ERTH2404
Lecture 2: Minerals and Igneous rocks

Amethyst Quartz

Photo: Natural Resources Canada

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Reading Material

- Please read Kehew's book to complement the material presented in this lecture:

  Chap. 3 p. 74-94;

- The lab manual is an excellent source of information on minerals

1- Lecture contents

- Mineral characteristics
  - Physical properties
  - Crystal structure
- Mineral classification
- Mineral identification

What is a **mineral**?

- Naturally occurring solids
- Inorganic (ie not produced by an organism)
- Homogeneous solid
- Ordered atomic arrangement (crystal structure)
- Specific (fixed) chemical composition

- Note: there are almost 4000 minerals… but 25 comprises 99% of the volume of the Earth's crust!

Are these minerals?

- Bone? Seashell? Amber?
  - No, they are organic materials
- Glass?
  - No, it has no crystal structure
- Mineral water?
  - No, it is water with dissolved solids
- Diamond?
  - Yes, composed of pure carbon

What is a rock?

- It is a natural solid aggregate of one or more minerals
- Minerals are the building blocks of rocks

- Mono mineralic Rock: composed of one mineral
  - Ex: Limestone ($CaCO_3$); Halite (NaCl)

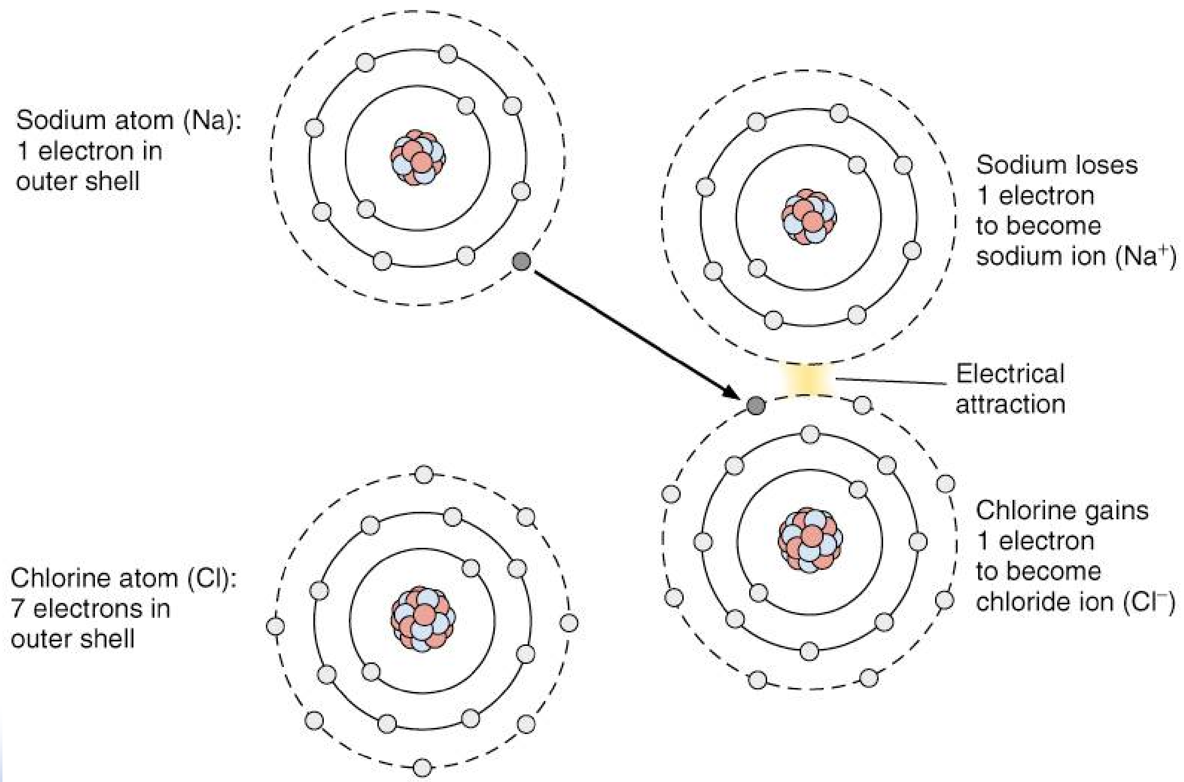
- Poly mineralic Rock composed of several minerals
  - Ex: Granite (feldspar, quartz, hornblende, biotite)

Crystalline structure

- Minerals have orderly internal structure
  - Array of atoms in a regular repeating structure
  - Dependent on the chemical bonds between atoms
  - You can cut pieces until you reach the atom level, and the chemical composition remains the same
- **Crystal**: the macroscopic expression of the crystalline structure
  - Internal structure expressed by external plane faces

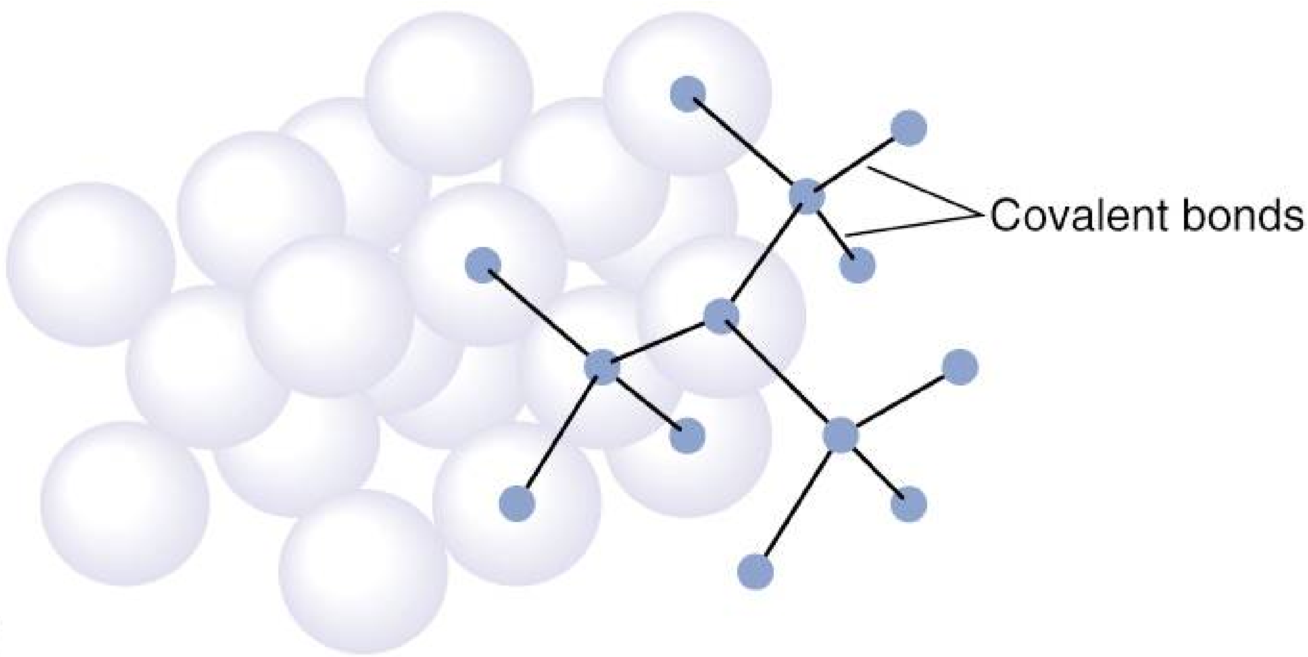
Ionic bonds

- Attraction between two oppositely charged ions
- When one atom donates one or more electron to an atom of another element
- Ex: NaCl



Covalent bonds

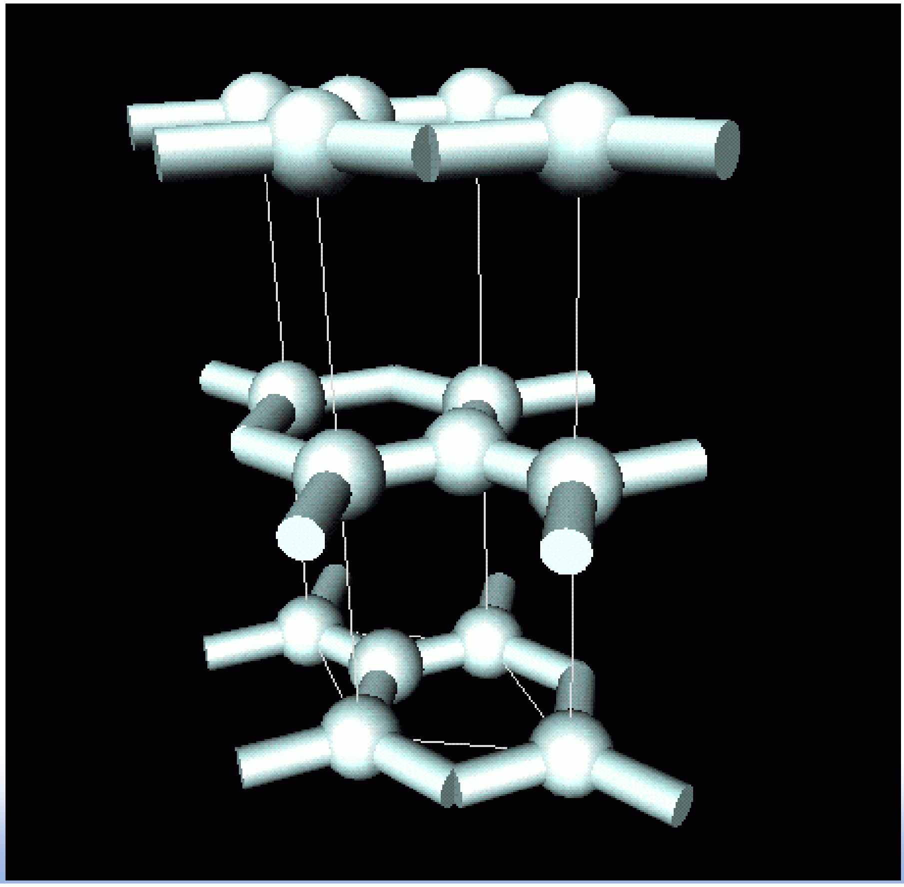
- Sharing of electrons between atoms
- Ex: quartz, diamonds, graphite



(a)

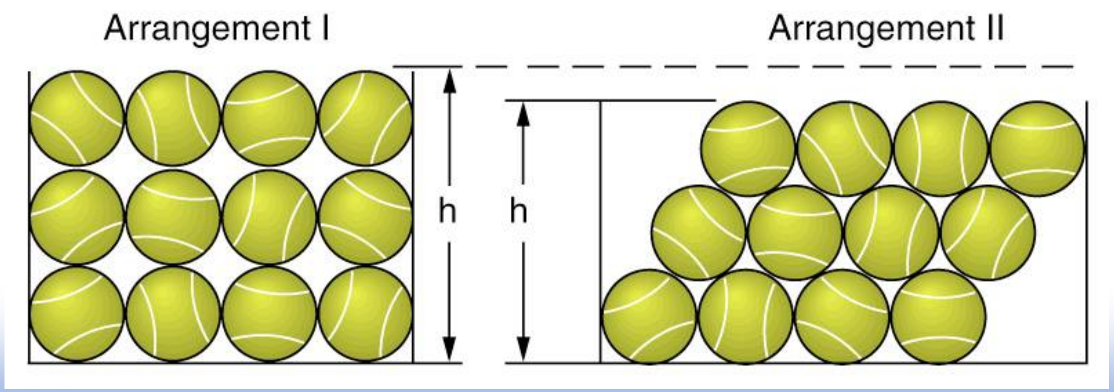
Van der Waals Bonds

- Weak electrostatic attraction between layers
- Ex: Micas, inter-layer links of graphite



Mineral classification

- Minerals are classified according to:
  - Chemical composition
  - Internal structure
- **Polymorphs**:
  - Minerals with the same chemical composition but different crystalline structures
  - Therefore, different properties

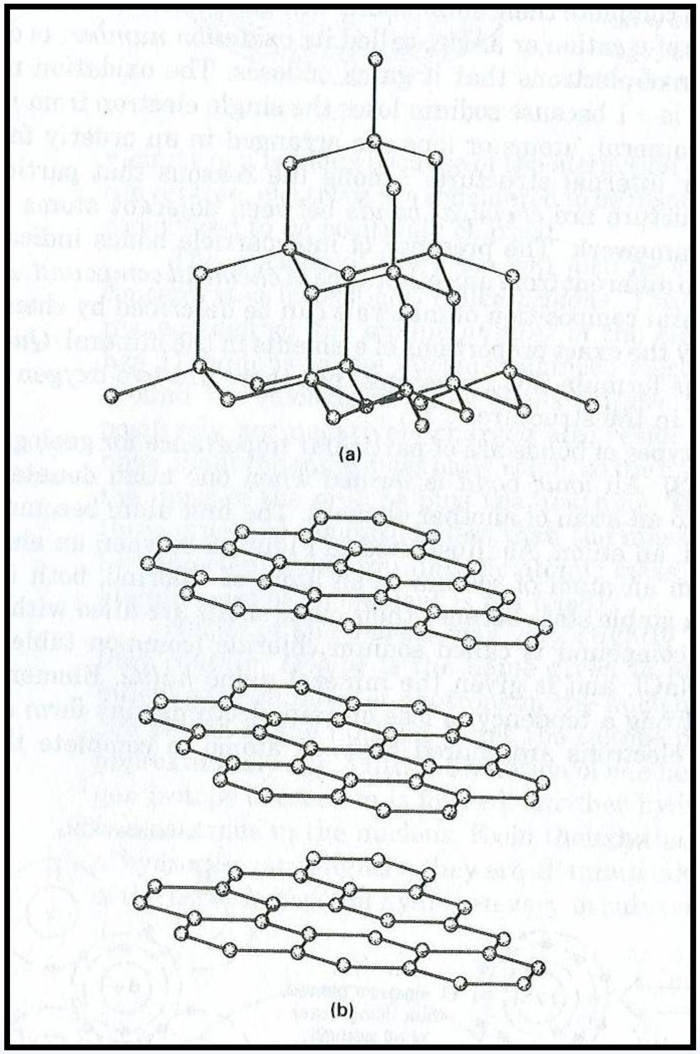


Polymorphs: Carbon

- Diamond
  - 3D structure where each atom is bound to 4 neighbors
  - Hardest mineral known

- Graphite
  - Sheet-like hexagonal structure where each atom is bound to 3 neighbors
  - One of the softest mineral

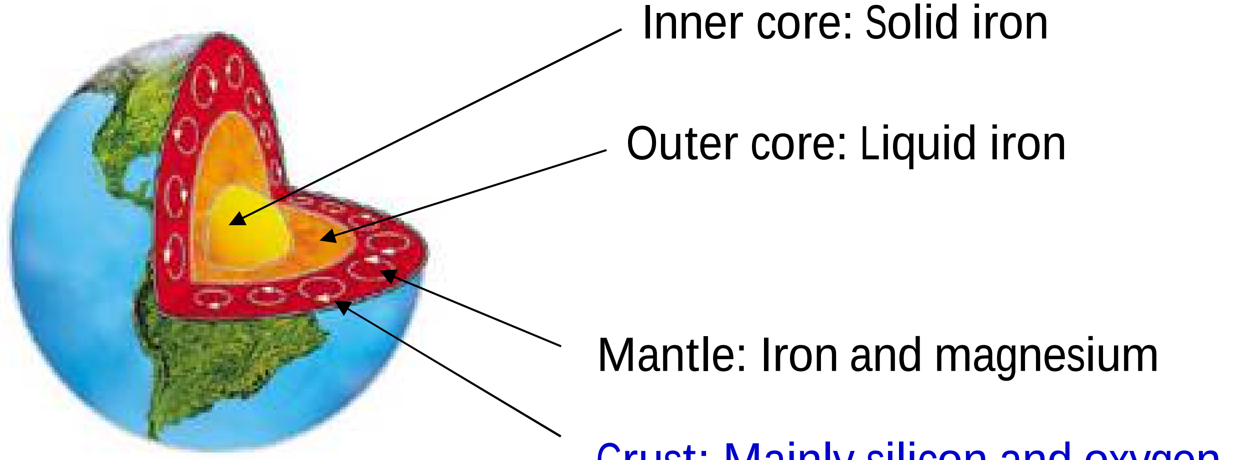
Polymorphs: Carbon



Ref.: Kehew, A.E. 1998. Geology for Engineers & Environmental Scientists. 2nd Edition. Fig. 2.4. Shown with permission.

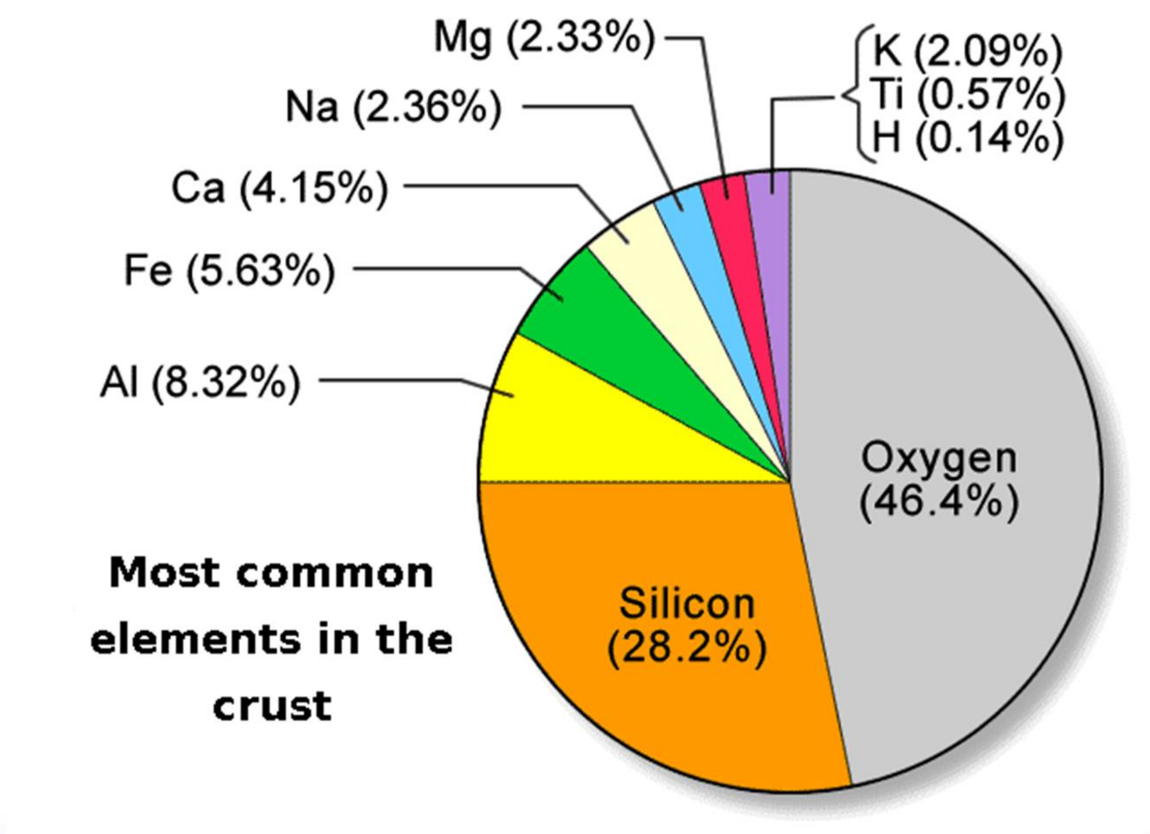
Mineral classification

- As a result of planetary differentiation:
  - 8 elements comprise 98% of the Earth's crust
- Silicon and oxygen account for 95% of crustal volume
  and 74 % of crustal mass.



Mineral classification

- Composition of the Earth's crust (% weight)



Source: American Geophysical Union
https://blogs.agu.org/martianchronicles/2012/05/30/whats-that-rock-made-of-good-question/

Mineral growth

- Minerals can grow by
  - Solidification of a melt
  - Precipitation from solution
  - Solid state diffusion (metamorphic rocks)
  - Biomineralization (shells)
  - Fumarolic mineralization (from a gas)
- Once the ‘seed’ has formed, other molecules adhere to the seed and the mineral grows.

Mineral classification

- 4000 minerals known

- 25 minerals make more than 99% of the volume of the crust
- You will see < 20 minerals

- Mineral grouped by chemical properties

Mineral Groups

Group	Group Formula	Example
Silicates	$[SiO_4]^{4-}$	Quartz
Oxides	$[O^{2-}]$	Magnetite
Sulfides	$[S^{2-}]$	Pyrite
Sulfates	$[SO_4]^{2-}$	Gypsum
Halides	$[Cl, F]^{1-}$	Halite
Carbonates	$[CO_3]^{2-}$	Calcite
Hydroxides	$[OH]^{1-}$	Iron Ore
Phosphates	$[PO_4]^{3-}$	Apatite
Native elements		Copper, Gold

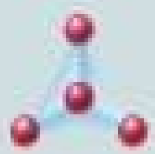
Silicate Mineral Groups

- Comprise the most rock-forming minerals
  - Due to abundance of Si and O in crust

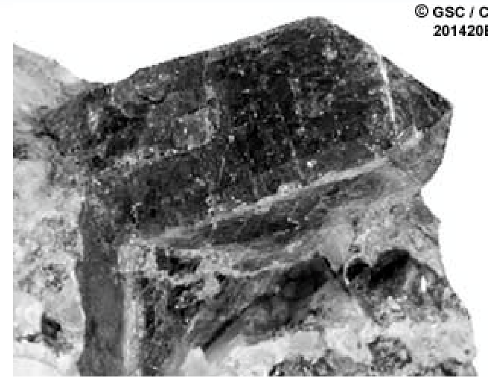
1. Isolated tetrahedra
2. Single chain
3. Double chain
4. 2-dimensional sheet
5. 3-dimensional framework

Silicate: Isolated tetrahedra

- Basic building block is the silicon-oxygen tetrahedron
  - Four available O ions surrounding a smaller Si ion

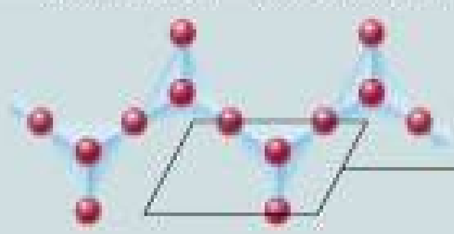
Silica tetrahedra (central Si^{4+} not shown)	Composition of a single unit	Mineral example
	$(SiO_4)^{4-}$	Olivine, $(Mg, Fe)_2 SiO_4$

Silicates: Single Chains



- Pyroxenes (two types)
  - Mg-Fe series (orthopyroxene)
  - Ca-Mg-Fe series (clinopyroxenes)
  - Together with olivine form rest of Earth's mantle

One dimensional single chain (2 free O's per ST)

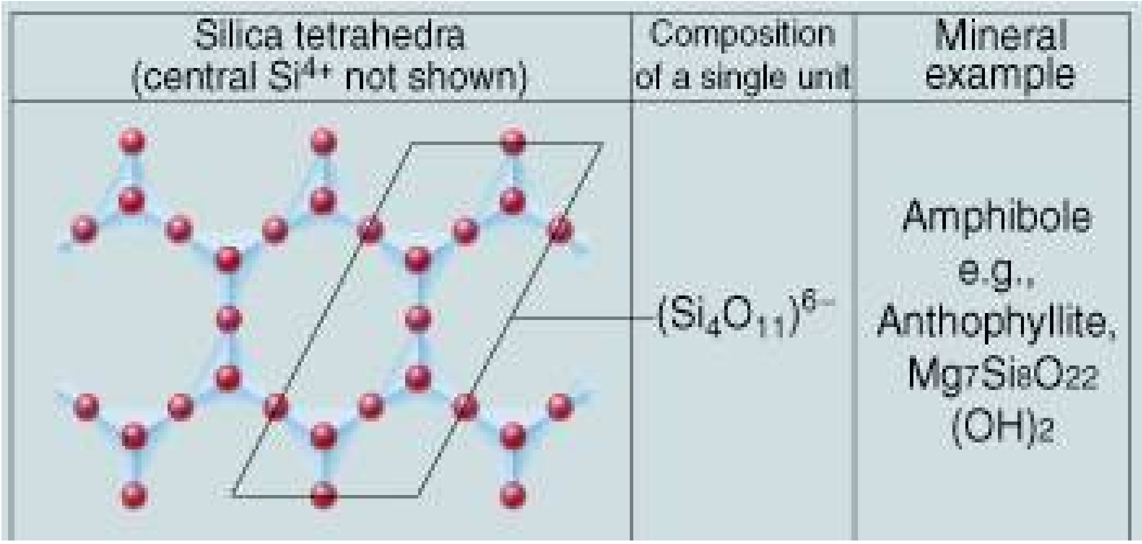


Silica tetrahedra (central Si^{4+} not shown)	Composition of a single unit	Mineral example
(diagram above)	$(SiO_3)^{2-}$	Pyroxene e.g., Enstatite, $MgSiO_3$

Silicate: Double Chains

- Amphiboles:
  - Compositionally diverse:
  - Mg, Fe, Ca, al, Na, K, OH^-

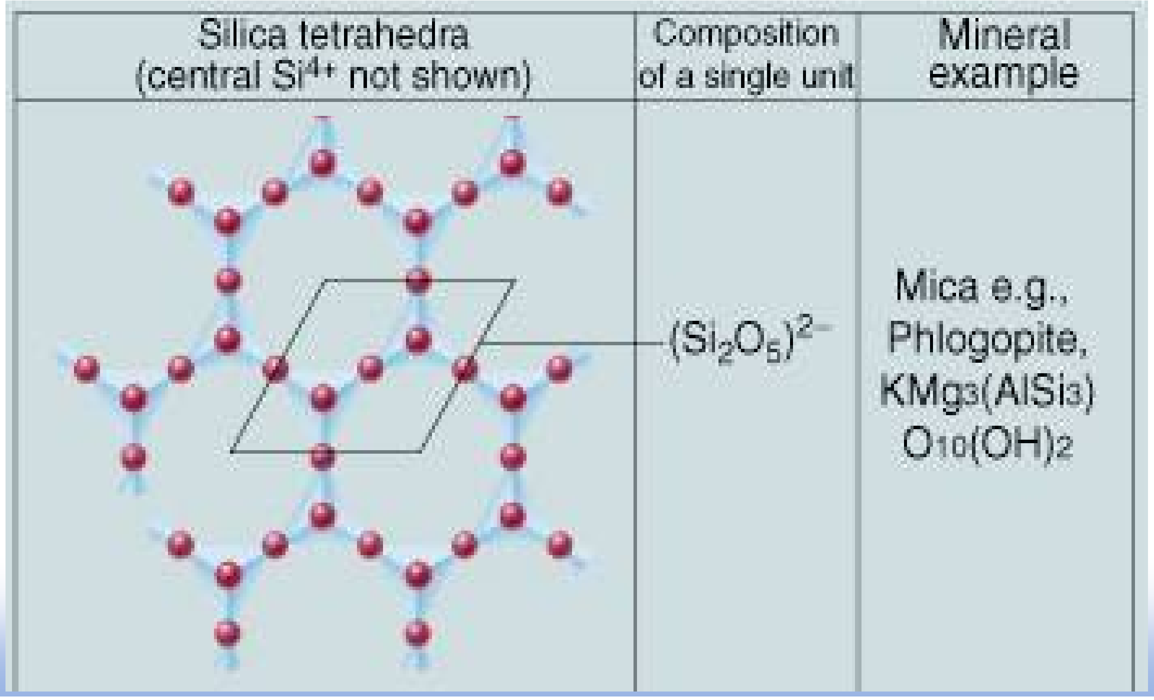
One dimensional
double chain
(2 free O's per ST)



Silicate: 2-dimensional Sheets

- Distinctly layered crystals
  - layers peel apart
- Elements fit between sheets
- Mica

Two-dimensional sheets



Silicate: 2-dimensional Sheets

- Clay minerals
  - General term for a variety of complex minerals
  - Most originate as products of chemical weathering
- Thin stacked sheets
  - Sheet surface is negatively charged which attracts water

Silicate: 2-dimensional Sheets

Clay minerals

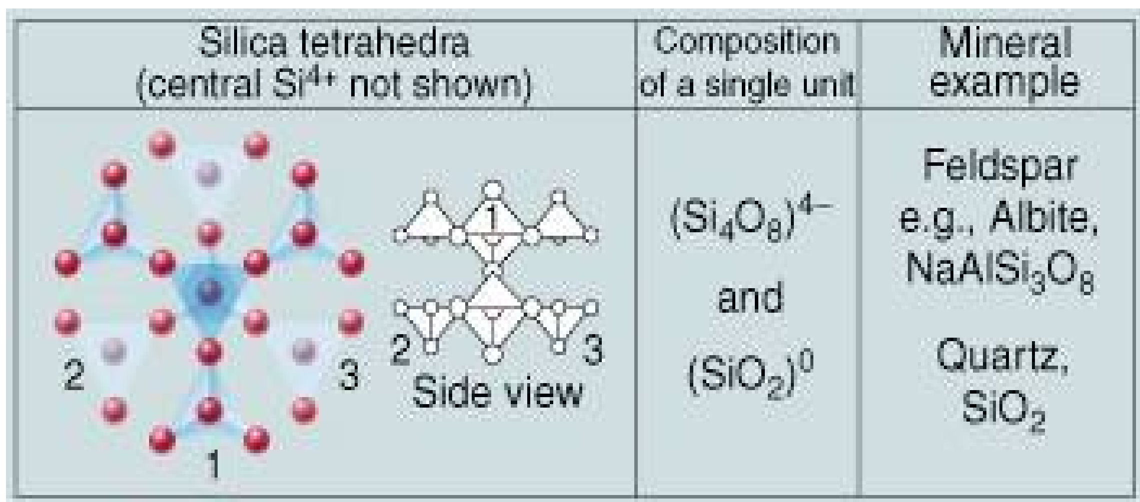
- Engineering implications: some clay minerals swell when exposed to water causing damage to foundations

- Soils with a high content of expansive minerals can form deep cracks in drier seasons or years; such soils are called vertisols.
- Soils with smectite clay minerals, including montmorillonite and bentonite, have the most dramatic shrink-swell capacity.

Silicate: 3-dimensional framework

- Complex structures
  - Most common minerals in continental crust
- Feldspars: Ca – Na – K substitution in lattice

Three-dimensional sheets

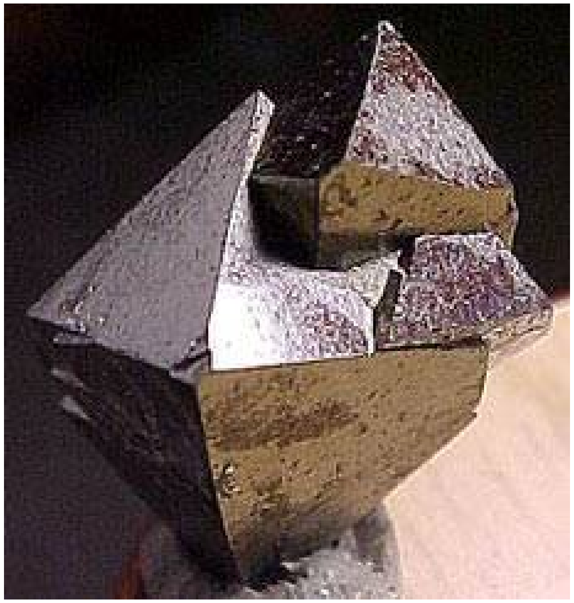


Silica tetrahedra (central Si^{4+} not shown)	Composition of a single unit	Mineral example
2 3 1 Side view	$(Si_4O_8)^{4-}$ and $(SiO_2)^0$	Feldspar e.g., Albite, $NaAlSi_3O_8$ Quartz, SiO_2

Non-Silicate Minerals: Oxides

- Oxides $[O]^{-2}$ are important ore minerals

Hematite Fe_2O_3

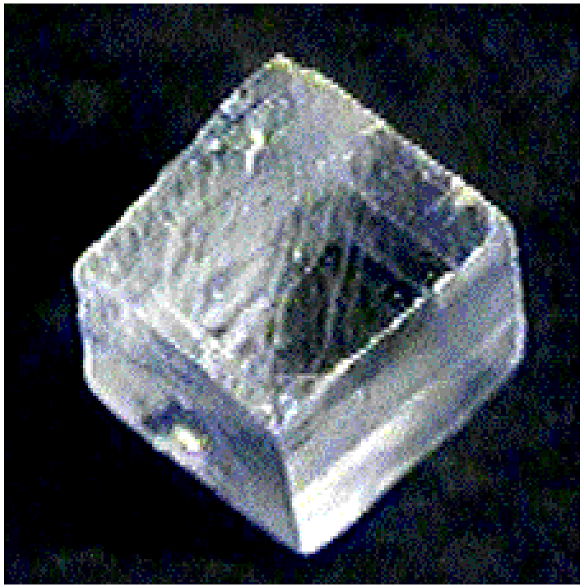


Magnetite Fe_3O_4

Non-Silicates: Carbonates

- $[CO_3]^{-2}$

Dolomite $(Mg,Ca)CO_3$



Calcite $CaCO_3$

Non-Silicates: Sulfides

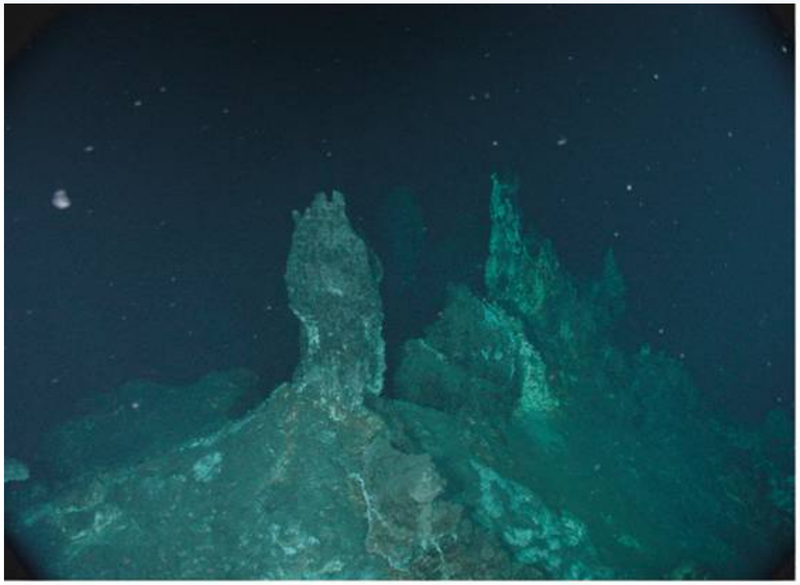
- Sulphides $[S]^{-2}$ contain sulfur and one or more metals
- Important source of metallic ore

Galena (PbS)

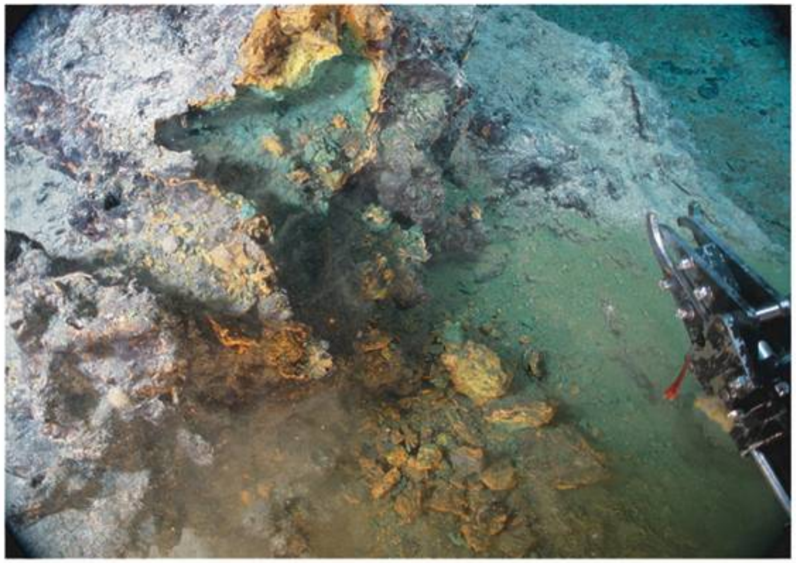
Sphalerite (ZnS)

Non-Silicates: Sulfides

- Modern sulfides found at the seafloor of hydrothermal vents



Active Chimneys on Ridgetop Vent Group Note Absence of Tubeworms



Sulfide Mound, Magic Moutain

Non-Silicates: Phosphates

- $[PO_4]^{-3}$
- One of very few minerals produced and used by biological systems (bone material)
- Hydroxylapatite is a major component of tooth enamel

Non-Silicates: Halides

- $[Cl,F]^-$

Sylvite (KCl)

Halite (NaCl)

Non-Silicates: Native elements

- **Minerals** composed of only one element, such as copper, sulfur, gold, silver, and diamonds.

Sulfur

Gold

Non-Silicates: Sulfates

- $[SO_4]^{-2}$

Gypsum ($CaSO_4 \cdot 2H_2O$) Desert Rose

Non-Silicates: Sulfates

- Extraordinary selenite crystals discovered in Caves of Naica (Mexico)
  - Selenite is a variety of gypsum
  - Known as the “Cave of Crystals”
  - Depth 350m, average temperature 45C, humidity 100%

- Filmed by Discovery Channel, 2011
  - http://youtu.be/IaMZAJ2L_1Y
  - Time: 3:18

Non-Silicates: Sulfates

- Extraordinary gypsum crystals discovered in Lechuguilla Cave
  - Known as the Chandelier Ballroom

- Filmed in BBC Planet Earth series, 2006
  - http://www.bbc.co.uk/programmes/p00mrw8f
  - http://www.bbc.co.uk/programmes/p0037p4w

Mineral Identification

- How do we identify minerals?
- Mineral identification is critical to rock identification
- See lab manual
- Watch video: **Identifying Minerals**
  https://youtu.be/32NG9aeZ7_c

Mineral Identification

- **Diagnostic property**
  - Key properties used to identify a mineral
  - Typically require several diagnostic properties to identify a mineral

Mineral Identification

- Qualitative/semi-quantitative properties
  1. Luster
  2. Color
  3. Streak
  4. Crystal Habit
  5. Hardness
  6. Cleavage
  7. Fracture
  8. Others

Luster, Color, Streak } Interaction with light

Crystal Habit → Crystal growth

Hardness, Cleavage, Fracture } Strength

Video on mineral identification

Mineral Identification

- **Lustre**: the way that light is reflected from mineral surface
  - Metallic or non-metallic?
  - Glassy? Greasy?

Mineral Identification

Metallic

Non-metallic

Color

- Based on visible light spectrum
- Can be caused by impurities
    - Amethyst , violet quartz is violet due to iron impurities
- Diagnostic for some minerals, but not for others

Sulfur

Sulfur Photo from MII, courtesy of the Smithsonian Institution

Streak

- Color of the mineral in powder form
- Non-metallic minerals: white
- Metallic minerals: varies, but diagnostic

Hematite - red

Crystal habit

- The crystal form of the mineral
  - Requires slow growth of faces

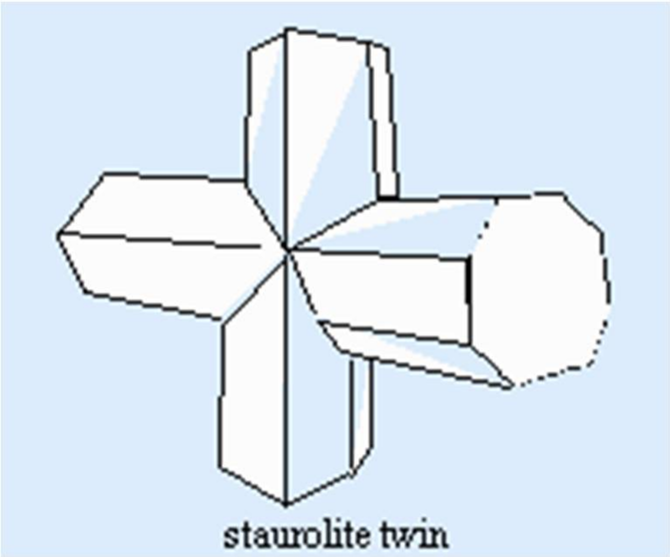
Quartz

Sulfur

Galena

Crystal habit: Twinning

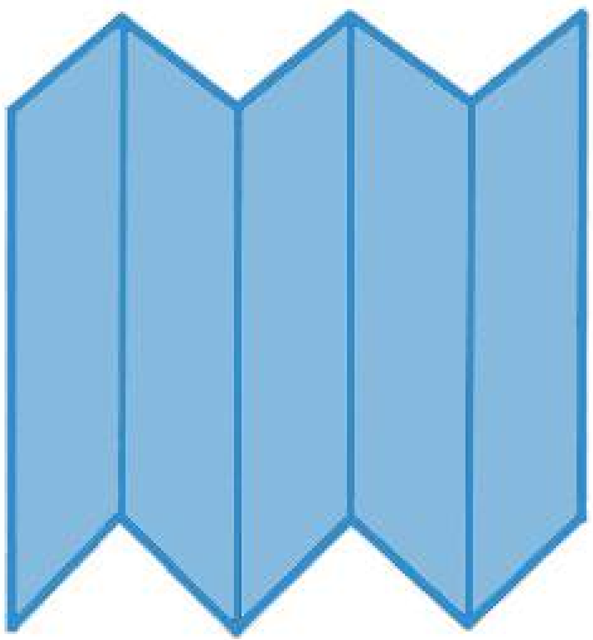
- Crystals grow in twins



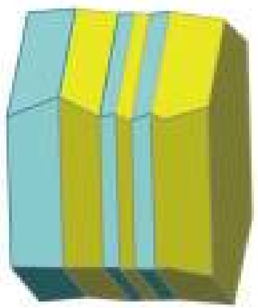
Growth or Penetration Twins

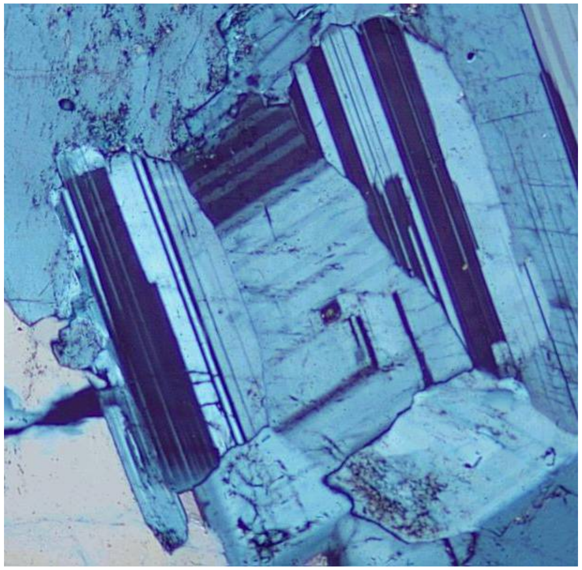
Staurolite

Twinning



Polysynthetic Twins





Plagioclase (albite twin)

Hardness

- Resistance that a smooth
  surface of a mineral offers to scratching without rupturing
  - Hardness is related to the strength of atomic bonds and is controlled by the weakest bond
  - Function of the size and the charge of ions in the crystal structure
  - Scale of hardness developed by Frederich Mohs (1812): relative and non-linear scale

Hardness

Table 3 - Mohs Hardness Scale

Hardness	Index Mineral
1	Talc
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Orthoclase
7	Quartz
8	Topaz
9	Corundum
10	Diamond

→ Fingernail (2.2)

→ Copper Penny (3.1)

→ Steel nail (5)

→ Glass (5.5)

Streak plate (7)

Lab Manual, p. 5

Cleavage

- Breakage of surfaces along planes of weakness in the lattice

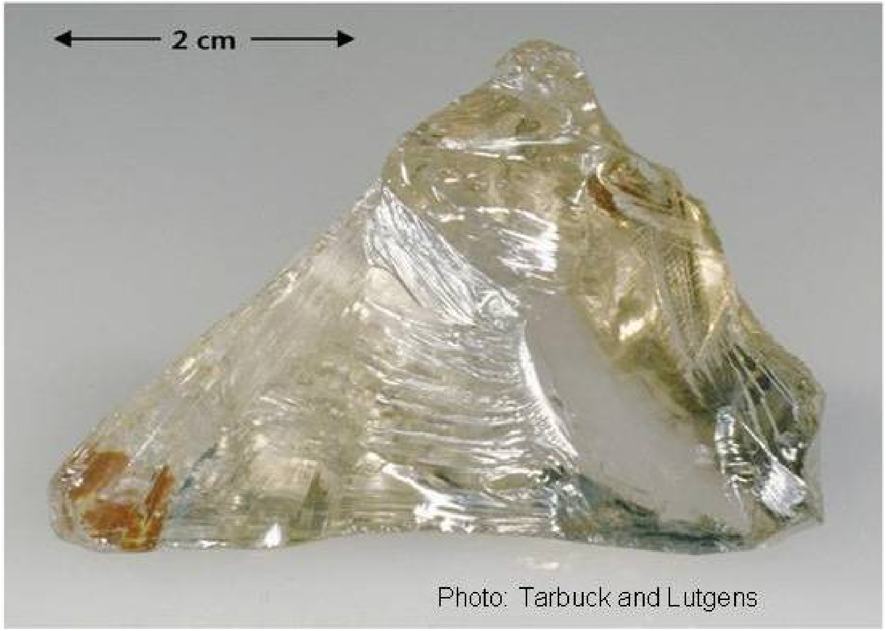
Galena - cubic

Amphibole - prismatic

Fracture

- **Conchoidal**: fracture of brittle materials that does not follow a plane of weakness; fracture that results in a smooth rounded surface resembling the shape of a scallop shell.

Quartz has no planar weakness



Other: Density

- Specific gravity: weight of mineral relative to weight of equal volume of water

Silicates: 2.5 - 3.3

Gold: 15!

Other: Magnetism

- Degree to which a material is attracted by a magnet

Magnetite
(Fe_3O_4)

Pyrrhotite
(FeS)

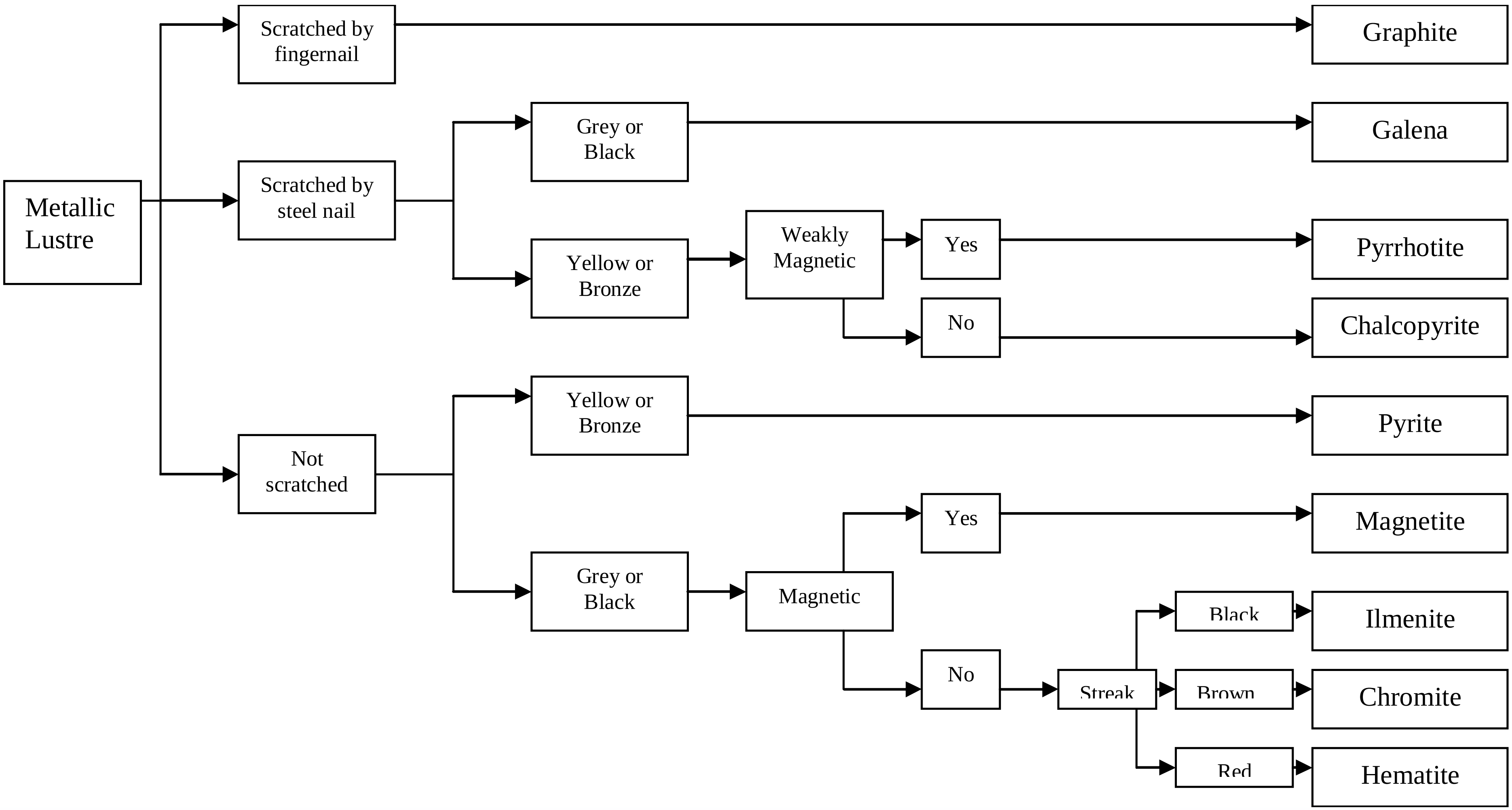
Other properties

- Taste (halite)
- Soapy / Greasy feel (talc, graphite)
- Reaction with acid (calcite)
- Perthitic texture - exsolution of streaks of one mineral inside another (K-Na feldspar; orthopyroxene)

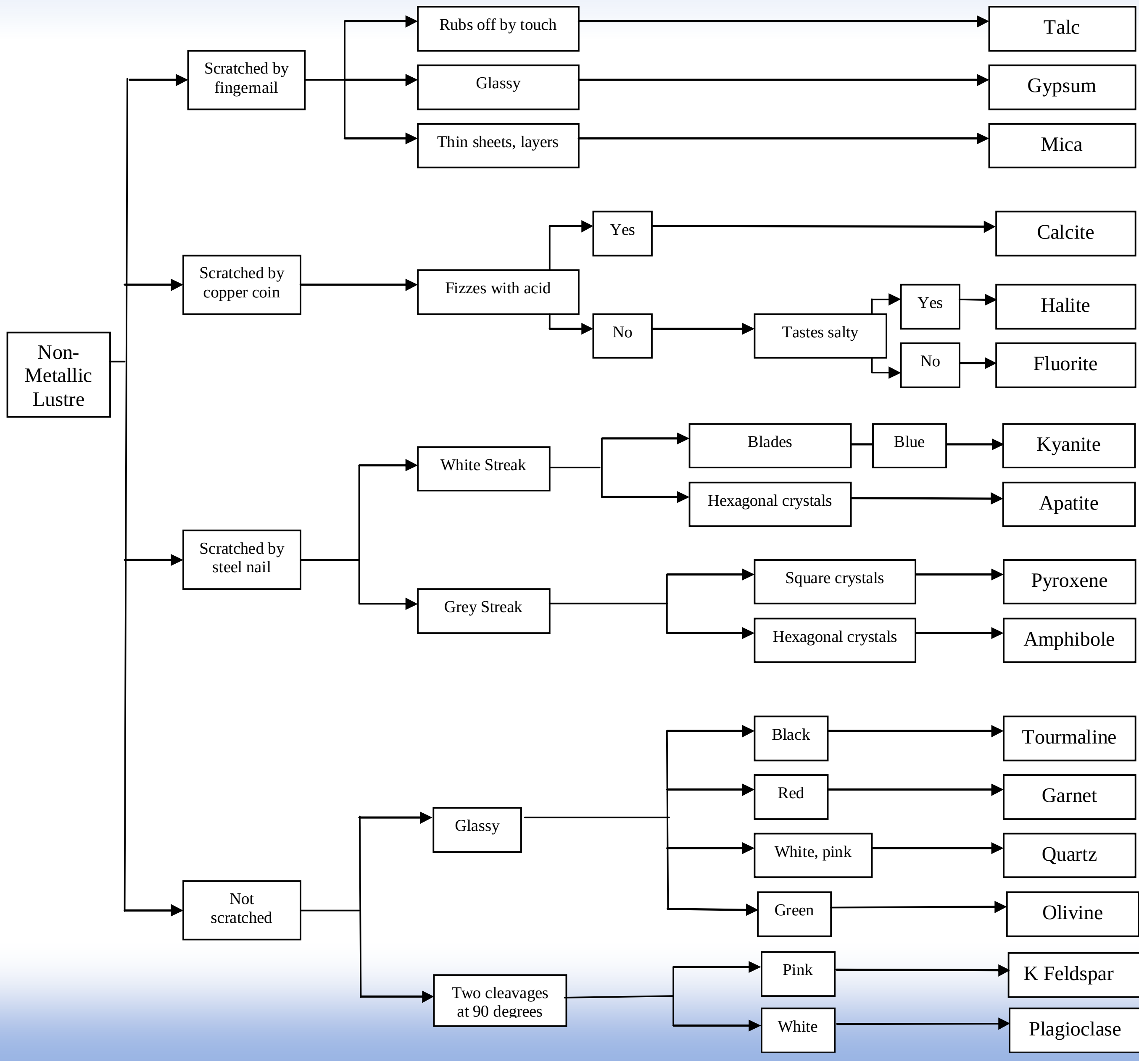
Other properties

- Perthitic texture in K-feldspar
  - Contrasting between pink and white

Identifying Minerals



Identifying Minerals



Identifying Minerals

Step 1: Metallic or non-metallic lustre?

Step 2: Verify the hardness

- Does the mineral scratch your fingernail?
- Copper coin?
- Metal Nail?
- Ceramic plate?

Step 3a: Verify streak, powder form of mineral

Step 3b: Examine the cleavage

Step 3c: Test for other unique properties

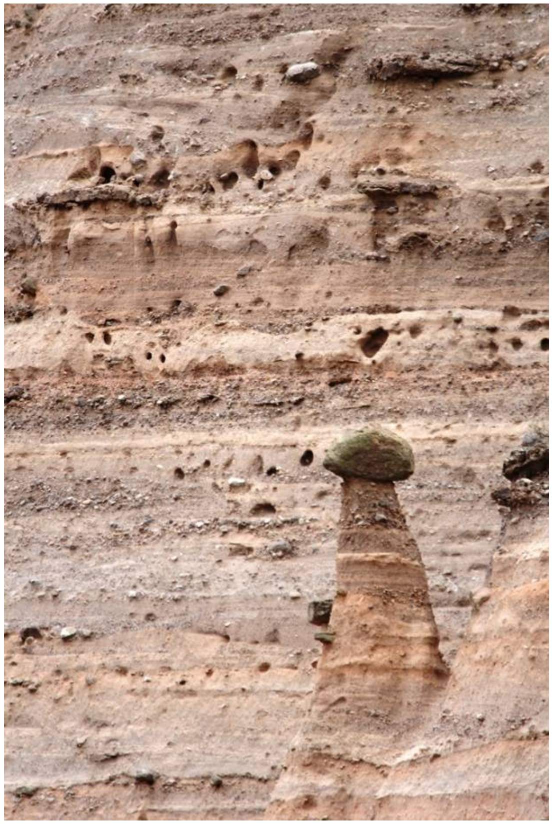
Carletonite

- [K,$Na_4Ca_4Si_8(CO_3)_4$(OH,F) · H_2O]
- Silicate mineral
- Named after Carleton University where it was first recognized by Prof. V. Chao
- Found in only one locality: Mont St-Hilaire, Québec

Several crystals of Carletonite. 2.8 x 2.7 cm. Photo by John Veevaert

Lecture: Igneous Rocks

Maurice Lamontagne



Kasha-Katuwe National Monument,
New Mexico (Photo: M. Lamontagne)

Yosemite NP (Photo: M. Lamontagne)

Bandelier National Monument, NM
(Photo: M. Lamontagne)

Reading Material

- Please read Kehew's book to complement the material presented in this lecture:

  Chapter. 4: Igneous Rocks and Processes

- Also, the lab manual on Igneous rocks

Review of Minerals

- What is a mineral?

  - Naturally occurring, inorganic, atomic arrangement, specific chemical composition

- Rocks are composed of one or more mineral

- Properties used to diagnose minerals
  - Luster, color, streak, crystal habit, hardness, cleavage, fracture, others

Lecture objectives & contents

- The relationship between igneous rocks and other rock types
- Properties and classification of igneous rocks
  - Mineral composition
- Intrusive and Extrusive processes
- Engineering considerations

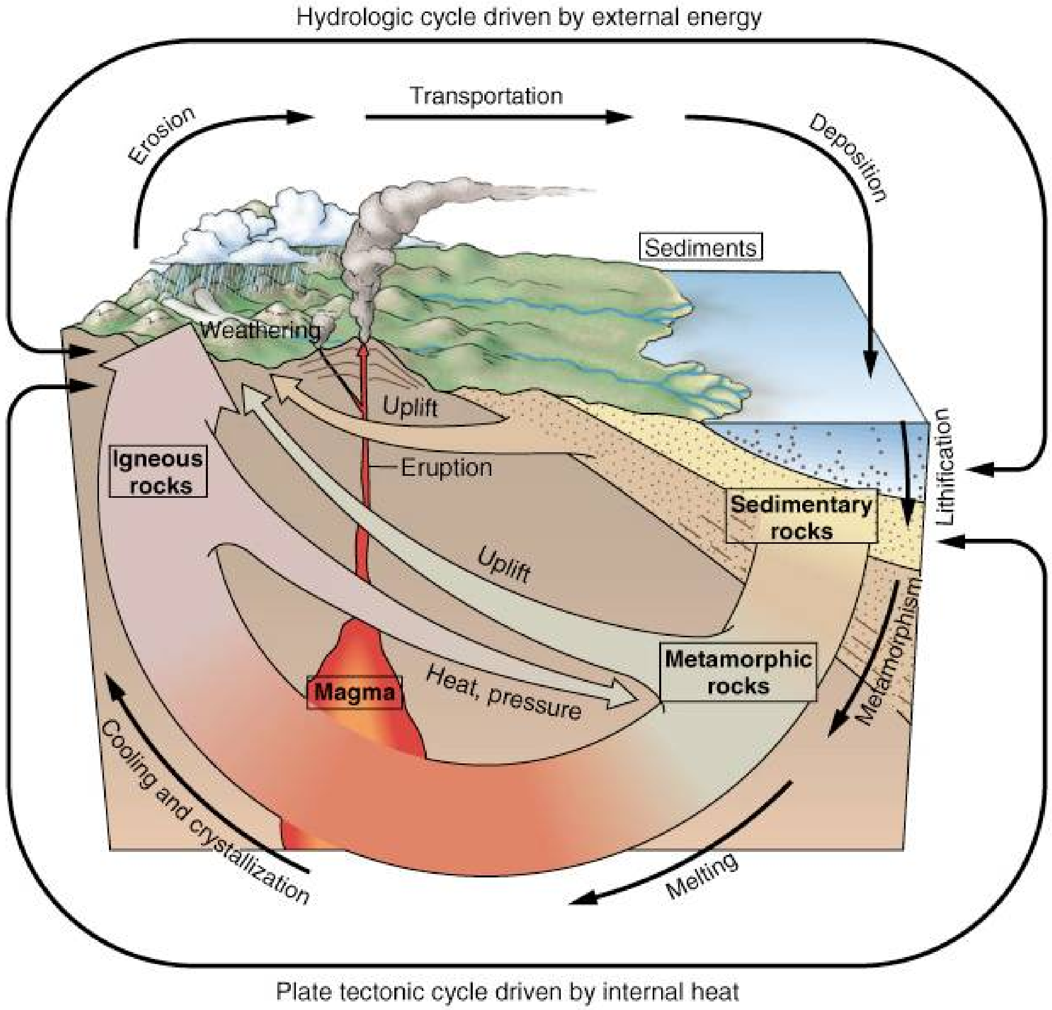
Introduction to Rocks

- Three rock types:
    - Igneous
    - Sedimentary
    - Metamorphic

- Igneous + metamorphic = 95% of rocks of the Earth's crust

The Rock cycle

- Theoretical concept predating plate tectonics
- Rock types:
  - Igneous,
  - sedimentary
  - metamorphic



Rock types

- **Igneous rocks** form by cooling and solidification from a liquid called magma
- **Sedimentary rocks** form by the erosion and deposition of rock fragments (ex: sandstone) or by precipitation (ex: salt)
- **Metamorphic rocks** form by the modification of the mineralogy of existing rocks by heat, pressure or fluids

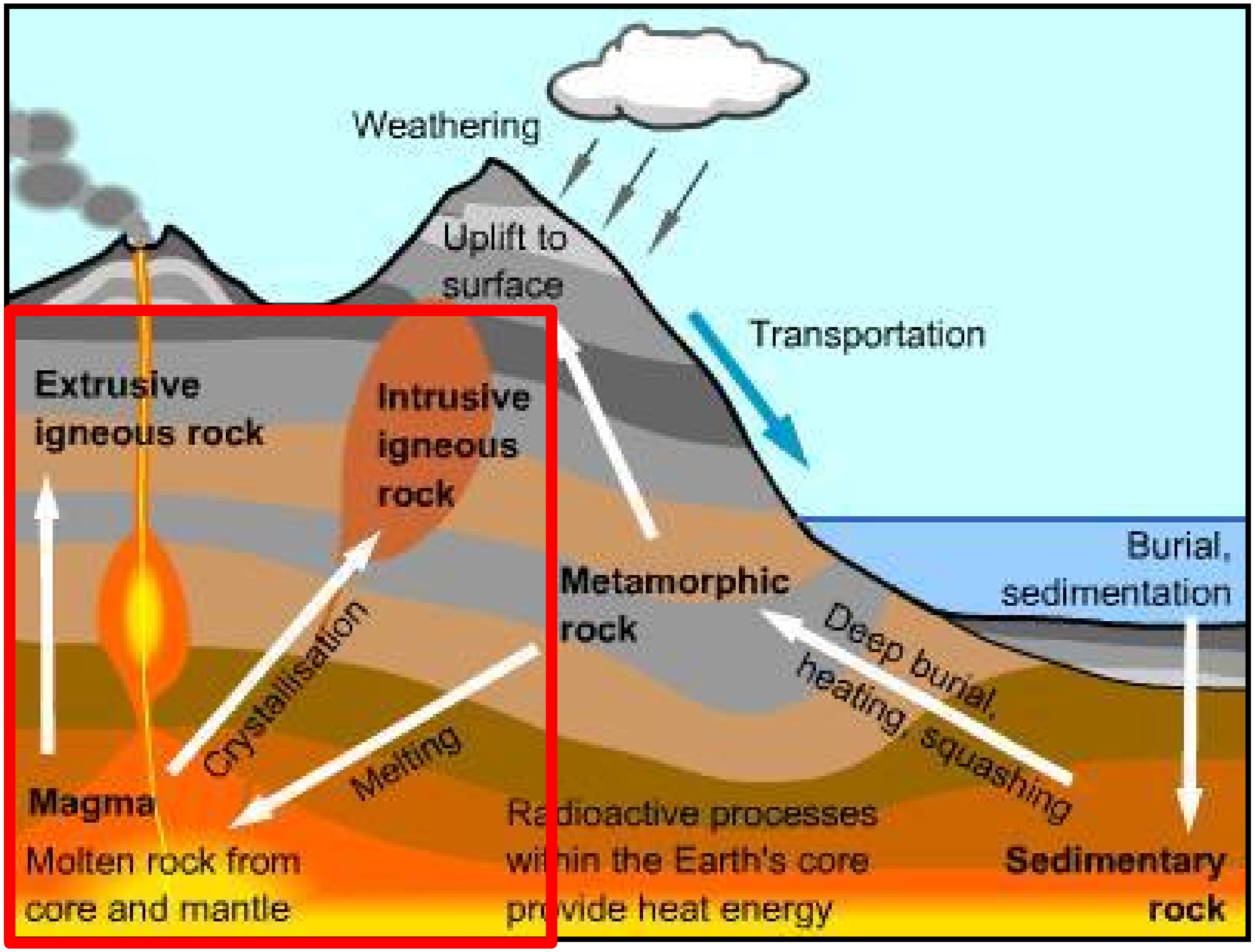
Igneous Rocks

- **Crystallization**: the process of mineral formation in a cooling magma

- Types:
  - **Extrusive**: volcanic (cooling at surface)
    - small grains

  - **Intrusive**: plutonic (cooling at depth)
    - larger grains, minerals have time to crystallize

Rock cycle: Igneous Rocks



Source: British Broadcasting Corporation (BBC)

- Igneous rocks are formed from melting of any type of pre-existing rocks

Igneous Rocks

- Volcanic materials:
  - **Magma** (“ointment” in Greek): partially molten rock below the Earth’s surface
  - **Lava** (“to wash” in Latin): magma that reaches the surface
- Three main components
  - **Melt**: liquid portion
  - **Pyroclastic (Solids)**: ash, cinders, bombs, minerals crystallized from the melt
  - **Gases (Volatiles)**: H_2O, CO_2, SO_2

Igneous Rock Classification

- All properties are closely related to the cooling environment and magma behavior

  1. Intrusive or Extrusive?

- **Texture**: size, shape, and arrangement of mineral grains

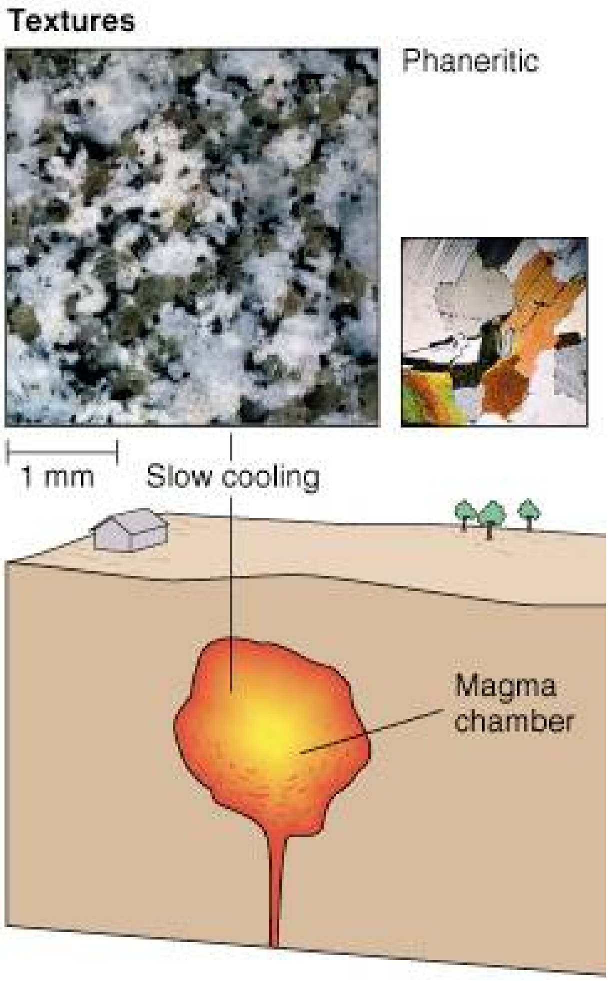
Extrusive vs Intrusive

- Cooling rate controls grain size
- **Intrusive (plutonic)**
  - Cooling slowly at depth leads to uniformly large grain size
- **Extrusive (volcanic)**
  - Cooling quickly at surface, leads to small grain size
  - Can have two phases of cooling, one at depth and remainder at surface: big and small crystals

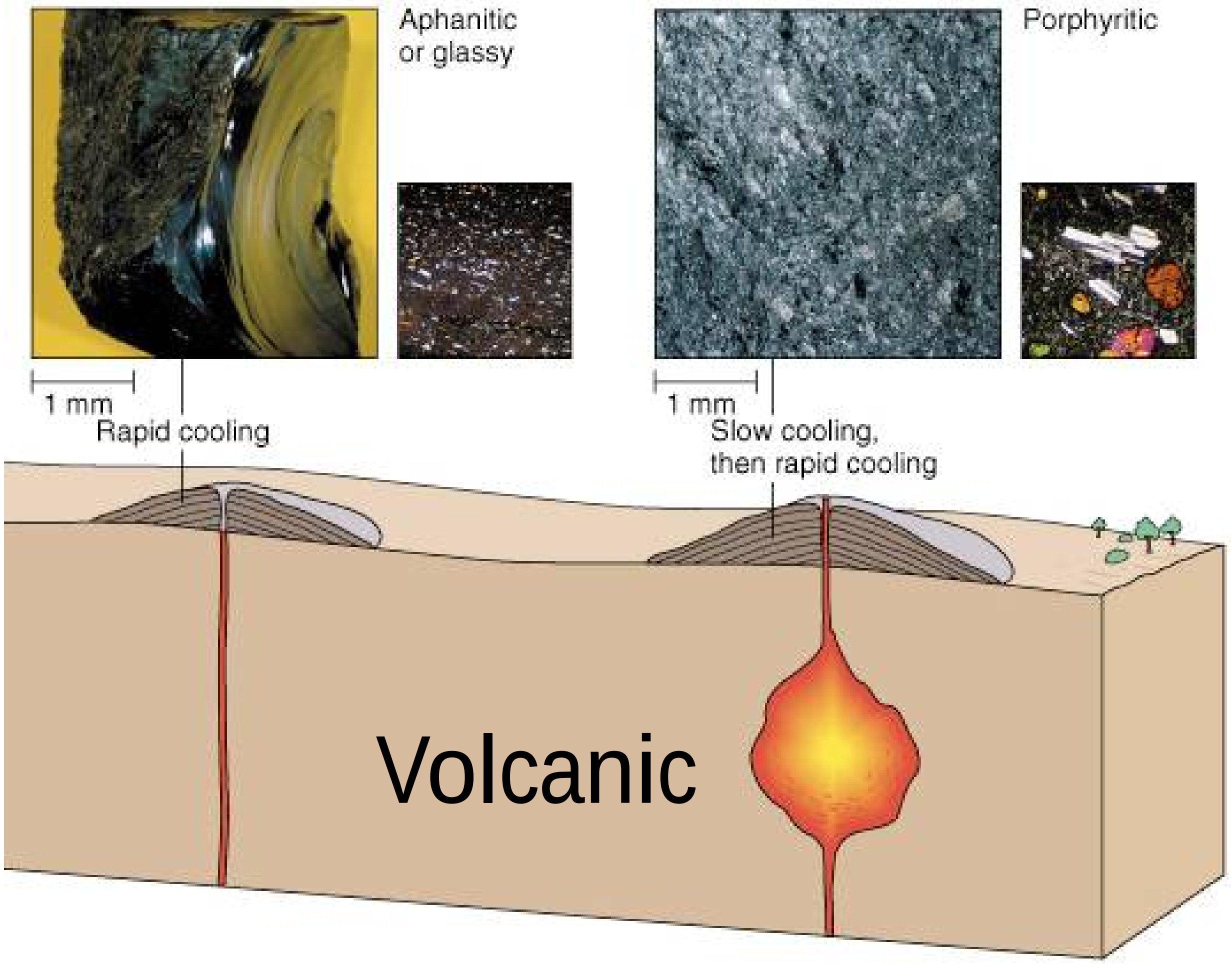
Intrusive (plutonic)

Plutonic

Porphyritic granite
www.turnstone.ca/shap.htm



Extrusive (volcanic)



Igneous rock identification

1. Intrusive or Extrusive?

2. Mineral composition

Minerals and Chemistry

- Key characteristic: % of silica (SiO_2)
- **Felsic** rocks: rich in silica
  ($SiO_2 \geq 66\%$)
  (Feldspar + silica)
- Intermediate rocks: $52\% \geq SiO_2 \geq 65\%$
- **Mafic** rocks: rich in ferromagnesian
  minerals ($45\% \geq SiO_2 \geq 51\%$)
  (Magnesium + ferric)
- Ultramafic rocks: $45\% < SiO_2$

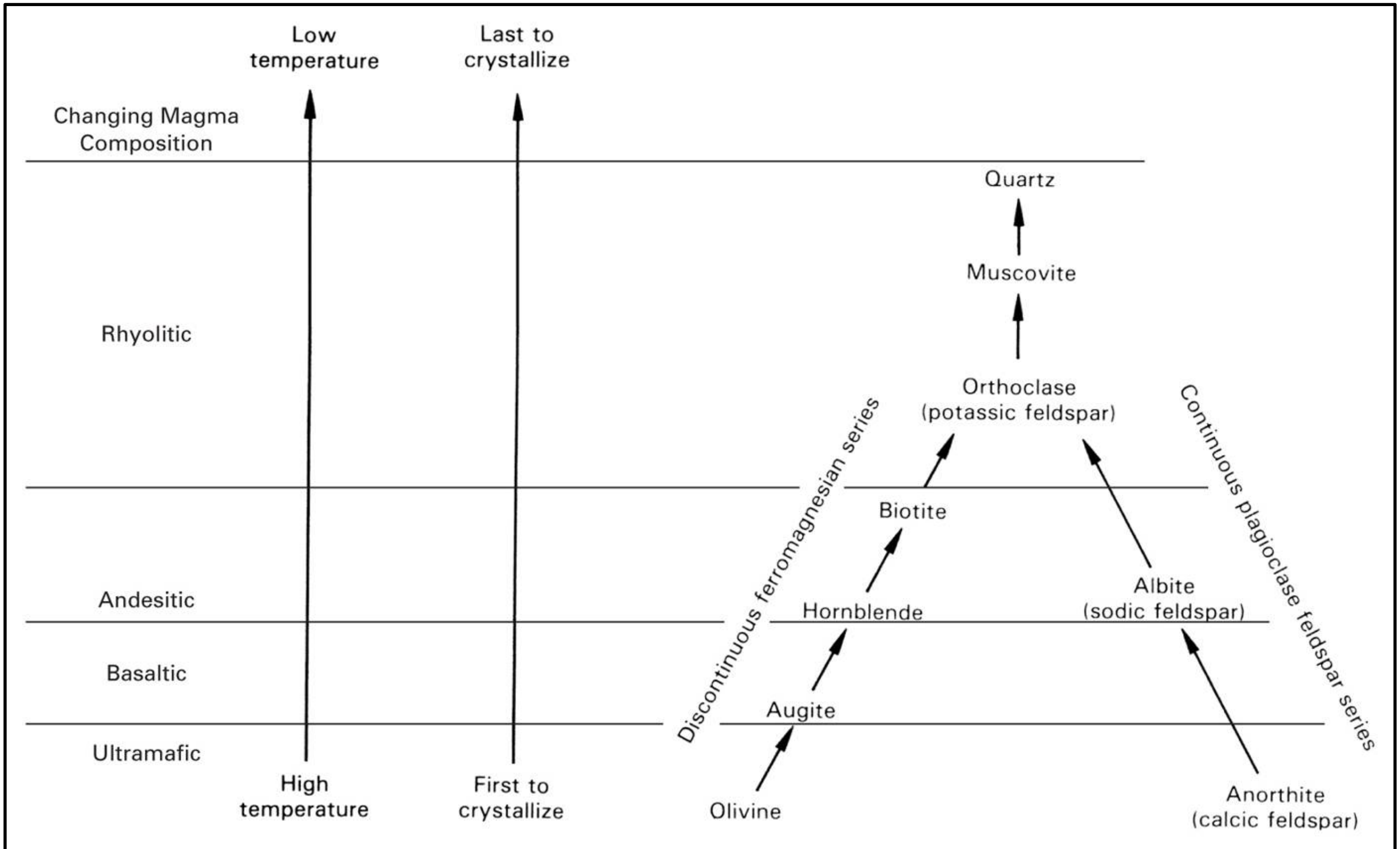
Pale

Dark

Minerals and Chemistry

Minerals	SiO_2	Igneous Rock Type
Olivine, pyroxene	< 45%	Ultramafic
Olivine, pyroxene, Ca-feldspar	45-57%	Mafic
Na-feldspar, amphibole	57-65%	Intermediate
Biotite, K-feldspar, quartz	> 65%	Felsic

Bowen’s Reaction Series



Crystallization temperature

- High Temperature: olivine, pyroxene, Ca-feldspar
- Intermediate Temperature: amphibole, Na-feldspar, + biotite
- Low Temperature: Biotite, Na-K feldspar, quartz

- Previous mineral may dissolve as new ones form
- Branch depends on presence of element
    - Felsic or Mafic minerals

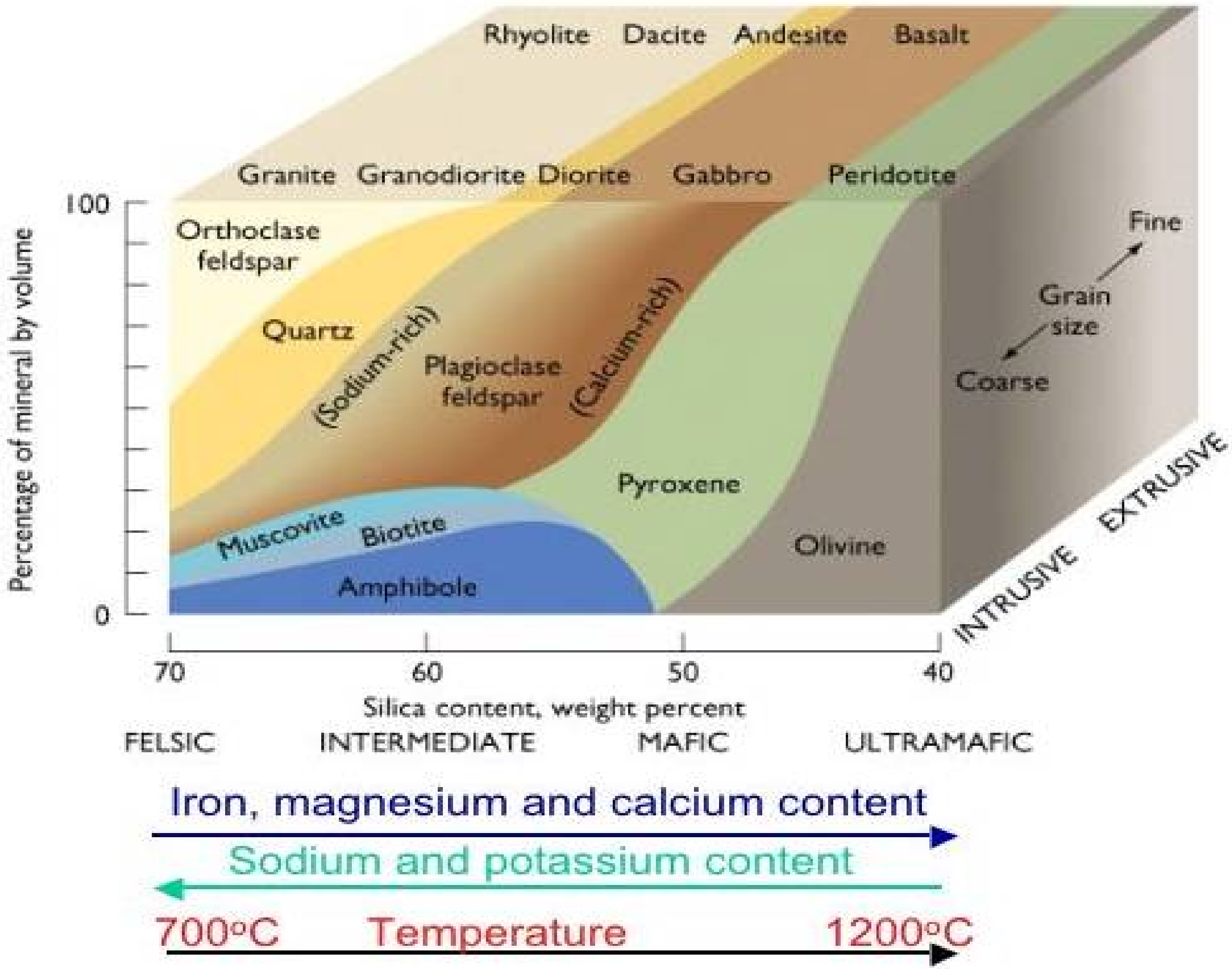
Minerals and Chemistry

- **% SiO_2 controls magna viscosity and therefore magma behavior and eruptive style**

- High % SiO_2:
  - Viscous magma
  - Low-temperature (600-900^{o}C)
  - Tend to produce large plutonic bodies or explosive eruptions

- Low % SiO_2:
  - Fluid magma
  - High-temperature (1000-1250^{o}C)
  - Large, peaceful outpouring at the Earth's surface

Classification



Classification

	Igneous rock type	Comp / Texture
Fast	Extrusive	Glassy
Cooling		Aphanitic
Slow	Intrusive	Phaneritic

Classification

High $\% SiO_2$ → Low $\% SiO_2$

Cooling	Igneous rock type	Comp / Texture	Felsic	Intermediate	Mafic
Fast	Extrusive	Glassy			
	Extrusive	Aphanitic			
Slow	Intrusive	Phaneritic			

Pale → Dark

Classification

High % SiO_2 → Low % SiO_2

	Igneous rock type	Comp / Texture	Felsic	Intermediate	Mafic
Fast	Extrusive	Glassy	Obsidian		
Cooling	Extrusive	Aphanitic	Rhyolite	Andesite	Basalt
Slow	Intrusive	Phaneritic	Granite	Diorite	Gabbro

Pale → **Dark**

Cooling based textures

Cooling environment	Cooling rate
Extrusive	Very fast
	Fast
Intrusive	Slow

Cooling based textures

Cooling environment	Cooling rate	Texture		Grain diameter [mm]
Extrusive	Very fast	Non-crystalline	No grains formed	–
	Fast	Crystalline	Fine-grained	< 1
			Medium-grained	1 – 5
Intrusive	Slow		Coarse-grained	> 5

Cooling based textures

- **Phaneritic** texture (intrusive):
  - Coarse, uniform grains
  - Slow cooling in the subsurface
  - Easily seen with eye

- **Aphanitic** texture (extrusive):
  - fine grained
  - Fast cooling at the surface
  - you may need a hand lens to see the crystals

Extrusive vs Intrusive Rocks

Extrusive
Cools quickly: Aphanitic
Rhyolite

Intrusive
Cools slowly: Phaneritic
Granite

Extrusive vs Intrusive Rocks

What is this type of fracture?

Cools very quickly: glassy, no crystalline structure

Volatile-based textures

Cooling environment	Cooling rate	Texture	Volatiles escaping?
Extrusive	Very fast	Non-crystalline	YES
			No
	Fast	Crystalline	YES
			No
Intrusive	Slow		No

Volatile-based textures

<table>
<tr><th>Cooling environment</th><th>Cooling rate</th><th>Texture</th><th>Volatiles escaping?</th><th colspan="2">Igneous texture</th></tr>
<tr><td rowspan="5">Extrusive</td><td rowspan="2">Very fast</td><td rowspan="2">Non-crystalline</td><td>YES</td><td colspan="2">Pumiceous</td></tr>
<tr><td>No</td><td colspan="2">Glassy</td></tr>
<tr><td rowspan="3">Fast</td><td rowspan="5">Crystalline</td><td>YES</td><td colspan="2">Vesicular</td></tr>
<tr><td rowspan="2">No</td><td colspan="2">Aphanitic</td></tr>
<tr><td rowspan="2">two-stage cooling</td><td rowspan="2">Porphyritic</td></tr>
<tr><td rowspan="2">Intrusive</td><td rowspan="2">Slow</td><td rowspan="2">No</td></tr>
<tr><td colspan="2">Phaneritic</td></tr>
</table>

Volatile based textures

- Pumice
  - Highly vesicular
  - Frothy appearance
  - Simultaneous cooling and depressurization freezes the bubbles
  - Considered a glass!

Commonality?

Rhyolite

Granite

Obsidian

Pumice

Classification

High $\% SiO_2$ → Low $\% SiO_2$

	Igneous rock type	Comp / Texture	Felsic	Intermediate	Mafic
Fast	Extrusive	Glassy	Obsidian		
Cooling		Aphanitic	Rhyolite	Andesite	Basalt
Slow	Intrusive	Phaneritic	Granite	Diorite	Gabbro

Pale → **Dark**

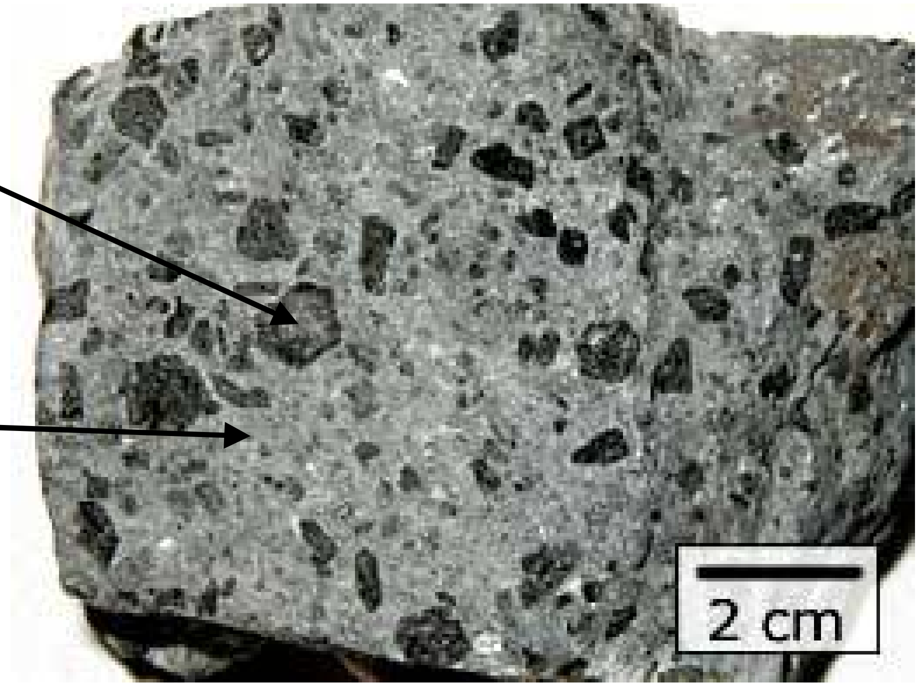
Volatile-based textures

- Magma poor in volatiles
  - **Porphyritic** texture: grains of two sizes indicate a two-stage cooling process
    - **Phenocrysts**: large grains/crystals formed first and had time to grow in magma chamber before magma reached the surface
    - **Matrix**: finer grains than phenocrysts second in contact with the atmosphere

Volatile based textures

Phenocryst: crystal

Matrix: fine grained, surrounding phenocrysts



Matthew Nyman, TERC

Porphyritic texture

Volatile based textures

- Magma rich in volatiles
  - **Vesicles**: small holes on top of lava flows through which gases escape
  - **Amygdule**: infilling of vesicle with secondary mineral (ex: quartz, calcite)

Intrusive & Extrusive processes

We now examine the intrusive processes
that create plutonic rocks

Pluto: The Greek God of the underworld

Intrusive processes

- **Intrusion**: movement of magma from a magma chamber to a different subsurface location
- **Plutons**: bodies of rocks formed by the intrusion of magma into older rocks, named **country rocks**
  - Vast majority of magmas solidify at depth: 87%
  - Represent magmas that did not reach surface to cause an eruption; now exposed due to erosion

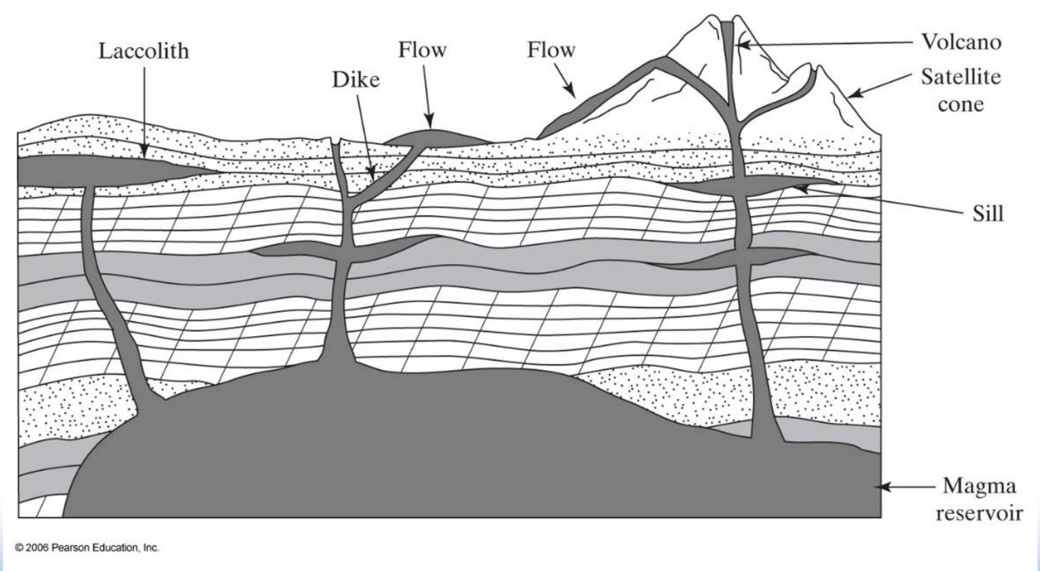
Types of plutons

- Plutons are classified according to:
  - Size and shape
  - Relation with country rocks
    - **Concordant**: parallel to country rock layering
    - **Discordant**: cutting across country rock layering

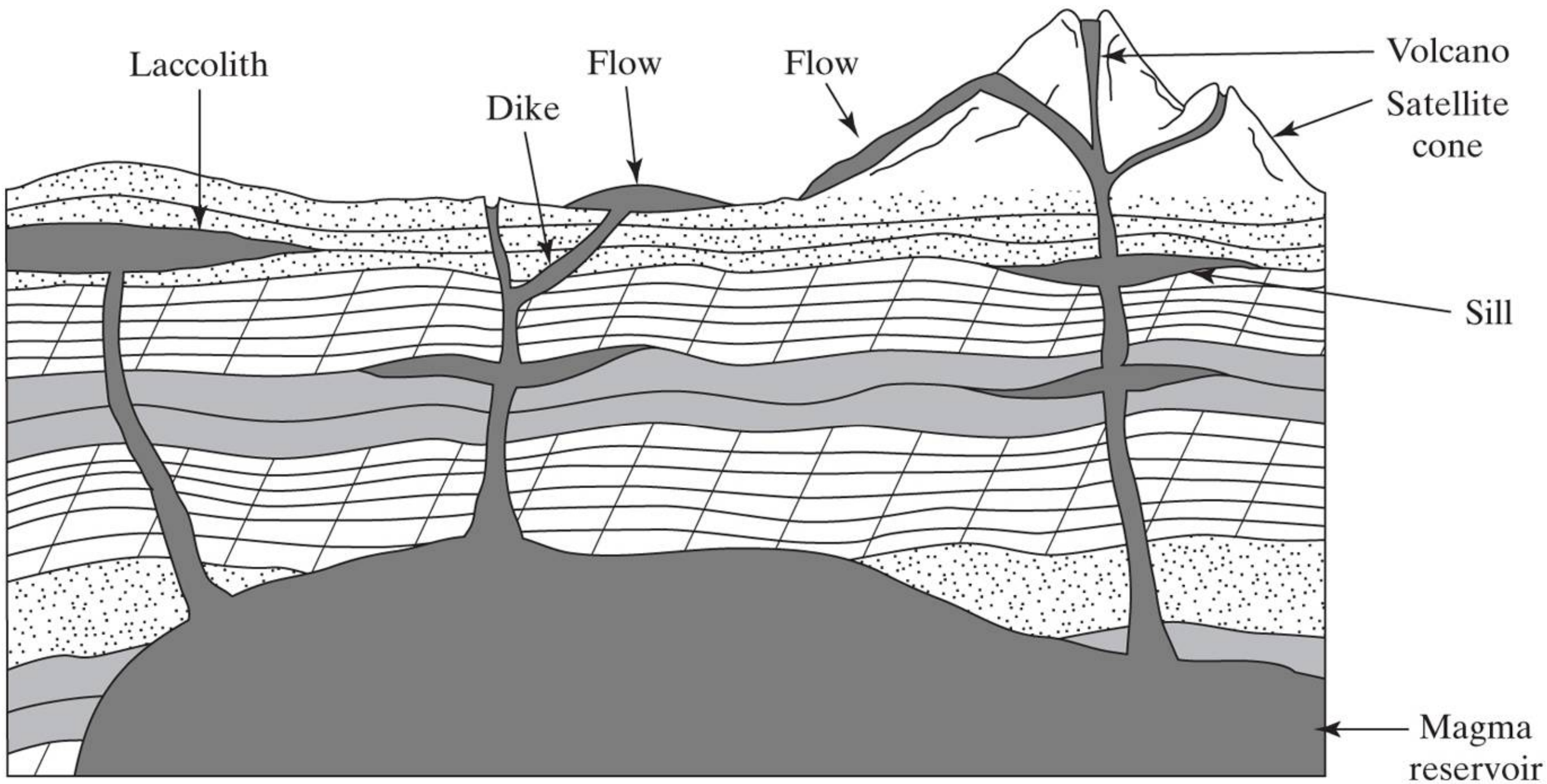
- **Pluton**: large, massive intrusion
- **Sill, Dyke**: thin, tabular intrusions
- **Batholith**: assemblage of plutons

Pluton classification

<table>
<tr><th colspan="2" rowspan="2">Shape</th><th colspan="3">Relation with country rock</th></tr>
<tr><th>Concordant</th><th colspan="2">Discordant</th></tr>
<tr><td rowspan="2">Non-tabular</td><td rowspan="2">Thick and broad</td><td rowspan="2">Laccolith</td><td>< 100 km^2</td><td>Stock</td></tr>
<tr><td>> 100 km^2</td><td>Batholith</td></tr>
<tr><td>Tabular</td><td>Thin in one dimension</td><td>Sill</td><td colspan="2">Dyke</td></tr>
</table>



Intrusions



Laccolith
Dike
Flow
Flow
Volcano
Satellite cone
Sill
Magma reservoir

Batholiths

- Non-tabular discordant pluton
- Majority have a composition of granodiorite to granite
- Represent uplifted, eroded roots of subduction-related volcanic complexes

Batholiths

Yosemite NP, Half Dome

Photo: Lamontagne

- Granite
- http://on.natgeo.com/Sh7ICg

Extrusive Processes

- **Volcanism**: process by which magma rises into the crust and is extruded onto the Earth's surface and into the atmosphere

- Extruded volcanic material:
  - Lava
  - **Pyroclastic** material (**tephra**): material formed by volcanic explosion or aerial expulsion from a volcanic vent
  - Volatiles: mainly H_2O, CO_2, SO_2

Lava

- Lava viscosity
  - Increases with volatile content
  - Increases with % SiO_2

Low SiO_2	→	High SiO_2
Basaltic lava		**Felsic**
Fluid		Viscous
Flows quickly over large distances		Flows slowly
Ex. Pahoehoe		Example. Aa

Lava

- **Felsic** lava (Si, Al, K, Na)
  - Flows slowly
  - Lava flows with jagged upper surface: **aa**

- **Basaltic** lava (Mg, Fe)
  - Flows quickly over large distances
  - Lava flows with smooth upper surface
  - **Pahoehoe**: flow wrinkles

Lava




USGS

aa flow

pahoehoe

External links: Hawaii lava flows

- Hawaii is well know for aa and pahoehoe lava flows
-
    - USGS Hawaii: http://hvo.wr.usgs.gov/

Columnar jointing

- **Columnar jointing**: vertical polygonal structure formed during cooling

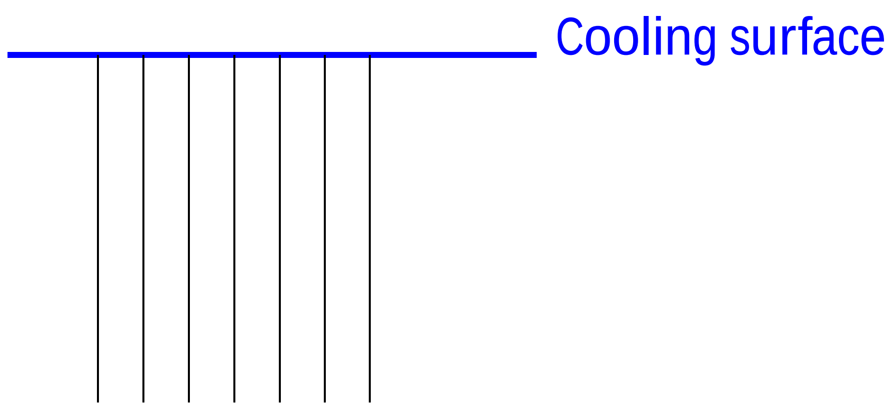
- Cracks formed during cooling of igneous rocks
  - Rocks cool from the outside in, causing shrinkage
  - Present in intrusive and extrusive rocks
    - Common in basaltic lava flows

- Side view: columns
  - Fissures grow at 90° to the cooling surface
- Top view: hexagons
  - Fissures develop preferentially in 3 directions at 120° to each other

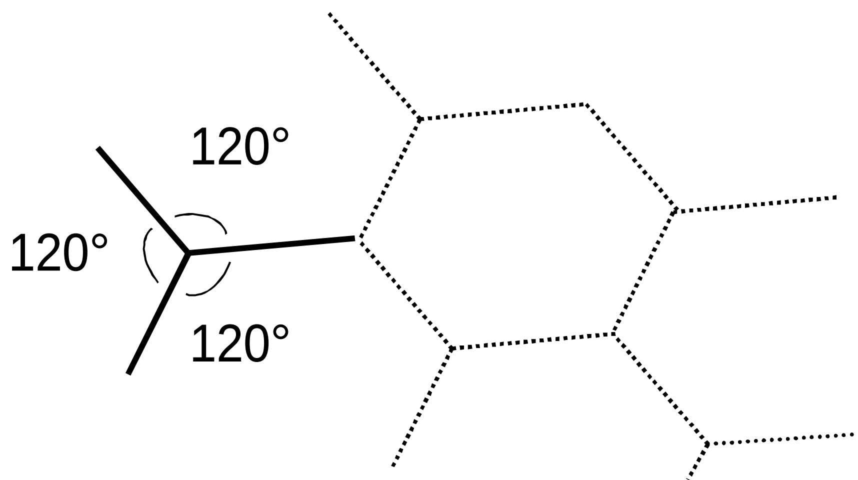
Columnar jointing:

vertical polygonal structure formed during cooling during cooling of magma or lava

<u>Side view:</u>
columns
Fissures grow at 90° to the cooling surface



<u>Top view:</u>
hexagons
Fissures develop preferentially in 3 directions at 120° to each other



- Rocks cool from the outside in, causing shrinkage
- Present in shallow intrusive and extrusive rocks
- Common in basaltic lava flows

Columnar jointing

Giant Causeway, Northern Ireland

Photographs: P. Fernberg

Tephra:

Solid matter, such as ash, dust, and cinders, that is ejected into the air by an erupting volcano

- Tephra classified according to particle size:

Particle diameter [mm]	Unconsolidated material
	Tephra
< 2	**Ash**
2 – 64	**Lapilli**
> 64	**Blocks / Bombs**

- **Blocks**: ejected as solid fragments with angular shapes
- **Bombs**: ejected as incandescent lava fragments which were semi-molten when airborne

Pyroclastic rocks

Pyro: fire Clastic: fragments

Particle diameter [mm]	Unconsolidated material	Consolidated material
	Tephra	Pyroclastic rock
< 2	**Ash**	Ash **tuff**
2 – 64	**Lapilli**	Lapilli tuff
> 64	**Blocks / Bombs**	Volcanic breccia

- Pyroclastic rocks are transitional between igneous and sedimentary rocks
  - "Igneous on the way up.... sedimentary on the way down!“
- **Tuff**: pyroclastic rock formed from volcanic ash and lapilli

Pyroclastic rocks

- Processes converting tephra into pyroclastic rocks:
  - When tephra is very hot, particles fuse together and form a glassy rock
  - Further cementing can occur from agents transported by groundwater
- Lava bombs
  - https://youtu.be/dJ7cXhkrSzc

Engineering implications

- For intrusive igneous rocks
- Uniformity and great strength
  - Dense interlocking network of crystals
- Applications: (when unfractured)
  - Provide adequate foundation support for large structures
  - Water reservoirs
    - Low permeability
  - Kitchen countertops

Engineering implications

- For extrusive igneous rocks
  - Variability
    - Vesicular: can be highly permeable
    - Interlayering of lava flows and pyroclastic material
- Used extensively as engineering material
  - Concrete, rock fill, railroad ballast, highway base

Engineering implications

- Fracturing
  - Columnar jointing can allow significant movement of ground water
- Weathering
  - Ferromagnesian minerals present in mafic igneous rocks may decay if exposed to air and water

Next: Sedimentary Rocks