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2 ***Chapter 4 – Igneous Rocks***

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- Igneous rocks form as molten rock (magma) cools and solidifies
- General characteristics of magma:
  - Parent material of igneous rocks
  - Formed by partial melting in the Earth’s crust
  - Magma at surface is called lava
    - Lava may be emitted explosively or nonviolently

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- The Nature of Magma
  - Consists of three components:
    - Liquid portion = melt
    - Solids, if any, are crystals of silicate minerals
    - Volatiles are dissolved gases in the melt that vaporize at surface pressure
      - Most common volatiles in magma:
        - Water vapor (H_2O)
        - Carbon dioxide (CO_2)
        - Sulfur dioxide (SO_2)

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- From Magma to Crystalline Rock
  - Crystallization is the cooling of magma which results in the systematic arrangement of ions into orderly patterns.
  - Silicon and oxygen atoms link together first to form silicon–oxygen tetrahedra.
  - As heat loss continues, the tetrahedra join with each other and other ions to form crystal nuclei.
  - Minerals that form earliest have space to grow and have better developed crystal faces than those that form later.

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- Igneous Processes
  - Magma that crystallizes *at depth* forms plutonic or intrusive igneous rocks
    - These rocks are observed at the surface following periods of uplifting and erosion of overlying rocks.
  - The solidification of lava or volcanic debris forms volcanic or extrusive igneous rocks.

9 **Extrusive Versus Intrusive Igneous Rocks**

10 **Igneous Compositions**

- Igneous rocks are composed mainly of silicate minerals.
  - Dark (or *ferromagnesian*) silicates
    - Rich in iron and/or magnesium
      - Examples include olivine, pyroxene, amphibole, and biotite mica
  - Light (or *nonferromagnesian*) silicates
    - Contain more potassium, sodium, or calcium than iron and magnesium
      - Examples include quartz, muscovite mica, and feldspars

11 **Igneous Compositions**

12 **Igneous Compositions**

- Igneous rocks are divided into two broad groups:
  - Granitic (Felsic) versus Basaltic (Mafic) Compositions
  - Granitic or felsic composition
    - Light-colored silicates
    - Composed almost entirely of quartz and potassium feldspar

    - Termed felsic (*fel*dspar and *si*lica) in composition
    - High silica (SiO_2) content
    - Contain about 10% dark silicate minerals
    - Major constituent of continental crust

13 **Igneous Compositions**

  - Basaltic or mafic composition
    - Contain at least 45% dark silicates and calcium-rich feldspar
    - Contain no quartz!
    - Termed mafic (*ma*gnesium and *fe*rrum, for iron) in composition
    - Higher density than granitic rocks
    - Comprise the ocean floor and many volcanic islands
    - Also forms extensive lava flows on the continents

14 **Igneous Compositions**

15

- Other Compositional Groups
  - Andesitic or intermediate composition
    - Contain 25% or more dark silicate minerals (amphibole, pyroxene, and biotite mica)
    - Associated with volcanic activity on the seaward margins of the continents and volcanic island arcs.
  - Ultramafic composition
    - Rare composition of mostly olivine and pyroxene
    - Composed almost entirely of ferromagnesian minerals
    - Peridotite is an example and the main constituent of the upper mantle.

16 **Igneous Compositions**

- Silica Content as an Indicator of Composition
  - Crustal rocks exhibit a considerable range of silica content (40% in ultramafic to 70% in felsic)
    - The chemical makeup of an igneous rock can be inferred directly from the silica content.
  - Silica content influences magma behavior
    - Granitic magmas have high silica content, are viscous (thick), and erupt at a lower temperature.
    - Basaltic magmas have much lower silica content, more fluid like behavior, and erupt at a higher temperature.

17 **Igneous Textures: What Can They Tell Us?**

- Texture describes the overall appearance of a rock based on the size, shape, and arrangement of mineral grains.
  - Reveals a great deal about the environment in which the rock formed
- Factors influencing igneous rock texture:
  - Rate of cooling
    - Slow rate = fewer but larger crystals
    - Fast rate = many small crystals
  - Amount of silica
  - Amount of dissolved gases

18 **Igneous Textures: What Can They Tell Us?**

19 **Igneous Textures: What Can They Tell Us?**

- Types of Igneous Textures
  - Effect of cooling on rock texture is straightforward, however a magma body may migrate to a new location or erupt before it completely solidifies—resulting in many variations:
  - Aphanitic (fine-grained) texture
    - Rapid rate of cooling; microscopic crystals
  - Phaneritic (coarse-grained) texture

- Slow cooling; large, visible crystals
- Porphyritic texture
  - Large crystals (phenocrysts) are embedded in a matrix of smaller crystals (groundmass)

20 **Igneous Textures: What Can They Tell Us?**

21 **Igneous Textures: What Can They Tell Us?**

- Types of Igneous Textures
  - Vesicular texture
    - Rocks contain voids left by gas bubbles in the lava
    - Common feature of an extrusive igneous rock
  - Glassy texture
    - Very rapid cooling
    - Ions are frozen in place before they can unite in an orderly crystalline structure
  - Pyroclastic (fragmental) texture
    - Forms from the consolidation of individual rock fragments ejected during explosive eruptions
  - Pegmatitic texture
    - Exceptionally coarse-grained; form in late stages of crystallization of magmas (rocks are called pegmatites)

22 **Igneous Textures: What Can They Tell Us?**

23 **Igneous Textures: What Can They Tell Us?**

24 **Igneous Textures: What Can They Tell Us?**

25 **Naming Igneous Rocks**

- Igneous Rocks Classification
  - Based on texture and mineral composition
    - Mineralogy is influenced by the chemical composition of the parent magma, texture results from cooling history.
  - Rocks with the same composition but different texture are given different names.

26 **Classification of Igneous Rock**

27 **Naming Igneous Rocks**

- Granitic (Felsic) Igneous Rocks
  - Granite
    - Course-grained (phaneritic)
    - One of the best known and most abundant igneous rocks
    - 10–20% quartz, roughly 50% potassium feldspar
    - Small amounts of (<10%) dark silicates
    - Some granites have a porphyritic texture
      - These contain elongated feldspar crystals a few centimeters long
  - Rhyolite
    - Extrusive (fine-grained/aphanitic) equivalent of granite
    - Composed essentially of light-colored silicates
    - Typically buff to pink or light gray in color
    - Less common and less voluminous than granite

28 **Granite Formation**

29 **Naming Igneous Rocks**

- Granitic (Felsic) Igneous Rocks
  - Obsidian
    - Dark-colored, glassy rock
    - Forms when silica-rich lava cools quickly at Earth's surface
    - Usually black to reddish-brown in color
    - Similar chemical composition to granite
    - Dark color is the result of small amounts of metallic ions in an otherwise clear, glassy substance

- Pumice
  - Glassy textured rock with vesicular texture that forms when large amounts of gas escape from the lava
  - Voids are quite noticeable and matrix resembles fine shards of intertwined glass
  - Typically found in deposits with obsidian
  - Will float when placed in water

30 **Pumice**

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- Andesitic (Intermediate) Igneous Rocks
  - Andesite
    - Medium-gray, fine-grained rock
    - Volcanic origin
    - Commonly exhibits a porphyritic texture
  - Diorite
    - Intrusive equivalent of andesite
    - Coarse-grained rock
    - Looks like gray granite, but lacks visible quartz crystals
    - Can have a salt-and-pepper appearance

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- Basaltic (Mafic) Igneous Rocks
  - Basalt
    - Very dark green to black, fined-grained rock
    - Composed mostly of pyroxene and calcium-rich plagioclase feldspar
    - When porphyritic, contains small, light-colored feldspar or olivine phenocrysts
    - Most common extrusive igneous rock
    - Upper layers of oceanic crust, Hawaiian Islands, and Iceland are composed of basalt

33 **Basalt**

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- Basaltic (Mafic) Igneous Rocks
  - Gabbro
    - Intrusive equivalent of basalt
    - Very dark green to black, phaneritic rock
    - Composed mostly of pyroxene and calcium-rich plagioclase feldspar
    - Uncommon on the continental crust but makes up a significant portion of the oceanic crust

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- Pyroclastic Rocks
  - Composed of fragments ejected during a volcanic eruption
  - *Tuff*
    - Most common pyroclastic rock
    - Composed of ash-sized fragments cemented together
  - *Welded tuff*
    - Ash particles are hot enough to fuse together
    - Can contain walnut-sized pieces of pumice and other rock fragments
    - Covers vast portion of previous volcanically active areas of the western United States

36 **Welded Tuff**

37

- Pyroclastic Rocks
  - *Volcanic breccia*
    - Composed of particles larger than ash
    - Includes streamlined lava blobs, broken blocks of vent walls, ash, and glass fragments
  - Names do not imply mineral composition and are identified with a modifier

- Example: *rhyolite tuff*

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- Earth's crust and mantle are primarily composed of solid rock.
- Magma is generated in the uppermost mantle
  - Greatest amounts are produced at divergent plate boundaries
  - Lesser amounts are produced at subduction zones
  - Can also be generated when crustal rocks are heated sufficiently to melt

39

- Generating Magma from Solid Rock
  - Geothermal gradient: temperatures in the upper crust increase about 25°C per kilometer
  - Rocks in the lower crust and upper mantle are near their melting points
    - Tectonic processes trigger melting by reducing the melting point
      - Decrease in pressure
      - Addition of water
      - Increase in temperature of crustal rocks

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- Decompression Melting
  - Melting occurs at higher temperatures with increasing depth (and increasing confining pressure).
  - Reducing confining pressure lowers the melting temperature = decompression melting
  - Solid, hot mantle rocks will ascend to regions of lower pressure, inducing melting.
    - Divergent plate boundaries
    - Mantle plumes at hot spots

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- Addition of Water
  - Water and other volatiles act as salt does to melt ice
    - Causes rock to melt at lower temperatures
  - Occurs mainly at subduction zones
  - As an oceanic plate sinks, heat and pressure drive water from the crust and overlying sediments
  - Fluids migrate into the overlying wedge of mantle
  - The addition of water lowers the melting temperature of the mantle rocks to trigger partial melting.

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- Temperature Increase: Melting Crustal Rocks
  - Mantle-derived basaltic magma buoyantly rises toward the surface
    - There is "ponds" beneath the less dense crustal rocks
  - Heat from these magma sources can melt the surrounding crustal rocks.
  - Crustal rocks can also melt from heat generated during the continental collisions that result in the formation of large mountain belts.

46 **How Magmas Evolve**

- A single volcano may extrude lavas that vary in composition
- Bowen's Reaction Series
  - Minerals crystallize in a systematic fashion based on their melting points.
    - The first to crystallize is olivine
  - As minerals crystallize, the composition of the liquid portion of the magma continually changes.
    - When one-third of the magma has crystallized, the remaining melt will be severely depleted in iron, magnesium, and calcium.

47 **Bowen's Reaction Series**

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- Magmatic Differentiation and Crystal Settling
  - Crystal settling
    - Earlier-formed minerals are denser than the liquid portion of the magma and sink to the base of the magma chamber.
  - When the remaining magma solidifies, the mineralogy will be different from the parent magma.
  - Magmatic differentiation
    - The formation of one or more secondary magmas from a single parent magma.

49 **Crystal Settling**

50 **How Magmas Evolve**

- Assimilation and Magma Mixing
  - Assimilation
    - As magma migrates through the crust, it may incorporate some of the surrounding rock into the chamber, melting and changing the chemical composition.
  - Magma mixing
    - During the ascent of two chemically different magma bodies, the more buoyant mass may overtake the slower-rising body, merging them, and their melts mixing by convective flow.

51 **Assimilation and Magma Mixing**

52 **Partial Melting and Magma Composition**

- Incomplete melting of rocks is known as partial melting.
  - This process produces most magmas
  - During partial melting, the melt is enriched in ions from minerals with the *lowest* melting temperature.
    - Partial melting of *ultramafic* rocks yields *mafic magmas*
    - Partial melting of *mafic* rocks yields *intermediate magmas*
    - Partial melting of *intermediate* rocks yields *felsic magmas*

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- Formation of Basaltic Magmas
  - Most magma that erupts is basaltic (mafic) magma
  - Most originate from partial melting of mantle rocks at oceanic ridges
    - These melts are called *primary* or *primitive* magmas because they have not yet evolved.

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- Formation of Andesitic and Granitic Magmas
  - Andesitic magma can form in two ways
    - Magmatic differentiation of mantle-derived basaltic magma
    - Basaltic magmas assimilating crustal rocks
  - Granitic magmas
    - Most form when basaltic magma ponds beneath the continental crust, heating and melting the much-lower melting temperature felsic minerals.
    - Can also form from magmatic differentiation of andesitic magma

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57 **Intrusive Igneous Activity**

- Most magma is emplaced at depth in Earth
  - Intrusive Igneous Bodies
  - A pluton is cooled, emplaced magma into preexisting rocks
  - Classification of plutons
    - Plutons are classified by their shape and their orientation relative to the surrounding rock:

- Tabular – table-like
  - Discordant – cut across existing structures
  - Concordant – are parallel to features like sedimentary strata
- Massive – blob shaped

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- Tabular Intrusive Bodies
  - Dike—a tabular, discordant pluton
    - Magma was forcibly injected into fractures cutting across bedding planes
    - Transport magma upward
    - Parallel groups are called dike swarms
    - Can also radiate from a volcanic neck like spokes on a wheel

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- Tabular Intrusive Bodies
  - Sill—a tabular, concordant pluton
    - Nearly horizontal; magma exploits weaknesses along bedding planes
    - Tend to accumulate magma and increase in thickness
    - Closely resembles buried lava flows
    - May exhibit columnar jointing
      - Occurs when igneous rocks cool and develop shrinkage fractures that produce elongated, pillar-like columns that often have six sides.

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- Massive Intrusive Bodies: Batholiths, Stocks, and Laccoliths
  - Batholith
    - Largest intrusive body
    - Occur as linear structures several hundred kilometers long
    - Surface exposure of 100+ square kilometers (smaller bodies are termed stocks)
    - While expansive, most are less than 10 km thick
    - Typically composed of felsic to intermediate rock types

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- Emplacement of Batholiths
  - Magma at depth is much less dense than the surrounding rock.
  - In the mantle, the more buoyant magma pushes aside the host rock and rises in Earth through a process called *shouldering.*
  - As it encounters more cool and brittle rock, blocks of this rock are dislodged and sink into the magma – this is called *stoping.*
    - Evidence of this is seen as blocks of country rock, called xenoliths, encased in plutons.

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- Massive Intrusive Bodies: Batholiths, Stocks, and Laccoliths
  - Emplacement of Batholiths
    - Nearer to Earth's surface, the rocks are cooler and brittle
    - Upward movement is accomplished by stoping, where the overlying blocks of country rock sink through the magma
      - Xenoliths are suspended blocks of country rocks found in plutons

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- Massive Intrusive Bodies: Batholiths, Stocks, and Laccoliths
  - Laccoliths

- Forcibly injected between sedimentary strata
- Causes the overlying strata to arch upward
- Overinflated sills

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