

PHYS 3800 Physical Geology

Chapter 7: Metamorphism: A Process of Change



Introduction

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



Fig. 7.11a

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.

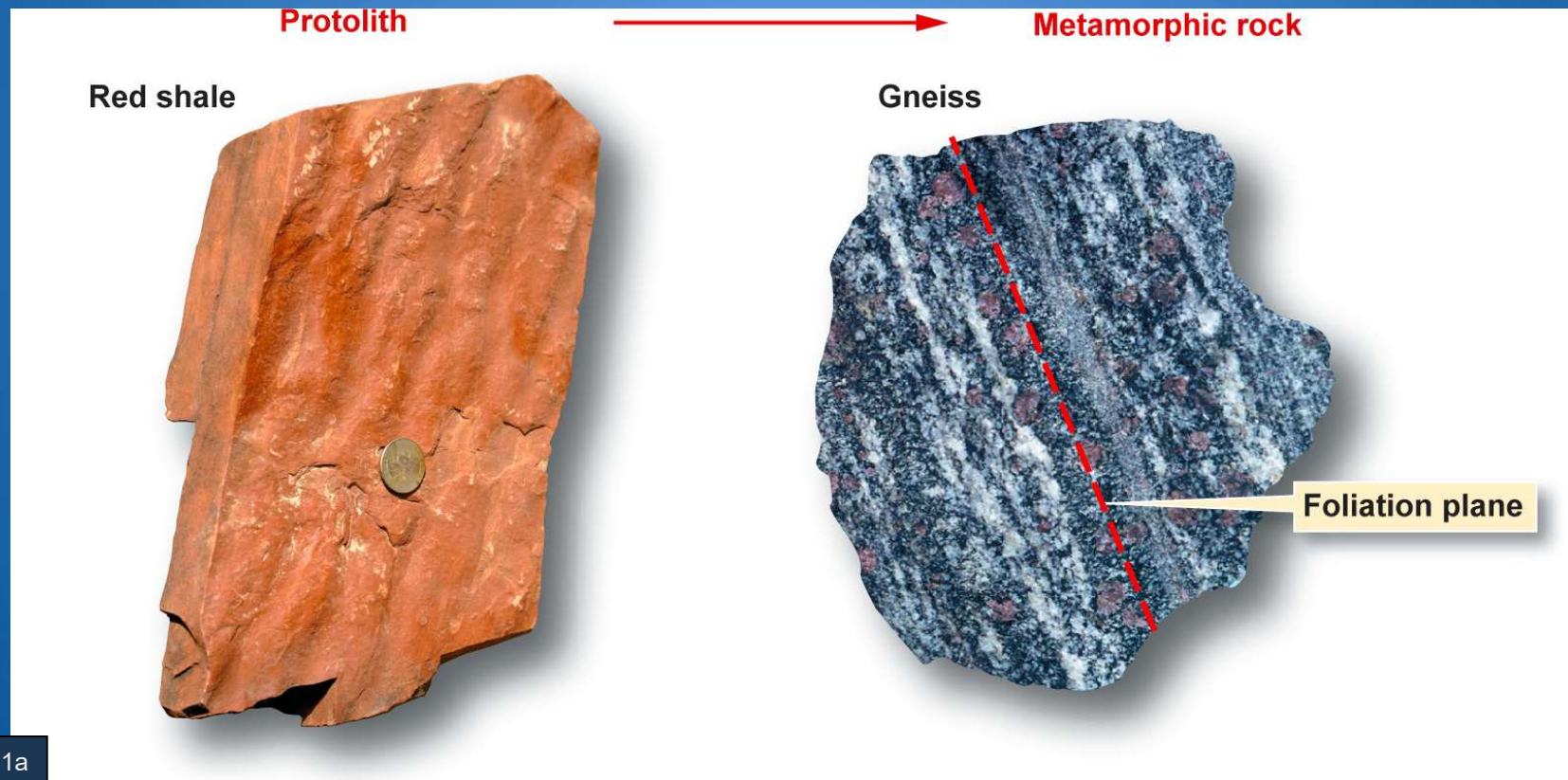


Fig. 7.1a

What Is a Metamorphic Rock?

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

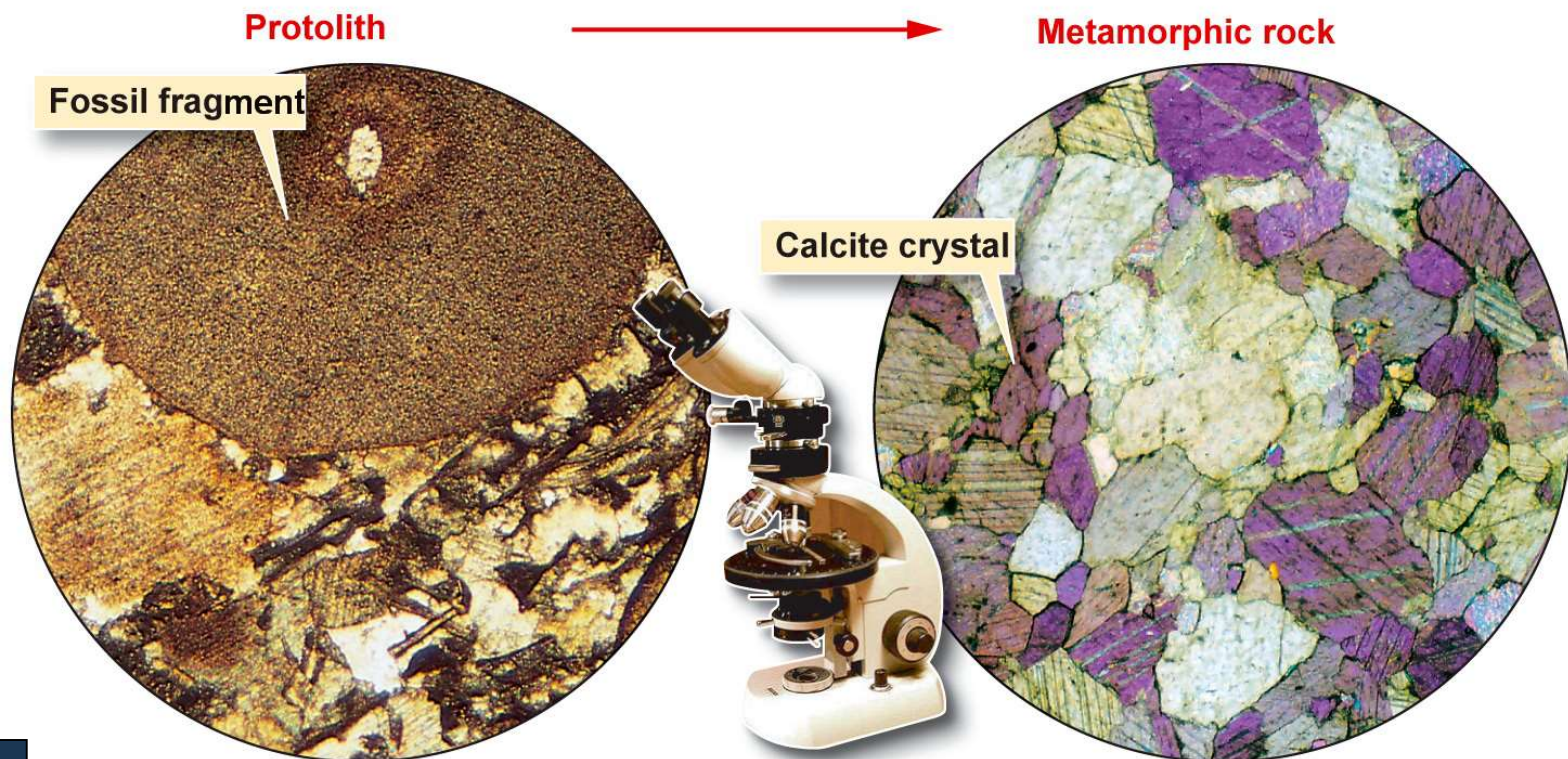


Fig. 7.1b

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 doesn't change.
 - Example: Limestone → Marble.

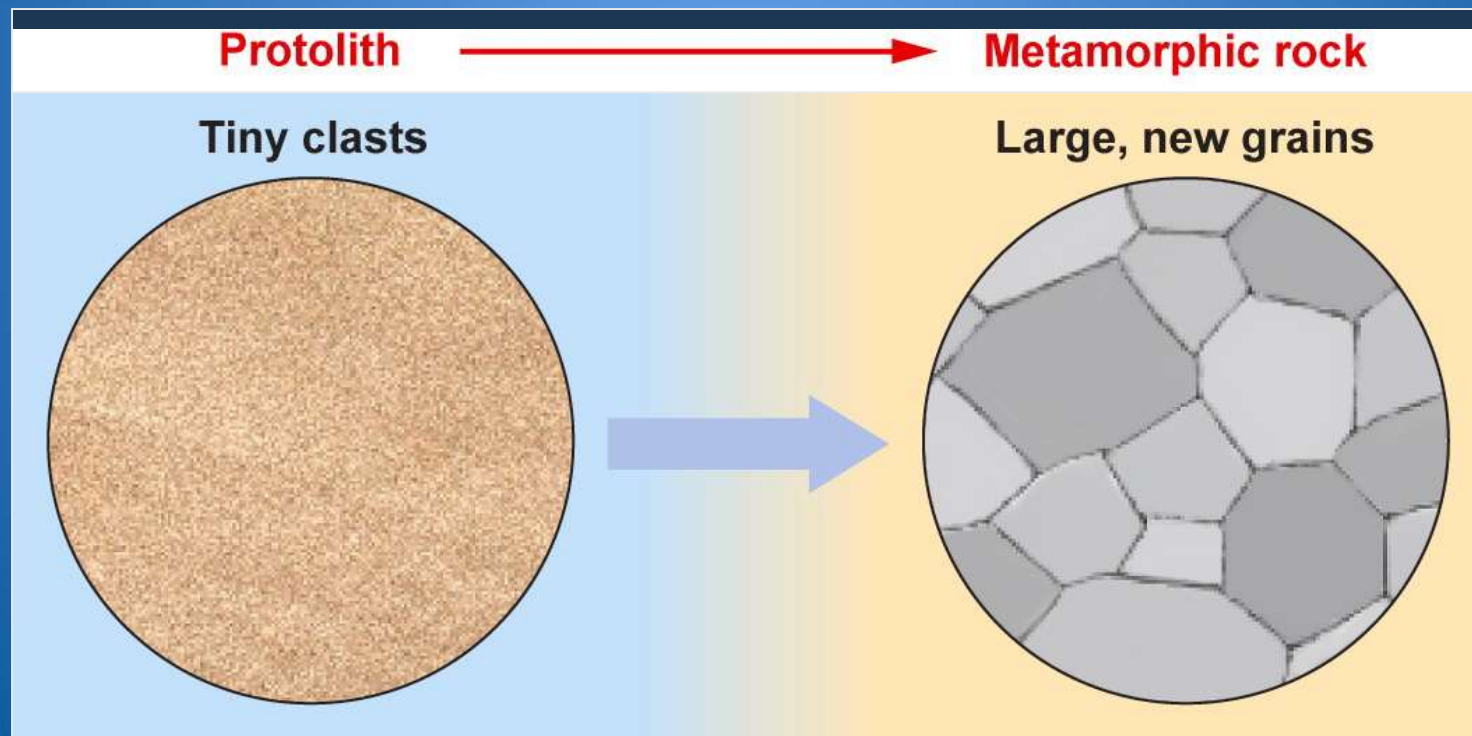


Fig. 7.2a

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.

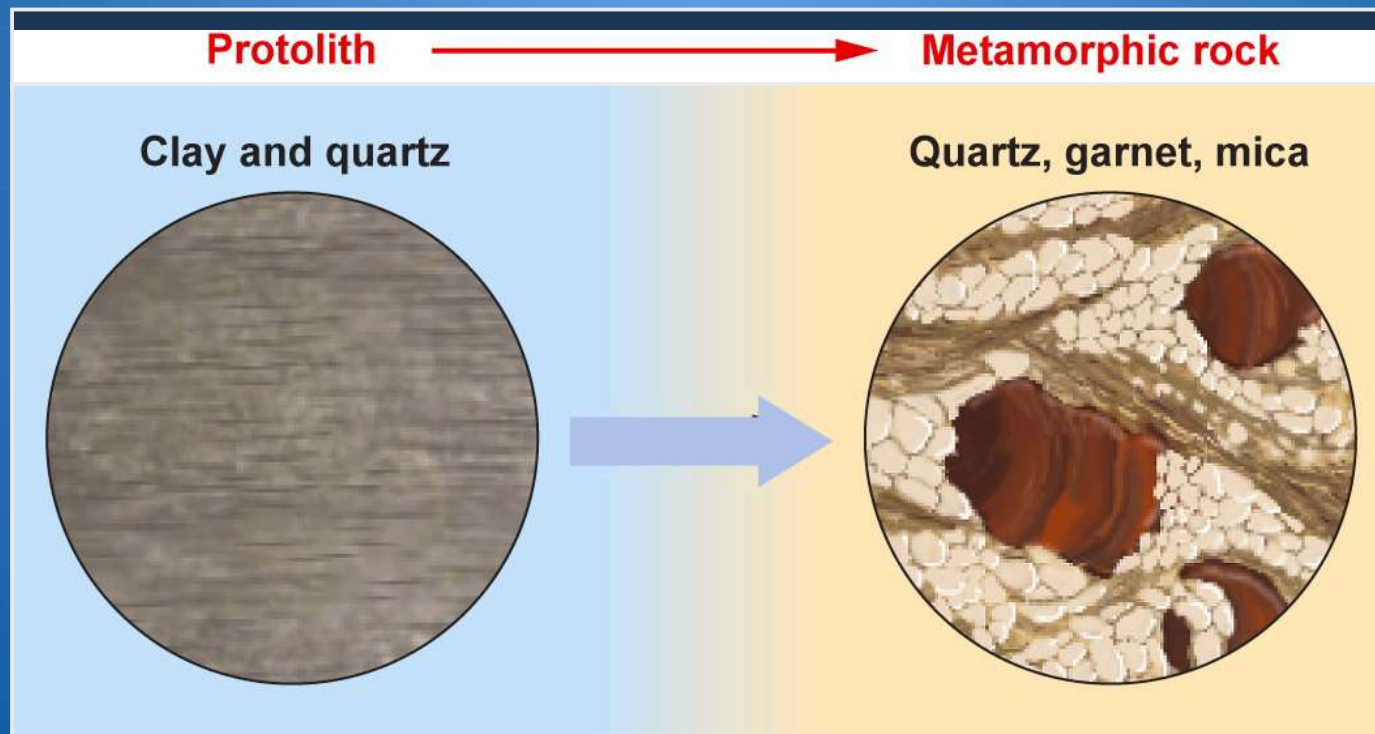


Fig. 7.2b

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.

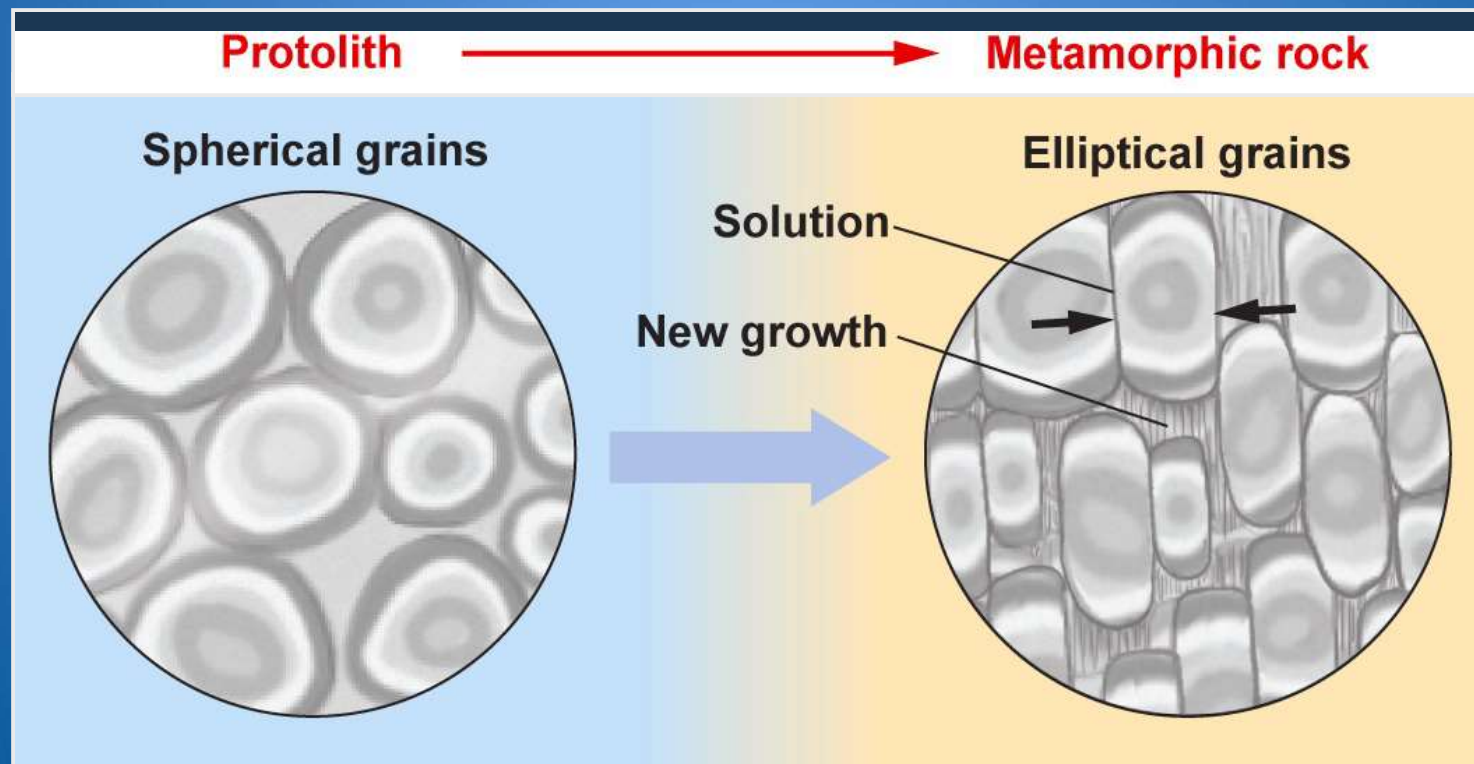


Fig. 7.2c

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.

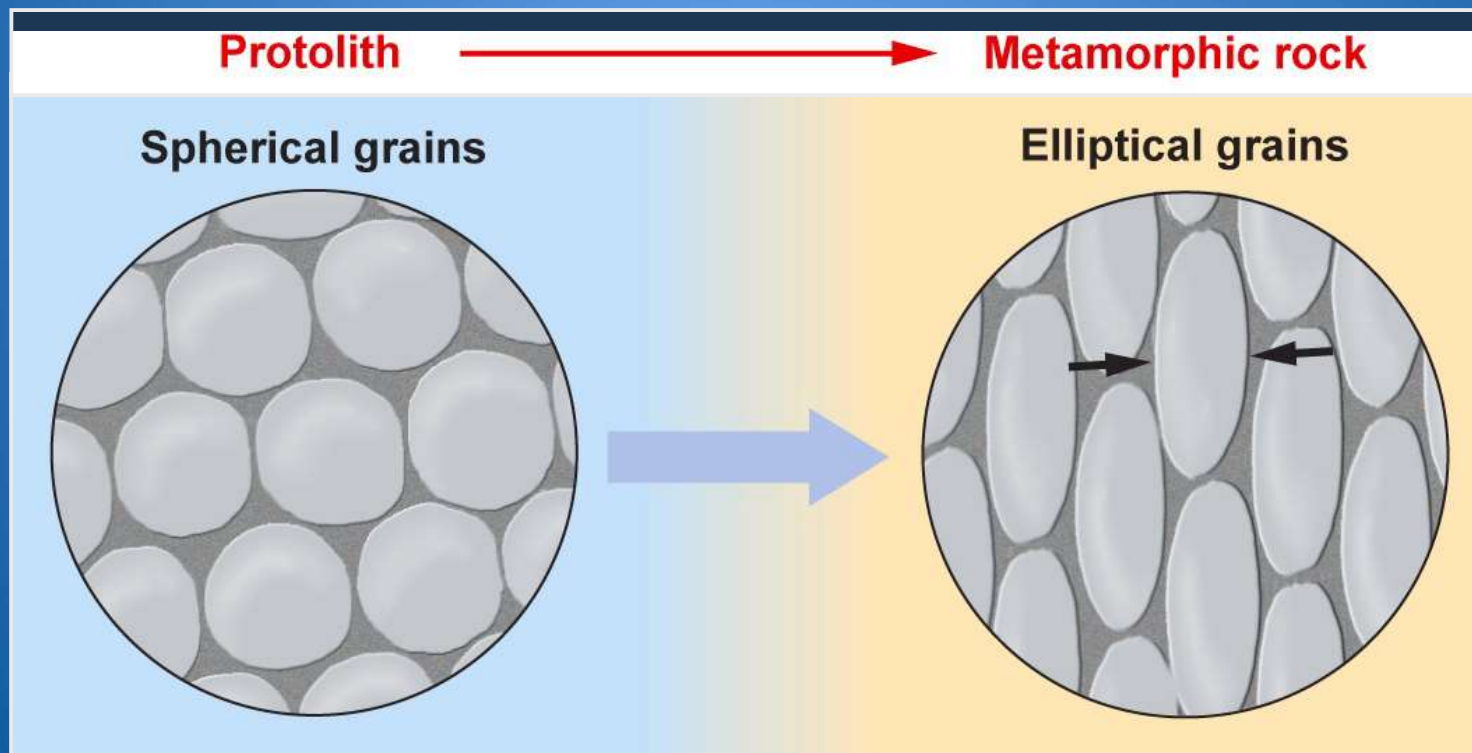
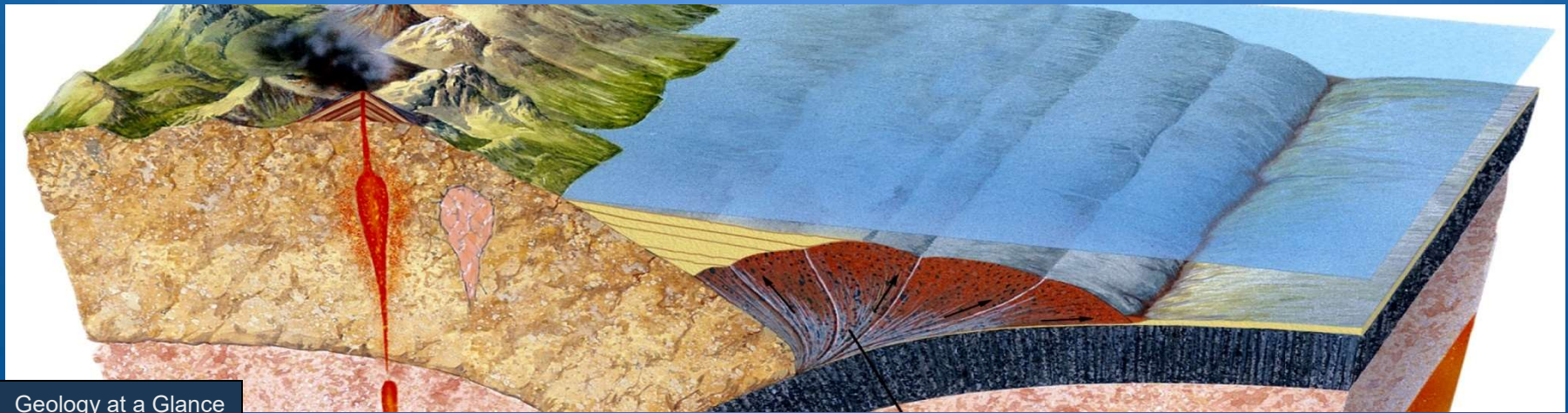


Fig. 7.2d

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 250°C and 850°C.
 - Between diagenesis and melting (up to 1200°C).
- Heat energy breaks and reforms atomic bonds.
 - Solid-state diffusion: migration of atoms between grains.
 - New minerals form.

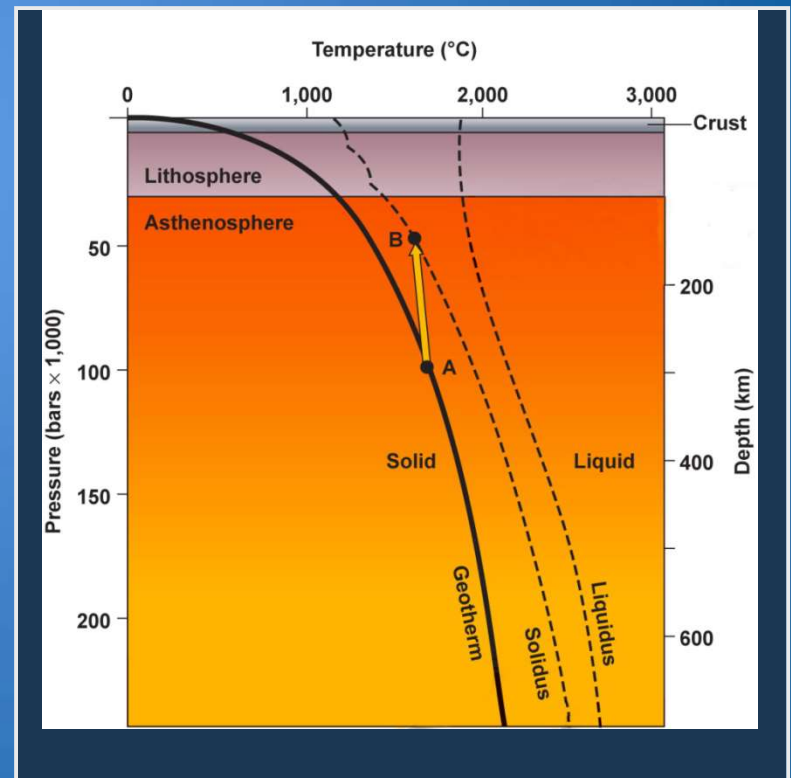


Fig. 4.3a

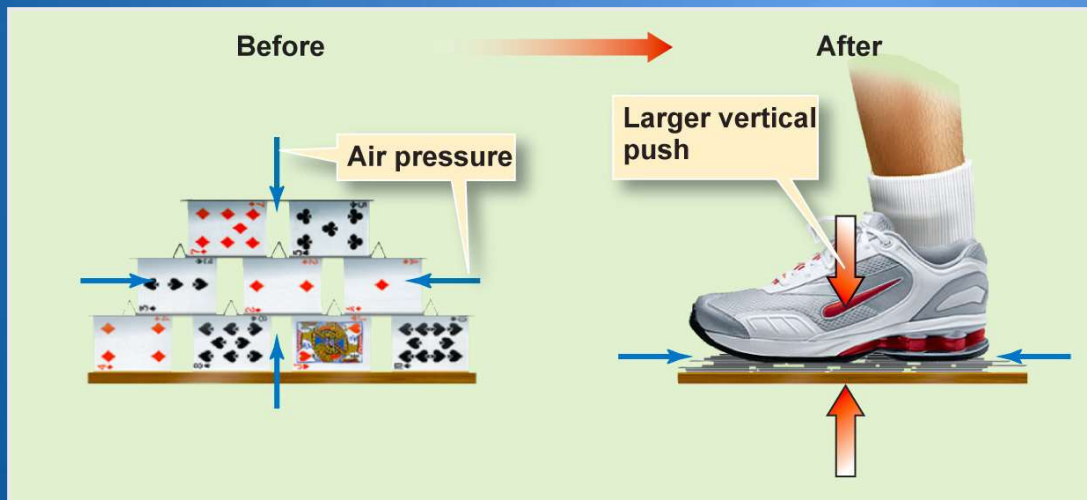
Metamorphism Due to Pressure (P)

- P increases with depth in the crust.
 - Metamorphism occurs mostly in 2–12 kbar range
- 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.



Horizontal compression

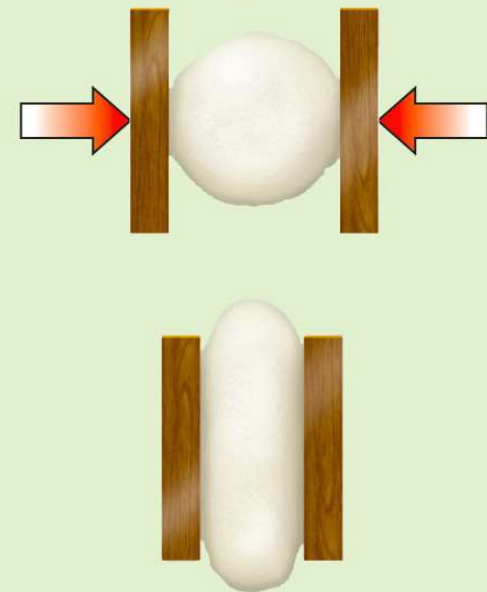


Fig 7.3a, b

Metamorphism via Shear

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

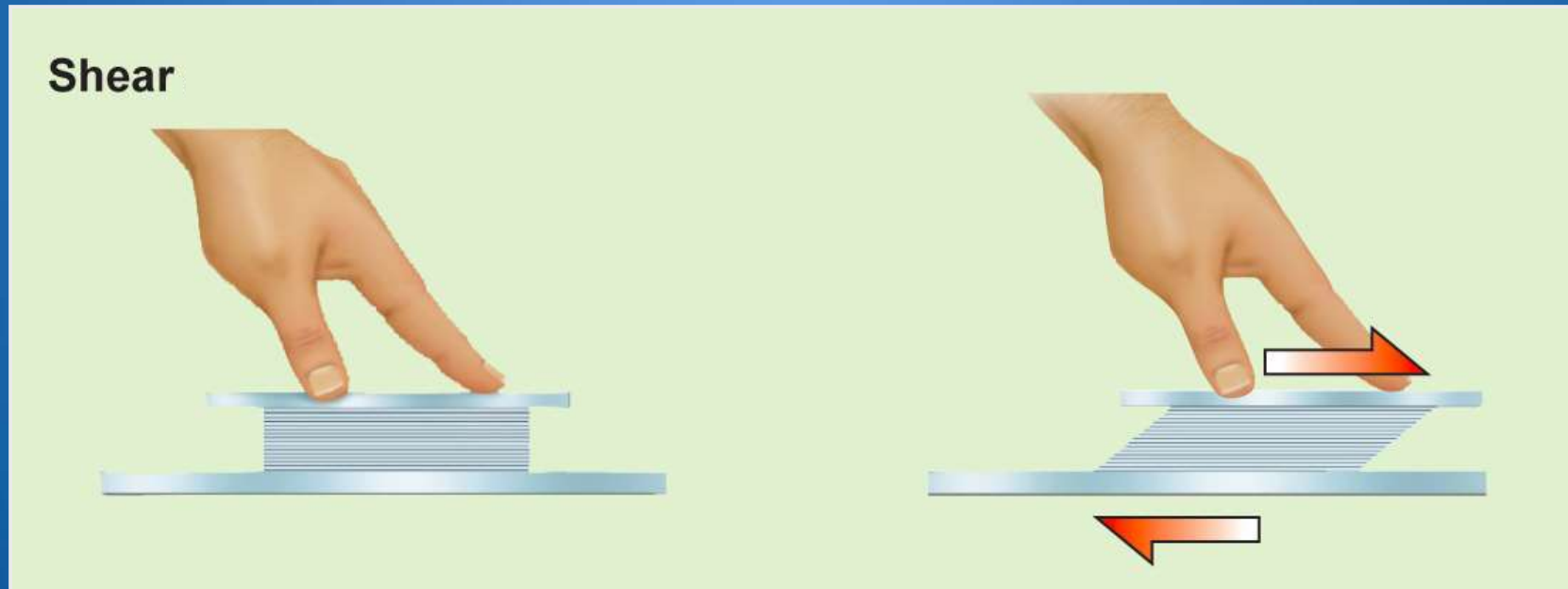


Fig. 7.3c

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.

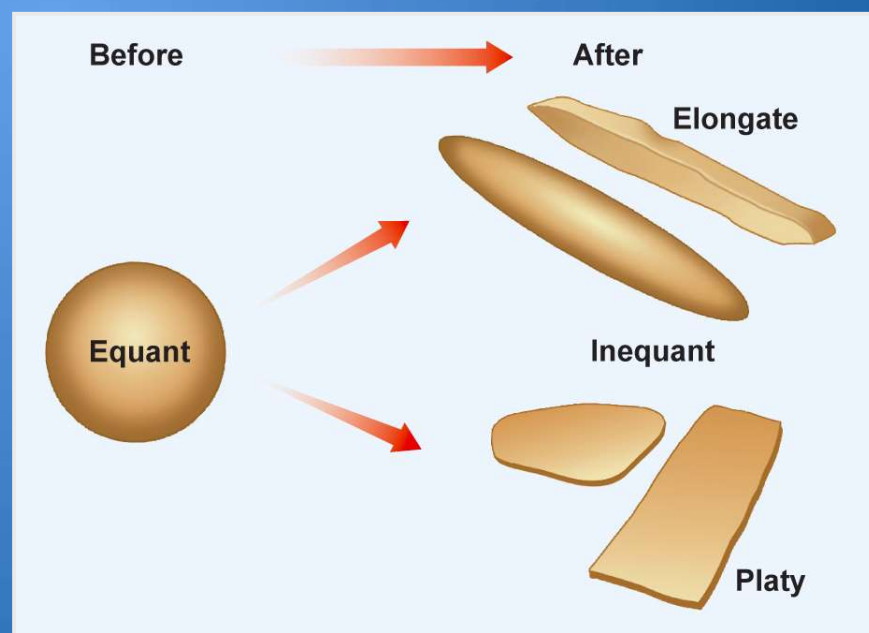


Fig. 7.3d

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.

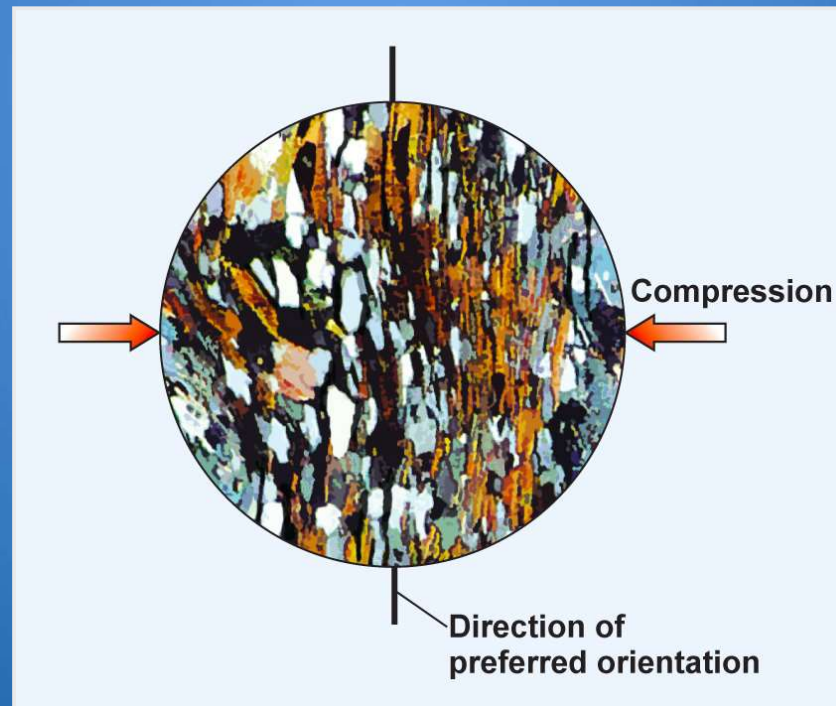


Fig. 7.3e

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*.



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.

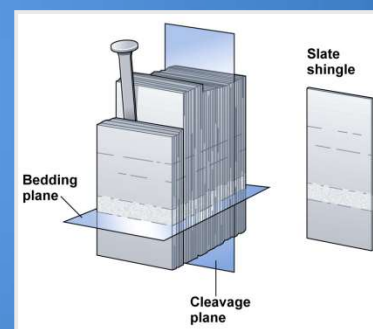
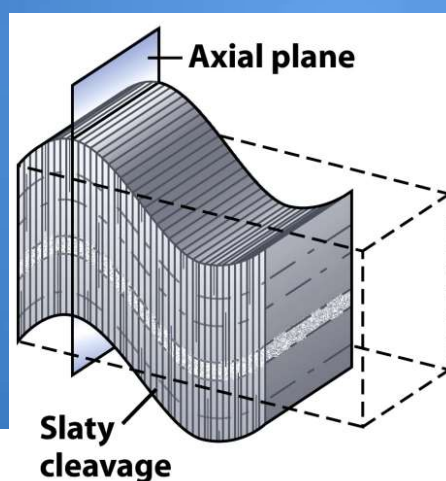
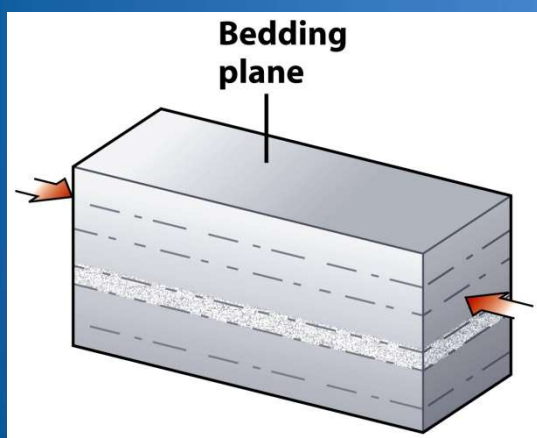
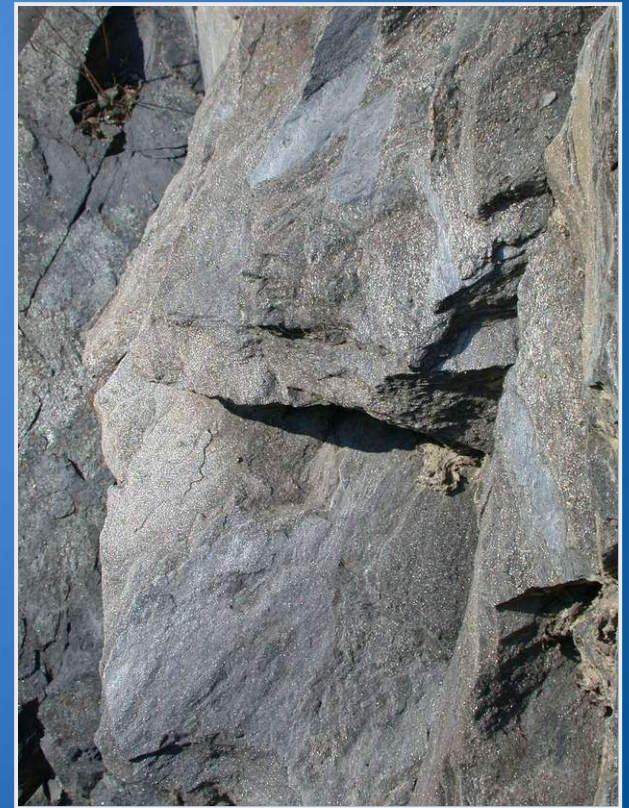


Fig. 7.4a, b

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.



Fig. 7.5b

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).



Fig. 7.6a

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.

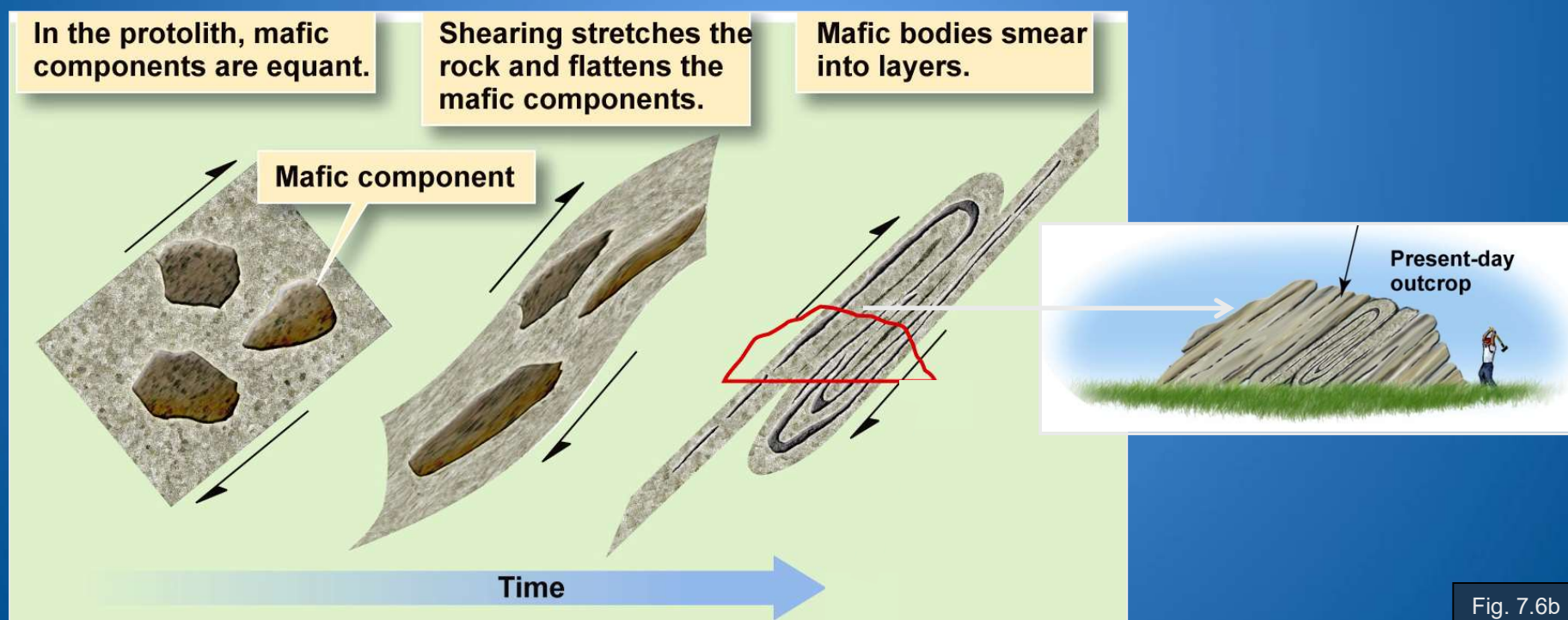


Fig. 7.6b

Foliated Metamorphic Rocks

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

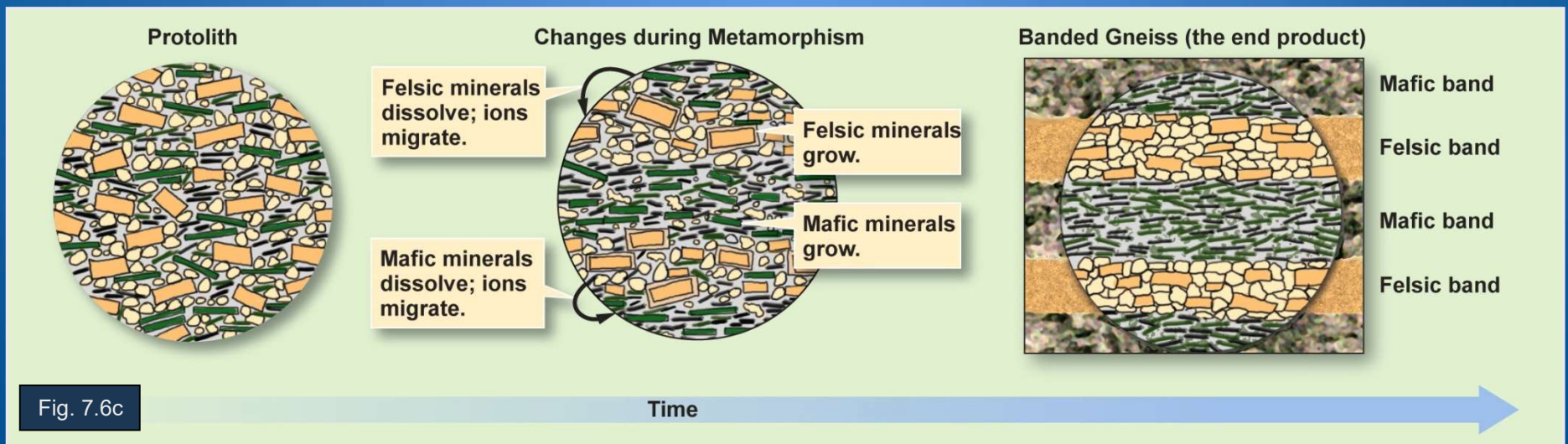


Fig. 7.6c

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 minerals.
 - 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.



Fig. 7.7a

Metamorphic Alteration

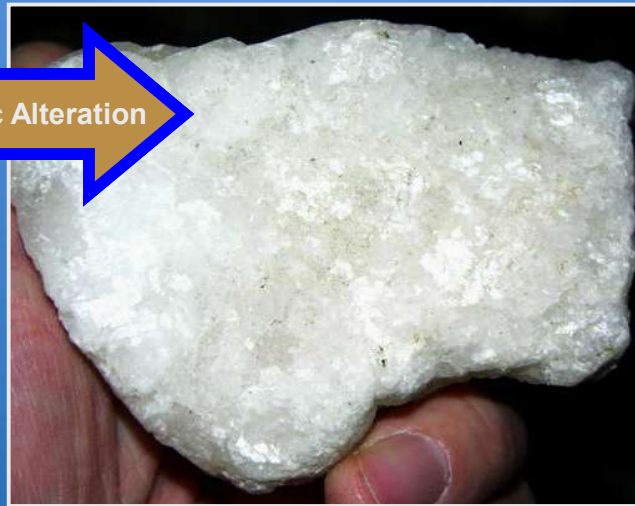


Nonfoliated Metamorphic Rocks

- **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



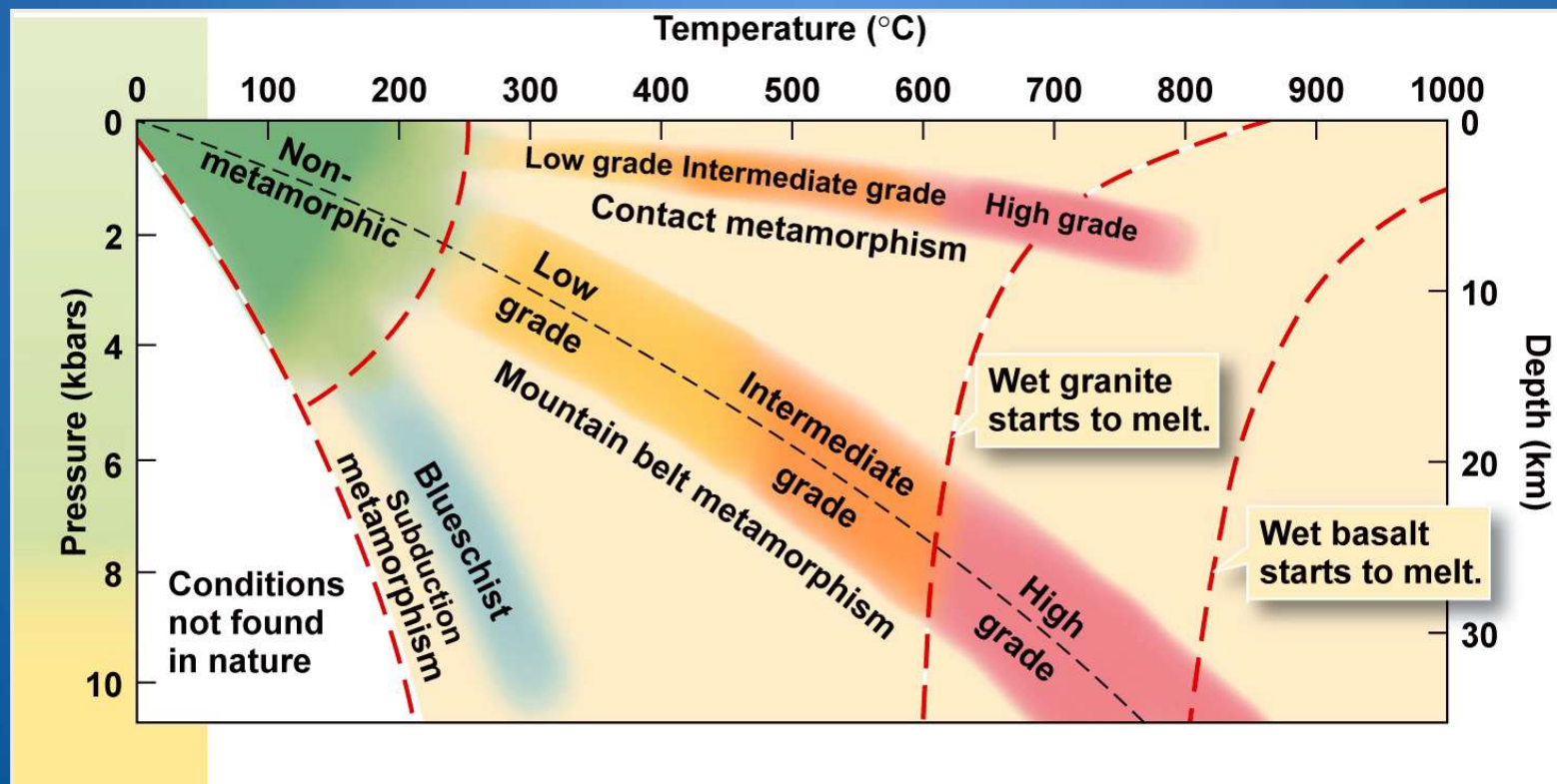
Metamorphic Alteration

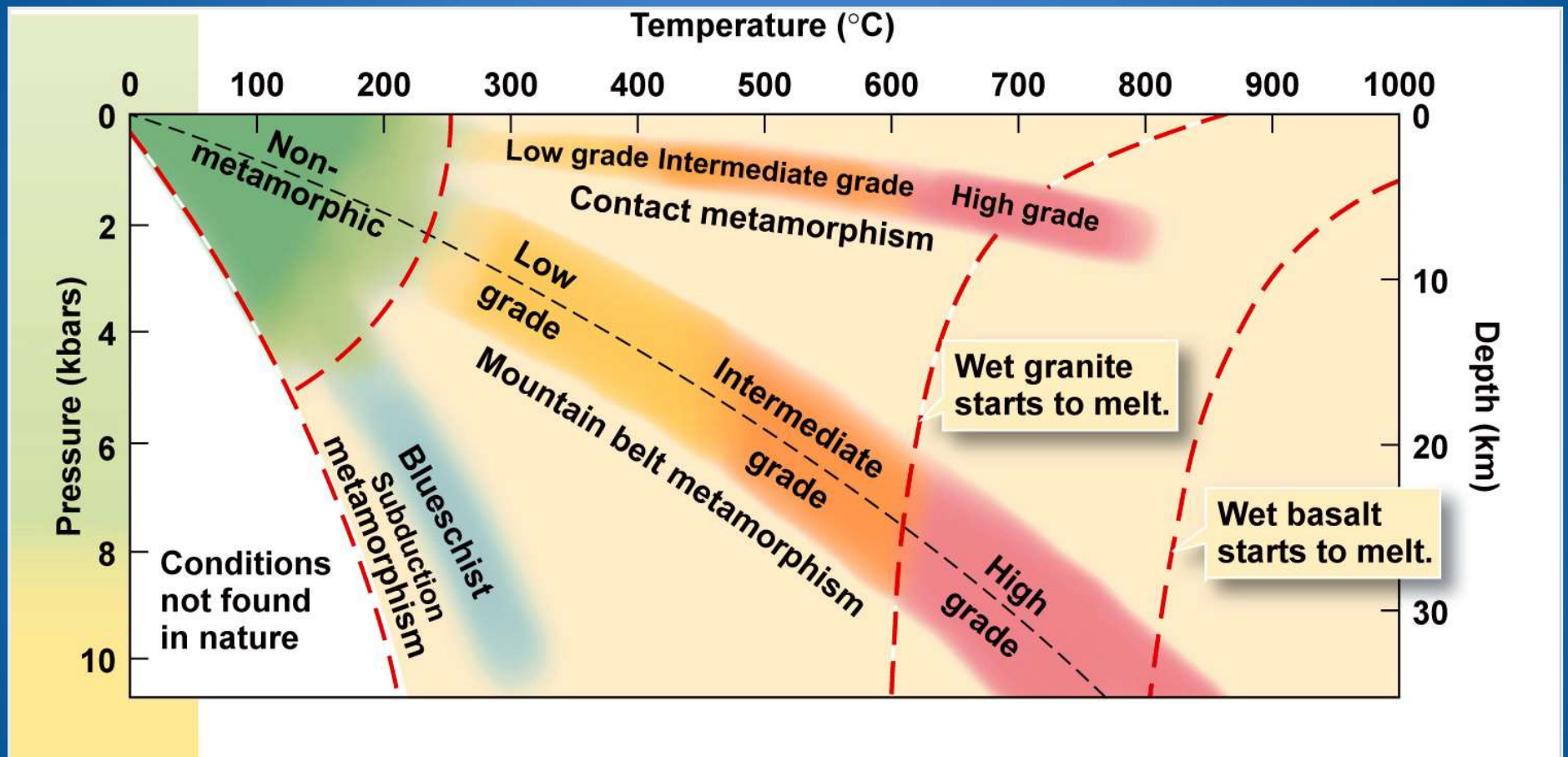


Metamorphic Grade

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

Fig. 7.8a



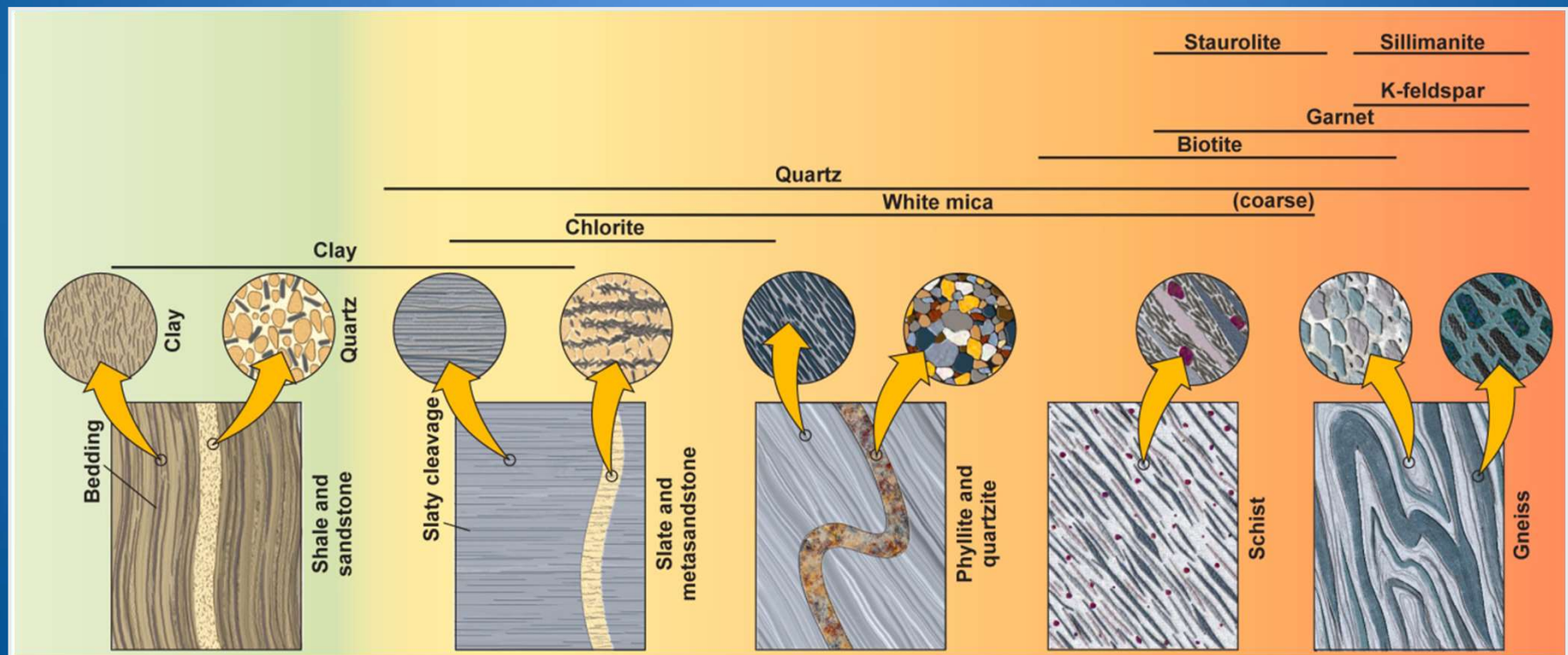


Metamorphic Grade

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

Low Grade → Intermediate Grade → High Grade

Fig. 7.8b



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*.

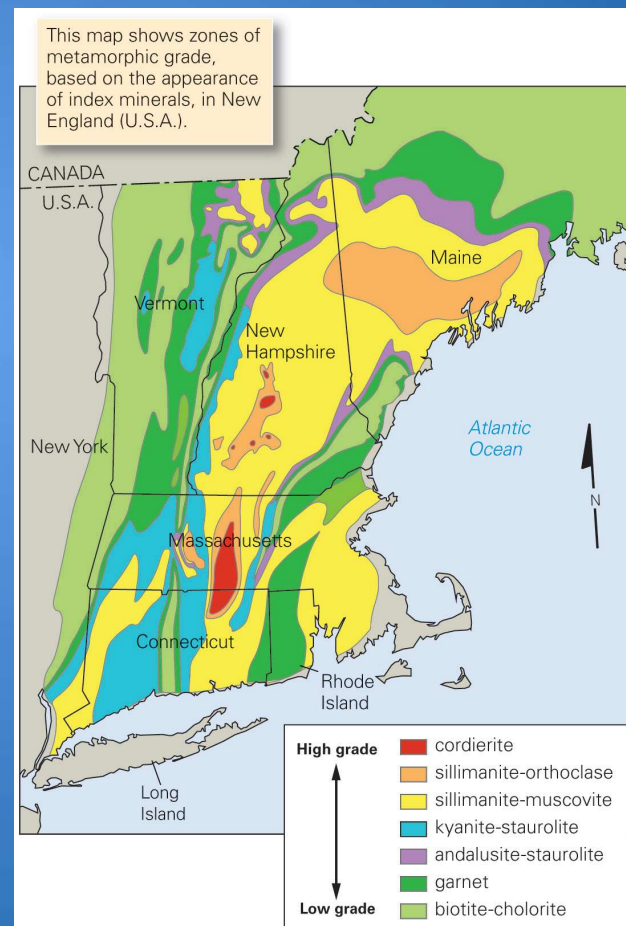


Fig. 7.8c

This map shows zones of metamorphic grade, based on the appearance of index minerals, in New England (U.S.A.).

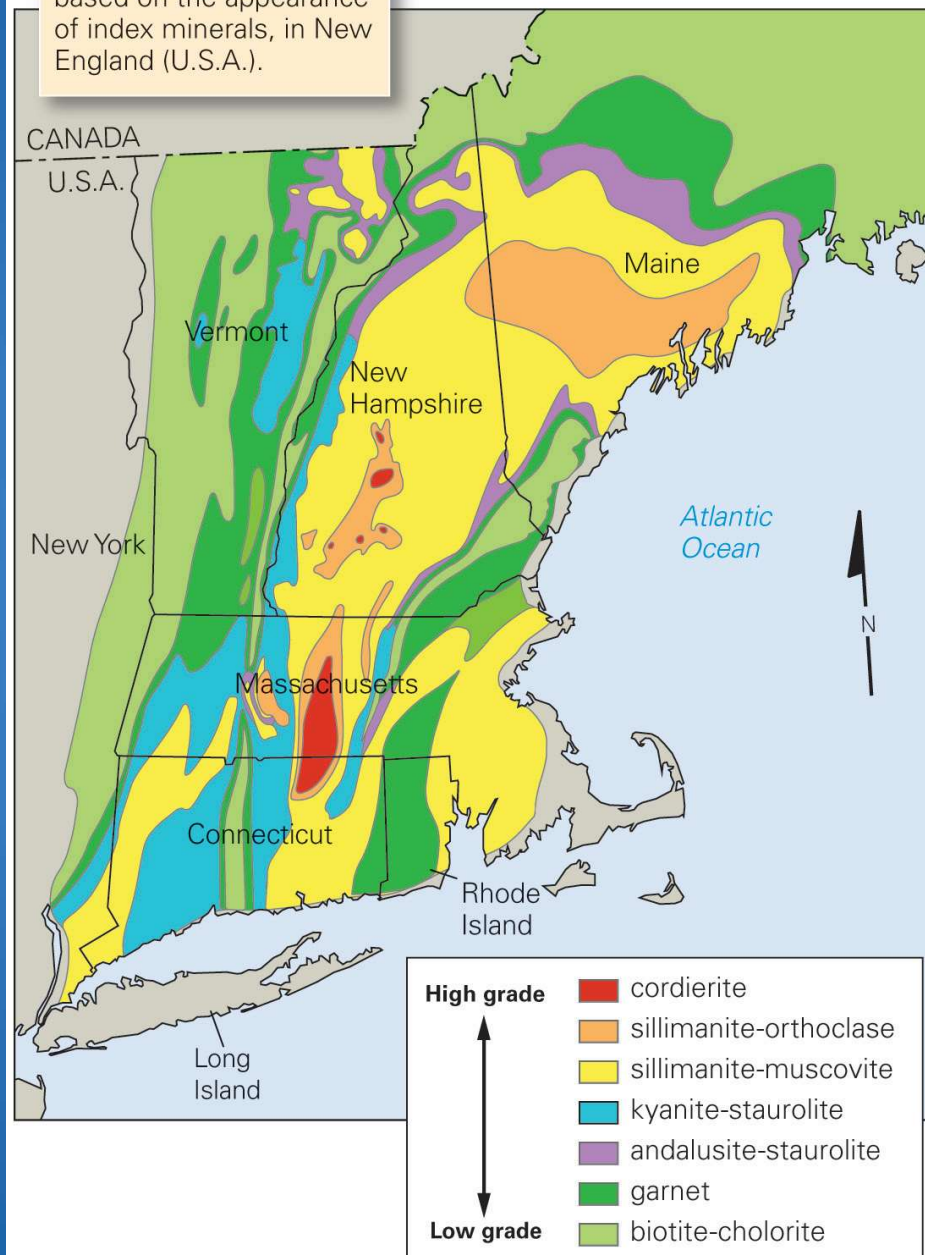
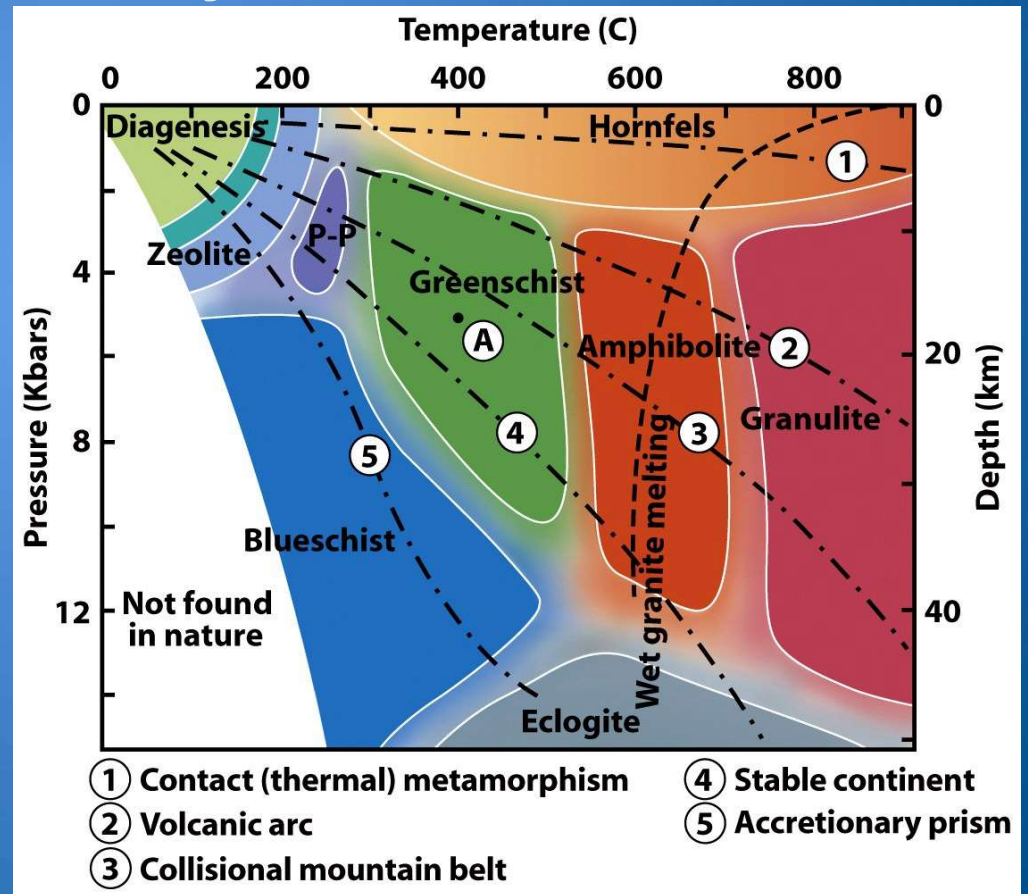
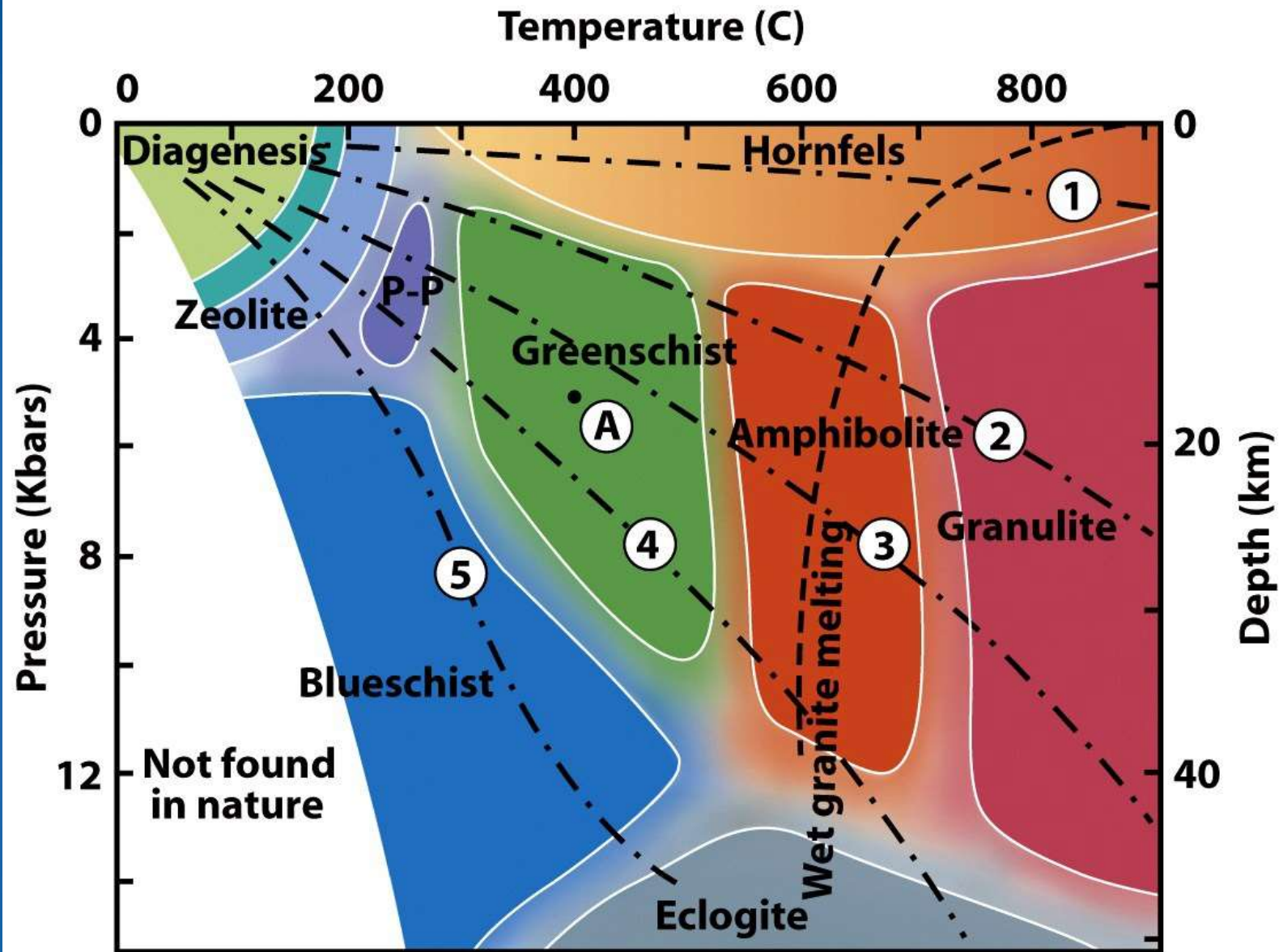


Fig. 7.8c

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.





- ① Contact (thermal) metamorphism
- ② Volcanic arc
- ③ Collisional mountain belt
- ④ Stable continent
- ⑤ Accretionary prism

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).

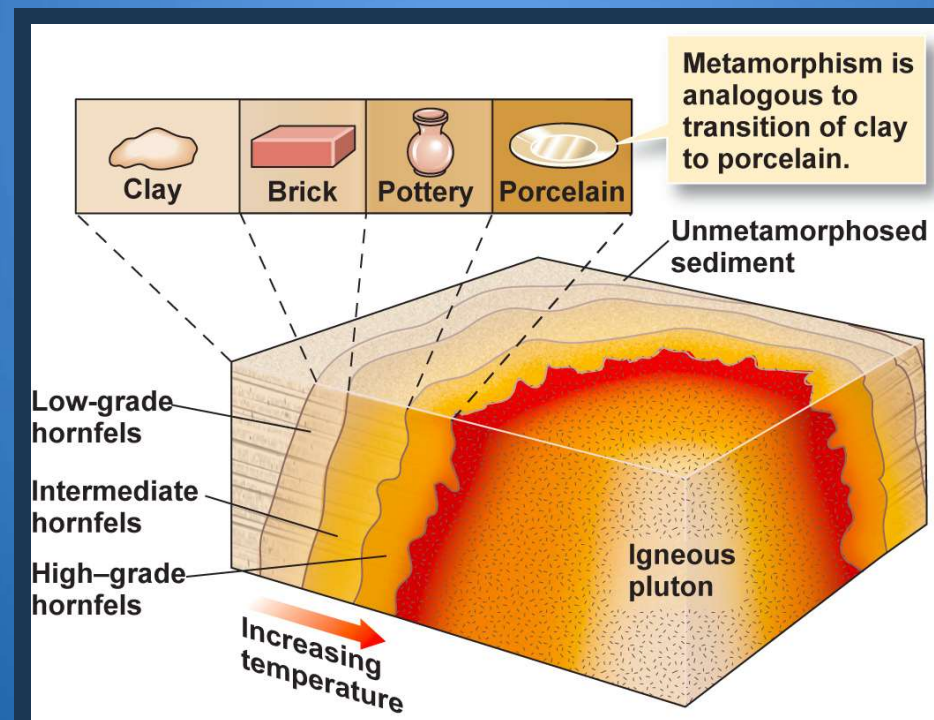


Fig. 7.9a

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.

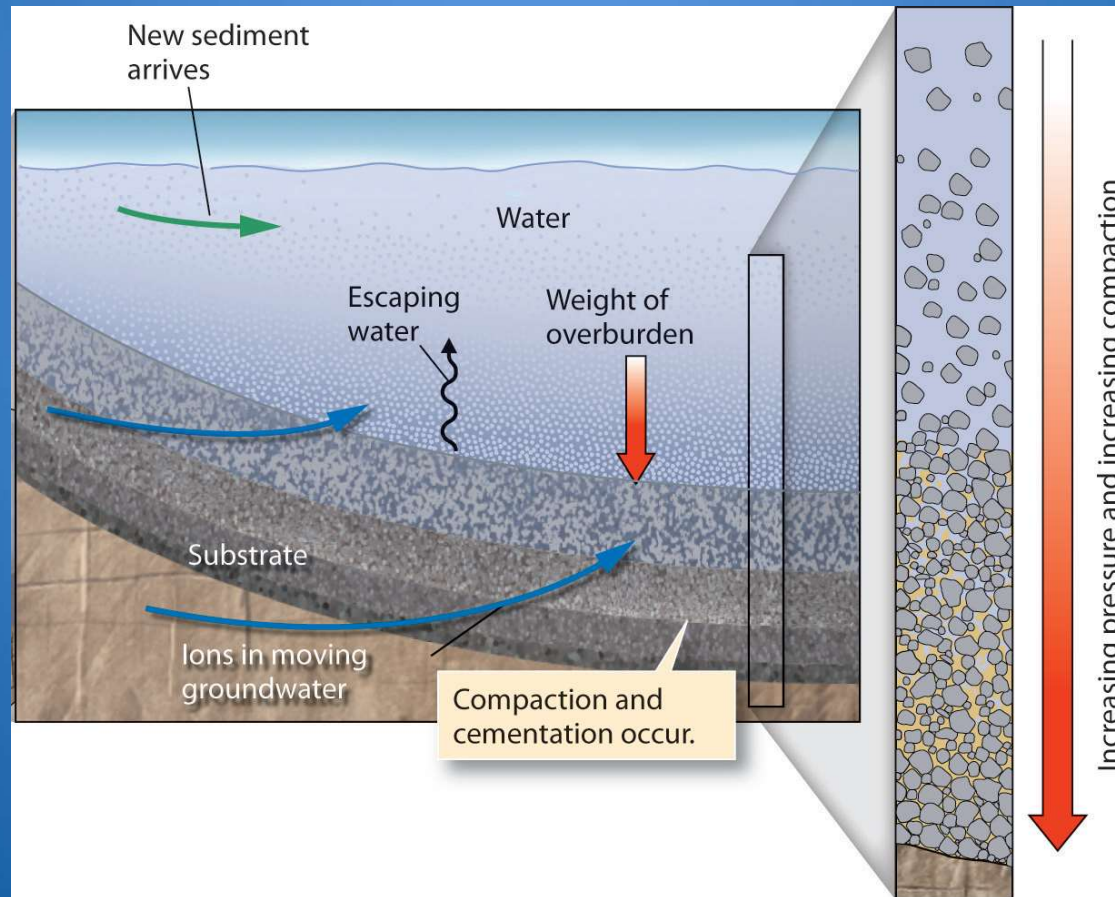


Fig. 6.2b

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.

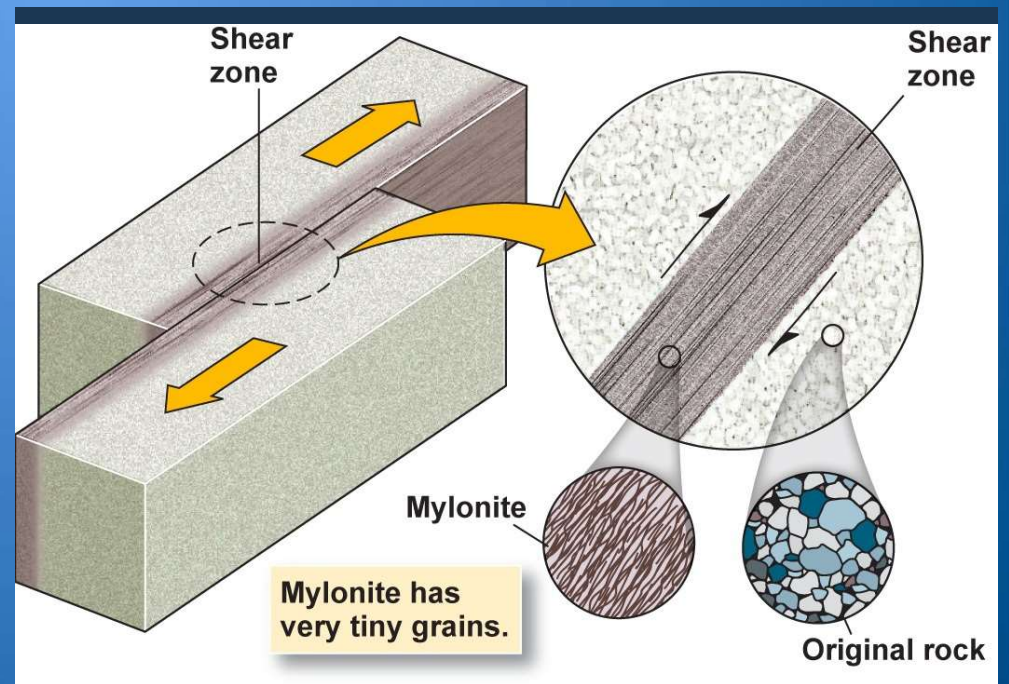


Fig. 7.9b

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.

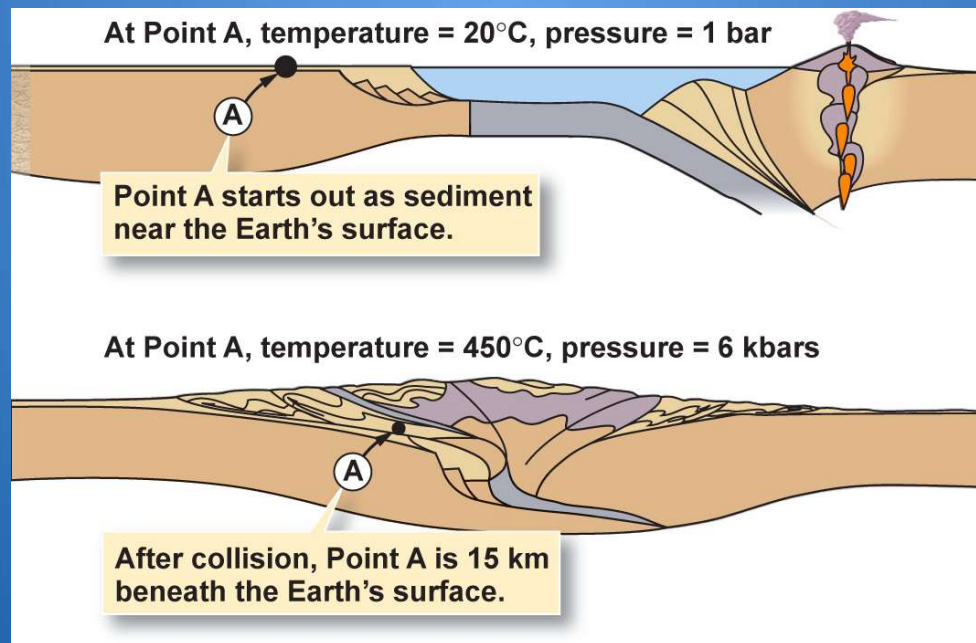


Fig. 7.9c

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.

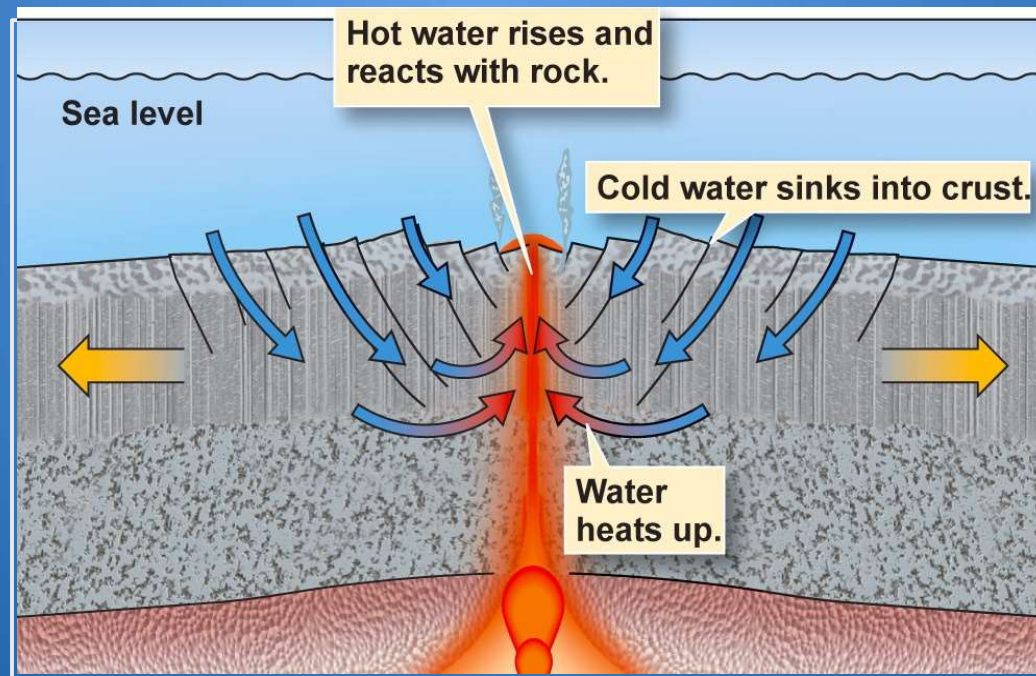
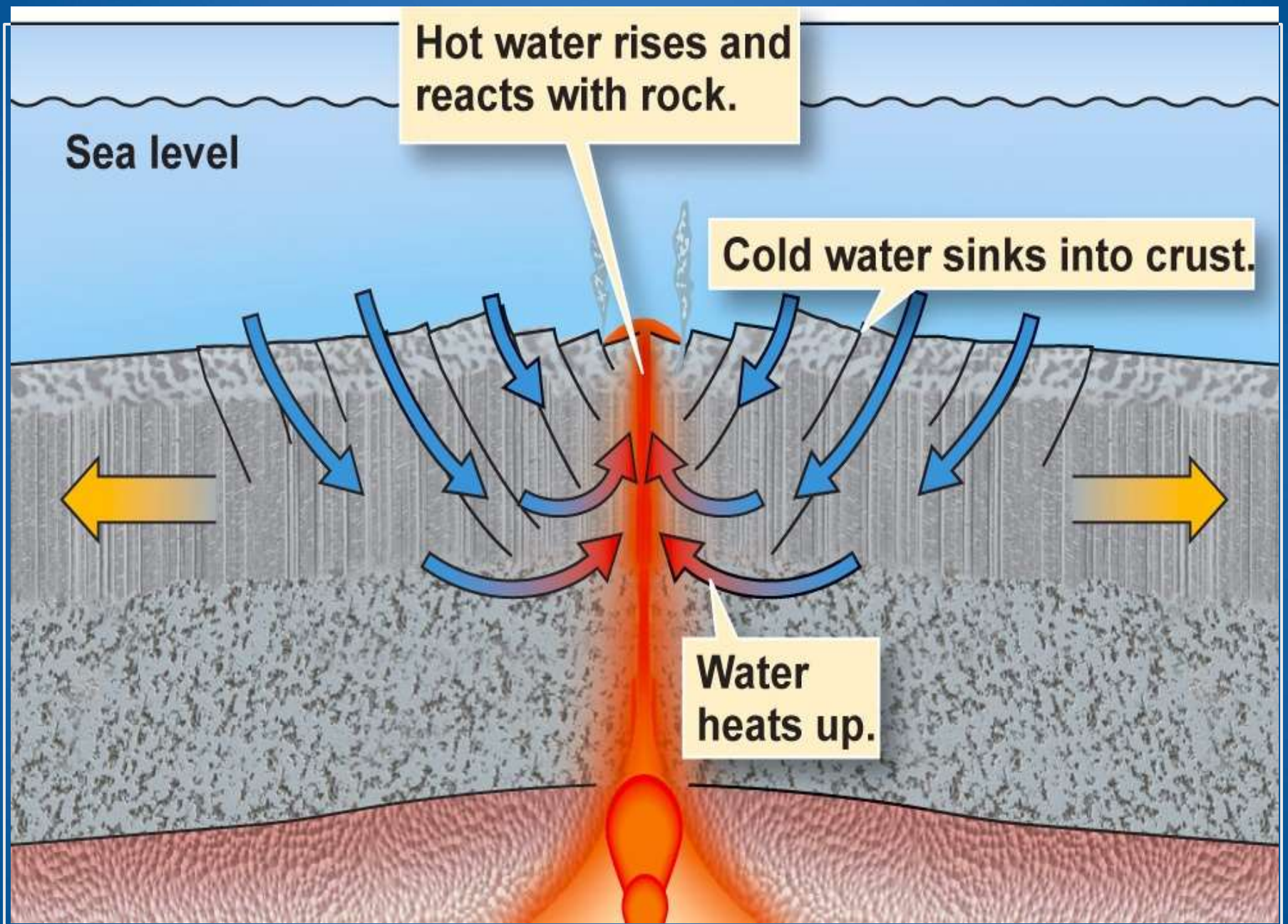
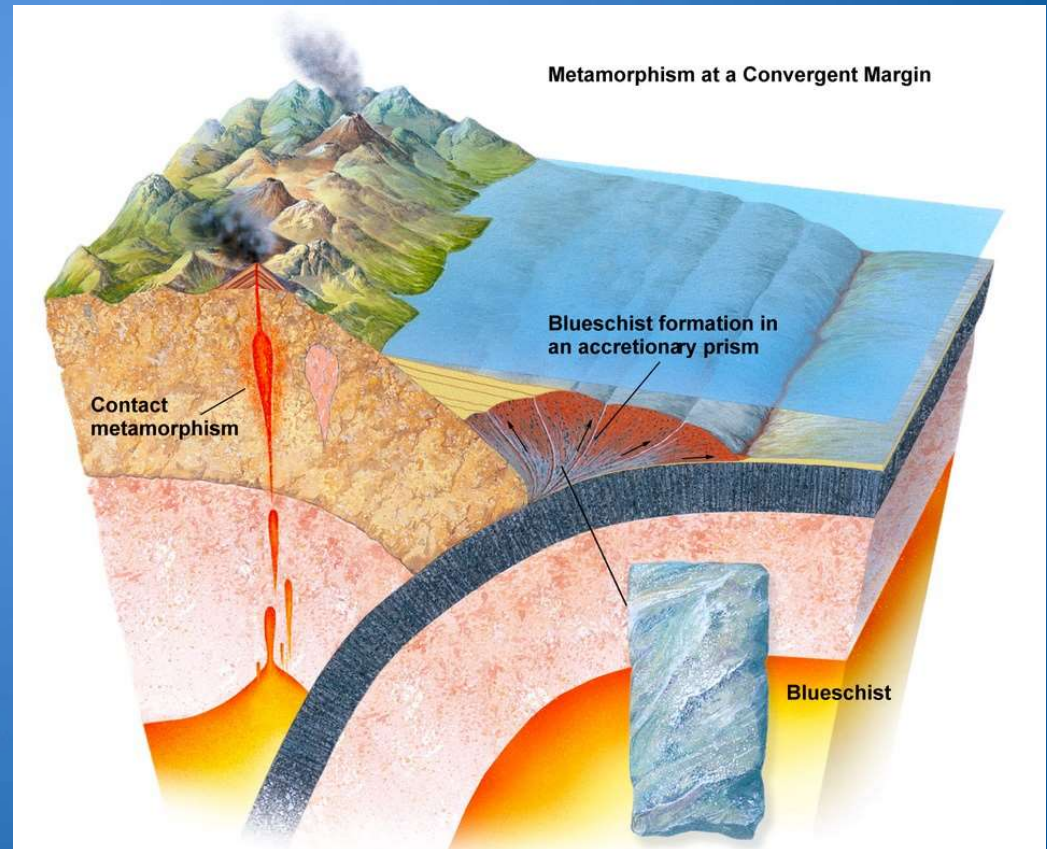


Fig. 7.9d



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

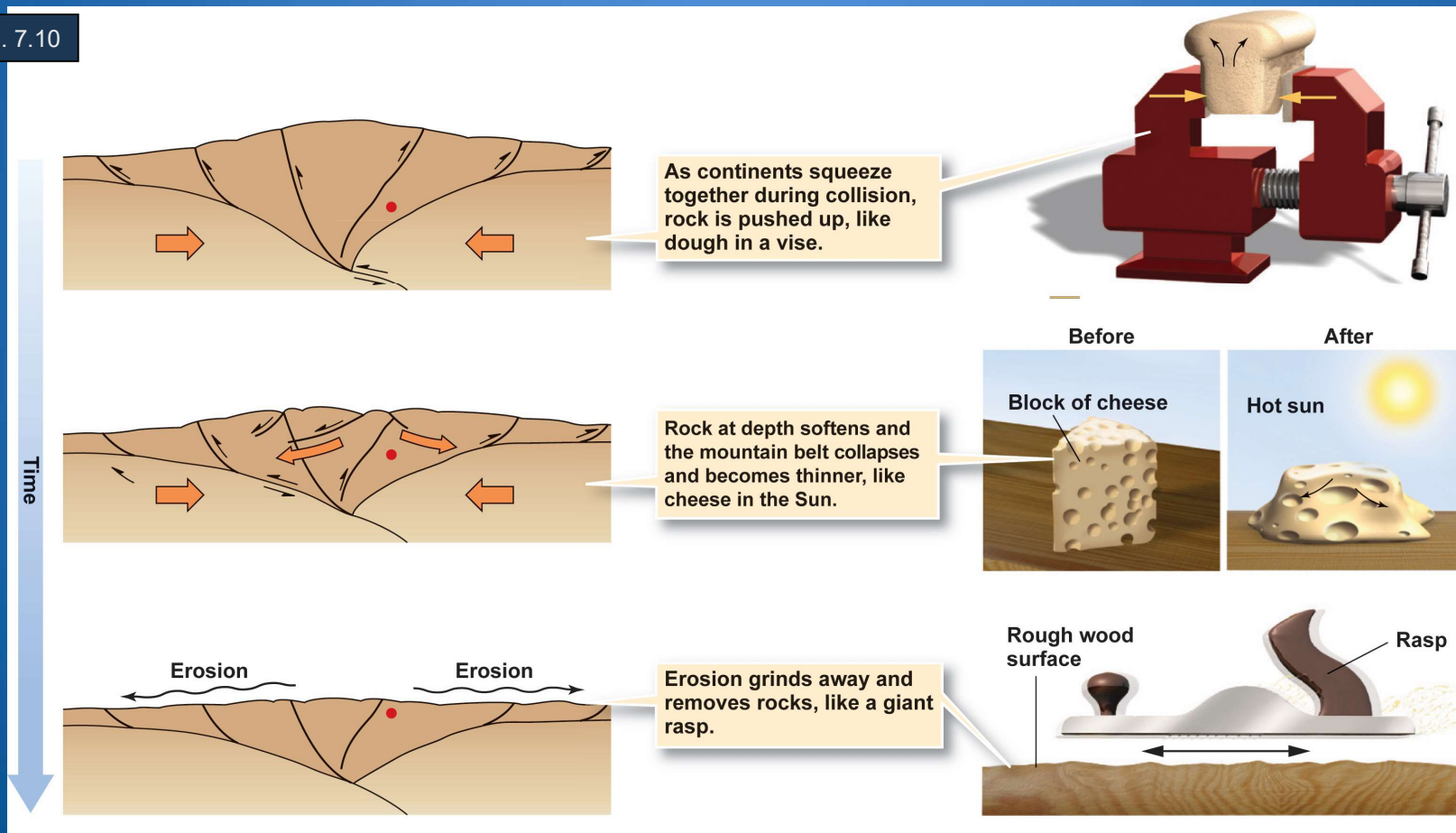
- Rarely, Earth is struck by a comet or asteroid.
- Impacts generate a compressional shock wave.
 - Extremely high pressure.
 - Heat that vaporizes or melts large masses of rock.
- These conditions generate high-pressure minerals.



Exhumation

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

Fig. 7.10



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.

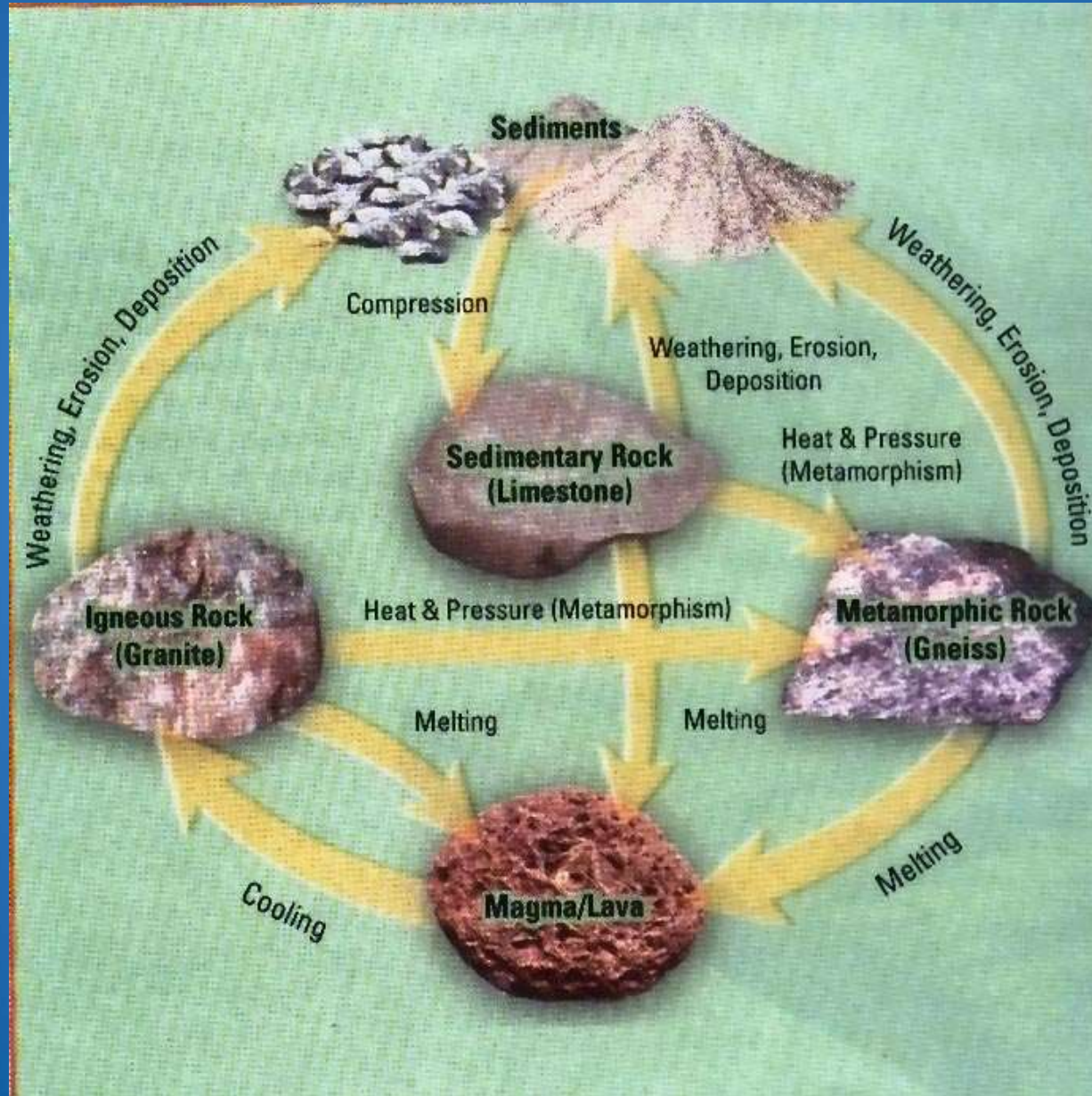


Fig. 7.11

Useful Web Resources

- **Wikipedia Metamorphic Rock Page**
 - http://en.wikipedia.org/wiki/Metamorphic_rock
- **A database For Metamorphic Petrology Database**
 - <http://metpetdb.rpi.edu/metpetweb/#home>
- **Geology.com Metamorphic Rocks Page**
 - <http://geology.com/rocks/metamorphic-rocks.shtml>

The Rock Cycle



Rock Cycle

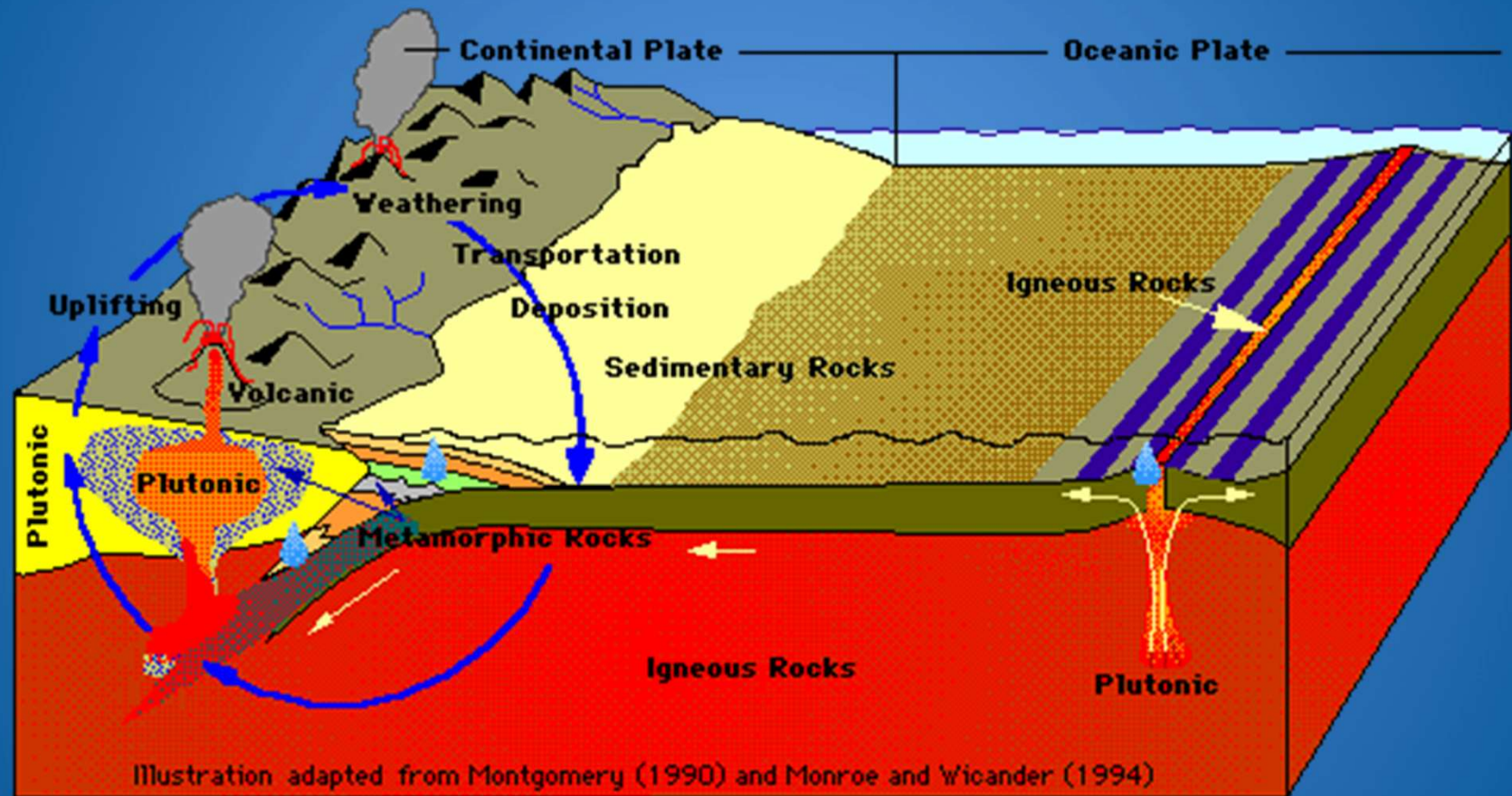


Illustration adapted from Montgomery (1990) and Monroe and Wicander (1994)

 **Areas of Contact Metamorphism**
 **Fluid Alteration Area**
 **Magnetic Polarity Zones**