Origin and Differentiation of the Earth

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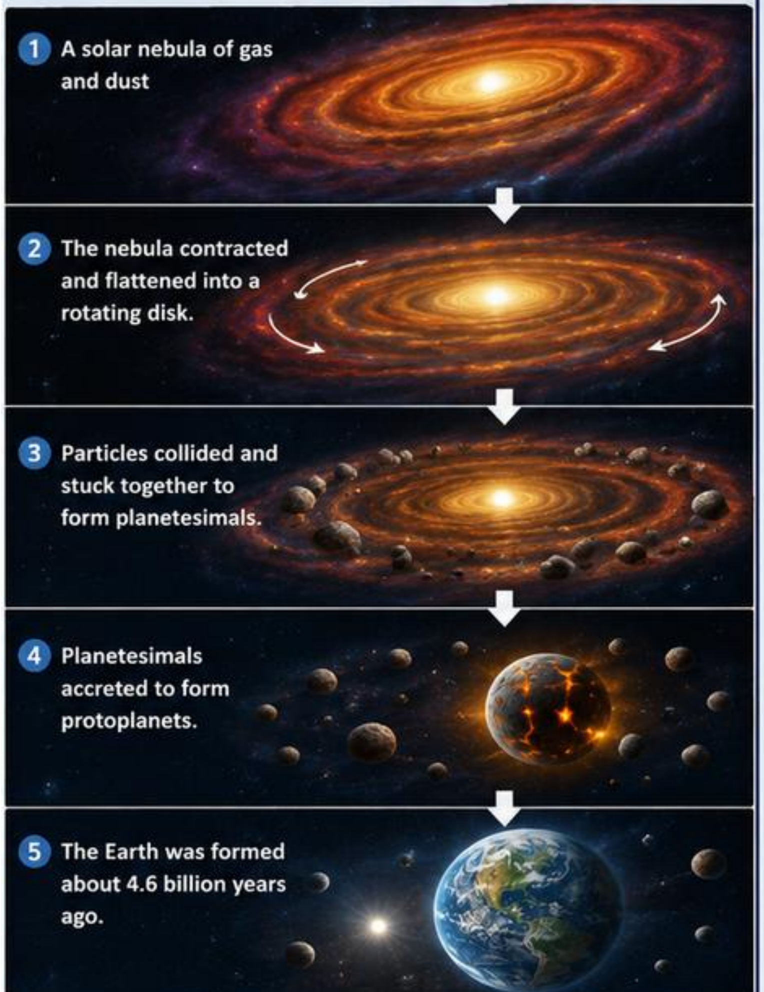
ORIGIN OF THE EARTH

Nebular Hypothesis (Kant–Laplace Hypothesis)

About 4.6 billion years ago, a giant rotating cloud of gas and dust called the solar nebula began to contract.



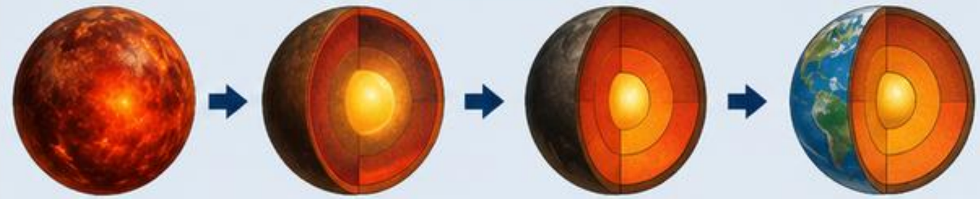
Key Points

- Age of the Earth – about 4.6 billion years.
- Formed by accretion of planetesimals from the solar nebula.
- Initially very hot, molten and undifferentiated.
- Gradually cooled and differentiated into layers.

DIFFERENTIATION OF THE EARTH

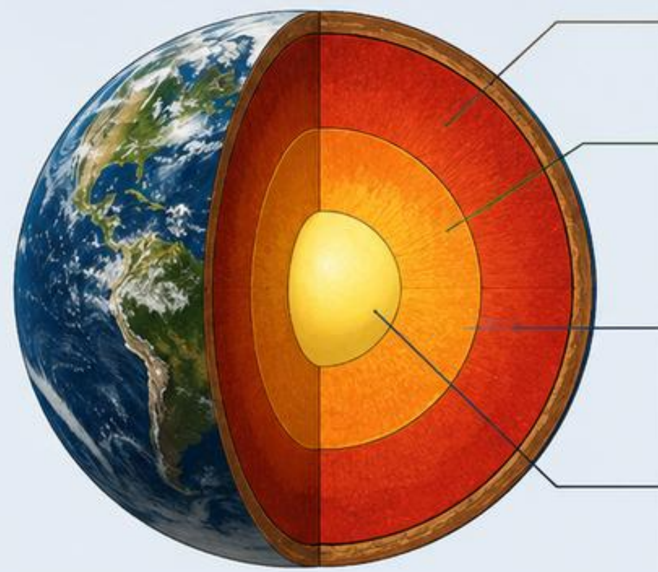
Differentiation is the process by which the Earth's interior separated into distinct layers due to density differences.

Process of Differentiation



1. The early Earth was hot and completely molten.
2. As it cooled, denser materials (iron and nickel) sank towards the center.
3. Lighter materials (silicates) moved upward to form the mantle and crust.
4. Eventually, Earth differentiated into crust, mantle and core.

Present Interior Structure of the Earth



Crust
- Thin, outermost solid layer.
- Thickness: 5–70 km
- Composed of rocks.

Mantle
- Thickest layer.
- Thickness: about 2900 km
- Composed of silicate rocks.
- Mostly solid but behaves plastically.

Outer Core
- Liquid layer.
- Thickness: about 2200 km
- Composed mainly of iron and nickel.

Inner Core
- Solid layer.
- Radius: about 1220 km
- Composed mainly of iron and nickel.

Key Points

- Density and temperature differences caused gravitational separation.
- Heavier elements sank; lighter elements rose.
- Resulted in a layered structure – crust, mantle, outer core and inner core.
- This process formed the dynamic planet we live on.

Sequence of Differentiation of the Earth

Earth differentiation is the process by which the early Earth separated into layers of different composition and density due to intense heat generated during its formation.

1. Accretion of the Earth

About **4.6 billion years ago**, Earth formed from dust and gas in the solar nebula.

Collisions of planetesimals led to the growth of the proto-Earth.

2. Heating of the Early Earth

Heat was produced by:

- Gravitational compression
- Meteorite impacts
- Radioactive decay of elements

The Earth became partially or completely molten.

3. Density-Based Separation

Heavy materials sank toward the center.

Lighter materials rose toward the surface.

This process is called **gravitational differentiation**.

4. Formation of the Core

Dense elements such as **iron (Fe)** and **nickel (Ni)** migrated inward.

They formed the **core**, consisting of:

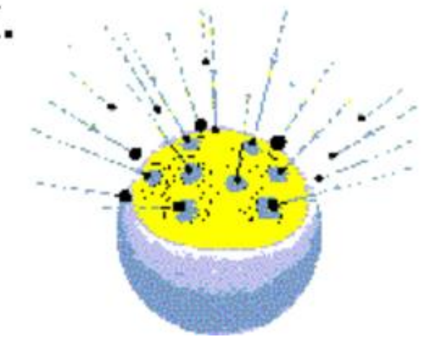
- Inner core (solid)
- Outer core (liquid

5. Formation of the Mantle
Intermediate-density silicate minerals remained above the core.
These materials formed the **mantle**.
6. Formation of the Crust
The lightest silicate materials rose to the surface.
Cooling and solidification produced the **primitive crust**.
7. Development of the Atmosphere and Hydrosphere
Volcanic outgassing released gases such as water vapour, carbon dioxide, and nitrogen.
As Earth cooled, water vapor condensed to form oceans.
This led to the formation of the **hydrosphere** and early **atmosphere**.

Final Layered Structure of the Earth
Crust – light silicate rocks
Mantle – dense silicate rocks
Outer Core – liquid iron and nickel
Inner Core – solid iron and nickel
Flow Diagram
Accretion → Heating → Melting → Density Separation → Core Formation → Mantle Formation → Crust Formation → Atmosphere & Hydrosphere Development

Phase I

I.



The Earth formed by the process known as A**ccretion.** This process is "gravity-driven", and involves gravitational attraction of material in the vicinity of the solar disk to the growing Earth.

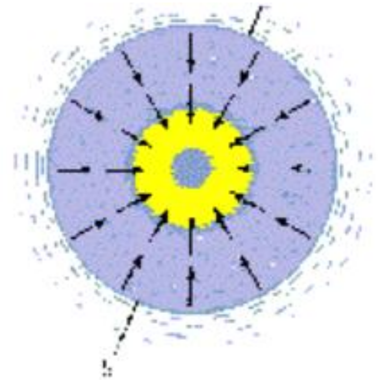
The process continues to this date with meteorite impacts, but must have occurred at a very high rate while the planet was initially forming.

Release of energy during impact of the accreting bodies produced **heat**. Owing to the fact that the rocky material which comprises the Earth is a good heat insulator, heat from the accretion process was maintained below the Earth's surface, as each hot layer was subsequently covered by, and insulated by overlying accretion debris

Phase II

As the Earth grew larger, it's gravitational field increased and it began to compact as a result of the growing mass of largely unconsolidated material.

II.



The process of compaction also produced heat, which further served to increase the temperature within the still-forming planet. At this stage of planetary formation, the Earth was "warm" with internal temperatures probably reaching as high as 1500 degrees Centigrade.

Phase III

In addition to heat generated by the processes of accretion and compaction, the newly formed Earth also contained relatively small quantities of radioactive elements (esp. isotopes of U, K and Rb).

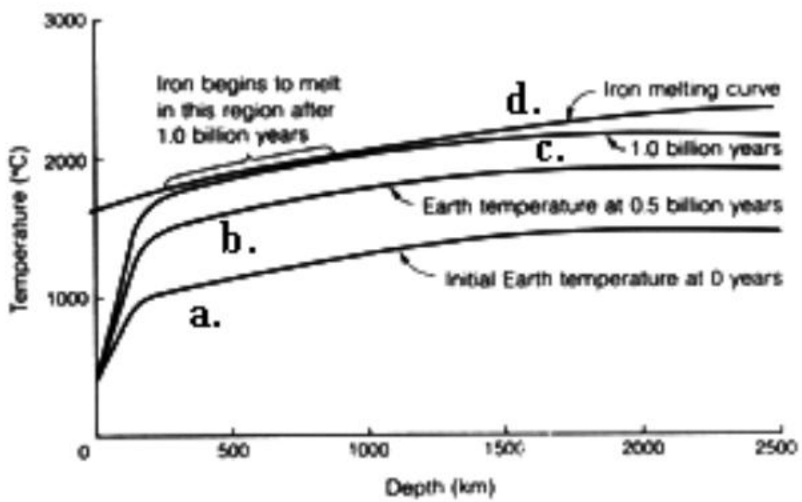
[Some of these isotopes, such as U(238) have a half life of about 4.5Ga, and consequently about twice as many radioactive atoms existed at this time relatively to the present.]

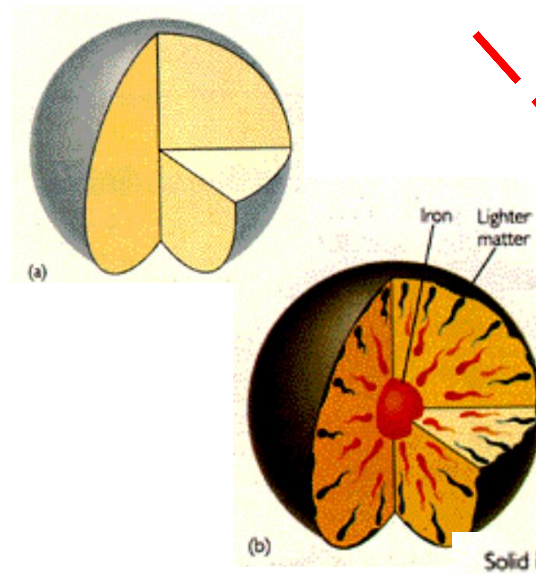
As these radioactive atoms spontaneously disintegrate by nuclear fission, energy is released in the form of heat.

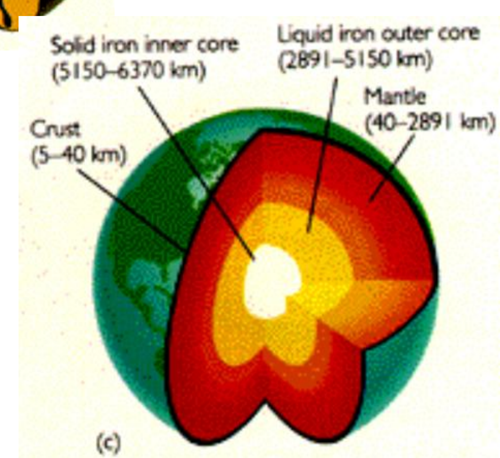
Immediately following accretion, the Earth must have been uniform or homogeneous in composition. Furthermore, it would have lacked both an atmosphere and hydrosphere.

The three main processes involved in planetary formation ***(I, II and III above***) each contributed heat to the newly formed planet.

The lowermost curve (a) gives the temperature vs depth profile immediately after accretion and compaction (i.e., without radioactive heat production). Radioactive decay resulting in a warming of the interior as indicated by curves b and c. At some point in time, radioactive heating resulted in temperatures exceeding the melting point for iron (curved).







The differentiation resulted in formation of an iron-rich core (ca. 90% Fe, 10% Ni), a low density crust rich in silicon, aluminum and oxygen, and an intermediate density mantle rich in magnesium, silicon and oxygen.

Once temperatures were high enough for iron (and other lower-melting-point minerals) to begin to melt, a profound event occurred. This event is known as the **Iron Catastrophy.**

Once the interior began to partially melt, high density, iron-rich liquids began to sink toward the centre of the earth, while low-density liquids rose toward the surface. In other words, the planet began to differentiate (separate) into a density stratified body.

As dense material sank toward the centre, more energy was released in the form of heat, causing the temperatures to increase even more, resulting in more melting, more sinking of iron, and more heat being released (a positive-feedback process).

It is likely that much of the Earth melted in this process. There is strong evidence to suggest that the outer portions of the Moon became completely molten, thus forming a magma ocean. The same may have also happened on the Earth.

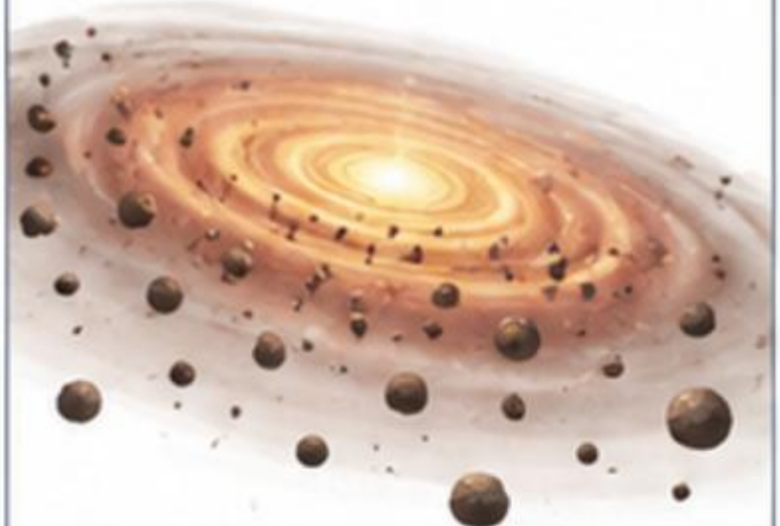
When Earth formed about 4.5 billion years ago, it was a uniform ball of hot rock. Radioactive decay and leftover heat (primordial heat) from planetary formation caused the ball to get even hotter. Eventually, after about 500 million years, our young planet's temperature heated to the melting point of iron — about 1,538° Celsius. This pivotal moment in Earth's history is called the iron catastrophe.

The iron catastrophe allowed the greater, more rapid movement of Earth's molten, rocky material. Relatively buoyant materials, such as silicates, water, and even air, stayed close to the planet's exterior. Droplets of iron, nickel and other heavy metals gravitated to Earth's centre, becoming the early core. This important process is called planetary differentiation.

The efficiency of the differentiation can be judged by the following table showing the relative abundance of elements in the whole Earth compared to that in the crust:

Element	Wt.% in Whole Earth	Wt. % in Crust
Oxygen	30	46
Iron	35	6
Silicon	15	28
Magnesium	13	4
Nickel	2.4	<1
Calcium	1.1	2.4
Aluminum	1.1	8
Sodium + Potassium	<1	4.4

1 Accretion (4.6 billion years ago)



- Earth formed from dust and gas in the solar nebula.
- Through collisions and accretion of planetesimals, the proto-Earth grew.

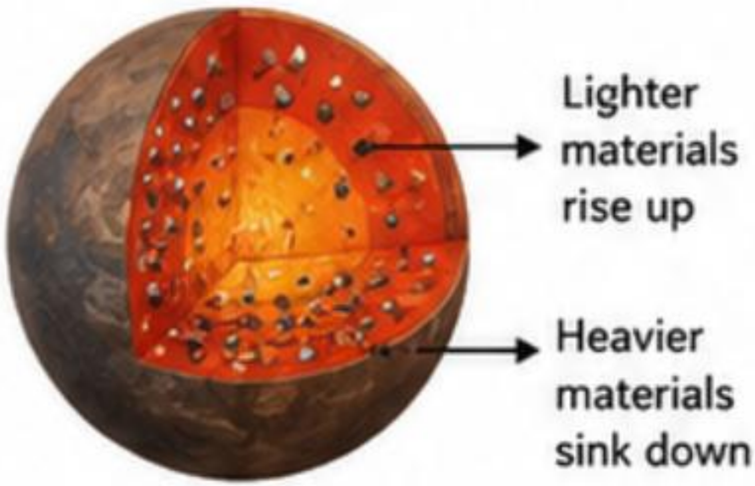
→

2 Heating of the Early Earth

- Heat produced by
  - gravitational compression
  - meteorite impacts
  - radioactive decay
- The Earth became partially or completely molten.

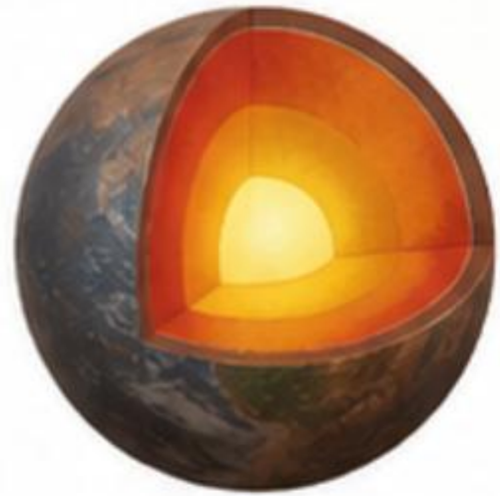
→

3 Density-Based Separation (Gravitational Differentiation)



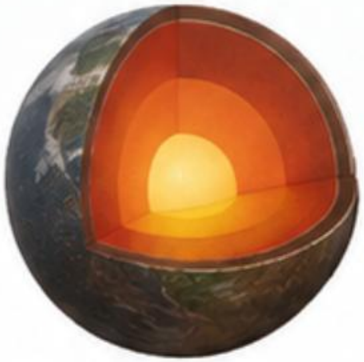
- Due to gravity, materials separated according to their density.
- This process is called gravitational differentiation.

4 Formation of the Core (Dense Materials Sink)



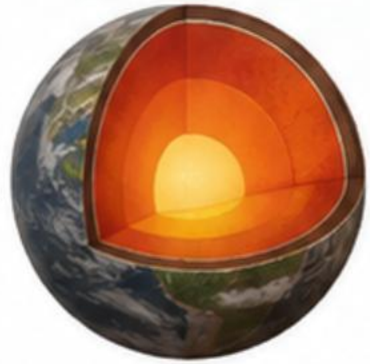
- Dense elements like iron (Fe) and nickel (Ni) moved towards the centre.
- They formed the core:
  - Outer core (liquid)
  - Inner core (solid)

5 Formation of the Mantle (Intermediate Materials)



- Silicate materials of intermediate density remained above the core.
- These formed the mantle.

6 Formation of the Crust (Lightest Materials Rise)



- The lightest silicate materials rose to the top.
- Cooling and solidification formed the primitive crust.

7 Development of Atmosphere and Hydrosphere

- Volcanic outgassing released gases (H_2O vapour, CO_2, N_2, etc.).
- As Earth cooled, water vapour condensed to form oceans.
- This led to the formation of the atmosphere and hydrosphere.

Key Point

Differentiation transformed the Earth from a homogeneous, molten body into a layered planet with distinct internal structures.

Overall Sequence (Flow)

Accretion

↓

Heating

↓

Melting

↓

Density Separation
(Gravitational Differentiation)

↓

Core Formation

↓

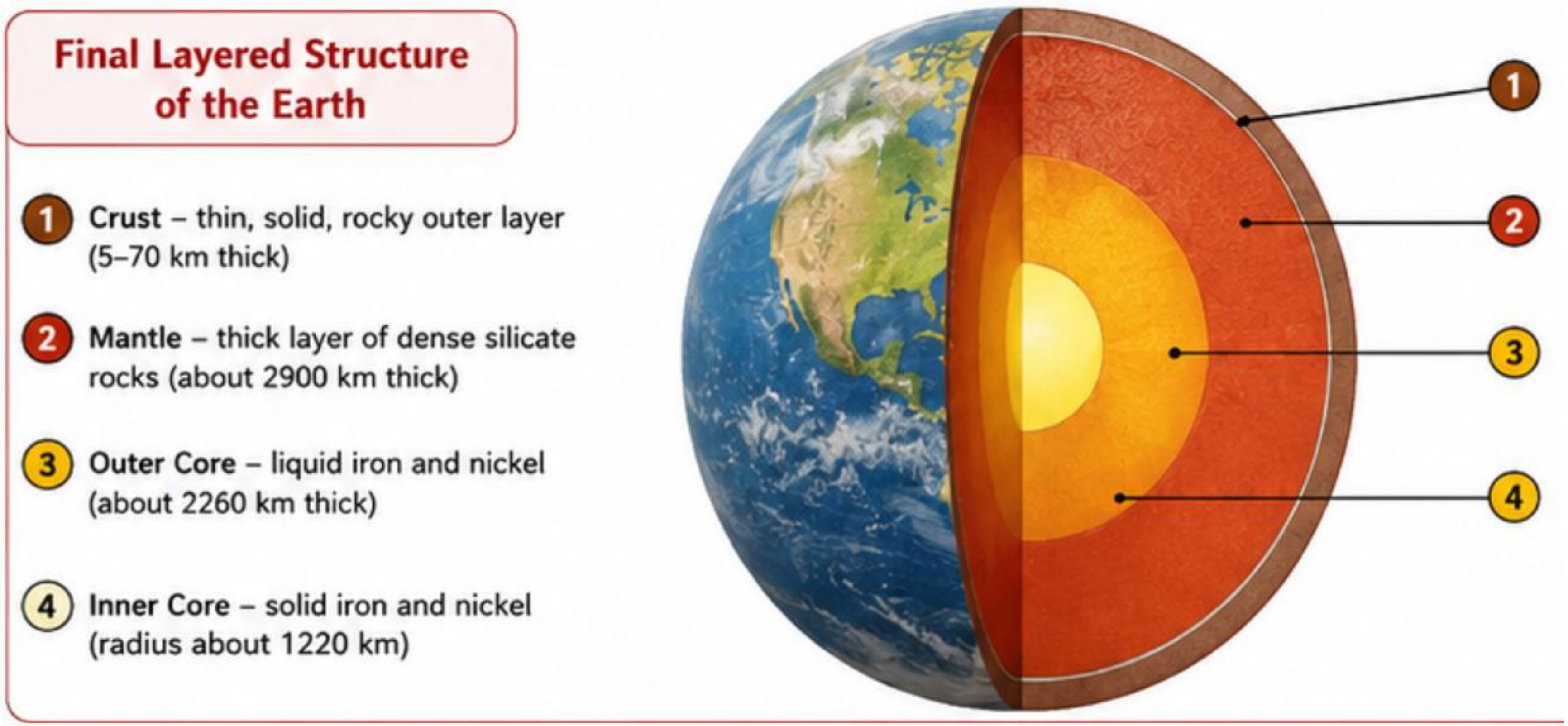
Mantle Formation

↓

Crust Formation

↓

Atmosphere & Hydrosphere Development


Final Layered Structure of the Earth
1 Crust – thin, solid, rocky outer layer (5–70 km thick)
2 Mantle – thick layer of dense silicate rocks (about 2900 km thick)
3 Outer Core – liquid iron and nickel (about 2260 km thick)
4 Inner Core – solid iron and nickel (radius about 1220 km)
1
2
3
4

Thank You