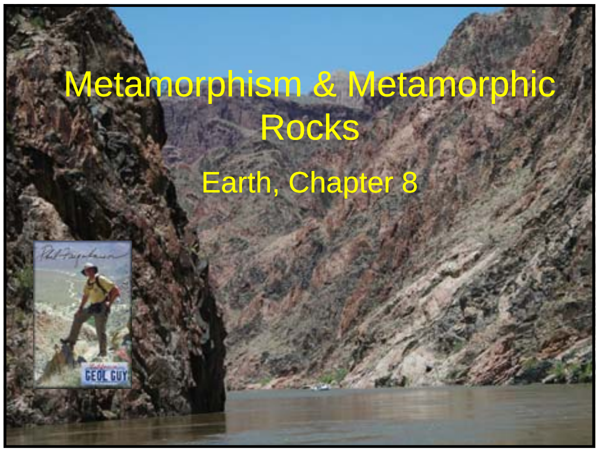
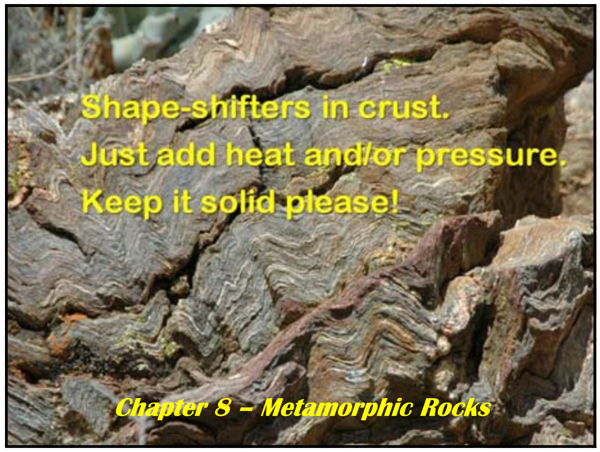
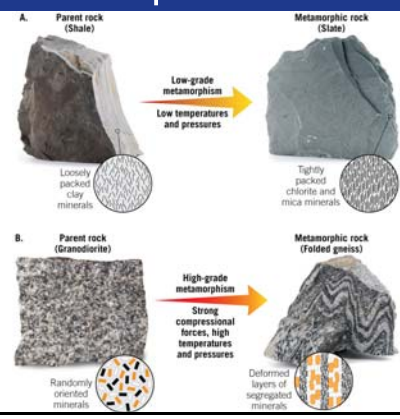




What Is Metamorphism?

- **Metamorphism** means to "change form"
  - The transition of one rock into another by temperatures and/or pressures unlike those in which it formed
  - Changes in **mineralogy** and sometimes chemical composition
- Every metamorphic rock has a **parent rock** (the rock from which it formed)
  - Parent rocks can be igneous, sedimentary, or other metamorphic rocks

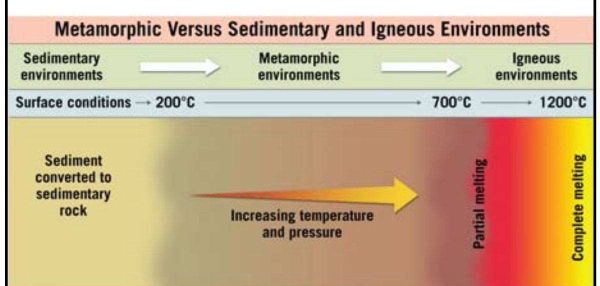
What Is Metamorphism?



What Is Metamorphism?

- **Metamorphic grade** is the degree to which the parent rock changes during metamorphism
  - Progresses from low grade (low temperatures and pressures) to high grade (high temperatures and pressures)
- During metamorphism, the rock must remain essentially solid

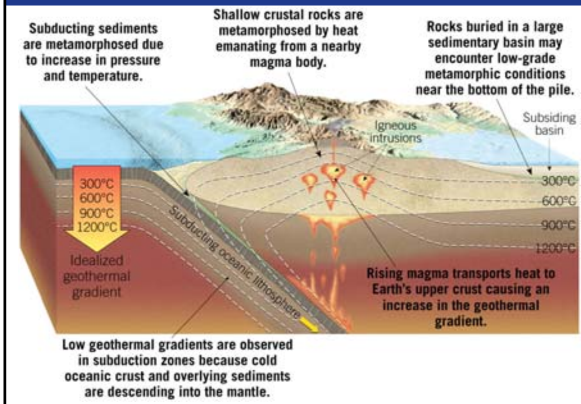
Metamorphic Grade



What Drives Metamorphism?

- Heat
  - Most important agent
    - Provides the energy needed for chemical reactions
    - **Recrystallization** is the process of forming new, stable minerals larger than the original
  - Two sources of heat:
    - Geothermal gradient: an increase in temperature with depth (about 25ºC per kilometer)
    - Contact metamorphism: rising mantle plumes

What Drives Metamorphism?



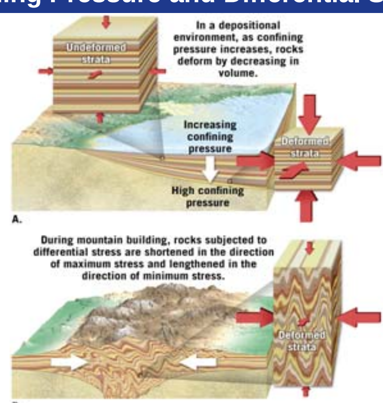
What Drives Metamorphism?

- **Confining Pressure**
  - Forces are applied equally in all directions
    - Analogous to water pressure
  - Causes the spaces between mineral grains to close

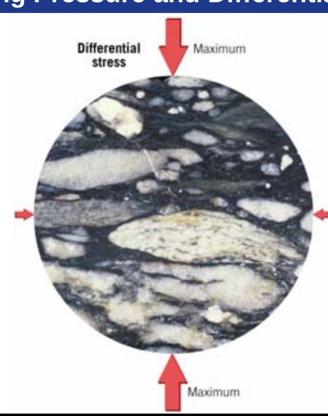
What Drives Metamorphism?

- **Differential Stress**
  - Forces are unequal in different directions
    - Stresses are greater in one direction
- **Compressional stress**
    - Rocks are squeezed as if in a vice
    - Shortened in one direction and elongated in the other direction
    - In high pressure and temperature environments rocks are *ductile* and will stretch, flatten, or fold

Confining Pressure and Differential Stress



Confining Pressure and Differential Stress



What Drives Metamorphism?

What Drives Metamorphism?

- **Chemically Active Fluids**
  - Water becomes a hot ion-rich fluid
    - *Hydrothermal solution*
  - Enhances migration of ions
  - Aids in recrystallization of existing minerals
    - Can change overall chemical composition
  - In some environments, fluids can transport mineral matter over considerable distances

What Drives Metamorphism?

- The Importance of Parent Rock
  - Most metamorphic rocks have the same overall chemical composition as the original parent rock
    - Except for loss/gain of volatiles (H_2O, CO_2)
  - Mineral makeup determines the degree to which each metamorphic agent will cause change

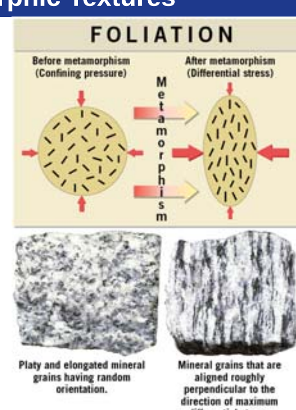
Metamorphic Textures

- **Texture** describes the size, shape, and arrangement of mineral grains
  - Metamorphic rocks can display preferred orientation of minerals, where the platy mineral grains exhibit parallel to sub-parallel alignment
  - Called **foliation**
    - Describes any planar arrangement of mineral grains or structural features within a rock

Metamorphic Textures

- **Examples of foliation**
  - Parallel alignment of platy and/or elongated minerals
  - Parallel alignment of flattened mineral grains or pebbles
  - Compositional banding of dark and light minerals
  - Cleavage where rocks can be easily split into slabs

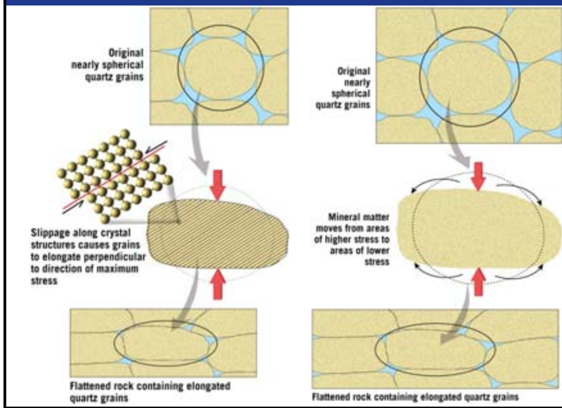
Metamorphic Textures



Metamorphic Textures

- Foliation can form in various ways, including:
  - *Rotation* of platy minerals
  - *Recrystallization* that produces new minerals perpendicular to the direction of maximum stress
  - *Flattening* spherically shaped grains

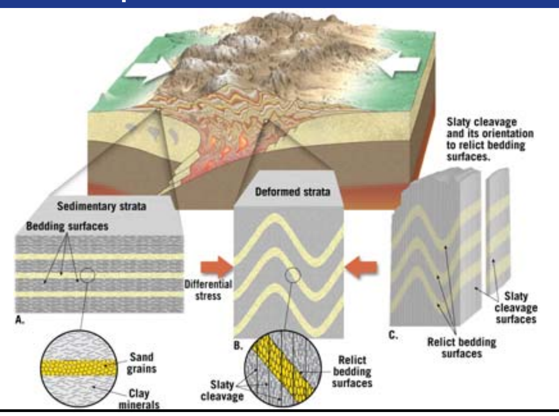
Metamorphic Textures



Metamorphic Textures

- Foliated Textures
  - **Rock** or **Slaty Cleavage**
    - Rocks split into thin slabs
    - Develops in beds of shale with low-grade metamorphism

Metamorphic Textures

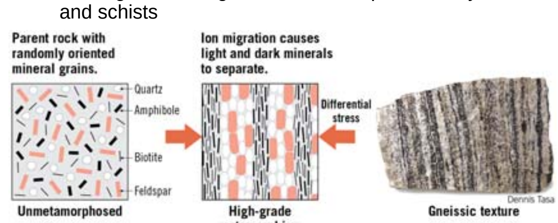


Metamorphic Textures

- Foliated Textures
  - **Schistosity**
    - Platy minerals are discernible with the unaided eye
      - Mica and chlorite flakes begin to recrystallize into large muscovite and biotite crystals
    - Exhibit a planar or layered structure
    - Rocks having this texture are referred to as schist

Metamorphic Textures

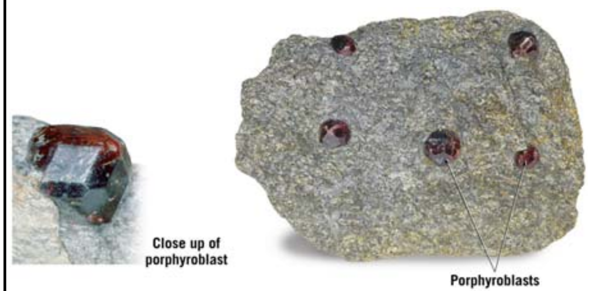
- Foliated Textures
  - **Gneissic texture**
    - During high-grade metamorphism, ion migration results in segregation of minerals into light and dark bands
    - Metamorphic rocks with this texture are called gneiss
    - Although foliated, gneisses do not split as easily as slates and schists



Metamorphic Textures

- Other Metamorphic Textures
  - **Nonfoliated** metamorphic rocks are composed of minerals that exhibit equidimensional crystals and lack foliation
    - Develop in environments where deformation is minimal, and from parent rocks with equidimensional minerals (e.g., quartz and calcite)
  - **Porphyroblastic textures**
    - Unusually large grains, called *porphyroblasts*, are surrounded by a fine-grained matrix of other minerals

Garnet-Mica Schist



Common Metamorphic Rocks

- Foliated Rocks
  - **Slate**
    - Very fine-grained, resembles shale
    - Most often generated from low-grade metamorphism of shale, mudstone, or siltstone
  - **Phyllite**
    - Degree of metamorphism between slate and schist
    - Platy minerals are larger than slate but not large enough to see with the unaided eye
    - Glossy sheen and wavy surfaces
  - Both slate and phyllite exhibit rock cleavage

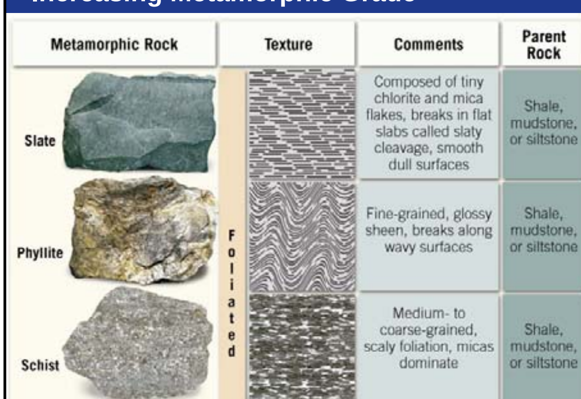
Common Metamorphic Rocks

- Foliated Rocks
  - **Schist**
    - Medium- to coarse-grained
    - Parent rock is shale that has undergone medium- to high-grade metamorphism
    - The term *schist* describes the texture
    - Platy minerals (mainly micas) predominate
    - Can also contain porphyroblasts

Common Metamorphic Rocks

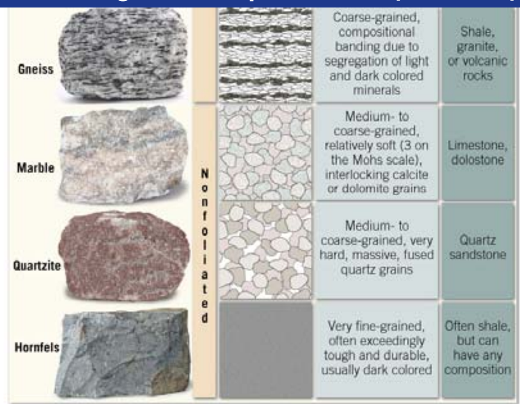
- Foliated Rocks
  - **Gneiss**
    - Medium- to coarse-grained metamorphic rock with a banded appearance
    - The result of high-grade metamorphism
    - Composed of light-colored, feldspar-rich layers with bands of dark ferromagnesian minerals

Increasing Metamorphic Grade



Metamorphic Rock	Texture	Comments	Parent Rock
Slate	Foliated	Composed of tiny chlorite and mica flakes, breaks in flat slabs called slaty cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite	Foliated	Fine-grained, glossy sheen, breaks along wavy surfaces	Shale, mudstone, or siltstone
Schist	Foliated	Medium- to coarse-grained, scaly foliation, micas dominate	Shale, mudstone, or siltstone

Increasing Metamorphic Grade (continued)



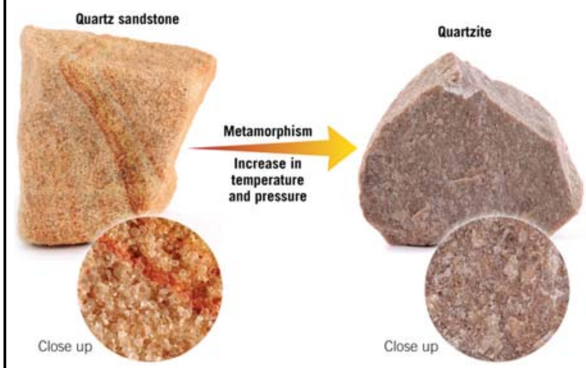
Common Metamorphic Rocks

- Nonfoliated Rocks
  - **Marble**
    - Crystalline rock from limestone or dolostone parent
    - Main mineral is calcite
      - Calcite is relatively soft (3 on the Mohs scale)
      - Used as a decorative and monument stone
      - But… weathers easily in acid rain
    - Impurities in the parent rocks provide a variety of colors of marble

Common Metamorphic Rocks

- Nonfoliated Rocks
  - **Quartzite**
    - Formed from a parent rock of quartz sandstone
    - Quartz grains are fused together
    - Pure quartzite is white
      - Iron oxide may produce reddish or pink stains
      - Dark minerals may produce green or gray stains
      - Cross-bedding and other sedimentary structures can be preserved in quartzite
  - **Hornfels**
    - Parent rock is shale or clay-rich rocks
    - Fine-grained with variable mineral composition
    - “Baked” by an intruding magma body

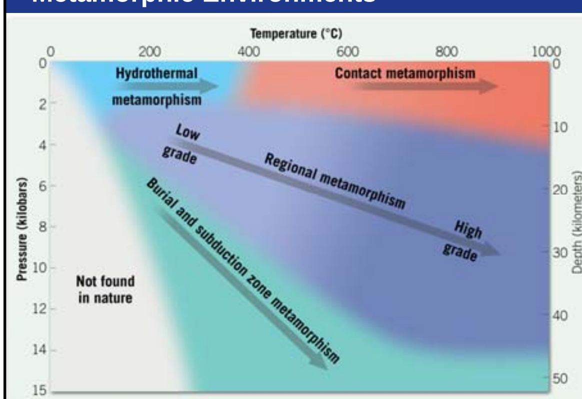
Quartzite



Metamorphic Environments

- Metamorphism occurs in a variety of environments
  - In the vicinity of plate margins
  - Associated with igneous activity
    - *Contact* or *thermal metamorphism*
    - *Hydrothermal metamorphism*
    - *Burial metamorphism*
    - *Subduction zone metamorphism*
    - *Regional metamorphism*

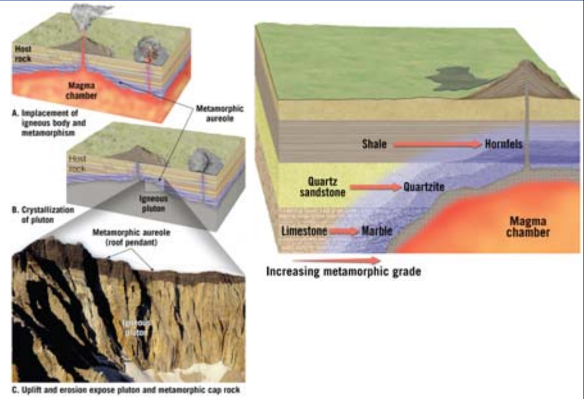
Metamorphic Environments



Metamorphic Environments

- **Contact, or Thermal, Metamorphism**
  - Results from a rise in temperature when magma invades a host rock
  - Occurs in the upper crust (low pressure, high temperature)
  - The zone of alteration (**aureole**) forms in the rock immediately surrounding the magma
  - Aureoles consist of distinct *zones of metamorphism*

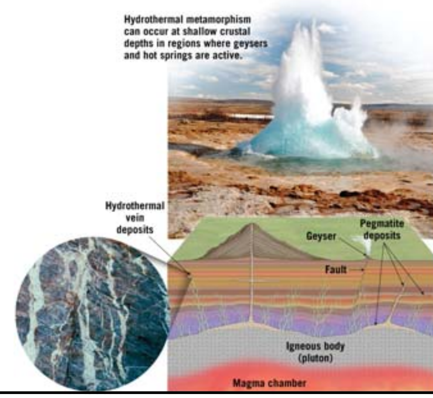
Contact Metamorphism



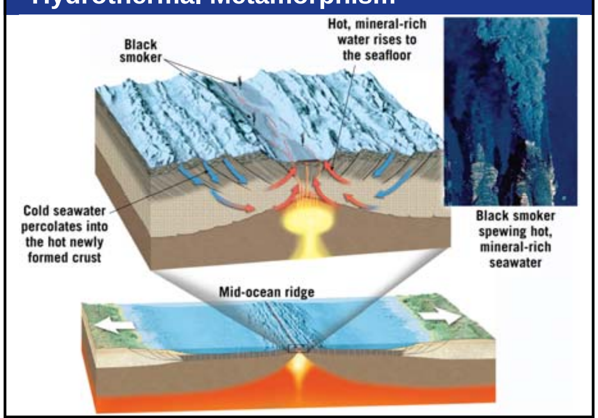
Metamorphic Environments

- **Hydrothermal Metamorphism**
  - Chemical alteration caused by hot, ion-rich water circulating through pore spaces and rock fractures
  - Typically occurs along the axes of mid-ocean ridges
    - Black smokers are the result of the fluids gushing from the seafloor
  - Also occurs associated with hot springs and geysers

Hydrothermal Metamorphism



Hydrothermal Metamorphism



Hydrothermal Metamorphism


Serpentinite


Soapstone

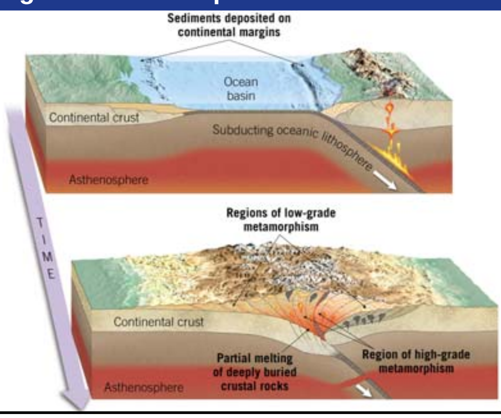
Metamorphic Environments

- **Burial Metamorphism**
  - Associated with very thick sedimentary strata in a subsiding basin
    - Confining pressure and heat drive recrystallization
- **Subduction Zone Metamorphism**
  - Sediments and oceanic crust are subducted fast enough that pressure increases before temperature
    - Differential stress drives metamorphism

Metamorphic Environments

- **Regional Metamorphism**
  - Common, widespread type of metamorphism
  - Produces the greatest quantity of metamorphic rock
  - Associated with mountain building and the collision of continental blocks
  - Crust is shortened, thickened, folded, and faulted

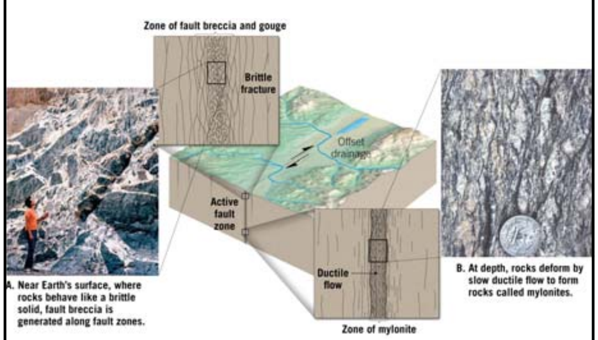
Regional Metamorphism



Metamorphic Environments

- Metamorphism Along Fault Zones
  - Occurs at depth and high temperatures
  - Pre-existing minerals deform by ductile flow
    - Minerals form a foliated or lineated appearance
    - Rocks formed in these regions are called **mylonites**
- **Impact Metamorphism**
  - Also called shock metamorphism
  - Occurs when *meteoroids* strike Earth's surface
    - Product of these impacts (called *impactites*) are fused fragmented rock plus glass-rich ejecta that resemble volcanic bombs

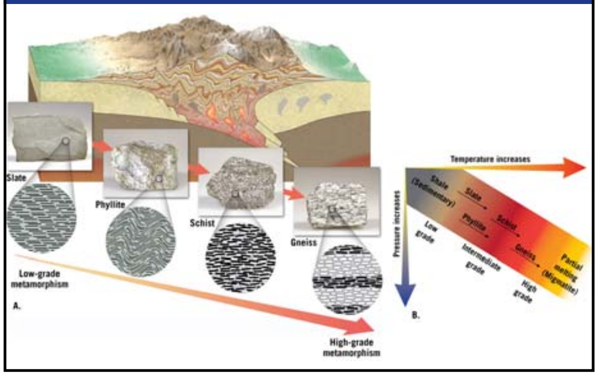
Metamorphism Along a Fault Zone



Metamorphic Zones

- **Textural Variations**
  - In areas where regional metamorphism has occurred, rock texture varies based on intensity of metamorphism
    - Slate is associated with low-grade metamorphism
    - Phyllite and schist are intermediate
    - Gneiss is associated with high-grade metamorphism

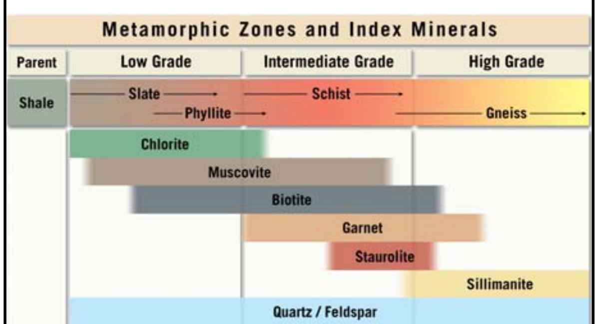
Textural Variations Caused by Regional Metamorphism



Metamorphic Zones

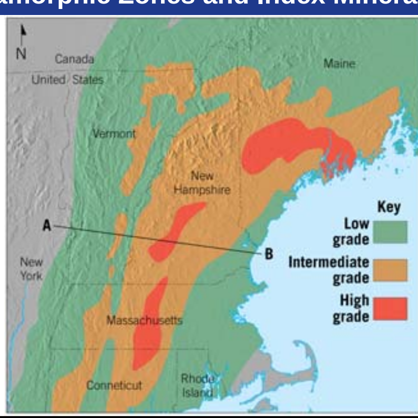
- Index Minerals and Metamorphic Grade
  - Changes in mineralogy occur from regions of low-grade metamorphism to regions of high-grade metamorphism
  - **Index minerals** are good indicators of metamorphic grades, and thus zones of metamorphism
  - **Migmatites** are rocks that have been partially melted
    - Represent the highest grades of metamorphism
    - Transitional to igneous rocks

Metamorphic Zones and Index Minerals



Metamorphic Zones and Index Minerals

Metamorphic Zones and Index Minerals

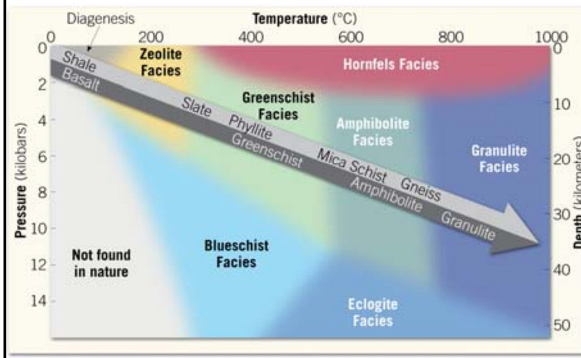


Migmatite

Interpreting Metamorphic Environments

- **Common Metamorphic Facies**
  - Metamorphic rocks that contain the same mineral assemblage and formed in similar metamorphic environments
    - Mineral assemblages can be used to determine the pressure and temperature conditions the rock formed under
    - Metamorphic facies include:
      - *Hornfels*, *zeolite*, *greenschist*, *amphibolite*, *granulite*, *blueschist*, and *eclogite*

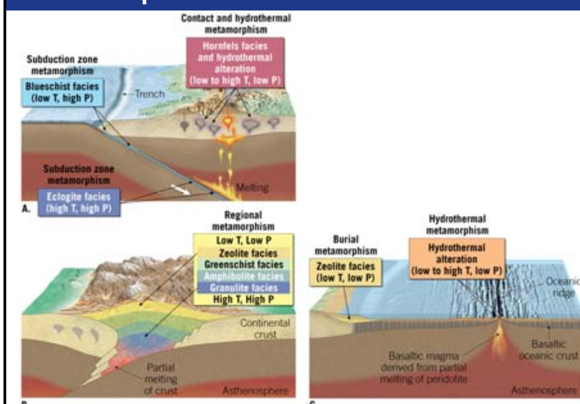
Metamorphic Facies



Interpreting Metamorphic Environments

- Metamorphic Facies and Plate Tectonics
  - High-pressure, low-temperature metamorphism is associated with the upper section of **subduction zones**
  - Regional metamorphism is associated with **colliding continental blocks**
  - Low pressure, low- to high-temperature metamorphism is associated with **divergent plate boundaries**

Metamorphic Facies and Plate Tectonics



Metamorphic Facies and Plate Tectonics

A. Blueschist forms in low-temperature, high-pressure environments

B. Eclogite forms in high-temperature and extreme high-pressure environments

Interpreting Metamorphic Environments

- Mineral Stability and Metamorphic Environments
  - Some minerals are only stable at certain temperature and pressure regimes
    - Examples include **andalusite**, **kyanite**, and **sillimanite**, all having the same chemical composition but forming under different metamorphic conditions
  - Knowing the range of temperatures and pressures associated with mineral formation can aid in interpreting the metamorphic environment

Minerals Used to Predict Metamorphic Environments