ENVE 201 Notes

Contents

Chapter 1

Overview

1.1 Study of Earth

- *Geology* (also called *geoscience*) is the study of the Earth.
- It encompasses studies that characterize:
  - The formation and composition of this planet.
  - The causes of mountain building and ice ages.
  - The record of life's evolution.
  - The history of climate change
  - Practical problems such as pollution, resources recovery, and natural disaster
- Understanding natural Earth processes better prepare us to thrive in our *environment*.

1.2 Environment

- The word "Environment" is derived from the French word "Environ" which means "surrounding".
- Environment is a collection of systems including all living and nonliving things on Earth that sustain all life – *complex of many variables*!
- Environment includes water, air, land, human beings and other living creatures such as plants, animals and micro-organisms.
- The natural environment consist of five interlinking systems namely, the geosphere, the hydrosphere, the cryosphere, the biosphere, and the atmosphere.

1.3 Earth System at a Glance

- The **geosphere** (or lithosphere) consists of the solid part of our planet.

- The **hydrosphere** consists of all water at or near the surface of the Earth.
- The **cryosphere** consists of frozen water, mostly in glaciers.
- The **biosphere** consists of living organisms, from bacteria to whales.
- The **atmosphere** is the envelope of gas that encircles the planet.

Earth system interacts!

Chapter 2

Birth of the Earth

2.1 Scientific Cosmology

- The systematic study of the overall structure and history of the Universe.
- The Universe contains two basic entities:

  Matter – the substance that makes up objects

  Energy – the inherent ability of a region of space and the matter within it to do "work"

- In this lecture, we will learn
  - Architecture of the overall Universe (including our Solar System)
  - Formation of the Universe – Big Bang Theory
  - Production of Sun, the Earth, and other celestial objects

2.2 Structure of the Universe

2.2.1 Galaxies

- An immense group of **stars** held together by gravity.
- Our sun is one of over 300 billion **stars** in the Milky Way Galaxy.

2.2.2 Star

- An immense sphere of incandescent gas that emits intense energy.
- Stars, including our sun, are distant from each other, but all share similar structures.

2.2.3 Solar System

- The Sun's gravitational pull holds many objects in orbit, forming the Solar System.
- Approximately 99.8% of the Solar System's mass is contained within the Sun; the remaining 0.2% consists of a wide variety of objects.
- Solar System includes *planets*, *moons*, *asteroids*, *dwarf planets*, and *comets*.

2.2.4 Planets

- The astronomers' definition of a planet:
  1) An object that orbits a star
  2) Roughly spherical
  3) Cleared its neighborhood of other objects (planet's gravity has pulled in all particles of matter in its orbit)
- Solar system includes eight planets:
  - Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune
- Until 2005, astronomers considered Pluto to be a planet.
  - Why is Pluto's planet status revoked?
  - Pluto has not cleared its orbit!

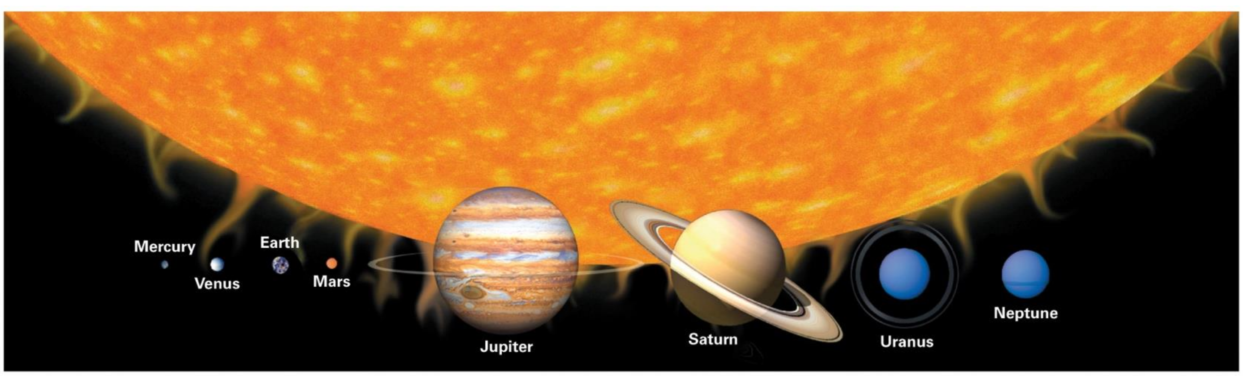

Figure 2.1: Relative sizes of the planets.

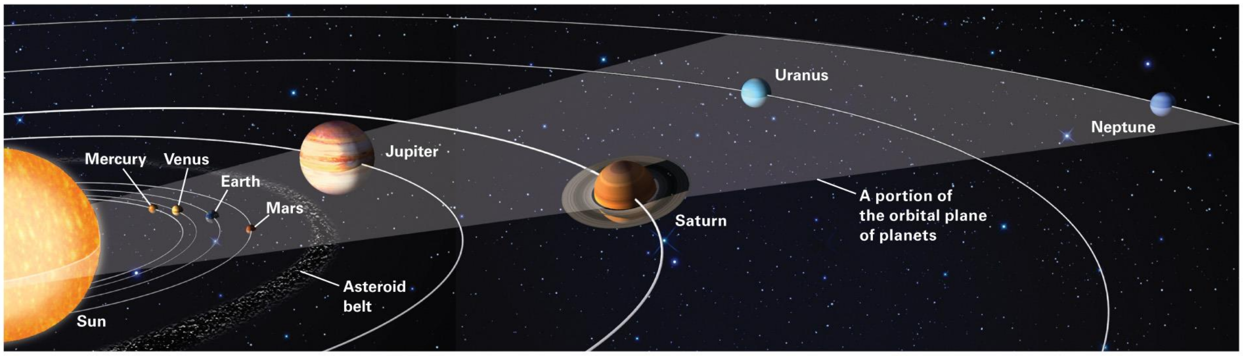

Figure 2.2: Relative positions of the planets.

All planetary orbits lie roughly in the same plane.

Terrestrial Planets (inner planets)

- Mercury, Venus, Earth, and Mars
- Closer to the Sun & relatively small
- A shell of rock surrounding a ball of metal

Giant Planets (outer planets)

- Jupiter, Saturn, Uranus, and Neptune
- Most of the matter in Jupiter and Saturn consists of hydrogen and helium as a gas, liquid, or as a strange liquid-metal state – referred to as *gas giants*.
- Most of the matter in Neptune and Uranus consists of water, carbon dioxide, and methane that has been frozen into solid ice – referred to as *ice giants*.

2.2.5 Moons

- A solid object that orbits a planet.
- All planets except Mercury and Venus have moons.
  - Earth has the Moon.
  - Mars has two.
  - Jupiter has at least 63.
  - Saturn has at least 62.
- Moons vary greatly in size, composition, and surface characteristics.

2.2.6 Other Objects

Asteroids

- Relatively small rocky or metallic objects that orbits the Sun.
- Most lie in the region between the orbits of Mars and Jupiter.

Kuiper Belt and Oort Cloud Objects

- A trillion icy bodies that form a donut-like ring **outside Neptune's orbit** make up the Kuiper Belt.
- More distant ones form the spherical-shaped Oort Cloud.

Dwarf Planets

- Asteroids and Kuiper Belt objects with a diameter greater than ~ 900 km.
- Maybe up to 200 dwarf planets present, only five have yet been identified.
- Pluto and Eris are the largest known dwarf planets.

Comets

- Kuiper Belt and Oort Cloud objects that follow elliptical orbits that bring them into the inner Solar System.

2.3 Formation of the Universe – The Big Bang

- According to the Big Bang Theory, all matter and energy in the Universe was initially concentrated in an infinitesimally small point.
- This point suddenly exploded, making the beginning of the Universe.
- The initial expansion, known as the inflation epoch, occurred extremely rapidly and lasted less than a second.
- Following this brief period, the Universe continued to expand (at a slower rate).

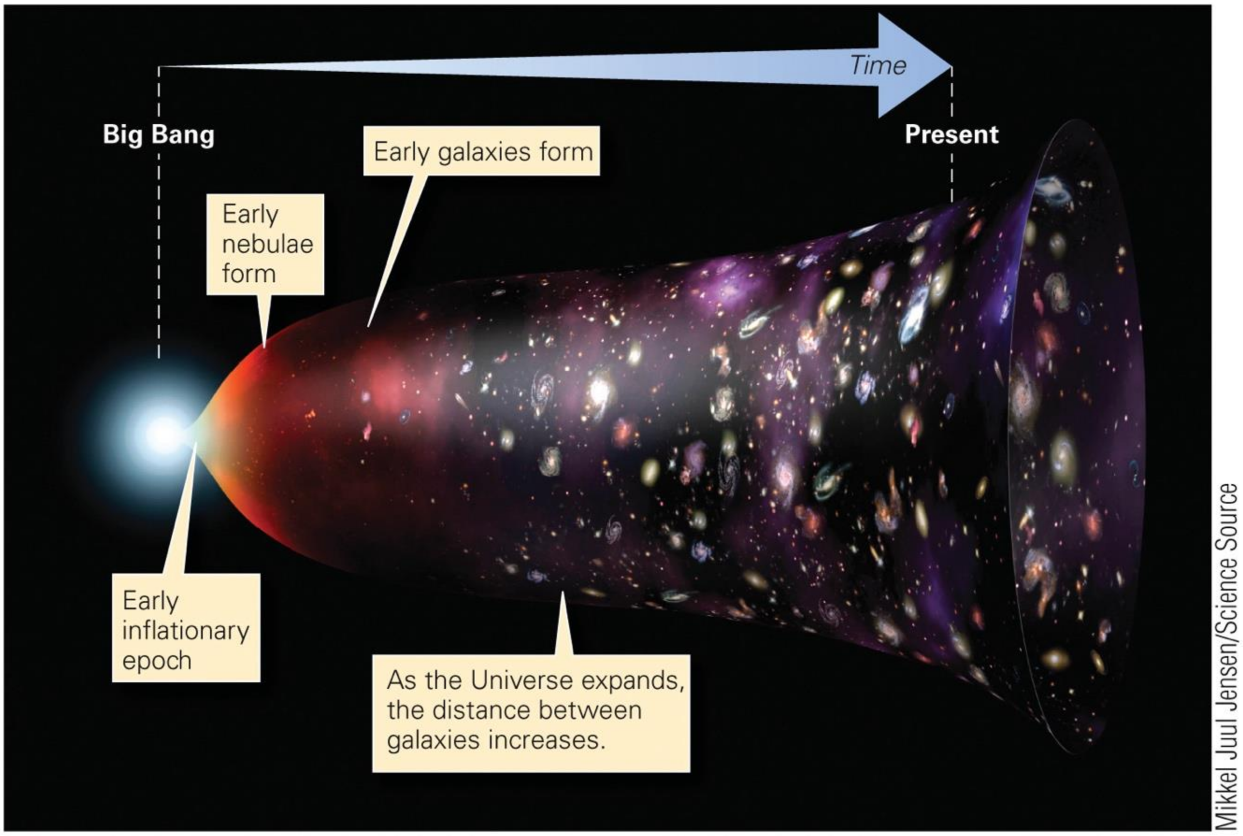

Figure 2.3: The concepts of the expanding Universe and the Big Bang.

2.4 Birth of the First Stars

- By the time the Universe reached its 200 millionth year, it was filled with immense, slowly swirling dark nebulae–giant clouds of dust and gas–separated by vast, empty voids.

Figure 2.4: A representation of a starless nebula in the early Universe (modified from a Hubble Space Telescope photograph)

2.4.1 Formation Process

- With the gravitational pull, a nebula began to draw in surrounding ice and gas, increasing its mass and density.
- As it grew, the cloud's slow swirling motion transformed into a rotation around a central axis, forming a disk-like shape.
- As gravity continued to pull material inward, the inner region of the disk collapsed into a dense, hot core.
- Eventually, the core became hot enough to emit light–this glowing core marked the birth of a *protostar*.

2.4.2 From Protostar to Star

- As the protostar accumulated more mass, its core grew even denser and hotter.
- Under these extreme conditions, hydrogen nuclei began to move rapidly and fuse into helium in a process known as nuclear fusion.
- Once fusion began, the protostar ignited, and the first true star was born.
- Around 800 million years after the Big Bang, stars lit up the Universe.
- This process repeated over and over, giving rise to the first generation of stars, marking a new era in cosmic evolution.

2.5 Supernova

- The larger the star, the hotter it burns, and the faster it runs out of fuel and dies. The explosion of a giant star produces a supernova!

2.5.1 Crab Nebula

- One of the largest ever taken by NASA's Hubble Space Telescope.
- A six-light-year-wide expanding remnant of a star's supernova explosion.
- Japanese and Chinese astronomers recorded this violent event in 1054 CE.

2.6 Formation of the Solar System – The Nebular Theory

- How the planets and other objects in our Solar System originated?
- *The nebular theory (or condensation theory)* – the Sun and all other objects in the Solar System formed from material that had been swirling about in a nebula.
- Tiny particles of ice and dust condensed within a nebula.
- Gradually, more atoms and molecules stuck to these particles, forming larger clumps.
- Once these clumps grow big enough, their gravity pulled them together, growing into even larger bodies.
- As gravity pulled the swirling gas and dust inward, the nebula flattened into a spinning disk with a dense, central region.
- This central "bulb" became the *Sun*, while the rest of the disk became the *protoplanetary disk*.
- Within this disk, dust and rocky debris collided and stuck together to form *planetesimals*.

- These planetesimals, acting like vacuum cleaner, attracted more material and gew into *protoplanets*–early versions of the planets we see today.

2.7 Differentiation of the Earth's Interior

- Early on, the composition of the Earth (planetesimals) was fairly uniform.
- When temperatures got hot enough, iron began to melt.
- Then, the iron accumulated at the center of the planet to create the core.

2.8 Formation of the Moon

- Soon after the Earth formed, a protoplanet collided with Earth, blasting debris around it, and the Moon formed from the ring of debris.

2.9 Formation of Earth's Ocean and Atmosphere

- Unlike the other terrestrial planets, Earth is unique for having liquid water oceans and an atmosphere rich in nitrogen (N_2) and oxygen (O_2). However, this wasn't always the case.

2.9.1 Earth's Early Atmosphere

- When Earth first formed, its atmosphere likely consisted mostly of lightweight gases–hydrogen (H_2) and helium (He)–similar to the Sun.
  - Where did hydrogen and helium go?
  - Where did the ocean and atmosphere come from?
- As the planet warmed, the initial light gases–hydrogen (H_2) and helium (He) – escaped Earth's gravitational pull.
- These were replaced by gases released through volcanic eruptions, known as *volatile materials*. This outgassing from Earth's interior led to the formation of a new atmosphere, primarily composed of water vapor, carbon dioxide (CO_2), ammonia (NH_3), and methane (CH_4).
- When the Earth cooled enough for water vapor to condense, rain *began to fall* and the *oceans gradually accumulated*.
- *CO_2 dissolved into the oceans* and *precipitated as solid compounds*, reducing its concentration in the atmosphere.
- Later, *photosynthetic organisms* emerged, gradually increasing oxygen (O_2) in the atmosphere and changing Earth's environment dramatically.

Chapter 3

Interior of the Earth

3.1 Quick Facts About Earth

- The third planet from the Sun and the fifth-largest planet.
- The only place we know of inhabited by living things.
- Length of days: 23.9 hours
- Length of year: 365.25 days
- Distance from Sun: 93,327,712 miles (150,196,428 km)
- The name Earth is at least 1,000 years old. It was taken from Old English and Germanic. Imply it means "the ground".

3.2 The Earth System

- Only the Earth currently has liquid water among the Solar System's planets.
- The Earth lies within the *habitable zone* – the distance from the Sun at which temperatures range between the boiling and freezing points of water.
  - On planets closer to the Sun than the habitable zone, all water evaporates.
  - On planets farther away, all water exists only as solid ice.
- Earth has the potential for life!

3.3 The Size of Earth

- Eratosthenes observed that if the Earth were spherical, the Sun's rays could not strike two distant locations at the same angle at the same time.

  - At noon in Syene (modern Aswan), the Sun was directly overhead and cast no shadow.
  - At the same time in Alexandria, about 5,000 stadia ($\approx$ 800 km) to the North, a vertical tower cast a shadow.
  - Eratosthenes measured the angle between the two and the Sun's rays to be 7.2°.
  - Since 7.2° is $\frac{1}{50}$ of a full circle, he concluded that the Earth's circumference must be 50 times the distance between the two cities and it is 250,000 stadia ($\approx 39,300$ km).

- *Very close to the modern accepted value (40,075.017 km)!*

3.4 Earth's Rotation

- Earth completes one rotation every *23.9 hours* and it takes *365.25 days* to complete one trip around the sun!
- Foucault proved that the Earth spins on its axis

3.4.1 Foucault's Pendulum Experiment

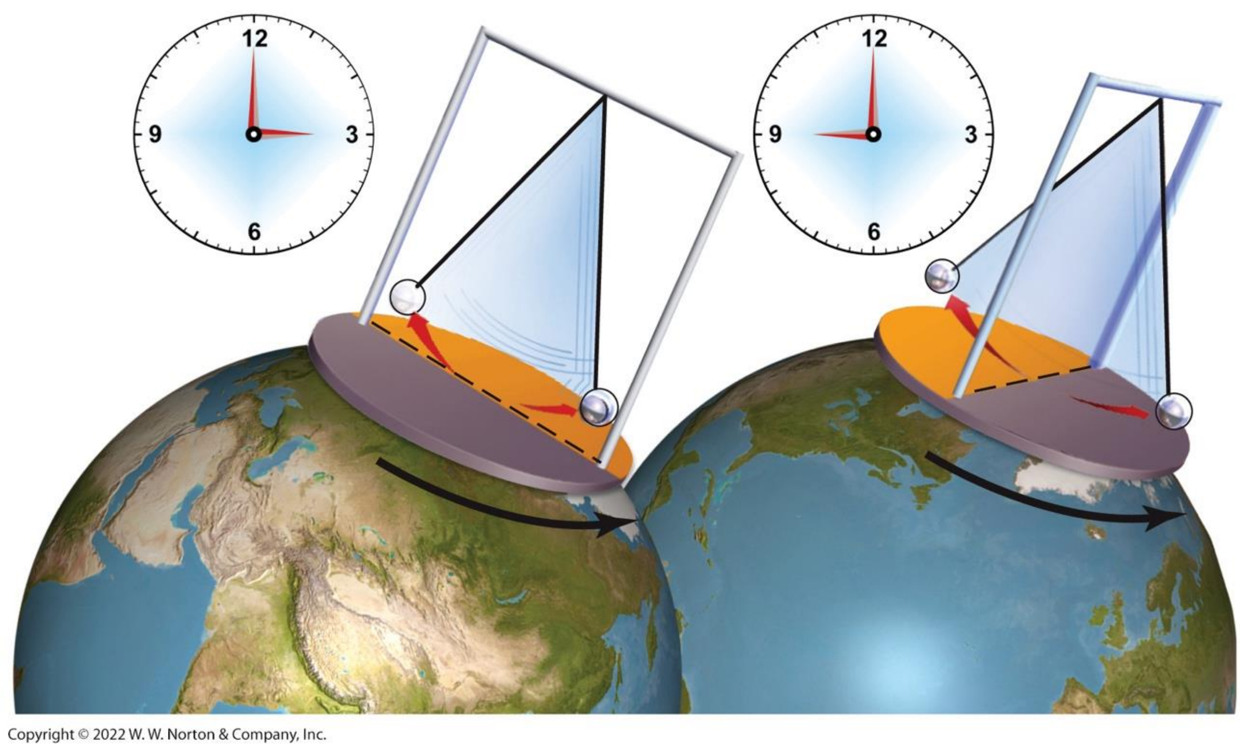

Figure 3.1: Foucault's Pendulum Experiment

- At Time 1 (left), the plane in which the pendulum swings is the same as the plane of its frame.

- At Time 2 (right), 6 hours later, the plan in which the pendulum swings is perpendicular to the plane of its frame.

3.4.2 Earth's Axis of Rotation

- Earth's axis of rotation is tilted 23.5° with respect to the plane of Earth's orbit around the Sun.
  - This tilt causes our yearly cycle of seasons.

3.5 Earth's Structure

- By the end of the 19^{th} century, researchers realized that the Earth resembles a hard-boiled egg in that it had three principal layers.
  1. A not-so-dense crust (like an eggshell),
  2. A thicker and denser solid mantle in the middle (like an egg white),
  3. A very dense core (yolk).
- Earthquake (seismic) waves allowed geologists to refine the model of Earth's interior.
- Earth is composed of four main layers:
  - Inner core
  - Outer core
  - Mantle
  - Crust

3.5.1 Earth's Crust

- Outermost layer of the Earth
- Two types of crust:
  - Oceanic crust underlies the seafloor and is thinner (7-10 km) and denser.
  - Continental crust underlies continent and is thicker (25-70 km) and less dense.
- Earth's crust is comprised of, mostly, eight different elements. Of these, oxygen and silicon account for 74.3% by weight.

3.5.2 Earth's Mantle

- 2,820- to 2,890-km thick shell that surrounds the core.
- The mantle can be divided into two sublayers: upper mantle and lower mantle.
- Almost all of the mantle is solid rock, but the mantle at a great depth stays so hot that it is enough to flow (at a rate of less than 15 cm/year).
- The temperature of the mantle vary with location:
  - Warmer regions of mantle are less dense than adjacent cooler regions.
  - Warmer regions tend to flow upward, while cooler regions flow downward.
  - *The mantle undergoes very flow convection!*

3.5.3 Earth's Core

- The core is the densest layer - consists of iron alloy ($>$ 80% iron mixed with nickel and lesser amounts of sulfur, oxygen, silicon, and other elements).
- Core is divided into two parts:
  - Outer core (2,890-5,155 km) consists of liquid iron alloy.
  - Inner core (5,155-6,371 (the center) km) consists of solid iron alloy.
  - Even though the inner core is hotter than the outer core, the inner core stays solid because it endures immense pressure.
- The iron alloy of the outer core can flow, and this flow generates the Earth's magnetic field.

3.5.4 Pressure and Temperature Inside the Earth

- Pressure increases with depth, and at the Earth's center, it is estimated to reach about 3,600,000 atm.
- Temperature also increases with depth, approaching 6,000°C at the core.
- The rate of temperature increase with depth is called the *geothermal gradient*.
  - 15-30°C/km in the upper part of crust.
  - At greater depth, less than 10°C/km.

3.6 Earth's Surface

- Dry land covers 30% of the surface.
- Water covers the remaining 70% of the surface, but most surface water contains salt and resides in the oceans.
- *Topography* shows variation in elevation on both the land surface and beneath the ocean.
- A *hypsometric curve* indicate the proportion of Earth's solid surface at different elevations.
  - Earth's surface is mostly continent (plains and shelf) or ocean floor.
  - Mountains and deep-sea trenches cover relatively little area.
  - Change in sea level would dramatically change the area of dry land.

3.7 Earth's Atmosphere

- The Earth is wrapped in a gaseous cloak called the atmosphere.
- This atmosphere is made of a mixture of gases that we call air.
  - Nitrogen (78%) and oxygen (21%) are the dominant.
  - Other gases include argon, carbon dioxide, neon, methane, ozone, carbon monoxide, and sulfur dioxide.
  - Air also contains variable amounts of water vapor at lower elevation.
- Other terrestrial planets have atmosphere, but mostly CO_2 gas.
- The density of the atmosphere increases closer to the Earth's surface, and atmospheric pressure decreases with elevation.
- However, temperature does not follow a simple decrease–it varies by layer.
  - Troposphere
  - Stratosphere
  - Mesosphere
  - Thermosphere
- All weather occurs in the *Troposphere*.

3.8 Earth Materials

- Of the 92 naturally occurring elements that make up the Earth, 91.2% of the Earth's mass consists of only 4: iron, oxygen, silicon, and magnesium.
- The elements of Earth materials bond together to form a great variety of materials that can be classified into several basic categories:

Organic chemicals - A carbon-containing compound that occurs in living organisms.

Minerals - A solid, natural substance in which atoms are arranged in an orderly pattern.

Glass - A solid in which atoms are not arranged in an orderly pattern.

Melts - A melt forms when solid materials become hot and transform into liquid.

Rocks - A coherent aggregate of mineral crystals or grains, or a mass of natural glass.

Grains - Either individual crystal within a rock or individual fragment derived from a once-larger mineral sample or rock body.

Sediment - An accumulation of loose grains.

Metals - A solid composed entirely of metal atoms.

Volatiles - A material that can exist as a gas under the conditions found at the Earth's surface.

3.9 Earth's Magnetic Field

- Our planet's rapid rotation and molten nickel-iron core give rise to a magnetic field.
- Solar wind distorts the magnetic fields into a teardrop shape in space.
- The magnetic field deflects most solar-wind particles, serving as a first shield - Magnetosphere.
- The magnetic field is what causes compass needles to point to the North Pole regardless of which way you turn.
- The Earth's magnetic field behaves like a dipole, similar to an imaginary bar magnet inside the planet.
- Magnetic field lines flow into the magnetic south pole and emerge out of the magnetic north pole.

Chapter 4

Continental Drift

4.1 Continental Drift

- Alfred Wegener, a German meteorologist, proposed that the continents had once fit together like pieces of a giant jigsaw puzzle, making one vast supercontinent named *Pangaea*.
- The phenomenon that Wegener proposed came to be known as *continental drift*.
- Wegener presented observations to support the theory of continental drift:
  - The fit of the continents
  - Locations of past glaciations
  - The distribution of climate belts
  - The distribution of fossils
  - Matching geologic units

4.1.1 Evidence 1 - The Fit of the Continents

- North America, South America, Africa, and Europe appear to fit together.
- When all continents are joined, they form a single supercontinent called Pangaea, with remarkably few overlaps or gaps.
- Wegener concluded that the continents once did fit together in the geologic past.
- Later, Edward Bullard used a computerized reconstruction to align the continental shelves. His results showed how although the fit is not perfect, the mismatches are minimal and the overall alignment is striking.

4.1.2 Evidence 2 - Locations of Past Glaciations

- Flowing glacier transport sediments of all sizes, and hard grains carve scratches, called *striations*, into the underlying rock.
- The distribution of the glacial deposits (*till*) and the orientation of the striations were mapped.
- All late Paleozoic glaciated regions align adjacent to one another on this map, forming a single continuous ice sheet.

4.1.3 Evidence 3 - The Distribution of Climate Belts

- Paleozoic sedimentary rocks record clues to past climate at the time of sediment deposition.
  - In tropical swamps and jungle regions → thick accumulation of plant material, which later transform into coal.
  - In subtropical regions → extensive salt deposits and the growth of large sand dunes.
- *Wegener's observation*:
  - In the equatorial Pangaea belt, late Paleozoic rocks contain abundant coal seams and the relics of reefs.
  - In the subtropical Pangaea belt, rock layers preserve desert dunes and salt layers.
- On today's map, these deposits appear scattered across different continents and latitudes.

4.1.4 Evidence 4 - The Distribution of Fossils

- Different continents host different species, since land-dwelling or coastal organisms cannot cross vast oceans. Overtime, these species evolve independently on separate continents.
- *Wegener's observation*:
  - He mapped fossil occurrences of late Paleozoic and early Mesozoic land-dwelling species
  - The distribution shows that identical fossils appear on continents that were once joined in Pangaea.

4.1.5 Evidence 5 - Matching Geologic Units

- Observation if the Atlantic Ocean did not exist:
  - Distinctive belts of rock in South America would align seamlessly with those in Africa.

  - Paleozoic mountain belts on both coasts would connect to form continuous ranges.
- A modern construction illustrates:
  - The geologic units and mountain belts line up almost perfectly.
  - The outlines of today's continents drawn in white for reference.

4.1.6 Criticism of Wegener's Ideas

- Although Wegener presented strong observational evidence for continental drift, he could not explain the *mechanism*: "What force could possibly be great enough to move the immense mass of a continent?"
- As a result, most geologists of his time *rejected* the theory of continental drift.
- In the three decades that followed Wegener's death, geologists discovered the existence of huge convection cells in the Earth's mantle. These convection currents transport hot rock slowly upward from the deep mantle up to the base of the crust.
- *Continental movement, seafloor spreading*, and *subduction* are now explained by the concept of plate tectonics.

4.2 Seafloor Mapping

4.2.1 Scattered Soundings (Depth Measurements) Before World War II

- Depth was measured by lowering a cable with a lead weight. When the weight hit the seafloor, the length of the cable would indicate the depth.
- Each sounding could take hours, so measurements were sparse.

4.2.2 Sonar After World War II

- Ships emitted sound pulses that traveled to the seafloor and returned as echoes.
- With the known speed of sound in water: distance = velocity $\times$ time.
- Sonar allowed rapid, continuous depth recording, producing detailed seafloor profiles.

4.3 Bathymetric Map of the Seafloor

- *Bathymetric profile* (yellow line, $Y - Y'$) is a graph of depth versus location along a line.
- By sailing back and forth across the ocean and collecting many such profiles at different locations, investigators compiled enough data to construct a *bathymetric map* of the seafloor.

4.4 Seafloor Sediments and Heat Flow

New observations on the oceanic crust:

Sediments thicken and age away from ridges : A layer of clay and microscopic shells becomes progressively thicker and older with increasing distance from the mid-ocean ridge axis, showing that ridges are younger than the deeper ocean floor.

Heat flow is highest at ridges : Heat rising from Earth's interior varies across the seafloor, with greater heat flow beneath mid-ocean ridges. This suggests molten rock is rising into the crust at ridge axes, carrying heat upward.

- Harry Hess' concept of *seafloor spreading*:
  - Hot mantle rises beneath mid-ocean ridges and melts.
  - At the ridge axis, this melts solidifies to create new oceanic crusts.
  - Once formed, the crust cracks, splits apart, and gradually moves away from the ridge.
  - This process explained *the creation of new seafloor*.

4.5 Seafloor Subduction

- Geologists realized that if new ocean floor forms at mid-ocean ridges, the old ocean floor must be consumed elsewhere:
  - Deep-sea trenches are the site where oceanic crust bends and sinks back into the mantle.
  - Frequent earthquakes along trenches confirm this downward movement.
  - *Subduction* is the process by which oceanic floor descends into the Earth's interior at trenches, balancing seafloor spreading.

4.6 Locations of Earthquakes

- Earthquakes occur in distinct seismic belts, not scattered randomly across the globe.
- Their distribution in ocean basins traces the outlines of mid-ocean ridges, transform faults, and deep-sea trenches.

Chapter 5

Plate Tectonics

5.1 Theory of Plate Tectonics

- The outer layer of the Earth, called the *lithosphere*, is broken into large rigid pieces known as tectonic plates. These plates move slowly over the softer, ductile *asthenosphere* beneath them.
- In geology, the development of plate tectonic theory marked a true scientific revolution.

5.2 Basic Principles of Plate Tectonics Theory

- The Earth's lithosphere is divided into plates that move relative to one another.
- The motion of one plate relative to its neighbor takes place by slip along plate boundaries.
- Continents are parts of some plates, so as the plates move, the continents are carried along with them.
- Because of plate tectonics, the Earth's surface is dynamic–the positions of continents and oceans change continuously over geologic time.

5.3 Lithosphere and Asthenosphere

5.3.1 Lithosphere

- Includes of the crust and the uppermost part of the upper mantle.
- Acts as a relatively rigid, hard layer. When subjected to stress, it does not flow but instead bends (elastic deformation) or breaks (faulting, fracturing).

5.3.2 Asthenosphere

- Made of upper mantle that is hotter and more ductile than the lithosphere.

- Can flow slowly when stressed, similar to convection in boiling water, but on geological timescales (million of years).

5.4 Lithosphere Plates

- The lithosphere is broken into ~ 20 discrete plates.

  Major plates (12) : Cover large surface areas (e.g., Pacific, African plates).

  Microplates : Smaller plates, often along plate boundaries or fragmented regions.

5.4.1 Plate Boundaries

- Defined as the contact zones where two plates meet.
- Many plate boundaries coincide with continental margins, the transition between continental crust and oceanic crust.

5.5 Location of Earthquakes and Plate Boundaries

- The distribution of earthquakes (red dots) is not random.
- Most earthquakes occur in narrow seismic belts, which trace the location of plate boundaries. The fracturing and sliding that take place along these boundaries as plates move generate the earthquakes.
- In contrast, plate interiors remain relatively earthquake-free because very little movement occurs within them.

5.6 Three Types of Plate Boundaries

- The three types of plate boundaries are distinguished by the nature of relative plate movement.

  Divergent boundary two plates move away from each other.

  Convergent boundary two plates move towards each other; downgoing plate sinks beneath the overriding plate.

  Transform boundary two plates slide past each other on a vertical fault surface.

5.7 Divergent Boundaries and Seafloor Spreading

- Two oceanic plates move apart (diverge) by the process of seafloor spreading at mid-ocean ridges.
- As the plates move apart, new ocean floor forms along the divergent boundaries.

- Rising asthenosphere melts beneath the ridge axis.

5.8 Mid-Ocean Range

- All new seafloor forms at mid-ocean ridges, and as it moves away from the ridge axis, it becomes progressively older.
- The ridge itself sits much shallower than the surrounding abyssal plains.
- Along its length, the ridge is segmented and offset by transform-fault fracture zones.

5.8.1 Seafloor Age Map

- The youngest oceanic crust lies along ridge axis.
- The oldest oceanic crust is found farthest from the ridge axis, near subduction zones where the seafloor is eventually recycled back into the mantle.

5.9 Convergent Boundaries and Subduction

- At convergent boundaries, two plates move toward each other.
- When at least one of these plates is oceanic, it bends and sinks into the asthenosphere beneath the overriding plate. This process is called *subduction*.
- Because of this, convergent boundaries are also known as subduction zones.
- Subduction has important implications:
  - It consumes old oceanic lithosphere, recycling it back into the mantle.
  - For this reason, geologists often call convergent boundaries *consuming boundaries*.
  - At the surface, they appear as long, deep oceanic trenches.

5.10 Earthquakes at Subduction Zones

- As the downgoing plate descends, it grinds along the base of the overriding plate. This friction produces large earthquakes, which often occur relatively close to the Earth's surface near trenches.
- Earthquakes also occur within the downgoing plate itself as it bends and sinks into the mantle ($\sim$ 660 km). This distinct band of earthquakes marking this sinking slab is called a Wadati-Benioff zone.
- At depths greater than 660 km, plates continue sinking into the mantle. However, earthquakes stop occurring because the slab material adjusts to high pressures and temperatures in a more ductile manner rather than fracturing.

5.11 Transform Boundaries

- Researchers discovered that mid-ocean ridges are not continuous lines but are broken into short segments.
- These segments are offset at their ends.
- At each offset, a fracture zone develops. This fracture zone runs at a right angle to the ridge axis and connects one ridge segment to the next.
- At a transform boundary, one plate slides slideways relative to its neighbor along a vertical fault. The slip direction is horizontal.
- No new plate is created, and no old plate is consumed at a transform boundary.
- Fracture zone intersects the end of each ridge segment at a right angle and links it to the next ridge segment.
- Only the segment of the fracture zone between two ridge segments is active – earthquakes happen only along the active transform fault.

5.12 Special Locations

5.12.1 Triple Junctions

- A triple junction is a place where three plates intersect.

5.12.2 Hot Spot Volcanoes

- Hot spot volcanoes form where a stationary plum of hot mantle rises and melts through a moving tectonic plate, creating a chain of volcanoes
  - Active volcano represents the present-day location of the magma source.
  - The younger and active volcano moves off the hotspot and become inactive, and another, still younger one forms.
  - Associated chain of inactive volcanic islands is known as a hotspot track, and it provides clues to the direction and rate of plate movement.
- Big Island of Hawai'i lies over 4,000 km from the nearest ridge or trench (oceanic hot spot).
- Yellowstone National Park lies into the interior of the North American Plate (continental hot spot).

5.13 Formation of Plate Boundaries – Rifting

- Most new divergent boundaries form when a continent splits and separates into two continents.
- When continental lithosphere stretches and thins, faulting takes place, and volcanoes erupt. Eventually, the continent splits in two, and a new ocean basin forms.
- Continental rifting is the initial process and seafloor spreading is a later, more advanced stage of this process.
- Rift valley in Iceland
  - Stretches along the Mid-Atlantic Ridge, where the North American and Eurasian tectonic plates are pulling apart from each other.
  - The Thingvellir rift grows about one centimeter (0.4 in) each year.

5.14 Death of Plate Boundaries – Continental Collision

- A convergent boundary ends when buoyant lithosphere enters a subduction zone.
- Subduction continues until the oceanic plate is fully consumed, and then the two continents collide.
- During collision:
  - The oceanic plate detaches and sinks into the mantle.
  - Rocks in the collision zone are broken, bent, and compressed, forming large mountain ranges.
  - The Earth's surface rises, and the crust thickens significantly due to the stacking and deformation of rock layers.

5.15 Different Geological Settings

- Five geological settings related to volcanism
  - Island arc (oceanic-oceanic subduction)
  - Continental arc (oceanic-continental subduction)
  - Hot spot
  - Mid-ocean ridge
  - Rift

5.16 Velocity of Plate Motions

- The velocity of plate motion can be described in two ways:

  Relative plate velocity describes motion of one plate relative to another.

  Absolute plate velocity describes motion of one plate compared to a fixed reference plate.

- Estimating absolute plate velocity comes from the assumption that the location of a hot spot does not change much over time, in which case the hot-spot track on a plate provides a record of the plate's absolute velocity.
- Plate velocities can now be measured using global positioning system (GPS) satellites.
- GPS measurements in southern California show that the region west of the San Andreas fault system, a plate boundary, is moving northwest up to 6 cm/year. The length of an error represents the velocity.

5.17 Changing Face of Earth

- As a result of plate tectonics, the map of Earth's surface changes slowly and continuously.
- The assembly and the later breakup of Pangaea during the past 400 million years.

Chapter 6

Plate Tectonics

6.1 Consequences of Tectonic Activity

The movement and interaction of tectonic plates lead to several major geological events.

Volcano an opening (vent) where molten rock reaches the Earth's surface. Volcanoes can also form mountains built from the products of repeated eruptions.

Earthquake episodes of ground shaking caused by the sudden release of energy as plates slip along faults.

Mountain building the formation of mountain belts. This involves uplift (the crust rising) and deformation (rocks bending, breaking, or flowing) due to stress as compression, tension, or shearing.

6.2 Volcanoes

- Beneath a volcano, magma rises through cracks in the crust and collects in a **magma chamber**.
- When pressure builds up, some of this magma erupts at the surface–either through the central vent or along the volcano's flanks.
- The style of eruption depends largely on the viscosity of the magma.
  - High-viscosity magma
  - Low-viscosity magma
- Because of this variation, volcanoes come in many different forms.

6.3 Products of Volcanic Eruptions

- Volcanic eruption transfers materials from inside the Earth to our planet's surface.

- Products of an eruption come in different forms:

  Lava flows molten rock that moves over the ground.

  Pyroclastic debris fragments blown out of a volcano.

  Volcanic gases expelled vapor and aerosols

6.3.1 Lava Flows

- Outpouring of molten rock, or magma, during eruption.
- Lava can be thin and runny or thick and sticky depending on viscosity, which is due to composition (especially silica content), temperature, and gas content.
- Higher silica $\rightarrow$ higher viscosity $\rightarrow$ less ability to flow.

  Basaltic (mafic) lavas low silica, low viscosity $\rightarrow$ runny, travel long distance

  Ryolitic (felsic) lavas high silica, high viscosity $\rightarrow$ thick, pile up near the vent

  Andesite lavas intermediate properties

6.3.2 Pyroclastic Debris

Fragmented igneous materials forcefully ejected from a volcano.

- Basaltic eruptions produce relatively little pyroclastic debris.
- Andesitic and Rhyolitic eruptions are much richer in silica and often generate immense quantities of pyroclastic debris, much more than basaltic eruptions.

6.3.3 Volcanic Gases

- Most magma contains dissolved gases (volatiles):
  - Water vapor (H_2O), Carbon Dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S).
- As magma rises toward the surface, dissolved gases escape because:
  - Lower pressure near the surface reduce the ability of magma to hold gas.
  - Crystallization excludes gases (they don't fit into crystals), so gas concentration in the melt increases until bubbles form.
- Eruption style:
  - Low-viscosity basaltic magma: gases escape easily $\rightarrow$ eruptions are typically gentle
  - High-viscosity rhyolitic magma: gases are trapped, pressure builds up $\rightarrow$ eruptions are often explosive and violent.

6.3.4 Other Volcanic Deposits

Pyroclastic deposits fragments ejected during an eruption that accumulate directly from ash clouds in the atmosphere or from hot avalanches of debris rushing down the volcano's flank.

Volcanic-sedimentary deposits volcanic material that has been reworked and redeposited after the eruption–for example, by debris flows or lahars carrying volcanic ash and rock downslope.

Fragmented lava deposits angular debris produced when lava breaks apart while flowing on the surface, without being ejected into the air.

6.4 Geological Settings of Volcanism

- Different styles of volcanism occur at different locations on Earth.

6.4.1 Mid-Ocean Ridge Submarine Eruptions

- Mid-ocean ridge volcanoes develop along fissures parallel to the ridge axis.
- Products of mid-ocean ridge volcanism cover 70% of Earth's surface.
- Mid-ocean ridge volcanoes are not all continuously active.
- We don't generally see this volcanic activity, because the ocean hides most of it beneath a blanket of water.

6.5 Volcanism of Continental Rifts

- Igneous activity of rift zones occurs because the thinning and stretching of the continental lithosphere reduces the pressure on the underlying asthenosphere.
- As the asthenosphere rises to shallower depths, it partially melts, producing magma.
- Some of this magma rises directly to the surface, erupting as lava flows or volcanic cones.
- A portion of the magma, however, stalls and crystallizes at the base of the crust or within crustal fractures, forming intrusive igneous bodies.

6.6 Volcanic Arcs at Convergent Boundaries

- Most subaerial volcanoes on the Earth lies along convergent boundaries (subduction zones).
- Island arc: magma rises from the mantle through the oceanic crust.

- Continental arc: volcanoes grow on continental crust.
- The **Ring of Fire** defines the location of most subduction-related volcanoes.

6.7 Hot-Spot Volcanism

- Host spots are volcanic regions fed by mantle plumes. Unlike plate boundary volcanism, hot spot volcanism occurs in the middle of tectonic plates.
- Oceanic host spots are created when rising mantle plumes undergo decompression melting beneath oceanic lithosphere (e.g., Hawaiian Islands).
- Continental hot spots occur when mantle plumes rise beneath continents, causing partial melting of both mantle and continental crust (e.g., Yellowstone).

6.8 Volcanic Hazards Due to Eruptive Materials

- Threat from lava flows
  - Basaltic lava from effusive eruptions is the greatest thread because it can spread over a broad area.
- Pyroclastic debris flows
  - Pyroclastic flows can move extremely fast (100-300 km/h) and are so hot (500-1,000°C) that they represent a profound hazard to humans and the environment.
- Volcanic Ash and Lapilli
  - During a large explosive eruption, ash and lapilli erupt into the air, later fall back to the ground. Ashfalls can completely bury landscapes, killing plants and crops.

6.9 Other Hazards Related to Eruptions

6.9.1 Threat of blast

- When explosions are eject sideways, they can create severe blast hazards.

6.9.2 Threat of landslide

- Eruptions commonly trigger large landslides along a volcano's flanks.
- Volcanic debris, composed of ash and solidified lava that erupt earlier, can move downslope fast (250 km/h) and far.

6.9.3 Threat of lahars

- Mixing volcanic ash and other debris with water produces a lahar, an ash slurry that resembles wet concrete, very thick and dense.
- Lahars may develop when heavy rains happen during an eruption, or in regions where snow and ice cover an erupting volcano, for the eruption melts the snow and ice, thereby generating a supply of water.

6.9.4 Threat of earthquakes

- Earthquakes accompany almost all major volcanic eruptions because the movement of magma break rocks underground.

6.9.5 Threat of tsunamis

- Where explosive eruptions occur at an island arc; the blast and the underwater collapse of a caldera can generate huge sea waves or tsunamis, tens of meters high.

6.9.6 Threat of gas

- Volcanoes erupt not only solid material, but also large quantities of gas such as water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S).
- Usually, eruption of gases accompanies the eruption of lava and ash.

6.10 Active, Dormant and Extinct Volcanoes

- The threat from a volcano depends on the likelihood of eruption.
- Tectonic processes will eventually shut off volcanoes' magma source, then erosion takes over.

  Active erupting, recently erupted, or likely to erupt

  Dormant hasn't erupted in hundreds to thousands of years

  Extinct no longer capable of erupting

- How to determine?
  - Examine the historical record
  - Determine the age of erupted rocks
  - Search for evidence that the volcano sill lies within a tectonically active area
  - Examine the landscape character of the volcano (shape)

6.11 Predicting Eruption

- Long-term prediction comes from:
  - Recurrence interval - the average time between eruptions
  - Age of erupted layers making up the volcano
- Indicators for volcanic unrest:

  Earthquake activity movement of magma generates vibrations in the Earth.

  Changes in heat flow the presence of hot magma increases the local heat flow, the amount of heat passing upward through rock.

  Changes in shape As magma fills the magma chamber inside a volcano, it pushes outward and cna cause the surface of the volcano to bulge.

  Increase in gas and steam emission Gases bubbling out of the magma and steam formed as the magma heats groundwater percolate upward through cracks in the Earth and rise from the volcanic vent.

6.12 Earthquake

The shaking of the Earth's surface resulting from a sudden release of **energy**, most of which is a consequence of **plate movement**.

- Before an earthquake, rock bends elastically, like a stick arch in your hands.
- Eventually, the rock break, and sliding suddenly occurs a fault. This break generates vibrations.
- When the vibrations produced, the land surface lurched back and forth and bounced up and down - the ground shaking is called an earthquake.
- Almost 1 million detectable earthquakes happen every year.
- Most cause no damage or causalities, either because they are too small or because they occur in unpopulated areas.
- A few hundred earthquakes per year rattle the ground sufficiently to crack buildings and injure their occupants.
- Every 5 to 20 years, on average, a great earthquake triggers a horrific calamity.

6.12.1 Causes of the Earthquakes

- Seismic activity can result from a variety of geologic and human-induced processing including:
  - Sudden formation of a new fault
  - Sudden slip on an existing fault
  - Phase change in minerals
  - Volcanic activity
  - Giant landslides
  - Meteorite impacts
  - Underground nuclear explosions

6.13 Location of an Earthquake

- Hypocenter (focus):
  - Actual point inside the Earth where an earthquake begins.
  - The spot along the fault where rocks first rupture and start slipping, releasing seismic energy.
- Epicenter:
  - The point directly above the hypocenter, projected up to the Earth's surface.

6.14 Faults and Related Features

- Fault: a fracture or break in the Earth's crust along which rocks or sediments have moved relative to each other.
  - Blind faults: Some faults do not extend to the Earth's surface while they are active.
  - When a fault does intersect the surface, it can offset the ground. This offset creates a fault scarp.
  - Fault line (fault trace): visible line where the fault plane meets the Earth's surface.
- Movement along faults:
  - Miners described fault motion observing the relative movement of the hanging wall compared to the footwall.

6.14.1 Basic Types of Faults

Normal Fault

- Hanging wall moves down relative to footwall.
- Faults form during extension (stretching) of the crust.

Reverse fault (steep) or a thrust fault (shallow)

- Hanging wall moves up relative to footwall.
- Faults form during compression (squeezing or shortening) of the crust.

Strike-slip fault

- Blocks slide past each other horizontally.
- No vertical displacement takes place.

6.14.2 Development of New Faults

- Faults form when tectonic forces add stress (push, pull, or shear) to rock. Think of a block of rock held by clamps:
  - When force is applied, the rock bends slightly at first without breaking.
  - With continued stress, small cracks begin to form inside the rock. These cracks slowly grow and start to connect with each other.
  - Eventually, the connected cracks create a continuous fracture that cut across the entire block of rock.

6.14.3 Foreshocks, Mainshock, Aftershocks

Foreshocks

- Sometimes, smaller earthquakes occur before the mainshock.
- They happen as minor cracks develop.

Mainshock

The largest and most powerful earthquake in a sequence. It usually releases the bulk of accumulated stress along a fault.

Aftershocks

- After the mainshock, a series of small quakes called aftershocks often follow.
- These occur because the fault system doesn't settle into a stable configuration immediately after the main rupture.
- Aftershocks may continue for weeks, months, or even years.

6.14.4 Seismic Waves

- Earthquake energy moves through rock and sediment in the form of vibration, and this movement is called seismic waves, or earthquake waves.
- Different types of seismic waves travel at different velocities.

P-waves travel by compressing and expanding the material parallel to the wave-travel direction. P-waves are the fastest seismic waves, and they travel through solids, liquids, and gases.

S-waves travel by moving material back and forth, perpendicular to the wave-travel direction. S-waves are slower than P-waves, and they travel only through solids, never liquids or gases.

Surface waves travel along Earth's exterior. Surface waves are the slowest and most destructive.

6.14.5 Record of Earthquakes

Sesimographs – instruments that record ground motion.

- A weighted pen on a spring traces movement of the frame.
- Vertical motion is recorded as up-and-down movement; horizontal motion is recorded as back-and-forth motion.

Seismogram – the data record from a seismograph.

- Seismogram depicts earthquake wave behavior, particularly the arrival times of the different waves, which are used to determine the distance to the epicenter.
- Seismic waves arrive at a station in sequence.
  - P-waves are first (fastest).
  - S-waves are second (slower).
  - Surface waves are last.
- Measure the time difference between the arrival of P-waves and S-waves.

- Because P-waves and S-waves travel at different velocities through the Earth, this time gap increases with distance from the epicenter.
- Locating an Earthquake epicenter:
  - Use travel-time curves for P- and S-waves to find out how far away an earthquake occurred.
  - The S–P interval gives the distance from the seismograph station to the epicenter.
  - On a map, draw a circle around each seismograph station with a radius equal to that calculated distance.
  - The point where the circles overlap marks the earthquake's epicenter.

6.14.6 Size of Earthquake

- Seismologists have developed two scales to define size:

  Mercalli intensity scale depends on human perception of ground shaking and the damage resulting from it at given locality.

  Magnitude scale focuses on the measured amount of ground motion, as recorded by a seismograph at a specified distance from the epicenter.
    - Richter scale
    - *Moment magnitude scale* – provide the most accuracte representation of an earthquake size (most common).

6.14.7 Where Do Earthquakes Occur?

- Shallow earthquakes happen in the top 60 km of the Earth.
- Intermediate earthquakes take place between 60 and 330 km.
- Deep earthquakes occur down to a depth of $\sim$ 660 km.
- Shallow earthquakes occur at divergent and transform boundaries.
- Intermediate and deep earthquakes occur at convergent boundaries.

6.14.8 Earthquakes at Plate Boundaries

- Divergent boundary (mid-ocean ridges)
  - Two oceanic plates form and move apart.
  - Divergent boundary consists of spreading segments linked by transform faults.
- Two types of faults develop at divergent boundaries:
  - *Normal faults* at the spreading ridge axis;

  - *Strike-slip faults* along the transforms.

- Earthquakes along mid-ocean ridges have foci at depths of less than 25 km, and classified as shallow earthquakes.
- Mid-ocean ridge earthquakes don't cause damage.

Transform-Plate Boundary

- Most are strike-slip faults.
- All transform-fault earthquakes have a shallow focus, so the larger earthquakes on land cause immense damage.
- The San Andreas fault cuts through western California where the Pacific plate shears north and the North American plate south.
- The San Francisco earthquake of 1906 (M_W of 7.9) serves an example of a continental transform-fault earthquake.

Convergent Boundary

- One plate subducts under another, and several different kinds of earthquakes take place (shallow, intermediate, and deep earthquakes):

  Normal faults form where the downgoing slab bends, seaward of trench.

  Large thrust faults occur at the contact between downgoing and overriding plates. Shear on the faults can produce disastrous, shallow earthquakes.

- Convergent boundaries host shallow, intermediate and deep earthquakes.
- The earthquakes occur in downgoing slab as it sinks into the mantle, and a sloping band of seismicity called a *Wadati Benioff zone*.
- Earthquakes are rare below 660 km as the mantle becomes too ductile.

6.14.9 Earthquakes Due to Continental Rifting

- The stretching of continental crust at continental rifts generates normal faults.
- Shallow earthquakes rattle the landscape.
- In contrast to mid-ocean ridge earthquakes, earthquakes in rifts occur on land and can be located under or near populated areas.
- Earthquakes in Africa occur mostly along the East African rift.

6.14.10 Earthquakes Due to Collision

- Two continents collide when the oceanic lithosphere that once separated them has been completely subducted.
- Such collision produce great mountains.
- Earthquakes in Southern Asia occur primarily in crust deforming due to the collision of Eurasia and India.

6.14.11 Intraplate Earthquakes

- Some earthquakes (about 5%) affect the interiors of plates and are not associated with late boundaries, active rifts, or collision zones.
- Intraplate earthquakes are caused by the stress applied to continental lithosphere triggers lip on pre-existing faults in the crust – long-lived weak "scars" in the crust.

6.14.12 Earthquake Waves

Earthquake Waves arrive in a distinct sequence with different motions.

P-waves are first to arrive. They produce a rapid, bucking, up-and-down motion.

S-waves arrive next (second). They produce a pronounced back-and-forth motion. This motion is much stronger than that from P-waves. S-waves cause extensive damage.

Surface waves are delayed traveling along the exterior.

L-waves follow quickly behind the S-waves. They cause the ground to writhe like a snake.

R-waves are the last to arrive. The land surface undulates like ripples across a pond. These waves usually last longer than the other kinds. R-waves cause extensive damage.

6.14.13 Earthquake Damages Due to Vibration

- Building floors "pancake".
- Bridges and roadways topple.
- Bridge support crush.
- Masonry walls break apart.

6.14.14 Earthquake Hazards

Landslides

- A landslide is the downslope tumbling, sliding, or flow of soil, rock or debris under the influence of gravity.
- Strong shaking can destabilize steep slopes or ground made up of loose or weak sediment, causing them to suddenly give way.
- Landslides frequently accompany earthquakes in places with topographic relief (hills, mountains, or steep valleys).

Liquefaction

- During strong shaking, seismic waves increase the pressure of water in the pore spaces of saturated sediments. As pore-water pressure rises, friction between grains is reduced.
- The sediment temporarily loses its strength and behave like a fluid (slurry).
  - Sandy soil can behave like quicksand.
  - Clay-rich soils can transform into quickclay.
- Liquefaction causes soil to lose strength. Land, and the structures on it, will slump and flow. Buildings may founder and topple over intact.

Fire

- Fire is a common result of earthquakes.
- The shaking during an earthquake can tip over lamps, stoves, or candles with open flames, and it may break wires or topple power lines, generating sparks.
- Firefighters are often powerless to combat fire without road access, no water, and too many hot spots.
- Fire may greatly magnify the destruction and tool in human lives.

Tsunamis

- Tsunami means harbor wave in Japanese.
- Tsunamis result from displacement of the sea floor by an earthquake, submarine landslide, or volcanic explosion that displaces the entire volume of overlying water.

6.14.15 Earthquake Prediction

- Can we predict earthquakes? Yes and no.
- We *can* predict in the long term (tens to thousands of years).
- We *cannot* predict in the short term (hours and weeks).
- Hazards can be mapped to assess risk and develop building codes, implement land-use planning, and disaster response.
- Earthquakes have precursors:
  - Clustered foreshocks
  - Crustal strain
  - Level changes in wells
  - Gases (Rn, He) in wells
  - Unusual animal behavior

6.14.16 Preparedness

- Map active faults and areas likely to liquefy from shaking.
- Develop construction codes to reduce building failures.
- Regulate land use to control development in hazard areas.

Chapter 7

Minerals

7.1 Minerals

- Minerals have a specialized geologic definition: naturally occurring, (mostly) inorganic crystalline solids formed by geologic processes and with a definite chemical composition.
- Minerals make up most rocks and sediments of the solid Earth.
- Minerals used as resources by mankind:
  - Industrial minerals provide the raw materials for manufacturing chemicals, concrete, and wallboard.
  - Ore minerals are the source of valuable metals, like copper and gold (e.g., Malachite is a type of copper ore ($Cu_2[CO_3][OH]_2$); it contains copper plus other chemicals
  - Gems delight the eye in jewelery.
- Certain minerals pose health and environmental hazards.

7.2 Mineral vs Glass

- Both mineral and glass are solids, but minerals are crystalline, while glass is not.
  - Atoms, ions, or molecules in a *mineral* are ordered into a geometric arrangement.
  - Atoms, ions, or molecules in *glass* are arranged in a semi-chaotic way, in small clusters or chains that are neither oriented in the same way nor spaced at regular intervals.

7.3 Crystals

- A crystal is a single, continuous (uninterrupted) piece of a crystalline material bounded by flat crystal surfaces, called crystal faces, that form naturally as the crystal grows.

- The angle between two adjacent crystal faces of any mineral specimen is identical to the angle between the corresponding faces of any other specimen of the same mineral.
  - e.g., the angle between the faces of the columnar part of a quartz crystal is exactly 120°.
- *All minerals are crystalline, but not all crystals are minerals!*
- Crystals come in a variety of shapes, including cubes, trapezoids, pyramids, octahedrons, blades, needles, columns, and obelisks.
- The geometry of the arrangement defines the crystal structure.

7.4 Inside a Mineral

- X-ray diffraction (XRD) is still used today to identify minerals!
- When an X-ray beam passes through a crystal, it interacts with the regularly spaced atoms inside.
- Because the spacing between atomic planes is similar to the wavelength of X-rays, the beam is diffracted (bent and scattered).
- This diffraction produces a distinctive pattern of spots or rings on a detector screen.

7.5 Crystal's Structure

- The geometry of the atomic packing and the nature of chemical bonding determine the mineral's properties.
  - The way elements are packed into a mineral crystal lattice depends upon the size and the charge of the ions of that element.
  - A large central cation requires a large number of anions; a smaller central cation, fewer anions.
  - e.g., sodium (Na^+) and chloride (Cl^-) ions are bonded in a cubic lattice by ionic bonds to form the mineral halite ($NaCl$), commonly known as salt.

7.5.1 Polymorphs

- Minerals that share the same chemical composition but have different crystal structures, meaning their atoms are arranged differently.
- Diamond vs. Graphite (both Carbon)
  - In diamond, each carbon atom bonds with four neighbors in a tight tetrahedral structure, making diamonds extremely hard.

  - In graphite, carbon atoms form flat sheets arranged in hexagons. The sheets are held together by weak bonds, so they easily slide past each other–this is why graphite is soft and works as "lead" in pencils.

7.6 Formation of Minerals

A new mineral crystal can form in one of five ways:

Solidification of a melt

Precipitation from a water solution - atoms, molecules, or ions dissolved in water bond together and separate out from the water.

Precipitation from a gas - typically occur around volcanic vents or geysers.

Solid-state diffusion - atoms migrate through the crystal and new minerals grow inside the rock.

Biomineralization - minerals can form at interfaces between the physical and biological components of the earth system.

7.7 Growth of Crystals

- The first step in forming a crystal happens when the chance assembly of a seed, an extremely small crystal, takes place.
- Once the seed exists, other atoms in the surrounding material attach themselves to the faces of the seed, and the seed grows into a crystal.
- As the crystal grows, its faces move outward but maintain the same orientation.
- A growing crystal develops its particular crystal shape based on the geometry of its internal crystal structure.

7.8 Destruction of Minerals

A mineral can be destroyed by melting, by dissolution, or by some other chemical reactions:

Melting involves heating a mineral to a temperature at which thermal vibrations of the atoms or ions in the crystal structure break the chemical bonds holding them to the lattice.

Dissolution takes place when a mineral is immersed in a solvent, such as water.

Chemical reactions can destroy a mineral when it comes in contacts with reactive materials.

7.9 Mineral Identification

Mineral identification requires learning mineral physical properties.

7.9.1 Color

- The color or a mineral results from how it interacts with light.
- Minerals absorb specific wavelengths of light, and the color we see is the combination of wavelengths that are not absorbed.
- Small amounts of chemical impurities can change the color dramatically. For example, trace amounts of iron can make quartz appear purple (amethyst) or yellow (citrine).

7.9.2 Streak

- The streak of a mineral is the color of its powdered form, produced by scraping the mineral across an unglazed ceramic plate.
- The streak color can be the same or different from the minerals' outward appearance.
- Streak color is often more consistent and reliable than external color, which may vary due to impurities or surface weathering.
  - e.g., Calcite always leaves a white streak, even though whole crystals may appear white, pink, or clear.
- Limitations: the streak test works best for minerals with a hardness of < 6 on the Mohs scale (so that it can be ground/powdered against the porcelain plate).

7.9.3 Luster

- Luster refers to the way a mineral surface scatters light.
- The two main subdivisions of luster are metallic and nonmetallic:

  Metallic luster : minerals that look like metal

  Nonmetallic luster : minerals that do not look like metal

7.9.4 Hardness

- Hardness indicates a mineral's ability to resist scratching, which depends on the strength of the bonds in its crystal structure.

Relative hardness : hard minerals can scratch softer ones, but soft minerals cannot scratch harder ones.

Mohs hardness scale : Friedrick Mohs arranged common materials in order of relative hardness.

- e.g. If your fingernail (hardness ~ 2.5) scratches a mineral, that mineral must be softer than 2.5.

7.9.5 Crystal Habit

- Crystal habit describes the external shape of a well-formed crystal or the overall appearance of a group of crystals that grew together.
- Habit reflects the internal atomic arrangement of the mineral.
- Common descriptive terms include cubic, prismatic, bladed, platy, and fibrous.
  - Wulfentie commonly forms thin, tabular plates.
  - Kyanite typically forms bladed crystals.

7.9.6 Cleavage

- Cleavage is the tendency of a mineral to break along specific planar surfaces that correspond to zones of weaker atomic bonding within the crystal lattice.
- The number of cleavage planes and the angles between them are diagnostic features used in mineral identification.
- Cleavage can be distinguished from crystal faces because cleavage repeats throughout the mineral, whereas crystal faces are just the external growth surfaces of the crystal.

7.9.7 Fracture

- Minerals that lack cleavage break by fracture, which may appear irregular or uneven.
- Conchoidal fracture is a special type of fracture that produces smoothly curving, clamshell-shaped surfaces. This is commonly seen in glass, quartz, and obsidian.
- Fracture is distinct from cleavage because it does not follow any specific atomic planes within the crystal structure.

7.9.8 Others

Other less common physical properties that are useful for identifying minerals:

Effervescence reactivity with acid

Magnetism magnetic attraction

Taste & smell

Feel tactile response

Elasticity response to bending

Diaphaneity relative transparency

Pizoelectricity electric charge when squeezes

Pyroelectricity electric charge when heated

Refractive Index degree of bending light

Malleability ability to be pounded into thin sheets

Ductility ability to be drawn into this wires

Sectility ability to be shaved with a knife

Specific Gravity

7.10 Hazardous Minerals

Some minerals contain toxic chemicals that can pose serious health risks.

- Arsenopyrite contains arsenic, which can release poisonous compounds when weathered.
- Asbestos is a fibrous silicate mineral; when inhaled, its needle-like fibers can lodge in human lungs, causing diseases such as asbestosis, mesothelioma, and lung cancer.
- Pulverized silicates (like quartz dust) can cause silicosis, a chronic lung disease, when inhaled over long periods.

7.11 Mineral Classification

Mineralogists distinguish **seven principal classes** of minerals:

Silicates all silicates contain the ${SiO_4}^{4-}$ anionic group.

Sulfides consists of a metal cation bonded to a sulfided anion (${S_2}^{-}$).

Oxides consist of metal cations bonded to oxygen atoms.

Halides the anion in a halide is a halogen or salt producing ion (such as chloride (Cl^-) or fluoride (F^-)).

Carbonates in carbonate minerals, the molecule ${CO_3}^{2-}$ serves as the anionic group.

Native metals consist of pure masses of a single metal.

Sulfates consist of metal cations bonded to ${SO_4}^{2-}$.

7.11.1 Silicates

- Silicates are the major rock-forming minerals, making up over 95% of the continental crust.
- All silicates contain the $SiO_4{}^{4-}$ anionic group, also called the silica tetrahedron. In this structure, four oxygen atoms surrounds a single silicon atom, forming a pyramid-like shape with four triangular faces.
- Silicate minerals are grouped based on how these silica tetrahedra are arranged and linked together.
- The arrangement depends on how many oxygen atoms are shared between tetrahedra, which in turn determines the silicon-to-oxygen ratio in the mineral.
  - Isolated tetrahedra (independent)
  - Single-chain silicates
  - Double-chain silicates
  - Sheet silicates
  - Framework silicate

7.11.2 Gemstones and Gems

- A gemstone is a mineral that holds special value because it is rare and considered beautiful.
- Gemstones can form in several ways, including solidification from melt, diffusion, precipitation, or chemical interaction between rock and water near Earth's surface.
- When a gemstone is cut and polished, it becomes a gem, ready to be set into jewelry.
  - Precious stones include diamond, ruby, sapphire, and emerald
  - Semiprecious stones include topaz, tourmaline, aquamarine, and garnet
  - Most gemstones are transparent crystals, often showing vibrant colors that add to their appeal.

Table 7.1: Precious and Semiprecious Materals Used in Jewelry

Gem Name	Material/Formula	Comments
Amber	Fossilized tree sap	Composed of organic chemicals; amber is not strictly a mineral.
Amethyst	Quartz/SiO_2	The best examples precipitate from water in openings in igneous rocks; a deep purple version of quartz.
Aquamarine	Beryl/$Be_3Al_2Si_6O_{18}$	A bluish version of emerald.
Diamond	Diamond/C	Brought to the surface from the mantle in igneous bodies called diamond pipes; may later be mixed in deposits of sediment.
Emerald	Beryl/$Be_3Al_2Si_6O_{18}$	Occurs in coarse igneous rocks (pegmatites)
Garnet		
Jade		
Opal		
Pearl		
Ruby		
Sapphire		
Topaz		
Tourmaline		
Turquoise		

Chapter 8

Mineral Resources

- Geologists divide mineral resources into two categories.

  Metallic mineral resources include gold, copper, aluminum, iron, or other metals.

  Nonmetallic mineral resources include building stone, gravel, sand, gypsum, phosphate, and salt, used in construction or for chemical production.

- *What is a metal?*

8.1 Metal

- Metals are opaque, shiny, and smooth solids that conduct electricity.
- These properties come from metallic bonds, in which electrons are delocalized - free to move easily from atom to atom.
  - In contrast, covalent or ionic bonds in nonmetallic materials do not allow this kind of electron mobility.
- The behavior of a metal depends on:
  - The strength of bond between atoms;
  - The architecture of its crystal structure.
- Metals are also known for their mechanical properties:

  Ductility the ability to be drawn into thin wires.

  Malleability the ability to be hammered into thin sheets.

8.2 Discovery of Metals

8.2.1 Early Metals

Gold (ca. 6,000 BCE) likely the first humans encountered because it occurs naturally in pure (native) form.

Copper (ca. 5,000 BCE) first metal smelted from ores. Initially used in pure form, but too soft for durable tools.

Bronze (ca. 3,300 BCE) discovery of alloying copper with tin created bronze, which is stronger and harder. Marked a major leap in tool and weapon production, leading to the Bronze Age.

8.2.2 Iron Age

Iron (ca. 1,200 BCE) more abundant than copper and tin, but harder to smelt (requires higher temperatures). Compared with copper or bronze, iron offered greater strength, hardness, and abundance, eventually replacing bronze for tools, weapons, and building materials.

Steep (ca. BCE, widely used by ∼1,000 CE) an alloy of iron and carbon, stronger and more versatile that pure iron.

Stainless steel (1,913 CE) alloy of iron with chromium, highly resistant to corrosion. Revolutionized modern engineering, especially in medicine, food, and infrastructure.

8.2.3 Modern Metals

Aluminum (1,825 CE) lightweight, corrosion-resistant; now essential for aviation, packaging, and construction.

Other 19th-20th Century Discoveries Include:

Titanium (1791) lightweight, strong, corrosion-resistant.

Uranium (1789) key for nuclear energy in the 20th century.

Rare Earths (1790s-1900s) a set of 17 nearly indistinguishable lustrous silvery-white soft heavy metals. Now critical for electronics and green energy.

- Scandium (Sc)
- Yttrium (Y)
- Cerium (Ce)
- Neodymium (Nd)
- Lanthanum (La)
- Dysprosium (Dy)
- Samarium (Sm)
- Terbium (Tb)
- Praseodymium (Pr)
- Gadolinium (Gd)

- Europium (Eu)
- Ytterbium (Yb)
- Holmium (Ho)
- Lutetium (Lu)
- Thulium (Tm)
- Erbium (Er)
- Promethium (Pm)

8.3 Native Metals

- Native metals (gold, silver, copper, iron) occur naturally in their pure, metallic form, rather than as part of a compound.
- Native metals are relatively rare in nature, which is why they are so valuable. In fact, native metals make up only a tiny fraction of the world's current metal supply.

8.4 Ore Minerals

- Naturally occurring minerals that contain a sufficient concentration of valuable elements, typically metals, to be extracted and processed.
- Ores are often associated with gangue minerals, which are non-valuable materials that need to be separated from the desired ore minerals.
- Principal metals in most common use today:
  - Aluminum from Bauxite
  - Iron from Hematite and Magnetite
  - Copper from Chalcopyrite
  - Zinc from Sphalerite
  - Lead from Galena

8.5 Smelting

- A high-temperature process that extracts a metal from its ore.
- When minerals decompose during smelting, the process yields a metal (useful product) and a nonmetallic residue known as slag.
- Different ores require different smelting techniques at varying temperatures.

8.5.1 Smelting vs Melting

- Melting involves heating a substance to its melting point, causing it to change from a solid to a liquid without a chemical change.
- Smelting is a more complex process that includes melting but also involves a chemical reaction to remove oxygen and separate the metal from impurities.

8.6 Ore-forming Processes

- Ore deposits typically require specialized geological processes to concentrate valuable metals or minerals into economically recoverable amounts.
  - Magmatic processes
  - Hydrothermal processes
  - Metamorphic processes
  - Sedimentary processes
- Whereas, other deposits form by more common geologic processes like erosion, deposition, or evaporation.
- c.e., metals and many useful minerals are typically present in the Earth's crust in very low concentrations. To make mining economical, nature must concentrate them far beyond their average abundance!

8.7 Ore Deposits

Magmatic process as magma cools, certain materials crystallize earlier or segregate into dense layers. This can concentrate metals like chromium, nickel, or platinum.

Hydrothermal process hot fluids dissolve metals, travel through fractures, and precipitate valuable minerals in veins when conditions (temperature, pressure, chemistry) change.

Metamorphic process metamorphism can remobilize and re-concentrate minerals under high pressure and temperature.

Sedimentary process metals like iron, manganese, or uranium can concentrate in chemical sedimentary rocks (e.g., banded iron formations).

- Banded iron formations (BIFs) consist of alternating layers of gray hematite (Fe_2O_3) and iron-rich red chert (jasper).
- Manganese nodules grow slowly on the sea floor and are rich in MnO_2 and trace elements.

8.8 Ore Exploration and Production

Prospecting geologists and prospectors look for visible traces of ore minerals in rock outcrops.

Geological surveys measurements of magnetism, gravity, or radioactivity can reveal anomalies in the Earth's field that may indicate hidden ore bodies.

Geochemical surveys soil, water, sediments, and even plants (biota) are analyzed.

Drilling and sampling once an ore deposit is suspected, geologists drill boreholes to collect subsurface rock samples. This helps determine the shape, size, and extent of the deposit.

Production (mining) the type of mining depends on the proximity of the ore body to the surface.

Open-pit mining used when ore bodies are close to the surface. It involves removing overburden and excavating the ore in large benches. This method is cheaper and safer.

Underground mining necessary for deeper ore bodies. It involves shafts and tunnels to access ore. Although it reaches greater depths, it is more expensive and hazardous, with risks like tunnel collapses, poisonous gases, and explosions.

8.9 Mining and Ore Processing

- Miners extract crude ore (yellow)
- Waste rock is often piled in waste rock dumps.
  - Not all rock removed contains valuable minerals.
  - Waste rock is the unmineralized or low-grade rock that must be separated and dumped.
- The crude ore is transported to processing facilities
- Ore goes to concentration and chemical separation ponds
  - Valuable minerals are separated from waste through flotation, leaching, or other chemical methods.
- After separation, the valuable portion is collected as concentrated metal.
- The leftover slurry of ground rock and processing chemicals is called tailings.
  - Tailings are stored in tailings ponds, often held back by dams to prevent them from flowing downstream.
  - These storage areas are major environmental concerns, as failures can release toxic material.

8.10 Mining and Environment

- Mineral extraction and processing leaves significant ecological footprints.

8.10.1 Land disturbance

- Mining reshapes landscapes through open pits, waste dumps, and tailing ponds.
- Removal of vegetation and topsoil leads to erosion and loss of biodiversity.

8.10.2 Waste Rock and Tailings

- Waste rock piles may leach harmful chemicals, especially if they contain sulfide minerals (leading to acid mine drainage).
- Tailings pongs store toxic slurries of fine particles mixed with processing chemicals. Dam failures have caused catastrophic downstream destruction.

8.10.3 Water Pollution

- Acid Mine Drainage (AMD): When sulfide-rich waste reacts with water and oxygen, it produces sulfuric acid, dissolving heavy metals (like arsenic, lead, and mercury) into rivers and groundwater.
- Cyanide and mercury contamination from gold mining can poison ecosystems.

8.10.4 Air Pollution

- Dust from blasting, hauling, and crushing contributes to particulate air pollution.
- Smelting releases sulfur dioxide (SO_2), which can form acid rain.
- GHG from fuel use and processing add to climate change impacts.

8.11 Nonmetallic Rock and Mineral Resources

- Common nonmetallic resources are used in construction, agriculture, industry, and chemical processes.
  - e.g., limestone, crushed stone, granite, marble, gypsum, phosphate, pumice, clay, and, salt, and sulfur.
- Dimension stone: intact slabs and blocks of rock
  - e.g., granite, marble, limestone
  - Workers carefully cut rock from quarry walls to preserve intact pieces.

- Crushed stone (aggregate): broken rock used as raw material for cement, concrete, and asphalt.
- Concrete and mortar: rock-like mixtures made of aggregate (sand, gravel, or crushed rock) held together by cement.
- Cement is the powder that consists of lime (CaO), quartz (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3). It acts as the binder in concrete and mortar.
  - Natural cement was first developed by the Ancient Romans and is made from volcanic ash + limestone heated in kilns. Rarely produced today.
  - Portland cement is most common modern cement. It is made by carefully mixing crushed limestone, sandstone, and shale in correct proportions.

8.12 Nonmetallic Minerals for Homes and Farms

Clay forms from the chemical weathering of silicate rocks. It is used for bricks, pottery, porcelain, and other ceramics.

Quartz (silica) sourced from quartz sand (beach or sandstone). It forms glass and is also used in photovoltaic cells for solar panels.

Gypsum mixed with water into a slurry and layered paper. It produces gypsum board (drywall) for building construction.

Plastics derives from oil extracted from underground reserves.

Asbestos come from serpentine, formed by the reaction of olivine with water. Asbestos was historically used for fireproofing and insulation.

8.13 How Long will Resources Last?

- Mineral resources are nonrenewable - once an ore deposit or a limestone hill is mined, it's gone forever.
- Industrialized countries consume vast amounts of mineral resources each year.
- Strategic minerals are of particular concern: manganese, platinum, chromium, and cobalt. These metals are alloyed with iron to make special-purpose sheets (e.g., aerospace industry).

Chapter 9

Rocks

9.1 Why Study Rocks?

- Foundation for geology: Understanding rocks in essential for interpreting many geologic processes such as volcanic eruptions, mountain building, weathering, erosion, and earthquakes.
- Environmental history: Every rock preserves evidence about the conditions under which it formed, offering a "record" of Earth's geologic past.

9.2 What is Rock?

- *Rock* – to a geologist, rock is coherent, naturally occurring solid that consists of an aggregate of minerals or, less common, a body of glass.

  Coherent rocks hold together; they don't crumble easily. To separate them into smaller pieces, you have to physically break them.

  Naturally occurring: Only materials formed by natural geologic processes count as rocks (man-made concrete, for example, does not)

  Aggregate of minerals or glass Most rocks are collections of mineral grains or crystals, but some–like volcanic glass–consist of solid glass.

9.2.1 Coherent Solids

- Rocks are coherent solids because the grains within them are bound together in one of two ways:

  Clastic rocks (cememntation) The grains are held together by natural cement. This cement is made of minerals that precipitated from water in the pore spaces between the grains.

  Crystalline rocks (interlocking) The mineral grains interlock with each other, much like pieces of a jigsaw puzzle. This happens during the crystallization of minerals from a melt (igneous rocks) or recrystallization during metamorphism.

9.3 Chemical Composition of Rocks

Not all rocks contain the same chemicals.

Silicate minerals the most abundant: the majority of Earth's crust is made up of silicate minerals, which are built from silicon (Si) and oxygen (O). These two elements together make up almost 75% of the crust's composition.

Carbonate minerals Biogenic Contribution: at or near Earth's surface, living organisms play a significant role in rock formation. Many organisms play a significant role in rock formation. Many organisms extract calcium (Ca) and carbonate ($CO_3{}^{2-}$) ions from water to form shells and skeletons. Over time, these materials accumulate and solidify into carbonate rocks such as limestone and dolostone.

9.4 Rock Cycle

- Although rocks may seem like permanent, unchanging masses, they are part of a continuous rock cycle that transforms one rock type into another over long periods of time.
- What drives the rock cycle?

  Earth's internal heat form igneous and metamorphic rocks.

  Energy from the sun (external) weathering and the transport of weathered materials.

9.5 Rock Classification

In geology, rocks are classified based on how they form. In the modern genetic scheme, there are three main rock classes:

Igneous rocks form by the solidification of molten rock, either magma or lava.

Sedimentary rocks form either by cementing together grains broken off from pre-existing rocks or by precipitation of minerals from water solution at or near the Earth's surface.

Metamorphic rocks form when pre-existing rocks change in texture or mineral composition due to increase in temperature, pressure, or stress.

9.6 Physical Characteristics of Rocks

Individual rock types are often distinguished from one another based on their physical characteristics, including:

- Grain size and shape
- Rock composition

- Texture – crystalline, clastic, or glassy.
- Layering – e.g., bedding or foliation.

9.7 Igneous Rocks

- Igneous rocks are formed by the freezing (solidification) of molten rock. They make up a great variety of rocks in the Earth's crust.
- How they form in nature:
  - Hot molten rock fountaining from a volcanic opening may build up around the vent or flow downhill as lava.
  - As lava flows, it can burn and melt the ground in its path.
  - While cooling, the surface of the lava darkens and hardens, creating a crust that insulates the still-hot material beneath.
  - Eventually, the lava stops moving and solidifies completely into a hard, black solid.

9.8 Formation of Melts

Geologists use specific terms for molten rock:

Magma molten rock that remains beneath Earth's surface.

Lava molten rock that reaches the Earth's surface.

Volcano a vent through which lava emerges. When lava flows or explodes out of the vent, we call that a volcanic eruption.

Pyroclastic debris the fragmental materials ejected during explosive eruption.

Geologist classify igneous rocks by where the melt solidifies:

- Extrusive igneous rock
- Intrusive igneous rock

9.9 Igneous Rock Classification

9.9.1 Extrusive Igneous Rock

- Form when lava cools and solidifies above ground.
- Can also form by the cementing or welding togethering of pyroclastic debris.

9.9.2 Inclusive Igneous Rock

- Form when magma pushes into pre-existing rock below the surface and then cools and solidifies underground.
- Magma may accumulate in large, irregularly shaped magma chambers or intrude into rock as thin sheets or dikes.

9.10 Chemical Variability of Molten Rock

Geologists distinguish among four major compositional types of molten rock depending on the proportion of silica relative to the combination of magnesium oxide and iron oxide that a melt contains.

Mafic melts contain a relatively high proportion of magnesium oxide and iron oxide relative to silica.

Ultramafic melts have an even higher proportion of magnesium oxide and iron oxide relative to silica.

Felsic melts have a relatively high proportion of silica relative to magnesium oxide and iron oxide.

Intermediate melts are so named because their composition lies partway between those of mafic and felsic melts.

Table 9.1: The Four Categories of Magma

Felsic (or silicic) magma	67–76% silica*
Intermediate magma	53–66%
Mafic magma	46–52%
Ultramafic magma	38–45%

* The numbers provided are 'weight precent', meaning the proportion of the magma's weight that consist of silica.

9.11 Factors Affecting the Compositions of Melts

Source-rock composition the composition of a melt reflects the composition of the solid rock from which it was derived.

Partial melting temperatures at sites of magma production typically do not become high enough to melt the entire source rock. Instead, magma tends to migrate away from the melting site before the rock has completely melted. As a result, only a portion of the original rock undergoes melting to produce magma. Magmas formed by partial melting are generally more felsic, while more silica-rich components often remain in the still-solid residue of the source rock.

Assimilation as magma sits in a magma chamber before bully solidifying, it may incorporate chemical components from the surrounding wall rock. This can occur through the dissolution of wall rock into the magma or from blocks that break off, sink, and partially melt within the magma body.

Magma mixing magmas formed in different locations and from different source rocks may migrate into the same magma chamber, where they mix to form a hybrid melt with a composition distinct from either original magma.

9.12 Movement of Molten Rock

Why does magma rise? Magma in the Earth rises for two reasons:

Buoyancy magma is less dense than the surrounding rock, so a buoyant force acts on it, driving it upward.

Pressure from overlying rock the weight of the overlying rock creates pressure at depth, which squeezes the magma and forces it to move upward.

What controls the speed at which molten rock flows?

- The speed of molten rock movement depends on its viscosity, or resistance to flow. Not all molten rock has the same viscosity–this property is primarily influenced by:

  Temperature High temperatures lower viscosity.

  Volatile content More volatiles (e.g., water, gases) lower viscosity.

  Silica content Higher silica increases viscosity, making the magma thicker and slower-moving.

9.13 Viscosity of Molten Rock

- Mafic lava (less silica content)
  - Mafic lava contains more volatiles and has relatively low viscosity.
  - Because of its fluidity, it can erupt in fountains, travel long distances, and form thin, widespread lava flows.
- Felsic to intermediate lava (higher silica content)
  - Felsic lava is typically cooler, contains fewer volatiles, and has high viscosity.
  - The high silica content results in more silicon-oxygen tetrahedra, which tend to form long chains that restrict flow. This structure makes felsic melt significantly more viscous than mafic melt.
  - When felsic lava erupts, it often forms a lava dome – a mound shaped accumulation of lava near the volcano's vent.

9.14 Solidification of Molten Rock

Cooling occurs as magma rises toward the Earth's surface, where the surrounding crust is significantly cooler.

- If magma becomes trapped underground as an intrusion, it gradually loses heat to the surrounding wall rock. When its temperature drops below the freezing point, it solidifies.
- If magma reaches the surface and erupts as lava, it cools rapidly due to contact with much cooler air or water.
- In some cases, magma solidifies due to the loss of volatiles, which can reduce its ability to remain molten.

9.15 Factors Affecting the Cooling Time of Magma

- Several factors influence how quickly magma cools and solidifies:

  Depth of Intrusion magma intruded deep within the crust, where surrounding rock is also hot, cools more slowly than magma closer to the surface.

  Shape and size of the magma body heat escapes from the surface of a magma body. Therefore, for a given volume, the larger the surface area, the faster it cools.

  The presence of circulating groundwater groundwater flowing through the surrounding wall rock can carry away heat, much like a coolant in an engine, accelerating the cooling process.

9.16 Igneous Rocks Characterization

- Igneous rocks are described by the color and texture.
- Color generally reflects the rock's composition–influenced by grain size and by the presence of trace amounts of impurities.
- Textures reveal something about the history of how the melt cooled.
  - Crystalline texture
  - Fragmental texture
  - Glassy texture

9.17 Igneous Rock's Texture

Crystalline igneous rocks consist of mineral crystals that intergrow when the melt solidifies, so that they fit together like jigsaw puzzle pieces.

- The interlocking of crystal in rocks happens because the rock does not solidify instantly. Rather different crystals grow at different rate and at different times, and they interface with each other as the crystal grow.

Fragmental igneous rocks form pyroclastic debris and consist of igneous chunks, grains, or flakes that are packed together, welded together, or cemented together after they have solidified.

Glassy igneous rocks are rocks made of a solid mass of glass or of glass surrounding isolated small crystals.

9.18 Classifying Igneous Rocks

9.18.1 Crystalline Igneous Rocks

- The name applied ot a given rock sample depends on both the composition and the grain size of the sample.
- Color and density of an igneous rock provide clues to its composition:
  - Felsic rock tend to be tan or pink/maroon and have low density.
  - Mafic rock tend to be black or dark gray and have relatively high density.

9.18.2 Fragmented Igneous Rocks

- Accumulations of pyroclastic debris are called pyroclastic deposits. When these deposits consolidate into a solid mass, it becomes a pyroclastic rock.
- Geologists distinguish the types of pyroclastic rocks based on grain size:

  Tuff (left) fine-grained pyroclastic rock fragmented rock composed of ash

  Volcanic breccia (right) consists of angular fragments of pyroclastic debris

9.18.3 Glassy Igneous Rocks

- Glassy texture most commonly in felsic igneous rocks because the high concentration of silica inhibits diffusion, and therefore, the growth of crystals.
- In some cases, a rapidly cooling lava freezes while it still contains gas bubbles; these bubbles remain as open holes known as *vesicles*.

  Obsidian a vesicle-free felsic glass.

Tachylite a relatively rare vesicle-free magic glass.

Pumice a felsic volcanic rock that contains abundant vesicles (it floats on water).

Scoria a mafic volcanic rock with many vesicles.