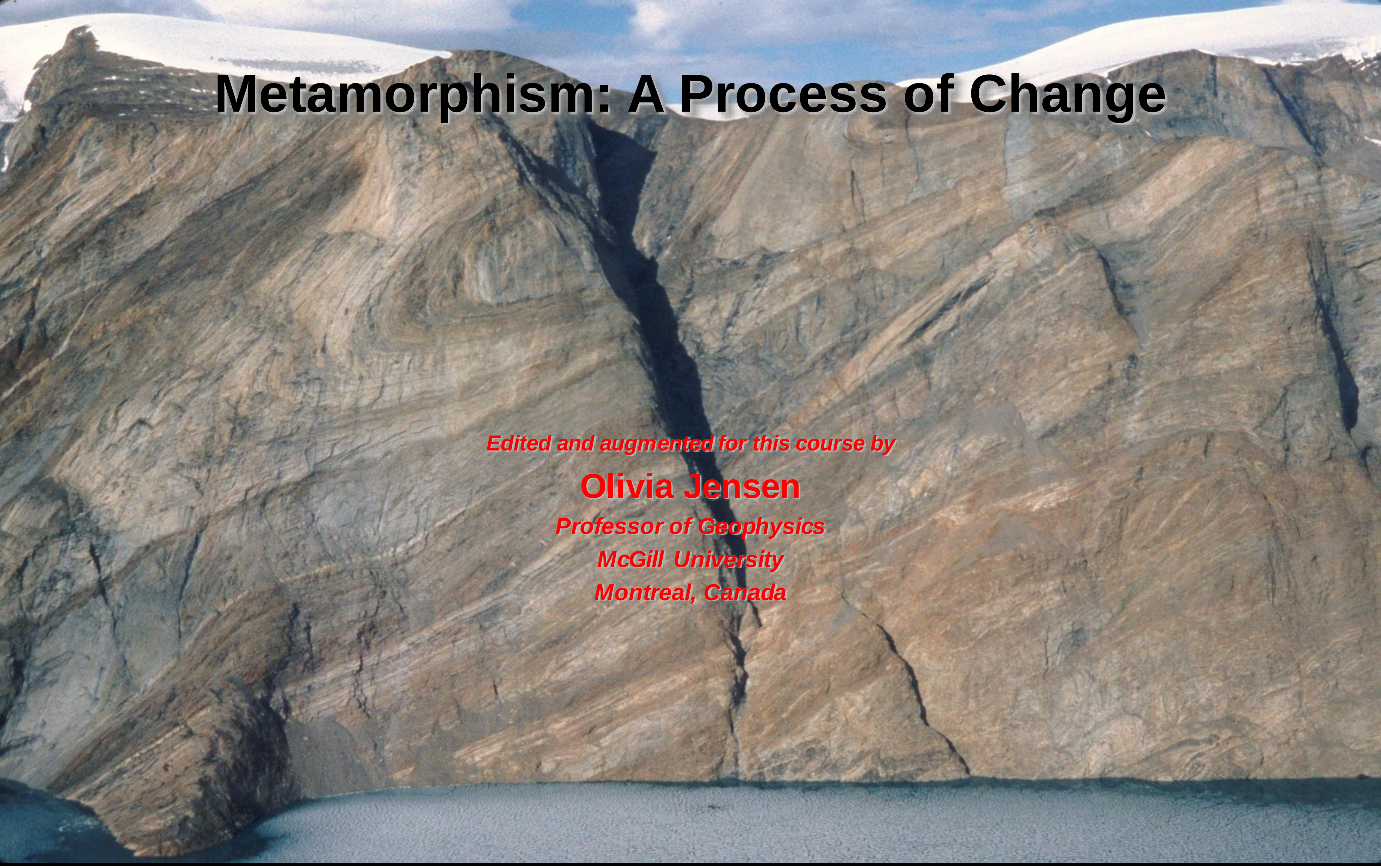


Metamorphism: A Process of Change

Edited and augmented for this course by

Olivia Jensen

Professor of Geophysics

McGill University

Montreal, Canada

Updated by:

***Rick Oches**, Professor of Geology & Environmental Sciences*

Bentley University

Waltham, Massachusetts

Based on slides prepared by:

***Ronald L. Parker**, Senior Geologist*

Fronterra Geosciences

Denver, Colorado

Introduction

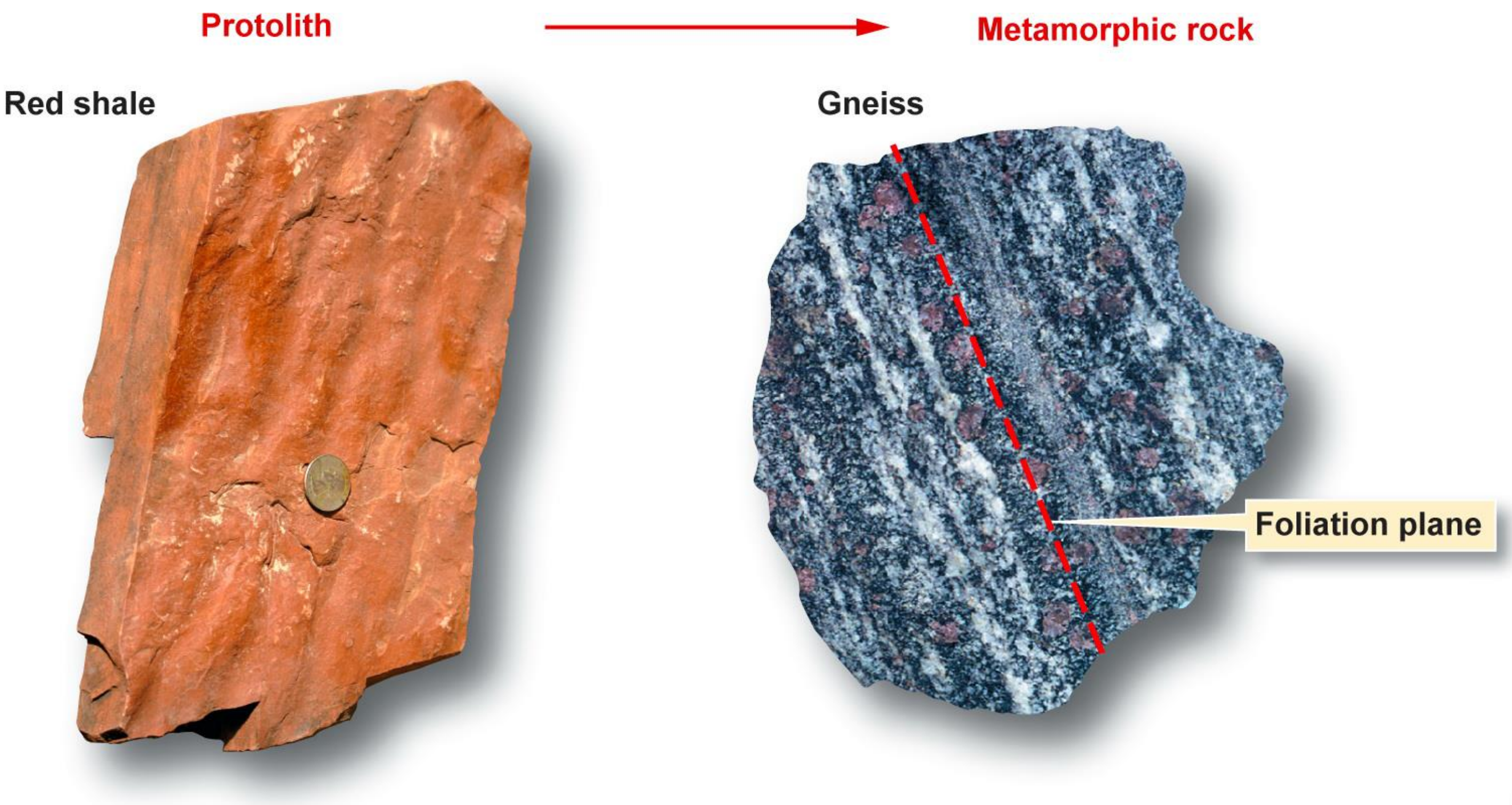
- **Metamorphic rock—solid-state alteration of a protolith.**
  - **Meta = change.**
  - **Morphe = form.**
- **Protoliths are preexisting rocks.**
- **Metamorphism can alter any protolith.**

Introduction

- Protoliths undergo slow solid-state changes in:
  - Texture.
  - Mineralogy.
- Metamorphic changes are due to variations in:
  - Temperature.
  - Pressure.
  - Tectonic stresses.
  - Amount of reactive water.

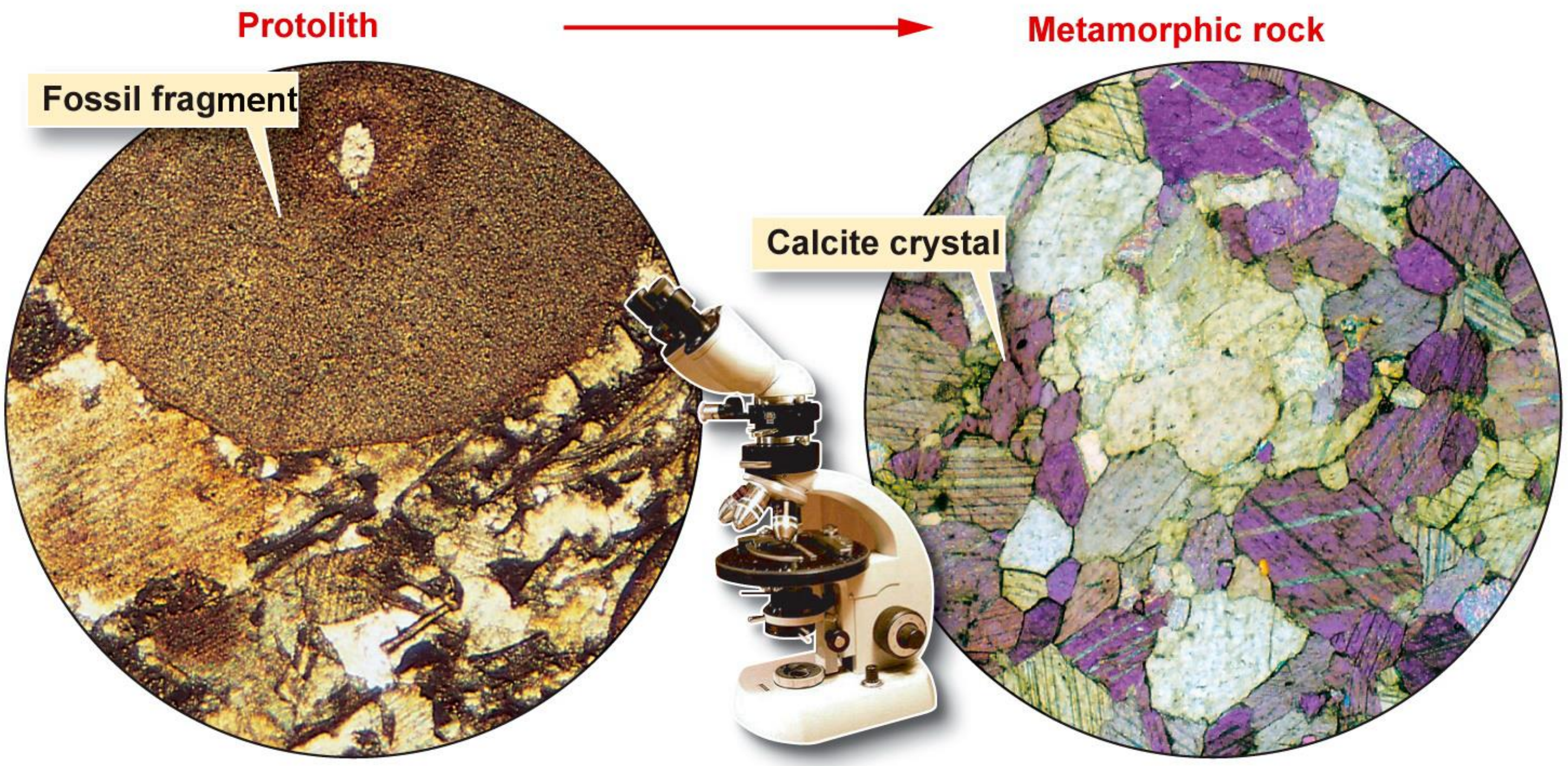
What Is a Metamorphic Rock?

- **Metamorphism changes mineralogy.**
  - **Red shale -- quartz, clay, and iron oxide.**
  - **Gneiss -- quartz, feldspar, biotite, and garnet.**



What Is a Metamorphic Rock?

- **Metamorphism changes texture.**
  - **Unique texture -- intergrown and interlocking grains.**

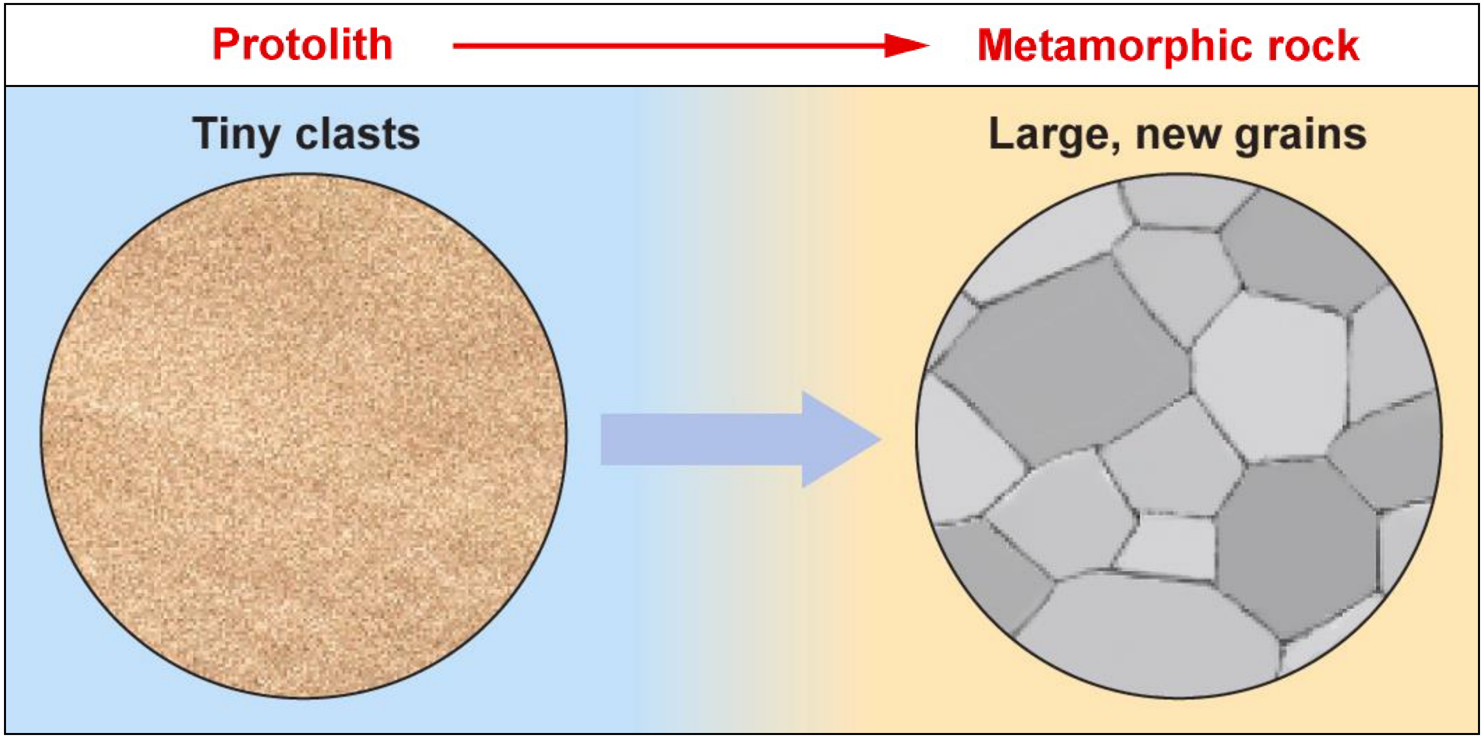


What Is a Metamorphic Rock?

- Metamorphism often creates foliation.
  - A texture defined by:
    - Alignment of platy minerals (i.e., micas), or:
    - Creation of alternating light/dark bands.

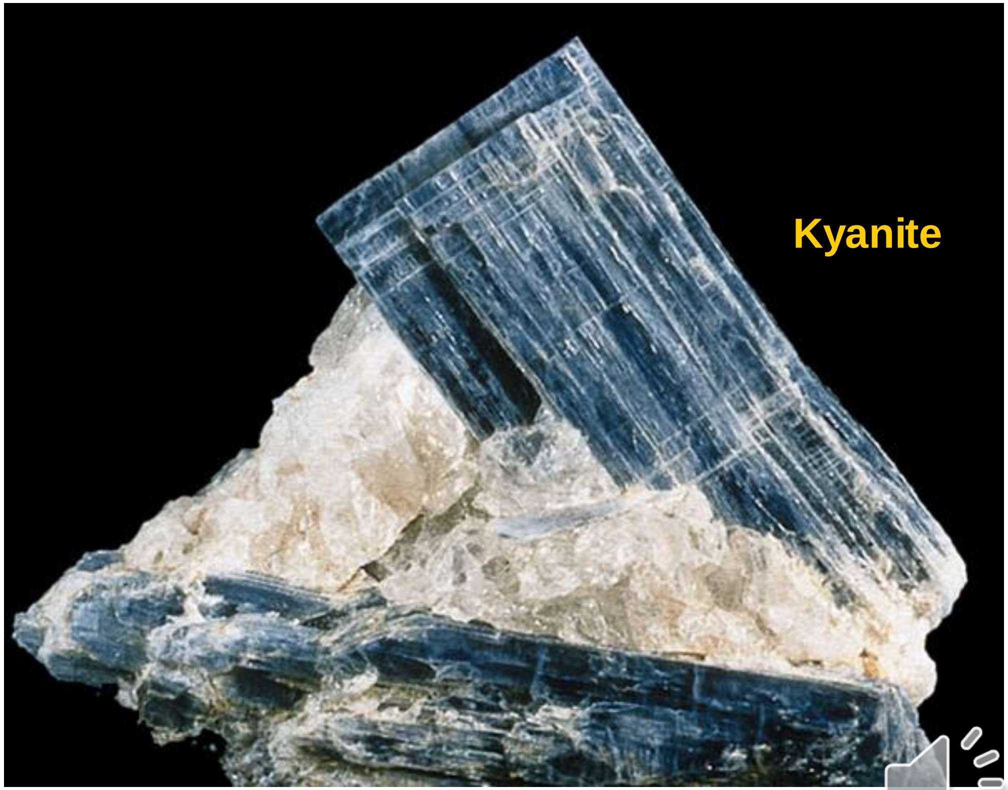
Metamorphic Processes

- Recrystallization—minerals change size and shape.
- Mineral identity need not change.
  - Example: Limestone ➔ Marble.



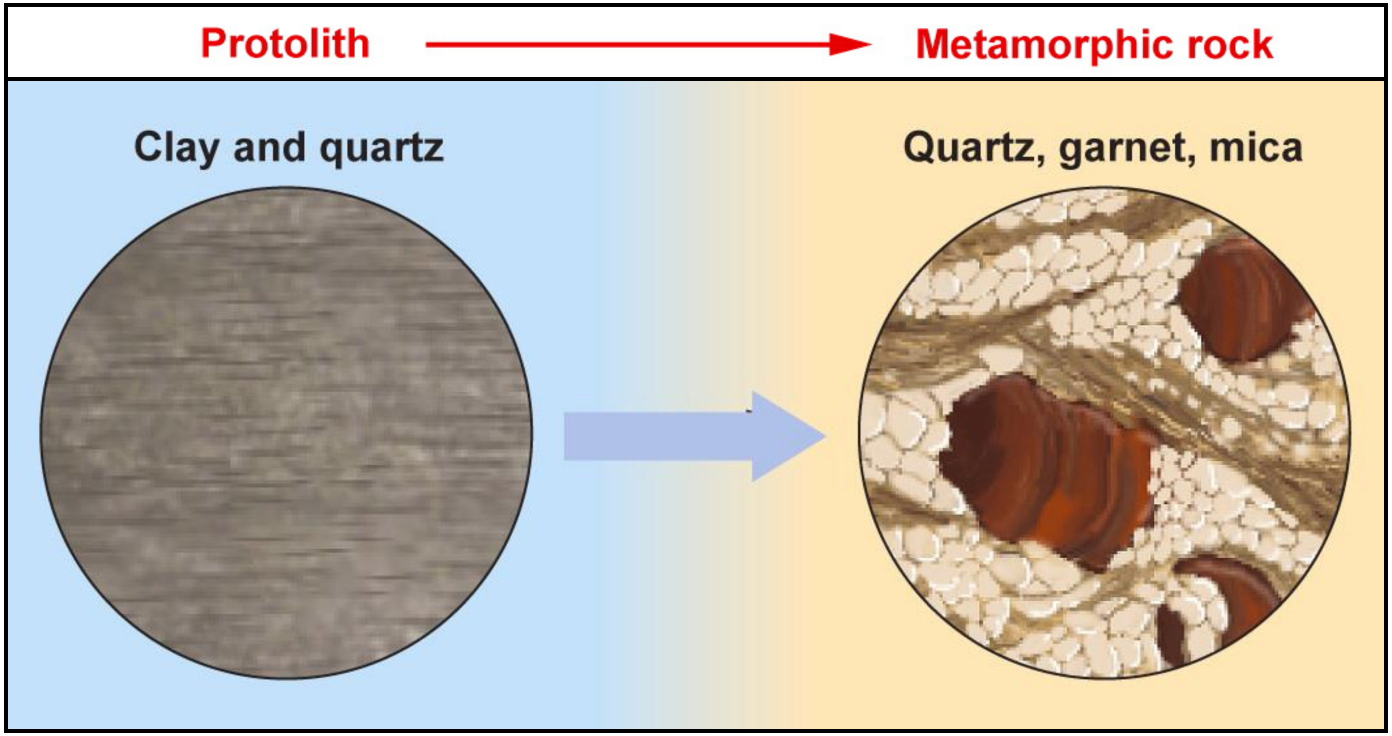
Metamorphic Processes

- Phase change—new minerals form with:
  - The same chemical formula.
  - Different crystal structure.
    - Example: Andalusite ➔ Kyanite.



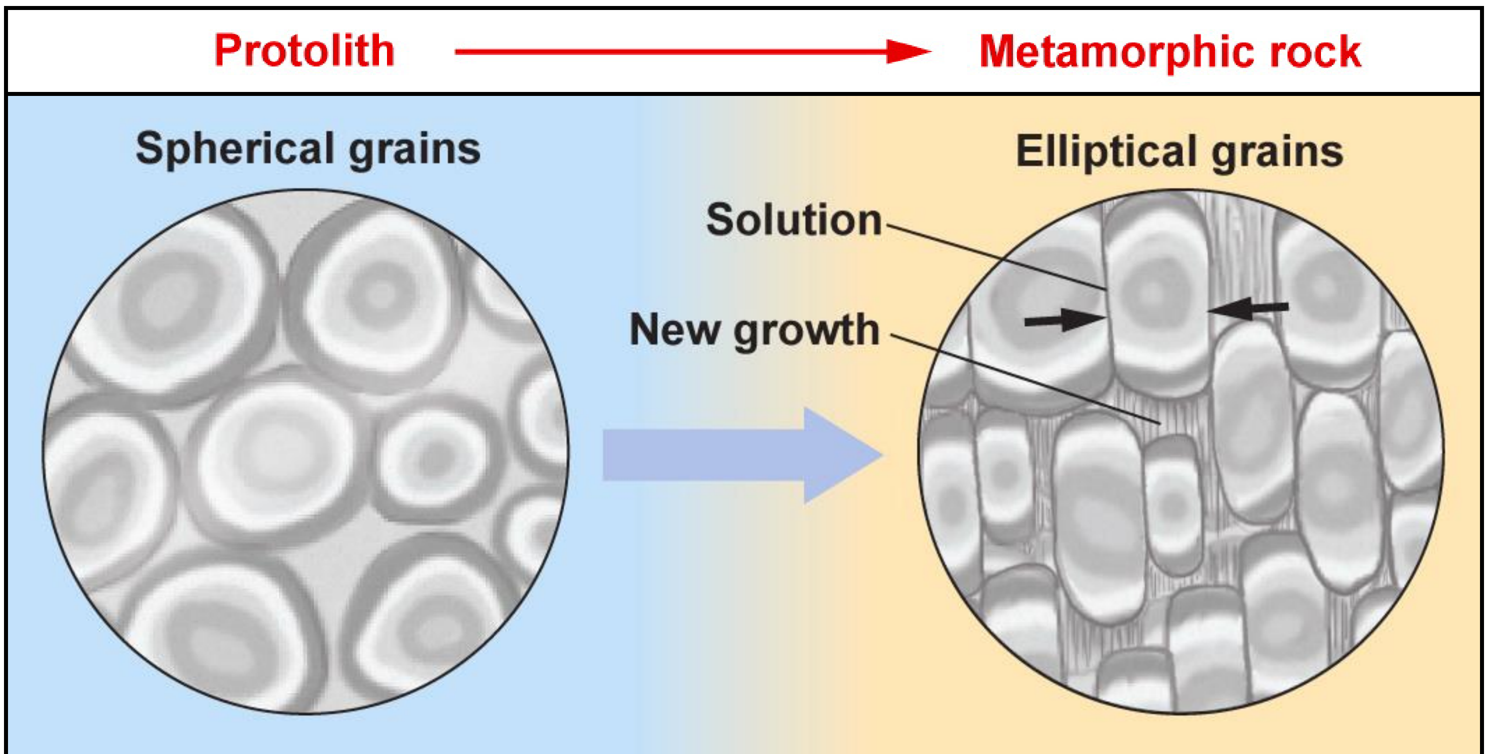
Metamorphic Processes

- Neocrystallization—new minerals form from old.
  - Initial minerals become unstable, change to new minerals.
    - Original protolith minerals are digested in reactions.
    - Elements restructure to form a new mineral assemblage.
  - Example: Shale ➔ garnet mica schist.



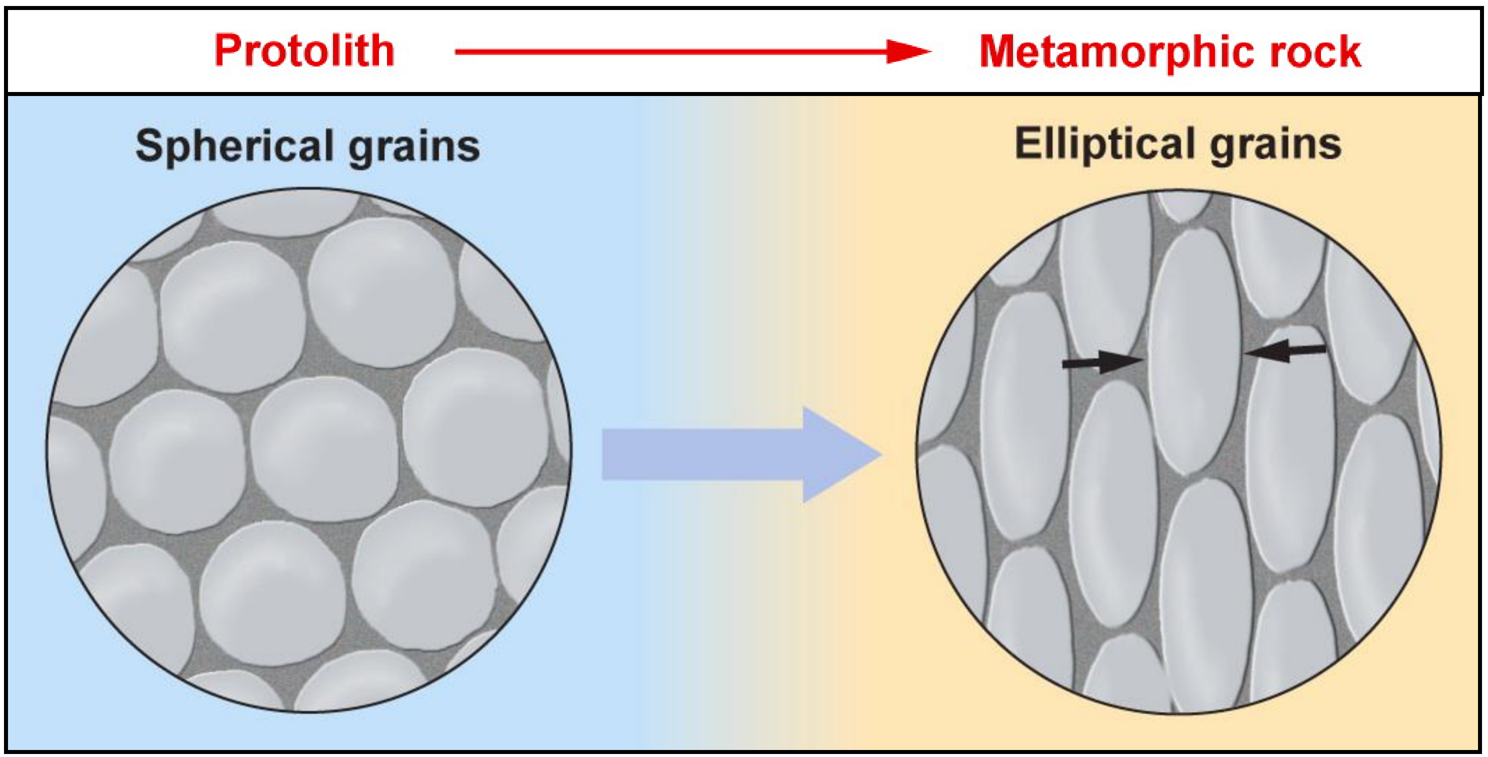
Metamorphic Processes

- Pressure solution—mineral grains partially dissolve.
  - Dissolution requires small amounts of water.
  - Minerals dissolve where their surfaces press together.
  - Ions from the dissolution migrate in the water film.



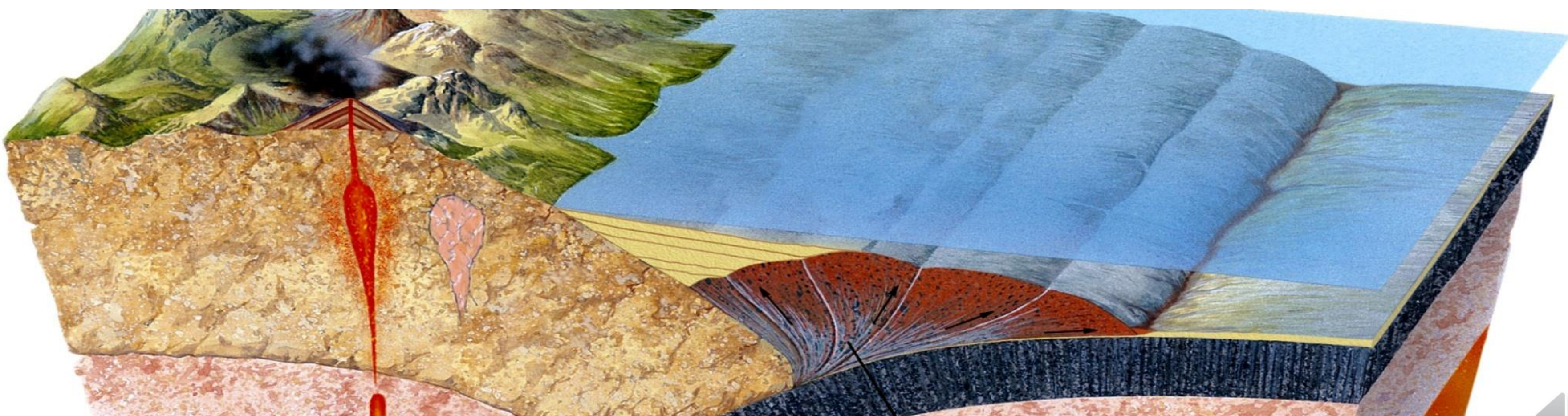
Metamorphic Processes

- Plastic deformation—mineral grains soften and deform.
  - Requires elevated temperature and pressure.
  - Rock is squeezed or sheared.
  - Minerals change shape without breaking like a plastic.



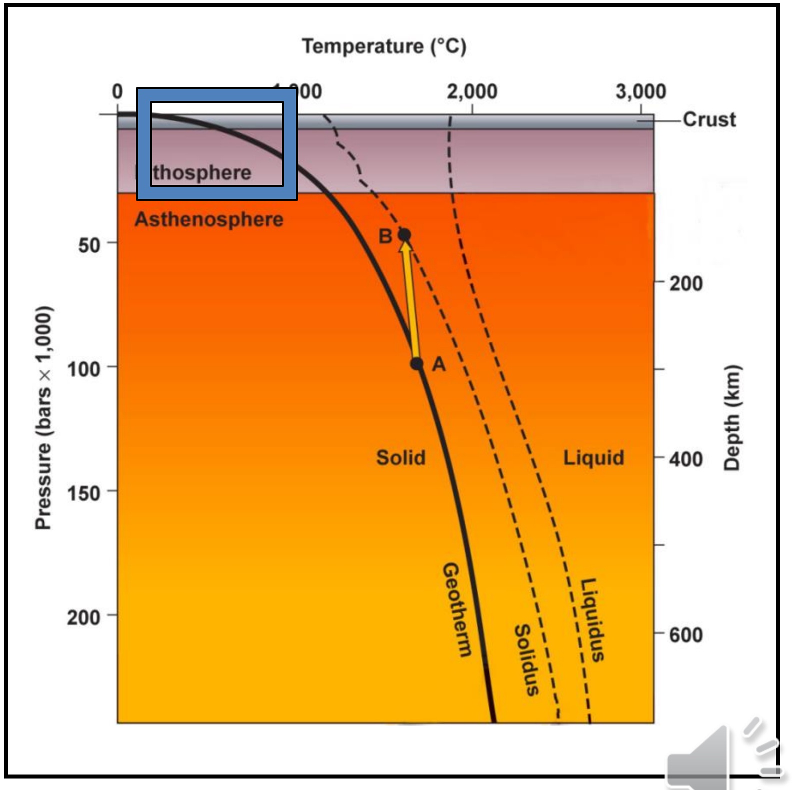
Causes of Metamorphism

- The agents of metamorphism are:
  - Heat (T).
  - Pressure (P).
  - Compression and shear.
  - Hot fluids.
- Not all agents are required; they often do co-occur.
- Rocks may be overprinted by multiple events.



Metamorphism Due to Heat (T)

- One cause of metamorphism is heat.
  - Most metamorphism occurs between 250ºC and 850ºC.
  - Between diagenesis and melting (up to 1200ºC).
- Heat energy breaks and reforms atomic bonds.
  - Solid-state diffusion: migration of atoms between grains.
  - New minerals form.

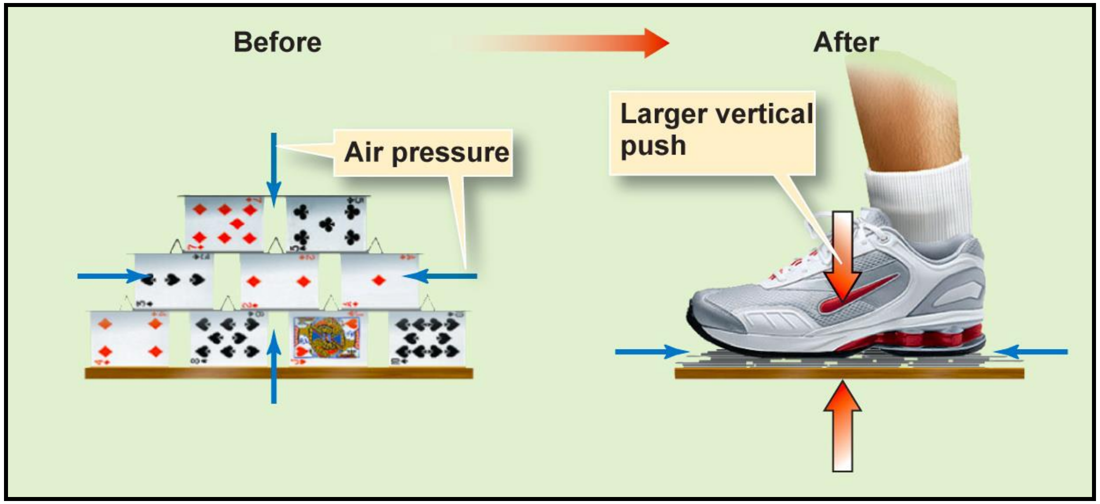


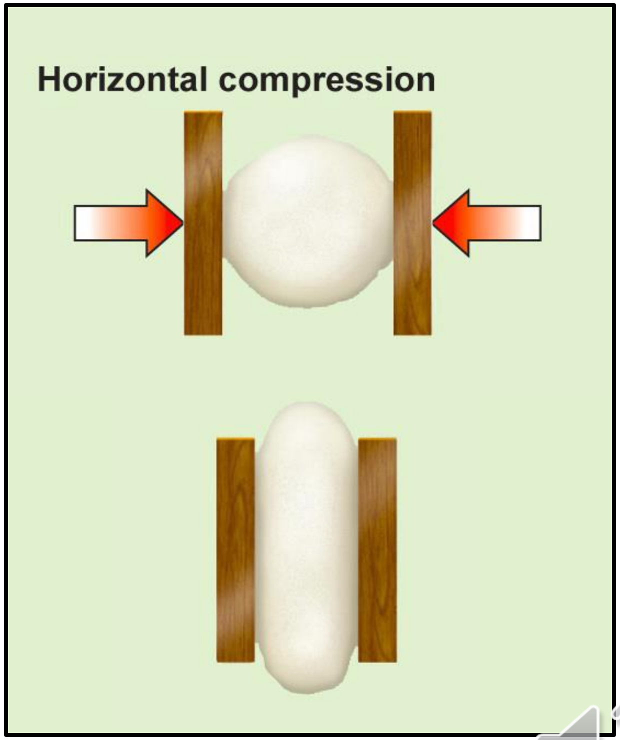
Metamorphism Due to Pressure (P)

- P increases with depth in the crust.
  - Metamorphism occurs mostly in 2–12 kbar range;
    that is between about 5km and 40km depth
- Increase in P packs atoms more tightly together.
  - Creates denser minerals.
  - Involves phase changes or neocrystallization.
- Formation and stability of many minerals depends on both P and T.

Metamorphism via Compression

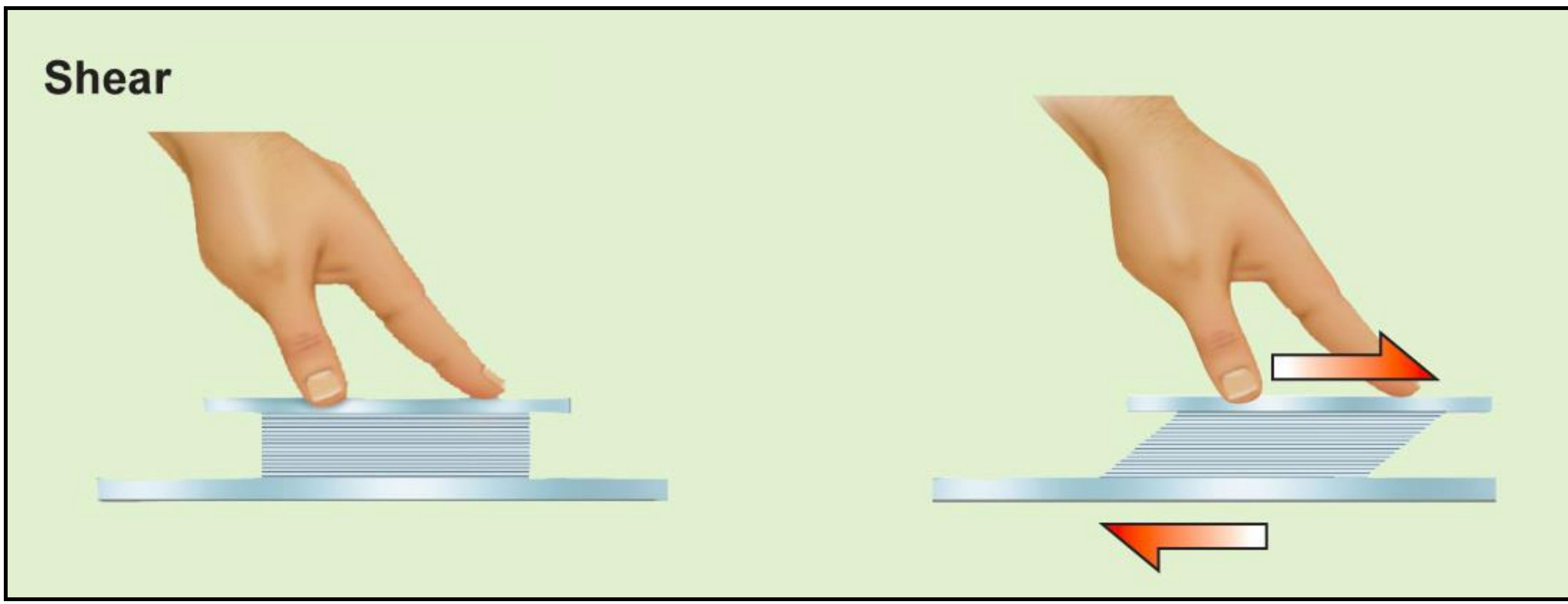
- Compression – stress greater in one orientation.
- Different from pressure (P), which is equal in all directions.
- Compression is a common result of tectonic forces.





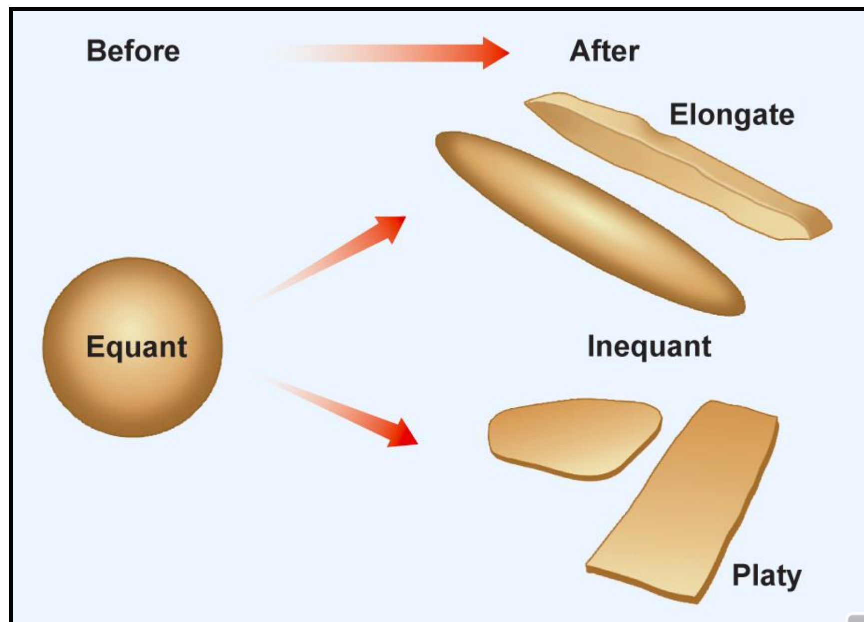
Metamorphism via Shear

- Shear—moves one part of a material sideways.
  - Causes material to be smeared out.
  - Like sliding out a deck of cards.



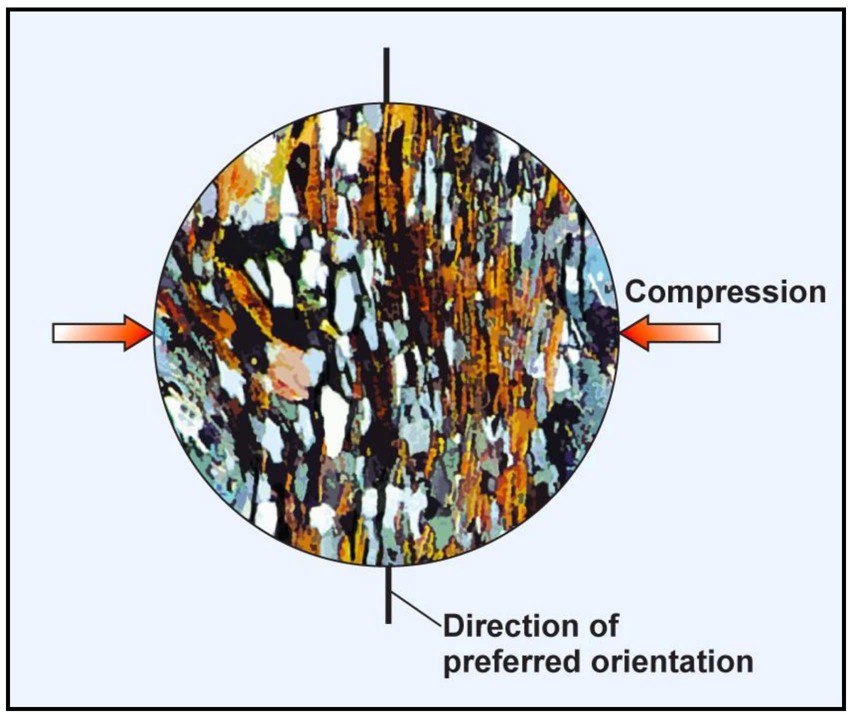
Compression and Shear

- Compression and shear applied together causes mineral grains to change shape.
  - Equant—roughly equal in all dimensions.
  - Inequant—dimensions not the same.
    - Platy (pancake-like)—one dimension shorter (i.e., micas).
    - Elongate (cigar-shaped)—one dimension longer (i.e., staurolite).
- Preferred orientation of inequant minerals is a common feature of metamorphic rocks.



Development of Preferred Orientation

- Compression and shear combine with elevated T and P.
  - Cause rocks to change shape without breaking.
  - Internal textures of deforming rocks can also change.
    - Minerals rotate into preferred orientations.
    - Minerals grow in preferred directions relative to stretching.



Hydrothermal Fluid Metamorphism

- Hot water with dissolved ions and volatiles.
- Hydrothermal fluids facilitate metamorphism.
  - Accelerate chemical reactions.
  - Alter rocks by adding or subtracting elements.
- Hydrothermal alteration is called *metasomatism*.

  It is often associated with mineralization of ore deposits

- On [ore genesis]()

Types of Metamorphic Rocks

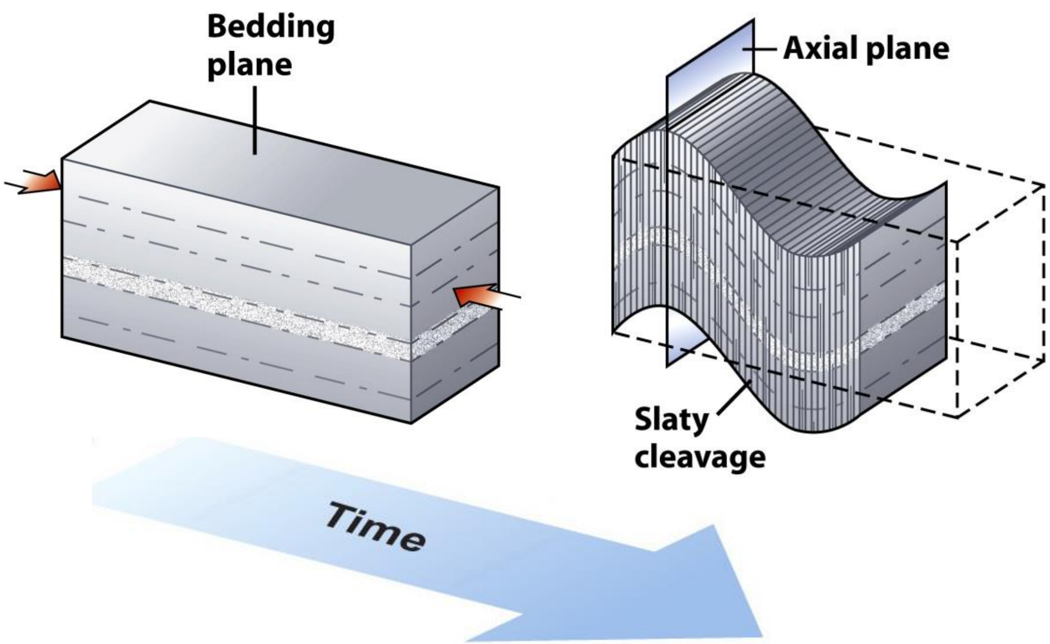
- Two major subdivisions—foliated and nonfoliated.
  - Foliation—parallel surfaces or layers in metamorphic rocks.
    - Alignment of inequant grains or compositional banding.
    - Classified by composition, grain size, and foliation type.

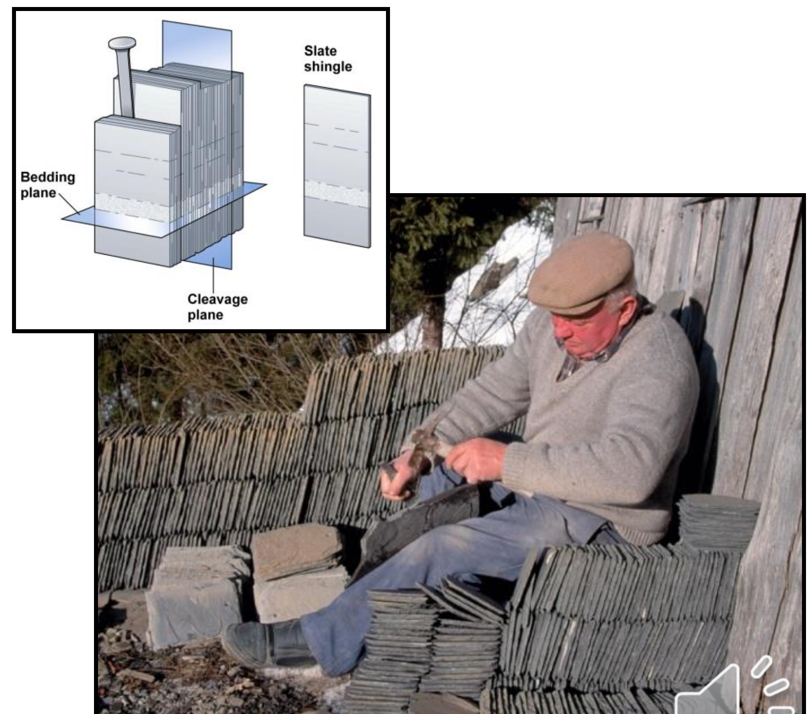
Types of Metamorphic Rocks

- Two major subdivisions of metamorphic rocks.
  - Nonfoliated—no planar fabric evident.
    - Minerals recrystallized without compression or shear.
    - Comprised of equant minerals only.
    - Classified by mineral composition.

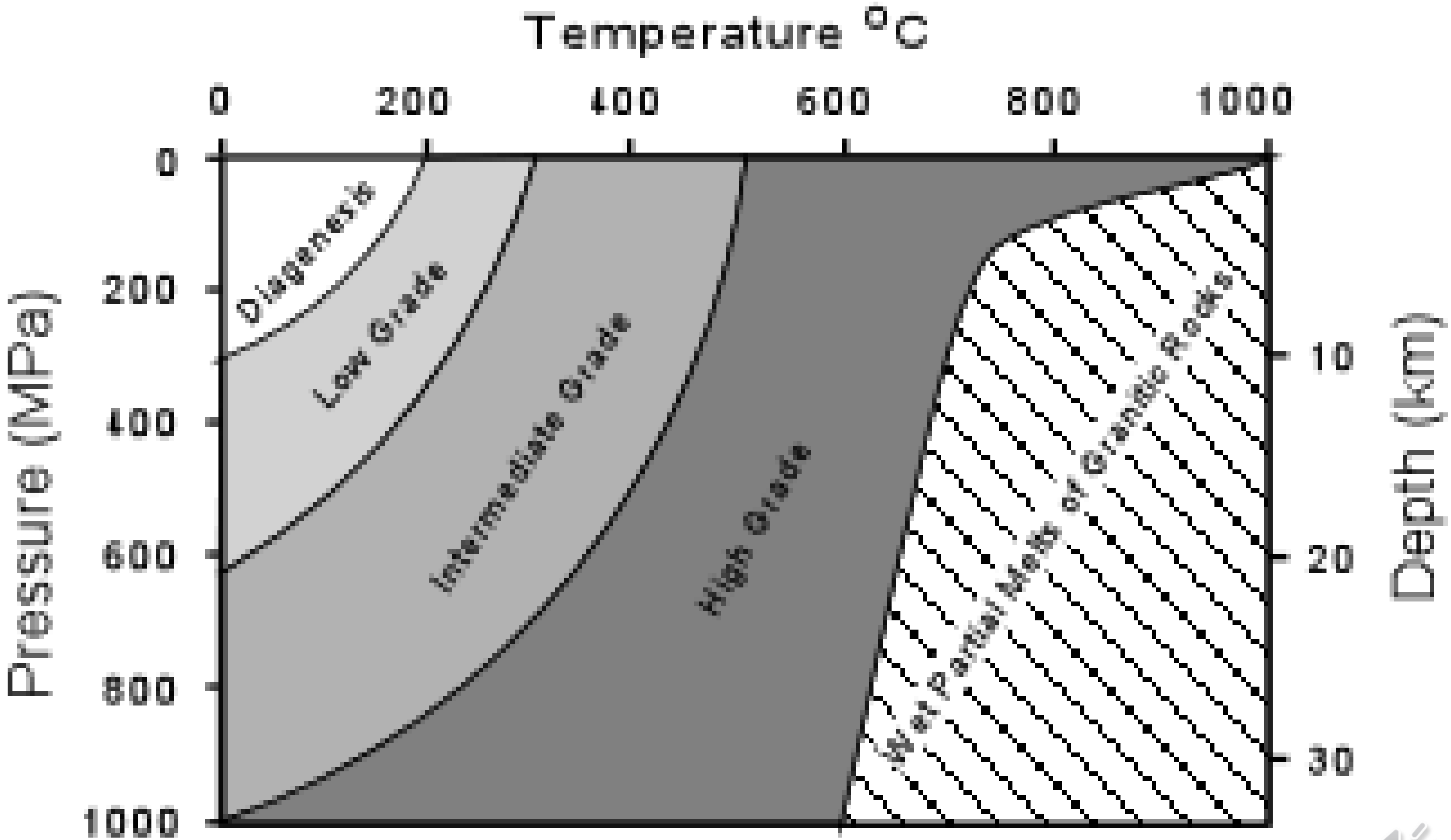
Foliated Metamorphic Rocks

- **Slate—fine-grained, low grade metamorphic shale.**
  - **Has a distinct foliation called slaty cleavage.**
    - **Develops by parallel alignment of platy clay minerals.**
    - **Slaty cleavage develops *perpendicular* to compression.**
    - **Slate breaks along foliation creating sheets used for roofing.**





Metamorphic Grade



Foliated Metamorphic Rocks

- **Phyllite—fine-grained mica-rich rock.**
  - **Formed metamorphism of slate.**
  - **Clay minerals neocrystallize into tiny micas.**
  - **Has silky sheen called phyllitic luster.**
  - **Phyllite is between slate and schist.**

Foliated Metamorphic Rocks

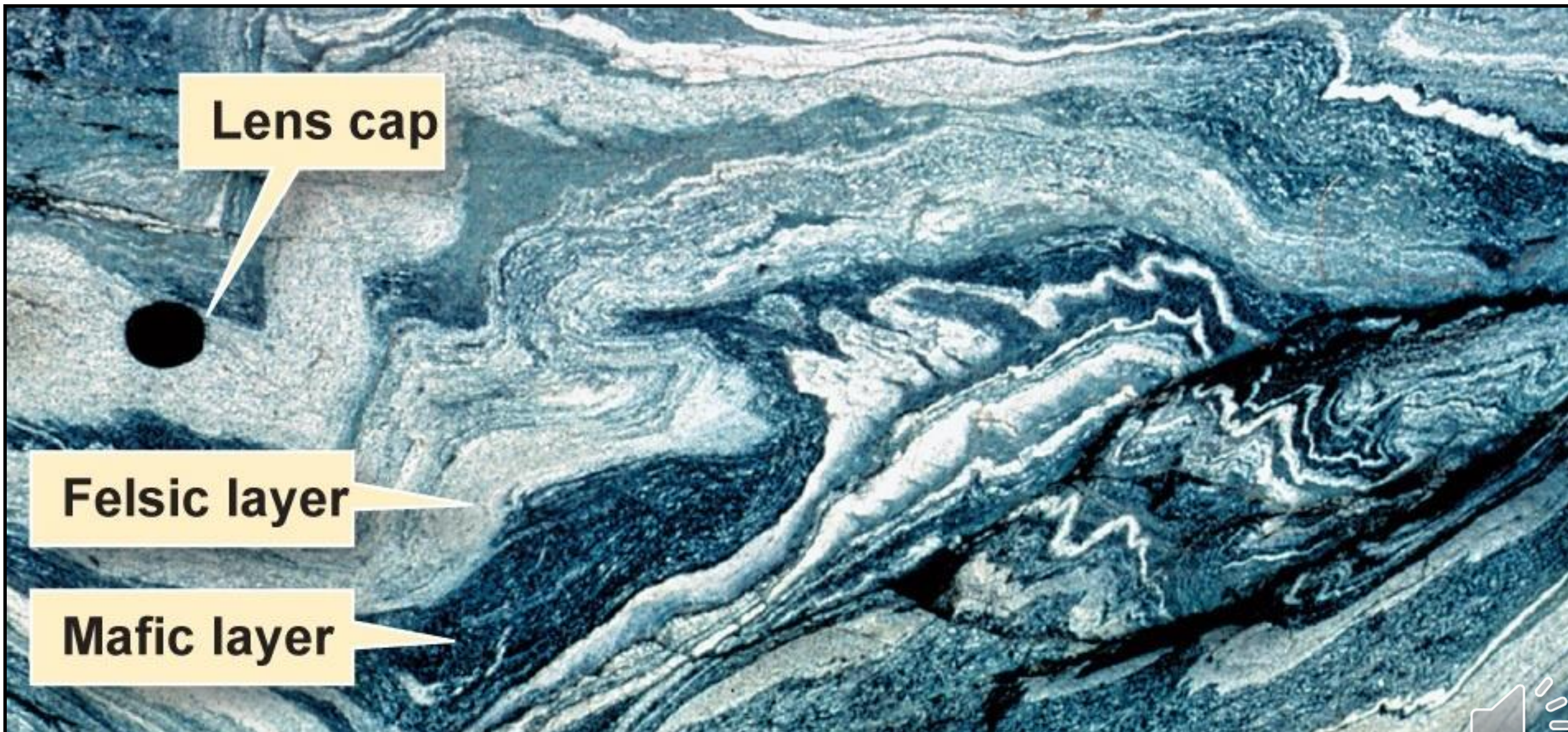
- **Metaconglomerate—metamorphosed conglomerate.**
  - **Pebbles and cobbles are flattened by:**
    - **Pressure solution.**
    - **Plastic deformation.**
  - **Foliation is defined by the flattened clasts.**

Foliated Metamorphic Rocks

- **Schist—fine to coarse rock with larger micas.**
  - **Forms at higher temperature than does phyllite**
  - **Has a distinct foliation from large micas called schistosity.**
  - **Schist has abundant large micas—biotite and muscovite.**

Foliated Metamorphic Rocks

- **Gneiss—distinct compositional bands, often contorted.**
  - **Light bands of felsic minerals (quartz and feldspars).**
  - **Dark bands of mafic minerals (biotite or amphibole).**

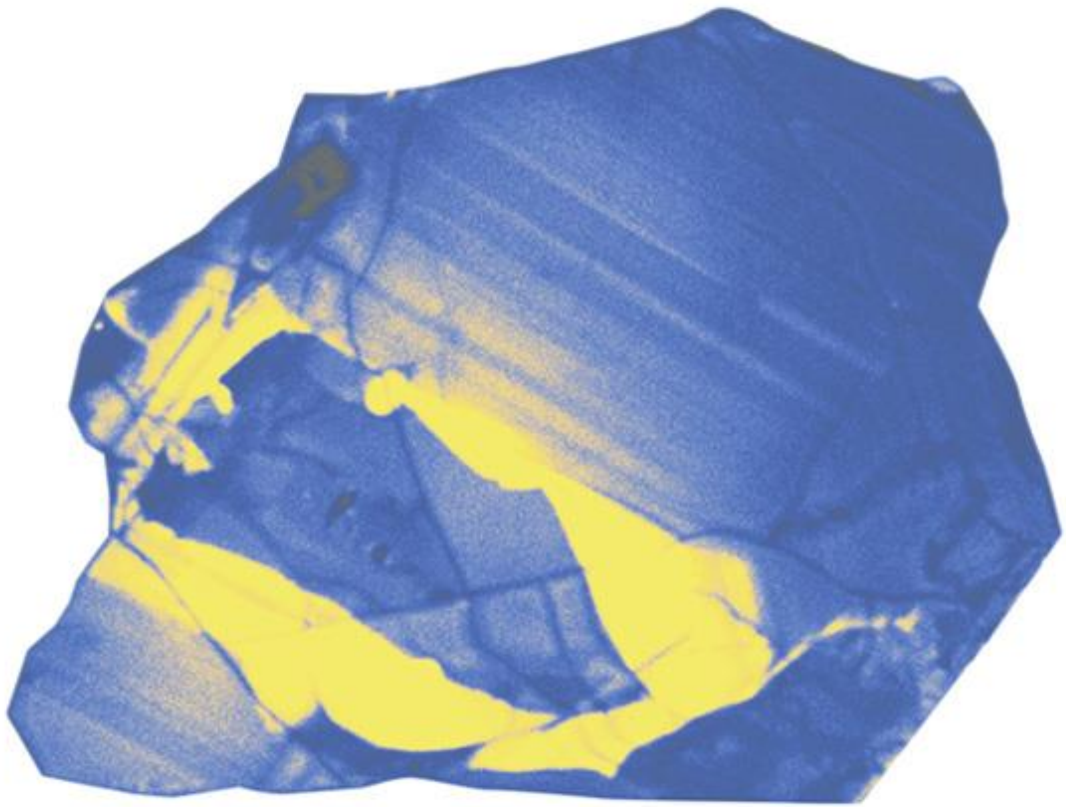


Nuvvuagittuq Faux Amphibolites

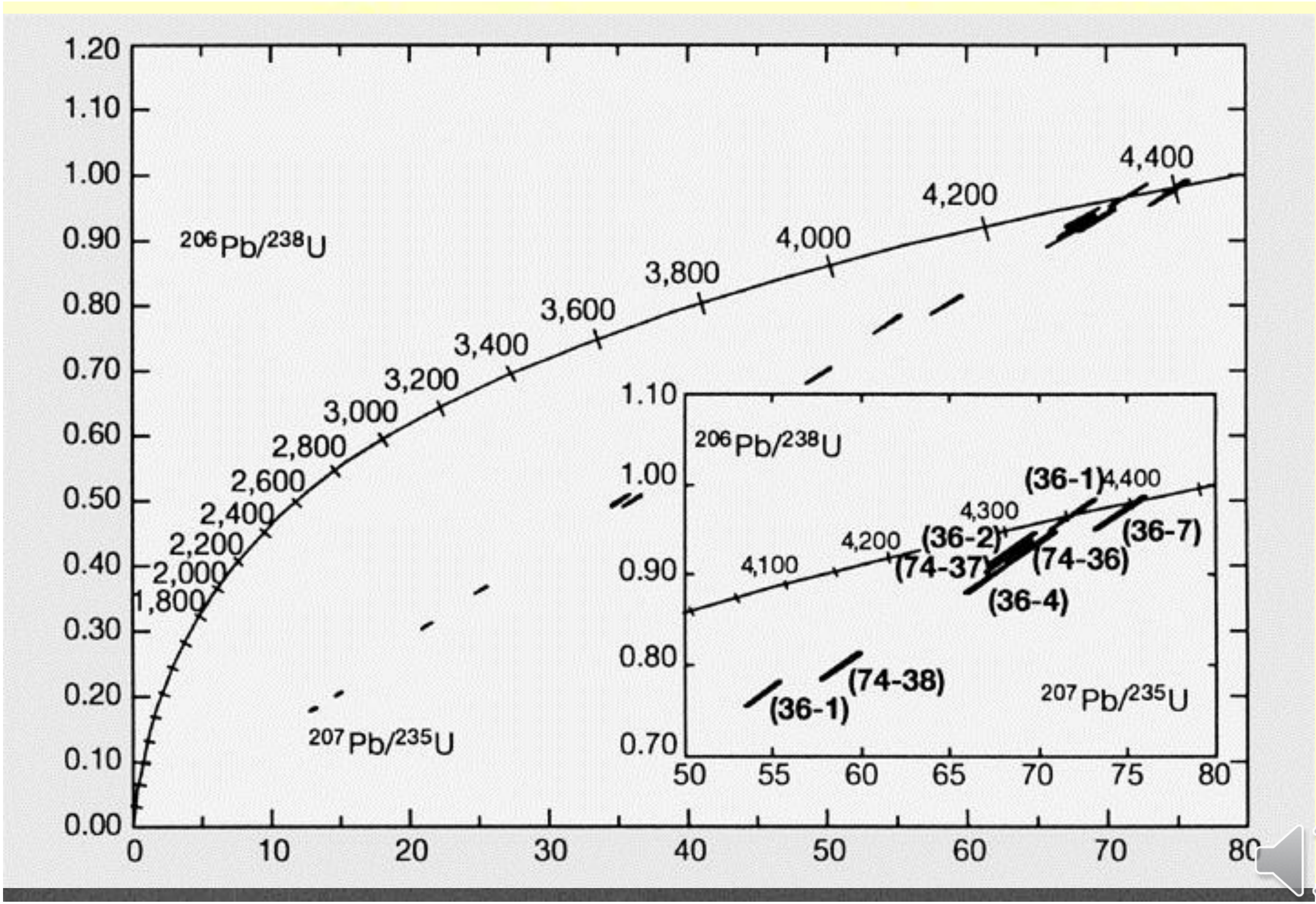
- The source magma that formed this metamorphic rock has been age-dated to 4.28Ga.

The Earliest Mineral on Earth

- This zircon crystal found in the Jack Hills region of Western Australia is the oldest known mineral grain on Earth: 4.404Ga.



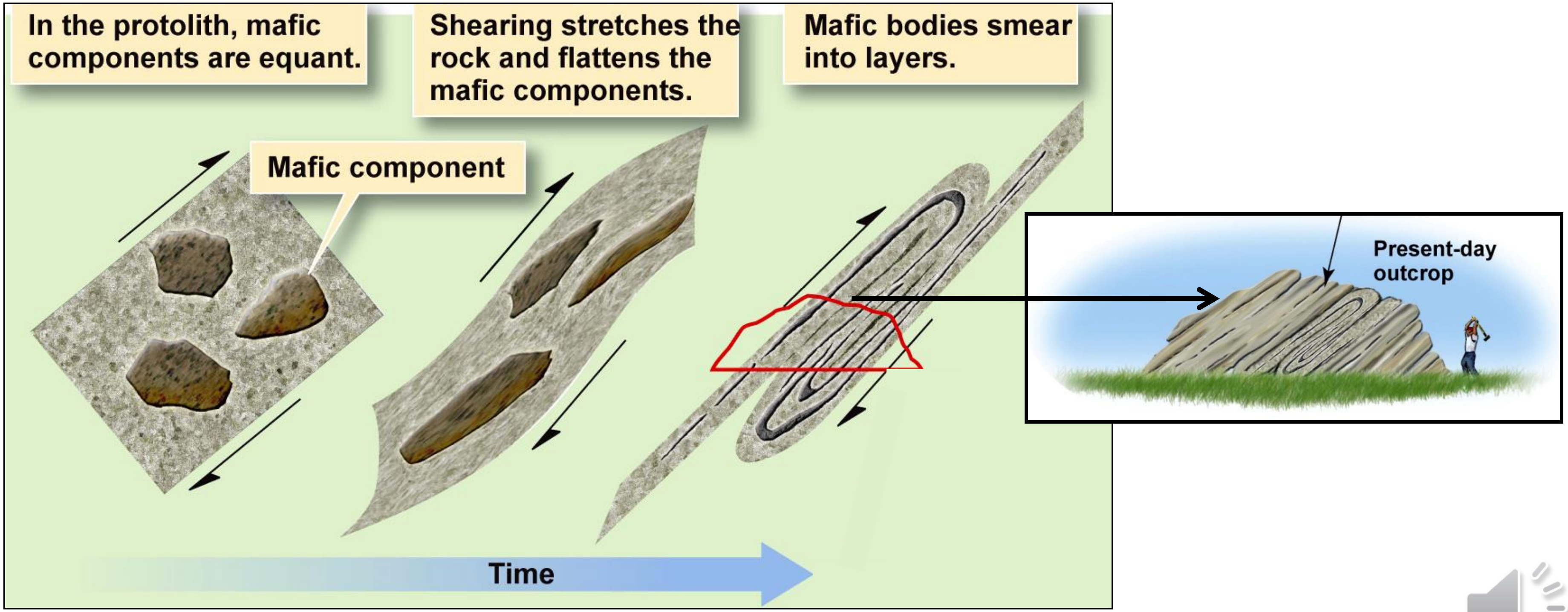
Jack Hills of Western Australia



Images from: http://geoscience.wisc.edu/geoscience/people/faculty/john-valley/the-earliest-piece-of-the-earth/

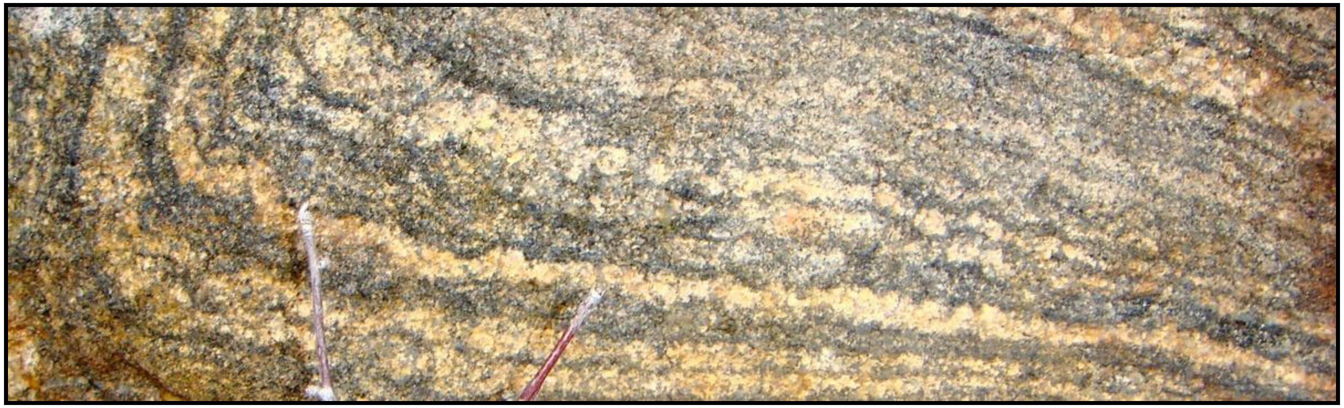
Foliated Metamorphic Rocks

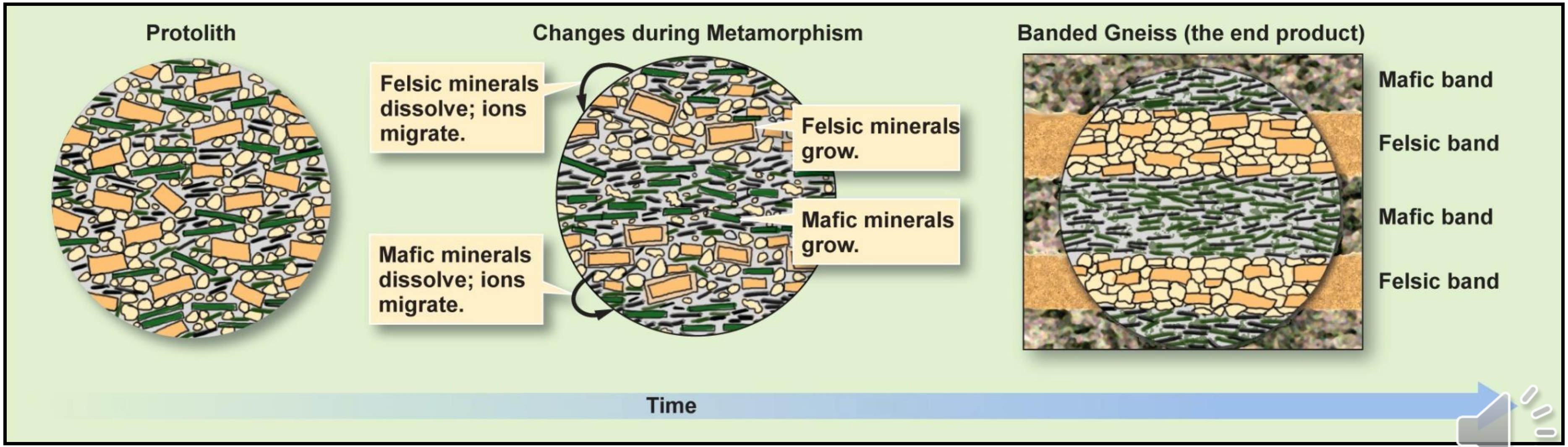
- Gneissic banding develops in several ways.
  - Original layering in the protolith.
  - Extensive high-T shearing.
  - Metamorphic differentiation: minerals segregate into different layers.



Foliated Metamorphic Rocks

- Compositional banding —solid-state differentiation.
- Chemical reactions segregate light and dark layers.



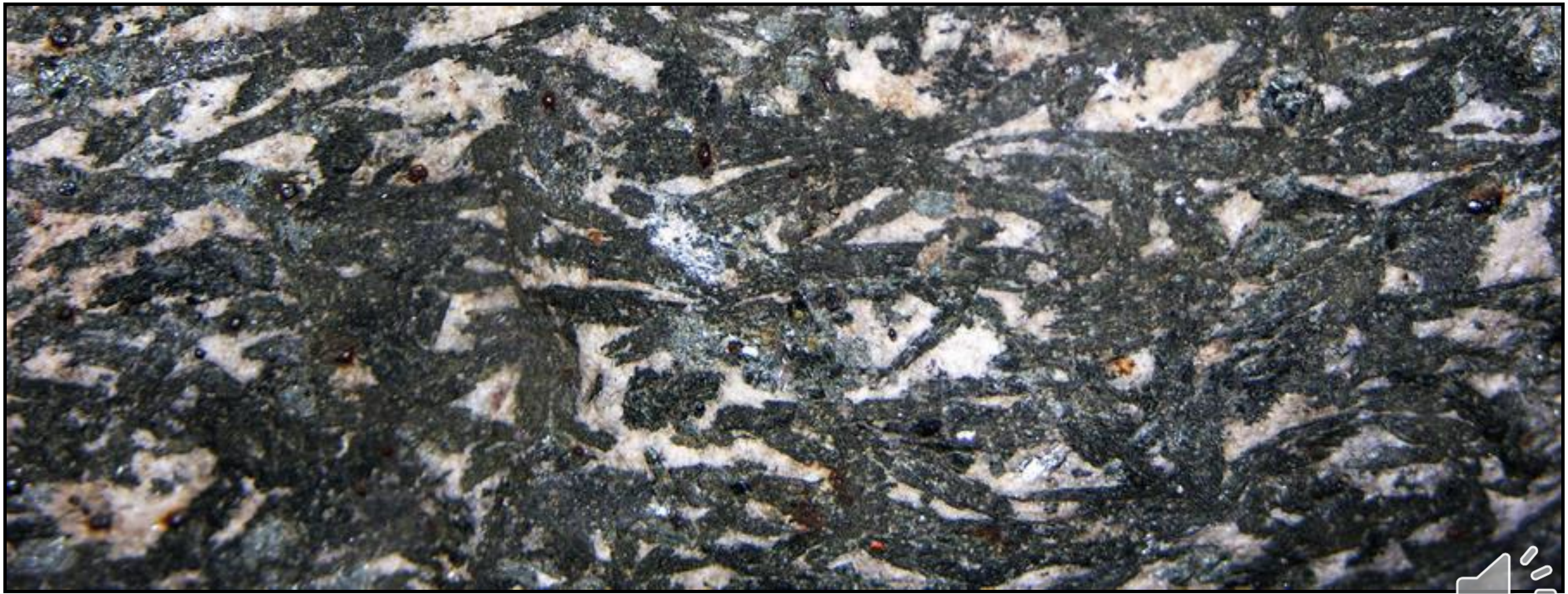


Foliated Metamorphic Rocks

- Migmatite is a partially melted gneiss.
- It has features of igneous and metamorphic rocks.
- Mineralogy controls behavior.
  - Light colored (felsic) minerals melt at lower T.
  - Dark colored (mafic) minerals melt at higher T.
- The felsic bands melt and recrystallize in the gneiss.

Nonfoliated Metamorphic Rocks

- Nonfoliated rocks lack a planar fabric.
  - Absence of foliation possible for several reasons:
    - Rock not subjected to differential stress.
    - Dominance of equant minerals.
    - Absence of platy minerals like clays or micas.

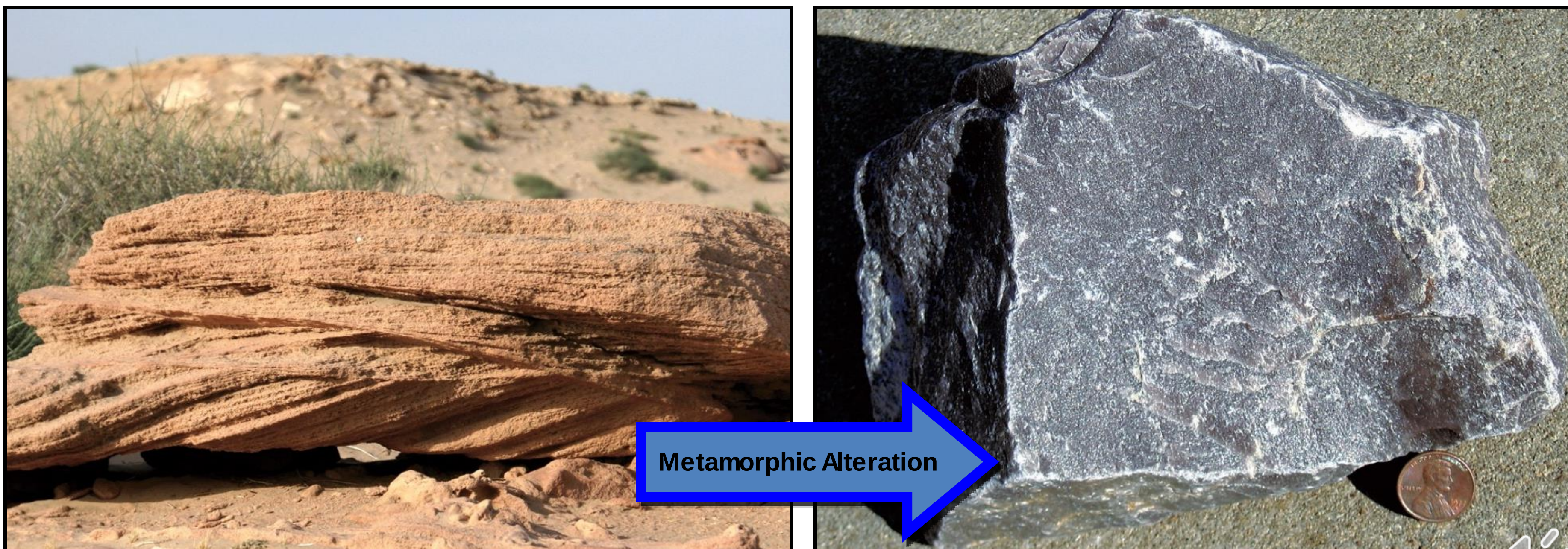


Nonfoliated Metamorphic Rocks

- **Hornfels—fine-grained, variety of metamorphic clay minerals that sedimented as mudstone protolith.**
  - **Associated with plutonic intrusions.**
  - **Composition depends on protolith, pressure, temperature.**

Nonfoliated Metamorphic Rocks

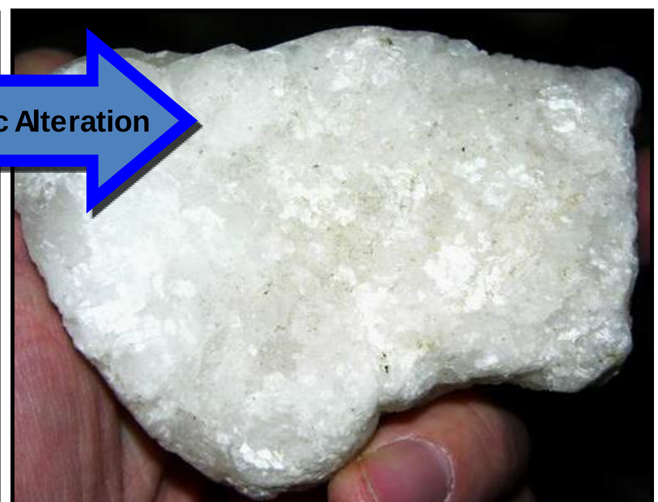
- **Quartzite—almost pure quartz in composition.**
  - **Forms by alteration of quartz sandstone.**
  - **Sand grains in the protolith recrystallize and fuse.**
  - **Like quartz, it is hard, glassy, and resistant.**
  - **Breaks by conchoidal fracture cutting through grains.**



Nonfoliated Metamorphic Rocks

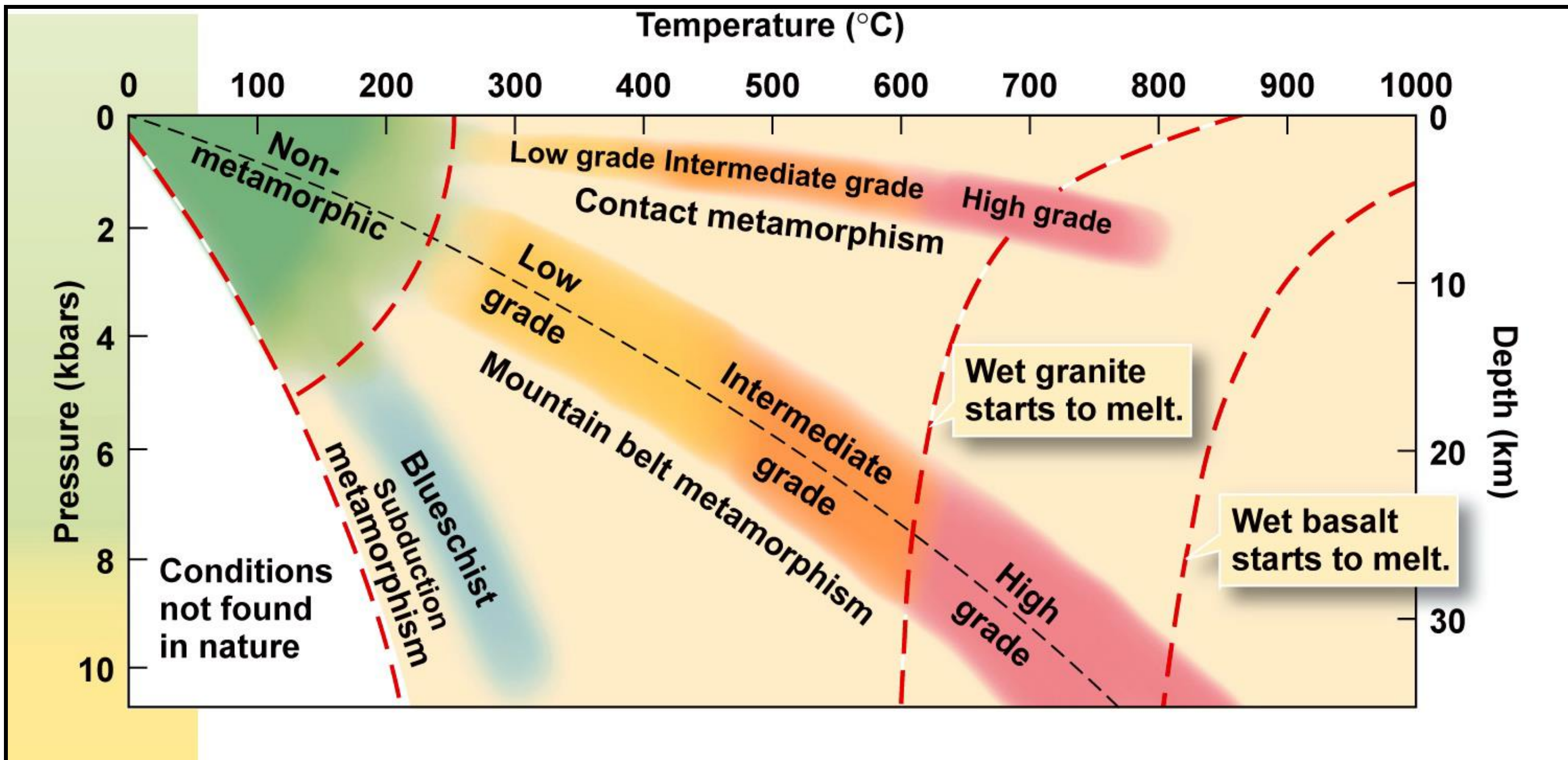
- Marble—coarsely crystalline calcite or dolomite.
  - Forms from a limestone protolith.
  - Extensive recrystallization completely changes the rock.
  - Original textures and fossils in the parent are obliterated.
  - A favorite stone for sculpture.
  - Exhibits a variety of colors.
  - Marble may have color banding

Metamorphic Alteration



Metamorphic Grade

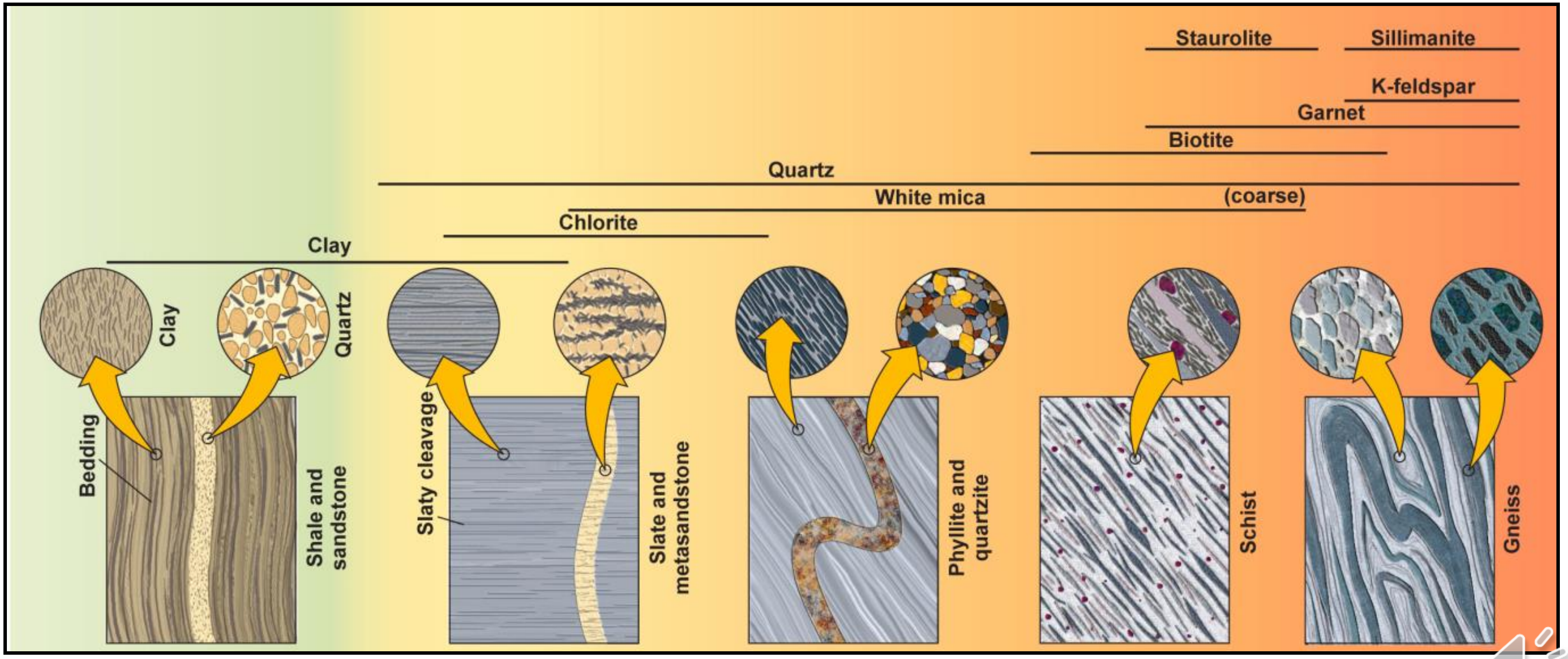
- Different minerals are stable as T and P changes.
- Metamorphic *grade* is a measure of intensity.
  - Low grade—weaker metamorphism.
  - High grade—intense metamorphism.



Metamorphic Grade

- Metamorphic grade determines mineral assemblages.
- As grade increases, new and larger minerals form.

Low Grade → Intermediate Grade → High Grade

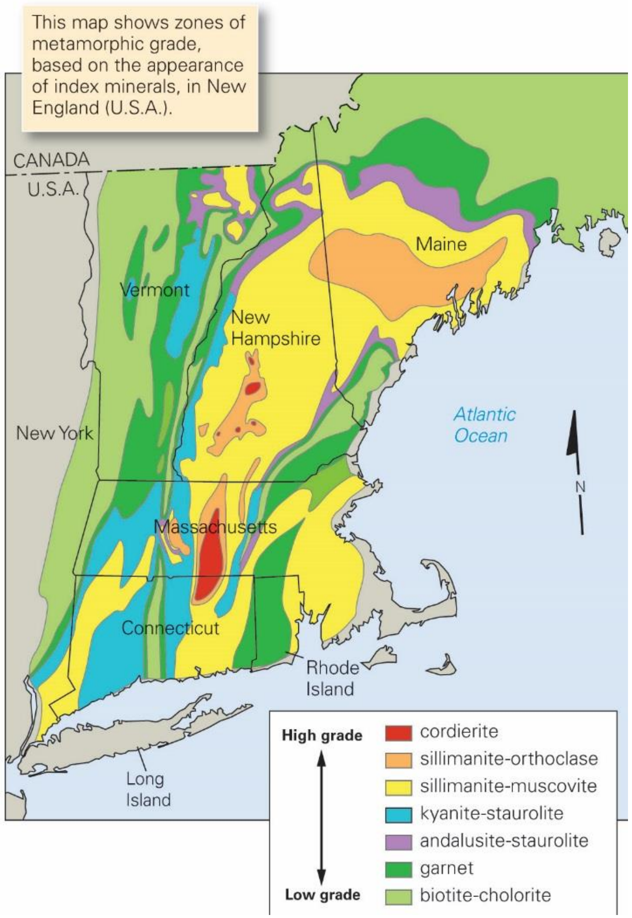


Metamorphic Grade

- **Example: increasing metamorphism of shale protolith.**
  - **Low grade—shale protolith.**
    - **Clays recrystallize into larger, aligned clays to yield a slate.**
    - **Clays neocrystallize into tiny, aligned micas in a phyllite.**
  - **Intermediate grade**
    - **Micas recrystallize and grow large to form a schist.**
    - **New minerals grow in the schist.**
  - **High grade**
    - **Micas decompose; elements recombine into new minerals.**
    - **Neocrystallization yields quartz and feldspars in a gneiss.**

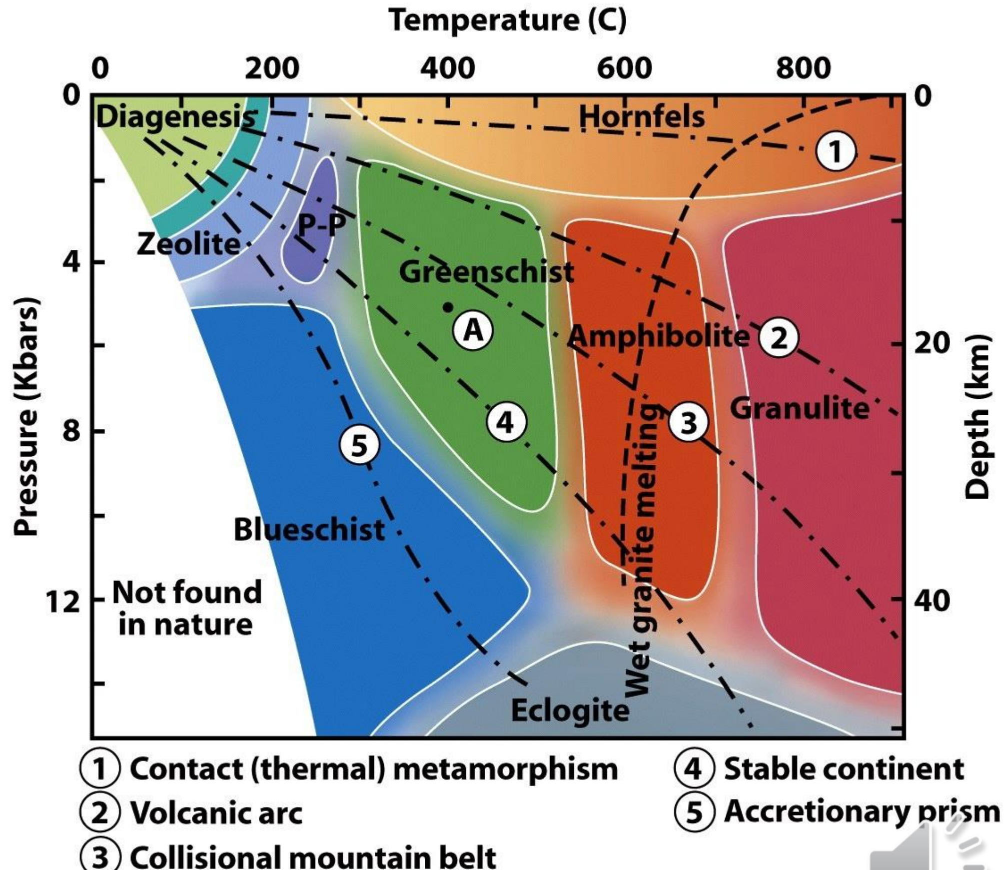
Index Minerals

- **Index minerals indicate a specific P and T range.**
- **Metamorphic Zones are defined by index minerals.**
- **Index mineral maps.**
  - **Define metamorphic zones.**
  - **Boundaries are *isograds*.**



Metamorphic Facies

- Mineral assemblages from a specific protolith at specific P and T conditions.
- Create rocks that are predictably similar.
- Named for a dominant mineral.

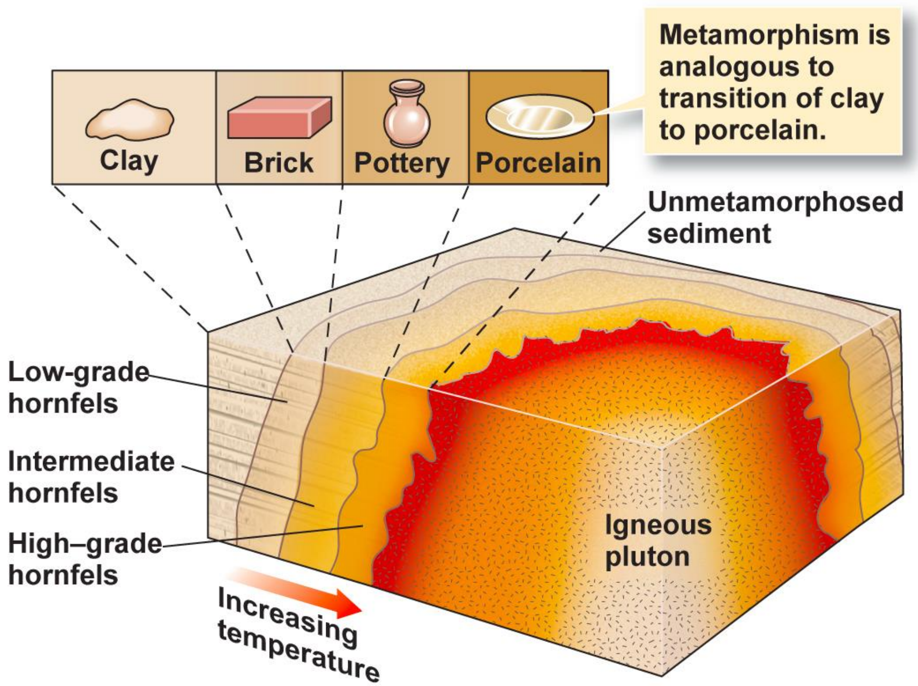


Metamorphic Environments

- The types (and settings) of metamorphism are:
  - Thermal or Contact—heating by a plutonic intrusion.
  - Burial—increases in P and T by deep burial in a basin.
  - Dynamic—shearing in a fault zone.
  - Regional—P and T alteration due to orogenesis.
  - Hydrothermal—alteration by hot water leaching.
  - Subduction—high-P/low-T alteration in subduction zones.
  - Shock—extreme high P resulting from a bolide impact.

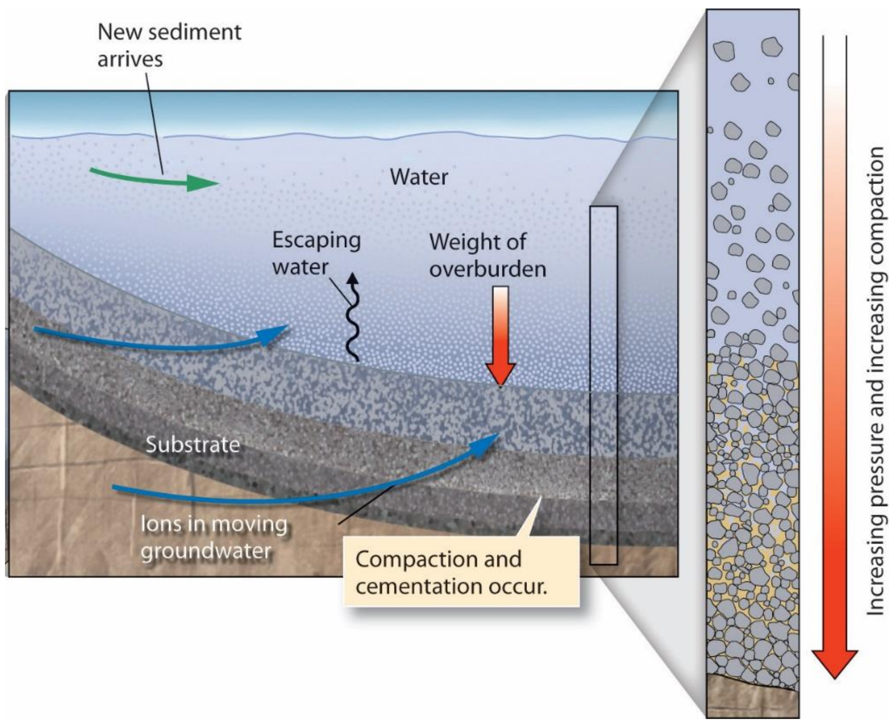
Thermal (Contact) Metamorphism

- Due to heat from magma invading host rock.
- Creates zoned bands of alteration in host rock.
  - Called a contact (or metamorphic) aureole.
  - The aureole surrounds the plutonic intrusion.
    - Zoned from high (near pluton) to low grade (far from pluton).



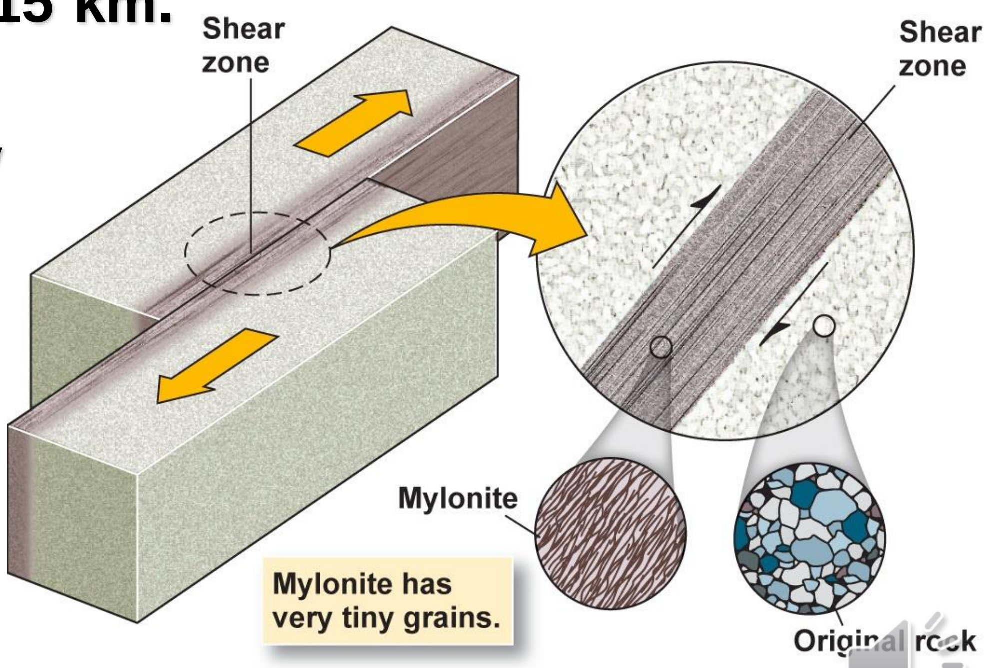
Burial Metamorphism

- **As sediments are buried in a sedimentary basin:**
  - **P increases because of the weight of the overburden.**
  - **T increases because of the geothermal gradient.**
  - **At about 8–15km depth, metamorphic reactions begin.**



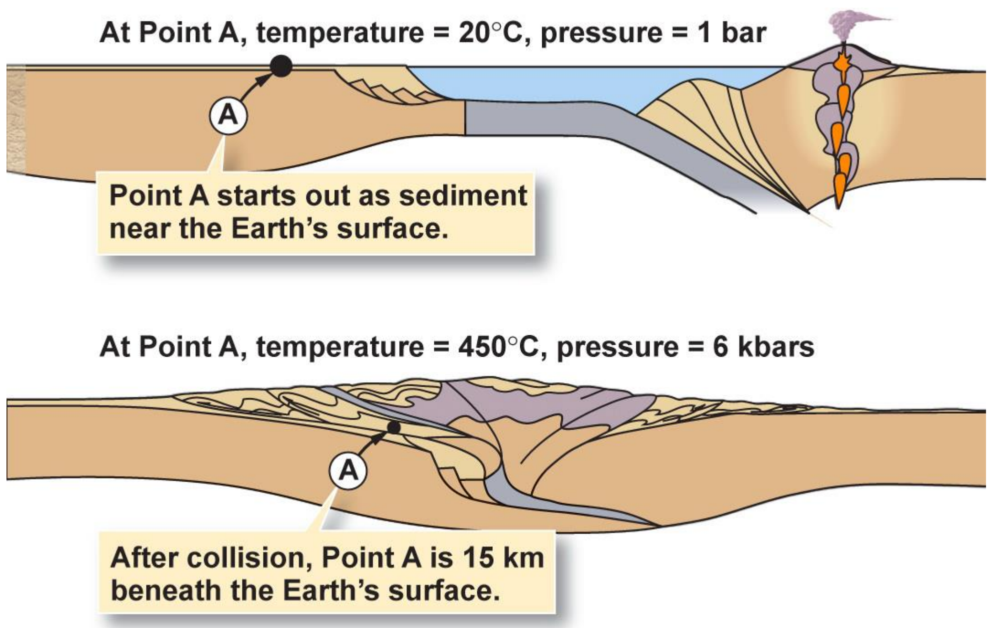
Dynamic Metamorphism

- Breakage of rock by shearing at a fault zone.
- Fault location determines type of alteration.
  - Shallow crust—upper 10–15 km.
    - Rocks behave in a brittle fashion.
    - Mineral grains crush forming fault breccia.
  - Deeper crust—below 10–15 km.
    - Rocks are ductile.
    - Minerals smear like taffy to form mylonite.



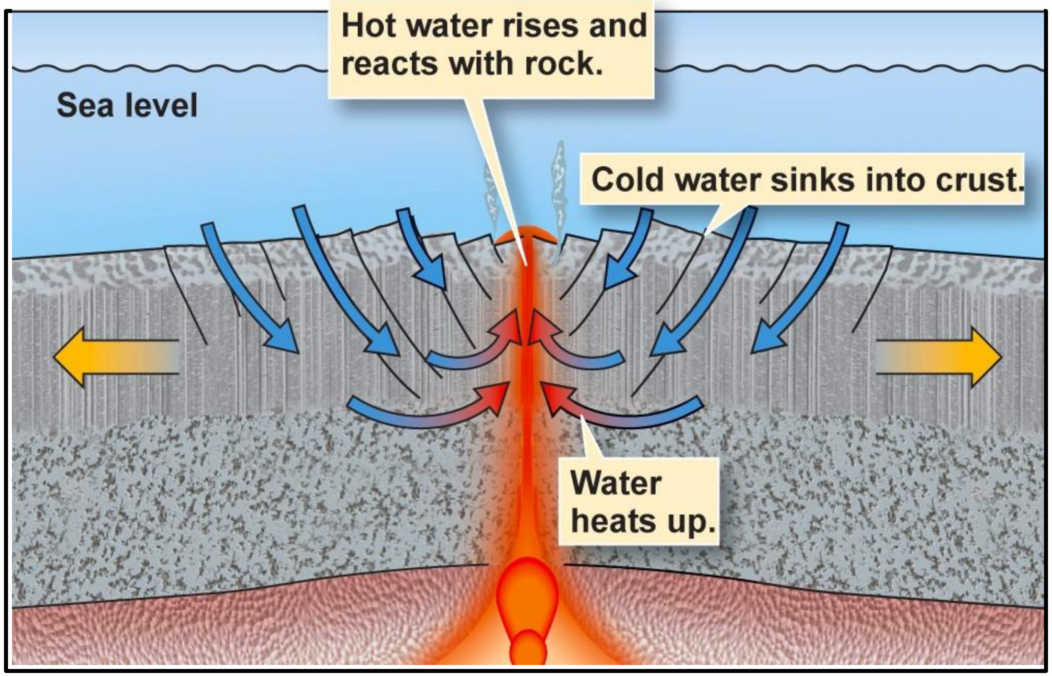
Dynamothermal Metamorphism

- Also called "Regional Metamorphism"
- Tectonic collisions deform huge "mobile belts."
  - Rocks caught up in mountain building are:
    - Heated via the geothermal gradient and plutonic intrusions.
    - Squeezed and heated by deep burial.
    - Smashed and deformed by compression and shearing.



Hydrothermal Metamorphism

- Alteration by hot, chemically aggressive water.
- A dominant process near mid-ocean ridge magma.
  - Cold ocean water seeps into fractured crust.
  - Heated by magma, this water then reacts with mafic rock.
  - The hot water rises and is ejected via black smokers.



Serpentinization…

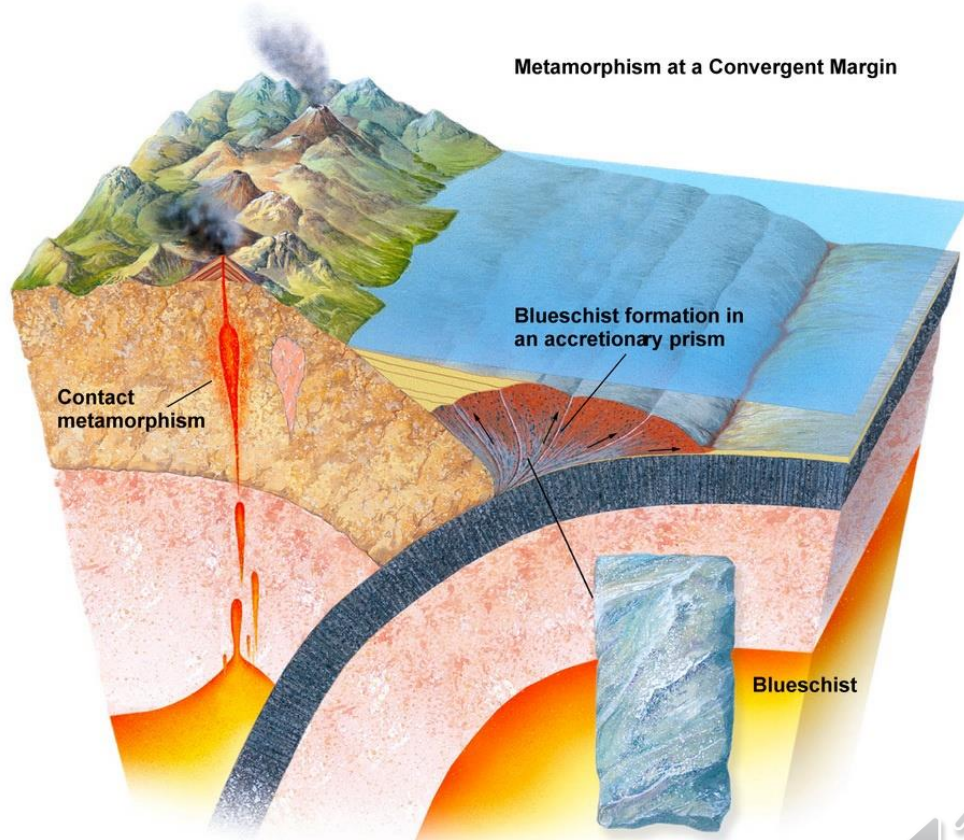
- A low temperature metamorphic process that often occurs in the ultramafic rocks near mid-ocean ridges…

- Olivine in contact with water at relatively low temperatures forms serpentinite rocks

https://en.wikipedia.org/wiki/File:Serpentinite.JPG

Subduction Metamorphism

- Subduction creates the unique blueschist facies.
- Trenches and accretionary prisms have:
  - A low geothermal gradient—low T, high P.
  - These conditions favor glaucophane, a blue amphibole mineral.

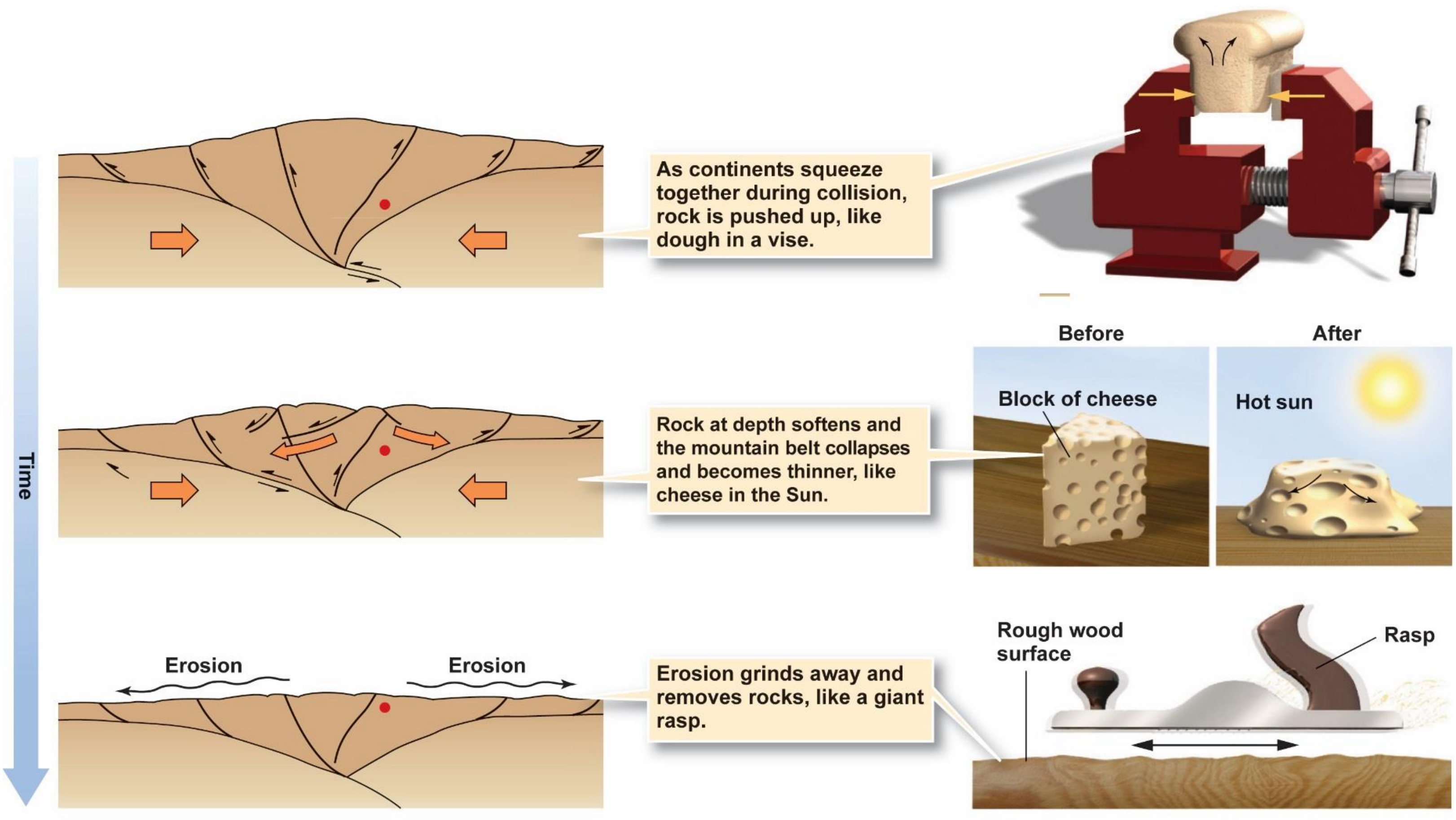


Shock Metamorphism

- Rarely, Earth is struck by a comet or asteroid.
- Impacts generate a compressional shock wave.
  - Extremely high pressure.
  - Heat that vaporizes or melts large masses of rock.
- These conditions generate high-pressure minerals.

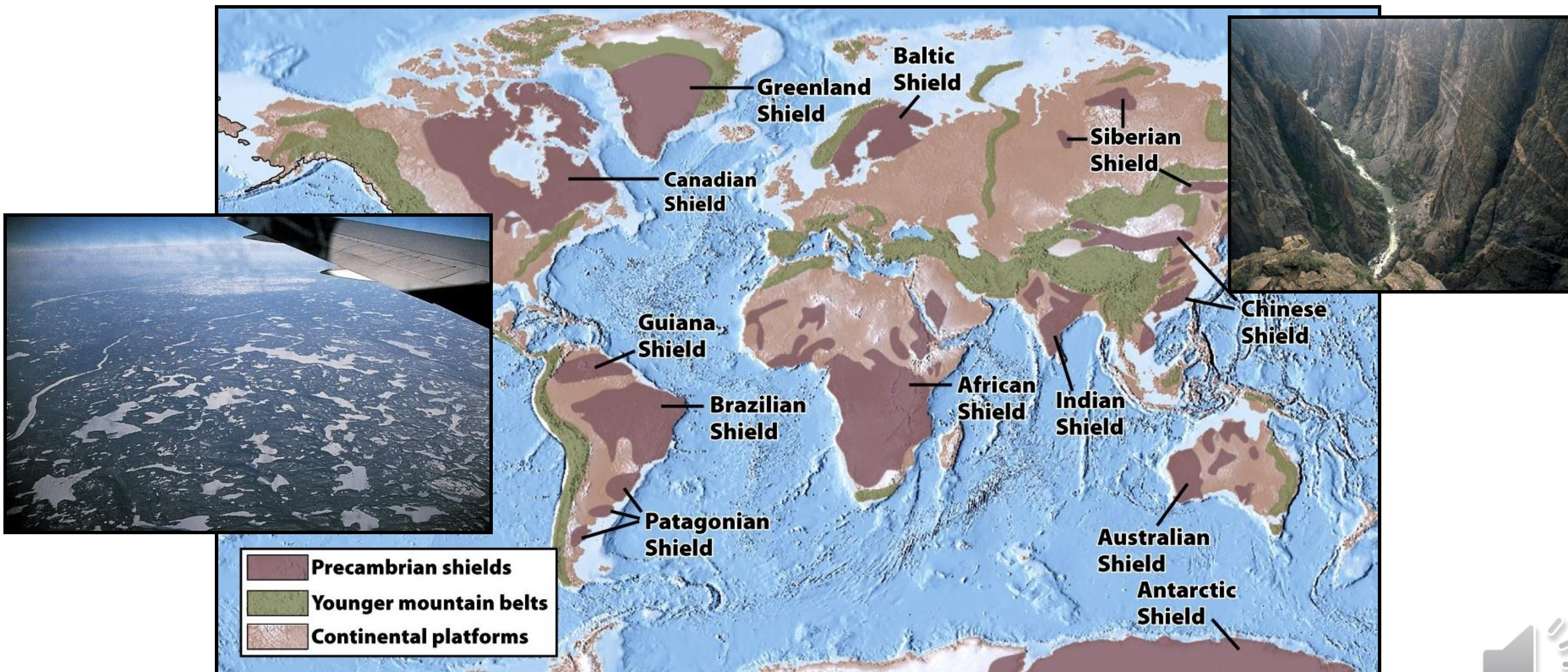
Exhumation

- How do metamorphic rocks return to the surface?
- Exhumation is due to uplift, collapse, and erosion.

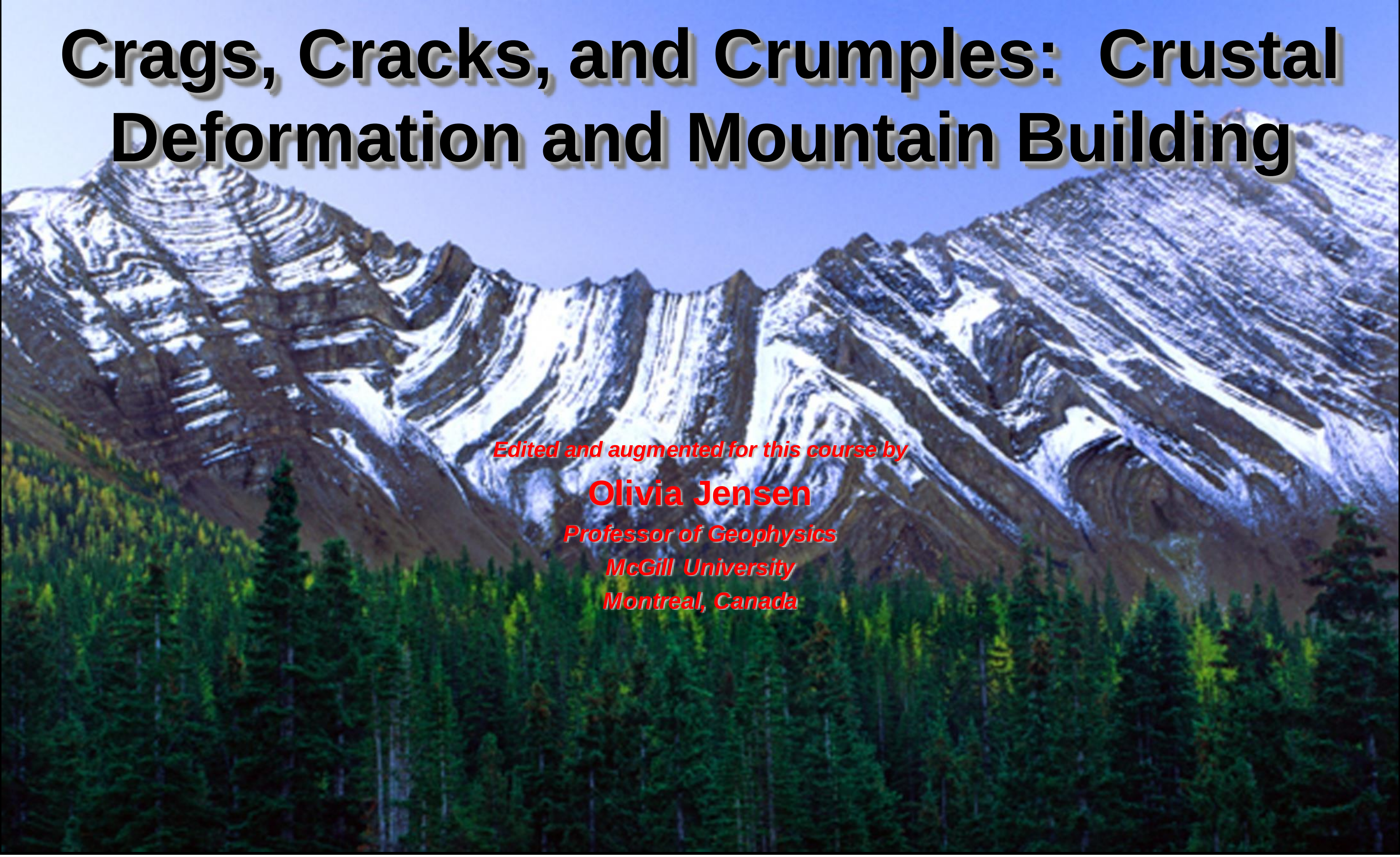


Finding Metamorphics

- Large regions of ancient high-grade rocks—called shields—are exposed in continental interiors.
- Shields are eroded remnants of orogenic belts.
  - Shield rocks form the basement under sedimentary cover.



Crags, Cracks, and Crumples: Crustal Deformation and Mountain Building



Edited and augmented for this course by

Olivia Jensen

Professor of Geophysics

McGill University

Montreal, Canada

Updated by:

***Rick Oches**, Professor of Geology & Environmental Sciences*

Bentley University

Waltham, Massachusetts

Based on slides prepared by:

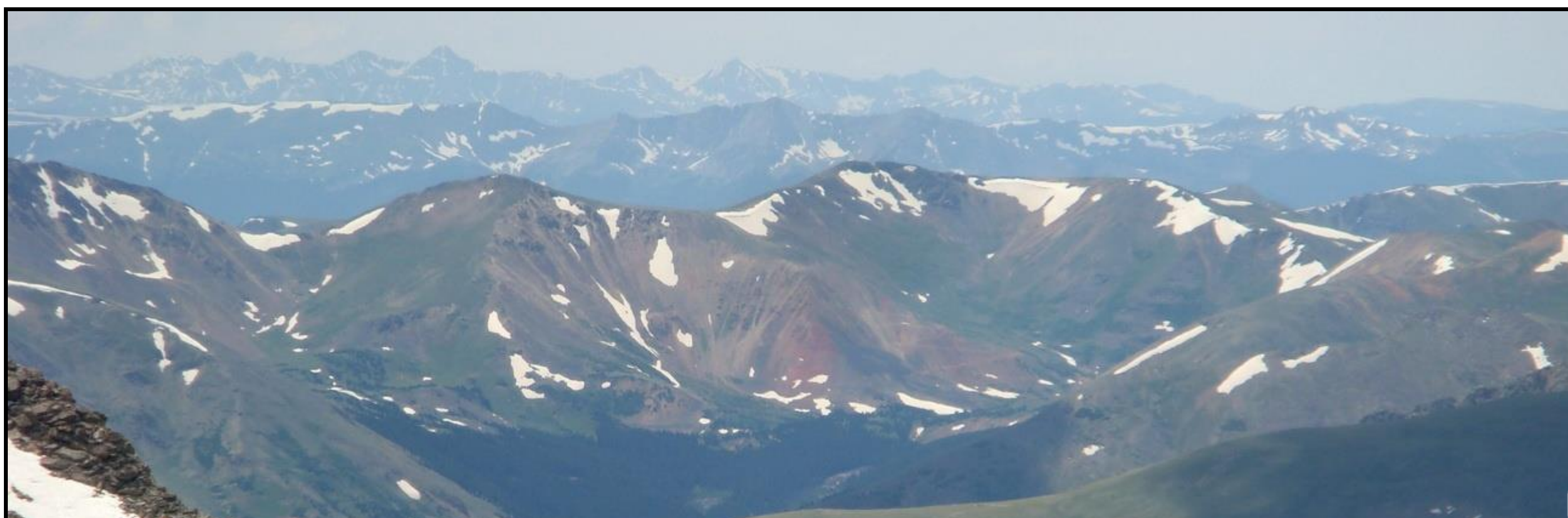
***Ronald L. Parker**, Senior Geologist*

Fronterra Geosciences

Denver, Colorado

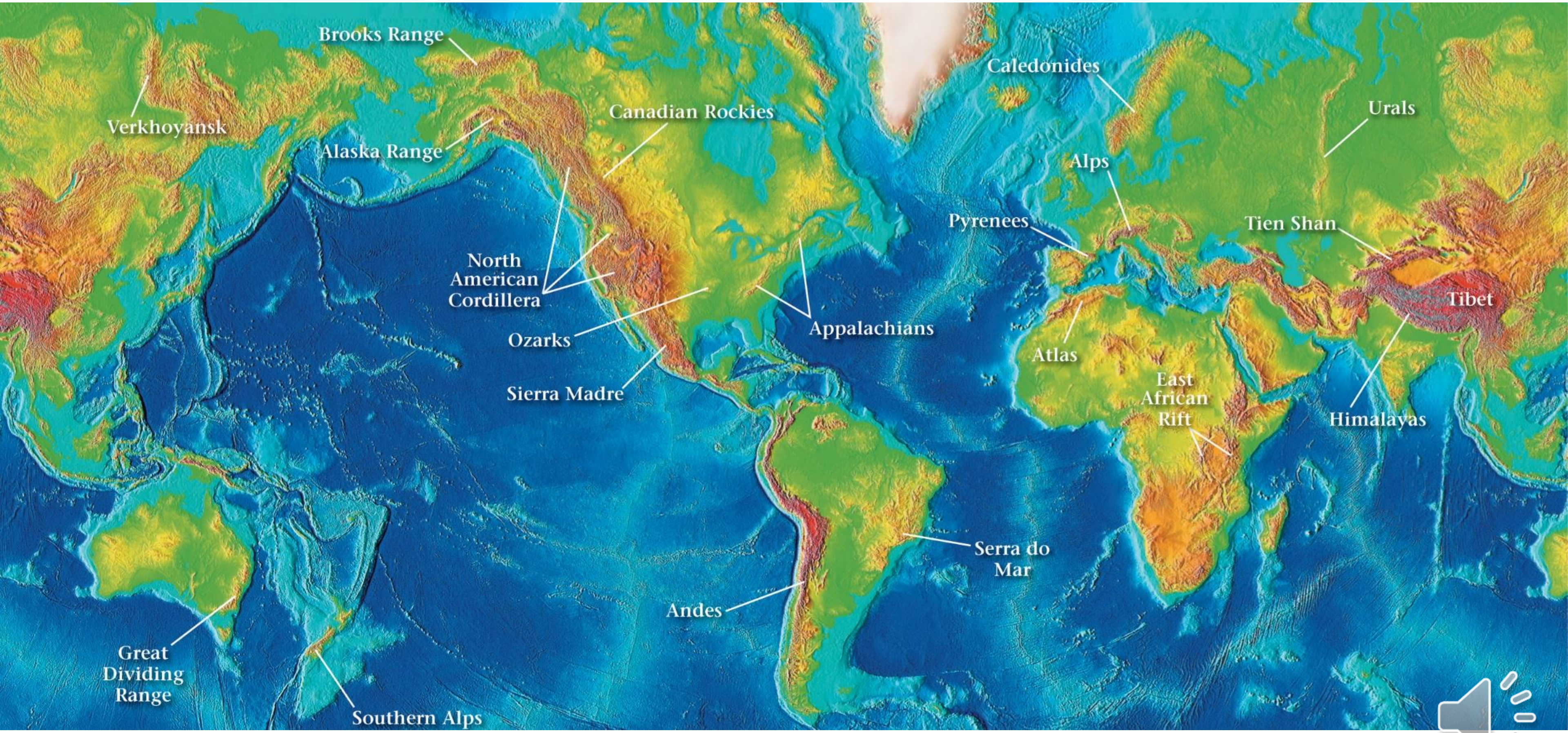
Mountains

- Mountains are attractive landscape features.
- They provide vivid evidence of tectonic activity.
- They are manifestations of geologic processes.
  - Uplift
  - Deformation
  - Metamorphism (Note: studying metamorphism can tell us much about the history of a mountain range.)



Mountains

- Mountains frequently occur in elongate, linear belts.
- Mountain building is a process called orogenesis.

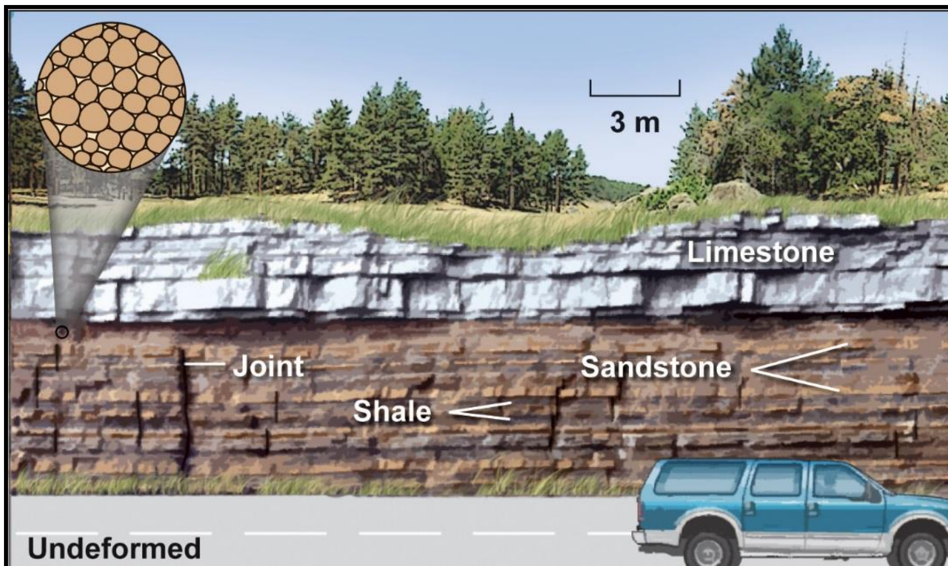


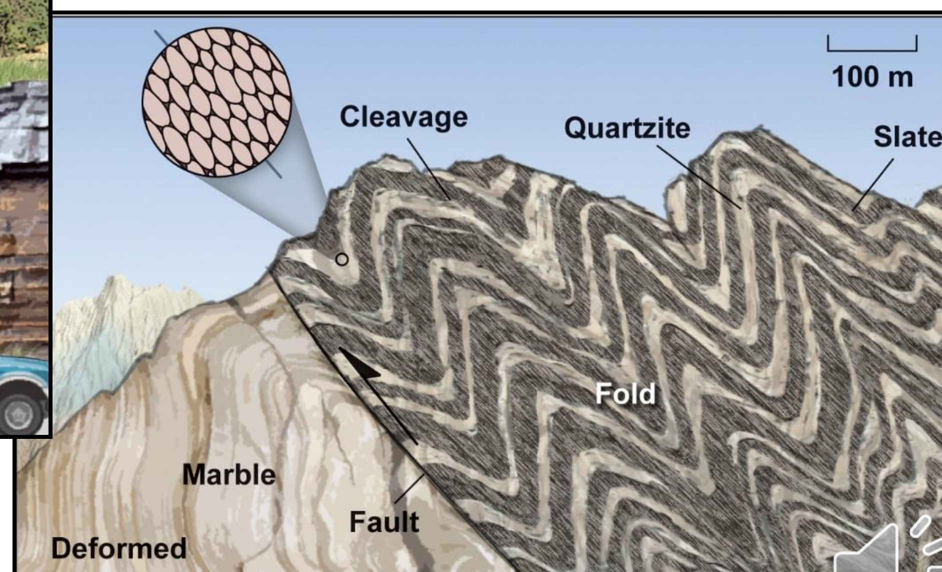
Orogenisis – the building of Mountains

- Mountains are born and have a finite life span.
  - Young mountains are high, steep, and still growing upward.
  - Middle-aged mountains are lowered by erosion.

Deformation

- Deformation changes the character of the rocks.
  - Undeformed (unstrained):
    - Horizontal beds, spherical sand grains, no folds or faults
  - Deformed (strained):
    - Tilted beds, metamorphic alteration, folding and faulting



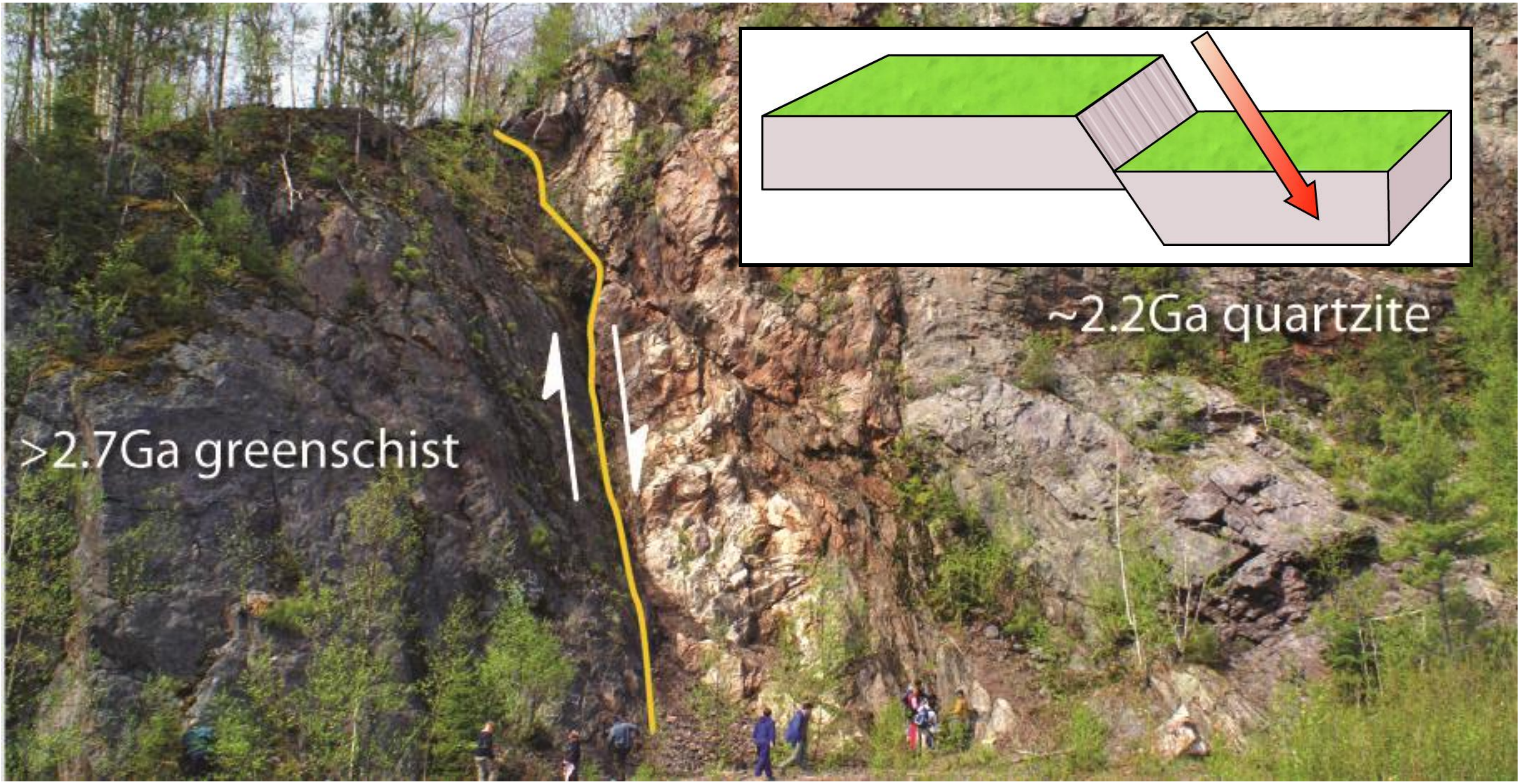


Deformation

- Deformation results in one or all of the following:
  - Displacement—change in location
  - Rotation—change in orientation
  - Distortion—change in shape
- Deformation is often easy to see.

Deformation

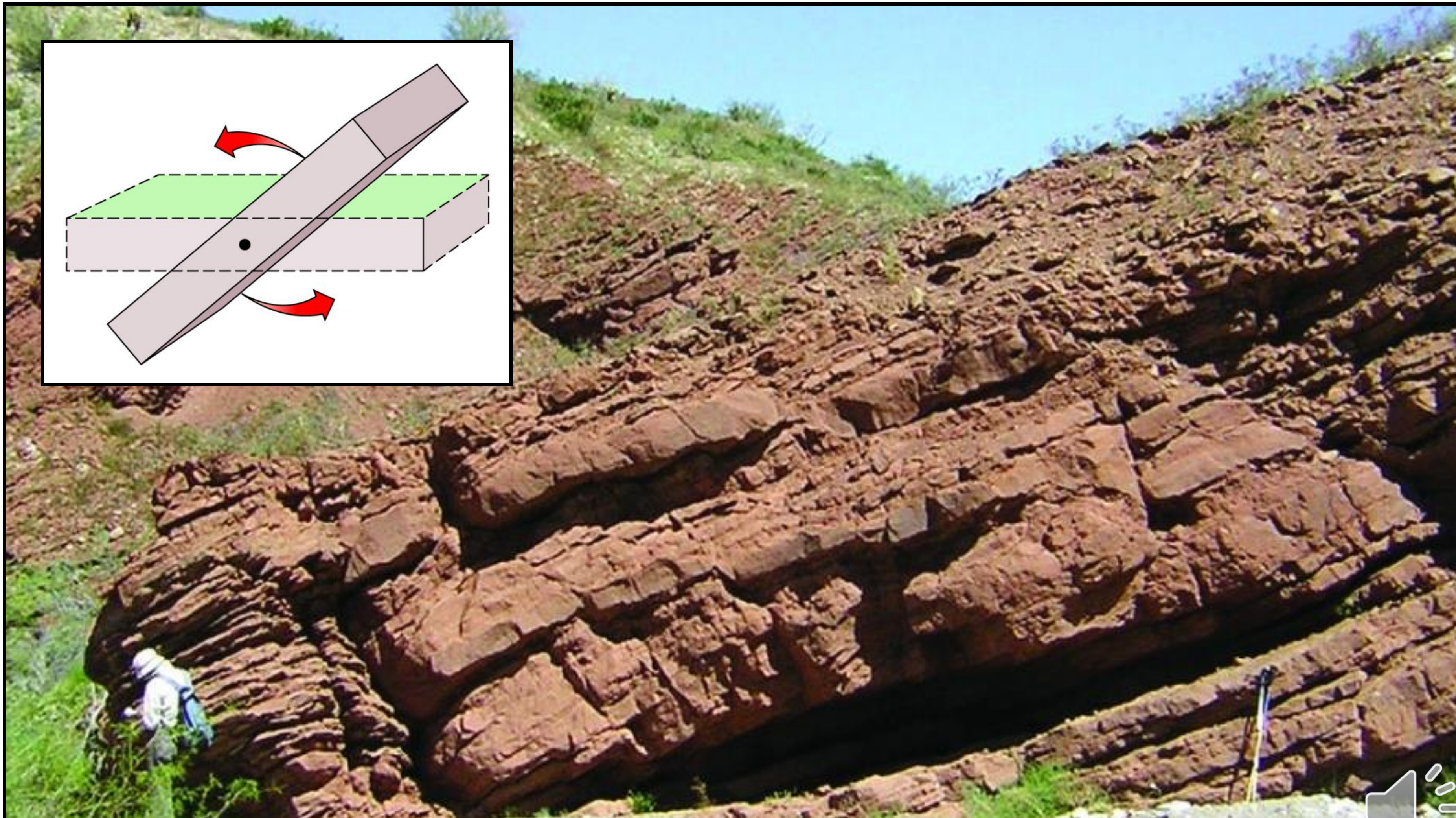
- **Displacement—change in location by faulting**



Greenschist: low grade metamorphic rock

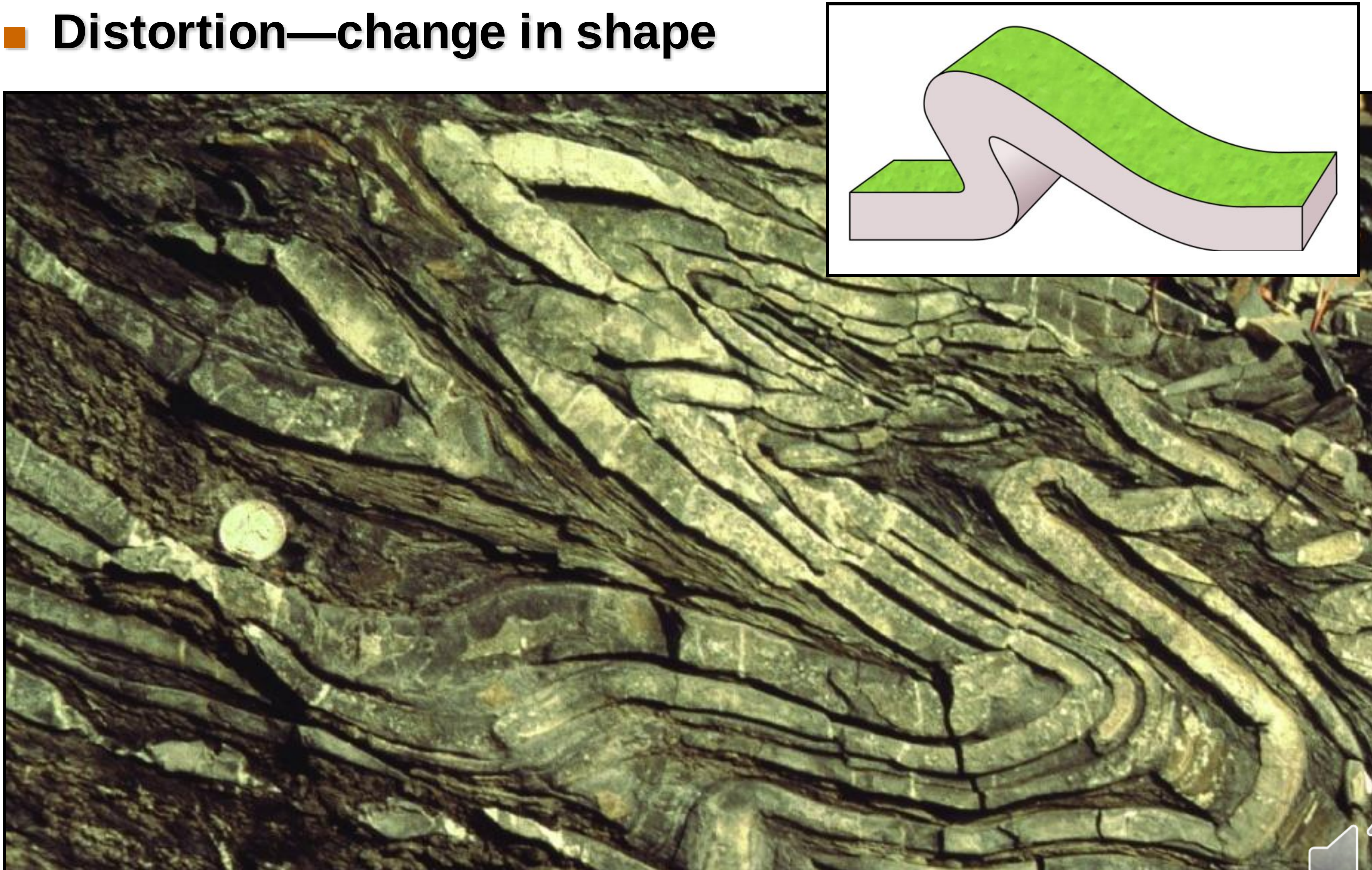
Deformation

- **Rotation—change in orientation**



Deformation

- **Distortion—change in shape**

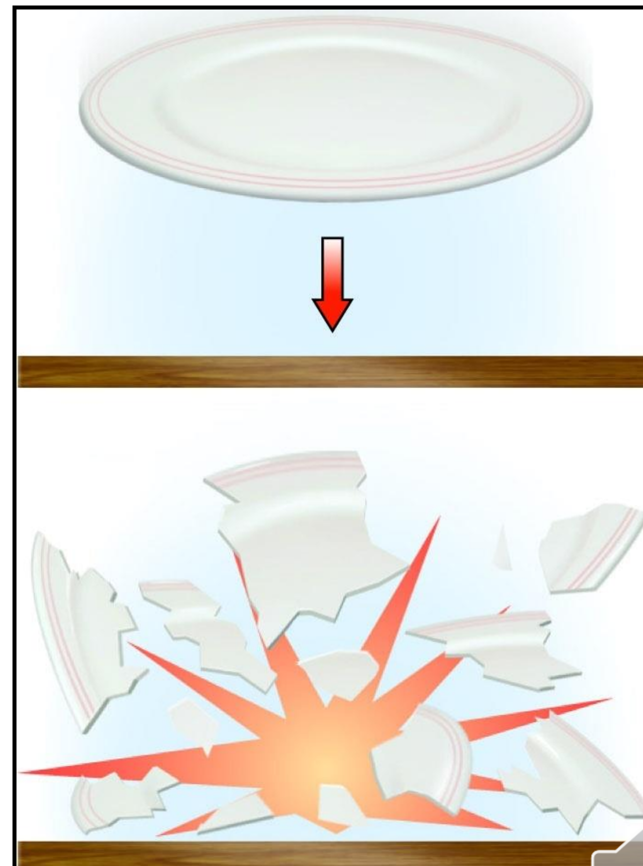


Brittle vs. Ductile Deformation

- **There are two major deformation types: brittle and ductile.**
  - **The type of deformation depends on:**
    - **Temperature**
    - **Pressure**
    - **Deformation rate**
    - **Composition**

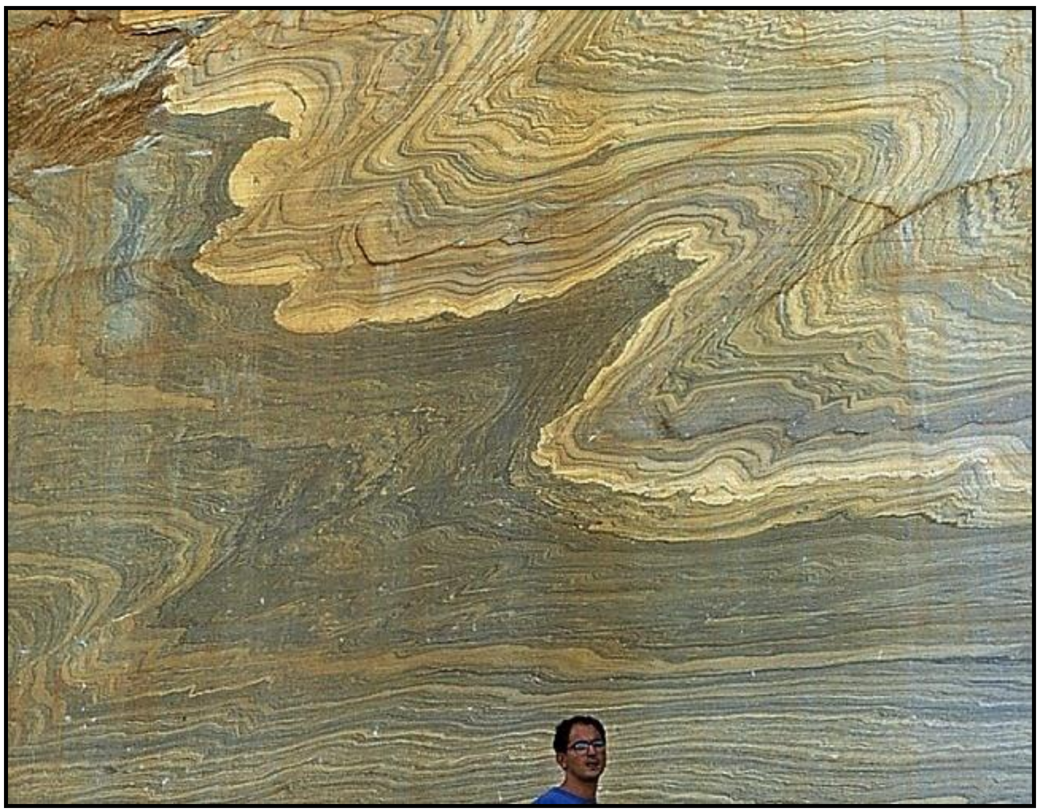
Brittle vs. Ductile Deformation

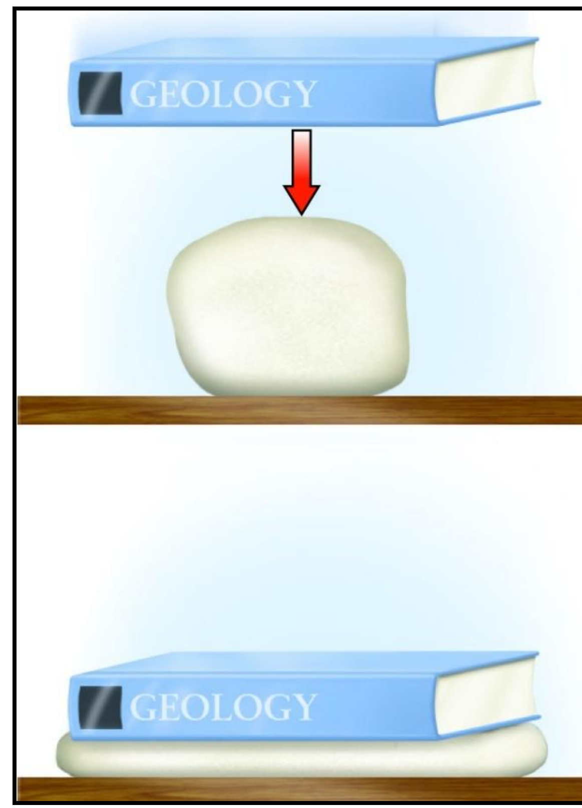
- **Brittle deformation—rocks break by fracturing.**
  - **Brittle deformation occurs in the shallow crust.**



Brittle vs. Ductile Deformation

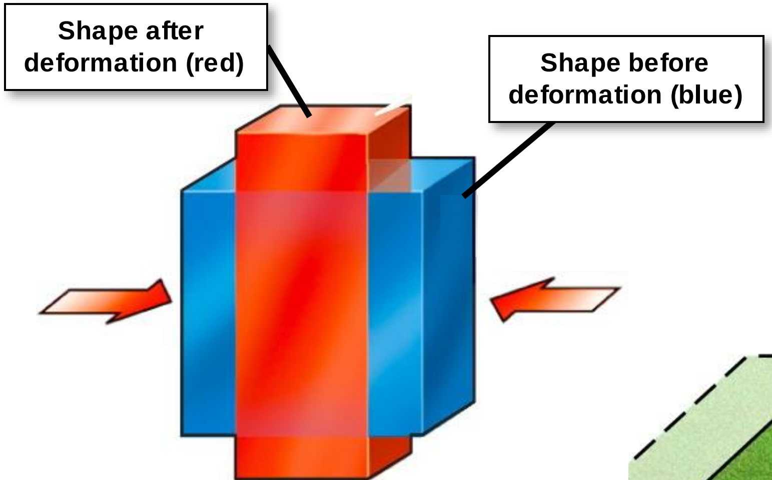
- Ductile—rocks deform by flowing and folding.
  - Occurs at higher P and T in the deeper crust.
- Transition to ductile deformation occurs at about 10–15 km depth in the continental crust.

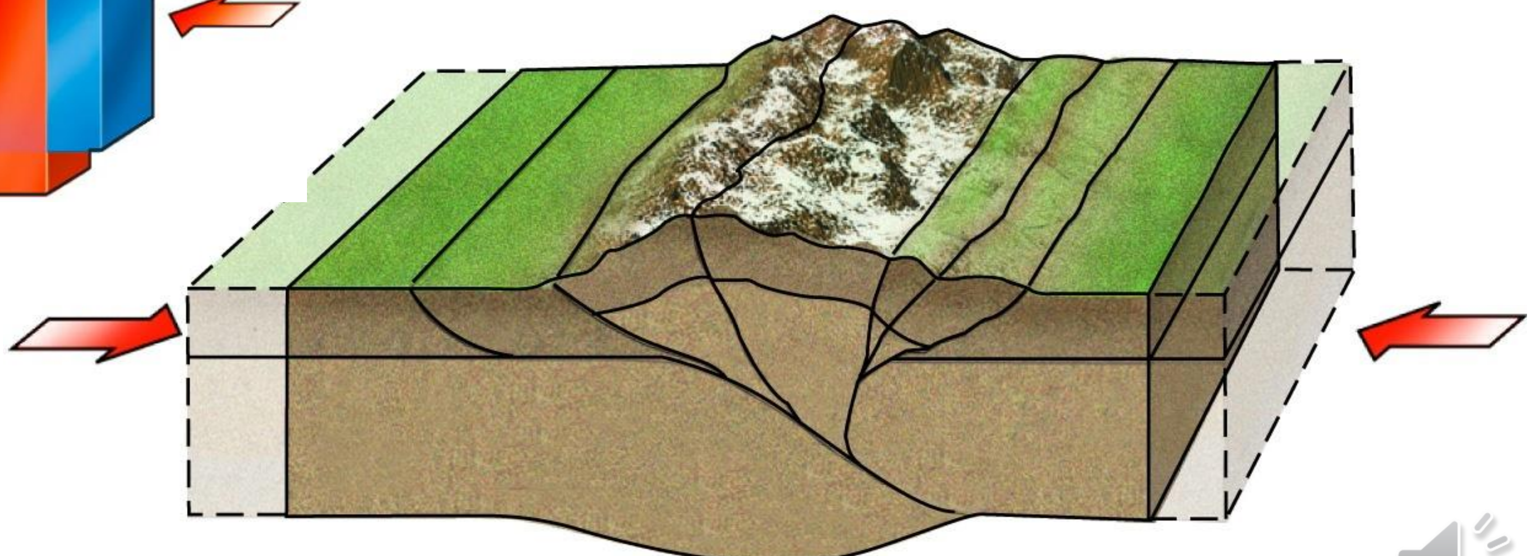




Stress, strain and fracture

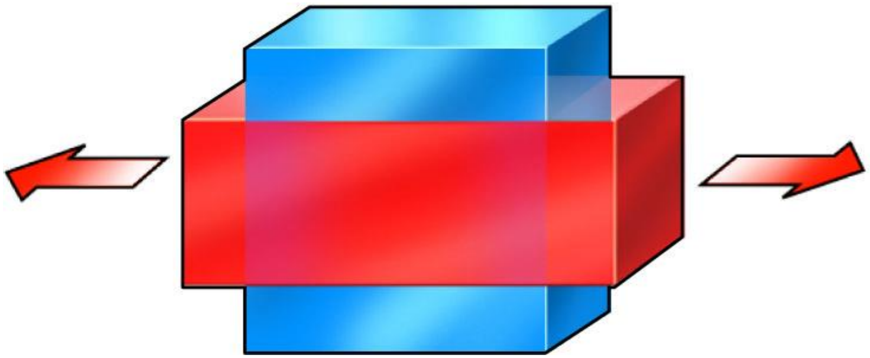
- Compression takes place when an object is squeezed.
  - Horizontal compression drives collision.
    - Shortens and thickens material.

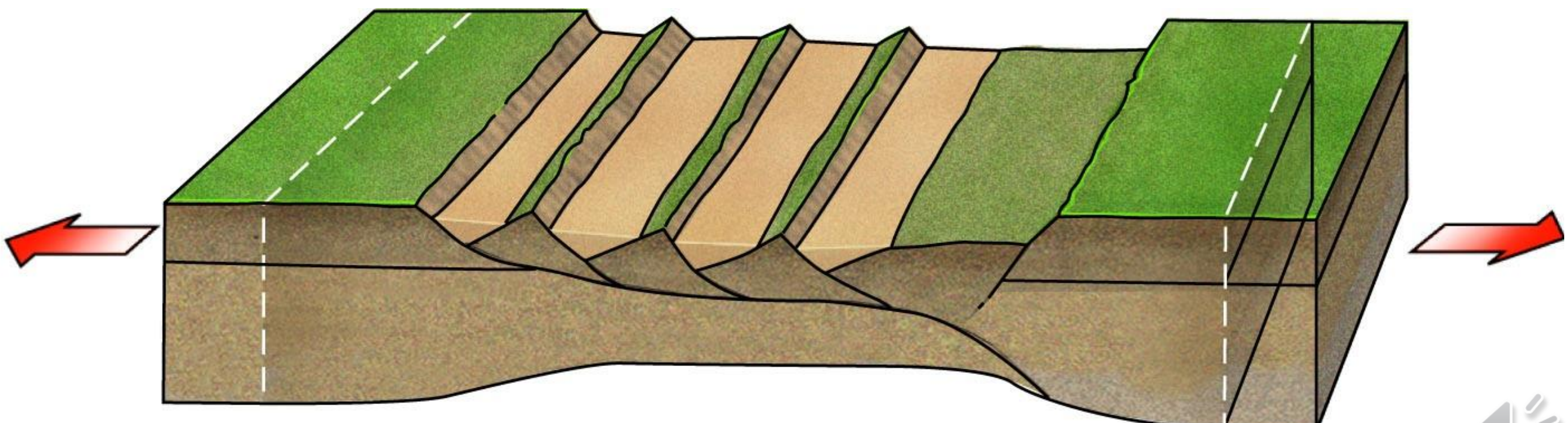




Stress

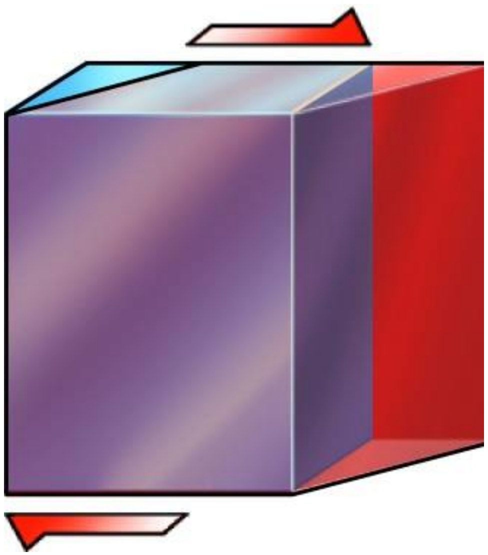
- Tensions occur when the ends of an object are pulled apart.
  - Horizontal tension drives crustal rifting.
    - Stretches and thins material.

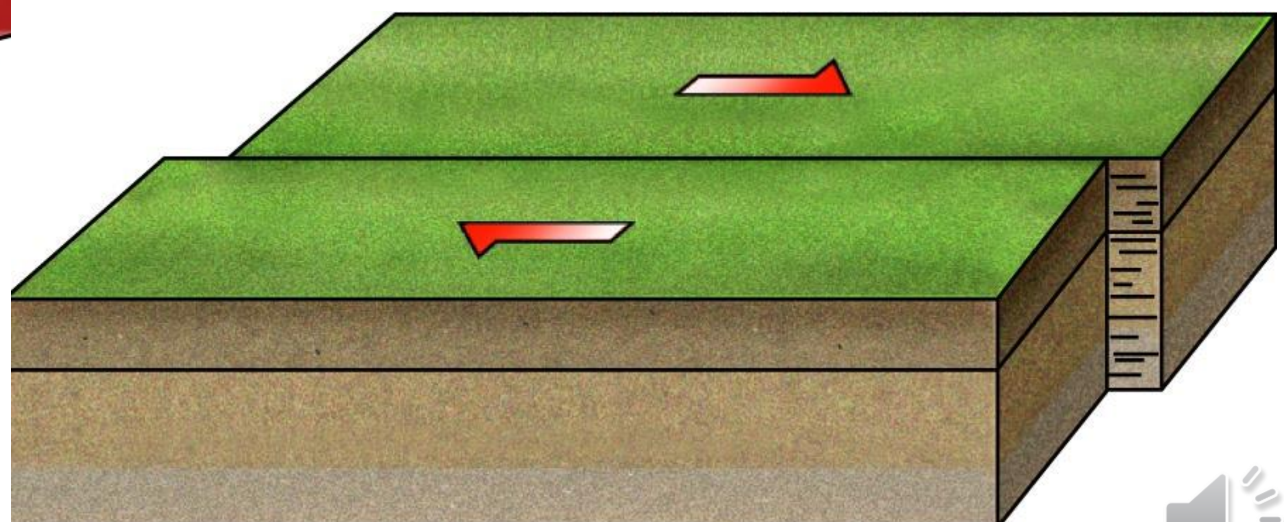




Stress

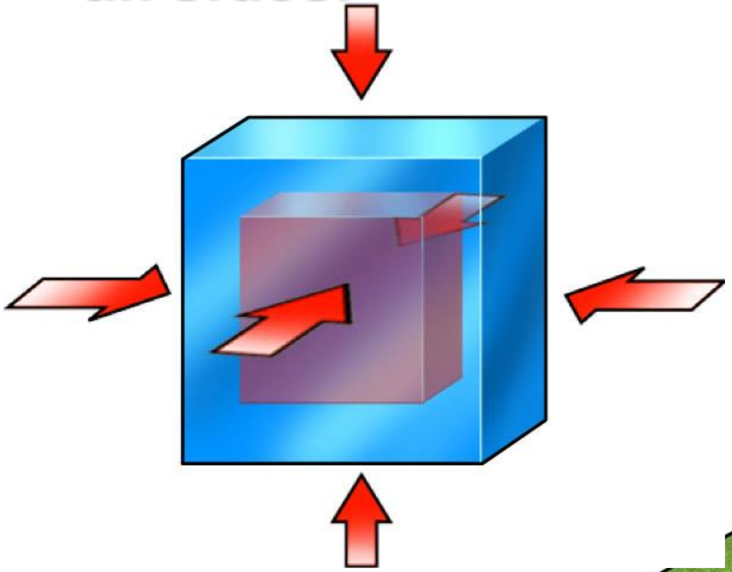
- Shear develops when surfaces slide past one another.
  - Shear stress neither thickens nor thins the crust.

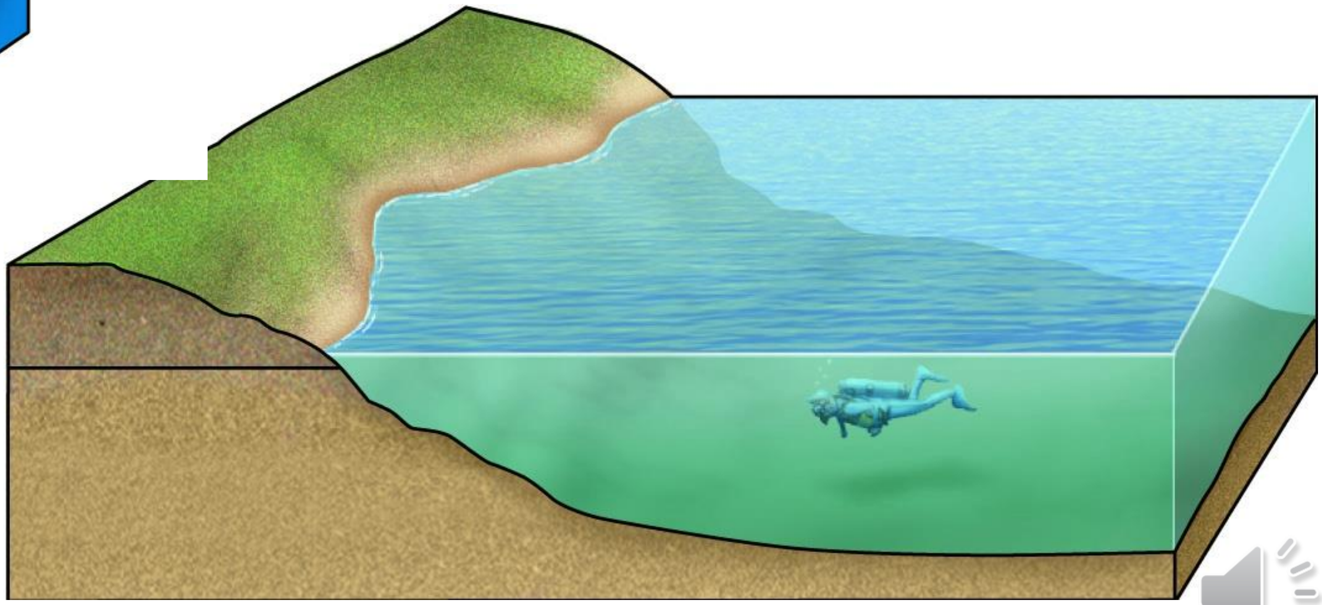




Stress

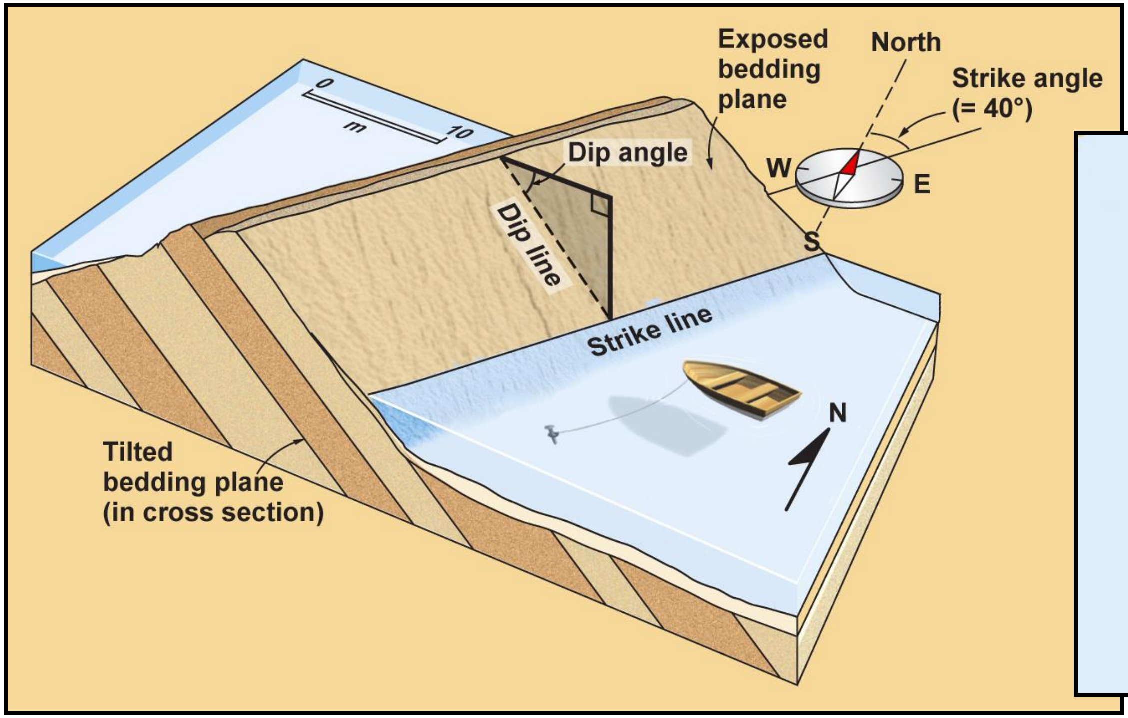
- **Pressure occurs when an object feels the same stress on all sides.**

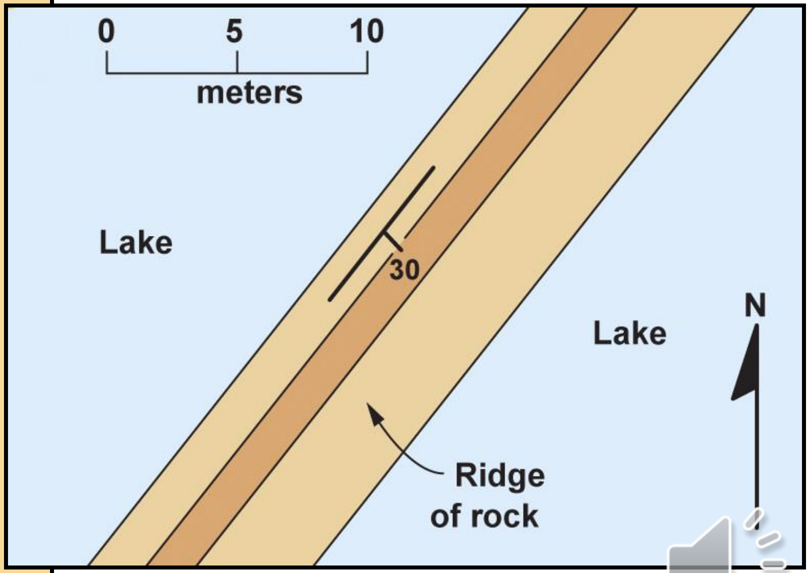




Geologic Structures

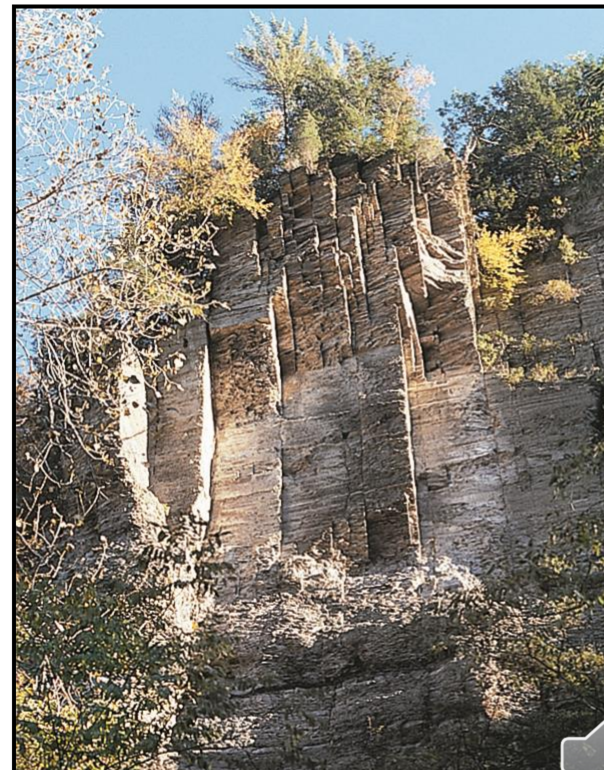
- Geometric features are created during rock deformation.
  - Planar and linear features are present in deformed rock.
- The 3-D orientation of a plane is described by strike and dip.
  - Strike—horizontal intersection with a tilted surface.
  - Dip—the angle of the surface down from the horizontal.





Joints and Veins

- Joints are planar rock fractures without any offset.
- They develop from tensile tectonic stress in brittle rock.
  - Systematic joints occur in parallel sets.
- Joints often control weathering of the rock they occur in.



Joints and Veins

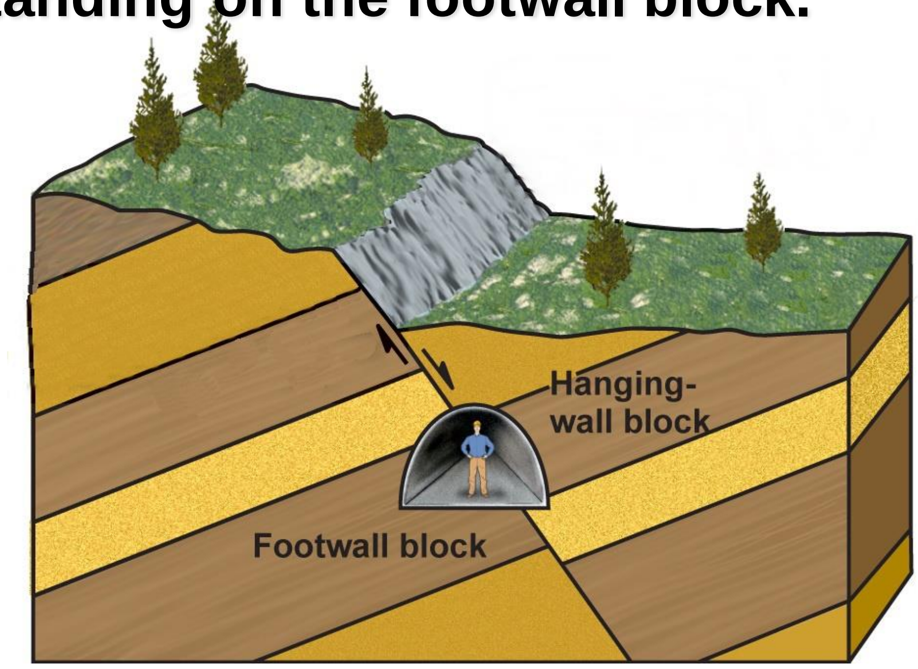
- Groundwater often flows through joints.
- Dissolved minerals in groundwater precipitate in joints.
- Joints filled with minerals are called veins.

Faults

- Faults are planar fractures showing displacement.
  - They are abundant in the crust and occur at all scales.
  - Sudden movements along faults cause earthquakes.
  - Faults can be active or inactive.

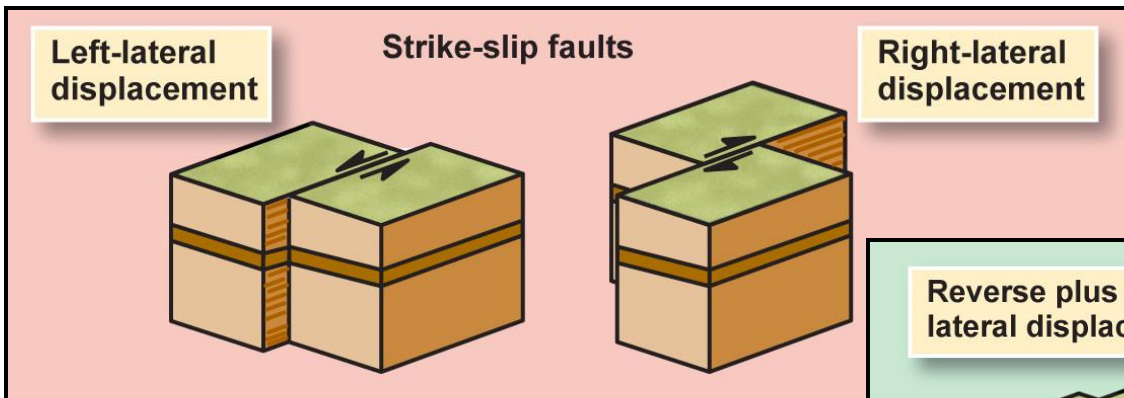
Fault Orientation

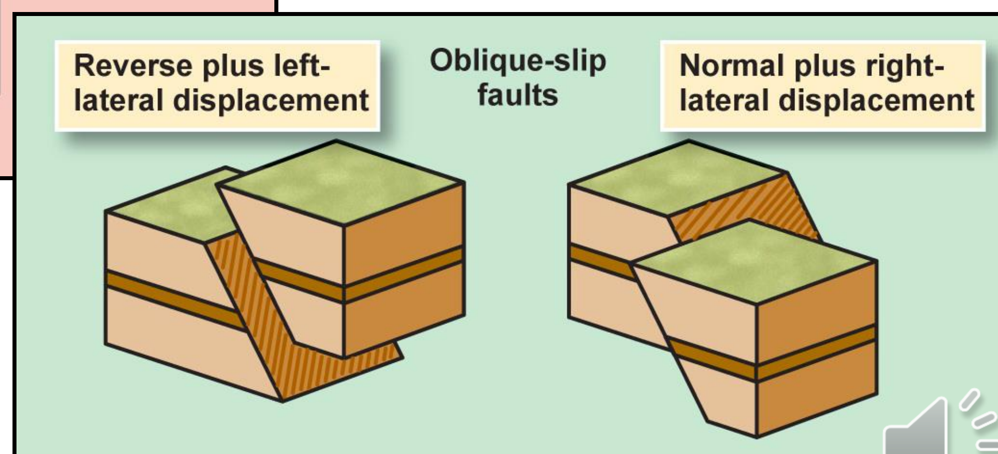
- On a dipping fault, the blocks are classified as the:
  - Hanging-wall block (above the fault), and the
  - Footwall block (below the fault).
- When you stand in a tunnel excavated along the fault:
  - Your head is near the hanging-wall block.
  - You are standing on the footwall block.



Fault Classification

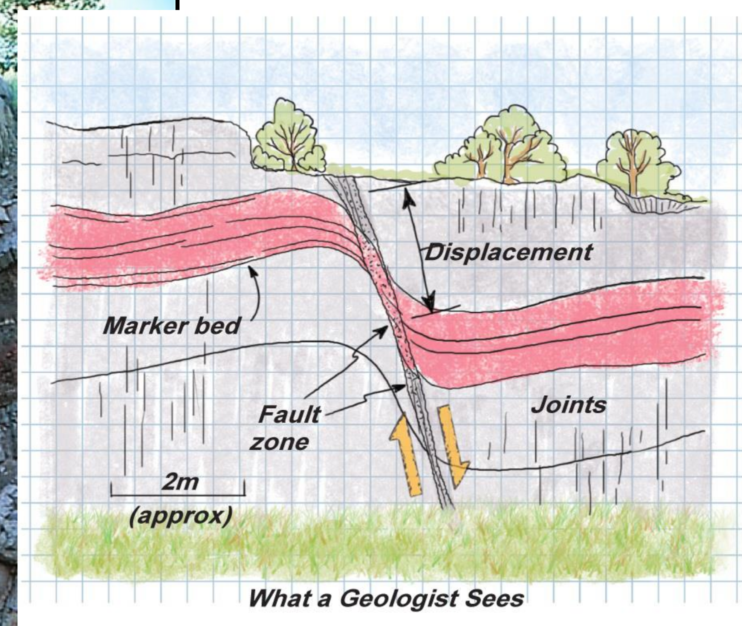
- Fault geometry varies—vertical, horizontal, dipping.
- The relative motion of the offset blocks varies.
  - Dip slip—blocks move parallel to the dip of the fault.
  - Strike slip—blocks move parallel to fault plane strike.
  - Oblique slip—components of both dip slip and strike slip.





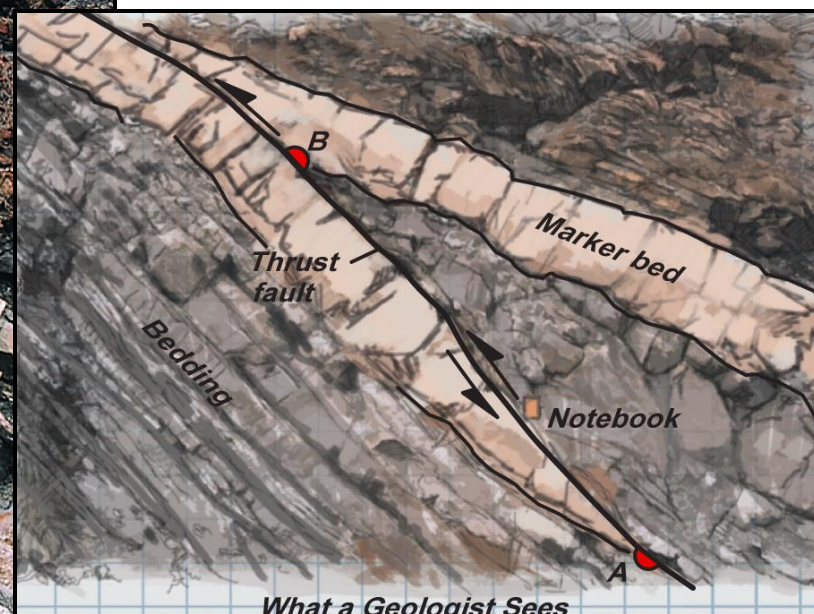
Normal Faults

- The hanging wall moves down relative to the footwall.
- They accommodate crustal extension (pulling apart).
- The fault below shows displacement and drag folding.



Reverse and Thrust Faults

- The hanging wall moves up relative to the footwall.
- Reverse faults—fault dip is steeper than 35º.
- Thrust faults—fault dip is less than 35º.
- They accommodate crustal shortening (compression).

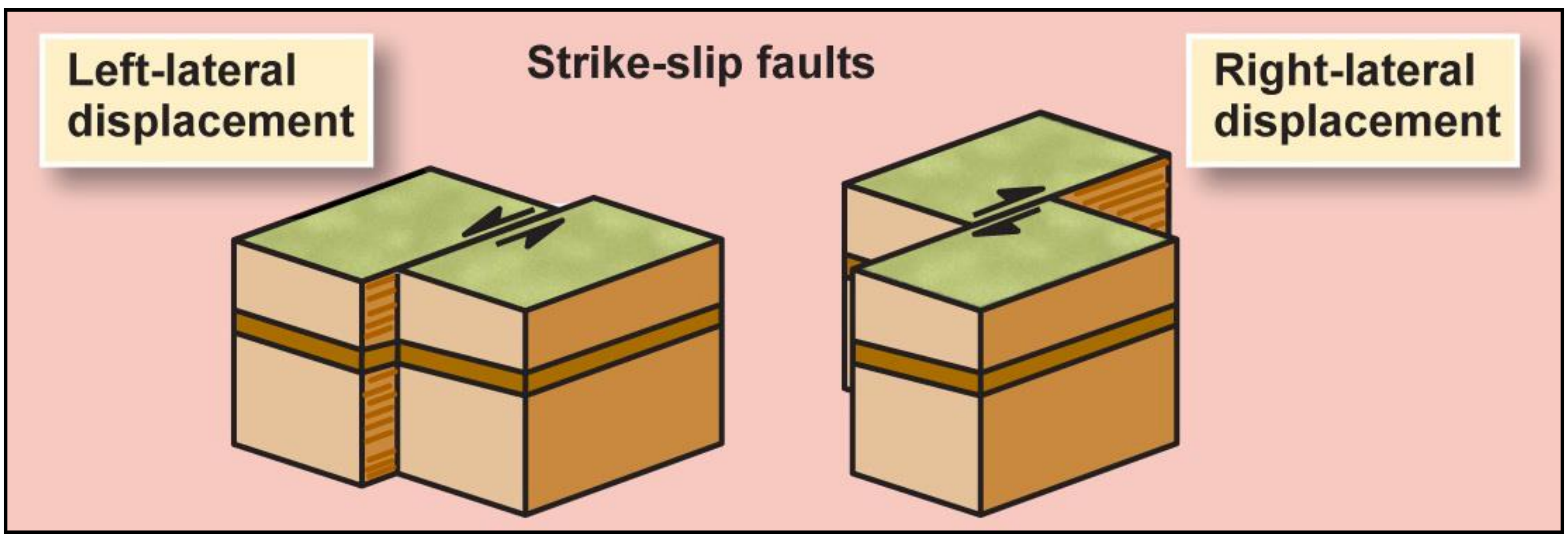


Thrust Faults

- Reverse fault with a gentle dip
- Results in crustal shortening.
- Often the result of continental collisions.

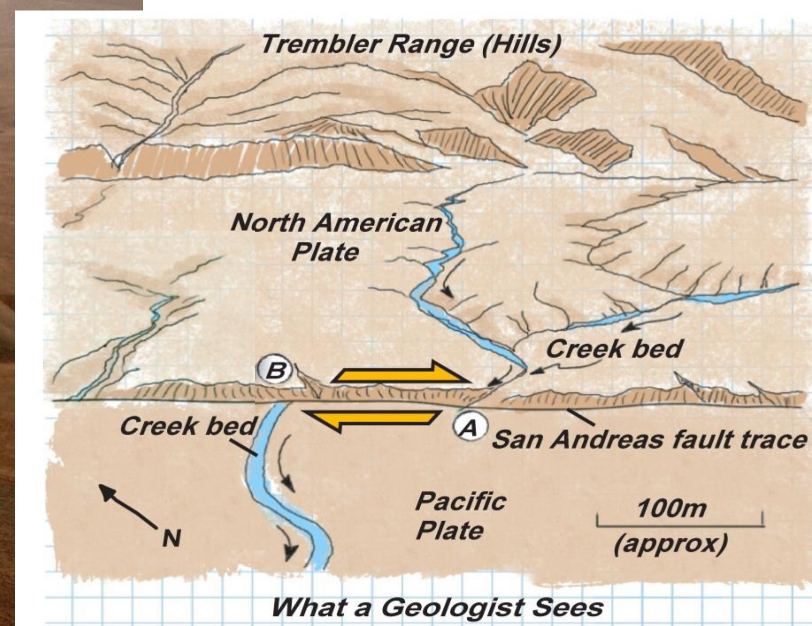
Strike-Slip Faults

- Fault motion is parallel to the strike of the fault.
- Usually vertical, no hanging-wall/footwall blocks.
- Classified by the relative sense of motion.
  - Right lateral—opposite block moves to observer's right.
  - Left lateral—opposite block moves to observer's left.
- Large strike-slip faults may slice the entire crust.



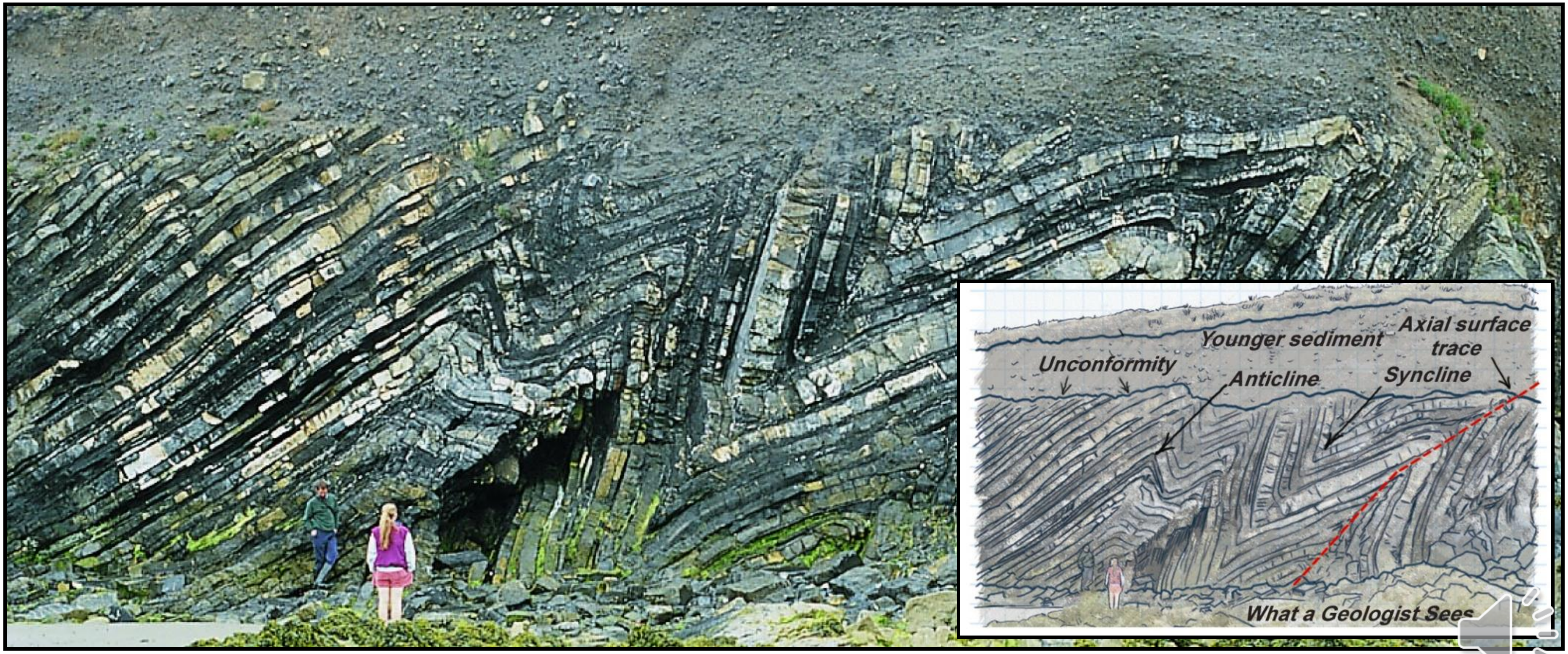
Faults

- Faults may offset large blocks of Earth.
- The amount of offset is a measure called displacement.
- The San Andreas (below)—displacement of hundreds of kms.



Ductile Deformation

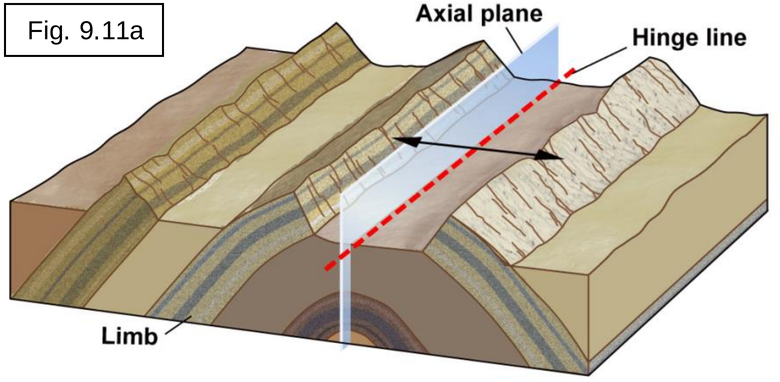
- Layered rock may be deformed into complex folds.
- Folds occur in a variety of shapes, sizes, and geometries.
- Orogenic settings produce large volumes of folded rock.
- Folded rock may record multiple events of deformation.



Fold Geometry

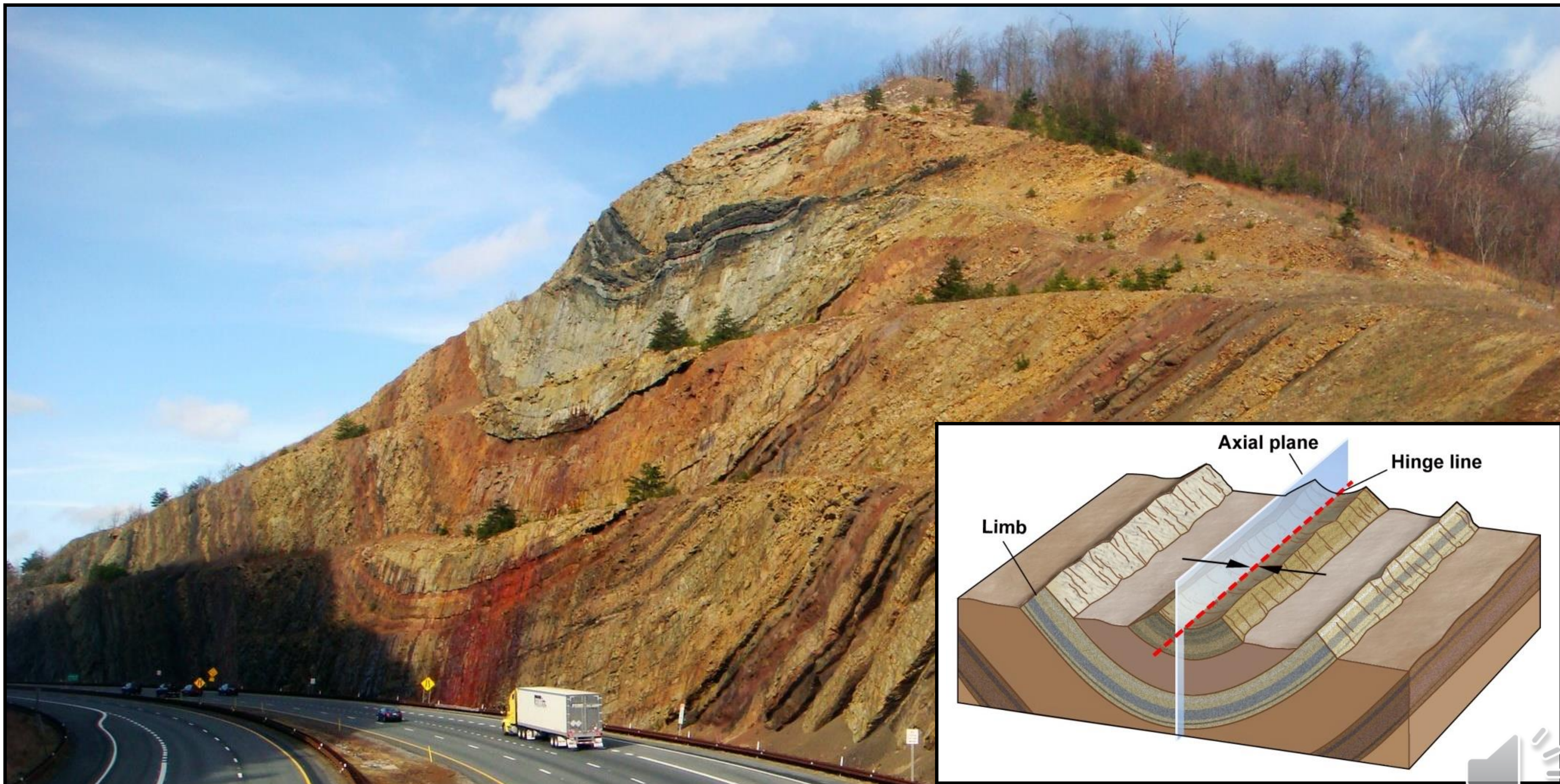
- An anticline is a fold that looks like an arch.
  - The limbs dip out and away from the hinge.

Fig. 9.11a



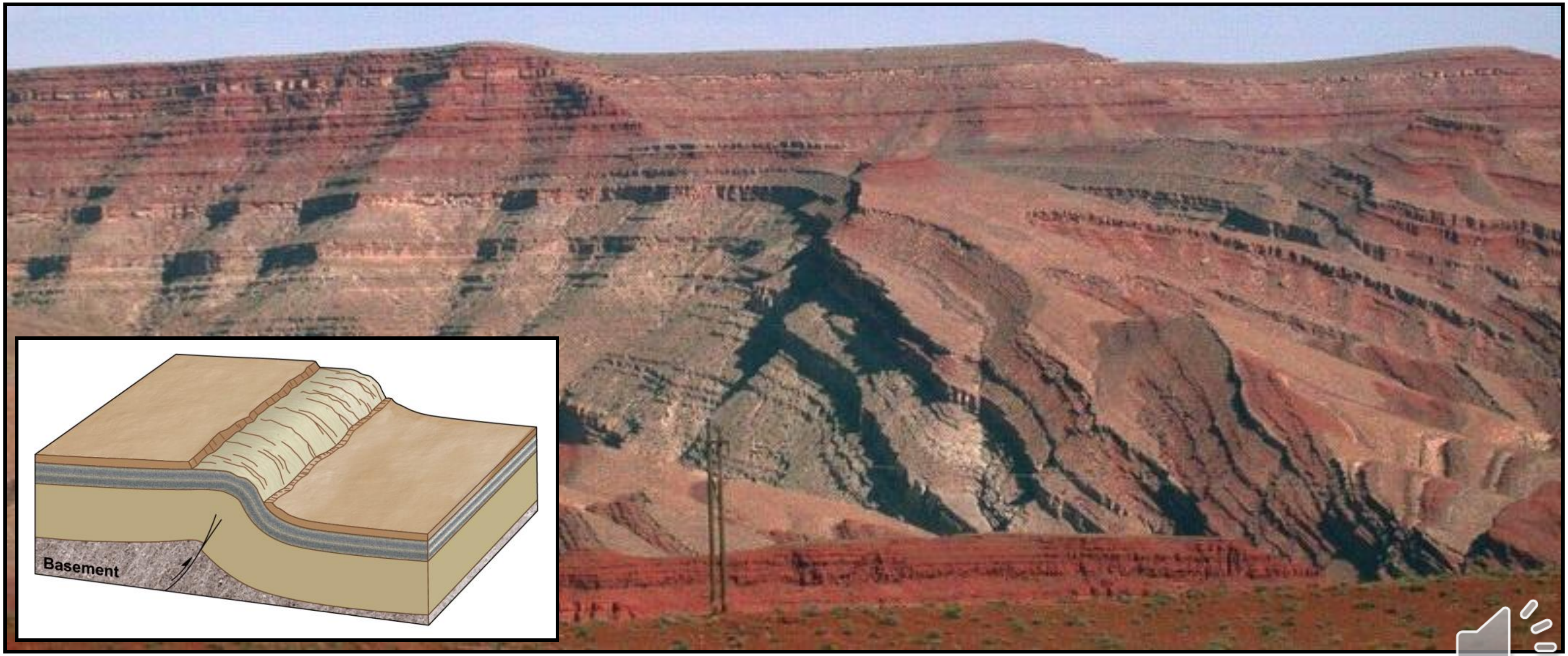
Fold Geometry

- A syncline is a fold that opens upward like a trough.
  - The limbs dip inward and toward the hinge.



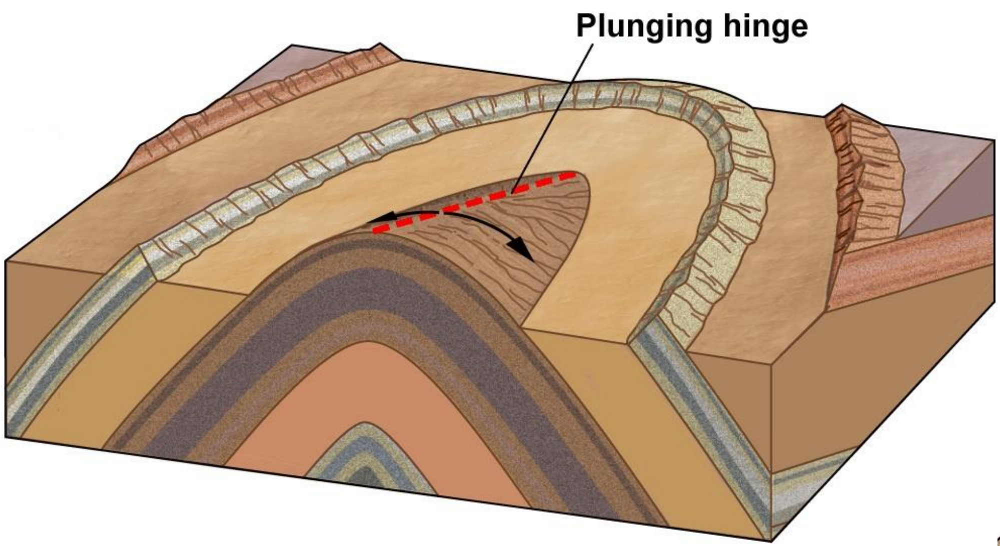
Fold Geometry

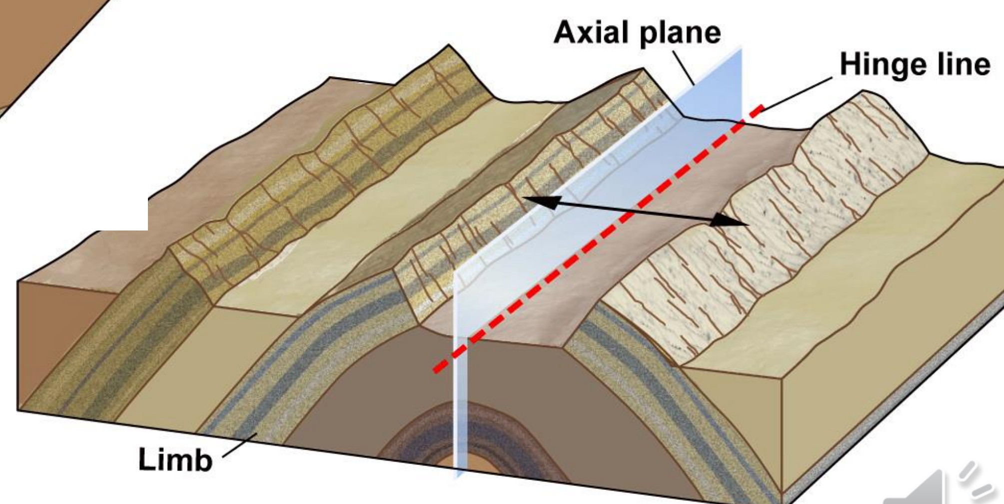
- A monocline is a fold-like carpet draped over a stair step.
  - These faults do not cut through to the surface.
  - Displacement folds the overlying sedimentary cover.



Fold Geometry

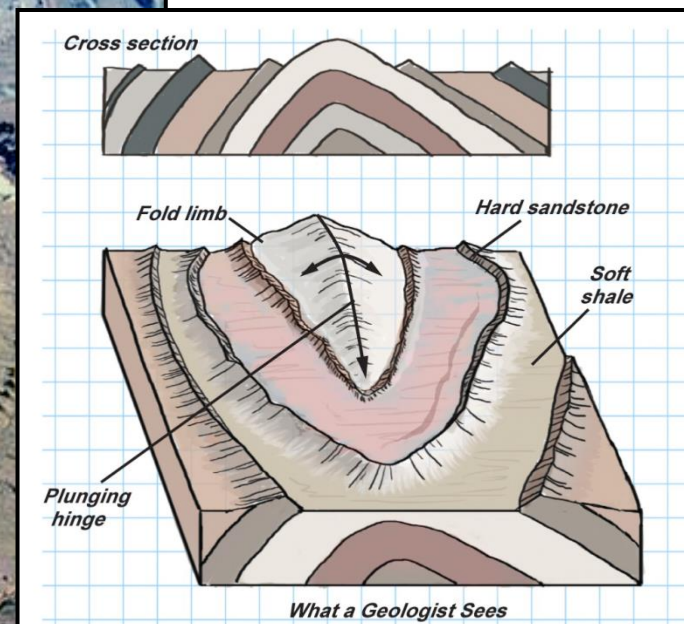
- Folds are described by the geometry of the hinge.
  - A plunging fold has a hinge that is tilted.
  - A nonplunging fold has a horizontal hinge.





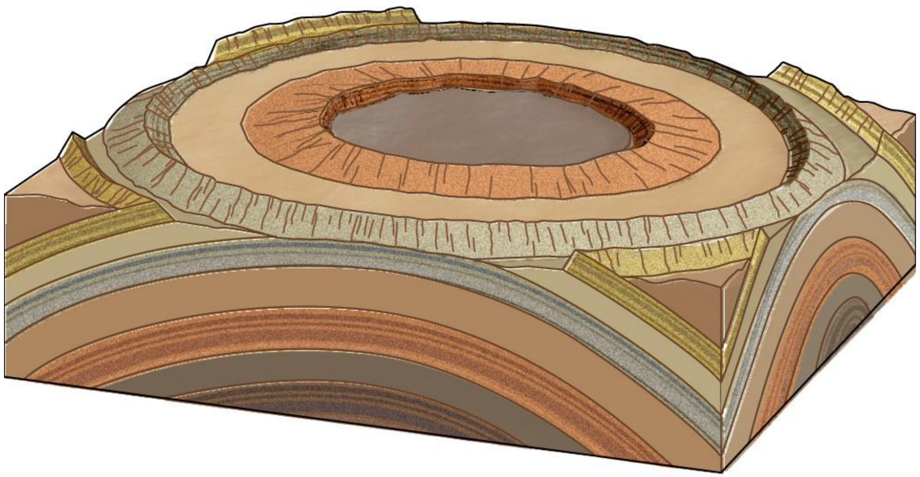
Fold Geometry

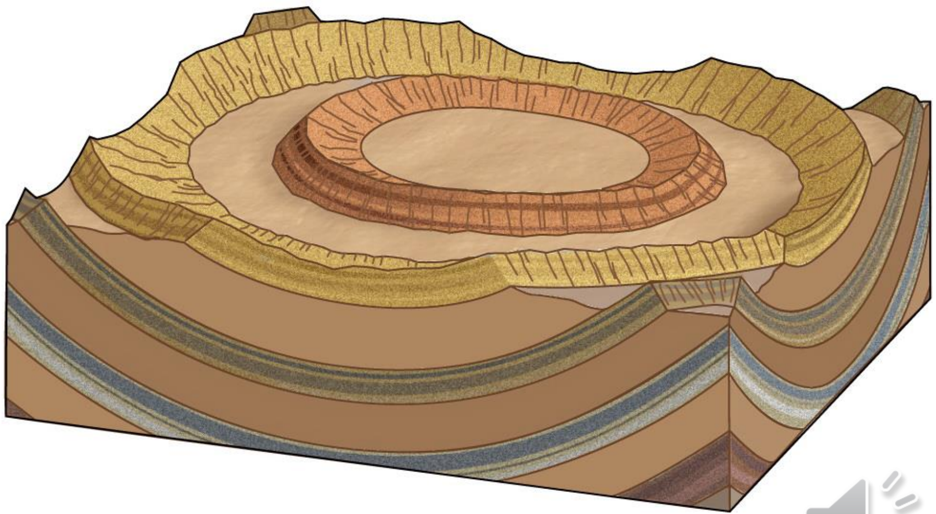
- Sheep Mountain, Wyoming, is a plunging fold.
- Large plunging folds create prominent landforms.
  - Resistant sandstones form highs; eroded shales are lows.



Fold Geometry

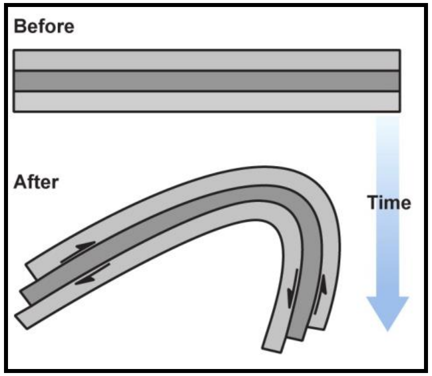
- Some large folds yield a circular outcrop pattern.
  - A dome is a fold that looks like an overturned bowl.
  - A basin is a fold shaped like an upright bowl.
- Despite circular landforms, these are quite different.
    - A dome exposes older rocks in the center.
    - A basin exposes younger rocks in the center.

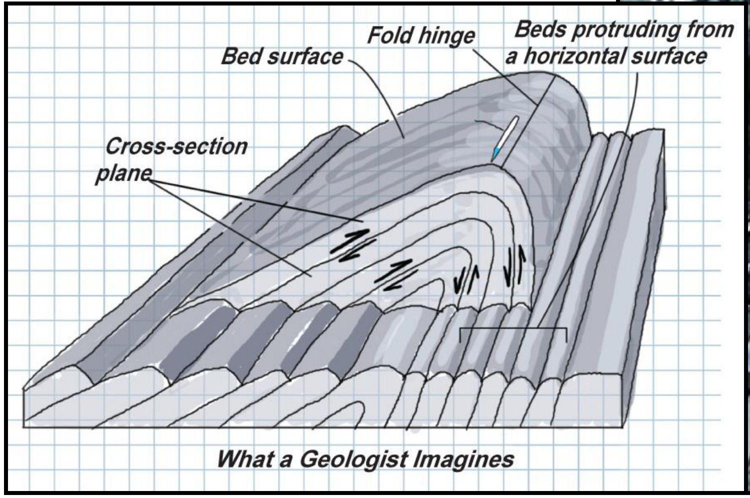




Forming Folds

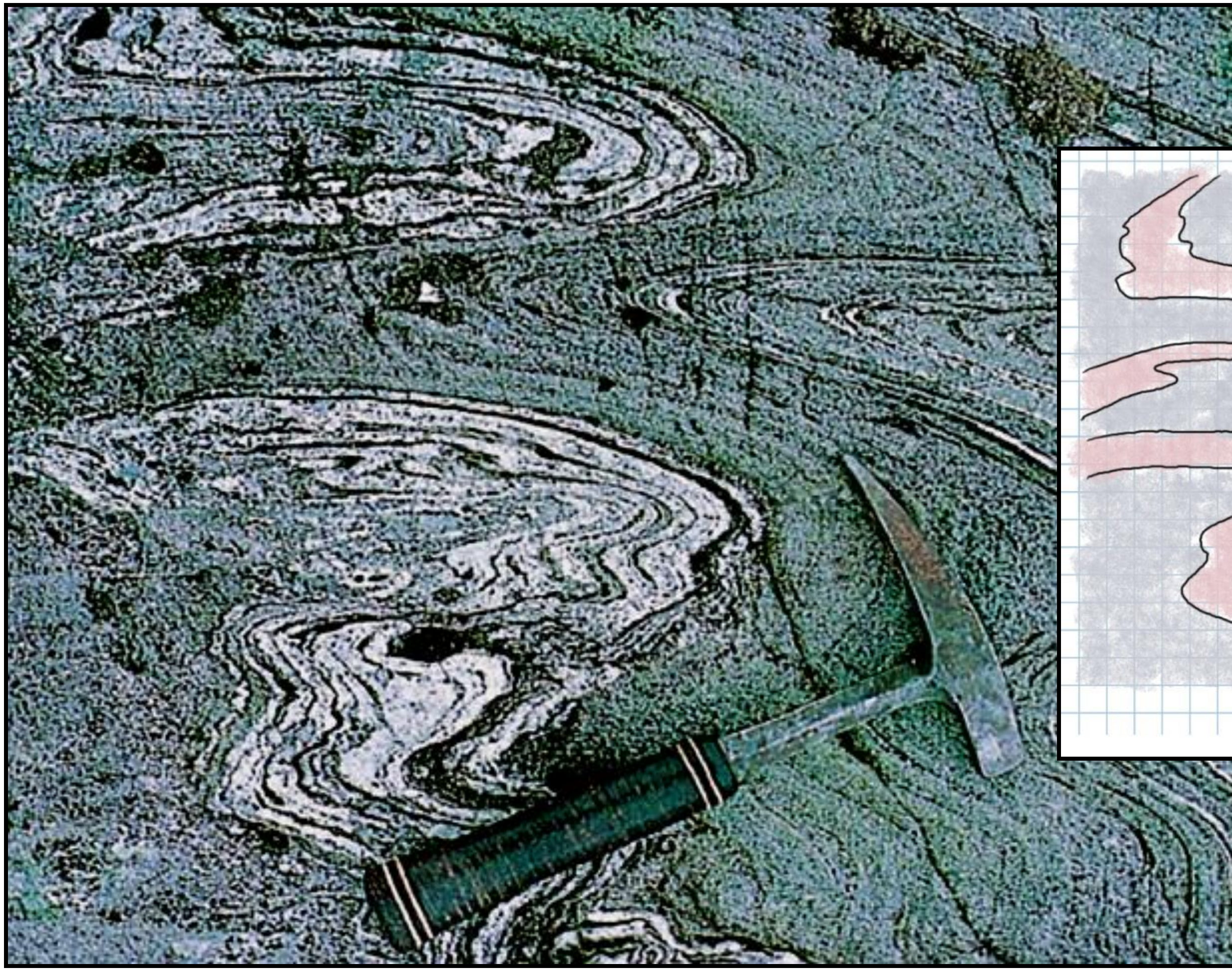
- Folds develop in two ways: flexural slip and passive flow.
  - In flexural slip, layers slide past one another.
  - It is like the movement when a deck of cards is bent.

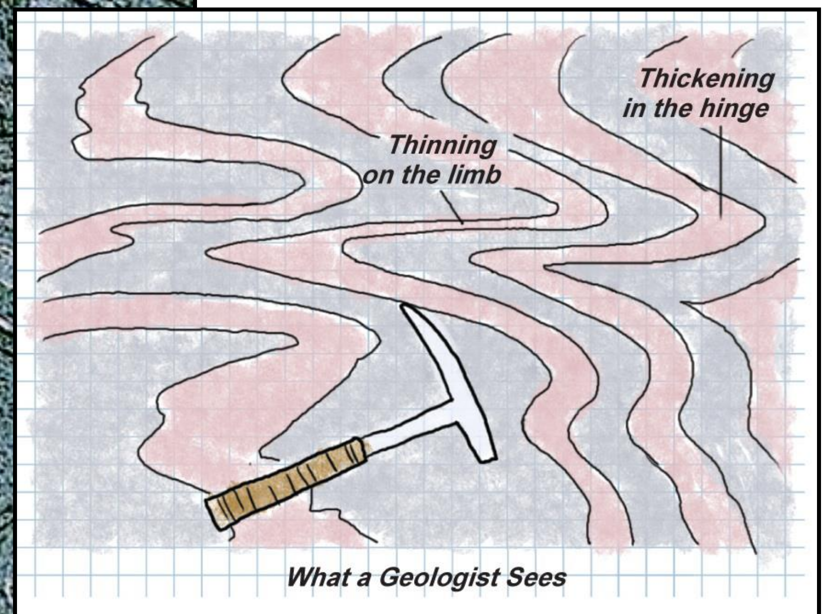




Forming Folds

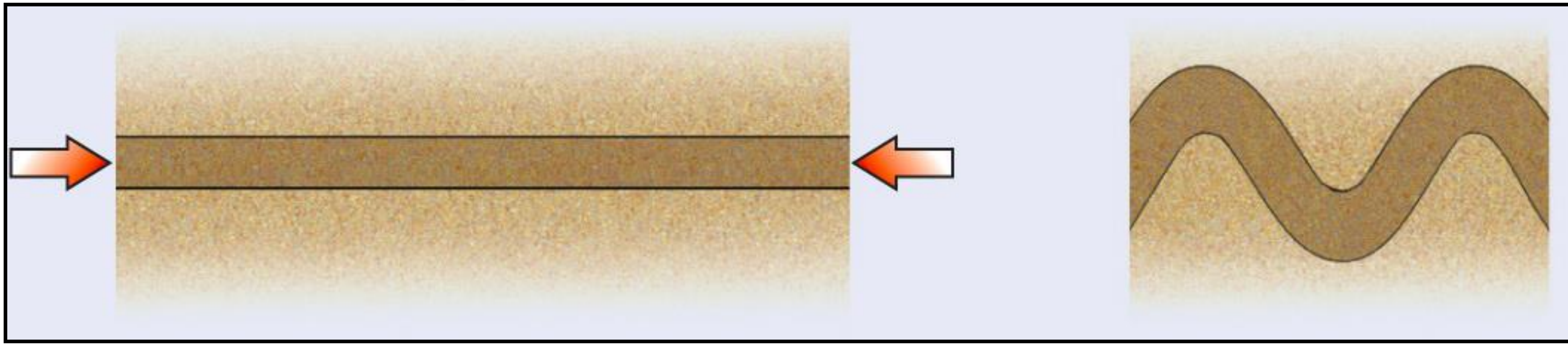
- Folds develop in two ways: flexural slip and passive flow.
  - Passive-flow folds form in hot, soft, ductile rock at high T.



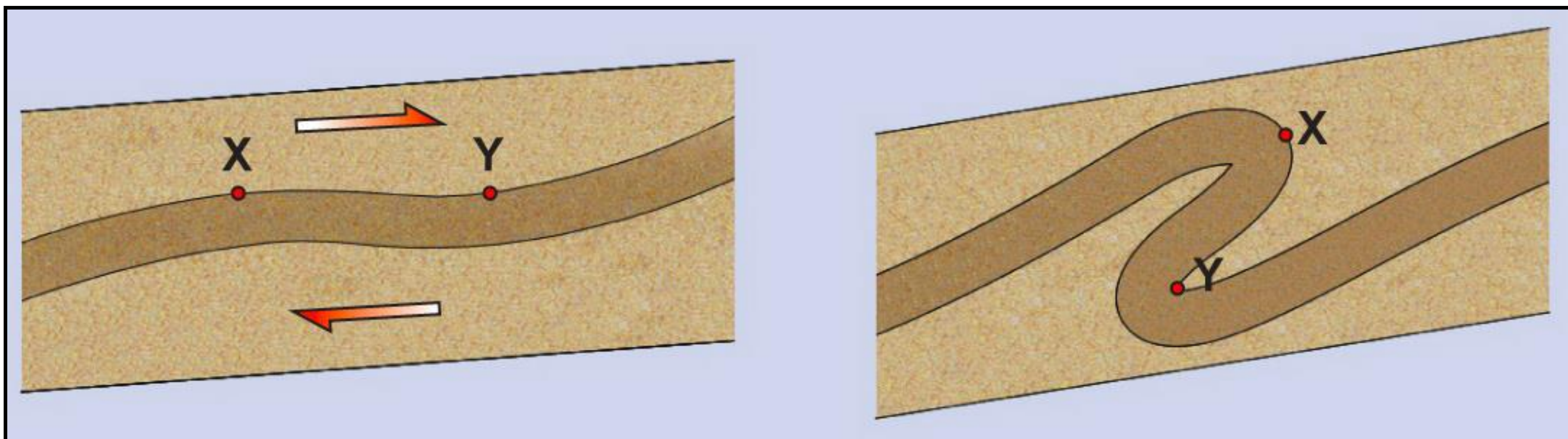


Forming Folds

- Horizontal compression causes rocks to buckle.



- Shear causes rocks to fold over on themselves.

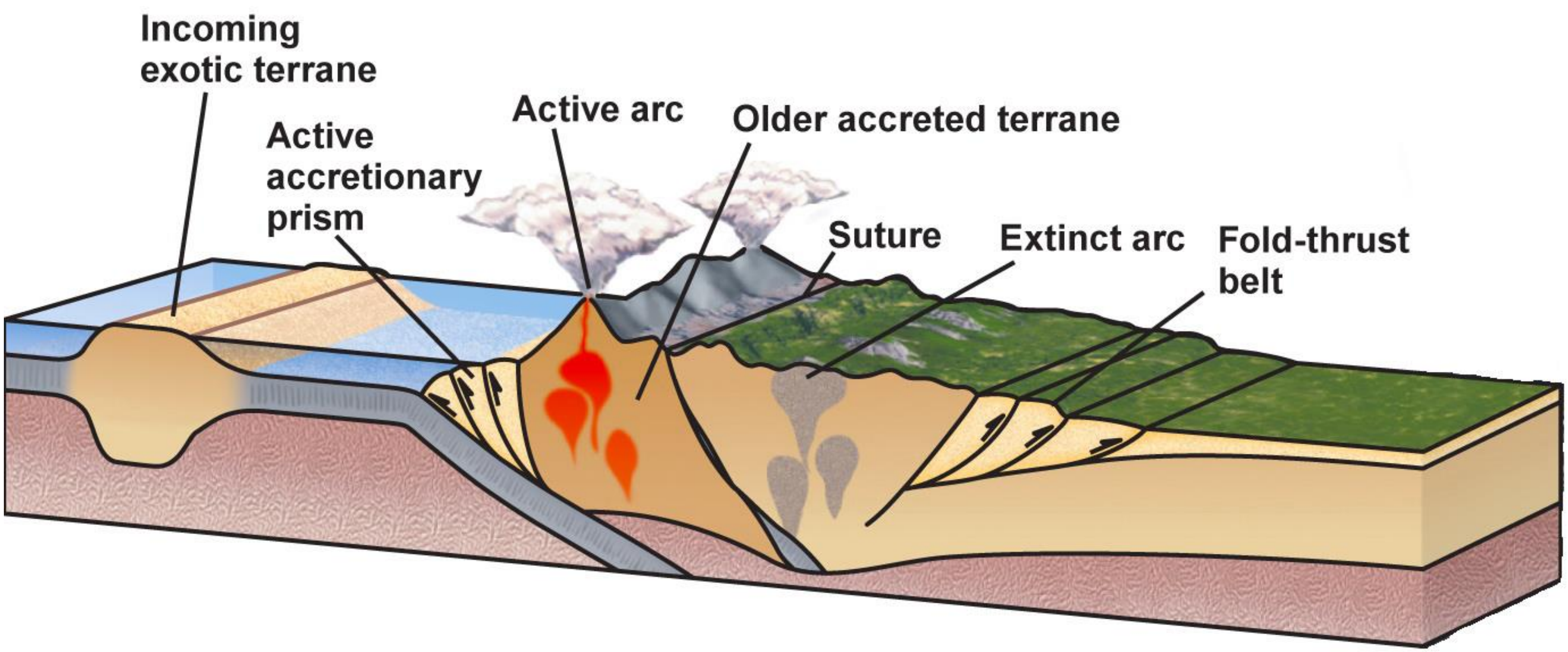


Mountain Building

- Mountain uplift is driven by plate tectonics.
  - Convergent plate boundaries
  - Continental collisions
  - Rifting
- Linear plate boundaries make linear mountain belts.

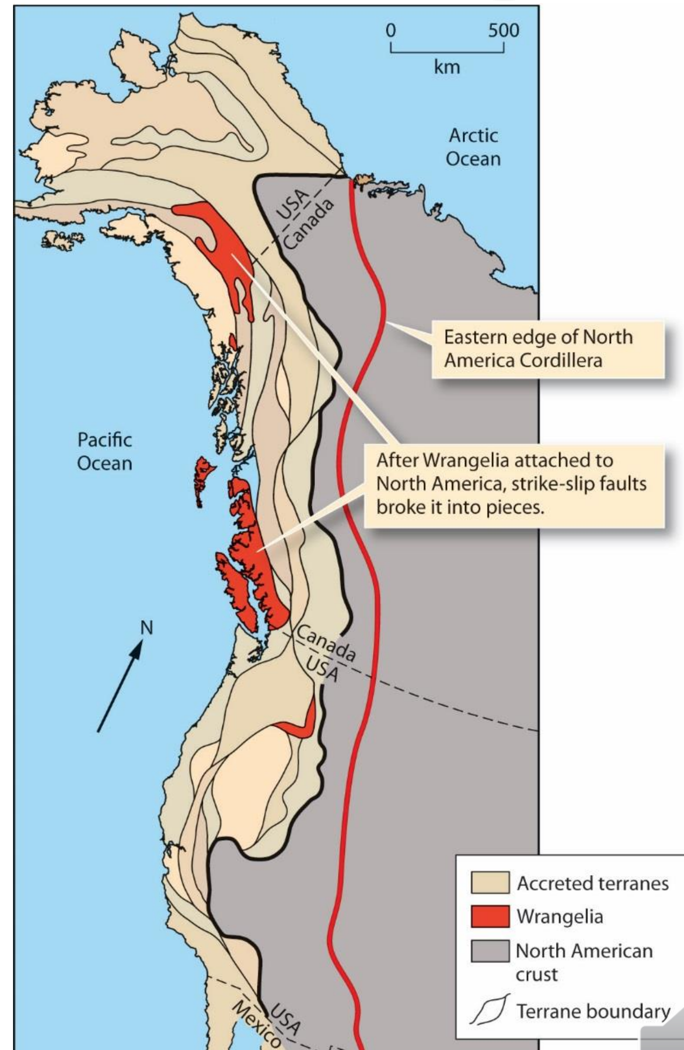
Causes of Mountain Building

- Subduction (convergent) boundaries create mountains.
  - Compression shortens and uplifts overriding plate.
  - A fold-thrust belt develops landward of the orogen.
  - Thrust faults merge, forming a ***detachment*** at depth.



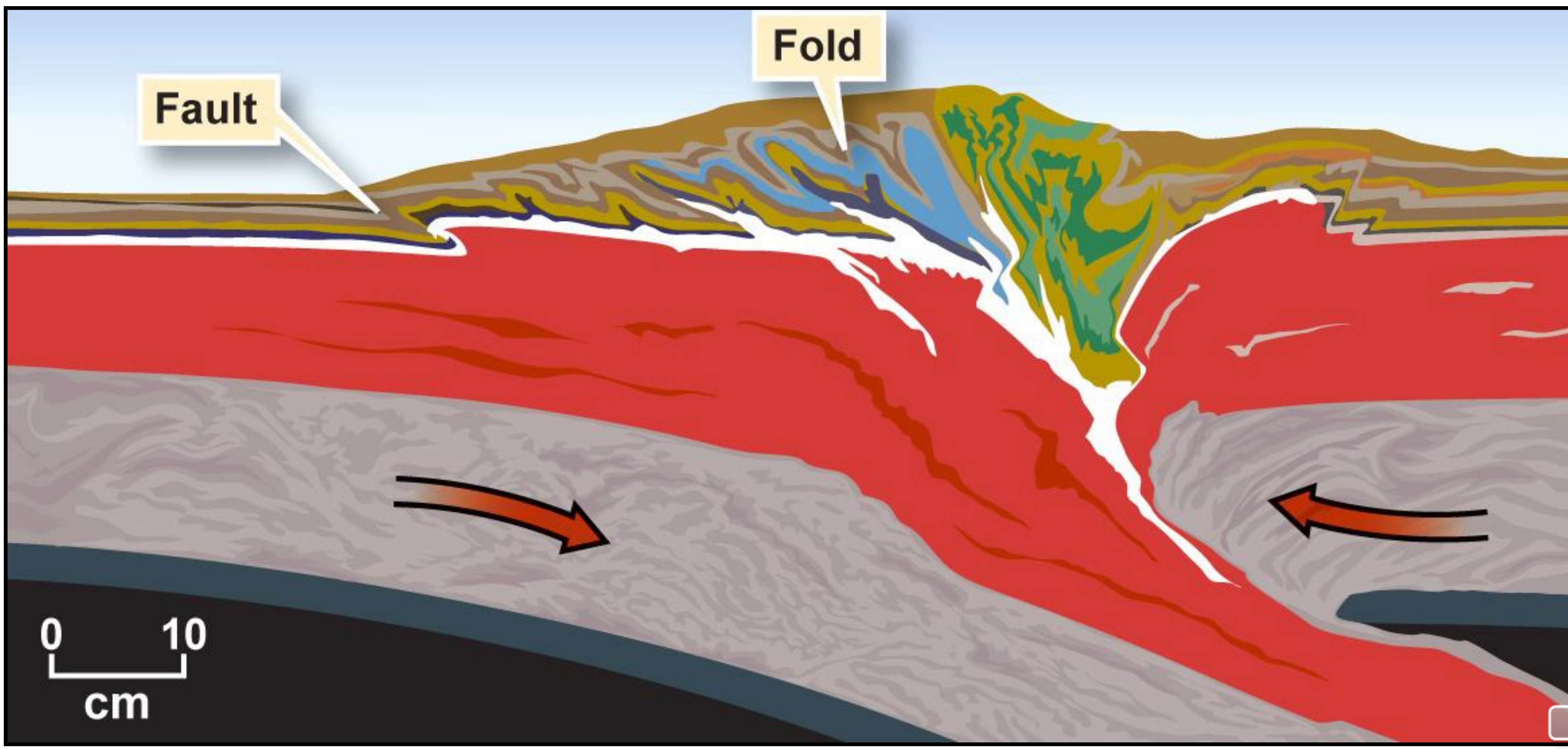
Causes of Mountain Building

- Exotic terranes may be added to subduction margins.
  - Consist of island fragments of continental crust.
  - Too buoyant to subduct; sutured onto the upper plate.
    - Terrane geology is very different from that of surroundings.
    - Western North America has numerous exotic terranes.
  - Accretionary Orogens form.



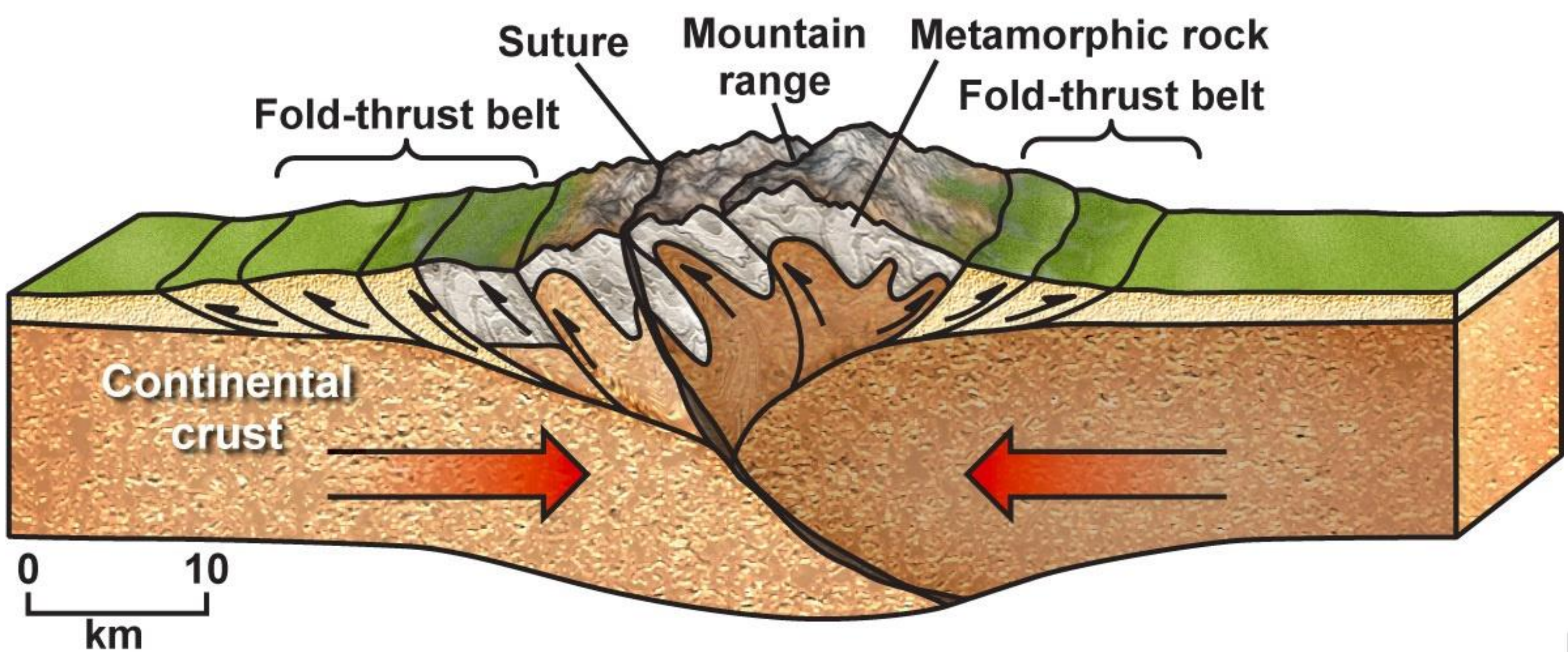
Causes of Mountain Building

- Continental collision follows ocean basin closure.
  - Complete subduction of oceanic lithosphere.
  - Brings two blocks of continental lithosphere together.
- Buoyant continental crust shuts down subduction.



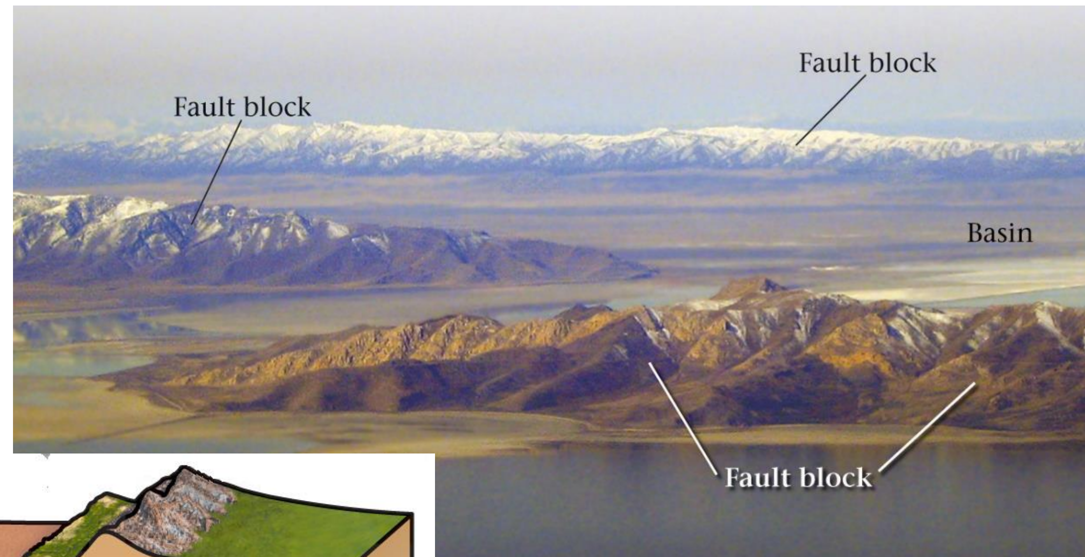
Causes of Mountain Building

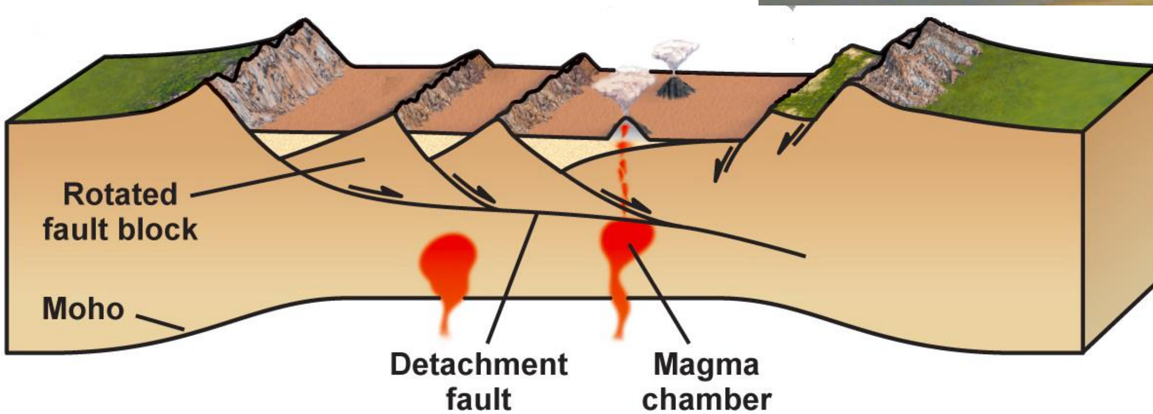
- Crustal thickening results from continental collisions.
  - Fold-thrust belts created on margins of the orogen.
  - Center of belt consists of high-grade metamorphic rocks.
- Crust in collision zone may be twice its normal thickness.
- Thrusting brings metamorphic rocks up to shallow depths.



Causes of Mountain Building

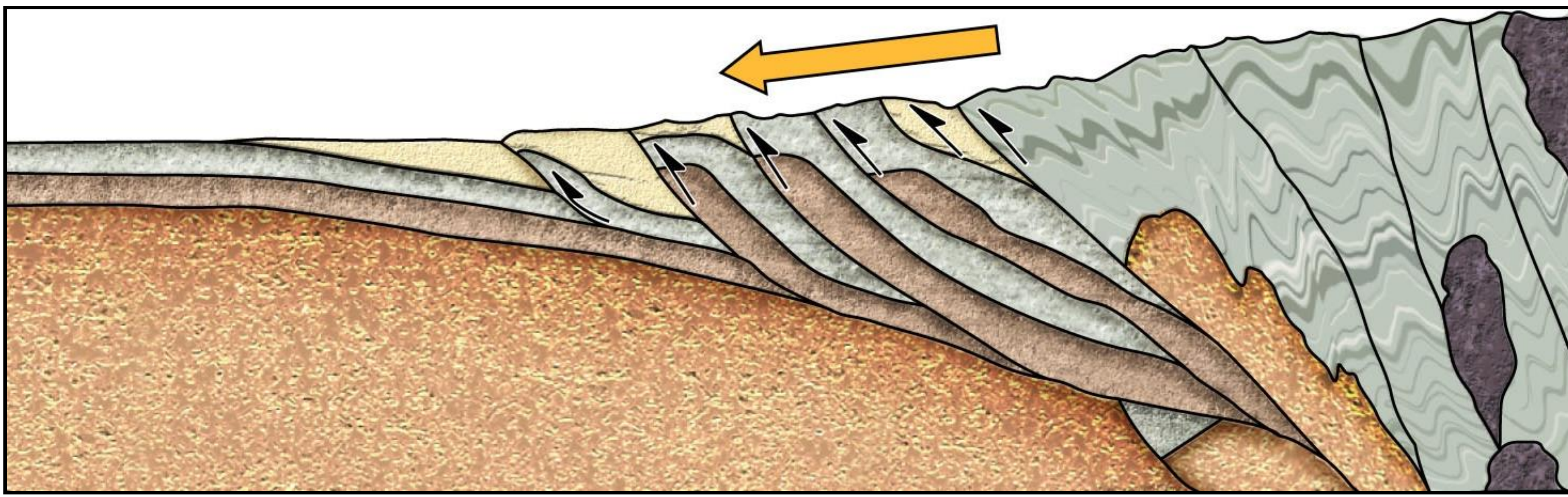
- Continental rifting creates mountains.
  - Normal faulting creates fault-block mountains and basins.
  - Decompressional melting adds volcanic mountains.





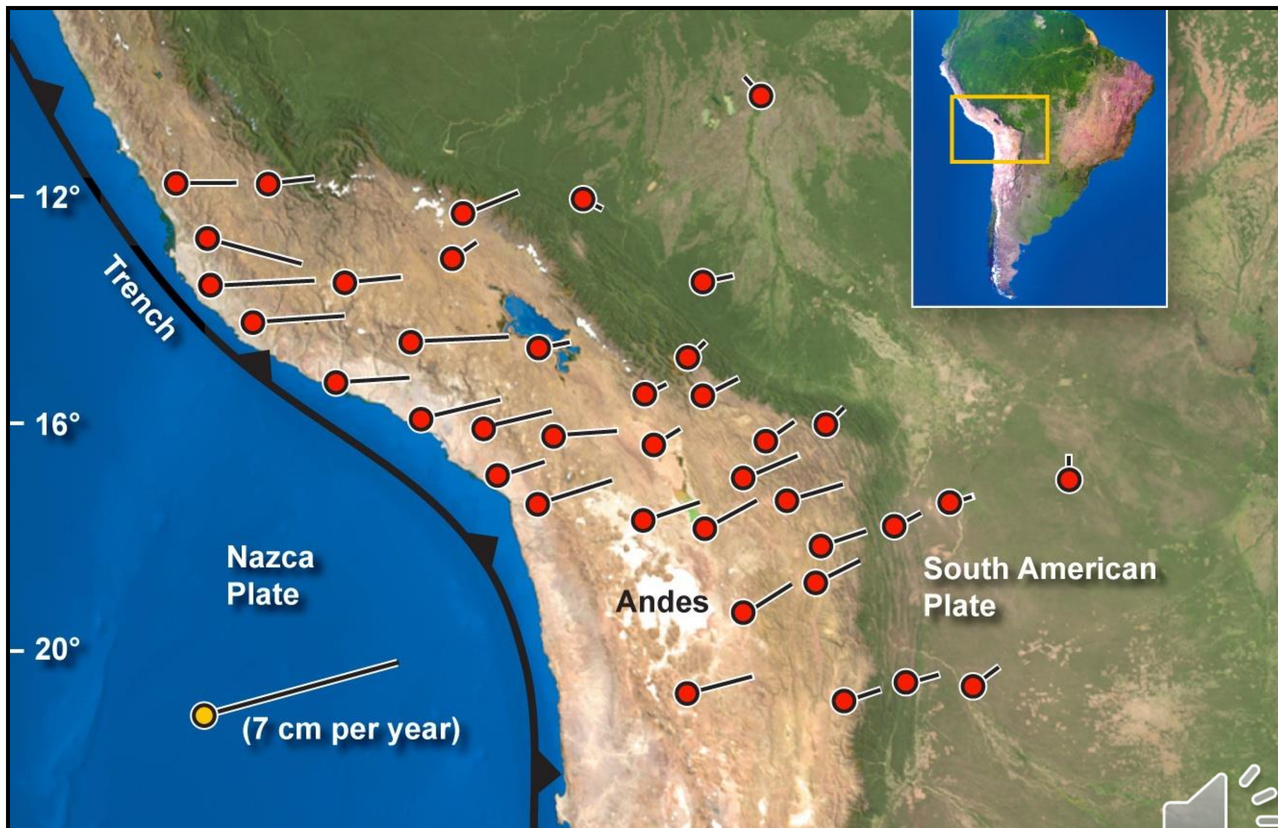
Forming Rocks in and near Mountains

- Orogeny leads to the formation of all three rock types.
  - Igneous activity beneath collisions and rift zones
  - Erosion of uplifted rocks and sedimentation in basins
  - Metamorphism associated with continental collisions



Modern Orogenesis

- Modern instrumentation can measure mountain growth.
- Global positioning systems (GPS) measure rates of:
  - Horizontal compression
  - Vertical uplift

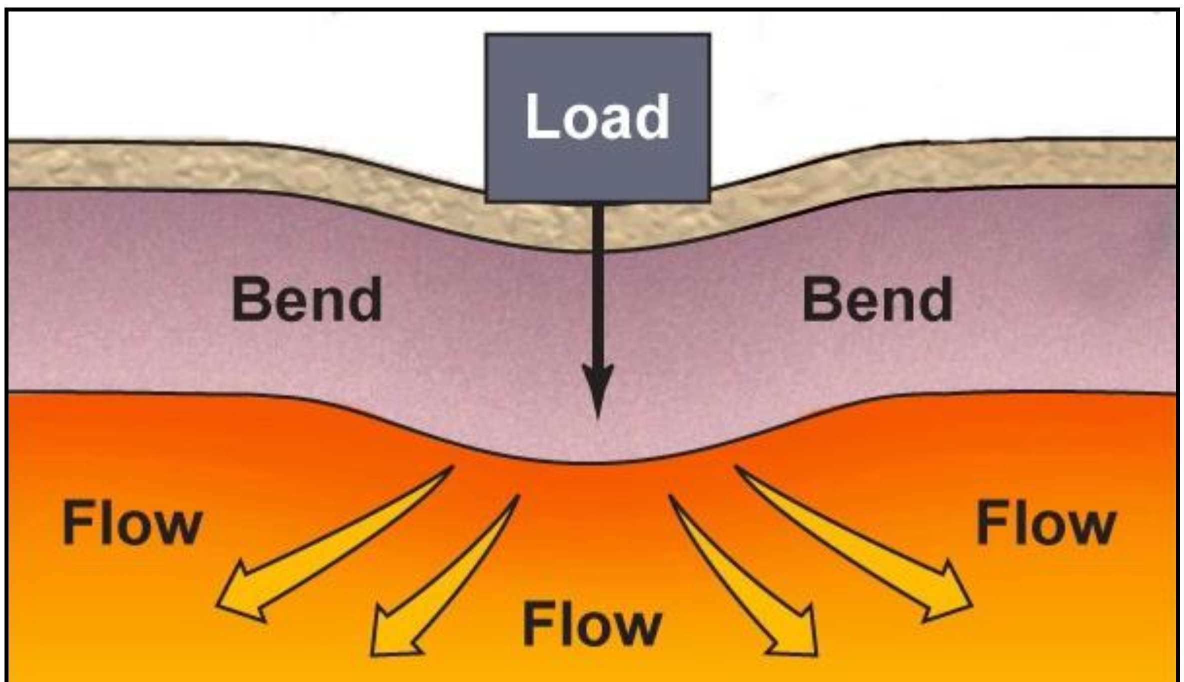


Mountain Topography

- Mountains require elevation changes on Earth’s surface.
- Mount Everest is 8.85 km above sea level and is made of sediments deposited in ocean water.

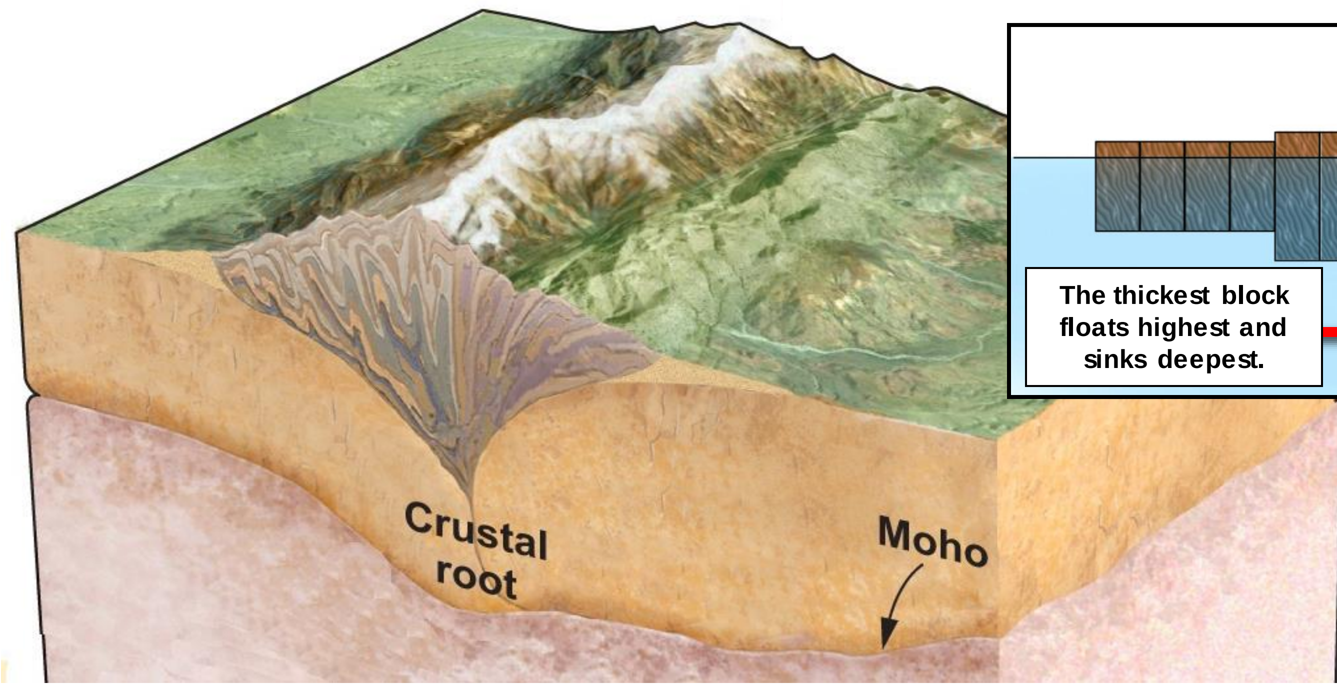
Why are Mountains High?

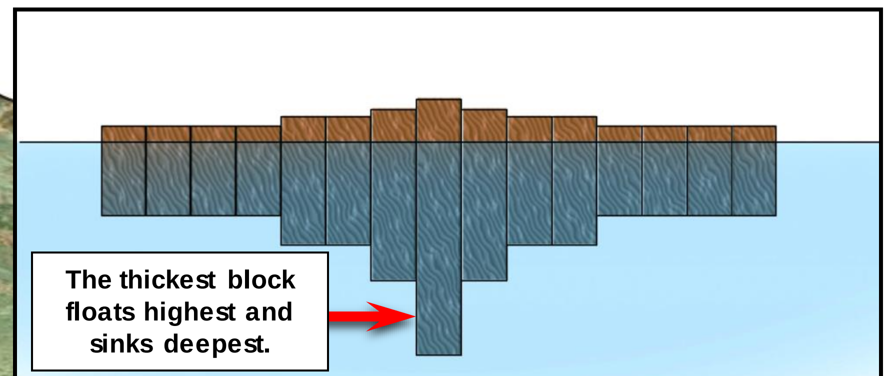
- Surface elevation is a balance between forces; *isostasy*.
  - Gravitational attraction pulls plates into the mantle.
  - Buoyancy floats lithosphere on top of the mantle.
  - Adding or removing weight resets isostatic equilibrium.
  - Change in lithospheric thickness or density alters isostasy.



Isostasy

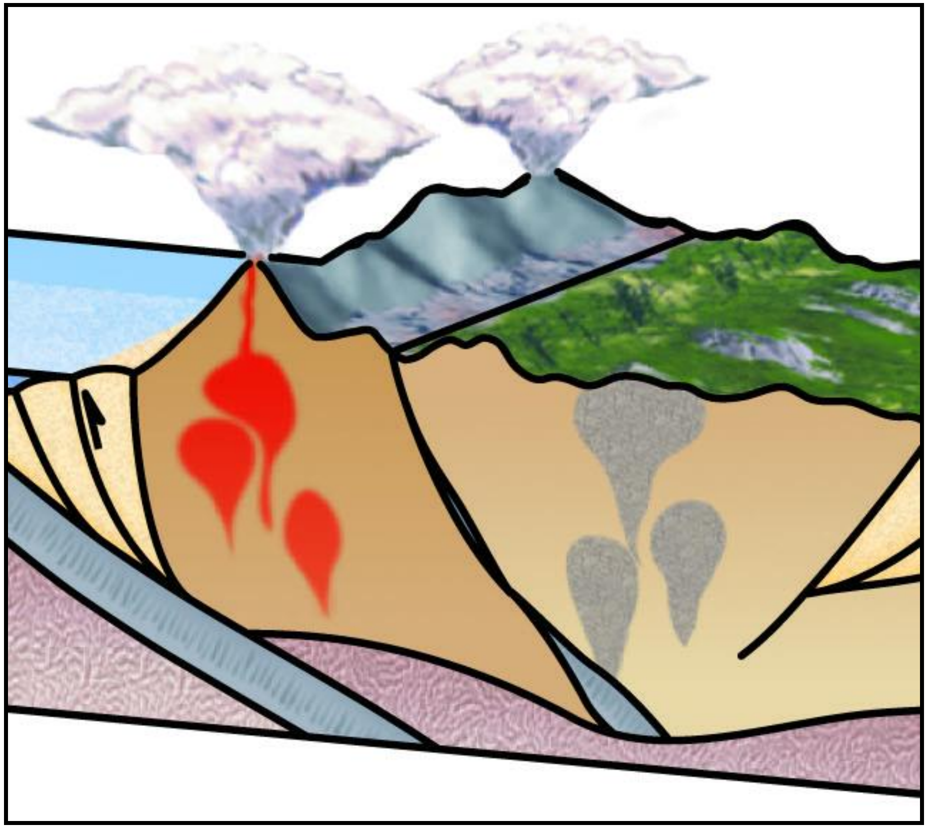
- Convergent-margin horizontal compression causes:
  - Horizontal shortening
  - Vertical thickening
- These processes can double crustal thickness.
- A thick crustal root develops beneath mountain ranges.





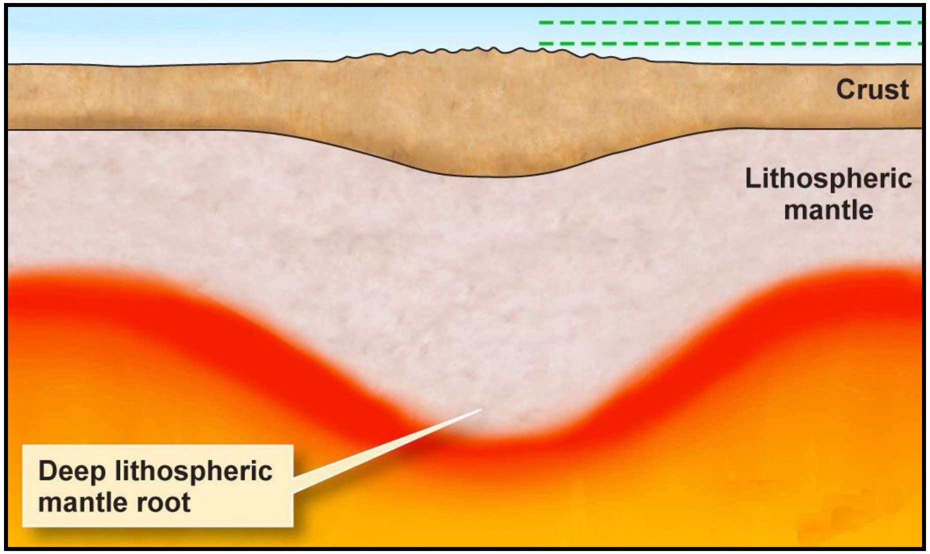
Why Are Mountains High?

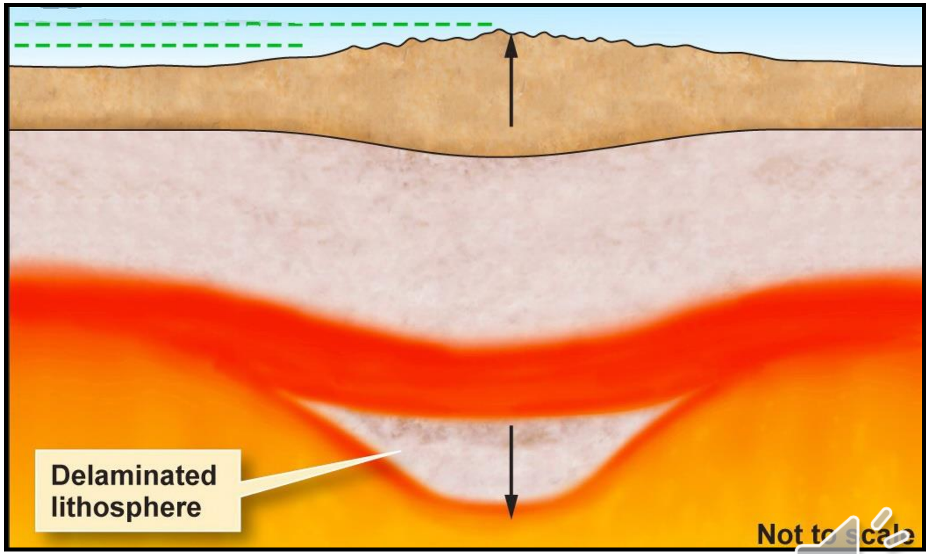
- Adding igneous rock can thicken the crust.
  - Volcanic material is added to the surface.
  - Plutons are added at mid-crustal levels.



Why Are Mountains High?

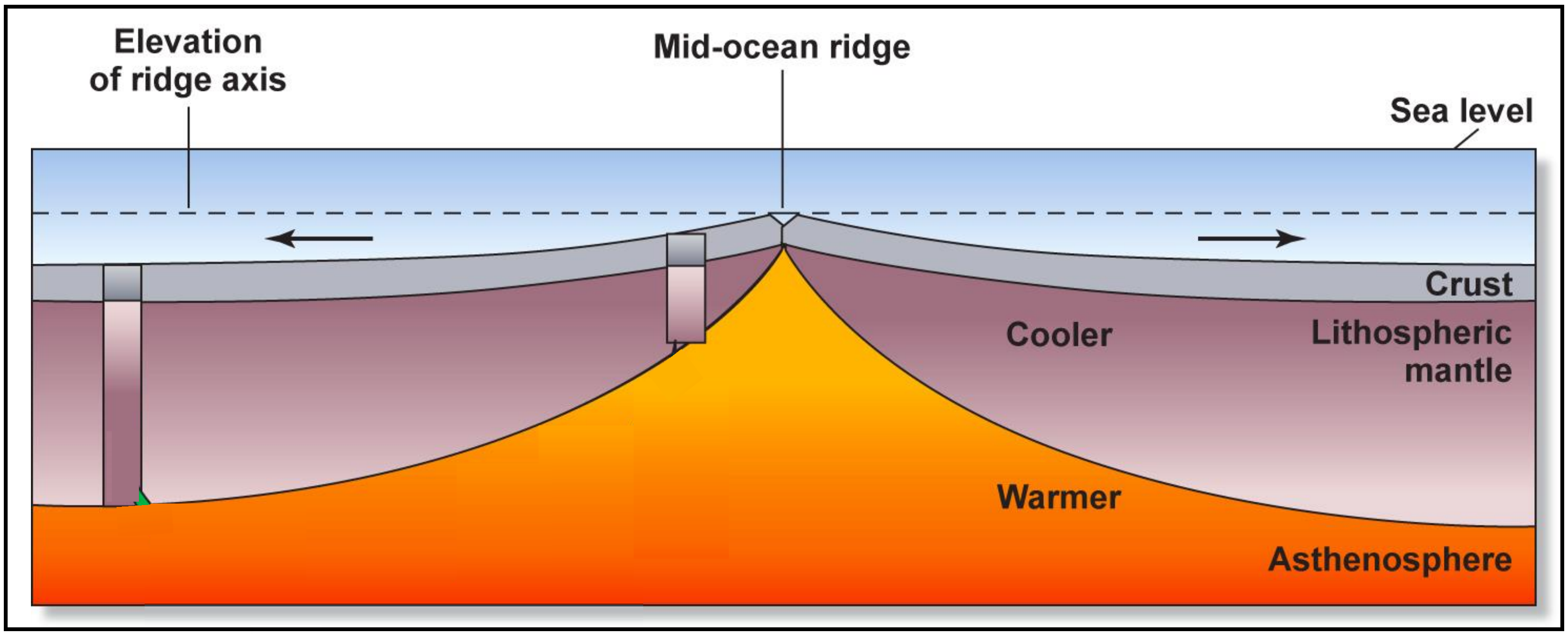
- Removal of lithospheric mantle can cause uplift.
  - Similar to removing ballast from a ship—rises in water.
- The Tibet Plateau bears evidence of ***delamination***.





Why Are Mountains High?

- Thinning and heating lithosphere during rifting
  - Rising asthenosphere heats lithosphere.
  - Heated lithosphere is less dense, rises.
  - Creates elevated mid-ocean ridge mountains.

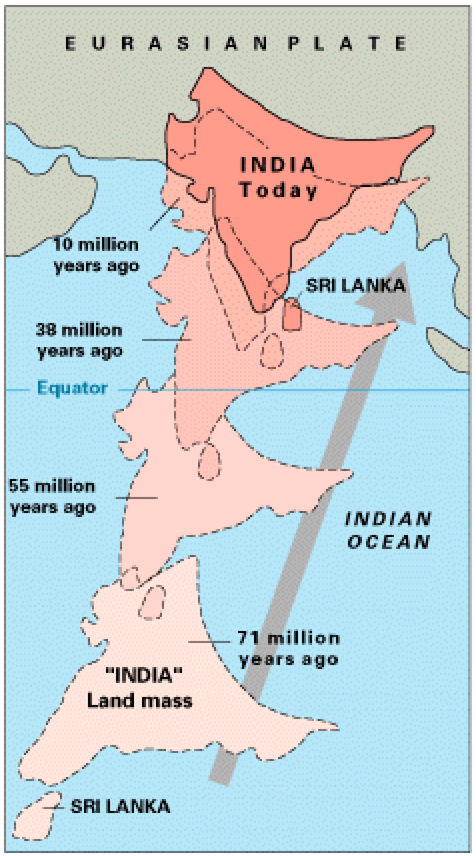


What Goes Up…

- Mountains reflect a balance between uplift and erosion.
- Mountains are steep and jagged due to erosion.
- Rock characteristics control erosion.
  - Resistant layers form cliffs.
  - Easily eroded rocks form slopes.

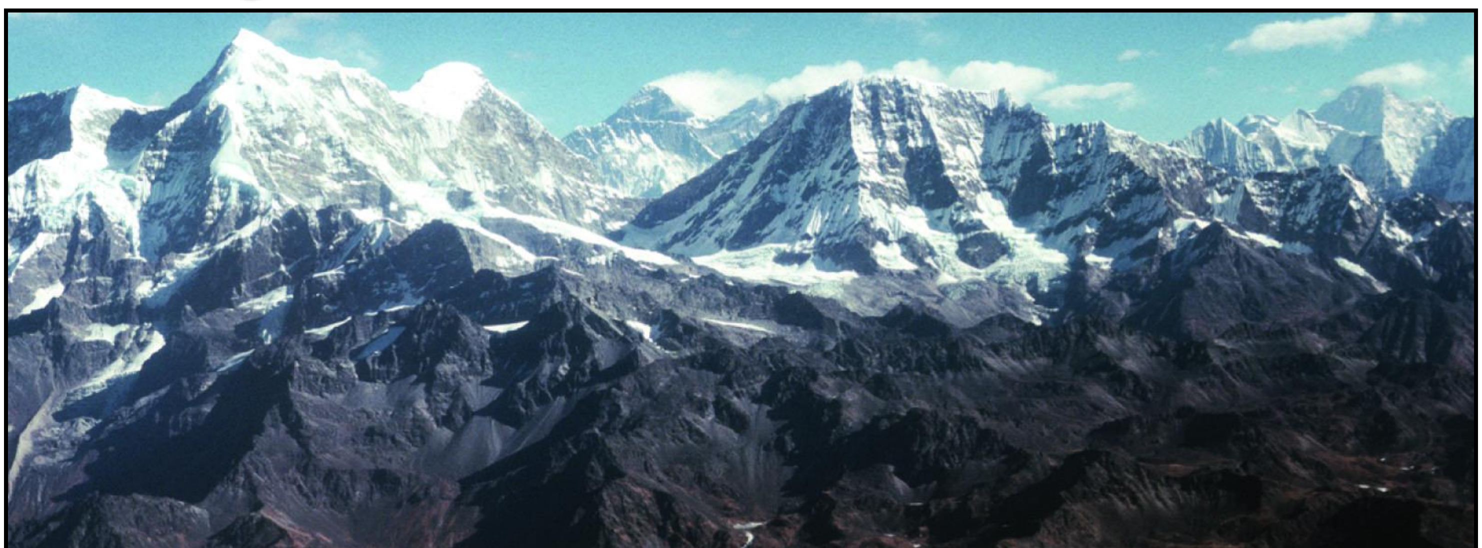
Himalayan Plateau

- The Himalayas are uplifted through the collision of the Indian plate with the Eurasian plate. India is still pushing northward at about 4 cm/yr relative to the Eurasian plate.



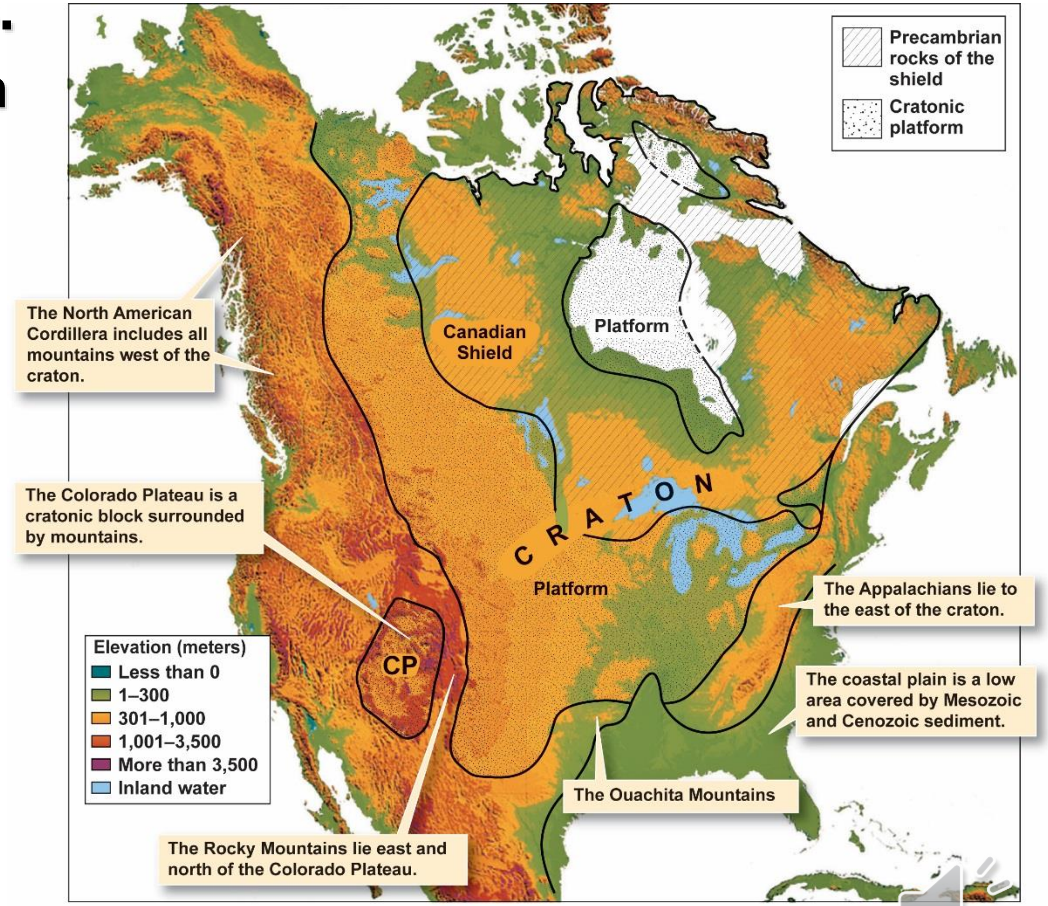
…Must Come Down

- The Himalayas are the maximum height possible. Why?
- There is an upper limit to mountain heights.
  - Weight of high mountains overwhelms rock strength.
    - Orogenic collapse—deep, hot rocks forced outward.
    - The mountains then collapse downward like soft cheese.
- Uplift, erosion, and collapse exhume deep crustal rocks.
  - Unroofing, or exhumation



Cratons

- A craton is crust that hasn't been deformed in 1 Ga.
- Low-geothermal gradient; cool, strong, and stable crust.
  - Two cratonic provinces.
    - Shields—Precambrian metamorphic and igneous rocks.
    - Platforms—shields covered by layers of Phanerozoic strata.



Cratonic Platforms

- Sedimentary rocks covering Precambrian basement.
- Series of domes and basins
  - Thick accumulations of sediment in basins
  - Erosion created bull's-eye-shaped domes.
- Formation called ***epeirogeny***.