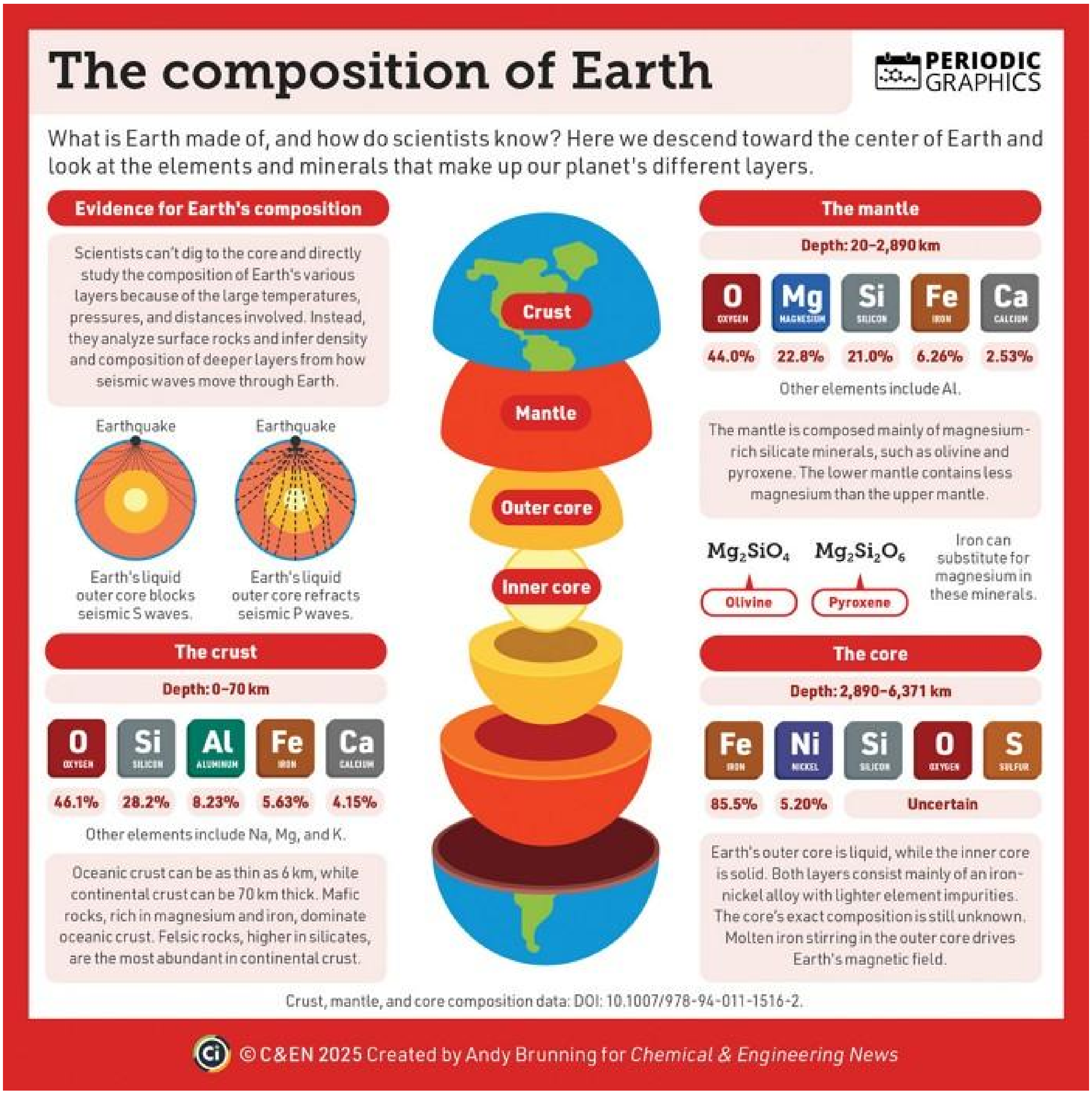
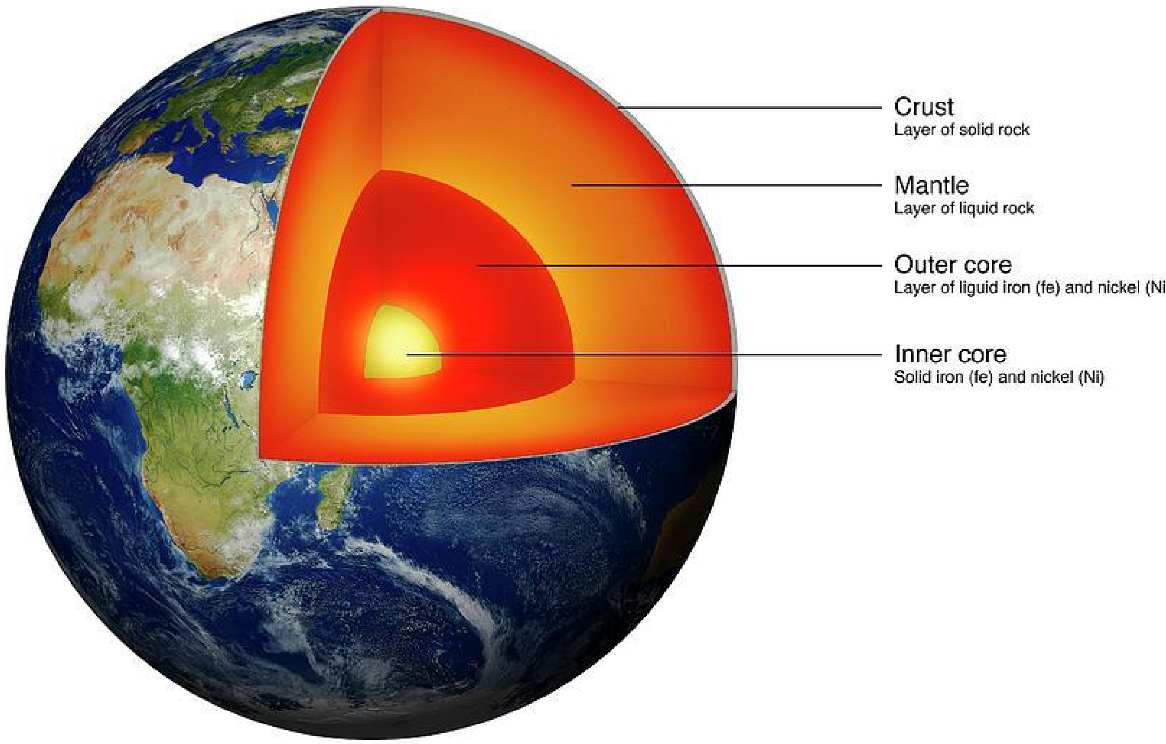
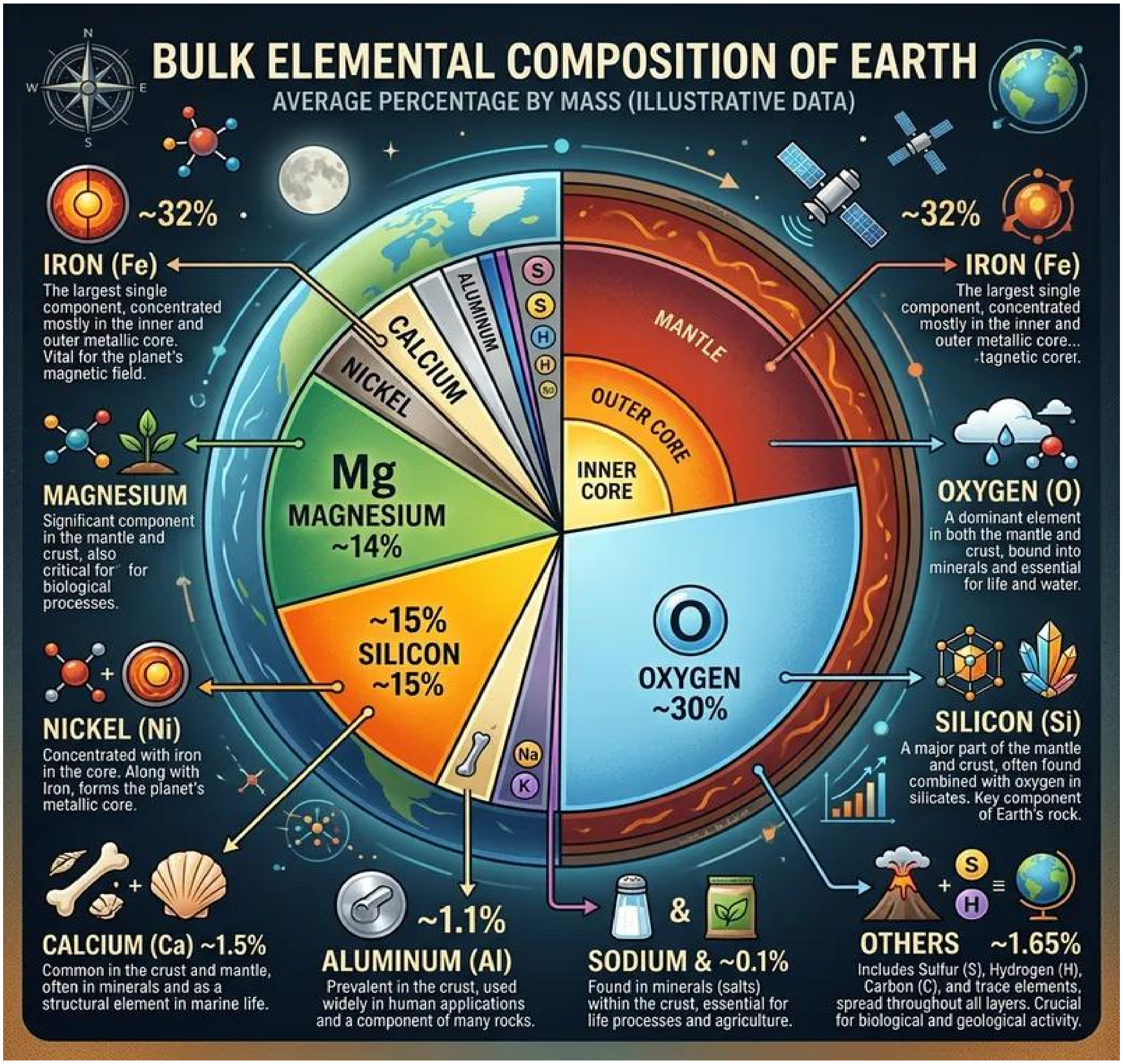
Chemical Composition of the Earth

The chemical composition of Earth is fundamental to understanding **geochemical cycles, mineral formation, plate tectonics, volcanism, weathering, soil formation, environmental processes, and the evolution of the planet**. Earth is chemically heterogeneous, and the abundance and form of elements vary considerably among the **crust, mantle, outer core, inner core, hydrosphere, and atmosphere**.




Crust
Layer of solid rock
Mantle
Layer of liquid rock
Outer core
Layer of liguid iron (fe) and nickel (Ni)
Inner core
Solid iron (fe) and nickel (Ni)



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Major Elements of the Earth

At the whole-Earth scale, the dominant elements by mass are approximately:

Element	Symbol	Approx. abundance (% by mass)	Major occurrence
Iron	Fe	**32.1**	Core
Oxygen	O	**30.1**	Silicate minerals, oxides
Silicon	Si	**15.1**	Silicate minerals

Magnesium	Mg	**13.9**	Mantle silicates
Nickel	Ni	**1.8**	Core
Sulfur	S	**1.5**	Core and mantle
Calcium	Ca	**1.4**	Crust and mantle
Aluminium	Al	**1.4**	Crust
Others	—	**2.7**	Na, K, Ti, Cr, Mn, etc.

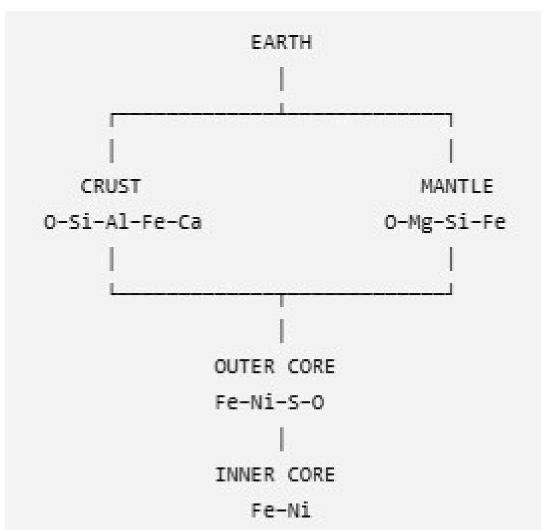
Important: These values represent approximate bulk-Earth composition and differ somewhat among geochemical models because Earth's core composition cannot be sampled directly.

Key interpretation

The first four elements—**Fe, O, Si and Mg—account for more than 90% of Earth's mass**. This immediately reveals the fundamental chemical nature of Earth: it is essentially an **iron-rich metallic core surrounded by an oxygen-rich silicate mantle and crust**.

Chemical Composition of Earth's Major Layers

A useful way to understand Earth's chemistry is to examine its internal differentiation.



A. Earth's Crust

The crust is the chemically diverse outer solid shell of Earth.

Approximate elemental composition of continental crust

Element	**Approx. % by mass**
Oxygen (O)	**46.6**
Silicon (Si)	**27.7**
Aluminium (Al)	**8.1**
Iron (Fe)	**5.6**
Calcium (Ca)	**3.6**
Sodium (Na)	**2.8**
Potassium (K)	**2.6**
Magnesium (Mg)	**2.1**
Others	**0.9**

Thus, **oxygen and silicon together constitute about three-quarters of the crust by mass**.

The dominant minerals are therefore largely **silicates and aluminosilicates**.

Examples include:

- Feldspars
- Quartz
- Pyroxenes
- Amphiboles
- Micas
- Olivine
- Clay minerals

Continental vs oceanic crust

The chemical composition of continental and oceanic crust is not identical.

Continental crust tends to be richer in **Si, Al, Na and K**, whereas **oceanic crust** is relatively enriched in **Fe, Mg and Ca** and is dominated by basaltic rocks.

3. Chemical Composition of the Mantle

The mantle extends from approximately **Moho depth to ~2,900 km**.

It is predominantly composed of **silicate minerals rich in Mg and Fe**.

Major elements include:

O > Mg > Si > Fe > Ca > Al

Important mantle minerals include:

- **Olivine** — $(Mg,Fe)_2SiO_4$
- **Pyroxenes** — Mg-Fe-Ca silicates
- **Garnet** — complex Mg-Fe-Ca-Al silicate
- High-pressure silicate phases in the transition zone and lower mantle.

Geochemical significance

The mantle is the principal reservoir involved in:

- Magmatism
- Volcanism
- Mantle convection
- Plate tectonics
- Crust formation
- Long-term carbon cycling

Chemical Composition of the Core

The core is fundamentally different from the crust and mantle.

It is dominated by **metallic iron and nickel**, together with smaller quantities of lighter elements.

Inner Core

Approximate composition:

- Fe: **~90–95%**
- Ni: **~5–10%**
- Minor/trace light elements

The inner core is predominantly solid because of the enormous pressure at Earth's centre.

Outer Core

The outer core is liquid and is composed principally of:

- Fe
- Ni
- S
- O
- Other light elements

The movement of electrically conducting liquid metal in the outer core generates Earth's **geomagnetic field** through the geodynamo.

Why Are the Elements Distributed Unequally?

Earth's present chemical structure is largely the consequence of **planetary differentiation**.

Simplified differentiation sequence

```
              ACCRETION OF EARTH
                      ↓
             Heating of the planet
                      ↓
          Partial/near-global melting
                      ↓
          ┌───────────┴───────────┐
          ↓                       ↓
  Dense metallic Fe–Ni     Silicate material
          ↓                       ↓
        Sinks                Remains above
          ↓                       ↓
        CORE                   MANTLE
                                  ↓
                          Partial melting &
                          volcanic activity
                                  ↓
                                CRUST
```

Major controlling factors

1. Density: Dense metallic Fe-Ni migrated toward Earth's centre.

2. Chemical affinity: Elements partitioned according to their affinity for metal, silicate or sulfide phases.

3. Melting behaviour: Partial melting redistributed elements between magma and residual solids.

4. Crystallization: As magma cooled, minerals crystallized and preferentially incorporated particular elements.

5. Plate tectonics: Recycling of crustal material continuously modifies Earth's chemical reservoirs.

6. Geochemical Classification of Elements

For MSc students, elemental classification according to **Goldschmidt's geochemical classification** is particularly important.

Class	Chemical affinity	Examples	Typical association
Siderophile	Iron-loving	Fe, Ni, Co, Pt, Au	Core/metallic phases
Lithophile	Silicate/oxygen-loving	O, Si, Al, Mg, Ca, Na, K	Crust and mantle
Chalcophile	Sulfur-loving	Cu, Zn, Pb, Ag, Hg	Sulfide minerals
Atmophile	Volatile/gas-loving	H, C, N, noble gases	Atmosphere, hydrosphere

This classification helps explain why particular elements are concentrated in particular parts of Earth.

7. Chemical Composition of the Atmosphere

Although the atmosphere represents only a very small fraction of Earth's total mass, it is environmentally extremely important.

Approximate composition of **dry air by volume**:

Gas	Approx. %
Nitrogen (N_2)	**78.08**
Oxygen (O_2)	**20.95**
Argon (Ar)	**0.93**
Carbon dioxide (CO_2)	~0.04%*
Other gases	Trace

*CO_2 concentration varies with time and location.

Trace gases such as **CH_4, N_2O, O_3 and water vapour** have concentrations much smaller than N_2 and O_2 but can exert major effects on climate and atmospheric chemistry.

8. Chemical Composition of the Hydrosphere

Water is composed primarily of:

H_2O

However, natural waters contain numerous dissolved substances.

Major ions include:

- Na^+
- K^+
- Ca^{2+}
- Mg^{2+}
- Cl^-
- SO_4^{2-}
- HCO_3^-

In seawater, **Na^+ and Cl^- are particularly important**, while freshwater chemistry varies considerably according to geology, climate, soil, biological activity and human influence.

9. Chemical Composition of Earth's Crust: Why Oxygen Dominates

A common misconception is that oxygen is abundant only because of atmospheric O_2.

In reality, most oxygen in the solid Earth occurs **chemically bound in minerals**.

For example:

Quartz: SiO_2

Olivine: (Mg,Fe)2SiO4

Feldspar

Complex **Al–Si–O minerals** containing K, Na or Ca.

Therefore:

Oxygen is the dominant element of the crust because silicate and oxide minerals contain large quantities of chemically bound oxygen.

10. Bulk Earth vs Earth's Crust

This distinction is extremely important for postgraduate students.

Feature	**Bulk Earth**	**Earth's crust**
Dominant element	**Fe**	**O**
Second major element	**O**	**Si**
Third	**Si**	**Al**
Major reservoir	Core	Silicate minerals
Character	Metallic + silicate	Predominantly silicate
Fe abundance	Very high	Relatively lower
Mg abundance	Very high	Lower

Thus, **one must not use crustal composition as a representation of the composition of the entire Earth**.