

**People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
University of Science and Technology of Oran
(Mohamed Boudiaf)
Faculty of Natural and Life Sciences**



Geology



Lectures

By Dr. Mahboubi Abdessamed

Preface

This book is intended for students with a limited background in geology, particularly those pursuing bachelor's and master's degrees in Biology, but it may also serve as a useful reference for first- and second-year undergraduate students in Geology. Geology is one of the fundamental sciences, consciously or unconsciously referenced in our daily lives. Since the rise of civilizations, humans have interacted closely with the Earth. In prehistoric times, for example, basic knowledge of rocks was essential for shaping weapons and producing fire, while an early understanding of topography played a crucial role in establishing the first human settlements, ensuring safety, and facilitating communication and trade between communities. As will become clear throughout this book, geology serves as a bridge between disciplines, connecting fields as diverse as biology and astrophysics. The study of the universe's origin, for instance, draws upon both astronomical and geological perspectives. The relationship between geology and biology is particularly significant and is explored in paleobiology. Geology provides the framework for understanding Earth's history, its rocks; fossils; and landscapes, while biology focuses on living organisms and their evolution. Fossils preserved in geological formations allow scientists to reconstruct ancient ecosystems and

trace how geological events shaped biological evolution. Life and Earth are thus inseparably linked: early organisms transformed the atmosphere into an oxygen-rich environment, while many rock types, such as limestone, coal, and petroleum deposits, exist largely because of biological activity. Several branches of geology are directly connected to biological sciences, including paleontology, paleobotany, and paleoecology. Fossil plants, for example, offer insights into evolutionary trends, soil origins, and the interactions between vegetation and the geological substrate. By studying these records, we gain a deeper understanding of how past life evolved and adapted in response to geological and environmental changes. Evolution itself can be viewed as the product of the dynamic interplay between geology and biology. Shifts in Earth's geological history frequently forced organisms to adapt, leading to new evolutionary pathways; the Cambrian explosion, for instance, coincided with significant changes in the availability of minerals, enabling the rise of organisms with hardened bodies. Another important discipline, biogeography, examines how geographic location influences species distribution and ecosystem development, highlighting the complex relationships between geology, climate, and biology, and becoming especially relevant in the context of global climate change. Geology also plays a central role in human economies and societies. As geologists often remark: "If it can't be grown, it must be mined." From metals and fuels to industrial minerals and construction materials, our modern world depends on Earth's resources, and exploring and managing these resources requires highly trained geologists with knowledge extending beyond geology itself to chemistry, physics, mathematics, hydrol-

ogy, and computer modeling. Indeed, geology is a multidisciplinary science. It draws upon physics and chemistry to explain processes such as crystallization, metamorphism, and igneous activity, while also intersecting with biology, agriculture, and environmental science in fields such as soil chemistry and geobiology. This cross-disciplinary nature makes geology a comprehensive and integrative science, providing not only knowledge of the Earth's structure and processes but also essential insights into life, ecosystems, and sustainable resource use. Ultimately, geology is more than the study of rocks, it is the study of the Earth as a whole. By connecting physical, chemical, and biological sciences, geology offers a broad and unified perspective on the natural world, one that is essential for understanding both our planet's past and its future.

This book is divided into three chapters: an overview of geology, where we explore the shape and structure of the Earth; external geodynamics, which examines the natural processes that shape landscapes through erosion, transport, and sedimentation, with special attention to stratigraphy and paleontology as the two pillars of this field; and internal geodynamics, which focuses on deep Earth processes such as plate tectonics, volcanism, and earthquakes.

Contents

1	Overviews	8
1.1	Introduction	8
1.2	The earth within the solar system	12
1.3	Shape of earth	13
1.4	Structure of the Earth	14
1.4.1	The Crust	15
1.4.2	The Mantle	16
1.4.3	The core	17
2	External Geodynamic	18
2.1	Introduction	18
2.2	Weathering	18
2.2.1	Mechanical Weathering	19
2.2.2	Chemical weathering	22
2.3	Erosion	23
2.3.1	Erosion by water	23
2.3.2	Erosion by wind	26
2.4	Consequences of Weathering and erosion	27

2.4.1	Weathering and Soil Formation	27
2.4.2	Mass wasting	28
2.5	Sediment transport	29
2.5.1	Bedload	29
2.5.2	Suspended load	29
2.5.3	Wash load	30
2.6	Sedimentary environments (Deposition)	30
2.6.1	Continental	31
2.6.2	Transitional	32
2.6.3	Marine	33
2.7	Stratigraphy	34
2.7.1	The Importance of Stratigraphy in Geology	34
2.7.2	Fundamental Principles of Stratigraphy	36
2.7.3	Time in Stratigraphy	37
2.8	Paleontology	42
2.8.1	What is Palaeontology?	43
2.8.2	Branches of Palaeontology	44
2.8.3	What is a Fossil?	44
2.8.4	Processes of Fossilization	45
2.8.5	Conditions for Fossilization	48
2.8.6	Importance of Fossils	50
2.9	Suggested readings	54
3	Internal Geodynamics	57
3.1	Tectonic plates	57

3.1.1	Introduction	57
3.1.2	Definition of Plate tectonics	59
3.1.3	Modern Evidences of plate tectonics	59
3.1.4	Plate Mobility	61
3.1.5	Plate Tectonics on Other Planets	67
3.2	Volcanism	70
3.2.1	Introduction	70
3.2.2	Components of a Volcano	70
3.2.3	Tectonic context of volcanoes	71
3.2.4	Volcanic Products	75
3.2.5	Type of volcanoes	78
3.2.6	Volcanic Eruptions	80
3.3	Earthquakes	83
3.3.1	Introduction	83
3.3.2	Definition	83
3.3.3	Origin of Earthquakes	84
3.3.4	Measuring earthquakes	85
3.3.5	Seismic Waves	87
3.3.6	Locating Earthquakes Using P and S Waves	88
3.3.7	Distribution of Earthquakes	88
3.3.8	Seismic Risk	90
3.4	Overview of earthquakes in Algeria	92
3.4.1	First Period – Pre-1910	92
3.4.2	Second Period – Post-1910 (1910–1979)	94

3.4.3	Third Period – Post-1980	94
3.4.4	Historical Seismicity (267 A.D.–2021)	95
4	Suggested readings	96

Chapter 1

Overviews

1.1 Introduction

The origin of the Universe remains a fascinating topic that has attracted the attention of numerous scientists from diverse disciplines, including geology. The Earth, being readily accessible for observation and study, serves as a primary reference point for geologists, astronomers, and astrophysicists. Compared to other planets, earth is distinguished by unique conditions favorable to life in its many forms. Its long and complex geological history, spanning approximately 4.57 billion years, is marked by successive major biological events alternating between periods of adaptive radiation and episodes of mass extinction (Benton Harper, 2009; Knoll, 2003). Beyond biological milestones, Earth's history has been shaped by numerous geological processes that have sculpted its surface and interior, including plate tectonics, volcanism, erosion, and weathering. Geology, as a natural science, studies Earth in its entirety. Although etymologically derived from geo (Earth) and

logos (study), the discipline encompasses the investigation of terrestrial materials (e.g., rocks), major internal structures (e.g., tectonic plates), and the dynamic processes affecting both the deep interior and the surface. It also extends to the history of life, from microorganisms to large vertebrates, with the aim of reconstructing the evolution of the biosphere through geological time. Geology is inherently interdisciplinary, drawing on physics, chemistry, mathematics, biology, astronomy, computer science, and statistics to unravel complex phenomena, whether ancient or modern. Unlike many other sciences, it frequently operates on extremely long timescales (millions to billions of years) while also addressing rapid events such as earthquakes and volcanic eruptions that occur in seconds or minutes (Fowler, 2005). Geology plays a fundamental role in our understanding of the world. Before attempting to explain complex astronomical phenomena, it is essential to comprehend terrestrial processes that directly affect daily life. The discipline helps answer core questions about the origin of Earth, life, and their evolution. Since the Industrial Revolution, geology has become central to the global economy by enabling the exploration and exploitation of natural resources such as water, oil, natural gas, industrial minerals, and metals. In Algeria, for instance, geologists are pivotal in discovering new petroleum reservoirs critical to sustaining the national economy. Moreover, geology contributes to mitigating the impacts of natural hazards, earthquakes, volcanic eruptions, and landslides, through risk assessment and the development of prevention strategies. It is also indispensable for understanding current climate change: by providing data on past climates, geology helps identify the drivers of present

global warming. Finally, it enables the evaluation of anthropogenic impacts on the environment and the formulation of strategies to prevent future degradation. A robust understanding of Earth's geological processes also informs comparative planetology and the study of other planets in the solar system. The roots of geological thought can be traced back to Ancient Greece (5th to 7th century BCE), where early interpretations were proposed regarding the formation of rocks, mountains, and even the origin of fossils. Among the most influential thinkers was Aristotle (384–322 BCE), who offered an initial classification of the mineral world in his work *Meteorologica*. He divided minerals into two categories: metals and fossils. This mineralogical classification remained authoritative until the 16th century. Aristotle also made early attempts to understand changes in sea level and their impact on the geography of continents. Later, the Roman poet Ovid expanded upon these ideas in *Metamorphoses*, describing transformations in Earth's landscapes. The Golden Age of Islam brought significant advancements in geological knowledge, particularly in the understanding of earthquakes, river dynamics, and sediment deposition. In the 8th century, Jabir Ibn Hayyan (721–815) explored crystallization processes in rocks, paving the way for major developments in crystallography and mineralogy. Later, Abu Rayhan Al-Biruni (973–1048), one of the first Muslim naturalists and philosophers, proposed that many continental regions were once submerged under oceans. This hypothesis was supported by his observations of petrified shell remains and marine fossils, leading him to conclude that Earth's surface had changed over vast periods of time. Another towering figure was Ibn Sina (Avicenna)

(980–1037), who made foundational contributions to geology and the natural sciences. In 1027, he published *Kitab al-Shifa* (The Book of Healing), a vast scientific encyclopedia that included sections on mineralogy, meteorology, and geological processes. Within this work, he proposed early hypotheses on the origin of earthquakes, mountain formation, fossilization, sedimentary rock formation, and even meteorites. Ibn Sina’s field methodology allowed him to categorize the natural world into three domains: animal, plant, and mineral. Because of his groundbreaking insights, he is often referred to as the “Father of Geology”, especially for his theories on the origin of mountain ranges. In the 18th century, Scottish naturalist James Hutton (1726–1797) laid the foundation for modern geology. He introduced one of the most transformative concepts in the field: actualism, also known as uniformitarianism. This principle holds that the geological processes we observe today, such as erosion, sedimentation, and volcanic activity, have operated in the same manner throughout Earth’s history. This idea revolutionized the understanding of ancient environments by allowing scientists to interpret the past through present-day processes. The rapid development of modern technology, including instruments such as seismographs, GPS systems, and space-based telescopes and planetary rovers, has accelerated the pace of discovery in Earth science. These advancements not only deepen our understanding of the physical properties of Earth but also allow us to study other planets in our solar system with increasing precision.

1.2 The earth within the solar system

The origin and evolution of the Earth are closely linked to the history of the Universe and the Solar System. According to the widely accepted Big Bang theory, the Universe originated approximately 13.8 billion years ago from an extremely hot and dense singularity. In its early stages, the Universe consisted of a “quark soup” at temperatures around 10^{12} K and infinite density. As it expanded and cooled, the four fundamental forces, gravity, electromagnetism, strong nuclear force, and weak nuclear force, separated, allowing the formation of subatomic particles, atomic nuclei, and ultimately atoms such as hydrogen, helium, and lithium about 300,000 years after the Big Bang. Matter gradually organized into galaxies, which are large systems of stars of various morphologies, including spiral, elliptical, and lenticular types, with the observable Universe containing roughly one trillion galaxies, including the Milky Way. Stars form within galaxies through the gravitational collapse of hydrogen clouds. Composed primarily of hydrogen and helium, stars generate heavier elements, including carbon and oxygen, via nuclear fusion. At the end of their life cycles, massive stars may explode as supernovae, dispersing enriched material into space. This material contributes to the formation of new star systems, including the solar nebula—a rotating accretion disk formed from the collapse of an interstellar cloud. Within this disk, particles coalesced to form planetesimals, and repeated collisions over approximately 100 million years led to the formation of the planets, including Earth. Earth formed approximately 4.5 billion years ago. Shortly afterward, a Mars-sized body, Theia, collided with the proto-Earth, ejecting material

that coalesced to form the Moon. During this early period, the Earth remained largely molten and experienced intense bombardment by meteorites, many of which carried water molecules that contributed to the formation of oceans and the planet's gradual cooling. The Solar System also contains asteroids, small rocky remnants of larger bodies, and comets, composed of ice and silicate dust. When comets approach the Sun, sublimation of their surfaces produces characteristic glowing tails. Meteorites, fragments of asteroids or planets, fall to Earth annually in large quantities (80,000 tons), ranging from a few grams to several tons, and are classified as stony (e.g., chondrites), metallic, or mixed types. Large impacts may form craters and induce shock metamorphism, while meteorites provide valuable information on early Solar System conditions and planetary composition.

1.3 Shape of earth

The actual shape of the Earth is not a perfect sphere but a geoid (Figure 1.1), which is an irregular, slightly flattened sphere bulging at the equator and compressed at the poles due to the planet's rotation, gravitational forces, and uneven mass distribution. The geoid represents an equipotential surface where gravity is vertical at all points, meaning that if a marble were placed anywhere on it, it would remain stationary. Local variations in topography, ocean depth, ice thickness, underground water, and magma flows cause minor differences in gravity, typically less than 1% between extreme points. While the geoid approximates the Earth's shape, it is affected by surface features such as mountains and valleys, as well as by uneven ocean levels caused

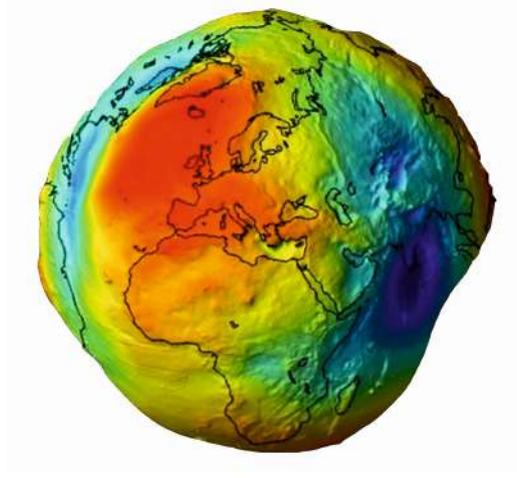


Figure 1.1: shape of earth according the European space agency

by salinity and currents. Advanced satellite missions, have allowed precise mapping of the geoid, revealing subtle deviations from a smooth ellipsoid; for example, the geoid varies only about -106 to 85 meters relative to a reference ellipsoid, despite exaggerations in visual models for clarity. Thus, the geoid provides a scientifically meaningful representation of Earth's shape, reflecting variations in mass distribution and gravity, rather than simply the topography or the presence of oceans.

1.4 Structure of the Earth

The Earth's interior is characterized by a layered organization, resulting from structural and chemical stratification. This stratification reflects distinct mechanical behaviors and lithological compositions for each unit. The different layers are separated by major discontinuities, which have been revealed through seismic, geochemical, and thermal studies. Three main layers form

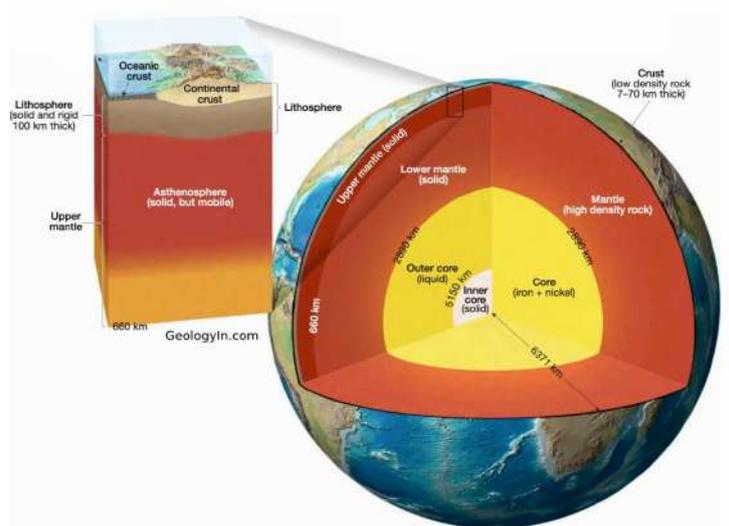


Figure 1.2: earth's layered structure (GeologyIn.com)

the internal structure of the Earth: the crust, the mantle, and the core.

1.4.1 The Crust

The crust, also known as the Earth's outer shell, is the surface layer of the planet. Although it accounts for only about 2% of the Earth's total volume, it plays a crucial role in the planet's geodynamics. The crust is divided into two types: continental crust and oceanic crust (Figure 2). The continental crust is mainly composed of plutonic rocks such as granite and granodiorite, along with metamorphic rocks like gneiss and schist. It is rich in minerals such as quartz, feldspars (plagioclase and orthoclase), and micas (biotite and muscovite). Its thickness ranges from 15 to 20 kilometers under plains, reaching up to 70 to 80 kilometers beneath major mountain ranges such as the Himalayas or the Andes. Its relatively low density lies between 2.4 and 2.7. In contrast, the oceanic crust is primarily composed of volcanic rocks like

basalt and plutonic rocks such as gabbro. These are rich in ferromagnesian minerals, including plagioclase, pyroxene, and olivine. The oceanic crust is much thinner, with an average thickness of 5 to 7 kilometers, but it has a higher density, ranging from 2.8 to 3.2. The boundary between the crust and the mantle is marked by the Mohorovičić discontinuity (Moho), characterized by a sudden increase in seismic wave velocity due to a change in chemical composition.

1.4.2 The Mantle

Located beneath the crust, the mantle is the Earth's largest layer by volume, making up approximately 84% of the total. It is predominantly composed of peridotite, a rock rich in olivine and pyroxenes. The mantle is divided into two major sections: the upper mantle and the lower mantle (Figure 2). The upper mantle includes both the lithosphere and the asthenosphere. The lithosphere is rigid and brittle, encompassing the crust and the uppermost part of the mantle. Its thickness varies depending on the region: from 100 to 120 kilometers beneath the oceans, and up to 200 kilometers beneath the continents. Below lies the asthenosphere, a ductile layer extending from about 100 to 300 kilometers deep. This plastic zone is marked by a low seismic wave velocity (Low Velocity Zone - LVZ) and is the site of convection currents responsible for the movement of tectonic plates. The lower mantle, also known as the mesosphere, stretches from 700 to 2,890 kilometers in depth. It is solid and very dense. The boundary between the mantle and the core is identified by the Gutenberg discontinuity, where seismic S-waves

disappear, indicating the presence of a liquid medium in the subsequent layer.

1.4.3 The core

The Earth's core, which constitutes about 14% of the planet's volume, is mainly composed of iron (about 80%) and nickel (about 20%). It is divided into two distinct parts: the outer core and the inner core. The outer core lies between 2,850 and 5,150 kilometers in depth and is in a liquid state. It is within this fluid layer that the Earth's magnetic field is generated through a dynamo mechanism, resulting from the movement of liquid iron. This magnetic field plays a crucial role in protecting the planet from solar wind. The inner core, also called the inner seed, is solid and extends from the center of the Earth to a depth of about 6,371 kilometers. The transition between the liquid outer core and the solid inner core is marked by the Lehmann discontinuity, which has been identified by the distinct behavior of seismic waves at this depth (Figure 1.2).

Chapter 2

External Geodynamic

2.1 Introduction

External geodynamics studies the action of external atmospheric agents such as wind, continental waters, seas, oceans, ice, glaciers, and gravity on the Earth's surface layer. These phenomena lead to slow destruction and modeling of rocky landscapes and relief, during which materials detach and, once deposited, form sedimentary rocks. Similarly, the effects on the landforms, their evolution, and the modeling process are studied by geomorphology.

2.2 Weathering

Weathering is the set of physical and chemical processes that alter rocks once they are exposed at Earth's surface. In contrast to the stable, high-pressure conditions at depth, surface environments involve fluctuating temperatures, low pressure, abundant atmospheric gases, and the prese Weathering oper-

ates through two distinct processes: mechanical weathering, which breaks rocks into smaller fragments, and chemical weathering, which alters minerals into more stable forms at Earth's surface. These processes are interdependent, mechanical breakdown exposes fresh surfaces to chemical reactions, while chemical alteration weakens rocks, enhancing mechanical disintegration. Their combined action produces two key outcomes: sedimentary particles and dissolved ions contribute to the formation of sedimentary rocks, while soils sustain life on Earth and, together with the action of water, play a key role in the decomposition and disintegration of rock.

2.2.1 Mechanical Weathering

Mechanical weathering is the physical breakdown of rocks into smaller fragments without altering their chemical composition. The main processes include:

Pressure Release (Unloading and Exfoliation): When overlying material is removed, confining pressure on the rock decreases. This reduction in stress allows the rock to expand and fracture, a process known as exfoliation. Granitic rocks typically exfoliate parallel to the surface due to their homogeneity, while sedimentary and metamorphic rocks fracture along bedding or foliation planes (Figure 2.1)

Frost Wedging and Frost Heaving: Water entering cracks expands by about 9% upon freezing, exerting stress that progressively widens fractures. This process, called frost wedging, is most effective in regions with frequent freeze-thaw cycles, such as mountainous terrains, where it generates talus

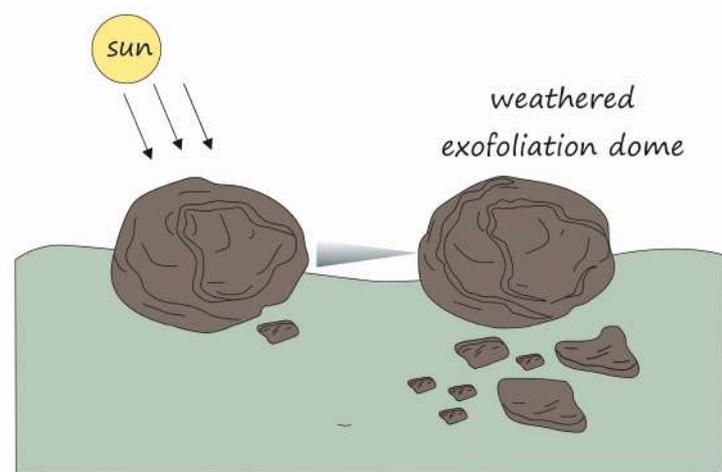


Figure 2.1: exfoliation of granitic rock

slopes at the base of cliffs. A related phenomenon, frost heaving, occurs in soils when ice lenses grow and lift overlying materials, often damaging roads and infrastructure.

Salt crystallization: In arid or coastal environments, saline water infiltrates pores and cracks. As the water evaporates, salt crystals grow, exerting pressure that loosens mineral grains and weakens the rock structure. Over time, this process can lead to granular disintegration and rock breakdown even away from the coastline (Figure 2.2).

Biological Activity: Plant roots can penetrate tiny fractures and exert considerable force as they grow, widening cracks and eventually breaking rocks apart. Burrowing animals disturb soils and expose fresh rock surfaces to weathering, indirectly accelerating physical disintegration (Figure 2.3). Mechanical weathering is strongly enhanced by erosion, which removes loosened material and exposes new surfaces to further breakdown.

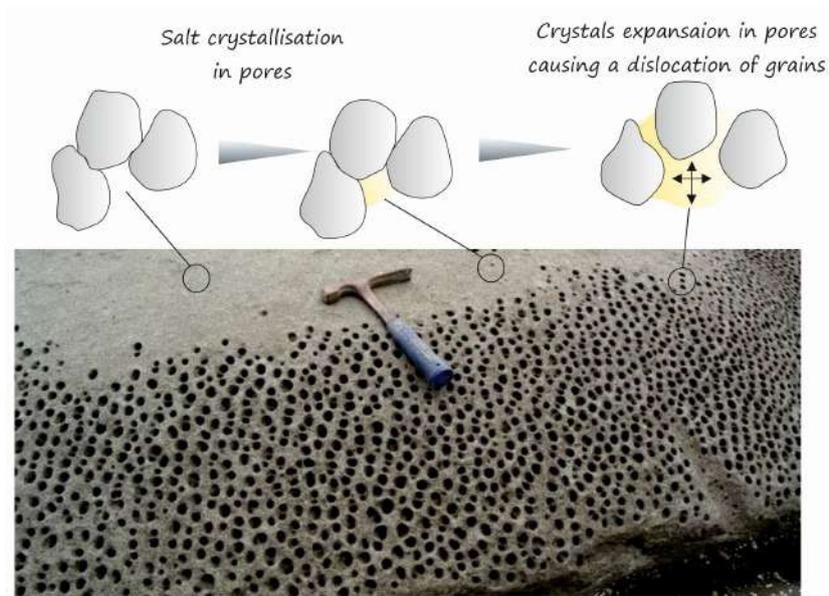


Figure 2.2: Salt crystallization of coastline facies



Figure 2.3: Biological weathering caused by tree roots (left) and bivalves (right)

2.2.2 Chemical weathering

Chemical weathering involves the alteration of minerals that become unstable when exposed to surface conditions. The specific changes depend on both the mineral type and the environmental context. For example, quartz is highly resistant to chemical weathering, whereas feldspar readily alters. The intensity of chemical weathering is greatest in warm, humid climates and minimal in cold, arid regions. Key factors driving chemical weathering at the surface include the presence of water, oxygen, and carbon dioxide, the latter of which forms weak carbonic acid when dissolved in water, promoting mineral breakdown.

Dissolution: Dissolution occurs when a solid mineral or rock dissolves in water. Many evaporitic sedimentary rocks, such as sulfates (gypsum, anhydrite) and halides (halite, sylvite, carnallite), dissolve through this process. When these minerals are removed, they create surface grooves and cavities known as lapiaz.

Hydration: it involves the chemical combination of water with a mineral, often expanding its crystal structure. For example, anhydrite transforms into gypsum, increasing in volume by up to 50%. Drying reverses the effect, causing contraction and cracking. This phenomenon is pronounced in clay minerals such as montmorillonite.

Oxidation: It is the reaction of minerals with oxygen, usually in water, involving electron transfer. Iron-containing minerals are particularly affected, forming insoluble oxides that impart reddish, ochre, or brown colors to landscapes.

Hydrolysis: it is the breakdown of minerals by reaction with water. Dissociation of water into ions attacks mineral crystal lattices, particularly feldspars and feldspathoids, producing clay minerals such as kaolinite, illite, and montmorillonite. This process is accelerated in warm, humid climates.

Carbonation: it occurs when carbon dioxide, dissolved in water as carbonic acid, reacts with minerals containing calcium, magnesium, sodium, or potassium. This leads to the formation of carbonates and bicarbonates, shaping features like karst landscapes in limestone regions.

2.3 Erosion

Erosion is closely related to weathering but differs in that it involves not only the breakdown of rocks and soils but also the movement and eventual deposition of the resulting fragments. It occurs through the action of natural agents such as wind, running water in rivers, and the slow movement of glaciers. Unlike erosion, weathering occurs in situ and involves the breakdown of rock into smaller fragments at the Earth's surface without significant displacement. In other words, weathering weakens and fragments the material, while erosion and transport actively remove and relocate it, shaping landscapes over time.

2.3.1 Erosion by water

Water is one of the main forces that shape the land. It moves soil and rocks in different ways depending on how much rain falls, how water runs off, and the type of land.

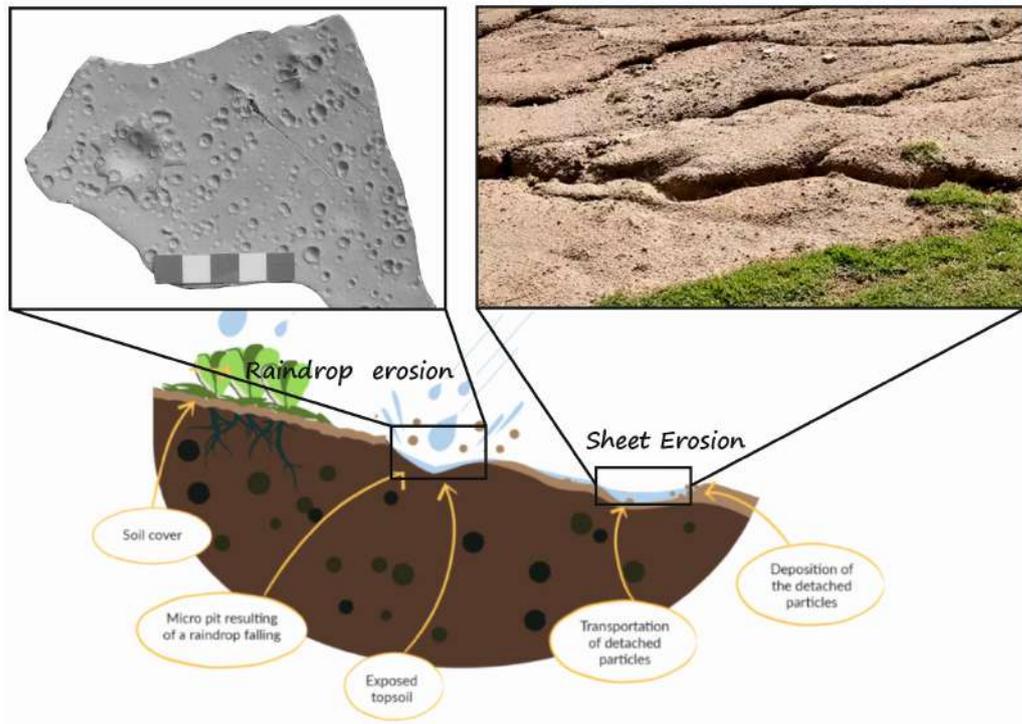


Figure 2.4: Raindrop and sheet erosion of soil

Raindrop impact: this happens when raindrops hit the soil. The impact breaks up clumps of soil and spreads tiny particles around. This is usually a very weak type of erosion and often disappears after ploughing or gardening. Some soil particles stay on the surface, while others may land on plants, especially small seedlings (Figure 2.4).

Sheet erosion: it occurs when rainwater flows evenly over the land, forming a thin layer that carries soil away. This happens when the ground cannot absorb water fast enough (Figure 2.5).

Linear erosion: this erosion happens when water gathers into small channels and cuts into the soil. It can form rills (small grooves), gullies (larger channels), or even floodplain patterns in areas with rivers or seasonal



Figure 2.5: Linear and mass erosion

streams. The severity depends on how much water flows and the risk to land, buildings, or people (Figure 2.5).

Mass movement: it occurs when heavy rainfall makes the soil too wet and gravity pulls it downhill. This includes landslides, mudflows, and other fast-moving soil and rock flows (Figure 2.6).

Fluviatile erosion: Rivers and streams shape the land through erosion, which depends on the water's energy. Steeper upper sections have faster flow and more energy, while flatter lower sections have slower flow. This causes differential erosion, changing the river's profile over time. Rivers erode in two main ways:

Vertical erosion: the river cuts down into its bed, deepening the channel (Figure 2.6).

Lateral erosion: the river wears away its banks, widening the channel. This can cause loss of agricultural land. Dense vegetation along banks can help prevent this (Figure 2.6).

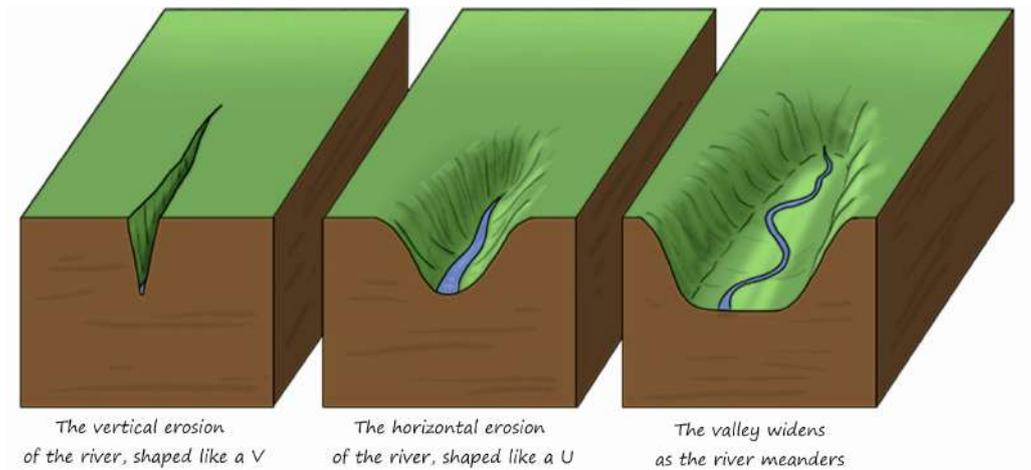


Figure 2.6: erosion dynamic in fluvial environment

2.3.2 Erosion by wind

wind can also move soil and sand, especially in dry or sparsely vegetated areas. Wind erosion works mainly in two ways: deflation and accumulation.

Deflation: deflation is when the wind lifts and removes soil or sand from the surface. This can expose plant roots and leave rocky surfaces behind. The strength of deflation depends on the wind speed and how abrasive the particles are. Deflation can be very weak or very strong, sometimes reaching a level where it causes serious land damage (Figure 2.7).

Corrosion: the corrosion happens when wind blows sand against rocks, slowly wearing them down. Soft rocks get small holes or pits, brittle rocks can crack or form deeper channels, and hard rocks become smooth and shiny. The sand grains also change shape as they keep hitting the rocks.

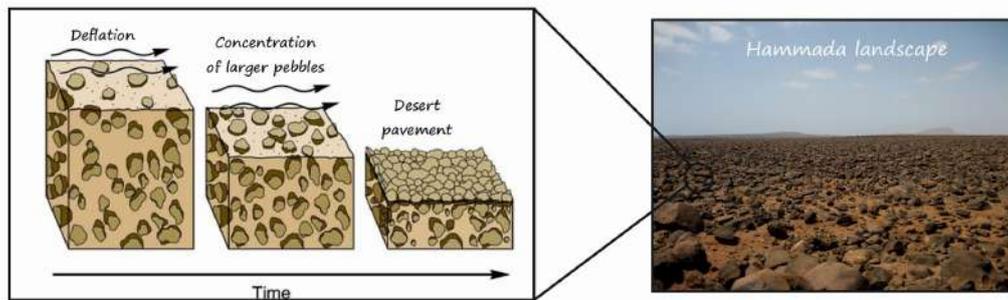


Figure 2.7: Deflation phenomena leading to the formation of a hammada landscape

2.4 Consequences of Weathering and erosion

2.4.1 Weathering and Soil Formation

Weathering breaks down rocks into smaller particles and is essential for soil formation. Soil is the top layer of Earth that supports plant growth, containing a mixture of minerals (45%), organic matter (5%), and air/water (50%). Soil texture depends on the proportions of sand, silt, and clay, and climate influences its composition. For example, warm climates with chemical weathering tend to produce clay-rich soils. Soil forms through a combination of organic matter accumulation, mechanical and chemical weathering, and is affected by factors like climate, vegetation, parent material, slope, and time. Water and wind can erode soil. On slopes, fast-flowing water washes away soil, while raindrops break up soil particles. Wind erosion is worsened by removing vegetation or leaving soil bare. Farming and tillage on slopes also increase soil movement downhill.



Figure 2.8: Mass Wasting

2.4.2 Mass wasting

Mass wasting is the downhill movement of rock or soil due to gravity. It is influenced by slope angle, material strength, and water content. Key types of mass wasting include:

Rock Fall: rocks break off steep slopes, often due to freeze-thaw cycles, and fall to the slope below.

Rock slide: rocks slide along a surface, usually following fractures or bedding planes. Very slow movement is called sacking (Figure 2.8).

Rock avalanche: Rapid rock slides that break into many pieces and move like a fluid, cushioned by air (Figure 2.8).

Creep / Solifluction: very slow movement of soil (millimeters to centimeters per year), often caused by freeze-thaw or wetting-drying cycles. Evidence includes leaning trees, fence posts, or curved tree trunks (“pistol butt”) (Figure 2.8).

Slump: movement of a large mass along a curved surface, often caused by water-saturated thick deposits.

2.5 Sediment transport

Sediment transport is the movement of small particles, both organic (like plant material) and inorganic (like minerals), carried by water or wind. The stronger the water flow, the more sediment it can move. Sediment can either stay suspended in the water as it travels downstream or roll and slide along the riverbed.

2.5.1 Bedload

Bedload is the portion of sediment transport that moves along the bottom of a waterway by rolling, sliding, or bouncing. Unlike suspended sediment, bedload maintains intermittent contact with the streambed, and its movement is irregular and discontinuous. It occurs when the force of water flow is strong enough to overcome the weight and cohesion of the particles, though these particles typically move more slowly than the surrounding water because the flow is insufficient to fully suspend them. Bedload transport can happen during both low flows, which mobilize smaller particles, and high flows, which move larger ones. It generally accounts for about 5–20% of total sediment transport, and in stronger flows, some smaller bedload particles may be lifted into the water column and carried as suspended load (Figure 2.9).

2.5.2 Suspended load

When water flow is strong enough, it can lift sediment particles into the water column, creating what is called the suspended load. This is different from suspended sediment, which refers to any particles floating in the water

whether it is moving or not. Suspended load, however, specifically means the sediment carried downstream by flowing water. The moving water generates turbulence, or small upward currents, that keep particles from settling to the bottom. The size of particles that can stay suspended depends on the strength of the flow, smaller particles remain suspended more easily, while larger ones tend to sink unless the water flow becomes stronger and more turbulent (Figure 2.9).

2.5.3 Wash load

The wash load is a subset of the suspended load consisting of the finest particles (typically <0.00195 mm) that remain permanently suspended, even in low or no-flow conditions. Unlike larger suspended sediments, they do not settle because their size allows them to stay afloat by colliding with water molecules. During periods of flow, the wash load and suspended load become indistinguishable. Wash load is a major contributor to turbidity in lakes and slow-moving rivers; as flow rate increases, turbidity rises due to greater suspended sediment transport. While turbidity cannot directly quantify sediment transport, it provides an approximation of suspended sediment concentrations at specific sites (Figure 2.9).

2.6 Sedimentary environments (Deposition)

Sedimentary environments are places where sediments are deposited (Figure 10), both on land and in the sea. Each environment has specific physical, chemical, and biological conditions. Physical factors include water

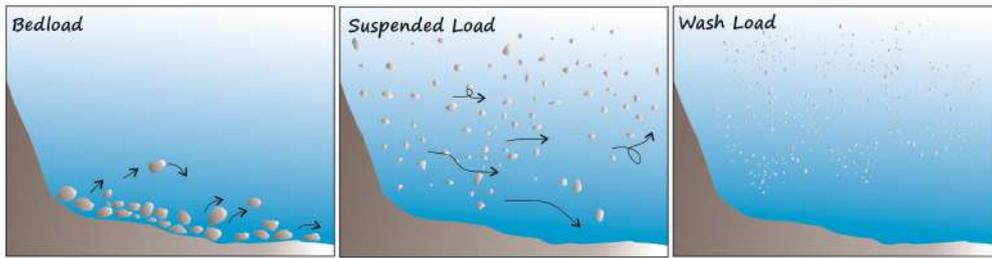


Figure 2.9: Sediment transport dynamic

depth, current strength, and flow duration. Chemical factors include salinity (amount of dissolved salts), pH (acidity or basicity), oxidation conditions, pressure, and temperature. Biological factors relate to the types of plants and animals living there. These conditions, along with the source of the sediments and the transport process, control the nature of the deposited sediments. To classify these environments, geologists often use a geomorphologic approach, which means defining them by their landforms or landscape features. Sediments are deposited in three main environments: continental, transitional (marginal marine), and marine. Each environment has unique conditions and can be divided into sub-environments.

2.6.1 Continental

Fluvial: braided fluvial are characterized by multiple channels separated by bars or small islands, created by fluctuating water flow and an abundant supply of coarse sediment. Their deposits typically consist of alternating layers of gravels, sands, and channel fills. In contrast, meandering rivers feature a single winding channel that transports finer sediment. Bars develop on the inside of channel bends, while the adjacent floodplains accumulate silts

and clays often rich in plant material. The resulting deposits represent an alternation of sands and gravels with finer-grained floodplain sediments.

Alluvial fans: Form at mountain bases where fast streams slow down and drop coarse, poorly sorted, angular sediment.

Glacial deposits: Left behind by glaciers, ranging from valley glaciers to continental ice sheets. A common rock is diamictite (pebbly mudstone).

Eolian: Deposits in deserts, recognized by dune structures and horizontal layering.

Lacustrine: Fine, laminated sediments with ripples, mudcracks, footprints, and freshwater fossils (plants, shells).

2.6.2 Transitional

Deltas : Form where rivers meet standing water. Sediments grade from coarse near the river mouth to fine clays offshore, creating upward-coarsening sequences.

Estuaries: Semi-enclosed bodies of brackish water where rivers meet the sea. They mix fresh and salt water, creating highly productive habitats with abundant nutrients.

Lagoons: Shallow, quiet waters separated from the open sea by reefs, islands, or sandbanks. Sediments are mostly fine-grained.

Beaches: Shallow coastal zones dominated by waves and currents. Sediments are well-sorted sands with cross-bedding, laminations, and burrows.

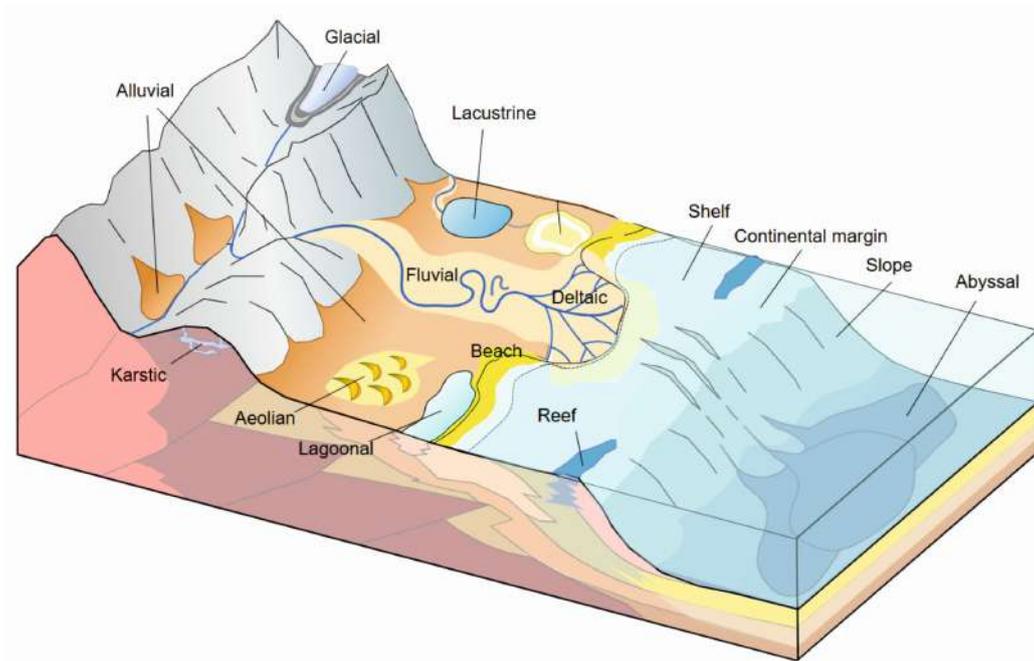


Figure 2.10: main depositional environments

2.6.3 Marine

continental shelf: it is the shallow marine zone near the land, about 100–150 meters deep. Sand and mud move to the shelf through underwater valleys called submarine canyons. When too much sediment builds up, it flows down the slope as underwater mudflows called turbidity currents. These deposits, called turbidites, have coarse layers at the bottom and finer layers on top. Repeated turbidites show how sediments accumulate on the slope and rise.

Deep marine: In the deep sea, on the abyssal plains, the seafloor is 2.5 to 6 km below sea level. These areas get little sediment from continents. Most sediment comes from windblown dust and volcanic material, forming thin layers of clay and shale.

2.7 Stratigraphy

Stratigraphy is a branch of geology concerned with the study of the formation, composition, sequence, and correlation of layered rocks. Since the Earth as a whole shows a form of stratification, all types of rocks—igneous, sedimentary, and metamorphic—can be studied through stratigraphic methods. However, stratigraphy mainly deals with the analysis of sedimentary layers. The foundations of modern stratigraphic principles were established in the 18th and 19th centuries by geologists such as Niels Stensen, James Hutton, Georges Cuvier, William Smith, and Charles Lyell. By the early 20th century, geologists already had the necessary tools to describe, order, and correlate rock strata. Soon after, advances in radiometric dating, which uses minerals with unstable isotopes, provided a reliable way to determine the absolute ages of rocks in suitable conditions. Since the 1950s, additional efforts have focused on creating international standards for stratigraphic terminology and the formal designation of “type-sections” or stratotypes, especially for units used in chronostratigraphy

2.7.1 The Importance of Stratigraphy in Geology

Before the development of modern dating methods such as radiocarbon analysis, geologists relied on stratigraphy as the first systematic tool for understanding the passage of time. The guiding principle was straightforward: the deeper a layer is within a sequence, the older it is. Although not highly precise, this approach was sufficient to establish relative ages of rocks and artifacts and to reveal anomalies, such as strata that had been overturned or

displaced by tectonic forces. Stratigraphy serves as a valuable record of both natural and human history. In geology, it preserves evidence of events such as floods, volcanic eruptions, and earthquakes. In archaeology, it documents how humans modified landscapes through building, digging, and leaving artifacts. Because of this, artifacts recovered without stratigraphic context lose much of their scientific value, as they are detached from the temporal and environmental framework that gives them meaning. The study of rock layers also provides insights into past environments. By analyzing sedimentary sequences, scientists can reconstruct whether a region was once underwater, a desert, or a forest. This has practical applications beyond historical reconstruction: stratigraphy guides the search for minerals, oil, gas, and groundwater, and it helps geologists detect tectonic activity such as faulting, thrusting, and overturning of rock layers. Over time, the discipline evolved from simple lithostratigraphy, which focuses on comparing layers by their physical characteristics, to sequence stratigraphy, which examines groups of strata deposited under similar environmental conditions. This shift greatly expanded its explanatory power, since the properties of rocks are closely tied to the settings in which they formed. Sequence stratigraphy, in particular, is a critical tool for predicting the distribution of natural resources. One of the most significant applications of stratigraphy is in petroleum geology. The formation of oil and gas reservoirs depends on the interplay of four elements: source rocks, reservoir rocks, traps, and seals. Stratigraphic analysis makes it possible to reconstruct how these elements originated and when they became active. For example, sandstones often serve as effective reservoirs,

while shales function as source rocks or seals. In essence, stratigraphy is far more than the study of stacked layers. Each stratum preserves a chapter of Earth's story, from natural processes to human activity. Its ability to reconstruct environments, inform archaeological interpretation, and guide resource exploration establishes stratigraphy as one of the most fundamental and versatile tools in Earth sciences.

2.7.2 Fundamental Principles of Stratigraphy

Superposition: The principle of superposition is fundamental in stratigraphy. It applies particularly to sedimentary layers that have retained their primary depositional position. This principle states that any sedimentary layer is younger than the one it overlies. In gently deformed terrains, the younger layers are found at the top, and the age of the layers increases progressively downward (Figure 8). This principle also applies to volcanic terrains, where successive lava flows accumulate vertically according to their respective ages (Figure 2.11).

Original horizontality: this principle asserts that sedimentary rocks are initially deposited as flat, horizontal layers. Any tilting or folding observed in these layers occurs later, typically due to tectonic forces such as faults or folding.

Lateral Continuity: This principle states that a single layer has the same age across its entire lateral extent, provided no disturbance occurred after deposition.

Cross-cutting relations: According to the principle of cross-cutting

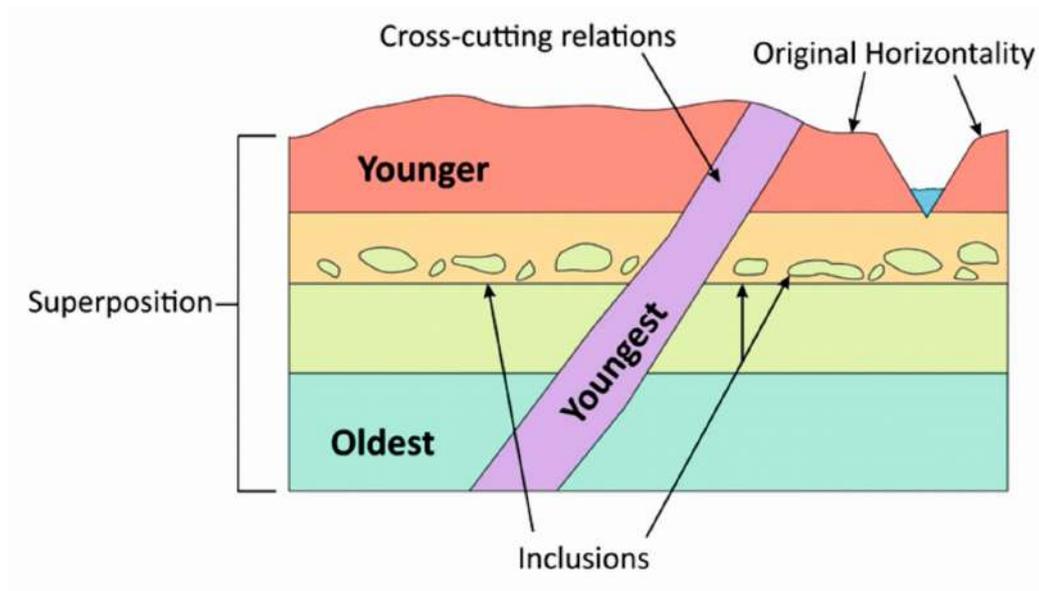


Figure 2.11: Fundamental Principles of Stratigraphy

relationships, a dike or sill must be younger than the rock layers it intrudes. For example, a purple dike that cuts across green, yellow, and red strata is younger than all of those rocks.

Inclusion: Rock fragments enclosed within another rock are necessarily older than the surrounding layer that contains them.

2.7.3 Time in Stratigraphy

The concept of time in geology differs from that in astrophysics or classical/quantum physics. Geological time frames vary depending on the event studied: they can span billions of years (e.g., Earth's formation), millions of years (e.g., tectonic plate movements), thousands of years (e.g., climate changes), or even minutes and seconds (e.g., earthquakes and volcanic eruptions). Stratigraphy considers not only when an event first occurs but also

its duration. In this context, the duration of an event refers to the interval between its initial occurrence and its conclusion. For instance, the lifespan of a fossil is measured from its first appearance to its extinction, including the period when it was most abundant. However, stratigraphic chronology has limitations, especially when comparing simultaneous events. To overcome this, geologists compare multiple stratigraphic sections to reconstruct the relative arrangement of geological units. Despite this, diachronism—differences in timing between layers and events—remains a persistent source of bias. Establishing the synchrony of events is particularly challenging for ancient rocks, as older formations are more likely to have undergone erosion and diagenesis, which can obscure critical information necessary for reliable correlations with other regions.

Relative Dating: Relative dating establishes the age of a rock or fossil by comparing it to the age of surrounding layers or other objects, rather than determining its exact numerical age. This method is only reliable when the layers remain in their original sequence. To determine relative ages, geologists apply the six fundamental principles of stratigraphy. This approach, often referred to as age dating, allows scientists to reconstruct the order of geological events. Correlation plays an important role in relative dating. By comparing rock units according to their lithology (rock type, composition, or texture) or fossil content (biostratigraphy), geologists can extend age relationships across large regions. If two layers match in rock type or contain the same fossil species, it is inferred that they were deposited during the same time interval and are therefore of equivalent age. Using the princi-

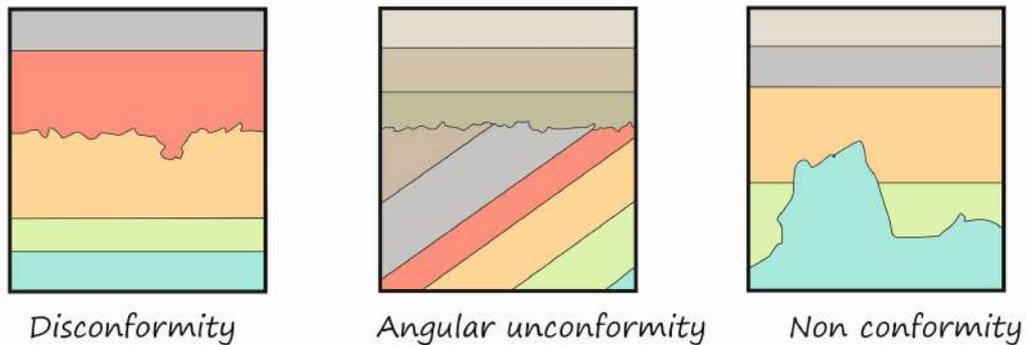


Figure 2.12: main unconformities in stratigraphy

ples of original horizontality and superposition, geologists conclude that the oldest rocks occur at the bottom of an undisturbed sequence, as these were deposited first. However, interpreting rock sequences can be complicated by unconformities, which represent gaps in the geological record caused by erosion or non-deposition. There are three main types of unconformities (Figure 2.12):

Angular unconformity: where older, tilted or eroded layers are overlain by younger, horizontal strata.

Disconformity: where periods of erosion or non-deposition occur between parallel layers.

Nonconformity: where sedimentary layers are deposited directly on eroded igneous or metamorphic rocks, representing very long-time gaps.

Relative dating also relies on biostratigraphy, which is the correlation of rock units based on their fossil content. Fossils that are particularly useful for this purpose are called index fossils (or guide fossils). These species are ideal markers because they were widespread geographically, existed for



Figure 2.13: example of some fossil indexes

relatively short geological intervals, were abundant, and are easy to identify (Figure 13). Their presence allows geologists to assign relative ages and recognize equivalent chronostratigraphic units across different regions. For instance, trilobites are commonly used as index fossils because their evolutionary history and extinction events are well known, allowing reliable correlations between distant rock layers. By contrast, fossils that occur across long geological intervals are less useful for relative dating, since they cannot provide precise time markers. Relative ages can also be determined by applying Lyell's principle of cross-cutting relationships, which states that any rock or feature (such as a fault, sill, or dike) that cuts across existing layers must be younger than the layers it intrudes.

Absolute Dating: absolute, or geochronometric, dating assigns numerical ages to rocks and geological events by measuring the atomic properties

of the minerals within them. Unlike relative dating, which only establishes whether one rock is older or younger than another, absolute dating can provide an actual age in years. Atoms are made up of protons and neutrons. The number of protons defines the element, while the number of neutrons determines the isotope of that element. Some isotopes are unstable and undergo radioactive decay, transforming into different, more stable isotopes. This decay occurs through processes such as:

Beta decay,: Beta decay, where a neutron becomes a proton while releasing an electron

Alpha decay, where the nucleus emits two protons and two neutrons (an alpha particle), producing a new isotope (Figure 2.14).

In this system, the original isotope is referred to as the parent, and the product of the transformation is called the daughter isotope. Importantly, radioactive isotopes become incorporated into the crystalline structure of igneous rocks as they cool, providing a measurable record of time. A key concept in radiometric dating is the half-life, which is the time required for half of the parent isotopes in a sample to decay into daughter isotopes. For example, if a radioactive isotope has a half-life of 4,000 years, after this time half of the original parent atoms remain. After 8,000 years, only one-quarter remains, and after 12,000 years (three half-lives), only one-eighth remains. By measuring the ratio of parent to daughter isotopes in a sample and knowing the half-life, scientists can calculate the absolute age of the rock. This technique is called radiometric dating. One of the best-known forms of radiometric dating is radiocarbon dating, used to determine the ages of once-

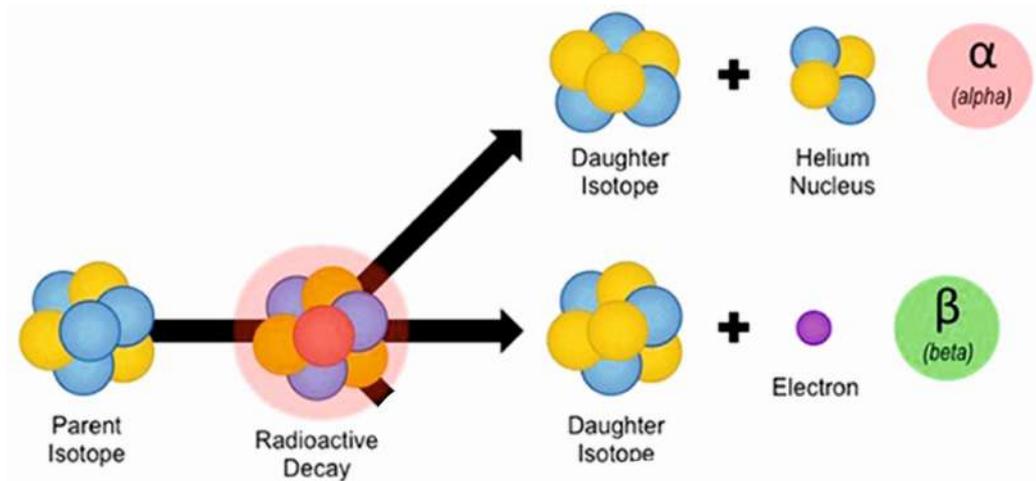


Figure 2.14: Radioactive decay of select elements can be a useful tool to date rocks and minerals (physci.mesacc.edu)

living organisms such as plants, wood, and even paper made from organic material. Living organisms take in carbon as both stable carbon-12 and radioactive carbon-14. When the organism dies, carbon intake ceases, and carbon-14 begins to decay at a fixed rate. By measuring the remaining C-14 in a sample, scientists can determine how long ago the organism died. The half-life of carbon-14 is 5,730 years, making this method reliable for dating materials up to about 70,000 years old (roughly 12 half-lives). Beyond this range, the remaining C-14 is too minimal for accurate measurement.

2.8 Paleontology

A fossil is the preserved evidence of pre-existing life within sedimentary rocks. Such evidence of palaeobiological history may consist of shells, bones, pollen, footprints, wood, coprolites (fossilized excrement), and other remains or traces. The techniques used to extract fossils depend on both the na-

ture of the fossil and the lithology of the enclosing rock, and may involve either chemical or physical methods. Fossils are further classified according to size: **Microfossils** (millimetric to micrometric scale), such as conodonts and foraminifera.

Macrofossils (from several millimetres to metric scale), such as ammonites and dinosaurs.

2.8.1 What is Palaeontology?

Palaeontology is the scientific study of ancient life, based on the analysis of fossilized remains and traces of organisms preserved within geological formations. By integrating methods from both geology and biology, palaeontologists reconstruct the morphology, ecology, and evolutionary history of extinct organisms. This discipline provides essential insights into the processes that shaped past ecosystems and the evolutionary pathways leading to modern biodiversity. The significance of palaeontology lies in its ability to demonstrate that life on Earth has undergone profound changes over geological time. By studying fossils in progressively older strata, scientists can establish an evolutionary framework that documents the succession of species, communities, and entire ecosystems. Palaeontology is inherently interdisciplinary. Its geological dimension allows the correlation of strata and the establishment of relative ages of rock units, while its biological perspective enables reconstructions of how ancient organisms lived and evolved. For this reason, palaeontologists must possess a dual expertise as both geologists and biologists, capable of interpreting lithological as well as biological evidence.

2.8.2 Branches of Palaeontology

Over time, palaeontology has developed several sub-disciplines, each addressing specific categories of evidence or methods of interpretation:

Palaeobotany : the study of fossil plants.

Palaeozoology : the study of fossil animals (although this term is less frequently employed).

Palaeobiology :the biological interpretation of fossil material, often focused on functional morphology, physiology, and evolutionary biology.

Palaeoecology : the reconstruction of ancient communities and their environmental settings.

Micropalaeontology : the study of microscopic fossils, frequently used in stratigraphy and palaeoenvironmental reconstructions.

Palynology : a specialized branch of micropalaeontology dealing with fossil pollen and spores.

2.8.3 What is a Fossil?

A fossil is the preserved evidence of pre-existing life within sedimentary rocks. Such evidence of palaeobiological history may consist of shells, bones, pollen, footprints, wood, coprolites (fossilized excrement), and other remains or traces. The techniques used to extract fossils depend on both the nature of the fossil and the lithology of the enclosing rock, and may involve either chemical or physical methods (Figure 2.15). Fossils are further classified according to size

Microfossils (millimetric to micrometric scale), such as conodonts and



Figure 2.15: Macrofossils and microfossils from terrestrial and marine environments

foraminifera.

Macrofossils (from several millimetres to metric scale), such as ammonites and dinosaurs.

2.8.4 Processes of Fossilization

Fossils can be preserved in various ways, depending on the nature of the organism and the surrounding environment. These preservation types are broadly classified into three categories: unaltered soft parts, unaltered hard parts, and altered hard parts.

Preservation of Unaltered Soft Parts (Exceptional Preservation: In rare and ideal conditions, entire organisms—including both soft and hard tissues—can be preserved with remarkable fidelity. In such cases, delicate

soft parts remain intact, providing detailed information about the organism's structure. This type of preservation occurs in several ways:

Amber: Fossilized tree resin from ancient conifers can trap insects due to its stickiness. Over time, the resin hardens and becomes buried, eventually forming amber. For example, the Vastan lignite mine in Gujarat, India, yields amber with exquisitely preserved insects (Figure 2.16).

Freezing: Organisms that fall into glacial crevasses or permanently frozen soils can be preserved with minimal decay. Low temperatures and oxygen-poor conditions prevent decomposition. The woolly mammoth from the Pleistocene of Siberia is a classic example.

Rapid Burial by Volcanic Ash or Sandstorms: Sudden coverage of ecosystems by ash or sand can preserve organisms in exceptional detail. Well-preserved Cretaceous fossils from China and Mongolia illustrate this process (Figure 2.16).

Preservation of Unaltered Hard Parts: Many invertebrates possess hard structures such as shells or skeletons composed of stable minerals like calcium carbonate, calcium phosphate, or silica. In some cases, these hard parts remain unchanged over millions of years, even if the soft tissues decay. Fossil shells often closely resemble modern counterparts, demonstrating remarkable durability.

Preservation of Altered Hard Parts: Alteration of hard parts usually begins after an organism is buried under sediments. Porous structures, such as bone marrow, allow mineral-rich groundwater to permeate and modify the original material. Pressure from overlying sediments accelerates these

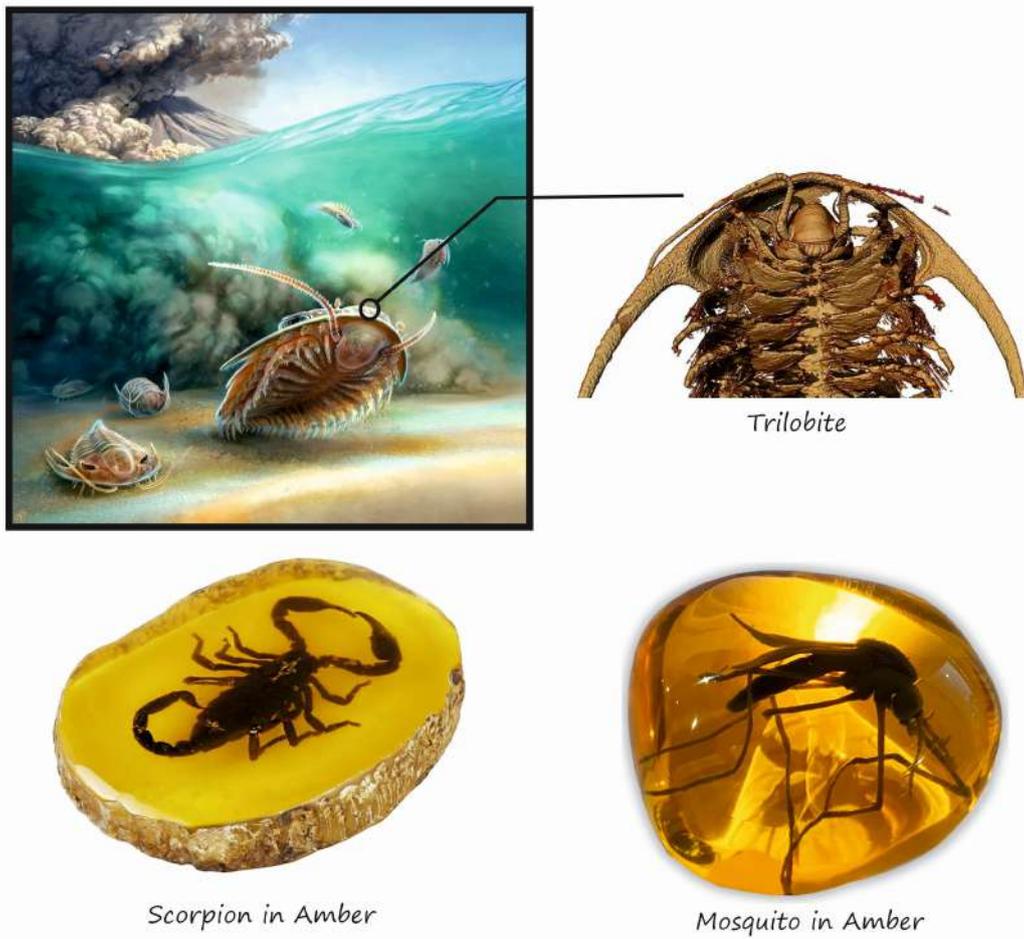


Figure 2.16: Upper illustration: Reconstruction of two trilobite species moments before burial by a volcanic ash flow approximately 510 million years ago (El Albani et al., 2017). Lower illustration: Exceptional preservation of a scorpion and a mosquito trapped in amber.

changes, leading to several fossilization processes:

Permineralization (Petrifaction): Porous materials such as bones, shells, and wood undergo slow mineral replacement. Groundwater carrying dissolved minerals fills the pores and gradually precipitates, partially or completely replacing the organic material with silica, calcite, or pyrite. This molecule-by-molecule replacement preserves fine structural details. Examples include petrified wood, dinosaur bones, and elephant tusks.

Replacement: Similar to permineralization, this process involves complete dissolution of the original hard parts, followed by deposition of new minerals (e.g., silica, calcite, hematite, pyrite) in their place.

Carbonization: Soft tissues of animals and plant stems or leaves lose hydrogen, nitrogen, oxygen, and other volatile elements under pressure, leaving behind a thin carbon film. These films preserve the shape of the organism and are commonly found in coal seams.

Molds and Casts: When a shell or skeleton is buried in sediment, it may dissolve over time, leaving an impression (mold) of the original organism. If this void is later filled with minerals or sediment, it forms a cast that replicates the original shape (Figure 2.17).

2.8.5 Conditions for Fossilization

Like extant organisms inhabiting diverse environments—such as marine, freshwater, terrestrial plains, or mountainous regions—it is generally inferred that prehistoric organisms occupied similar ecological niches. However, the potential for fossilization is not uniform across all environments. Both the

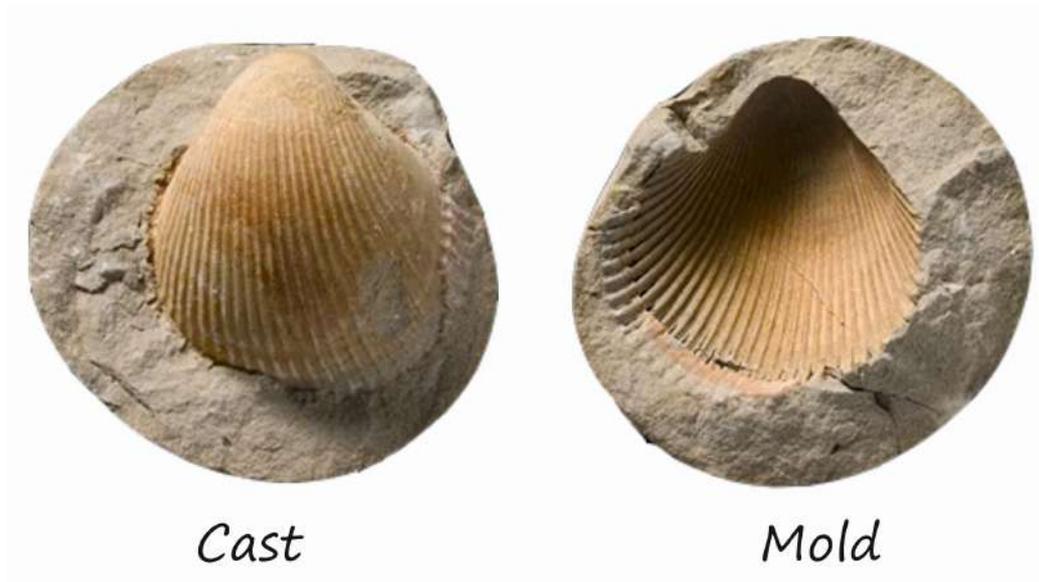


Figure 2.17: Cast and mold of a fossil bivalve, showing both the external and internal impressions of the shell.

biological characteristics of the organism and the nature of its depositional environment are critical determinants of preservation. The principal factors promoting fossilization are as follows:

Presence of hard anatomical structures: Organs or tissues with durable components, such as shells, bones, teeth, and woody tissues, exhibit greater resistance to decay and are therefore more likely to be preserved. In contrast, soft-bodied organisms, including insects, worms, and cnidarians, undergo rapid decomposition post-mortem and are infrequently fossilized.

Rapid burial: Prompt entombment under sedimentary deposits restricts exposure to oxygen and mitigates degradation by scavengers, thereby enhancing preservation potential.

Depositional environment: Environmental conditions exert a significant influence on the probability of fossilization. Marine organisms, for

instance, are more frequently preserved than terrestrial ones (Milsom and Rigby, 2010), due to the higher likelihood of rapid sediment accumulation. Terrestrial organisms, conversely, are exposed to greater risks of decay and scavenging, diminishing their chances of preservation.

2.8.6 Importance of Fossils

Fossils are crucial for understanding Earth's history and the evolution of life. They serve as natural records of past life and provide valuable information in several areas:

Evolution of Life: Fossils document the gradual development of life forms over geological time, establishing ancestor-descendant relationships. Primitive organisms, such as bacteria, blue-green algae, or Ediacara fauna, are found in older rocks (Precambrian and Lower Palaeozoic), while more advanced forms like vascular plants, mammals, and birds appear in younger rocks (Phanerozoic). These patterns support the theory of organic evolution and form the basis of the geological time scale, which is divided from oldest to youngest as:

Archeozoic: Most primitive life or absence of life

Proterozoic: Earlier life

Palaeozoic: Ancient life

Mesozoic: Middle life

Cenozoic: Recent or modern life

Dating Rocks: Sedimentary rocks are deposited in layers, with the oldest at the bottom and younger layers above. Fossils within these layers

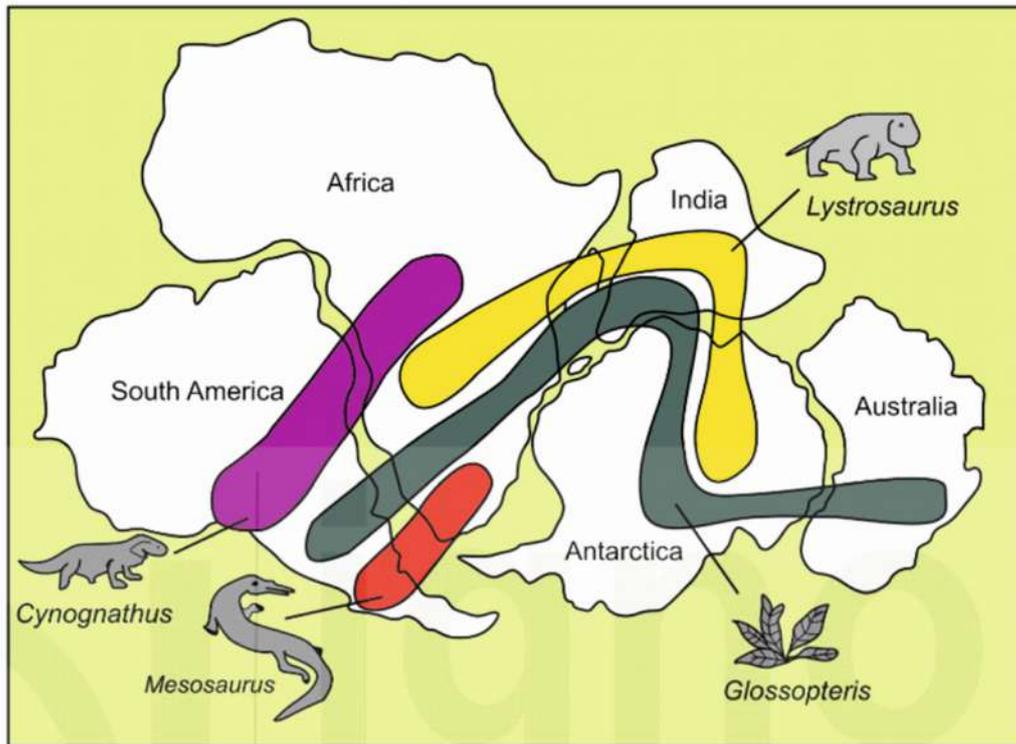


Figure 2.18: Late Palaeozoic palaeogeographic reconstruction of Gondwanan landmasses based on fossils of land animals and plants (Source: simplified after Benton and Harper, 2009)

allow relative dating of rocks, a field known as biostratigraphy. Index fossils—species with short-lived but widespread existence—are especially useful for dating and correlating rock layers. Examples include trilobites (Lower Palaeozoic) and ammonites (Mesozoic). Fossils also enable correlation of geographically separated rock sequences.

Palaeogeography: Fossils help reconstruct the past distribution of land and sea. For instance, fossils from the Himalayas indicate the region was once a sea before tectonic uplift formed the mountains. Similarly, fossil evidence supports the existence of the supercontinent Gondwana, which included present-day South America, Africa, Australia, Antarctica, and India

(Figure 2.18).

Palaeoclimate: Certain organisms are adapted to specific climates. Fossils of reptiles, for example, indicate warm past climates, while plant fossils such as cycads point to tropical or subtropical conditions. Leaf morphology, such as smooth or toothed margins, also provides clues about ancient climate.

Palaeoenvironment : Fossils indicate past environments. Marine settings are characterized by foraminifers, corals, trilobites, and ammonoids, while terrestrial or freshwater environments are represented by plants, fungi, insects, amphibians, and mammals (Figure 2.19).

Oil and coal exploration : Fossils are essential in locating oil and coal deposits, which originate from ancient plants and animals. Microfossils help determine the age and correlate the spatial distribution of source, reservoir, and cap rocks in petroleum exploration, as well as coal seams. Commonly used microfossils include foraminifers, calcareous nannofossils, and palynomorphs (pollen and spores).



Ediacara fossil



Placoderm fossil



Dinosaur fossil



Mammoth fossil

Figure 2.19: Reconstruction of the biosphere through geological eras

2.9 Suggested readings

Anderson, R.S., Anderson, S.P., 2010. *Geomorphology: The Mechanics and Chemistry of Landscapes*. Cambridge University Press.

Behrensmeyer, A.K., et al. (Eds.), 2000. *Taphonomy: Process and Bias Through Time*. Springer.

Benton, M.J., Harper, D.A.T., 2020. *Introduction to Paleobiology and the Fossil Record*, 2nd ed. Wiley-Blackwell.

Boggs Jr., S., 2014. *Principles of Sedimentology and Stratigraphy*, 5th ed. Pearson.

Bridge, J.S., Demicco, R.V., 2008. *Earth Surface Processes, Landforms and Sediment Deposits*. Cambridge University Press.

Briggs, D.E.G., Crowther, P.R. (Eds.), 2001. *Palaeobiology II*. Blackwell Science.

Catuneanu, O., 2019. *Principles of Sequence Stratigraphy*, 2nd ed. Elsevier.

Coe, A.L. (Ed.), 2022. *The Sedimentary Record of Sea-Level Change*. Cambridge University Press.

Collinson, J., Mountney, N., Thompson, D., 2019. *Sedimentary Structures*, 4th ed. Dunedin Academic Press.

Dey, S., 2014. *Fluvial Hydrodynamics: Hydrodynamic and Sediment Transport Phenomena*. Springer.

Dixon, J.C., Thorn, C.E., 2005. *Chemical Weathering in Terrestrial Ecosystems*. Elsevier.

Foote, M., Miller, A.I., 2013. *Principles of Paleontology*, 3rd ed. W.H.

Freeman.

Garcia, M.H., 2008. Sedimentation Engineering: Processes, Measurements, Modeling, and Practice. American Society of Civil Engineers.

Goudie, A.S., Viles, H.A., 2016. Geomorphology in the Anthropocene. Cambridge University Press.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., 2020. The Geologic Time Scale 2020. Elsevier.

James, N.P., Dalrymple, R.W., 2010. Facies Models 4. Geological Association of Canada.

Julien, P.Y., 2010. Erosion and Sedimentation. Cambridge University Press.

Koutsoukos, E.A.M., 2020. Applied Stratigraphy. Springer.

Middleton, G.V., Southard, J.B., 1984. Mechanics of Sediment Transport. Society for Sedimentary Geology (SEPM).

Nichols, G., 2009. Sedimentology and Stratigraphy, 2nd ed. Wiley-Blackwell.

North American Commission on Stratigraphic Nomenclature, 2005. The North American Stratigraphic Code. AAPG Bulletin.

Prothero, D.R., 2013. Bringing Fossils to Life: An Introduction to Paleobiology, 3rd ed. Columbia University Press.

Reading, H.G., 2009. Sedimentary Environments: Processes, Facies and Stratigraphy, 3rd ed. Blackwell Science.

Summerfield, M.A., 2014. Global Geomorphology. Routledge.

Viles, H.A., 2013. Weathering in the Anthropocene: A Soiled Geomor-

phology?. Progress in Physical Geography.

Chapter 3

Internal Geodynamics

3.1 Tectonic plates

3.1.1 Introduction

The Earth is composed of layers with distinct compositions and physical properties: the solid inner core, the fluid outer core, the viscous mantle, and the solid lithosphere. The lithosphere, forming the Earth's outer shell, consists of the upper mantle and the crust. There are two types of lithosphere: oceanic, with a 5–8 km thick basaltic crust, and continental, with a 30–40 km thick granitic-dioritic crust. The lithosphere is fragmented into plates, whose edges are called plate boundaries. The Earth has seven major plates, Africa, Antarctica, Australia, Eurasia, North America, South America, and Pacifica, and several minor plates, such as Adria, Arabia, the Caribbean, Nazca, and the Philippines (Figure 3.1). Most plates consist of both continental and oceanic lithosphere. Plate movements can be approximated as rigid-body

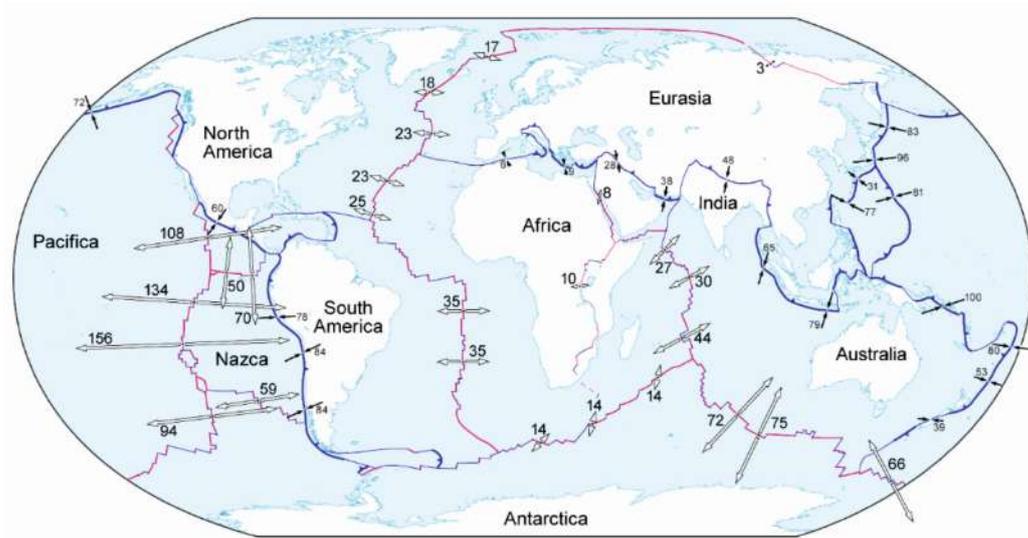


Figure 3.1: plate organization of the present day plate tectonics (files.ethz.ch)

motions, generating interactions at plate boundaries. Plate boundaries move and change shape over time, and the global mosaic of plates is periodically reorganized. Plate tectonics, the study of these motions and their consequences, allows linking surface geological and geophysical structures with movements driven by deep Earth processes. Thermal gradients between the hot interior and cold exterior drive convection in the mantle, which in turn moves lithospheric plates. Geodynamics, a branch of Earth Sciences, seeks to explain large-scale features of the Earth using mechanical and dynamic principles. It is now accepted that the repeated amalgamation and breakup of continental lithosphere, along with the creation and subduction of oceanic lithosphere, have profoundly shaped Earth's evolution since the Archaean. Within this plate-tectonic framework, large-scale deformation represents the local response of the lithosphere to induced stresses.

3.1.2 Definition of Plate tectonics

Plate tectonics describes the movement of rigid lithospheric plates over the more ductile asthenosphere. The dominant driving mechanism is thought to be mantle convection, in which heat from Earth's interior—primarily generated by the decay of radioactive elements—creates currents that transport material. These currents exert forces on the overlying plates, causing them to move. Additional forces also contribute to plate motion. For instance, differences in plate density can cause one plate to sink beneath another (slab pull), while rising magma at mid-ocean ridges pushes plates apart (ridge push). Together, these mechanisms explain the dynamic nature of Earth's surface. A useful analogy is a pot of boiling water: floating pieces on the surface (plates) shift as the underlying water (magma) circulates and bubbles.

3.1.3 Modern Evidences of plate tectonics

Following the Second World War, rapid advances in marine geophysics, oceanography, and paleomagnetism provided decisive new arguments in favor of continental mobility. The deployment of multi-beam sonar systems on research vessels enabled the accurate mapping of the ocean floor. Complementary methods such as dredging and coring allowed systematic sampling of seafloor rocks and sediments, while manned and unmanned submersibles provided direct access to samples at great depths, sometimes several thousand meters below sea level.

Ocean Floor Morphology: One of the most striking discoveries was the identification of a vast interconnected system of submarine mountains,

the mid-ocean ridges, extending for more than 60,000 kilometers across the world's oceans. These ridges are composed almost exclusively of volcanic rocks, mainly basalts. Their morphology is highly distinctive: they rise 1,000 to 2,000 meters above the surrounding abyssal plains, and their axial regions are marked by narrow rift valleys bounded by faults. Such structures are strongly indicative of extensional tectonics and seafloor spreading processes.

Distribution of Seismic and Volcanic Activity: Earthquakes are not randomly distributed across the globe but rather align along elongated, relatively narrow belts that traverse both oceans and continents. These seismic zones coincide with major volcanic belts, where most of the Earth's active volcanoes are located (Figure 3.2). This close association indicates that geological activity is concentrated along well-defined linear zones of global extent. Similarly, deep ocean trenches, some exceeding 10,000 meters in depth (for example, the Mariana Trench at -11,500 m), are concentrated mainly along the Pacific margins, where they are closely associated with both seismicity and volcanism (Figure 3.2).

Age and Thickness of Oceanic Sediments: Chronostratigraphic studies revealed that the age and thickness of oceanic sediments increase progressively with distance from mid-ocean ridges (Figure 3.3). In the Atlantic, for instance, sediments located directly above the ridge axis are young and thin, whereas sediments found near the continental margins of Africa and North America are considerably thicker and may date back to the Jurassic (150–200 million years ago). Importantly, this distribution of sediment ages is symmetrical with respect to the ridge axis, providing strong evidence for

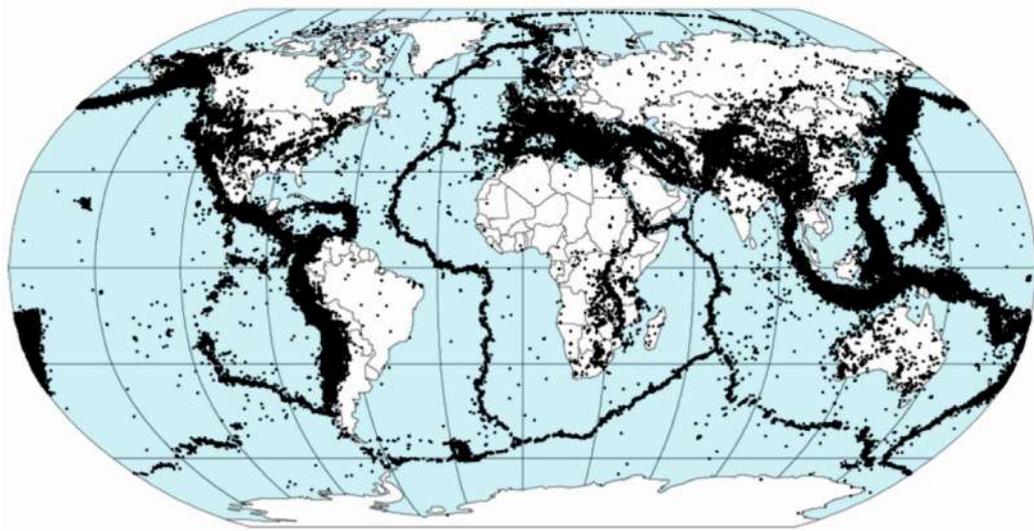


Figure 3.2: Distribution of earthquakes

seafloor spreading (Figure 3.3).

Paleomagnetism: Paleomagnetic research demonstrated that Earth’s magnetic field has undergone numerous polarity reversals through geological time. Magnetic surveys of the ocean floor revealed a striking pattern: bands of normal and reversed magnetic polarity are arranged symmetrically on either side of ridge axes. This “magnetic striping” constitutes one of the most compelling confirmations of seafloor spreading and plate motion (Figure 3.4).

3.1.4 Plate Mobility

Convection: The movement of tectonic plates is often explained by mantle convection, which drives the displacement of the overlying lithospheric plates. Convection is a deep thermal phenomenon caused by density contrasts within mantle rocks. These movements are expressed through Archimedes’ principle, favoring the rise of hot, buoyant materials toward the surface due to

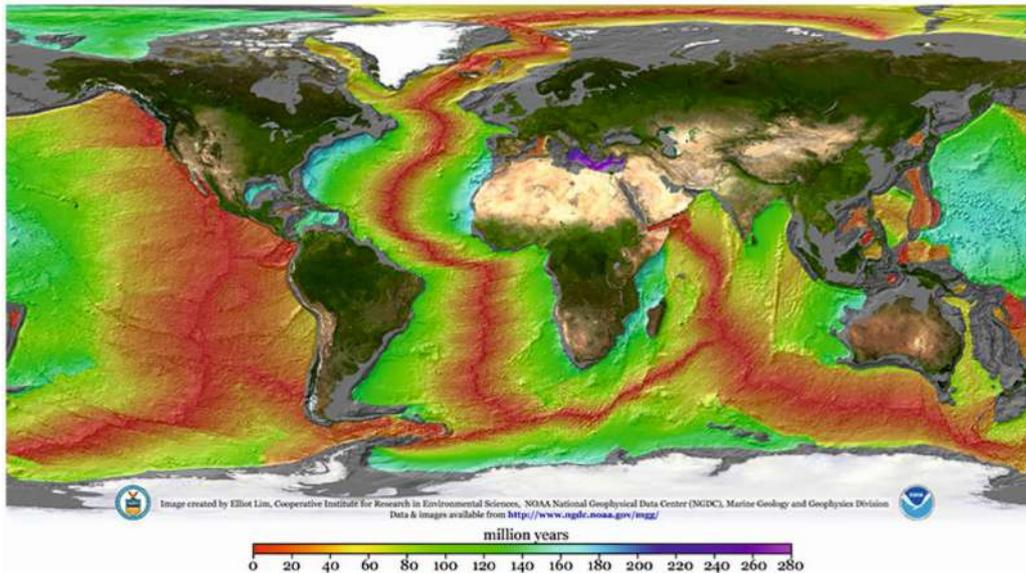


Figure 3.3: Reconstruction of the present-day mid-ocean ridge (after NOAA/NCEI).

their lower density. Conversely, when these hot materials cool near the surface, they become denser and sink back downward. This geological process has occurred intermittently throughout the geological eras. Origin of Mantle Convection: Mantle convection arises from existing density anomalies in mantle rocks. Three models describe how thermally induced density anomalies can develop within the mantle (Figure 3.5):

Heating from below and cooling from above: An inverse density gradient is established because the upper mantle becomes denser than the lower mantle, producing downward flows.

Uniform heating and top cooling: Downward movements caused by cooling at the upper mantle are accompanied by more diffuse upward flows resulting from the overall heating of the basal mantle. The interaction of these flows contributes to thermal equilibrium by reducing the temperature differ-

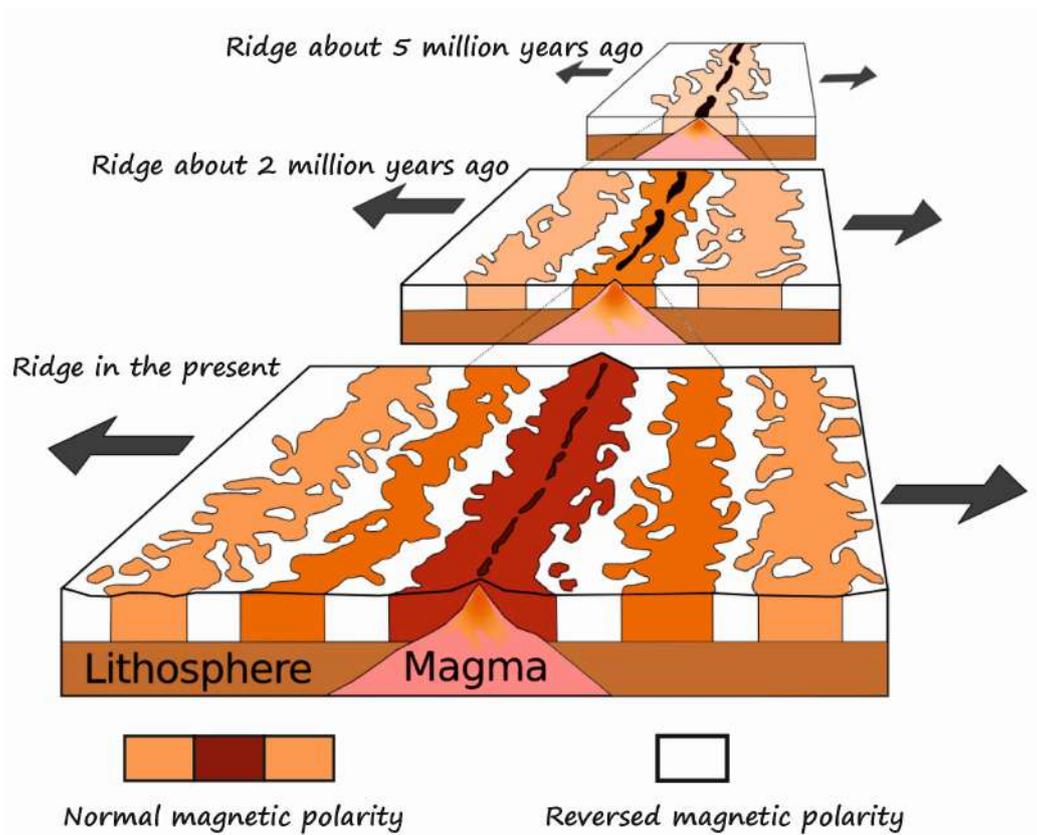


Figure 3.4: Magnetic stripes form as new oceanic crust records Earth's magnetic reversals during sea-floor spreading. The models illustrate the ridge (a) 5 Ma, (b) 2 Ma, and (c) at present (IAS.EXAM.com)

ence between the two ends of the mantle.

Mixed system: In reality, mantle dynamics reflect a mixed system (Figure). It results from the interaction of cooling from above with dual heating of the mantle mass, both by mantle radioactivity and by heat originating from the core. Internal heating of the mantle is two to three times greater than that of the core. Mantle heat is primarily produced by the radioactive decay of elements such as Uranium (^{235}U and ^{238}U), Thorium (^{232}Th), and Potassium (K). These elements are almost absent in the core but highly concentrated in the mantle, making the mantle a more significant source of heat than the core.

Plate Boundaries: The Earth's lithosphere is divided into plates that move relative to each other. This movement causes interactions at plate boundaries, which are classified into three main types: divergent, convergent, and transform boundaries. These boundaries shape the Earth's surface, forming oceans, mountains, and volcanic regions, and indirectly influence ecosystems and biodiversity.

Divergent boundaries: At divergent boundaries, plates move apart (Figure 3.6). This process usually occurs along mid-ocean ridges, where magma rises from the mantle to form new oceanic crust, a mechanism known as seafloor spreading. On continents, this begins with rifting, where the crust stretches and forms elongated valleys called grabens. Examples include the East African Rift, which has a western branch passing through lakes Kivu, Tanganyika, and Malawi, and an eastern branch including Mount Kenya, the Natron Basin, and the Afar Depression. Rifting may be accompanied by vol-

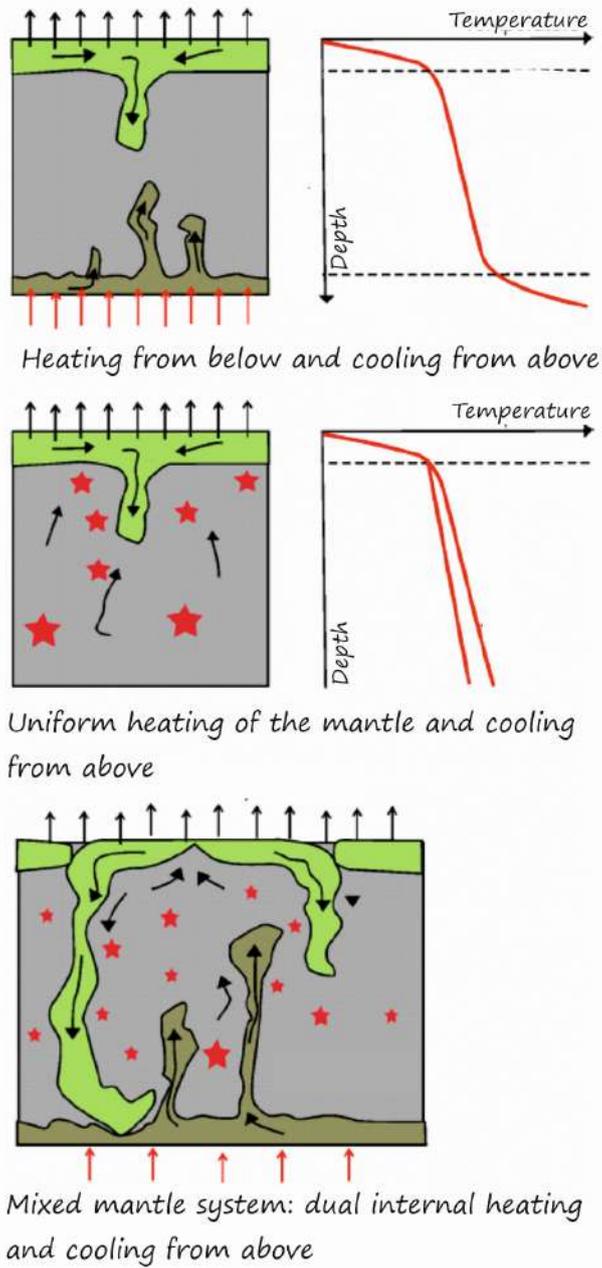


Figure 3.5: Mantle convection is driven by heating from below, top cooling, or a combination of both, creating upward and downward mantle flows.

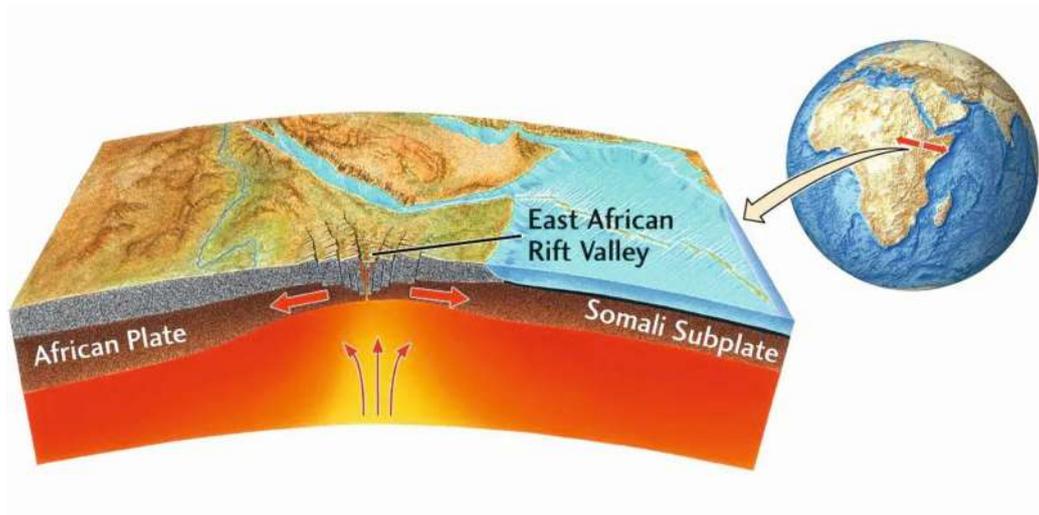


Figure 3.6: Divergent boundaries at mid-ocean ridges. Rifting may be accompanied by volcanic activity, as observed in the Afar Depression (geologyin.com)

canic activity, such as the Virunga volcanoes in Africa or the Eifel volcanoes in Europe. If rifting continues, the continent eventually splits, allowing the formation of a new ocean, as in the present-day Red Sea. Mid-ocean ridges are sites of continuous crustal formation, and the new basalt records symmetrical magnetic patterns due to Earth's magnetic field reversals. Spreading rates vary from less than 1 cm/year at ultraslow ridges to more than 20 cm/year at fast ridges.

Convergent Boundaries: Convergent boundaries occur where tectonic plates move toward each other. At these boundaries, one plate may be forced beneath another in a subduction zone, giving rise to earthquakes, volcanic activity, and deep-sea trenches. Convergent boundaries are classified into three types based on the nature of the colliding plates (Figure 3.7).

Continental-Continental Collisions: When two continental plates collide,

the crust is compressed, thickened, and uplifted, forming extensive mountain ranges. A prime example is the Himalayas, created by the northward movement of the Indian Plate into the Eurasian Plate, resulting in the massive uplift of the crust (Figure 3.7).

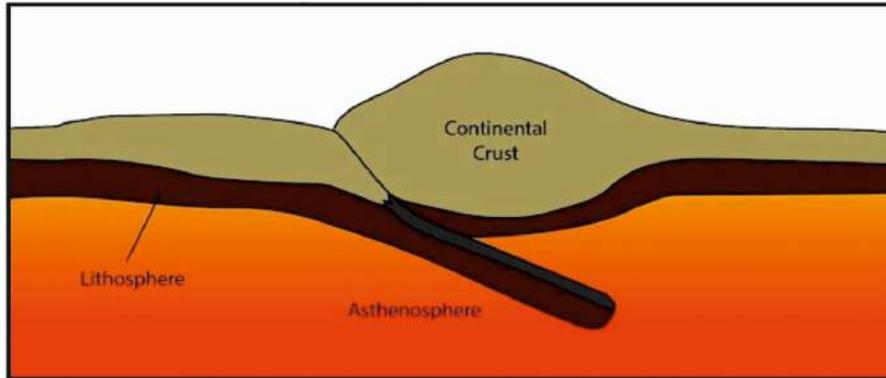
Continental-Oceanic Collisions: When a continental plate converges with an oceanic plate, the denser oceanic plate is subducted beneath the lighter continental plate. As it descends into the mantle, water and other volatiles released from the subducting plate trigger partial melting of the overlying mantle. The resulting magma rises to the surface, forming volcanic arcs, such as the Andes Mountains, where the Nazca Plate subducts beneath the South American Plate (Figure 3.7).

Oceanic-Oceanic Collisions: When two oceanic plates converge, one plate is forced beneath the other, forming a subduction zone. Melting of mantle material above the subducted plate produces magma that rises to create volcanic island arcs, exemplified by the Mariana Islands, which are accompanied by deep ocean trenches and active volcanism (Figure 3.7).

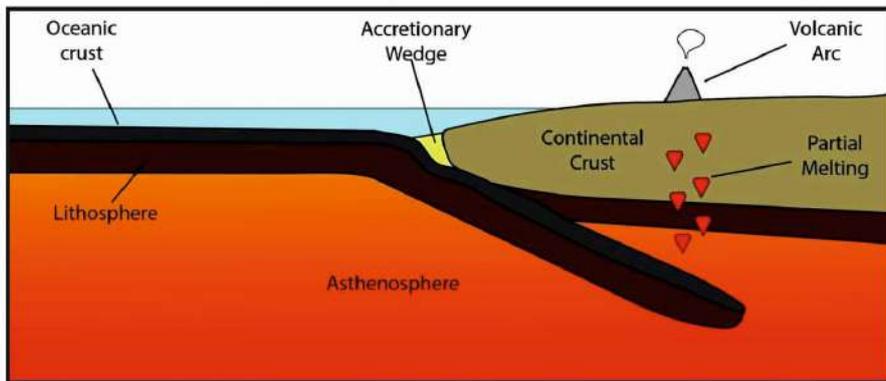
3.1.5 Plate Tectonics on Other Planets

The Earth formed alongside the other planets of the solar system approximately 4.56 billion years ago. This raises the question of whether processes similar to Earth's plate tectonics have occurred on other planets. The outer gas giants—Jupiter, Saturn, Uranus, and Neptune, have low densities, consist mainly of gases, and lack a solid surface. Plate tectonics cannot develop on these planets. The four inner planets—Mercury, Venus, Earth, and

Continental-Continental Collision



Continental-Oceanic Collision



Oceanic-Oceanic Collision

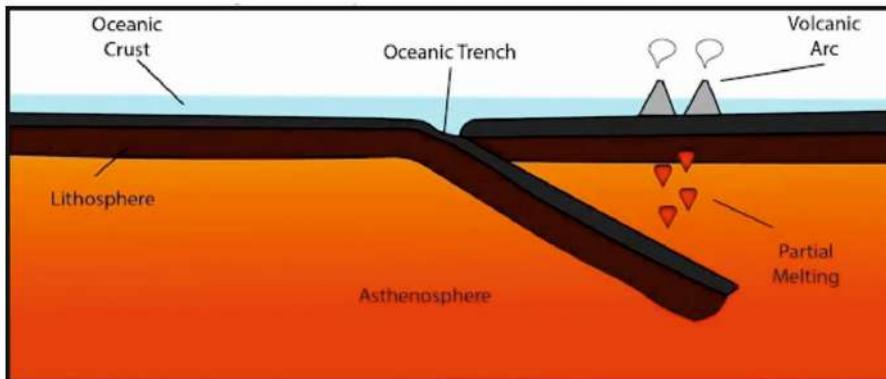


Figure 3.7: different convergent boundaries (geologyin.com)

Mars—are rocky bodies with solid surfaces. Volcanic activity has shaped their evolution, producing primarily basaltic magmas. However, geological structures characteristic of plate tectonics, such as mid-ocean ridges and subduction zones, are observed only on Earth. A planet's geological activity depends on its internal energy, mostly from radioactive decay of isotopes such as K, ^{232}Th , ^{235}U , and ^{238}U . Mercury and Mars are much smaller than Earth and have limited internal heat, likely rendering them inactive. Venus, with a size close to Earth, could be geologically active, but its extremely high surface temperature (465°C) prevents the presence of liquid water, oceans, and surface weathering. On Earth, internal energy drives oceanic crust formation, plate recycling in subduction zones, and continental crust formation. Water allows low-temperature alteration of crust, sediment transport, and mantle hydration during subduction, facilitating the formation of the asthenosphere, which enables lithospheric plate movement. On Venus and Mars, there is no evidence for mid-ocean ridges, and basalt melting is inhibited in the absence of water. Venus and Mars are therefore considered one-plate planets. Water is thus essential for the development and maintenance of plate tectonics on Earth.

3.2 Volcanism

3.2.1 Introduction

Volcanic eruptions are an essential indicator of the Earth's internal dynamics. Typically, the most active volcanoes are located along tectonic plate boundaries. For instance, in a divergent tectonic context (oceanic spreading), submarine volcanoes form along mid-ocean ridges and contribute to the renewal of the oceanic crust. Volcanoes can also manifest in other tectonic settings, which will be discussed further below. Today, volcanoes are increasingly studied and have become significant for the economic and social life of various countries. However, they can also pose a hazard to local populations, particularly in cases of explosive eruptions. On the other hand, volcanoes can offer considerable benefits. The weathering of volcanic rocks contributes to the formation of fertile soils for agriculture, and some volcanoes are highly attractive for tourism.

3.2.2 Components of a Volcano

Magma chamber: This is a reservoir located 10–50 km within the lithosphere. It serves as the accumulation point for magma rising from the mantle. When the magma chamber is depleted following an eruption, the volcano collapses, forming a caldera (Figure 3.8).

Volcanic conduits: These are underground voids connecting the crater to the magma chamber. They correspond to fractures that allow magma to ascend due to buoyant forces.

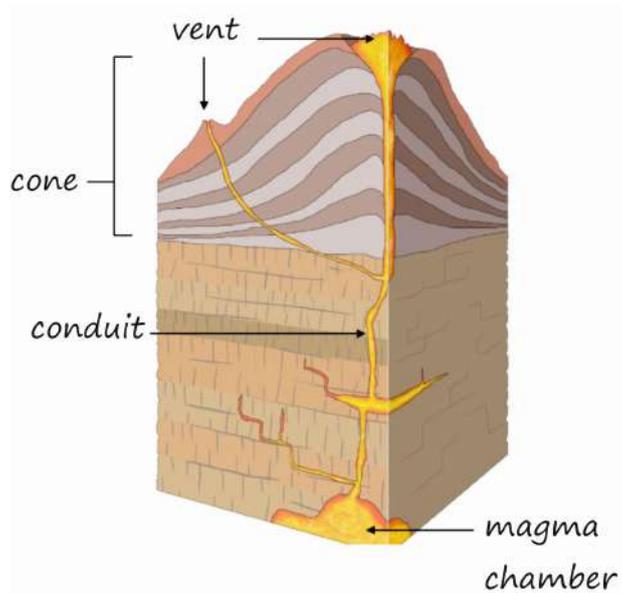


Figure 3.8: main components of a volcano

Vent: The crater is the passage through which magma reaches the Earth's surface. Its diameter varies considerably depending on the volume of erupted volcanic products.

Cone: A volcano typically resembles a mountain with steep sides, often forming a truncated cone topped by a crater and a plume of smoke. This type is called a stratovolcano. Other types have gently sloping walls extending over tens of kilometers, such as shield volcanoes. In some cases, the volcano's external relief is absent; instead, it features a large depression several hundred meters deep and several kilometers wide, known as a caldera.

3.2.3 Tectonic context of volcanoes

Mid-ocean ridge volcanoes : The oceanic ridge system coincides with divergent plate margins. Magma produced by partially melted upper mantle

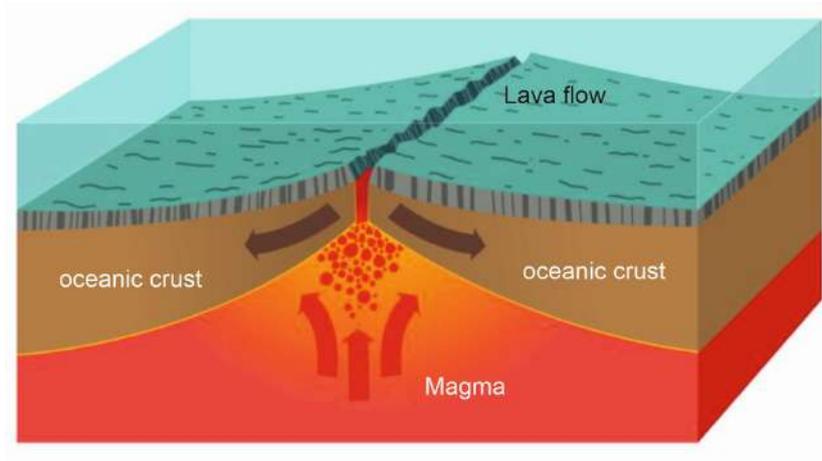


Figure 3.9: Mid-ocean ridge volcanoes (freepik.com)

rocks (asthenosphere) rises through fractures, causing submarine eruptions. Magma cools rapidly on contact with water, forming pillow lava. When the magma chamber is not connected to any fracture reaching the surface, magma cools at depth, forming gabbros. New volcanic layers are more prominent closer to the ridge, while alteration by ocean waters increases with distance. Subsequent oceanic sedimentation can cover the volcano to a thickness of hundreds of meters (Figure 3.9).

Continental rift volcanoes : This stagprecedes oceanic spreading and is marked by the ascent of mantle magmatic rocks. It produces extensive depressions spanning hundreds or thousands of kilometers. The lithosphere becomes weakened, and numerous volcanic centers emerge as magma ascends through fractures. Volcanic activity can be both explosive and effusive, forming various types of volcanoes, including stratovolcanoes and shield volcanoes. In advanced stages, an oceanic ridge may form, signaling the birth of a new ocean. The most famous example of this tectonic setting is the

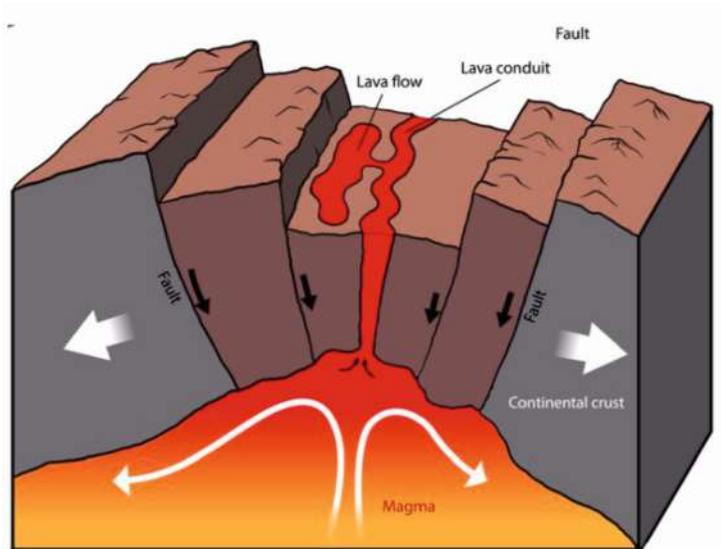


Figure 3.10: Continental rift volcanoes (freepik.com)

East African Rift Valley, a major fault system extending from the Jordan Valley in the Middle East through the Red Sea to Mozambique over approximately 6,500 km. The formation of a new ocean is observed in this region, accompanied by volcanic activity generating new oceanic crust Figure (3.10).

Continental margin volcanoes: These volcanoes are located at the boundary between oceanic and continental lithospheric plates (Figure 3.11). When ridge activity is intense, older rocks are pushed toward continental margins by newer rocks. During direct contact, the denser oceanic crust subducts beneath the continental crust—a process known as subduction. As oceanic rocks descend, temperature rises, releasing water from minerals. This water induces partial melting of mantle peridotites, generating hydrated magma that accumulates in volcanic chambers. The high-water content increases magma viscosity, often resulting in explosive eruptions. Stratovolca-

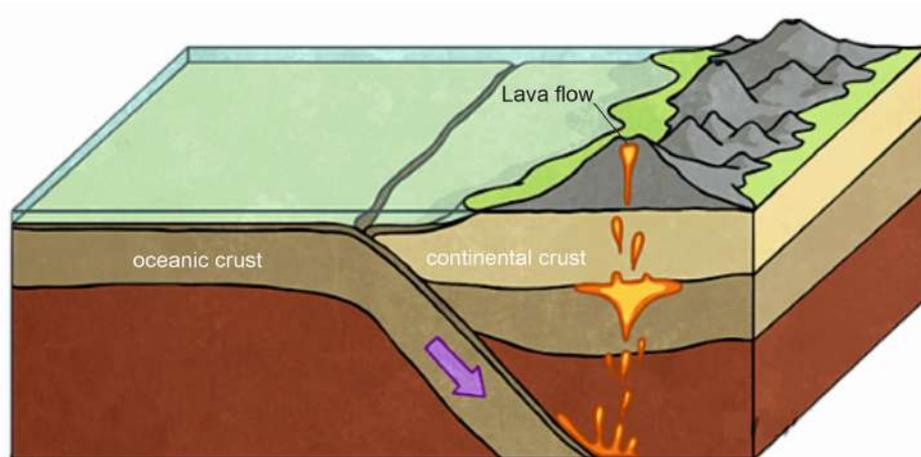


Figure 3.11: Subduction volcano (freepik.com)

noes and calderas in Central America and the Andes are typical examples. A similar process occurs when two oceanic plates converge. The older, denser plate subducts, and the hydrated peridotites melt at depth to form viscous magma. This magma ascends to form volcanic arcs parallel to the plate boundary, as seen in the Aleutian Islands (Alaska), the Philippines, and New Zealand.

Hotspot volcanoes: This volcanism occurs independently of plate boundaries. Certain regions, called hotspots, are far from plate boundaries but feature upwelling magma from depth. Hotspots are relatively stationary compared to the overlying tectonic plates. As the plate moves over the hotspot, a chain of volcanoes forms, with the oldest located farthest from the hotspot. This alignment provides insights into the plate's movement, speed, and direction. Famous examples include the Hawaiian and Galápagos Islands (Figure 3.12).

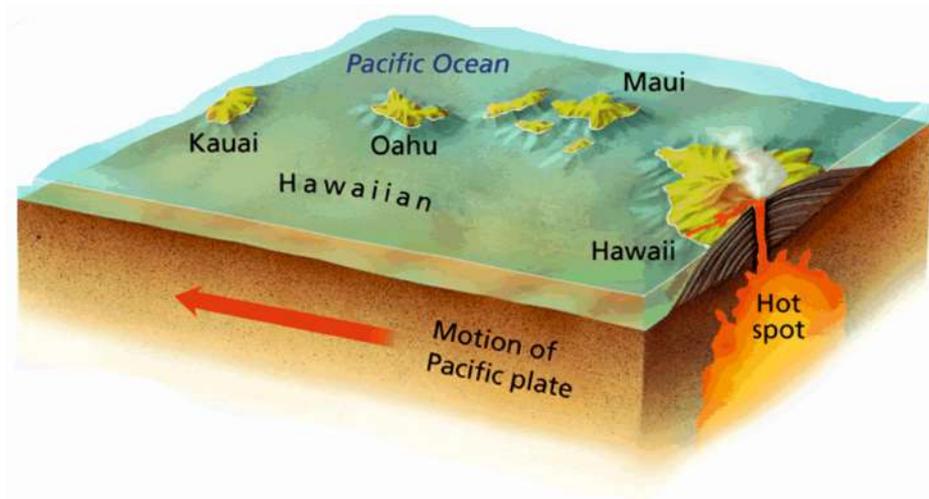


Figure 3.12: active hotspot in Hawaii. This hotspot has been around for millions of years and created the islands Hawaii, Maui, Oahu and Kauai.

3.2.4 Volcanic Products

Magma is a mixture of molten silicates, solid debris, and dissolved fluids. Upon eruption at the Earth's surface, it produces three main types of products: lava, volcanic gases, and pyroclastic materials. These products vary depending on magma composition, gas content, and environmental conditions (Figure 3.13).

Lava: Lava refers to degassed magma and the rock resulting from its solidification. Its viscosity depends on silica content and temperature: higher silica and lower temperature increase viscosity. Basaltic lavas can be classified into several types:

Pahoehoe : Fluid, gas-rich lava with a smooth, ropy surface, typical of Hawaiian basaltic flows.

Aa : More viscous, gas-poor lava with a rough, broken surface.

Pillow lava: Characteristic of submarine mid-ocean ridges (MORBs),

formed when lava extrudes into water and cools rapidly, producing pillow-shaped structures.

Columnar basalt: During solidification, lava flows may develop a prismatic structure known as columnar basalt.

Volatiles (Gaseous Products): Dissolved gases in magma are released when pressure decreases near the Earth's surface, sometimes triggering explosive eruptions. Common volcanic gases include:

- Water vapor (H₂O) • Carbon dioxide (CO₂)
- Nitrogen (N₂)
- Sulfur oxides (SO₂)
- Carbon monoxide (CO)
- Hydrogen chloride (HCl)
- Halogen gases such as fluorine and chlorine

Gas emissions occur from the crater and nearby vents called fumaroles. Sulfur-rich fumaroles are termed solfataras, while cold CO emissions are called mofettes.

Pyroclastic Materials: Solid fragments ejected during explosive eruptions are collectively termed pyroclasts or tephra. They are classified by size:

- Dust: <0.25 mm
 - Ash: 0.25–4 mm, capable of traveling long distances
 - Lapilli / Cinders: 4–32 mm basaltic fragments
 - Volcanic blocks: >64 mm, solid when ejected
 - Volcanic bombs: >64 mm, molten when ejected; frothy rhyolitic fragments

that can float on water are called pumice.

Pyroclastic deposits can consolidate into coherent rocks:



Figure 3.13: different materials from volcanic eruption

- Tuffs: From consolidated ash and dust
- Agglomerates and volcanic breccias: From consolidated bombs and blocks

Volcanic Flows and Deposits:

- Tephra fall: Accumulation of pyroclastic debris through vertical air fall.
- Pyroclastic flows: Fast-moving avalanches of incandescent ash and gas, often produced by lava dome collapse.
- Lahars: Rapid mudflows formed when water mixes with hot pyroclastic material, sometimes reaching speeds of 30 km/h

3.2.5 Type of volcanoes

Viscosity is a fundamental factor in volcanology. Magma with high viscosity (very sticky) typically produces volcanoes with steep slopes of about 30–35°. Because this lava does not travel far from the vent, it accumulates in successive layers, forming cone-shaped volcanoes known as stratovolcanoes (Figure 3.14). In contrast, shield volcanoes are created by the eruption of highly fluid basaltic lava, which can flow over great distances. This results in broad volcanoes with gentle slopes of less than 10°.

Composite volcanoes : Composite volcanoes, so called also stratovolcanoes, by comparison, are more steeply sided and distinctly conical. They are formed from viscous lava that resists flowing, causing it to build up around the vent. Because gases become trapped within this sticky magma, stratovolcanoes are more likely to produce explosive eruptions. Andesite—named after the Andes Mountains—is the most common volcanic rock associated

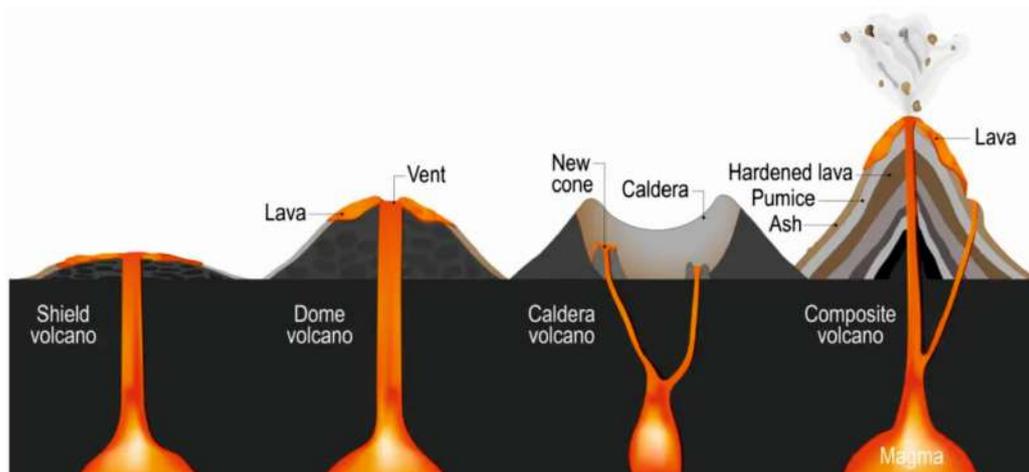


Figure 3.14: type of volcanoes

with stratovolcanoes, although other rock types can also be erupted in different tectonic settings.

Lava domes: Lava domes develop when extremely viscous magma extrudes at the surface but cannot travel far. Instead, it accumulates directly above the vent, forming a dome-shaped mass. A well-documented example is the Soufrière Hills volcano on Montserrat in the Caribbean, where repeated phases of dome growth and collapse have been observed.

Calderas: Calderas are formed when an exceptionally large eruption empties the underlying magma chamber. The unsupported roof then collapses, creating a steep-walled depression that may span tens of miles. In some cases, caldera formation occurs when the summit of a stratovolcano is removed during a massive eruption—effectively blowing the top off the volcano.

3.2.6 Volcanic Eruptions

Two main types of volcanic eruptions are distinguished (Figure 3.15):

Effusive eruptions : These involve the outflow of fluid lava, typically basaltic, which loses its gaseous components upon reaching the surface. Lava movement is primarily controlled by the volcano's slope and the distance from the crater. The steeper the slope, the faster the lava will flow, and the farther it can travel; however, its speed decreases significantly as it cools. Depending on the cooling environment, magma can take various forms. For example, pillow lavas characterize submarine volcanoes, while on continents, lava can form sharp rock spires known as columnar lavas.

Explosive eruptions Explosions occur due to the sudden release of dissolved gases from the magma as pressure decreases during its ascent. Three factors govern this explosive behavior: magma viscosity, gas content, and eruption rate (the volume of material expelled during the eruption). Several categories of explosive eruptions are recognized:

Hawaiian eruption : Hawaiian eruptions are the gentlest type, involving fluid basaltic lava with little gas. They produce broad shield volcanoes through steady lava flows, often from summit vents and fissures. Activity may start as a "curtain of fire" along fissures before focusing at a few vents. Lava fountains can reach hundreds of meters and may form spatter cones or feed lava flows. Hawaiian eruptions can last for years and sometimes create lava lakes.

Strombolian eruption: Strombolian eruptions are driven by gas bubbles bursting in magma. They produce short, explosive bursts every few minutes,

ejecting lava fragments and scoria to heights of hundreds of meters. These eruptions build cinder cones of pyroclastic material. Compared to Hawaiian eruptions, they are noisier, less continuous, and generate fewer lava flows.

Vulcanian eruption : it occurs when viscous magma traps gases, leading to explosive blasts that shatter the vent cap. They eject ash columns 5–10 km high along with volcanic bombs and blocks. Magma is typically andesitic to dacitic. Lava dome growth and collapse often trigger renewed activity and pyroclastic flows.

Peléan eruption : this eruption result from the collapse of lava domes made of viscous magma. This produces fast pyroclastic flows that race down slopes at very high speeds, making them extremely destructive. A common precursor is the growth of a lava dome or spine at the summit.

Plinian eruption : it releases gas-rich magma that forms towering eruption columns 2–45 km high. Columns are sustained by expanding gases and winds, spreading ash widely. They differ from Strombolian and Vulcanian eruptions by being continuous rather than episodic.



Figure 3.15: type of eruptions

3.3 Earthquakes

3.3.1 Introduction

Earthquakes are the direct consequence of tectonic plate movements. For a long time, this global phenomenon has attracted particular attention from the scientific community because of its impact on human populations. The intensity of an earthquake, as well as the extent of the damage it can cause, varies considerably depending on the tectonic and geodynamic context of each region. Between 500,000 and 1 million earthquakes are recorded worldwide each year, but only about 100,000 are felt by humans, of which around 1,000 can be devastating. In recent human history, the Valdivia earthquake in Chile has been the most powerful, with a recorded magnitude of 9.5. This earthquake was the result of a 18 cm subduction of the Nazca oceanic plate beneath the Chiloé block. The consequences were dramatic, with about 5,000 deaths and 2 million people left homeless. Recent data from 2019 show that the most intense seismic activity occurred in Indonesia and the Philippines, while the strongest magnitude was recorded in the Pastaza region of Ecuador (7.5 on the Richter scale). That year, more than 71 deaths were attributed to earthquakes.

3.3.2 Definition

An earthquake is the sudden release of accumulated strain energy within the Earth's crust, resulting in seismic waves that radiate outward from the source. It occurs when stresses in the crust exceed the strength of the rock,

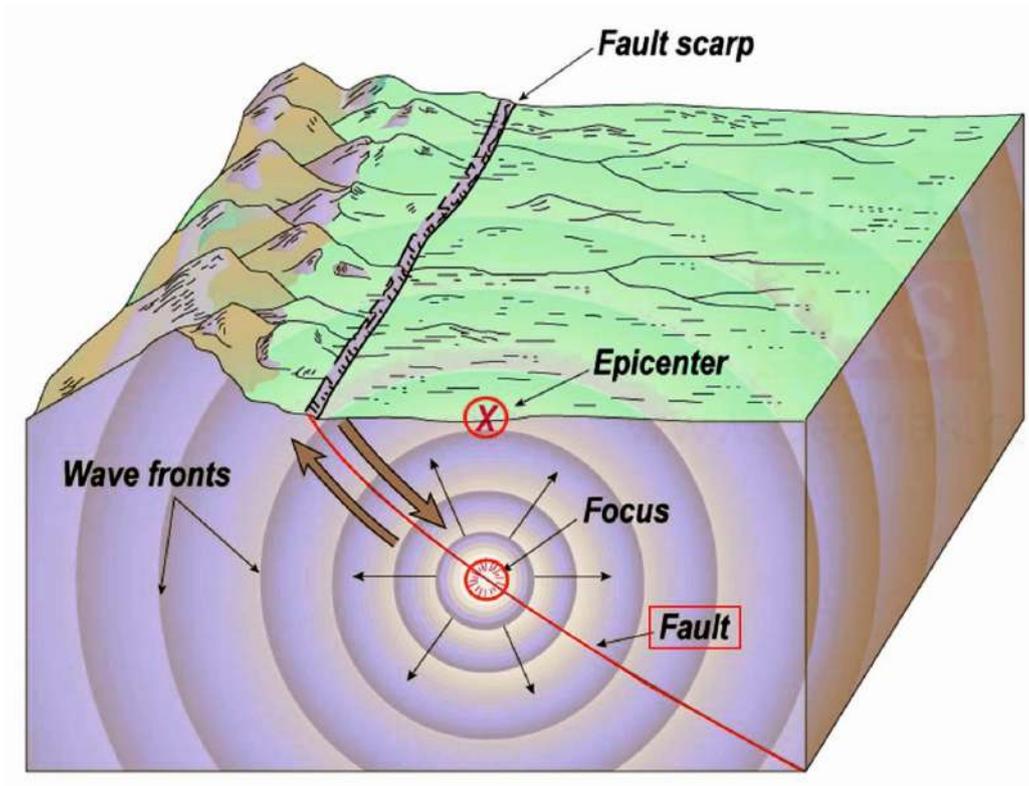


Figure 3.16: earthquake releasing seismic waves from the focus beneath the epicenter.

causing it to rupture along lines of weakness, either along pre-existing faults or newly formed fractures. The point where the rupture initiates is called the focus or hypocenter, which may lie several kilometers beneath the surface, while the point directly above it on the Earth's surface is referred to as the epicenter (3.16).

3.3.3 Origin of Earthquakes

Earthquakes are closely linked to the activity and mechanical behavior of tectonic plates. When the lithosphere, whether continental or oceanic, is

subjected to tectonic stress, it accumulates energy up to a certain threshold. Once the elastic limit is exceeded, the rock fractures, forming faults. The sudden release of energy along these faults propagates to the surface through seismic waves, producing ground shaking (Figure 28). If tectonic stresses are interrupted, rocks will continue to fracture in order to release the energy accumulated along previously formed faults. These faults are considered weak points in the lithosphere. Consequently, earthquakes are most often triggered within the lithosphere, since it is rigid in nature. The origin of earthquakes is sometimes related to volcanic phenomena. During an explosive volcanic eruption, seismic tremors may occur due to the energy stored as a result of the magma's viscous nature. Earthquakes may also result from large-scale landslides or even from uncontrolled human activity, such as the use of explosives for fishing or during mining operations.

3.3.4 Measuring earthquakes

Mercalli scale: This scale is based on earthquake intensity. It describes in detail the material damage caused by earthquakes. It has twelve degrees of intensity, ranging from first-degree earthquakes (I) to catastrophic earthquakes (XII).

I – Instrumental: Very weak earthquake, recorded only by seismographs.

II – Very slight: Felt by a few people at rest or at high altitudes.

III – Slight: Light tremor felt by many indoors; nothing noticeable outdoors.

IV – Fairly strong: Considerable shaking felt by many indoors.

V – Moderate: Felt by most people; sleepers are awakened; doors slam, dishes break, trees sway.

VI – Strong: Felt by everyone; slight damage to poorly built structures.

VII – Very strong: Many people fall; considerable damage to moderately built structures.

VIII – Destructive: Drivers have difficulty controlling vehicles; many chimneys collapse; well-built structures suffer superficial damage; trees break; water levels in wells change.

IX – Devastating: Severe damage to most structures; ground cracks open.

X – Disastrous: Foundations of many buildings destroyed; dams and bridges heavily damaged; rivers diverted; surface faults appear; railways distorted.

XI – Catastrophic: Collapse of most constructions (buildings, bridges, dams, etc.).

XII – Cataclysmic: Nearly all infrastructure destroyed.

Richter scale : This scale measures the amount of energy released during an earthquake. Its magnitude is logarithmic, ranging between 0 and 9. An earthquake of magnitude 6 on the Richter scale is actually 10 times more powerful than one of magnitude 5, and 100 times more powerful than one of magnitude 4 (Figure 29). The size of an earthquake depends on the fault's length and the amount of slip along it. Since faults lie deep underground, scientists measure earthquakes using seismographs. Seismograms show wiggly lines: small, short wiggles indicate minor earthquakes, while long, large wiggles indicate major ones. The length of the line reflects the fault size, and

the height of the wiggle shows the slip.

3.3.5 Seismic Waves

Seismic waves are classified into three main types: P-waves, S-waves, and surface waves. P-waves and S-waves are also called body waves (Figure 3.17).

P-waves : P-waves, or primary/pressure waves, are the fastest seismic waves. In air, they behave like sound waves, traveling at about 330m/s, but can reach up to 5000m/s in granite. Their high speed makes them the first to be detected by a seismograph. P-waves move by compressing and expanding the material in the direction of wave travel, similar to compressing a stretched slinky along its length.

S-waves : S-waves, or secondary/shear waves, are slower than P-waves and move the ground perpendicular to the wave direction. They cannot travel through air or water. Their motion is like lifting and releasing a section of a stretched slinky to create transverse waves. S-waves often cause more damage than P-waves due to their larger amplitudes.

Surface waves : Surface waves travel along or just beneath the Earth's surface and are usually generated when the earthquake source is near the surface. They are slower than S-waves but can have larger amplitudes, making them very destructive. There are two main types:

Rayleigh waves : Move the ground in an elliptical motion, similar to ripples on water. They can sometimes be observed directly, such as cars moving in a parking lot. *Love waves*: Cause horizontal shearing of the ground and

usually travel slightly faster than Rayleigh waves.

3.3.6 Locating Earthquakes Using P and S Waves

Seismograms help locate earthquakes by showing P and S waves, which shake the ground differently. P waves travel faster than S waves, so they arrive first. The time difference between them indicates how far the earthquake is, similar to seeing lightning before hearing thunder. P waves compress and stretch the ground in the direction they travel, while S waves move it sideways. This time difference tells distance but not direction. To find the exact location, scientists use triangulation. They draw circles around three or more seismograph stations, with each circle's radius equal to the distance to the earthquake. The intersection of the circles marks the epicenter (Figure 3.18).

3.3.7 Distribution of Earthquakes

: The distribution of earthquakes is not random; it follows a well-defined pattern dictated by plate tectonics (Figure 3.19). Most earthquake foci coincide with tectonic plate boundaries.

Earthquakes at mid-ocean ridges: During the regeneration of oceanic crust, shallow earthquakes occur at depths not exceeding 20 km. Their magnitude is generally low.

Earthquakes of the Pacific Belt: These are associated with the Alpine and peri-Alpine belt extending from North Africa to Central Asia (Himalayas and Indonesia). Foci may reach depths of up to 70 km.

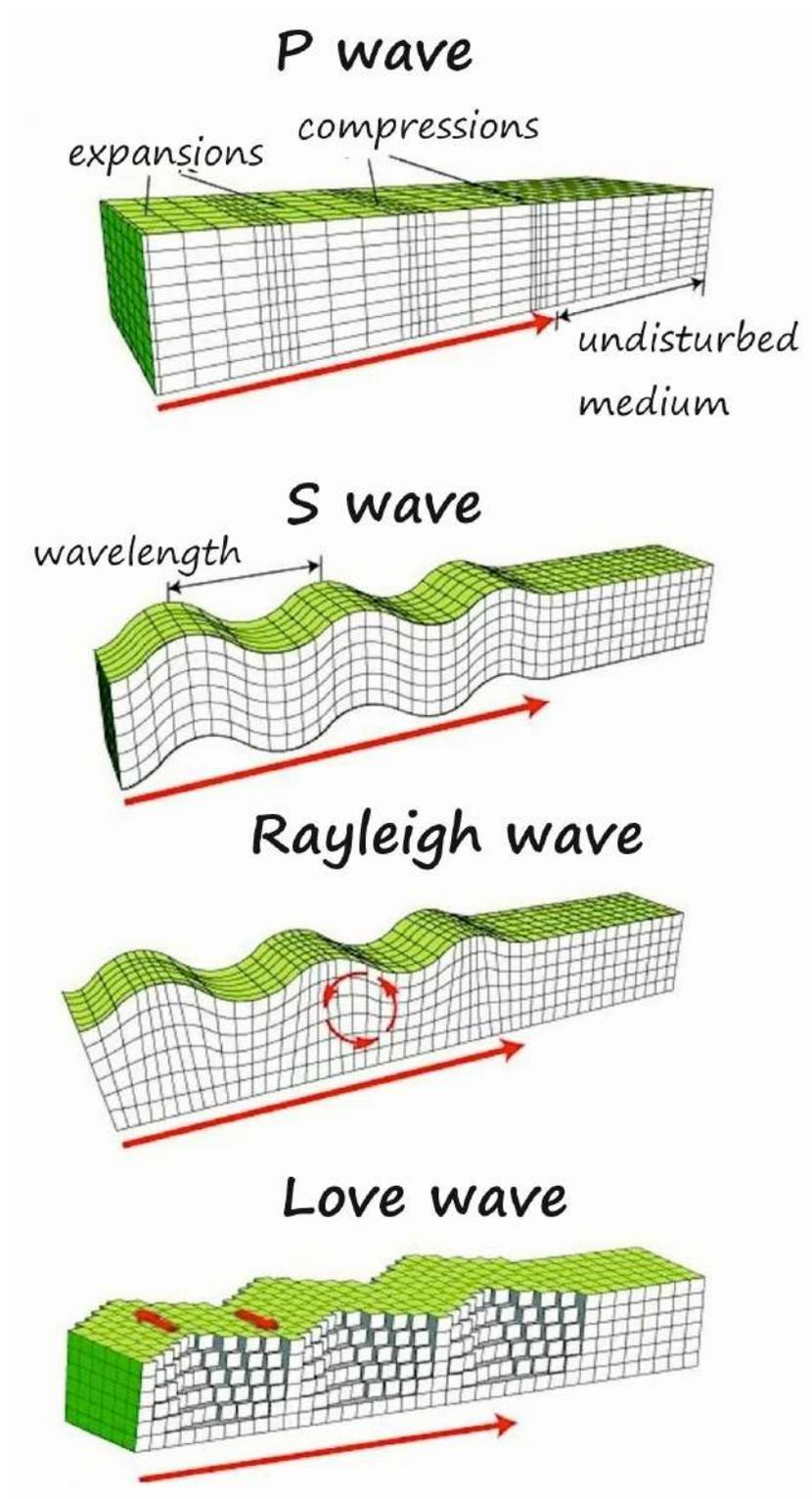


Figure 3.17: main seismic waves

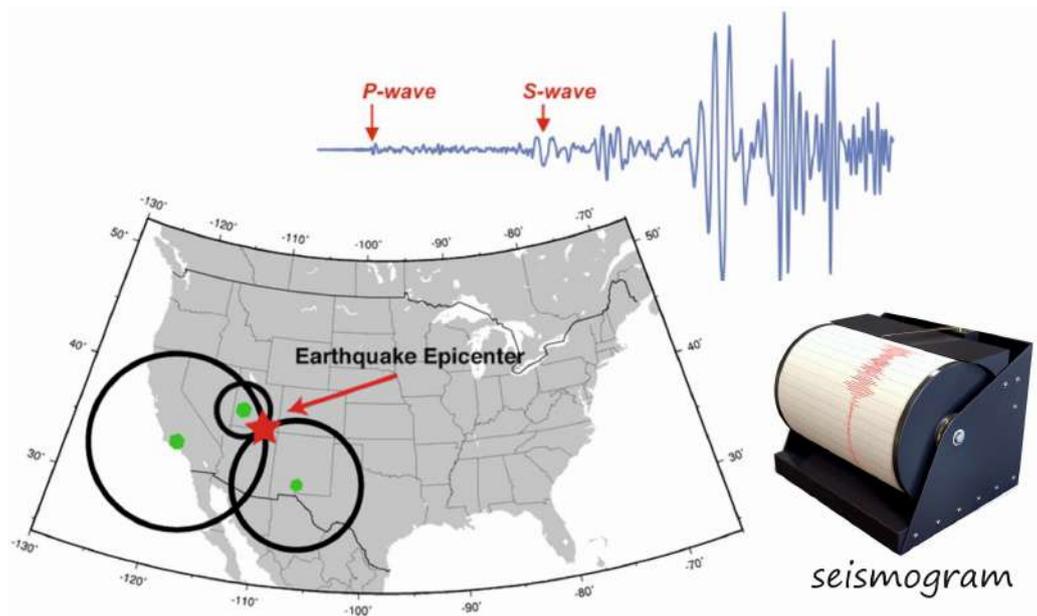


Figure 3.18: way of locating earthquake by using three seismogram (on right) in USA (usgs.gov)

Earthquakes of the Alpine Belt: These coincide with oceanic trenches (subduction zones). About 80% of global seismic energy is released in these regions. The depth of earthquake focus here ranges from 300 km to 700 km.

Based on depth, three types of earthquakes are distinguished (Figure 32):
 Deep earthquakes: occurring at depths greater than 300 km. Intermediate earthquakes: occurring between 60 km and 300 km. Shallow earthquakes: occurring at depths of less than 60 km.

3.3.8 Seismic Risk

Seismic risk is associated with the potential effects of an earthquake on exposed elements such as structures, soils (landslides, etc.), people, and economic activity. It therefore depends on the hazard (aleatory action), the

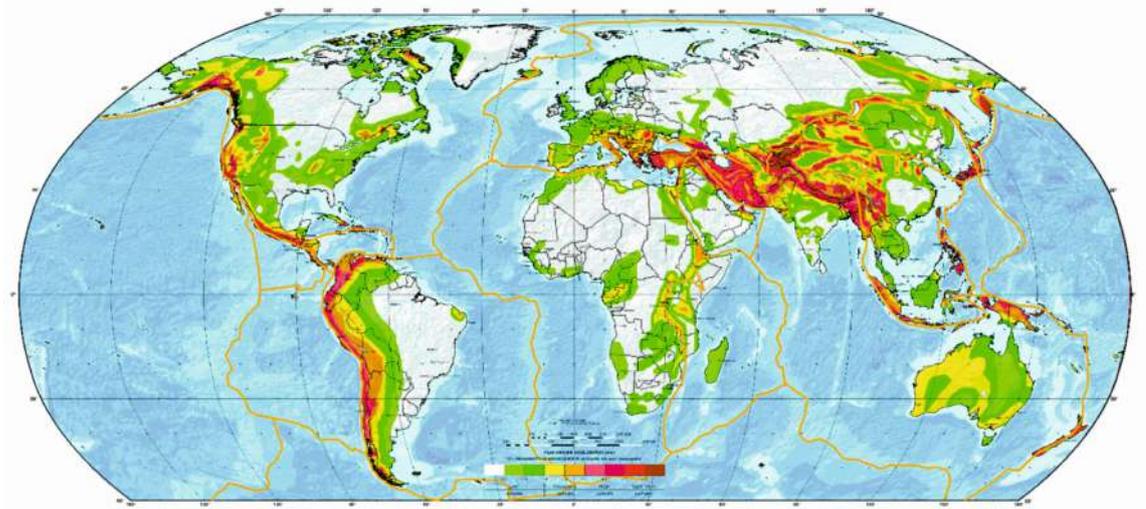


Figure 3.19: Global seismic hazard map (Giardini et al. 1999)

characteristics of the structures or soils, and the exposed elements. If structures or soils can be characterized by a vulnerability parameter, and the focus is specifically on the risk to buildings, then:

$$\text{Seismic risk} = \text{Seismic hazard} \times \text{Vulnerability}$$

Two fundamentally different methods are used to evaluate the seismic risk associated with a building:

Detailed structural analysis approach: A model of the structure is created and analyzed to determine internal stresses, which are then compared to reference strengths and deformations for each structural element. This comparison allows determination of the safety level or the risk associated with the structure. This procedure is very time-consuming, taking roughly one month per building.

Statistical database approach: A statistical database of structural performance, recorded from previous earthquakes, is used. The building is characterized by a global vulnerability coefficient. By referring to the database,

the seismic risk for the structure is estimated. This procedure is fast, taking roughly one hour per building, and is used for global evaluations of a city or region. Seismic risk for a building is expressed as a percentage of damage or as the ratio of repair cost to reconstruction cost. Risk studies can also be conducted in terms of human or economic losses for the affected city or country.

3.4 Overview of earthquakes in Algeria

Algeria is among the most seismically active areas along the Nubia–Eurasia convergent boundary. Seismic catalogues and research have reported numerous destructive earthquakes, especially along the coast (Oran, Mascara, Chlef, Tipasa-Chenoua, Algiers, Zemmouri, Constantine, Béjaia, Djidjelli), with magnitudes between 5.9 and 7.3. This seismicity results from the Nubia–Eurasia collision and is concentrated in the Tell Atlas. To study Algerian seismicity, researchers divided it into three periods related to the development of seismological instrumentation:

Pre-1910 (macroseismic observations and first catalogues).

Post-1910 (instrumental beginnings, Bouzaréah Observatory).

Post-1980 (installation of the Algerian Telemetered Seismological Network, after the 1980 El Asnam earthquake)

3.4.1 First Period – Pre-1910

During this phase, earthquakes were studied mainly through macroseismic effects. Alexis v(1847–1870) was a pioneer, publishing annual lists of earth-

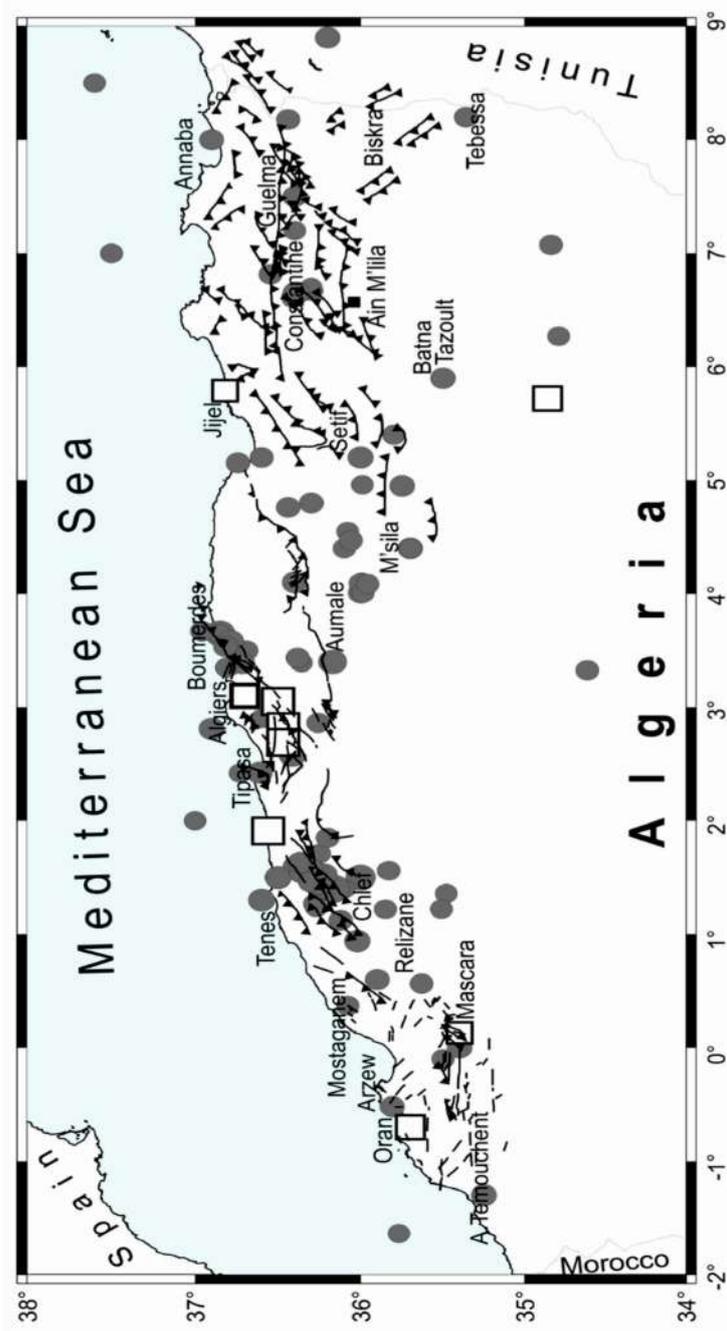


Figure 3.20: Seismicity map of Northern Algeria occurred between 1365 and 2021: grey circles correspond to the instrumental seismicity with $M \geq 5.0$ and white squares correspond to a historical seismic event with I VI (Bezzeghoud and Ayadi, 2022)

quakes felt in Algeria. Later, Chesneau (1892) and Montessus de Ballore (1892, 1906) expanded this work. Montessus even produced a seismicity map of the Maghreb in his 1906 book *Les tremblements de Terre, géographie sismologique* (Bezzeghoud and Ayadi, 2022).

The Algerian Meteorological Service, created in 1874, also contributed, producing lists of earthquakes in its bulletins between 1889 and 1908

3.4.2 Second Period – Post-1910 (1910–1979)

Seismology entered the instrumental era with the installation of Bosh-Mainka seismographs at the Bouzaréah Observatory in 1910. The first recorded signal was the February 25, 1911 Aumale earthquake. A. Hée (1919–1950) published extensive studies on Algerian seismicity, including catalogues and frequency analyses (Bezzeghoud and Ayadi, 2022).

3.4.3 Third Period – Post-1980

The destructive El Asnam earthquake (October 10, 1980, Ms 7.3) marked a turning point. It led to the creation of CNAAG in 1980, later renamed CRAAG in 1986. Researchers such as H. Benhallou produced foundational works on historical seismicity. Catalogues covering 1365–1992 (Mokrane et al. 1994), 1900–1992 (Benouar 1994), and later updates extended the seismic record (Bezzeghoud and Ayadi, 2022).

The 1790 Oran earthquake (M_{6.0}–6.5) has been re-evaluated, showing its destructive impact and tsunami generation observed in Spain. Similarly, the 2003 Zemmouri earthquake (M_w 6.8) caused 2271 deaths, 11,455 injuries,

and destruction of over 20,000 buildings (Bezzeghoud and Ayadi, 2022).

3.4.4 Historical Seismicity (267 A.D.–2021)

Seismic records extend back to antiquity:

267 A.D.: An earthquake damaged Négrine (Tebessa Province) and Lambèse (Tazoult).

419 A.D.: A violent earthquake hit Sitifis (Sétif).

1009 and 1049: Earthquakes reported in Algiers.

Numerous destructive events occurred in the following centuries, such as Algiers in 1365, Oran in 1790, Mascara in 1819, Blida in 1825, Chlef in 1954, and Algiers in 2003

Chapter 4

Suggested readings

Anderson, R.S., Anderson, S.P., 2010. *Geomorphology: The Mechanics and Chemistry of Landscapes*. Cambridge University Press.

Behrensmeier, A.K., et al. (Eds.), 2000. *Taphonomy: Process and Bias Through Time*. Springer.

Benton, M.J., Harper, D.A.T., 2020. *Introduction to Paleobiology and the Fossil Record*, 2nd ed. Wiley-Blackwell.

Bezzeghoud, M., Ayadi, A., 2022. The history of seismology and historical seismicity in Algeria: an overview. *Mediterranean Geoscience Reviews* 4(4), 361–381.

Boggs, S. Jr., 2014. *Principles of Sedimentology and Stratigraphy*, 5th ed. Pearson.

Bolt, B.A., 2005. *Earthquakes: 2006 Centennial Update*, 5th ed. W.H. Freeman.

Bormann, P. (Ed.), 2012. *New Manual of Seismological Observatory Practice (NMSOP-2)*. Helmholtz Centre Potsdam.

- Bridge, J.S., Demicco, R.V., 2008. *Earth Surface Processes, Landforms and Sediment Deposits*. Cambridge University Press.
- Briggs, D.E.G., Crowther, P.R. (Eds.), 2001. *Palaeobiology II*. Blackwell Science.
- Cashman, K.V., Sparks, R.S.J., 2013. How volcanoes work: A 25 year perspective. *Geological Society of America Bulletin*.
- Catuneanu, O., 2019. *Principles of Sequence Stratigraphy*, 2nd ed. Elsevier.
- Chesneau, M., 1892. Note sur les tremblements de terre en Algérie. *Annales des Mines*, 9e série, I, 5–46.
- Coe, A.L. (Ed.), 2022. *The Sedimentary Record of Sea-Level Change*. Cambridge University Press.
- Collinson, J., Mountney, N., Thompson, D., 2019. *Sedimentary Structures*, 4th ed. Dunedin Academic Press.
- Condie, K.C., 2015. *Plate Tectonics and Crustal Evolution*, 2nd ed. Elsevier.
- Cox, A., Hart, R.B., 1986. *Plate Tectonics: How It Works*. Blackwell Scientific.
- Dey, S., 2014. *Fluvial Hydrodynamics: Hydrodynamic and Sediment Transport Phenomena*. Springer.
- Dixon, J.C., Thorn, C.E., 2005. *Chemical Weathering in Terrestrial Ecosystems*. Elsevier.
- Foote, M., Miller, A.I., 2013. *Principles of Paleontology*, 3rd ed. W.H. Freeman.

- Francis, P., Oppenheimer, C., 2004. *Volcanoes*, 2nd ed. Oxford University Press.
- Frisch, W., Meschede, M., Blakey, R.C., 2011. *Plate Tectonics: Continental Drift and Mountain Building*. Springer.
- Garcia, M.H., 2008. *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice*. American Society of Civil Engineers.
- Geller, R.J., 2011. *Shake-up: Earthquake Science and Safety in Japan*. University of Tokyo Press.
- Goudie, A.S., Viles, H.A., 2016. *Geomorphology in the Anthropocene*. Cambridge University Press.
- Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., 2020. *The Geologic Time Scale 2020*. Elsevier.
- Hée, A., 1919. Tremblements de terre Algériens. *Annales de l'Institut de Physique du Globe de Strasbourg*, 15–16.
- Hée, A., 1950. Catalogue des séismes Algériens de 1850 à 1911. *Annales de l'Institut de Physique du Globe de Strasbourg VI*, 41–49.
- Hough, S.E., 2016. *Earthshaking Science: What We Know (and Don't Know) about Earthquakes*. Princeton University Press.
- Jackson, J., 2006. Fatal attraction: living with earthquakes, the growth of villages into megacities, and earthquake vulnerability in the modern world. *Philosophical Transactions of the Royal Society*.
- James, N.P., Dalrymple, R.W., 2010. *Facies Models 4*. Geological Association of Canada.
- Julien, P.Y., 2010. *Erosion and Sedimentation*. Cambridge University

Press.

Kearey, P., Klepeis, K.A., Vine, F.J., 2009. *Global Tectonics*, 3rd ed. Wiley-Blackwell.

Koutsoukos, E.A.M., 2020. *Applied Stratigraphy*. Springer.

Lay, T., Wallace, T.C., 1995. *Modern Global Seismology*. Academic Press.

Lockwood, J.P., Hazlett, R.W., 2010. *Volcanoes: Global Perspectives*. Wiley-Blackwell.

Middleton, G.V., Southard, J.B., 1984. *Mechanics of Sediment Transport*. SEPM.

Moores, E.M., Twiss, R.J., 2014. *Tectonics*, 2nd ed. W.H. Freeman.

Nichols, G., 2009. *Sedimentology and Stratigraphy*, 2nd ed. Wiley-Blackwell.

North American Commission on Stratigraphic Nomenclature, 2005. *The North American Stratigraphic Code*. AAPG Bulletin.

Oreskes, N., 2003. *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Westview Press.

Parfitt, E.A., Wilson, L., 2008. *Fundamentals of Physical Volcanology*. Wiley-Blackwell.

Perrey, A., 1847. Note sur les tremblements de terre en Algérie et dans l'Afrique Septentrionale. *Mémoires de l'Académie des Sciences, Arts et Belles-Lettres de Dijon 1845–1846*, 299–323.

Prothero, D.R., 2013. *Bringing Fossils to Life: An Introduction to Paleobiology*, 3rd ed. Columbia University Press.

- Pyle, D.M., 2017. *Volcanoes: Encounters through the Ages*. Bodleian Library.
- Reading, H.G., 2009. *Sedimentary Environments: Processes, Facies and Stratigraphy*, 3rd ed. Blackwell Science.
- Reiter, L., 1990. *Earthquake Hazard Analysis: Issues and Insights*. Columbia University Press.
- Scarth, A., Tanguy, J.-C., 2001. *Volcanoes of Europe*. Oxford University Press.
- Schminke, H.-U., 2004. *Volcanism*. Springer.
- Scholz, C.H., 2019. *The Mechanics of Earthquakes and Faulting*, 3rd ed. Cambridge University Press.
- Schubert, G., Turcotte, D.L., Olson, P., 2001. *Mantle Convection in the Earth and Planets*. Cambridge University Press.
- Self, S., 2006. *Volcanoes and the Environment*. Cambridge University Press.
- Şengör, A.M.C., 2015. *The Large-Wavelength Deformations of the Lithosphere*. Geological Society of America.
- Sigurdsson, H. (Ed.), 2015. *The Encyclopedia of Volcanoes*, 2nd ed. Academic Press.
- Simkin, T., Siebert, L., 1994. *Volcanoes of the World: A Regional Directory, Gazetteer, and Chronology of Volcanism during the Last 10,000 Years*, 2nd ed. Smithsonian Institution.
- Stein, S., Wysession, M., 2003. *An Introduction to Seismology, Earthquakes, and Earth Structure*. Blackwell Publishing.

- Summerfield, M.A., 2014. *Global Geomorphology*. Routledge.
- Van der Pluijm, B.A., Marshak, S., 2004. *Earth Structure: An Introduction to Structural Geology and Tectonics*, 2nd ed. W.W. Norton.
- Viles, H.A., 2013. Weathering in the Anthropocene: A soiled geomorphology? *Progress in Physical Geography*.
- Windley, B.F., 2021. *The Evolving Continents*, 5th ed. Wiley.
- Yeats, R.S., 2012. *Active Faults of the World*. Cambridge University Press.