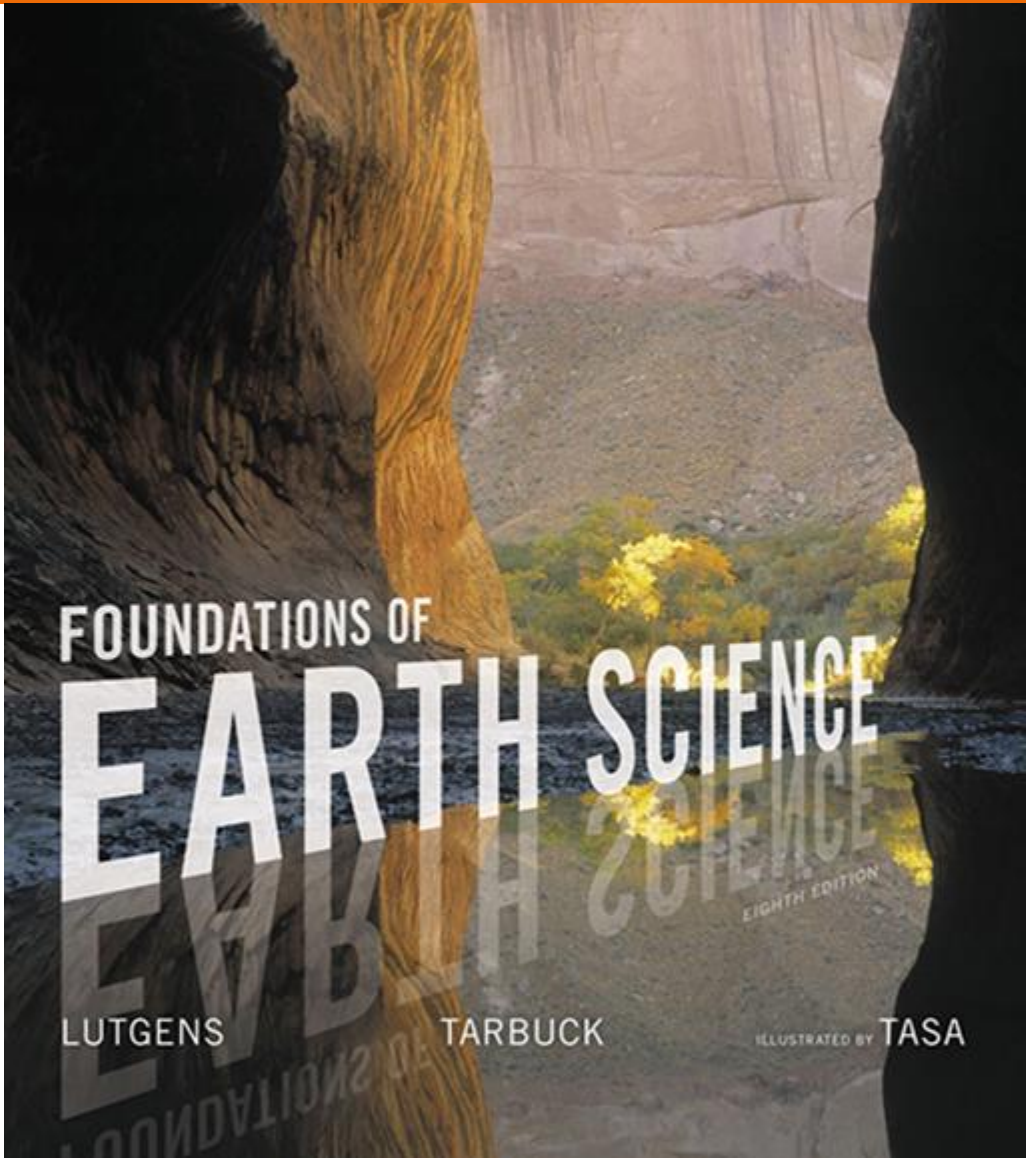
Foundations of Earth Science

Eighth Edition



Rocks: Materials of the Solid Earth

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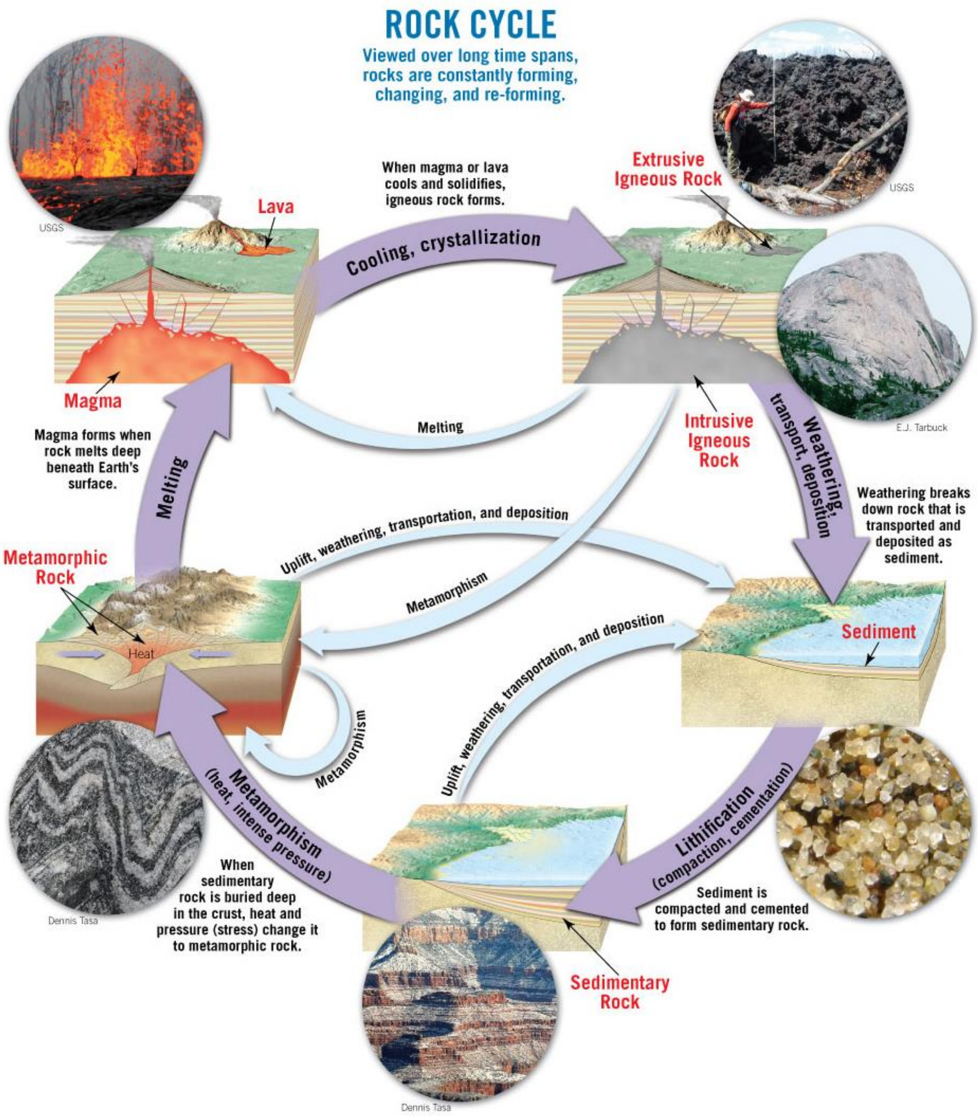
Focus Question 2.1

- Sketch, label, and explain the rock cycle.

Focus Question 2.1



Earth as a System: The Rock Cycle

- The **rock cycle** describes the interactions between the components of the Earth system
  - Origin of igneous, sedimentary, and metamorphic rocks and how they are connected
- Any rock can be transformed into any other rock type under the right conditions

The Basic Cycle

- The rock cycle begins with magma
  - Forms from melting in Earth’s crust and upper mantle
  - Less dense magma rises toward the surface
  - Erupts at surface as lava or cools within crust
  - Cooling is called crystallization or solidification
- Igneous rocks are crystallized from
  - ***Magma*** (within the crust)
  - Or ***lava*** (at Earth’s surface)

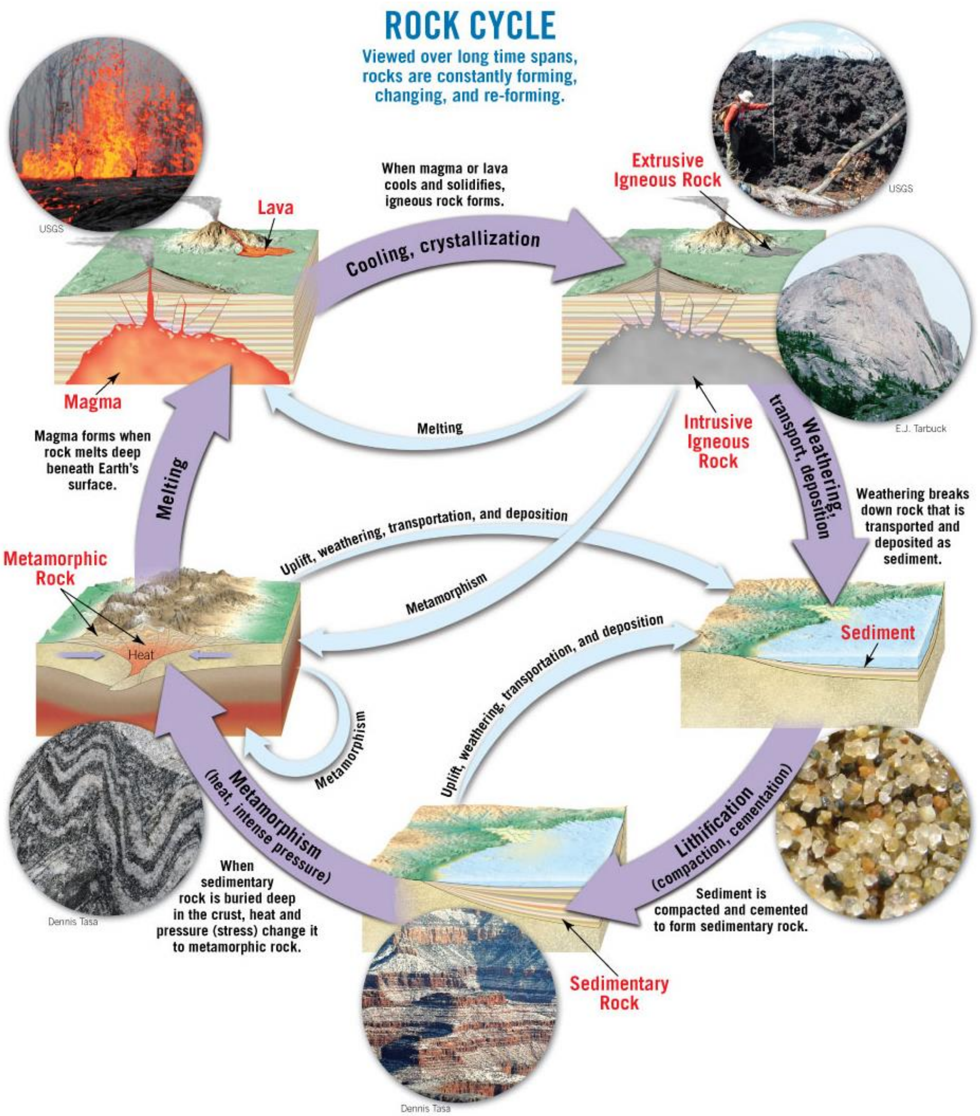
The Basic Cycle

- Igneous rocks exposed at Earth's surface undergo ***weathering***
  - Atmosphere decomposes rock
  - Generates loose material or dissolves it
- Loose material is called ***sediment***
  - Transported by gravity, running water, glaciers, wind, waves, etc.
  - Most sediment is transported to the ocean, but some is deposited in other environments

The Basic Cycle

- Deposited sediment undergoes ***lithification***
  - "Conversion into rock" by
    - Compaction
    - Cementation
- Deformed by great heat and pressure if deeply buried or incorporated into a mountain chain
  - ***Metamorphism***
- Eventually enough heat will melt the rock and generate magma

The Basic Cycle



The Basic Cycle

- Rocks are not stable unchanging masses over geologic time scales
  - Rock cycle happens over millions or billions of years
- Different stages of the rock cycle are occurring today all over Earth's surface
  - New igneous rocks are forming in Hawaii
  - The Colorado Rockies are eroding and material is being carried to the Gulf of Mexico

Alternative Paths

- Rocks do not always go through the rock cycle from igneous to sedimentary to metamorphic
  - Igneous rocks may remain deeply buried and then become metamorphosed
  - Sedimentary and metamorphic rocks may be uplifted and eroded into sediment instead of melted
- The rock cycle is driven by Earth's internal heat and external processes, including weathering and erosion

Focus Questions 2.2

- Describe the two criteria used to classify igneous rocks.
- Explain how the rate of cooling influences the crystal size of minerals.

Igneous Rocks: “Formed by Fire”

- **Igneous rocks** form when magma or lava cools and crystallizes
  - **Magma** is generated most commonly by melting in the mantle, but some is generated by melting the crust
  - Rises because it is less dense than surrounding rock
  - Magma that reaches Earth’s surface is known as **lava**

Igneous Rocks: “Formed by Fire”

- Solidification of lava at Earth’s surface creates **extrusive** or **volcanic** igneous rocks
  - Most volcanic eruptions are not violent
  - Abundant in the northwest (Cascades, Columbia Plateau)
  - Many oceanic islands are volcanic (Hawaii)

Igneous Rocks: “Formed by Fire”

- Most magma never reaches the surface, and instead solidifies as **intrusive** or **plutonic** igneous rocks
- Only exposed at the surface by uplift and erosion
  - Mount Washington (New Hampshire)
  - Stone Mountain (Georgia)
  - Mount Rushmore and the Black Hills (South Dakota)
  - Yosemite National Park (California)

Igneous Rocks: “Formed by Fire”

From Magma to Crystalline Rock

- Magma contains ***ions*** including silicon and oxygen, ***gas*** (water vapor) confined by pressure, and some ***solid crystals***
- Crystallization occurs as mobile ions arrange into orderly patterns during cooling
- As cooling continues, more ions are added to the crystals until all of the liquid becomes a solid mass of interlocking crystals

From Magma to Crystalline Rock

- Rate of cooling strongly influences crystal size
  - Slow cooling results in fewer, larger crystals
  - Quick cooling results in a large number of small intergrown crystals
  - Instantaneous cooling (“quenching”) results in randomly distributed atoms, no crystal growth, and formation of volcanic glass
    - Volcanic ash is actually tiny shards of glass
- Crystallization is also influenced by magma composition and dissolved gas

Igneous Compositions

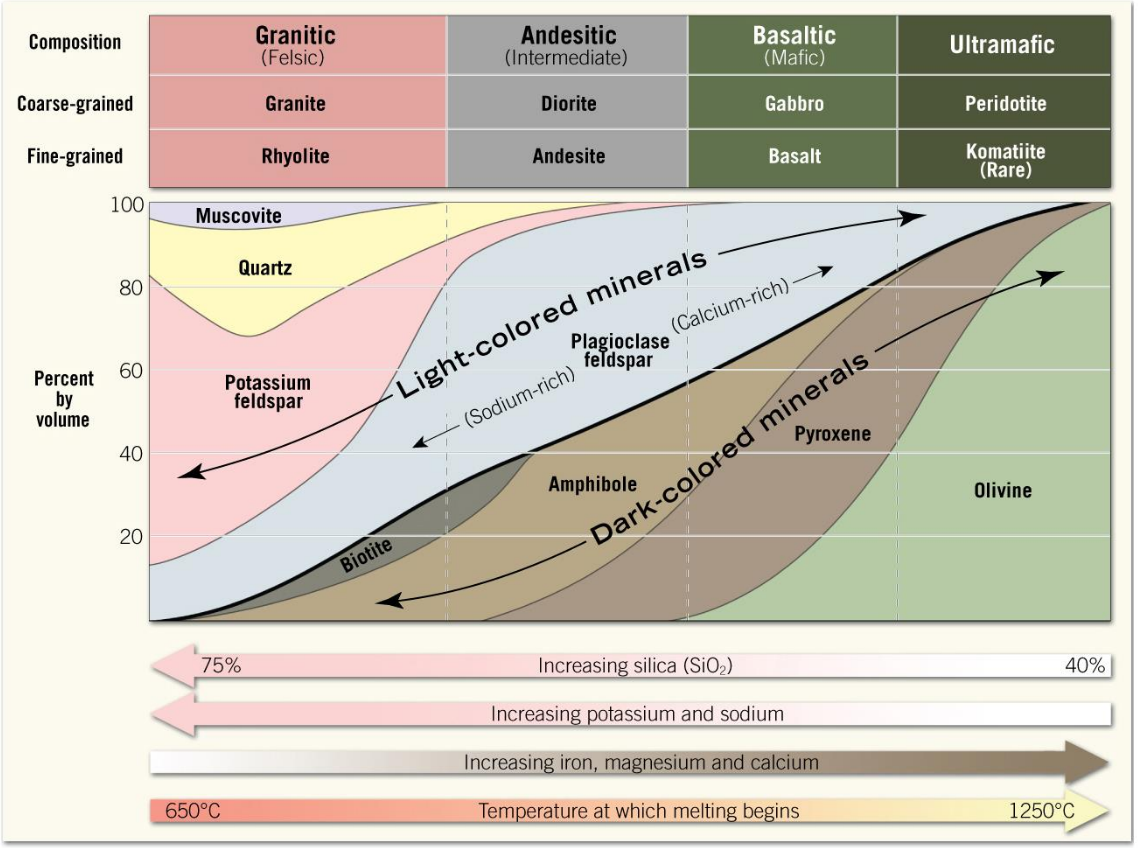
- Igneous rocks are mainly composed of silicate minerals
- Silicon and oxygen + Al, Ca, Na, K, Mg, and Fe make up 98% of most magmas
- Also includes small amounts of trace elements
  - Titanium, manganese, gold, silver, uranium, etc.
- During crystallization, these elements combine to form two major groups of silicate minerals

Igneous Compositions

- **Dark silicates** are rich in iron and/or magnesium and relatively low in silica
  - Olivine, pyroxene, amphibole, biotite mica
- **Light silicates** contain greater amounts of potassium, sodium and calcium and are richer in silica
  - Quartz, muscovite mica, feldspars
  - Feldspars are most abundant mineral group
    - 40% of most igneous rocks

Igneous Compositions

- Igneous rocks can be divided into broad groups according to proportions of light and dark minerals



Igneous Rocks: "Formed by Fire"

- Granitic (***felsic***) rocks
  - Igneous rocks of **granitic composition** are made up almost entirely of light-colored silicates
    - Quartz and potassium feldspar
  - Felsic = feldspar + silica
  - Most contain ~10% dark silicate minerals
    - Biotite mica, amphibole
  - ~70% silica
  - Major constituent of continental crust

Igneous Rocks: "Formed by Fire"

- Basaltic (***mafic***) rocks
  - Contain at least 45% dark silicate minerals and Ca-rich plagioclase but no quartz
  - Mafic = magnesium + ferrum (iron)
  - Darker and more dense than granitic rocks because of iron content

Igneous Rocks: “Formed by Fire”

- Andesitic (***intermediate***) rocks
  - **Andesitic** falls between granitic and basaltic composition
  - Mixture of both light- and dark-colored minerals
    - Contain at least 25% dark-silicate minerals
    - Amphibole and plagioclase feldspar
  - Associated with volcanic activity at continental margins

Igneous Rocks: “Formed by Fire”

- ***Ultramafic*** rocks
  - Contain mostly dark-colored minerals
    - Olivine and pyroxene
  - For example, peridotite and dunite
  - Rare at Earth’s surface
  - Main constituent of upper mantle

What Can Igneous Textures Tell Us?

- The **texture** of a rock is described based on the size, shape, and arrangement of mineral grains
- Texture can be used to make inferences about a rock's origin, for example:
  - Large crystals indicate slow cooling
  - Slow cooling is common in magma chambers deep in the crust
  - A rock with large crystals probably formed deep in the crust

What Can Igneous Textures Tell Us?

- **Fine-grained texture**
  - Cooled rapidly at the surface or in small masses in the upper crust
  - Individual crystals are too small to see with the naked eye
- **Coarse-grained texture**
  - Solidified at depth while insulated by surrounding rock
  - Masses of interlocking crystals roughly the same size (large enough to be seen by the naked eye)

What Can Igneous Textures Tell Us?

- **Porphyritic texture**
  - Different minerals crystallize under different temperature and pressure conditions
  - One mineral can reach a large size before other minerals start to form
  - Large crystals **(phenocrysts)** in a matrix of smaller crystals **(groundmass)**
- **Vesicular texture**
  - Exhibits voids left by gas bubbles that remained when lava solidified
  - Form in upper zone of a lava flow

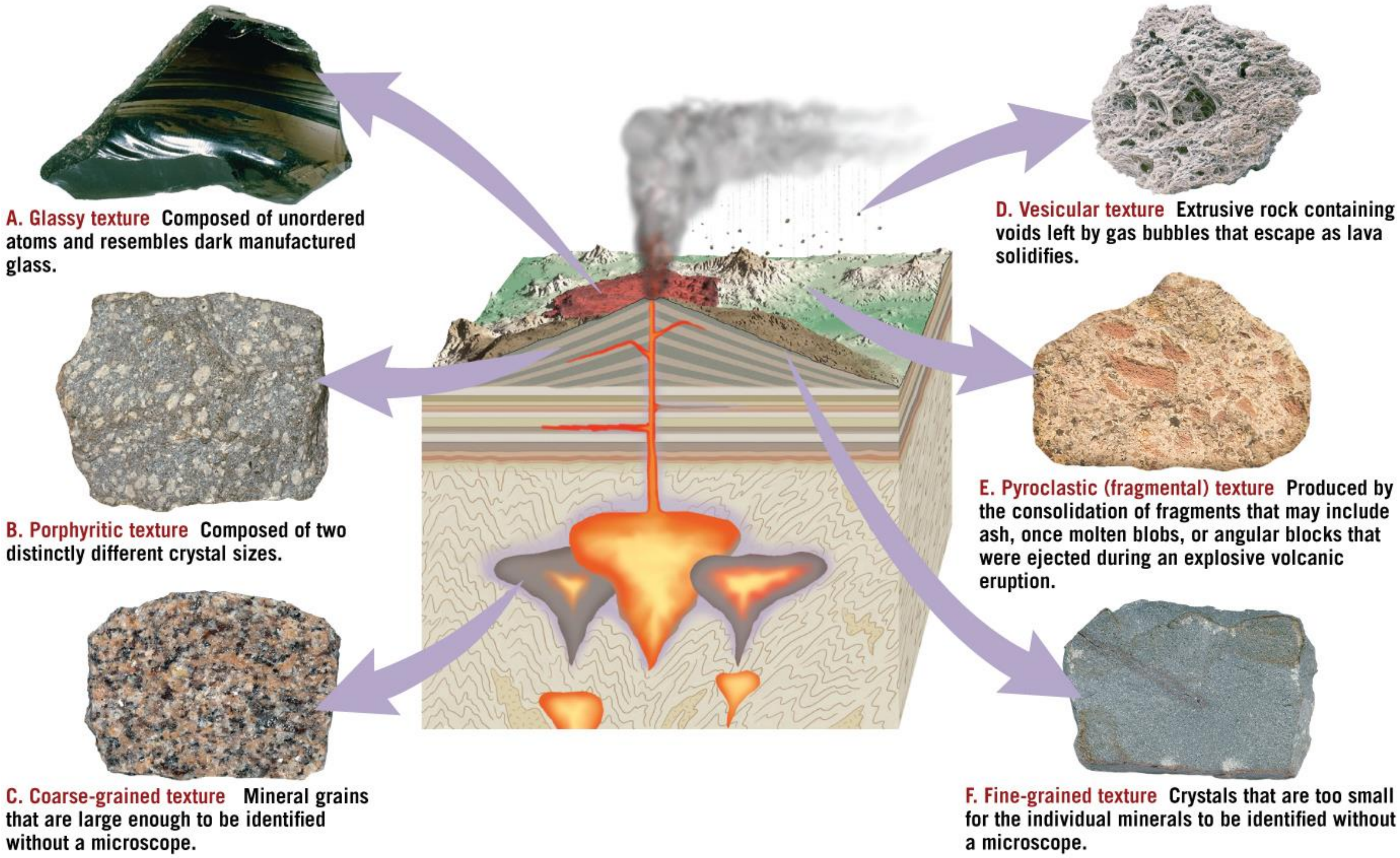
What Can Igneous Textures Tell Us?

Scoria, an extrusive igneous rock with a vesicular texture,

What Can Igneous Textures Tell Us?

- **Glassy texture**
  - Develops when rocks cool rapidly
  - Ions freeze in place before they can arrange themselves in an orderly crystalline structure
- **Pyroclastic (fragmental) texture**
  - Composed of individual rock fragments ejected during explosive volcanic eruptions
  - Particles could be very fine ash, molten blobs, or large angular blocks

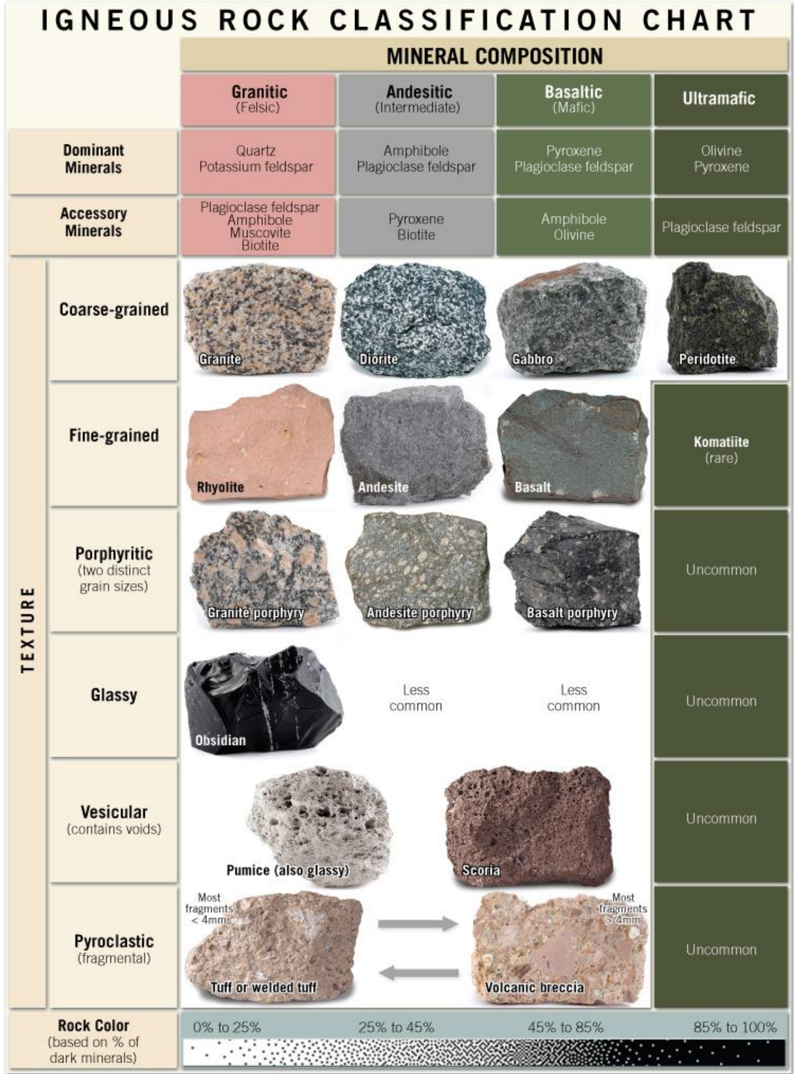
What Can Igneous Textures Tell Us?



Common Igneous Rocks

- Igneous rocks are classified by texture and mineral composition
  - Texture results from cooling history
  - Mineral composition derives from parent magma and environment of crystallization

Common Igneous Rocks



Common Igneous Rocks

- **Granite**
  - Coarse-grained
  - Forms when magma solidified slowly at depth
  - Uplifted during mountain building

Common Igneous Rocks

Common Igneous Rocks

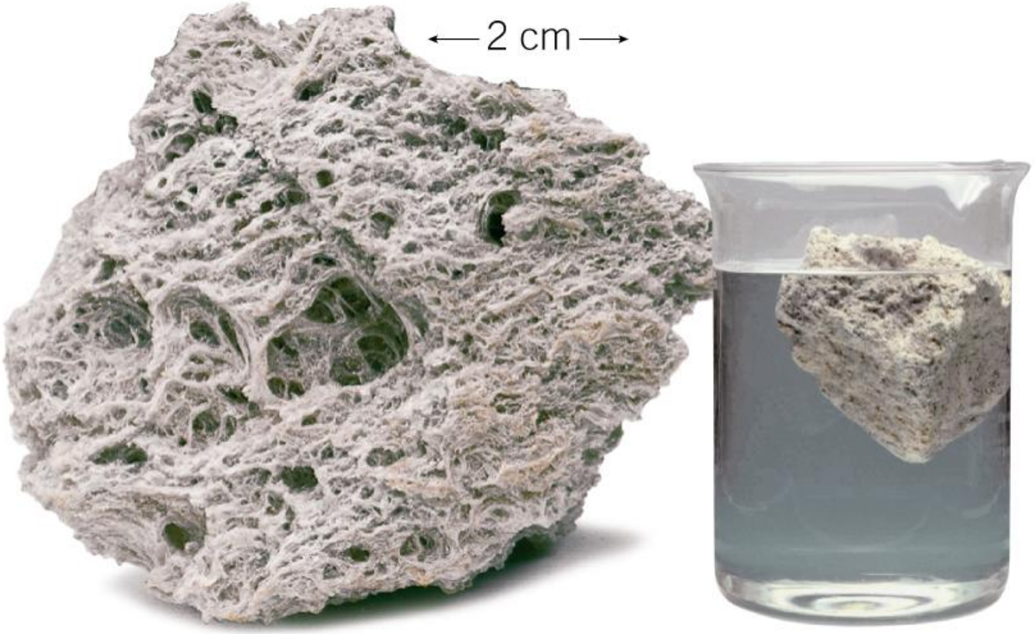
- **Rhyolite**
  - Extrusive fine-grained equivalent of granite
  - Light-colored silicates, usually buff, pink, or light grey
  - Frequently contains voids and fragments of volcanic glass
  - Cooled rapidly at Earth’s surface

Common Igneous Rocks

- **Obsidian**
  - Natural volcanic glass
  - Dark in color (from metallic ions), but felsic composition

Common Igneous Rocks

- **Pumice**
  - Vesicular volcanic glass
  - Gas escape from molten lava forms a frothy, gray rock
  - Many pieces float in water because of vesicles



Common Igneous Rocks

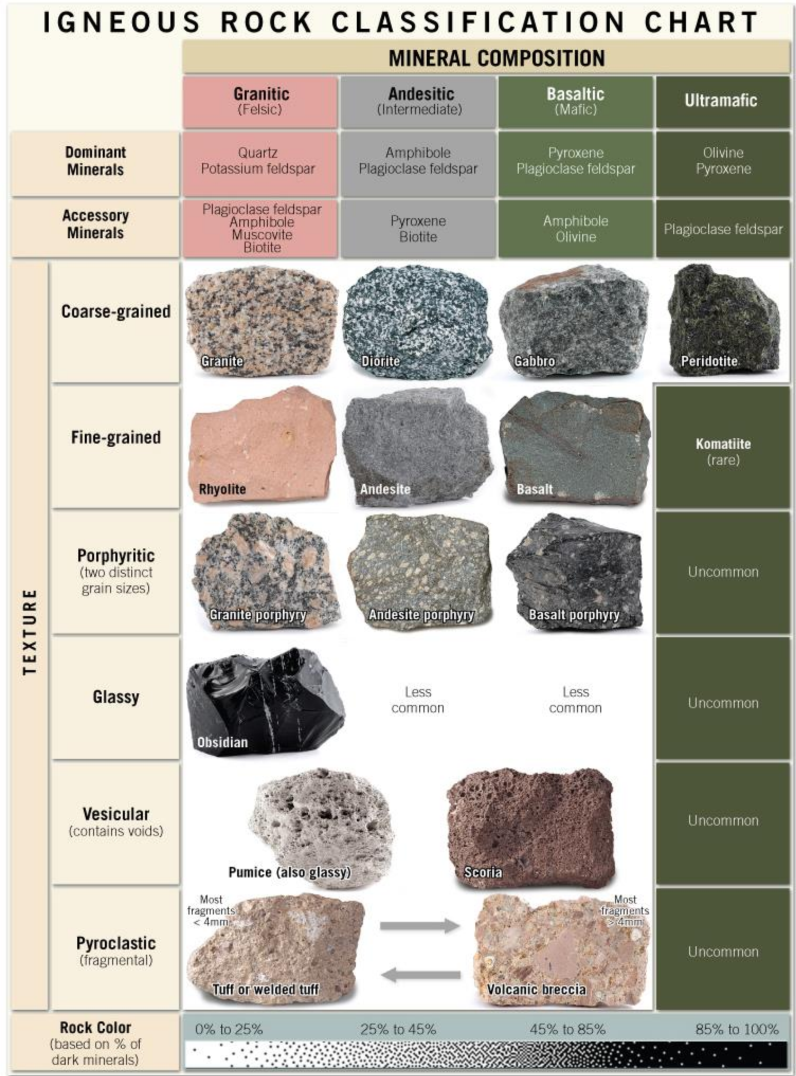
- **Andesite**
  - Medium-gray extrusive igneous rock
  - Fine-grained or porphyritic with phenocrysts of plagioclase feldspar or amphibole
  - Major constituent of volcanos along the Pacific Rim
    - Andes Mountains
    - Cascade Range
- **Diorite**
  - Coarse-grained intrusive equivalent of andesite
  - Few or no visible quartz crystals

Common Igneous Rocks

- **Basalt**
  - Most common extrusive igneous rock
  - Dark green to black, fine-grained
  - Contains pyroxene, olivine, and plagioclase feldspar
  - Relatively common at Earth's surface
    - Volcanic islands (e.g., Hawaii, Iceland)
    - Upper layers of the oceanic crust
    - Central Oregon and Washington
- **Gabbro**
  - Coarse-grained intrusive equivalent of basalt
  - Not commonly exposed at Earth's surface
  - Significant component of oceanic crust

Common Igneous Rocks

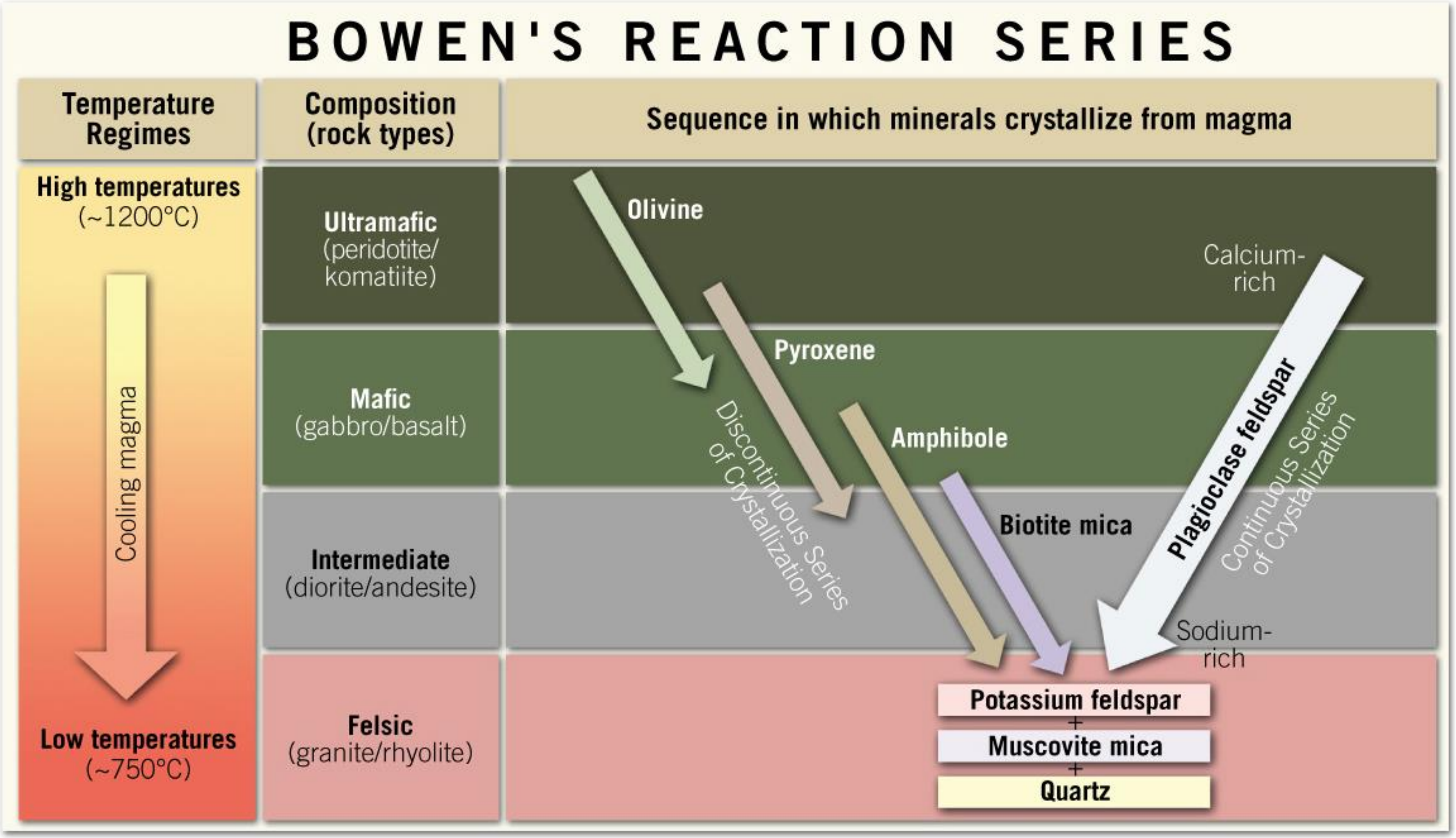
Common Igneous Rocks



How Different Igneous Rocks Form

- Magma can evolve
  - Different rock types can be generated from the same melt
- Bowen's reaction series describes which minerals solidify at specific temperatures
  - First to crystallize is olivine, then pyroxene and plagioclase
  - Amphibole and biotite at intermediate temperatures
  - Muscovite and potassium feldspar during late cooling
  - Quartz is last to solidify
- Minerals that form in the same temperature range tend to be associated in the same igneous rocks

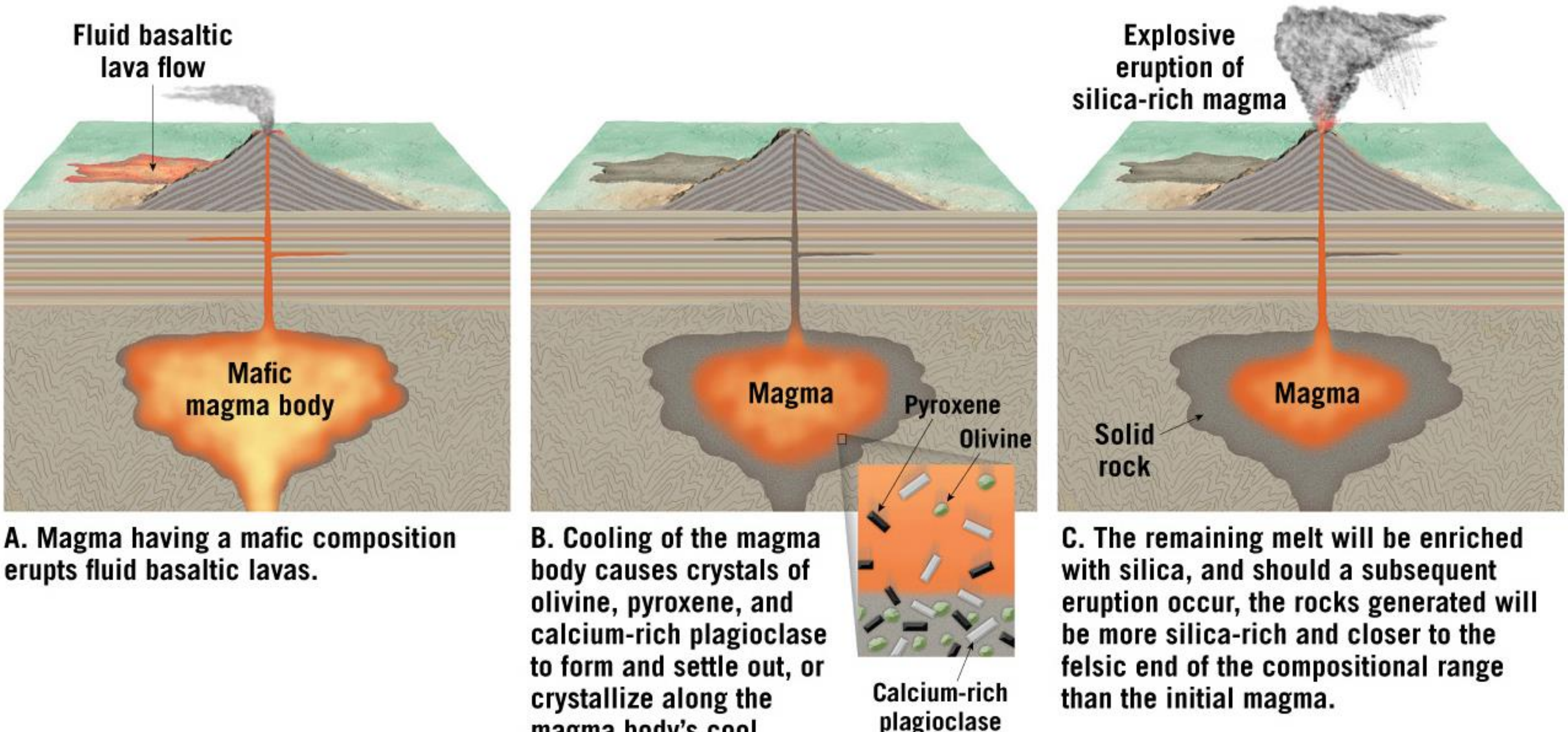
How Different Igneous Rocks Form



How Different Igneous Rocks Form

- **Magmatic differentiation** is the formation of one or more secondary magmas from a single parent magma
  - Explains diversity of igneous rocks
  - Magma composition continually changes during cooling
  - As crystals form, certain elements are selectively removed, resulting in a depleted magma
  - **Crystal settling** occurs when dense minerals sink to the bottom of a magma chamber

Igneous Rocks: “Formed by Fire”



A. Magma having a mafic composition erupts fluid basaltic lavas.

B. Cooling of the magma body causes crystals of olivine, pyroxene, and calcium-rich plagioclase to form and settle out, or crystallize along the magma body’s cool margins.

C. The remaining melt will be enriched with silica, and should a subsequent eruption occur, the rocks generated will be more silica-rich and closer to the felsic end of the compositional range than the initial magma.

Focus Questions 2.3

- Define weathering.
- Distinguish between the two main categories of weathering.

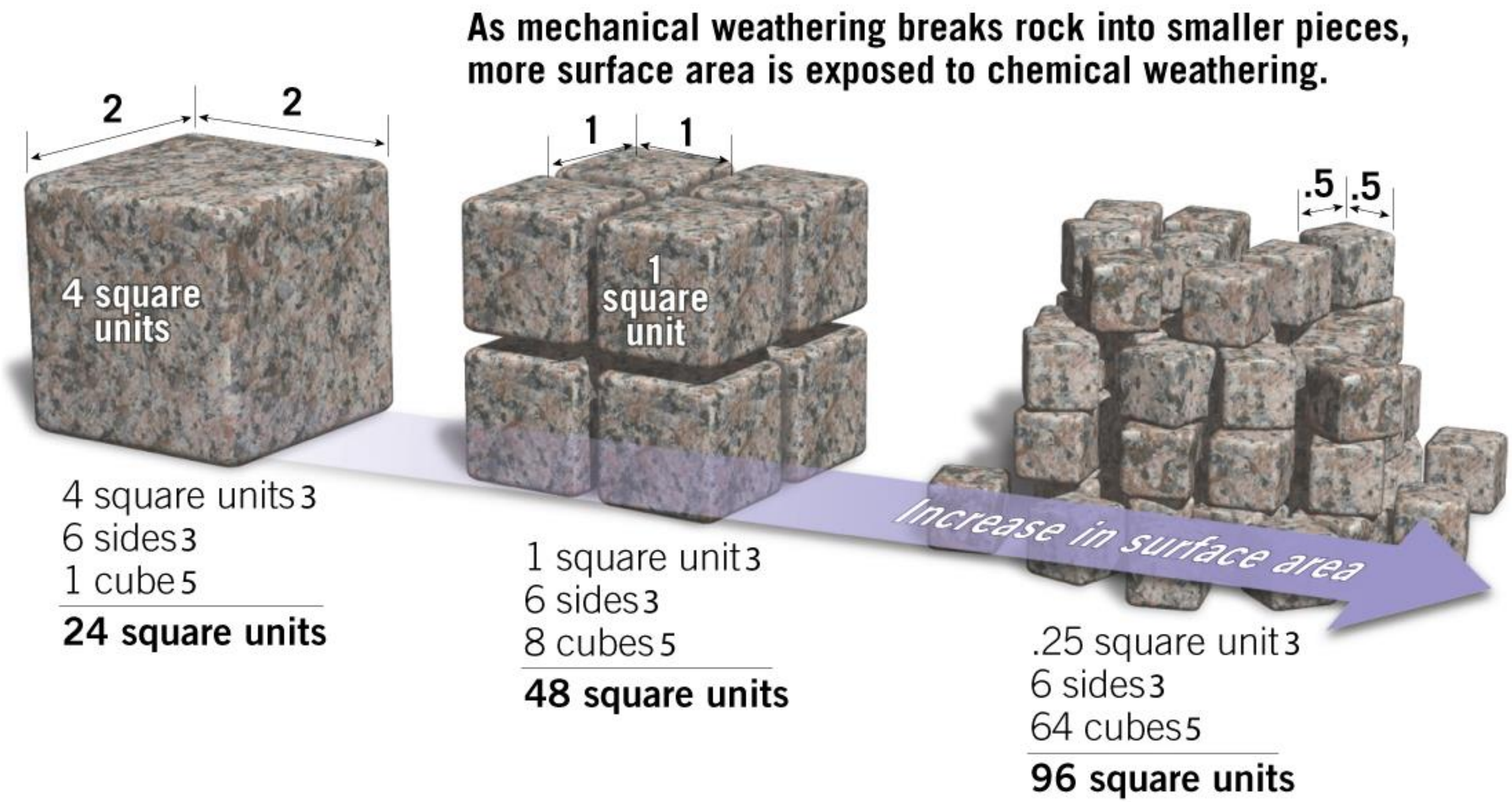
Weathering of Rocks to Form Sediment

- Weathering is the transformation of a rock to reach equilibrium with its environment
  - Natural response of materials to a new environment
  - Two basic categories: ***mechanical*** and ***chemical***
    - Generally occur simultaneously
    - ***Erosion*** transports weathered rock

Mechanical Weathering

- **Mechanical weathering** is the process of breaking down rocks into smaller pieces
  - Each piece retains the same physical properties of the original material
  - Increases surface area available for chemical weathering

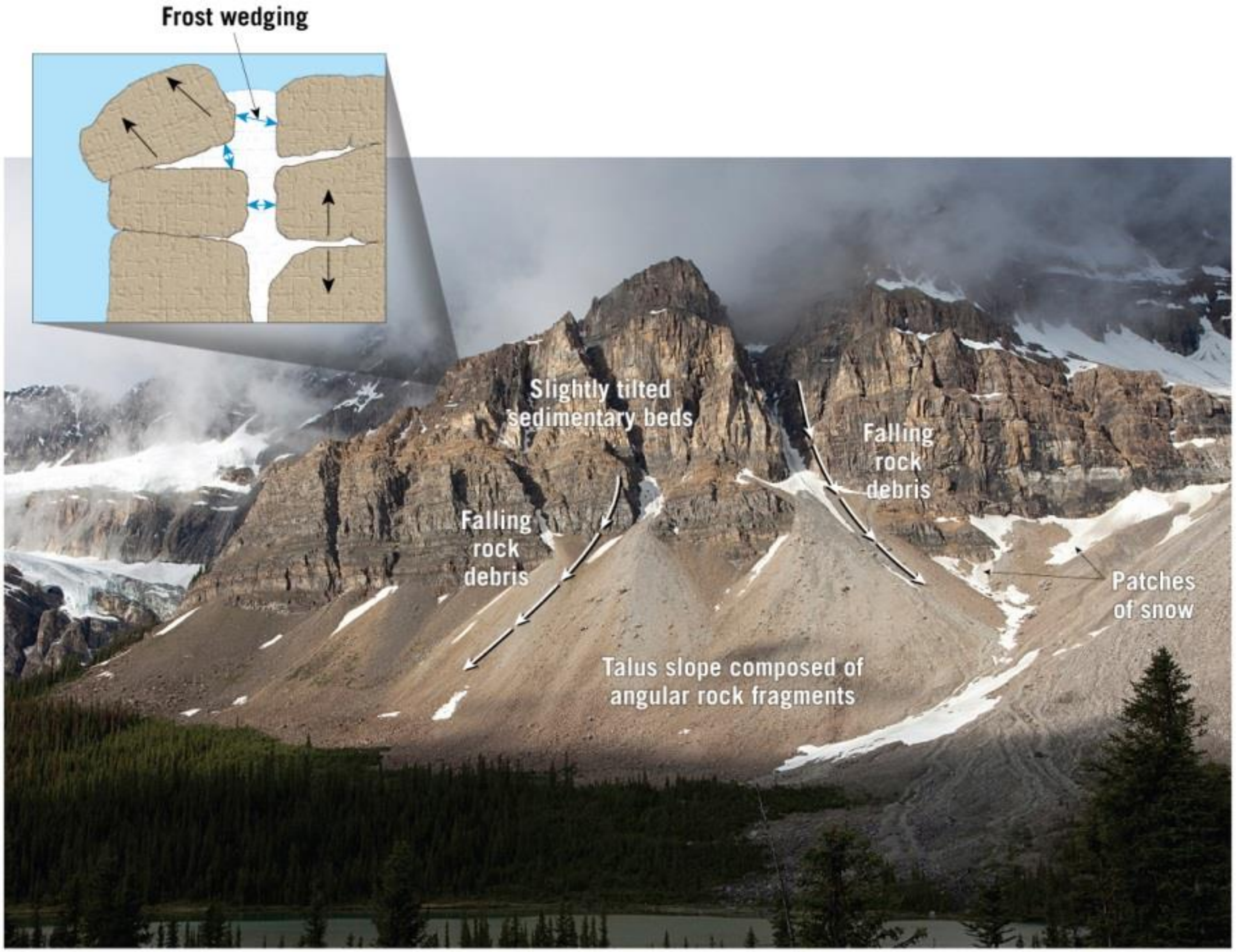
Mechanical Weathering



Mechanical Weathering

- **Frost wedging**
  - Ice expands ~9% when it freezes
  - Traditional explanation: water fills cracks in rocks and expands
  - Recent research: lenses of ice grow within cracks and pore spaces of rock until rock is weakened and fractures

Mechanical Weathering



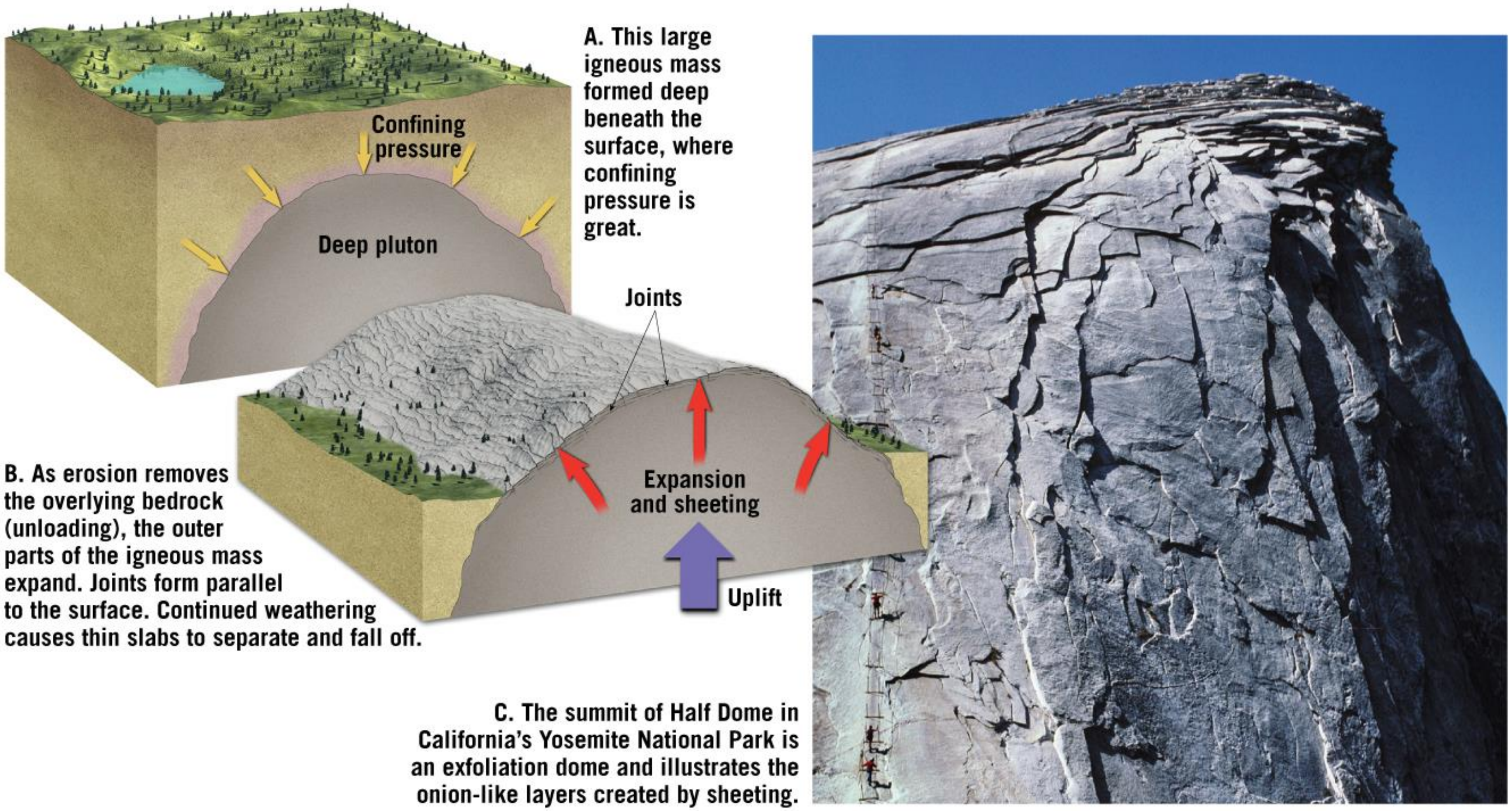
Mechanical Weathering

- **Salt Crystal Growth**
  - Sea spray or salty groundwater evaporate in rock's crevices and pore spaces
  - Salt crystals grow larger and weaken the rock by pushing apart surrounding grains or enlarging tiny cracks
  - Common on rocky shorelines and in arid regions

Mechanical Weathering

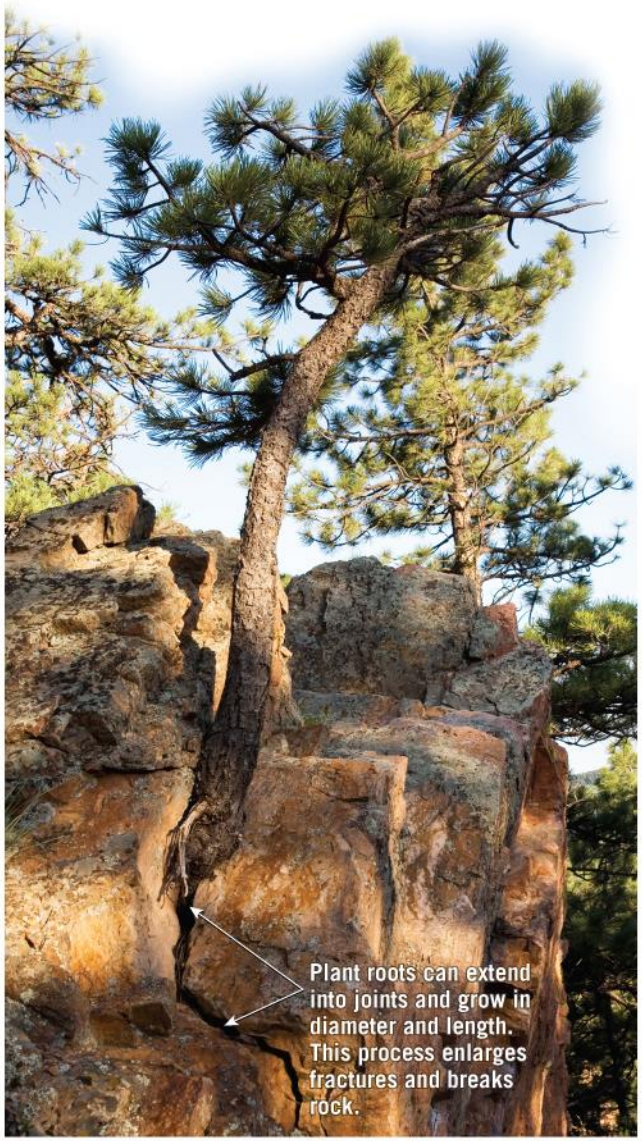
- **Sheeting** occurs when concentric slabs of intrusive igneous rock break loose
  - Removal of overlying rock reduces pressure and outer layers expand and separate
  - Continued weathering results in **exfoliation domes**

Mechanical Weathering



Mechanical Weathering

- **Biological activity** also breaks rocks apart
  - Plant roots grow into cracks and wedge the rock apart
  - Burrowing animals expose rock to increased weathering
  - Decaying organisms produce acids, which contribute to chemical weathering



Chemical Weathering

- **Chemical weathering** alters the internal structure of minerals
  - Elements are removed or added
  - Original rock is transformed into new stable material
  - Makes outer portions of some rocks more susceptible to mechanical weathering
- Water is most important agent of chemical weathering
  - Oxygen dissolved in water causes ***oxidation***
  - Carbon dioxide dissolved in water is ***carbonic acid***
    - Feldspar minerals are broken down into clay minerals
    - Silica is carried away by ground water
- Quartz is very resistant to chemical weathering

Products of Chemical Weathering

- Chemical weathering of a silicate rock by carbonic acid
  - Feldspar minerals are broken down into clay minerals
  - Silica is carried away by ground water
  - Quartz is very resistant to chemical weathering

Products of Chemical Weathering

Table 2.1 Products of Weathering

Mineral	Residual Products	Material in Solution
Quartz	Quartz grains	Silica
Feldspars	Clay minerals	Silica, K^+, Na^+, Ca^{2+}
Amphibole	Clay minerals Iron oxides	Silica, Ca^{2+}, Mg^{2+}
Olivine	Iron oxides	Silica, Mg^{2+}

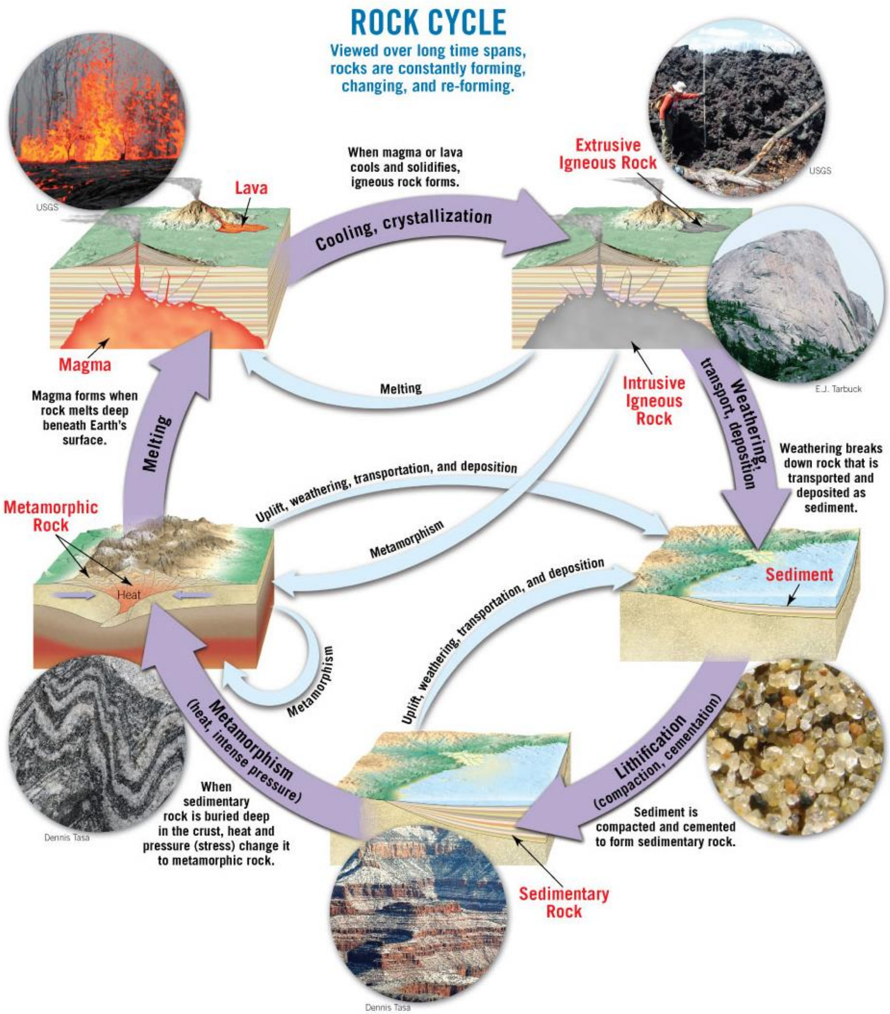
Focus Questions 2.4

- List and describe the different categories of sedimentary rocks.
- Discuss the processes that change sediment into sedimentary rock.

Sedimentary Rocks: Compacted and Cemented Sediment

- **Sedimentary rocks** form after weathering breaks rocks down, gravity and erosional agents transport and deposit the **sediment,** and the sediment becomes lithified
- Most sedimentary rock is deposited by solid material settling out of a fluid
- Sedimentary rocks make up ~5% of Earth's outer 10 miles, but account for 75% of all continental rock outcrops
  - Used to reconstruct details about Earth's history
  - Economically important
    - Coal, petroleum and natural gas, metals, fertilizer, construction materials

Sedimentary Rocks: Compacted and Cemented Sediment



Types of Sedimentary Rocks

- Sedimentary rocks are classified in two groups
  - **Detrital sedimentary rocks** form from solid particles weathered from other rocks
  - **Chemical and biochemical sedimentary** form from ions carried in solution

Types of Sedimentary Rocks

- ***Detrital*** sedimentary rocks
  - Contain a wide variety of minerals and rock fragments
    - Clay and quartz are most common
  - Distinguished by particle size
    - Also useful for determining environment of deposition
    - Higher energy carries larger particles
  - Mineral composition is also used to classify detrital sedimentary rocks

Types of Sedimentary Rocks

Detrital Sedimentary Rocks

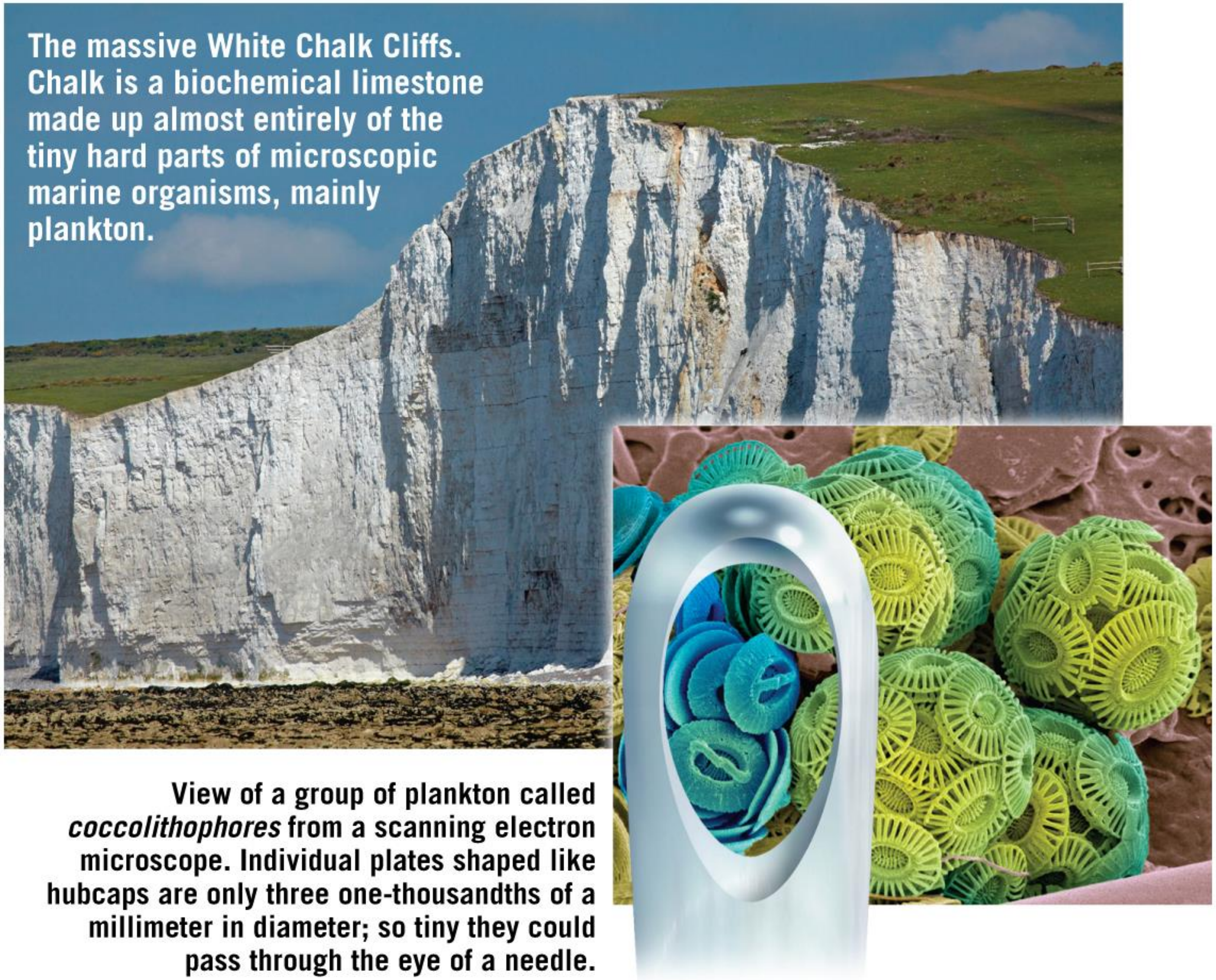
Particle Size	Sediment Name	Rock Name	
Coarse (over 2 mm)	**Gravel** (Rounded particles)	**Conglomerate**	
	Gravel (Angular particles)	**Breccia**	
Medium (1/16 to 2 mm)	**Sand**	**Sandstone**	
		Arkose*	
Fine (1/16 to 1/256 mm)	**Silt**	**Siltstone**	
Very fine (less than 1/256 mm)	**Clay**	**Shale or Mudstone**	

*If abundant feldspar is present the rock is called arkose.

Types of Sedimentary Rocks

- ***Chemical*** sedimentary rocks
  - Water carries ions in solution
  - Solid material precipitates to form chemical sediments
    - E.g. salt left behind when saltwater evaporates
  - Materials precipitated by organisms are known as ***biochemical sediments***
    - E.g. shells and hard parts
- Limestone is composed of calcite ($CaCO_3$)
  - Nearly 90% is formed by organisms

Types of Sedimentary Rocks



Types of Sedimentary Rocks

- Examples of chemical sedimentary rocks:
  - **Coquina**: loosely cemented shell fragments
  - **Chalk**: hard parts of microscopic organisms
  - **Travertine**: inorganic limestone that forms in caves
  - **Chert, flint, jasper, and agate**: microcrystalline quartz
  - **Salt and gypsum** form in ***evaporite deposits***
  - **Coal** consists mostly of ***organic matter***

Types of Sedimentary Rocks

Types of Sedimentary Rocks

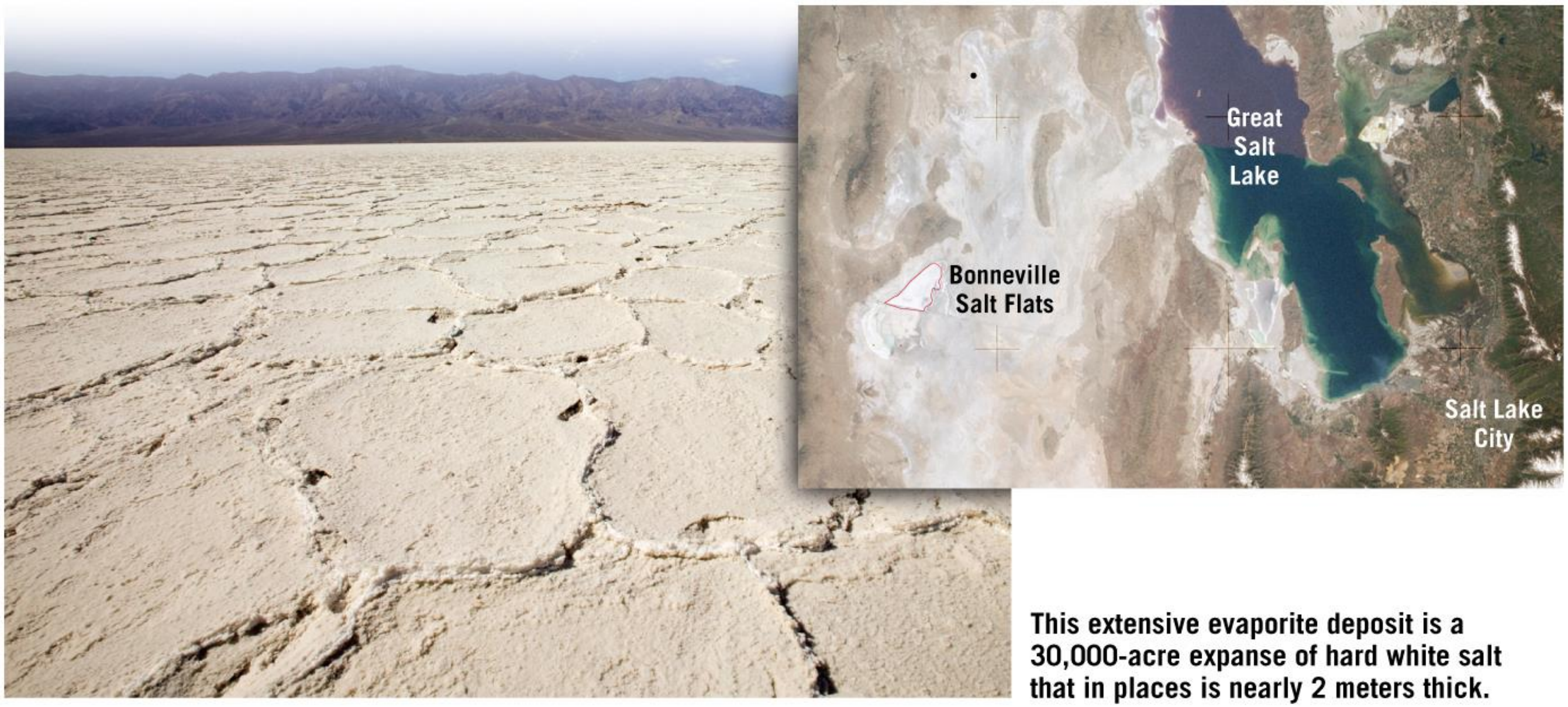

A. Flint


B. Jasper


C. Chert arrowhead

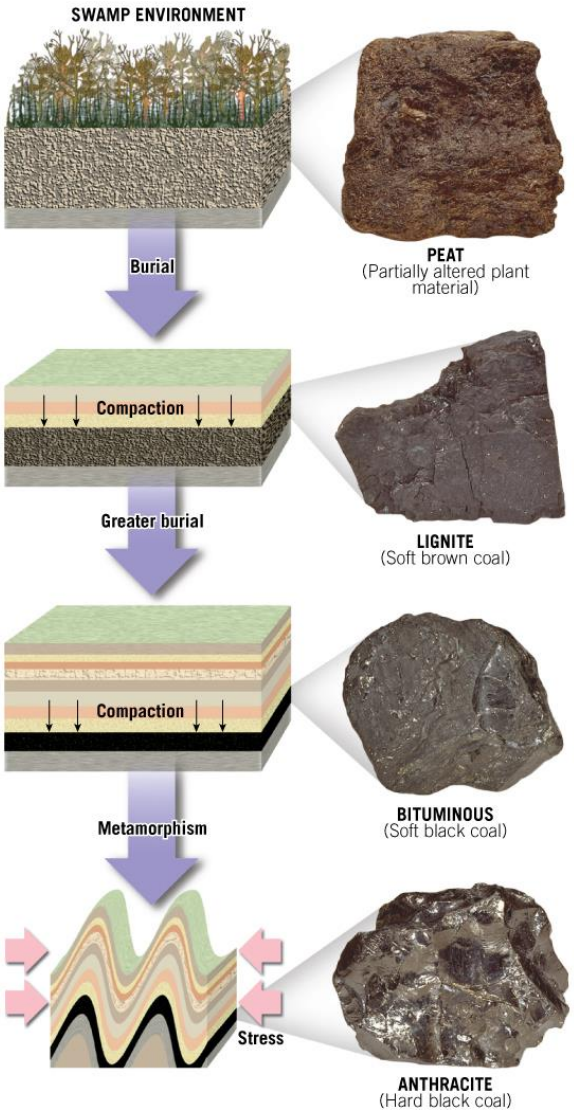

D. Petrified wood

Types of Sedimentary Rocks



This extensive evaporite deposit is a 30,000-acre expanse of hard white salt that in places is nearly 2 meters thick.

Types of Sedimentary Rocks



Types of Sedimentary Rocks

Chemical, Biochemical, and Organic Sedimentary Rocks

Composition	Texture	Rock Name
Calcite, $CaCO_3$	Fine to coarse crystalline	Crystalline Limestone 
	Very fine-grained crystals	Microcrystalline Limestone 
	Fine to coarse crystalline	Travertine 
Biochemical Limestone	Visible shells and shell fragments loosely cemented	Coquina 
	Various size shells cemented with calcite cement	Fossiliferous Limestone 
	Microscopic shells and clay	Chalk 
Quartz, SiO_2	Very fine crystalline	Chert (light colored) 
Gypsum $CaSO_4 \bullet 2H_2O$	Fine to coarse crystalline	Rock Gypsum 
Halite, NaCl	Fine to coarse crystalline	Rock Salt 
Altered plant fragments (organic matter)	Fine-grained	Bituminous Coal 

Lithification of Sediment

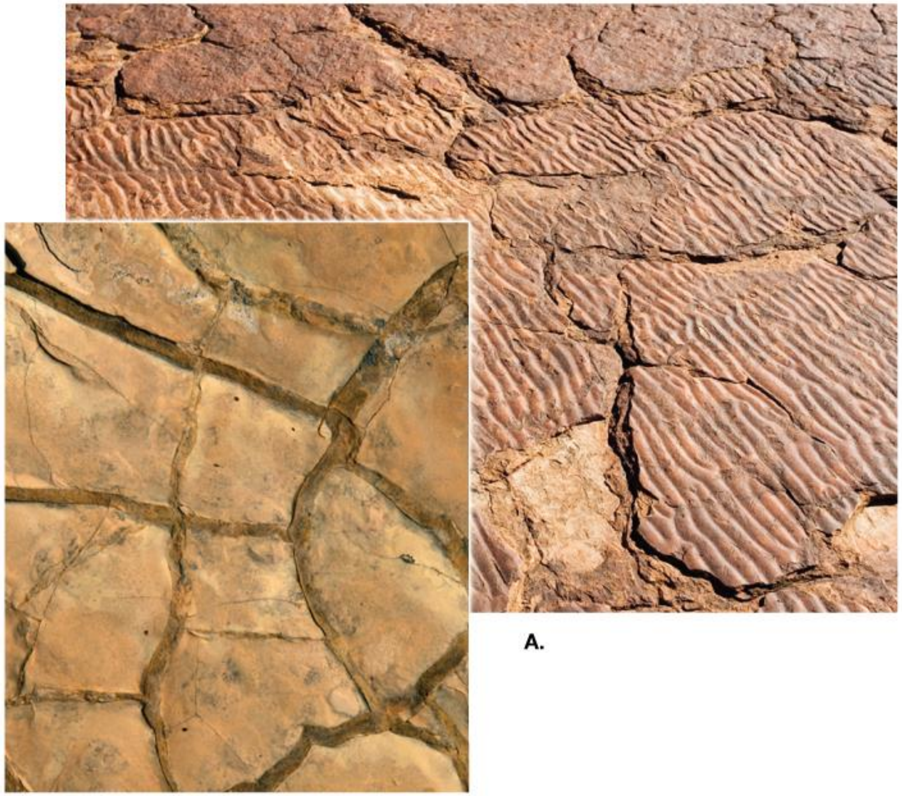
- **Lithification** is the process by which sediment is transformed into sedimentary rock
  - *Compaction* occurs when grains are pressed closer together so that pore space is reduced
    - Weight of accumulated sediment
    - Most significant in fine-grained rocks
  - *Cementation* occurs when water containing dissolved minerals moves through pores
    - Cement precipitates, fills pores, and joins particles together
    - Calcite, silica, and iron oxide are common cements
    - Significant in coarse-grained rocks

Features of Sedimentary Rocks

- Sedimentary rocks form in layers called **strata** or **beds**
  - Characteristic of sedimentary rocks
  - Thickness ranges from microscopic to tens of meters
  - Bedding planes ark the end of one episode of sedimentation and the beginning of another
- **Fossils** are traces or remains of life found in some sedimentary rocks
  - Important clues of ancient environment
  - Can be used to match up rocks of the same age found in different places

Features of Sedimentary Rocks

- Sedimentary rocks provide evidence for deciphering past environments



A.

B.

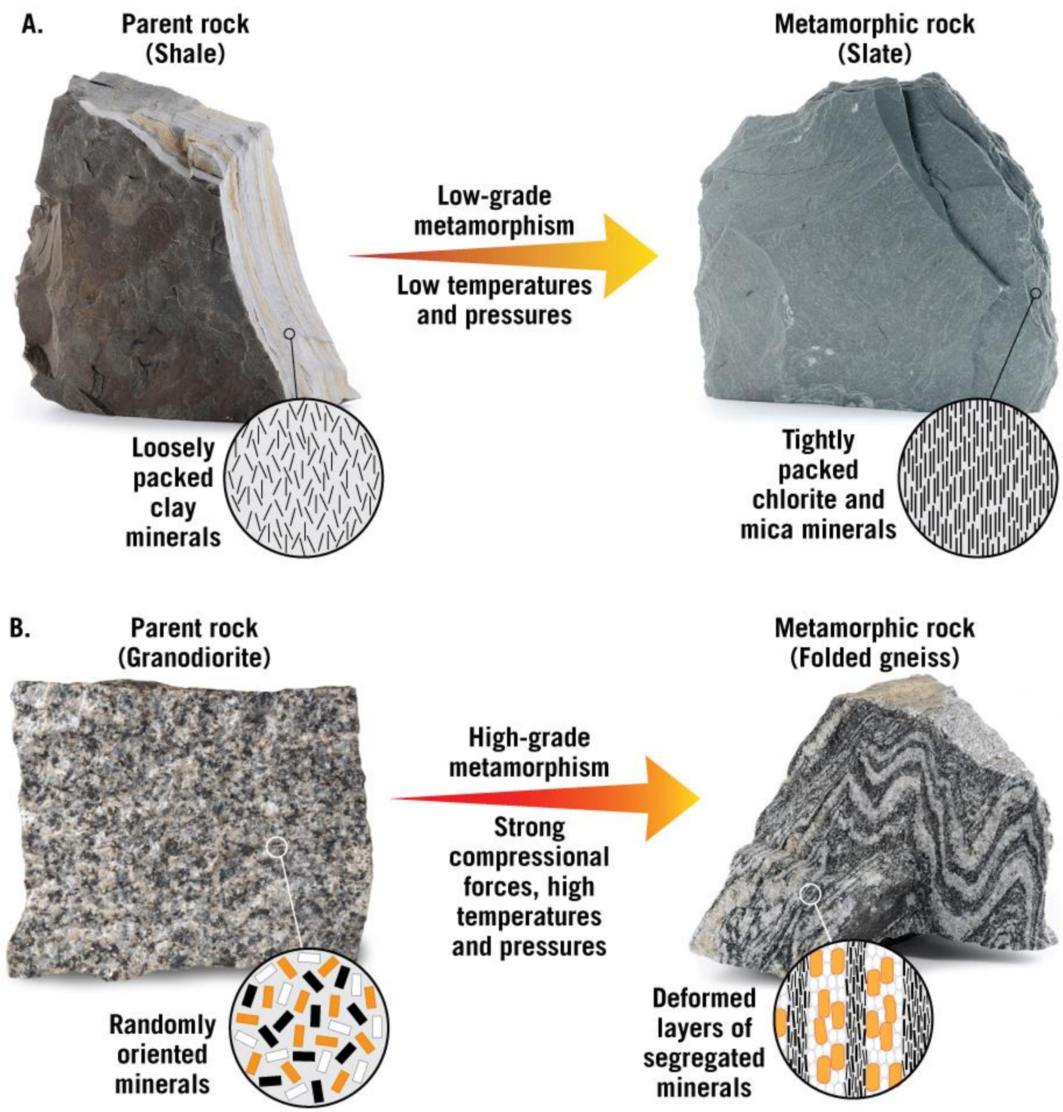
Focus Questions 2.5

- Define metamorphism.
- Explain how metamorphic rocks form.
- Describe the agents of metamorphism.

Metamorphic Rocks: New Rock from Old

- **Metamorphic rocks** are produced when preexisting parent rock is transformed
  - Parent rock can be igneous, sedimentary, or metamorphic
- **Metamorphism** occurs when parent rock is subjected to a different physical or chemical environment
  - Elevated temperature and pressure
  - Changes mineralogy, texture, and sometimes chemical composition
  - Equilibrium with new environment
- Metamorphism progresses incrementally
  - Low-grade (slight changes) to high-grade (substantial changes)

Metamorphic Rocks: New Rock from Old



Metamorphic Rocks: New Rock from Old

- Most metamorphism occurs in one of two settings:
  - **Contact metamorphism**
    - Rock temperature increases because of intruding magma
  - **Regional metamorphism**
    - Pressure and high temperature during mountain building

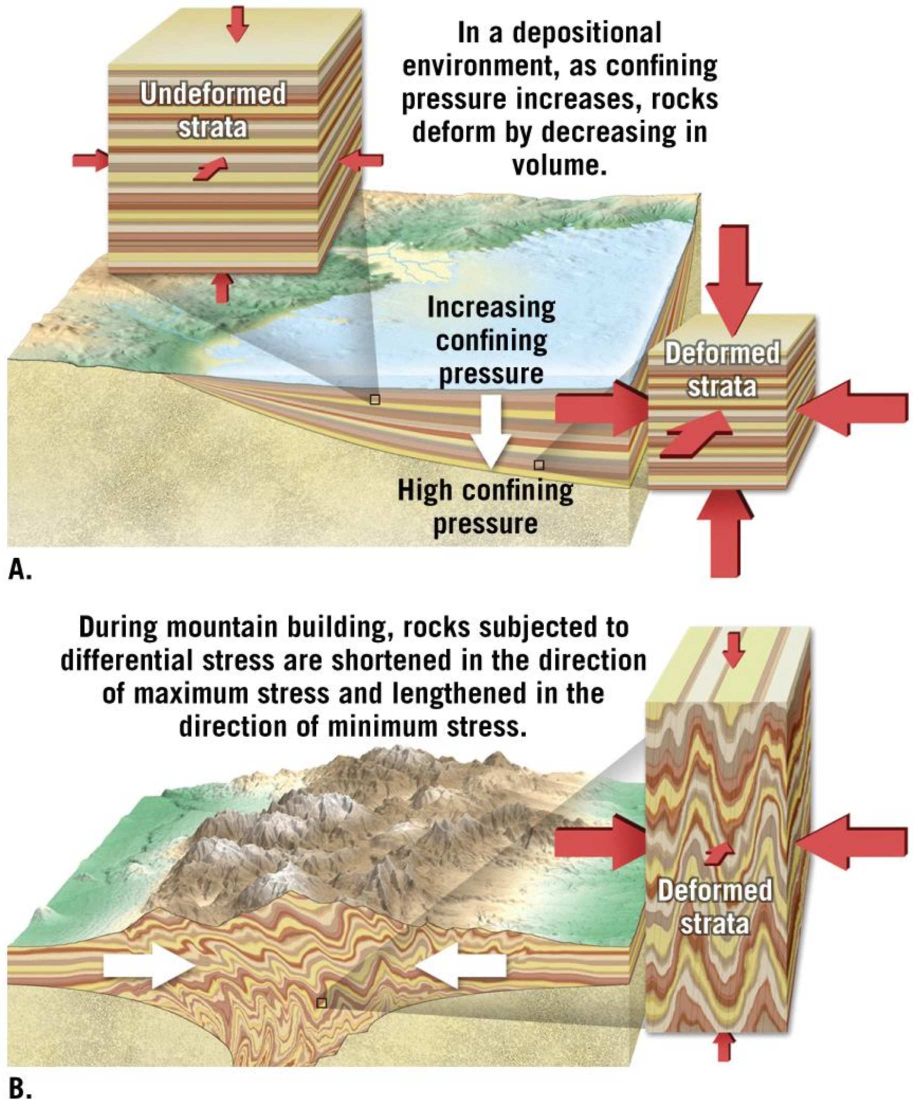
What Drives Metamorphism?

- Agents of metamorphism
  - **Heat** (from intrusion of magma or burial)
    - Chemical reactions and recrystallization of new minerals
  - **Confining pressure** (equal in all directions because of burial)
    - Compaction and recrystallization of new minerals

What Drives Metamorphism?

- **Differential stress** (greater in one direction because of mountain building)
  - Deformation and development of metamorphic textures
  - Rocks can react by breaking (brittle) or bending (ductile) depending on temperature
- **Chemically active fluids** (hydrothermal fluid rich in ions)
  - Catalyze recrystallization reactions
  - Can dissolve a mineral from one area and precipitate it in another
  - Can change chemical composition of surrounding rock

What Drives Metamorphism

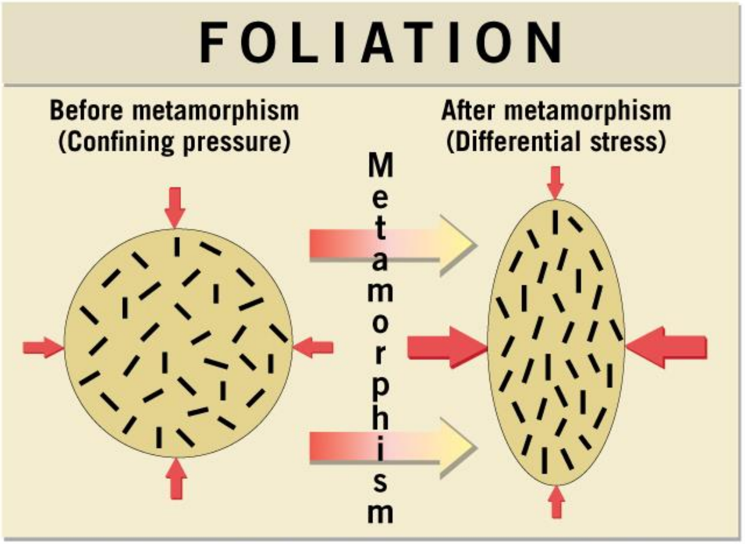


Metamorphic Textures

- Metamorphism can change the texture of a rock
  - Low-grade metamorphism makes rocks compact and more dense
  - High-grade metamorphism causes recrystallization and growth of visible crystals

Metamorphic Textures

- **Foliation** is the development of a flat arrangement of mineral grains or structural features



Platy and elongated mineral grains having random orientation.

When differential stress causes rocks to flatten, the mineral grains rotate and align roughly perpendicular to the direction of maximum differential stress.

Metamorphic Textures

- Foliation is characteristic of regional metamorphism
- Driven by compressional stress
  - Causes mineral grains to develop parallel alignment
- Includes:
  - Parallel alignment of micas
  - Parallel alignment of flattened pebbles
  - Separation of light and dark minerals
  - Development of rock cleavage

Metamorphic Rocks Textures

- **Nonfoliated** rocks occur when deformation is minimal and parent rock is composed largely of stable minerals

Common Metamorphic Rocks

COMMON METAMORPHIC ROCKS

Metamorphic Rock		Texture		Comments	Parent Rock
Slate		Foliated		**Fine-grained**, 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**
Gneiss		Foliated		**Coarse-grained**, compositional banding due to segregation of light and dark colored minerals	**Shale, granite, or volcanic rocks**
Marble		Nonfoliated		**Medium- to coarse-grained**, relatively soft (3 on the Mohs scale), interlocking calcite or dolomite grains	**Limestone, dolostone**
Quartzite		Nonfoliated		**Medium- to coarse-grained**, very hard, massive, fused quartz grains	**Quartz sandstone**

Common Metamorphic Rocks

- Common foliated metamorphic rocks:
  - Slate has characteristic rock cleavage
    - From metamorphism of shale or volcanic ash
  - Phyllite has larger mineral grains than slate, which give it a glossy sheen and wavy surface
  - Schist is formed by regional metamorphism of shale
  - Gneiss is a banded metamorphic rock that may have intricate folds

Common Metamorphic Rocks

Metamorphic Rocks: New Rock from Old

- Common nonfoliated metamorphic rocks:
  - Marble is a coarse crystalline rock
    - From metamorphism of limestone
  - Quartzite is very hard because of fused quartz grains
    - From metamorphosed quartz sandstone