydrothermal circulation—larger intrusions produce wider aureoles.



\*Low grade – slight metamorphism, high grade – intense metamorphism. Metamorphic grade is a measure of intensity of T and P conditions that lead to alteration. Different T & P conditions occur in different geologic settings. I.e, deep burial might get a high grade metamorphic rock. Blueschist – high P, low T condition found near subduction zones.

*The protolith is the major control on the resulting metamorphic rock composition and mineralogy.* As the metamorphic grade increases, metamorphic reactions release water. Hence, high grade metamorphic rocks and minerals tend to be drier. These “drier” minerals are more stable at higher T & P. So if see slate, we can identify that it must have been shale and was created under these certain conditions which tells us about plate tectonics. A key indicator: the more a rock undergoes metamorphism, it loses more water, and therefore drier rocks have been more metamorphized. Metamorphic reactions release water → drier minerals. E.g. Clay (low grade) → chlorite → muscovite → biotite (high grade).

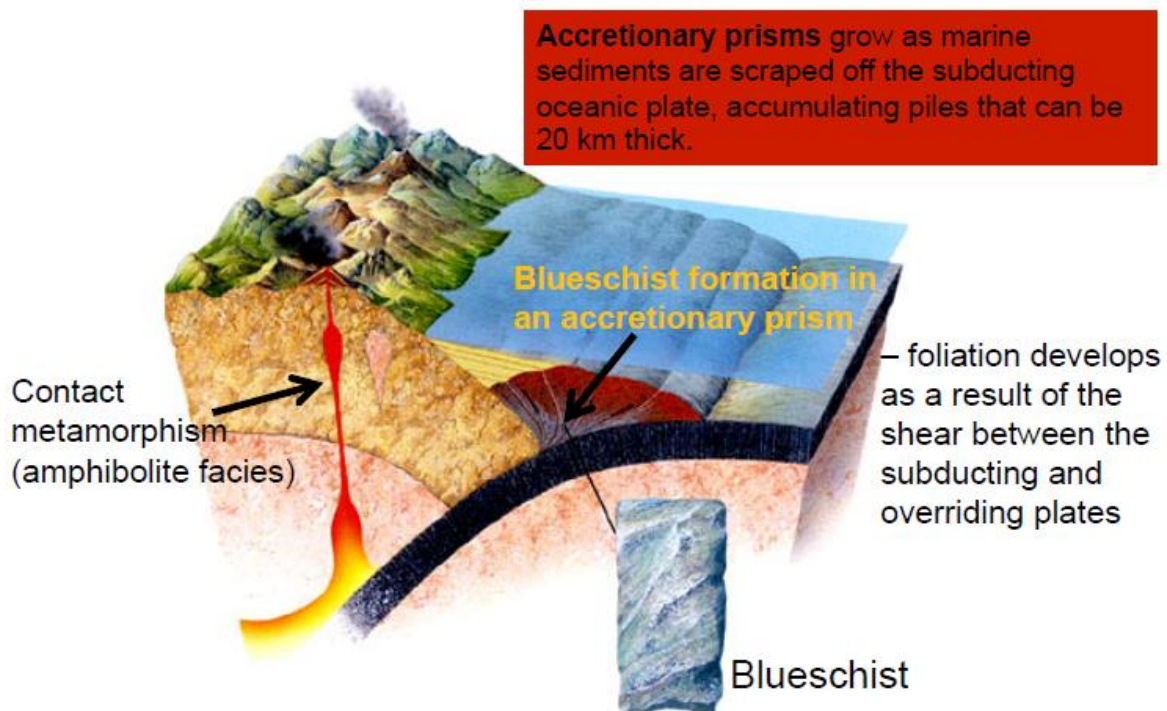
□ The local metamorphism caused by igneous intrusion can be called either thermal metamorphism to emphasize that it develops in response to heat without a change in pressure and without differential stress, or contact metamorphism, to emphasize that it develops adjacent to the contact of an intrusion with its wall rock.

**Metamorphic facies:** A set of metamorphic mineral assemblages indicative of a certain range of pressure and temperature and each reflects a specific protolith composition. A metamorphic

facies is a set of mineral assemblages that indicate a certain range of P & T conditions. A given metamorphic facies include several different kinds of rocks that differ from each other in terms of composition (i.e., mineral content) but all rocks of a given facies formed under roughly the same T & P conditions. This is a useful way to describe and categorize metamorphic rocks. E.g. Basalt can be metamorphized into different facies, like greenschist facies (chlorite) or blueschist facies (Na-amphibole/glaucophane).

**Settings: Where do we see metamorphic rocks?**

## Metamorphism at a convergent margin



Subduction zones are key places. We end up with a wedge (accretionary prism) with different P & T conditions in the subduction zone. Mountain belt building can produce different metamorphic rocks. Basalt is what you end up with in accretionary prisms.

Metamorphism is due to heat from a body of magma invading host rock. It creates zoned bands of alteration called a metamorphic or contact aureole, zoned from high grade (near pluton) to low grade (away from pluton).

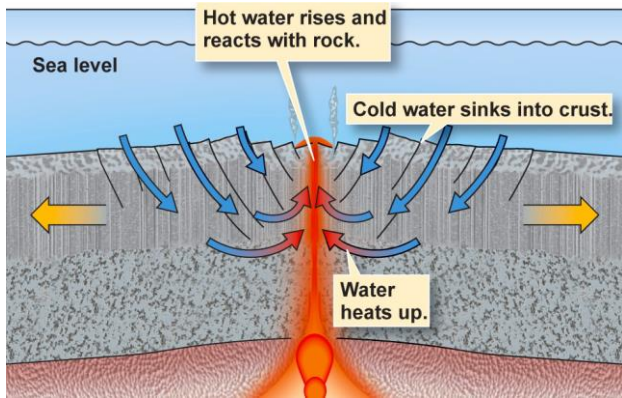
According to the plate tectonics theory, plutons intrude into the crust at convergent plate boundaries, in rifts, and during the mountain building that takes place when continents collide.

**Dynamic metamorphism (shearing in a fault zone):** Involves breakage of rock by shearing within a fault zone. In the shallow crust (0 -15 km) rocks are brittle and crushed to form fault breccia. In the deeper crust (15 km and deeper) the rocks are ductile. Rocks in fault zones smear like taffy to form mylonite.

**Regional metamorphism (P & T change due to orogenesis):** Tectonic collisions deform huge “mobile belts” hundreds to thousands of km long. Directed compression smashes preexisting rocks and buries them deeply, where they are heated by the geothermal gradient and plutonic intrusions. The heat and pressure of orogenesis creates huge volumes of metamorphic rocks, more than any other mechanism.

**Burial metamorphism (deep burial in a basin):** Metamorphism due only to the consequences of very deep burial is called burial metamorphism. Diagenesis occurs at shallow depths upon burial of sediments, but at depths of 8-15 km, depending on the geothermal gradient, T may rise high enough for metamorphic processes to occur.

**Hydrothermal metamorphism at mid ocean ridges (alteration by hot water leaching):** At mid-ocean ridges, hot, chemically aggressive water chemically alters the basalt. The process starts when cold ocean water seeps into the fractured crust. Heated by magma, this water then reacts with the mafic rock and is ejected via black smokers. The mafic rock is metamorphically altered - metasomatism. Super-critical water (between gas and liquid) is introduced.



**Metamorphism in subduction zones (high-P and low-T alteration):** Trenches and accretionary prisms have a low geothermal gradient. These conditions produce a unique low-T, high-P mineral assemblage called blue schist, after glaucophane, a blue amphibole mineral. Foliation develops as a result of the shear between the subducting and overriding plates

**Shock metamorphism (extreme high P from a bolide impact):** When Earth is struck by a comet or asteroid, the impact generates extremely high pressure and heat. These conditions vaporize rock and/or generate high-pressure minerals.

**Retrograde metamorphism:** You have metamorphism which is heat and pressure applied. Retro would be the reverse of that = cooling and depressurizing, water can also be introduced.

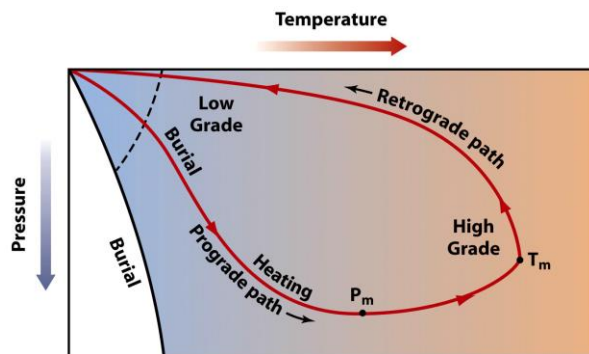


Figure 8-20 Earth: Portrait of a Planet 3/e  
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Metamorphic map: Index minerals can be used to identify the metamorphic grade of a rock.

- Isograds are lines of equal metamorphic grade.

The regions between two **isograds** define metamorphic zones, typically named after an index mineral that was not present in the previous, lower grade zone. Large regions of ancient high-grade metamorphic rocks are exposed in continental interiors. Called shields, these are the eroded remnants of orogenic belts. Shield rocks form the basement under sedimentary cover over much of the world.

PROTOLITH	LOW	INTERMEDIATE	HIGH	PARTIAL MELTING
Basalt (mafic)	Greenschist	Amphibolite	Mafic granulite	
	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	

FIGURE 8.17

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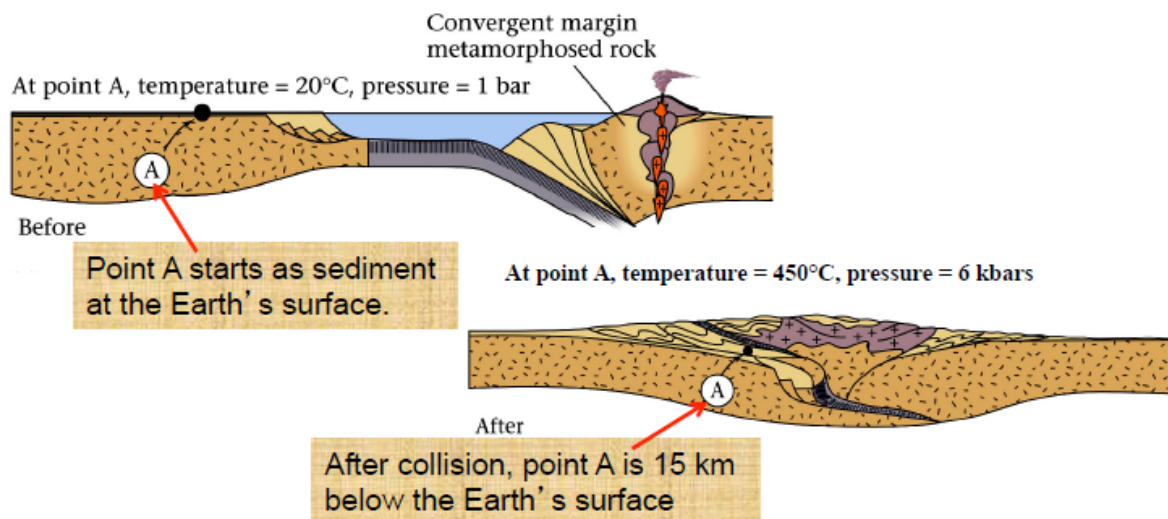
The conditions under which metamorphism occurs are not the same in all geologic settings because the geothermal gradient, the extent of differential stress and their interactions with hydrothermal fluids depend on the geological environment.

Metamorphic rocks can move through time...

## Metamorphic path during continental collision

During continental collisions, large slices of continental crust slip up and over other portions of the crust

→ **regional metamorphism**



Tectonic collisions deform huge "mobile belts" hundreds to thousands of km long. Directed compression smashes preexisting rocks and buries them deeply, where they are heated by the geothermal gradient and plutonic intrusions. The heat and pressure of orogenesis creates huge volumes of metamorphic rocks, more than any other mechanism.