# GEOLOGY

Year 2018-19

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# Lesson 1: INTRODUCTION TO GEOLOGY

## CONCEPT AND DEFINITION OF GEOLOGY

**Geology:** Ancient Greek (*ge: earth; -logia: the study of*). Literally, the study of Earth. It was first used by Aldrovandi in 1603.

## AREAS

### ***Physical geology***

Examines the materials composing Earth (minerals and rocks) and the internal (volcanism) and external (erosion) processes that operate beneath and upon its surface.

### ***Historical geology***

Understands the origin of Earth and its development through its 4.6 billion year history. It arranges chronically the physical and geological changes of Earth.
The study of physical geology logically preceds the study of Earth history because we must first understand how Earth works before we attempt to unravel its past.

## GEOLOGY AND HUMANKIND

Earth has resources that are used by the humankind, like water, coal, gas, oil, minerals…
People influence Earth processes, altering the composition of the atmosphere (pollution episodes, global climate
change…) and altering Earth's surface building cities, roads….
Earth influences our life with natural hazards, for example, tsunamis, floods, volcanoes, earthquakes…

## EARTH'S SPHERES

Our planet is not a static and unchanging mass. It is a dynamic body with many interacting parts:

**Biosphere**

Includes all life. It is concentrated near the surface in a zone that extends from the ocean floor upward for several
kilometers into the atmosphere.

**Hydrosphere**

Oceans are the most prominent feature of the hydrosphere. They cover nearly 71% of Earth's surface, and it
makes up 97% of Earth's water.
Hydrosphere also includes fresh water found in streams, lakes and glaciers, as well as that found underground.

**Atmosphere**

Is a gas layer surrounding Earth. It's a thin, tenuous blanket of air.

**Geosphere (Solid earth)**
Extends from surface to the center of the planet. It's the largest of Earth's four spheres.
Based on the chemical composition, we can difference different layers:

- Crust: thin (7-70 km), outermost layer. Made of low density rocks. Made up of oceanic and continental types of crust.
- Mantle: relatively thick layer of Earth. Made of high density rocks.
- Core: located in the center. It's the thickest layer and it's made of iron.

Based on how the materials behave (physical properties), we can difference layers:

- Lithosphere: solid and rigid. 100 km thick. Made of the crust and the uppermost part of the mantle.
- Astenosphere: solid but mobile (semifluid). Up to 700 km thick. Made of the mantle under the lithosphere.
- Core: two layers: inner core, solid and outer core, liquid.

# PLATE TECTONICS

Earth's lithosphere is broken into slabs (lithospheric plates) that are in continuous motion. These plates move very slowly.
Types of plate boundaries

- Convergent boundary: plates move together
- Divergent boundary: plates pull apart
- Transform fault: plates slide past each other

# EARTH AS A SYSTEM

Earth is a dynamic body with many separate but highly interacting parts or spheres. A system is any size group of interacting parts that form a complex whole.
Earth system science studies Earth as a system composed of numerous parts or subsystems (for example,hydrologic cycle, rock cycle...)
Earth has two main sources of energy:

- Sun: drives external processes such as weather, ocean circulation and erosional processes
- Earth's interior: drives internal processes including volcanoes, earthquakes and mountain building

Earth is a dynamic ever changing planet. Sometimes the changes are rapid and violent, as when severe storm, landslides and volcanic eruptions occur. Conversely, many changes take place so gradually that they go unnoticed during a lifetime. For example, uplift of mountain ranges takes tens to hundreds of millions of years to occur.
That's why the most common time unit in Geology is a million year.

## SCIENTIFIC INQUIRY

The goal of science is to discover patterns in nature and to use the knowledge to predict the way it works. Science assumes the natural world is consistent, predictable and comprehensible through careful and systematic study. The scientific method gathers facts through observation and formulates hypotheses and theories.

Hypothesis: tentative or untested explanation of a natural phenomenon, it requires further observation or testing to see if it is valid (for example, earth-centered model of the universe: apparent daily motion of the sun, moon and stars around earth)

Theory: well tested and confirmed hypothesis, widely accepted, best explanation for observable facts (for example, the theory of plate tectonics: origin of mountains, earthquakes and volcanic activity; the evolution of the continents and the ocean basins through time).

Scientific knowledge is gained through scientific method, following systematic steps:

- Raise a question about the natural world
- Background search: collect scientific data that relate to the question
- Construct a hypothesis
- Develop observations and/or experiments that test the hypothesis
- Analyze data: results may support, partially support or not support the hypothesis
- Reexamine the hypothesis and accept, modify or reject it
- Share with scientific community for critical evaluation and additional testing

## GEOLOGICAL DISCIPLINES

- Geochronology: the study of time and history of Earth (related to astronomy)
- Planetary geology: the study of the geology of the planets
- Paleontology: the study of fossils (related to biology)
- Economic geology: the study of mineral and energy resources
- Environmental geology: the study of environment
- Geochemistry: the study of the chemistry of the Earth (related to chemistry)
- Hydrogeology: the study of water resources
- Mineralogy: the study of minerals
- Petrology: the study of rocks
- Geophysics: the study of Earth's interior (related to physics)
- Structural geology: the study of rock deformation
- Seismology: the study of earthquakes
- Geomorphology: the study of landforms
- Oceanography: the study of oceans
- Paleogeography: the study of ancient geographic features and locations
- Stratigraphy/sedimentology: the study of layered rocks and sediments

## EARTH SCIENCE

It comprehends all sciences that seek to understand Earth.

It includes geology (the study of earth), oceanography (the study of oceans), meteorology (the study of the
atmosphere and the processes that produce weather) and astronomy (the study of universe).

## HISTORICAL DEVELOPMENT OF GEOLOGY

***17th century:***

- Ulisse Aldrovandi and the origin of Geology
- Nicolas Steno: three defining principles of stratigraphy

***18th century:***

- James Ussher (mid-1600s): Catastrophism. It is based on a young age of the planet.
- James Hutton (late 1700s): Principle of uniformitarianism. Earth must be much older than had previously been supposed.
- Plutonists vs Neptunists

***19th century:***

- Charles Lyell (mid-1800s): Principles of Geology
- Charles Darwin: the origin of species

***20th century:***

- Radiometric dating and estimation of the Earth's age
- Alfred Wegener (1915): Continental drift
- The theory of plate tectonics (1960s): Two separate geological observations: seafloor spreading and continental drift.

## FUNDAMENTAL PRINCIPLES

***Actualism:***

"*The present is Key to the past*" Charles Lyell.

We can interpret where and how rocks were formed.

Other fundamental principles:

- Relative dating principles:
    - Principle of superposition
    - Principle of original horizontality
    - Principle of lateral continuity
    - Principle of cross-cutting relationships
    - Principle of inclusions
    - Principle of fossil succession

# Lecture 2: GEOLOGIC TIME

## HISTORICAL NOTES

Earth is 4.6 billion years old.

Historical evolution of the Geologic time concept:

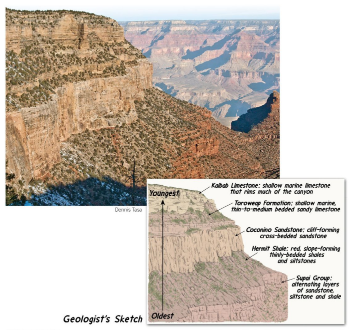
- Catastrophism:
  - James Ussher, mid-1600s
  - Landscape developed by catastrophes
  - Concluded Earth was only a few thousand years old

Modern geology

- Uniformitarianism
  - Fundamental principle of geology
  - "The present is the key to the past"
- James Hutton
  - Theory of the Earth
  - Published in the late 1700s

## RELATIVE DATING AND PRINCIPLES

Placing rocks and events in their proper sequence of formation.




### PRINCIPLE OF SUPERPOSITION

Steno, 1669

Oldest rocks are on the bottom. Superposition is well illustrated in the Grand Canyon.

### PRINCIPLE OF ORIGINAL HORIZONTALITY

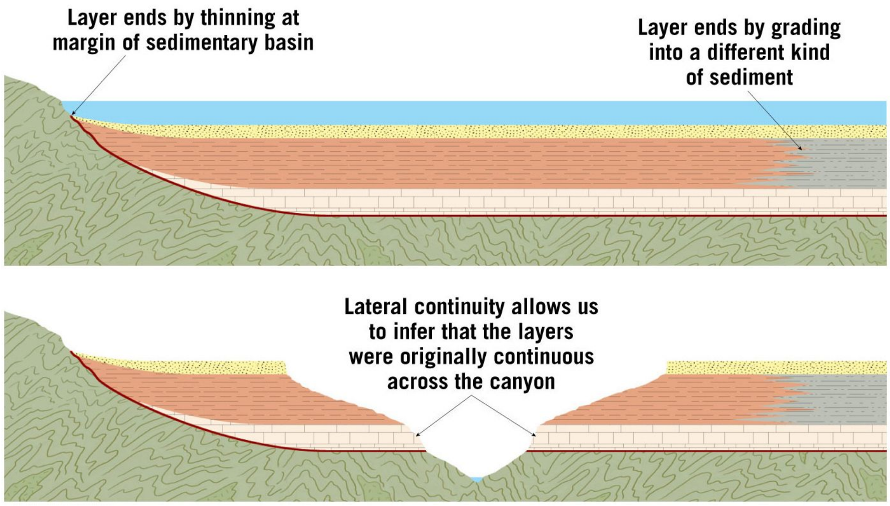
Steno, 1669

Sediments are deposited horizontally

### PRINCIPLE OF LATERAL CONTINUITY

Steno, 1669

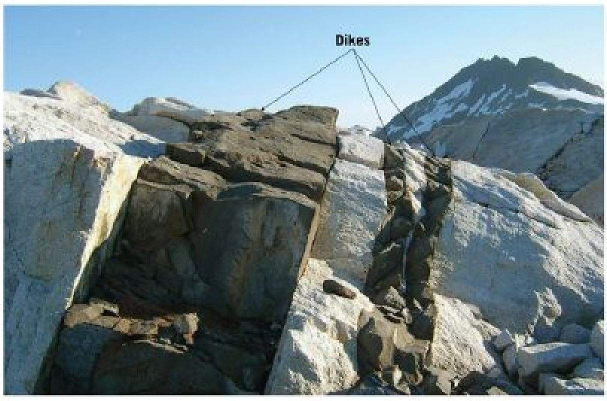
Sedimentary beds originate as continuous layers that extend in all directions.



## PRINCIPLE OF CROSS-CUTTING RELATIONSHIPS

Younger feature cuts through an older feature. (Hutton, 1795)

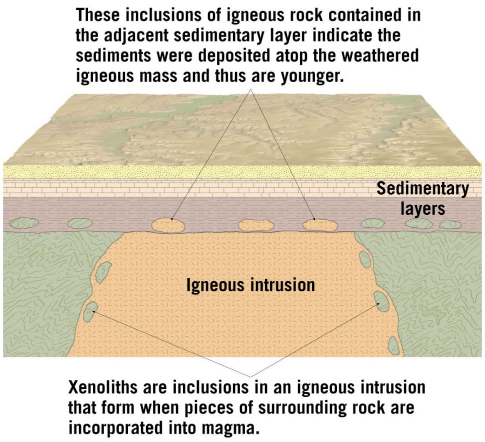

Cross-cutting fault. The rocks are older than the fault that displaced them.




Cross-cutting dike. An igneous intrusion is younger than the rocks that are intruded.

## PRINCIPLE OF INCLUSIONS

A rock contained within another (rock containing the inclusions is younger).




## UNCONFORMITIES

Types of unconformities:

- Angular unconformity: tilted rocks are overlain by flat-lying rocks
- Disconformity: strata on either side are parallel
- Nonconformity
    - Metamorphic or igneous rocks below
    - Younger sedimentary rocks above

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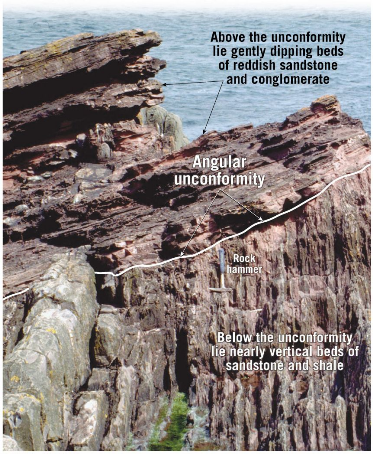
<td>
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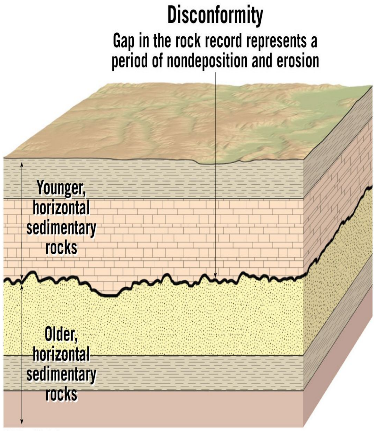
<td>
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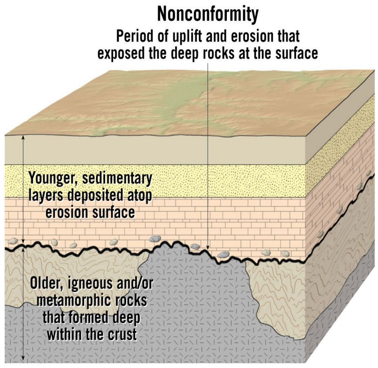
<td>
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Correlation of rock layers:
Matching rocks of similar age often relies upon fossils.

## FOSSILS

Fossils are remains or traces of prehistoric life.

## TYPES OF FOSSILS

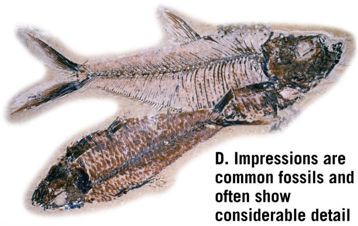
- Not altered: teeth, bones and shells
- Petrified: cavities and pores are filled with precipitated mineral matter
- Mold: shell or other structure is buried and then dissolved by underground water
- Cast: hollow space of a mold is filled with mineral matter


B. This trilobite photo illustrates mold and cast

- Carbonization: particularly effective at preserving leaves and delicate animal forms. Fine-grained sediment encases the remains of an organism. Pressure squeezes out the liquid and gaseous components and leaves behind a thin residue of carbon.


C. A fossil bee preserved as a thin carbon film

- Impression: replica of the fossil's surface preserved in fine-grained sediment.
- Preservation in amber: hardened resin of ancient trees surrounds an organism
- Indirect evidences:
    - Traces: animal footprints made in soft sediment that later turned into sedimentary rock
    - Burrows: holes in sediment, wood or rock made by an animal, may later become filled with mineral matter and preserved
    - Coprolites: fossil dung and stomach contents
    - Gastrolith: highly polished stomach stones used to grind food by some extinct reptiles (dinosaurs)


D. Impressions are common fossils and often show considerable detail

**CONDITIONS THAT FAVOR PRESERVATION OF AN ORGANISM AS A FOSSIL**

- Rapid burial (protect from the surface environment, where destructive processes operate
- Possession of hard parts (usually are quickly eaten by scavengers or decomposed by bacteria)

Only a tiny fraction of the organisms that have lived during the geologic past have been preserved as fossils.

**FOSSILS AND CORRELATION**

*Principle of Fossil Succession, Smith 1796*

Fossil organisms succeed one another in a definite and determinable order, and therefore any time period can be recognized by its fossil content. Correlation: matching rocks and fossils of similar age to different regions.

**Index fossils** are fossils that were geographically widespread and existed for a short span of geologic time.

**Fossil assemblages** are groups of fossils typically found together that can be used to establish the age of the layer in which they are found.

Overlapping ranges of fossils help dating rocks.

# ABSOLUTE DATING

## NUMERICAL DATING WITH NUCLEAR DECAY

Method: radioactivity and radiometric dating

*ATOMIC STRUCTURE*

- Nucleus
    - Protons (positively charged)
    - Neutrons (neutral charge)
- Orbiting the nucleus are electrons (negatively charged)

Practically all of an atom's mass (99,9%) is in the nucleus.

The **atomic number** is an element's identifying number (atoms of the same elements always have the same number of protons, so the atomic number stays constant). It's the number of protons in the atom's nucleus.

The **mass number** is the number of protons plus the number of neutrons in an atom's nucleus.

The **atomic weight** is the weighted average mass of an atom of an element based on the relative natural abundance of that element's isotopes.

An **isotope** is a variant of the same parent atom. It has a different number of neutrons and mass number.

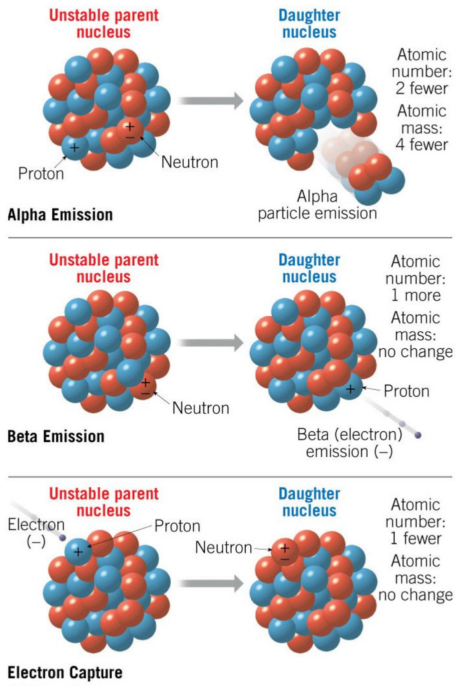
Uranium's nucleus has always 92 protons, so its atomic number is always 92. Its neutron population varies, so uranium has three isotopes (234U, 235U, 238U). These are mixed in nature, they look the same (same behaviour in chemical reactions) and they are all radioactive.

*CHANGES TO ATOMIC NUCLEI*

Stable vs unstable isotopes: the forces that bind protons and neutrons to keep them together.

**Radioactivity** (unstable)

- Spontaneous breaking apart (nuclear or radioactive decay) of atomic nuclei
- Radioactive decay
    - Parent: an unstable isotope
    - Daughter products: isotopes formed from the decay of a parent
    - Types of radioactive decay:
        - Alpha emission
        - Beta emission
        - Electron emission




*TYPES OF RADIOACTIVE DECAY*

Alpha emission

Nucleus emits an alpha particle (2 protons + 2 neutrons or a helium atom)

Atomic number is decreased by 2 and mass number decreased by 4.

Beta emission

Nucleus emits an electron (beta particle) when nucleus decays to produce the electron plus a proton. Atomic number increased by 1, no changes in mass number.

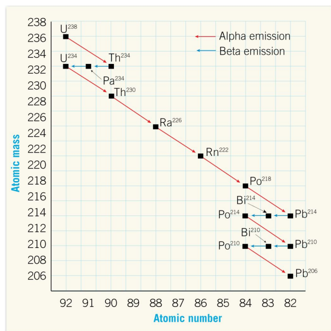
Electron capture

Nucleus captures an electron. The electron combines with a proton to form an additional neutron. Atomic number decreased by 1, no changes in mass number.

*RADIOACTIVE ISOTOPES*

The path from parent to daughter is not always direct.

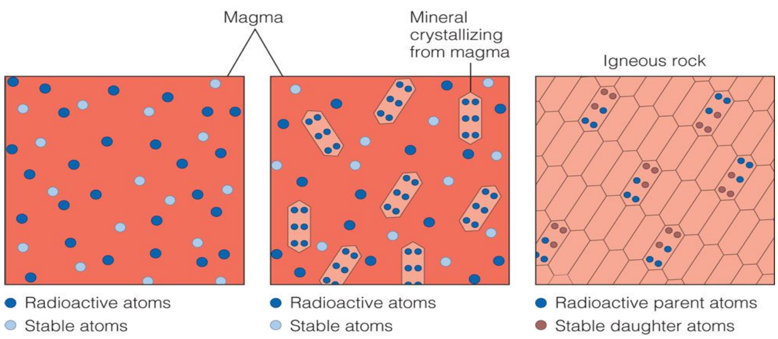
For example, in Uranium238, there are 13 intermediate steps to reach the stable daughter. It emits 8 alpha particles and 6 electrons to reach, Lead-206 (atomic number 82, mass number 206), its stable daughter.



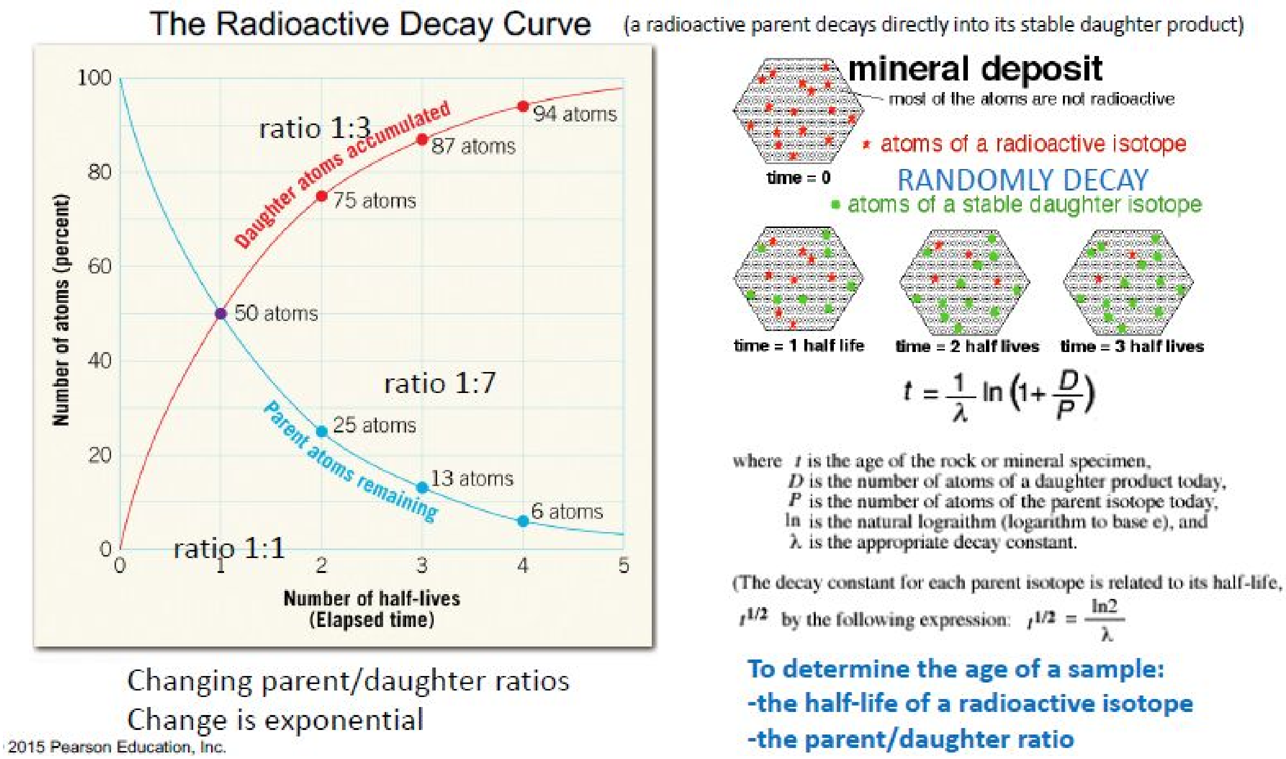

*RADIOMETRIC DATING*

It's the calculation of the rocks' age and minerals that contain particular inestable isotopes.

Inestable isotopes found in rocks can be used to know the age of the rock, because the decay rate of the isotope is known.



The **half-life** of an isotope is the time required for half of the radioactive nuclei to decay. (Rate of radioactive decay)




The principal radioactive isotope pairs used in radiometric dating are used only for dating rocks that are million of years old. Analytical techniques make it possible to detect tiny amounts of its stable daughter products in rocks younger than 100000 years.
These techniques are frequently used, because the stable daughter products are an abundant constituent of many common minerals like micas and feldspars.

<u>*CARBON-14 DATING*</u>

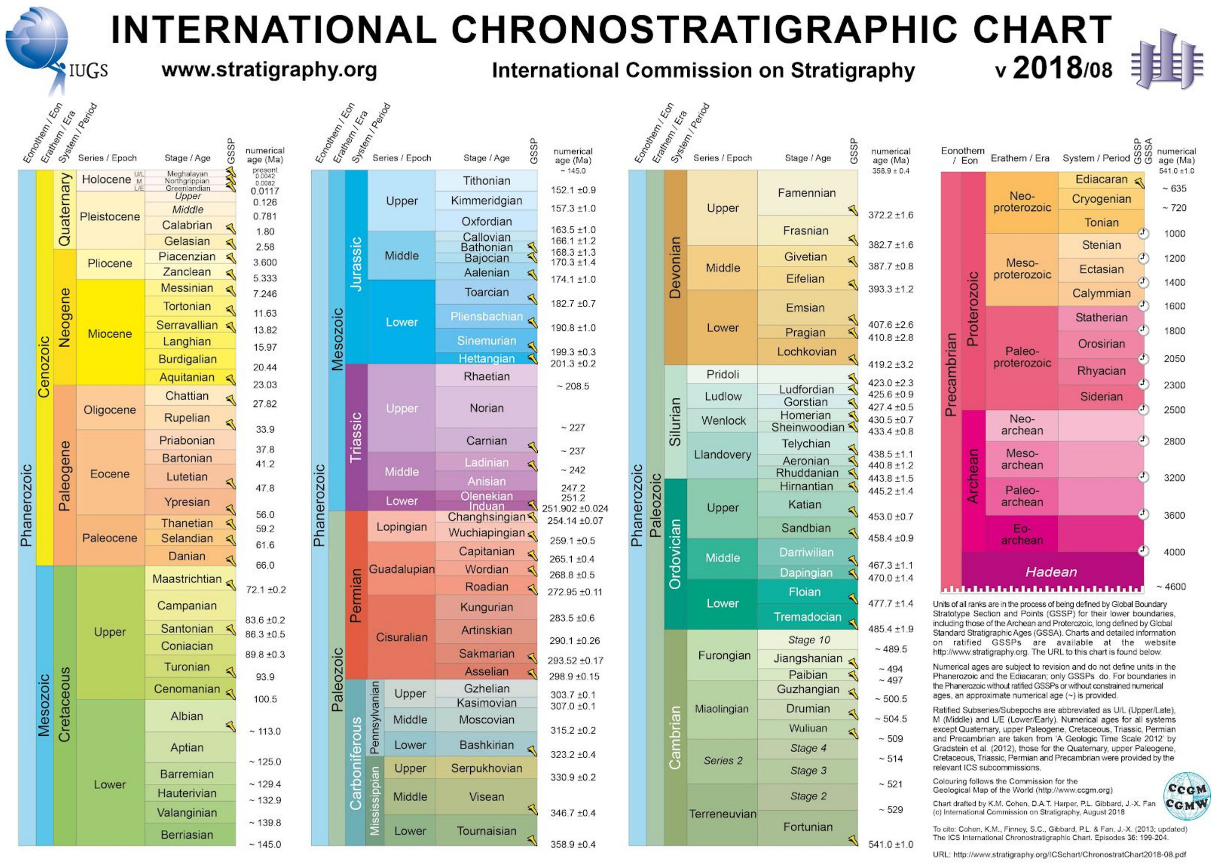
Carbon-14 dating or radiocarbon dating is a radiometric dating method to study recent Earth history.
This isotope has a half life of only 5730 years, so it is used to date very recent events. Carbon-14 is produced in upper atmosphere, where it incorporates into carbon dioxide and it's absorbed by living matter (wood, charcoal, bones, flesh, cloth, shells...). It is a useful tool for anthropologists, archeologists, historians and geologists who study very recent Earth history.

<u>*SOURCES OF ERROR IN RADIOMETRIC DATING*</u>

- Complex procedure (we must determine the quantities of parent and daughter atoms precisely)
- Requires a close system (no leakage of parent or daughter isotopes)
- Some radioactive materials do not decay directly into the stable daughter product

Cross-checks are used for accuracy (using two different methods).

## GEOLOGIC TIME SCALE




Divides geologic history into units of varying length. These units were originally created using relative dating (relative dating techniques: fossils...).

There are four basic units that make up the geologic time scale:

**Eon:** greatest expanse of time

- Phanerozoic ("visible life")
- Proteorozoic ("before life")
- Archean (Archaios= ancient)
- Hadean: the oldest eon: It refers to the earliest portion of Earth's history. It's an informal term that refers to the "hellish" conditions that existed

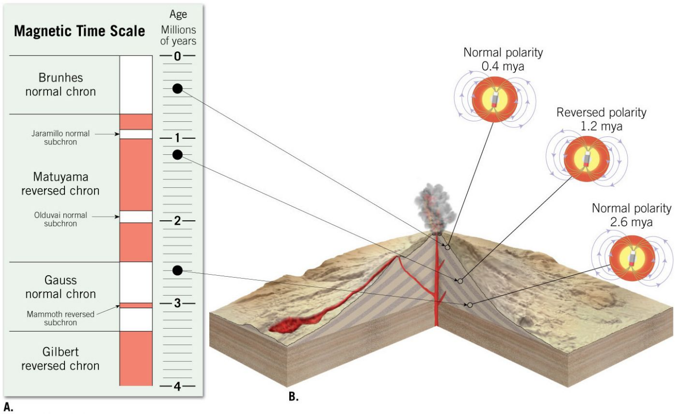
**Era:** profound worldwide changes in life-forms. They are subdivisions of an eon. Subdivisions of Phanerozoic eon:

- Cenozoic (recent life)
- Mesozoic (middle life)
- Paleozoic (ancient life)

Eras are subdivided in **periods**, less profound changes in life forms. Periods are divided into **epochs.**

## PALEOMAGNETISM

Paleomagnetism measures the ancient orientation of the Earth's magnetic field to help determine the age of rocks. It allows us to establish stratigraphic order and to date rocks.
Magnetic minerals (iron titanium oxides and iron oxides) that occur naturally in rocks point toward magnetic north. These record the orientation (polarity) of the Earth's magnetic field.
Using radiometric dates and measuring the ancient magnetic polarity in volcanic and sedimentary rocks we can know the polarity of Earth in the moment the rock formed.
**Normal polarity** is when the magnetic north pole is close to the geographic north pole, and **reversed polarity** when the magnetic north is near the geographic south pole.
Reversals of the Earth's magnetic field are global, easy to recognize and they occur abruptly.
Geologists can measure the paleomagnetism of rocks. Other lines of evidence are needed to correlate the site to the Geomagnetic polarity time scale or GPTS. Once we correlate a particular paleomagnetic reversal to a known reversal in the GPTS, the numerical age of the entire sequence can be determined.

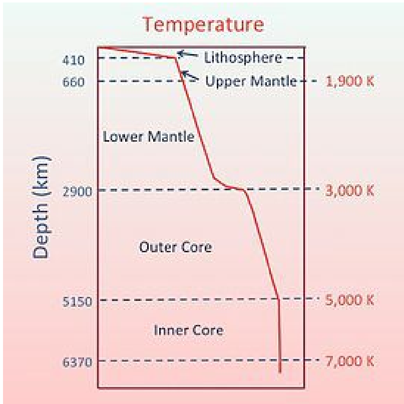


# Lecture 3: STRUCTURE OF EARTH

## PHYSICAL PROPERTIES OF THE EARTH

There are two types of planets in the solar system according to their internal structures:

- Terrestrial (Earth-like) planets:
    - Mercury, Venus, Earth and Mars
    - Small, dense and rocky
    - Made up largely of metals and silicate minerals
    - Large cores of iron and nickel
- Jovian (Jupiter-like) planets:
    - Jupiter, Saturn, Uranus and Neptune
    - Large, low density and gaseous
    - Thick atmospheres composed of hydrogen, helium, methane and ammonia




### *GEOTHERMAL GRADIENT*

Geothermal gradient is the rate of increasing temperature with respect to increasing depth in the Earth's interior.

### *VOLCANISM*

Magma originates when essentially solid rock, located in the crust and upper mantle, melts.

Most active volcanoes on land are located along the margins of the ocean basins, circum-Pacific belt (Ring of Fire). Denser oceanic lithosphere subducts under continental lithosphere.

Factors that influence the generation of magma from solid rock: role of heat:

Earth's natural temperature increases with depth (geothermal gradient). It's not sufficient to melt rock at the lower crust and upper mantle. Geothermal gradient changes in plate boundaries because there is more or less pression. In divergent plate boundaries, melting point is higher because there is a decrease in pressure. In the case of convergent plate boundaries, melting point is decreased due to the addition of water.

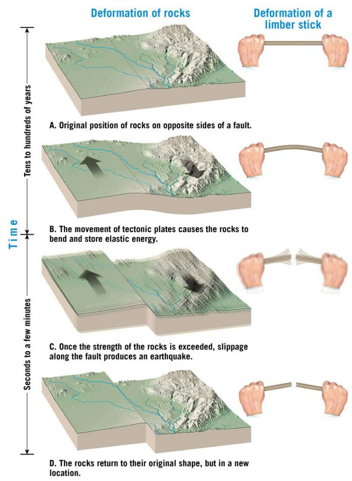
Global distribution of igneous activity is not random: most volcanoes are located on the margins of the ocean basins (intermediate, andesitic composition). Second group of volcanoes is confined to the deep ocean basins (basaltic lavas). Third group includes those found in the interiors of continents.

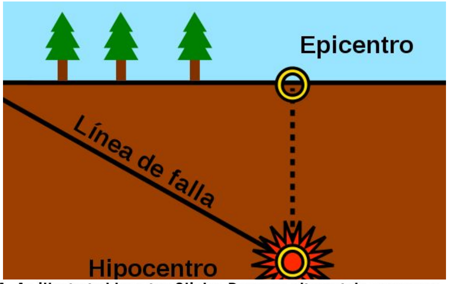
### *EARTHQUAKES*

Vibration of earth produced by the rapid release of energy. Earthquakes are associated with movements along faults.

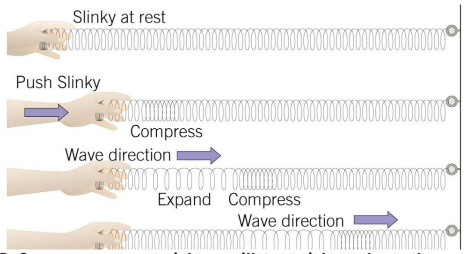
Mechanism for earthquakes was first explained by H.Reid:

- Rocks "spring back"- a phenomena called elastic rebound
- Vibrations (earthquakes) occur as rock elastically returns to its original shape

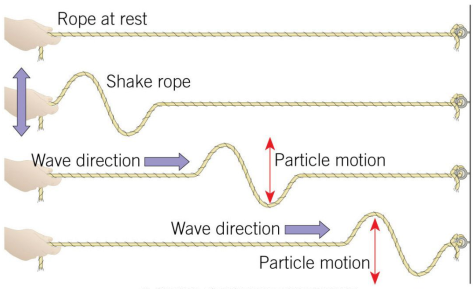





A. As illustrated by a toy Slinky, P waves alternately compress and expand the material through which they pass.




B. S waves cause material to oscillate at right angles to the direction of wave motion.



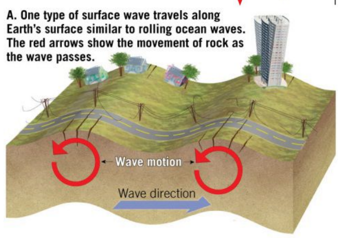

<u>Locating an earthquake</u>: The energy is released in all directions

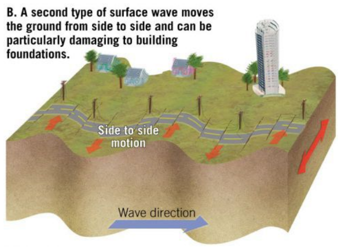
- Focus (hypocenter): the place within Earth earthquake waves originate
- Epicenter: point on the surface, directly above the focus (<100 km depth, 90% of all earthquake)

Types of earthquake waves:

- Body waves:
  - Primary (P) waves: (slinky)
    - Push-pull (compressional) motion
    - Travel through solid, liquid and gas
    - Greatest velocity of all earthquake waves
    - Wave direction = particle motion

  - Secondary (S) waves: rope
    - “Shake motion”
    - Travel only through solid
    - Slower velocity that P waves (P waves travel 1.7 times faster than S waves)
    - Particle motion direction is perpendicular to the wave direction
- Surface waves
  - Complex motion
  - Slowest velocity of all waves
  - Two types: rayleigh ocean waves (wave motion) and love waves (move the ground from side to side)



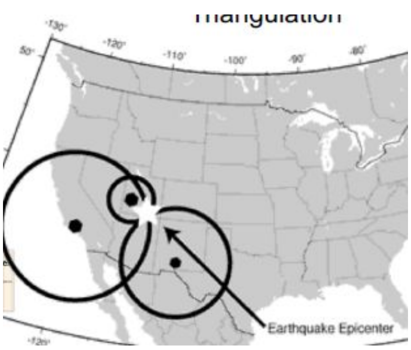




***Seismology***

It’s the study of earthquakes. The instrument used to record the seismic wave is the seismograph and record we get is a seismogram. In a seismogram we can see the difference in the arrival times between P and S recordings.

3 station recordings are needed to locate an epicenter:

- Circle equal to the epicenter distance is drawn around each station
- Point where three circles intersect is the epicenter




95% of energy from earthquakes in a few narrow zones (closely to plate boundaries):

- Circum-pacific belt 80%
- Alpine-himalayan belt 15%

The rest in transform faults (major strike-slip faults that accomodate motion between two tectonic plates; along oceanic spreading ridges and strike-slip faults (within plate interiors) 5% eg. San Andreas Fault.

# STRUCTURE AND COMPOSITION OF THE EARTH

## *EARTH'S LAYERED STRUCTURE*

Most of our knowledge of earth's interior comes from the study of P and S earthquake waves.

Travel times of P and S waves through earth vary depending on the properties of the materials (composition/behaviour). S waves only travel through solid.

As a wave travels through Earth, the path it takes depends on the velocity.

Some of a wave's energy is reflected back to the surface. If we know the velocity of the waves and the time it takes to travel we can calculate the depth of the boundary.

Energy is released in all directions, but in order to understand the way the waves work waves are drawn as lines to understand the path of the wave forms.

We can use waves to interpret the layering of earth. The velocity of the waves change with depth. There are two main rapid changes in the velocity of the waves:

- the boundary between the crust and the mantle (Mohorovivic discontinuity)
- the boundary between the mantle and the core

S waves don't travel through fluid so they can't go to the inner core.

***Behaviour of P and S waves***

*Density and elasticity of the materials increase with depth. If density of rock increases, velocity of waves decreases, if elasticity increases, velocity increases. Elasticity increases faster than density.*

*Density increases means that molecules are larger that's why velocity decreases . (More density, less velocity).*

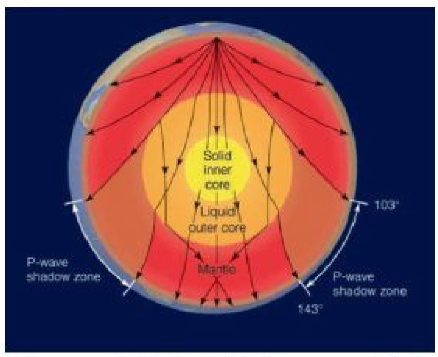
*If a material is elastic as you move the particle they go back to their original position. Material is more elastic it's easier for the waves to travel through the materials.*

*P waves move faster than secondary waves, and we know that S waves don't travel through liquid.*

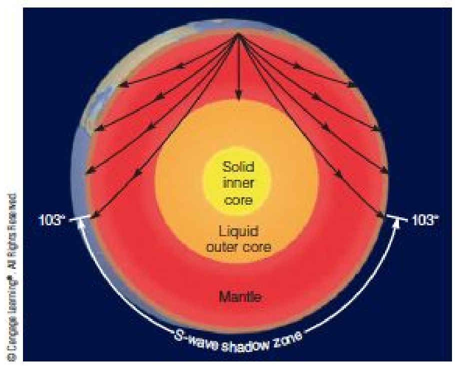
*If earth was uniform, waves would travel in the same way through the interior of earth. There wouldn't be changes in velocity so they wouldn't be any changes in the paths of the waves.*

<u>P- and S-waves shadow zones</u>

- Discontinuity at a depth of 2900 km (core-mantle boundary)
  - P wave velocity decreases markedly
  - P waves are refracted in the core
  - Little P-wave energy reaches the surface (seismographs) in the area between 103 degrees and 143 degrees from an earthquake focus (P-wave shadow zone)
- S-waves are completely blocked by the core (S-wave shadow zone)
  - At locations greater than 103 degrees from an earthquake focus, no S-waves are recorded
  - The outer core must be liquid or behave as a liquid
- P-wave velocity increases at the base of the outer core
  - The inner core is thought to be solid




a P-waves are refracted so that no direct P-wave energy reaches the surface in the P-wave shadow zone.




b The presence of an S-wave shadow zone indicates that S-waves are being blocked within Earth.

**LAYERS BASED ON CHEMICAL COMPOSITION**

- Crust
    - Thin, rocky outer layer
    - Varies in thickness
        - Roughly 7km (5 miles) in oceanic regions
        - Continental crust averages 35-40 km (22-25 miles)
        - Exceeds 70 km (40 miles) in some montainous regions
    - Continental crust
        - Upper crust composed of granitic rocks
        - Lower crust is more akin to basalt (3,0 g/cm3)
        - Acerage density is about 2,7 g/cm3
        - Up to 4 billion years old (4000 my old)
    - Oceanic crust
        - Basaltic composition (upper part, lower part gabbro)
        - Density about 3,0 g/cm3
        - Younger (180 million years old or less) than the continental crust
        - Oceanic crust is younger because it's constantly being created in oceanic ridges.
- Mantle
    - Below crust to a depth of 2900 kms (1800 miles)
    - Composition of the uppermost mantle is igneous rock peridotite (made up of ferromagnesian silicates); changes at greater depths (wave velocity changes)
    - Density: 3.3-5.7 g/cm3 (variation because the variation of pressure and temperature)
    - It constitutes 80% of Earth's volume and 69% of its mass
- Outer core
    - Below mantle
    - Composition dominated by iron (about 12% S, Si, O, Ni, K)
    - Density: 9.9-12.2 g/cm3
- Inner core
    - Composed by iron and nickel

\- The core constitutes 16.4% of Earth's volume and about 30% of its mass

**LAYERS BASED ON PHYSICAL PROPERTIES**

- Lithosphere
    - Crust and uppermost mantle (about 100 km thick)
    - Cool, rigid, solid
    - Lithospheric plates
- Astenosphere
    - Beneath the lithosphere
    - To a depth of about 650 km
    - Weak layer of the upper mantle
    - Solid, mobile (plastic)
    - Partially molten (magma, low-velocity zone)
- Outer core
    - Liquid layer
    - 2270 km (1410 miles) thick
    - Convective flow of metallic iron within generates Earth's magnetic field
- Inner core
    - Sphere with a radius of 1216 km
    - Behaves like a solid (due to the immense pressure)

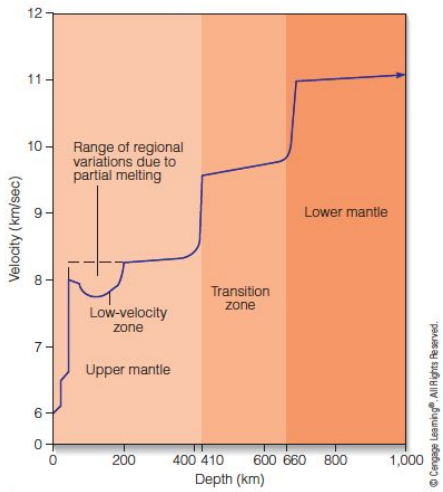
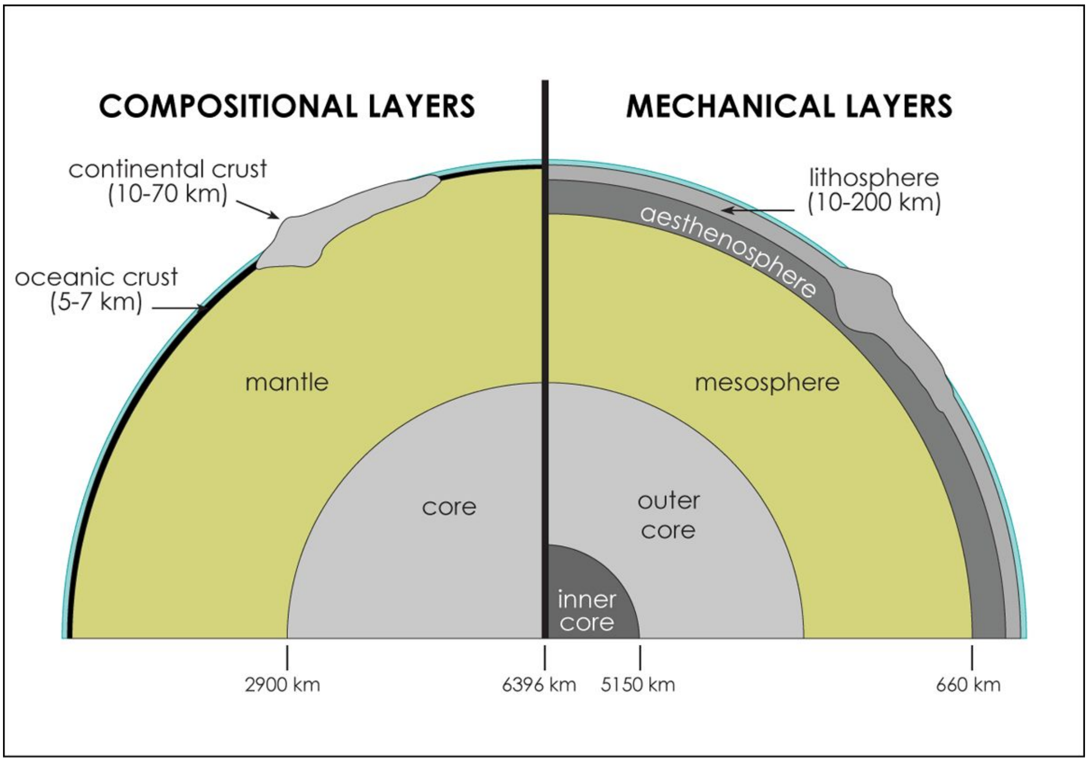


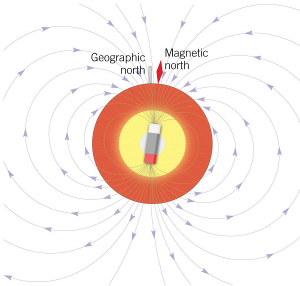

**Figure 9.28** Variation in P-Wave Velocity Variations in P-wave velocity in the upper mantle and transition zone.



**EARTH'S MAGNETIC FIELD**

Earth's outer core is fluid (liquid iron, electrically-conducting fluid). Earth's rotation/convective flow of metallic iron.

Magnetic minerals that occur naturally in rocks point toward magnetic north (magnetization, Curie point). They record the orientation (polarity) of the Earth's magnetic field (remanent magnetization).




**PALEOMAGNETISM**

Paleomagnetism measures the ancient orientation of the Earth's magnetic field to help determine the age of rocks, using radiometric dates and measuring the ancient magnetic polarity in volcanic and sedimentary rocks. Reversals of the Earth's magnetic field are global, they occur abruptly and they're easy to recognize. There are two types of polarity:

- Normal polarity: the magnetic north pole is close to geographic north pole
- Reversed polarity: the magnetic north is near the geographic south pole

Geologists can measure the paleomagnetism of rocks. They record ancient magnetic reversals. They can do this because every reversal looks the same in the rock record.

Other lines of evidence are needed to correlate the site to the Geomagnetic polarity time scale, for example fossils or radiometric dates. Once we correlate a particular paleomagnetic reversal to a known reversal in the GPTS, we can locate the numerical age of the rock.

This methodology allows us to establish stratigraphic order and to date rocks.

# Lecture 4: PLATE TECTONICS

***Origin and development of plate tectonic theory***

Before the 20th century they believed that continents were static. **Wegener** explained that continents moved and that they didn't have a permanent position: he proposed an idea of a huge continent where all the continents were together (*Pangaea*), published in 1912. He proposed that 2000 million years ago all the continents were together because the continents' coastlines matched.

He  provided some evidence about his idea.

The first evidence is that he realised that the coastline of different continents matched. They were some opponents to his idea, they said that since this supercontinent existed, there have been many processes that modified the coastline, so the coastline we see today is not the same as the coastline existed when *Pangaea* existed (deposition of sediments, erosion...). A few years later, in the 60s, they realised that if we look at the outer edge of the continent (the continental platform) the match is more accurate. About 900 meters depth, the fitting of the continents (the continental platform) is perfectly accurate.

He also realised that there are identical fossils across the ocean. For example, the Glossopteris fossil can be found in different continents that nowadays are apart. Either the specie were able to cross the ocean or the actual continents were once together.

Another evidence is that he realised that rocks and rock sequences match across continents. Different continents have the same rock sequences: same rock type and from the same time. Mountain ranges from different continents and with a similar trend suggest that these different continents could be together years ago.

When Wegener analysed  the rocks in different continents he found this evidence of cool conditions at the time. Apparently glacial  ice sheets were located where nowadays is a subtropical zone. One hypothesis was that there was a global cooling period. But they found coal deposits that there weren't formed in cool position. Zones where glacial ice sheets marks were found were somewhen in the south pole, and the zones where coal deposits were found were somewhen in the equator zone. Wegener suggested that continents were moving and their former locations.

When he proposed this hypothesis of the continental drift. It suffered a lot of criticism,: they were two main objections:

1) He wasn't able to provide an explanation to the cause of the movement of the continents, he proposed that sun's or moon's gravitational forces were responsible for the move of continents, as for tides. They object that if the gravitational forces were that strong the earth's rotation would stop.

2) He also said that continents moved across the ocean.

After World War II, the analysis of the ocean floor increased because it happened a improvement of the technology. We were able to reach the ocean floor and analyse it. It was proved that the ocean floor is younger than they expected, because it's always regenerating. The lithosphere is made of the crust and upper mantle, so depending or whether is made of oceanic or continental crust, the thickness of the lithosphere will vary.

The oceanic crust is more dense than continental crust. The oceanic crust is about 100 km thick, but if we approach the oceanic drift it will vary (it will be thinner). The continental crust is more thick.

If we compare the lithosphere to the asthenosphere, we can see that the lithosphere is a strong and rigid layer, but the asthenosphere is a weak layer where rocks are near their melting temperature. They have very different physical properties. According to the plate tectonics, they are detached from each other, so they will move independently.

### *Lithospheric plates and their edges*

The lithosphere is broken into 7 main lithospheric plates. The pacific plate is made of oceanic lithosphere and it occupies most of the pacific ocean. None of the plates is made of only continental lithosphere. Wegener was wrong about the continents moving through the oceans. Actually continents move together with the ocean.

This plates are in continuous motion. The interaction between these plates will happen mostly in the boundaries of the plates. If we put in a map the location of volcanoes and earthquakes, we'll see that most of them are located in the boundaries of the lithospheric plates.

There are three types of boundaries:

- Divergent plate boundary: two plates move apart and oceanic lithosphere is created in a rift (40%)
- Convergent plate boundary: two plates move toward each other, most of the times, one will subduct under the other. There is a destruction of oceanic lithosphere. (40%)
- Transform plate boundary: two plates slide past each other. There is no atmospheric production or destruction. (20%)

There is a balance, when oceanic lithosphere is created it's also destructed somewhere else.

<u>*Divergent plate boundaries*</u>

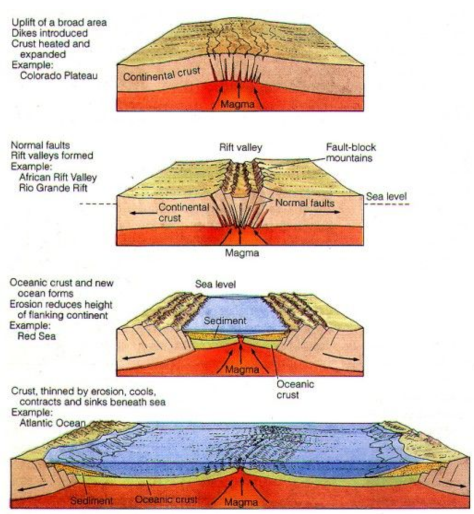
Most of the times, divergent plate boundaries will occur in the ocean ridges, where new seafloor is formed. Usually, the ocean ridges are elevated areas and sometimes they have a depression structure (Rift valley). As plates move away from each other, there is mantle upwelling that will create new seafloor. This areas are also known as spreading centres.

There is an elevated area where the hot magma from the mantle goes up. This is the longest mountain ridge in the world.

As the seafloor moves away from the oceanic ridge, the magma will cool out, the material will get denser and it will go down. That's why the seafloor moving from the oceanic ridge will be in more depth than the ridge and the sea depth will increase when we go away from the oceanic ridge. This phenomena is called thermal contraction.

Sometimes, the tension forces caused by the divergent plate boundary will create fractures in the lithosphere and some blocks will be created. Some of them will be subside, and a depression zone will be created: a rift valley.

When a divergent plate boundary occurs in a continent, what happen is that these tensional fracture will fracture the continental litosphere that will produce the upwelling of the mangle and it will end up breaking in two continents. Eventually an expansive new ocean basin will be created by the expansion of the oceanic ridge.



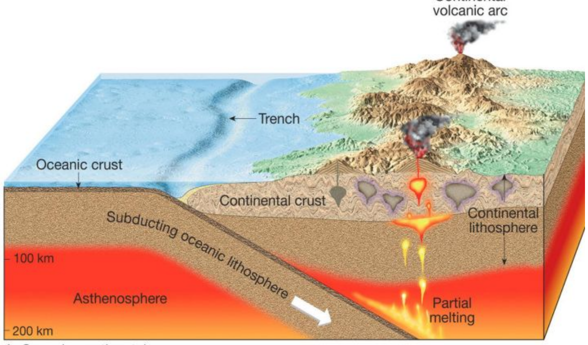
The rate of seafloor creation in the atlantic ocean is 2 cm/year, but in the pacific ridge is about 15 cm/year elongated fractures will be formed and a depression structure will be formed.

*Convergent plate boundaries (Destructive margins):*

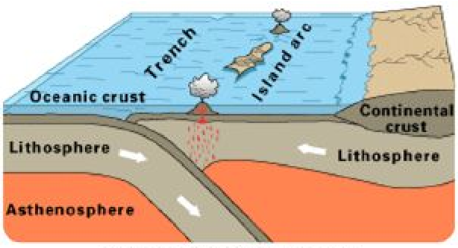
- Plates collide, an ocean trench forms and lithosphere is subducted into the mantle
- Angle of subduction (age, density): If we have a younger lithosphere, spreading centre will be near, and it will be less dense. (Younger → less density)
    - Seafloor spreading center proximity
        - Coast of chile, (younger lithosphere), forced subduction, great earthquakes
        - Western Pacific, thickest & densest, plunges into the mantle (almost vertical subduction)
- Types:
    - Oceanic-continental convergence
    - Oceanic-oceanic convergence
    - Continental-continental convergence

**Oceanic-continental convergence**

Denser oceanic slab sinks into the astenosphere. Pockets of magma develop and rise (water). Continental volcanic arc forms, for example, the Andes, the Cascade Range (Mt. Hood).



A. Oceanic-continental



Oceanic-oceanic convergence

**Ocean-ocean convergence**

Two oceanic slabs converge and one descends beneath the other. Often volcanoes are formed on the ocean floor, before at the continental platform. Volcanic island arc forms as volcanoes emerge from the sea (subduction is sustained). For example, Aleutian, Mariana and Tonga islands.

**Continent-continent convergence**

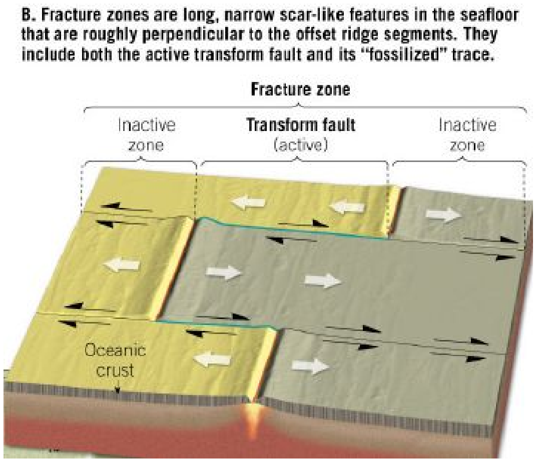
When subducting plates contain continental material, two continents collid. Buoyancy of continental material inhibits subduction. It can produce new mountain ranges such as the Himalayas. Deformed sedimentary and metamorphic rocks (often oceanic lithosphere) can be found.

*Transform fault boundaries*

Plates slide past one another (move parallel to boundary). No new crust is created or destroyed. Most of them connect two segments of a mid-oceanic ridge (even 2 trenches). They can also be cutting continental crust (San Andreas fault).

Two areas can be found:

- Active zone: the seafloor in both sides are moving in opposite direction
- Inactive zone: the seafloor is moving in the same direction




### ***Basic processes: the Wilson cycle***

It puts the convergence and the divergence of the tectonic plates in a cycle. (J. Tuzo Wilson)

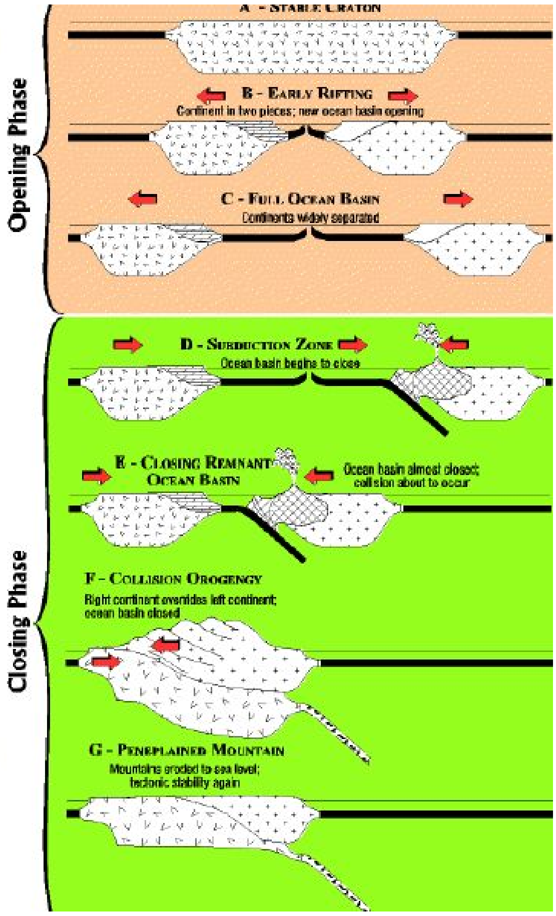
Stage A hot (low-density) mantle plume rises up → upwarping (updoming) of the lithosphere→ lithospheric extension and thinning (East African Rift)

Stage B Continental splitting (two continents)→ formation of a new ocean basin, oceanic crust (Red Sea)

Stage C The ocean basin widens (Atlantic Ocean)

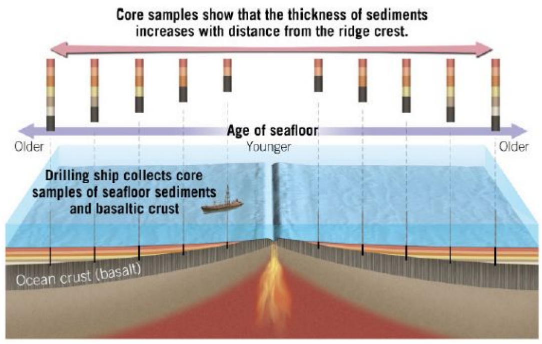
Stage D & E New convergent plate boundary→ subduction zone forms→ ocean basing begins to close (Pacific Ocean)

Stage F & G Ocean basin completely closes→ collision of continents→ creation of mountains (orogeny) → erosion (Alps, Himalaya)

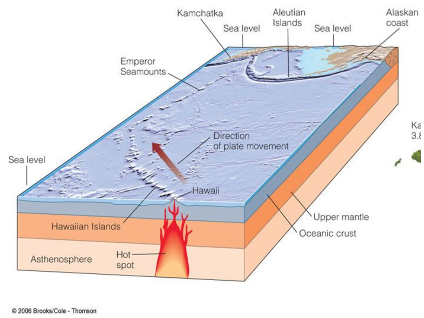


## *Testing the Plate Tectonics Model*

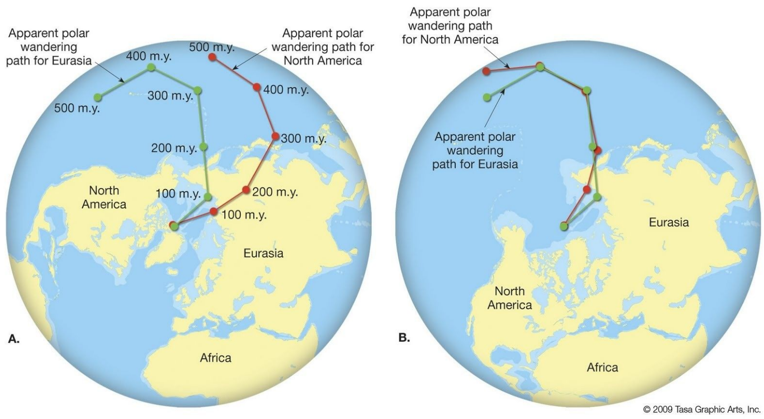
1. **Evidence from ocean drilling:** some of the most convincing evidence confirming seafloor spreading has come from drilling directly into ocean-floor sediments:
    - Age of deepest sediments
    - Thickness of ocean-floor sediments verifies seafloor spreading (thermal contraction)

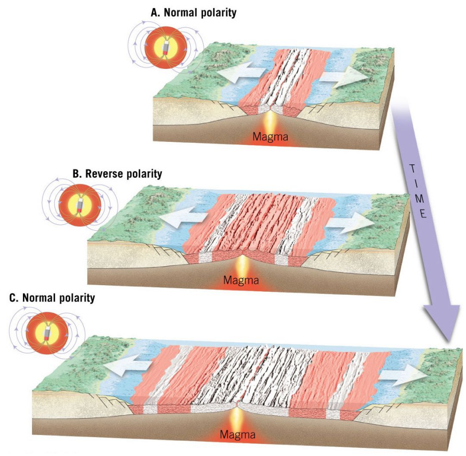



2. **Hot spots, hot spot tracks and mantle plumes**
   Caused by rising plumes of mantle material. Volcanoes can form over them (Hawaiian island chain).
   Mantle plumes are long-lived structures, some of them are originated at great depth, perhaps at the mantle-core boundary. They don't move.
   Hot spots don't move but the plate is moving, that's why island chains are created.
   They can also explain anomalous volcanic activity (Iceland).




3. **Paleomagnetism:** Probably the most persuasive evidence. Ancient magnetism is preserved in rocks. The paleomagnetic record shows polar wandering (evidence that continents moved) and Earth's magnetic field reversals (recorded in rocks as they form at oceanic ridges).

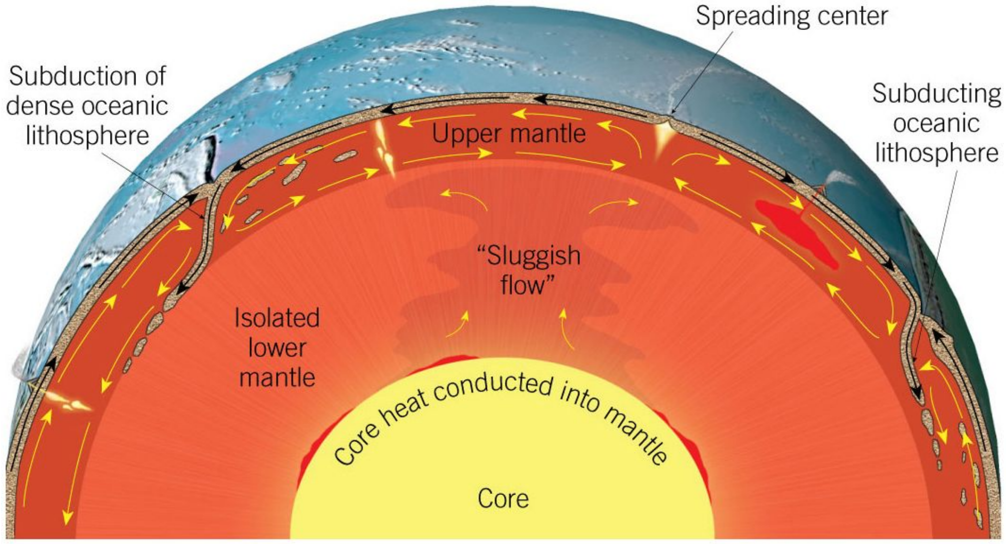


***What drives plate motion***

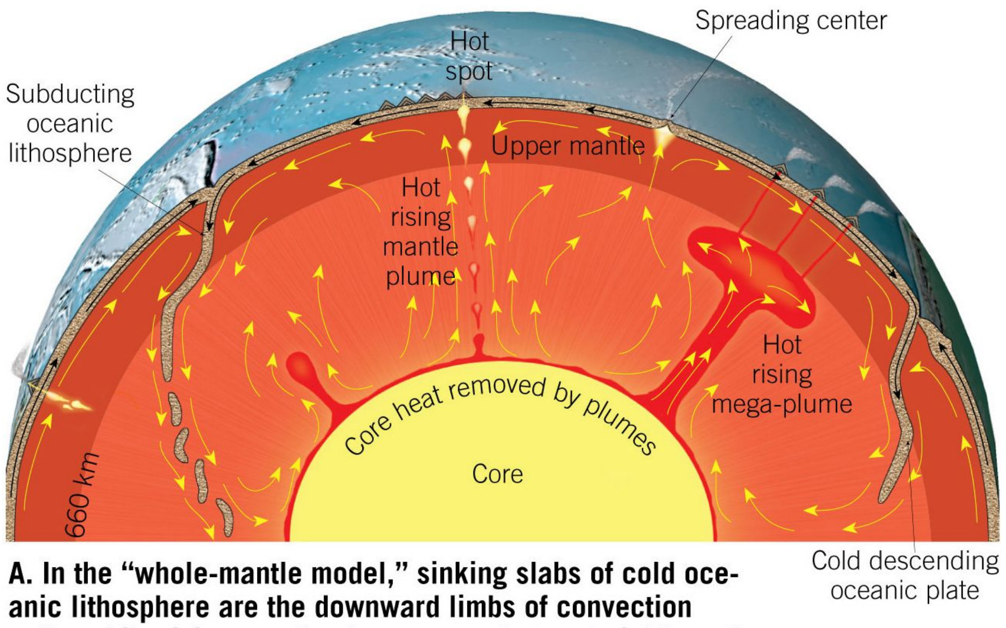
Earth's heat the key driving force: Mantle convective flow. Two models: Layering at 660 kilometers and Whole-mantle convection.

*Layering at 660 kilometers*




**B. The "layer cake model" has two largely disconnected convective layers. A dynamic upper layer driven by descending slabs of cold oceanic lithosphere and a sluggish lower layer that carries heat upward without appreciably mixing with the layer above.**

*Whole-mantle convection:* Convection occurs in all the mantle.

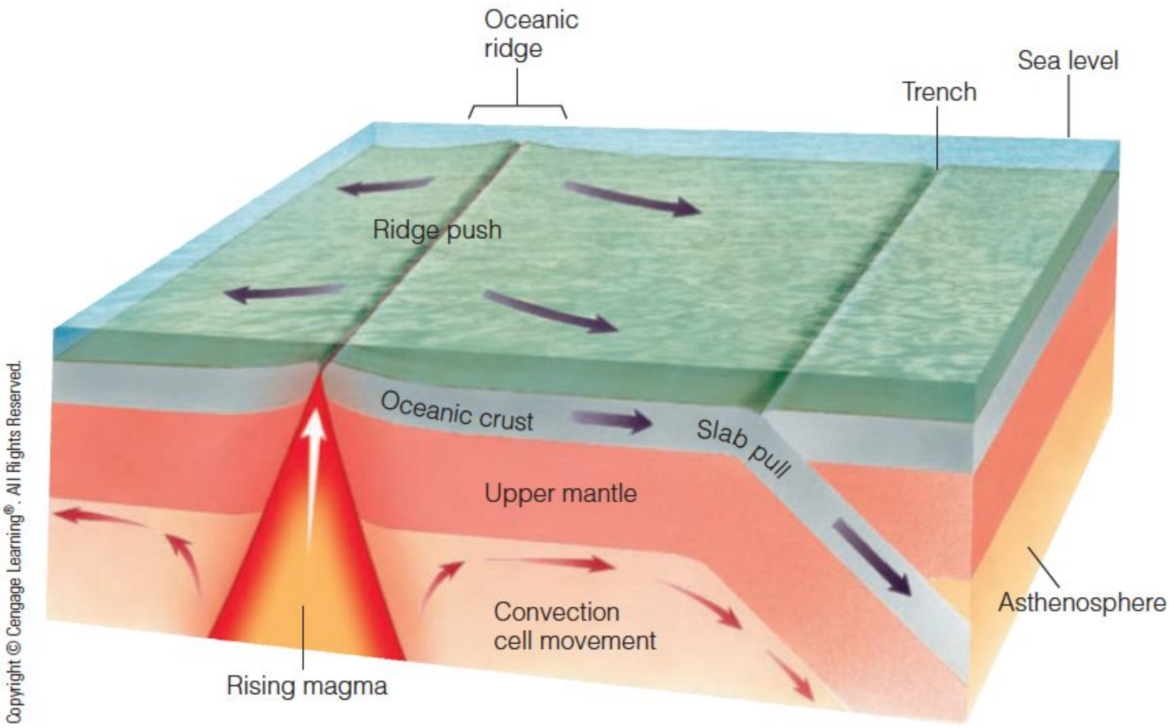



**A. In the "whole-mantle model," sinking slabs of cold oceanic lithosphere are the downward limbs of convection cells, while rising mantle plumes carry hot material from the core-mantle boundary toward the surface.**

**Forces acting on plates**

Slab-pull and ridge-push model:

- Descending oceanic crust pulls the plate
- Elevated ridge system pushes the plate



# Lecture 5:
# PLATE TECTONICS AND ITS IMPLICATIONS

## CONTINENTAL DRIFT

One of the main implication of plate tectonics is the movement of continents (Wegener, beginning of 20th century, he thought that they moved independently, now we know that they move entirely with oceanic lithosphere).

## DEFORMATION AND OROGENESIS

Deformation: general term that refers to all changes in the original form and/or size of a rock body. Most crustal deformation occurs along plate margins.

Deformation can be happen in the upper parts on the crust (faults) and as we go deeper in the crust we can found faults. Mountain buildings are relationed with compressional forces. Reverse faults, when they deep more than 45 degrees. These types are formed with compressional forces. There's a reduction horizontally and they go down vertically. When these reverse faults dip less than 45 degrees they are called thrust faults.
Folds: rocks bent into a series of waves. Most folds result from compressional forces which shorten and thicken the crust. (anticlinal, sinclinal).

Orogenesis: processes that collectively produce a mountain belt. Most mountain buildings occur in convergent boundaries.

- Andean-Type mountain building: oceanic-continental crust convergence (continental volcanic arcs). When the oceanic plate is subducting, an accreationary wedge is formed when this subducting plate drags the sediments. Also, water from the ocean is dragged under the continental lithosphere, lowering the melting point of the magma.
- Collisional mountain belts: where two plates with continental crust converge (eg. Indian and Eurasian plate: himalayan mountains

Earth's major mountain belts (Shields: covered by sedimentary rocks... oldest rocks) are associated with plate tectonics.

## EARTHQUAKES AND VOLCANOES

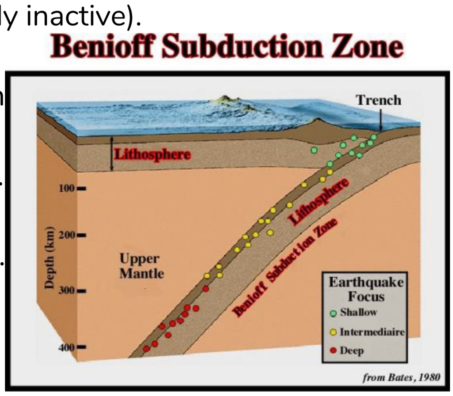
**Earthquake**: vibration of earth produced by the rapid release of energy, as the rock elastically returns to its original shape. Related to faults.

Most of the earthquakes happen in a few narrow zones: circum-pacific belt and alpine-himalayan belt.

Most of the times related to convergent plate boundaries. Some of them in transform faults and strike-slip faults (intraplate: old faults that were supposedly inactive).

To classify earthquakes, we can subdivide them in:

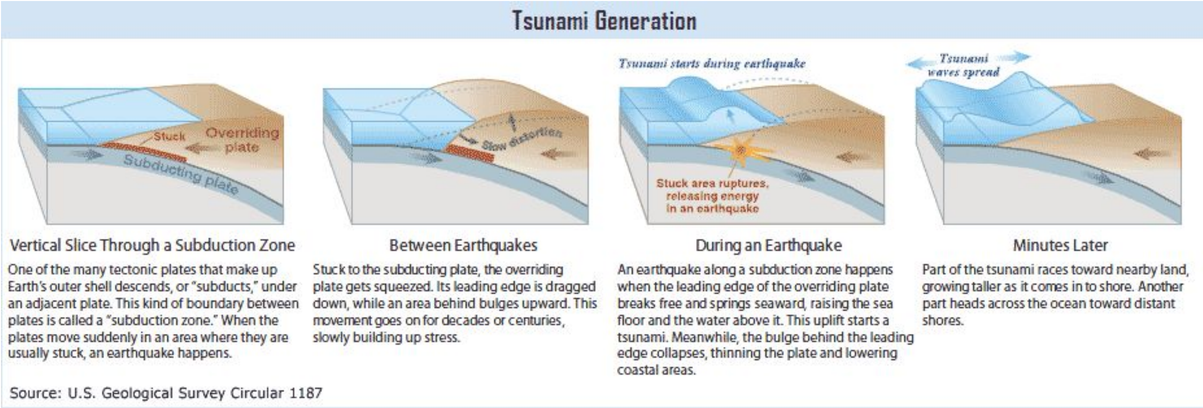
- Shallow earthquakes: focus above 60 km (transform faults and sometimes convergent boundaries)
- Intermediate earthquakes: 60-300 km focus. Convergent boundaries
- Deep earthquakes: more depth than 300 km. Convergent boundaries.



The inclined narrow zone where the focus is located is called Wadati-Benioff zone.

## TSUNAMIS

When its not able to accumulate more energy, there's a rupture and a tsunami is formed. Tsunamis are often associated with convergent plate boundaries (landslides...).




## VOLCANOES

Distribution also linked to plate tectonics.

Magma originates when essentially solid rock located in the crust and upper mantle, melts-

Factors that influence the generation of magma from solid rock:

- Geothermal gradient: Earth's natural temperature increases with depth. This is not sufficient to melt rock at the lower crust and upper mantle.
- Decompression melting: plate motions provide the mechanism by which mantle rocks melts to form magma:
- Introduction of water to mantle rock: in the subduction zone the oceanic lithosphere carries water that causes the partial melting of the mantle rocks to generate magma. The introduction of water causes rocks to melt at a lower temperature.

Most of volcanoes are located on the margins of the ocean basins. (Ring of fire)

Can also be found in deep ocean basis and in the interiors of the continents associated to mantle plums.

**Convergent boundary:**

- Descending plate partially melts
- Magma slowly rises upwards
- Rising magma can form:
  - Volcanic island arcs (aleutian islands)
  - Continental volcans (andes)

**Divergent boundary**:

The greatest volume of volcanic rocks is produced along the oceanic ridge system:

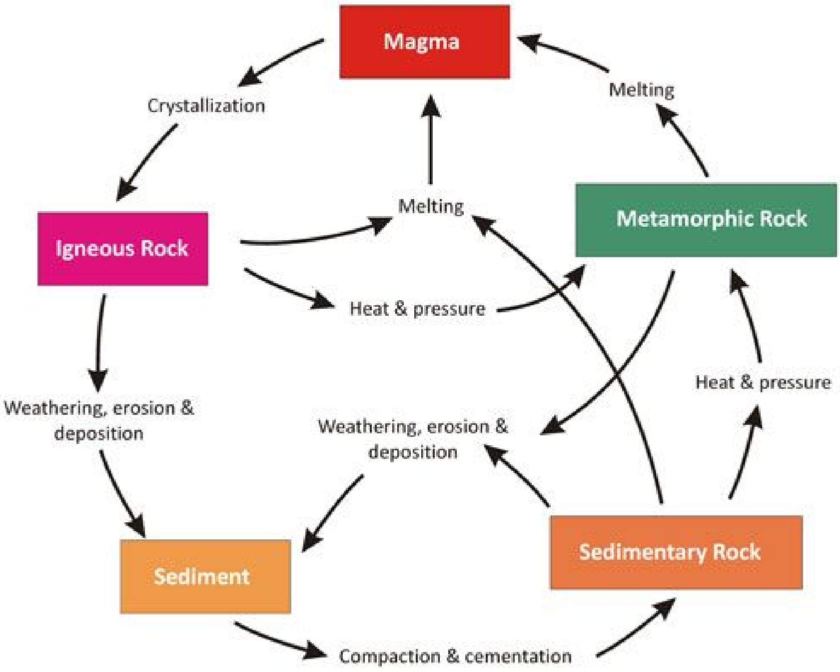
- Lithosphere pulls apart
- Less pressure on underlying rocks
- Partial melting occurs
- Large quantities of fluid basaltic magma are produced

**Intraplate volcanism:**

Activity within a rigid plate. Plumes of hot mantle material rise and form localized volcanic regions called hot spots. Explain the Hawaiian island or the anomalous volcanic activity of Iceland.

## THE ROCK CYCLE

Shows the interrelationship among the three rock types.Full cycle does not always take place due to shortcuts or interruptions




## CHANGES IN SEA LEVEL AND CLIMATE CHANGES

Global sea level:

Because of the huge ice sheets that covered north atlantic during the last glaciation, sea level fell about 100 meters.

There are evidence about ice sheets in Pangaea, near the south pole.

If the spreading rate of a divergent boundary is fast, it will cause a sea level rising, because the ridge will be higher. If the spreading rate is slow a sea level rising won't happen.

## BIOGEOGRAPHY AND EVOLUTION

One of the evidence that Wegener used to defend the continent motion was that he found fossils from the same specie in continents that now aren't together.

One of the main events that took place in the Cenozoic was the closure of the Isthmus of Panama that linked North and South America. Many scientists think that this closure caused a glaciation because ocean circulation changed. This closure also caused a land bridge that caused the movement of species from north to south and vice versa. It also caused a change in the ocean species in both sides of the Panama Isthmus.

# Lecture 6: EARTH MATERIALS

## EARTH'S ELEMENTAL COMPOSITION

Around 90 elements are naturally produced on Earth. The elements with the atomic number bigger than 92 are man made synthetically.
All different elements have different physical and chemical properties according to the number of electrons in their outer shell.
The most common elements in Earth are:

- Oxygen (46.6%)
- Silicon (27.7%)
- Iron (5%)
- Calcium (3.6%)
- Sodium (2.8%)
- Potassium (2.6%)
- Magnesium (2.1%)
- All other elements (1,5%)

## MINERALS: COMPOSITION AND PHYSICOCHEMICAL PROPERTIES

### DEFINITION

Minerals are building blocks of rocks. They must be:

- Natural (formed by natural geologic processes)
- Inorganic
- Solid
- Possess an orderly internal structure of atoms
- Have a definite chemical composition, expressed by a chemical formula. Some variations may occur.

Elements:

- Basic building blocks of minerals
- Over 100 are known
- Defined by their number of protons (atomic number)
- Groups of the same type of atoms

Rock forming minerals: most abundant atoms in Earth's crust are oxygen (46.6% by weight) and silicon (27.7% by weight).

**Mineral groups:**

- **Silicate** minerals are the most common type of minerals (more than 800 known silicates)
  - Account for >90% of Earth's crust
  - Silicon and oxygen make up the basic building blocks of silicate minerals
- **Nonsilicate** minerals are not as common as the silicates but important economically and includes:
  - Carbonates
  - Sulfates
  - Halides

## PROPERTIES OF MINERALS

Definite crystalline structure and chemical composition of minerals give them unique physical and chemical properties.

Primary diagnostic properties:

- Determined by observation or performing a simple test
- Several physical properties are used to identify hand samples of minerals

Physical properties of minerals: used in mineral identification

- Habit: common crystal shape
- Optical properties
    - Luster
    - Color
    - Streak
- Strength
    - Hardness
    - Cleavage
    - Fracture

### *CRYSTAL SHAPE OR HABIT*

Characteristic shape of a crystal or aggregate of crystals. Minerals tend to have one common crystal shape, but a few have two or more characteristic shapes.

The most common crystal habits are fibrous, bladed, banded or cubic.

*Steno's Law: Law of constancy of interfacial angles*

Regardless the crystal size, the angles between equivalent faces of the same mineral are consistent.

A. Fibrous B. Bladed C. Banded D. Cubic crystals

### *LUSTER*

It's the appearance of the mineral in reflected type. There are two types:

- Metallic luster: characteristic of metals
- Non metallic luster: it can be glassy, earthy, pearly, silky, oily

The luster of a metal can be also submetallic: its luster is metallic but much duller and less reflective.

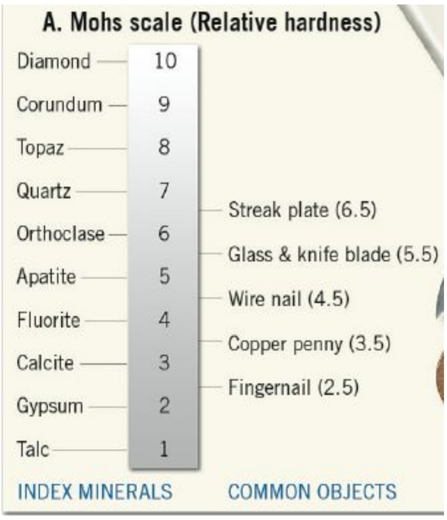
### *COLOR*

It's generally unreliable for identification. The same mineral can have different colors because ions of similar size can substitute the ions in the mineral slightly changing the composition of the mineral, which gives the mineral different colors. For example, quartz and fluorite.

### *CLARITY*
It's the clearness of the ability to transmit light of a mineral.
A mineral can be:
- Transparent (clear and see-through, like glass)
- Translucent (foggy, like a steamed-up shower door)
- Opaque (impervious to light, like metals)

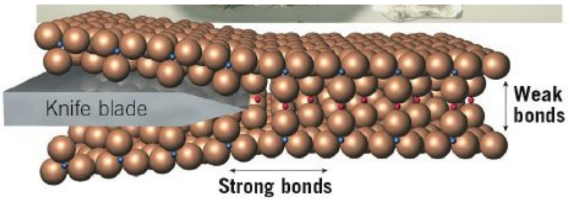
### *STREAK*
It's the color of a mineral in its powdered form. We can see the streak of a mineral rubbing it across a porcelain streak table. The color that the powder leaves it's characteristic of the mineral. Some of them may not leave powder because they're harder than the porcelain plate.

### *MINERAL STRENGTH*
It's how easily minerals break or deform under strress. Hardness is the resistance of a mineral to abrasion or scratching. All minerals are compared to a standard scale called the **Mohs scale** of hardness.




| HARDNESS | DESCRIPTION |
|---|---|
| Less than 2.5 | A mineral that can be scratched by your fingernail (hardness=2.5) |
| 2.5 to 5.5 | A mineral that cannot be scratched by a fingernail (2.5) and cannot scratch glass (5.5) |
| Greater than 5.5 | A mineral that scratches glass (5.5) |

### *CLEAVAGE*
Cleavage is related to atom bonding. It's the tendency of a mineral to break along planes of weak bonding (thin plates). Smooth, flat surfaces are produced. It is described by number of planes, angles between adjacent planes and the resulting geometrical shape.




### *FRACTURE*
Minerals with equally strong bonds have an absence of cleavage:
- Irregular (fractures rough)
- Conchoidal fractures ( like glass, with ribbed, smoothly curved surfaces)
- Splintery fractures
- Fibrous fractures

***TENACITY***

The mineral's resistance to breaking or deforming:

- Brittle materials will shatter into small pieces (halite)
- Malleable minerals are easily hammered into different shapes (many metals). Their shape can be changed, for example, gold.
- Sectile minerals, such as gypsum and talc, can be cut into thin shavings
- Elastic minerals, such as the micas, will bend and snap back to their original shape.

***DENSITY AND SPECIFIC GRAVITY***

Specific gravity is a related measure and more frequently used by mineralogists:

- It's the ratio of the weight of a mineral to the weight of an equal volume of water
- Most have a specific gravity between 2 and 3
- Metallic minerals can have more than twice that specific gravity (Galena: 7.5, Gold 20)

***TASTE***

Halite tastes like salt.

***FEEL***

Talc feels soapy, graphite feels greasy.

***STINKY STREAK***

Sulfur-bearing minerals have streaks that smell like rotten eggs.

***DOUBLE REFRACTION***

Some minerals split up in two the light that enters. For example, calcite.

***MAGNETISM***

It's the phenomena that some metals have to attract other metals.

***REACTION WITH HYDROCHLORIC ACID (EFFERVESCENCE)***

Carbonates, specially calcite, reacts with HCl.

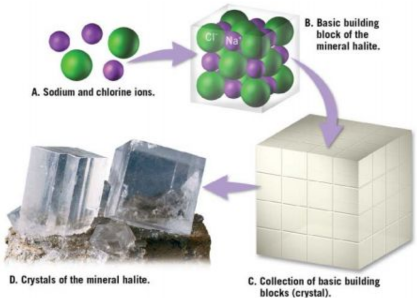
## MINERAL STRUCTURES AND COMPOSITIONS

All mineral samples are crystals or crystalline solids. Any natural solid with orderly, repeating internal structures is a mineral.

A mineral's structure is the atomic arrangement that results in the basic building blocks of a mineral crystal, called unit cells.

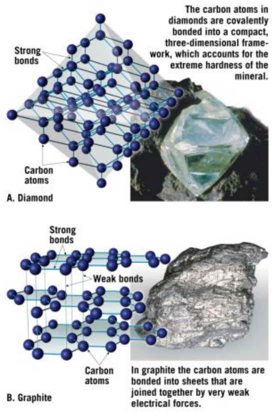
Minerals can be classified into seven crystal systems: the number, lenght...

Even if the sides change, the angles don't change.




### Polimorphs

Minerals with identical composition but different crystalline structures. Examples include diamond and graphite made entirely of carbon atoms. (In diamonds, all bonds are strong but in graphite there are strong and weak bonds, same happens with calcite and aragonite: $CaCO_3$).



# SILICATES

Rock forming silicates:

- Most common mineral group
- Contain the silicon-oxygen tetrahedron
    - Fundamental building block
    - Four oxygen ions surrounding a much smaller silicon ion
    - Single tetrahedra are linked together to form various structures
- General formula: $X_mY_n(Z_pO_q)W_r$

X: Large cations= $K^+$, $Ba^{2+}$, $Rb^+$, $Na^+$, $Ca^{2+}$
Y: Intermediate sized cations= $Fe^{3+}$, $Mg^{2+}$, $Ti^{4+}$, $Fe^{2+}$, $Al^{3+}$, $Mn^{2+}$
Z: Small cations= $Si^{4+}$, $Al^{3+}$
O: Oxygen= $O^{2-}$
W: Hydroxyl site (or large anions)= $OH^-$ (or $F^-$, $Cl^-$)

We can classify them in ferromagnesian and non ferromagnesian silicates.

***Silicate minerals with independent tetrahedra:***

- One of the simplest silicate structures
- Oxygen ions are bonded with positive ions: Mg2+, Fe2+, Ca2+
- Olivine and Garnet (granate)
- They form hard, dense equidimensional crystals that lack cleveage

**Joining silicate structures**

- Most silicate structures have a net negative charge (Except for quartz)
- Positive metal ions are required to balance the charge
- These positive ions bond with unshared oxygen ions in the tetrahedra. Most common ions are Fe2+, Mg2+, K+, Na+, Al3+, Ca2+

SiO4 tetrahedra can link to one another in a variety of configurations (**polymerization**). It accounts for the high variety of silicate minerals. Is achieved by sharing one two three or all 4 oxygen atoms with adjacent tetraedra.

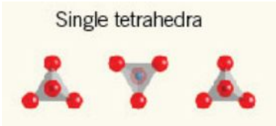
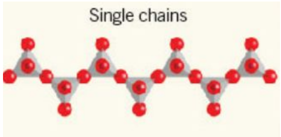
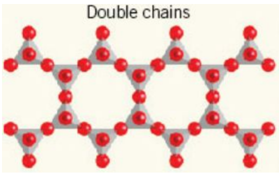
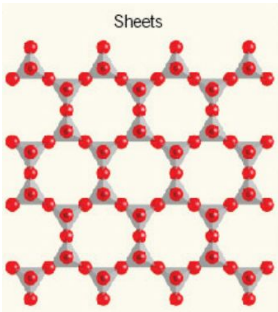
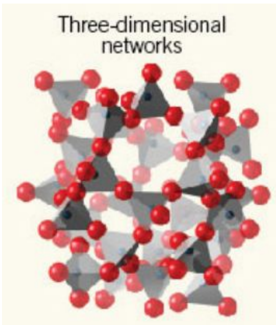
Tetrahedra can then form single chains, double chains, sheet structures or three dimensional frameworks.

*Silicate minerals with three dimensional framework*

All oxygen ions are shared between tetrahedra. This structure is the most common silicate structure. Examples include quartz and the feldespars.

*Classification of silicates*

We can classify the silicates based upon their tetrahedral arrangement

| | | | |
|---|---|---|---|
| Nesosilicates | Independent (isolated) tetrahedra |  | Olivine, garnet |
| Inosilicates | Tetrahedra arranged in single chains |  | Pyroxene |
| | Tetrahedra arranged in double chain |  | Amphybole |
| Phyllosilicates | Tetrahedra arranged in sheets |  | Mica group: biotite, muscovite |
| Tectosillicates | Three dimensional networks of tetrahedra (most abundant) |  | Feldespars (potassium feldespar, plagioclase...) and quartz |
| *Sorosillicates and cyclosilicates* | | | |

Most silicates form from molten rock cooling and crystalizing:

- The feldespars are the most common silicate group and make up more than 50% of Earth's crust
- Quartz is the second-most abundant mineral in the continental crust and the only common mineral completely of silicon and oxygen

Silicates are subdivided into light (non-ferromagnesian) and dark (ferromagnesian).

**Dark ferromagnesian silicates**

They contain iron and/or magnesium in their structure. They are generally dark in colour. Their specific gravity is between 3.2-3.6

- <u>Olivine group</u>
  They're formed in high-temperature. They go from black to green in color. They have a glassy luster and conchoidal fracture. They form small and rounded crystals. They are common in the oceanic crust and they constitute 50% of Earth's mantle.
- <u>Pyroxene group</u>
  Important components of dark-colored igneous rocks. Augite is the most common mineral in the pyroxene group. It's black in colour, and it has two distinctive cleavages at nearly 90º. It's the dominant mineral in basalt.
- <u>Amphibole group</u>
  Hornblende is the most common mineral in this group. It's usually black to dark green. It's very similar appearance to augite. It has two perfect cleavages exhibiting angles of 120º and 60º.
- <u>Biotite (Dark mica)</u>
  It's the iron rich member on the mica family. It has a excellent cleavage in one direction (sheet structure).
- <u>Garnet</u>
  It's composed of individual tetrahedra linked by metallic ions. It has a glassy luster, lacks cleavage and has conchoidal fracture (similar to olivine). It varies in color, but the most common color is brown-red. Well developed crystals have 12 diamond-shaped faces.

**Light nonferromagnesian silicates**

Generally light in color. Their specific gravity is around 2.7. It contains varying amounts of Al, K, Ca and Na, they don't have Fe or Mg.

- <u>Feldespar group</u>
  The most common mineral group. They are formed under a wide range of temperatures and pressures. They exhibit two directions of perfect cleavage at 90º. The two most common members are orthoclase (potassium feldespar) and plagioclase (sodium and calcium feldespar).
- <u>Quartz</u>
  The only common silicate composed entirely of oxygen and silicon. It's hard and resistant to weathering. It has a conchoidal fracture due to 3D framework. Often forms hexagonal crystals. It's colored by impurities (various ions).
- <u>Muscovite (mica)</u>
  Common member of the mica family. It has an excellent cleavage in one direction. The thin sheets formed are clear.

- Clay minerals
  Clay is a general term used to describe a variety of complex fine-grained minerals that have sheet structure. Clay makes up a large percentage of soil. Most originate as products of chemical weathering. They are the result from the metamorphism of magnesian minerals such as serpentine, pyroxene, amphibole and olivine, in the presence of carbon dioxide and water.

## NON SILICATE MINERALS

They are divided into groups based on the negatively charged ion or complex ion that the members have in common. They make up approximately 8% of the Earth's crust.

| Non-silicate group | Examples | Uses |
|---|---|---|
| Carbonates: composed of the carbonate ion ($CO_3^{2-}$) | Calcite ($CaCO3$), dolomite ($CaMgCO3$), magnesite, malachite | Primary costintuents in limestone and dolostone. |
| Halides | Halite (NaCl), Sylvine (KCl) | Common salt (halite) |
| Sulfides | Galena (PbS), Pyrite ($FeS2$), calchopyrite, sphalerite | Ore of lead, sulfuric acid |
| Sulfates | Gypsum, barite | |
| Oxides | Hematite, Magnetite... | Pigment, ore of iron |
| Native elements | Gold, copper, silver, diamond, graphite | |

## ROCKS: CONCEPT AND CLASSIFICATION

Rocks can be described as aggregate of the same or different minerals. Most rocks are aggregates of several different minerals. The term aggregate implies that the minerals are joined in such a way that their individual properties are retained.

Rocks can also be made of non mineral substances. For example, obsidian is formed by the fast solidification of magma happens, so it doesn't have a crystallization process due to the process being fast. The same happens with pumice, that is created when the fast solidification of a lava very rich in gases happens. That's why it's full of pores. Another example is coal, that is not formed with minerals because it consists of solid organic debris.

Rocks can be classified in three types: Igneous, metamorphic and sedimentary rocks.

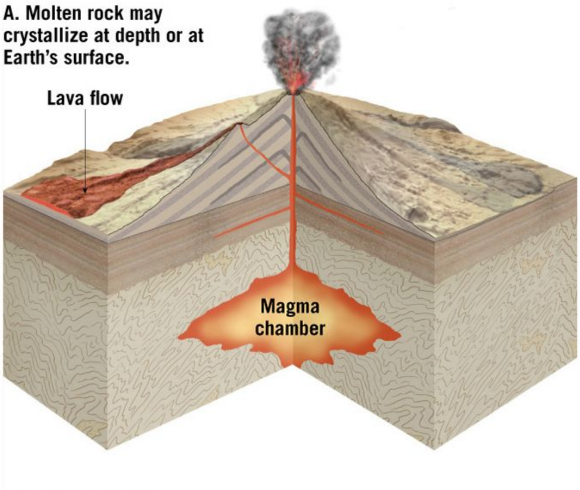
# Lecture 7: IGNEOUS ROCKS

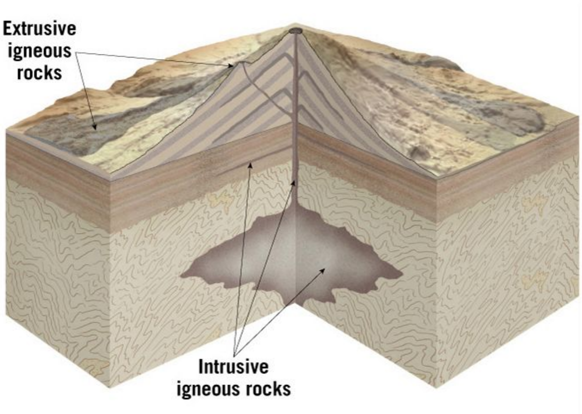
**The study of rocks.**

- **IGNEOUS ROCKS**: Mafic and felsic rocks, intrusive and extrusive
- **METAMORPHIC ROCKS:** Contact metamorphism and regional metamorphism
- **SEDIMENTARY ROCKS:** Detrital and chemical rocks. Geobiological processes. Biosedimentation. Biogenic crystals and biomaterials.

# Lecture 7.1: IGNEOUS ROCKS

These are formed when molten rock solidifies or crystalizes. The crystallization can happen depth. When magma solidifies at depth, we called the igneous rock plutonic or intrusive. We found this rocks at the surface due to uplifting and erosion.
The second type of igneous rock is when magma solidifies on the surface or very near the surface. These are called extrusive rocks or volcanic igneous rocks.
Magma is trapped at depth, lava refers to magma that makes its way to the surface.
Magma is composed by solids, liquids and gases. The liquid portion are the molten minerals. The solids are the crystals formed when magma starts to crystalize (silicate minerals). The volatiles, or dissolved gases, usually are water vapor, carbon dioxide and sulfur dioxide. Magma mostly will be kind of liquid, but it has other components.
As the magma cools down, it will crystalize, so the atoms will arrange and produce these orders/patterns that we call the crystals. There is a certain orders of crystallization in each mineral, associated to each's molten point. The mineral that solidifies the first... Crystal size will be associated to the rate of cooling. If magma cools down quickly, the crystals will be microscopic, and if the magma cools slowly, big crystals will be formed.



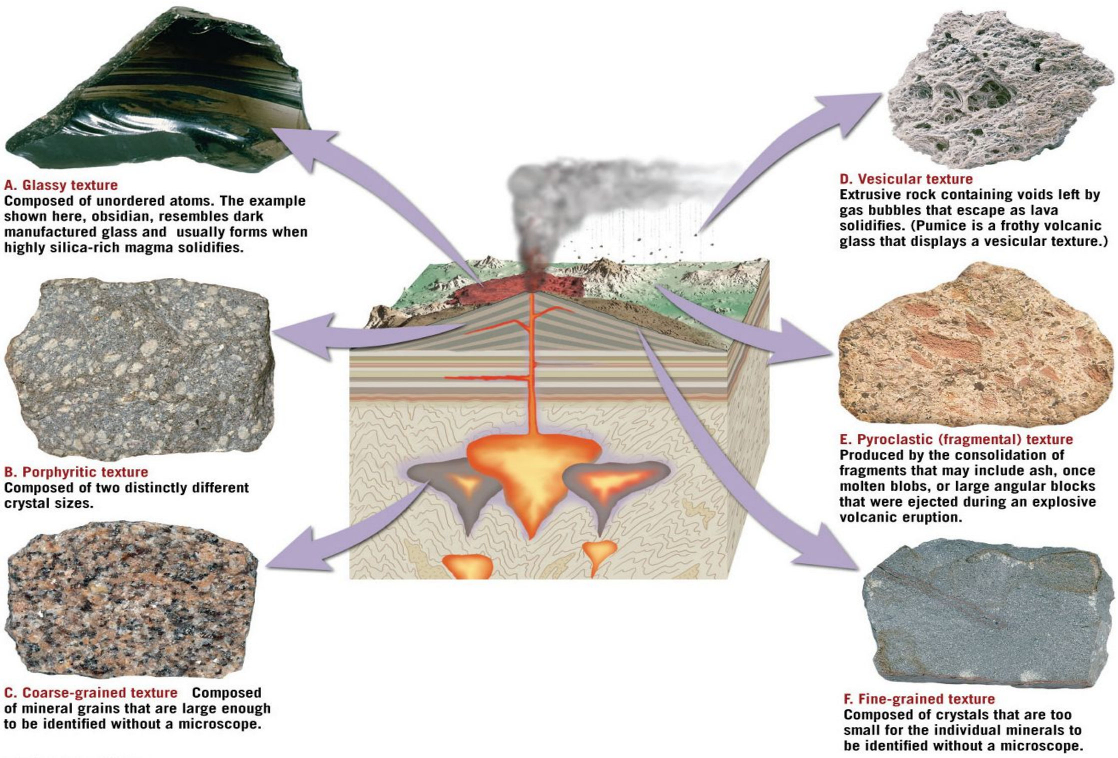




B. When magma crystallizes at depth, intrusive igneous rocks form. When magma solidifies on Earth's surface, extrusive igneous rocks form.

# IGNEOUS TEXTURES

The texture of a rock defines the shape, size and arrangement of the minerals that conform the rock. Depending on these parameters, we can define different textures in igneous rocks. It's defined by the rate of cooling, the amount of gases and the amount of silica.
Magma can also migrate to another location. The magma can also erupt before being solidified. All of these situations influence the texture.

- **Fine-grained texture or aphanitic texture**: when magma solidifies very rapidly. Crystals are very tiny, microscopic. These types of rocks will be formed mainly on the surface or on the upper crust.
- **Coarse-grained texture or phaneritic texture**: when magma cools slowly and large visible crystals are formed. These types of rocks will be formed in depth (more than 10 km).
- **Porphyritic texture**: two crystal sizes can be found: large crystals, also known as phenocrysts and the ground mass, or the fine grain mass surrounding the large crystals. These show than there were two rates of cooling.
- **Vesicular texture**: produced when gas rich lava rapidly cools down. The rock itself has a glassy texture and its presents voids or holes (vesicles), where the gas was located before the rock extruded. (Typical extrusive igneous rocks). They are not very dense, so they float on water.
- **Glassy texture**: the rate of cooling is very rapid, so it doesn't have an order or crystallisations. They are not minerals because they don't have crystalline structure. (Obsidian)
- **Pyroclastic texture**: when there's a explosive eruption, different particle sizes might be ejected, and when they solidify on the floor, these are formed. They look like sedimentary rocks. They can be made of ash. They don't have a arrangement.
- **Pegmatitic texture**: Exceptionally coarse-grained; they are formed in late stages of crystallization of magma. Larger than 1 cm in diameter.



## BOWEN'S REACTION SERIES

Igneous rocks are formed by dark silicates (ferromagnesian) and light silicates. Dark minerals will be formed by iron or magnesium and light minerals will be formed by calcium, sodium, potassium...

The sequence in which minerals crystalised will be responsible for the different rock types. The minerals crystallize in a systematic way, there is a way of crystallization.

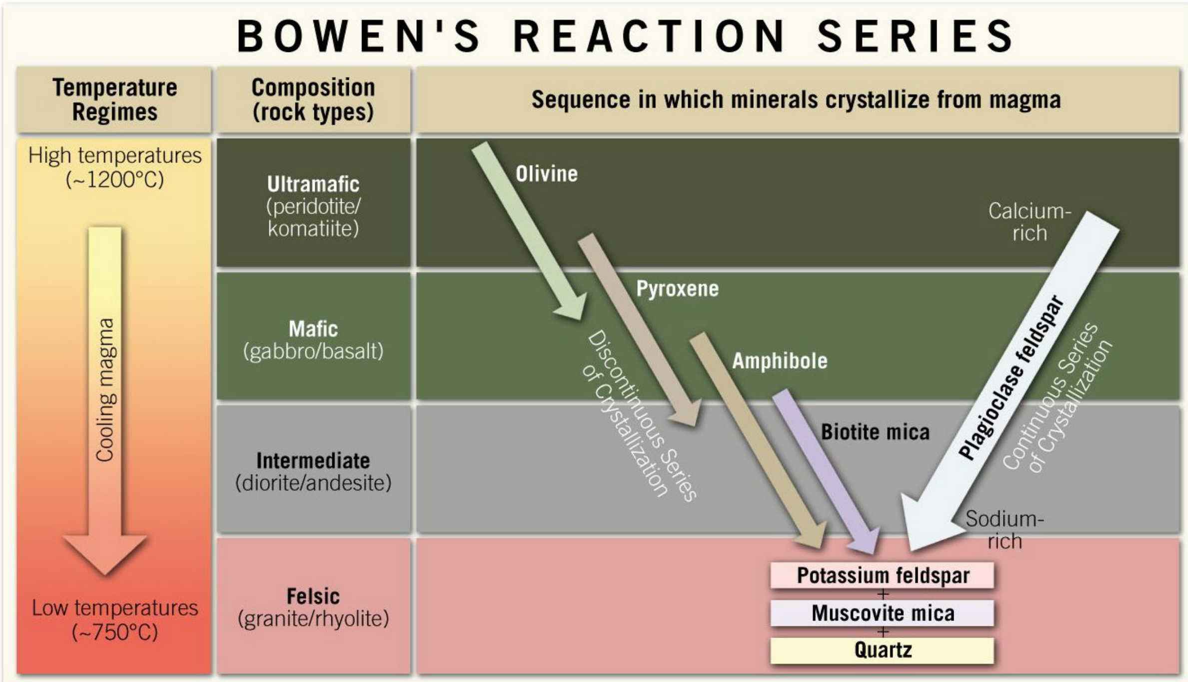
As minerals crystalize, the composition of the remaining magma will change.

Two sequences of crystallization:

- Discontinuous series of crystallization:
  - Ferromagnesian silicates of different internal structure (olivine, pyroxene, amphibole, biotite)
- Continuous series of crystallization
  - Non ferromagnesian minerals
  - Calcium rich plagioclases (anorthite, bytownite, labradotite)
  - Sodium rich plagioclases (andesine, oligoclase, albite)

Both series join to form potassium feldespar, muscovite and quartz.

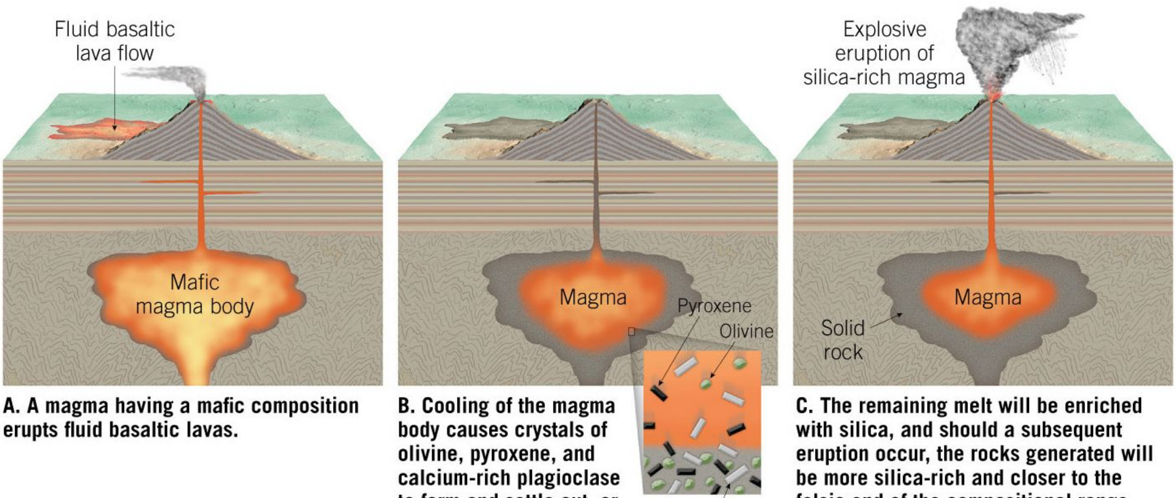
Bowen's reaction series is the sequence in which minerals crystallize to form a mafic magma.




## Magmatic differentiation and crystal settling:

The formation of one or more secondary magmas from a single parent magma.

1. A magma having a mafic composition erupts fluiding basaltic lavas
2. Cooling of the magma body causes crystals of olivine, pyroxene and calcium-rich plagioclase to form and settle out, or crystallize along the magma body's cool margins
3. The remaining melt will be enriched with silica, and should a subsequent eruption occur, the rocks generated will be more silica-rich and closer to the felsic end of the compositional range than the initial magma



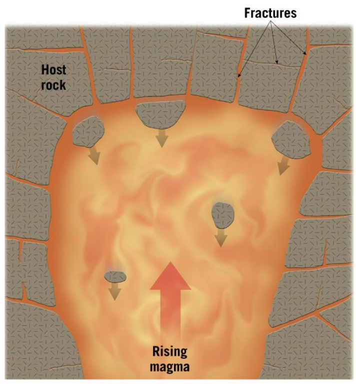

**A. A magma having a mafic composition erupts fluid basaltic lavas.**

**B. Cooling of the magma body causes crystals of olivine, pyroxene, and calcium-rich plagioclase to form and settle out, or crystallize along the magma body's cool margins.**

**C. The remaining melt will be enriched with silica, and should a subsequent eruption occur, the rocks generated will be more silica-rich and closer to the felsic end of the compositional range than the initial magma.**

## Assimilation and magma mixing

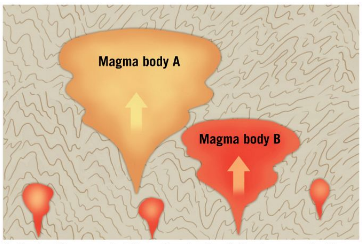
Assimilation: as magma rises, it can incorporate traces of the surrounding rocks. These will melt and alter the original composition of the magma.



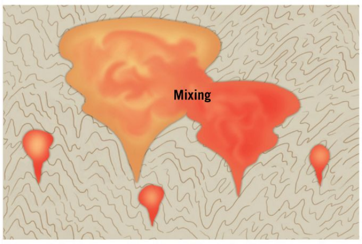

As magma rises through Earth's brittle upper crust, it may dislodge and incorporate the surrounding host rocks. Melting of these blocks, a process called *assimilation*, changes the overall composition of the rising magma body.

Mixing magma:

During the ascent of two chemically distinct magma bodies, the more buoyant mass may overtake the slower rising body. Once joined, convective flow will mix the two magmas, generating a mass that is a blend of the two magmatic bodies.




A. During the ascent of two chemically distinct magma bodies, the more buoyant mass may overtake the slower rising body.




B. Once joined, convective flow will mix the two magmas, generating a mass that is a blend of the two magma bodies.

## Partial melting and magma composition

When a rock is formed, the magma will be closer to its felsic composition.
The granitic magma can be formed by the melting of continental crust.
Incomplete melting of rocks is known as partial melting

- Partial melting of ultramafic rocks yields mafic magmas
- Partial melting of mafic rocks yields intermediate magmas
- Partial melting of intermediate rocks yields felsic magmas

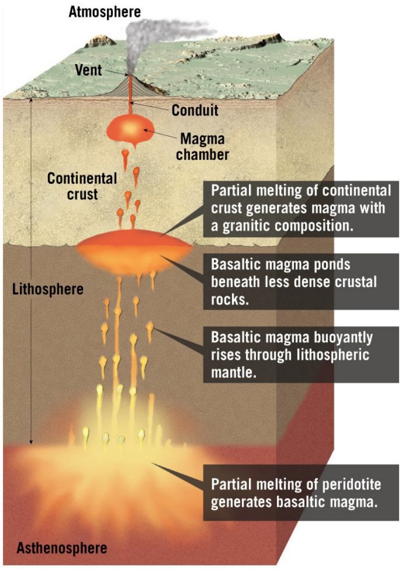
Partial melting generates a magma that is nearer the felsic end of the compositional spectrum than the parent rock from which it was derived.

**Formation of basaltic magmas**

Most magma that erupts is basaltic (mafic) magma. Most originate from partial melting of mantle rocks at oceanic ridges (also at subduction zones, partial melting of the mantle rock above subducting plate). These melts are called primary or primitive magmas because they have not yet evolved. Composed by 45-52% silica.

**Formation of granitic magma**

Granitic magmas are generated by the partial melting of the continental crust. Most from when hot basaltic magma ponds beneath the continental crust, heating and melting overlying crustal rocks (much lower melting temperature felsic minerals and silica rich). Can also be formed from magmatic differentiation of andesitic magma. It is composed by more than 65% of silica.




**Formation of andesitic magma**

Andesitic magma can be produced by the magmatic differentiation of mantle-derived basaltic magma (rising to the continental crust), iron-rich components sink. Can also be formed by basaltic magmas assimilating crustal rocks (silica rich). Partial melting of basaltic rocks. 53-65% silica.

## IGNEOUS COMPOSITIONS

Igneous rocks are divided into two broad groups:

Granitic (felsic) versus basaltic (mafic) compositions

- Granitic or felsic composition
    - Light-colored silicates
    - Composed almost entirely of quartz and potassium feldspar
    - Termed felsic (feldspar and silica) in composition
    - High silica ($SiO_2$) content (70%)
    - Contain about 10% dark minerals (biotite)
- Basaltic or mafic composition
    - Contain at least 45%d dark silicates and calcium-rich feldspar
    - Termed mafic (magnesium + ferrum)
    - Higher density than granitic rocks
    - Comprise the ocean floor and many volcanic islands
    - Silica content 45-52%

Other compositional groups

- <u>Andesitic or intermediate composition</u>
  - Contain 25% or more dark silicate minerals. 52-63% silica.
  - Associated with volcanic activity on the seaward margins of the continents and volcanic island arcs
- <u>Ultramafic composition</u>
  - Rare composition of mostly olivine and pyroxene, composed almost entirely of ferromagnesian minerals. 40% silica.
  - Peridotite is and example and the main constituent of the upper mantle

# <u>IGNEOUS ROCK CLASSIFICATION</u>

Based on texture and mineral composition. Mineralogy is influenced by the chemical composition of the parent magma, texture results by the rate of cooling.

**Igneous Rock Classification**

| Texture | Composition | | | | Interpretations | | |
|---|---|---|---|---|---|---|---|
| | Felsic<br>> 5% quartz<br>K-feldspar > Na-feldspar<br><15% dark minerals | Intermediate<br>< 5% quartz<br>Na-feldspar > K-feldspar<br>15-40% dark minerals | Mafic<br>no quartz<br>no K-feldspar<br>>40% dark minerals | Ultramafic<br>nearly 100% dark minerals | cooling rate | depth of crystallization | other |
| coarse-grained | granite | diorite | gabbro | peridotite | slow | plutonic | - |
| porphyritic | porphyritic rhyolite | porphyritic andesite | porphyritic basalt | n/a | slow/fast | plutonic/volcanic | - |
| fine-grained | rhyolite | andesite | basalt | n/a | fast | volcanic | - |
| glassy | obsidian | obsidian | obsidian | n/a | very fast | volcanic | - |
| vesicular | pumice | pumice | scoria | n/a | fast | volcanic | gas-rich lava |
| pyroclastic | volcanic tuff & breccia | volcanic tuff & breccia | volcanic tuff & breccia | n/a | n/a | volcanic | explosive eruption |

### GRANITIC (FELSIC) IGNEOUS ROCKS

**Granite**

Course grained (phaneritic). Composed by 10-20% quartz, roughly 50% potassium felspar. It has small amounts of (<10%) dark silicates. If it has a porphyritic texture it means that it has feldspar crystals.

**Rhyolite**

Extrusive (fine grained/aphanitic) equivalent of granite. Composed essentially of light-colored silicates. Typically buff to pink or light gray in color. Less common and less voluminous than granite.

**Obsidian**

Dark colored glassy rock. Forms when silica-rich lava cools quickly at Earth's surface. Usually, black to reddish-brown in color. Similar chemical composition to granite. Dark color is the result of small amounts of metallic ions.

**Pumice**

Glassy textured rock with vesicular texture that forms when large amounts of gas escape from the lava. Typically found in deposits with obsidian. Will float on water.

**BASALTIC IGNEOUS ROCKS**
**Gabbro**
Intrusive equivalent of basalt Very dark green to black phaneritic rock. Composed mostly of pyroxene and calcium-rich plagioclase feldspar. Uncommon on the continental crust but makes up a significant portion of the oceanic crust.
**Basalt**
Very dark green to black, fine-grained rocks. Composed mostly of pyroxene and calcium-rich plagioclase feldspar. When porphyritic, contains small light-colored feldspar or olivine phenocrysts. Most common extrusive igneous rock. Upper layers of oceanic crust, Hawaiian islands, and Iceland are composed of basalt.
**Scoria**
Vesicular texture. Darker, denser (sinks in water) and more crystalline than pumice. May contain phenocrysts. Basaltic or andesitic composition.

**INTERMEDIATE ROCKS**
**Diorite**
Intrusive equivalent of andesite. Coarse-grained texture. Looks like gray granite, but lacks visible quartz crystals. Can have a salt and pepper appearance.
**Andesite**
Medium-gray, fine grained rock. Volcanic origin. Commonly exhibits a porphyritic texture.
**Peridotite**
Coarse grained, dark colored, ultramafic igneous rocks. Usually contain olivine as their primary mineral, frequently with other mafic minerals such as pyroxenes and amphiboles.

**PYROCLASTIC ROCKS**
Composed of fragments ejected during a volcanic eruption.
**Tuff**
Most common pyroclastic rock. Composed of ash-sized particles cemented together.
**Welded tuff**
Ash particles are hot enough to fuse together. Can contain walnut-sized pieces of pumice and other rock fragments. Most fragments less than 4mm.
**Volcanic breccia**
Composed mainly of particles larger than ash. Includes broken blocks of vent walls, ash and glass fragments. Fragments more than 4mm.

The terms tuff and volcanic breccia do not imply mineral composition. These are identified with a modifier (eg, rhyolite ruff, ash-size particles of felsic composition).

# Lecture 7.3: SEDIMENTARY ROCKS

Sediments and sedimentary rocks cover approximately 75% of land (surface areas) and virtually all of the ocean basins. However, they only comprise around 5% of Earth's crust (volume).
They form layers, they can be considered pages of a book. They record ancient events and environments. They contain fossils, so we can study the evolution of life by studying sedimentary rocks. They cover basement rocks (igneous and metamorphic).

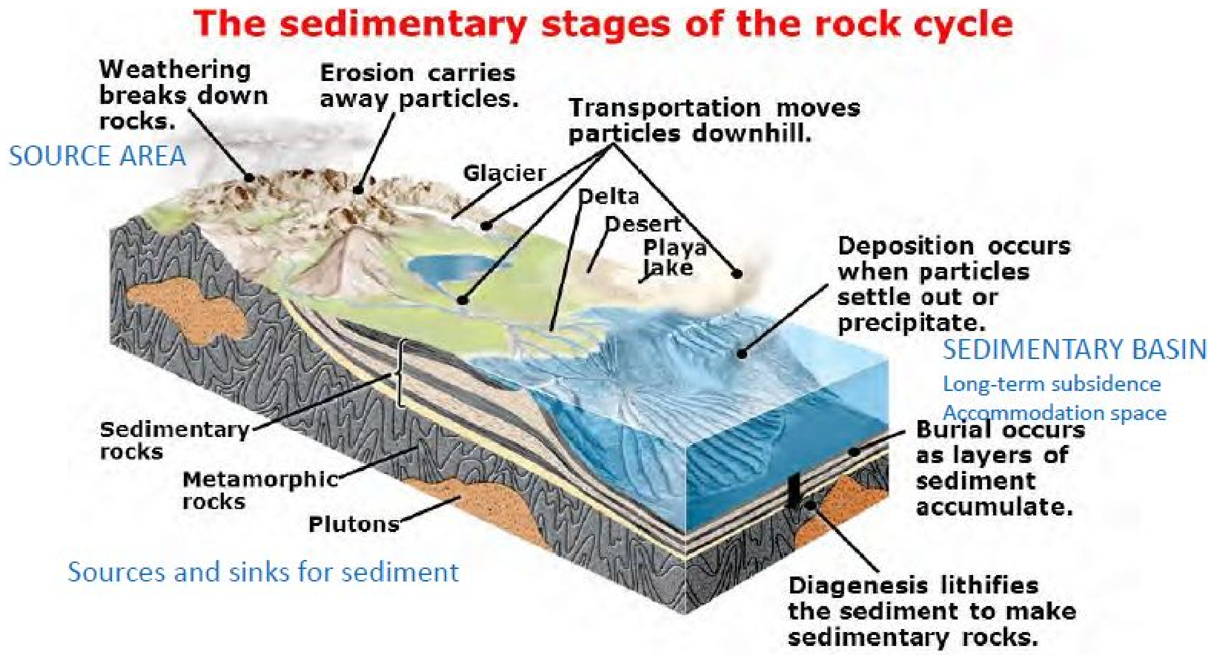
## SEDIMENTARY ENVIRONMENTS

An environment of deposition or a sedimentary environment is a geographic setting where sediment is accumulating.
Three types of environments:

- Marine: shallow and deep
- Continental: glacial, fluvial, eolian
- Transitional (shoreline): beaches, tidal flats, spits, bars, barrier islands, lagoons, deltas

## FROM SEDIMENT TO SEDIMENTARY ROCKS

They are made of pre-existing rocks of igneous, metamorphic or sedimentary origin. These sediments are made by weathering (particles or dissolved ions)
Source area: Weathering → transportation to the sedimentary region → sedimentation



## WEATHERING

**Weathering** is the transformation of solid rock into smaller fragments (clastic particles) or dissolved ions by physical, chemical or biological weathering. Weathering involves no moving agent of transport.

**Physical weathering**

It's the breaking of the solid rock into pieces and the separation of the different minerals. There are no chemical reactions, so there's not mineral alteration. Detrital particles are created.

*Stress release*

It's the breaking down of the rock associated to compression. Decompression causes rocks to crack.

*Insolation weathering (termoklastia)*

In areas where day and night temperatures fluctuate highly (in desserts), because of the differential thermal expansion and contraction the rock breaks apart.

*Ice wedging*

Water goes inside the cracks of the rock, and when temperature descends, the water inside the cracks freezes making the crack being widened and the rock break.

*Salt wedging*

Water containing dissolved salt may penetrate into cracks (coastal areas). When water evaporates, salt crystals are formed and the crack will be widened and the rock will break apart.

**Chemical weathering**

Causes the decomposition of rocks due to chemical reactions occurring between the minerals in rocks and the environment (eg. rainwater). No solid particles are formed, only water dissolved ions.

*Solution*

Dissolution of soluble minerals, typical of carbonates and evaporates.

*Hydratation/dehydratation*

Gain or loss of water molecules from a mineral. A new mineral formation is formed. Produces volume changes (physical weathering).

*Hydrolisis*

*Oxidation*

**Biological weathering**

Living organisms can break down the rock. When a tree grows, the roots break the rock. Bacteria, algae and lichens can produce chemicals that can break the rock, and some shells can also break the rock.

## EROSION

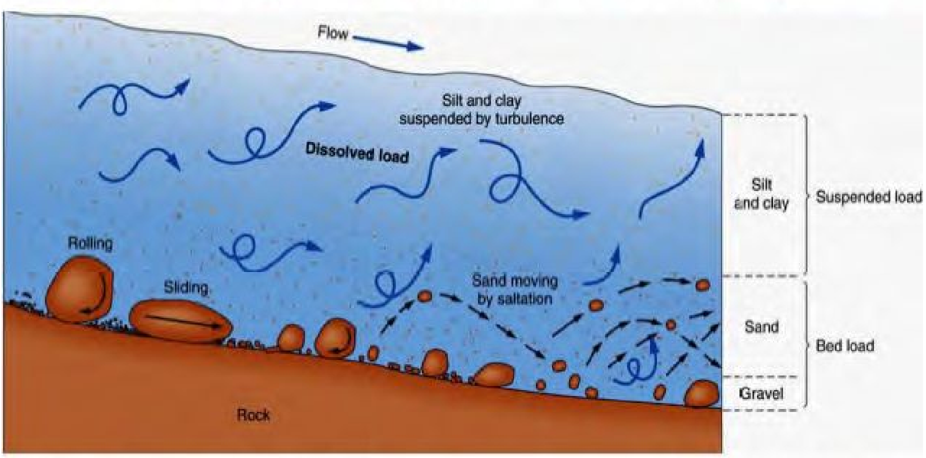
Erosion involves removal of solid material by a transporting agents. The way these solids are eroded is either by gravity or by a moving transport agent (running water, wind, ice).

## TRANSPORT

The transportation of the sediments: gravity (sliding down slopes), wind, running water (streams, rivers or ocean currents), ice.

**Modes of sediment transportation**

Transport refers to the processes by which the sediment is moving along (rolling, sliding, suspended….). It depends on the velocity, the size and weight of the particles and the density of the fluid. The sediments are sorted by density and mineralogy.



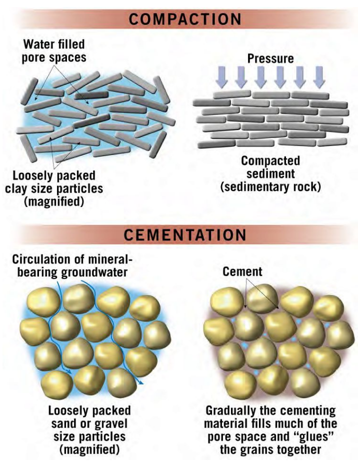

There are three ways in which sediment is transported by rivers, bedload (rolling, sliding, saltation), suspended load (floating), and dissolved load

## DEPOSITION (SEDIMENTATION)

Sediments can be transported as gravel, sand or mud and also as dissolved ions in water. When the energy of the transporting agent becomes too low to continue the transport, the sediments are deposited. These are deposited in a sedimentary environment (land or sea). Dissolved ions can be deposited (precipitated) by organic activity (e.g. sea shells) or by inorganic processes (e.g. evaporation).

## LITHIFICATION (DIAGENESIS)

Once the sediments arrive to the sedimentary region, loose sediments are turned into rock (compaction and cementation).




**Compaction**

Sediments are deeply buried by the weight of the overlying material (pressure). Then, pore space is reduced and water is eliminated. Sometimes, recrystallization happens, making the rock even harder.

**Cementation**

Precipitation of new minerals, (calcite, silica…) that will glue all the sediments together. The spaces filled with water will be occupied with sediment grains that will cement the sediments together After compaction and cementation of the loose sediments, these will be sedimentary rocks.

Lithification takes place below 200°C and 3Kb pressure, below the metamorphic realm.

# SEDIMENTARY ROCKS

**CLASSIFICATION OF SEDIMENTARY ROCKS**

- **Clastic/detrital sedimentary rocks:** produced from rock fragments (e.g. conglomerate)
- **Chemical sedimentary rocks:** produced by precipitation of dissolved ions in water
    - Inorganic precipitation (e.g. evaporites)
    - Organic precipitation: **Biochemical sedimentary rocks**: living organisms extract ions dissolved in water to produce their hard parts (e.g. biochemical limestone)
- **Organic sedimentary rocks:** produced by accumulation of biological debris (e.g. coal)

**Detrital Sedimentary Rocks**

| ClasticTexture (particle size) | Sediment Name | Rock Name |
|---|---|---|
| Coarse (over 2 mm) | Gravel (Rounded particles) | Conglomerate |
| | Gravel (Angular particles) | Breccia |
| Medium (1/16 to 2 mm) | Sand | Sandstone (Arkose)* |
| Fine (1/16 to 1/256 mm) | Mud | Siltstone |
| Very fine (less than 1/256 mm) | Mud | Shale or Mudstone |

*If abundant feldspar is present the rock is called Arkose.

**Chemical and Organic Sedimentary Rocks**

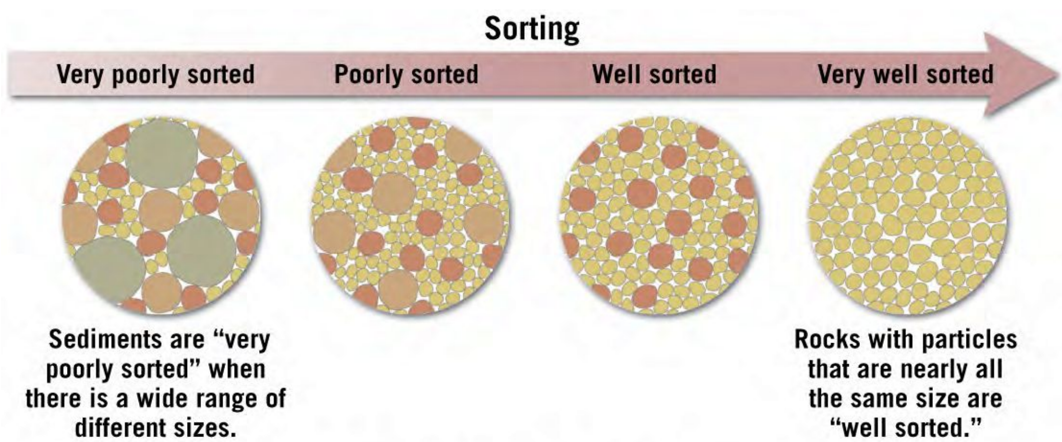
| Composition | Texture | Rock Name | |
|---|---|---|---|
| Calcite, $CaCO_3$ | Nonclastic: Fine to coarse crystalline | Crystalline Limestone | |
| | | Travertine | |
| | Clastic: Visible shells and shell fragments loosely cemented | Coquina | Biochemical Limestone |
| | Clastic: Various size shells and shell fragments cemented with calcite cement | Fossiliferous Limestone | |
| | Clastic: Microscopic shells and clay | Chalk | |
| Quartz, $SiO_2$ | Nonclastic: Very fine crystalline | Chert (light colored) Flint (dark colored) Jasper (red) Agate (banded) | |
| Gypsum $CaSO_4 \cdot 2H_2O$ | Nonclastic: Fine to coarse crystalline | Rock Gypsum | |
| Halite, NaCl | Nonclastic: Fine to coarse crystalline | Rock Salt | |
| Altered plant fragments | Nonclastic: Fine-grained organic matter | Bituminous Coal | |

## CLASTIC SEDIMENTARY ROCKS

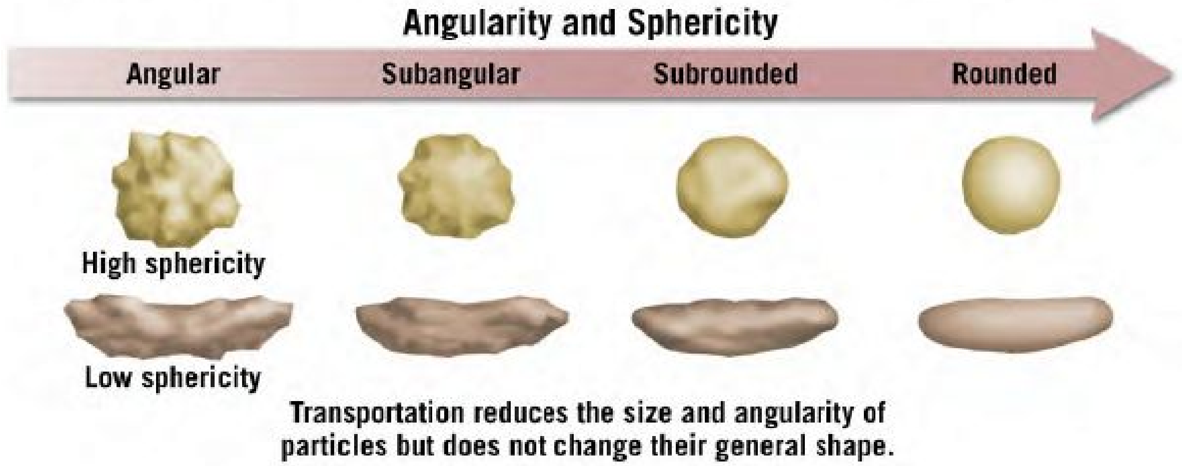
### TEXTURE

**Clasts** (fragments: silt-to gravel-size) and **matrix** (finer-grained material between clasts. There's no absolute size range for the matrix, for example, the matrix of a conglomerate is sand sized and clay sized for a sandstone.

**Sorting** is the degree of uniformity of particle size. If all the grains in a rock are of similar size, the rock is well sorted, and if all the grains in a rock are different sized, the rock is poorly sorted. This depends on the energy of the transporting agent. Very poorly sorted sediments will be closer to its source, and well sorted sediments will be farther from the source.



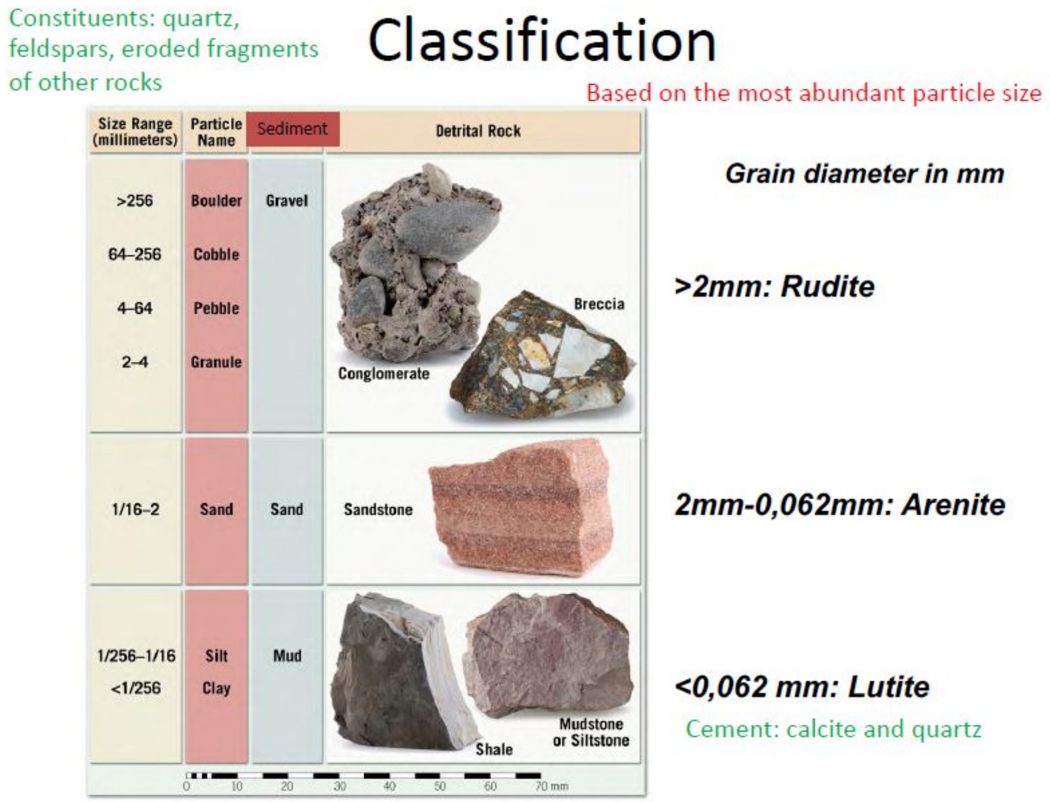
**Roundness and sphericity** is due to the transportation, that produces a reduction of the grain size (abrasion). In the transportation process, rounding off of the sharp corners and edges of grains happen. The degree of rounding is indicative of how far/the amount of time the sediments have been transported. Rounded sediments are typically transported to great distances, and angular sediments are only transported a short distance.




Particle's shape in terms of its
- *angularity* (the degree to which edges and corners are rounded)
- *sphericity* (how close the shape is to a sphere)

**Mineralogical maturity** is the extent to which the unstable minerals have been destroyed by weathering/transport.
**Textural maturity** is the extent to which persistent currents were available (sorting and rounding).

## CLASSIFICATION OF CLASTIC SEDIMENTARY ROCKS



**Rudite**

Contains abundant coarse grained clasts (pebbles, cobbles or boulders, gravel sized).

- In a **conglomerate**, the coarse grained clasts are well rounded. The clasts spent considerable time in the transportation process. These were deposited in a high energy environment (capable of carrying the large clasts.
- In a **breccia**, the coarse grained clasts are very angular. The clasts spent little time in the transportation process.

These are rarely composed entirely of gravel-sized material. Between the granules, there is finer sand and/or mud (matrix).

The proportion of matrix:

- **Clast-supported:** when the matrix is less than 15%, with clasts touching each other **(orthoconglomerate)**
- **Matrix-supported**: when the matrix is more than 15%, most of the clasts are completely surrounded by matrix **(paraconglomerate)**

**Sandstone**

Made of sand-sized particles mainly. They are formed in a variety of environments. They are the second most abundant sedimentary rock. Quartz is the most abundant mineral, but the nomenclature refers only to the size of the particles, some sandstones have no quartz at all.

- **Arenite:** the amount of matrix is less than 15%
- **Wacke:** the amount of matrix is between 15% and 75%
- **Mudstone:** most value of the rock is fine grained matrix (more than 75%)

**Lutite**

The rock contains over 75% of mud (fine-grained matrix).

- **Mudstone:** (silt and clay sized grains), massive/blocky. Similar to shale, but it doesn't break into thin flat layers
- **Siltstone** (silt size fragments)
- **Claystone** (clay sized grains)

They don't split into layers. The fine-grained clasts are deposited in non agitated water.

**Shale**

Fine grained (silt and clay sized particles) sedimentary rock. Distinguished from other mudstones because is fissile (readily splits into thin pieces along the laminations) and laminated (made up of many thin layers).

**CHEMICAL AND BIOCHEMICAL SEDIMENTARY ROCKS**

These are derived from material that was once in solution (dissolved ions). These were carried in streams or groundwater, and then precipitated to form sediment (subaquatic conditions), The precipitation can be inorganic (evaporation of marine water → halite) or organic (secretion by water-dwelling organisms → biochemical). The lithification of these sediments produce rocks.

**CLASSIFICATION OF CHEMICAL AND BIOCHEMICAL SEDIMENTARY ROCKS**

- **Carbonate rocks (limestones and dolostones)**
- Siliceous rocks (diatomites, chert...)
- **Evaporites (rock salt and rock gypsum)**
- Phosphatic rocks
- Iron deposits
- **Organic sedimentary rocks (coal and oil)**

**Carbonate rocks**

Carbonate ions ($CO_3^{2-}$).

<u>Biochemical limestone</u>

From the shells of marine organisms. Calcite is precipitated by organisms that form a shell or other skeletal structure. Accumulation of skeletal remains produces limestones.
Examples:

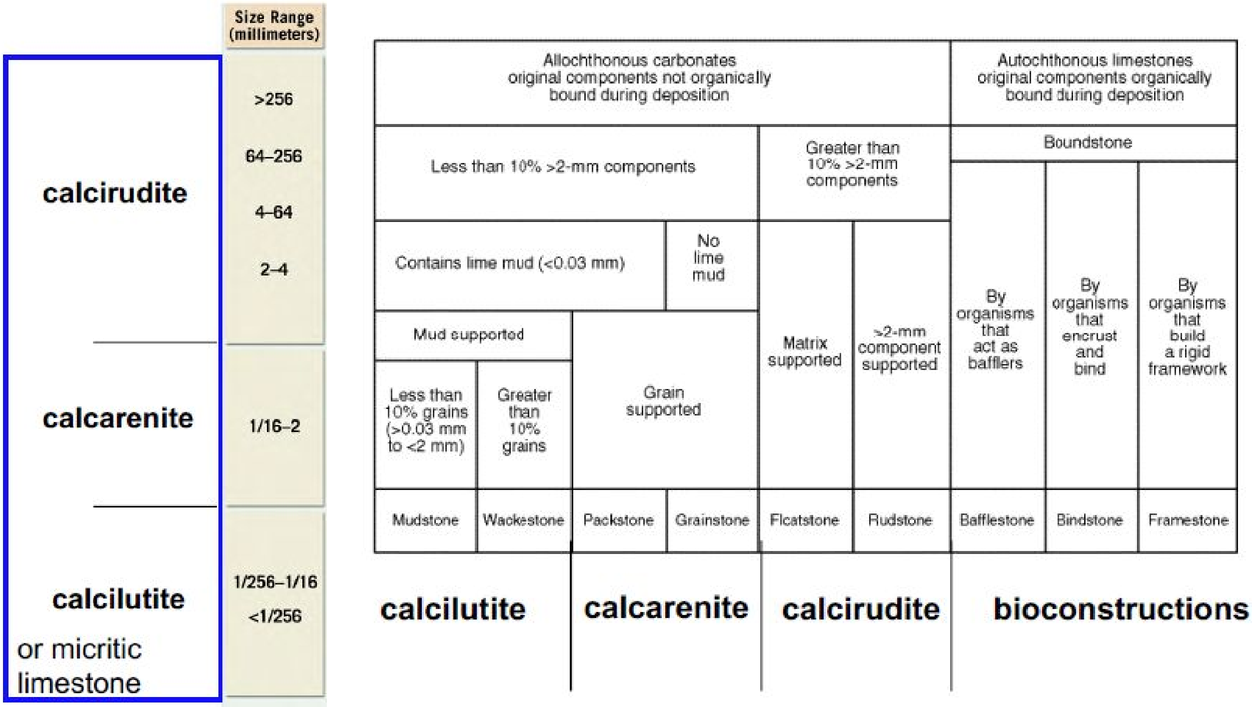
- Reef-building organisms: corals secrete a calcium carbonate skeleton and create reefs
- Coquina is composed of cemented shell fragments
- Chalk is composed of the hard parts of microscopic marine organisms

The accumulation and subsequent lithification of skeletal remains, shells and particles of calcium carbonate (calcite and aragonite). The remains may be small (e.g. shells of planktonic foraminifera, coccolithophorids, crystals from calcified algae) or large (e.g. bivalve shells, gastropods, echinoderms, cnidarians). The skeletal remains can remain in situ and forming bioconstructed limestones (gregarious organisms) or be reworked and transported forming detrital limestones (calcarenite and coquina). Bioconstructed limestones show variable internal structures, depending on the types of organisms involved (e.g. corals, travertines, stromatolites). Very fine carbonate sediment accumulations produce micritic limestones, with or without fossil remains (large or small).

Biochemical limestone can be formed by different components:

- **Ooids**: spherical sand-sized particles that have a concentric or radial internal structure. Inorganic precipitation around and existing grain of quartz (carbonate particles). Limestones produced entirely by ooids are known as oolitic limestones.
- **Micrite** or carbonate mud (less than 4 micrometres)
- **Sparite** or carbonate cement: precipitates from interstitial fluids or forms by recyrstallization of previous components of the carbonated rock (diagenesis). → the cement
- **Bioclasts**: e.g. shell parts
- **Oncoids/rodolites**

Carbonate rocks can be classified according to the size of most particles (= detrital rocks) or according to the depositional texture




<u>Dolostone</u>

Similar to limestone but contains magnesium. It's limestone that have been chemically modified by magnesium rich fluids flowing through the rocks and have converted to dolostones. Calcium carbonate is recrystallized to form a new mineral, dolomite ($CaMg(CO_3)_2$). The original texture cannot be recognized.

**Evaporites**

Sedimentary rocks formed from the progressive evaporation of saline solutions in marine or lacrustine environments. Produces halite (salt) and gypsum deposits.

**Coal**

Organic sedimentary rock made from organic carbon. Produced by the accumulation of the remains of plants. Often produced in tropical environments, where lush vegetation are. They need anoxygenic conditions so the organic debris doesn't oxide. Then compaction happens.

Peat > Lignite > Bituminous > Anthracite

Related to the compaction.

Peat: only the accumulation of organic debris, not a rock. Anthracite enters the metamorphic regions, so it's not technically a sedimentary rock.

# SEDIMENTARY STRUCTURES

Macroscopic features of sedimentary rocks. Processes that ocurred during or slightly after deposition (before lithification, when it was a sediment). Sometimes they might be preserved in the sedimentary bed or in the bedding planes.

**Stratification (bedding)**

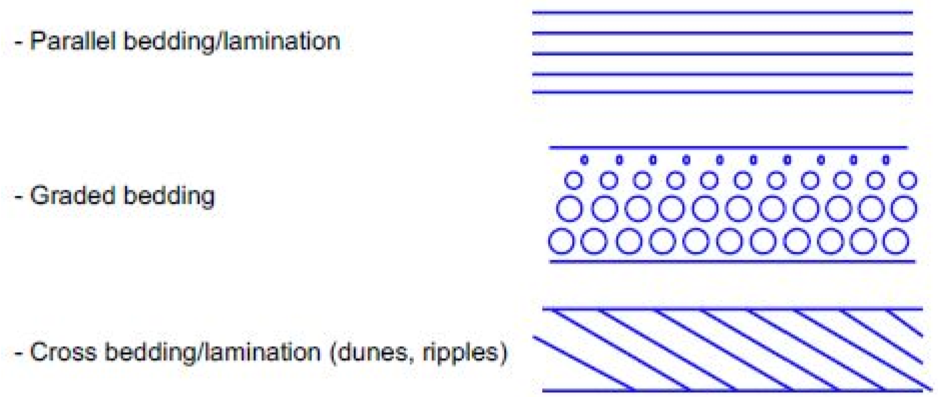
Main structure is bedding or stratification. Sedimentary layers are deposited in low lying areas, different sedimentary events produce different sedimentary layers. Each of the layers are called strata or beds. They can be many meters down to fine millimeter-size laminations. Bedding planes separate stratas. Can be associated to periods of erosion, nondeposition or changes in the depositional conditions.

Different strata can be distinguished in the grain size, different composition, different colour, differential weathering (associated to the composition). Differential weathering is a very easy characteristic that can be distinguished in the field, gives a quick answer of the bedding of a sequence.

Beds are strata thicker than 1 cm, and lamina are layers less than 1 cm thick. (Bedding/lamination according to the thickness of the sedimentary layers).

*Clasting sedimentary rocks → depositional structures*

Clastic sediments are eroded, transported and deposited by water and wind (currents). As a result several sedimentary structures are created. They give us information of the velocity, energy and direction of the currents.




<u>Parallel bedding and lamination</u>

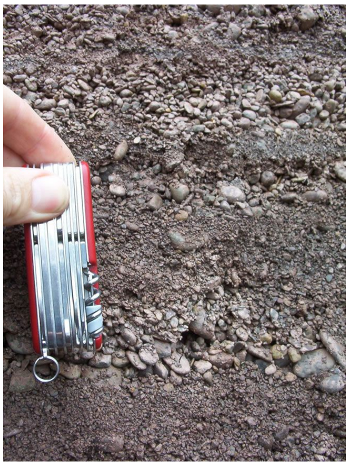
Separated by variations in color, composition and grain size. Bedding plane surfaces are parallel to the bedding. Created by the deposition from high flow velocity currents (swash zone → waves of a beach). It can also be created by the settling from standing body of water with very low flow velocity (pelagic sediments, oceanic basin) and lakes.

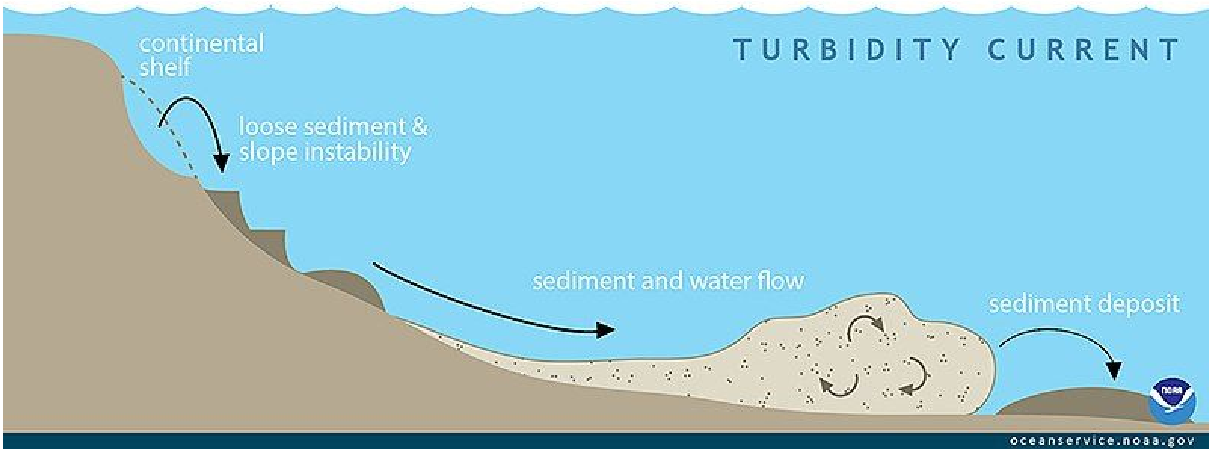
In lakes there is a seasonal change in deposition (coarse sediments during summer, fine grained during water.

<u>Gradded bedding</u>

Vertical gradations in grain size. For example, gradual decrease in sediment size from bottom to top of the bd. Velocity of the current decreases. Associated with submarine currents known as turbidity currents (water + sediments). Underwater flows of sediment and water have greater density than sediment-free water. A turbidity current flows downslope until it reaches the relatively flat seafloor. Normally triggered by movements, like earthquakes.

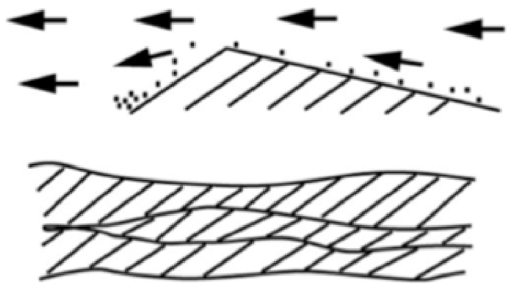
Beds deposited by turbidity currents are called turbidites. Each event produces a single bed. Decrease in sediment size from bottom to top.






<u>Cross bedding</u>

The beds are inclined at an angle to the main bedding. Incline beds give us information about the flow direction at the time of deposition. They can be found in sand dunes, dunes, beach deposits... Can be associated to wind or water currents. Sediments are moved from the stoss side to the lee side. The direction the beds are dipping indicates paleocurrent (Wind or wind direction).



**Ripple marks**

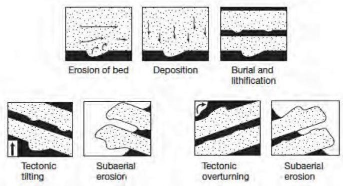
Formed as a consequence of water flowing over loose sediment.

Ripples: produced by finer grained sediments (silt to sand). Length 5 to 20 cm

Dunes can have ripples superimposed (gañin).

**Flute marks**

Sole marks (bedding-plane markings, erosional structures). Throughs eroded in soft sediment by unidirectional flows. They are filled with sand (flute casts in sand → turbidites). Often preserved in turbidites.




**Mudcracks**

Polygonal cracks created when muddy sediments dry out: they shrink and create cracks. In a rock, exposed at the earth's surface and rapidly buried.

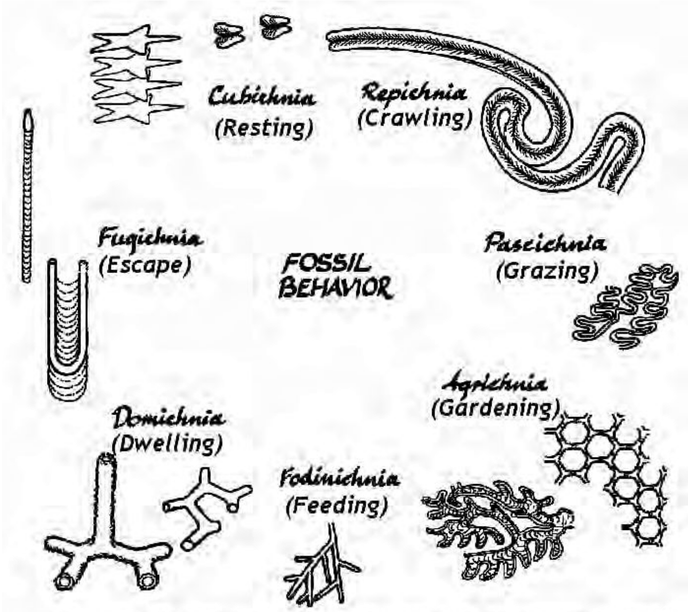
**Raindrop marks**

Tiny craters (slightly raised edges) created by falling rain (soft sediment surfaces).

**BIOGENIC SEDIMENTARY STRUCTURES**

**Bedding-plane markings** (on bedding surfaces or within beds).

Often produced by invertebrates (organisms that don't have hard parts, for example, worms).




Modified From Ekdale, Bromley & Pemberton, 1984

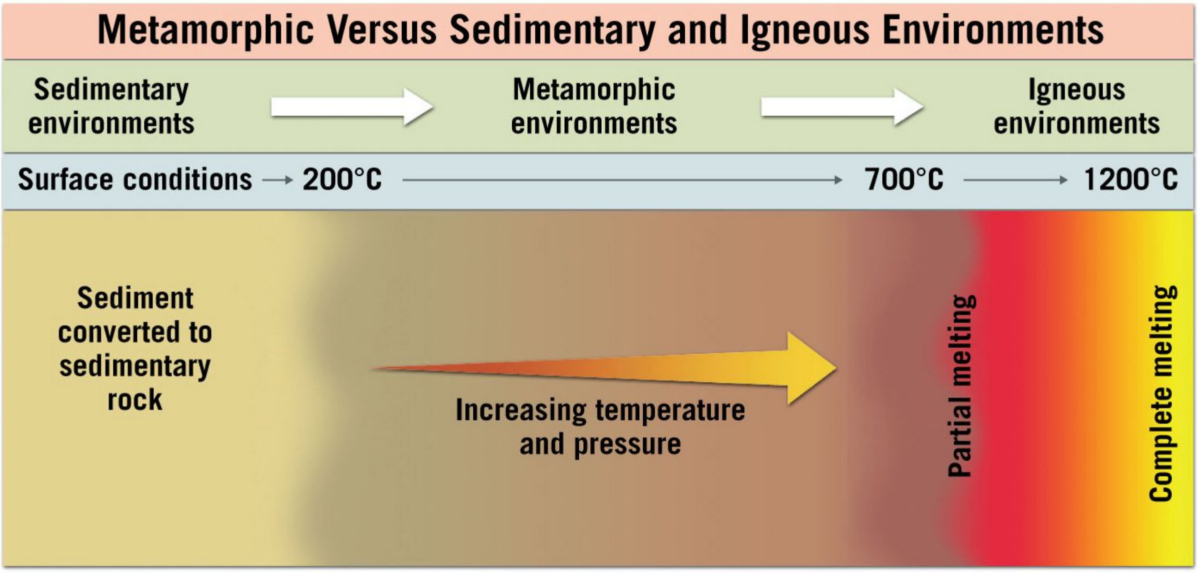
# Lecture 7.2: METAMORPHIC ROCKS

Metamorphism means to "change form":

- Changes in mineralogy and texture (chemical composition)
- During metamorphism, the rock must remain essentially solid
- Takes place where pre existing rock is subjected to temperatures and pressures unlike those in which it formed (higher than 3 kbar and 200°C)
- They are produced from preexisting rocks: igneous, sedimentary or other metamorphic rocks

## METAMORPHIC GRADE

Is the degree to which the parent rock changes during metamorphism. Progresses from low grade (low temperatures and pressures) to high grade (high temperatures and pressures).




The grade can be shown in the mineralogy or texture of the rock.
Low grade, for example, shale becomes slate. (Eskistoa → arbela)
High grade, for example, obliterate the original texture and often change the mineralogy of the parent rock, identity parent. (For example, creation of folds).

## METAMORPHIC AGENTS

<u>*Heat*</u>

Sources of heat:

- Geothermal gradient: an increase in temperature with depth
- Heat released when a magma body cools

Provides the energy needed for chemical reactions (atoms vibrate more rapidly, migrate, crystalline structure). Recrystallization is the process of forming new, stable minerals larger than the original.
Mineralogy may or may not change:

- Quartz sandstone → Quartzite
- Shale → slate
    - Mineralogy changes (Atoms rearranged into new crystalline structures)
    - Overall chemical composition remains unchanged

*Pressure*

Confining pressure from burial and differential stress.

**Confining pressure from burial** (happens in sediment compaction). Forces are applied equally in all directions (greater than in sedimentary rocks). Convert mineral matter into denser forms, more compact crystalline structures. Causes the spaces between to close, creating new denser minerals.

**Differential stress** (directed pressure) occurs during mountain building. Forces are unequal in different directions. Stresses are greater in one directions. Rocks are squeezed, and shortened in one direction (maximum stress) and elongated in the other direction (minimum stress).

*Chemically active fluids*

Mainly water and other volatiles.

Water becomes a hot ion-rich fluid (expelled from a magma body as it cools): hydrothermal solution. Enhances migration of ions (exchange of ions between fluids and host rocks). Aids in recrystallization of existing minerals: can change overall chemical composition (new atoms): metasomatism. Eg, calcite into wollastonite: silica rich hydrothermal solution invades limestone and carbon dioxide escapes. In some environments, fluids can transport mineral matter over considerable distances.

# METAMORPHIC TEXTURES

Texture describes the size, shape and arrangement of mineral grains. Metamorphic rocks can display preferred orientation of minerals, where the platy/elongated mineral grains exhibit parallel to sub-parallel alignment (preferred orientation).

Foliation describes any planar arrangement of mineral grains or structural features within a rock. In strongly deformed metamorphic rocks (folding, compressional stress):

*Examples of foliation*

- Parallel alignment of platy (micas) and/or elongated (amphiboles) minerals (rotation)
- Recrystallization (new mineral grains, recrystallize perpendicular to the direction of maximum stress)
- Parallel alignment of flattened mineral grains or pebbles
- Compositional banding of dark and light minerals (layered appearance)
- Cleavage where rocks can be easily split into tabular slabs

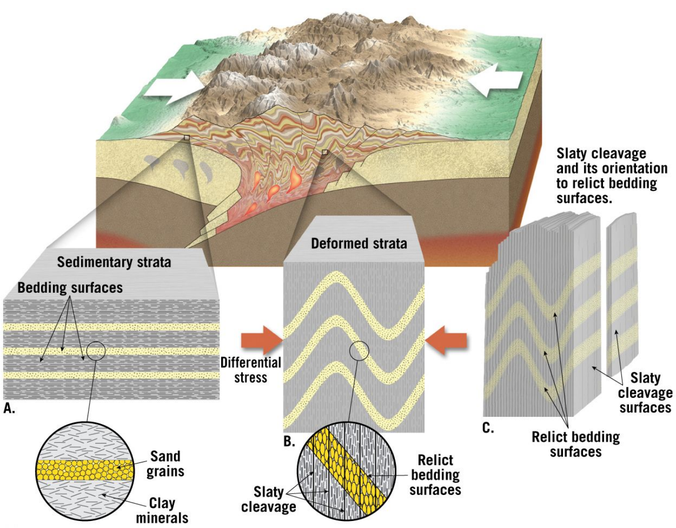
**FOLIATED TEXTURES**

*Rock or Slaty cleavage*

Rocks split into thin slabs. Develops in beds of shale (lutita) with low-grade metamorphism.

*Schistosity*

Platy minerals are discernible with the unaided eye. Mica and chlorite flakes begin to recrystallize into larger muscovite and biotite crystals. Minerals exhibit a planar or layered structure (Schistosity). Rocks having this texture are referred to as schist.



Gneissic texture
During high-grade metamorphism, ion migration results in segregation of minerals into light (quartz and feldspar crystals) and dark (amphibole and biotite) bands. Metamorphic rocks with this texture are called gneiss. Although foliates, gneisses do not split as easily as slates and some schists.

Nonfoliated texture
Nonfoliated metamorphic rocks are composed of minerals that exhibit equidimensional crystals and lack foliation (eg, quartz, calcite). Resembles a coarse-grained igneous rock.

Porphyroblastic texture
Unusually large grains, called porphyroblasts are surrounded by a fine-grained matrix of other minerals.

## METAMORPHIC ENVIRONMENTS

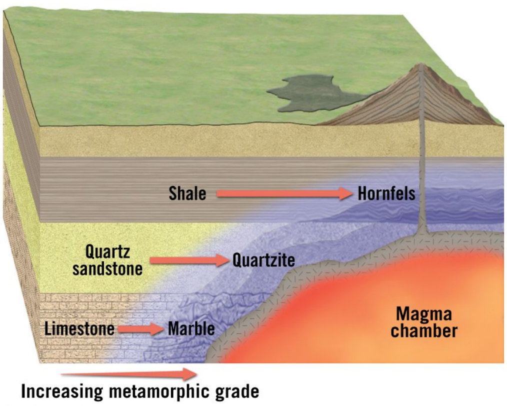
Metamorphism occurs in a variety of environments.

- In the vicinity of plate margins
- Associated with igneous activities

Contact or thermal metamorphism and regional metamorphism. More examples like hydrothermal, burial, subduction zone, fault zones and impact metamorphism.

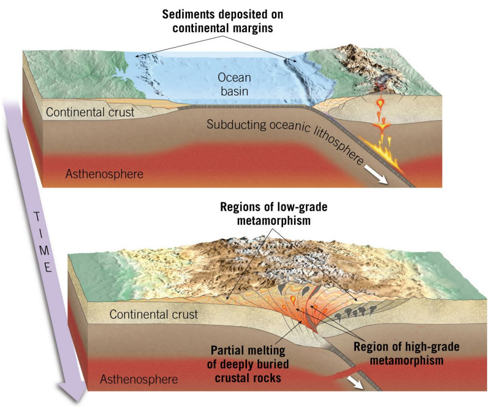
***Contact or thermal metamorphism***

Occurs near a body of magma (intrusive igneous body). There is not directional stress, so there are not foliated textures. It results from a rise in temperature when magma invades a host rock. Occurs in the upper crust (low pressure, high temperature). The zone of alteration (aureole) forms in the rock immediately surrounding the magma (few meters, severa kilometers). Aureoles consist of distinct zones of metamorphism.
*Roof pendant*: the rock was once the roof of a magma chamber.




***Regional metamorphism***

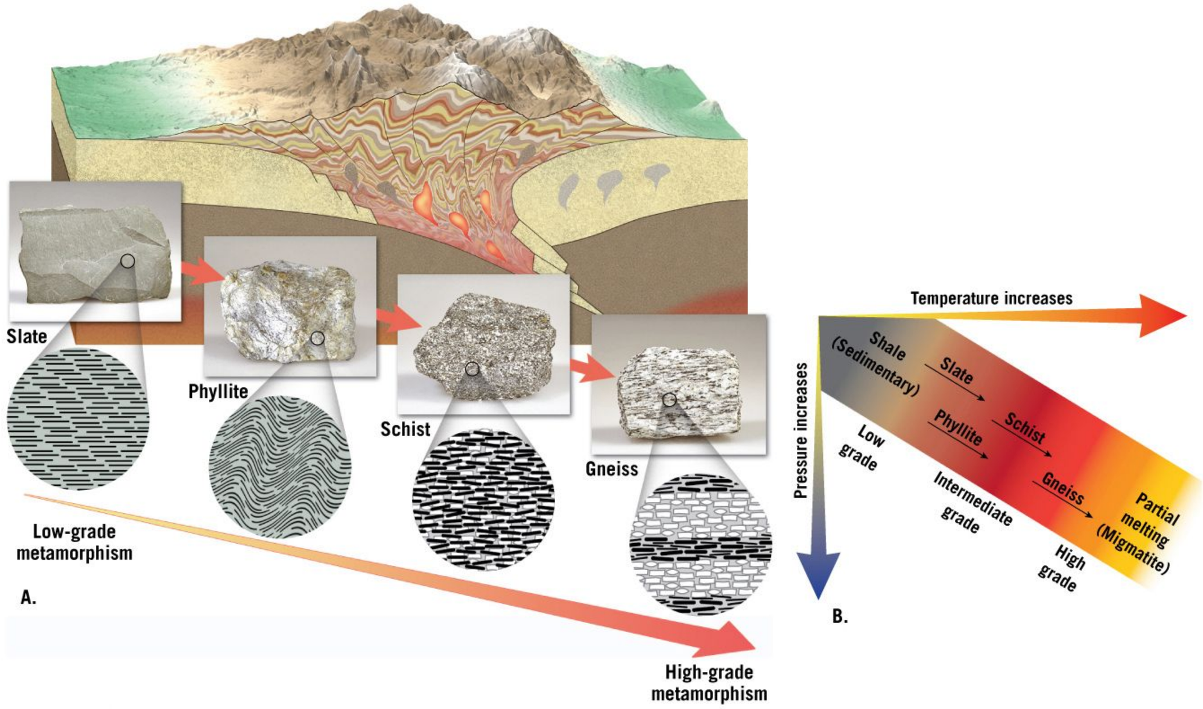
The most common, widespread type of metamorphism. It produces the greatest quantity of metamorphic rocks. Associated with mountain building. Directed pressures and high temperatures during mountain building, the collision of continental blocs. Crust is shortened, thickened, folded and faulted.  Usually, in these regions of mountain building we might find igneous and metamorphic rocks. Because the temperature is so high, rock melting happens and igneous rocks appear.



<u>Textural variations caused by regional metamorphism</u>

In areas where regional metamorphism has occurred, rock texture varies based on intensity of metamorphism:

- Slate is associated with low grade metamorphism
- Phyllite and schists are intermediate
- Gneiss is associated with high grade metamorphism

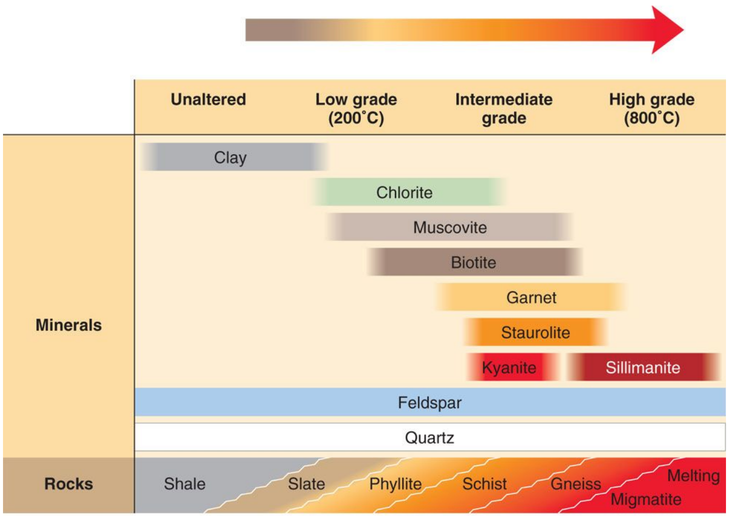



**FOLIATED TEXTURE ONLY ASSOCIATED WITH REGIONAL METAMORPHISM AND MOUNTAIN BUILDING (Compressional forces and modification of the crust).**

# <u>METAMORPHIC ZONES</u>

Index minerals and metamorphic grade:

- Changes in mineralogy occur from regions of low-grade metamorphism to regions of high-grade metamorphism
- Index minerals are good indicators or metamorphic grades, and thus zones of metamorphism
- Migmatites are rocks that have been partially melted. They represent the highest grades of metamorphism. They are transitional to igneous rocks.




Light-colored (felsic) minerals in (gneiss), melt
Dark-colored (mafic) minerals remain solid
Melt solidifies, migmatite (igneous+metamorphic rock)

# METAMORPHIC ROCKS

## FOLIATED ROCKS

### Slate

Very fine grained, resembles shale (too small to be visible to the human eye). Most often generated from low-grade metamorphism of shale, mudstone or siltstone. Exhibits rock cleavage, breaks into slabs.

### Phyllite

Degree of metamorphism between slate and schist. Platy minerals are larger than slate but not large enough to see with the unaided eye. Glossy sheen and wavy surfaces. Exhibits rock cleavage.

### Schist

Medium to coarse-grained. Platy minerals (mainly micas) predominate (Can also contain porphyroblasts). Strongly foliated (parallel alignment of minerals). Parent rock is shale that has undergone medium- to high-grade metamorphism. The term schist describes the texture, so there are different types based on its composition (mica schists, composed of muscovite and biotite).

### Gneiss

Medium-to coarse-grained metamorphic rock with a banded appearance. They are the result of high-grade metamorphism. Composed of light-colored, feldspar-rich layers with bands of dark ferromagnesian minerals. Strong segregation of silicate minerals, so they have a banded texture.

## NONFOLIATED ROCKS

### Marble

Crystalline rock from limestone or dolostone parent. Large, interlocking calcite crystals (main mineral). Impurities in the parent rocks provide a variety of colors.

### Quartzite

Formed from a parent rock of quartz sandstone (very hard metamorphic rock). Quartz grains are fused together (moderate- to high-grade metamorphism). Sand grains recrystallize and the silica cement that binds them as well.

Pure quartzite is white, but iron oxide may produce reddish or pink stains and dark minerals may produce green or gray stains. Cross-bedding and other sedimentary structures can be preserved in quartzite.

### Hornfels

Fine-grained with variable mineral composition (parent rock). Parents most often are shale or clay-rich rocks. “Baked” by an intruding magma body at shallow depth (contact metamorphism, 700-800°C). Gray to black, hard and often conchoidal fracture.

# Lecture 8: STRATIGRAPHY

**Stratigraphy** is the study of rock layers, vertical sequence and lateral variations.

## PROCESSES AND SEDIMENTARY ENVIRONMENTS

An environment of deposition or a sedimentary environment is a geographic setting where sediment is accumulating. Sites are characterized by particular combinations of geologic processes and environmental conditions.

- Continental environments: dominated by stream erosion and deposition.
- Marine environments:
    - Shallow marine (to about 200m), across the platform. Receives huge quantities of terrestrial sediments. Warm seas with minimal terrestrial sediments have carbonate-rich muds and debris from coral reefs.
    - Deep marine (seaward of continental shelves). Primarily fine sediments that accumulate on the ocean floor. Turbidity currents (submarine landslides) are the exception.
- Transitional environments: the shoreline is the transition zone between marine and continental environments (examples: beaches, tidal flats, deltas, lagoons, spits, bars, barrier islands...

## SEDIMENTARY STRUCTURES

Sedimentary structures are useful as paleocurrent direction indicators. When sedimentary rock successions are found, we assume that the oldest rock are on the bottom and the newest on the top, but sometimes this can be reverted, so these structures are used to know the original succession of layers.

## STRATUM AND STRATIFICATION

The basic unit in stratigraphy is the **stratum** (bed, layer) (pl. Strata). It has certain characteristics that make it distinguishable from the layers above, under and on the sides.
Each strata will have the top, the bottom and the thickness. The thickness must be measured at a right angle to the bending plane.

## THE STRATIGRAPHIC COLUMN

The stratigraphic column is a sequence of layers of different types of rock, deposited over geologic time (representation). Oldest rocks are drawn on the bottom and the youngest ones on the top. Each of the layers are related to a certain depositional event. The thickness of a stratum doesn't always represent the duration of the event. If we find a thicker layer doesn't mean that the depositional event took longer than a thinner layer.
Even though we find continuous sequences in the rock, when they are put in the column a time gap can be found (for example, erosion processes could remove previous layers).

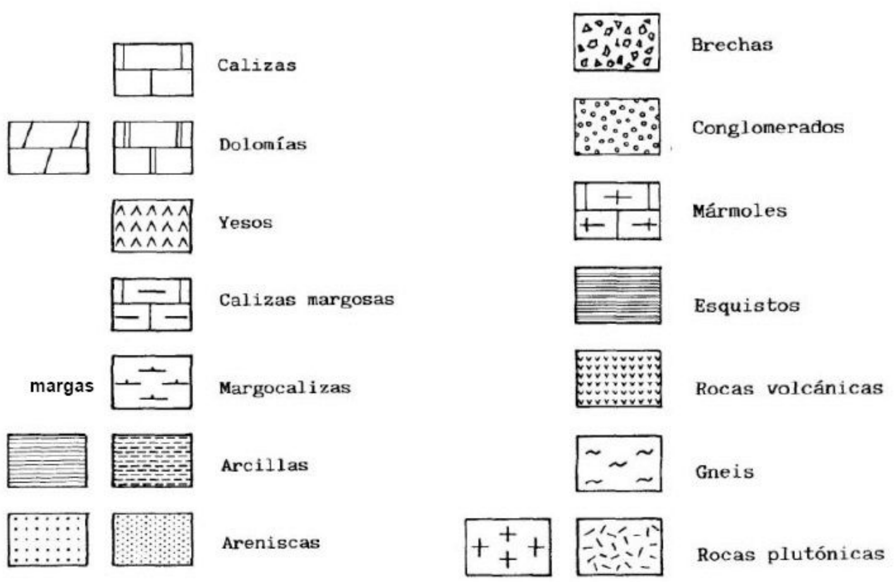
The age of the stratum can be measured with relative dating:

- Principle of superposition (oldest rock on the bottom, youngest on the top). Sometimes the strata can be reverted due to tectonic events.
- Principle of original horizontality: sediments are deposited horizontally. However, due to the action of tectonics folded rocks can be found.

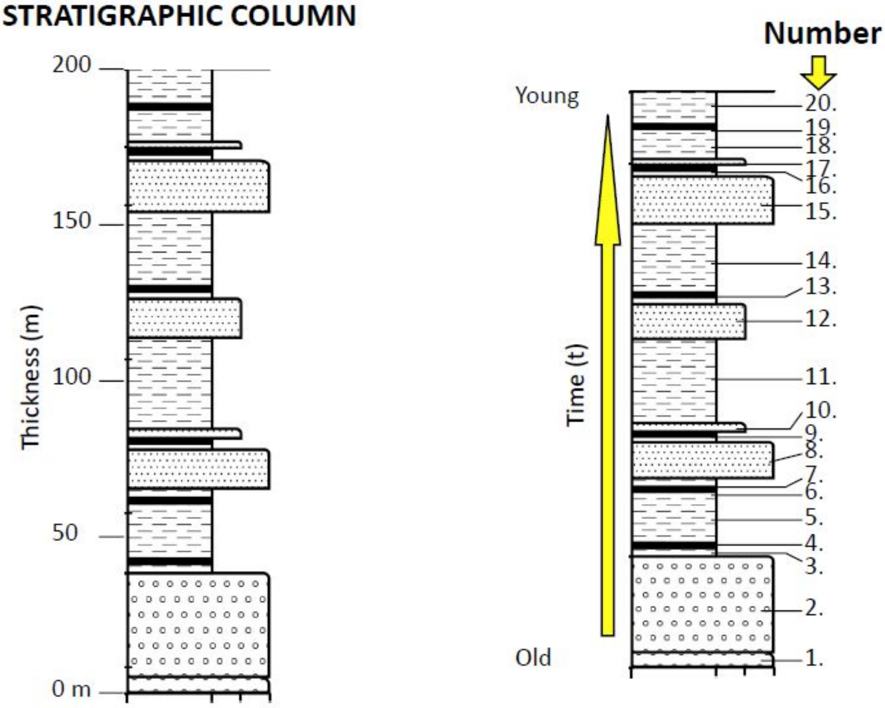
Once the order of deposition has been determined (which ones are younger/older), thickness and lithology (type of sediment/rock) are studied.

Then, the stratigraphic column is drawn with the symbols:

**SÍMBOLOS DE LITOLOGÍAS DE USO COMÚN**




**STRATIGRAPHIC COLUMN**



# STRATIGRAPHIC UNITS

Classification of rock bodies based on inherent properties.
Material stratigraphic units:

- Lithostratigraphic units
- Biostratigraphic units
- Chronostratigraphic units

***Lithostratigraphic units***

Units based on the lithologic properties of the rock bodies (Sedimentary, igneous or metamorphic rocks) and their relative stratigraphic positions (or relationship to others which lie above, below, or lateral to it).
Lithologic character is influenced by conditions of formation. This are the basic units of geologic mapping.
Kinds of lithostratigraphic units: (hierarchy)

- Group: two or more formations
- **Formation**: primary unit of lithostratigraphy
- Member: named lithologic subdivision of a formation

**Formation** is a body of material which can be identified by its lithological characteristics (chemical and mineralogical composition, texture, primary sedimentary structures and fossil content) and by its stratigraphic position.

***Biostratigraphic units***

Units based on the fossil content of the rock bodies.
Distinct units. the organisms whose fossil remains define them show evolutionary changes through geologic time. This makes the fossil assemblages of any one age distinctive from any other.
The fundamental unit of the biostratigraphy is the **biozone**. Biozones are units of stratigraphy which are defined by the **fossil taxa** (usually species or subspecies) that they contain. Biozones can group together to form a superzone or subdivide into subzones. They are named from the common taxon (or occasionally taxa) that define the biozone.

***Chronostratigraphic units***

Units based on the time of formation of the rock bodies. Chronostratigraphic units are defined as encompassing all rocks formed within certain time spans of Earth history regardless of their compositions or properties.
Each of these chronostratigraphic unit has its own geochronologic unit.

**Table 3**

**Conventional Hierarchy of Formal Chronostratigraphic and Geochronologic Terms.**

| Chronostratigraphic | Geochronologic |
|---|---|
| Eonothem | Eon |
| Erathem | Era |
| System* | Period* |
| Series* | Epoch* |
| Stage† | Age |
| Substage | Subage or age |

** If additional ranks are needed, the prefixes sub and super may be used with these terms.*
*† Several adjacent stages may be grouped into a superstage (see section 9.C.3).*

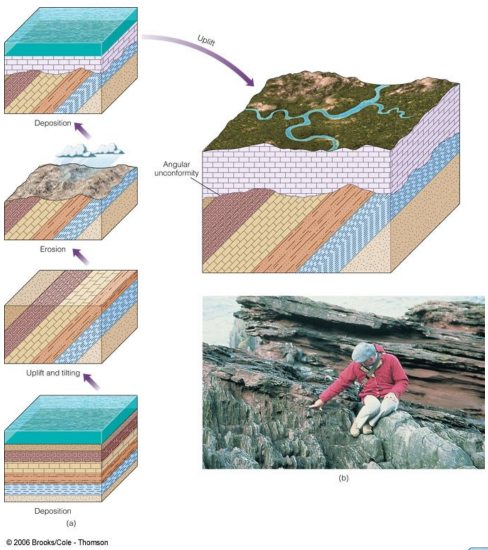
## STRATIGRAPHIC CORRELATIONS

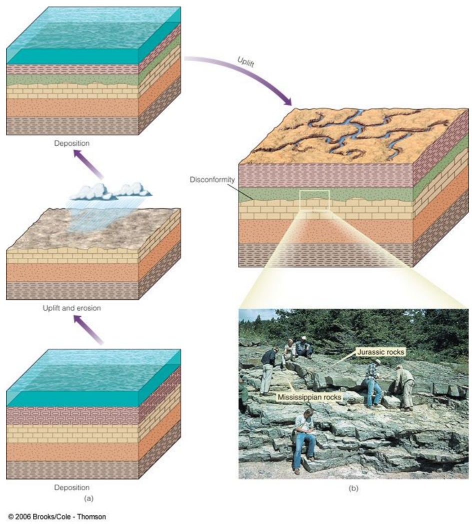
Used to complete stratigraphic columns.
When outcrops are physically near, the principle of lateral continuity (sedimentary beds originate as continuous layers that extend in all direction) can be used to correlate different outcrops. Lithology is used to know that they are the same rock type and then they're correlated.
Key beds are also used to correlate, for example ash deposits. During volcanic eruptions, ashes are scattered over large areas and they sediment in a very rapid time.
Fossils are used to correlate different outcrops too. Fossil organisms succeed one another in a definite and determinable order, and therefore any time period can be recognized by its fossil content. The fossils used are index fossils (geographically widespreads and existed for a short span of geologic time). When index fossils are not available, fossil assemblages are used (overlapping ranges of fossils, a group of fossils typically found together that are used to establish the age of the layer in which they are found).

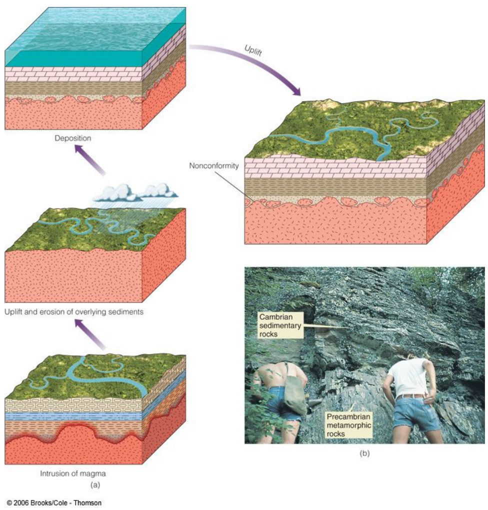
## DISCONTINUITIES

**Discontinuities** are breaks in the rock record.

- Angular unconformity: tilted rocks are overlain by flat-lying rocks
- Disconformity: strata on either side are parallel (erosion)
- Nonconformity:
    - Metamorphic or igneous rocks below
    - Younger sedimentary rocks above
- Paraconformity: strata on either side are parallel (nondeposition)



# 9. SEDIMENTARY BASINS

- Definition, origin and morphology of sedimentary basins
- Mechanism that control the evolution and infilling of the basins
- Vertical and lateral facies evolution
- Depositional sequences

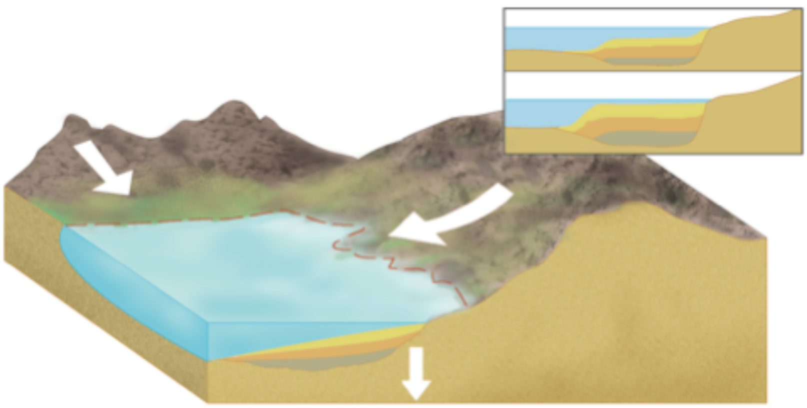
Sedimentary rocks are important because:

- They cover a large part of earth surface (yet the volume is very little). The sediment cover is generally very thin ( 5 percent lithosphere, volume)
- Record paleontological and paleoclimatic, data used to reconstruct the geological history of the earth
- Contain most of the geological resources (oil, gas, coal, water, minerals, rocks…) (80 percent)

Sedimentary basins are places where sediments and sedimentary rocks are depositied. If we go from the smallest scale —> we have the STRATUM (f. e. Sand depositied by a flooding event) sedimentation occurs in a short time scale Then, we have FORMATION (a group of strata that contains the sandstone layer, among many others) Sedimentation is produced by multiple events, in a longer time arrival, finally we have SEDIMENTARY BASIN (Earth's region where the formation containing the sandstone layer that other characteristics were depositied). It represents multiple events and settings that extend over wider areas
LATERAL CONTINUITY: FIRTS LIMITED, THEN KILOMETRIC AND FINALLY PLURIKILOMETRIC

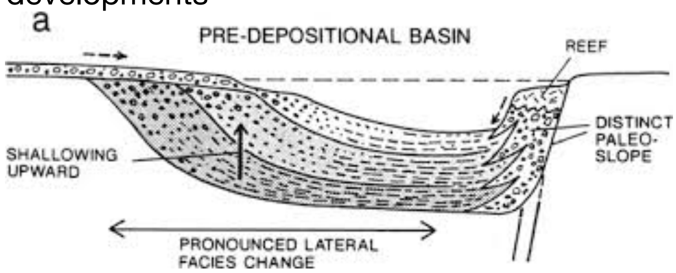
**DEFINITION:**
Sedimentary basins are places where sediments and sedimentary rocks are depositied. A sedimentary basin is a low-lying (continental or oceanic) area of the Earth's crust that has been subjected to progressive sinking (**subsidence**), and where sediemnts from the erosion of the rocks around it (**source area**) accumulate.

*source area: elevated continental regions between basins

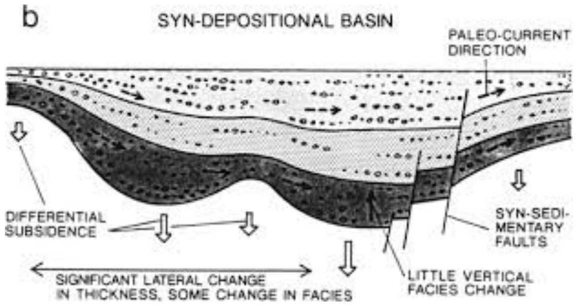


Accumulated layers of sediment on the bottom of the basin

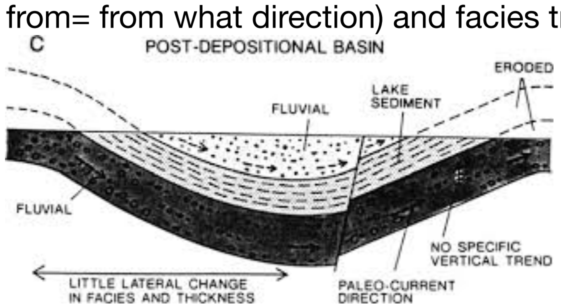
**PRE-DEPOSITIONAL BASIN:**
(any low-lying area where sediments can accumulate)
Etctonic movements (create a morphological basin) predate sediment accumulation
Water depth in the basin decreaxses with time
The basin morphology controls sediment transport as well as vertical and lateral facies developments




**SYN-DEPOSITIONAL BASIN:**
(any low-lying area where sediments can accumulate)
Sediments accumulation is affected by syn-depositional tectonic movements
Tectonic movements control varying thickness of sediments
**Sedimentation occurs at the same time as (subsidence) (?)




**POST-DEPOSITIONAL BASIN:**
The deposition of sediments largely predates tectonic movements forming a basin structute (sheet-like fluvial and lake sediments)
Later, some part get eroded and giving it a shape of a morphological basin
No relationship between paleocurrents(paleocorrientes=where the sedimentary comes from= from what direction) and facies trends, and the basin




We just need to know some things, such as that sedimentary basins can create prior to sedimentation, at the same time, or post

**<u>SOURCE AREA:</u>**

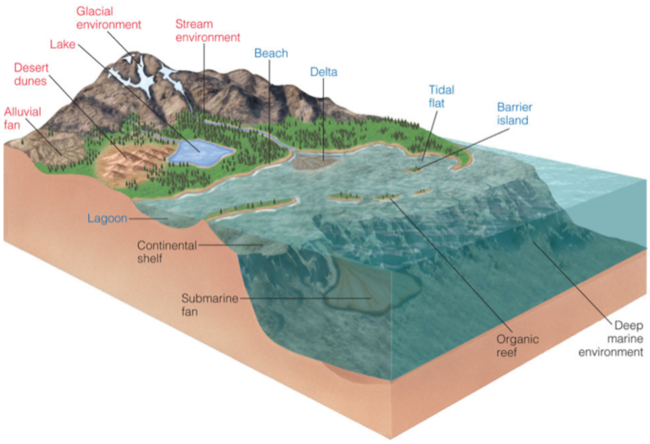
Sediments (sedimentary rocks) accumulate in sedimentary basins, low-lying areas of the Earth's crust (continental or oceanic) that have been **subjected to progressive sinking** (**subsidence**)

Sediment source: elevated continental areas (source area)

**In summary:** sedimentary basin and source areas

Sedimenatry basin: low lying region (depression). Long-term subsidence. Sediment accumulation. Thick sedimentary infill.

source: elevated region. Old rock outcrops. Weathering, erosion, transport. Sediment source




Sedimentary environments:
Continental (red)
Transitional (blue)
Marine (black)

A small part of the sediment is deposited in sedimentary basins located on the continents (rivers, lakes), although the majority are deposited in the ocean basins, from the coastline to the ocean floor



**<u>SOURCES OF SEDIMENT:</u>**

- <u>WEATHERING:</u>

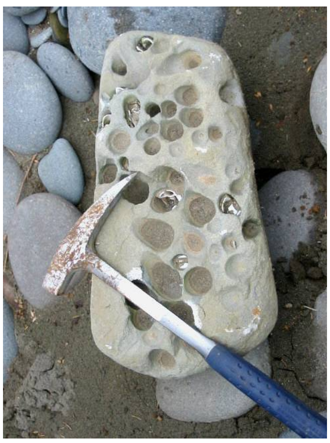
Old rocks in the source area are eroded

Weathering by atmospheric (physical, chemical) and biologicak agents.

**Physical weathering**: produces rock fragmentation, solid particles.

**Chemical weathering:** modifies the chemical composition of the rocks and produces dissolved ions

**Biological weathering:** changes in rocks produced by living organisms. Tree roots, digging in soft sediment(worms, moles, ants), boring into hard substrate (bivalves, echinoderms, sponges..), secreted fluids…



- <u>EROSION AND TRANSPORT:</u>

Weatherig products (solid particles) can stay in place and form a soil.
Transported to low-lying areas (dissolved ions and solid particles), where sedimentation occurs (sedimentary basins: marine & continental (rivers and lakes))
Continental transport agents:

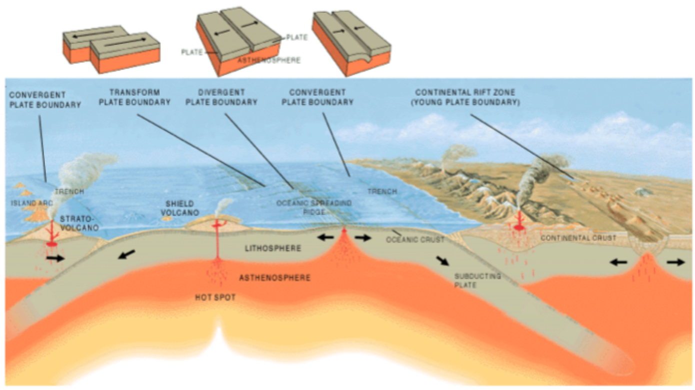
- Rivers (90 percent of solid particles and dissolved ions)
- Glaciers (7 percent)
- Wind (3 percent)

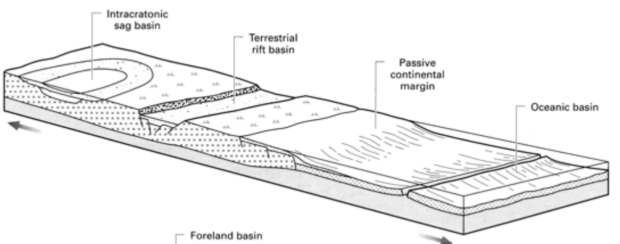
elevation—> physical weathering—> amount of solid particles
Wet and warm climates—> chemical weathering, products mainly dissolved particles

**In summary:**
A sedimentary basin is a low lying area (continental or oceanic) of the earth's crust that has been subjected to progressive sinking (subsidence), and where sediments from the erosion of the rocks around it (source area ) accumulate.
They allow the deposition of thick sedimentary sequences (progressive sinking and sedimentation).
Characteristic: Forms, Dimensions, Thickness of the Sedimentary infill, Location, Tectonically active/inactive (duration).

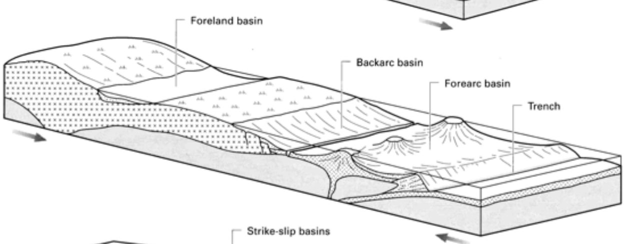
**<u>ORIGIN:</u>**
Most (yet not all) sedimentary basins occur in areas of active plate tectonics
Basins due to extension
Basins due to convergence
Strike-slip basins

Were not gonna study all the types of sedimentary basins

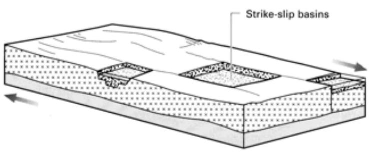



BASINS DUE TO EXTENSION

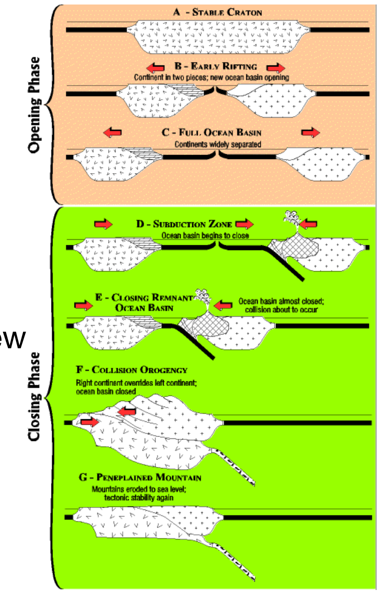



BASINS DUE TO CONVERGENCE




STRIKE-SLIP BASINS

**THE WILSON CYCLE:**



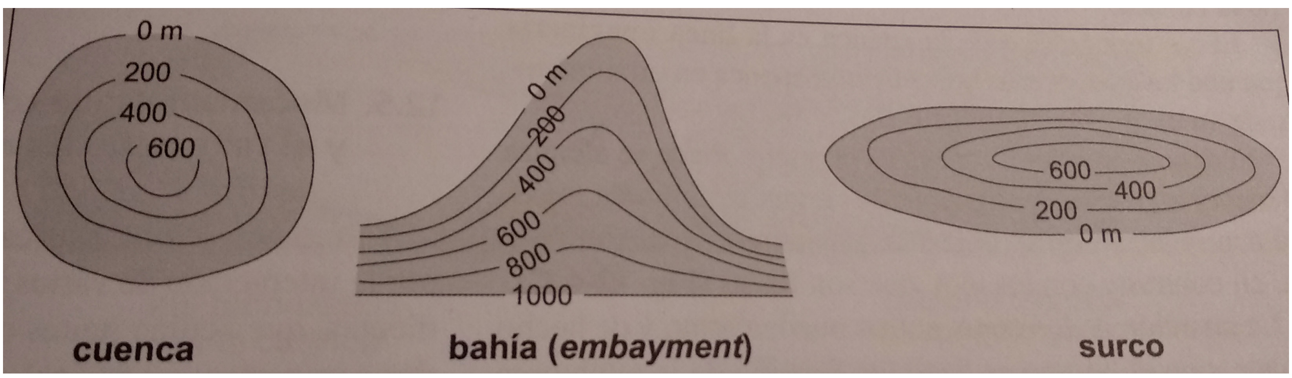

Esentially sedimentary rocks will go through extension and compression.
The opening and closing of an ocean basins (in the context of Plate Tectonics)

Stage A hot (low-density) mantle plume rises up → upwarping (updoming) of the lithosphere→ lithospheric extension and thinning (East African Rift)
Stage B Continental splitting (two continents)→ formation of a new ocean basin, oceanic crust (Red Sea)
Stage C The ocean basin widens (Atlantic Ocean)
Stage D & E New convergent plate boundary→ subduction zone forms→ ocean basing begins to close (Pacific Ocean)
Stage F & G Ocean basin completely closes→ collision of continents→ creation of mountains (orogeny) → erosion (Alps, Himalaya)

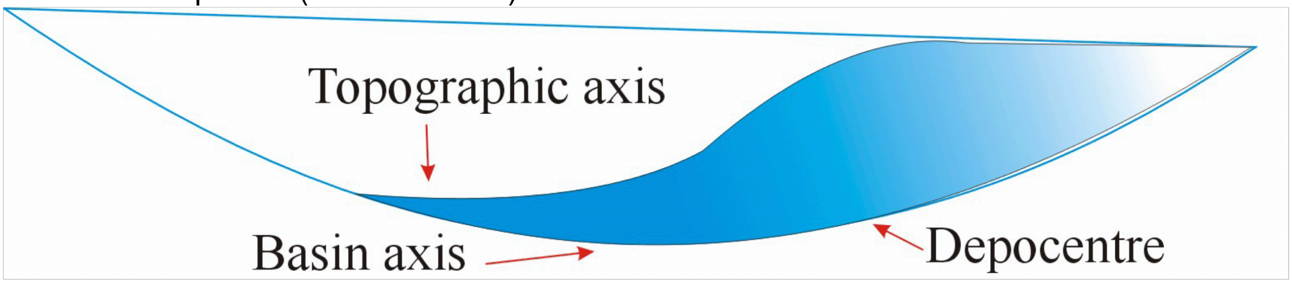
We can distinguish between:
1) Active sedimentary basins, where sediment is being accumulated
2) Inactive and slightly deformed sedimentary basins, which show more or less their original shape and sedimentary infill
3) Inactive and strongly deformed sedimentary basins, with and incomplete sedimentary fill that has been partially lost due to erosion (f.e. in a mountain belt)

WHEN WE DESCRIBE A SEDIMENTARY BASIN:
If it is active it means that sediments are still being accumulated, if its not active, we might see the original shape of the basins but sometimes it has been so altered that we can't distinguish it.

**MORPHOLOGY:**
The shape of the basin is very variable, there are three main types:
- Basin (sensu stricto): subcircular in plan and structurally closed. Bowl shaped.
- Enbayment: areas which are not completely closed structurally. They open out into a deeper area.
- Trough: linear basins, structurally closed and elongated.



The sedimenary infill is almost never homogeneous or uniform
The depocenter's location changes as time goes by. It is the area that has the thickest amount of depositin (sedimentation)




**MECHANISM:**

The evolution and characteristics of a sedimentary basin, as well as the sediments that are deposited in its interior, are controlled by four factors:

**1) Subsidence:**

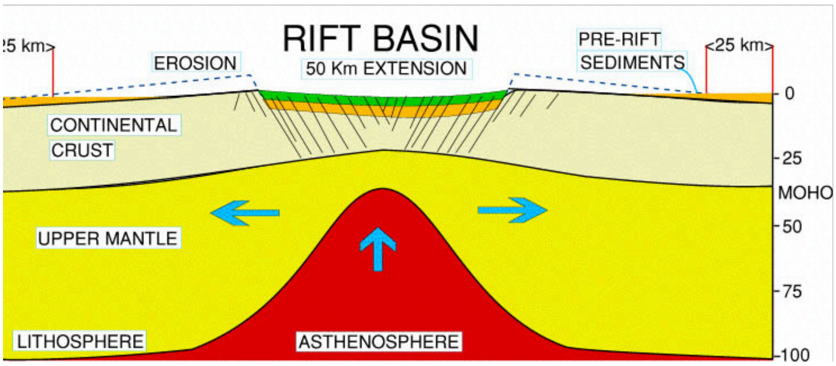
These three mechanisms will produce or enhance subsidence:

- Crustal extension:

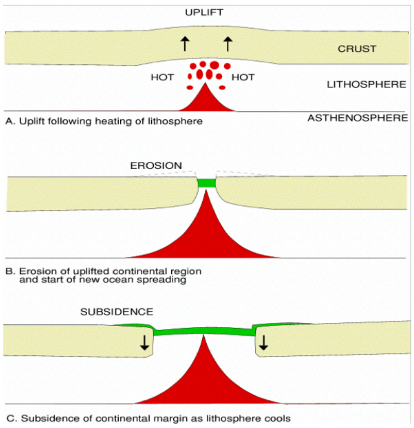
Where lithospheric plates move away from each other.
If we have extension:

- the rigid crust stretches and fractures. Normal faluts, sinking of blocks (subsidence). Formation of grabens (depressions)
- The strenching and thinning of the crust

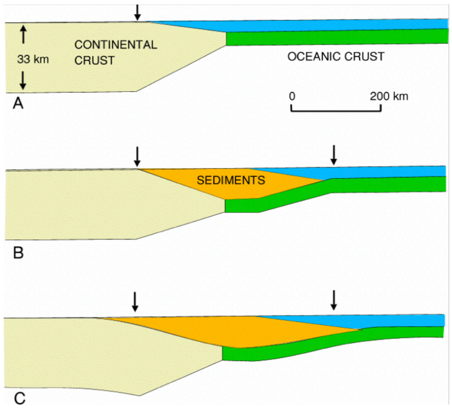
* when a rock is displaced and a rock is fragmented—-FAULT (that is called fault)
East African rift valley: is being formed by the separation of the eastern africa from the rest of the continent
The red sea




- Cooling: the previous stretched and heated crust during the rift pahse. Later cools downm, and it sink (subsidence) (is the same as thermal subsidence)



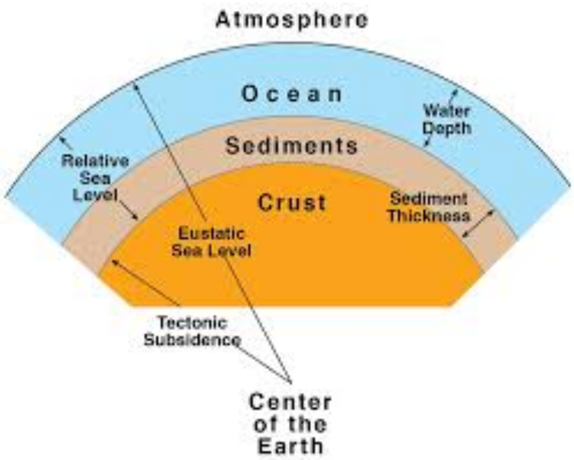
- Sedimentary load: The sediment deposited in the sedimentary basin can produce very thick sequences (various km) . Important sediment load above the underlying crust. Crust sinks (it is also called as crustal flexure)




**2) Sea-level changes:**

Sea levels are responsible for the accomodation of the sediments in the orilla. Accomodation spaces depend on the sea levels.

- Over geologic time sea level has fluctuated by hundreds of meters (ice sheets)
- Relative changes of sea level create space for sediment accumulation (accommodations space)
- Eustatic and relative sea-level (RSL) changes.



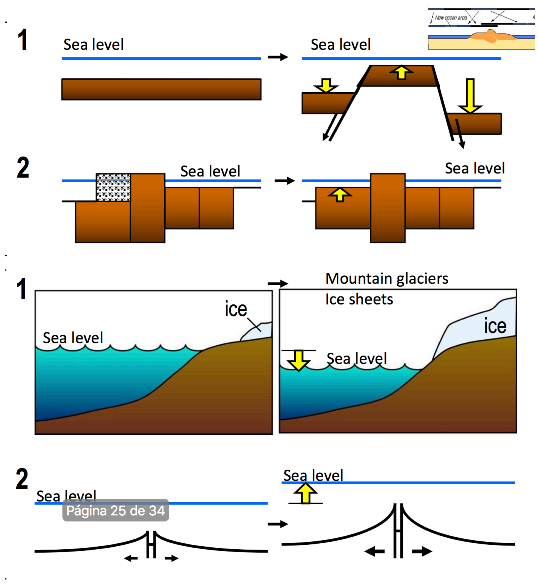

**The mechanisms that explain the change of the sea levels:**

**Relative sea level changes (RSL):** the height of the sea's surface relative to the surface of the solid Earth (local SL). It changes depending on the location. There are two types:

- Tectonics: Earthquakes and Reactivation of faults
- Isostasy (GIA): Glacier growth/melting (land uplift/ subsidence)

**Eustatic sea level changes:** the height of the sea surface to the center of the Earth. (global SL). There are two types:

- Glacial/interglacial periods: glacier growth/melting (mass) and Thermal expansion/contraction (volumen)
- Mid-ocean ridge activity: rate of sea-floor spreading

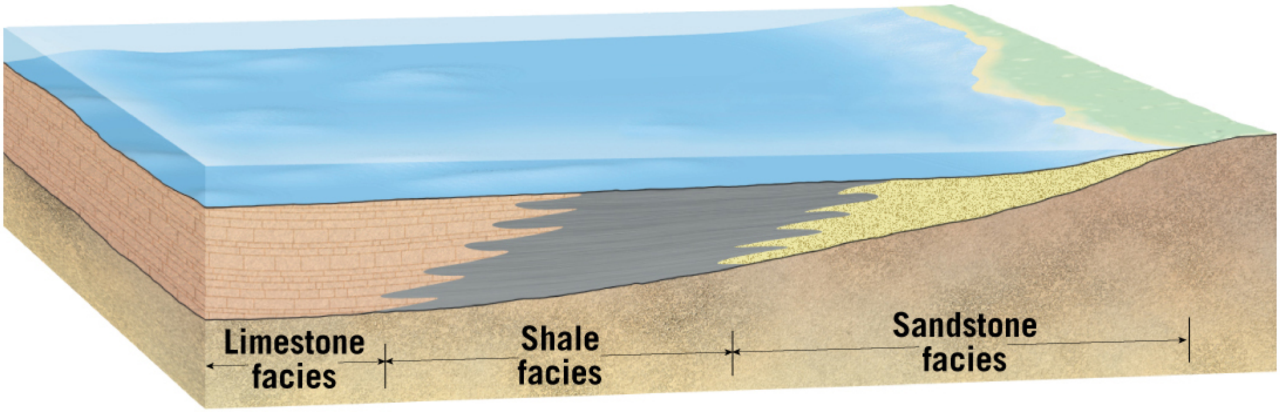


Isostasys happened during the last glaciacion. If the crust is beneath an ice sheet—> it sinks, so when the ice sheet melted, the crust came up, the crust near the sinked crust also went up, so the sea level there is much higher than the average sea level.

**3) Climate:**
It can somehow influence the type of sediments that we might find in the sedimentary basins.
If the climate is dry (hot), we might find: evaporitic deposites, crystallization due to evaporation…
If the climate is wet (temperate), we might find: clastic sediments (siliciclastic), transported and deposited by fluvial currents…

**4) Living organisms:**
The infilling are microorganisms.
Great Barrier Reef (australia): Current basin filled with biogenic deposits (bioconstructions, calcium carbonate skeletons of corals)
White Cliffs of Dover (UK): Cretaceous chalk deposits. Accumulation of calcium carbonate shells of coccolithophores.

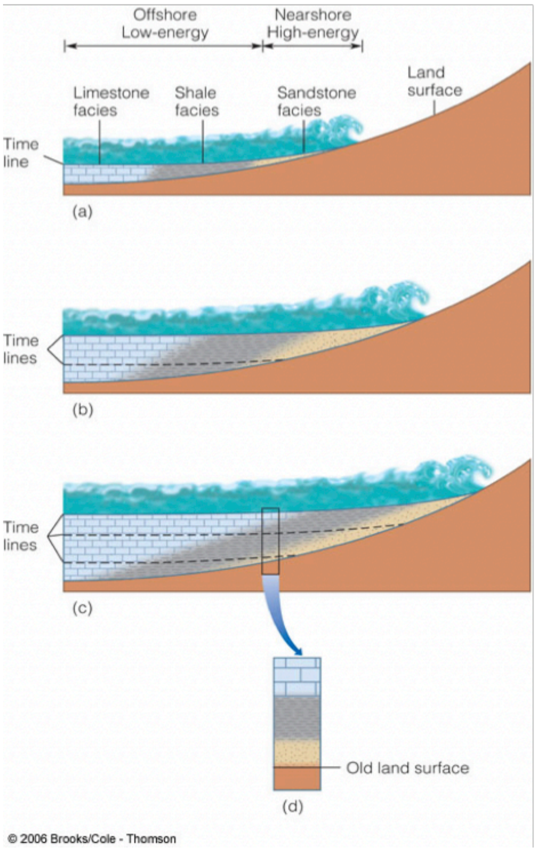
**<u>VERTICAL AND LATERAL FACIES EVOLUTION:</u>**
We'll find different sediment in different enviroments.
- Different sediments often accumulate in adjacent environments
  - For example, when sand is depositing on a beach (high energy), mud is being deposited offshore (quiet environment, low energy)
  - Carbonate sediments accumulate offshore, in a low-energy environments, where there is an important biological activity
  - Sandstone, shale, limestone



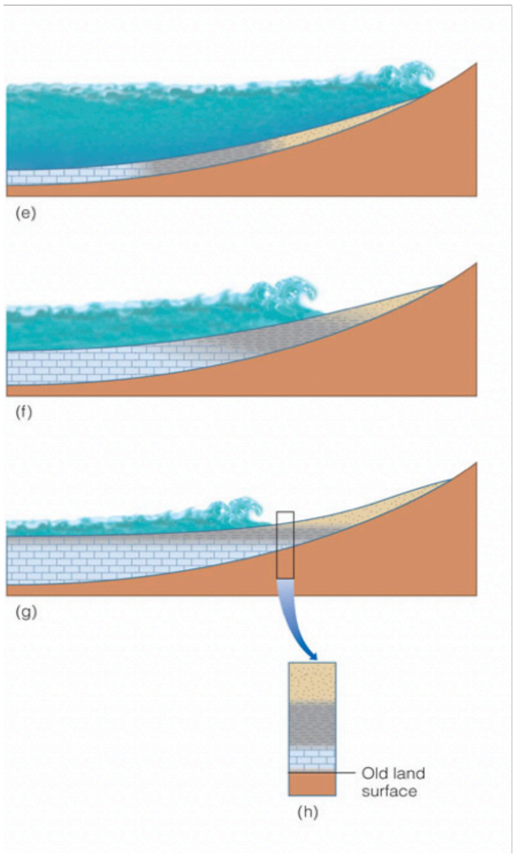

- Changes in the past environments can be seen when a single layer of sedimentary rock is traced laterally
  - Each unit (facies) possesses a distinctive set of characteristics (composition, texture, paleontological remains) reflecting the conditions of a particular environment (at a particular time) (*they are distinguish thanks to those characteristics)
    > Reef facies: limestones with corals
    > Marl facies with ammonites
  - Transitions between different facies are gradual

**Sea-level changes: trangression and regression**

**TRANSGRESSION:** deepening




**REGRESSION:** shallowing




**Accomodation space:**

- The infilling dynamics of marine sedimentary basins is controlled by the accomodation space
- Accomodation space: the space available for potential sediment accumulation (water depth space between sea level and ocean floor)
- This space in controlled by:
  - Sea level changes (global or eustatic)
  - Uplift or sinking of part of the sea floor (tectonics)
  - Changes in rates of sediment influx
- Changes in accomodation space:
  - Reduced - regression (the oceanward migration of the shoreline)
  - Increased - transgression (the landward migration of the shoreline)

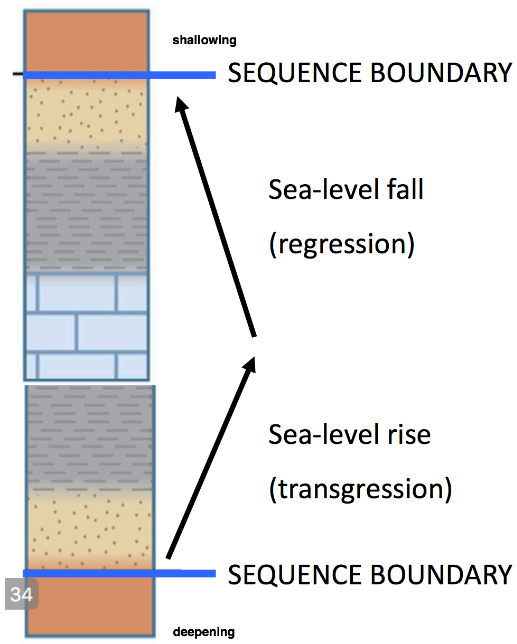
**Relationship between sea level and sediment supply:**

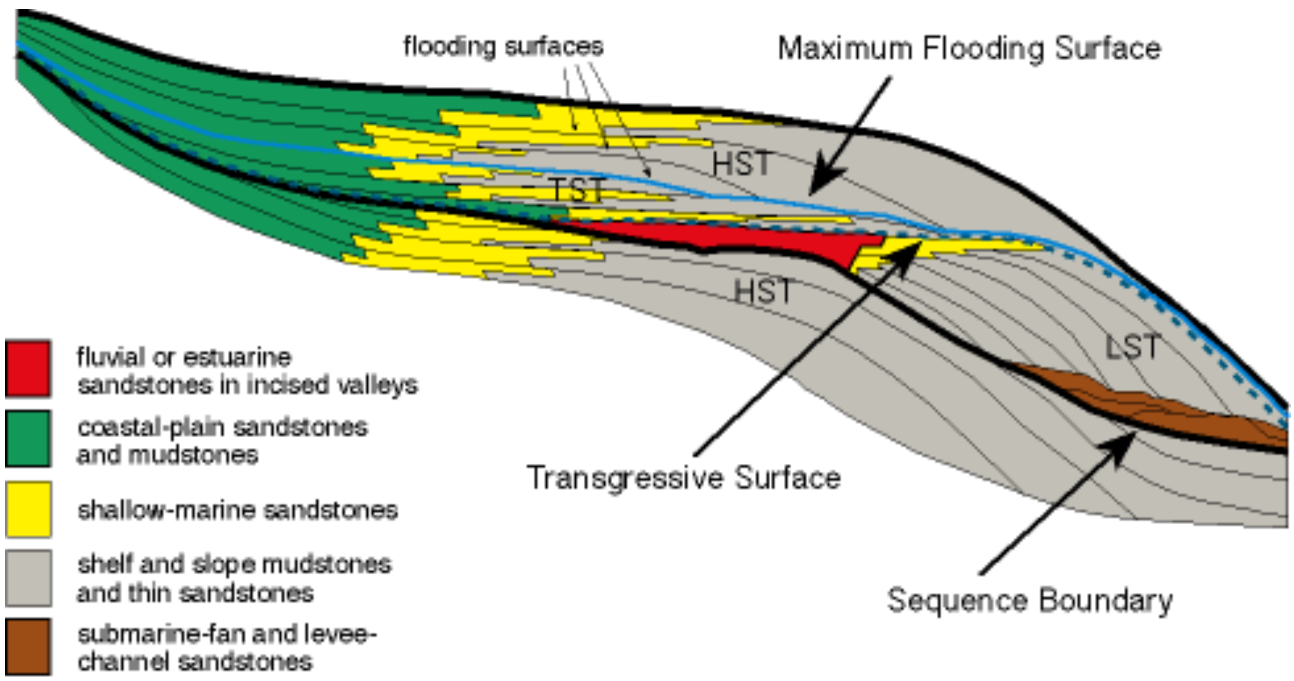
The accomodation space can be increased or reduced depending on the RSL rise or fall

- Under RSL rise (depending upon the sediment input)
  - Transgression (rate of RSL > rate of sediment supply)
  - Regression (rate of RSL rise < rate of sediment supply)
  - Stationary shoreline ( rate of RSL rise = rate of sediment supply)
- Under RSL fall
  - Regression (shift of facies basinward) (we will have a regression)

**<u>DEPOSITIONAL SEQUENCES:</u>**

The body of sediments deposited in a sea-level cycle is called a **sequence.**
If the sequence was created during a cycle that lasted between 0.5 and 10 Myr it is called a **depositional sequence.**
Depositional sequences are enveloped by two erosional surfaces or discontinuities (**sequence boundaries**). These boundaries are the product of a sea-level fall that erodes the subaerially exposed sediment surface of the earlier sequence.
The **internal organization** of the sediments within the depositional sequence shows:
-lower part in which the facies migrate landward (**a deepening-upward sequence**) = transgression
- upper part in which the facies migrate seaward (**a shallowing-upward sequence**)
= regression



# 10. The Fossil Record

- Concept of paleontology
- Historical development of paleontology
- The Fossils and fossil record
- Fossilization processes
- Subdivisions of paleontology:
    - Taphonomy
    - Paleobiology (paleoecology, paleobiogeography and evolutionary paleontology)
    - Biochronology
- Interest and application of paleontology

## Concept of paleontology

Etymology:
- *palaios*: old, ancient
- *ontos*: being, creature
- *logos*: the study

**Paleontology** is the study of the life of the past (fossils).

## Historical development of paleontology

**Early greeks:** some fossils were marine organisms → the land was under water at some point.
**Medieval times:** *"Vis plastica"* Fossils were created naturally, they were not ancient organisms.
**Renaissance**: Leonardo Da Vinci: fossils as fossils
**17$^{th}$ century:** Hooke and the invention of the microscope → detailed description of fossils
**18$^{th}$ century:** Cuvier → comparation of living and fossiled organisms (elephant/mammoth)
**19$^{th}$ century:**
- Smith and the principle of fossil succession
- Evolution theories:
    - Lamarck → organism changes during the life due to adaptation.
    - Darwin → the origin of species and natural selection

**20$^{th}$ century:**
- Gould and Eldredge → punctuated evolution theory
- Seilacher → trace fossils and ichnofossils

## Fossils and the fossil record

A fossil is any remain or trace of past life. These can be grouped differently.

Fossils can be body fossils (mold, cast…), ichnofossils or trace fossils and chemical fossils. The last two are associated with the activity of the organism.

A body fossil is the whole organism or some parts of it.
Chemical fossils are chemicals found in rocks that provide an organic signature for ancient life (related to radiocarbon dating…)

The **preservation** of a fossil is conditioned by different factors:
- Different lithologies
- Posession of hard parts
- Rapid burial
- Little oxygen (no decomposition)

Fossils can be mostly found in sedimentary rocks; formed underwater where sedimentation is bigger than erosion. The location of a fossil is also related to the lithology, for example, is much rarer to find fossils in sandstone than in limestone.

Even if fossils are mainly found in sedimentary rocks, they can be also located in igneous and metamorphic rocks. Dinosaur footprints can be found in volcanic ash and fossils can be found in low grade metamorphism rocks, like slate.

The totality of fossils is known as **the fossil record**.
The fossil record and the stratigraphic record make the **geologic record.** (Igneous rocks and metamorphic rocks are also part of the geologic record).

The fossil record is not a representative sample of organisms alive at the time. Some organisms don't have hard parts, like worms or jellyfish… Maybe, the fossilization conditions are not ideal (rapid burial) or happened in a continental environment and not in underwater environment, where erosion is more important than sedimentation.

A fossils is something lithified that is older than more or less 13000 years. However, the fossil term can be used for more recent organisms.

Even though the fossil record doesn't represent the biosphere of the past, the fossil record is the only thing that can be used to interpret and analyse the biosphere of the past.

# Fossilization processes

- **Incrustation**
- **Inclusion**
- **Mineralization**

# Subdivision of paleontology

- General paleontology
  - Taphonomy
  - Paleobiology (paleoecology, paleobiogeography, evolutionary paleontology)
  - Biochronology (biostratigraphy)
- Descriptive paleontology (systematic paleontology)
  - Paleozoology (vertebrate and invertebrate paleontology)
  - Paleobotany
  - Micropaleontology
  - Paleoichnology
  - Palynology

**TAPHONOMY**
Term coined by the Russian paleontologist I.A. Efremov (1940) "the study of the transition (in all details) of organic remains from the biosphere into the lithosphere".

**Taphonomic processes**:

- Necrology: why and how the organism dies
- Biostratinomy: all the processes that has occurred since the organism died until it was buried
- Fossildiagenesis: the processes that take place once the organism was buried until it was transformed into a rock.

*Biostratinomic processes*

- Biological processes (scavengers)
- Chemical processes (oxygen-rich environments, pH, carbonate compensation depth)
- Physical processes (transport, breakage)

*Fossildiagenetic processes*

These are the processes that take place once the organism was buried until it was transformed into a rock. During and after burial animal and plant remains undergo physical and chemical change, for example, carbonization, silification, phosphatization, pyritization….

A **fossil assemblage** is a group of fossils found together in a strata.

**Biocoenosis:** life assemblage, all organisms inhabiting certain habitat.

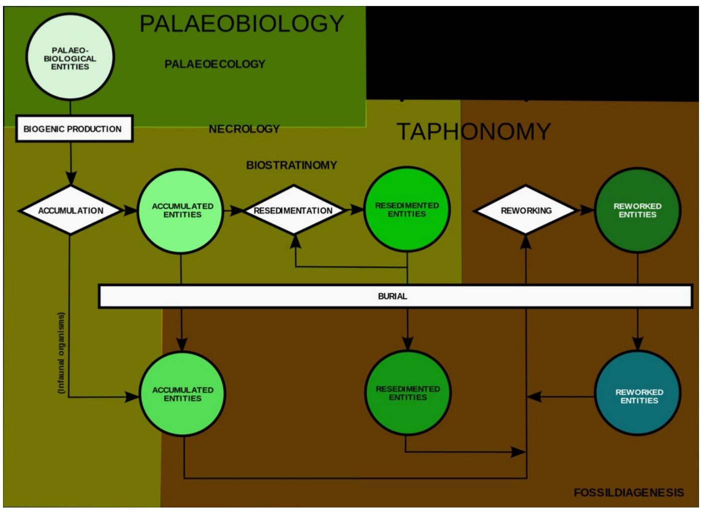
After death, it becomes the **thanatocoenosis**; that is the dead assemblage (remains of organims that died together).

After biostratinomic processes it becomes the **taphocoenosis**, that is the burial assemblage (unconsolidated sediments). They are the remains of organisms that were buried together.

After diagenesis, it becomes the **oryctocoenosis**, that is the fossil assemblage, all fossils in a stratum (after burial and diagenesis).

In a stratum we can find different fossils according to if the fossilization environment was the same one as the one in which the fossil actually lived:

- **Autochthonous fossils:** they are in place, they were buried where they lived and after taphonomic processes they were accumulated.
- **Allochtonous fossils**: they are not in place, they have been transported and buried in a place where they did not live, and they were resedimented
- **Reworked fossils:** from older deposits (not contemporary). Buried, uplifted and eroded, mixed with younger fossils and buried again.
- **Infiltrated fossils:** younger fossils reworked into an older deposit (not contemporary), by fluids, through animal burrows or root cavities.



The **fossil record** has its own nature and dynamics: paleobiological origin and location in the lithosphere. Taphonomic and biological processes are independent and improbable.

## PALEOBIOLOGY

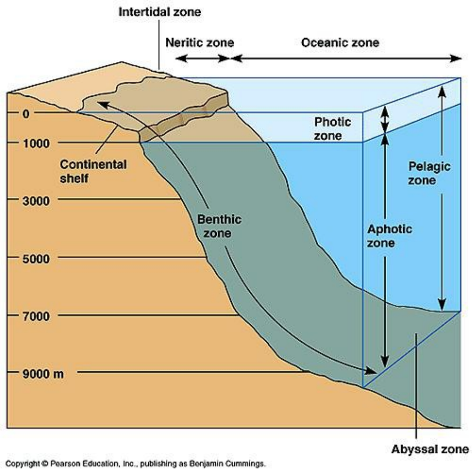
### Paleoecology

Paleoecology is the study of fossil organisms, the relationships with each other and their surrounding environment.

Paleoecological deduction: actualism → "The present is the key to the past"

It studies extinct species, there is a lack of modern analogies, which are not always applicable.

Before applying these studies, the type of fossil (autochthonous, allochthonous, reworked) has to be determined. The studies are also different depending on environments; terrestrial environments are scattered and mixed, and marine environments are good for reconstructions, due to gradual sedimentation, the quiet environment and the place preservation. The time averaging is the artificially enhance of the diversity of an assemblage; it can be a dead community, recolonized and material from elsewhere.




Zonation of organisms with depth: platform, bathyal and abyssal.

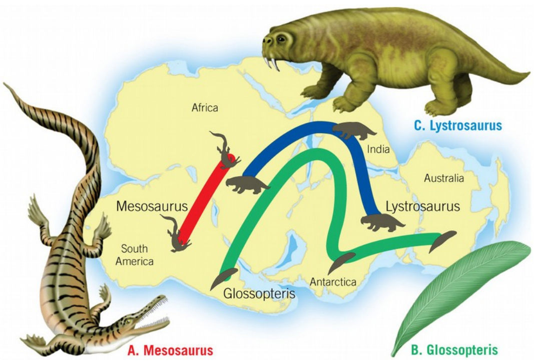
Zonation of organisms with light: photic and aphotic zone.

Benthic organisms can be epifaunal, infaunal, mobile or sessile. Pelagic organisms can be nectonic or planktonic (living in marine currents).

### Paleobiogeography

It is the study of the geographic distribution of past organisms. Living organisms have a defined geographic range, due to climate, sea-level changes and the relative position of continents and oceans.

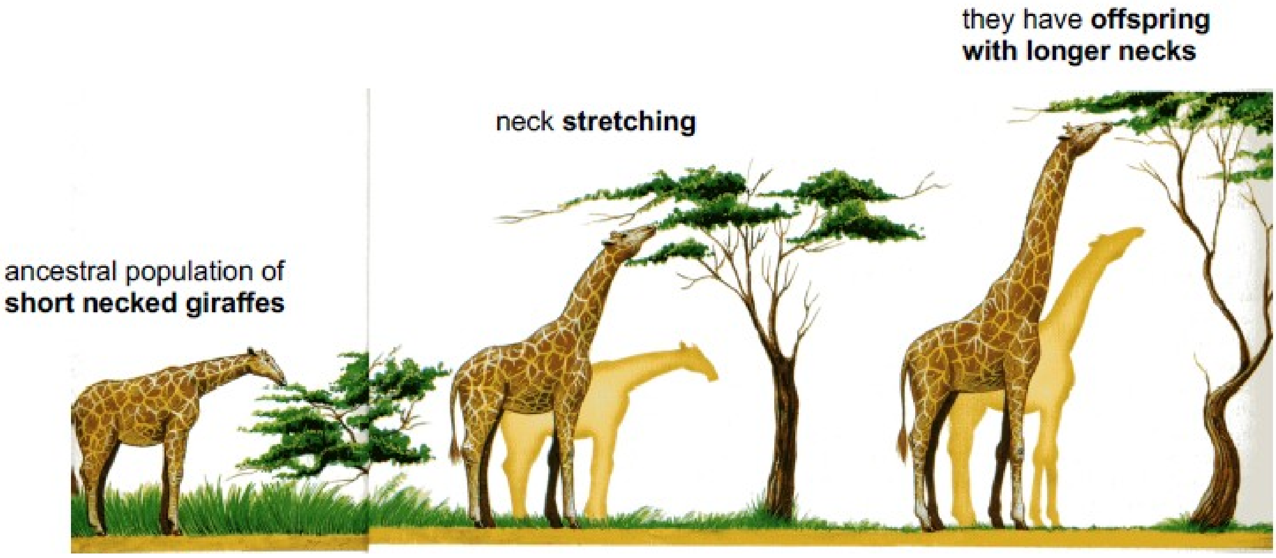
The geographic distribution of late paleozoic and triassic organisms served as an evidence for Alfred Wegener's Continental Drift theory.



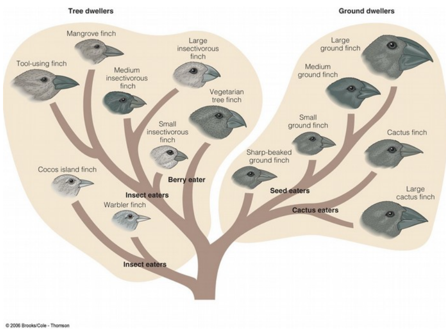

### Evolutionary paleonthology

Organisms have descended with modification from their related ancestors. *The fixity of species says that all present-day species had been created in their present form and had changed little or not at all.* This science joins paleontology and the perspective of time.

Jean-Baptiste de Lamarck (1744-1829) wrote in 1859 the book *Philosophie zoologique*, where he talked about the Theory of inheritance of acquired characteristics, based on the facts "the function makes the organ" and that the environmental changes makes the organism to adapt and evolve.




Charles Darwin did a five year voyage (1831-1836) aboard the HMS Beagle to the Galapagos islands, and he did important observations.



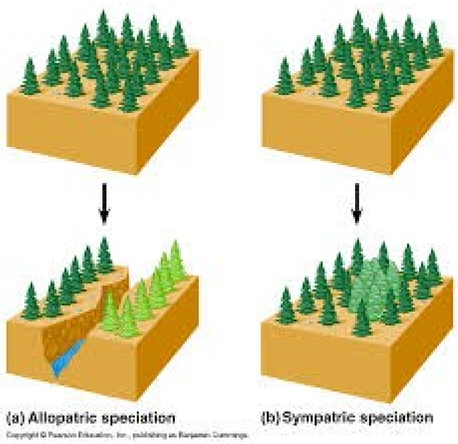

He saw that the island's scarcity of food made all the birds to have different physical characteristics. For example, he saw that every bird had to change its beak shape to eat the food that the different islands had, to survive.

The contribution of Charles Darwin and Alfred Wallace was the **Natural Selection theory.**

Natural selection works on the existing variation in a population. Mechanism for evolution:

1. Organisms possess heritable variations (size, color, speed, agility)
2. Some variations are mover favorable that others (acquiring resources, avoiding predators)
3. Those with favorable variations are more likely to survive
4. They can pass on their favorable variations

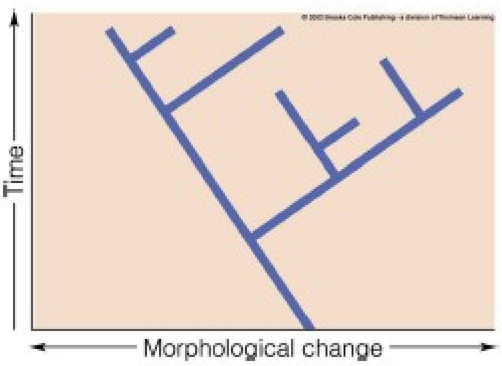
**The modern synthesis or neo-Darwinian view of evolution** associates the classical Darwinism and genetics, studying the hereditary units or genes. They discovered that what created variations were changes in genes called mutations.

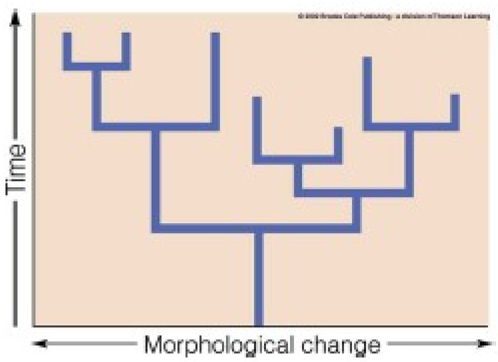



<u>Allopatric speciation:</u> a new species evolves from a small population that became isolated from its parent population (geographical barrier)

Sympatric speciation (phyletic): the gradual accumulation of minor changes makes the origin of a new species.
Rates of evolution
Gradualism vs punctuated equilibrium

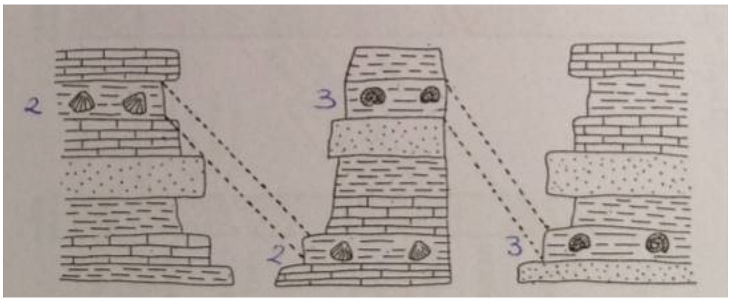
Punctuated equilibrium is when little or no change takes place in a species during most of its existence.




Fossils support evolution, as they provide evidence for evolution. There are still missing links that connect descendants with ancestors. For example, there is a missing link between reptiles and birds; there is a transitional fossil that shows characteristics of both ancestors and descendants, in this case, this fossil has teeth and feathers.

**BIOCHRONOLOGY (BIOSTRATIGRAPHY)**
**Biochronology** organizes the fossil record in time (irreversible process of evolution). **Biostratigraphy** is the use of fossils in dating rocks (using them in stratigraphic correlation)




William Smith (1769-1839): the principle of faunal succession.

**INTEREST AND APLICATION OF PALEONTOLOGY**
1. Origins
2. Curiosity about different worlds
3. Climate and biodiversity change
4. The shape of evolutionary
5. Extinction
6. Dating rocks

# 11. Origin and evolution of the biosphere

- History of life in the Precambrian
- The primitive atmosphere and the origin of life
- Oldest paleontological data
- Oxygenation of the atmosphere
- The origin of eukaryotic organisms and the ...

**THE BIRTH OF A PLANET AND EARTH'S EVOLUTION**

Hydrogen and helium formed shortly after the Big Bang, after subatomic particles joined together and formed these elements. These elements formed clouds, and these clouds condensed producing stars. Heavier elements formed in these stars. Nuclear fusion of stars will produce the elements with an atomic number up to 26. The rest of elements (n>26) are produced by the explosive death of stars.

The solar system formed from a solar nebula 4600 my ago. A solar nebula is a rotating cloud of interstellar dust and gases. Contraction of the solar nebula forms the protosun, and the remaining debris forms a flattened disk rotating around the protosun. This debris will produce the ice, rock and the metallic material that after several collisions will produce the planetesimals. The collision of accretions formed 8 protoplanets and moons. Earth's moon formed from the collision of a Mars-sized object with Earth.

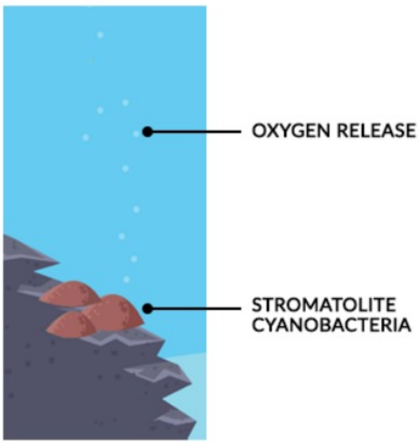
**HISTORY OF LIFE IN THE PRECAMBRIAN**

For us, geologic time starts 4600 million years ago. Precambrian accounts for 88% of Earth's history, and it means "early life" or "ancient age". It started 4.6 billion years ago and ended 541 million years ago. It includes the Hadean (4.6 – 4 billion), the Archean (4 – 2.5 billion) and the Proterozoic (2.5 billion – 541 million).

The Earth's repeated collisions with planetesimals and the decay of radioactive elements cause an increase on Earth's temperature. Early Earth was covered by a magma ocean. The earliest known rocks found belonged to the Hadean eon, when a chemical differentiation was happening; the Earth's different materials started layering by density, so the most dense materials were *buried*. When this chemical differentiation happened, all the gases escaped, creating the primitive atmosphere.

**EARTH'S PRIMITIVE ATMOSPHERE**

This primitive atmosphere consisted mainly of hydrogen, helium, water vapour, carbon dioxide, sulfur dioxide and nitrogen.




Helium and hydrogen escaped into space; during volcanic out-gassing gases were released and basic ingredients of life were erupted, such as, carbon, hydrogen, oxygen and nitrogen, but still there was not any free oxygen.

Water vapor condensed into clouds, cooling the Earth, and then, due to the strong rainfalls, the oceans were created. 3.5 billion years ago, photosynthesizing bacteria (cyanobacteria) released oxygen into Earth's oceans.

Initially, this oxygen bonded with iron dissolved in the oceans, creating banded iron formations (alternating layers of iron-rich rocks).
The great oxygenation event happened 2.5 billion years ago, when the oxygen that was trapped on the oceans was released to the atmosphere, creating the ozone layer that still protects organisms from solar or ultraviolet radiation.

**ORIGIN OF LIFE**
For the NASA, life is "a self-sustaining chemical system capable of Darwinian evolution".

Amino acids are the essential molecules for proteins; there are many hypotheses for the formation of aminoacids:

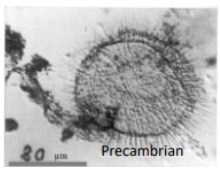
- Panspermian or extraterrestrial model (universal seeding): the amino acids were brought to Earth from asteroids – they arrived already made. Evidences are the presence of carbonaceous chondrites and amino acid-like compounds.
- Synthetized from a lightning strike
- Developed in hydrothermal vents or hot springs; even if there's no light there is abundat fauna. Chemosynthetic bacteria can use hydrogen sulfide released by this hydrothermal vents to convert carbon dioxide into organic matter.

**EARTH'S FIRST LIFE**
Chemical traces suggest life may have existed 3.8 billion years ago. $\delta^{13}C$ was found in the Isua group rocks in Greenland, which is indicative of organic activity.

**EARTH'S OLDEST FOSSILS**
Prokaryotes are Earth's first living organisms. First known organisms were single-celled bacteria which lacked a nucleus. 3.5 billion years ago photosynthetic cyanobacteria-like prokaryotes lived in layered mats on top of mounds called stromatolites (first bioconstructions).

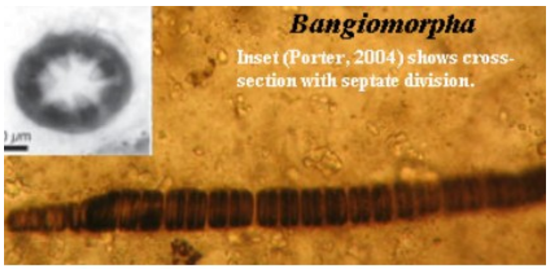
These stromatolites are slimy materials created by the cyanobacteria and trapped sediments (precipitation of calcite), creating a layered structure. They can also create oncolites, which create spherical layered structures.

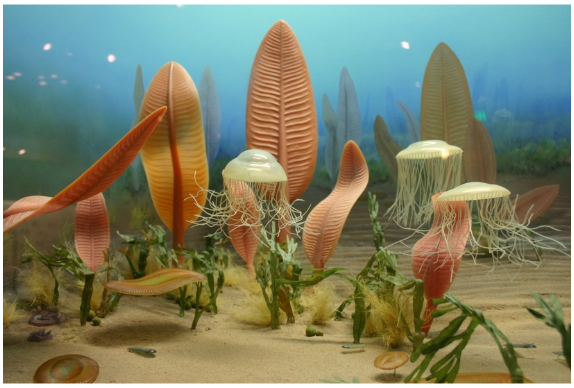
**EARTH'S FIRST EUKARYOTES**
Eukaryote cells contain a nucleus. These are more advanced organisms than prokaryotes.


Acritarchs are eukaryotes that existed 1.6 – 1.9 billion years ago. They were microscopic single-celled organisms. They were organic-walled organisms; some of them were spiny and others smooth.

1200 million years ago, the first microscopic multicelled organisms were born. These were the Bangiomorpha red algae. This was the origin of sexual reproduction.

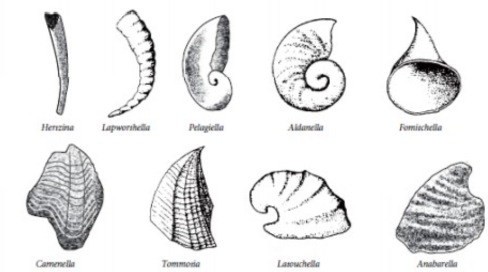




The first macroscopic multi-celled organisms found were the Ediacara biota (600 million years ago). They were sea-dwelling (photic) biota which lived in the seabed. Their body was soft, and their fossils, mostly mold and cast, were preserved in shallow-water siliciclastic sediments. Originally the name was assigned to a variety of modern invertebrate groups (worms, jellyfish…) but the modern interpretation is unrelated to modern metazoans.


In some Ediacaran localities, conical shells called Cloudina assemblages were present. They were the earliest organisms with dead parts.

The Tommotian fauna is a small shelly fauna from the Precambrian-Cambrian transition. This was the first major appearance of hard skeletal material in the fossil record.




**THE PRECAMBRIAN-CAMBRIAN BOUNDARY**

In this boundary a biological crisis happened where the Ediacara biota went extinct and the cyanobacterias' and acritarchs' diversity decreased.

# 12. Diversification of life in the Phanerozoic

- History of life in the Paleozoic (541-252 my ago)
- History of life in the Mesozoic (252-66 my ago)
- History of life in the Cenozoic (66 million years ago- present)

## HISTORY OF LIFE IN THE PALEOZOIC

- Appearance of skeletonized animals (Precambrian)
- Radiation and evolution of marine invertebrates
- Earliest vertebrates: fishes
- Amphibians
- Reptiles
- Plants establish on land (before animals)
- Massive extinction: end of Permian

### The Cambrian explosion

Ediacara biota, the first macroscopic multicelled organisms became extinct in the Precambrian-Cambrian boundary.

All major invertebrate (animals lacking backbones) groups first appear in the Cambrian: jellyfish, sponges, worms, mollusks, arthropods… In the early Cambrian, there was a major evolutionary innovation in animals with skeletons.

There was an explosive development of new types of animals that caused this sudden life change.

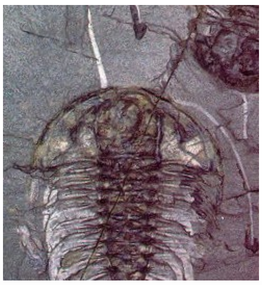
There is evidence of some Precambrian shelled organisms; Cloudina (earliest organisms with hard parts) and Tommotian fauna (small shelly fauna from the Precambrian-Cambrian transition. This was the first major appearance of hard skeletal material in animals.

The early diversification of animals (including skeletonized) was caused by the Proterozoic glaciation, the Cambrian global warming (stimulated evolution), the change in the chemistry of the oceans: triggering of shell precipitations and the emergence of predatory lifestyle (the most important evidence: it is believed that the creation of shells was to protect themselves from predators).

Large skeletonized animals of the Cambrian explosion

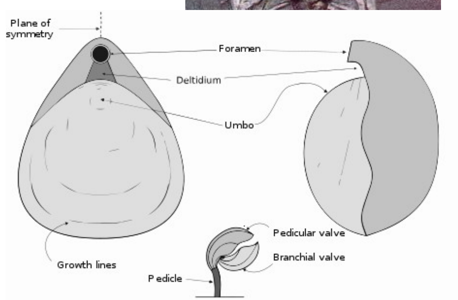
Large skeletonized animals were created in the Cambrian explosion. Almost all of the major invertebrate phyla evolved during the Cambrian, and trilobites, brachiopods and archaeocyathids were created.

***Trilobites***



Class Trilobita, phylum Arthropoda (Cambrian-Permian)
Flexible exoskeleton of a protein called chitin. Made up about 50% of the total fauna. They were mobile benthonic organisms. They were sediment-deposit feeders (mud-burrowing scavengers) and they crawled or swam along the seafloor(when crawled-→ ichnofossils, eg. Cruziana). They lived in the marine platform. The Cambrian period is also known as the golden age of Trilobites.

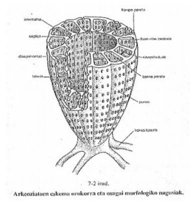
***Brachiopods***



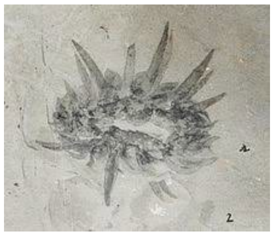
Class Inarticulata, phylum Brachiopoda (Cambrian-recent)

They are a benthonic, sessile (attached to the substrate with the pedicle) group. They were suspension feeders. They are quite similar to bivalbs, but their two valves have different size and shape. No tooth-and-groove features.

***Archaeocyatha***
Class Archaeocyatha, phylum Porifera (Cambrian)



These were the first animals to build bioconstructions (first reefs in the Cambrian). They were benthonic and sessile organisms, and they were suspension feeders. They lived in shallow and warm water platform (20-30m).



***The Burguess Shale biota***
One of the most famous fossil-bearing deposit is the Burguess Shale (Canada). Fossils in this place were soft-bodied fossils, the fossils are carbonaceous impression on black muds. They show very different forms from today f.e. Wiwaxia.

<u>Paleozoic marine community (invertebrates)</u>
The Paleozoic marine community consisted in reef like structures: bryozoans, stromatoporoids, and tabulate and rugose corals (Ordovician) (Cambrian – archaeocyatids).

The mass extinction in the Ordovician made a decrease of the biodiversity (brachiopods and bryozoans…). In the extensive glaciation, sea level fell and surface waters cooled down.

Reefs were formed by stromatoporoids and tabulate and rugose corals (Silurian and Devonian).

The mass extinction in the Devonian triggered a biodiversity decrease (Stromatoporoids, tabulate and rugose corals) due to a global cooling that produced a decrease in the coral community.

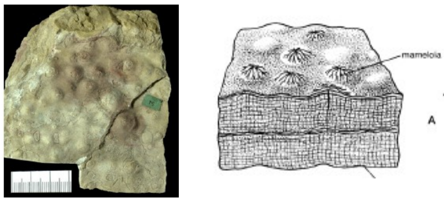
***Bryozoans***
Phylum Bryozoa (Ordovician-present)


www.fossiel.net © Arjen de Ruiter

They are benthic and sessile organisms that formed colonies. The colony sizes were very little (centimeters). They produced calcareous exoskeletons. *Fenestella.*

***Stromatoporoids***

Phylum Porifera, class Demospongea, order Stromatoporoida. (Cambrian-Oligocene).




They had a similar organization to sponges. They created a skeleton of laminated calcite that formed vertical pillars. They lived in shallow tropical waters, where they formed reefs.

***Tabulate and rugose corals***

Phylum Cnidaria, class Anthozoa, order Tabulate and Rugose (Ordovician-Permian).

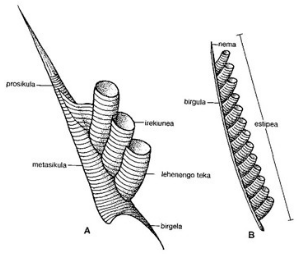
RUGOSE


TABULATE

They were marine and sessile organisms that lived in shallow waters (<20m). The rugose type could be found as solitary or colonial, and had a developed septa. The tabulate type were colonial and they lacked a septa or it was poorly developed.

***Graptolites***

Phylum Hemichordata, class Graptolithina (Cambrian-Carboniferous)



14-3 irud.
Graptolitoen eskeletoaren egitura.
A) Sikula eta lehenengo teka. B) Errabdosoma.

They were marine colonial organisms, with a chitinous skeleton. They are very abundant in lower Paleozoic black slate. They were planktonic (wide range of salinity and temperature) or benthic (shallow waters).

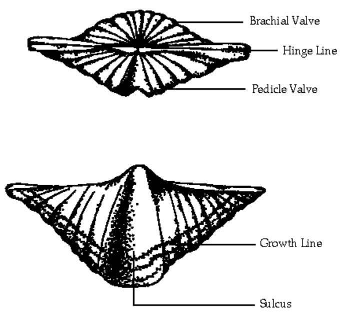
***Cephalopods***

Phyllum Mollusca, class Cephalopoda (Cambrian-recent)

They are marine organisms, mostly nectonic but some of them are benthic. They have arms or tentacles in their head; their descendants are the modern squid, octopus and nautilus. They move by expelling inner water or gas. They were the first truly large organisms on Earth (up to 10 m). The most abundant in the Paleozoic was the Orthoceratoid (Cambrian-Triassic).

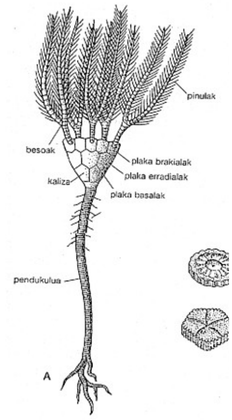
***Brachiopods***

Phylum Brachipoda, class Articulata (Cambrian-recent)




They are benthic organisms with two valves of different size and shape. They have tooth-and-groove features. Strophic brachiopods were very abundant in the Paleozoic. They have a calcium carbonate shell and a pedicle to get attached to the substrate. They are suspension feeders.

After the Devonian massive extinction, patchy reefs were formed by blastoids, crinoids, brachiopods and bryozoans.




***Crinoids***
Phylum Echinodermata, class Crinoidea (Cambrian/Ordovician? - recent)

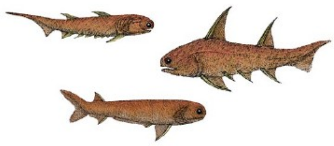
They are marine benthic organisms with a pedicle to get attached to the substrate. They have 5-10 large arms for feeding purposes. They have a pentaradial symmetry and a calcium carbonate exoskeleton.

***Blastoids***
Phylum Echinodermata, class Blastoidea (Silurian-Permian)

They were marine benthic organisms that lacked arms. They had a pentarradial symmetry and a calcium carbonate exoskeleton.

Due to a widespread volcanic activity that triggered the acidification of the oceans, the **Permian extinction** event occurred, where many marine invertebrate organisms were extinct, such as trilobites, tabulate and rugose corals and blastoids.

<u>Early vertebrates: Fish</u>
These are the most primitive vertebrates. The oldest and most primitive among all fishes is the Ostracoderm (class Agnatha), that was feed on detritus and lived from the late Cambrian until nowadays (living: lamprey, hagfish).


Acanthodians

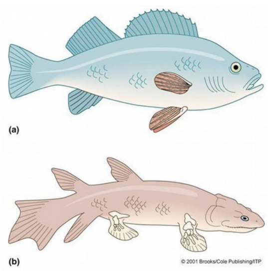
The first jawed fish were the Acanthodians (Lower Silurian-Permian).

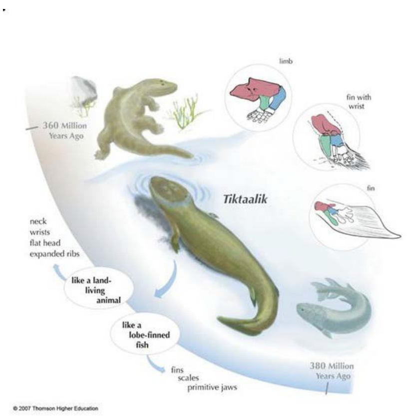
Placoderms (late Silurian-Devonian) were plate skinned fish. They lived in freshwater or in the sea and had bony and sharp teeth.


Placoderms

The Devonian was the age of the fish, when the major groups were present; such as Acanthodians, Placoderms, Ostracoderms, cartilaginous fish (sharks, rays) and bony fish (tuna, salmon).

EVOLUTION OF FISH
There are two types of bony fishes: Ray-finned fishes (subclass Actinopterygii) that are supported by thin bones (trout, bass, perch, salmon, tuna…) and lobe-finned fish (subclass Sarcopterygii), with muscular fins and articulating bones. The amphibians evolved from the lobe-finned fish.






Amphibians

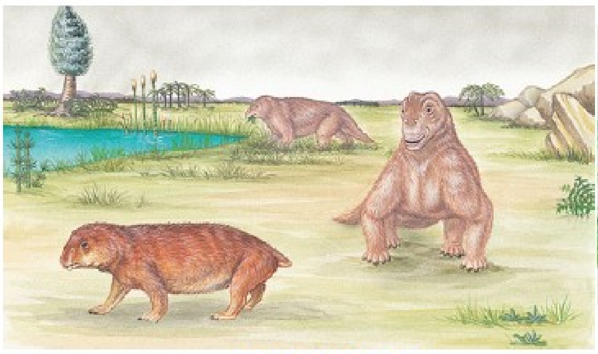
The amphibians were vertebrates that evolved by moving to land. The lobe-finned fishes adapted to land and became the first amphibians in the Devonian, and used their muscular fins to move from one pond to another. Anyway, they were not fully adapted to life out of water.

They were not the first land-living organisms, because they were plants in the Ordovician.

Reptiles

The first true terrestrial vertebrates were the reptiles, in the Carboniferous. They were better adapted to live on land, because they have a waterproof skin (tough and with scales) that avoids dessication and dehydration. They lay shell-covered eggs on land (amniote eggs), and they became widespread, because they didn't need to go back to the water.

In the Permian, there were pelycosaurs (finback reptiles) and therapsds (mammal-like reptiles)



Therapsids

Pelycosaurs (sail-back)

At the end-Permian mass extinction, 90% of marine invertebrate species and 70% of terrestrial vertebrate species (e.g. pelycosaurs) went extinct. Therapsids diversified in the Triassic and evolved into mammals.

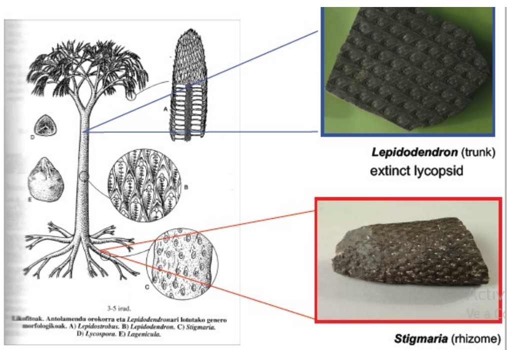
First land plants

Plants were the first land-living organisms. The first plant were Bryopthite-like plants (non vascular) in the Ordovician. They were small and without any deep roots. They lived in moist areas, and due to their secretion of organic acids they could dissolve rocks.

Diversification of plants occurred in the Silurian and Devonian.

***Lycopsids***

In the Silurian, seedless vascular plants (with spores) were present, such as Lycophyta. They were present until nowadays, and they can be small (Devonian) or high plants (Carboniferous).



***Equisetopsida***
Present in coal-forming swamps. (Devonian- recent).

They are the extinct genus of horsetails.


***Annularia*** (leaves)

***Pteridosperms***
Present from the Carboniferous to the Mesozoic.


***Calamites*** (trunk)

The end-Permian extinction summary

Due to the intense volcanic activity different gases were released; carbon dioxide triggered the greenhouse warming and sulfur dioxide acid rain. After this, 90% of marine invertebrate species and 70% of terrestrial vertebrate species went extinct.

In the case of plants, Lycopsids and Sphenopsids were reduced to small forms, and the diversification of Gymnosperms happened.

**HISTORY OF LIFE IN THE MESOZOIC**

Mesozoic is also known as the age of the reptiles, and it happened 252-66 million years ago. The main event of this age is the fragmentation of the supercontinent Pangea that caused changes in the ocean circulation and climate.

Mesozoic and Cenozoic marine fauna

There was an increase of burrowing organisms (bivalves and echinoids), predators (cephalopods and marine reptiles) and complexity among marine invertebrate fauna.

***Scleractinian corals***
Phylum Cnidaria, class Anthozoa, order Scleractinia (Triassic-recent)

They can be solitary or colonial, with a light and porous aragonitic skeleton and a well-developed septa. They are marine organisms (cold to tropical waters). They live in simbiosis with Zooxanthellae algae that captures zooplankton.

***Ammonites***

Phylum Mollusca, class Cephalopoda, subclass Ammonoidea (Devonian-Cretaceous)
"head footed".

They had a thin aragonitic, planisipirally coiled and ornamented shell. They were predator organisms.

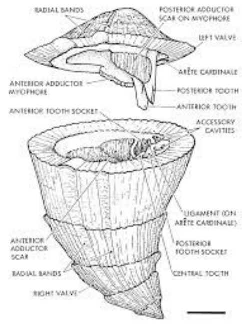
***Belemnites***

Phlym Mollusca, class Cephalopoda, subclass Coleoidea (Carboniferous-recent)

They had an internal skeleton, and a bullet-shaped guard of calcite. They were predators that could live nearshore or in the open ocean.

*Phylum Molusca, class Bivalvia (Cambrian- recent)*
*Bivalves are twin-valved organisms with bilaterally symmetric exoskeleton composed of calcium carbonate (usually aragonite). They are marine organisms: infaunal shallow burrowers, infaunal deep burrowers, epifaunal, borers… or fresh water organisms.*

***Rudists***



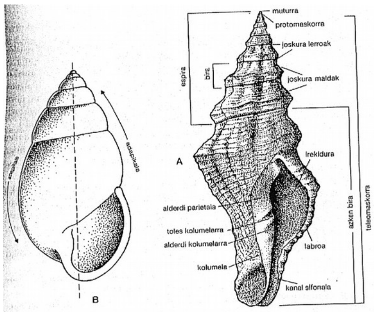

Phylum Molusca, class Bivalvia (Jurassic- Cretaceous)

They built extensive "reefs" in the Cretaceous (Ereño, Gorliz…). They lived in shallow platform. They are inequivalved; they had a large valve attached and a small valve or cap free.

***Gasteropods***

Phylum Molusca, class Gasteropoda (Cambrian-recent)

They are the most variable type of mollusks, which have usually aragonitic and conical shell, with the gill and anus above the head. They can be burrowers, swimmers, attached to the substrate… They can be found in marine, fresh water and terrestrial environments.




10-18. irud.

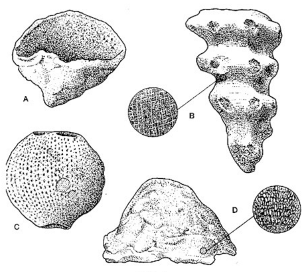
**Gastropodoak. A) Maskorraren morfologia orokorra. B) Deskribapenean erabiltzen diren noranzko nagusiak.**

***Sponges***

Phylum Porifera (Cambrian-recent)

The most abundant sponges are Demosponges (class Demospongiae)

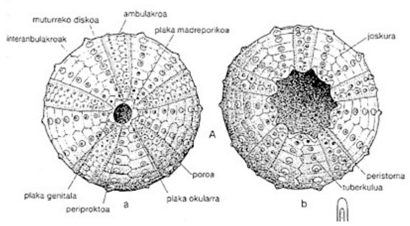
They are sac-shaped organisms with a central cavity which is a filter for nutrients. They are sessile or benthic, and they have calcareous or siliceous spicules. They create bioconstructions (reefs) in shallow platforms.




6-5 irud.

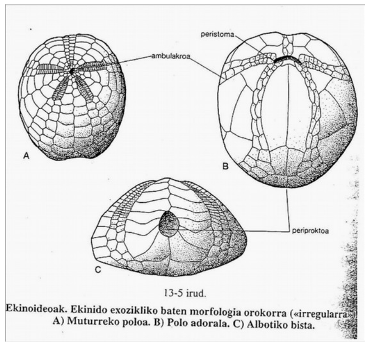
**Ezagutzen diren belaki moten adibideak. A) Belaki karetsua. B) Belaki hexaktinelidoa. C) Demosponja. D) Esklerosponja.**

***Echinoids***
Phylum Echinodermata, class Echinoidea (Ordovician-recent)




They became the most abundant group in the Mesozoic and in the Cenozoic. They are benthic and free moving. They are made of a single crystal of calcite plates, and they have spines or radioles.

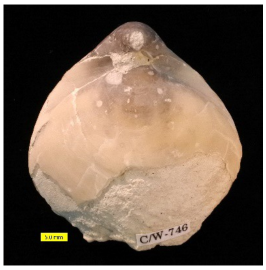
Regular echinoids have a globular shape and are radially symmetrical. Their variety goes from epifaunal to infauna, and they have a periproct on the appical (upper) surface to eject the waste.



13-5 irud.
Ekinoideoak. Ekinido exozikliko baten morfologia orokorra («irregularra»). A) Muturreko poloa. B) Polo adorala. C) Albotiko bista.

Irregular echinoids have a variable shape (heart shaped) and are bilaterally symmetrical. They are mostly infaunal, and they periproct is laterally located.

***Articulated brachiopods***
Phylum Brachiopoda (Cambrian-recent)

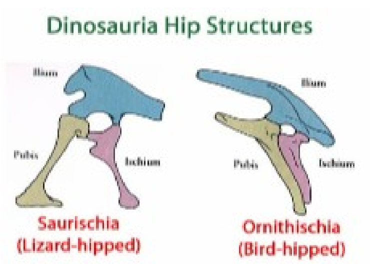


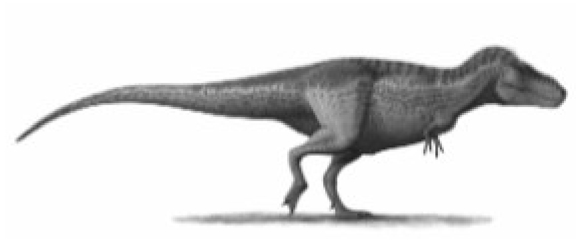

They are benthic organisms with two different valves, tooth-and-groove features and a pedicle attached to the substrate. They are suspension feeders and the modern marine fauna are astophic.

<u>Reptiles</u>
Reptiles returned to the sea.

They also started to fly. The Pterosaurs were the first flying vertebrates. They had membranous wings for rudimentary flight. They existed from late Triassic until the Creteaceous.

Dinosaurs evolved in the late Triassic and became the dominant terrestrial vertebrates. They could be herbivorous (Stegosaurus) or carnivorous (Theropods). They could have lizard-like pelvis (Saurischia) or bird-like pelvis (Ornithiscia). They could be bipedal and quadrupedal.



<u>The origin of birds</u>
Birds evolved from a group of small Theropods. They were organisms with feathered wings and reptilian characteristics. One of the ancestors is the Archaeopteryx, they have found fossils from the Upper Jurassic in Germany.

*A Pterosaur's fossil was found in China. These flying reptile's fossils locate the feathers 70 million years earlier. They were found in China, and they lacked feathers, but they were ancestors of them.*

<u>Mammals</u>
They evolved from ancient Therapsids (mammal-like reptiles) in the late Triassic. During the Mesozoic, most of them were small. They could be carnivorous, insectivorous, herviborous or omnivorous, and aquatic, terrestrial or aerial.

<u>Plants</u>
Gymnosperms appeared in the Triassic and Jurassic, and angiosperms (flowering plants) in the Cretaceous.

<u>End-Cretaceous extinction</u>
It happened 65 million years ago, and it provoked the extinction of dinosaurs. There was an asteroid impact and volcanic eruption that triggered this massive extinction.

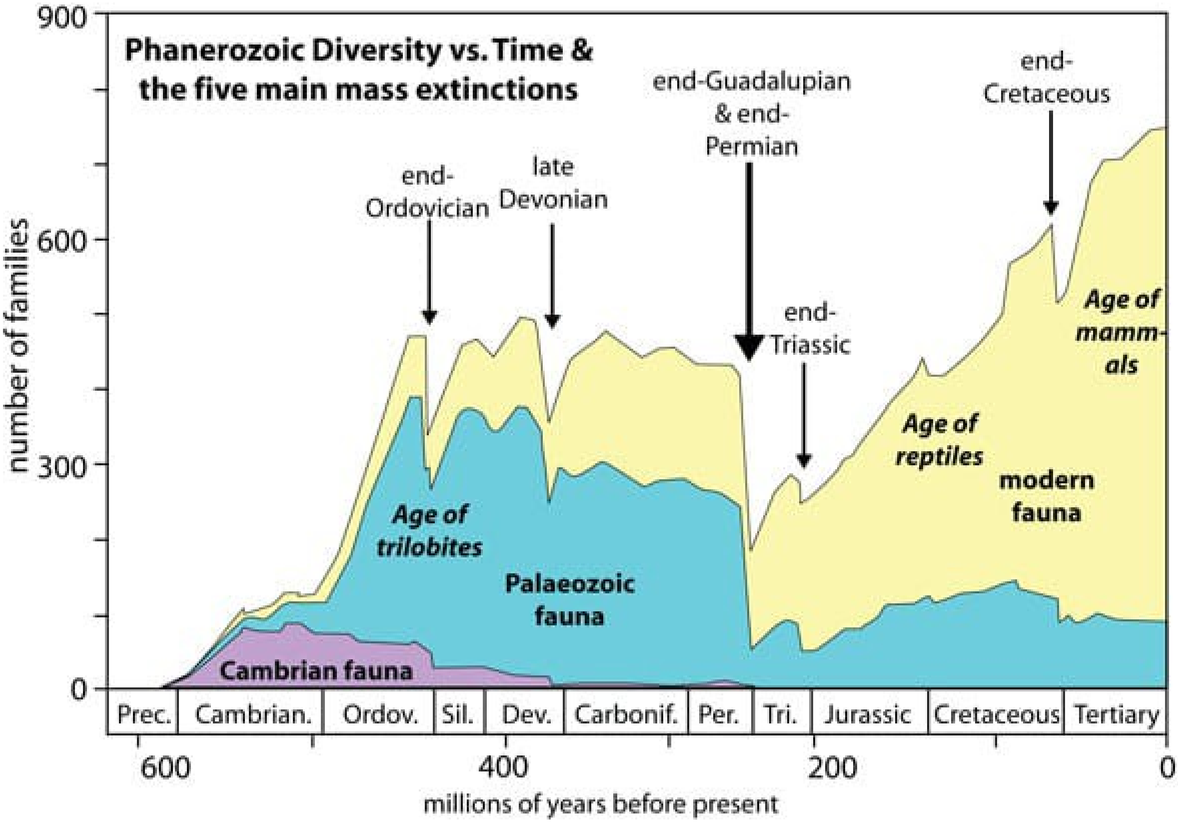
**HISTORY OF LIFE IN THE CENOZOIC**
The Cenozoic is also known as the age of mammals.

In marine environments, cephalopods (ammonites and belemnites) and marine reptiles (ichtyosaurs, plesionaurs, mosasaurs) become extinct at the end Cretaceous mass extinction and the Nektonic community (can swim against currents, active swimming) replace them. Fishes and marine mammals evolved in the Cenozoic.

In terrestrial environments, mammals replaced the reptiles as the dominant land animals. Earliest mammals (rodent-like mammals) coexisted with dinosaurs in the Mesozoic. Angiosperms replaced the gymnosperms as the dominant plants, and grasslads appeared in the Miocene.

The Paleocene-Eocene thermal maximum (PETM) was a Climate Change time, that created tropical ecosystems, mostly in the ice-free Eocene. The start of the Eocene is characterized by the radiation of placentals or marsupials due to the PETM high temperatures, and the extinction of non-avian dinosaurs.

**THE FIVE/SIX MASS EXTINCTIONS**

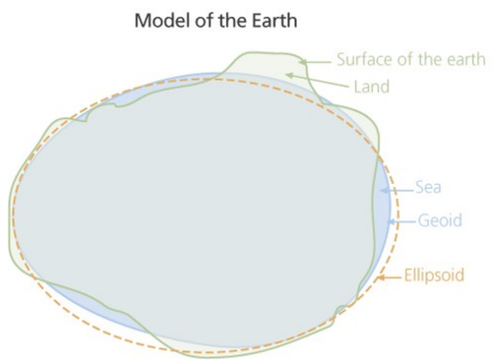


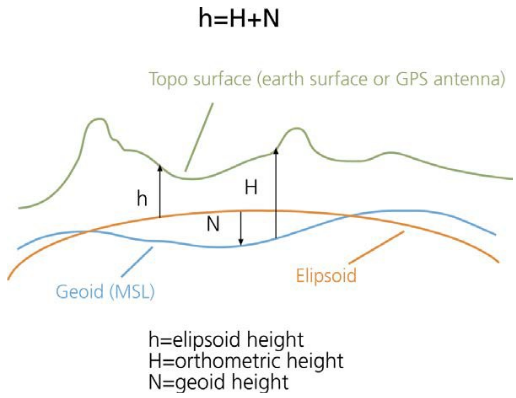

- End Ordovician extinction (443M): there was a decline in tabulate and rugose corals, echinoderms, nautiloids, conodonts, achritarcs, graptolites, trilobites, brachipods, bryozoans, ostracods and primitive fishes
- Late Devonian extinction (368 M): There was a decline in tabulate and rugose corals, brachiopods, trilobites, ammonoids, crinoids, bryozoans, stromatoporoids, formaminifera, ostracords, conodonts and achritarcs. Placoderm fishes went extinct.
- End Permian extinction (252 M): There was a decline in ostracods, ammonoids, bryozoans, brachiopods, bivalves, terrestrial plants and tetrapoda. Tabulate and rugose corals, trilobites and fusulinids (benthic macroforaminifera) went extinct.
- End Triassic extinction (201 M): There was a decline in brachiopods, ammonoids, bivalves, gastropods, marine and terrestrial reptiles and amphibians, and conodonts went extinct.
- End Cretaceous extinction (66 M): There was a decline in reptiles, fishes, amphibians, plants, mammals, foraminifera and nanoplankton, and some reptiles, pterosaurs, non-avian dinosaurs, ammonites, belemites and rudists went extinction.
- The 6th extinction: (nowadays) a lot of species are gone/or facing extinction, f.e. sumatran rhino, Panamanian golden frog...

# 13. Shape and size of the Earth

The geoid is the shape that the ocean surface would take under the influence of the gravity and rotation of Earth alone, if other influences such as winds and tides were absent.

The Earth ellipsoid is a mathematical figure approximating the Earth’s form.



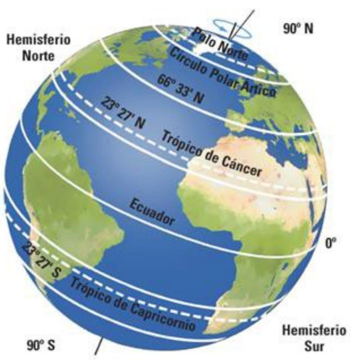

**THE GEOGRAPHICAL NETWORK**

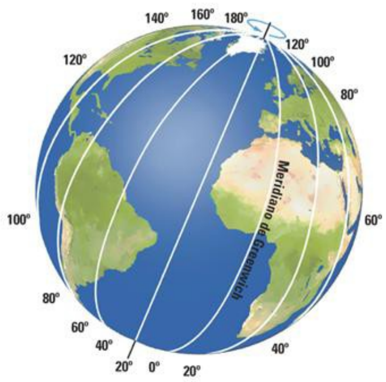
**Cardinal directions**

North, east, south and west.

**Parallels and meridians**

Parallels and meridians are imaginary lines used to locate locations on Earth.




Parallels are parallel lines to the equator. The principal parallel is the equator. It goes from 0 to 90º. When it gets closer to the poles the circles get smaller. Parallels separate northern and southern hemispheres.

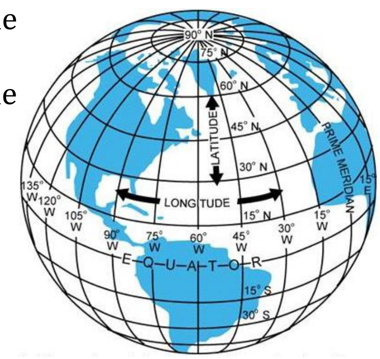
Meridians are lines from pole to pole. The principal meridian is the Greenwich meridian. It goes from 0 to 180 degrees. They separate eastern and western hemispheres.

**Latitude and longitude**

Geographic coordinates;

Latitude: the number of degrees (angular distance) from the equator → north and south latitude

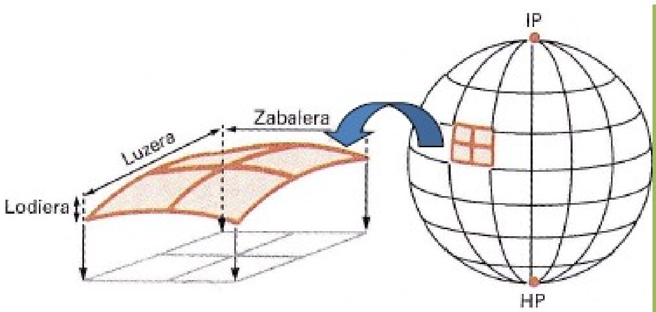
Longitude: the number of degrees (angular distance) from the prime meridian → east and west longitude




**MAP PROJECTIONS AND COORDINATE SYSTEMS**

**Cartography** is the science of making maps. It's the representation of the Earth or a part of the Earth. There are different types of maps: topographic maps, geologic maps, hydrogeologic maps, geomorphologic maps…

**Map projection** is a representation of the Earth or a part of the Earth on a flat surface.




9.2 IRUDIA
Proiekzio kontzeptua.

(X, Y, and elevation)

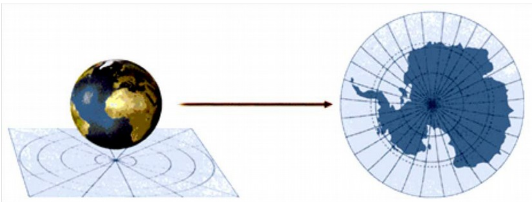
**Geographic coordinates**
Spherical coordinates from Earth's center
(latitude, longitude)
Unprojected
Units: decimal degrees

**Cartesian coordinates**
Planar coordinates (X, Y)
Projected onto a 2-dimensional flat plane
Units: meters

Flattenable surfaces: flat plane, cone, cylinder…

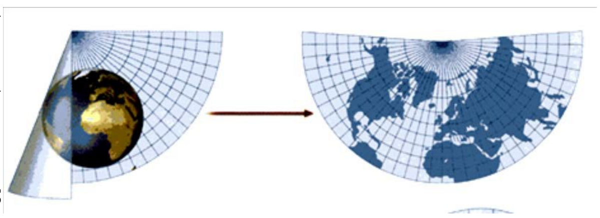
There will be a distortion: shape, area, distance or direction.

***Planar (or azimuthal) projection***
The plane usually centered upon a hole
Paralells form concentric circles
Meridians straight and convergent towards the poles.



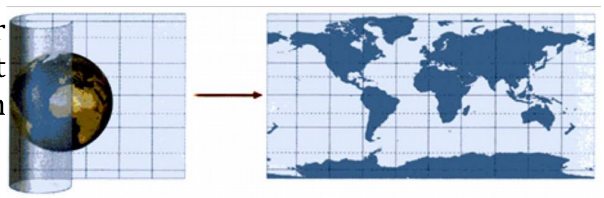
***Conical projection***
The line of contact (cone&globe) → a parallel in the mid-latitudes
Parallels are curved and concentric arcs, and meridians straight and convergent.

Deformation is little in mid-latitudes, increases as we move away.

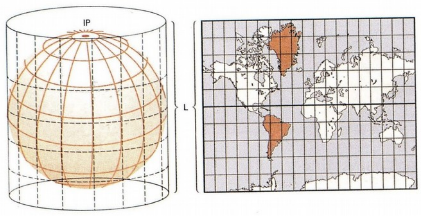


***Cylindrical projection***
Earth's surface projected onto a cylinder frequently tangent to the equator. Straight meridians and parallels, variable distance between parallels.

Deformation: little near the equator, increases to the poles. Consistent shape, variable area.

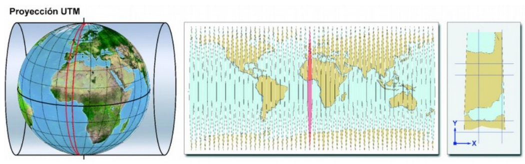


- ***Mercator projection***



Earth's axis parallel to cylinder axis. Meridians and parallels at right angles. Shape consistent, size of features is variable (to the poles). Away from the equator deformation increases.

- ***UTM (universal transverse mercator) projection***
  Describes UTM zones (husos horarios). The cylinder is planes 60 times for each zone. Different meridians as central lines. Great for mapping narrow areas.
  60 utm zones, (6º) and 20 designations
  A, b, y z zonak eztaude eztakit zeba???? bean amak ulertukou




**Coordinate systems**

- Longitude: from the Greenwich meridian 0-180º E or W
- Latitude: from the equator, 0-90º N or S
- The UTC divided by 1000. For calculation, distance in meters X 1000

**Scale** is the relationship between a distance on a map and the corresponding distance on the ground. It can be fractional (1:100.000) or graphic ( 0__________10km)

**INTERPRETATION OF TOPOGRAPHIC MAPS**

Representation of the **relief.**

- An orientation indicator (a north arrow)
- Geographic and/or UTM coordinates
- Scale
- Height or elevation (above sea level): contour lines: connect points on a map that have the same elevation above sea level

**Obtaining contour lines**

Contour lines connect all the points on a map with the same elevation above sea level.

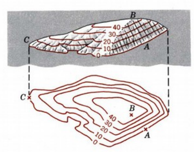
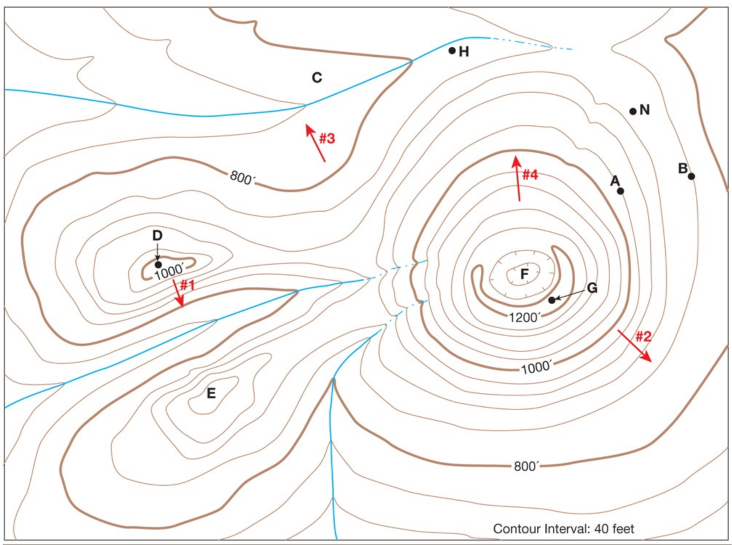
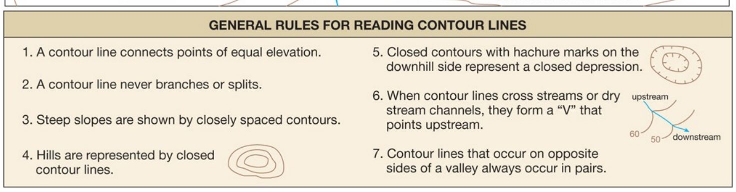



Figura A I.16. En la vertiente escarpada de la isla las curvas de nivel aparecen más juntas.

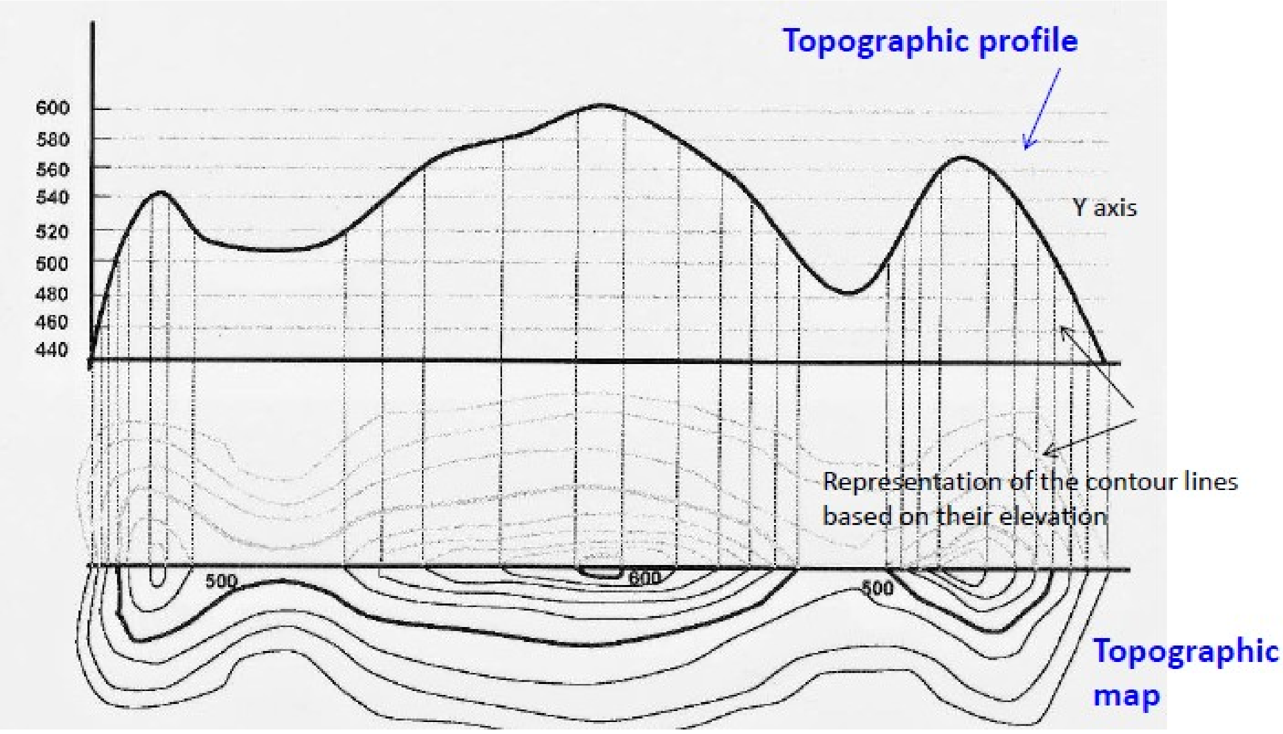


GENERAL RULES FOR READING CONTOUR LINES

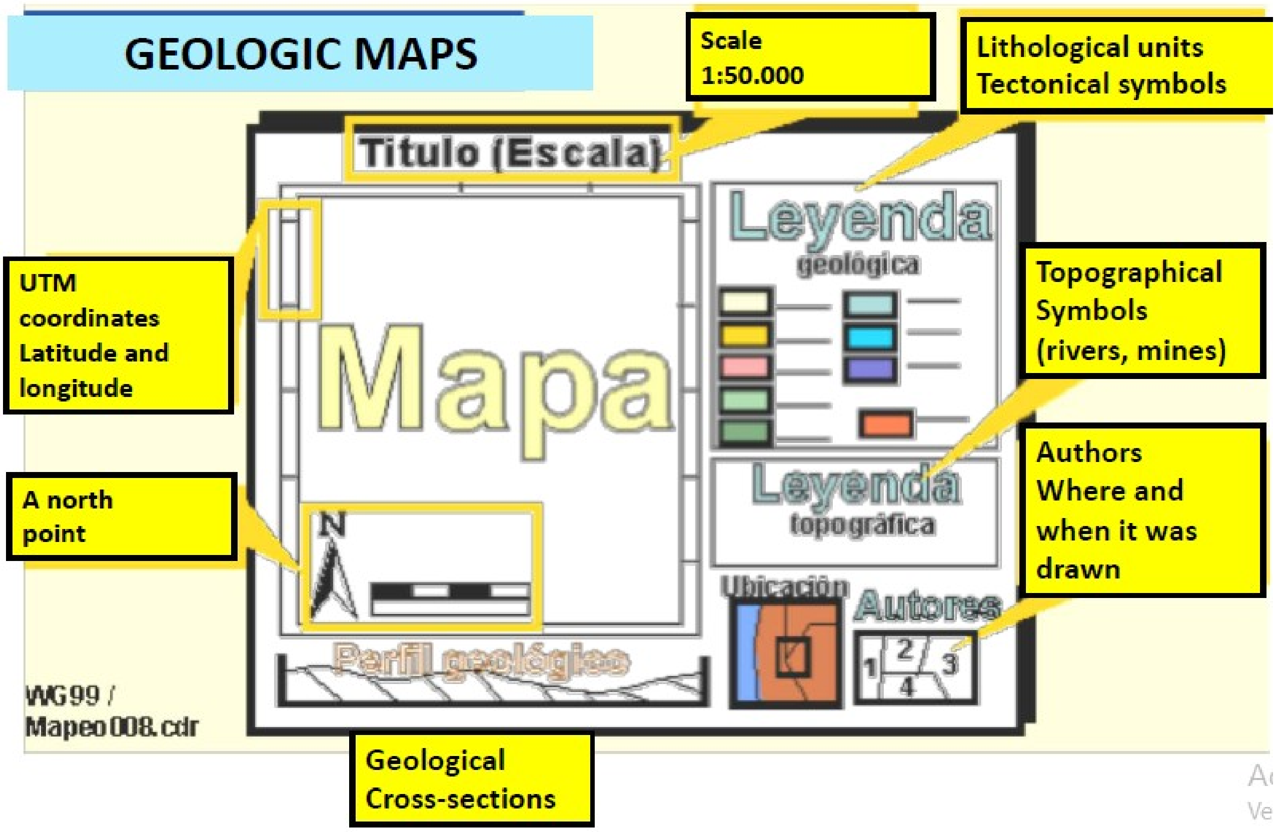
1. A contour line connects points of equal elevation.
2. A contour line never branches or splits.
3. Steep slopes are shown by closely spaced contours.
4. Hills are represented by closed contour lines.
5. Closed contours with hachure marks on the downhill side represent a closed depression.
6. When contour lines cross streams or dry stream channels, they form a "V" that points upstream.
7. Contour lines that occur on opposite sides of a valley always occur in pairs.

**TOPOGRAPHIC PROFILE**




A topographic map is like the view from an airplane, and a topographic profile is the side view.

**GEOLOGIC MAPS**



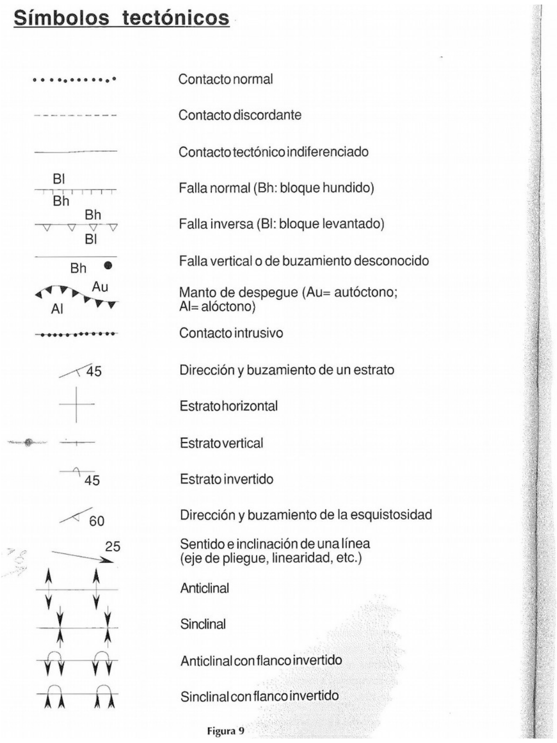
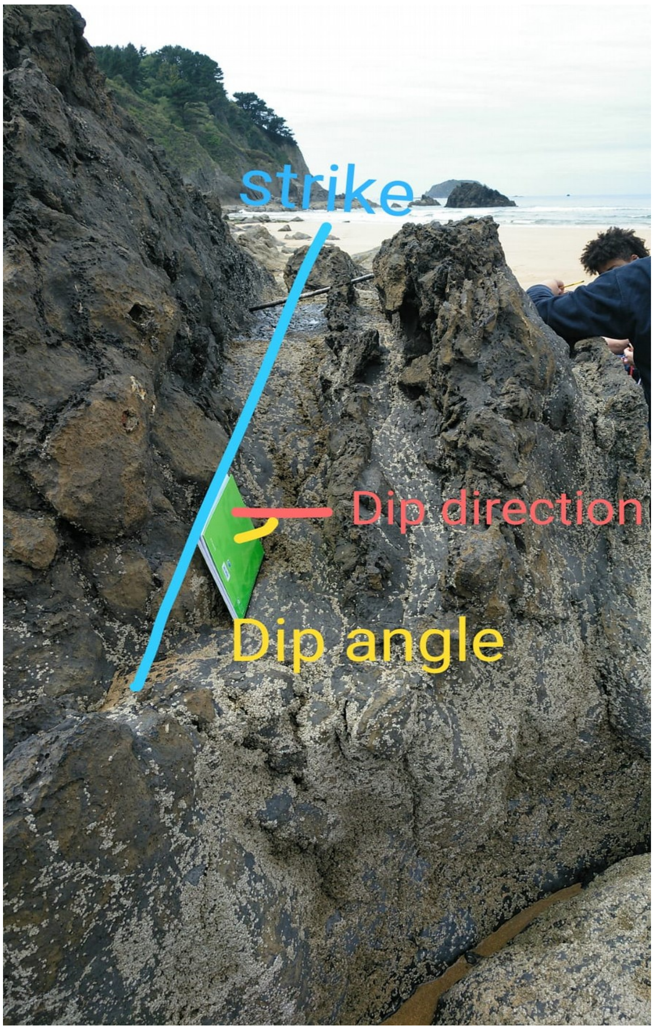



Figura 9

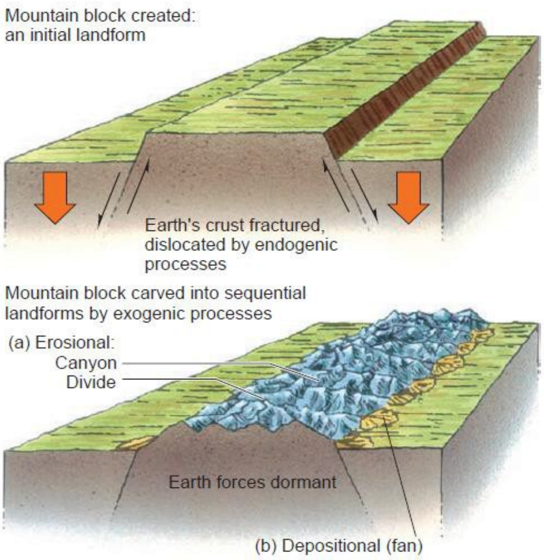

Figura 10



# 14. Geomorphology

- Initial and sequential landforms
- Factors responsible for relief formation
- Fluvial geomorphology
- Karst relief
- Marine morphology
- Glaciers and pleistocene ice sheets
- Aeolian geomorphology

## INITIAL AND SEQUENTIAL LANDFORMS




**12.2 Initial and sequential landforms**
An initial landform is created, here by tectonic activity, then carved into sequential landforms.

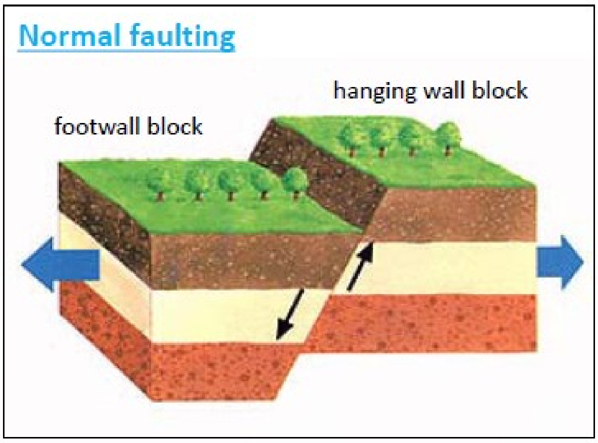
**Initial landforms** are created by endogenic (internal) processes, by tectonic processes (faults, folds, magmatism, volcanism…)

Sequential **landforms** are created by exogenic (external) processes, such as weathering, mass movements, erosion by rivers, glaciers, winds….

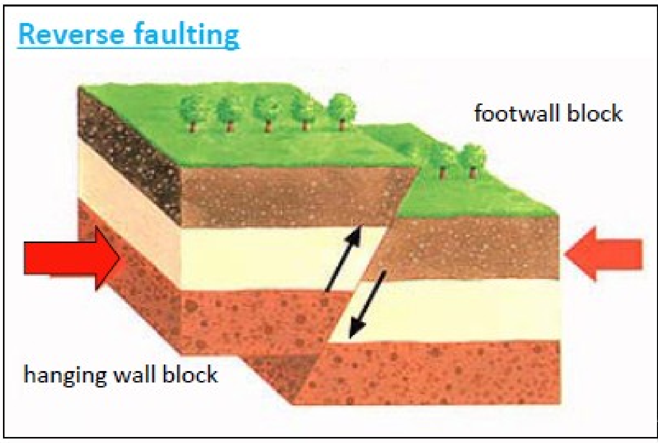
### Tectonic processes

*Faulting*
Differential stress causes deformation: stress=force/area

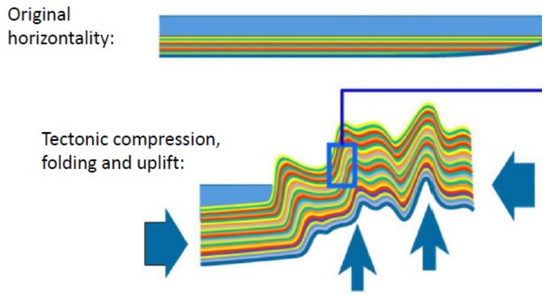
**Divergent plate boundaries**
**Tensional stress:**

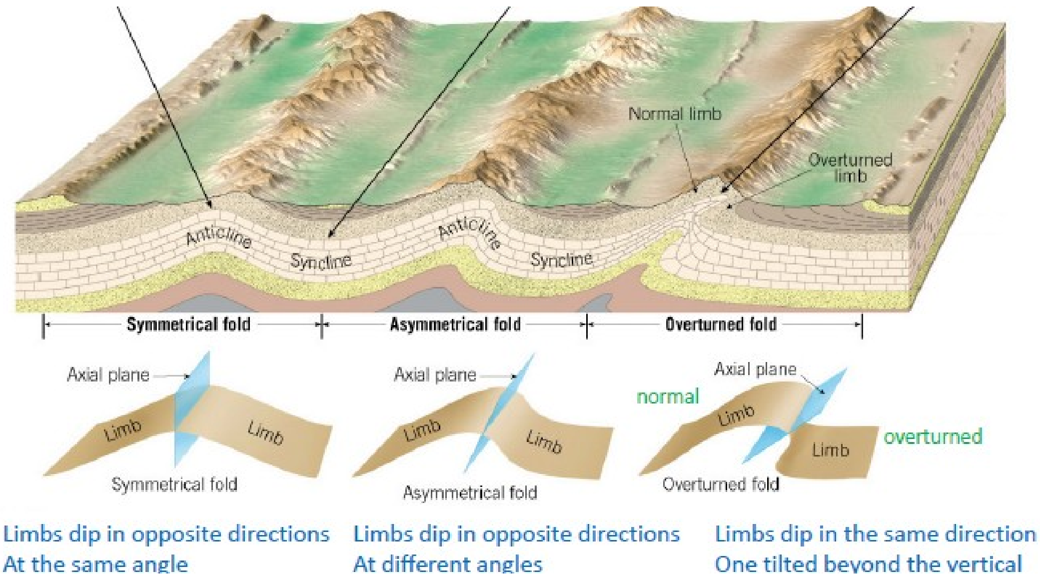



**Convergent plate boundaries**
**Compressional stress:**



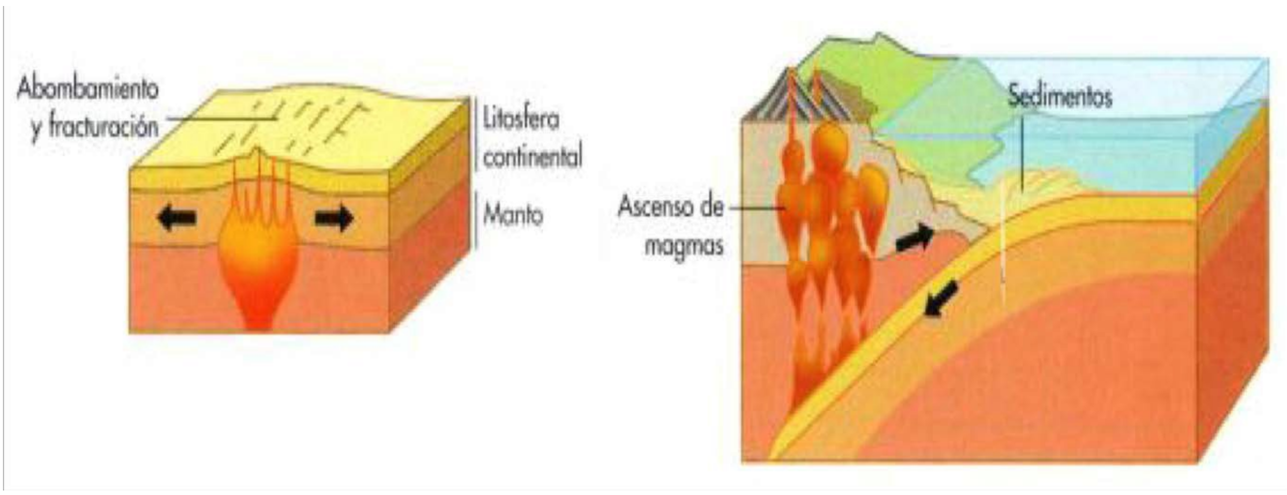
*Folding and uplifting*




*Magmatism and volcanism*

Uplifting → positive relief



Sequential landforms (erosion).
Folded sedimentary strata. Anticlines not always as ridges and synclines not always as valleys.

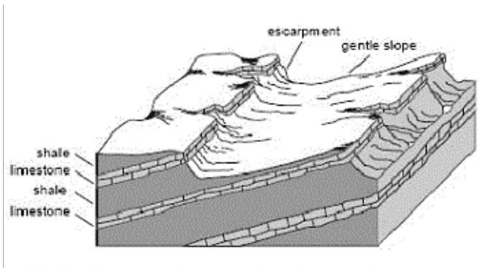
Ridges and valleys are created by differential weathering and erosion. Sandstones, limestones and igneous rocks will be more present in ridges, and shale, slate and marl will be more present in valleys due to the lithology; as the first rocks are harder so it will be more difficult to erosion them.

Inverted reliefs → anticlinal valley (f.e Urdaibai) or synclinal ridge.

**FACTORS RESPONSIBLE FOR RELIEF FORMATION**

- **Tectonic processes**: folds, faults, volcanoes...
- **Lithology**
- **Climate**: temperature and precipitation → weathering
- **Erosion:** water, wind, ice, gravity...
- **Human activity:** quarries, dikes, dams…

Lithology: depending on the materials, the weathering and erosion will be different due to the different hardness of the materials.



*Cuesta topography developed in gently dipping, alternating hard and soft rock layers.*

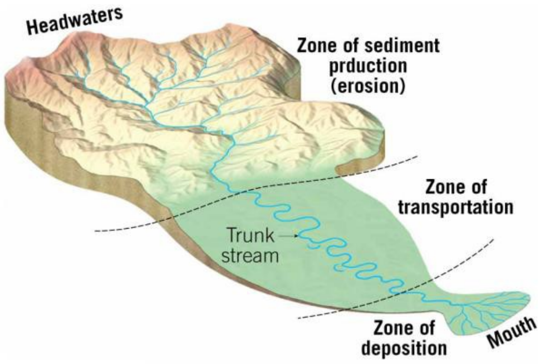
*Cuesta topography* created due to the differential erosion.

Gravity and mass movements happen after weathering breaks rocks apart. Due to the mass movement, debris flows downslope.

**FLUVIAL GEOMORPHOLOGY**

- Stream erosion
    - Abrasion (physical)
    - Corrosion (chemical)
- Sediment transportation by streams
    - Dissolved load
    - Suspended load
    - Bed load (saltation, sliding, rolling)
- Sedimentation by streams
- Meandering and braided channels
- Base level
- Evolution of rivers (valley deepening and widening)
- Stream terraces

## Zones of a river




Coarse sediment upstream
Ocean: fine sediment; clay, silt and fine sand.
Sediment is being eroded, transported and deposited along the entire length of the stream. The dominant process is different in each zone (erosion, transportation and deposition).
Larger sized particles upstream, and finer sized particles in the end, close to the final destination which usually tends to be the sea.

## Streamflow

<u>3 Factors</u> affecting flow velocity

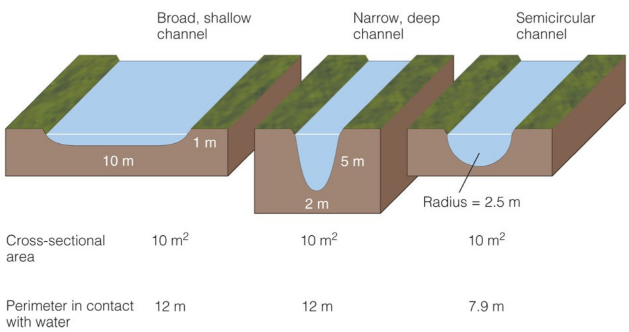
- The slope or gradient of the stream (vertical drop over a distance)
  - A steeper gradient has more gravitational energy to drive channel flow. (more gravitational energy that will transform into kinetic energy. Aldapa gexo → azkarro).

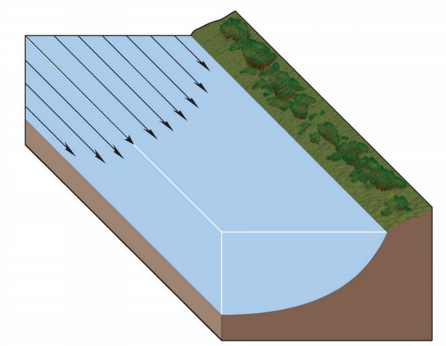
- Channel shape
  - The most efficient channel has a small wetted perimeter compared to its cross-sectional area (less frictional resistance)

Same cross sectional area, but the wetter perimeter is smaller, so there is less friction and the velocity will be faster. (semicircular channel)

- Discharge (precipitation)
  - Discharge is the volume of water passing by a certain point in a certain amount of time
  - Multiplying a stream's cross-sectional area by its flow velocity Q=VxA (m3/sec)
  - When discharge increases, the width and depth increase (reduces friction)
  - Flow velocity will increase

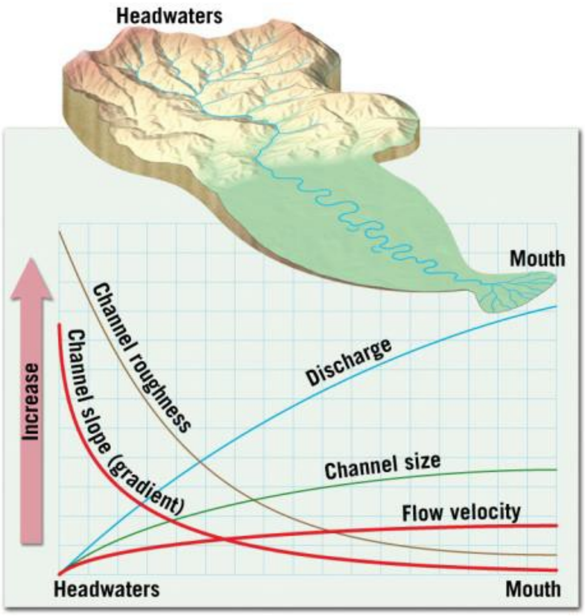
Frictional resistance is found near the banks and the bed of the stream channel.



**Changes downstream**

A longitudinal profile is a cross-sectional view of a stream. Most longitudinal profiles have a concave shape (decrease in slope). Head or headwater is the source of the stream. Mouth is the downstream point where the stream empties into a larger body of water (river, lake, ocean).




General overview of a river as we go down in a river (longitudinal profile):

- Gradient: *decrease* (Upper part → big gradient, then is gentler)
- Discharge; *increase* (Because there is more water in the river)
- Channel size: *increase* (Because there is more water in the river, because ibai gexo juntatzei)
- Sediment particle size: *decrease*
- Flow velocity: *decrease*

Channel slope decreases but flow velocity increases because:

- Channel size and discharge increases
- Channel roughness decreases

*Gradient is steeper or gentler as the slope decreases. Discharge will increase because tributaries (ibai txikixek, afluentes) join the larger river. Channel size increases to accommodate the growing volume of water. Sediment particle size will be reduced, so the channel roughness will be reduced as well. In the upper part, there will be bigger sized particles on the bottom of the river that will make the channel rough, but as sediment particle size is reduced they're also smoothed so the channel roughness will be reduced as there won't be more bigger sized particles in the bottom of the channel. In general, there will be a slightly high velocity that will compensate the decrease in slope (if we take in account the decrease in channel roughness and the increase in the channel size ...)*

<u>Stream erosion</u>

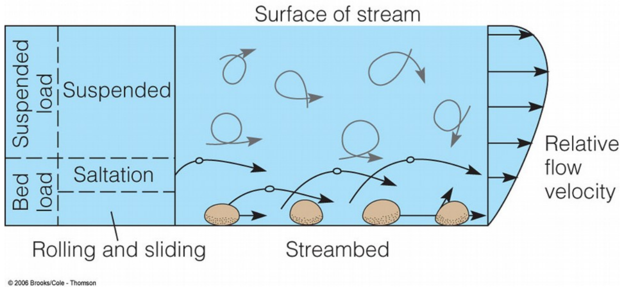
- Solid particles from the banks

- *Land falls by gravity (eroi sedimentuk, ordun ibaxek hartu laizkettu o erosionau ta it incorporates them to the flow).*

<u>Abrasion (physical weathering):</u> the motion of little particles (sand and graved) will erode bed and banks of a bedrock channel. There is a reduction in the size of transported sediments and particles are smoothened and rounded due to the physical abrasion. (Explanation to the smoothing, rounding and size decreasing as we go down in a river)

* Chemical weathering can also happen (corrosion) in soluble bedrock limestone.

**Sediment transportation by streams:** based on the particle size

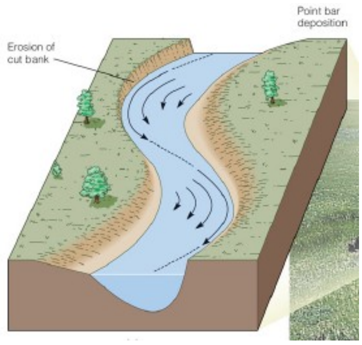



- Dissolved load (by groundwater, percolates - dissolved ions)
- Suspended load (largest part): very fine sand, silt and clay (*during a flood event we might get larger particles f.e coarse grained gravel...*)
- Bed load (saltation, sliding and rolling): coarse sands and gravels that move along the bed
  - Saltation: collision or lifted by the current (intermittent lifted → eztao denbora osun lifted bestela suspended load izengo zan)
  - Sliding and rolling along the bottom: particles too large for saltation

**Competence:** heaviest particles a stream can transport.
As velocity increases, it will be able to transport larger sized particles. And also, if the discharge is larger, the competence will also increase.
In summary, most of the erosion and transportation will be produced during flooding event, when the competence is increased.

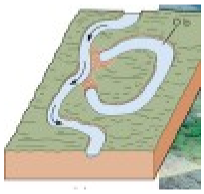
**Capacity:** maximum amount of solid load (bed and suspended) a stream can transport
Conditioned by the velocity and the discharge of the river.

**Meandering streams**
A single channel with meanders.




Cut bank-→ where the velocity is greatest and erosion happens.
Point bar → where the sediments eroded from the cut bank accumulate.

Transport mostly in suspension: mud and sands (fine gravel)

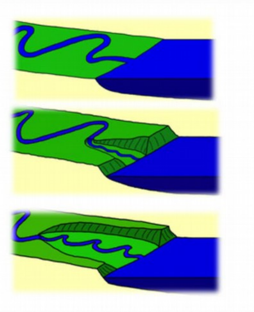


Bends can migrate towards the cut bank and they end up joining, making an area isolated (OXBOW LAKE).

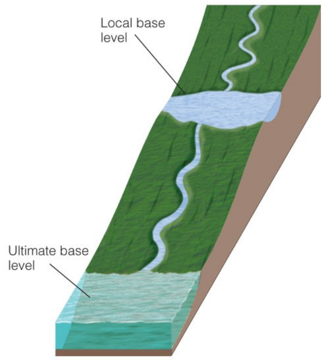
**Braided streams**
Very large bed load and high sediment supply. They tend to carry much more sediments as bed load, they won't have a single channel.
A river at the end of a glacier. Summer, large discharge, in periods of low discharge, less water it will deposit the sediments, forming the bars.

## Base level

Conditioned by the location of the ocean or the lake. (lake –> local base level, ocean ultimate base level)

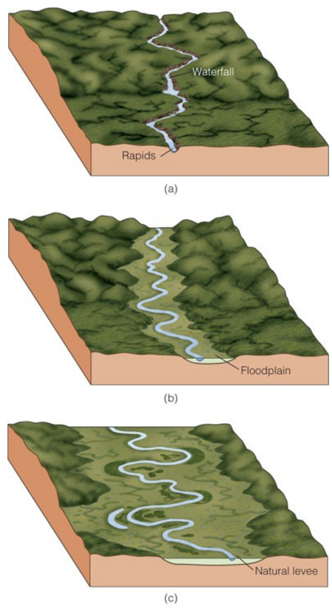


Downcut of the channel to equilibrate with the position of the sea level, to lead (the water to the sea). Sea level is always the ultimate base level. Depending the height, the river will excavate to be in equilibrium with the sea level.




(b)

## Stream evolution






Youthful stream:

- Steep sloping = well above base level
- Downcutting dominates (Erosion)
- V-shaped valleys

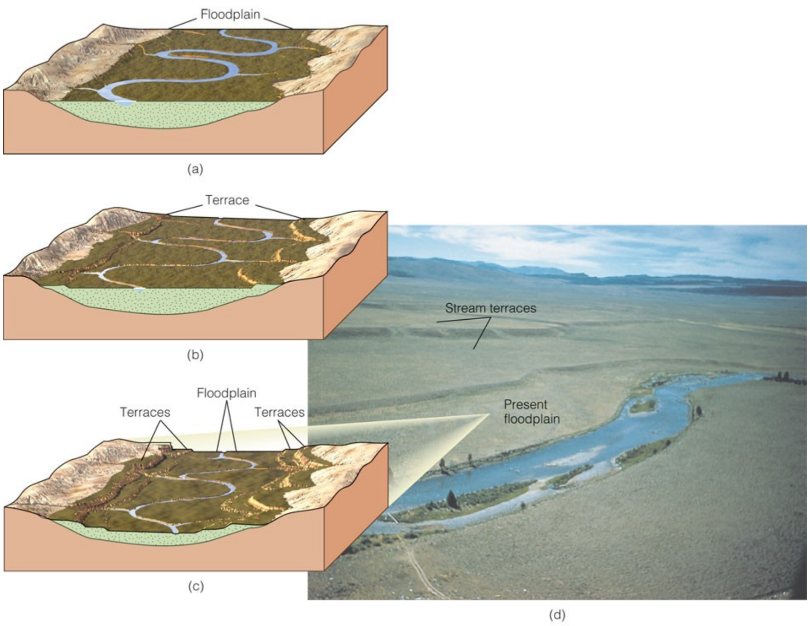
Mature stream

- Gentle slope and a floodplain
- Meanders and flood plain relatively similar width

Old age

- Very gentle slope
- Very broad flood plains (5-8 times the channel width)

## Stream terraces





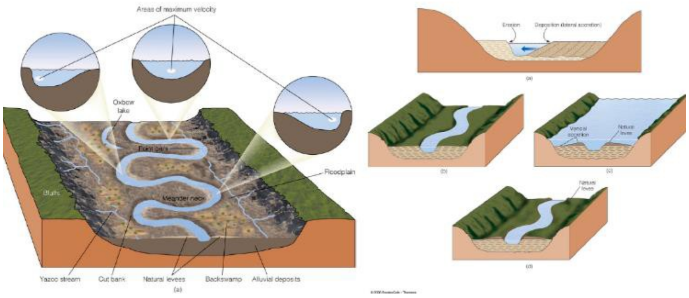

**1.** Stream meandering on its floodplain
**2.** Downward erosion (Drop in base level); produces a new floodplain (lateral erosion) and the terrace will be the elevated remnant of the former floodplain.
**3.** Downward erosion (Second drop in base level). Second set of terraces.

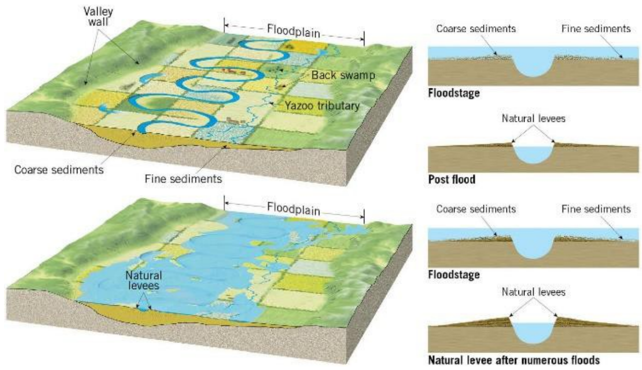
## Natural levees and floodplain deposits

VELOCITY, EROSION
DEPOSITION, POINT BARS
LATERAL ACCRETION
SAND AND GRAVEL

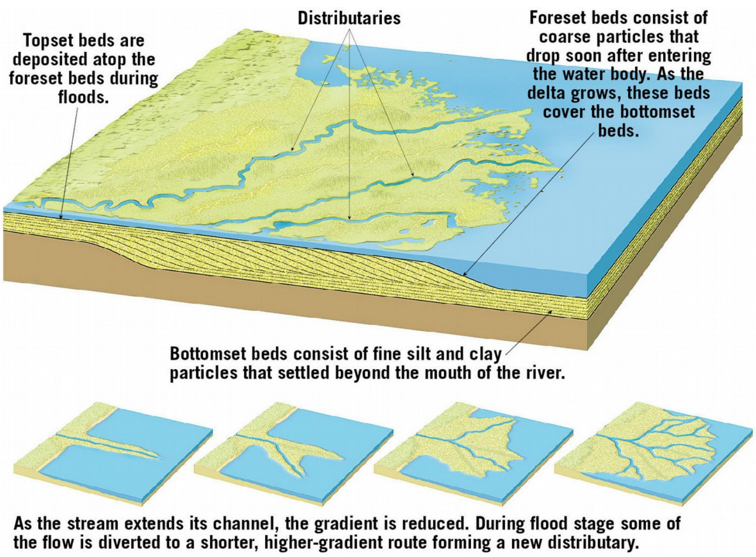
MUDS (PERIODICALLY OVERFLOW, BANKS)

MEANDERING RIVERS, FLOODS
NATURAL LEVEES
VELOCITY/DEPTH DROP
SAND MARGINS, MUD SETTLE
GENTLE SLOPE (DIFFERENTIAL GRAIN SIZE)

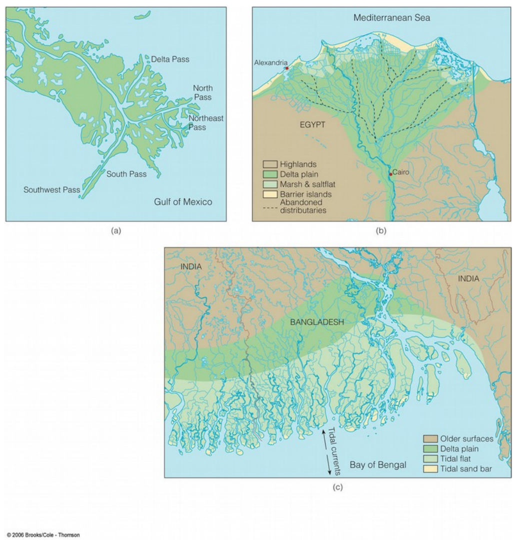





## Deltas

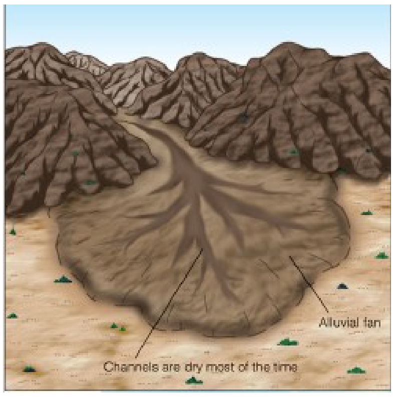



In sediment charged streams, when it arrives to a standing body of water (lake or ocean),velocity slows down and sediments are deposited.
Progradation happens, where shoreline moves toward the lake or ocean.




Different types of deltas:
- Stream dominated deltas: finger-like sand bodies
- Wave-dominated deltas: barrier islands reworked by waves
- Tide-dominated deltas: tidal sand bars II tidal currents

**Alluvial fans**




These are fan-shaped deposits found in mountain fronts. Happens when velocity is reduced due to the sudden drop in the gradient; when it goes from a steep gradient to a flat lowland.

This geomorphology is common in arid climates with little vegetation and poor stabilization of sediments. Due to the periodic rainstorms, the surface runoffs.

**KARST RELIEF**

Karst relief is a special relief created when slightly acidic rainwater reacts with the calcite found in limestone.

There are two types of processes: endokarst (groundwater) and exokarst (surface processes)

<u>EXOKARST</u>

***Lapiaz:*** deep grooves separated by ridges. It can be covered by soil. The grooves can be from a few millimetres to several metres deep.

***Karst canyon:*** a steep-walled and narrow chasm.

***Doline (or sinkhole):*** funnel-shaped closed depression. A dissolution doline happens when the dissolution of soluble rock below the soil happens. Collapse doline happens when a cave's roof collapses.

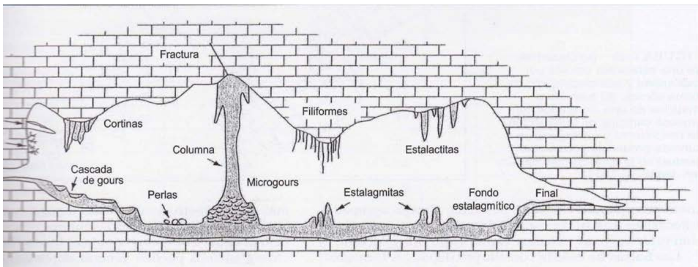
***Uvala***: when adjacent dolines merge (hundreds of meters in diameter)

***Polje:*** larget depressions in karstic landscapes. Wide closed depression, very flat bottom, with rivers often flowing through them.

***Karst spring:*** natural discharge of water (groundwater). Precipitation of dissolved carbonate creates calcareous tufa, porous carbonate deposits.

<u>ENDOKARST</u>

Dissolution mainly up to the water table. Vertical and horizontal caves.



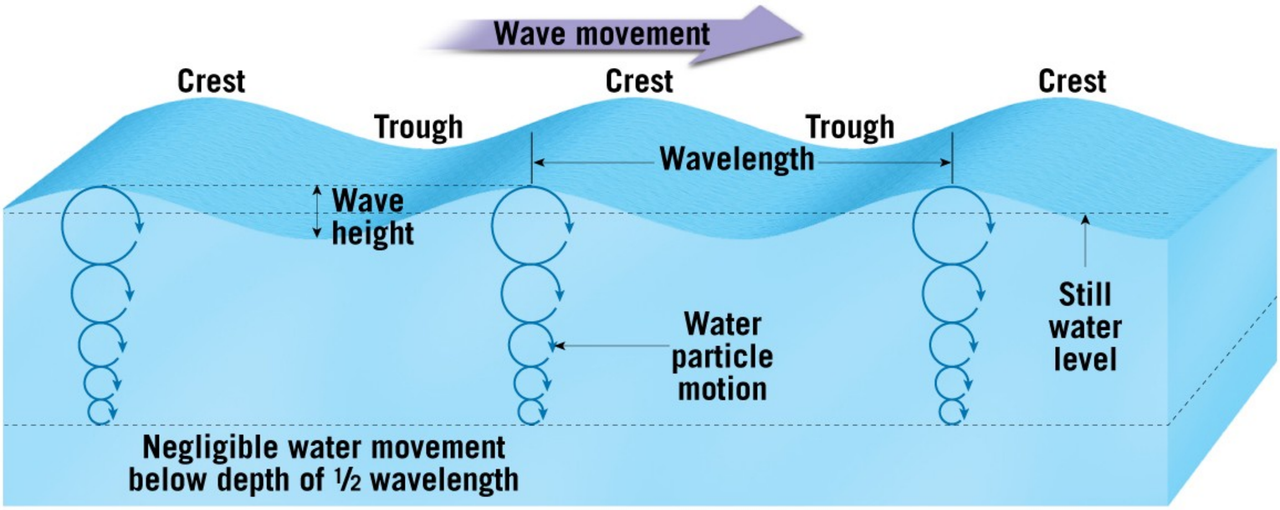

Location, orientation and shape controlled by geological features that facilitate dissolution (e.g. bedding planes…)

**Deposits** by gravitational collapse or carried and deposited by stream.

Speleothems, carbonate precipitation: stalactites, stalagmites, columns, drip curtains…

**COASTAL MORPHOLOGY**
Geomorphology controlled by physical processes: waves, tides and nearshore currents.

**Waves**
Oscillations of a water surface due to wind: erosion, transport and deposition of sediment

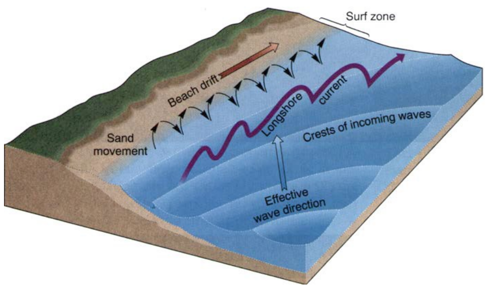



Period: the time it takes for one full wavelength to pass.

The wave base is unaffected by surface waves.

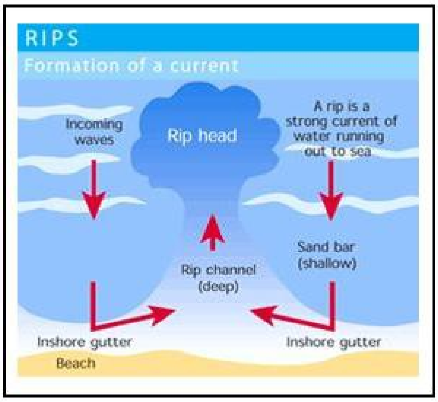
When the waves approach the shore, wave shape changes → sharp-crested waves (breakers)

Waves bend nearly parallel to the shoreline. Wave energy is dispersed in bays, and concentrated on headlands.




**Longshore currents**
Sand movement on the beach. Water flows parallel to the shoreline and sediment is transported in a zig-zag pattern.

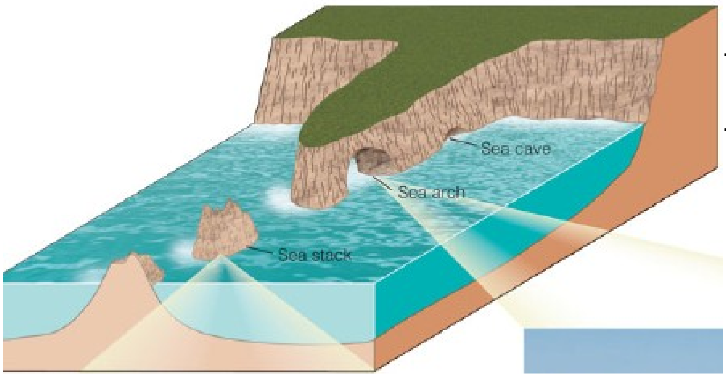
**Rip currents**
Water goes back to the sea, narrow and perpendicular to the shore.



## Wave erosion

- Sea cliff (steep slopes): storm waves abrasion makes base to migrate landward
- Wave-cut platform (gently sloping surface): and wave-built platform or terraces

-Marine terrace: tectonically uplifted

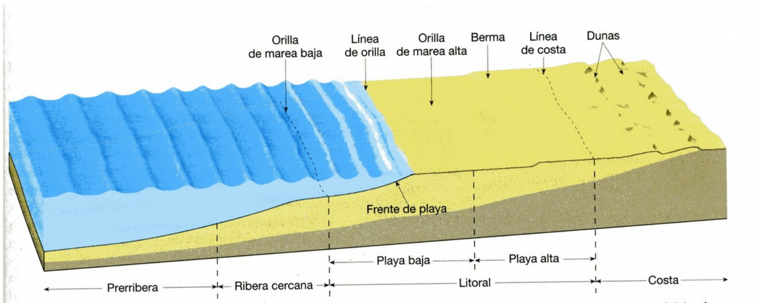



- Sea caves: opposite sides of a headlands
- Sea archs: to caves join
- Sea stacks: collapses

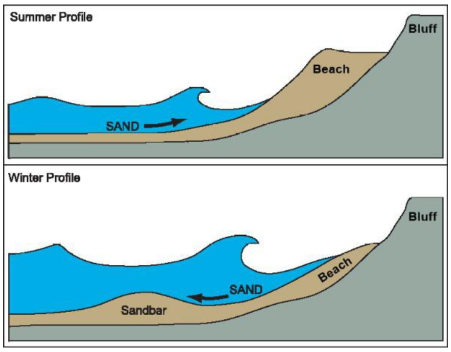
## Sediment deposit

Results from longshore currents

- Beach: unconsolidated sediment above low tide (Sand dune, sea cliff)
    - Backshore: berm (dry)
    - Foreshore: covered by water when high tide and exposed when low tide
      Winter storms erode so the profile of the beach changes.

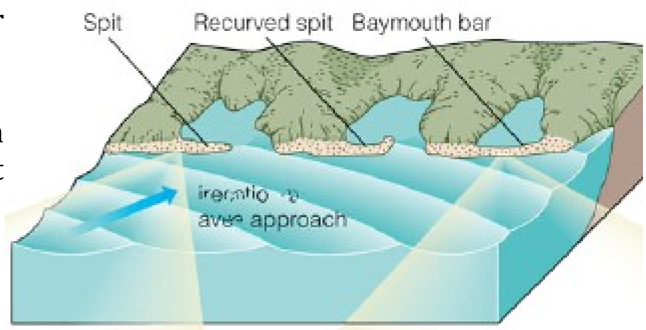


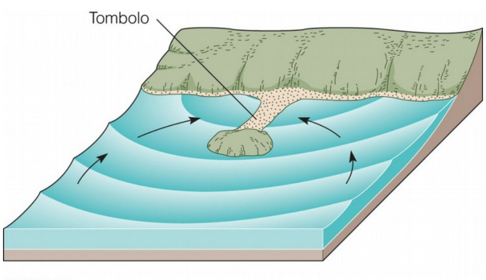

▲ **Figura 20.2** La zona litoral está formada por varias partes. La playa es una acumulación de sedimento en el borde continental del océano o de un lago. Puede considerarse un material de tránsito a lo largo de la costa.




- Continuations of a beach: spit → Baymouth bar → coastal lagoon

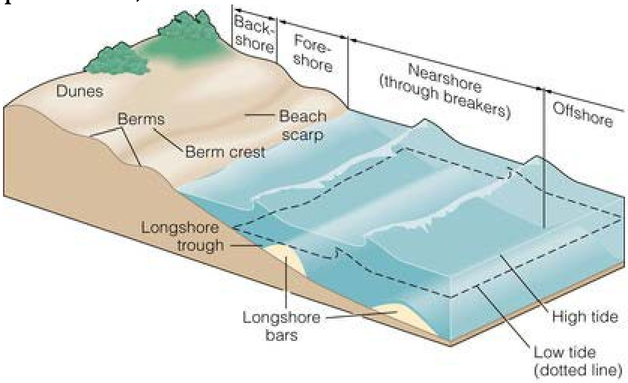
- Tombolo: narrow sediment accumulation between the island and the shore line, at right angles to the shoreline.

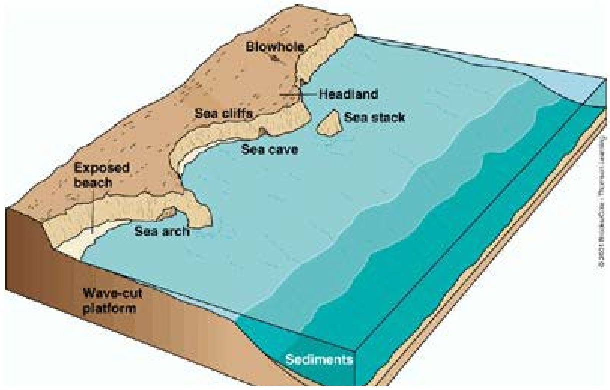


## Types of coasts

- Depositional coasts: sandy beaches, deltas, barrier islands…
- Erosional coasts: steep and irregular; beaches in protected areas, sea-cliffs, wave-cut platforms, sea stacks…




- Wave dominated coasts: sea cliffs, wave-cut platforms, headlands, bays, beaches, tombolos, spits, coastal lagoons… (hemengo hondartzak)

- Tide dominated coasts: sand lower estuary and mud upper estuary. Tidal flats and salt marshes. (Urdaibai)

- River dominated coasts: deltas, floodplain and marshes

## Submergent and emergent coasts

- 120 m lower (LGM) Holocene marine transgression
- Formerly glaciated regions. Because of the isostatic rebound (the rise of land masses after the lifting of the huge weight of ice sheets during the last glacial period, which has caused isostatic depression.

## GLACIERS AND PLEISTOCENE ICE SHEETS

A **glacier** is a body of ice on land moving downslope/outward. (Excluding sea ice and icebergs).

## Valley glaciers

Confined to a mountain valley. The slope determines the direction of flow. It's long and narrow.
- Piedmont glacier → spread onto a plain
- Tidewater glacier → terminate in the sea

## Continental glaciers

Ice sheets of at least 50000 km$^2$. They are unconfined and flow outward in all directions. (Greenland, Antartica)

## Glacier formation

When more snow falls than melts (warmer season) → net accumulation

Snowflakes (10% solid) → granular ice → firm → glacial ice (90% solid)

## Glacier motion

Accumulated ice thickness: 40 m--> plastic flow (permanent deformation)
Basal slip: liquid water (base) reduces friction. Glacier slides over the rock.
Basal sliding and plastic flow EXPLANATION: A valley glacier has various components of flow. First, the entire glacier moves as a single mass over the underlying rock surface. The pressure from the weight of the glacier generates a layer of water that helps the ice glacier move downslope. This process is called basal sliding. In addition to basal sliding, which slowly moves the glacier downslope as a unit, plastic flow causes glacial ice buried underneath more than about 50 meters to move like a slow-moving, plastic stream. The central and upper portions of a glacier, as do those portions of a stream, flow more quickly than those near the bottom and sides, where friction between the ice and valley walls slows down the flow. In general, the rate of plastic flow is greater than the rate of basal sliding.
Velocity: slope, thickness, temperature
Friction with walls and floor
Valley glaciers are more rapid. Continental glaciers are at higher latitudes (frozen, little basal slip)
Top: brittle behavior
When slope increases ice is stretched

## Glacier budget

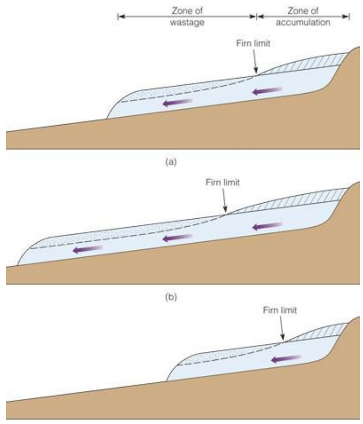
The glacial budget is a term used to describe how glaciers change, move, grow, and shrink throughout the seasons. The glacial budget is affected by things that make them grow such as ice, snow, and debris; the shape that is takes as it forms; how it moves through the water; and by what makes them shrink such as evaporation/vapor, breakage as it hits objects, and melting. Sometimes the glacier can gain more accumulation than what it loses over the course of a year which is called zone of accumulation. Other times the glacier loses more mass than it gains which is called zone of ablation. This constant growth and loss at various rates changes how fast the glaciers move and in what direction they go. All these concepts make up the glacial budget.

Expand & contract
Upper part in a valley glacier: zone of accumulation (permanent snow cover)
Lower part: zone of wastage : melting, sublimation, and calving of icebergs → accumulation
Antarctica is a zone of accumulation and the ocean the zone of wastage.

<u>Firn limit:</u>
In spring and summer snow begins to melts → it's a wastage season.
Stable firn limit: glacier has a balanced budget, terminus remains in place

Firn limit moves down (terminus advances) → positive budget
Firn limit moves up (terminus retreats) → negative budget

Because of the climate change glacier retreat is happening in all the glaciers in the planet.



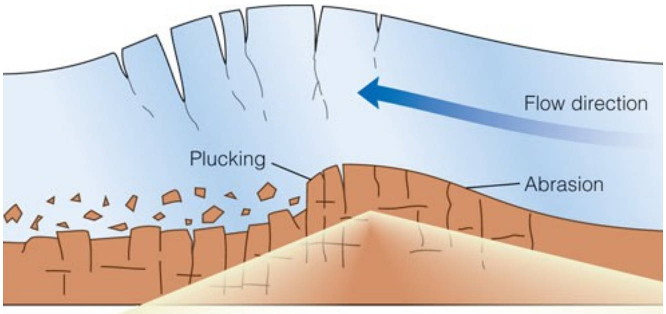
**Erosion**

OBSTACLE ( e.g. a small hill)

Plucking: glacial ice freezes in the cracks of the bedrock and then pulls away rock fragments downstream

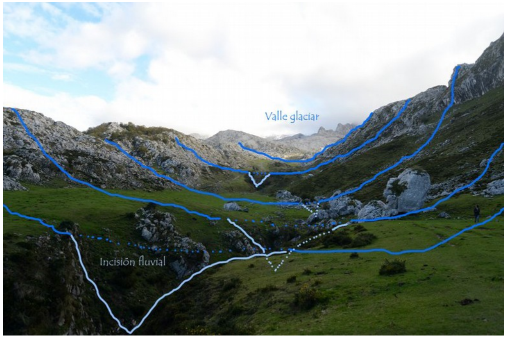
Abrasion: smoothes the upstream

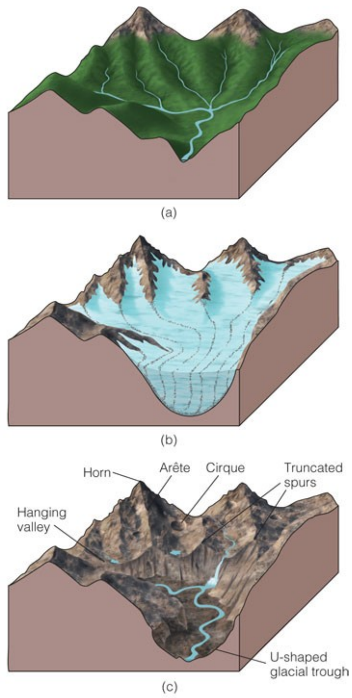
anywhere else –> sediment carrying ice –> GLACIAL POLISH AND GLACIAL STRIATIONS




*Origin of a roche moutonnée. As the ice moves over a hill, it smooths the "upstream" side by abrasion and shapes the "downstream" side by plucking.*

When a stream flows over a U-shaped valley it transforms into a V-shaped valley.




*Erosional landforms: Horn, Cirque, U-Shaped glacial trough, hanging valley*

A fiord is a glacial valley filled by the ocean (steep-walled embayment):

**Transport and deposit**

Glaciers can transport any size of sediment.

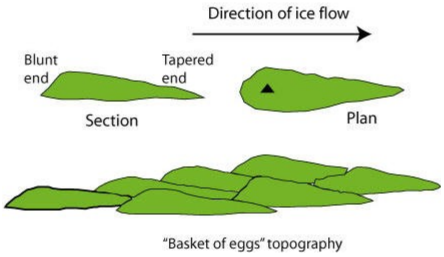
In continental glaciers, most sediment is transported in the lower part of the ice sheet, and in valley glaciers, sediment is transported on the floor and walls (abrasion, plucking, rock fragments fall onto its surface).

Glacier deposits moraines.

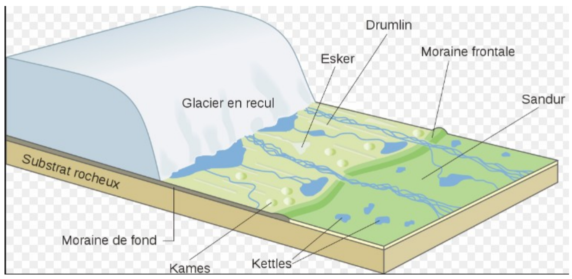
Tills are any sediment deposited directly by glacial ice. They are not sorted and they are angular. There's no layering. Landforms are composed of till, moraines and drumlins.

Drumlins are elongated hills made of till (subglacial debris).

Glacial erratics are large isolated rock fragments transported and deposited by the glacier and located to a distance from the source. *(Tipiko harri haundixek)*



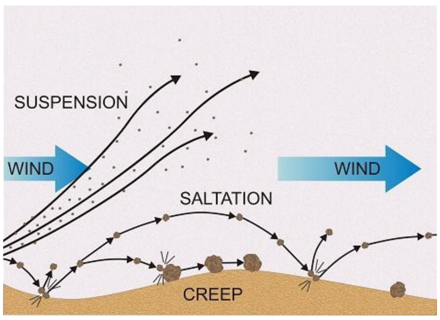

Kame → mound-like hill of stratified drift
Esker-→ deposited by streams flowing beneath the ice
Kettle lakes → fine fluvial sediments from glacial melting




## AEOLIAN GEOMORPHOLOGY

Deserts are located between 20º and 30º of latitude.

### Sediment transportation

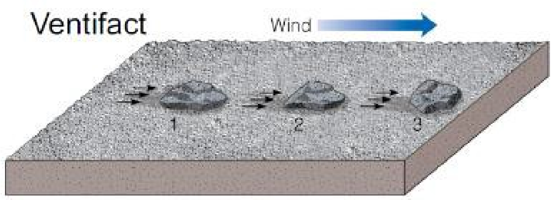


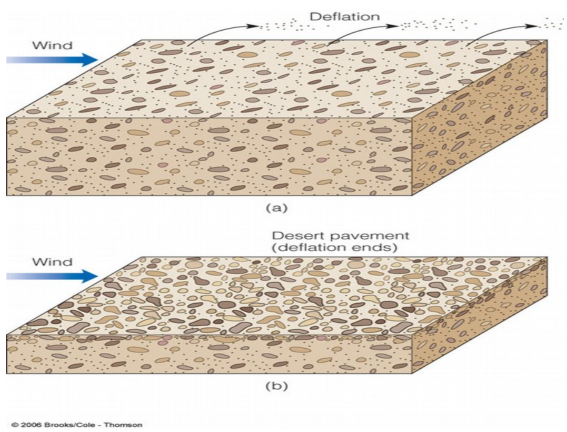

### Erosion

2 types of wind erosion: abrasion and deflation

-Abrasion: Yardangs and Ventifacts (A ventifact forms when wind-bone particles abrade the surface of a rock forming a flat surface. If the rock is moved, additional flat surfaces are formed.)
-Deflation: fine-grained material is removed by wind leaving a concentration of larger particles that form desert pavement

Yardang



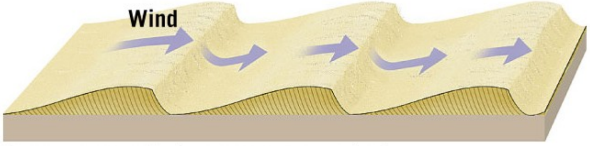



## Wind deposits

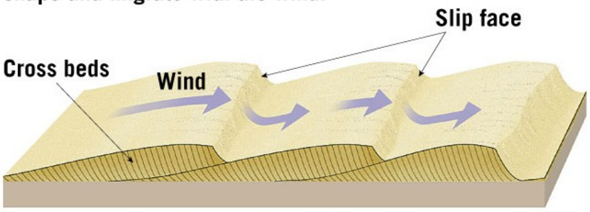
DUNES

-ERG, sand sea (erg (also sand sea or dune sea)= la región arenosa de un desierto.)

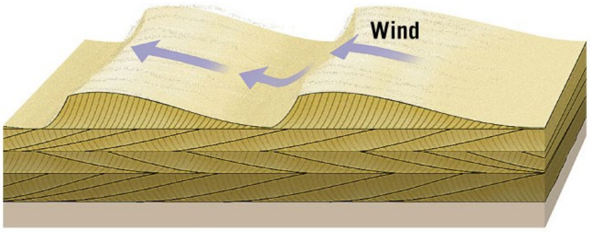
-Mounds (montículos) or ridges (krestak) of wind-deposited sand




Dunes commonly have an asymmetrical shape and migrate with the wind.



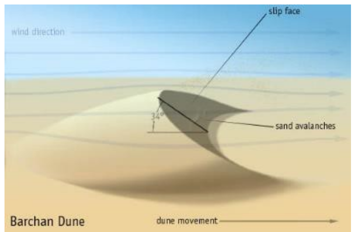

Sand grains deposited on the slip face at the angle of repose create the cross-bedding of dunes.



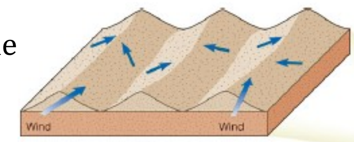

When dunes are buried and become part of the sedimentary rock record, the cross bedding is preserved.

Cross beds are an obvious characteristic of the Navajo Sandstone in Zion National Park, Utah.

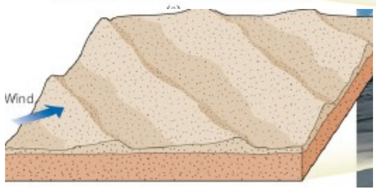
TYPES OF DUNES:



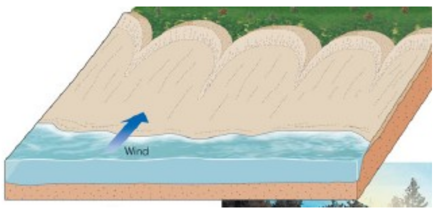

- **Barchan dunes:** crescent-shaped dune
  - Tips point downwind
  - Small (up to 30m high)
  - Flat dry surface with little vegetation



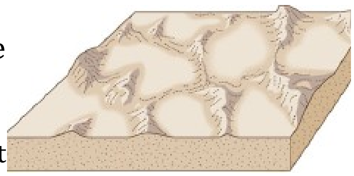

- **Longitudinal dunes**: a large, elongated dune lying parallel to the prevailing wind directions
  - Limited sand supply
  - When winds converge from slightly different directions, they create a principal direction




- **Transverse dunes**: long ridges perpendicular to the prevailing winds
  - Abundant sand and little or not vegetation




- **Parabolic dunes:** they are formed when vegetation begins growing on the ends of a sand dune, holding them in place while the rest of the dune moves ahead. U-shaped mounds of sand with convex noses and elongated arms. The elongated arms are held in place by vegetation
  - Common in coastal areas with abundant sand
  - Strong onshore winds



- **Star dunes**: sand dunes that form in a sandy dessert when the direction of wind changes a lot (very large)

LOESS: particles transported very long distances. Is a clastic silt-sized sediment formed by the accumulation of wind-blown dust.

# 15. Soils

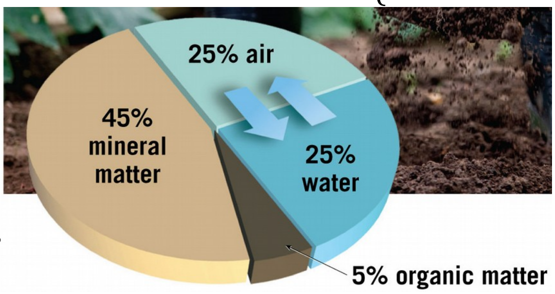
- Soils: concept, structure and composition
- Controls of soil formation
- Polar soils, temperate soils, tropical soils, soils from equatorial regions

## Soils: concept, structure and composition

### *CONCEPTS*

***Regolith***: weather material: rock fragments, mineral fragments produced by weathering of parent material (bed rock (rock underneath) or loose particles that are on a stream body (pebbles, loose grains) that are the parent material of the soils).

***Soil*** evolves from the regolith. It is characterized by some layers (**horizons**) that constitute a vertical layering.
**Soil is produced by weathering** and **biological activity**. Is a combination of **solid** (mineral matter and organic matter), **liquid** (water) and **gas** (air). The mineral matter accounts around 45%, organic matter 5% (half of the soil is solid) and the other half will be air and water.
The organic matter is composed of **leaf litter** (orbela) and the **hummus**. The pore spaces between the particles will be filled with water or air ($CO_2$ or $O_2$). The amount of water will depend on precipitation and permeability.



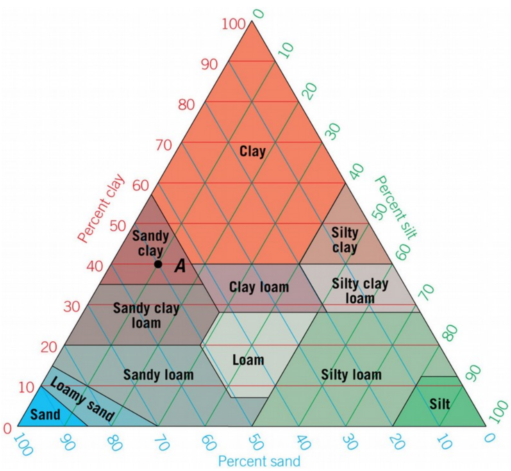

Porosity (the spaces, pores) and permeability (how well the spaces are connected, how easy water can percolate)

Regolith has less components than the soil, it doesn't have organic matter.

### *STRUCTURE AND COMPOSITION*

The **particle size** in the soil: there are different particle sizes in a soil. We can define three different textures:
- Sand (large size)
- Silt
- Clay (small size)

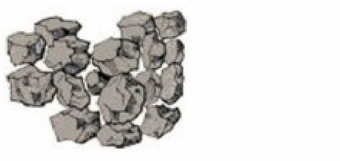
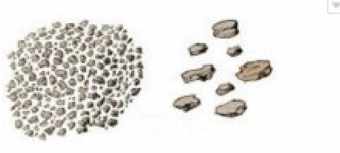
Depending on the relative particle size the texture of a soil can be defined → *trianguloa*
Loam: there's no particle size that predominates over the other two.




Texture is important because it gives us information about how easily can the soil transfer water or air. For example, if the soil is sandy, the water can percolate easier because the pores are bigger and are connected well, so it will dry very easily. In a clay soil, water cannot percolate that easy so it will be wet for a longer time.

Each soil has a different **color**, and a color chart is used to measure the composition of the soil (Munsell Soil Color Chart).

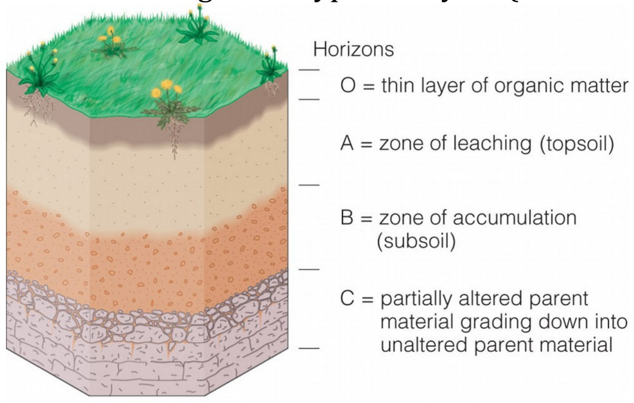
Soil particles tend to clump to give a soil its **structure.**
There are four basic soil structures:

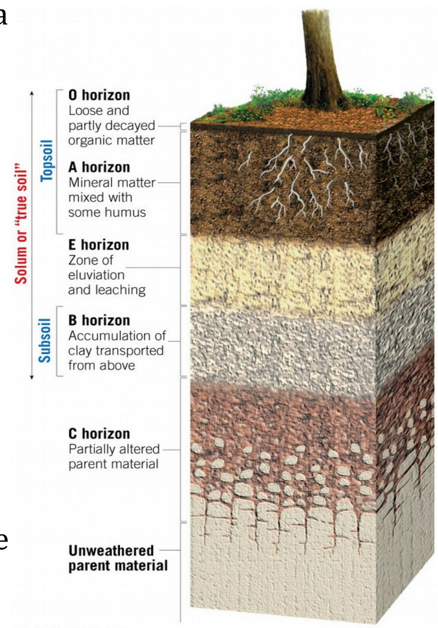
| | |
|---|---|
| Platy |  |
| Prismatic |  |
| Blocky |  |
| Spheroidal |  |

These different structures will influence the porosity and permeability of a soil (how well water is infiltrated). For example, the prismatic or blocky soils tend to be better for water infiltration, and platy or spheroidal soils are more difficult for water infiltration.

## ***SOIL PROFILE***

Soil forming processes operate from the surface downward. Different layers are known as horizons.
A horizon is a vertical section of a soil that show a sequence of layers.
We can distinguish 4 types of layers (horizon 0,A,B,C)




Horizon 0: loose and partly decayed organic matter. We can find living organisms in this horizon.
Horizon A: mineral matter mixed with some hummus.
Horizon 0 and horizon A form the **topsoil**.
Horizon E is where the eluviation and leaching processes happen.
Horizon B is where the accumulation of clay transported from above happen: zone of accumulation (**subsoil**)
Horizon C is the partially altered parent material grading down into the unaltered parent materials.

ELUVIATION: Water moves down, it will carry the clay sized particles.
LEACHING: Water moves down, it can dissolve some of the soluble inorganic components of the soil and carry them downwards.

This would be an ideal soil profile. Even though we study this general profile, we can find different profiles. Sometimes the horizons cannot be distinguished in some soils. This is related to the maturity of a soil. If it has developed horizons means that the climate conditions were good (?) (MATURE SOILS)
If they don't have horizons are inmature soils, for example we can found them in steep slopes.

TOP HORIZON organic matter (plant litter and hummus, living organisms)
A (sometimes with E horizon, we will include it in A horizon) (some hummus and mainly mineral matter)
B (leached and eluviated material from A horizon accumulates (soluble materials and fine grained material)
C (partially altered parent material)
Top horizon and a horizon topsoil and b is subsoil. C horizon is the regolith. Has had some changes, has been weathered, but it has not changed sufficiently to be a soil.

# Controls of soil formation

Parent material

It can be the bedrock or it can be some loose sediment that are on stream valleys. If the parent material is the bed rock the soil is known as the residual soil. If the parent material is loose sediment (has been carried form elsewhere and deposited) is known as transported soil (it doesn't mean that the soil has been transported, it means that the parent material has been transported by ice, wind, water… and have been accumulated in a stream valley and then they became the parent material of this soil.

It can also condition the rate of weathering, so it will also control the soil formation. Limestone, granite... can be easily dissolved by acid water. For example, the weathering of granite will produce plate minerals. The rate of weathering will influence the type of product the soil has.

Depending on the parent material, it will has a different pH, that is related to different vegetation.

Two different soils can be produced from the soil material or two soil materials can produce the same soil, because parent material is not the only factor that influences soil formation.

Topography

The angle of the slope will influence the type of soil. Steep slopes will have very little soil or no soil, because erosion doesn't give time for soil formation. In steep slopes also most of the water instead of being infiltrated.

Very thick soils and dark (a lot of organic matter) can be found in stream deposits.

Orientation

Depending of the orientation of the sun to the slope. In a soil located in the northern hemisphere a slope orientated to the south will be warmer. This is related to the temperature and moisture of the soil.

Time
Time is a very important factor in geological processes. For example, in a inmature soil horizons cannot be distinguished, but in a mature soil horizons are very well distinguished. As time goes by, the soil will look less and less like the parent material: will have more organic matter, will suffer more leaching… it will look like a mature soil.

Climate: the most important factor (temperature, precipitation)
*Hot and humid climate → strong chemical weathering...chemical reactions occur fast due to the heat*
*More precipitation → more leaching, less precipitation → water will go from the bottom to the top*

Vegetation and animals
This organic matter will be a product of the vegetation. Worms can mix the soil because the holes… they make, similar to the roots of trees.→ Horizons cannot be distinguished because of the mixing??

# Types of soils

### *LATERITE*

They are formed in tropical and subtropical regions (hot temperature and strong rainfalls). This type of soil is rich in iron oxide (red colored). Organic decomposition happens rapidly so there's a thin or none 0 horizont (humus). A horizon is absent due to strong leaching. B horizon is formed by thick masses of iron and aluminium oxides (chemical weathering and leaching products from A horizon).

### *PODZOL*

Podzols can be found in northern coniferous forests (e.g. easter Canada and USA). In cold (slow soil formation) and wet climates (precipitation exceeds evaporation). 0 horizon is thin and is made of needles and cones; these decompose slowly to form humus. A horizon is ash-gray colored due to strong leaching. B horizon is red (yellow) colored due to the deposition of iron leached from above.

### *BROWN SOIL*

Formed in deciduous forest (Europe, Russia and North America). In temperate maritime climate (mild winters and summers, quite wet all year). There are no clear horizons. The O horizon is made of leaf debris; it is a rich humus layer (mild acid humus). A horizon has a dark brown color (minerals are leached out, more humus). B horizon is a brown layer (deep roots).

### *GLEY*

Slow water drainage. Often found at the foot of hills. There are located in waterlogged sites. Appear in cold climate (slow weathering).
- O horizon: abundant organic matter accumulation (peat)
- A horizon: poorly drained (dark gray color to it) , frozen
- B horizon: is blue, gray (reducing conditions from $Fe^{3+}$ to $Fe^{2+}$)

### *CALICHE*

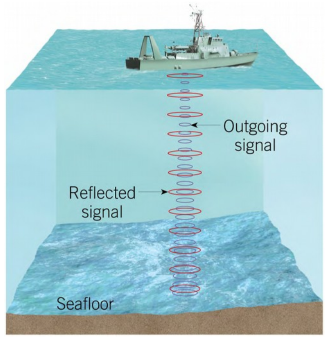
Typical in arid and semiarid areas (less precipitation than evaporation). There is an upward movement of water through capillary actions; water evaporates, dissolved materials precipitate (Calcareous hardpan, costras). In carbonate rocks. Little vegetation and little humus.

# 16. Marine geology

- Topography of the ocean basins
- Global ocean: physicochemical characteristics
- Ocean circulation
- Deep-sea sediments

**OCEAN FLOOR**

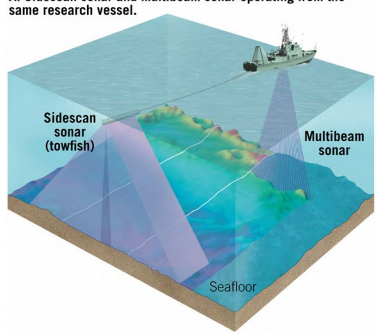
Bathymetry is the study of depth.




In the 19th century, the crew of a ship discovered the deepest place on Earth; by dropping a rope with knots to measure.

Nowadays, more sophisticated mechanisms are used: echo sounders. Sound waves are "thrown away" and when they touch another surface than water (animals, rocks…), the waves get bounced back to the point where they have been emitted. As the velocity of sound waves on water is known, the depth can be measured by a simple equation.

**A. Sidescan sonar and multibeam sonar operating from the same research vessel.**

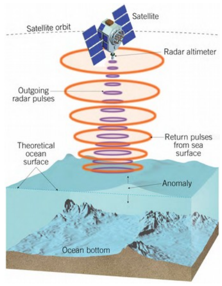



A map on 3D can be made using this methods:

- Side scan sonar (towfish): place where we transmit the sound wave. Sidescan sonar and multibeam sonar operating from the same research vessel.
- Multibeam sonar transmit more than one wave so we know the depth at a wider area

The depth is measured and then represented by seismic profiling.

*The problem is that the ship needs to go very slowly so the problem is that we would need a hundred of ships and some years to know all the depth all over the world but the resolution is very good done.*

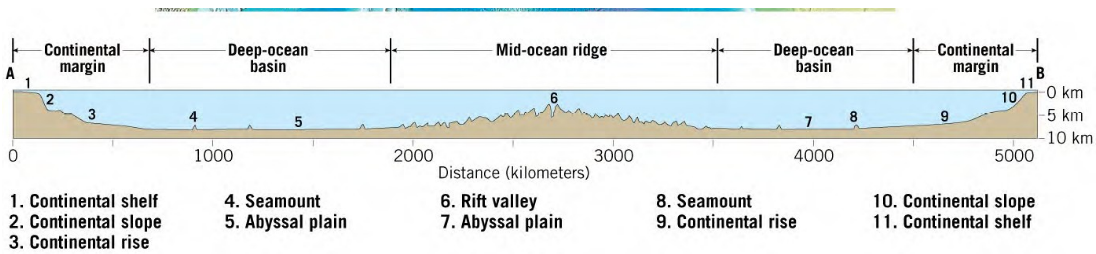



Some of them waves can be transmitted by some of the sediments that are on the sea. Makes us able to know the sedimentary section (the infilling of the ocean bottom). That's because the infilling is different in every strata so velocities change when strata change.

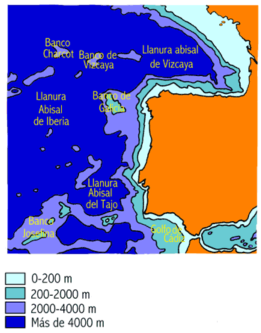
There are other methods to investigate the ocean floor:

- Satellite altimeter
- Ocean drilling

**TOPOGRAPHY OF THE OCEAN FLOOR**



3 main (and symmetric) areas can be distinguished: the continental margin, the deep ocean basin and the mid-ocean ridge.

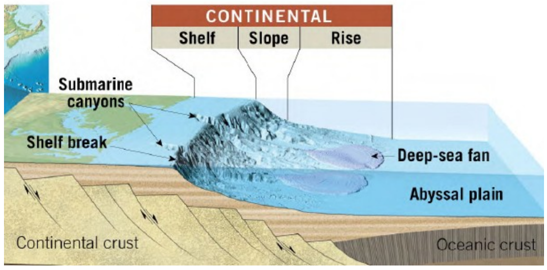



### Continental margin

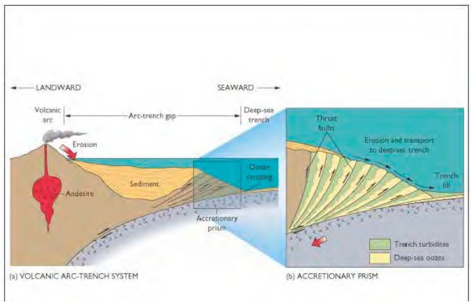
Is located between the actual land and the deeper areas.

Due to their location respect to plate boundaries two types of continental margins can be distinguished:

- **Passive continental margin**: far away of the plate boundary (the closest one is the ocean ridge). Three parts can be distinguished:
  - Continental shelf: almost flat surface
  - Continental slope: 5-25º slope. It's located between the shelf and the rise.
  - Continental rise: much slower slope than the continental slope. It is a wedge related to the accumulation of sediment. It's related to turbidity currents.



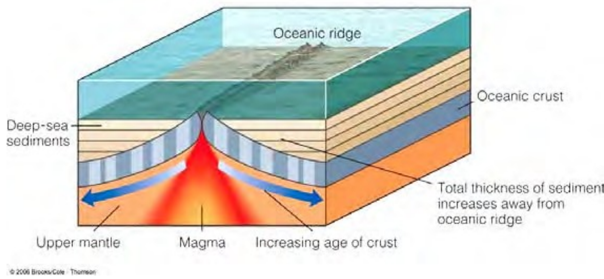

- **Active continental margin:** when the subduction zone is located in the margin
  - Characterized by subduction zones
  - Oceanic crust subducted beneath the leading edge of a continental zone
  - Zone prone to earthquakes and intense volcanism can water can enter on the mantle and trigger the volcanism → rock's melting point decreases when water gets in contact with it
  - Sediments on top or fragments of oceanic crust can produce an accreationary wedge




### Mid-ocean ridges

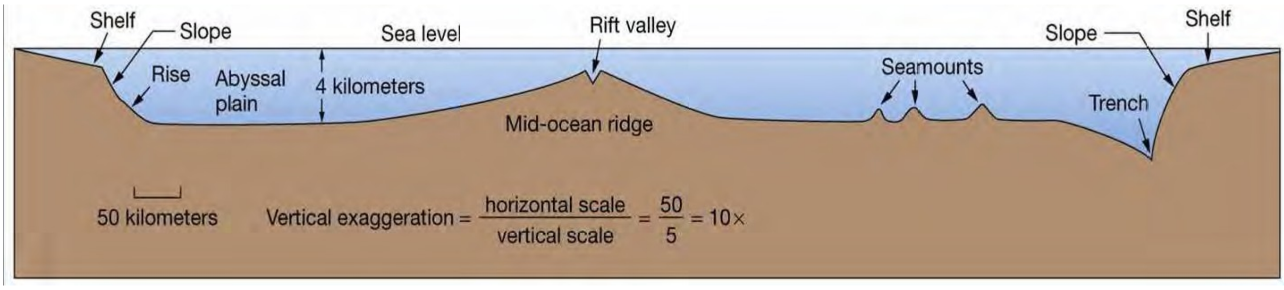
These are associated to divergent boundaries. Ocean ridges are kind of underwater mountain ridges, actually, these are the longest mountain ridges in the world.

The name of the ridge is associated to their location respect the continent (f.e. mid Indian ridge, located in the middle of the Indian ocean, east Pacific ridge, located in the east of the Pacific ocean).

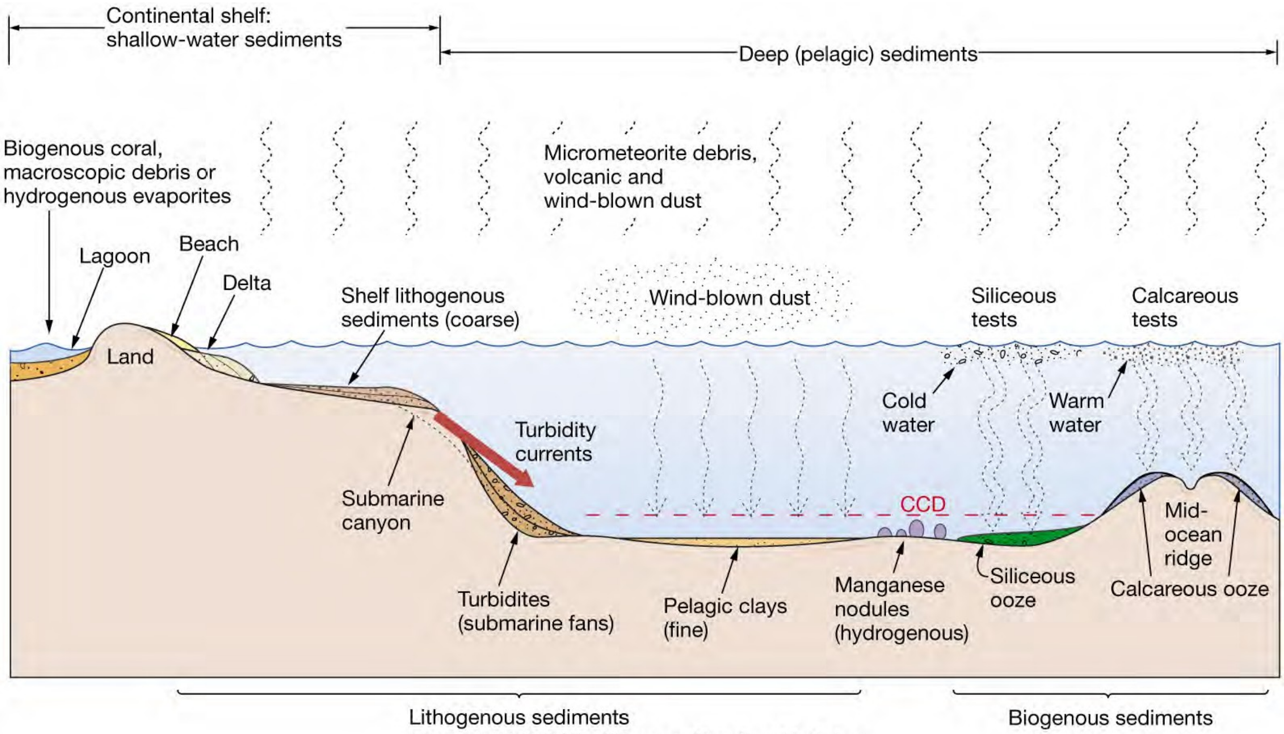



Oceanic ridges are elevated regions. As they move, they will contract and became denser so they will go deeper, that's why the "middle" is higher than the rest.

**Deep ocean basin**
There are two main areas.
The abyssal plain is the flat deep bottom of the ocean (3000 to 6000 meters deep).
Sometimes, the abyssal plain is "interrupted" by sea mouths: mid ocean ridges or volcanoes (islands).




**DEEP SEA SEDIMENTS**
Minerals and metals deposited in oceanic ridges. In the ocean ridge there's no sediment deposition, iron, lead, gold… next to the ocean ridges there are deep-sea hydrothermal vents that expell high temperature … rich in metals that produce black smokers. They support a very important group of organism, there's no sun light so they depend on chemosintesis by bacteria.





Pillow lavas: are an example of underwater volcanism (circular shape). As the lava is expelled it will get in touch with cold water, so the outer part will freeze but the inner part is still molten. They form spherical shapes.

Two types of sediments: terrigenous sediments (sediments that come from the continent) and biogenic sediments (associated to the accumulation of shells… of organisms, most of the time planktonic organisms).

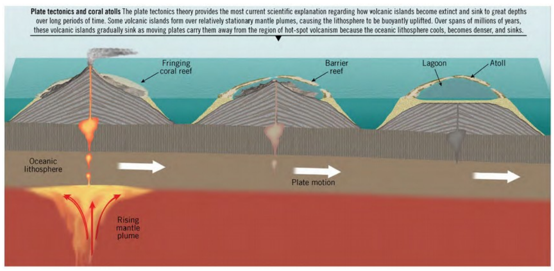
**Biogenous sediments**
Calcareous or sedicious composition.
Calcareous composition sediments, also known as calcareous ooze, formed by foraminifera. These secret calcium carbonate and the shell is preserved in the sediment. Most of them are benthic, some are planktonic. These are carried by the currents. Aglutinated foraminifera in estuaries → ingurutik hartzettube grain sized particles and they build their lo k sea de eso. Another type that produces calcareous ooze are coccolithophores.

**Terrigenous –or Lithogenic- sediments**
Finer sized particles will travel more, so they will be farther in the ocean.

They will be somehow mixed (the sediments). They are red because they are rich in iron oxides.
**Pelagic sediments**
Fine grained particles

**Turbidites**
Gravitational mass movements. They fall down slope; can be triggered by seismic activity… They start to mix with sea water, producing turbidity currents: mixture of sediments and water. This will be. They produce graded beds. The current loses energy → the biggest particle will be settled and then the smallest ones…
hemipelagic sediments → marl
pelagic sediments → limestone

**CONTINENTAL SHELF**
Bioconstruction reefs, calcarenites deposits, terrigenous imput (muds, sandy layer)




Coral atolls are islands with the form of a ring that normally has a lagoon inside that is connected with the sea. The plate tectonic theory could be able to explain its formation: some volcanic islands form from over relatively stationary mantle plumes, causing the lithosphere to be buoyantly uplifted. These islands gradually sink and forms a coral atoll.

Fringing reefs and barrier reefs.


Fringing Reefs

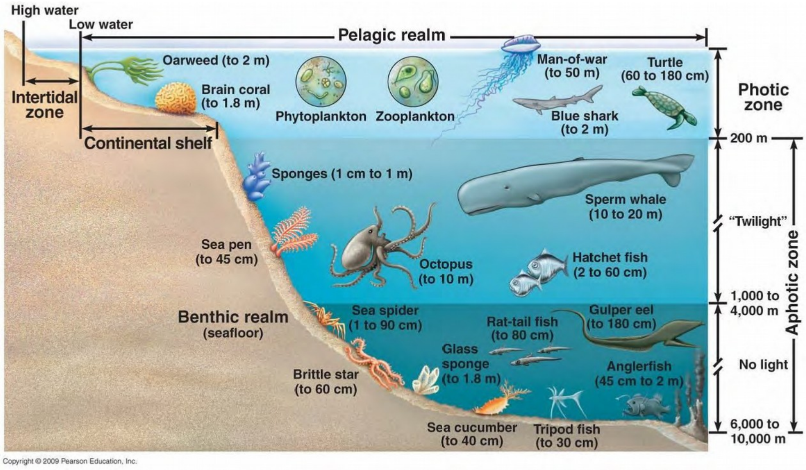

Barrier Reefs


Atolls

**GLOBAL OCEAN: PHYSICOCHEMICAL CHARACTERISTICS**

**Availability of sunlight**

The photic and the apphotic zone: boundary 200 m. The boundary will be shallower in the continent.



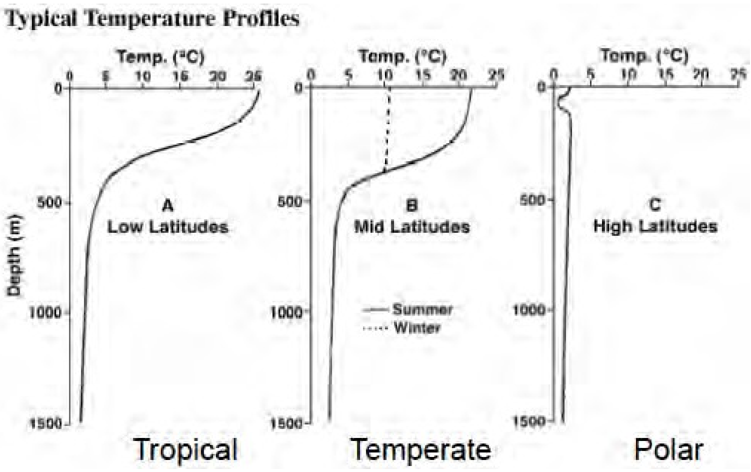

**Salinity**

Salinity depends on the amount of water. (35/100)

**Temperature**

TEMPERATURE ON THE SURFACE → asociated to solar radiation

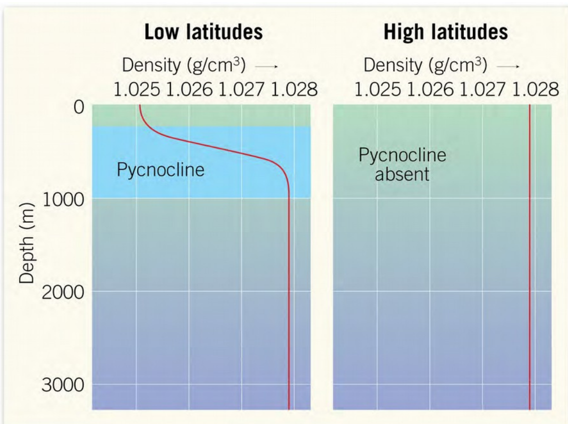
no thermocline in high latitudes




**Density**

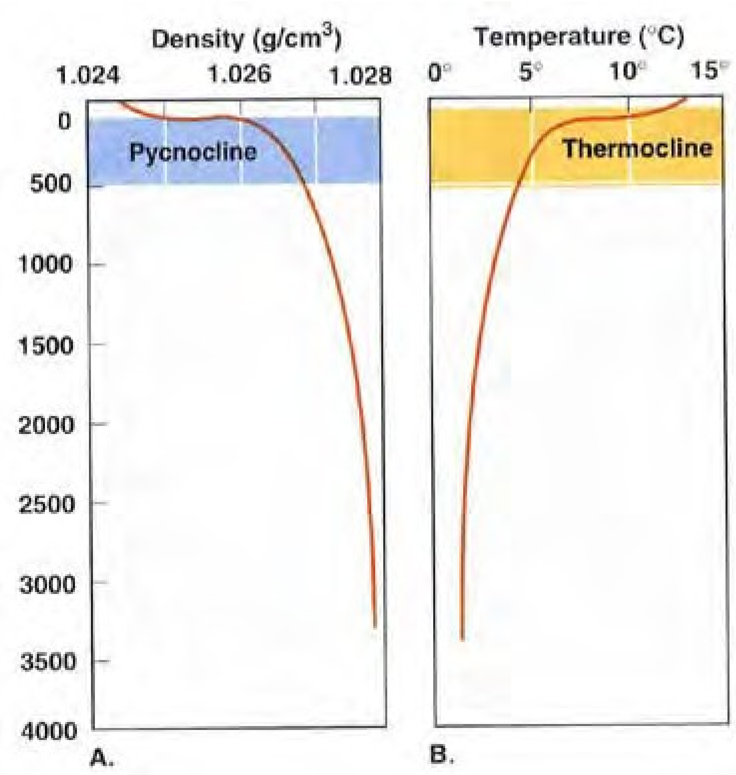
Density changes rapidly with depth.

Rapid density changes: pycnocline (in low latitudes)



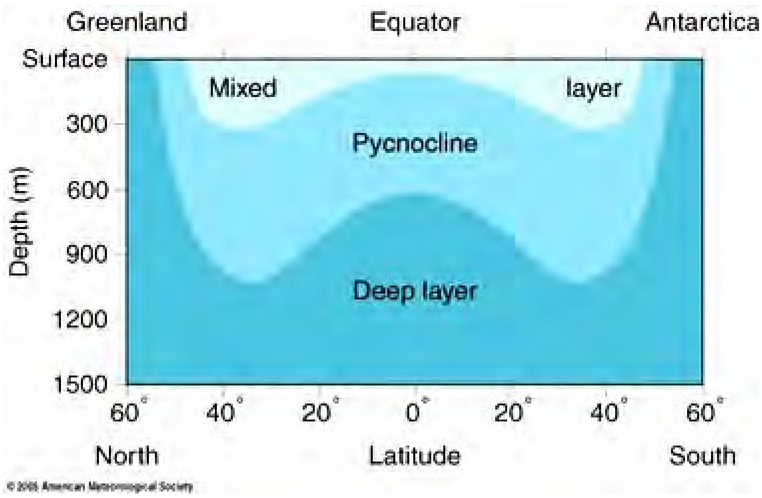
**Pycnocline, thermocline and halocline**

Rapid salinity change with depth: like density

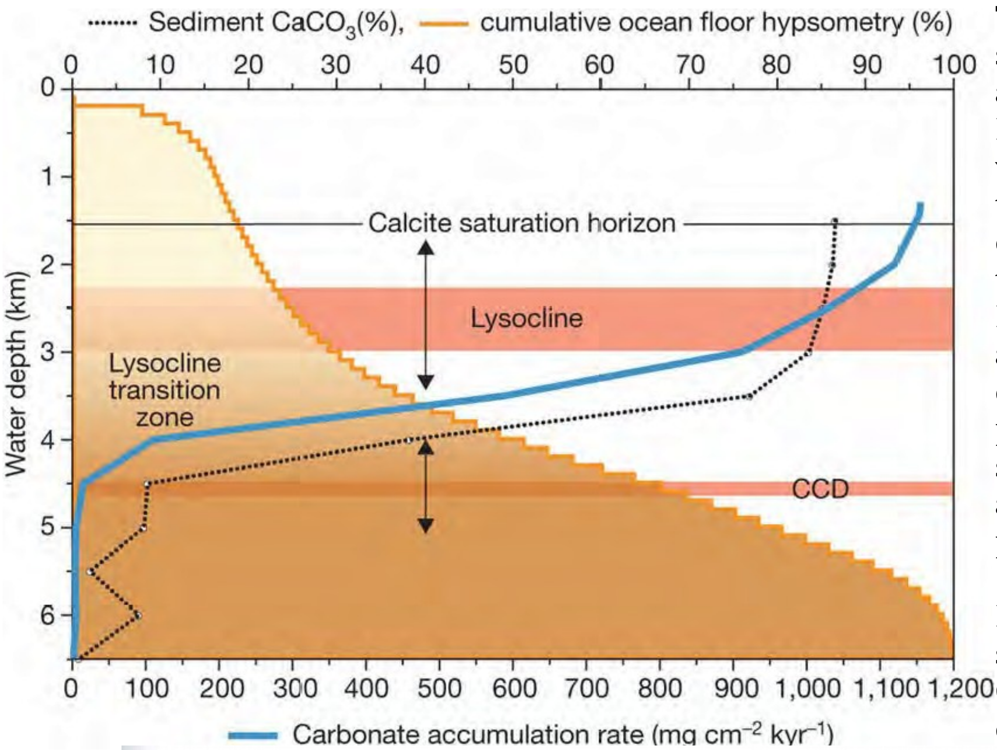



**OCEAN LAYERING**

In the poles there's no layering, there's a god vertical mixing of sea water.

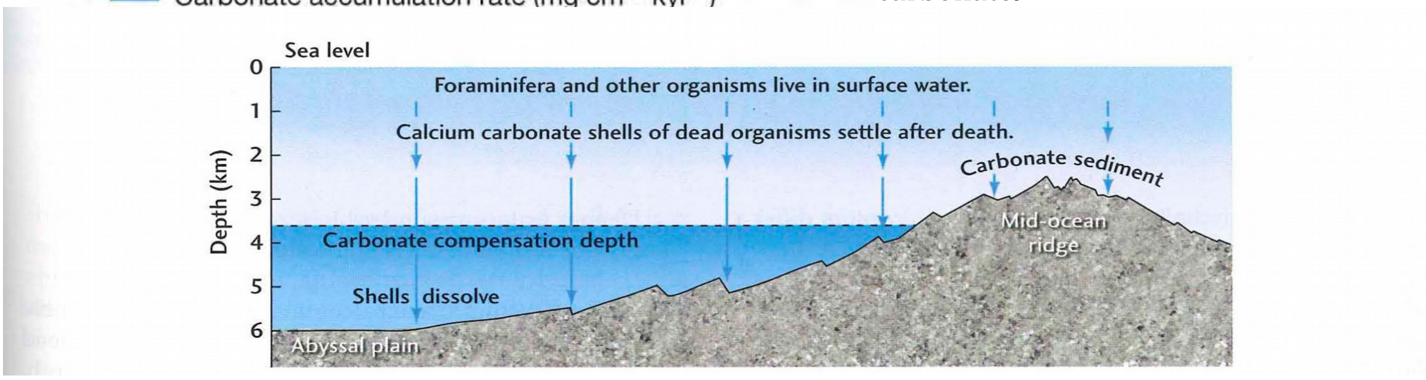


LYSOCLINE, CCD

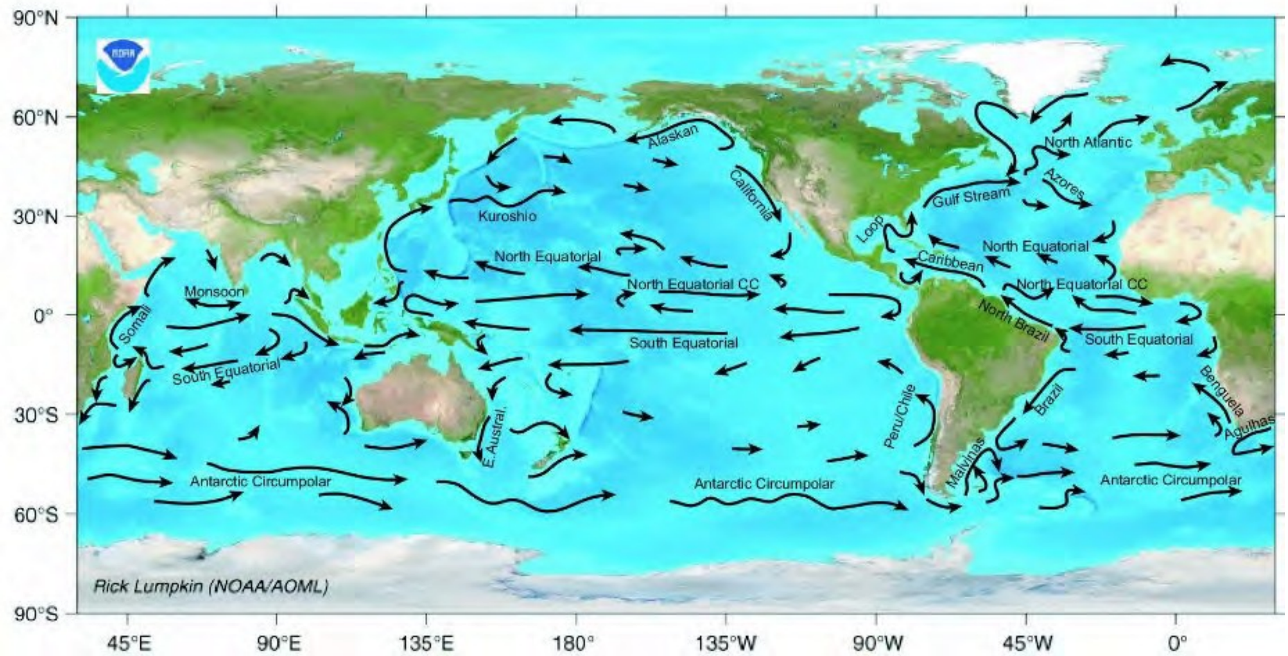



Two types of organic derived sediments: calcareous ooze and silicious ooze. Depending on the depth we will find one or other. Under the lysocine we will still have carbonate but we will start to see disolution. Foraminifera would be animal like protist, coccolithopora plant like protist. Diatome plant like silicious and radiolarians animal like silicious tested protist.

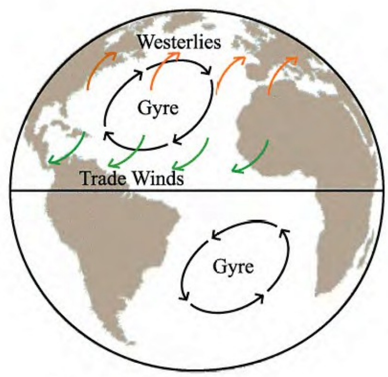
Disolution of carbonates start in lysocline, under the CCD there will no be any carbonate.



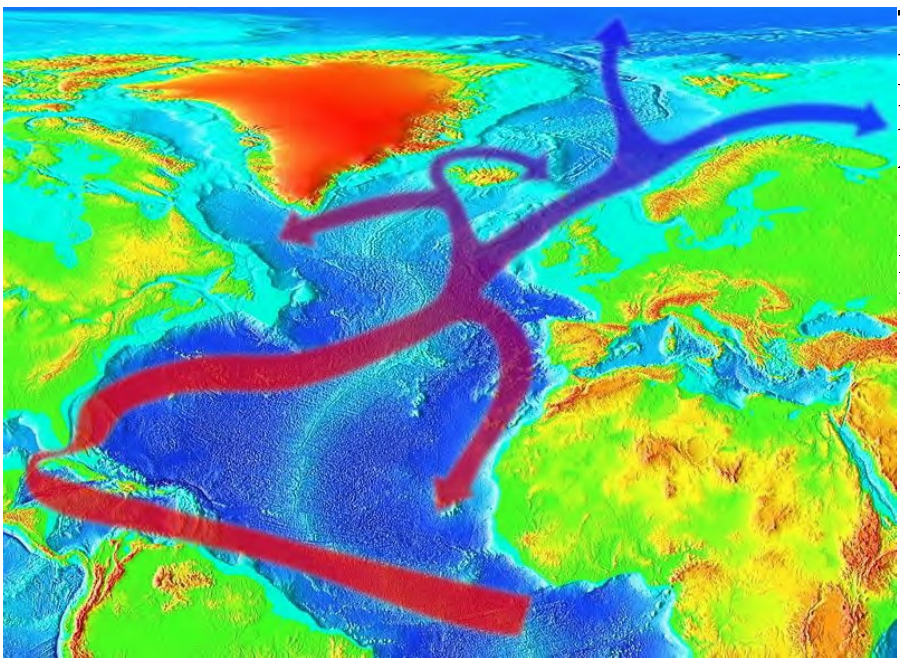
## OCEAN CIRCULATION




The shape of the ocean surface current is influenced by the predominant surface wind.
Pattern of global winds. Large circular moving. Loops of water in the atlantic oceean. 5 main gyres. Subtropical gyres (30º north or south laittude).
*Coriolis effect*: currents deflected to the right in the northern hemisphere and to the left in the southern hemisphere, this efect is due to the Earth's rotation.
The ocean surface current will follow the predominant

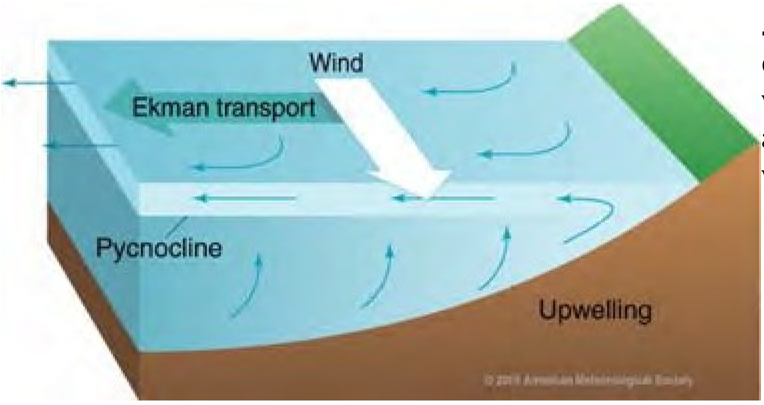



***Gulf stream***
Is responsible of the temperature and climate difference between two sides of the atlantic.



This motion brings warm water to the northern atlantic. The heat transport is responsible of the climate differences between two places in the same latitudes (NEW YORK TA BILBO, BILBO EPELO NAHIZ ETA LATITUDE IUELIN EON)

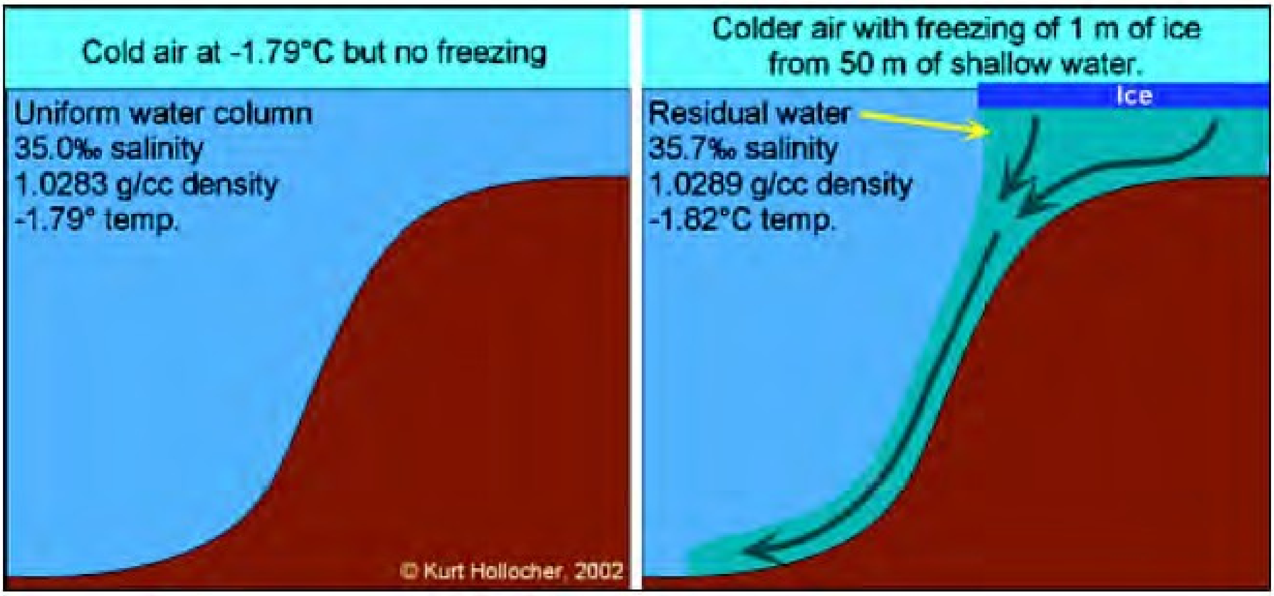
**Coastal upwelling**




.Wind travels parallel to the coast to the equator. The defflection of the surface water leaves this space in the surface, and then upwelling happens when deep waters go to the surface.

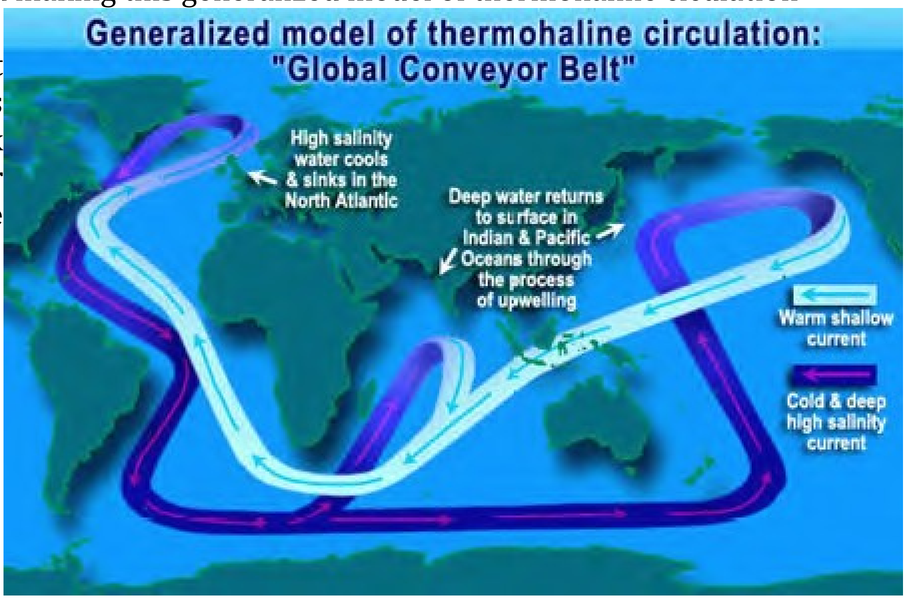
**Deep ocean circulation**

The formation of sea ice changes the salinity of the water underneath the sea ice. This formation will increase the salinity of the water. This makes it denser, making it sink. This is how deep ocean waters are produce. (f.e. north atlantic).




All of these 3 fenomena are linked making this generalized model of thermohaline ciculation

Responsible of heat transport and climate. So plate tectonics are important Segun kontinentik nola dauden kokaute → ur korrientik aldau eingoi → klimate aldau eingoa.



# 17. Natural resources

- Renewable and non-renewable resources
- Sources of materials: types of ore deposits
- Energy sources
- Coal formation and mining
- Hydrocarbons: oil, gas and bituminous rocks
- The hydrological cycle
- Use of resources and current environmental issues

## RENEWABLE AND NON-RENEWABLE RESOURCES

Renewable resources will be some materials that is replenished relatively fast (few years, decades…), for example, biomass (organic matter), energy from flowing water, wind, the sun…

Non-renewable resources are those that are replenished but the speed is very slow, so it takes millions of years to get these resources, for example, metals, petroleum, natural gas, coal, nuclear energy… They are considered non-renewable because there are fixed quantities in our lifetimes.

**NATURAL RESOURCES** (based on the composition)

- Metallic minerals
  - Abundant: Fe, Al, Cr, Ti, Mg, Mn (> 0,1%)
  - Scarce: Cu, Pb, Zn, Ni… (<0,1%)
- Non metallic minerals: can be interested in the element (fluoride) or in its physicochemical properties of the element, (for example, for industrial properties)
- Energy resources: oil, gas, coal, radioactive materials…
- Water (can also be included in energy resources)

**CONCEPTS**

Resource: in general, is the total amount of useful minerals we know or we think there are. Reserves + known deposits that are not yet economically or technologically recoverable + deposits inferred to exist but not yet discovered.

Reserves: already identified deposits from which minerals can be extracted profitably.

Ore deposit: a naturally occurring concentration of one or more metallic minerals that can be extracted economically.

Ore mineral (*Mea):* useful metallic minerals that can be mined at a profit. Contains the valuable substance. For example, chalcopyrite, bornite… are copper ores.

Gangue (*Ganga):* in the ore deposit, but do not contain the valuable substance. These will be removed.

If we think of how profitable an ore deposit might be; It can be non-profitable at first but due to demand can be profitable.  It can be non-profitable at first because the money needed to extract the ore deposit was very high, but due to technological advances, it can be cheaper to extract this ore deposit, so it will become profitable.

In an ore deposit there will be an anomalous concentration of metals.

TYPES OF ORE DEPOSITS

***Magmatic deposits***

Will generate high deposition of minerals. The magmatic differentiation of a basic magma will produce a deposition of minerals. Formation of large crystals. (pegmatitic)

***Hydrothermal deposits***

Vein deposits: precipitate mainly quartz, but also a variety of sulfide minerals, and sometimes gold, and silver within the veins of quartz.

Sometimes, the mineral deposits associated to hydrothermal fluids might be disseminated. Hot ion rich fluids can deposit large concentrations of mineral in the vein deposits or they can produce smaller disseminated deposits.

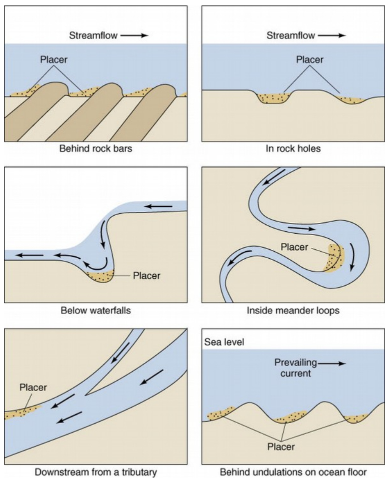
Sea water will percolate through the fractures, it will get hotter and will dissolve the rocks and when it very hot it will move upwards. When it gets in contact with cold water will create this massive sulfide deposits. Sphalerite (zinc sulfide) and chalcopyrite (copper and iron sulfide).

***Metamorphic deposits***

The intrusion of a magma body will produce new minerals. The aureole around the pluton will become metamorphic rock. Limestone → marble. Garnet and corondum are typical of metamorphic deposits (contact metamorphism).

***Placer deposits***

If we think about the processes produced by water currents (they produce sorting), we based them on the grain size, but in this case, the sorting will be associated to the specific gravity. The heavier particles will get together, and the lighter particles will travel longer. These minerals that are typical from placer deposits will be durable and chemically resistant, because they undergo large travel distances without being chemically altered.



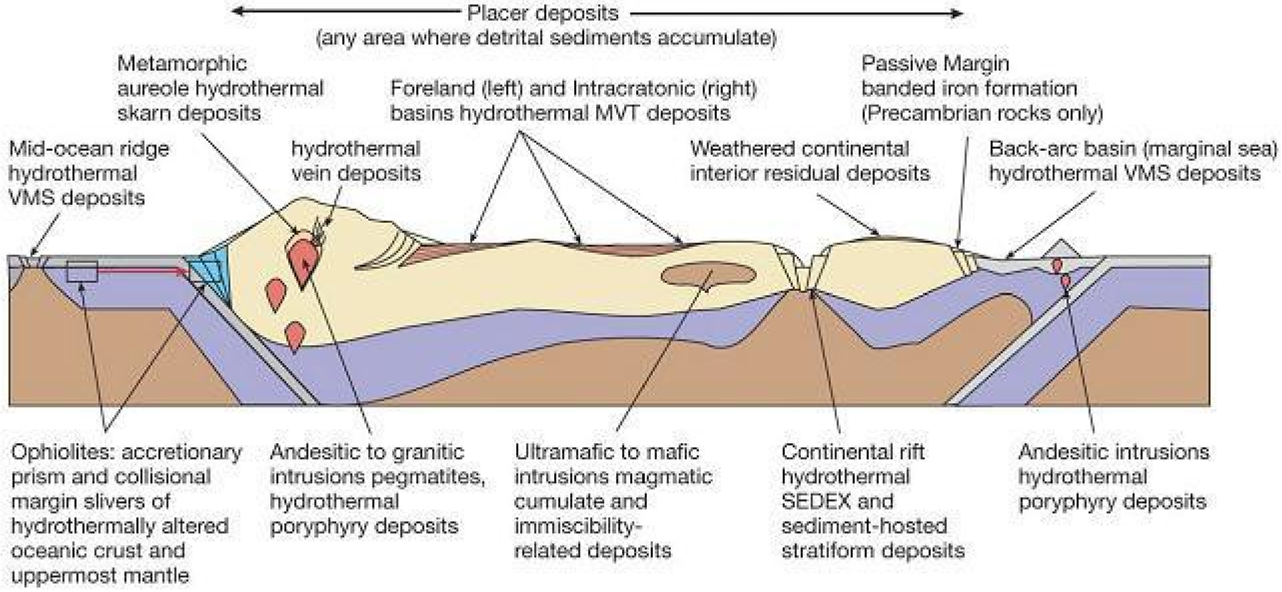

Typical of meander loops. They can be considered sedimentary deposits. Sorting is according to the specific gravities. The sediments are durable and chemically resistant.

If we follow these placer deposits upstream, we might find the source rock.

***Deposits formed by weathering***

Because of these weathering processes, the substance of interest will become very concentrated (secondary enrichment). Bauxite (hydrated aluminum oxide) is the principal ore of aluminum. Even though aluminum is a very abundant element, is usually forming silicates, where it is difficult to be extracted off. Due to these **secondary enrichment processes**, we can find aluminum concentrated in bauxites. These are formed in places where the soil is laterites; in tropical (warm, rainy) environments, where strong leaching happens. We will have a rich aluminum source rock, the weathering of this source rock will produce the accumulation of aluminum in a bauxite. After the weathering and leaching, as a result, this will happen (in a tropical environment).

**Plate tectonics**
The location of these ores is related to plate tectonics.




## NON METALLIC MINERAL RESOURCES

These resources won't be used as energy sources or they won't be extracted because of the metals they contain. They will be extracted because of the non-metals they contain or because the physicochemical properties they have and they are interesting for human use.

Building materials:
- Aggregate (Arido): crushed stone, sand and gravel
- Clay for bricks
- Cement: limestone and shale
- Concrete (hormigón): aggregate + cement

Industrial minerals: corundum and garnet as abrasives

# ENERGY SOURCES

**Non renewable:**
- Fossil fuels (coal, oil, natural gas)
- Nuclear energy

**Renewable:**
- Solar energy
- Wind energy
- Hydroelectric power
- Tidal power
- Geothermal energy
- Biomass

## COAL

### *Coal formation and mining*

Is formed by accumulation of large quantities plant remains in oxygen deficient environments (swamps), to avoid decomposition. There is a partially alteration of these plant remains by anaerobic bacteria, that will form **peat**, a soft brown material, where plant structures are easily recognized. *Sometimes the species can also be recognized. This is used to do radiocarbon dating.*

The burial of the peat will increase the temperature and the pressure and a compacted version of the peat is formed, **lignite**, which is the first type of coal. This is a soft brown coal.

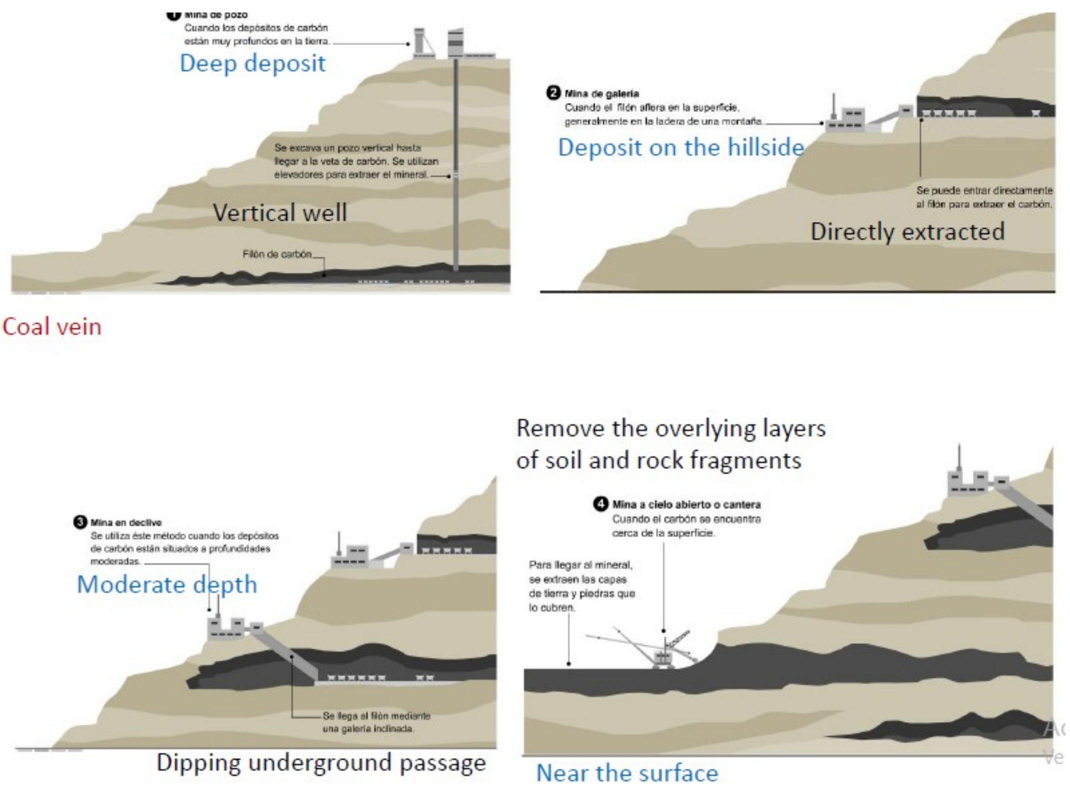
As the plant remains are being more and more compacted, water and the volatile components will be expelled and the material will be richer and richer in carbon.

The farther burial of the lignite will increase the amount of the sediment layers on top, so it will be more rich in carbon. The amount energy produced in the combustion will increase as the coal is more compacted…. A soft black coal is formed by more burial: **bituminous coal.**

The metamorphism of bituminous coal produces **anthracite**. This metamorphism is related to mountain building that will increase temperatures and pressure. It's a hard, shiny, black rock. It's less common type of coal and it's the most expensive type of coal to extract.

The carbon content will increase as the organic sediment is buried (when temperature and pressure goes higher and time goes forwards), so the coal will be darker and harder.

Many of the coal deposits (and the first ones) we can find are from the carboniferous, when plant accumulation in peatlands in warm and wet climates happened.
Regarding the extraction of coal, there are different extraction methods depending where the coal is located.



## HYDROCARBONS: OIL, GAS AND BITUMINOUS ROCKS

Petroleum and natural gas (compounds of hydrogen and carbon)

They are produced by accumulation of planktonic organisms that are buried very faster than they decompose. With the further burial of the organisms in anoxigenic environments oil and gas are created.

Oil and gas are mobile, so they will move from the sea bottom sediments (mud) to porous rocks (sandstone). Unless they find something to stop the way to get to the surface they will be trapped in traps.

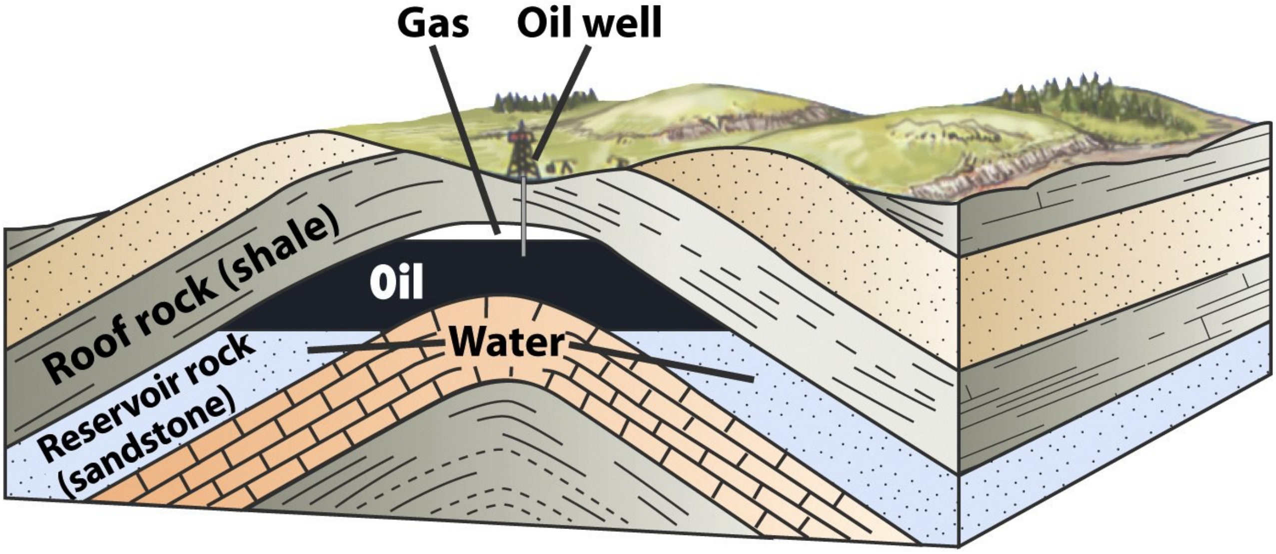
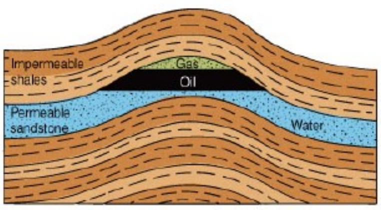


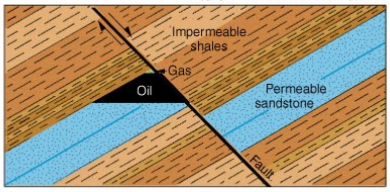

**Figure 11-10 Environment, 5/e**


In order to find large concentration of hydrocarbons, we need to find traps (something that stops the vertical upward movement of hydrocarbons).
In a trap we can distinguish two rock types:
1) The reservoir rock: the permeable and porous rock where we can find the petroleum and gas
2) The cap rock or roof rock: shale, impermeable to gas and petroleum and prevents upward migration.

These oil traps can be found in different geological formations: (anticline, faults and salt domes)



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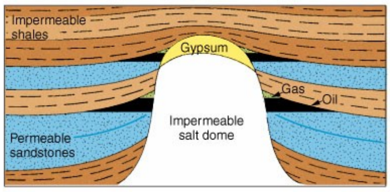


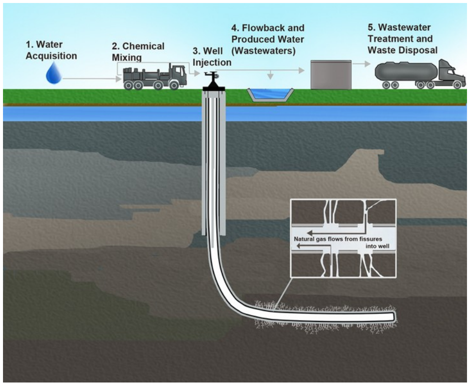

D

Seismic profiles are also used in order to learn the distribution of sedimentary layers underground so the location of oil and gas can figured out.

**BITUMINOUS ROCKS**
Black shales (accumulation of organic matter (>5% + clay/silt). Source rock for oil and natural gas.

OIL SANDS
Typical in Canada. Mixture of clay, sand, water and bitumen (viscous version of the regular oil, tends to be 5-15% of the deposit). Its much viscous, it cannot be simply pumped out. It is heated and the bitumen migrates. Its extraction is very expensive.

**EXTRACTION**
***Fracking***
Also known as hydraulic fracture.
Low permeability of some shale deposits. Prevents the natural mobility of natural gas reserves. Shatter the shale (fluid injection): makes cracks. Gas glows into wells and then its pumped up.
The fluid injected is water + chemical and sands. These chemicals are toxic and can leak into freshwater aquifers. The sand is used to keep the cracks open.
Once the gas is extracted, the wastewater has to be injected into deep disposal wells. This is proven to be related to earthquakes and groundwater contamination.




**NUCLEAR ENERGY**
Energy is released through nuclear fission of radioactive materials. (bombardment of uranium-235 atoms with neutrons). When the uranium nuclei splits, smaller nuclei, neutrons and heat energy is released through chain reactions.

## THE HYDROLOGICAL CYCLE
Distribution of water; the water goes from the continent to the ocean. Water is a very important resource for humankind, as its used for daily purposes and to get energy from hydroelectric energy.

## USE OF RESOURCES AND CURRENT ENVIRONMENTAL ISSUES
- Landscape alteration
- Direct pollution: groundwater, sea, air
- Subsidence
- Global warming

Greenhouse gases are not bad, they allow atmospheres temperature to be able to have life. The burning of fossil fuels and deforestation has increased the concentration of these gases and this is what triggered the melting of mountain glaciers and ice sheets, changes in oceanic and atmospheric circulation, sea level rise, extreme climate events, massive species extinctions…

# 18. Natural hazards

**Earthquakes and volcanoes**
**Floods**
**Mass movements**
Subsidence → asocciated to the oil withdrawal, water withdrawal, collapse of dolinas...
Atmosphere and severe weather
Coastal risks → tsunamis, abrassion platforms
Climate and climate change consequences → sea level rise, global warming

**EARTHQUAKES**
The focus is the place within Earth where earthquake waves originate, and the epicenter is the point on the surface directly above the focus. These are associated with plate boundaries.

To describe the intensity of the earthquake two scales are used; Mercalli and Richter.
The Mercalli intensity scale is related to the intensity of ground shaking and destruction (e.g., building damage). The Richter magnitude scale is associated to the energy released in the earthquake.

EFFECTS OF AN EARTHQUAKE:
- Shaking of the ground: passage of surface waves. The shaking will be larger in loose unconsolidated sediment than In solid bedrock. It will also varies according to the size of the earthquake, the distance from the epicenter, and the type of construction. It will be more shaky in non flexible materials (concrete) than in flexible materials (wood, steel).
- Ground rupture: is a change in the ground level
- Aftershocks: smaller earthquakes after the main earthquakes
- Fire: related to rapture of power lines and gas lines….
- Landslides: triggered by earthquakes in montainous regions
- Liquefaction: when ground shaking happens in a water-saturated unconsolidated sediment it behaves like a plastic material
- Tsunamis: huge waves triggered by underwater earthquakes

**VOLCANOES**
Associated to plate boundaries.

Consequences:
- Lava flow: associated to non-explosive eruptions (low gas content and low viscosity; basaltic composition)
- Pyroclastic flow: associated to explosive eruptions (high gas content and high viscosity; andesitic composition).
- Poisonous gas emissions: $HCl$, $H_2S$, $HF$...
- Mudflows (lahars): mixture of water and sediment that move downslope. They can occur during the eruption or years after. The eruption triggers the melting of snow or ice that is mixed with unconsolidated tephra and makes the mudflow. *Nevado del Ruiz*

**FLOODS**
Cities are along streams; in flat areas with sources of water. Sometimes, the buidlings are located in the floodplain, so the flood risk is high.

They are associated with heavy rain falls. In upstream floods, flash floods happen: heavy rains over a short period of time, so the flood affects a small area.

In downstream floods, heavy rains over an extended period of time. The flood affects a larger area due to the saturation of the soil.

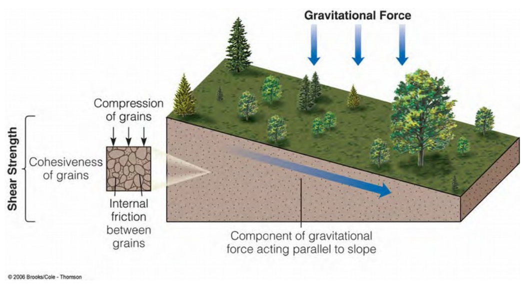
*Floods remain the single natural hazards causing the largest economic and social impacts worldwide.*

Human construction prevent infiltration of water into the soil because the buildings are made of impermeable materials: concrete, asphalt…

Flood mitigation and management.
1) Study fluvial systems and climate regimes (local and regional)
2) Infrastructure and soil use planning based on flood hazard maps

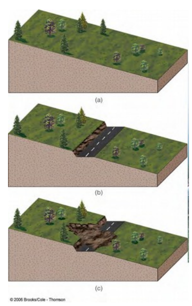
We can building:
- Dams
- Levees: artificial embankment along a waterway, helps protect nearby areas from floods
- Floodways

Storm sewers collect runoff from streets, parking lots and buildings to provide underground drainage

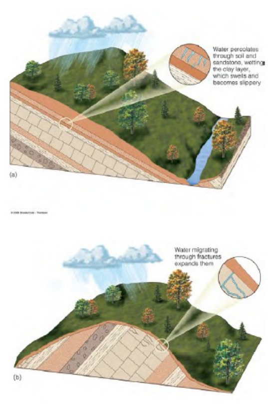



**MASS MOVEMENTS**
Mass wasting refers to the downslope movement of rock, regolith and soil under the direct influence of gravity.

Can be triggered by earthquakes



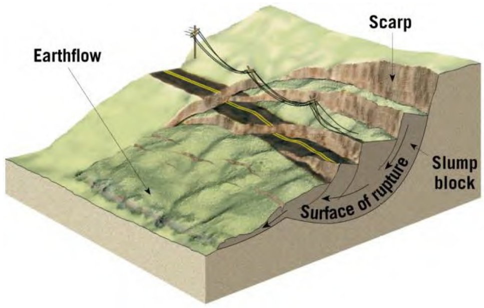
**Factors controlling mass wasting :**
*1) GRAVITY*
1. Oversteepened slopes unstable trigger mass
2. Weathering and climate
3. Water content: if we introduce water, the grains will be separated. There is less friction between the grains so its more unstable
4. Vegetation: protects against erosion
5. Geology
Rocks dipping in the same direction as a hill's slope are particularly susceptible to mass wasting. Undercutting of the base of the slope by a stream removes support and steepens the slope at the base. Water percolating through the soil and into the underlying rocks increases the weight, and, if clay layers are present, wets the clay, making the layers slippery.
Fractures dipping in the same direction as a slope are enlarged by chemical weathering, which can weaken the rocks and cause mass wasting.



RAPID FORMS OF MASS WASTING

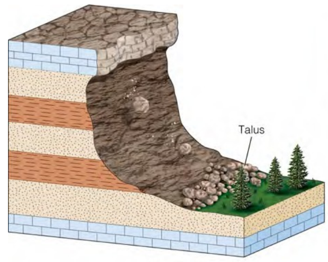
## Slump

A **slump** is the movement of a mass of rock or unconsolidated material as a unit along a curved surface (rotational slide).
It can involve a single mass or multiple blocks. Occurs along oversteepened slopes.




## Rock fall

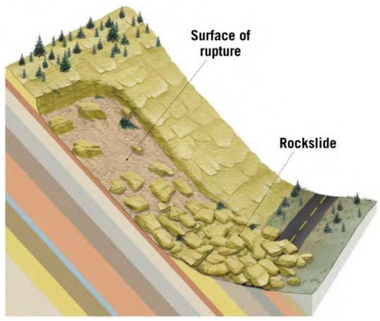
A piece of rock on a steep slope becomes dislodged and falls down the slope.



(a)

## Rockslide

A rockslide occurs when blocks of bedrock slide down a slope. A debris slide occurs when unconsolidated materials slides down a slope.
Generally they are very fast and destructive. Sometimes are triggered by the melting of snow or rainfall; so they are most common during the spring. They can also be triggered by earthquakes.




## Debris flow

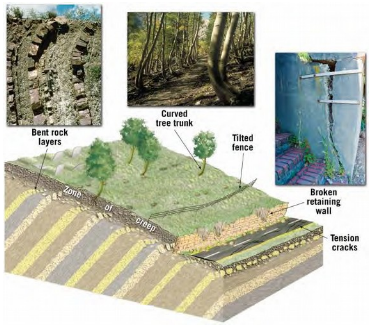
A debris flow is a rapid form of mass wasting that involves the flow of debris (soil and regolith) with water (mudflow if the material is fine grained).It tends to occur more frequently in semi-arid montainuous regions. Sudden rainfall or snowmelt washes large quantities of sediment into the river. If the debris is composed by volcanic material is known as lahar. It happens when there's a no vegetation to anchor the soil.


## Earthflow

Earthflows are formed on hillslides in humid regions during heavy precipitation or snowmelt. Water saturates the soil and regolith, usually rich in silt and clay that causes the flow of the soil. It is very viscous and it moves at slower rates than more fluid debris flows.

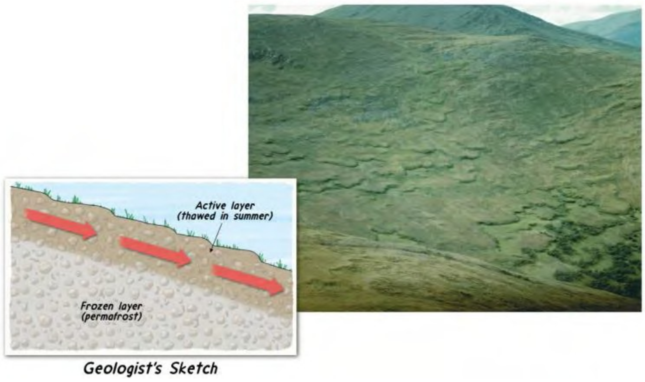
Creep

A creep is the gradual movement of soil and regolith downhill. Imperceptibly slow, aided by the alternate expansion and contraction of the material. Caused by freezing and thawing or wetting and drying.
It can be identified because causes fences and utility walls to tilt.



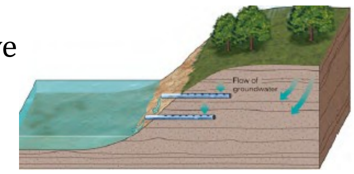

Solifluction

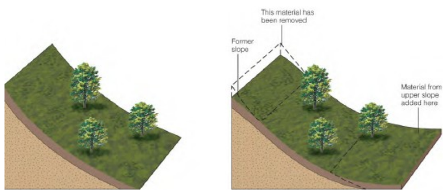
The solifluction is the downslope movement of water logged soils. Slow movements in areas underlain by permafrost. The upper (active) soil layer becomes saturated and slowly flows over a frozen surface below.

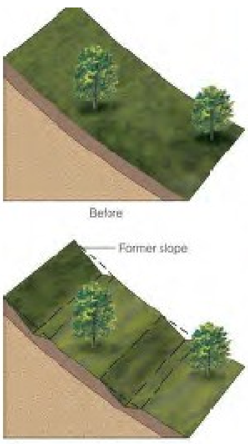


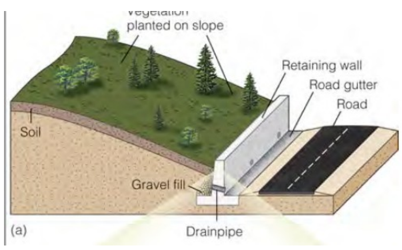

MITIGATION AND MANAGEMENT
1) Study the substratum and the hidrological regimen
2) Infrastructure and soil use planning based on slope maps and detailed geological maps

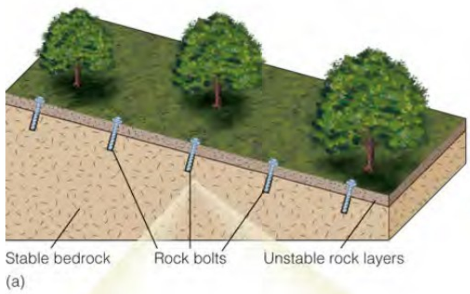
SOLUTIONS:
- Drainpipes that are perforated on one side into a hillslide to remove subsurface water
- Reducing the slope using the cut-and-fill method.
- Benching: making several cuts to reduce the overall slope
- Retaining walls with drainpipes
- Rock bolts secured in bedrock
- Wire mesh (sarie): retaining the rocks falling
- Camisa de hormigon → hormigoie jartzie gañetik tipo autopistatan



# 19. GEOLOGY OF THE BASQUE-CANTABRIAN BASIN

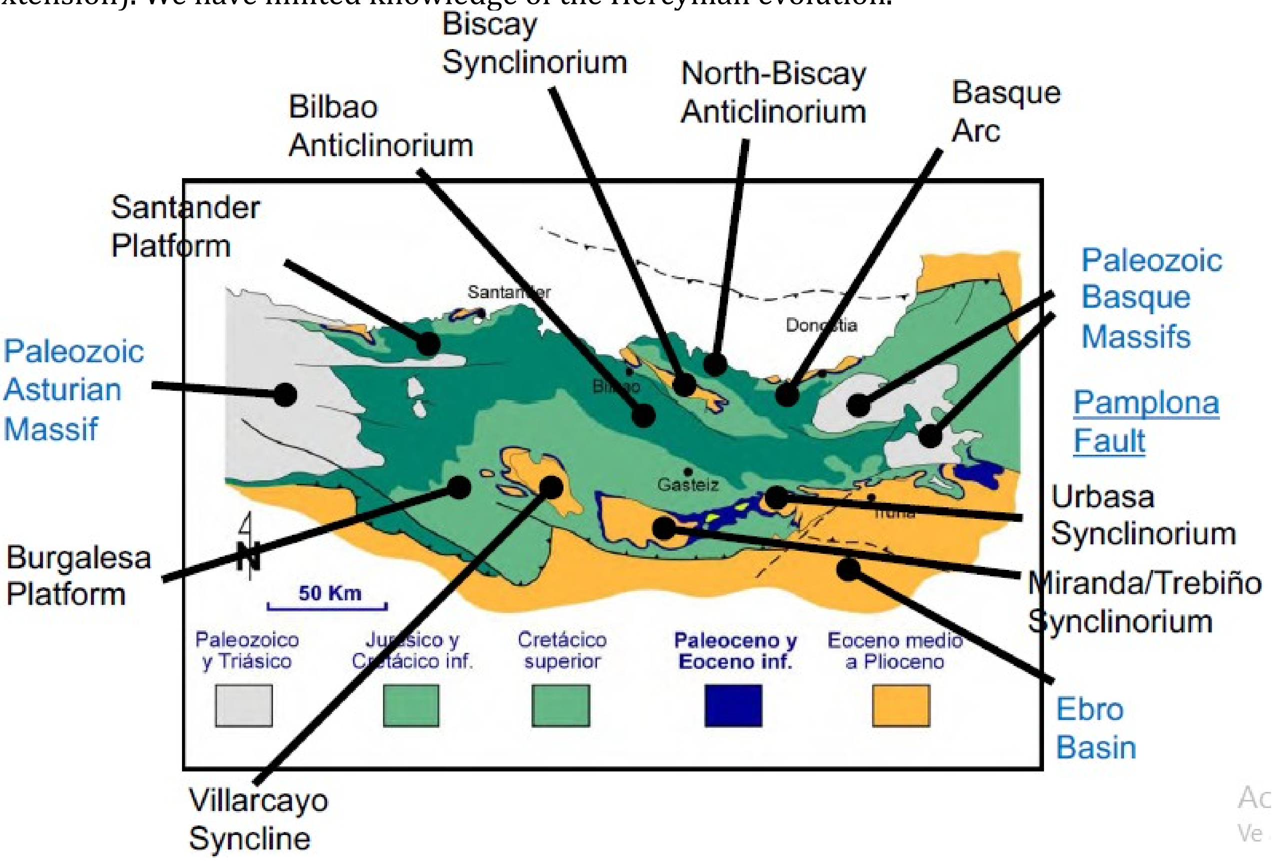
- The Hercynian orogeny (Paleozoic)
- The opening of the Bay of Biscay (Mesozoic)
- Pyrenean folding and sea withdrawal (Cenozoic)
- Recent times

## GLOBAL CONTEXT

The Basque-Cantabrian basin is an inverted basin. It's located to the north of the Iberian Peninsula, which is currently part of the southwestern tip of the eurasian plate. It has not always been like that…

The basin has the Cantabrian mountains to the west, that were affected by the Hercynian orogeny and the Pyrenees to the east, that were affected by the Alpine orogeny.

Nowadays we consider the region to be part of the Pyrenees (it is considered the western extension). We have limited knowledge of the Hercynian evolution.




## THE BASQUE-CANTABRIAN REGION DURING PALEOZOIC AND HERCYINIAN OROGENY

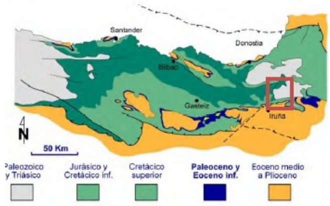
The oldest materials of the Basque-Cantabrian region are of Paleozoic age. For example, Cinco Villas and Alduides massif were affected by metamorphism related to Hercynian orogeny. The oldest rocks are from the Ordovician; they are detrital sedimentary rocks affected by metamorphism deposited in shallow seas.

In the Silurian and devonian alternating detrital sedimentary rocks and shallow-water limestones with abundant fossils (reef) were formed.

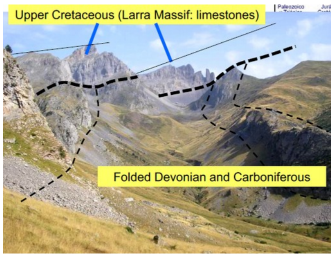
In the Carboniferous, deep marine basin with turbidite deposits (Culm facies) were formed.

During the Hercynian orogeny, a deformation of the Paleozoic succesion happened (erosion). There was a local plutonism episode related to this orogeny as well. (Aiako harria granitic complex: important mineralizations of blenda and galena).

The Basque-Cantabrian region in the Devonian was lovated in the northern tip of Gondwana.



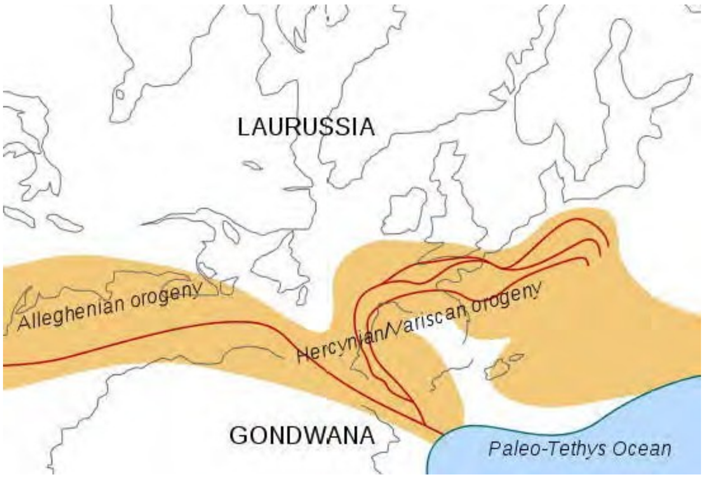

We can find different outcrops of Ordovician and Silurian rocks in Artesiaga, Nafarroa (Alduides Massif).




There are also outcrops of Devonian and Carboniferous rocks in Larra, Nafarroa. (Pyrenean Axial Zone, Alduides Massif).

We can also find limestones and dolostones in the same massif, in Eugui.

Paleozoic fauna: cruziana (trace fossils of trilobites), graptolites and trilobites, tabulate corals, rugose corals, stromatoporids (sponges), fenestelid bryozoans, brachiopods, crinoids…
Paleozoic flora → equisetum and ferns




The approach between Laurasia and Gondwana caused the progressive closure of the Lapetus ocean and the stacking of the microplates between both supercontinents, creating the Hercynian or Variscan chain.

The basque-cantabrian region occupied an external position withing the said chain.

The continental collision and partial superposition caused important **plutonism** and **hydrothermal processes**. (Granodiorites of Aiako harria, Gipuzkoa).

At the end of the Paleozoic, most of Iberia and western Europe were above sea level. The climate was warm but extremely dry.

The continental collision produced the supercontinent Pangea at the end of the Paleozoic, with an equatorial ocean to the East (Tethys).

The Paleozoic ends with the formation of the supercontinent.

**MESOZOIC: The Pangea breakup and the opening of the Bay of Biscay** **(general transgression)**
Most of the rocks surrounding us are of this age, due to the opening of the Bay of Biscay.

In the Triassic Pangea begins to break into smaller pieces. These caused the formation of new seas. The Hercynian reliefs were subjected to erosion, and were deposited in continental depressions in the Lower-Middle Triassic, and in shallow warm seas in the Upper Triassic and Lower Jurassic.

In general, we can see that in the Mesozoic there's a progressive and generalized transgression:

- Opening of the Mid Atlantic and the western mediterranean (middle Jurassic)
- Bay of Biscay (Upper Jurassic-Lower Cretaceous).

This caused the creation of the Iberian microplate.

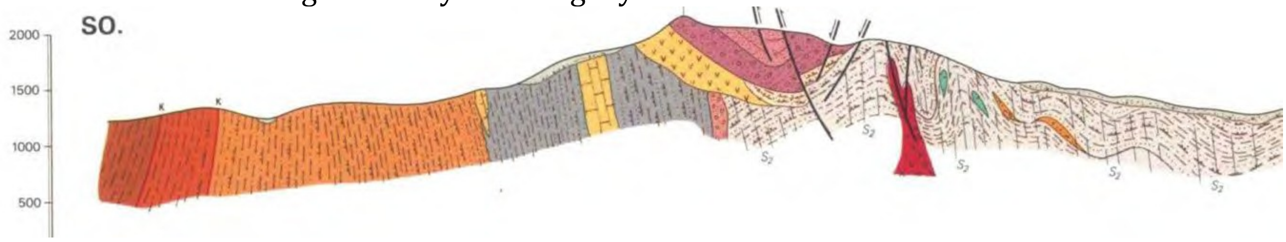
Marine transgression is more evident in the Jurassic. There were shallow seas where limestone and dolomite were deposited.

At the beginning of the Cretaceous the main opening of the Bay of Biscay happened. Associated to the opening, there are normal faults that formed elevated blocks (rudists and coral reefs) and depressions (deep water environments: black shales and turbidites).

The opening and marine transgression ended in the Upper Cretaceous. The areas that were elevated during the Hercynian orogeny are flooded and shallow-water limestones and in deep waters flysch deposition sequences were found.

The Mesozoic is represented by thick pile (>10 km) of Triassic, Jurassic and Cretaceous sedimentary rocks. Important volcanism during the Permian, Upper Triassic and Middle-Upper Cretaceous *main continental fragmentation pulses.*

Upper Permian and Triassic fluvial series with volcanic intercalations of Peña Labra and Pico Tres Mares in Cantabria, Iparla in Navarra…These lay unconformably above the Paleozoic materials folded during the Hercynian orogeny.




Upper Triassic is also characterized by gypsum-bearing evaporites (Keuper fascies). These were formed in shallow seas and coastal environments of high salinity. The plasticity of the Keuper has given rise to the formation of diapirs during the Cretaceous and Cenozoic. Sometimes these evaporites move upwards by themselves (because there is ome compression), and other times this materials will move upwards because certain faults facilitate these upward movements of this (f.e. Sopela). There are some outcrops of Triassic age evaporites: Salinas de Leniz, Salinas de Añana, Salinas de Rosío, Poza de la Sal, Cabezón de la Sal...

The first important pulse of the Mesozoic marine transgression, prior to the main opening of the Bay of Biscay, took place during the Jurassic. It's represented by successions of shallow-water limestones, which locally intercalate black shale levels. These are the main petroleum source rock in the region.

Black shales are accumulation of organic matter (>5%) and clay/silt.

There are not many outcrops of Jurassic rocks; we can find succesions of Jurassic and Cretaceous limestones in Aralar and successions of Jurassic limestones in Palencia.

The shallow water Jurassic limestones frequently contain stromatolites, layered rock formations created by cyanobacteria. They also contain ammonites and belemnites.

At the end of the Jurassic, the sea retreated, leaving behind some brackish lake areas, and terrestrial conditions with strong sedimentation re-established (Purbeck facies, sands and conglomerates).

These conditions persist through the beginning of the Cretaceous, with depositions of alternating clays, marls and sandstones (Weald formation).

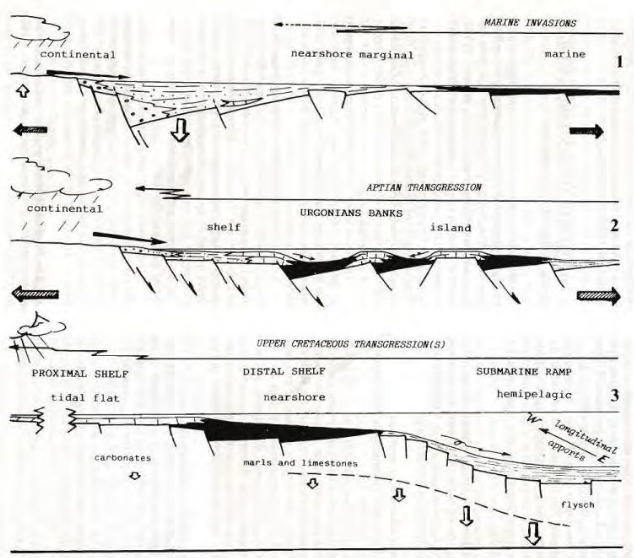
The opening of the Bay of Biscay between Armorica (A) and Iberia (I) during the Cretaceous:

Stage 1: terrestrial (fluvial) and restricted marine conditions (Weald facies)

Stage 2: shallow blocks (reefs) and deep depressions (deposition of deeper sediments) (Urgonian fascies). Characterized by differential subsidence (upper areas and lower areas).

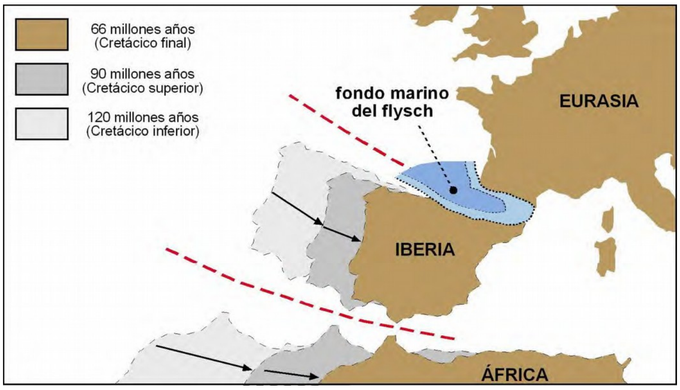
Stage 3: Activity of faults stop. Main transgression related to the sinking of the basin and associated with volcanism (Upper Cretaceous)

The opening of the Bay of Biscay as associated with the separation of Iberia from Armorica (Europe). At the same time, Africa was moving towards the southeast.




ıd development of the Basque segment of the passive. North Iberian margin (after Rat *et al.*, 1982, modified). 1. Beginning of the rifting (Wealden grabens), uppermo
crustal stretching (rotating blocks, Urgonian sedimentary systems), Aptian to middle Albian; 3. Distal subsidence (flysch troughs), Upper Albian to Eocene.

olución del margen pasivo norteibérico en el sector vasco (según Rat *et al.*, 1982, modificado). 1. Etapa de rifting (fosas weáldicas), Jurásico terminal; Barremiense; 2
bloques basculados, sistemas deposicionales urgonianos), Aptiense; Albiense medio; 3. Etapa de subsidencia distal (surcos de flysch), Albiense superior; Eocer

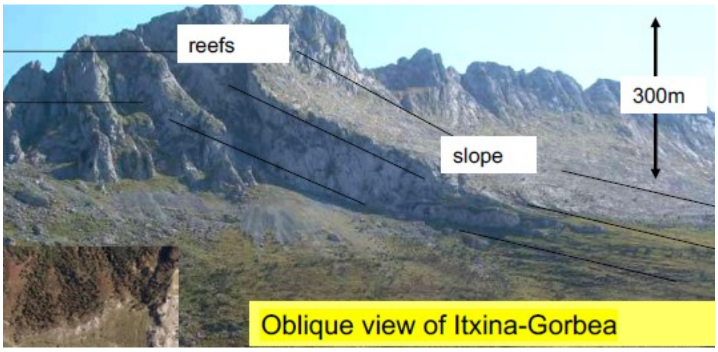



The Iberian plate did an anticlockwise rotation relatively to the European plate.

*Continental Rise or glacis: steep slope and then very gentle slope (the glacis), asocciated to the deposition of turbidites.*

The Urgonian complex was formed during the main separation stage. Due to the differential subsidence there is a wide range of sediments. Complex and variable paleogeography of the basin.

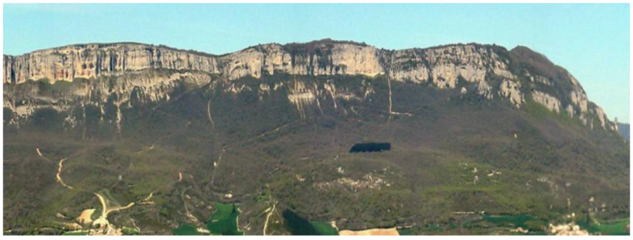
Outcrops of the Lower Cretaceous can be found in Gorbea. These are lower Albian coral-rudist reefs.




Rudists and corals were the major reef-builder organisms of the Cretaceous.

Another outcrop of the Urgonian complex are the red limestones of Ereño in the Lower Cretaceous.

UPPER CRETACEOUS (95-80 ma)
Maximum extension (Iberia and Eurasia). The elevated areas during the Hercynian orogeny were flooded (shallow water limestones) and in the depressions the flysch sequences can be found.



Outcrops of the upper Cretaceous can be found in Araba and Nafarroa. Shallow water limestones above the Paleozoic and Triassic bedrocks: Larra and Lokiz in Nafarroa, Salvada mountain range in Araba.

The Flysch in Zumaia is characterized by alternating layers of turbidites, marls and pelagic limestones. Body fossils and trace fossils can be found in these outcrops.

*Turbidites: sand layers deposited by submarine currents. Flute marks are produced in the soft sediments of the ocean floor but they are found in the bottom marks on the sand. These can be used to know the paleocurrents.*

In the Flysch the Cretaceous-Paleogene boundary can also be seen (Iridium rich layer).

Submarine basic volcanic activity in the deep flysch basin created columnar jointing. There are different outcrops in Fruniz and Errigoiti.

**CENOZOIC: Pyrenean folding and sea withdrawal**

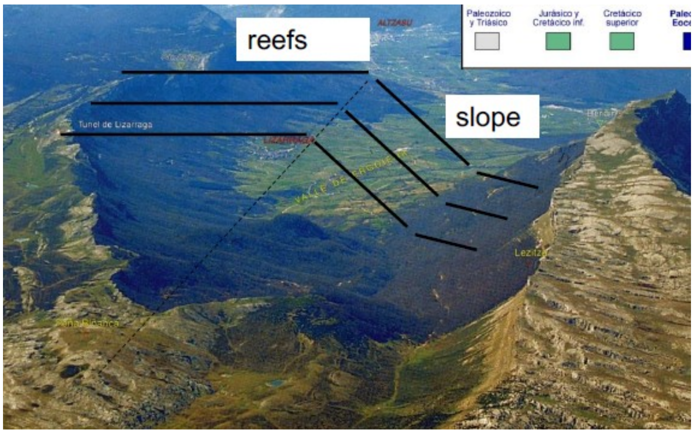
The first part of the Cenozoic (Paleocene and Eocene) is characterized by the recovery of life (new life forms) and the development of reefs in shallow areas and flysch succesions in deep marine environments.

The opening of the Bay of Biscay ceased and Iberia began moving northward. Eventually Iberia collided with southern France creating the Pyrenees (Alpine orogeny)

Compression events were happening due to the Alpine orogeny, so all the sediments deposited were deformated and uplifted. All those materials have been uplifted so the Basque Cantabrian basin is an inverted basin.

The best outcrops can be found in the Andia mountain range in Nafarroa (+ Urbasa, Leyre, Alaiz...).

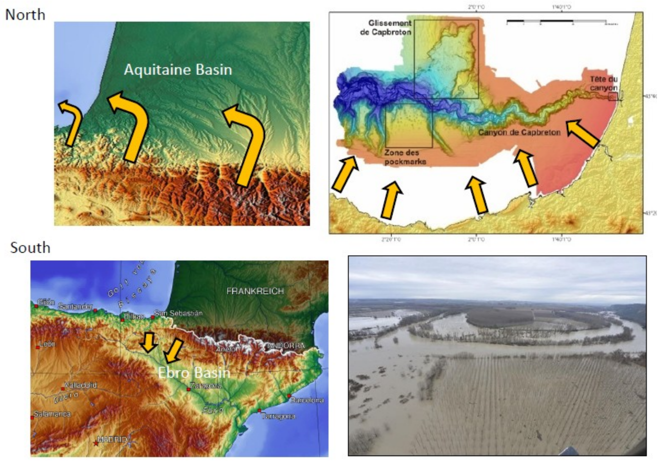
The main Paleocene reef components are corals and algae, and during the Eocene Nummulites and Alveoline proliferated.




All the materials uplifted in the Alpine orogeny were subjected to erosion. All these eroded materials were deposited in the basins to the north and to the south (Ebro basin).

The main Miocene outcrop is Falces formations; saline lakes that contained thick sequences of gypsum.

The lakes were fed by fluvial courses (sandstones) with extensive adjacent floodplains (clay) → Bardenas (western area of the Ebro basin).




The Miocene lake and river records contain numerous fossil remains: for example, African fauna (crocodiles., turtles, rhinoceros, hippopotamus) that prove the existence of extensive savannahs and freshwater swamps.

The Quaternary glaciations did also affect the Basque-Cantabrian region (alternating series of glacial and interglacial periods).

Therefore, there are some landforms associated to glaciers, the horn in El Roncal, the Glacial Valley (U shaped) in Belagua. As the glacier moves downward it excavates the landform.

Typical Karst morphologies, associated to the dissolution of the limestones can be also found in Larra, Itxina or Urbasa.

During the Holocene (last 12000 years), sea level rose due to global melting, leading to the formation of estuaries because the sea water flooded the past river valleys (f.e Urdaibai, Santoña, Orio, Bilbao…)