Chapter 16: Earth and Moon: Bases for Comparative Planetology
A Travel Guide to the Terrestrial Planets

Mercury is slightly more than a third the diameter of Earth, has no atmosphere, and is heavily cratered.

Planet Earth, the basis for the comparative planetology of the Terrestrial planets, is a water world. It is widely covered by liquid water, has polar caps of solid water, and has an atmosphere rich in water vapor and water-droplet clouds.

Venus, 95 percent the diameter of Earth, has a thick cloudy atmosphere that hides its surface from view. Seen through an Earth-based telescope, it is a featureless white ball.

Radio-wavelength radiation can penetrate the clouds, and radar maps of the surface of Venus reveal impact craters, volcanoes, and solidified lava flows.

Mars, slightly over half Earth's diameter, has a thin atmosphere and a rocky, cratered crust marked by volcanoes and old lava flows.

Earth's moon is only one-fourth Earth's diameter. It is airless and heavily cratered.

Polar cap of frozen water and carbon dioxide
Core, Mantle, Crust, Atmosphere

All terrestrial planets have a similar structure of:

- A liquid core
- A mantle of molten lava
- A crust of solid, low-density rocks
- An atmosphere (large range of compositions and pressures)
The Early History of Earth

Earth formed 4.6 billion years ago from the inner solar nebula.

Four main stages of evolution:

Two sources of heat in Earth’s interior:

• Potential energy of infalling material

• Decay of radioactive material

Most traces of bombardment (impact craters) now destroyed by later geological activity
Differentiation

- When earth was forming, gravity pulled high-density material to center.
- Lower-density material rises to surface.
- Material ends up separated by density.
Seismology

Direct exploration of Earth’s interior (e.g. drilling) is impossible. Earth’s interior can be explored through seismology:

Earthquakes produce seismic waves.

Seismic waves do not travel through Earth in straight lines or at constant speed.

They are bent by or bounce off transitions between different materials or different densities or temperatures.

Such information can be analyzed to infer the structure of Earth’s interior.
The Active Earth

About 2/3 of Earth’s surface is covered by water.

Mountains are relatively rapidly eroded away by the forces of water.
Most traces of bombardment (impact craters) on Earth have been destroyed by later geological activity.

For example, the Chicxulub Crater was caused by a large impact 65 million years ago, and only faint traces of this 110 mile wide crater remain.
Geological Processes

Earth’s surface still evolves due to:

• Erosion
  — Surface changes made by wind, water, or ice

• Impact cratering
  — Impacts by asteroids or comets

• Tectonics
  — Disruption of a planet’s surface by internal stresses

• Volcanism
  — Eruption of molten rock onto surface
Erosion by Water

• The Colorado River continues to carve the Grand Canyon.
Erosion by Ice

- Glaciers carved the Yosemite Valley.
Erosion by Wind

- Wind wears away rock and builds up sand dunes.
Impact Craters

Meteor Crater (Arizona)

While most craters from the early bombardment are no longer seen, we still find craters from later impact.
Tectonic Plates

Earth’s crust is composed of several distinct tectonic plates, which are in constant motion with respect to each other. → plate tectonics

Evidence for plate tectonics can be found on the ocean floor… … and in geologically active regions all around the Pacific.
Plate Tectonics

Tectonic plates move with respect to each other.

Where plates move toward each other, plates can be pushed upward and downward → formation of mountain ranges, some with volcanic activity, earthquakes.

Where plates move away from each other, molten lava can rise up from below → volcanic activity.
Active Zones Resulting from Plate Tectonics

Volcanic hot spots due to molten lava rising up at plate boundaries or through holes in tectonic plates.
Earth’s Tectonic History

Not long ago, Earth's continents came together to form one continent.

Pangaea broke into a northern and a southern continent.

Laurasia
Gondwanaland

Notice India moving north toward Asia.

The continents are still drifting on the highly plastic upper mantle.

Today
History of Geological Activity

Surface formations visible today have emerged only very recently compared to the age of Earth.
Outgassing

• Volcanism also releases gases from Earth’s interior into the atmosphere.
The Atmosphere

Earth had a primeval atmosphere from remaining gasses captured during formation of Earth.

Atmospheric composition severely altered (secondary atmosphere) through a combination of two processes:

1) Outgassing: Release of gasses bound in compounds in the Earth’s interior through volcanic activity.

2) Later bombardment with icy meteoroids and comets.

Composition of Earth’s atmosphere is further influenced by:

- Chemical reactions in the oceans
- Energetic radiation from space (in particular, UV)
- Presence of life on Earth
Human Effects on Earth’s Atmosphere

The Greenhouse Effect

Earth’s surface is heated by the sun’s radiation.

Heat energy is re-radiated from Earth’s surface as infrared radiation.

$\text{CO}_2$, but also other gases in the atmosphere, absorb infrared light.

$\rightarrow$ Heat is trapped in the atmosphere.

This is the Greenhouse Effect.

The Greenhouse Effect occurs naturally and is essential to maintain a comfortable temperature on Earth,

But human activity, in particular $\text{CO}_2$ emissions from cars and industrial plants, is drastically increasing the concentration of greenhouse gases.
Summary of Earth’s Formation and Structure

The four stages of formation:

1. **Differentiation**: Heavier elements sink while lighter elements rise, creating Earth’s core and thin crust.

2. **Cratering**: Space material continues to bombard Earth, creating craters.

3. **Flooding**: Lava and water fill lowlands, creating lakes and oceans.

4. **Slow Surface Evolution**: Earth’s surface continued to be changed by different processes such as erosion, tectonic and volcanic activity, and outgassing.
The Large-Impact Hypothesis

- Impact heated material enough to melt it
  → consistent with “sea of magma”
- Collision not head-on
  → Large angular momentum of Earth-moon system
- Collision after differentiation of Earth’s interior
  → Different chemical compositions of Earth and moon
From Earth, we always see the same side of the moon.

Moon rotates around its axis in the same time that it takes to orbit around Earth:

Tidal coupling:

Earth’s gravitation has produced tidal bulges on the Moon.

Tidal forces have slowed rotation down to same period as orbital period.
Lunar Surface Features

Two dramatically different kinds of terrain:

- **Highlands**: Mountainous terrain, scarred by craters
- **Lowlands**: ~ 3 km lower than highlands; smooth surfaces:
  - **Maria** (pl. of mare): Basins flooded by lava flows
Impact Cratering

Impact craters on the moon can be seen easily even with small telescopes.

Ejecta from the impact can be seen as bright rays originating from young craters.

A meteorite approaches the lunar surface at high velocity.

On impact, the meteorite is deformed, heated, and vaporized.

The resulting explosion blasts out a round crater.

Slumping produces terraces in crater walls, and rebound can raise a central peak.
Impact Cratering

Some meteorites found on Earth have been identified chemically as fragments of the moon’s surface, ejected by crater impacts.

The energy of an impact can melt rock, some of which falls back into the crater and solidifies. When the moon was young, craters could also be flooded by lava welling up from below the crust.
History of Impact Cratering

Rate of impacts due to interplanetary bombardment decreased rapidly after the formation of the solar system.

Most craters seen on the Moon’s (and Mercury’s) surface were formed within the first $\sim \frac{1}{2}$ billion years.

![Rate of Crater Formation](chart)

Notice the exponential scale in this graph of the cratering rate. Only half a billion years after the origin of the solar system, the cratering rate had fallen by a factor of 10,000. Today, the rate is very low, and no crater is known with certainty to have been formed on the moon in historic times.
Apollo Landing Sites

First Apollo missions landed on safe, smooth terrain. Later missions explored more varied terrains.

Apollo 11: Mare Tranquilitatis; lunar lowlands

Apollo 17: Taurus-Littrow; lunar highlands
Moon Rocks

All moon rocks brought back to Earth are **igneous** (= solidified lava)

No sedimentary rocks => No sign of water is ever present on the Moon.

Different types of moon rocks:

- **Vesicular** (= containing holes from gas bubbles in the lava) basalts, typical of dark rocks found in maria
- **Breccias** (= fragments of different types of rock cemented together), also containing anorthosites (= bright, low-density rocks typical of highlands)
- Older rocks become pitted with small micrometeorite craters.
The History of the Moon

Moon is small; low mass → rapidly cooling off; small escape velocity → no atmosphere → unprotected against meteorite impacts

Moon must have formed in a molten state (“sea of lava”)

Heavy rocks sink to bottom; lighter rocks at the surface

No magnetic field → small core with little metallic iron

Surface solidified ~ 4.6 – 4.1 billion years ago

Heavy meteorite bombardment for the next ~ ½ billion years

Alan Shepard (Apollo 14) analyzing a moon rock, probably ejected from a distant crater.
Origin of Mare Imbrium

- Near the end of the heavy bombardment, a giant impact creates a vast crater basin.
- Faulting in the crust produces rings of mountains, and lava flows fill the lowest regions.
- Today all but the outlines of the impact have been covered by dark lava flows.
Formation of Maria

Impacts of heavy meteorites broke the crust and produced large basins that were flooded with lava.
Summary of the Moon’s Formation and Structure

-The Moon was likely created when a large object impacted Earth after it differentiated.

-It is made out of rock, with no atmosphere or water.

-It is full of craters, with the flatlands were smoothed out by lava flooding the craters after they were crated.

-There is no plate tectonics or volcanic activity, so the craters on its surface will not be erased.