Patterns in Nature: Minerals

Edited and augmented for this course by

Olivia Jensen

Professor of Geophysics

McGill University

Montreal, Canada

Peridot (gemstone olivine)

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

Minerals

- Minerals are among the Earth materials that surround us.
- Almost 5,000 minerals are known.
- Around 50–100 new minerals are discovered annually.
- Human interest in minerals spans millennia.

A feathery ice crystal displays an ordered atomic structure.

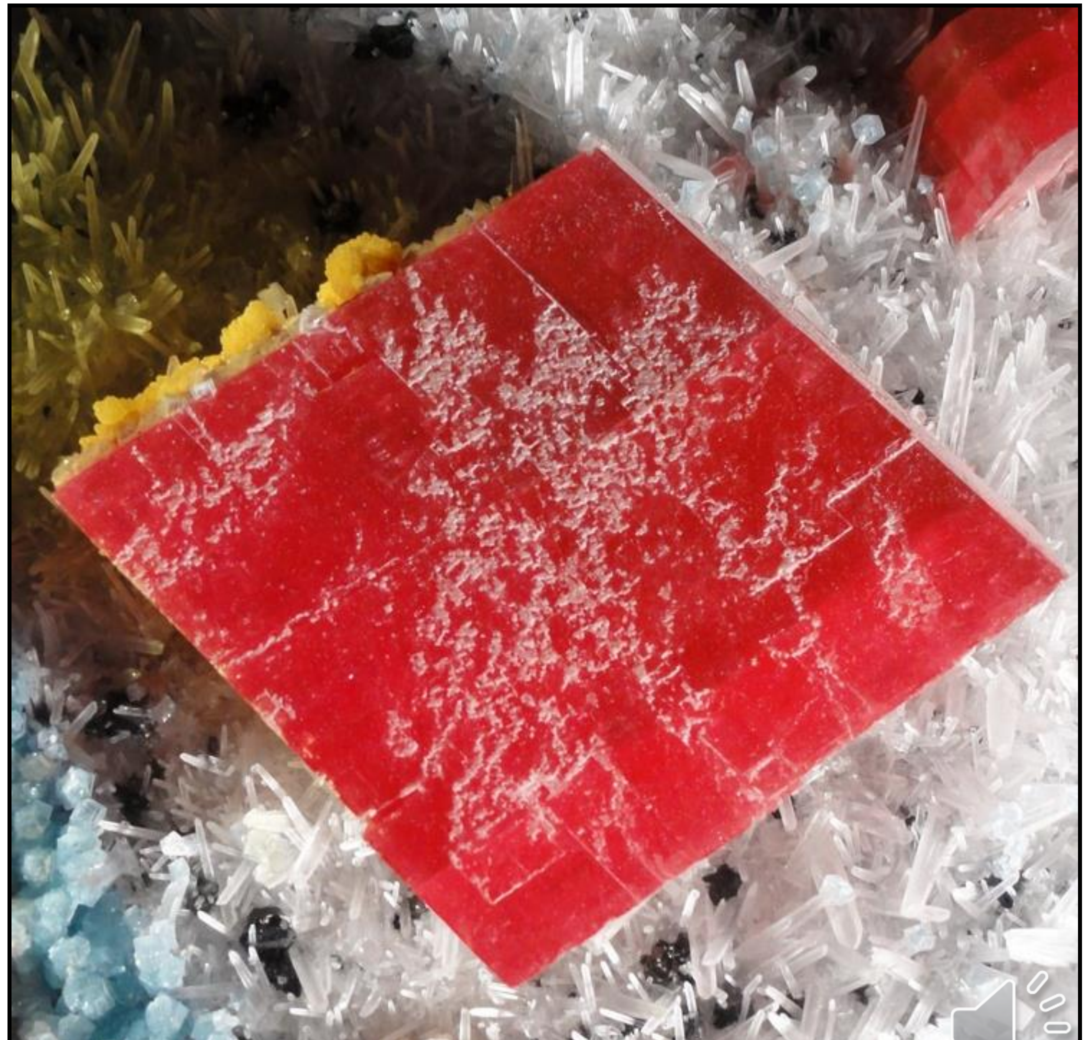
Why Study Minerals?

- **Minerals are the building blocks of the body of our planet.**
  - **Minerals make up all of the rocks and sediments on Earth.**
  - **Understanding Earth requires understanding minerals.**
- **Minerals are important to humans.**
  - ***Industrial minerals*—raw materials for manufacturing**
  - ***Ore minerals*—sources of valuable metals**
  - ***Gem minerals*—attract human passions**



What Is a Mineral?

- The geologic definition of a mineral is specialized:
  - Naturally occurring
  - Formed geologically
  - Solid
  - Crystalline structure
  - Most minerals are inorganic



- We can synthesize many minerals: diamond, sapphire, quartz

What Is a Mineral?

- They are mostly formed by geologic processes.
  - Freezing from a melt (such as volcanic magmas)
  - Precipitation from a dissolved state in water or other solvent
  - Chemical reactions at high pressures and temperatures
- Subtle distinction: living organisms *can* create minerals.
  - Called biogenic minerals to emphasize this special origin
    - Vertebrate bones (apatite)
    - Oyster, mussel, and clam shells (aragonite)
    - Other skeletal types
    - Our own tooth enamel (hydroxyapatite)

What Is a Mineral?

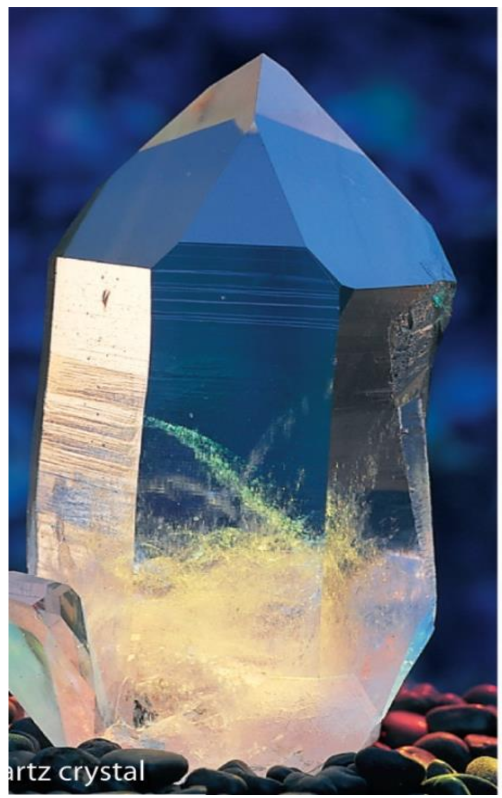
- Minerals are solid with a crystalline structure
  - A state of matter that can maintain its shape indefinitely
  - Minerals are not liquids or gases though they may be melted or vapourized. Ice is a mineral, water is not!

What Is a Mineral?

- Minerals have a definite elemental composition but are defined rather by their ***structure***.
  - Minerals "*can*" be defined by a chemical formula but more commonly they are defined as a structure.
    - Simple (largely defined by chemical formula)
      - Ice—H_2O
      - Calcite—$CaCO_3$ (may be coloured by trace impurities)
      - Quartz—SiO_2 (may be coloured by trace impurities)
    - Complex (many elements might be substituted)
      - Biotite (prototypical): $K(Mg, Fe^{2+})_3(AlSi_3O_{10})(OH)_2$
      - Hornblende—$Ca_2(Fe^{2+},Mg)(Al,Fe^{3+})(Si_7Al)O_{22}(OH,F)_2$

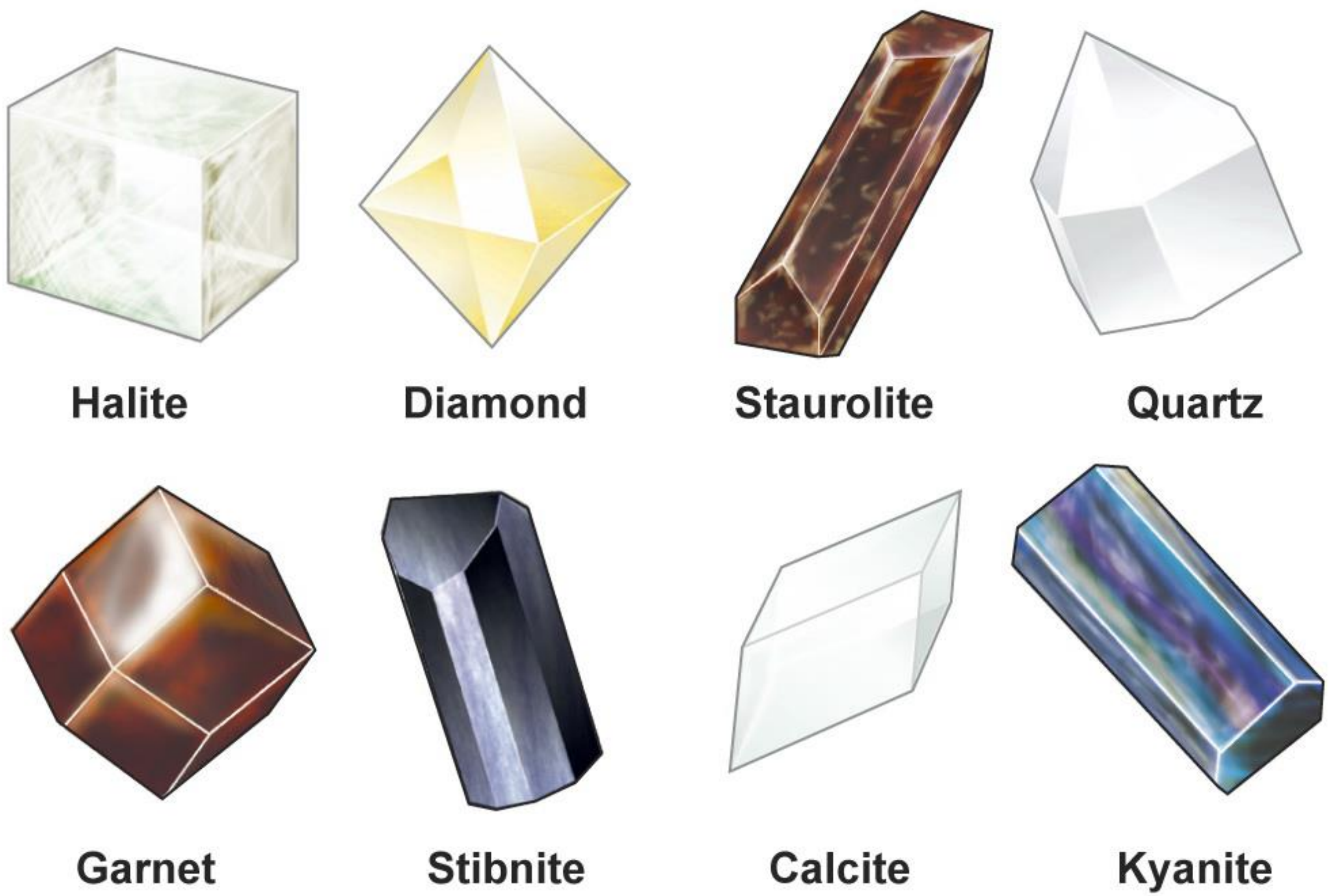
What Is a Crystal?

- A single, continuous piece of crystalline solid
- Typically bounded by flat surfaces (crystal faces)
- Crystal faces grow naturally as the mineral forms.
- Crystals are sometimes prized mineral specimens.



What Is a Crystal?

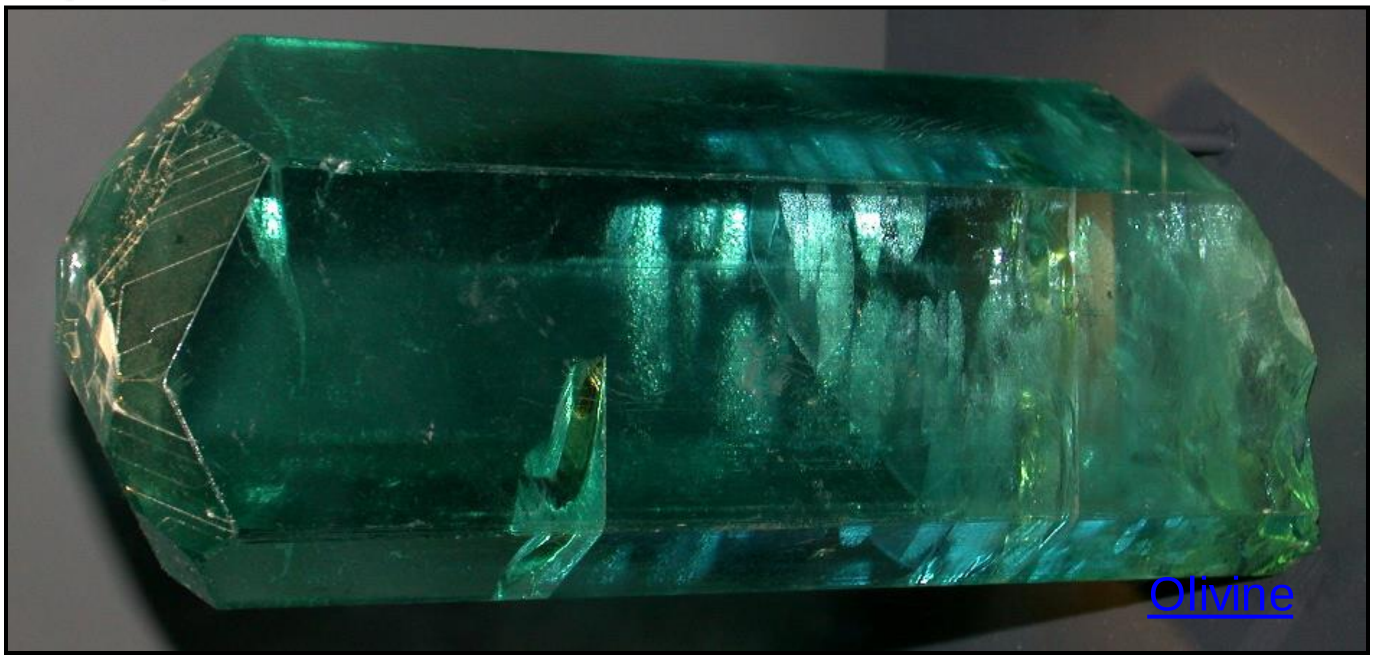
- Crystals come in a variety of shapes.
- Many descriptive terms describe crystal shape.



[Online mineral database]

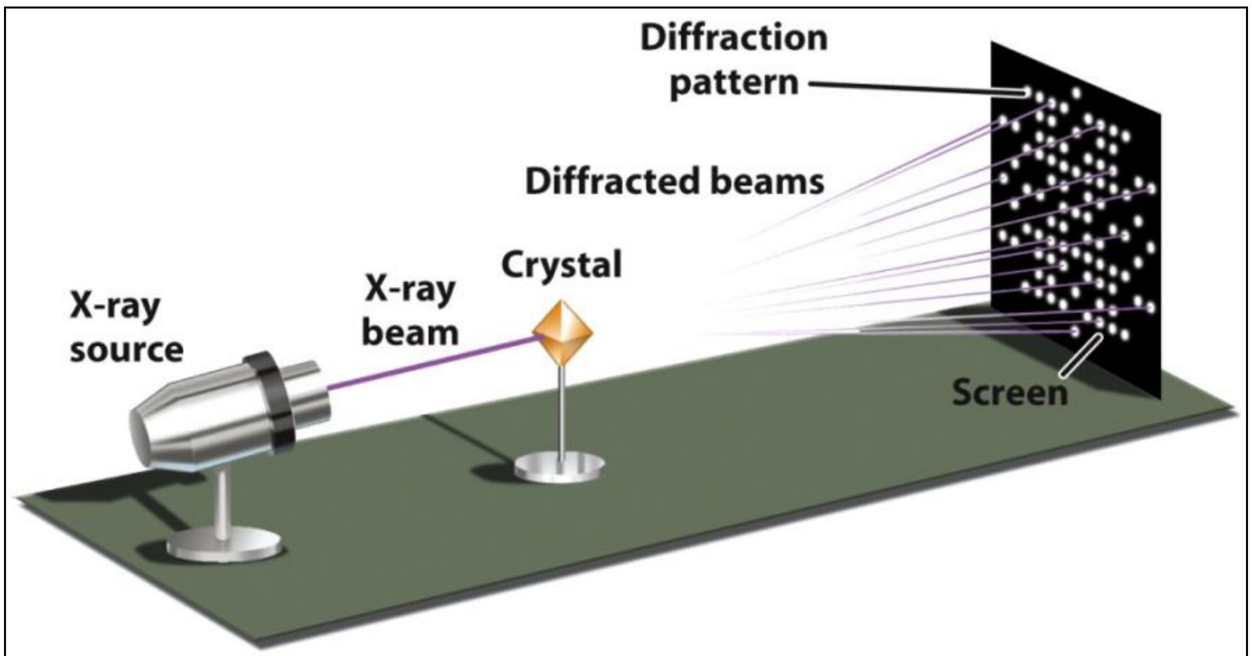
What Is a Crystal?

- People often consider crystals to be special.
  - Regular geometric form
  - Crystals interact with light to create attractive beauty.
- While some think crystals possess magical powers, we have no scientific evidence that crystals affect health or mood (OJ).



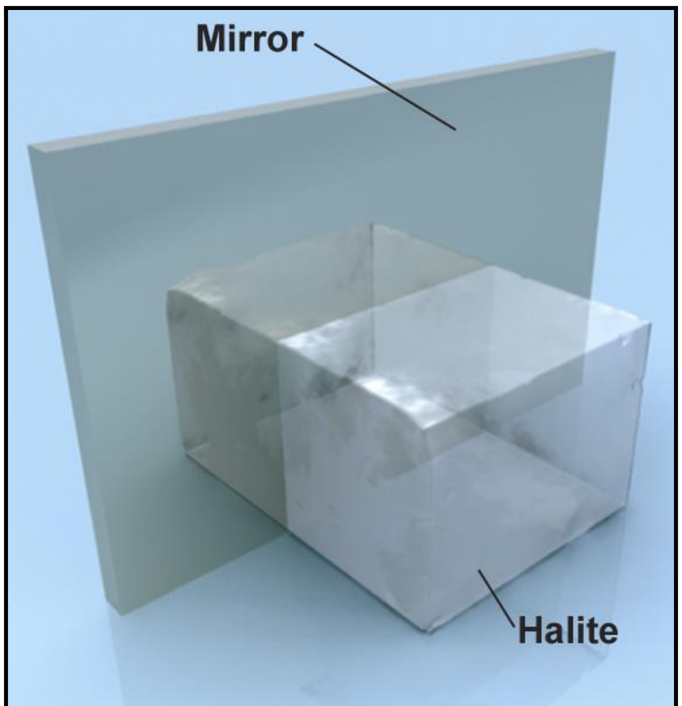
We Look Inside Crystals

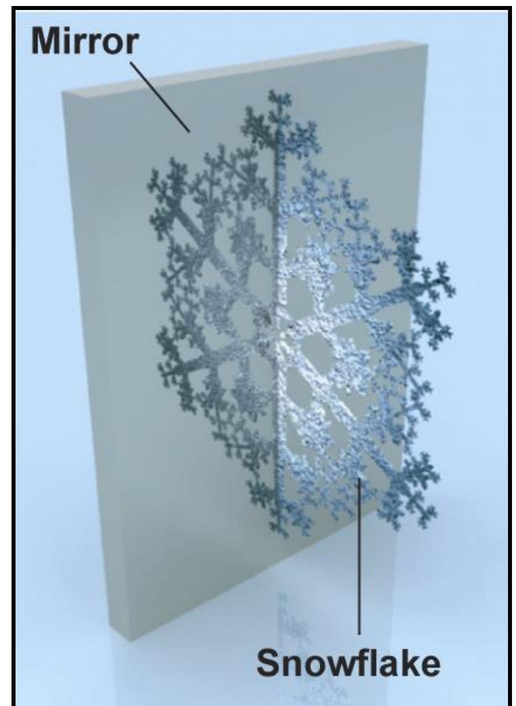
- Science has advanced the study of minerals.
  - 1912—Max van Laue proposed X-ray study of minerals.
  - X-ray diffraction (XRD) is still used to identify minerals.
    - X-ray beam passed through a crystal or crystal powder creates distinctive pattern
    - Diffraction pattern related to arrangement of atoms in crystals



Looking Inside Crystals

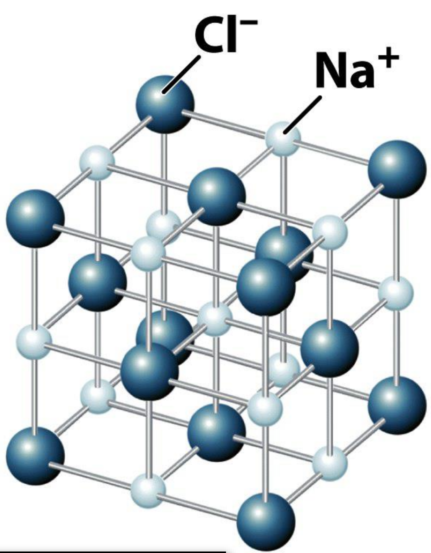
- Ordered atomic patterns in minerals display symmetry.
  - Mirror image(s)
  - Rotation about an axis (or axes)
- Symmetry characteristics are used to identify minerals.

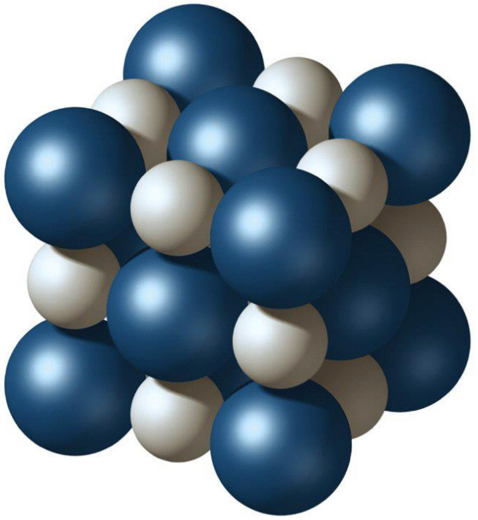




Looking Inside Crystals

- Ordered atoms like tiny balls packed tightly together
- Held in place by chemical bonds
- The way atoms are packed defines the crystal structure.
- Physical properties (hardness, shape) depend upon:
  - Identity of atoms
  - Arrangement of atoms.
  - Nature of atomic bonds

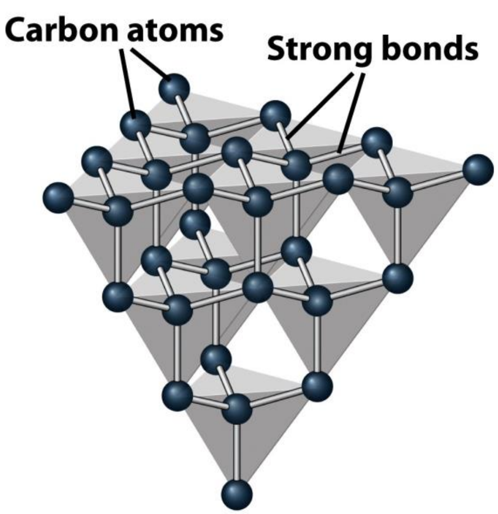


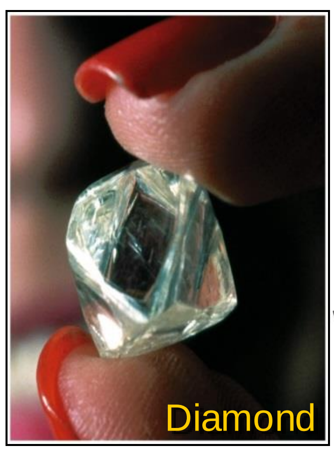


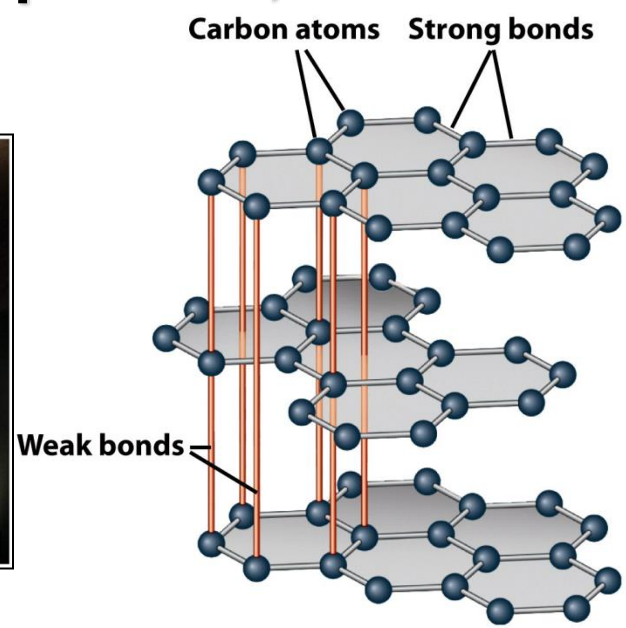
Sodium (Na^+) and Chloride (Cl^-) ions are bonded in a *cubic lattice* by *ionic bonds* to form the mineral Halite (NaCl), known as common salt.

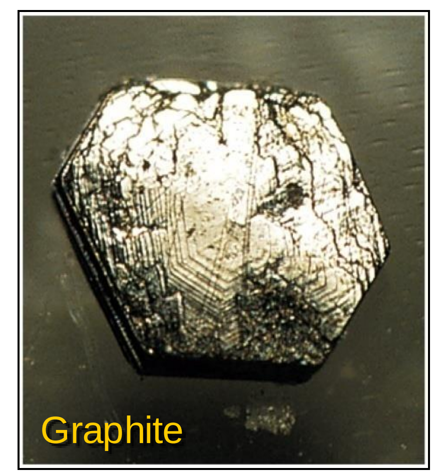
Looking Inside Crystals

- The nature of atomic bonds controls characteristics.
- Diamond and graphite are made entirely of carbon (C).
  - Diamond—atoms arranged in tetrahedra; hardest mineral
  - Graphite—atoms arranged in sheets; softest mineral
  - Fullerines and graphene
- Polymorph—same composition; different structure









Mineral Formation

- New crystals can form in five ways.
  - Solidification from a melt
    - Crystals grow when the melt cools.
    - Liquid freezes to form solid.

Mineral Formation

- New crystals can form in five ways.
  - Precipitation from a solution
    - Seeds form when a solution becomes saturated.

Mineral Formation

- New crystals can form in five ways.
  - Solid-state diffusion

Mineral structure -- garnet

- **The reddish minerals one sees in the previous slide are garnets. Like other minerals, garnets are fundamentally a structure rather than a stoichiometric chemical composition as in molecules.**
- **The structure of the garnet can be formed with various compositions, typically:**

  $X_3Y_2(Si\ O_4)_3$. The *X* site usually being occupied by divalent cations (Ca, Mg, Fe, Mn)$^{2+}$ and the *Y* site by trivalent cations (Al, Fe, Cr)$^{3+}$

Uvarovite: rare green garnet

Mineral Formation

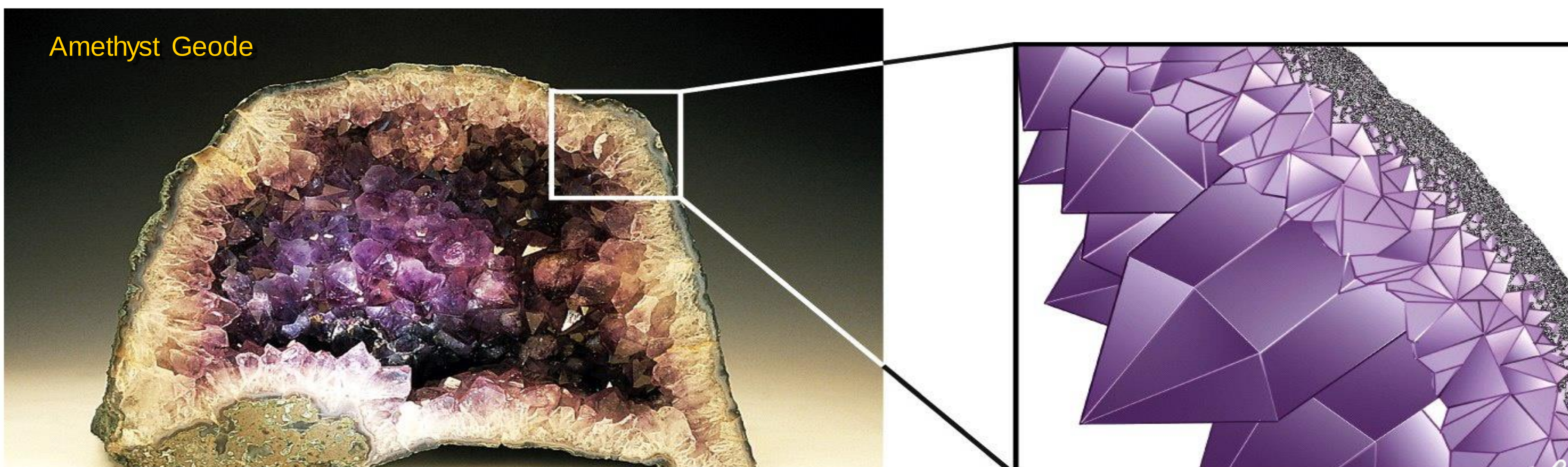
- New crystals can form in five ways.
  - Biomineralization: our tooth enamel is mineral apatite (OJ)

Mineral Formation

- New crystals can form in five ways.
  - Precipitating directly from a gas

Mineral Formation

- Mineral growth is often restricted by lack of space.
  - Anhedral—grown in tight space, no crystal faces
  - Euhedral—grown in an open cavity, good crystal faces
- Anhedral crystals are much more prevalent.
- Euhedral crystals grow into the open space in a <u>geode</u>.



Mineral Destruction

- Minerals can be destroyed by:
  - Melting—heat breaks the bonds holding atoms together
  - Dissolving—solvents (mostly water) break atomic bonds
  - Chemical reaction—reactive materials break bonds

Mineral Identification

- Mineral identification is a skill.
  - Requires learning diagnostic properties
    - Some properties are easily seen.
      - Color
      - Crystal shape
    - Some properties require handling or testing.
      - Hardness
      - Magnetization
      - Specific gravity

Physical Properties

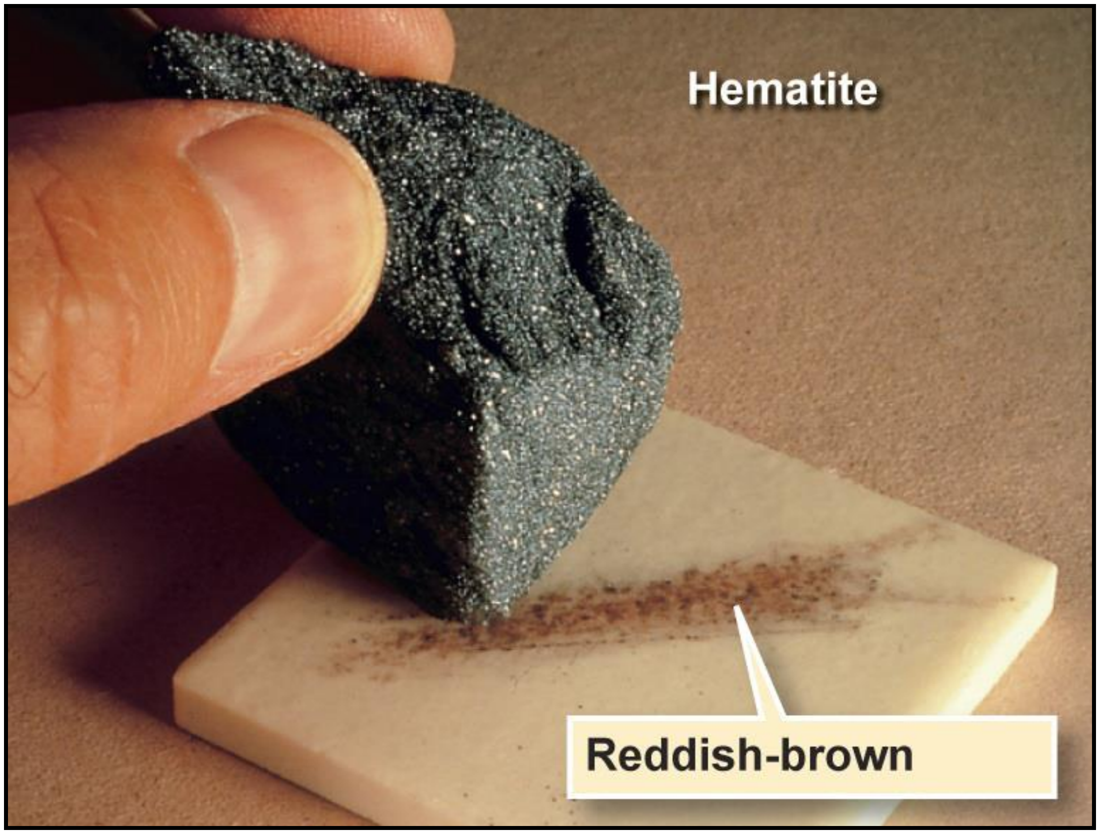
- Common Properties
  - Color
  - Streak on ceramic tile
  - Luster
  - Hardness
  - Specific gravity
  - Crystal habit
  - Fracture or cleavage

Color

- The part of visible light that is not absorbed by a mineral
- Diagnostic for some minerals
  - Malachite is a distinctive green.
- Some minerals exhibit a broad color range.
  - Quartz (clear, white, yellow, pink, purple, gray, etc.)
- Color varieties reflect trace impurities.

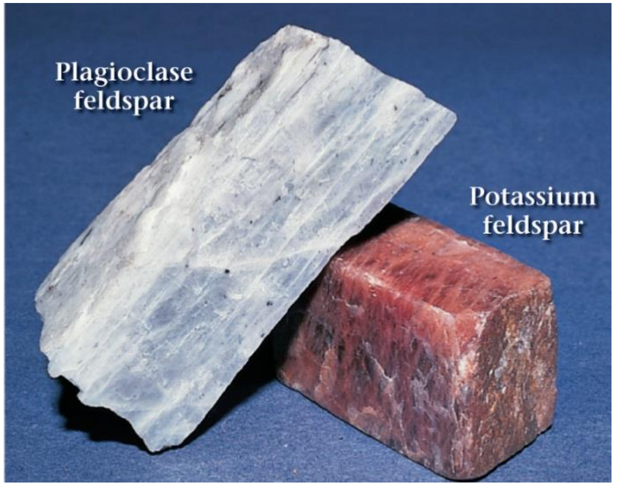
Streak

- Color of a powder produced by crushing a mineral
- Obtained by scraping a mineral on unglazed porcelain
  - Streak color is less variable than crystal color.



Luster

- The way a mineral surface scatters light
- Two subdivisions:
  - Metallic—looks like a metal
  - Nonmetallic
    - Silky
    - Glassy
    - Satiny
    - Resinous
    - Pearly
    - Earthy



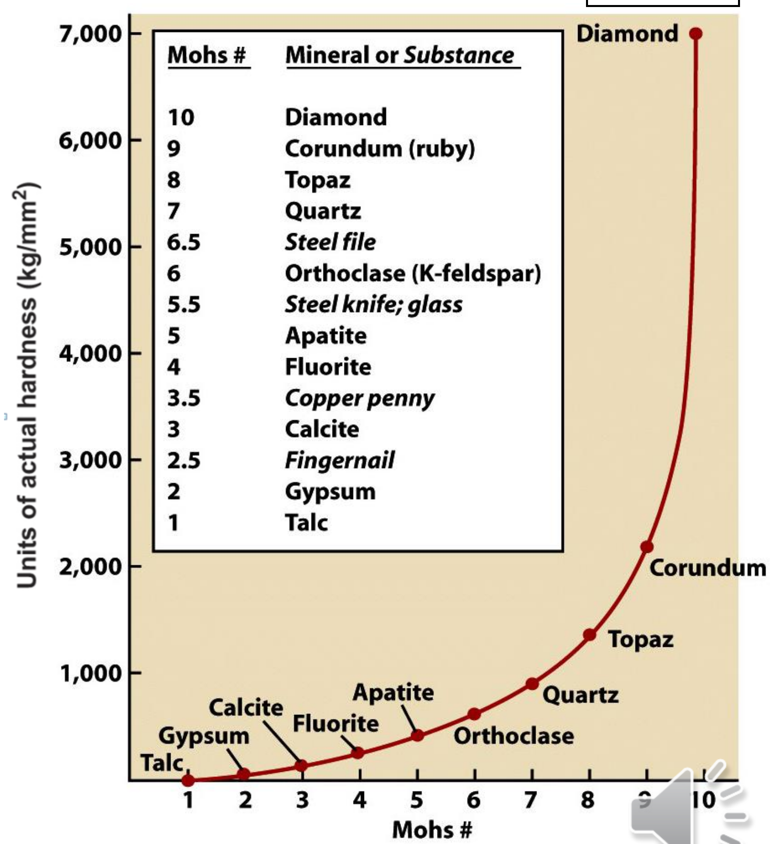
Hardness

- Scratching resistance of a mineral
- Derives from the strength of atomic bonds
- Hardness compared to the Mohs scale for hardness.

1. Talc, graphite
2. Gypsum ← Fingernail 2.5
3. Calcite ← Copper Penny 3.5
4. Fluorite
5. Apatite ← Glass - Steel 5.5
6. Orthoclase ← Steel File 6.5
7. Quartz
8. Topaz
9. Corundum
10. Diamond

[Online mineral database]

Table 3.1



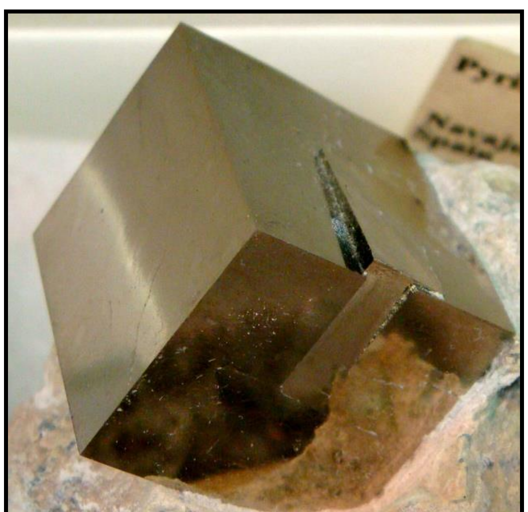
Mohs #	Mineral or *Substance*
10	Diamond
9	Corundum (ruby)
8	Topaz
7	Quartz
6.5	*Steel file*
6	Orthoclase (K-feldspar)
5.5	*Steel knife; glass*
5	Apatite
4	Fluorite
3.5	*Copper penny*
3	Calcite
2.5	*Fingernail*
2	Gypsum
1	Talc

Specific Gravity

- Represents the density of a mineral
- Mineral weight over the weight of an equal water volume
- Specific gravity is "heft"—how heavy it feels.
  - Galena—heavy (SG 7.60)
  - Quartz—light (SG 2.65)
- Galena "feels" heavier than quartz.

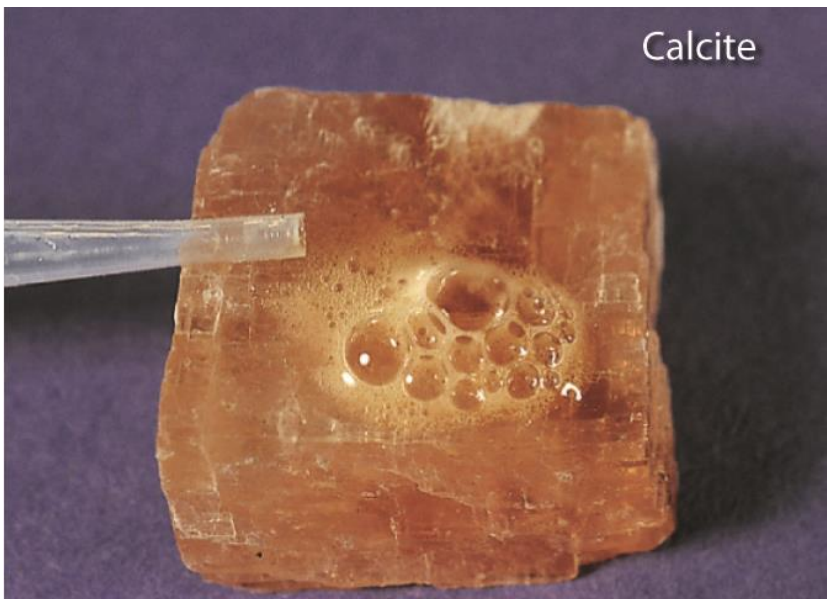
Crystal Habit (shape characteristic)

- A single crystal with well-formed faces, or
- An aggregate of many well-formed crystals
- Arrangement of faces reflects internal atomic structure
- Records variation in directional growth rates
  - Blocky or equant—equal growth rate in three dimensions
  - Bladed—shaped like a knife blade
  - Needle-like—rapid growth in one dimension, slow in others



Special Physical Properties

- **Special physical properties**
  - Effervescence—reactivity with acid (e.g., Calcite)
  - Magnetism—magnetic attraction (e.g., Magnetite)
  - Taste — lick test (e.g., Halite)

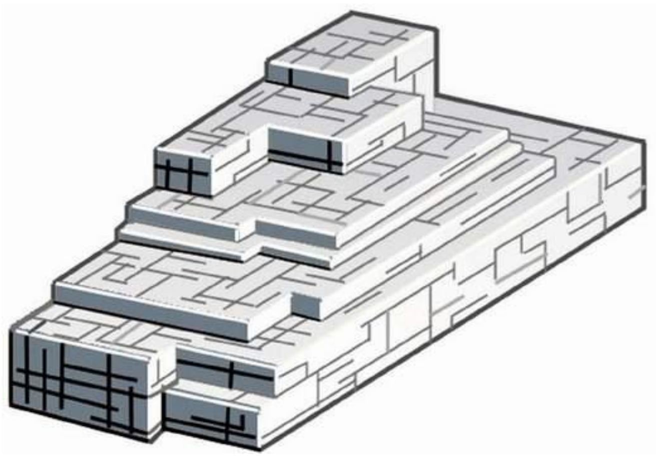


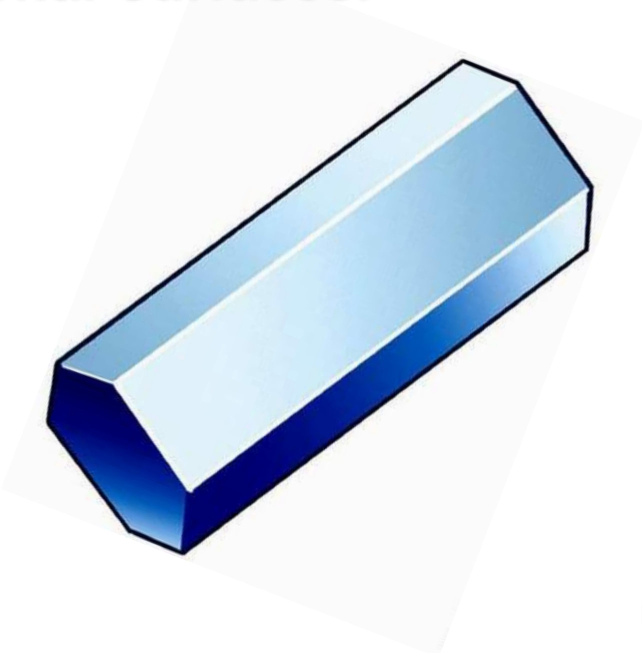
Fracture

- Minerals break in ways that reflect atomic bonding.
- Fracturing implies equal bond strength in all directions.
  - Example: quartz displays conchoidal fracture.
    - Breaks like glass—along smooth curved surfaces.
    - Produces extremely sharp edges.
    - Volcanic glass was used by native cultures to make tools.

Cleavage

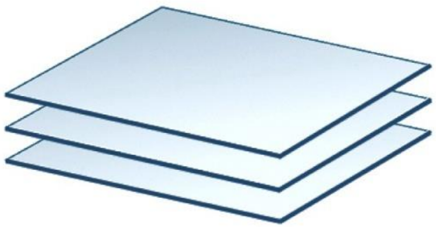
- Tendency to break along planes of weaker atomic bonds.
- Cleavage produces flat, shiny surfaces
- Described by the number of planes and their angles
- Sometimes mistaken for crystal habit
  - Cleavage is throughgoing; it often forms parallel steps.
  - Crystal faces only occur on external surfaces.



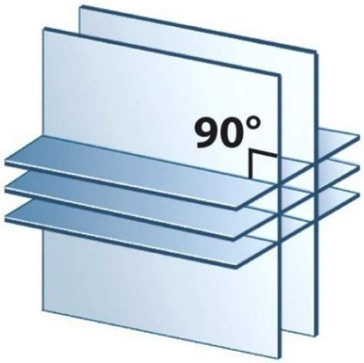


Cleavage

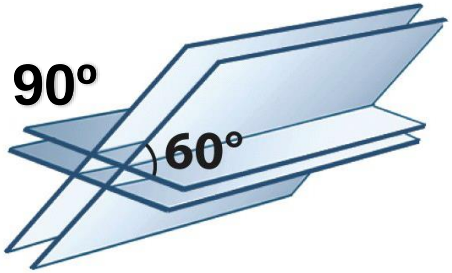
- Examples of cleavage
  - One direction



  - Two directions at 90º

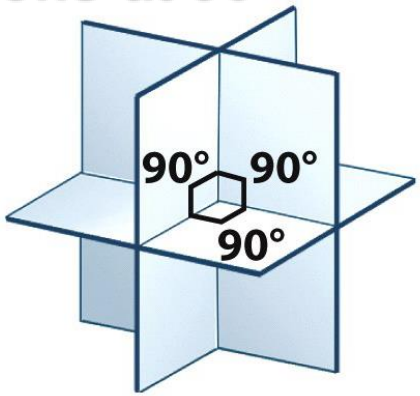


  - Two directions NOT at 90º

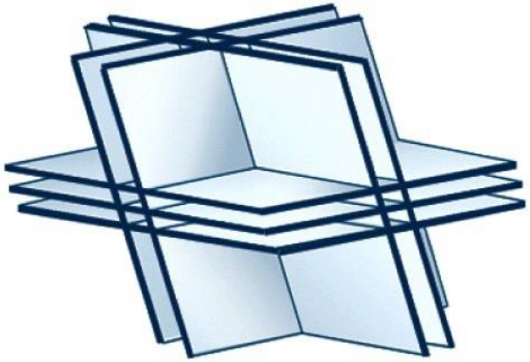


Cleavage

- **Examples of cleavage**
  - **Three directions at 90º**



  - **Three directions NOT at 90º**



Mineral Classification

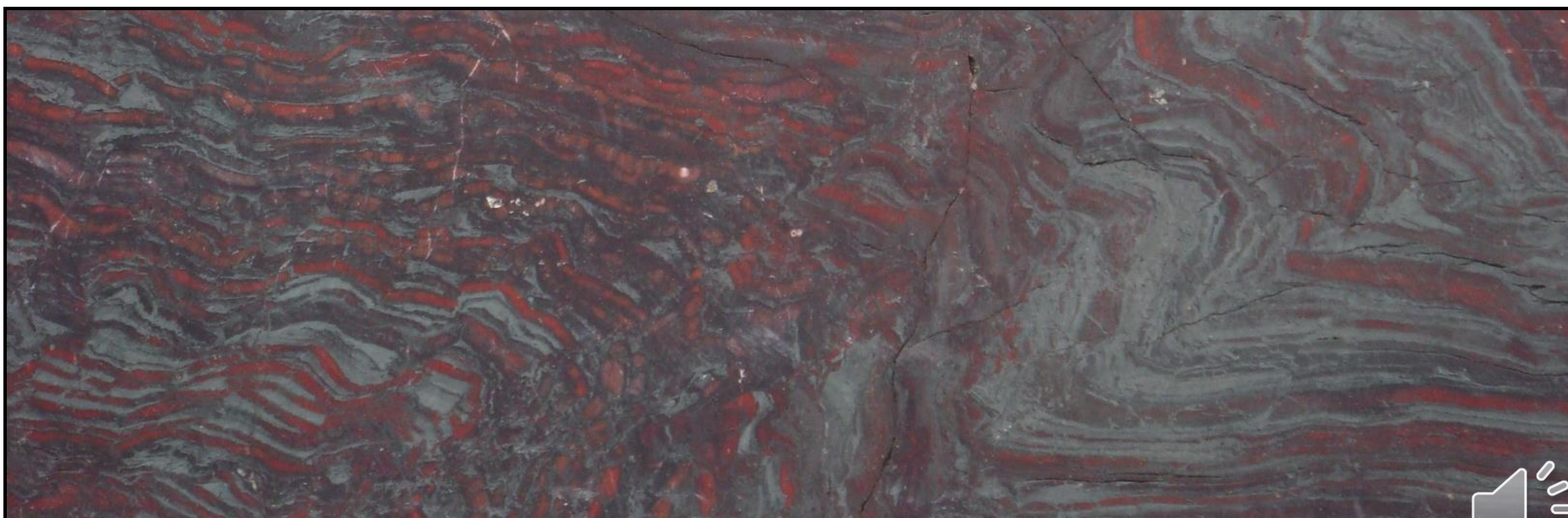
- Minerals can be separated into a few groups.
- J. J. Berzelius, a Swedish chemist, noted similarities.
  - Minerals can be separated by:
    - The principal anion (negative ion), or
    - Anionic group (negative molecule)
  - Example: sulfides (S^-) or carbonates (CO_3^{2-})
- The most abundant mineral class is the silicates (SiO_4^{4-}).

The Mineral Classes

- Minerals are classified by their dominant anion.
  - Silicates (SiO_2^{4-}) are called the rock-forming minerals.
  - Constitute almost the entire crust and mantle of Earth
  - They are the most common minerals.
  - Example: quartz (SiO_2)

Mineral Classes

- Oxides (O^{2-})
- Metal cations (Fe^{2+}, Fe^{3+}, Ti^{2+}) are bonded to oxygen.
- Examples:
  - Magnetite (Fe_3O_4)
  - Hematite (Fe_2O_3)
  - Rutile (TiO_2)



Mineral Classes

- Sulfides (S^-)
- Metal cations are bonded to a sulfide anion
- Examples:
  - Pyrite (FeS_2)
  - Galena (PbS)
  - Sphalerite (ZnS)

Mineral Classes

- Sulfates (SO_4^{2-})
- Metal cations bonded to a sulfate anionic group
- Many sulfates form by evaporation of seawater
- Examples:
  - Gypsum ($CaSO_4 \cdot 2H_2O$)
  - Anhydrite ($CaSO_4$)

Mineral Classes

- Minerals are classified by their dominant anion.
  - Halides (Cl^- or F^-)
  - Examples:
    - Halite ($NaCl$)
    - Fluorite (CaF_2)

Mineral Classes

- Minerals are classified by their dominant anion.
  - Carbonates (CO_3^{2-})
  - Examples:
    - Calcite ($CaCO_3$)
    - Dolomite ($(Ca,Mg)CO_3$)
    - Natrite (Na_2CO_3)

Mineral Classes

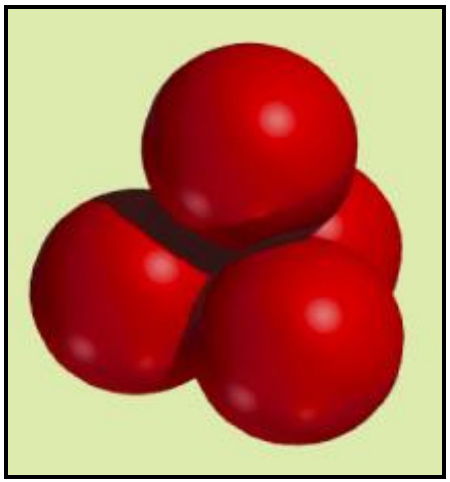
- Minerals with no (dominant) anion.
  - Native metals (common: Cu, Au, Ag)
  - Pure masses of a single metal or alloy
  - Examples:
    - Copper (Cu)
    - Gold (Au)
    - Silver (Ag)
    - Platinum (Pt)
    - And others
    - Electrum (Au/Ag)

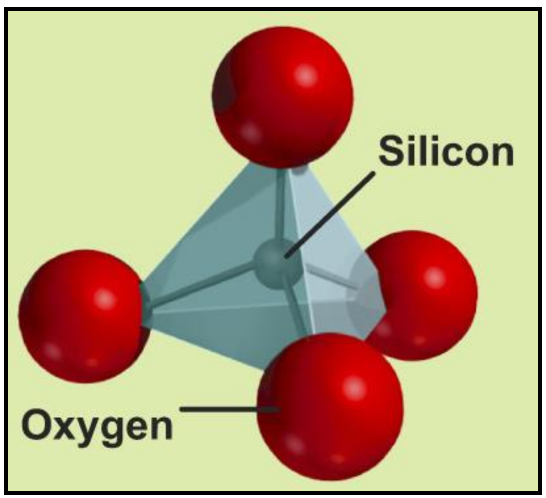
Silicate Minerals

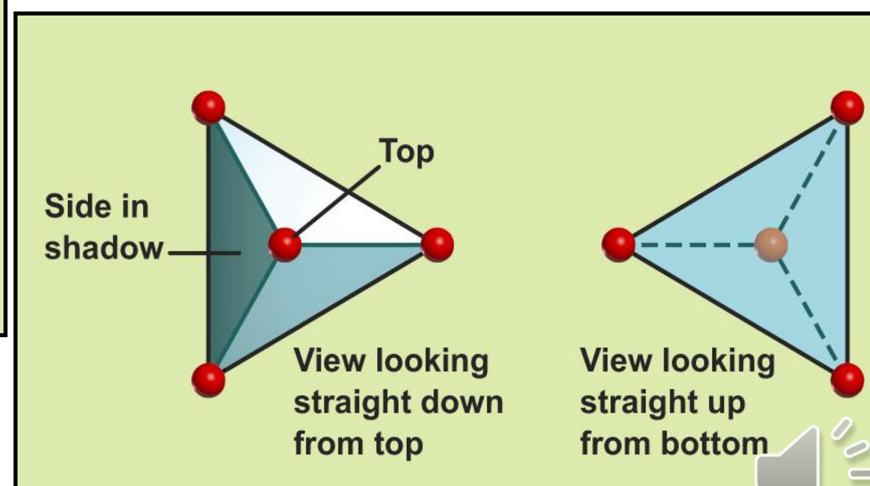
- Silicates are the most common minerals on Earth.
- They dominate Earth's crust and mantle.
  - Made of oxygen and silicon with other atoms

Silicate Minerals

- The SiO_4^{4-} anionic unit: the silicon-oxygen tetrahedron
  - Four O atoms are bonded to a central Si atom.
  - Define the corners of a four-sided geometric figure
  - The “silica tetrahedron” is the building block of silicates.

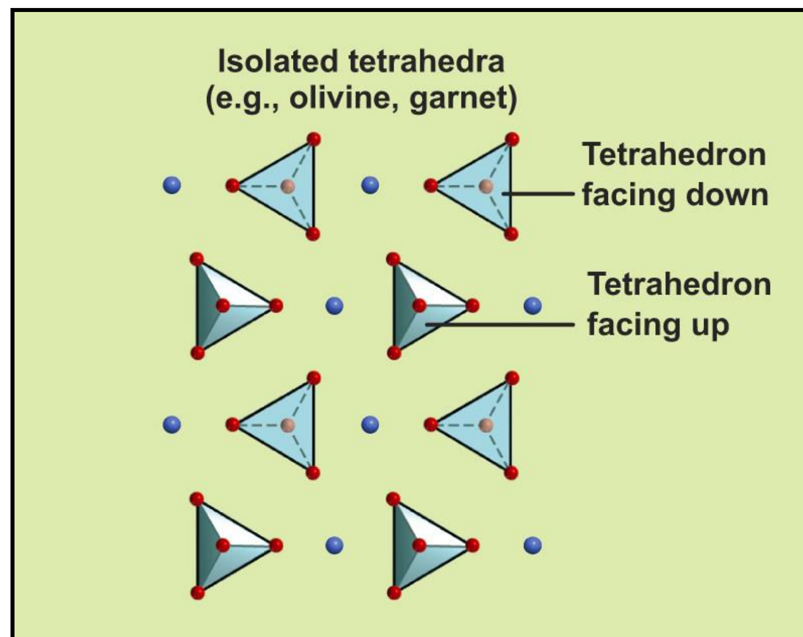






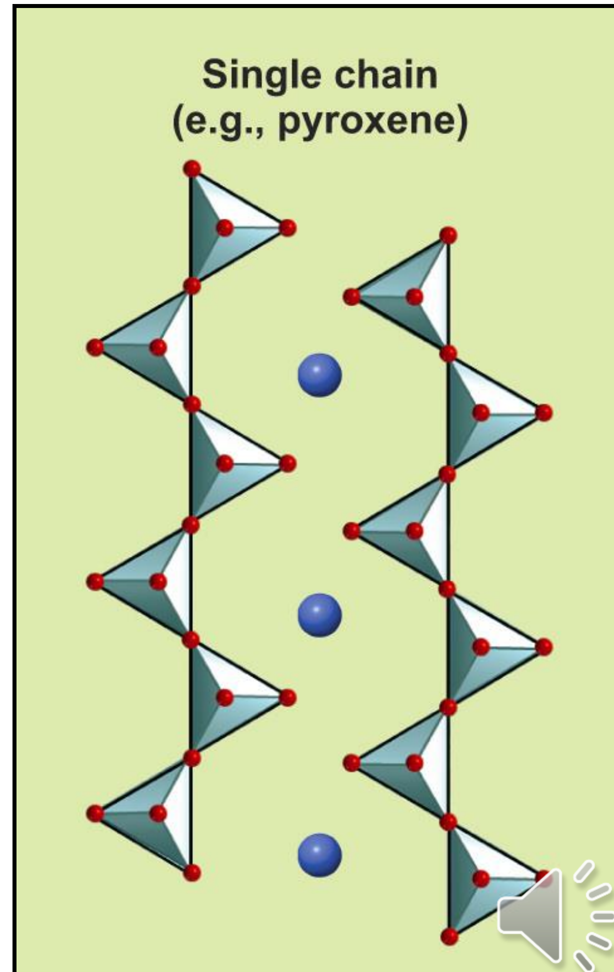
Silicate Minerals

- Independent Tetrahedra
  - Silica tetrahedra share no oxygens.
  - They are linked by cations.
  - Examples:
    - Olivine—a glassy green mineral, typically $(Mg,Fe)SiO_4$
    - Garnet—forms equant, 12-sided crystals



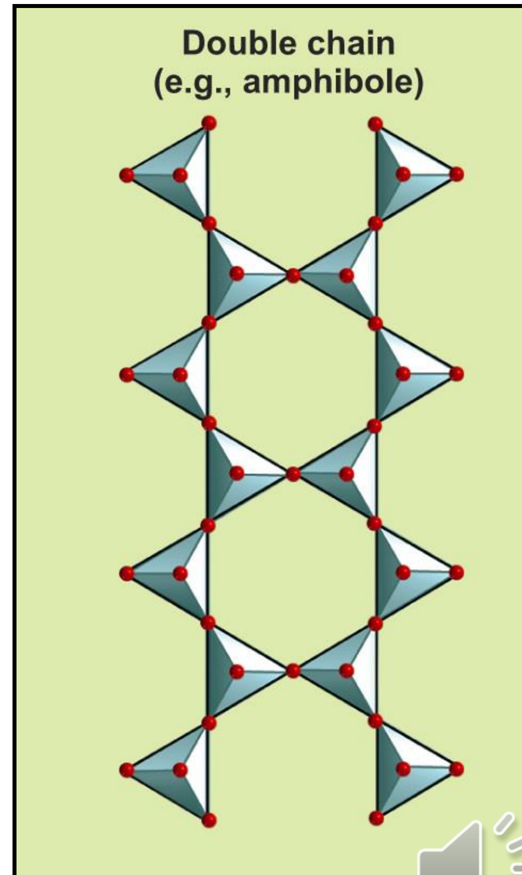
Silicate Minerals

- Single Chains
  - Silica tetrahedra link to share two oxygens
  - Example:
    - Pyroxenes
      - Dark, long crystals
      - Two cleavages near 90˚



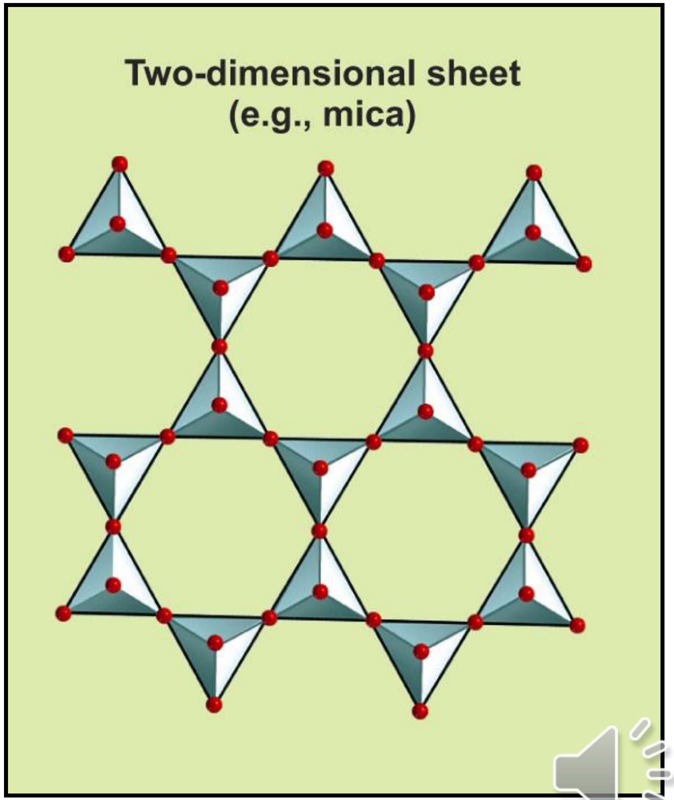
Silicate Minerals

- Double chains
  - Silica tetrahedra alternate sharing two and three oxygens.
  - Example:
    - Amphiboles
      - Dark, long crystals
      - Two cleavages at 60º and 120º



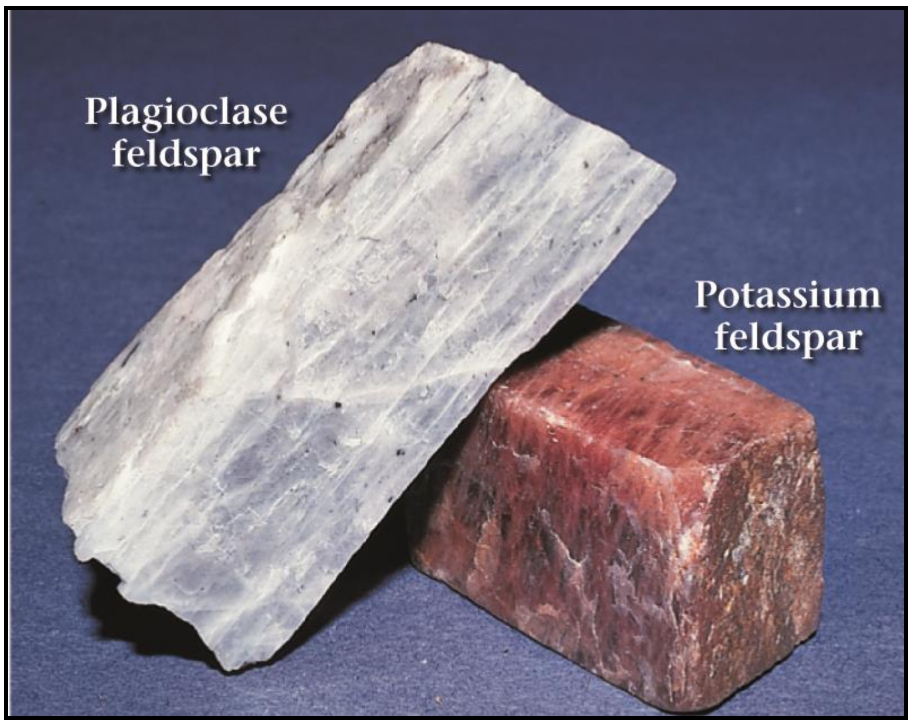
Silicate Minerals

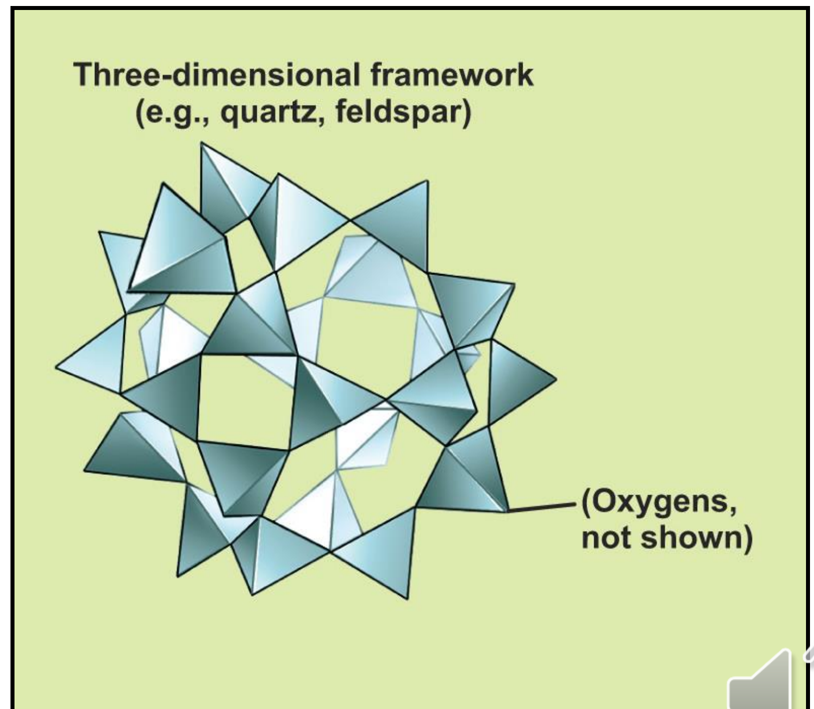
- Sheet silicates
  - Silica tetrahedra share three oxygens.
  - Create two-dimensional flat sheets of linked tetrahedra
  - Characterized by one direction of perfect cleavage
  - Examples: Micas, clays



Silicate Minerals

- Framework silicates
  - All four oxygens in each silica tetrahedron are shared.
  - Examples:
    - Feldspars—plagioclase and potassium feldspar
    - Silica (quartz) group—contains only Si and O



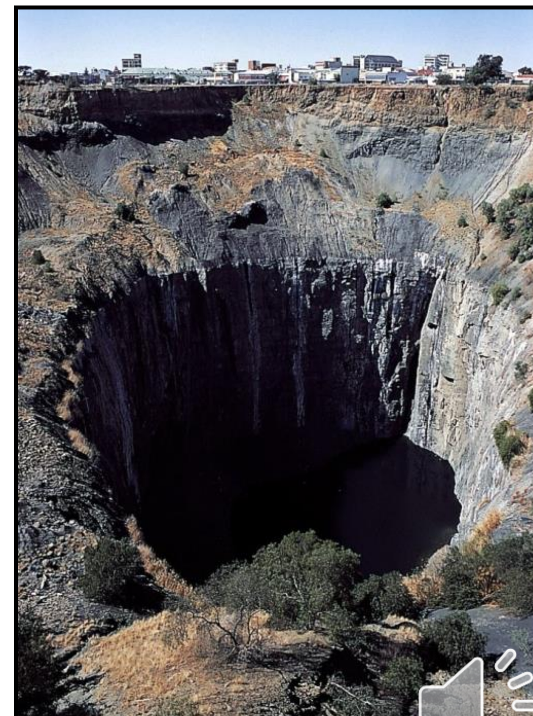


Gems

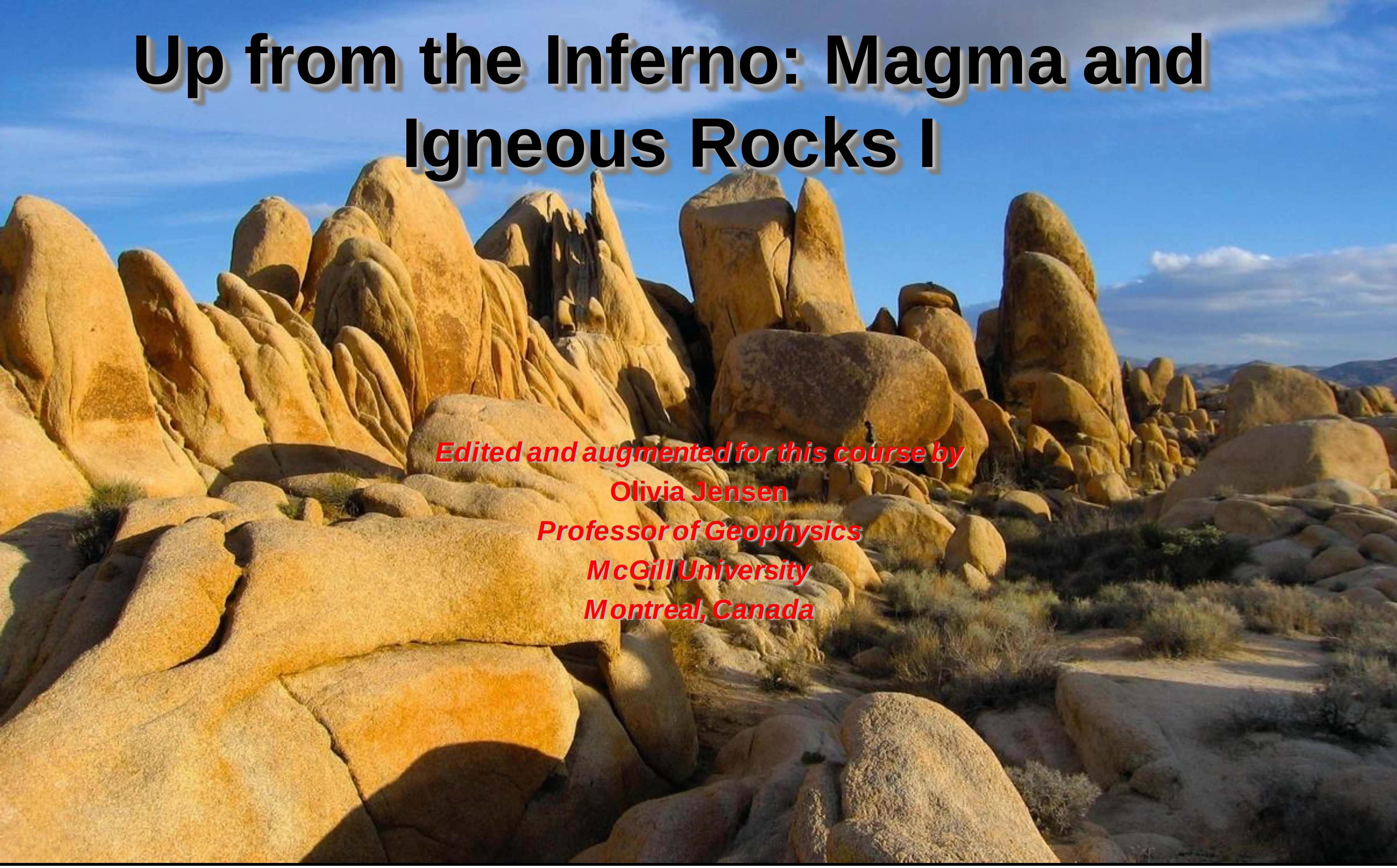
- Gemstones—a mineral with special value
  - Rare—formed by unusual geological processes
  - Beautiful—strikingly unique color, clarity, and luster
- Gem—a cut and polished stone created for jewelry
  - Precious—stones that are particularly rare and expensive
    - Diamond (C)
    - Ruby (Al_20_3)
    - Sapphire (Al_20_3)
    - Emerald ($Be_3Al_2(Si_6O_{18})$)
  - Semiprecious—less rare
    - Topaz ($Al_2(SiO_4)(F,OH)_2$)
    - Aquamarine ($Be_3Al_2Si_6O_{18}$)
    - Garnet ($X_3Z_2(SiO_4)_3$)
- Gemstone *facets are not natural crystal faces*

Whence Diamonds?

- Diamonds originate under extremely high pressure.
  - ~150 km deep—in the upper mantle
  - Pure carbon is compressed into the diamond structure.
- Rifting causes deep-mantle rock to move upward.
- Diamonds are found in kimberlite pipes.



Up from the Inferno: Magma and Igneous Rocks I



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

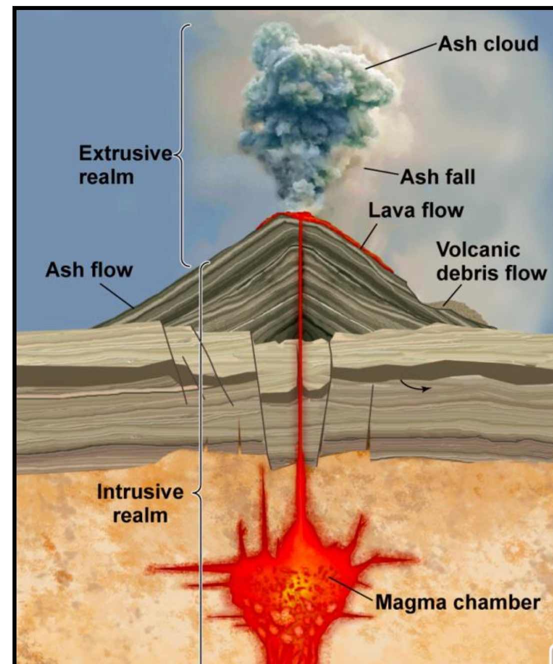
- Volcano—a vent where molten rock comes out of Earth
  - Example: Kilauea Volcano, Hawaii
    - Hot basaltic (~1,200^{o}C) lava pools around the volcanic vent.
    - Hot, syrupy lava runs downhill as a lava flow.
    - The lava flow slows, loses heat, and crusts over.
    - Finally, the flow stops and cools, forming an igneous rock.

Introduction

- Igneous rock is formed by cooling from a melt.
  - Magma—melted rock below ground
  - Lava—melted rock once it has reached the surface
- Igneous rock freezes at high temperatures (T).
  - 1,100ºC - 650ºC, depending on composition.
- There are many types of igneous rock.

Igneous Rocks

- Melted rock can cool above ground.
  - Extrusive igneous rocks—cool quickly at the surface
    - Lava flows—streams or mounds of cooled melt
    - Pyroclastic debris—cooled fragments
      - Volcanic ash—fine particles of volcanic glass
      - Volcanic rock—fragmented by eruption



Igneous Rocks

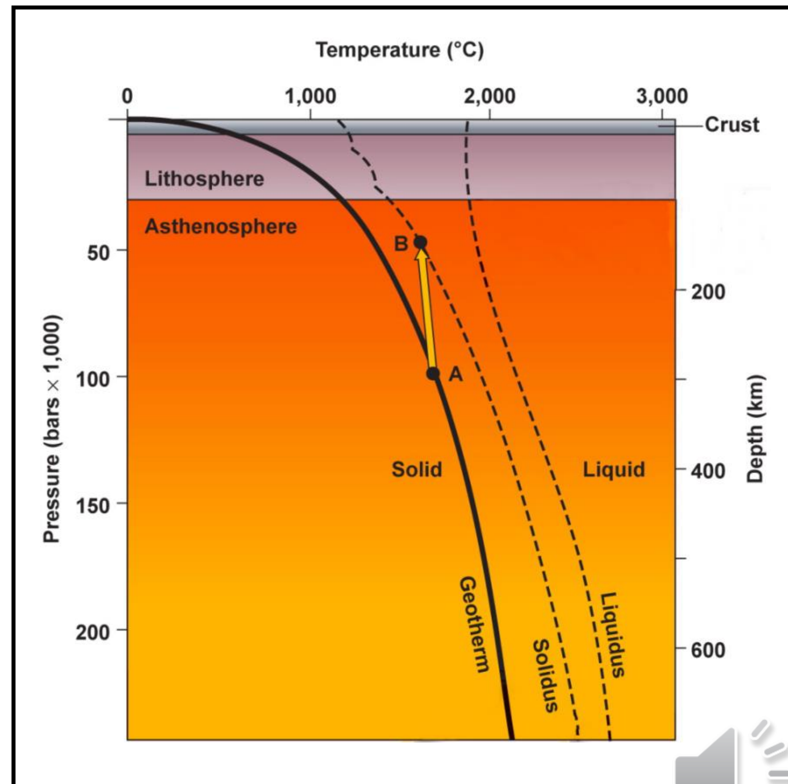
- Melted rock can cool below ground.
  - Intrusive igneous rocks—cool out of sight, underground
  - Much greater volume than extrusive igneous rocks
  - Cooling rate is slower than for extrusives.
    - Large volume magma chambers
    - Smaller volume tabular bodies or columns

Why Does Magma Form?

- Magma is not everywhere below Earth's crust.
- Magma only forms in special tectonic conditions.
  - Partial melting occurs in the crust and upper mantle.
  - Magma is fluid-like rather than "solid"
  - Melting is caused by
    - pressure release.
    - volatile addition.
    - heat transfer.

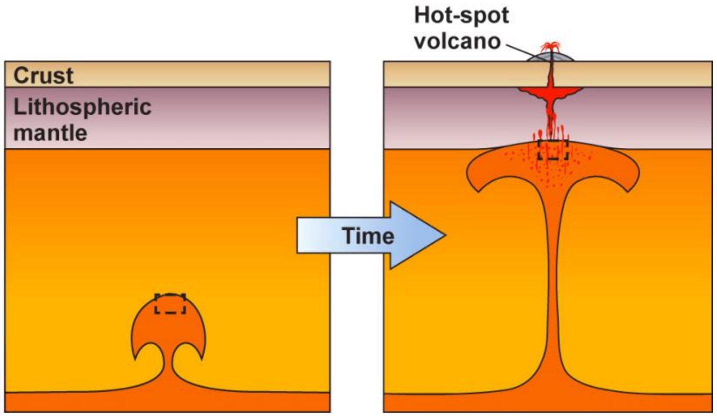
Causes of Melting

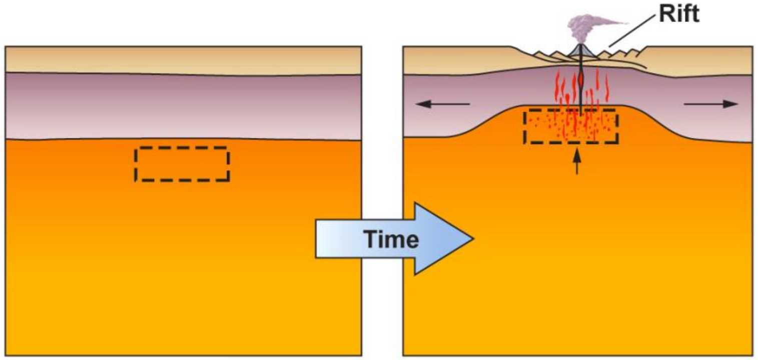
- Decrease in pressure (P)—decompression
  - The base of the crust is hot enough to melt mantle rock.
  - But, due to high P, the rock doesn't melt.
  - Melting will occur if P is decreased.
    - P drops when hot rock is carried to shallower depths.
      - Mantle plumes
      - Beneath rifts
      - Beneath mid-ocean ridges

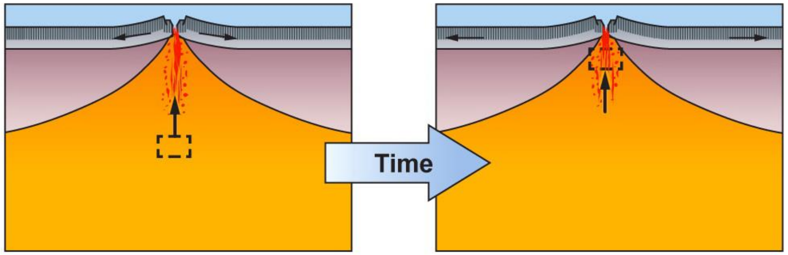


Causes of Melting

- P drops when hot rock is carried to shallower depths.
  - Mantle plumes
  - Beneath rifts
  - Under mid-ocean ridges

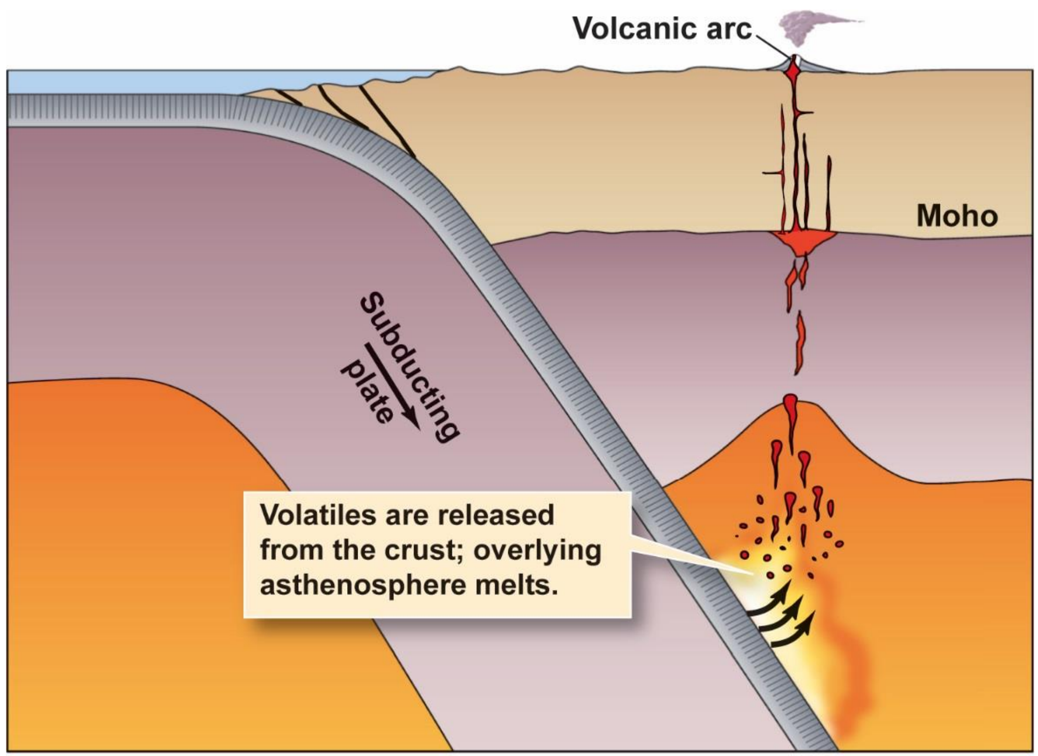






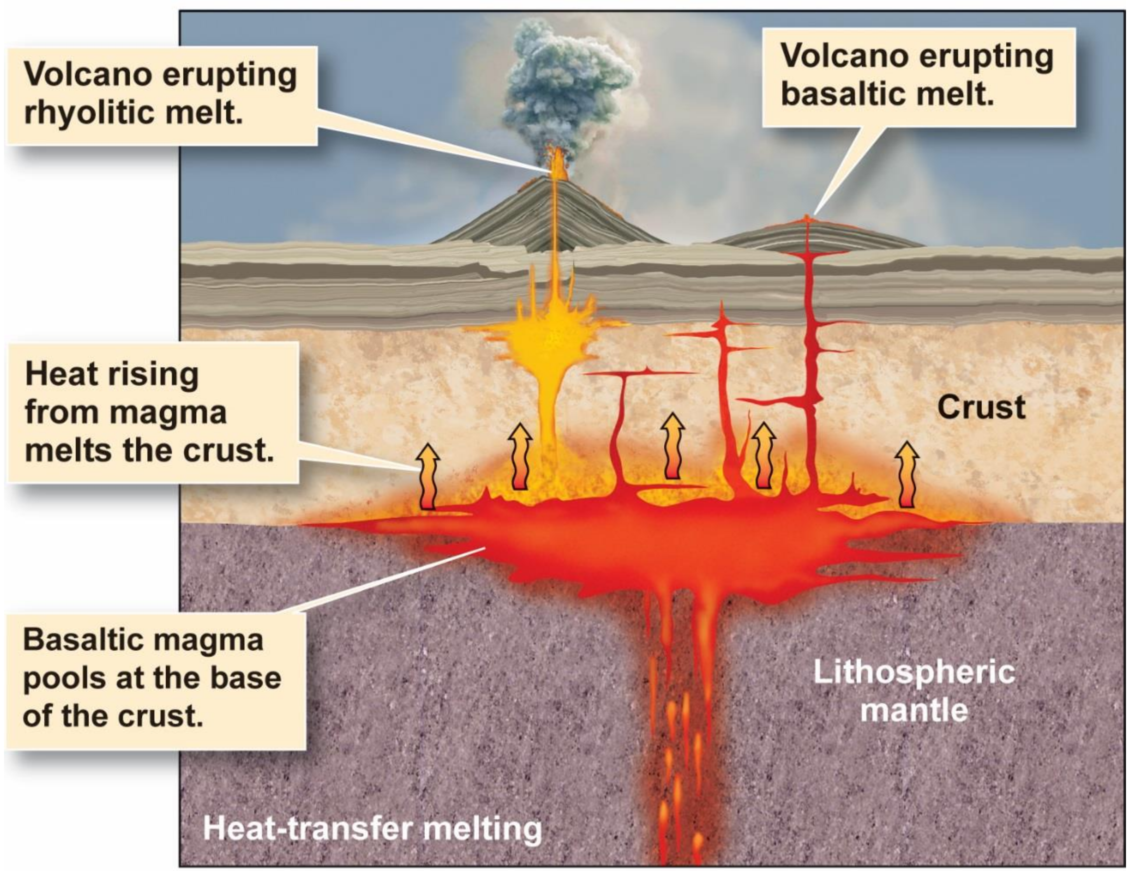
Causes of Melting

- Addition of volatiles (flux melting)
  - Volatiles lower the melting T of a hot rock.
  - Common volatiles include H_2O and CO_2.
  - Subduction carries water into the mantle, melting rock.



Causes of Melting

- Heat transfer melting
  - Rising magma carries mantle heat with it.
  - This raises the T in nearby crustal rock, which then melts.

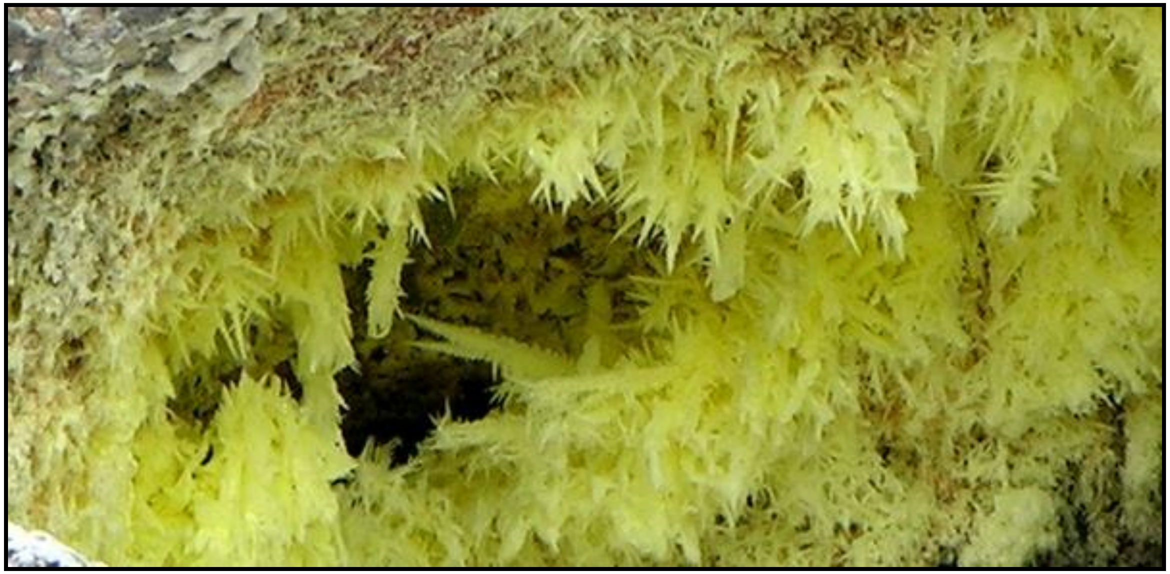


What Is Magma Made Of?

- Magmas have three components (solid, liquid, and gas).
  - Solid—solidified mineral crystals are carried in the melt.
  - Liquid—the melt itself is composed of mobile ions.
    - Dominantly Si and O; lesser Al, Ca, Fe, Mg, Na, and K
    - Other ions to a lesser extent.
  - Different mixes of elements yield different magmas.

What Is Magma Made Of?

- Gas—variable amounts of dissolved gas occur in magma.
  - Dry magma—scarce volatiles
  - Wet magma—up to 15% volatiles
    - Water vapor (H_2O)
    - Carbon dioxide (CO_2)
    - Sulfur dioxide (SO_2)
    - Nitrogen (N_2)
    - Hydrogen (H_2)



Major Types of Magma

- There are four major magma types based on % silica (SiO_2).
  - Felsic (feldspar and silica) 66–76% SiO_2
  - Intermediate 52–66% SiO_2
  - Mafic (Mg- and Fe-rich) 45–52% SiO_2
  - Ultramafic 38–45% SiO_2

Major Types of Magma

- Why are there different magma compositions?
- Magmas vary chemically due to
  - initial source rock compositions.
  - partial melting.
  - assimilation.
  - magma mixing.

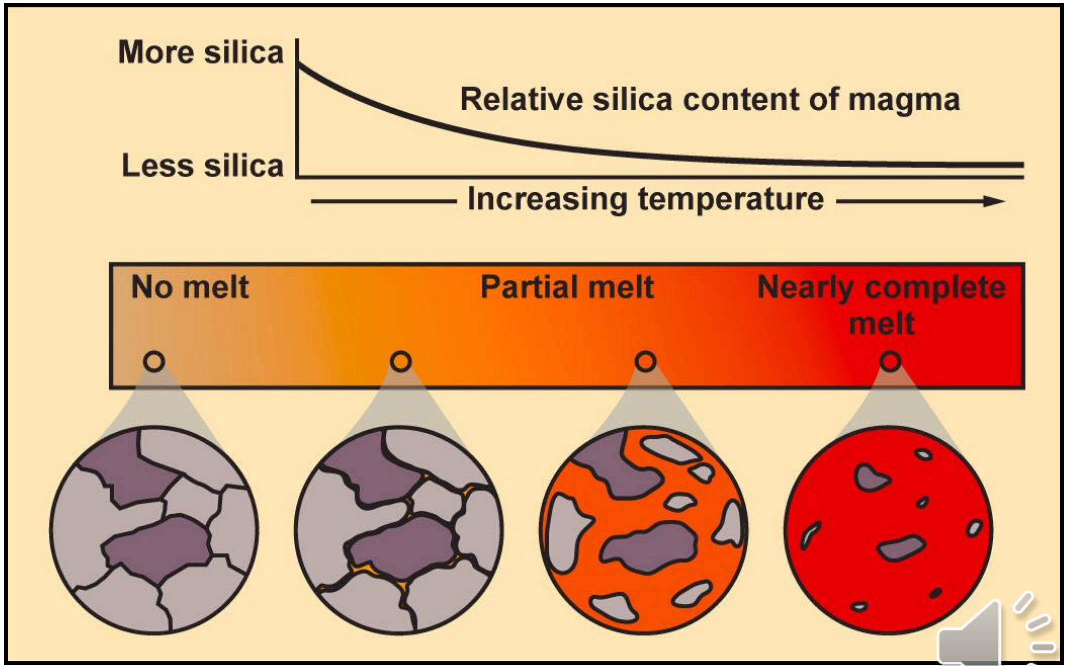
Magma Variation

- Source rock dictates initial magma composition.
  - Mantle source—ultra-mafic and mafic magmas.
  - Crustal source—mafic, intermediate, and felsic magmas.

Partial Melting

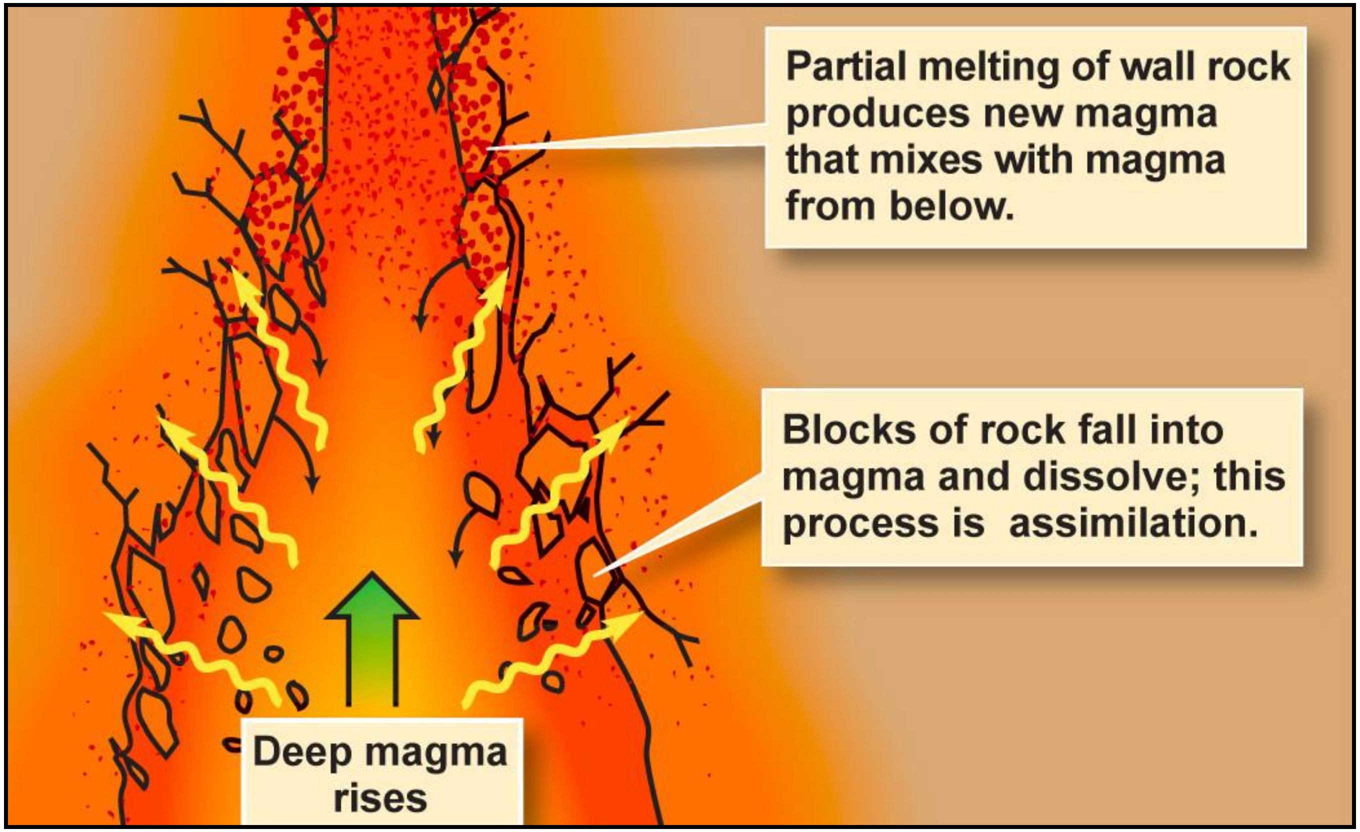
- **Upon melting, rocks rarely dissolve uniformly.**
- **Instead, only a portion of the rock melts.**
  - **Si-rich minerals melt first; Si-poor minerals melt last.**
- **Partial melting, therefore, yields a silica-rich magma.**
- **Removing the partial melt from its source create**
  - **felsic** (feldspar/silica) magmas forming granites and rhyolites
  - **mafic** (magnesium/ferric) magmas forming basalts and gabbros

Feldspars ($KAlSi_3O_8$ – $NaAlSi_3O_8$ – $CaAl_2Si_2O_8$) **comprise 60% of the crust**

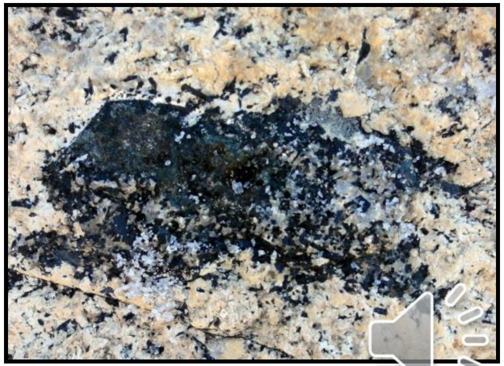


Assimilation

- Magma melts the wall rock it passes through.
- Blocks of wall rock (xenoliths) fall into magma.
- Assimilation of these rocks alters magma composition.



Mafic xenoliths in granite. The one below has partially dissolved.



Magma Mixing

- Different magmas may blend in a magma chamber.
- The result combines the characteristics of the two.
- Often magma mixing is incomplete, resulting in blobs of one rock type suspended within the other.

Magma Movement

- Magma doesn't stay put; it tends to rise upward.
  - Magma may move upward in the crust.
  - Magma may breach the surface—a volcano.
- This transfers mass from deep to shallow parts of Earth.
  - A crucial process in the Earth System
  - Provides the raw material for soil, atmosphere, and ocean

Magma Movement

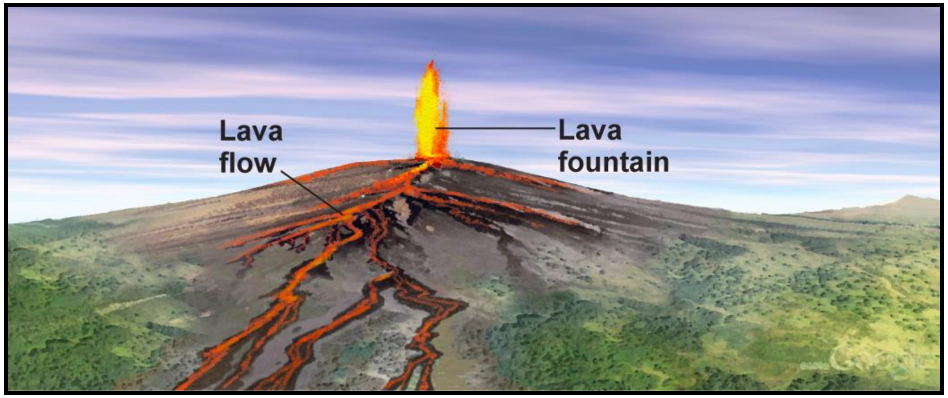
- Why does magma rise?
  - It is less dense than surrounding rocks.
    - Magma is more buoyant.
    - Buoyancy lifts magma upward.
  - Weight of overlying rock creates pressure.
    - Pressure squeezes magma upward.
    - It is like mud squeezed between your toes.

Magma Movement

- Speed of magma flow governed by viscosity.
  - Lower viscosity eases movement.
  - Lower viscosity is generated by
    - higher T.
    - lower SiO_2 content.
    - higher volatile content.

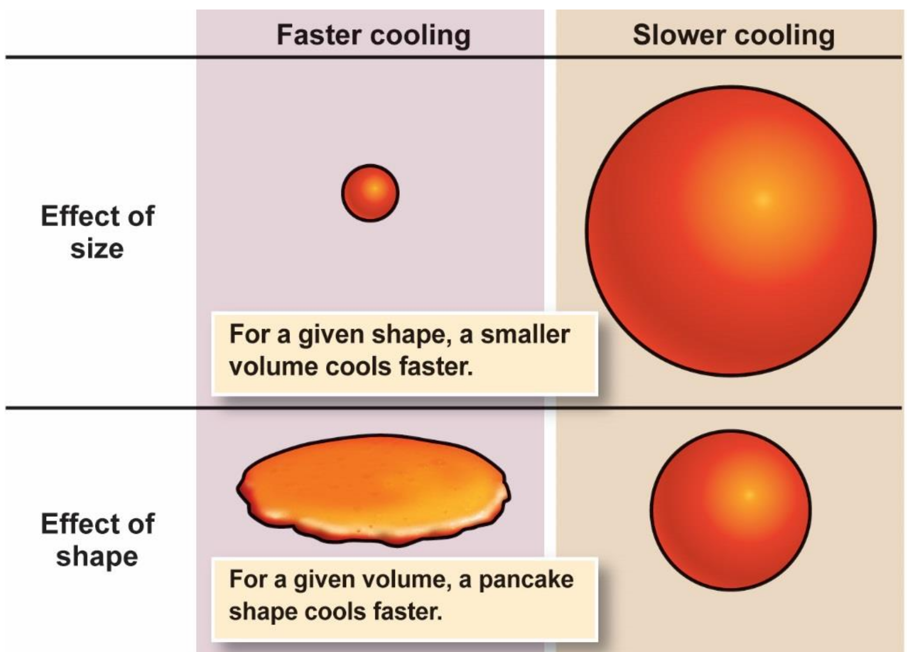
Magma Movement

- Viscosity depends on temperature, volatiles, and silica.
  - Temperature:
    - hot = lower viscosity; cooler = higher viscosity
  - Volatile content:
    - More volatiles—lower viscosity
    - Less volatiles—higher viscosity
  - Silica (SiO_2) content:
    - Less SiO_2 (mafic)—lower viscosity.
    - More SiO_2 (felsic)—higher viscosity.



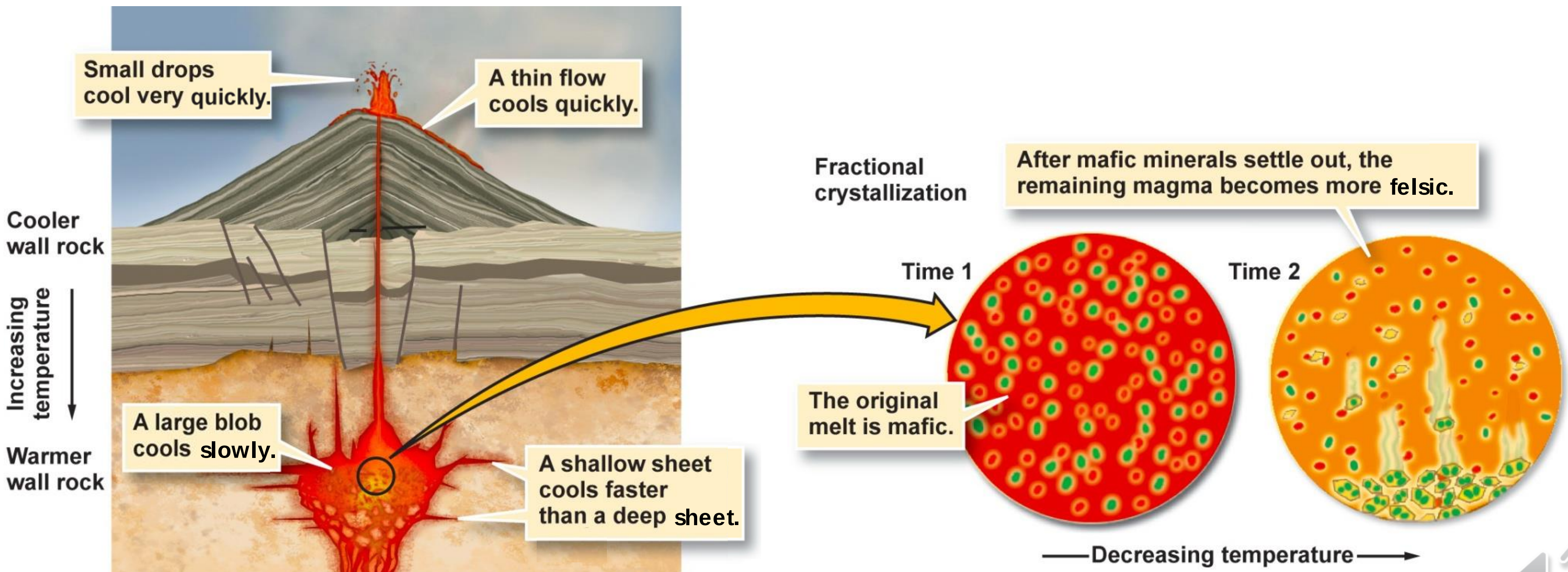
Making Igneous Rock

- Cooling rate—how fast does magma cool?
  - Depth—deeper is hotter; shallower is cooler.
    - Deep plutons lose heat very slowly; take a long time to cool.
    - Shallow flows lose heat more rapidly; cool quickly.
  - Shape—spherical bodies cool slowly; tabular faster.
  - Groundwater—circulating water removes heat.



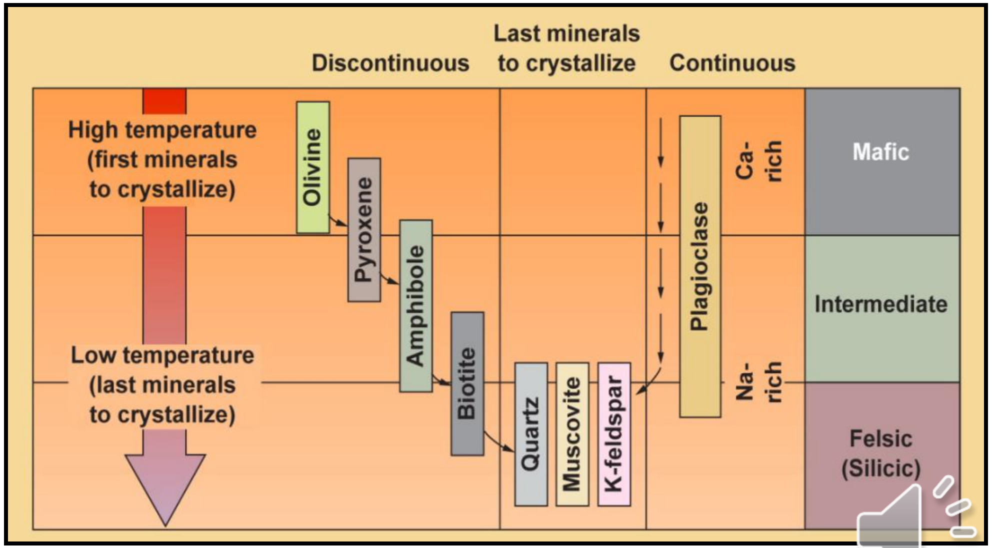
Making Igneous Rock

- Changes with cooling
  - Fractional crystallization—early crystals settle by gravity.
  - Melt composition changes as a result.
    - Fe, Mg, Ca are removed as early mafic minerals settle out.
    - Remaining melt becomes enriched in Si, Al, Na, and K.



Bowen's Reaction Series

- N. L. Bowen—devised experiments cooling melts (1920s).
  - Early crystals settled out, removing Fe, Mg, and Ca.
  - Remaining melt progressively enriched in Si, Al, and Na.
- He discovered that minerals solidify in a specific series.
  - Continuous—plagioclase changed from Ca-rich to Na-rich.
  - Discontinuous—minerals start and stop crystallizing.
    - Olivine
    - Pyroxene
    - Amphibole
    - Biotite



[Online mineral database]()