

## INTRODUCTION TO PHYSICAL GEOLOGY AND PLATE TECTONICS

**Why?** Geology (study of Earth) is important for energy and natural resources, solving environmental problems, building cities and highways, predicting and protecting against natural disasters like earthquakes, volcanic eruptions, landslides, floods

**Uniformitarianism:** fundamental principle “the present is the key to the past”

**How long?** geologic time is measured in billions of years

**Where and How?** After the Big Bang (~15 billion years ago) Earth may have formed by the **nebular hypothesis**: ~5 billion years ago a solar nebula of hydrogen and helium gravitationally contracted into a rotating disc with our Sun at the centre, and the planets and moons revolving around it

- within the disc, Earth evolved through many collisions of rocky and metallic fragments into a rocky sphere divided into a dense **core**, large **mantle**, and lighter **crust**

**Plate Tectonics:** the crust and uppermost mantle eventually split into rigid plates of **lithosphere** (sphere of rock) that move over Earth’s surface above the soft, convecting **asthenosphere** (weak sphere) by *Continental Drift*, based on...

*fit of the continents* - e.g. South America, Africa and other continents fit well together at 900 m depth which coincides with the edge of their continental shelves

*fossil evidence* - same type and age found on continents separated by ocean basins

*rock types and structural similarities* - match when continents are fit back together

*paleo climates* - evidence of ancient glaciations in warm areas of today - show the pattern of a single ice sheet if continents are refitted back together; also, ancient *coal fields* that formed in tropical swamps now occur in areas of cold climate

- Most geologic activity (e.g. earthquakes, volcanoes) occurs at *plate boundaries*; especially at *convergent* boundaries where denser oceanic lithosphere descends beneath lighter continental lithosphere; at depth it melts to produce magma which rises to the surface and erupts as volcanoes which in turn are eventually eroded and the sediment carried by streams to the ocean again

**Earth System and Rock Cycle:** Earth is a dynamic planet (system) of interacting hydrosphere, atmosphere, biosphere, and geosphere (solid earth)

- Matter (molecules) is recycled with changing conditions of depth (pressure), temperature, and rock type within Earth’s crust (e.g. convergent boundaries)
- The rock cycle and plate tectonics together produce many different types of rocks that are made up of different minerals

## MINERALS

Minerology- the study of minerals

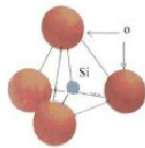
**Minerals** are solid chemical compounds that combine to form rocks. They are found in nature and vary in atomic bonding, molecular structure, and element composition, all of which determine their chemical, physical properties and permit their identification. (property examples: hardness, cleavage- the splitting of rocks or crystals in a preferred plane or direction)

an infinite number of chemical combinations are possible and almost 4000 natural minerals are known; however, only about 20 minerals dominate the Earth's crust

**Common Minerals:** natural solid compounds found commonly in Earth's crust

*Silicates* -

- Most abundant
- Made of the *silicon-oxygen tetrahedron* (silica,  $(\text{SiO}_4)^{-4}$ ) bonded to various metallic cations



► Ferromagnesian (dark) silicates: contain  $\text{Fe}^{+2}$  and  $\text{Mg}^{+2}$  cations

**olivine** - covalently-bonded single tetrahedra bonded to Fe, Mg cations; Fe, Mg *substitute* for each other to form a *group* of minerals;

**pyroxene** - *single chains* of tetrahedra ionically bonded to metallic cations, nearly  $90^\circ$  cleavage

**amphibole** - *double chains* of tetrahedra ionically bonded to metallic cations,  $120^\circ$  cleavage;

**biotite** - tetrahedral *sheets* ionically sandwich  $\text{K}^+$ , perfect platy cleavage

► Nonferromagnesian (light) silicates:

**muscovite** – tetrahedral sheets with perfect platy cleavage;

**feldspar** - strongly bonded 3-D network of silica tetrahedra, K variety is called *orthoclase* and Ca-Na group is called *plagioclase*;

**quartz** - made entirely of silica tetrahedra ( $\text{SiO}_2$ ) covalently bonded, hard, has no cleavage

► NonSilicate Minerals:

*Carbonates* - metals bonded to  $(\text{CO}_3)^{2-}$  group to form minerals like **calcite** ( $\text{CaCO}_3$ ; used for lime, cement) and **dolomite** ( $\text{CaMg}(\text{CO}_3)_2$ )

Minerals formed by evaporation: (evaporation of ancient shallow seas and salt ponds)

**halite** ( $\text{NaCl}$ ; table salt)

**gypsum** ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ; used to make plaster and drywall) are formed by evaporation of ancient shallow seas and salt ponds

*Ores of metals* include

- **hematite** ( $\text{Fe}_2\text{O}_3$ ; iron ore),
- **sphalerite** ( $\text{ZnS}$ , zinc ore),
- **galena** ( $\text{PbS}$ ; lead ore),

- native **gold** and **silver** that are important to our economy

**Conclusion:**

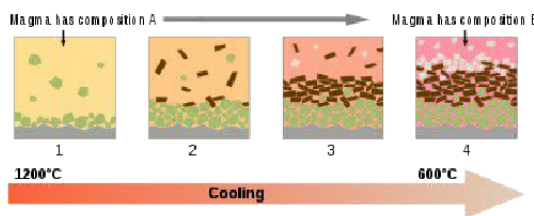
- many minerals tend to occur together because they were formed under similar pressure and temperature conditions, but with different combinations of elements
- minerals can be transformed into new minerals by being transported to another part of the rock cycle - the new minerals form from previous ones as pressure and temperature conditions change in the new environment

**IGNEOUS ROCKS**

**Igneous rocks** crystallize from molten silicate material called *magma* that forms at high temperatures and pressures deep in the Earth. Magma rises through the crust and either reaches the surface by volcanoes (called pyroclastic), making lava flow down the volcano which makes extrusive igneous rocks, or cools below surface (called plutonic), making intrusive igneous rocks

Igneous rock forms when magma cools and makes crystals. Magma is a hot liquid made of melted minerals. The minerals can form crystals when they cool. Igneous rock can form underground, where the magma cools slowly. Or, igneous rock can form above ground, where the magma cools quickly.

**How Magmas Evolve** - Bowen discovered which crystals settle in a magma chamber. Earlier dark crystals form first and remove heavy elements, leaving melt to get lighter as it mixes with sodium and other elements (magmatic differentiation- heavy stuff is separated from the lighter stuff)



According to *Bowen's Reaction Series*:

- Discontinuous series- different structures of the minerals (different molecular structures of olivine [single tetrahedra], pyroxene [single chains], amphibole [double chains], biotite [sheets])
  - Order of first to crystallize beginning at the elements with the highest temperature (starting with olivine)
- Continuous series (same plagioclase structure)- starts from calcium-rich to sodium-rich
- Also....Assimilation- host rock melts in magma, magma mixing

Schematic diagrams showing the principles behind fractional crystallisation in a magma. While cooling, the magma evolves in composition because different minerals crystallize from the melt. **1**: olivine crystallizes; **2**: olivine and pyroxene crystallize; **3**: pyroxene and plagioclase crystallize; **4**: plagioclase crystallizes. At the bottom of the magma reservoir, a cumulate rock forms.

- repeated *crystal settling* in a magma chamber results in the melt crystallizing through a series of minerals according to their decreasing melting temperatures - remaining crystals react with the melt that is enriched in lighter elements (*magmatic differentiation*); dark crystals form early, settle, and take heavy elements with them, then light crystals form from the remaining light elements, eventually to quartz; thus granite can ultimately evolve from an original magma having a basaltic composition

- magma composition can also change through *assimilation* (pieces of host rock fall into the magma and melt) and *magma mixing* where one body of magma invades another, producing a composition intermediate between the two

**Rock Composition:** from dark (*mafic*, less silica) to light (*felsic*, more silica) minerals

**Texture:** (size, shape, arrangement of crystals):

- Fine *aphanitic* (fast cooling magma, small crystals) formed by rapid cooling at or near the ground surface
- Coarse *phaneritic* (slow cooling magma, large crystals) formed by slow cooling below the surface;
- *Porphyritic*- larger crystals surrounded by smaller ones
- *Glassy* if lava was quenched so fast that crystals had no time to form (ex. glaciers)
- *Pyroclastic* (fragmental) when magma was ejected violently into the air then fell as particles onto the ground (airborne pieces of magma fell into the ground)

Extrusive Igneous Rocks: Glassy (pumice), Fine-grained

Intrusive Igneous Rocks: Coarse-grained, Porphyritic

**Naming Igneous Rocks** - use rock textures and mineral compositions (dark vs. light)

- *Felsic rocks* (70% silica) **granite** (in cores of mountains) and **rhyolite** (volcanic) are common in mountainous areas; granite is widely used for building stone, monuments, and headstones
- *Intermediate (andesitic)* (60%) **andesite** and **diorite** found near subduction zones
- *Mafic rocks (basaltic, darker)* (50%) **basalt** is the most abundant and common rock, forms oceanic crust and found in volcanic islands; **gabbro** found mainly in lower oceanic crust
- *Ultramafic* (45%) **peridotite** is the main rock in the upper mantle

	Felsic (light color)	Intermediate	Mafic (dark color)	Ultramafic
Coarse	Granite	Diorite	Gabbro	Peridotite
fine	Rhyolite	Andesite	Basalt	
Vesicular	Pumice		Scoria	
Glassy	Obsidian			
Minerals Present				
	QUARTZ K-FELDSPAR NA-PLAG	NA-Ca PLAG AMPHIBOLE	Ca PLAG PYROXENE	PYROXENE OLIVINE

### **Intrusive Igneous Bodies:**

- Most magma crystallizes at depth to form **plutons** with two orientations:
  - Discordant, cut across the host rocks
  - Concordant, parallel to host rocks

*dykes* - discordant bodies, where magma intruded fractures, tabular (broad and flat)

*sills* - concordant bodies, where magma squeezed between layers, tabular (broad and flat)

*laccoliths* - concordant bodies, lense shaped that has been intruded between rock strata causing uplift in the shape of a dome, bulge

*batholith* - discordant, >100 km<sup>2</sup> exposed in cores of mountain belts; original magma chamber, huge, a very large igneous intrusion extending deep in the earth's crust.

## **VOLCANOES**

Volcanic eruptions occur where magma reaches Earth's surface, often from gas buildup (carbon dioxide, methane)

**Materials Extruded:** hot, runny mafic lava tends to flow quietly downhill while cooler, viscous felsic magma tends to erupt violently, with *pyroclastic material*

### • Lava Flow

- Hot, runny *pahoehoe* with a surface resembling coils of rope (ropy)
- Cooler, blocky *aa* (*blocky*)
- *Pillow lavas* form underwater as lava repeatedly breaks through quenched tube ends
  - *Pyroclastic material* ranges from dust and *ash* to streamlined *bombs* and large blocks
  - *Nuée ardentes* (pyroclastic flows/ wet ash flow) of devastating hot glowing clouds of ash and gas
  - *Lahars of pyroclastics* mixed with rain, ice, and snow

**Volcanic Structures:** commonly cone-shaped mountains with a small *crater* at the top or a larger *caldera* (>1 km across) after magma chamber drains, rim and sides cave in

### **Types of volcanoes:**

- Large *shield* (broad dome of successive lava flows)
- Small *cinder cone* (mainly pyroclastic material)
- *Composite cone* (classic cone shape; mixture of flows and pyroclastic material)

**Fissure eruptions and lava plateaus:** *fissure eruptions* in the crust pour lava onto land - builds up thick piles of lava flows (*plateaus*) on continents (e.g. NW USA)

### **Plate Tectonics and Volcanic Activity:**

- Much igneous activity is concentrated at plate boundaries, including *convergent* boundaries where oceanic crust descends beneath the edges of lithospheric plates, producing volcanism above subduction zones

- generates basaltic magma that can differentiate into other types; common around the Pacific “Ring of Fire”
- Other igneous activity occurs at basaltic islands and submarine volcanoes called *seamounts* where basaltic lava flows out from the sea floor
- Some volcanism occurs above *mantle plumes* located under the middle of lithospheric plates, resulting in *intraplate* volcanoes (e.g. Hawaiian Islands)

## Weathering and Soils

### Weathering

After rocks are formed, they are weathered when exposed at the surface; this prepares material for transport by erosional processes in the rock cycle

- 2 main types of weathering include *mechanical* (disintegration) and *chemical* (decomposition) that act together and enhance the effectiveness of each other

**Mechanical:** breaking up rock into smaller pieces, providing more surfaces for chemical attack.

This includes:

- *Frost wedging:* water freezes in rock fractures (cracks) and expands 9%, breaking rock apart
- *Unloading:* rock surface expands after stuff on top is removed, slabs break off
- *Biologic activity:* roots grow in rock fractures and break open the fractures

**Chemical:**

- *Dissolution:* carbon dioxide dissolves in water to make weak carbonic acid that dissolves rock minerals (turns them into substances stable at surface conditions)
- *Oxidation:* dark silicates react with oxygen to form rusty Fe, Mg oxides and clay minerals
- *Hydrolysis:* orthoclase in granite changes to clay by exchanging the K<sup>+</sup> for tiny H<sup>+</sup> ions

**Rates of Weathering:** depend on how fractured rock is, types of minerals, climate

Rock Characteristics:

- *Light silicates* form closer to weathering conditions, [more stable](#)
- Marble is soluble, unstable
- *Dark silicates* form under higher P,T conditions [unstable](#) under weathering conditions
- *Climate:* weathering is faster, more intense in warm, wet climates; slow in polar areas

### Soil

- Results from weathering plus
- *Biologic activity* combined with weathering (produces regolith without biologic input)

Soil type depends on five factors:

- *Parent material:* rock or sediment on which soil forms, fertility
- *Time:* more time, greater intensity and depth of soil development on a parent material
- *Climate:* most important; soil forms slow in cold, dry areas, fast & deep in tropics
- *Plants, animals:* decompose to *humus*, release nutrients, hold soil moisture, aerate