قسم الجيولوجيا

جامعة جنوب الوادى

Geology (3)

Structural Geology & Geomorphology

3rd year Geology-Biology, Faculty of Education

Prepared by

Dr. Mohamed Ismail Abdelkareem

Geology Department, Faculty of Science

(2021/2022)

Basic information

Faculty: Education

Class: 3rd year

Specialization: Geology-Biology

Pages: 112

Department: Geology-Biology Department

Contents

List of figures

Course content

Up to date aspects of structural geology from micro to macro scale. To give insight and understanding of applied aspects of structural geology, including digital techniques of integrated structural data analysis, visualization and interpretation.

Knowledge:

Students will acquire knowledge about up to date aspects of theoretical and experimental structural geology from micro to macro scale. These include: knowledge on plate tectonics, geometry and description of faults; brittle and ductile structures analysis and characterization; folds, lineation and foliation characteristics. The course will also highlight applied aspects of structural geology, including digital techniques of integrated structural data analysis, visualization and interpretation.

Skills:

- Students will develop skills in the broad field of structural geology and will learn to examine structures and deformation processes at all scales in a holistic fashion, by integrating their knowledge in different geological fields.

- Compare and describe each of Earth's layers.

- Compare some of the ways geologists learn about Earth’s interior.

Learning methods and activities

Lectures, exercises and laboratory works.

Chapter One

Earth's structures and Plate Tectonics

1. Earth's structures

From outside to inside, Earth is divided into crust, mantle, and core. Each has a different chemical makeup. Earth can also be divided into layers with different properties (Fig. 1). The two most important are lithosphere and asthenosphere.

How Do We Know About Earth's Interior?

If someone told you to figure out what is inside Earth, what would you do? How could you figure out what is inside our planet? How do scientists figure it out? They use the information given to them by Earthquakes and meteorites.

- Seismic Waves

Waves of energy spread out from an earthquake's center. These are called **seismic waves**. Seismic waves change speed as they move through different materials. This causes them to bend. Some seismic waves do not travel through liquids or gases. Scientists use all of this information to understand what makes up the Earth's interior
The properties of seismic waves allow scientists to understand the composition of Earth's interior.

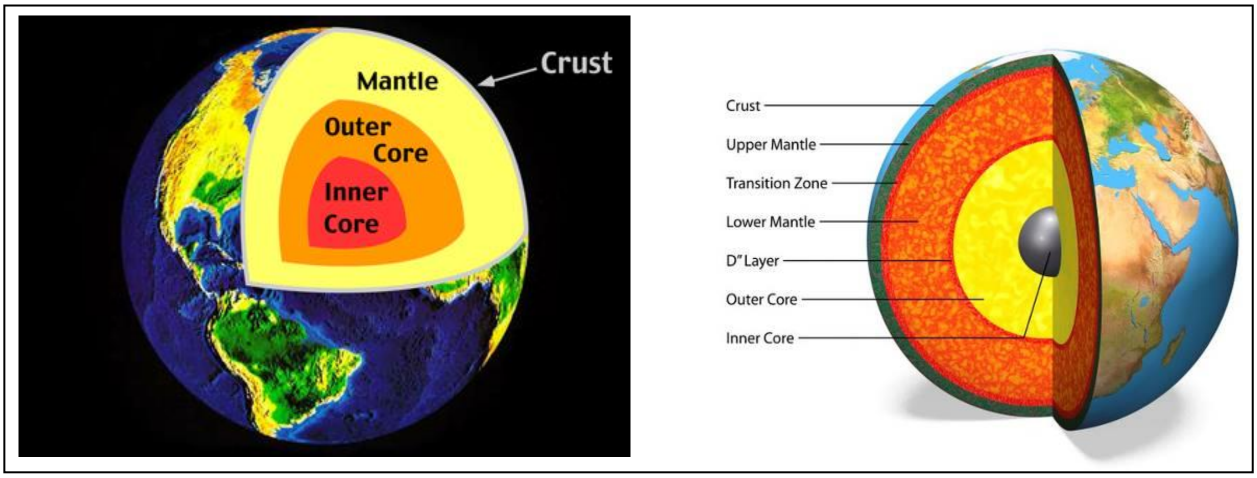


Fig. 1. Earth's structure

Meteorites

Scientists study meteorites to learn about Earth's interior. Meteorites formed in the early solar system. These objects represent early solar system materials. Some meteorites are made of iron and nickel. They are thought to be very similar to Earth's core. An iron meteorite is the closest thing to a sample of the core that scientists can hold in their hands!

- **Geological surveys: fieldwork, boreholes, mines**

1.1 The Crust

Crust, mantle, and core differ from each other in chemical composition. It is understandable that scientists know the most about the crust, and less about deeper layers. Earth's **crust** is a cool, thin, brittle outer shell. The crust is made of solid rock (Fig. 2). There are two kinds of crust, oceanic crust and continental crust. The crust is thinner under the oceans and muchthicker in mountain ranges.

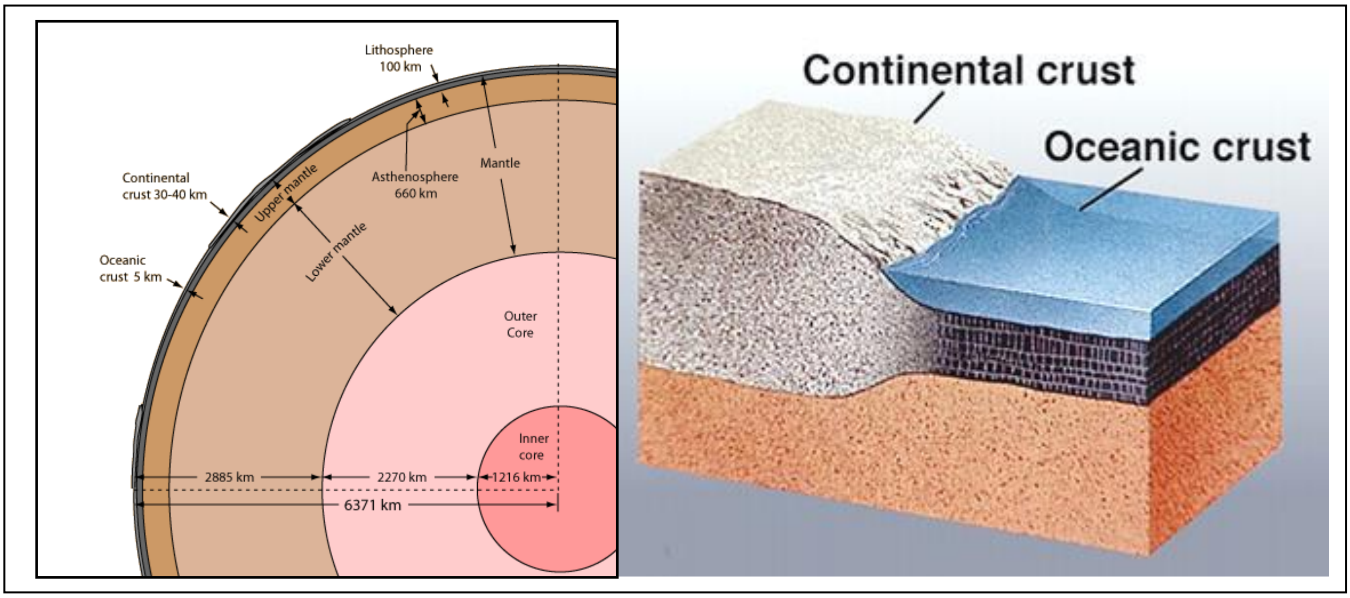


Fig. 2. Earth's structure (left) and Earth crust (right)

Oceanic crust

It is made of basalt lavas that flow onto the seafloor. It is relatively thin, between 5 to 12 kilometers thick (3 - 8 miles). The rocks of the oceanic crust are denser (3.0 g/cm3) than the rocks that make up the continents. Thick layers of mud cover much of the ocean floor.

Continental crust

It is much thicker than oceanic crust. It is 35 kilometers (22 miles) thick on average, but it varies a lot. Continental crust is made up of many different rocks but mainly igneous granite rock. All three major rock types — igneous, metamorphic, and sedimentary — are found in the crust. On average, continental crust is much less dense (2.7 g/cm3) than oceanic crust. Since it is less dense, it rises higher above (floating on) the mantle than oceanic crust.

The continental crust is thinnest in areas like the Rift Valleys of East Africa and in an area known as the Basin and Range Province in the western United States (centered in Nevada this area is about 1500 kilometers wide and runs about 4000 kilometers North/South). Continental crust is thickest beneath mountain ranges and extends into the mantle. Both of these crust types are composed of numerous tectonic plates that float on top of the mantle. Convection currents within the mantle cause these plates to move slowly across the asthenosphere.

1.2 The Mantle

Beneath the crust is the **mantle**. The mantle is made of hot, solid rock. Although the mantle is solid, it is often considered a semi-plastic solid because it slowly moves by the process of convection currents. Through the process of conduction, heat flows from warmer objects to cooler objects. The lower mantle is heated directly by conduction from the core. In the process of conduction, heat flows from warmer objects to cooler objects.

Convection in the Mantle

Hot lower mantle material rises upwards (Fig. 3). As it rises, it cools. At the top of the mantle it moves horizontally. Over time it becomes cool and dense enough that it sinks. Back at the bottom of the mantle, it travels horizontally. Eventually the material gets to the location where warm mantle material is rising. The rising and sinking of warm and cooler material creates a convection cell. The rising and sinking of mantle material of different temperatures and densities creates a convection cell.

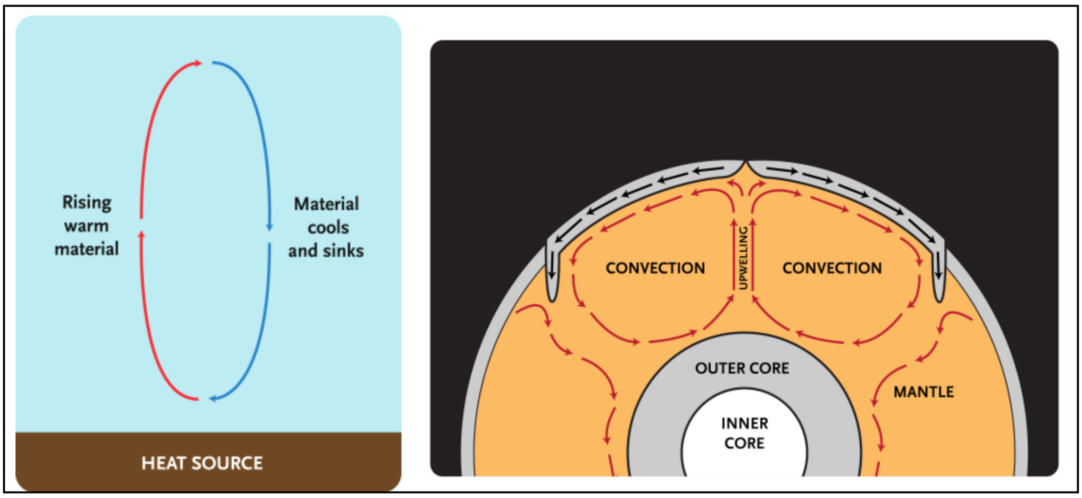


Fig. 3. Convection cell in the Mantle

1.3 The Core

The dense, iron **core** forms the center of the Earth. The core is a layer rich in iron and nickel that is composed of two layers: the *inner* and *outer cores*. The inner core is theorized to be solid and very dense with a radius of about 1220 kilometers. The inner core is extremely hot and solid because of the tremendous pressure it is under from all of the other layers pushing down above it and gravity pulling all of Earth's mass towards the center. The outer core is liquid nickel and iron. It is also extremely hot and surrounds the inner core and has an average thickness of about 2250 kilometers.

Scientists know that the core is metal from studying metallic meteorites and the Earth's density. Seismic waves show that the outer core is liquid, while the inner core is solid. Movement within Earth's outer liquid iron core creates Earth's magnetic field. These convection currents form in the outer core because the base of the outer core is heated by the even hotter inner core. Earth's magnetic field is created from the movements of liquid metal in the Earth's outer core.

Lithosphere and Asthenosphere

Lithosphere and asthenosphere are layers based on physical properties. The outermost layer is the **lithosphere (**Fig**.**4**)**. The lithosphere is the crust and the uppermost mantle. In terms of physical properties, this layer is rigid, solid, and brittle. It is easily cracked or broken. The lithosphere is also the zone of earthquakes, mountain building, volcanoes, and continental drift.

Below the lithosphere is the **asthenosphere**. The asthenosphere is also in the upper mantle. This layer is solid, but it can flow and bend. A solid that can flow is like silly putty (semi-platic).

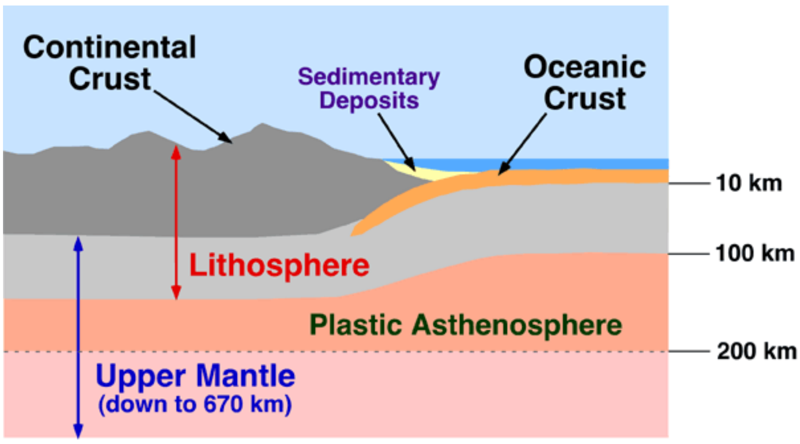


Fig. 4. Lithosphere and Asthenosphere

2. Plate Tectonics

Introduction

- Earth's lithosphere is divided into mobile plates.
- Plate tectonics describe the distribution and motion of the plates.
- The theory of plate tectonics grew out of earlier hypotheses and observations collected during exploration of the rocks of the ocean floor.

Although plate tectonics is a relatively young idea in comparison with unifying theories from other sciences (e.g., law of gravity, theory of evolution), some of the basic observations that represent the foundation of the theory were made many centuries ago when the first maps of the Atlantic Ocean were drawn. Geographer Abraham Ortellus noted the similarity between the coastlines of Africa, Europe and the Americas in the third edition of his Thesaurus Geographicus, published in 1596. Ortellus, adapting Plato's story of the demise of Atlantis, suggested that America was “torn away” from Europe and Africa and that the “projecting parts of Europe and Africa” would fit the “recesses” of America.

Such observations were little more than ideal speculation until Austrian climatologist ***Alfred Wegener*** used the fit of opposing coastlines as one of the pieces of evidence to support his hypothesis of continental drift. ***Continental drift*** proposed that the continents were once assembled together as a single supercontinent Wegener named **Pangaea** (Fig.5). Wegener was unable to suggest a suitable mechanism to explain the motion of the continents across Earth's surface and his hypothesis received relatively little support until technology revealed the secrets of the ocean floor. Scientists gradually amassed additional data that would resurrect Wegener's hypothesis over 30 years after his death. By the 1960s the building blocks were in place to support a new hypothesis, Seafloor spreading that would provide the mechanism for continental drift. Together these concepts would become the theory of plate tectonics.

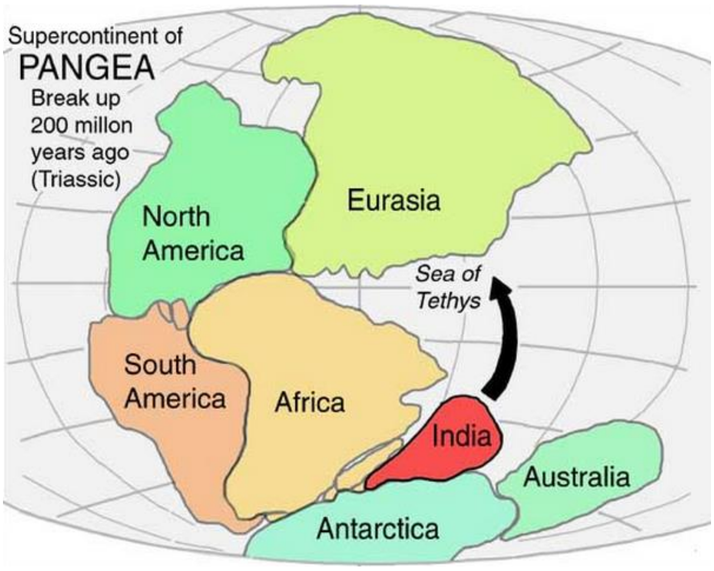


Fig.5. Supercontinent of Pangea

The theory of plate tectonics provides an example of the evolution of scientific thought. The theory of plate tectonics links Earth's internal processes to the distribution of continents and oceans; it is the big picture view of how the earth works. Plate tectonics reveals that the lithosphere is divided into eight major pieces ("plates") with several smaller plates. The plates are mobile, moving in constant, slow motion measured in rates of centimeters per year. The movements of plates over millions of years resulted in the opening and closure of oceans and the formation and disassembly of continents.

Plates interact along plate boundaries. There are three principal types of plate boundary (**divergent**, **convergent**, and **transform**). Plates move apart at divergent plate boundaries such as the oceanic ridge system that separates the North American and Eurasian plates in the North Atlantic Ocean. Plates crash into each other along convergent plate boundaries marked by volcanoes and mountain belts. Finally, plates slide past each other along a transform plate boundary such as the San Andreas Fault, California that separates the North American and Pacific plates.

The African plate is composed of both oceanic lithosphere (below Atlantic and Indian Oceans) and continental lithosphere (beneath Africa).

2.1 Continental Drift

- Alfred Wegener proposed the hypothesis that the continents were once assembled together as a supercontinent he named Pangaea.
- He noted that opposing coastlines were similar on opposite sides of the Atlantic Ocean, mountains belts matched when continents were reassembled, fossils matched between different continents, and climate evidence suggested continents were once in different locations.
- Wegener's observations supported his hypothesis but he could not offer a suitable explanation for how the continents had moved around Earth.
- The concept of continental drift was proposed by Alfred Wegener. Wegener suggested that the earth's continents once formed a single super-continent landmass that he named Pangaea. He suggested that Pangaea split apart into its constituent continents about 200 million years ago and the continents "drifted" to their current positions.
- Wegener’s principal observations were:

- Fit of the continents: The opposing coastlines of continents often fit together. An even better fit occurs if the edge of the continent shelf is used, a little offshore (Fig. 6). Wegener was not the first person to notice the similarities between continental coastlines. Early map makers several centuries before had made the same observation.

- Match of mountain belts, rock types: If the continents are reassembled as Pangaea, mountains in west Africa, North America, Greenland, and western Europe match up.

Distribution of fossils: The distribution of plants and animal fossils on separate continents forms definite linked patterns if the continents are reassembled (Fig.6).

- **Paleoclimates**: Wegener assembled geologic evidence that showed that rocks formed 200 million years ago in India, Australia, South America, and southern Africa all exhibited evidence of continental glaciations.

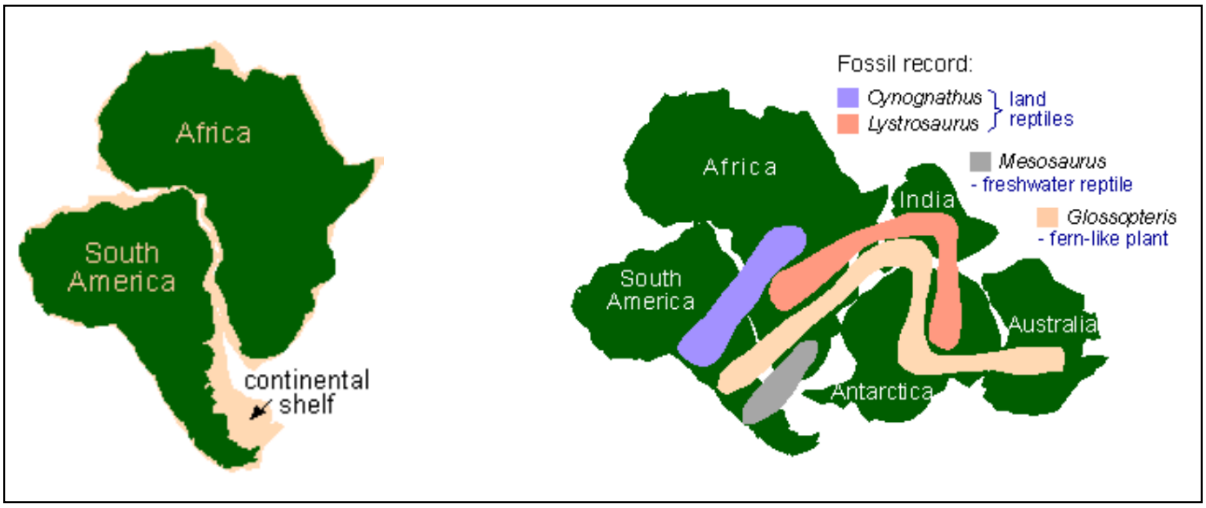


Fig.6. Continental shelf (left) and distribution of fossil record (right)

Evidence for continental drift was embraced by some scientists but was rejected by others, primarily because Wegener was unable to propose an acceptable mechanism to cause the continents to move. He suggested that the continents pushed through the rocks of the ocean floor because of tidal forces; much like a plow cuts through the soil. Unfortunately forWegener this idea was shown to be physically impossible. Consequently, continental drift, although providing acompelling explanation for the distribution of common featureson different continents, would wait another 50 years to make triumphant return.

2.2 Seafloor Spreading

An oceanic ridge system can be identified in all the world's oceans.

- Deep, narrow trenches are present along some continental margins and nearby volcanic island chains.
- Compass needles point to magnetic north during periods of normal polarity and to the magnetic South Pole during intervals of reverse polarity.
- The ocean floor rocks reveal a pattern of stripes that correspond with episodes of normal and reverse polarity in Earth's history.

- The youngest rocks in the oceans are present along the ocean ridge system; the oldest rocks are present along the margins of ocean basins.
- Seafloor spreading proposed that rising magma was forming new oceanic crust along the oceanic ridges and that old crust was destroyed at oceanic trenches.
- The concept of seafloor spreading was combined with the earlier idea of continental drift to create the theory of plate tectonics.
- Scientists gradually amassed additional data that would resurrect Wegener's hypothesis in the 30 years following his death. By the 1960s the building blocks were in place to support the new hypothesis, seafloor spreading that would provide the mechanism for continental drift. Together these concepts would become the theory of plate tectonics. The observations used to build support for seafloor spreading came from a range of specialists including oceanographers (studies of the seafloor), geophysicists (magnetic properties of rocks), seismologists (earthquakes), and geochronologists (determination of the age of rocks).

2.2.1. Seafloor Topography

The ocean floor varies considerably in depth and character. Beginning at the edge of the continents we can recognize four principal depth zones. The first depth level is the continental shelf, shallow ocean floor (0-150 meters; 0-500 feet) immediately adjacent to continental land masses. Beyond the shelf, the ocean floor steps down to the second depth level, the deep ocean basins known as the abyssal plains often over 4 kilometers below sea level. Scientists surveying the ocean floor discovered that heat flow was high along oceanic ridges and suggested that the ridge system was a source of volcanic activity.

2.2. 2. Paleomagnetism and the Ocean Floor

Earth’s magnetic field (Fig.7), originating from the partially molten rocks of the outer core, causes compass needles to point toward the magnetic poles. While the magnetic poles are found at high latitudes they are seldom coincident with the geographic poles. Just as we can define magnetic poles, it is also possible to generate a magnetic equator and lines of magnetic latitude. The orientation of the magnetic field varies with latitude and resembles a giant dipole magnet located in the Earth's interior The orientation of the magnetic field can be defined by its declination and inclination. Declination defines the orientation of the lines of magnetic force that stretch from one magnetic pole to another. The declination direction therefore points toward the magnetic poles. The inclination of the magnetic field varies between horizontal and vertical. The magnetic field is horizontal at the magnetic equator, steeper at high latitudes, and vertical at the magnetic poles. The magnetic field is inclined downward in the Northern Hemisphere and upward in the Southern Hemisphere.

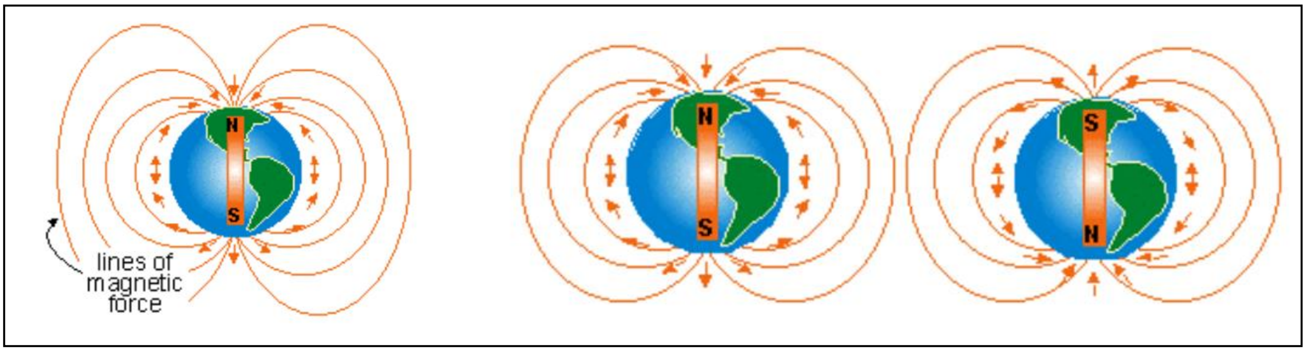


Fig.7. The Earth's magnetic field

Magnetic minerals, most commonly those with a high iron content, align parallel to Earth's magnetic field when they form during the cooling of magma. These minerals represent "fossil" compasses that record the orientation of the magnetic field at their time of formation (paleomagnetism – fossil magnetism). Magnetized minerals in ancient lava flows can therefore be interpreted to record the original latitude of the cooling magma when the rock formed.

Age of the Ocean Floor

Ages of igneous rocks on land can be determined using radioactive dating techniques (For a discussion of how geologists determine the absolute age of rocks, see Numerical Time section of the Geologic Time chapter). Ages can be matched with the history of magnetic reversals to identify the sequence and length of intervals of normal and reverse polarity (Fig. 8). The patterns of polarity in rocks of the ocean floor were used to establish the ages of rocks in the ocean basins.

Analysis of rock samples from the ocean floor reveals that the oceanic crust is relatively young in comparison to the continents. The oldest oceanic rocks are less than 200 Myrs (million years) old. In contrast the maximum age of the continental crust has been established as four billion years (4,000 million).

The seafloor spreading hypothesis lead to the conclusion that new ocean floor was created at the oceanic ridges. The oceanic lithosphere gradually moved away from the ridge creating a gap to fill with new material rising from below. The hypothesis implies the ocean basins (and hence Earth) will increase in size unless an additional mechanism can be found to compensate for the creation of new oceanic lithosphere. That mechanism was the destruction of old oceanic lithosphere along the trenches. When the concept of seafloor spreading was matched with Wegener's earlier idea of continental drift, the new theory of plate tectonics was born.

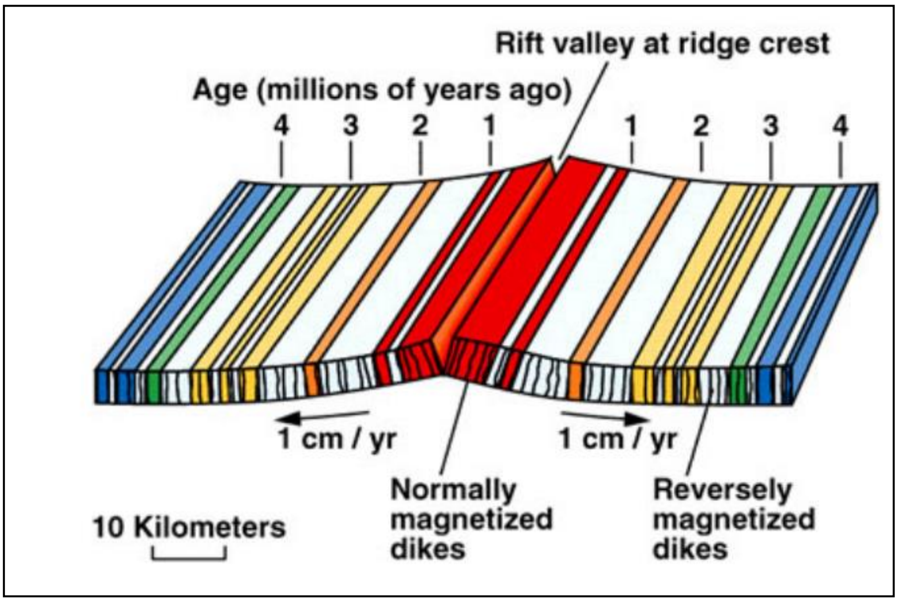


Fig. 8. The seafloor spreading and age of oceanic crust

3. Plate Tectonics

- Earth's lithosphere is divided into a series of major andminor mobile plates.
- Plates move at rates of centimeters per year.
- Plates may be composed of continental and/or oceaniclithosphere.
- The destruction of oceanic lithosphere below oceanictrenches explains the occurrence of earthquakes andvolcanoes adjacent to trenches.

3.1 Lithospheric Plates

The theory of plate tectonics proposes that the lithosphere is divided into eight major plates (North American, South American, Pacific, Nazca, Eurasian, African, Antarctic, and Indian-Australian) and several smaller plates (e.g., Arabian, Scotia, Juan de Fuca) that fit together like the pieces of a jigsaw puzzle. These plates are mobile, moving in constant, slow motion measured in rates of centimeters per year. The movements of plates over millions of years resulted in the opening and closure of oceans and the formation and disassembly of continents (Fig. 9). The theory links Earth's internal processes to the distribution of continents and oceans; it is the big picture view of how Earth works.

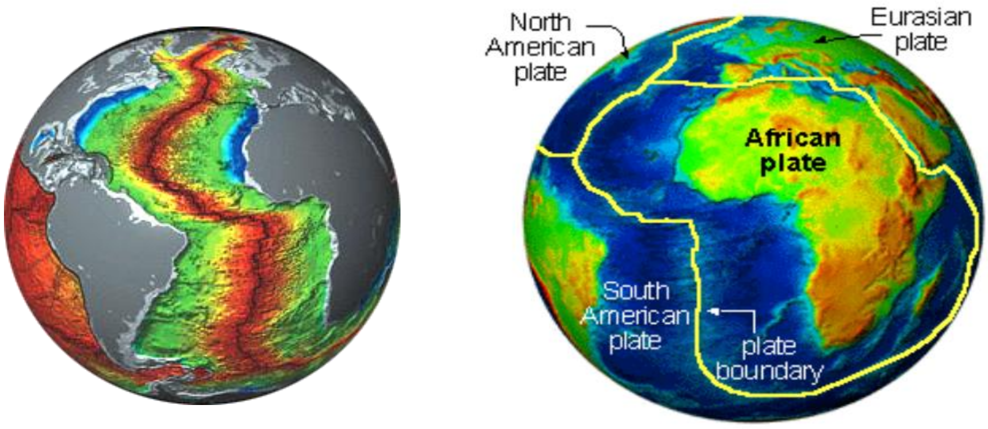


Fig. 9. The plate boundary of African plate

Plates are typically composed of both continental and oceanic lithosphere. For example, the South American plate contains the continent of South America and the southwestern Atlantic Ocean. Plate boundaries may occur along continental margins (active margins) that are characterized by volcanism and earthquakes. Continental margins that do not mark a plate boundary are known as passive margins and are free of volcanism and earthquakes. The Atlantic coastlines of North and South America are examples of passive margins.

Earthquakes and Volcanoes

Scientists had long recognized that volcanoes and earthquakes were present in greatest concentrations around the rim of the Pacific Ocean (Ring of Fire). Seismologists KiyooWadati and Hugo Benioff noted that the focal depths of earthquakes became progressively deeper underlying ocean trenches (Fig. 16). Prior to the seafloor spreading hypothesis there was no obvious explanation for the presence of these Wadati-Benioff zones. Now it is widely accepted that earthquakes occur as one plate bends and fractures as it descends beneath another into the asthenosphere.

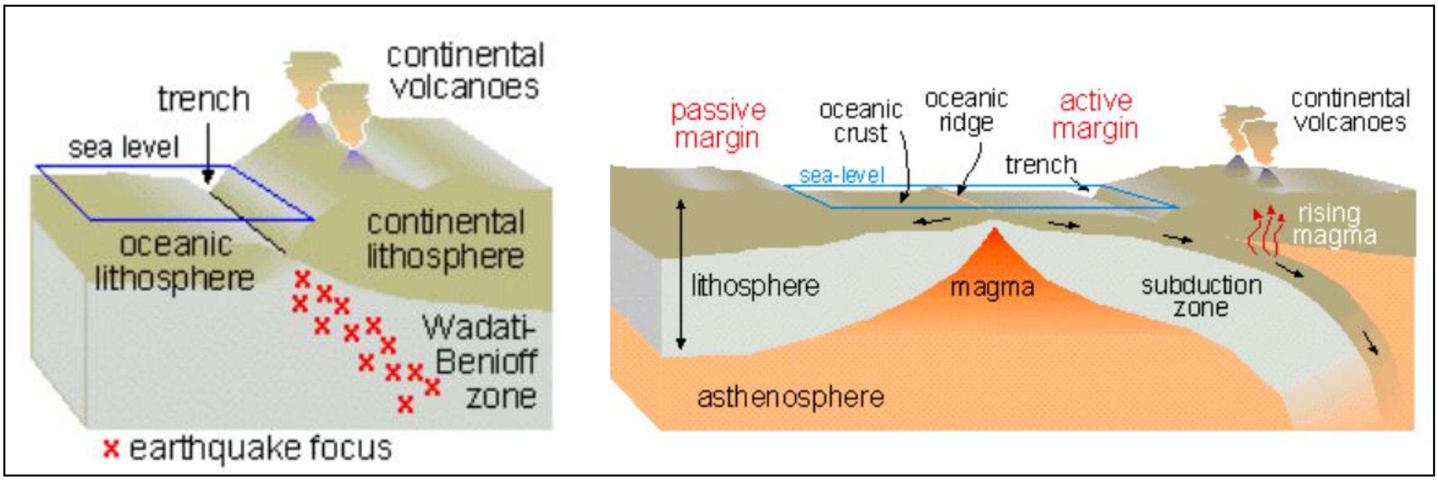


Fig. 10. Earthquakes vs. volcanoes (left), plate boundaries and margins

The ocean floor was being pulled or pushed into the mantle were it was heated to form magma which in turn generated volcanoes. The destruction of the oceanic lithosphere caused earthquakes down to depths of 700 to 800 km (440-500 miles), explaining the presence of the deepest earthquakes adjacent to oceanic trenches. The term subduction zone was coined to refer to locations marked by Wadati-Benioff zones where the oceanic lithosphere is consumed adjacent to a trench.

Plate tectonics theory join joined continental drift to sea-floor spreading to propose:

- The plate boundaries are mainly represented by oceanic ridges and trenches (Fig.10).
- Interactions at plate boundaries cause volcanic activity and earthquakes.
- The plates are in motion, moving away from ridges and toward trenches.
- Plates descend into the mantle below trenches in subduction zones.
- Plates typically contain both oceanic and continental lithosphere.
- Oceanic lithosphere is continually created and destroyed.
- Continental lithosphere cannot be destroyed but continents can be subdivided and assembled into supercontinents.

3.2 Plate Motions

The rates and directions of plate motions were originally determined by computing the distance of oceanic floor of a known age from the oceanic ridge system. Rates were computed by dividing age (years) by distance (centimeters). Such simple but effective calculations were compared to motion rates determined using the age of volcanic islands formed above mantle hot spots (e.g., Hawaii). Some volcanic islands in the interiors of plates form above fixed plumes of magma rising from the mantle. The locations of these mantle plumes are known as hot spots. The islands form as the plate moves over the magma source, much like a tectonic conveyer belt. Islands are progressively older with increasing distance from the hot spot. The relationship between age and distance yields the rate of plate motion.

Today satellite technology is used to determine the current rates of plate motion. Satellites anchored in space can record tiny movements of fixed sites on Earth, thus constraining the motions of plates. Rates of seafloor spreading range from a little as 1-2 centimeters per year along the oceanic ridge in the northern Atlantic Ocean to more than 15 cm/yr along the East Pacific Rise spreading center. Current seafloor spreading rates are approximately five times higher for the East Pacific Rise than the Mid-Atlantic Ridge. Spreading rates changed through time but consistently higher rates in the Pacific)cean basin can account for the contrast in size of the Atlantic and Pacific Oceans. The Pacific Ocean floor would be even wider if oceanic crust were not consumed at subduction zones along much of its margin.

The three types of plate boundaries are divergent, convergent, and transform.

3.2.1 Divergent Plate Boundaries

- Divergent boundaries (Fig. 11) begin by splitting apart segments of continental crust along rift valleys.

- Narrow oceans represent youthful divergent boundaries and wide oceans are indications of a long-lived ocean basin.
- Ocean ridges and subduction zones are boundaries between plates of lithosphere. A gap is created when oceanic lithosphere separates along the oceanic ridge. The gap is filled by magma that rises from the asthenosphere. The magma cools and solidifies to create new oceanic lithosphere.

The evolution of a divergent plate boundary has three recognizable stages. The birth of a divergent boundary requires that an existing plate begin to divide. This is happening today in East Africa, in an area known as the East African Rift zone. The African continent is slowly splitting in two. As the continental crust divides, magma from the asthenosphere fills in the gap. Several volcanoes are present in the rift zone.

Eventually the gap will form a narrow ocean (youth) much like the Red Sea to the north of the East African Rift zone. The Red Sea separates Saudi Arabia from Africa. A similar narrow sea, the Gulf of California, lies between much of Mexico and Baja California.

It takes millions of years to form a mature ocean, as rates of plate motions are slow (10-100 mm/yr). The oldest oceanic crust in the Atlantic and Pacific Oceans is the same age (~180 million years) but the Pacific is much wider than the Atlantic because it is spreading 2 to 3 times as fast.

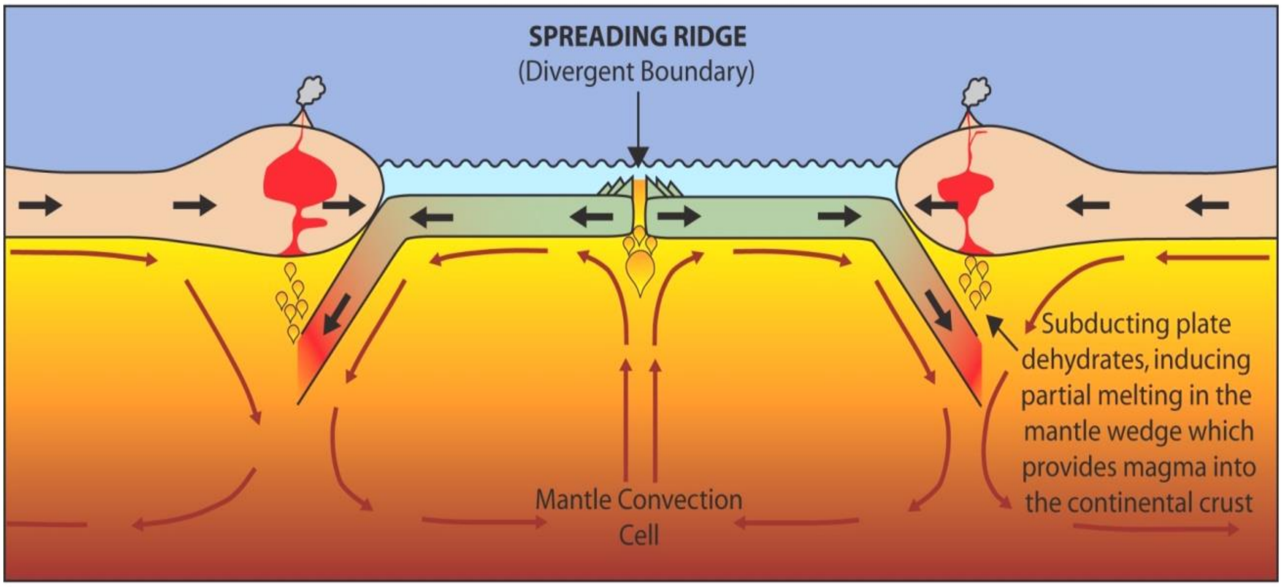


Fig. 11. Divergent plate boundary

3.2.2 Convergent Plate Boundaries

- The three types of plate boundaries are divergent, convergent, and transform.
- Interactions along convergent boundaries involve the collision of pairs of plates where oceanic lithosphere is often destroyed at subduction zones.
- Convergent boundaries may juxtapose oceanic lithosphere with oceanic lithosphere, continental lithosphere with oceanic lithosphere, and continents with continents.
- Convergent boundaries come in three varieties depending upon the type of lithosphere that is juxtaposed across a subduction zone.

- Oceanic Plate vs. Oceanic Plate Convergence

The older of the two plates descends into the subduction zone when plates of oceanic lithosphere collide along a trench. The descending plate carries water-filled sediments from the ocean floor downward into the mantle (Fig. 12). The presence of water altersthe physical and chemical conditions necessary for melting and **causes magma** to form. The magma rises up through the over-riding oceanic plate, reaching the surface as a volcano. As the volcano grows, it may rise above sea level to form an island.

- Trenches often lie adjacent to chains of islands (island arcs) formed by magma from the subducted plate. The Aleutian-Islands off the tip of Alaska were formed by magma generated when the Pacific Plate descended below some oceanic lithosphere on the margin of the North American Plate. Current volcanic activity on the island of Montserrat in the Caribbean is the result of subduction of the South American Plate below an island arc that marks the edge of the Caribbean Plate.

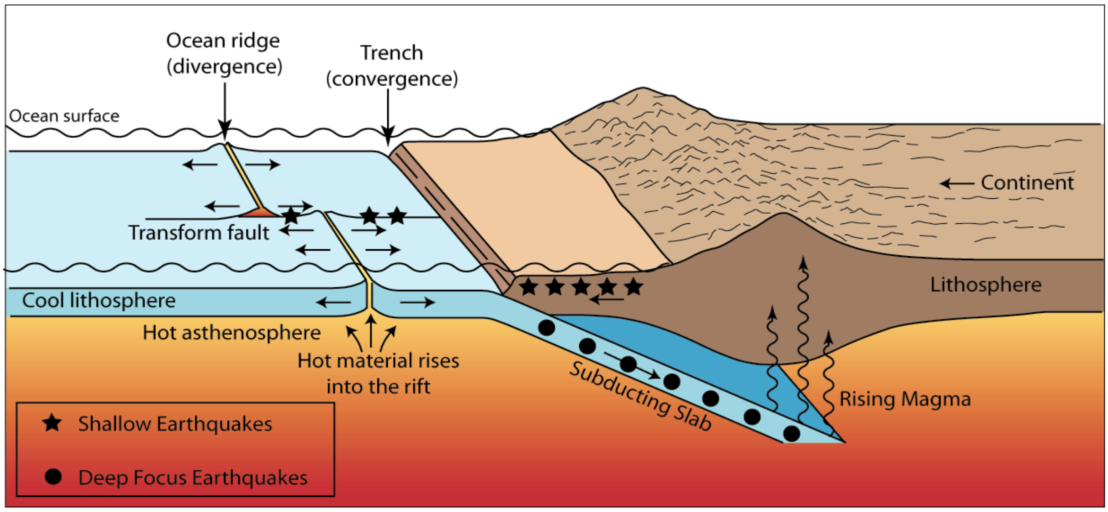


Fig. 12. Divergent plate boundary

- **Oceanic Plate vs. Continental Plate Convergence**

  When oceanic lithosphere collides with continental lithosphere, the oceanic plate will descend into the subduction zone (Fig.13). Oceanic lithosphere is denser than continental lithosphere and is therefore consumed preferentially. Continental lithosphere is almost never destroyed in subduction zones. The Nazca Plate dives below South America in a subduction zone that lies along the western margin of the continent. Convergence between these plates has resulted in the formation of the Andes Mountains (the second highest mountain range on Earth), extensive volcanism, and widespread earthquake activity. The largest earthquakes are concentrated along subduction zones.

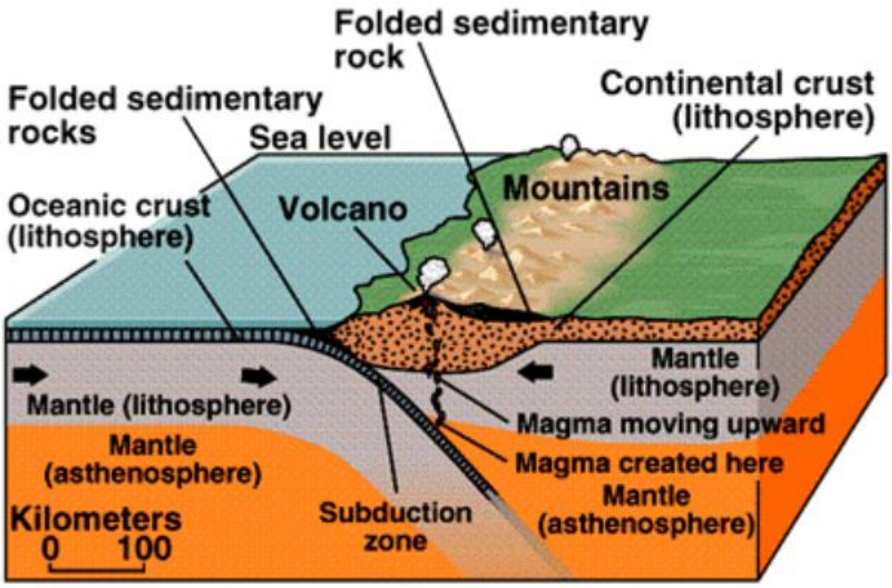


Fig. 13. Divergent plate boundary

- Continental Plate vs. Continental Plate Convergence

The tallest mountains in the world were formed (and continue to grow) as a result of continental collision. The Himalayan mountains mark the boundary between the Indian and Eurasian plates (Fig. 14). The collision of the plates began over 40 million years ago when India smashed into the belly of Asia. Continental lithosphere is relatively light and is deformed adjacent to subduction zones rather than consumed.

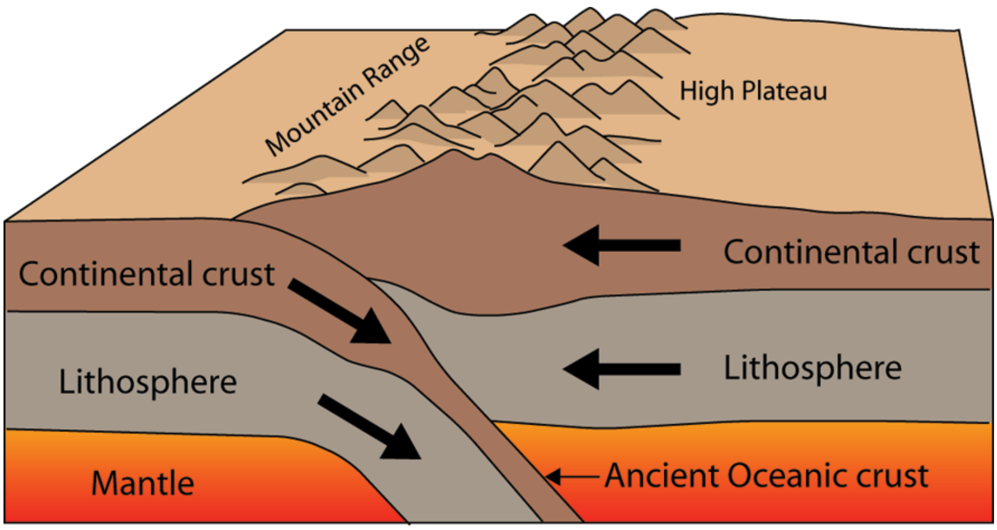


Fig. 14. Continental Plate vs. Continental Plate Convergence

3.2.3 Transform Plate Boundaries

The three types of plate boundaries are divergent, convergent, and transform (Fig. 15).

- Plates slide past each other at transform boundaries; lithosphere is neither destroyed nor created.
- The San Andreas Fault, California, is a transform boundary that separates the North American and Pacific Plates.
- Transform boundaries join sections of convergent and/or divergent boundaries. Most transform boundaries occur in ocean basins where they offset oceanic ridges. Plates on either side of a transform boundary slide past each other without either plate being consumed and without a gap opening between the plates. Recent analysis of satellite altimeter data has allowed scientists to use slight variations in the elevation of the ocean surface to determine the topography of the seafloor. Examination of oceanic ridges along the East Pacific Rise or Mid-Atlantic Ridge show offsets along transform boundaries.
- Some transform boundaries such as the San Andreas Fault in California or the North Anatolian Fault in Turkey occur on land. The San Andreas Fault joins two oceanic ridges. The southern end of the fault begins in the Gulf of California at the north end of a young ocean. The northern end of the fault becomes the Mendocino fracture zone offsetting a section

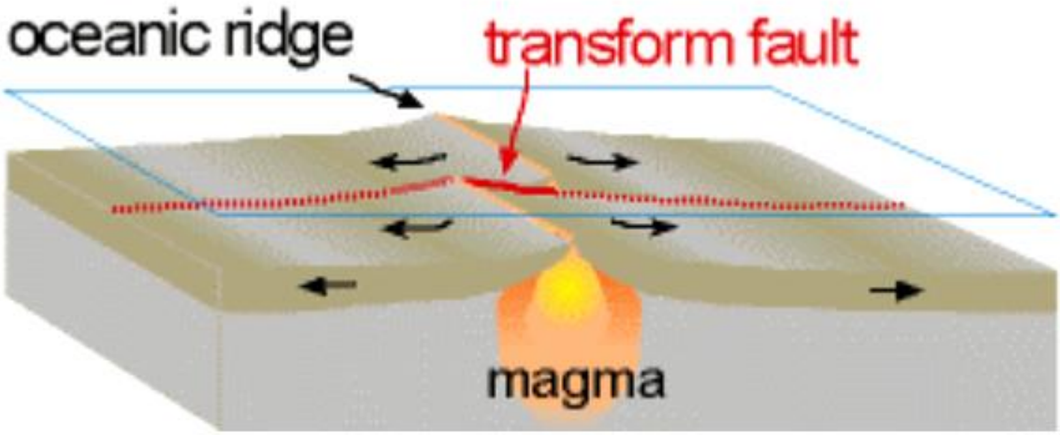


Fig. 15. Transform faults

Summary

What is the theory of plate tectonics?

The theory of plate tectonics proposes that the lithosphere (uppermost mantle and crust) is divided into a series of plates that fit together like the pieces of a jigsaw puzzle. These plates are mobile, moving in constant, slow motion measured in rates of millimeters per year. The movements of plates measured over millions of years resulted in the opening and closure of oceans and the formation and disassembly of continents (Fig.16).

2. What is the origin of the theory of plate tectonics?

The theory of plate tectonics is a combination of two earlier hypotheses, continental drift and seafloor spreading.

What is continental drift?

The concept of continental drift was proposed by Alfred Wegener who suggested that the continents once formed a single landmass he named Pangaea. He suggested that Pangaea split apart into its constituent continents about 200 million years ago and that the continents "drifted" to their current positions.

What observations did Wegener use to support the hypothesis of continental drift?

Wegener’s principal observations were: (a) Opposing coastlines of continents often fit together suggesting the continents were once a single continent. (b) Mountain belts match across continental margins if the continents are reassembled as Pangaea. (c) The distribution of fossils on separate continents match if the continents are reassembled as Pangaea. (d) Continents located near the South Pole during the assembly of Pangaea exhibit evidence of glaciation; rocks deposited on continents near the equator provide evidence of tropical conditions.

Why did Wegener and his concept of continental drift not receive more support from the scientific community?

Wegener's observations were ignored because he was unable to propose a mechanism to cause the continents to "drift". He suggested that the continents plowed through the ocean basins as a result of tidal forces but that idea was quickly discredited.

How are features on the seafloor related to the concept of seafloor spreading?

The ocean floor varies considerably in depth. An oceanic ridge system can be traced around the world. The deepest parts of the ocean (~10 km) are trenches found along the margins of some continents or adjacent to volcanic island chains. Sea-floor spreading proposed that rising magma was forming new oceanic crust along the oceanic ridges, the ocean floor was moving away from the ridges, and that old crust was destroyed at oceanic trenches.

What is magnetic polarity?

Magnetic polarity refers to the orientation of Earth's magnetic field. The magnetic field has switched polarity at irregular intervals during Earth history. Lines of magnetic force are oriented downward in the Northern Hemisphere during periods of normal polarity. During intervals of reverse polarity the inclination of the magnetic field is downward in the Southern Hemisphere.

What is paleomagnetism?

Paleomagnetism is the record of Earth's magnetic field preserved in rocks.

How do the ages of rocks on the ocean floor compare to the ages of rocks on the continents?

Rocks of the ocean floor are considerably younger (0-180 million years) than the majority of rocks that make up the continents (0-4 billion years). The age of the ocean floor varies with location and is consistently younger at the oceanic ridges and older along the ocean margins. The age of the oceanic crust increases symmetrically with distance from the ridge system in the Atlantic Ocean.

What are the principal elements in the theory of plate tectonics?

The plates are in motion, moving away from ridges and toward trenches. Plates descend into the mantle below trenches in regions termed subduction zones. Plates typically contain both oceanic and continental lithosphere. Oceanic lithosphere is continually created and destroyed. Continental lithosphere cannot be destroyed but continents can be subdivided and assembled into supercontinents. Interactions at plate boundaries cause volcanic activity and earthquakes.

Why are earthquakes and volcanoes associated with convergent plate boundaries?

The depth of earthquakes becomes progressively deeper underlying ocean trenches. Prior to the sea-floor spreading hypothesis there was no obvious explanation for the presence of these "Wadati-Benioff" zones. Earthquakes occur because of physical changes in the descending plate as it pushes into the asthenosphere. The oceanic lithosphere in the descending plate was heated to form magma which in turn generated volcanoes.

What are the three types of plate boundary?

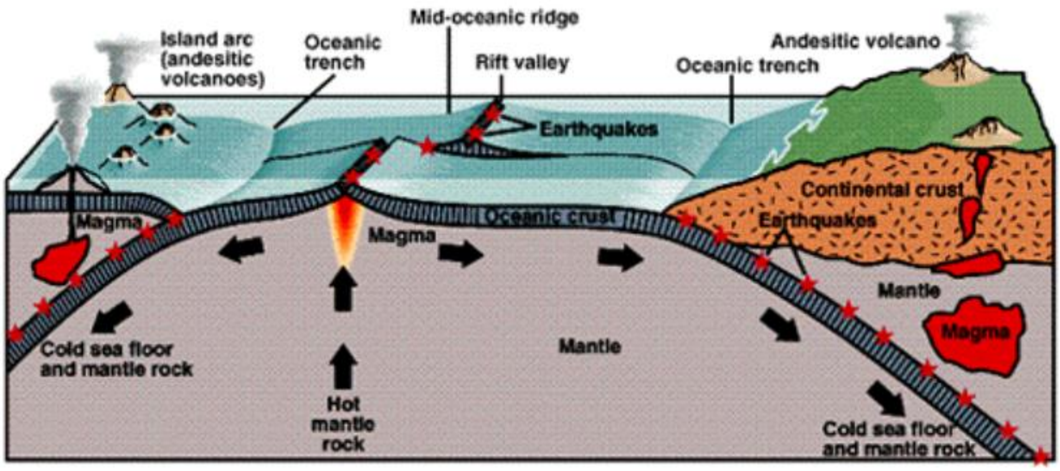
Divergent plate boundary - where plates move apart.Convergent plate boundary - where plates converge. Transform plate boundary - where plates slide past each other.

What are the different types of convergent plate boundary?

There are three types of convergent plate boundary, identified by the types of lithosphere (oceanic vs. continental) on either side of the boundary. Ocean-ocean convergence is recognized by the presence of volcanic islands along the margin of the overriding plate. Ocean-continent convergence results in a chain of volcanoes on the continental margin as continents always override oceanic lithosphere. Continent- continent collision forms mountain ranges but has no associated volcanism.

What are the characteristics of transform plate boundaries?

Transform boundaries join sections of convergent and/or divergent boundaries. Plates on either side of a transform boundary slide past each other without either plate being consumed and without a gap opening between the plates.



Think about it . . .
Make a concept map of the characteristics of the ocean floor using the features described above. Focus on finding common features related to topography, age, and paleomagnetism of the oceanic crust.

Fig. 16. The plate motions

Exercise # 1

The internal structure of the Earth

Read the definitions and fill in the blanks, and then label the diagram below

Crust - the _ _ _ _ _ surface of the Earth. The crust is quite thin like the _ _ _ _ of an orange and is thinner under the _ _ _ _ _ _.

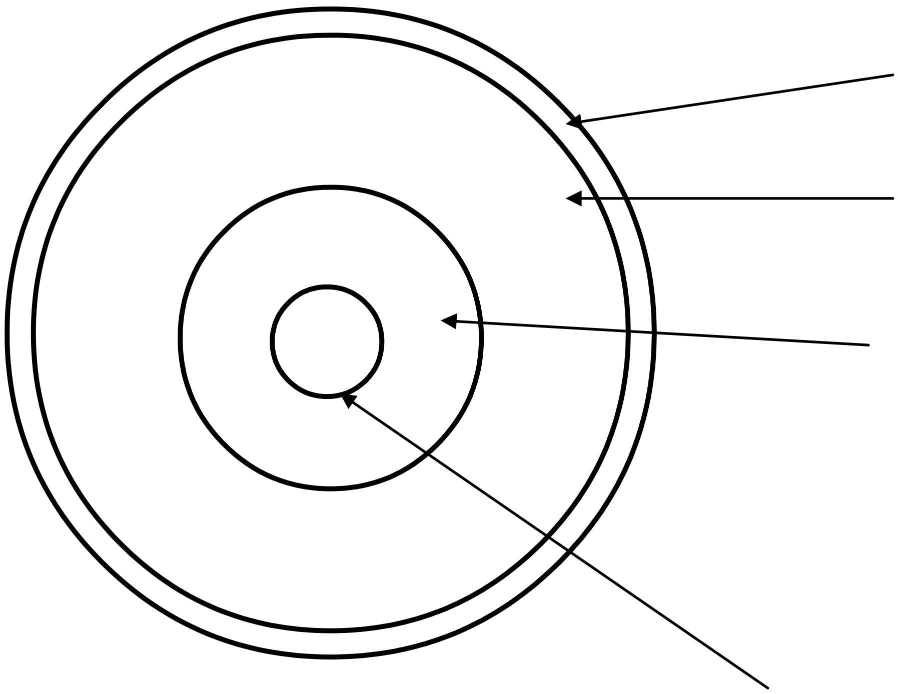
Inner core - the solid iron-nickel _ _ _ _ _ _ of the Earth that is very _ _ _ and under great pressure.

Mantle - a rocky _ _ _ _ _ located under the _ _ _ _ _. It is extremely hot – about _ _ _ _ degrees C.

Outer core – made of metal so hot that is _ _ _ _ _ _. This layer moves slowly and produces a _ _ _ _ _ _ _ _ _ field.

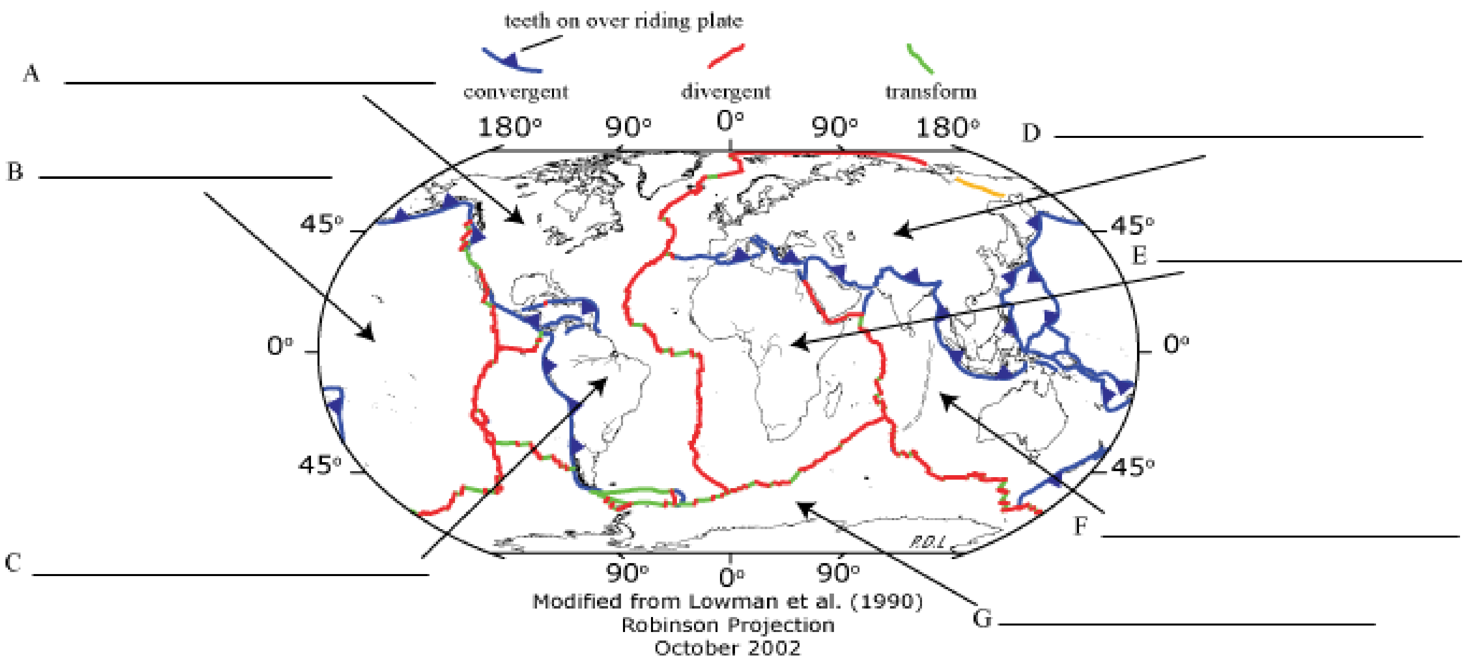
outer	**layer**	**oceans**	**centre**	**crust**

hot   skin   magnetic   liquid   5000



Exercise # 2

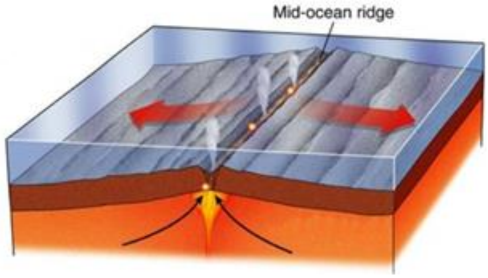
1. Who is the person that discovered the supercontinent?
a- Einstein b- Richardson c- Wegner d- Hess
2. What is the name of the supercontinent that existed millions of years ago?
a) Eurafrica b) Pangea c) Gondwana d) Europia
3- What type of plate boundary has the plates moving away from each other?
a) transform b) subduction c) convergent d) divergent
4- How do scientists learn about the interior (center) of the earth?
a) GPS b) Seismic c) electric d) practical array
5- What type of plate boundary has the two plates sliding past each other?
a) transform b) subduction c) convergent d) divergent
6- If a continentaly plate and an oceanic plate decided to slam into each other (subduction), which one would sink into the mantle? (Hint: think about which one is denser!!!)
a) oceanic plate b) transform plate c) continental plate
7- Which is the correct order for the layers of the Earth?
a) Inner mantle, outer mantle, core, outer core b) Crust, core, mantle, outer core
c) Crust, mantle, outer core, inner core
8- Where are earthquakes created?
a) At destructive plate boundaries b) At conservative plate boundaries c) At all plate boundaries



Exercise # 3

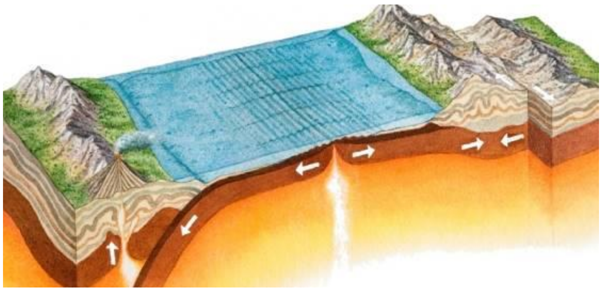
1. **<u>The process that continually adds new crust is:</u>**

- A.Subduction
- B.Earthquakes
- C. Sea-floor spreading
- D. Convection



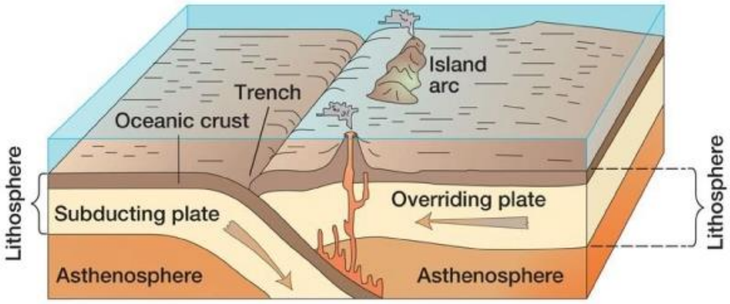
2. **<u>Where two plates rub past each other in opposite directions is a:</u>**

- A.Convergent boundary
- B. Transform boundary
- C.Hot spot
- D. Divergent boundary



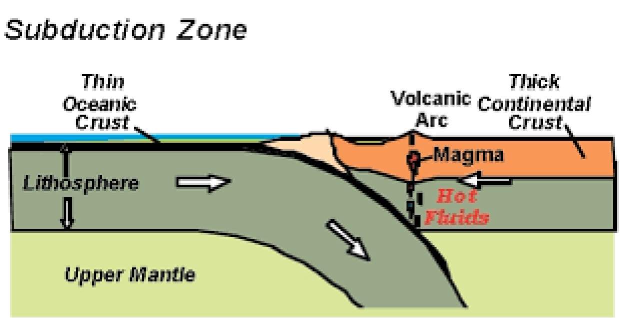
3. **<u>The place where two plates collide is called a:</u>**

- A.Transform boundary
- B.Hot spot
- C. Divergent boundary
- D.Convergent boundary



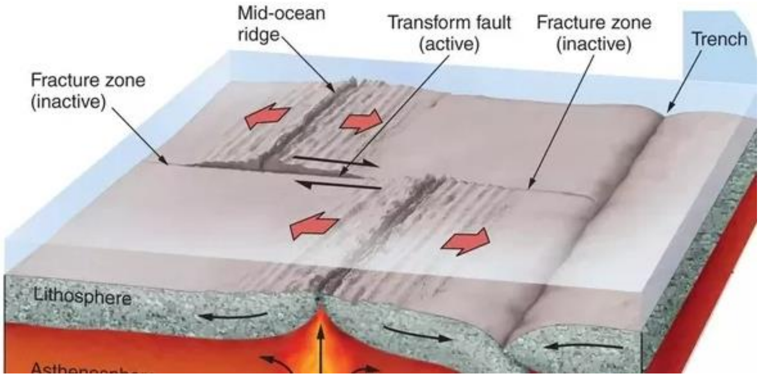
4. **<u>Subduction is when:</u>**

- A. Earthquakes occur along a transform boundary
- B.New crust is formed
- C.One plate slides under another
- D. New islands are formed

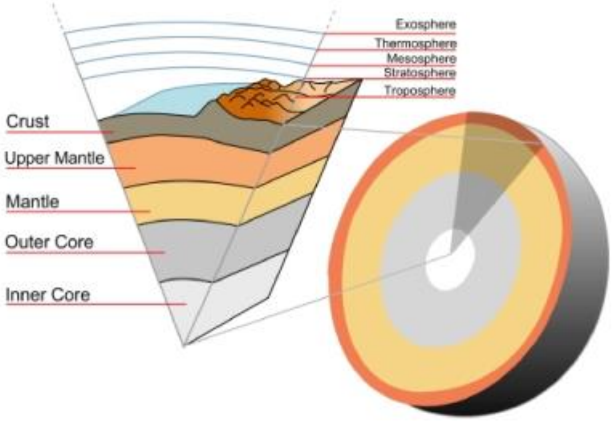


5. The mid-ocean ridge occurs along a:

- A. Convergent boundary where new crust is formed
- B.Transform boundary where the crust is subducted
- C. Divergent boundary where sea-floor spreading takes place
- D. The divergent boundary where subduction takes place



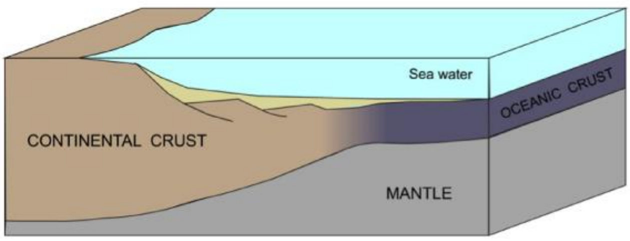
5. **The theory that states "pieces of Earth's crust are in constant, slow motion driven by movement in the mantle" is called:**



- A. The theory of continental drift
- B. The theory of Pangaea
- C. The theory of plate tectonics
- D. The theory of plate boundaries

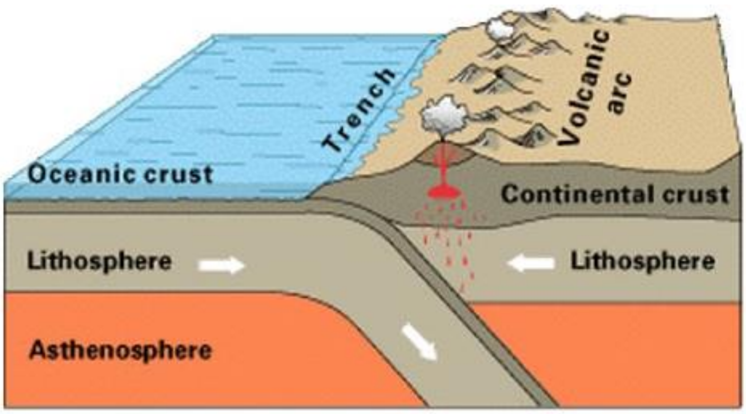
6. **Oceanic crust is ________________________ than continental crust.**

- A.Less dense
- B. More dense
- C. Less hot
- D.More hot



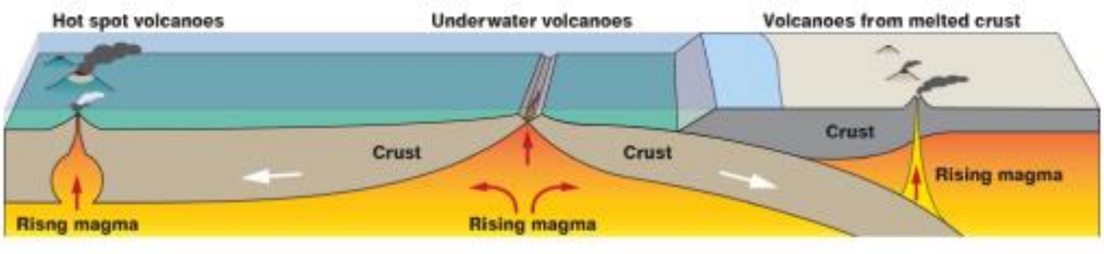
7. **Continental crust is ______________ than oceanic crust.**

- A. Hotter
- B. Colder
- C. Thicker
- D. Thinner

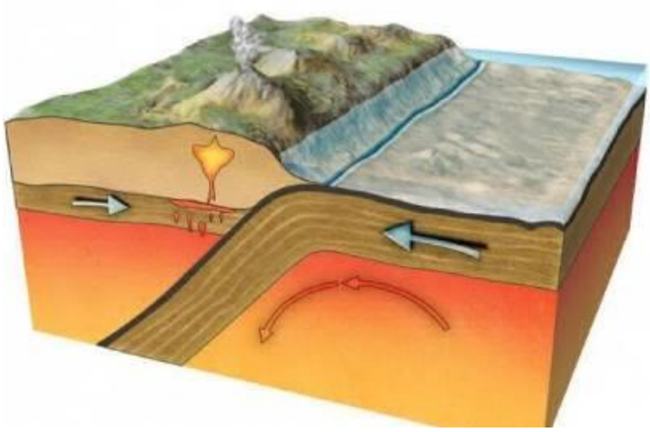


8. A place where an unusually hot part of the mantle rises through the crust causing volcanic activity is called a:

- A. Divergent boundary
- B. Hot spot
- C. Convergent boundary
- D. Transform boundary



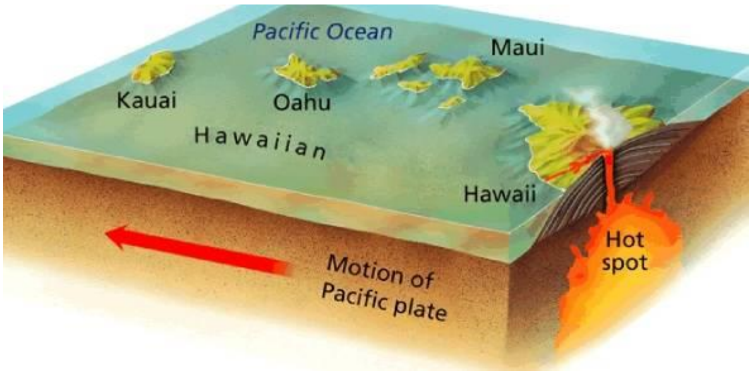
9. What causes the tectonic plates to move?



- A. Ocean currents
- B. Volcanoes
- C. The Coriolis effect
- D. Convection in the mantle

10. Hot spots are:

- A. Always moving around
- B. Stationary, they stay in the same place
- C. Constantly disappearing and reappearing
- D. What creates earthquakes



Exercise # 4

Earth's Structure

1. The outermost layer of the Earth is the __________________________. It is thickest under the __________________________ and thinnest under the __________________________.
2. What is the mantle made of?

3. The lithosphere is made up of the __________________________ and a small part of the __________________________ __________________________.
4. The lithosphere is divided into several constantly moving __________________________ that hold the __________________________ and the __________________________.
5. The plates of the lithosphere move on the __________________________, which is very hot and __________________________.
6. What does the word "malleable" mean?
   The outer core is the only __________________________ layer of the Earth.
7. The outer core is made up primarily of what two substances?

8. The inner core is extremely hot and __________________________. Like the outer core it is primarily made up of __________________________ and __________________________.

Plate Tectonics

9. What evidence did Wegner find that supports the hypothesis that the Earth's continents were once joined in a single large landmass?

10. According to plate tectonics theory Earth's outer layer, the __________________, is broken into several large ___________________, which hold the continents and the oceans, and are in constant motion.
11. Plate tectonics theory explains how ______________________________________, _____________________________________, and other geologic events occur.

Plates and Boundaries

12. The Earth's continents are constantly moving due to the motions of the __________________.

13. How does continental crust differ from oceanic crust?
14. The border between two tectonic plates is called a ________________________.
15. List the three types of plate boundaries and describe the motions of the plates at each.
16. Where do most divergent plate boundaries occur, in the interiors of continents or in the oceans?
17. What kind of plate boundary occurs between the Australian Plate and the Eurasian Plate?
18. In California, there is a transform boundary between the North American Plate and what other plate?

Slip, Slide, and Collide

19. What is a subduction zone?
20. Where an oceanic plate collides with a continental plate, why does the oceanic crust get pulled under the continental crust?
21. What geologic features would you expect to see near a subduction zone?
22. A chain of islands called a ________________________ ________________________ sometimes forms above subduction zones.
23. Why do earthquakes occur at subduction zones?
24. What geologic features typically form where two continental plates collide?
25. What happens when divergent boundaries occur in the middle of an ocean?
26. What forms when boundaries between continental plates diverge?
27. In a transform boundary, in which direction are the plates moving?
28. In transform boundaries, the plates can become “stuck”. What happens when the plates suddenly become “unstuck”?
29. What is the name of the famous transform boundary that runs through California?

Chapter two

Primary Structures

Goals: to be able to recognize and interpret primary structures including geologic contacts and mesoscale sedimentary, biogenic, and volcanogenic features; and 2) to determine facing directions using these structures.

Structures that form during deposition or crystallization of the rock.Formed when the rock did. — Serve as markers of deformation!!

- Depositional, intrusive, or volcanic contacts — Bedding probably most useful
- Sedimentary structures: Cross-beds, channels, ripples, flute casts, sole marks, mud

A) Primary structures in sedimentary rocks

1- Bedding (stratification)

It forms as a direct consequence of **<u>Steno's law</u>** of lateral continuity, that holds that a unit of sediment will extend laterally to the physical margins of the basin it is filing (Fig. 17):

"Material forming any stratum were continuous over the surface of the Earth unless some other solid bodies stood in the way."

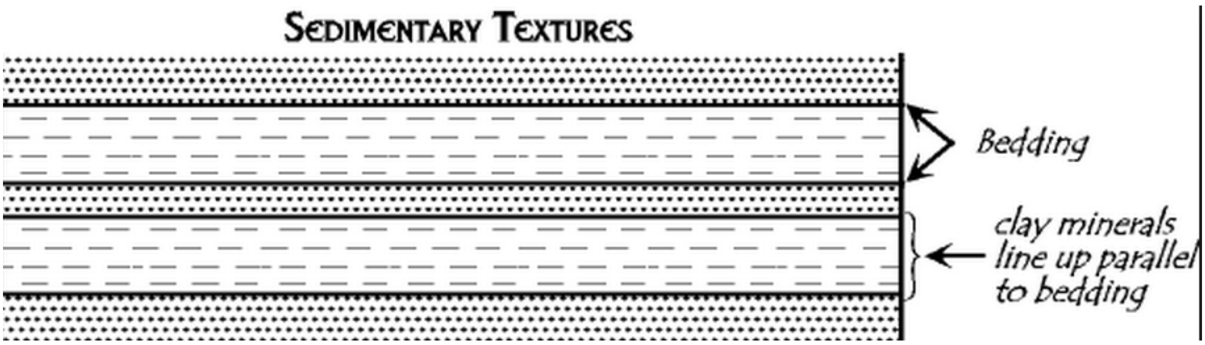


Fig. 17. Bedding

2- Cross-bedding

Cross beds can tell geologists much about what an area was like in ancient times. The direction the beds are dipping indicates paleocurrent, the rough direction of sediment transport. The type and condition of sediments can tell geologists the type of environment (rounding, sorting, composition…).

2.1 Tabular (planar) cross-beds

Tabular (planar) cross-beds consist of cross-bedded units that have large horizontal extent relative to set thickness and that have essentially planar bounding surfaces. The foreset laminae of tabular cross-beds have curved laminae that have a tangential relationship to the basal surface (Fig. 18).

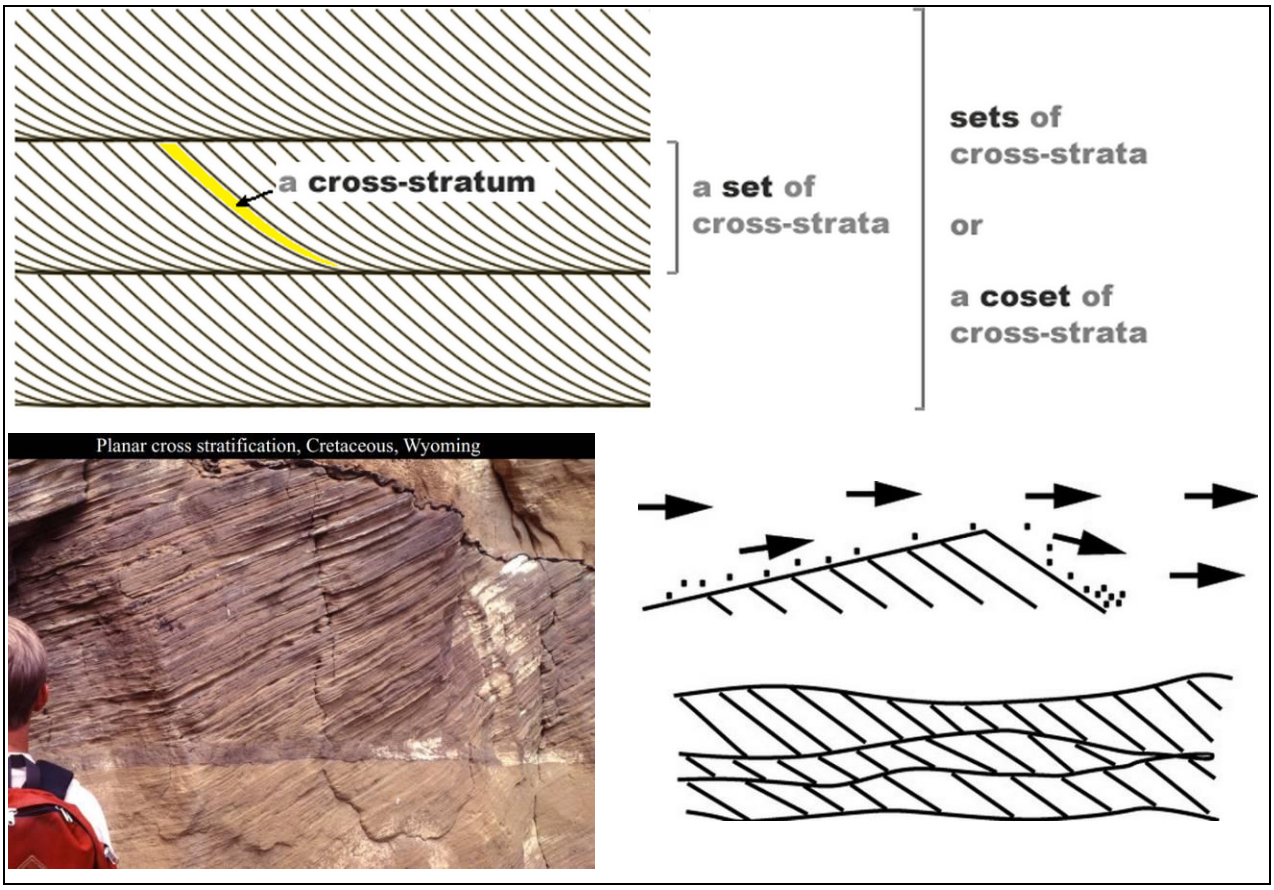


Fig. 18. Tabular (planar) cross-beds

2.2 Trough cross-beds

Cross beds are layers of sediment that are inclined relative to the base and top of the bed they are associated with. Cross beds can tell modern geologists many things about ancient environments such as- depositional environment, the direction of sediment transport (paleocurrent) and even environmental conditions at the time of deposition.

Trough cross-beds (Fig. 19) have lower surfaces which are curved or scoop shaped and truncates the underlying beds. The foreset beds are also curved and merge tangentially with the lower surface. They are associated with sand dune migration.

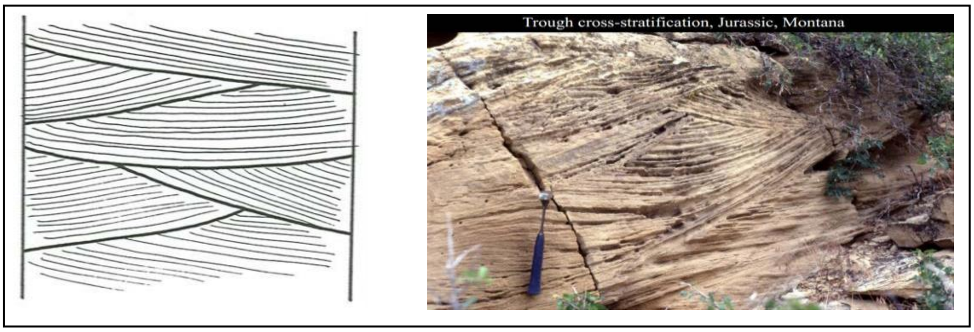


Fig. 19. Trough cross-beds

3. Ripple marks

Ripple marks are sedimentary structures (i.e. bedforms of the lower flow regime) and indicate agitation by water (current or waves) or wind. Ripple marks are characteristic of shallow water deposition. They are caused by waves or winds piling up the sediment into long ridges. Asymmetrical ripple marks can give an indication of current direction when formed in water, and when formed by wind, give wind direction (Figs. 20, 21).

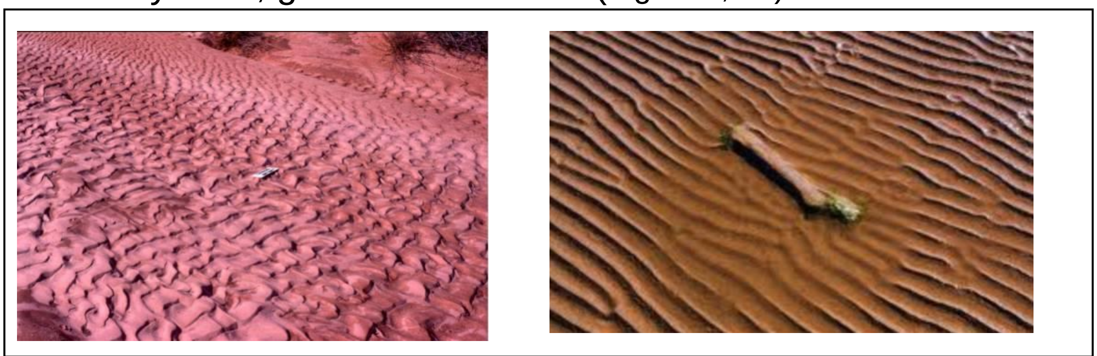


Fig. 20. Ripple marks

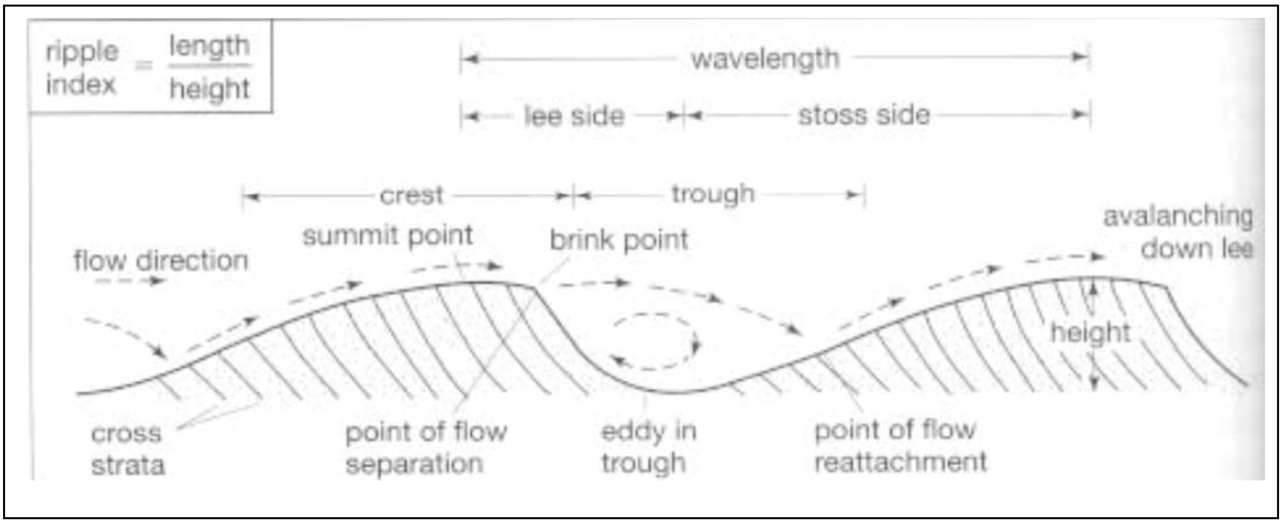


Fig. 21. Anatomy of ripple marks

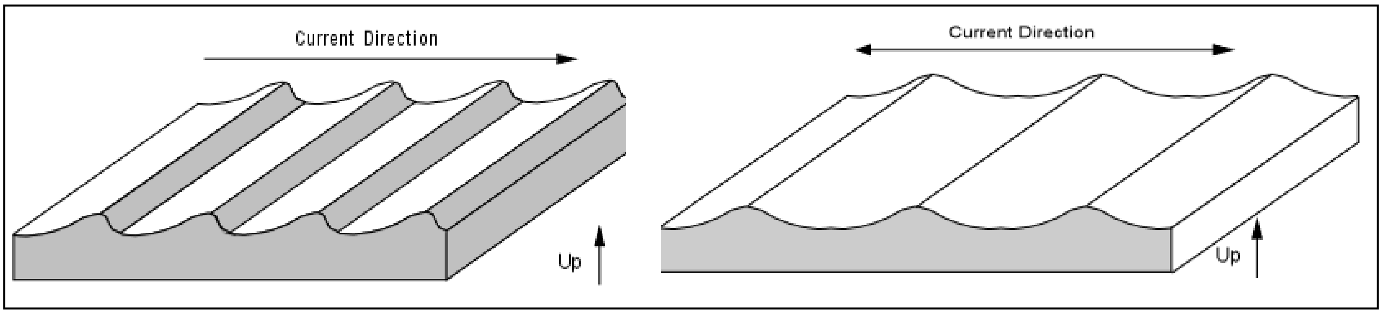


Fig. 22. Asymmetrical ripple marks (left), symmetrical ripple marks (right)

- Symmetrical ripples form when the water moves back and forth.

Symmetrical ripple marks occur in environments where there is a steady back and forth movement of the water, such as tidal action (Fig. 22).

4. Mudcracks

These structures result from the drying out of wet sediment at the surface of the Earth. The cracks form due to shrinkage of the sediment as it dries. In cross section the mudcracks tend to curl up, thus becoming a good top/bottom indicator. The presence of mudcracks indicates that the sediment was exposed at the surface shortly after deposition, since drying of the sediment would not occur beneath a body of water (Fig. 23).

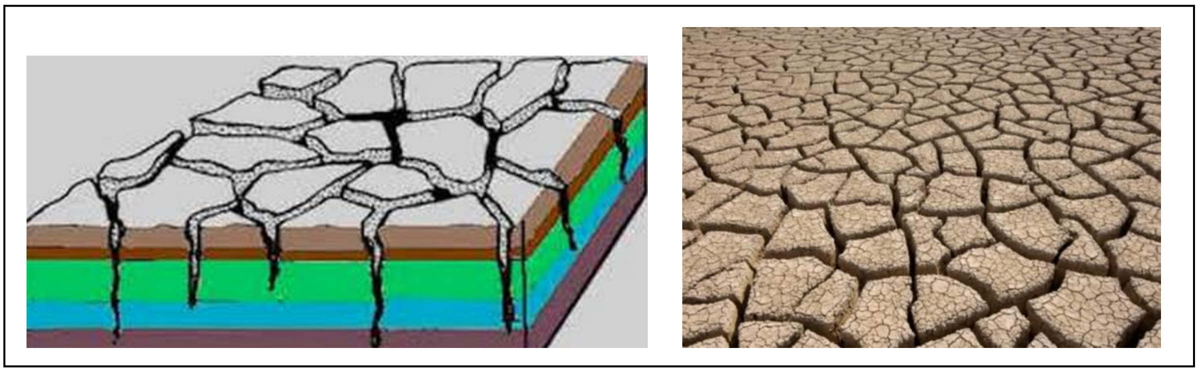


Fig. 23. Mud cracks

5. Graded Bedding

As current velocity decreases, the larger or more dense particles are deposited first, followed by smaller particles. This results in bedding showing a decrease in grain size from the bottom of the bed to the top of the bed. This gives us a method for determining tops and bottoms of beds, since reverse grading will not be expected unless deposition occurs under unusual circumstances. Note that reverse graded bedding cannot occur as current velocity increases, because each layer will simply be removed as the current achieves a velocity high enough to carry sediment of a particular size (Fig. 24).

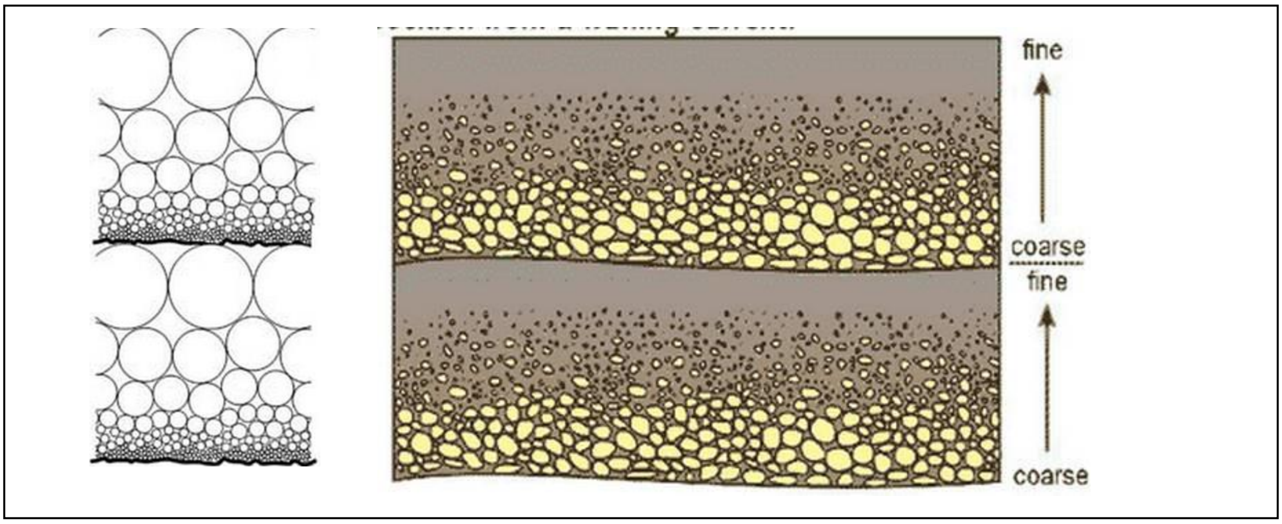


Fig. 24. Graded Bedding

B. Primary structures in igneous rocks

<u>1-Intrusions</u> by their nature do not typically show stratification, and cannot usually be used to determine tilting or way-up. However, in unravelling the structural history of a complex region, it is important to know the relative timing of intrusions, and this is where contact relationships are all important (Fig. 25).

<u>2- Volcanic rocks</u>

Volcanic rocks are typically stratified, but bedding is often much less clear than in sedimentary rocks. Sometimes the contacts between volcanic flows are conspicuous because they are weathered. Soil layers called 'bole', consisting of soft, clay-rich weathered lava are sometimes visible (Fig. 25).

Lava erupted under water typically forms baoon-like pillows typically 0.5 - 2 m in diameter, formed by rapid chilling. Later pillows conform in shape to those beneath them in a flow, giving a general indication of way-up.

Thick lava flows may shrink and crack as they cool, producing columnar joints. These typically form perpendicular to the base and top of a flow. As a result, the columns are elongated in the direction of the pole to bedding and therefore can be used to estimate the bedding orientation where bedding cannot be observed directly.

Note that columnar joints are common in sills too. Sills can be distinguished from flows only by looking at their contacts: sills show intrusive contacts top and bottome, whereas flows typically show one weathered surface.

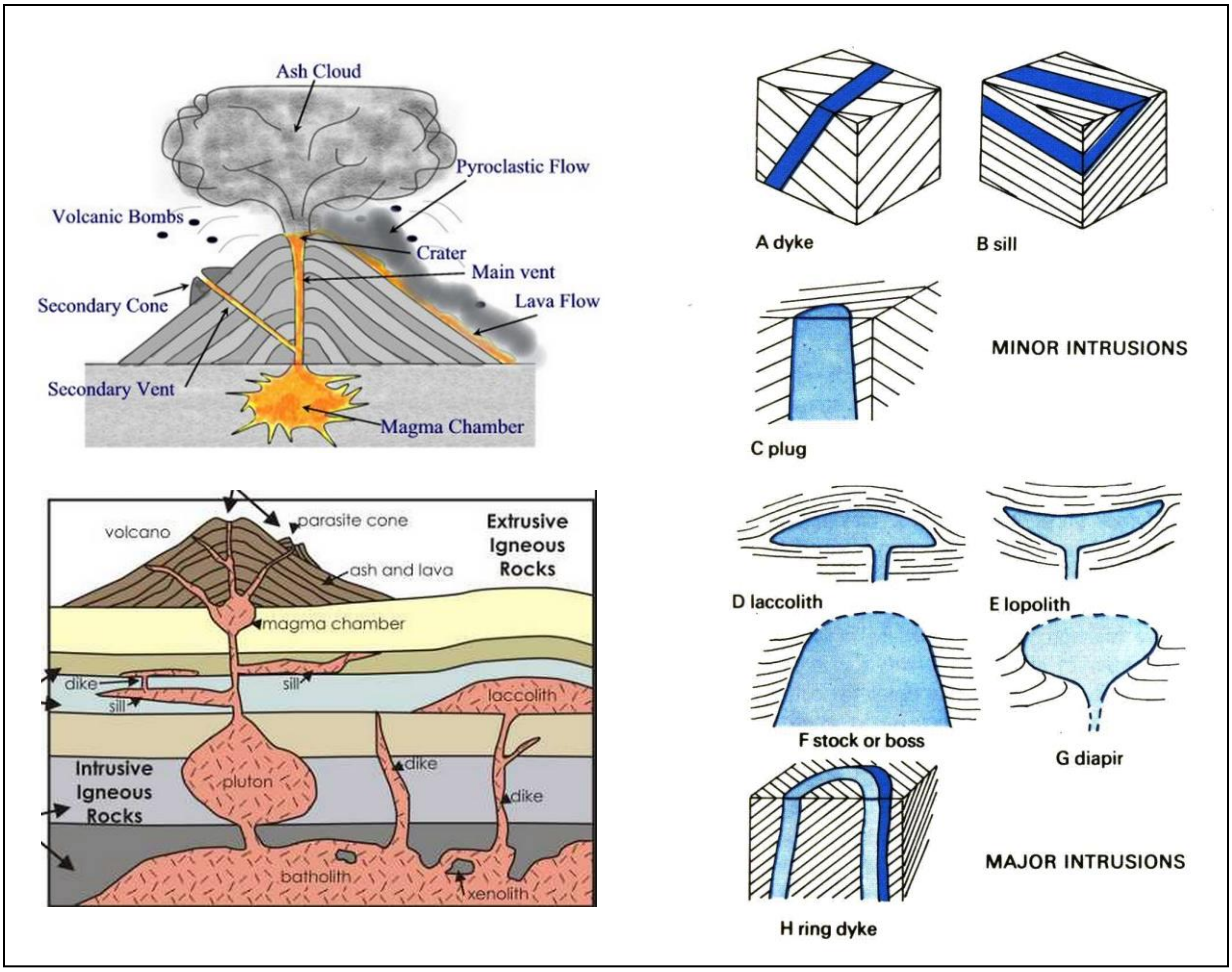


Fig. 25. Primary structures of igneous rocks

Dyke – If molten rock forces its way up through vertical cracks, it forms slabs of igneous rock called
dykes.

SILLS- If molten rock intrudes between two layers od sedimentary rock, the result is a sill. It may forma t any angle, depending on the slope of the rock layers.

A volcanic plug, also called a volcanic neck or lava neck, is
a volcanic landform created when magma hardens within a vent on an active volcano.

Laccolith is a sheet intrusion (or concordant pluton) that has been injected between two layers of sedimentary rock. The pressure of the magma is high enough that the overlying strata are forced upward, giving the laccolitha dome or mushroom-like form with a generally planar base.

Fig. 26. Columnar joints

A lopolith is a large igneous intrusion which is lenticular in shape with a depressed central region.Lopoliths are generally concordant with the intruded strata with dike or funnel-shaped feeder bodies below the body.

A stock is a discordant igneous intrusion having a surface exposure of less than 40 sq mi (100 km2), differing from batholiths only in being smaller.

Diapir; a geological structure consisting of mobile material that was forced into more brittle surrounding rocks, usually by the upward flowof material from a parent stratum. The flow may be produced by gravitational forces (heavy rocks causing underlying lighter rocks to rise), tectonic forces (mobile rocks being squeezed through less mobile rocks by lateral stress), or a combination of both. Diapirs may take the shape of domes, waves, mushrooms,

Exercise #5

1- Which of the following is NOT a type of sedimentary structure?

A. mudcracks B. graded bedding C. ripple marks **D. rock color**
E. cross-bedding

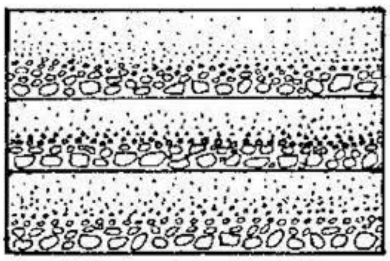
2- The type of sedimentary structure that describes a layer of sediment in which the grain size steadily decreases from the bottom to the top of the layer is called:

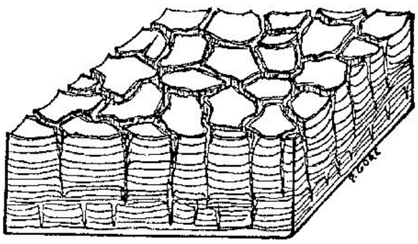
A. bedding B. cross-bedding C. graded bedding D. stratification
E. a bedding plane

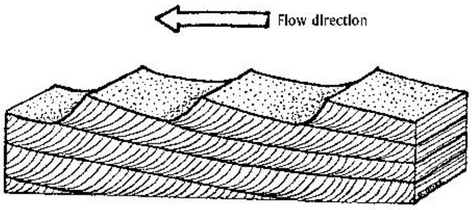
3- Which of the following sedimentary structures is common in sand dunes?

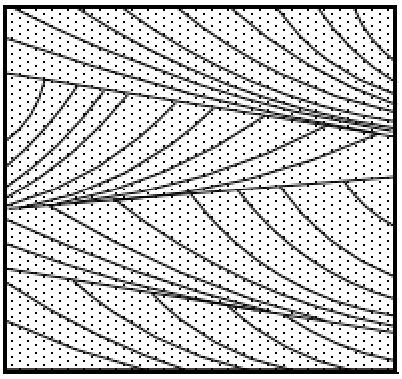
A. cross-bedding B. trace fossils C. graded bedding D. mudcracks
E. all of the above

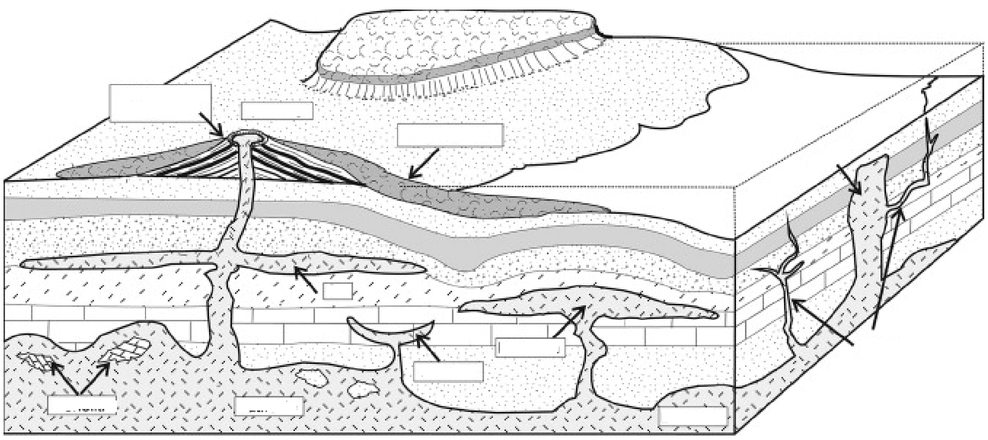
4- Define the following structures:











Chapter three

Ductile deformations: Folds

1. Introduction

Folds are wave like structures that produced by deformation of bedding, foliation or other planar surfaces in the rocks. They occur on all scales form microscopic to kilometers sizes. They form in all deformational environments from near surface brittle to lower-crust ductile and from simple shear to pure shear. They occur singly and in extensive fold trains.

Folds form under varied conditions of stress, hydrostatic pressure, pore pressure, and temperature gradient, as evidenced by their presence in soft sediments, the full spectrum of metamorphic rocks, and even as primary flow structures in some igneous rocks. A set of folds distributed on a regional scale constitutes a fold belt, a common feature of orogenic zones (Fig. 27).

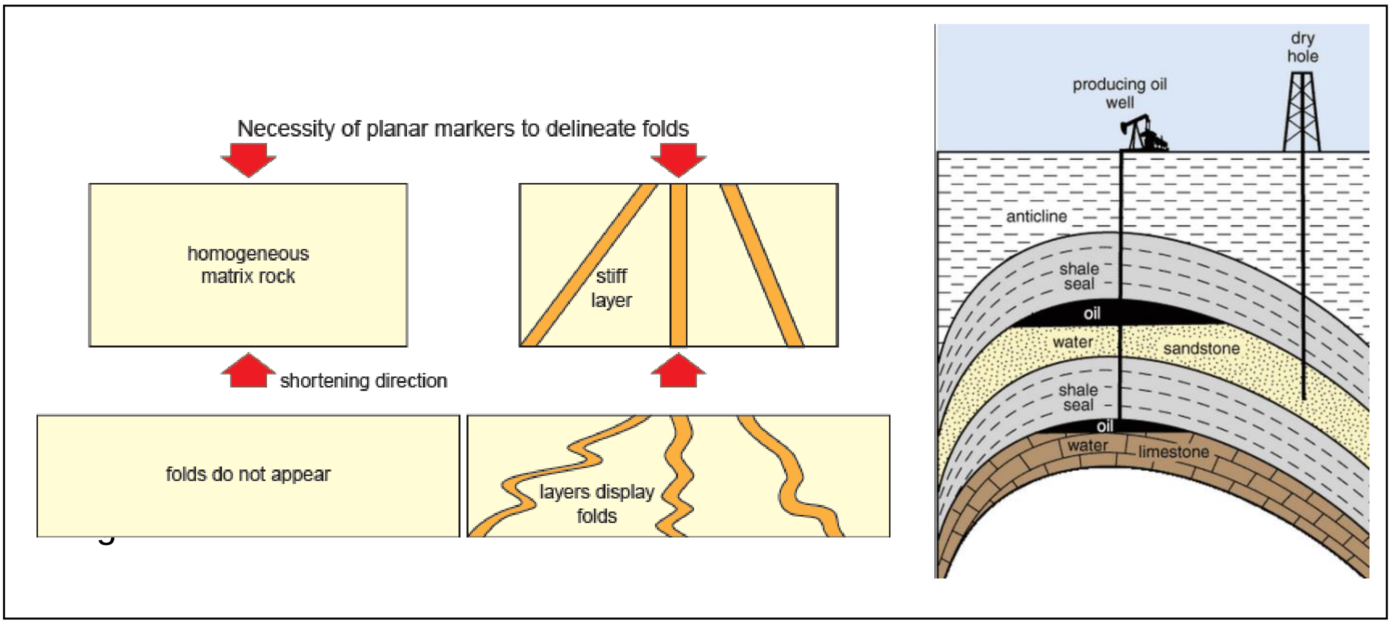


Fig. 27. folding mechanisms (left), producing oil from a fold (right)

Different folding mechanisms combine a few basic processes involving the geometrical (layer thickness and spacing) and physical (viscosity, viscosity contrast, anisotropy) properties of the rocks.

This lecture deals with some consideration on genetic, mechanical aspects concerning the development of folds. The important point to note is that stress alone is insufficient to cause folding: A planar surface must first exist to define the fold shape, and the orientation of this planar marker with respect to the stress direction controls in many ways the attitude of the resulting fold.

1.1 Importance of folding:

- Hydrocarbon traps.
- Concentration of valuable minerals (saddle-reef deposits) sulfide minerals localized in the hinges of the fold.

1.2 Scale types*:*

Folds in rocks vary in size from microscopic crinkles to mountain-sized folds. They occur singly as isolated folds and in extensive fold trains of different sizes, on a variety of scales.

microscopic (require magnification)

Mesoscopic (specimen and outcrop size)

macroscopic (larger scale)

Pumpelly's rule: small-scale structures are generally mimic larger-scale.

1.3 Anatomy of folds

- **Limb:** surface of low curvature. The limbs are the flanks of the fold and the hinge is where the flanks join together (Fig. 28).
- **Hinge point**: point of local maximum curvature. The hinge point is the point of maximum radius of curvature for a fold
- ***Hinge line or axis:*** The hinge points along an entire folded surface form a hinge line, which can be either ***a crest line*** or *a* ***trough line***. The trend and plunge of a linear hinge line gives you information about the orientation of the fold.**Crest and trough**: The crest of the fold is the highest point of the fold surface, and the trough is the lowest point.

- **<u>Axial plane</u>**:

  The axial surface is the surface defined by connecting all the hinge lines of stacked folding surfaces. If the axial surface is a planar surface then it is called the ***axial plane*** and can be described by the strike and dip of the plane.

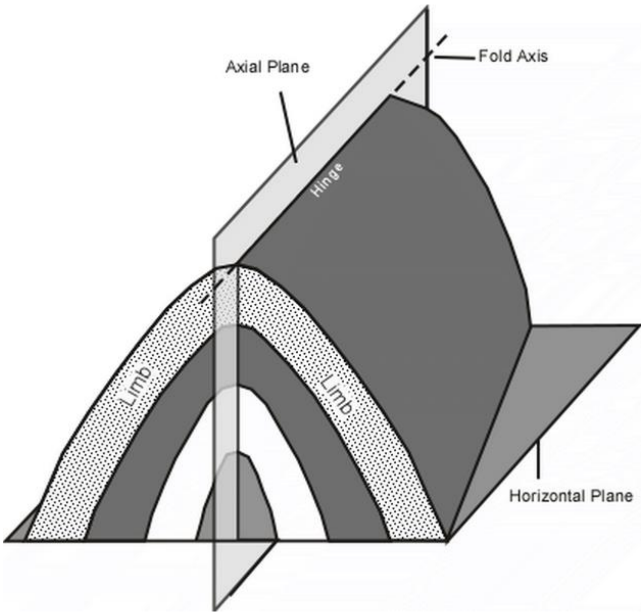


Fig. 28. Anatomy of fold

<u>1.4 Fold shape</u>

A fold can be shaped as a chevron, with planar limbs meeting at an angular axis, as cuspate with curved limbs, as circular with a curved axis, or as elliptical with unequal wavelength.

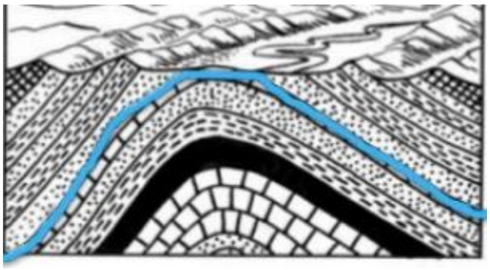
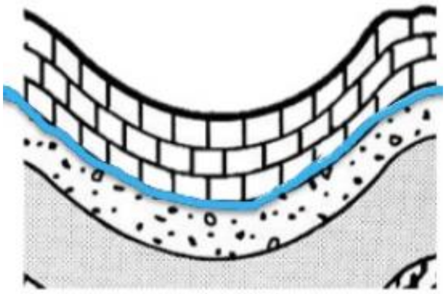
<u>1.5 Fold tightness</u>

Fold tightness is defined by the angle between the fold's limbs, called the interlimb angle. <u>Gentle folds</u> have an interlimb angle of between 180° and 120°, <u>open folds</u> range from 120° to 70°, <u>close folds</u> from 70° to 30°, and <u>tight folds</u> from 30° to 0°. <u>Isoclines, or isoclinal folds</u>, have an interlimb angle of between 10° and zero, with essentially parallel limbs.

1.6 Fold symmetry

Not all folds are equal on both sides of the axis of the fold. Those with limbs of relatively equal length are termed symmetrical, and those with highly

Table 1: Anticline vs. syncline

Anticline fold	**Syncline fold**
Anticline: linear, strata normally dip away from axial center, oldest strata in center irrespective of orientation.	Syncline: linear, strata normally dip toward axial center, youngest strata in center irrespective of orientation
	

unequal limbs are asymmetrical. Asymmetrical folds generally have an axis at an angle to the original unfolded surface they formed on.

Fig. 29. Fold symmetry

2. Type of folds

2.1 based on limb direction

Table 2: Folds based on limb direction		
Upright	**Overturned**	**Recummbent**
Folds whose axial plane dips at angles greater than 80 degrees and hinge line plunges at an angle less than 10 degrees	An asymmetrical **fold** is one in which the axial plane is inclined. An **overturned fold**, or overfold, has the axial plane inclined to such an extent that the strata on one limb are**overturned**	A **recumbent fold** has an essentially horizontal axial plane.

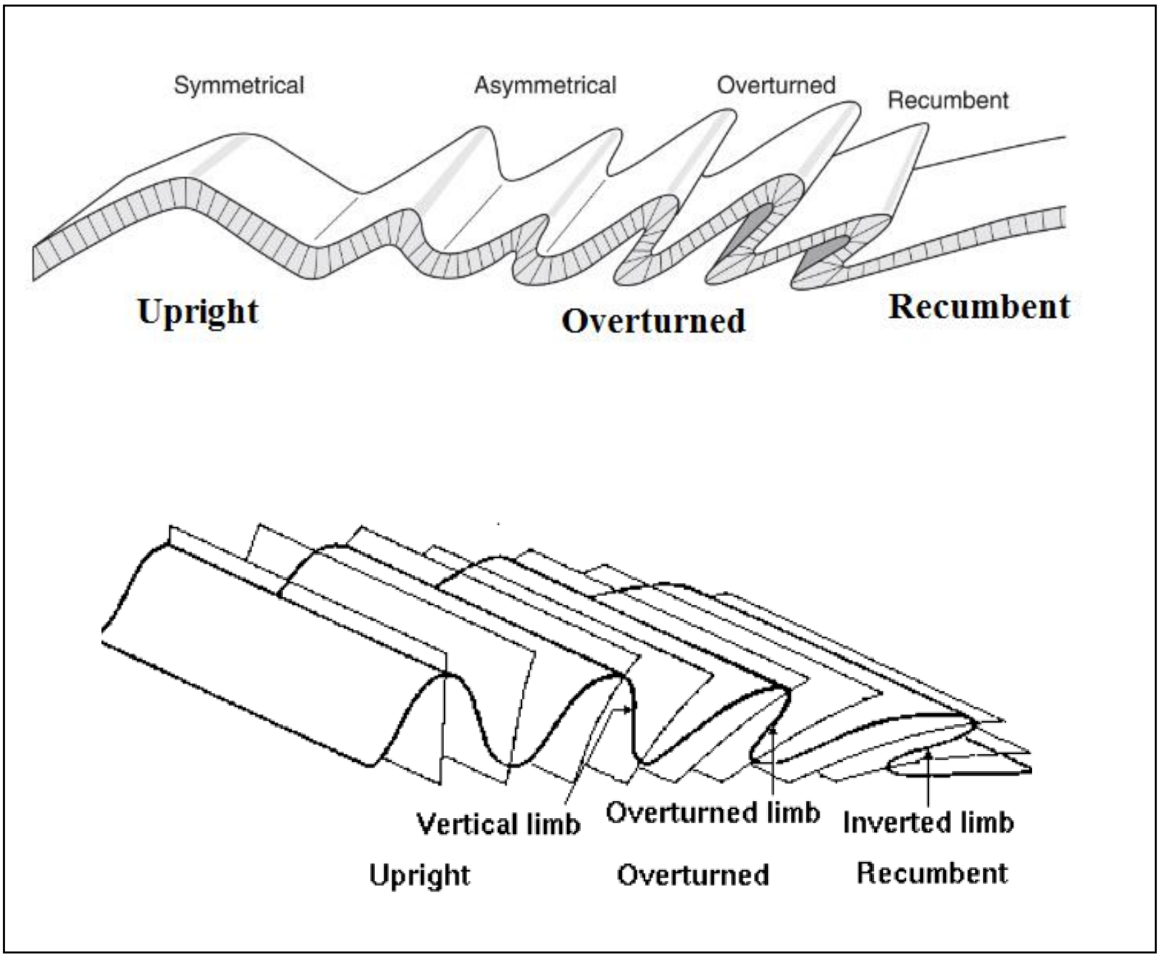


Fig. 30. Fold based on limb direction

Other fold types:

- An **isoclinal fold** is a **fold** in which the limbs are parallel. It may be upright, overturned, or recumbent (Fig. 31).

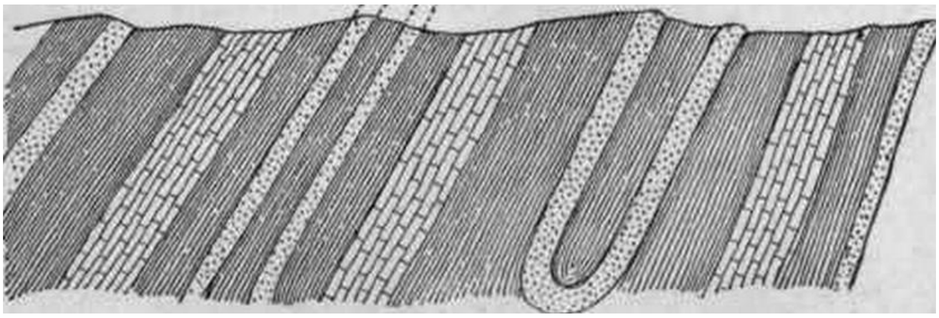
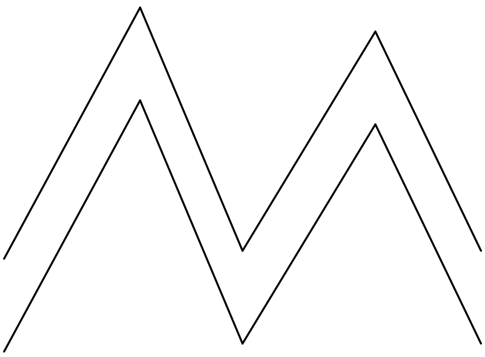


Fig. 31. isoclinal fold

- **Chevron folds**

  They are a structural feature characterized by repeated well behaved **folded** beds with straight limbs and sharp hinges. Well developed, these **folds**develop repeated set of v-shaped beds. They develop in response to regional or local compressive stress. Inter-limb angles are generally 60 degrees or less (Fig. 32).



- Fig. 32. Chevron folds

- A **dome** is such a **fold** that is convex upward; this means that its strata dip outward from a central area.
- A **basin** is such a **fold** that is convex downward; this means that its strata dip inward from a rim area

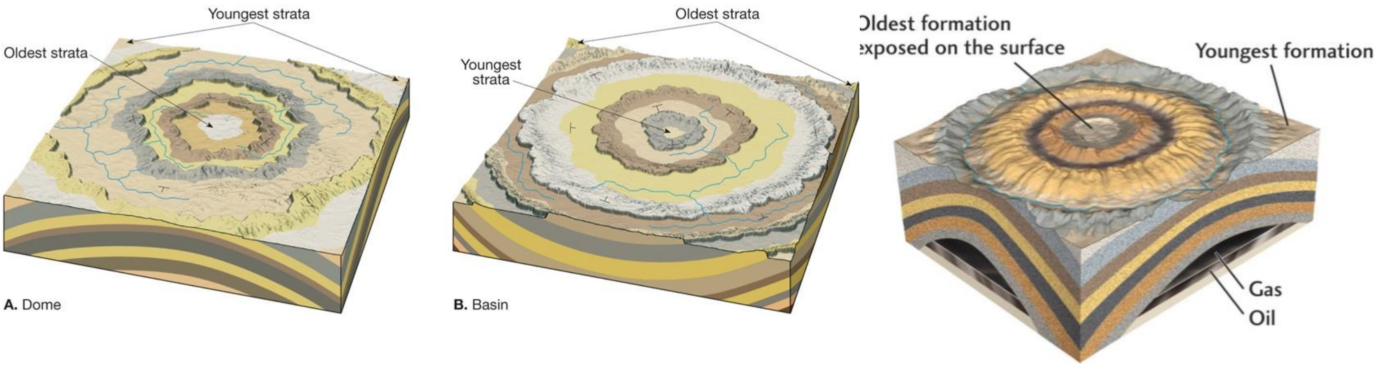


Fig. 33. Basin and dome

Plunging vs. non-plunging

In many types of **folds** the axis is horizontal or gently inclined, it may be steeply inclined or even vertical. The angle of inclination of the axis, as measured from the horizontal, is called the plunge. The portions of the fold between adjacent axes form the flanks, limbs, or slopes of a fold (Fig. 34).

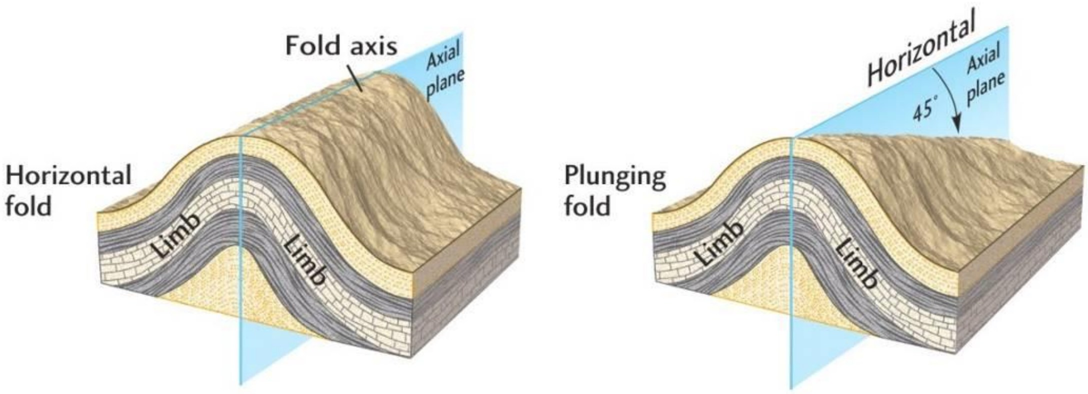
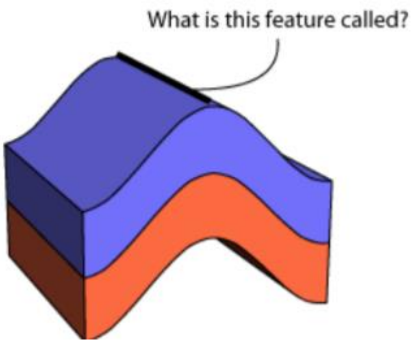
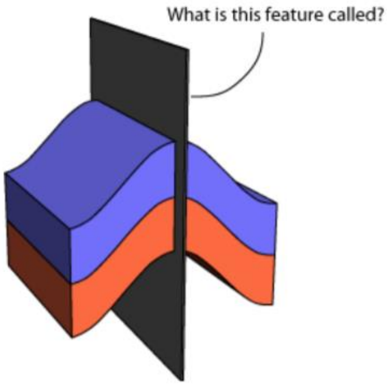


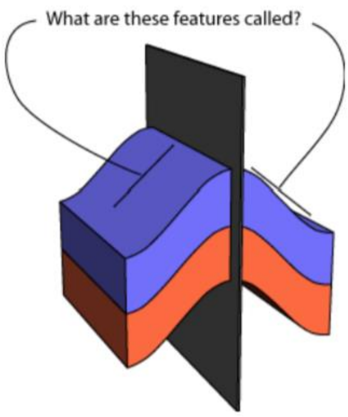
Fig. 34. Plunging vs. non-plunging

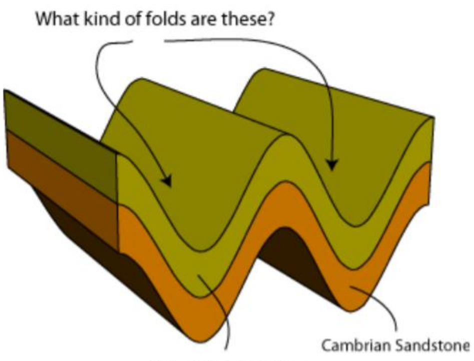
Exercise #6

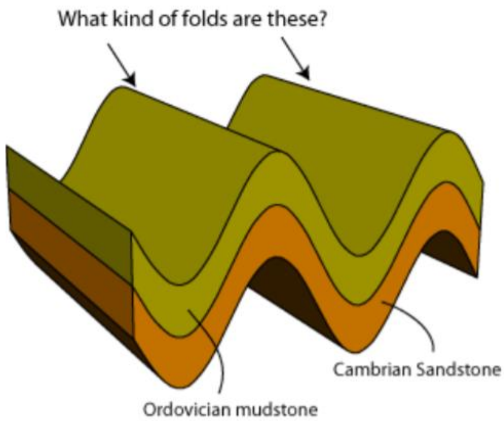
1. An anticline fold may be defined as a fold that:
(a) Is convex upward.(b) Has older rocks in the centre.
(c) The two limbs dip away from each other.(d) All above definitions are correct.
2. The line of maximum curvature in a fold is known as:
(a) Crest.(b) Axis.(c) Hinge.(d) Trough.
3- Anticline folds commonly formed resulting of ....
a) compressing b) bending c) shearing d) reversing
4- Tightness of fold measured by ....
a) rack b) strike c) plunge angle d) interlimb angle
5. Factors which increase the ductility ot a rock are:
(a) Temperature and pressure. (b) Rate of application of stress and temperature.
(c) Temperature and amount of intergranular fluids present in the rock.
(d) Pressure, rate of application of stress, temperature and amount of intergranular fluids present in the rock.
6. Please answer the question shown in the following illustration?











7: When the axis plungs directly down the dip of the axial plane; the fold is known as:
(a) Plunging fold.(b) Periclinal fold. (c) Reclined fold.(d) Flexure fold.

Chapter four

Fabrics and deformation mechanisms

1. Fabrics

A **fabric** is a particular arrangement of component features (called **fabric elements**) in a rock. This arrangement is usually regular: for instance the horizontal layers of sedimentary rocks are a kind of fabric, but we also refer to **random fabric**, which is by definition not regular (Fig. 35). We distinguish between **primary** and **secondary (tectonic)** fabrics: the first formed with the rock and includes, igneous flow lineation, sedimentary lamination and bedding and flow foliation. **Secondary** fabrics are ones that have formed as a result of deformation. Another key distinction is between **penetrative** or **continuous** fabric – which is observable at all scales, as opposed to **nonpenetrative** or **spaced** fabric, where there is obvious spacing between the fabric elements (e.g., solution cleavage seams or fractures). Finally we distinguish between **planar** fabrics – called **foliation** – and **linear** fabrics (**lineations**).

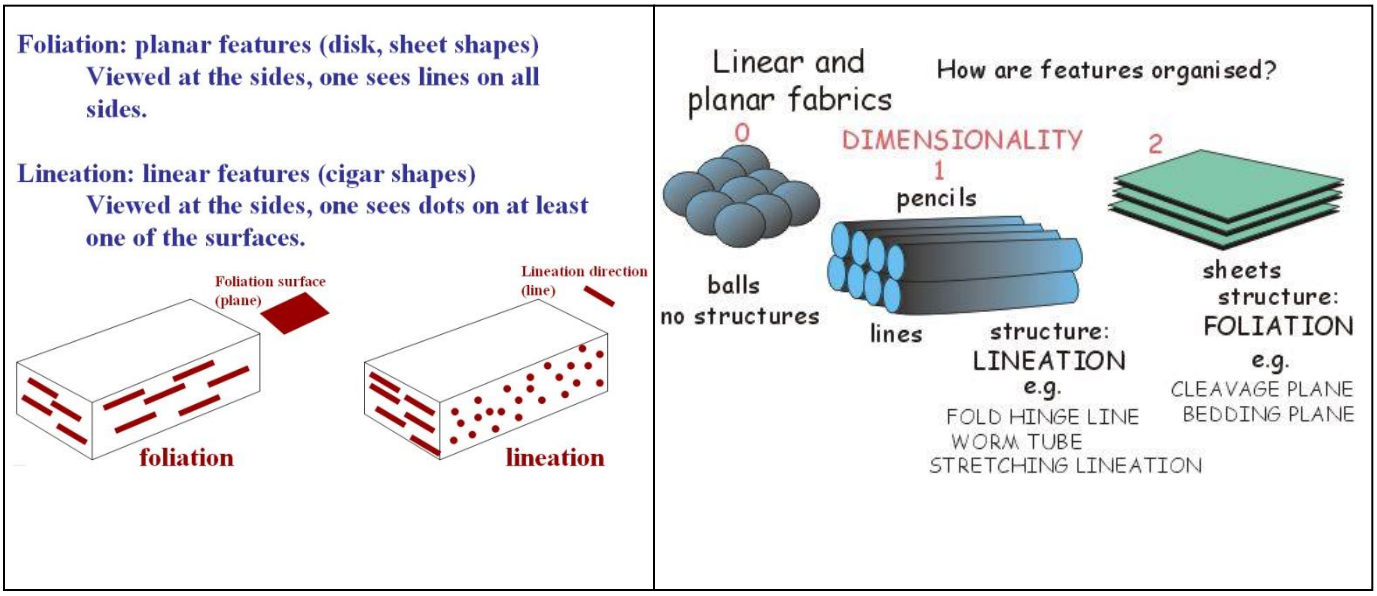


Fig. 35. Foliations vs. lineation

1.1 Foliations

A foliation is the general term for any kind of planar fabric, including: bedding, lamination, flow foliation, cleavage, schistosity and gneissosity. Many foliations are products of specific tectonic environments, including a particular orientation of principal strain axes. Depending on the rock, tectonic foliations may include spaced fracture cleavage, slaty cleavage, crenulation cleavage, schistosity, gneissosity.

Rocks can record many generations of fabrics, from the primary (eg. bedding) to fabrics associated with many generations of tectonic episodes. The relative timing of these is worked out using crosscutting relations. The physical appearance of the fabrics ultimately reflects the materials, metamorphic grade and strain rates and so careful observation and analysis of fabrics is crucial to teasing out the tectonic history of a deformed rock.

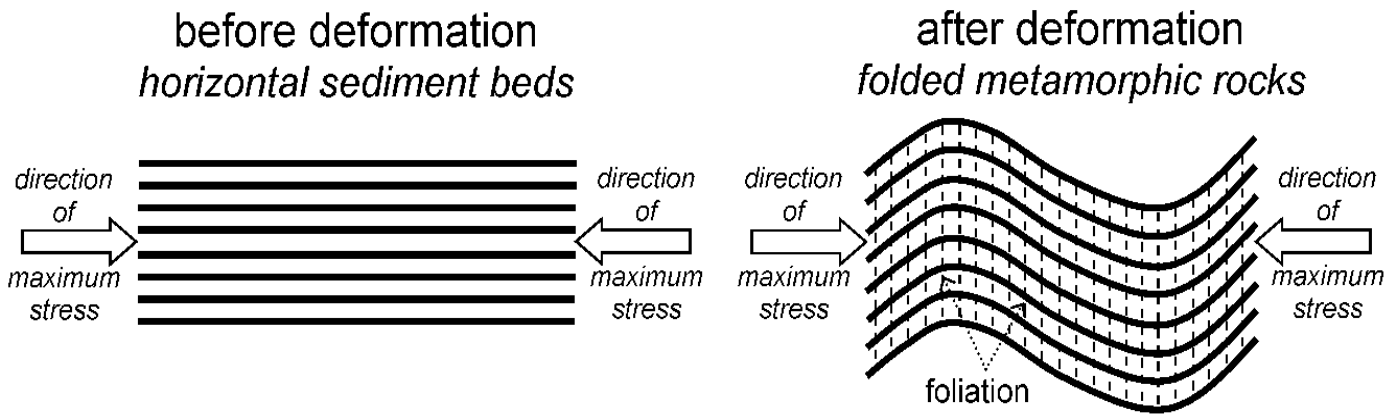


Fig. 36a. Rock deformation

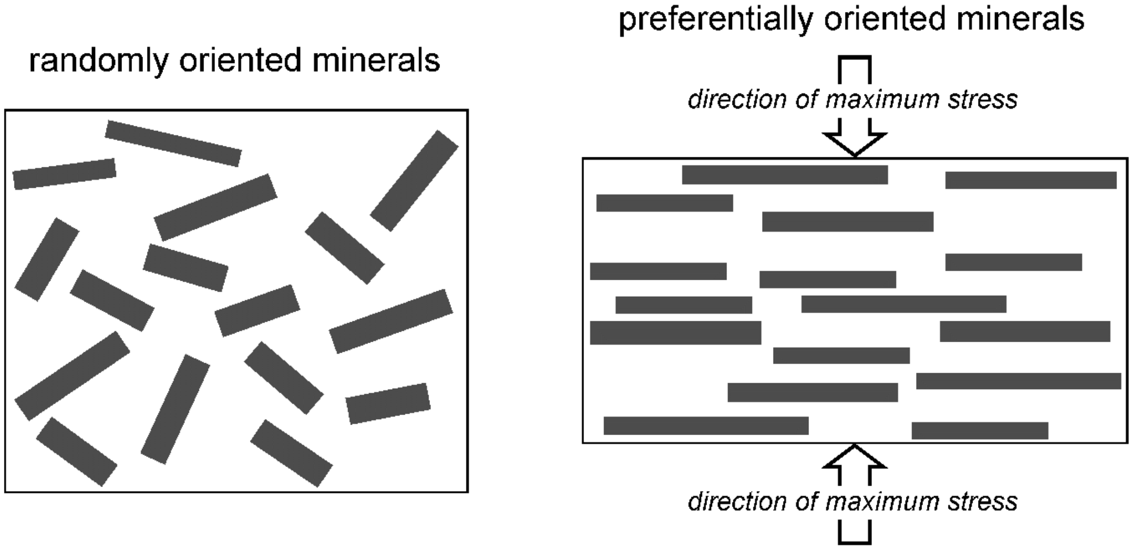


Fig. 36 b. Random vs. oriented minerals

Cleavage

Cleavage is a secondary (tectonic) fabric which imparts on the rock a tendency to part or split along it. The classic example is slate, where the cleavage is so perfect that the rock is easily quarried into thin, flat slabs for pool tables and roofing materials.

<u>Disjunctive cleavage</u>; a type of spaced cleavage defined by an array of more or less parallel fabric domains (called cleavage domains). Within each fabric domain, there is typically evidence of pressure solution (hence this is often called **solution cleavage** or **stylolitic cleavage**). These domains are separated by intervals called *microlithons*. The spacing of the cleavage domains (and hence the width of the microlithons) is quite variable, but commonly observed on a cm scale (Fig. 37).

Fig. 37. stylolitic cleavage

Pencil cleavage

It is characterized by the rock breaking into elongate, pencillike shards. Pencil cleavage appears to result from the intersection of two spaced cleavages, one of which forms due to the primary preferred orientation of clays (imparted during sedimentation and compaction), the second may for maxial planar to folds or perpendicular to layer parallel shortening. This causes detrital clays to fold and rotate, fine grained soluble materials to undergo pressure solution and new clay minerals to crystallize. When the original sedimentary parting and the new (spaced, and probably pretty weakly developed) cleavage intersect at fairly high angles, pencil cleavage results. With more strain, it is possible to get the complete erasure of the original parting and production of slaty cleavage.

Fig. 38. Pencil cleavage

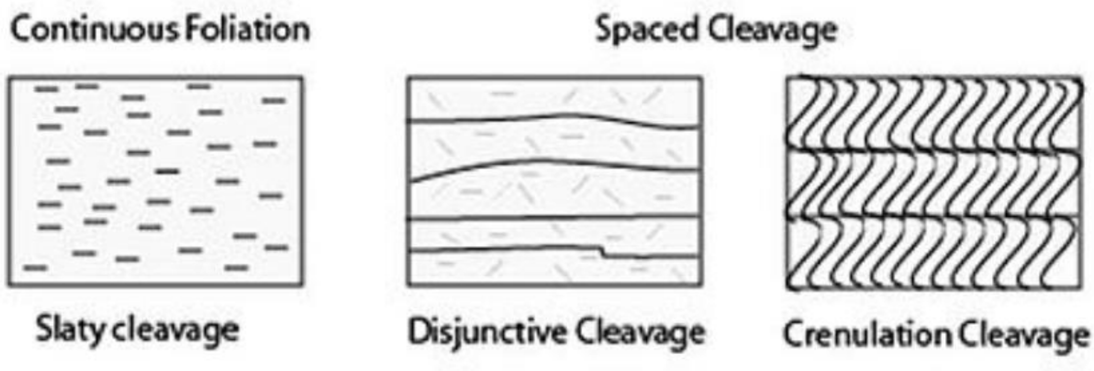
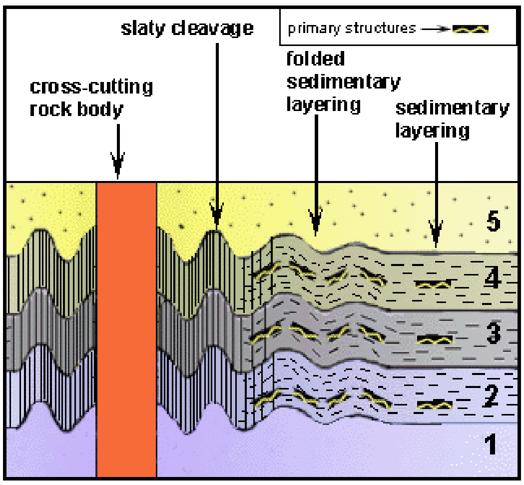


Fig. 39. Slaty and spaced cleavage

Slaty cleavage

Slaty cleavage forms by the same processes as outlined above: rotation and folding of detrital clays, pressure solution and recrystallization of clay minerals. The difference is that the cleavage domains are so tightly spaced that the fabric is completely penetrative and continuous at all but high power magnification. The formation of slaty cleavage is coincident with the onset of low grade metamorphism, particularly the transition from smectite(a poorly ordered clay) to illite (a much more ordered clay). This transition is temperature sensitive and measurable by XRD.



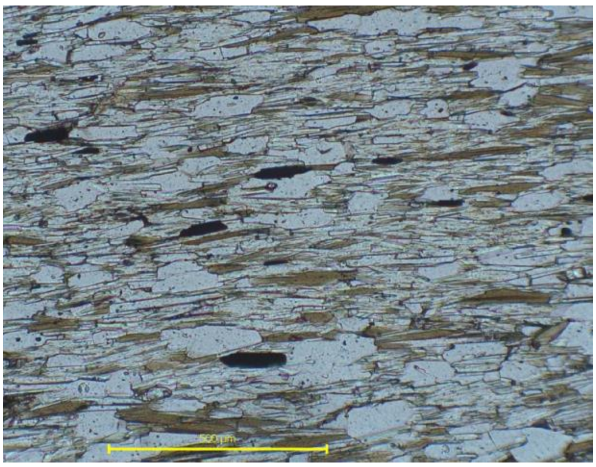


Fig. 40. Slaty cleavage

Phyllitic cleavage and schistosity

Phyllitic cleavage is characteristic of low grade (low greenschis). It is produced by the preferred alignment of clay and mica minerals. At the lowest metamorphic grade these will be illite, transitioning to white mica (sericite /muscovite) and chlorite at higher grades. If the cleavage is formed syn-deformationally, the phyllosilicate minerals grow with a strong preferred orientation (Fig. 41). At the hand sample scale, the preferred orientation of the phyllosilicates imparts a very strong parting or cleavage, although the phyllosilicates are very fine grained and individual minerals are usually not visible without magnification. At higher metamorphic grades, sericitechlorite assemblages are replaced with coarser muscovite and / or biotite, and the individual mica grains are visible under close inspection. At this point, the rock is referred to as a schist. Schistose rocks are usually named according to the assemblage of metamorphic minerals contained (biotite, muscovite, garnet, staurolite, kyanite, etc.).

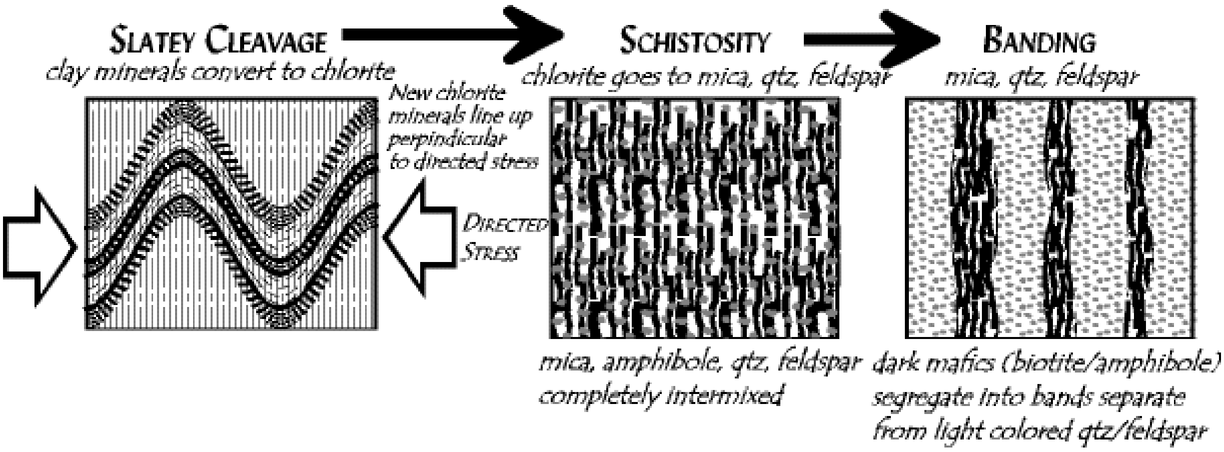


Fig. 41. Progression of fabrics

Crenulation cleavage If rocks containing an early, closely spaced cleavage (this can be slaty cleavage, phyllitic cleavage or schistocity) are shortened in a direction at a low angle to the original fabric, the older fabric folds at a very small scale. This produces a characteristic "wrinkled" appearance, somewhat like the baffles in an accordion. When a very regularly closely spaced cleavage is crenulated, the spacing of the small folds is very uniform, and fold hinges and fold limbs line up. This, and possibly pressure solution or shear thinning in the limbs defines a new foliation, which is called a crenulation cleavage. ***Crenulation cleavage*** can be symmetric or asymmetric. Eventually, pressure solution (which will tend to transport material from the limbs to the hinges) and shear of the limbs can lead to an almost complete obliteration of the early fabric. This process is called **transposition**, and the new fabric is called a **transposition foliation**.

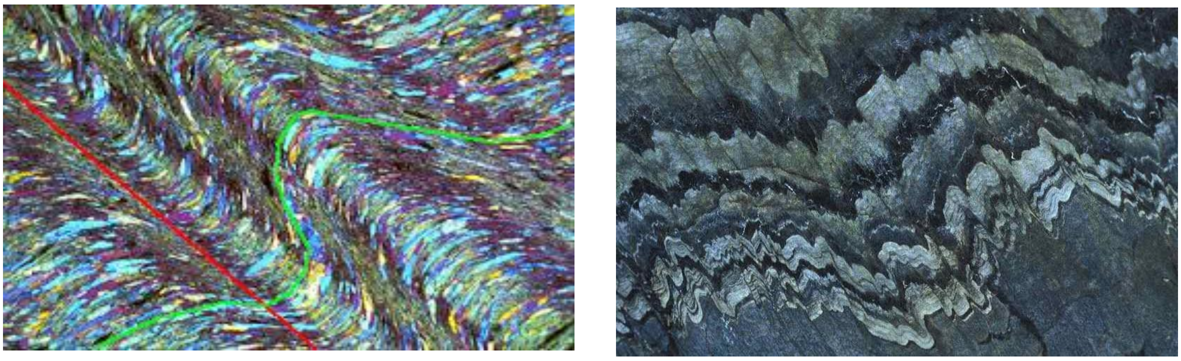


Fig. 42. Progression of fabrics

Gneissic layering. Gneissic layering is a coarse (mmto tens of cmscale) compositional layering in metamorphic rocks. This compositional banding can be produced a variety of different ways. **Primary** layering is inherited from the original sedimentary layering and compositional differences of a sedimentary protolith. **Transposition** layering is produced by isoclinal folding and shear of fold limbs of the original layering. Compositional layering can also be produced from metamorphic differentiation, or the injection of melts either along the layering or rotated through shear into the foliation.

Fig. 43. Gneissic layer

Foliations and folds

Planar fabrics can form in a shear zone, but often form in a specific geometrical relationship to a series of folds. Specifically, in folded rocks, planar fabrics are commonly parallel to the axial plane of the fold. Youmight find it useful to think of examples where this might not be the case (consider an interbedded quartzite and shale being folded). Foliations in folded terrains can be extremely useful: if they are truly parallel (or close to parallel) to the axial plane, the intersection of the layer being folded and the foliation will result in a line that is parallel to the fold axis. Moreover, there is a specific geometrical relationship between bedding and axial planar foliation that allows you to infer the position of fold closures. These are key relationships that are the bread and butter of field geology in folded terrains. SeeTM, section 13.5. In areas ofmultiple deformations, you can have synformal anticlines and antiformal synclines and so on. The key to working this out is to be able to establish “younging” (or “way up”), and the geometrical relationship between the limb of a structure and an axial planar fabric.

Once a foliation is formed, it can be modified by further deformation. Some processes: rotation during shear, small scale folding (crenulation), recrystallisation. The preservation of earlier generations of fabrics within porphyroblasts(eg. garnet) and within low strain zones (the hinges of later folds) is exploited by geologists who then label them S1, S2, S3 etc... Of particular importance is the concept of transposition foliation. Such a fabric is a composite fabric: multiple generations of planar features are found to be parallel. The common case is to find compositional layering (e.g. bedding, called S0) parallel to a tectonic fabric. How does this happen?

2.1.2 Lineations

A lineation is the generic termfor a linear fabric in a rock. An **intersection lineation** is formed by the intersection of two planes. Typically, an intersection lineation is formed by the intersection of a layer being folded and a cleavage parallel to the axial plane of that fold. In this case, the intersection lineation will formparallel to the fold hinge, so observation of the orientation of the intersection lineation can yield very useful information about the geometry of the folds in a region. A **mineral lineation** is defined by the preferred orientation of minerals, especially minerals that have a welldefined long axis, such as amphiboles. Since the orientation of metamorphic minerals often reflects the state of strain, it is very common to find minerals oriented parallel to a principal strain axis especially parallel to fold hinges. **Stretching lineations**are defined by the orientation of parts of the rock that have been strained such that they have awelldefined long axis. For example, cobbles in a conglomerate that have suffered strain will often be observed to a welldefined preferred orientation of their long axis. At a smaller scale, individual minerals – such as quartz grains

– can also be stretched, and form a lineation in the rock. Stretching lineations are usually interpretable as being parallel to the maximum principal strain axis.

Chapter five

Brittle Structure: Faults

1. Introduction:

Fault: is defined as a ruptures along which the opposite walls have moved past each other. Or **Fault:** are fractures or breaks in the earth's crust along which movement has occurred.

Faults can be:

1) Vertical faults where the blocks of the crust move up or down (Normal or reverse faults),

2) Horizontal faults when the blocks move sideways to each other (strike slip fault), and

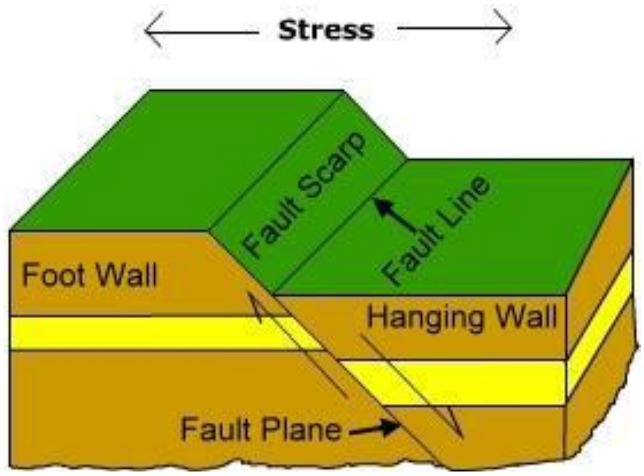
3) Compound faults where the movement is a combination of upward or downward and sideways.

The term **Joint** is used when the rocks fracture without movement.

2. Anatomy of faults:

Fault blocks:

The "fault blocks" are the two portions of rock separated by the fault plane. If the "fault plane" is tilted, the block above the fault plane is the "hanging wall" or "upper block" and beneath the fault plane is called "footwall block".



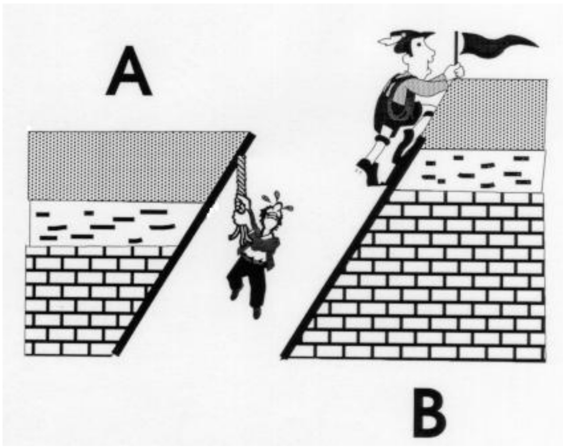


Fig. 44. Anatomy of fold

(a) Fault plane

Is defined as the plane or surface along which the blocks move. Or the area where blocks meet and move along a fault from the fault line down into the crust

(b) The hanging wall block would then be hanging overhead or the block above the fault.

(c) ***The footwall block*** is the block below the fault plane.

(d) ***Fault scarp:*** A steep-sided cliff generated as a result of fault movement.

(e) ***The strike and dip*** of fault are measured in the same way as they are for bedding or any planes.

The strike of fault plane :is the trend of a horizontal line in the plane of the fault (Fig. 45).

The dip of fault plane :is the angle between a horizontal surface and the plane of the fault.

vertical throw; vertical component of the net-slip

horizontal throw; horizontal component of the net-slip

Vertical throw is very different from **stratigraphic throw**. This distinction may be very important in directional drilling.

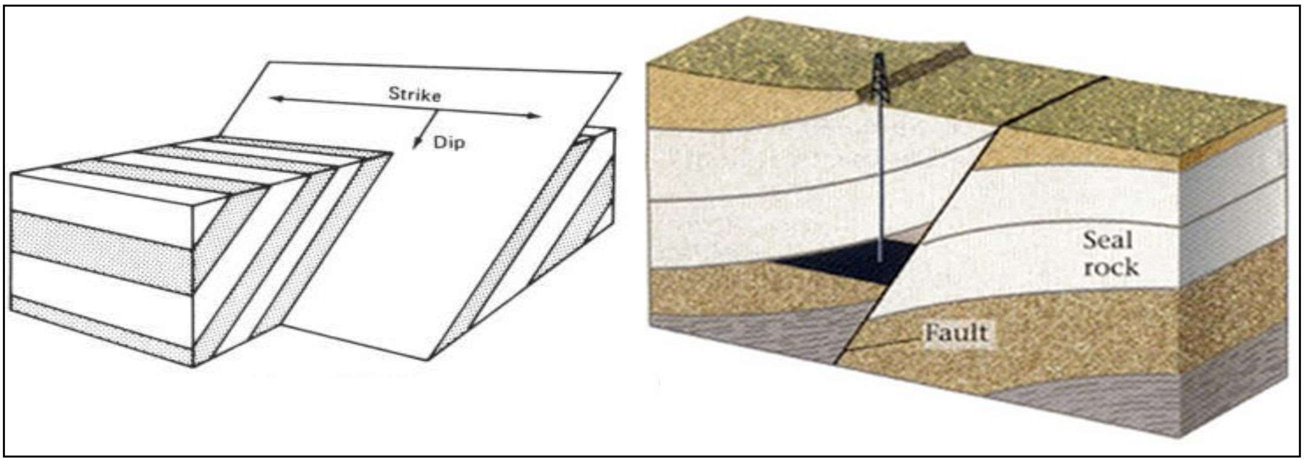


Fig. 45. Strike of a fault (left), fault trap (right)

Why faults are important?

It represents an oil trap.

Features associated with faults:

<u>1- Slickensides:</u>

Slickensides are parallel scratches on rock surfaces produced by relative motion or caused by frictional movement between rocks along the two sides of a fault.

Or Fault surfaces often show grooves, scratches and asymmetric fracture patterns called **slickensides**.

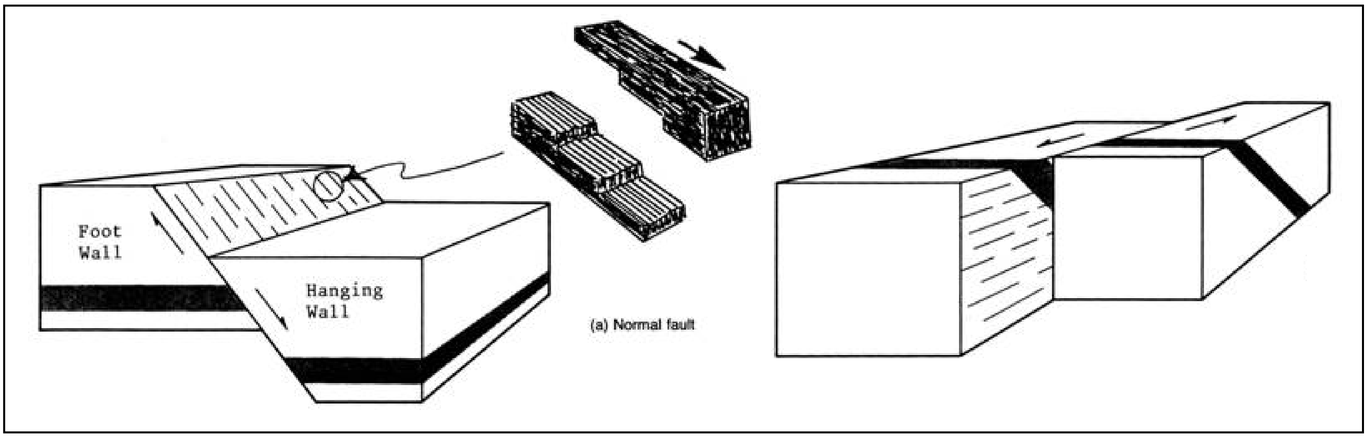


Fig. 46. Slickensides associated with faults

3- Faulted rocks

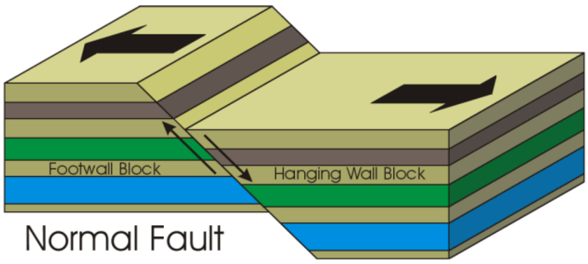
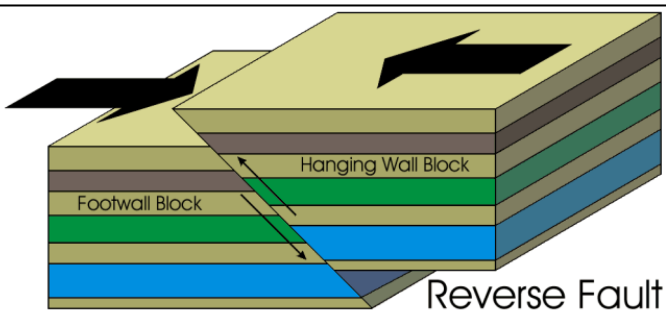
<u>The main types of fault rock include:</u>

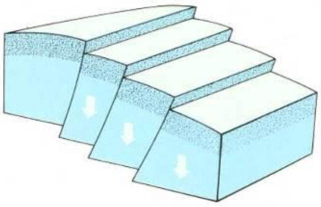
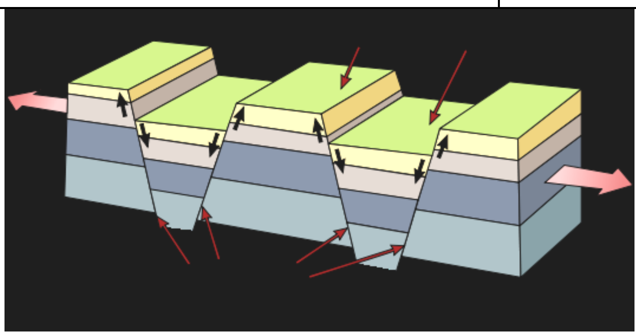
<u>(a) Cataclasite</u> - a fault rock which is cohesive with a poorly developed or absent planar fabric, or which is incohesive, characterised by generally angular clasts and rock fragments in a finer-grained matrix of similar composition.

<u>(b) Tectonic or Fault breccia</u> - a medium- to coarse-grained cataclasite containing >30% visible fragments.

<u>(c) Fault gouge</u> - an incohesive, clay-rich fine- to ultrafine-grained cataclasite, which may possess a planar fabric and containing <30% visible fragments. Rock clasts may be present.

<u>(d) Mylonite</u> - a fault rock which is cohesive and characterized by a well-developed planar fabric resulting from tectonic reduction of grain size, and commonly containing rounded ***porphyroclasts*** and rock fragments of similar composition to minerals in the matrix

Table 3: Classifications of Faults based upon apparent movement	
This classification is based on the apparent movement in vertical section	
Normal Fault	**Reverse Fault**
Normal fault is one in which the hanging wall, in a vertical section at angles to the strike of the fault, appears to have gone down relative to the footwall. .	is one in which the hanging wall, in a vertical section at right angles to the strike of the fault, appears to have gone up relative to the footwall.
	

2- Classifications of Faults based on fault Pattern a)In a Cross Section		
Step faults فوالق سلمية	Horst Faults فوالق بارزه	Graben fault فوالق حوضية
Which are aset of faults with their down throw in the same direction	Horst and Graben refer to regions that lie between normal faults and are either higher or lower than the area beyond the faults.	Horst and Graben refer to regions that lie between normal faults and are either higher or lower than the area beyond the faults.
	Which are tow faults bounded their up throw in between. A horst represents a block pushed upward by the faulting Horst and Graben are always formed together	Which are tow faults bounded their down throw in between. A graben is a block that has dropped due to the faulting. Horst and Graben are always formed together
		

Vertical versus horizontal

Strike-slip faults also called **wrench faults:-**are those along which displacement has been parallel, to the strike of the fault, the dip-slip component is small compared to the strike-slip component.

7.3.1 Right-slip (dextral) fault

Is one in which the opposite wall moved relatively to the right.

7.3.2 Left-slip (sinistral) fault

Is one in which the opposite wall moved relatively to the left

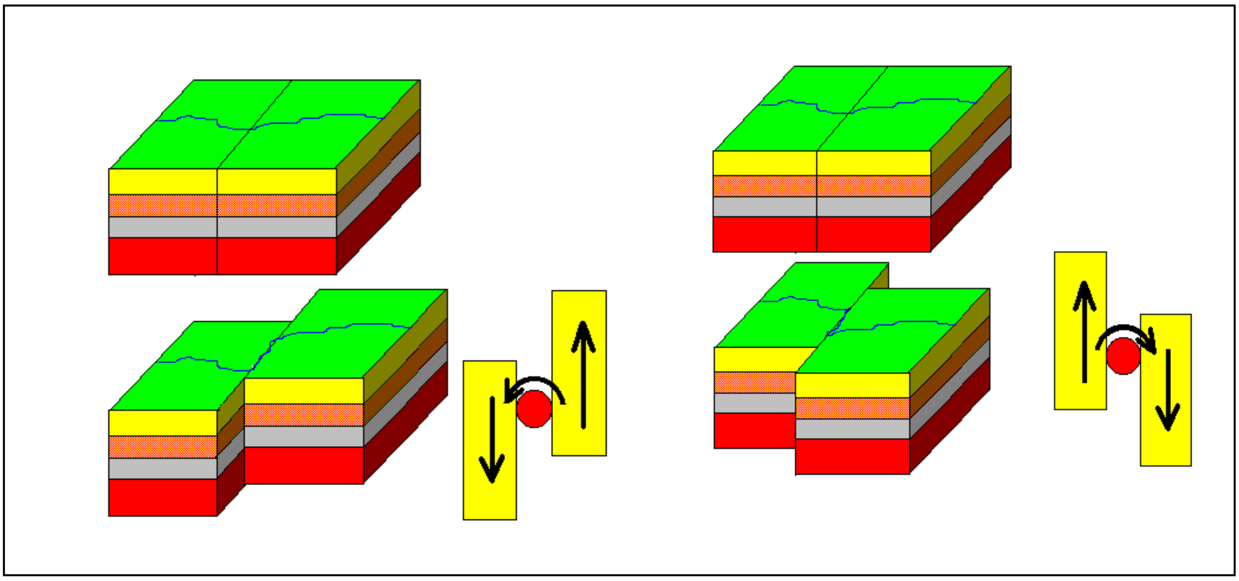


Fig. 47. Strike-slip faults

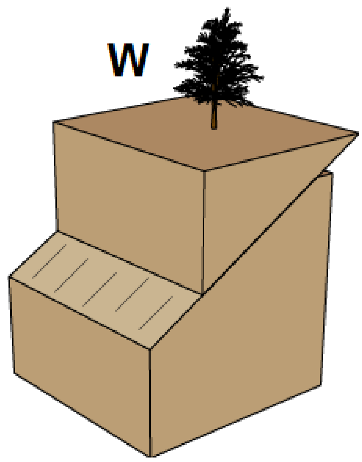
Exercise #7

1. A dip-slip fault consists of the dipping fault surface and hanging and footwall blocks. The hanging wall block lies ____________ the dipping fault surface.

2. In the following illustration what block is the **A** located on? What block is the **B** located on? What kind of fault is illustrated?....................

3. The footwall block lies ___________ a dipping fault surface.
4. What do you call a three dimensional surface separating Earth material of differing aspect?

4. In a dip-slip fault, if the hanging wall block moved up relative to the footwall block, then the fault is classified as a ____________________ .

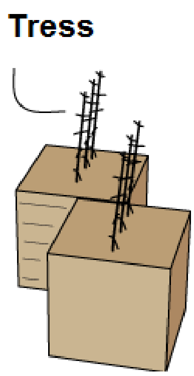


5. In a dip-slip fault, if the hanging wall block moved down relative to the footwall block, then the fault is classified as a ____________________ .

6. In the following illustration what block is the **W** located on? What kind of fault is illustrated?

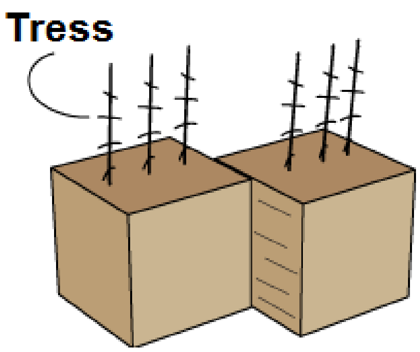
7- Imagine the following. A road is cut by a vertical dipping fault. As you walk along the road toward the fault, at the intersection of the fault and road, you have to turn to your right and walk some distance along the fault until you encounter the continuation of the road. What would you call the fault?

8- Imagine the following. A set of rail road tracks are cut by a vertical dipping fault. As you walk along the railroad tracks toward the fault, at the intersection of the tracks and the fault, you have to turn to your left and walk about 10 meters along the fault until you encounter the continuation of the railroad tracks. What would you call the fault?



9. In the following block diagram, what kind of fault is illustrated?

10. In the following block diagram, what kind of fault is illustrated?



Chapter six

Fractures: Joints

1. Introduction

A joint is a break (fracture) of natural origin in the continuity of either a layer or body of rock that lacks any visible or measurable movement parallel to the surface (plane) of the fracture. Although they can occur singly, they most frequently occur as joint sets and systems.
A **joint set** is family of parallel, evenly spaced joints that can be identified through mapping and analysis of the orientations, spacing, and physical properties.

A **joint system** consists of two or more interlocking joint sets. ***What are the differences between joints and faults?*** Faults differ from joints in that they exhibit visible or measurable lateral movement between the opposite surfaces of the fracture. As a result, a joint may have been created by either strict movement of a rock layer or body perpendicular to the fracture or by varying degrees of lateral displacement parallel to the surface (plane) of the fracture that remains “invisible” at the scale of observation.

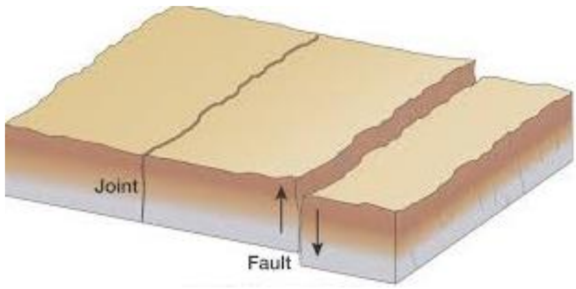


Fig.48. joints (left), faults vs. joints (right)

Joints are among the most universal geologic structures as they are found in most every exposure of rock. They vary greatly in appearance, dimensions, and arrangement, and occur in quite different tectonic environments. Often, the specific origin of the stresses that created joints and associated joint sets can be quite ambiguous, unclear, and sometimes controversial. The most prominent joints occur in the most well-consolidated, lithified, and highly competent rocks, such as sandstone, limestone, quartzite, and granite. Joints may be open fractures or filled by various materials. Joints, which are infilled by precipitated minerals, are called veins and joints filled by solidified magma are called dikes.

2. Formation

Joints result from brittle fracture of a rock body or layer as the result of tensile stresses. These tensile stresses either were induced or imposed from **(a)** outside, e.g. by the stretching of layers; the rise of pore fluid pressure as the result of either external compression or fluid injection; or the result of **(b)** internal stresses induced by the shrinkage caused by the cooling or desiccation of a rock body or layer whose outside boundaries remained fixed.

When tensional stresses stretch a body or layer of rock such that its tensile strength is exceeded, it breaks. When this happens the rock fractures in a plane parallel to the maximum principal stress and perpendicular to the minimum principal stress (the direction in which the rock is being stretched). This leads to the development of a single sub-parallel joint set. Continued deformation may lead to development of one or more additional joint sets.

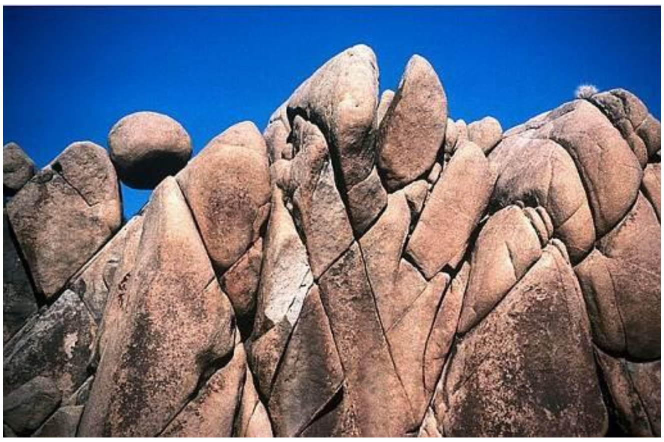


Fig.49. joints

3- Types of joints

Joints are classified either by the processes responsible for their (a) ***formation*** or their (b) ***geometry***

3.1 Classification of joints by geometry

The geometry of joints refers to the orientation of joints as either plotted on stereonets and rose-diagrams or observed in rock exposures. In terms of geometry, three major types of joints, nonsystematic joints, systematic joints, and columnar jointing are recognized.

3.1.1 Nonsystematic joints are joints that are so irregular in form, spacing, and orientation. They are so irregular, they cannot be readily grouped into distinctive, through-going joint sets.

3.1.2 Systematic joints are planar, parallel, joints that can be traced for some distance, and occur at regularly, evenly spaced distances on the order centimeters, meters, tens of meters, or even hundreds of meters. As a result, they occur as families of joints that form recognizable joint sets. Typically, exposures or outcrops within a given area or region of study contains two or more sets of systematic joints, each with its own distinctive properties such as orientation and spacing, that intersect to form well-defined joint systems.
Systematic joints can be subdivided based on:

1) the angle at which joint sets of systematic joints intersect :

(a)*conjugate* and **(b)*orthogonal*** joint sets.

The angles at which joint sets within a joint system commonly intersect is called by structural geologists as the ***dihedral angles***. When the dihedral angles are nearly 90° within a joint system, the joint sets are known as ***orthogonal joint sets*.**
When the dihedral angles are from 30 to 60° within a joint system, the joint sets are known as ***conjugate joint sets*.**

2)based on relations to the regional structure

Within regions that have experienced tectonic deformation, systematic joints are typically associated with either layered or bedded strata that has been folded into anticlines and synclines. Such joints can be classified according to their orientation in respect to the axial planes of the folds as they often commonly form in a predictable pattern with respect to the hinge trends of folded strata. Based upon their orientation to the axial planes and axes of folds, the types of systematic joints are:

Longitudinal joints – Joints which are roughly parallel to fold axes and often fan around the fold.

- *Cross-joints* – Joints which are approximately perpendicular to fold axes.
- *Diagonal joints* – Joints which typically occur as conjugate joint sets that trend oblique to the fold axes.
- *Strike joints* – Joints which trend parallel to the strike of the axial plane of a fold.
- *Cross-strike joints* – Joints which cut across the axial plane of a fold.

3.1.3 Columnar jointing الفواصل العمدانية is a distinctive type of joints that join together at triple junctions either at or about 120° angles. These joints split a rock body into long, prisms or columns. Typically, such columns are hexangonal, although 3-, 4-, 5- and 7-sided columns are relatively common. The diameter of these prismatic columns range from a few centimeters to several meters. They are often oriented perpendicular to either the upper surface and base of lava flows and the contact of the tabular igneous bodies with the surrounding rock. This type of jointing is typical of thick lava flows and shallow dikes and sills

Columnar jointing is also known as either columnar structure, prismatic joints, or prismatic jointing. Rare cases of columnar jointing have also been reported from sedimentary strata.

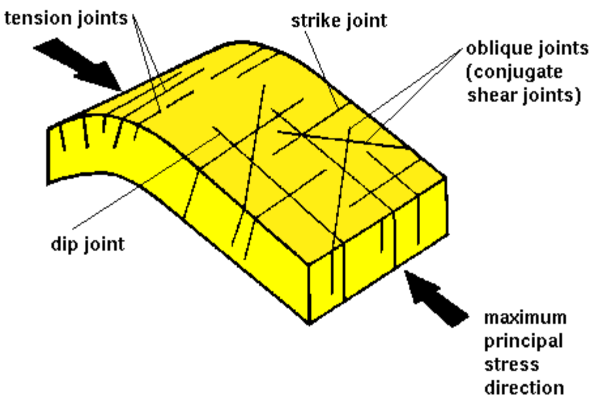


Fig. 50. Joints related to the regional structure (left), columnar joints (right)

3.2 Types of joints with respect to formation

Joints can also be classified according to their origin.

3.2.1 Tectonic joints are joints that formed by the relative displacement of the joint walls is normal to its plane as the result of brittle deformation of bedrock in response to regional or local tectonic deformation of bedrock. Such joints form when directed tectonic stress causes the tensile strength of bedrock to be exceeded as the result of the stretching of rock layers under conditions of elevated pore fluid pressure and directed tectonic stress. Tectonic joints often reflect local tectonic stresses associated with local folding and faulting. Tectonic joints occur as both nonsystematic and systematic joints, including orthogonal and conjugate joint sets.

1. Tension joints :

2. Compression joints

3. Shear joints

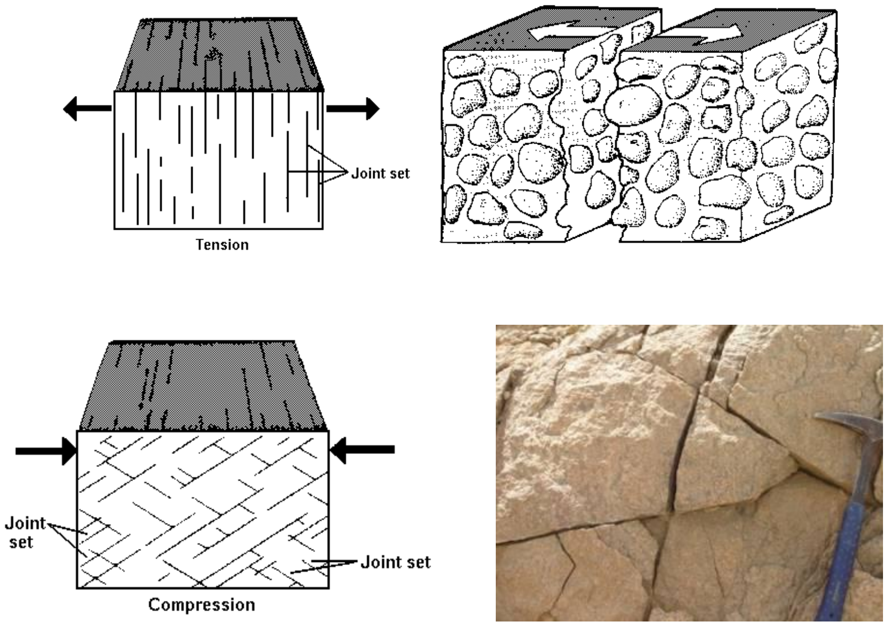


Fig. 51. Tension joints (left), compressional joints (right)

3.2.2 Hydraulic joints are joints thought to have formed when pore fluid pressure became elevated as a result of vertical gravitational loading. In simple terms, the accumulation of either sediments, volcanic, or other material causes an increase in the pore pressure of groundwater and other fluids in the underlying rock when they cannot move either laterally of vertically in response to this pressure.

3.2.3 Exfoliation joints are sets of flat-lying, curved, and large joints that are restricted to massively exposed rock faces in an deeply eroded landscape. Exfoliation jointing consists of fan-shaped fractures varying from a few meters to tens of meters in size that lie sub-parallel to the topography. The vertical, gravitational load of the mass of a mountain-size bedrock mass drives longitudinal splitting and causes outward buckling toward the free air.

Fig. 51. Exfoliation joints

3.2.4 Unloading joints or **release joints** are joints formed near the surface during uplift and erosion. As bedded sedimentary rocks are brought closer to the surface during uplift and erosion, they cool, contract and become relaxed elastically. This causes stress buildup that eventually exceeds the tensile strength of the bedrock and results in the formation of jointing.

3.4.5 Cooling joints are columnar joints that result from the cooling of either lava from the exposed surface of a lava lake or flood basalt flow or the sides of a tabular igneous, typically basaltic, intrusion.

4- Shear fractures versus joints

Some fractures that look like joints are actually shear fractures, which in effect are microfaults, instead of joints. Shear fractures do not form as the result of the perpendicular opening of a fracture due to tensile stress, but through the shearing of fractures that causes lateral movement of its faces. Shear fractures can be confused with joints. Shear fractures occur in sets of planar parallel fractures at an angle of 60 degrees and can be of the same size and scale as joints. As a result, some conjugate joint sets may actually be shear fractures. In case of such joint sets, it might be possible to distinguish joints from shear fractures by looking for the presence of slickensides, which are products of shearing movement parallel to the fracture surface.

5- Importance of joints

Joints are important not only in understanding the local and regional geology and geomorphology, but also are important in development of natural resources. Understanding the local and regional distribution, physical character, and origin of joints is a significant part of understanding the geology and geomorphology of an area. Joints often impart a well-develop fracture-induced permeability to bedrock. As a result, joints strongly influence, even control, the natural circulation (hydrogeology) of fluids, e.g. groundwater and pollutants within aquifers, petroleum in reservoirs, and hydrothermal circulation at depth, within bedrock. Thus, joints are important to the economic.

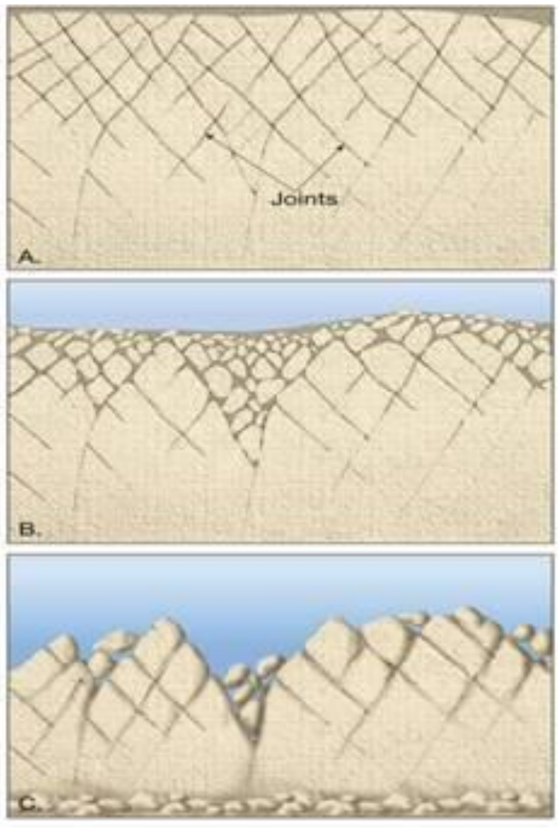


Fig. 52. Progression of joints (left), ore minerals within joints (right)

Exercise # 8

1- A break of a layer of rock that display no visible movement parallel to the fracture called....

(a) fault(b) joint (c) fold (d) primary structure

2- joint systems differs from **joint set** in that they consist of two or more interlocking joint sets

(a) True (b) False

3- Joints result from brittle fracture of a rock by internal forces such as ....

(a) fault (b) stretching (c) shrinkage (d) primary structure

4- Shrinkage of a rock body caused by the cooling or desiccation processes

(a) True (b) False

5- The measurable angle between intersection of joint sets within a joint system called.......

(a) rake (b) plunge (c) dihedral angle (d) dip angel

6- A joint system that diagonally interlocked called.........., however that they interlocked at 90 degree called......................

(a) faults (b) orthogonal (c) joint set (d) conjugate

7- ....joints are parallel to attitude of regional structure.

(a) cross (b) Longitudinal (c) cross-strike (d) conjugate

8- Columnar joints consider a tectonic joints

(a) True (b) False

Part 2

Geomorphology

Introduction

The course aims to introduce students to the modern study of earth surface processes and landforms. The concept of landform (terrain feature) development is central to this course. Lectures will be focused on understanding the topographic response to tectonic (geologic) and climatic forcing and the concept of dynamic equilibrium in the analysis of landscape evolution. In addition, we will explore how geomorphic systems are fundamentally influenced by — and, in turn, influence — the dynamics of Earth's crust (tectonics) as well as Earth's atmosphere, hydrosphere and biosphere. Students will become familiar to the various functions of the Earth systems and their responses to change and will learn how surface deposits, landforms and landscapes can be used to interpret Earth's history.

The Earth's surface is the "product" of two sets of opposing forces, one acting from within Earth's interior (internal forces) and the other from outside the Earth's crust (external). Internal forces, drawing energy from the Earth's interior, create major landforms such as mountain chains, volcanoes or oceanic basins. External forces fuelled by the Sun's energy act to level out the surface by tearing down mountains and filling up ocean basins with eroded sediments. Yet, the balance between these forces is uneven and perfect equilibrium is never achieved. It follows therefore that the Earth's surface remains rugged and ever-changing. The scientific field studying the Earth's "ruggedness" or morphology and the processes involved in its genesis is Geomorphology.

2) LAB EXERCISES Several practical exercises involving structural maps, block diagrams and map interpretation are planned for this course. Exercises provide a general picture of landscape relationships and landforms, and are therefore a useful tool in geomorphic studies. Map reading is an essential skill for all field scientists.

WHAT IS GEOMORPHOLOGY?

THE WORD “GEOMORPHOLOGY" COMES FROM THE GREEK ROOTS "GEO,“ “MORPH,” AND “LOGOS,” MEANING “EARTH,” “FORM,” AND “STUDY,” RESPECTIVELY. THEREFORE, GEOMORPHOLOGY IS LITERALLY “THE STUDY OF EARTH FORMS.”

Geomorphology is the study of landforms, their processes, form and sediments at the surface of the Earth (and sometimes on other planets). Study includes looking at landscapes to work out how the earth surface processes, such as air, water and ice, can mould the landscape. Landforms are produced by erosion or deposition, as rock and sediment is worn away by these earth-surface processes and transported and deposited to different localities. The different climatic environments produce different suites of landforms. The landforms of deserts, such as sand dunes and ergs, are a world apart from the glacial and periglacial features found in polar and sub-polar regions. Geomorphologists map the distribution of these landforms so as to understand better their occurrence.

So geomorphology is a diverse discipline. Although the basic geomorphological principles can be applied to all environments, geomorphologists tend to specialise in one or two areas, such aeolian (desert) geomorphology, glacial and periglacial geomorphology, volcanic and tectonic geomorphology, and even planetary geomorphology. Most research is multi-disciplinary, combining the knowledge and perspectives from two contrasting disciplines, combining with subjects as diverse as ecology, geology, civil engineering, hydrology and soil science.

- **Types of landforms**

Hills, valleys, floodplains, sinkholes, moraines, etc.

- **Types of landscapes**

Karst, Fluvial, Glacial

Geomorphic Branches

- Arid Geomorphology
- Coastal Geomorphology
- Glacial Geomorphology
- Humid Geomorphology
- Volcanic Geomorphology
- Karst Geomorphoogy

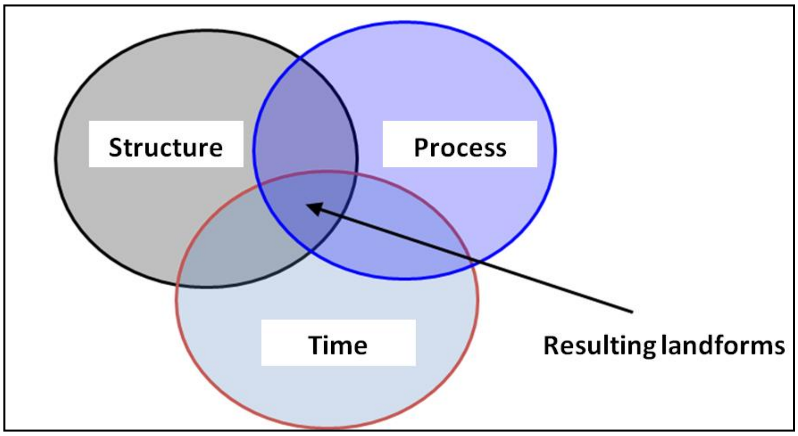


Fig. 53. Factors impact landforms

Relevance of geomorphology

- Geomorphology is important because people live on landforms and their lives are affected (sometimes catastrophically) by geomorphic processes:
    - Slope determines whether soil accumulates and makes arable land
    - Slope stability controls landslides
    - Mountains drastically affect the weather: rain shadows, monsoons
- This is also a two-way process: Human action is one of the major processes of geomorphic evolution:
    - People have been building terraced hillsides for thousands of years
    - People dam rivers, drain groundwater, engineer coastlines
    - People plant or burn vegetation on a huge scale
    - People are paving the world
    - People are changing the climate

Geomorphic items

- **Elevation**: height above sea level
- **Slope**: spatial gradients in elevation

  Relief: the contrast between minimum and maximum elevation in a region

- **Important**: a *mountain* is a feature of relief, not elevation (a high area of low relief is a *plateau*)

– Slope controls the local stability of hillsides and sediment transport
– Relief controls the regional erosion rate and sediment yield
– Elevation directly affects erosion and weathering only through temperature (Fig.54)

•

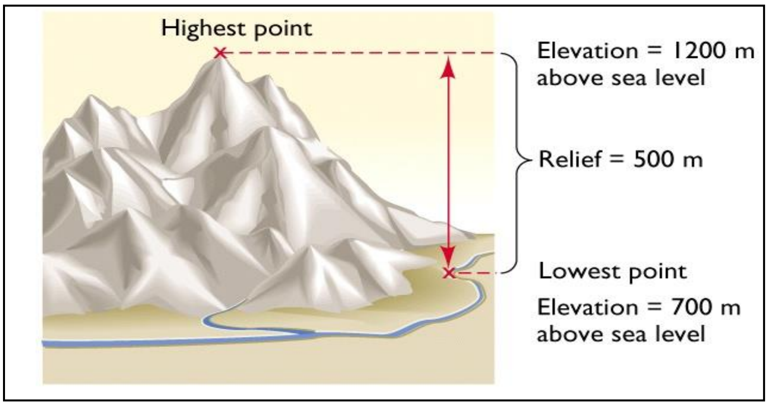


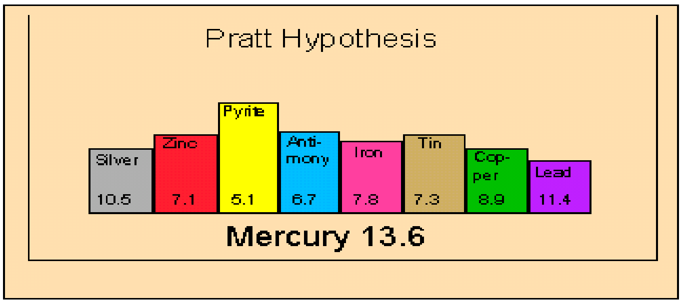
Fig. 54. Relief

Isostasy

1. the state in which pressures from every side are equal.
2. Geology . the equilibrium of the earth's crust, a condition in which the forces tending to elevate balance those tending to depress.

Variation in topography can be compensated through two end-member mechanisms: differences in the *thickness* of layers or differences in the *density* of layers.

- Isostatic compensation through *density* differences is *Pratt* isostasy (in the pure form each layer is of constant thickness).
- Isostatic compensation through differences in the *thickness* of layers (where the layer densities are horizontally constant) is *Airy* isostasy (Fig. 55).



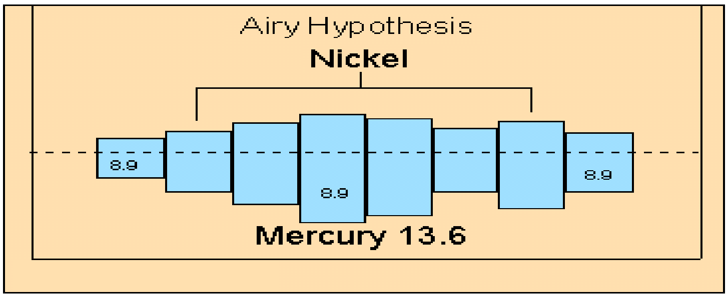


Fig. 55. Isostasy

Geomorphic Concepts

- In reality, both mechanisms operate together: neither the thickness nor the density of the crust is constant.

  However, since the density contrast between crust and mantle is larger than most internal density differences within either crust or mantle, the dominant mechanism of isostatic compensation is variations in crustal thickness, i.e. Airy isostasy

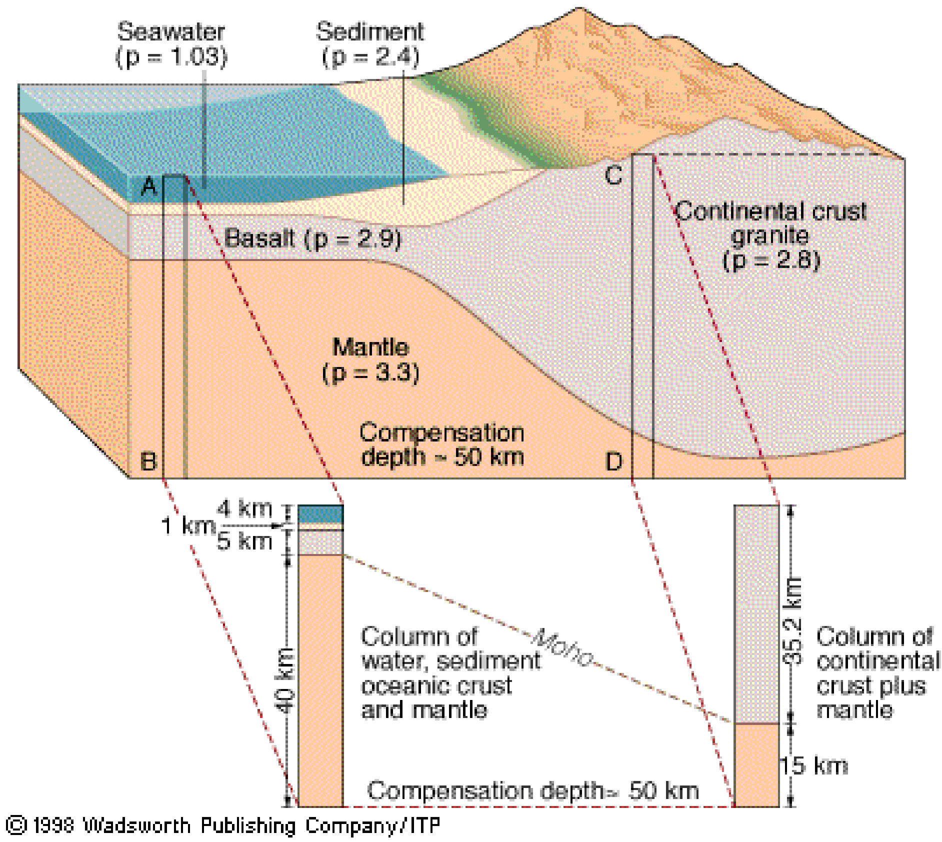


Fig. 56. isostatic compensation density differences

Concept 1: (uniformitarianism): "*Presence is the key to the past*"

The same physical processes and laws that today, operated throughout geologic time, although not necessarily always with the same intensity as now.

Concepts 2:

Geologic structure is a dominant control factor in the evolution of landforms and is reflected in them. Geologic structure in geomorphology means: Rock attitudes, presence or absence of joints, bedding planes, faults, folds, rock massiveness, the physical hardness of the constituent minerals, the susceptibility of mineral constituents to chemical alteration, the permeabiliy and impermeability of rocks and various other ways by which the rock differs from other at earth crust.

Concept 3:

Geomorphic processes leave their distinctive imprint upon landforms, and each geomorphic process develops its own characteristic assemblage of landforms.

Geomorphic process means physical and chemical ways by which the earth crust undergoes modification.

Geomorphic processes include:

A- Endogenic processes:

It produced from forces within earth crust (ex. Diastrophism and Volcanisms).

B- Exogenic processes:

It produced by external forces such as erosion, weathering and mass wasting.

Concept 4:

As the different erosional agencies act upon the earth surface, there is a sequence of landforms having distinctive characteristics at successive stages of their development. The stages include youth, maturity and old age.

Concept 5:

Most of geomorphic features we meet in present time were made in Quaternary age (Pleistocene)

Concept 6:

Complexity of geomorphic evolution is more common than simplicity.

Simple landscapes are the product of a single dominant geomorphic process.

Compound landscapes are the product of two or more geomorphic process.

Monocyclic landscapes are those that bear the imprint of only one cycle of erosion. It is restricted to such newly created land surfaces as a recently uplifted portion of the ocean floor, surface volcanic cone or areas buried beneath a cover of Pleistocene glacial materials.

Multicyclic landscapes have been produced during more than one erosion cycle.

Exhumed or resurrected landscapes are those that were formed during some past period of geologic time, buried beneath a cover and then at recent time, exposed to the surface by weathering.

A. Igneous landforms

1- EXTRUSIVE VOLCANIC LANDFORMS

Volcanic landforms are controlled by the geological processes that form them and act on the after they have formed. Thus, a given volcanic landform will be characteristic of the types of material it is made of, which in turn depends on the prior eruptive behavior of the volcano. Although later processes can modify the original landform, we should be able to find clues in the modified form that lead us to conclusions about the original formation process. Here we discuss the major volcanic landforms and how they are formed, and in some cases, later modified.

Types of lava:

- **Basaltic**: formed from magma low in silica, fluid magma, prevents sudden explosiveness

- **Andesitic/Rhyolitic**: formed from magma rich in silica, very viscous, violent explosive

The main types of extrusive volcanic landforms:

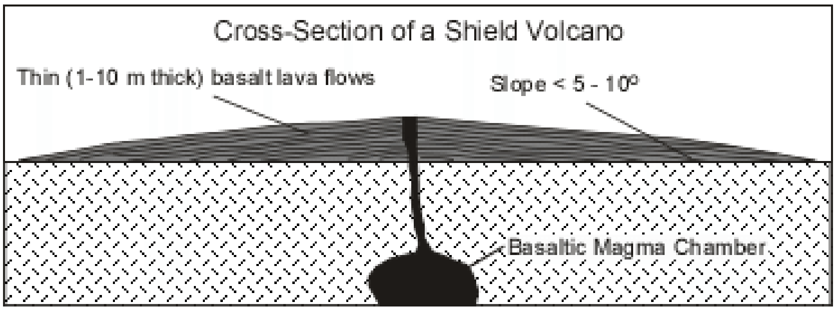


Fig. 57. Shield volcano

Shield Volcanoes

1- A shield volcano is characterized by gentle upper slopes (about 5^o) and somewhat steeper lower slopes (about 10^o).

2- Shield volcanoes are composed almost entirely of relatively thin lava flows built up over a central vent.

3- Most shields were formed by low viscosity basaltic magma that flows easily down slope away form the summit vent.

4- The low viscosity of the magma allows the lava to travel down slope on a gentle slope, but as it cools and its viscosity increases, its thickness builds up on the lower slopes giving a somewhat steeper lower slope.

5- Most shield volcanoes have a roughly circular or oval shape in map view.

6-Very little pyroclastic material is found within a shield volcano, except near the eruptive vents, where small amounts of pyroclastic material accumulate as a result of fire fountaining events.

7- Shield volcanoes thus form by relatively non-explosive eruptions of low viscosity basaltic magma.

Stratovolcanoes (also called **Composite Volcanoes**)

1. Have steeper slopes than shield volcanoes, with slopes of 6 to 10^{o} low on the flanks to 30o near the top.

2. The steep slope near the summit is due partly to thick, short viscous lava flows that do not travel far down slope from the vent.

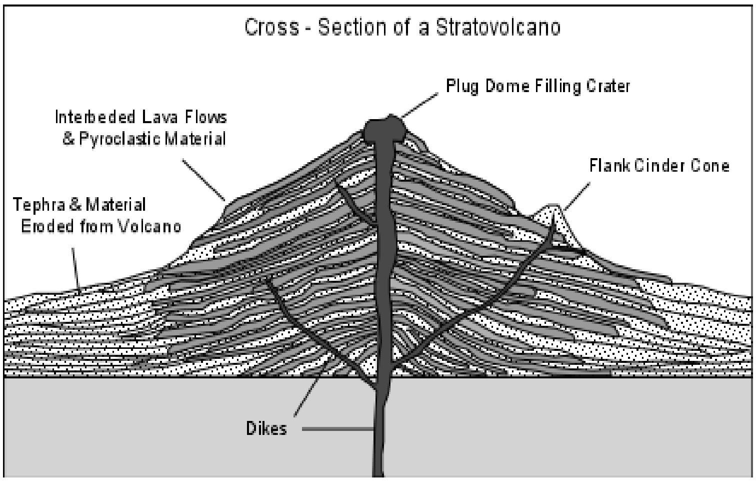


Fig. 58. Composite Volcanoes

3. The gentler slopes near the base are due to accumulations of material eroded from the volcano and to the accumulation of pyroclastic material.

4. Stratovolcanoes show inter-layering of lava flows and pyroclastic material, which is why they are sometimes called composite volcanoes.

Pyroclastic material can make up over 50% of the volume of a stratovolcano.

5. Lavas and pyroclastics are usually andesitic to rhyolitic in composition.

6. Due to the higher viscosity of magmas erupted from these volcanoes, they are usuallymore explosive than shield volcanoes.

Cinder Cones (also called **Tephra Cones**)

1. Cinder cones are small volume cones consisting predominantly of tephra that result from strombolian eruptions. They usually consist of basaltic to andesitic material.
2. They are actually fall deposits that are built surrounding the eruptive vent.
3. Slopes of the cones are controlled by the angle of repose (angle of stable slope for loose unconsolidated material) and are usually between about 25 and 35o.
4. Cinder cones often occur in groups, where tens to hundreds of cones are found in one area

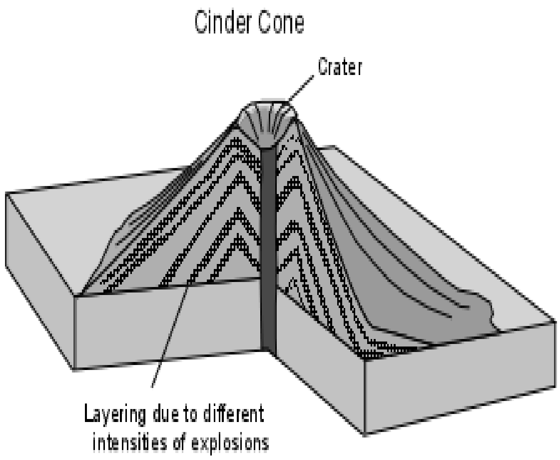
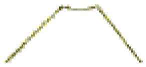
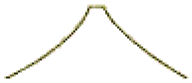


Fig. 59. Cinder cone Volcanoes

Comparison of the three main types of volcanoes:

Table 4: Three Main Types of Volcanoes*					
The three main types of volcanoes differ in shape, size, and make-up; the differences partly result from the different types of eruptions.					
Volcano Type	**Volcano Shape**	**Volcano Size**	**Volcano Materials**	**Eruption Type**	**Utah Example**
Cinder Cone	 Steep conical hill with straight sides	Small less than 300m high	cinders	Explosive	Diamond Cinder Cone, Washington County
Shield Volcano	 Very gentle slopes; convex upward (shaped like a warrior's shield)	Large over 10s of kms across	fluid lava flows (basalt)	Quiet	Cedar Hill, Box Elder County
Stratovolcano	 Gentle lower slopes, but steep upper slopes; concave upward	Large 1-10 km in diameter	numerous layers of lava and pyroclastics	Explosive	Mount Belknap, Tushar Mountains, Paiute County

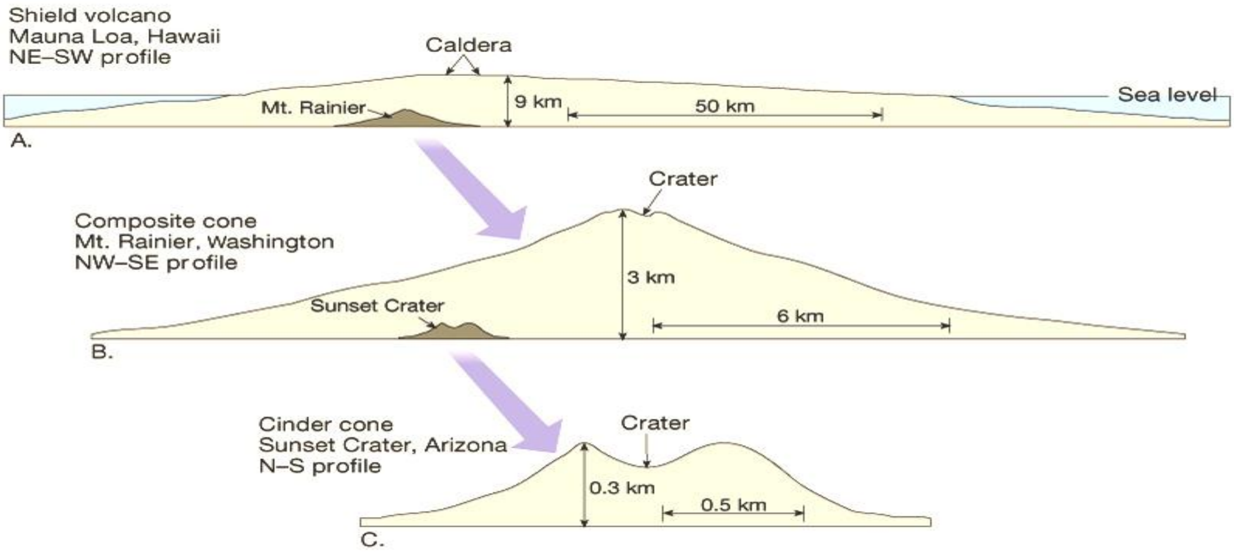


Fig. 60. Comparison of different volcanoes

A **caldera** is a cauldron-like volcanic feature usually formed by the collapse of land following a volcanic eruption. They are sometimes confused with volcanic craters. The word comes from Spanish *caldera*, and this from Latin *caldaria*, meaning "cooking pot". In some texts the English term *cauldron* is also used

Calderas - occur when gas builds up and huge explosion removes cone summit = a hole, may become flooded by the sea from lake within it

- Calderas are bowl-shaped collapse depressions formed by volcanic processes.
- Calderas most likely result from one of three collapse type events:
  - 1. Collapse of the summit following an explosive eruption of silica-rich pumice and ash pyroclastics
  - 2. Collapse of the summit following the subterranean or fissure drainage of the magma chamber
  - 3. Collapse of a large area following the discharge of silica-rich pumice and ash along ring fractures that may or may not have been previously active volcanoes

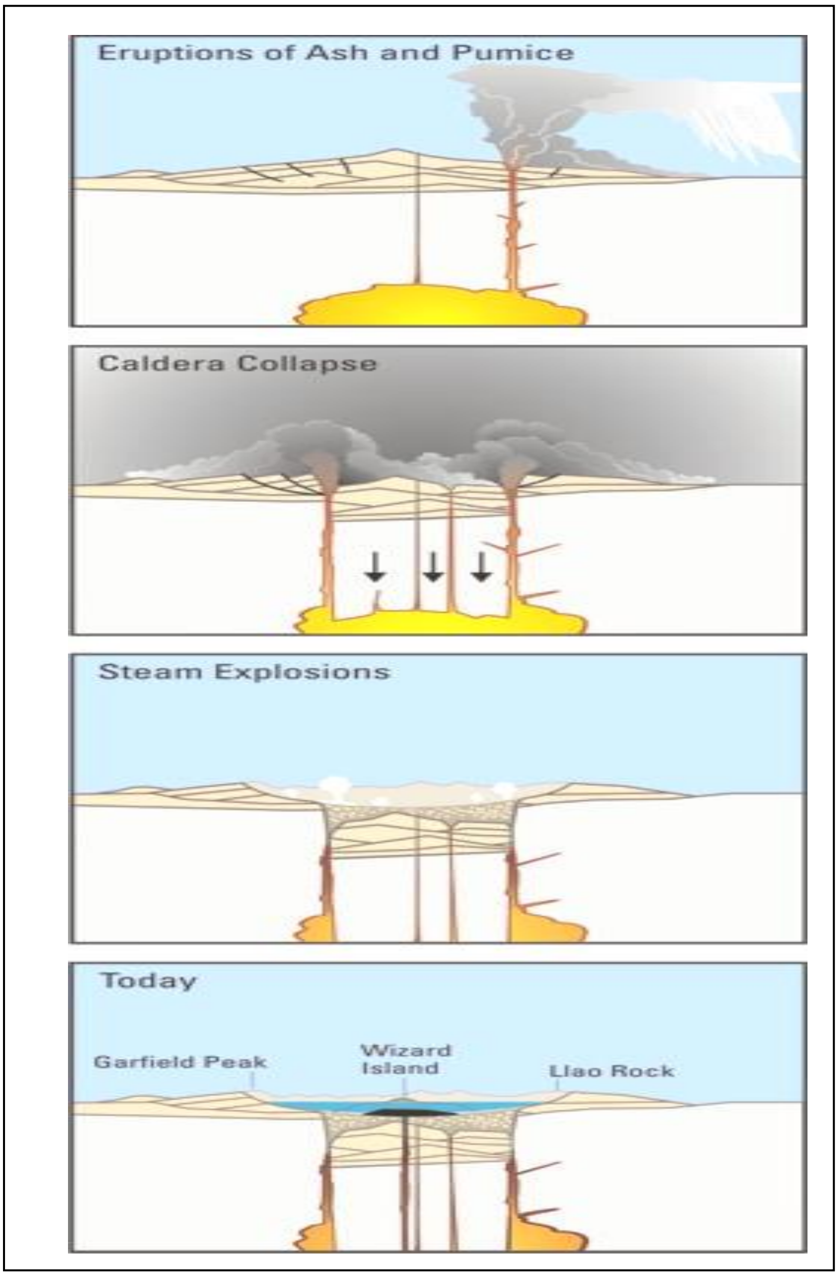


Fig. 61. Formation of caldera

- **Lava Plateaux -** formed from fissure eruptions, lava flows are basaltic in nature so flow for miles
- Lava domes are rounded, steep-sided mounds built by very viscous magma that is resistant to flow and builds up forming a dome.

The magma does not move far from the vent before cooling and it crystallizes in very rough, angular basaltic rocks.

A single lava dome may be formed by multiple lava flows that accumulate over time

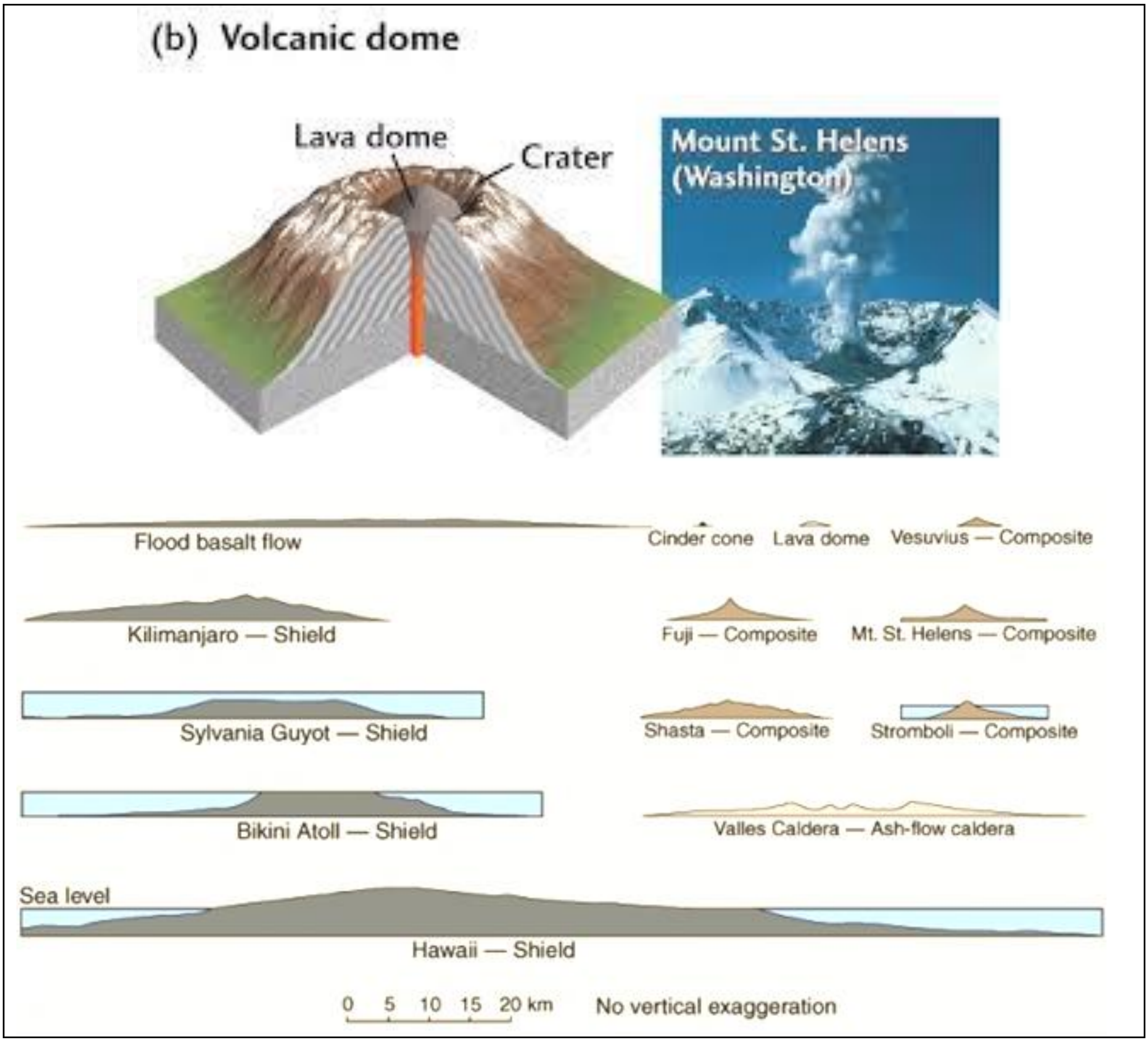


Fig. 62. Formation of caldera

2- INTRUSIVE VOLCANIC LANDFORMS

These are formed when magma solidifies underground. Magma forms in many different shapes and sizes, the most common are:

1**. Batholiths***:*

A batholith is an exposed area of (mostly) continuous plutonic rock that covers an area larger than 100 square kilometers Areas smaller than 100 square kilometers are called stocks However, the majority of batholiths visible at the surface (via outcroppings) have areas far greater than 100 square kilometers. These areas are exposed to the surface through the process of erosion accelerated by continental uplift acting over many tens of millions to hundreds of millions of years. This process has removed several tens of square kilometers of overlying rock in many areas, exposing the once deeply buried batholiths.

2. **Dykes**:

It formed when magma solidifies into vertical cracks, cutting across rock layers. When affected by erosion dykes may stand as a ridge.

3. Sills:

It formed when lava solidifies in between rock layers, after prolonged erosion, Sills may be exposed as escarpments and while they occur across a river valley they cause waterfalls and rapids.

4. Laccolith:

This is magma which solidifies in a shape similar to a mushroom. After prolonged erosion, it may form upland.

5. Lappolith:

This is a lenticular shaped magma, after erosion. It can be exposed as a shallow basin. Examples are the Bushveld igneous complex of South Africa

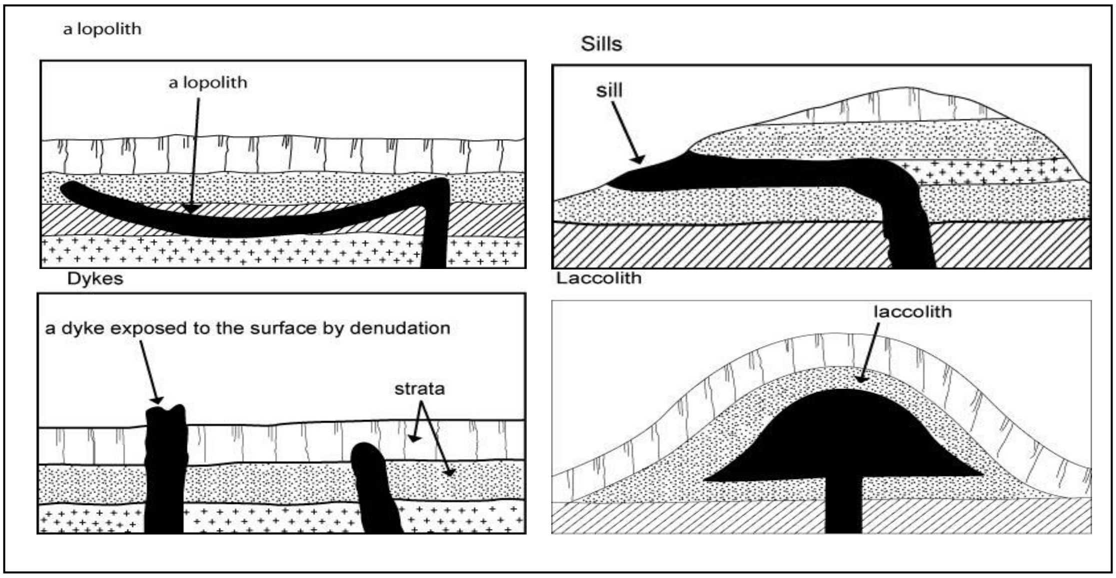


Fig. 63. Intrusive igneous rocks

3 -Minor Volcanic Forms

- **Solfatara -** small volcanic areas without cones, produced by gases escaping the surface
- **Geysers -** occur when water, heated explodes onto the surface
- **Hot springs/Boiling mud -** sometimes water heated below does not explode
- **Fumaroles –** an opening in or near a volcano, through which hot sulfurous gases emerge and super heated water, turning to steam as pressure drops when it emerges from the ground

Fig. 64. Minor volcanic forms

B. Deserts and Wind

1. Deserts form in land areas with low precipitation (typically less than 25 cm of rain per year).
2. Wind: The movement of air on the Earth's surface stems from the uneven distribution of solar heat. Hot air rises over the equator, drops out moisture, and descends as cool, dry air over latitudes 30 N and 30 S. Deserts are found at these latitudes.

Desert Types

- Subtropical Desert – 30^{o} Latitude

- Deserts on Leeward side of major Mountain ranges

- Interior Deserts- center of continents far from ocean

- Coastal desert- prevailing onshore wind cooled by cold ocean current

- Polar deserts- extremely cold and dry.

<u>Desert Landscape (Features)</u>

Weathering and desert streams create Desert features

- Weathering in Desert is mostly mechanical
  - A little chemical weathering produces manganese and iron-oxide stains, called desert vanish
- Stream Erosion
  - Arroyo- channel with water during periods of high discharge but dry most part of the year

- Pediments- large-scale gently inclined surfaces
- Inselberg- steep-sided knob of durable rock
- Playa- dry lake bed

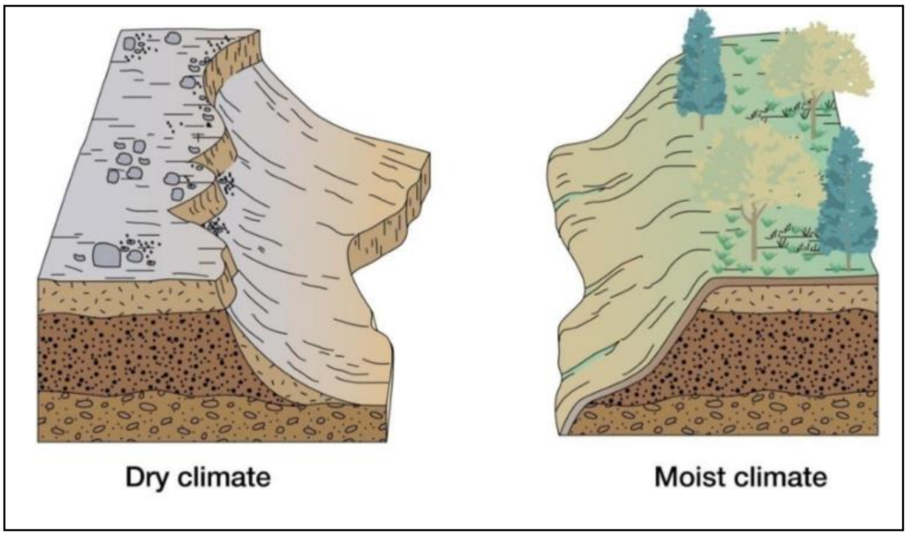


Fig. 65. Desert Landscape

Desert Landforms Produced By Water

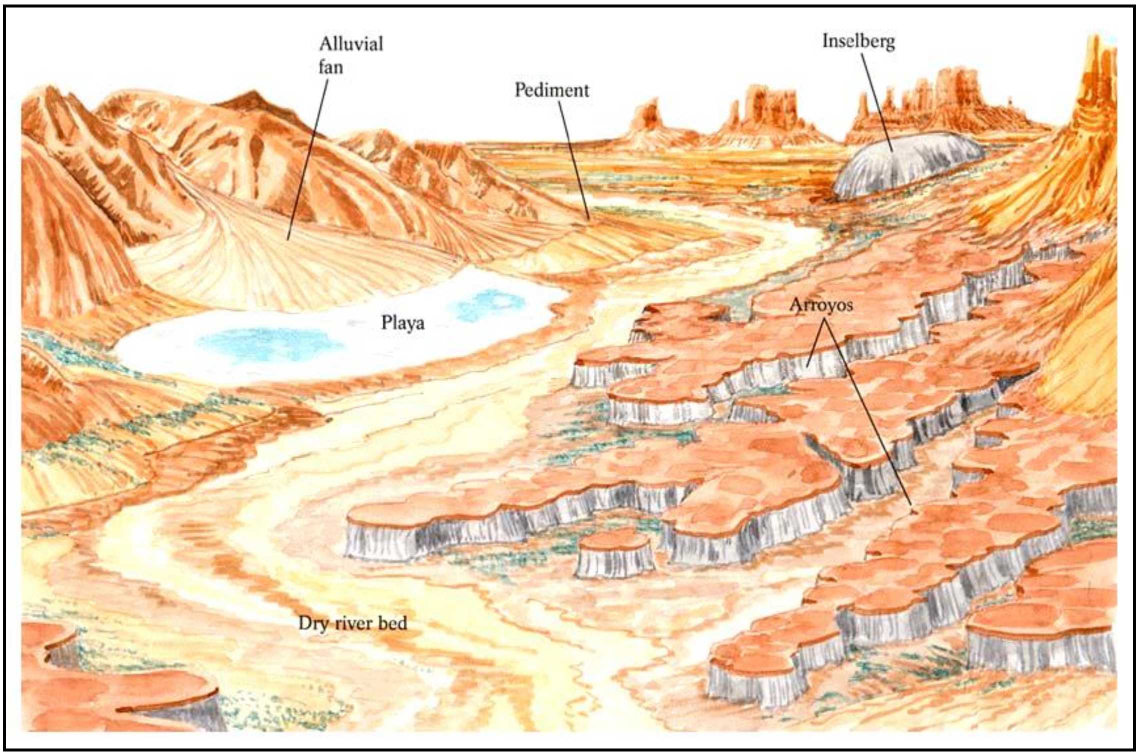


Fig. 66. Landforms produced by water

Wind-Created Features

Wind is a strong sculpting agent. It carves away rocks and sediments and deposits sediments elsewhere.

1. **Bed load**: The sand grains and other particles that wind (or water) carries on or just above the ground.
2. **Suspended load**: The fine particles that wind (or water) keeps aloft.
3. **Saltation**: The “jumping” of sand grains due to strong wind. Wind blowing perpendicular to a surface decreases the pressure on that surface. When the inertia of a sand grain is overcome, it begins to roll. When it hits other grains, they bounce into the air, where they are carried forward until gravity pulls them back down.
4. **Deflation**: A process by which wind carries fine particles away and leaves a compact surface of larger pebbles.
5. **Dunes**: Sand mounds or ridges that the wind creates. Dunes have a steep side called a slip face. Types of dunes include:

1. **Barchan dune**: A solitary dune shaped like a horseshoe, with its tips pointing away from the wind. Barchan dunes form on flat surfaces where sand supply is low.
2. **Transverse dune:** A long ridge of sand oriented perpendicular to the direction of the wind. Transverse dunes form where wind is steady and sand is plentiful.
3. **Longitudinal dune**: A dune that forms parallel to wind direction, in places where sand supply is limited.
4. **Parabolic dune**: A dune shaped like a barchan dune but with its tips pointing into the wind. Parabolic dunes form on beaches with abundant sand and are partly covered by vegetation.

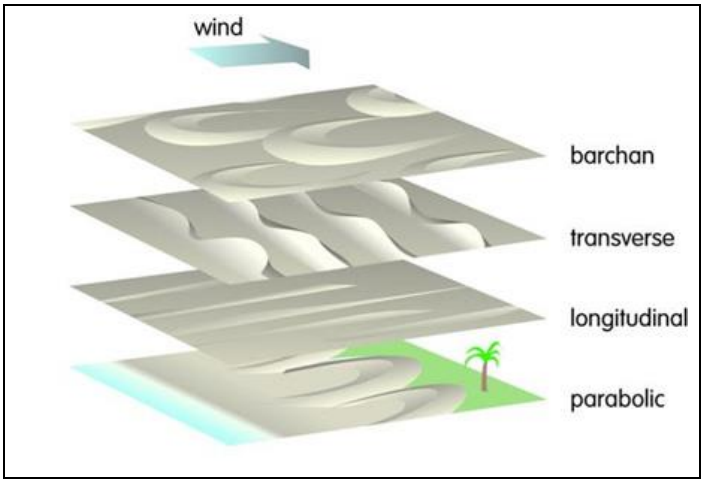


Fig. 67. Sand dunes

Desert dunes classification is based upon shape and includes barchan dunes, parabolic dunes, transverse dunes, linear (longitudinal) dunes, seif dunes, star dunes

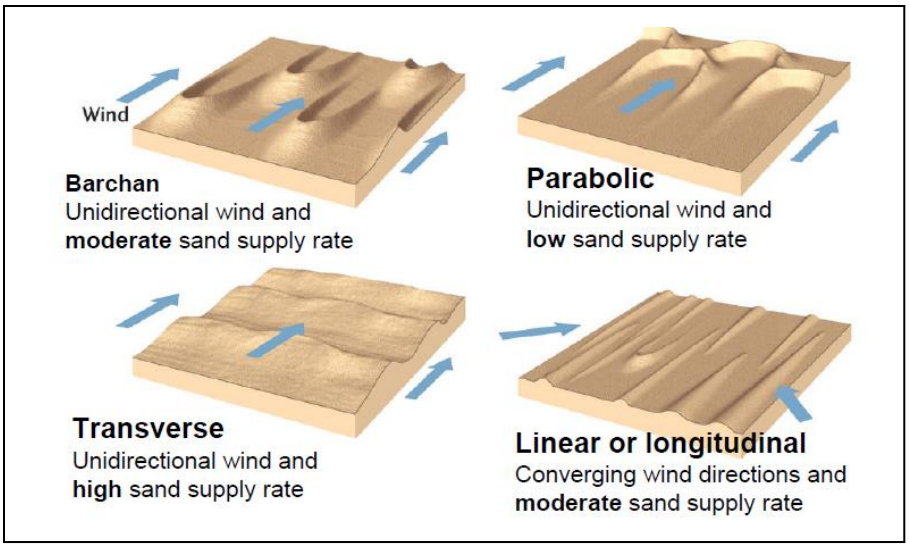
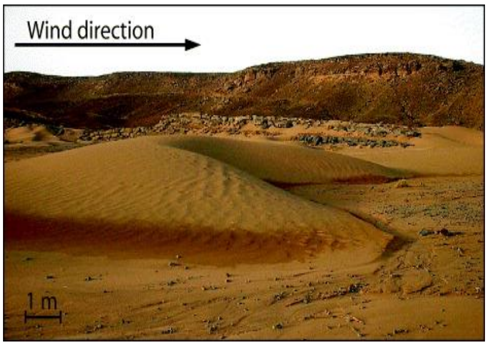


Fig. 68. Sand dunes

Barchan dunes

Crescent-shaped sand dunes .Barchans face the wind, appearing convex and are produced by wind action predominately from one direction. They are highly common, characteristic in sandy deserts all over the world and are arc-shaped, markedly asymmetrical in cross section, with a gentle slope facing toward the wind sand ridge, comprising well-sorted sand. This type of dune possesses two "horns" that face downwind, with the steeper slope known as the slip face, facing away from the wind, downwind, at the angle of repose of sand, approximately 30–35 degrees for medium-fine dry sand



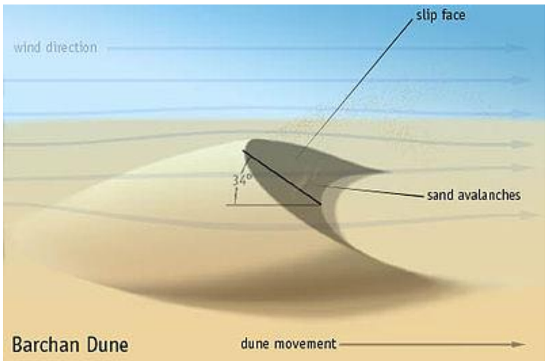


Fig. 69. Barchan dunes

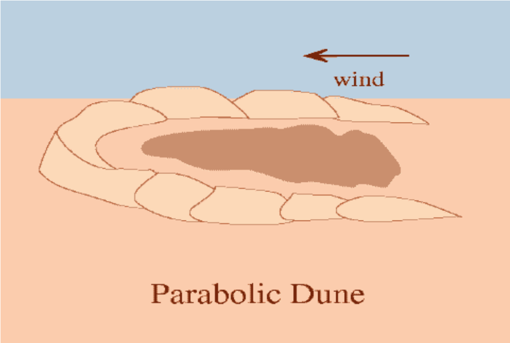
Parabolic Dune

Parabolic or **blowout dunes** are caused by breaching of partially stabilized ridges. With the arms anchored at the ridge, the center of the dune migrates downwind. As a result, the arms point upwind rather than downwind as with barchan dunes.

Longitudinal (Seif) dunes

Longitudinal dunes (also called Seif dunes, after the Arabic word for "sword"), elongate parallel to the prevailing wind, possibly caused by a larger dune having its smaller sides blown away. Seif dunes are sharp-crested and are common in the Sahara. They range up to 300 m in height and 300 km in length.

Seif dunes are thought to develop from barchans if a change of the usual wind direction occurs. The new wind direction will lead to the development of a new wing and the over development of one of the original wings. If the prevailing wind then becomes dominant for a lengthy period of time the dune will revert to its barchan form.



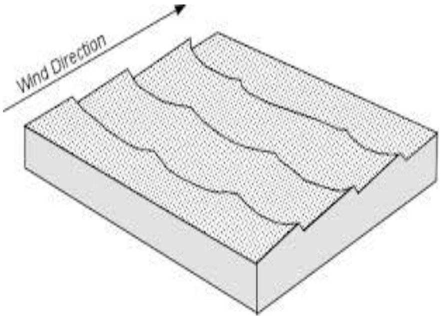



Fig. 69. Parabolic dune (left), Longitudinal dunes (middle), Longitudinal dunes (right)

Transverse dune

A large, strongly asymmetrical, elongated dune lying at right angles to the prevailing wind direction. Transverse dunes have a gently sloping windward side and a steeply sloping leeward side. They generally form in areas of sparse vegetation and abundant sand. Most beach dunes are transverse dunes

Star dunes

Radially symmetrical, star dunes are pyramidal sand mounds with slipfaces on three or more arms that radiate from the high center of the mound. They tend to accumulate in areas with multidirectional wind regimes. Star dunes grow upward rather than laterally.

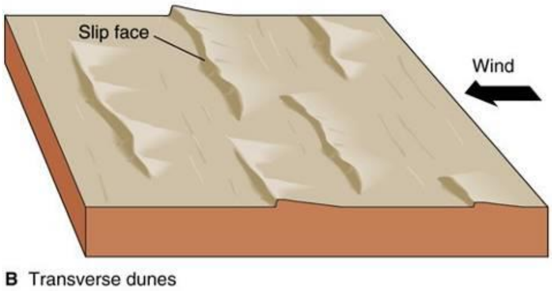


Fig. 70. transverse dune (left), star dunes (right)

Loess

Loess is an Aeolian sediment formed by the accumulation of wind-blown silt, typically in the 20–50 micrometer size range, twenty percent or less clay and the balance equal parts sand and silt, that are loosely cemented by calcium carbonate. Loess is homogeneous, porous, friable, pale yellow or buff, slightly coherent, typically non-stratified and often calcareous. Loess grains are angular with little polishing or rounding and composed of crystals of quartz, feldspar, mica and other minerals. Loess can be described as a rich, dust-like soil plateau (a high plain or tableland) is an area of highland, usually consisting of relatively flat terrain. A plateau is an elevated land. It is a flat topped table standing above the surrounding area. A plateau may have one or more sides with steep slopes.

Fig. 71. Loess deposits

Mesa

A mesa (Portuguese and Spanish for table) an elevated area of land with a flat top and sides that are usually steep cliffs. It takes its name from its characteristic table-top shape. a broad, flat-topped hill bounded by cliffs and capped with a resistant rock layer(Fig. 72).

Butte

Butte is an isolated hill with steep, often vertical sides and a small, relatively flat top; buttes are smaller than mesas, plateaus, and table landforms

In differentiating mesas and buttes, geographers use the rule of thumb that a mesa has a top that is wider than its height, while a butte has a top that is narrower than its height (Fig. 72).

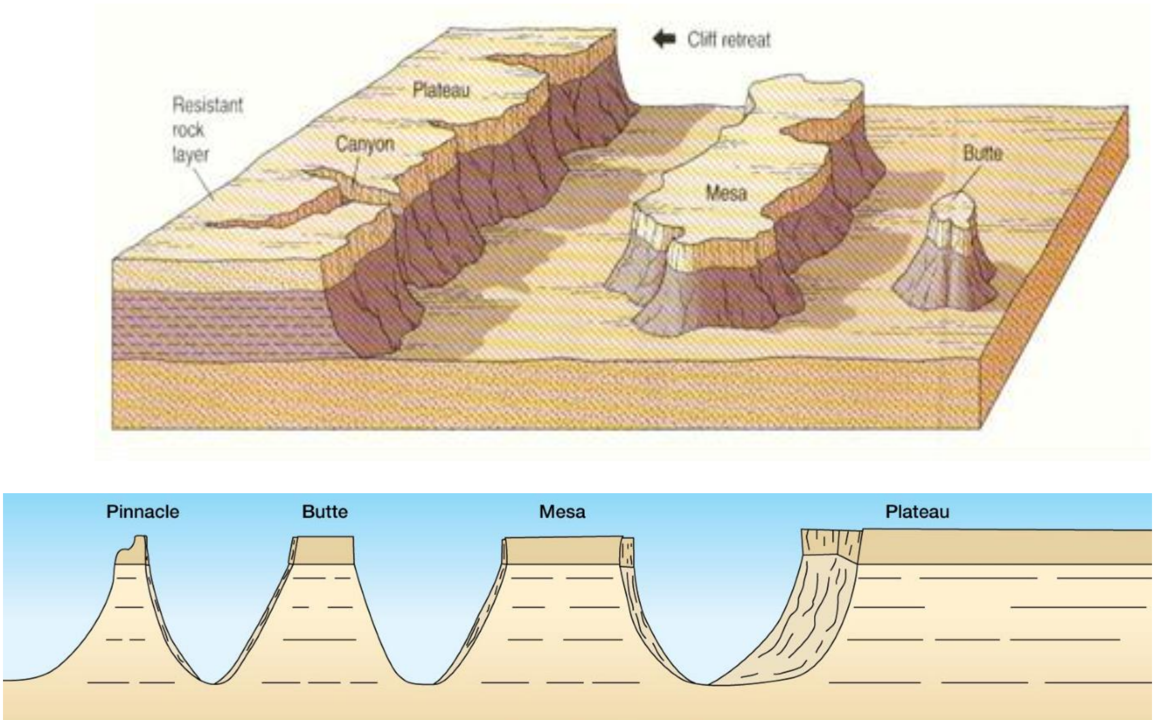


Fig. 72. Different landforms

A pediment is a very gently sloping (5°-7°) inclined bedrock surface. It typically slopes down from the base of a steeper retreating desert cliff, or escarpment, but may continue to exist after the mountain has eroded away. It is caused by erosion. It develops when sheets of running water (laminar sheet flows) wash over it in intense rainfall events. It may be thinly covered with fluvial gravel that has washed over it from the foot of mountains produced by cliff retreat erosion. It is typically a concave surface gently sloping away from mountainous desert areas

Bajadas merged groups of alluvial fans, which also may appear to gently slope from an escarpment, but are composed of material eroded from canyons, not bedrock.

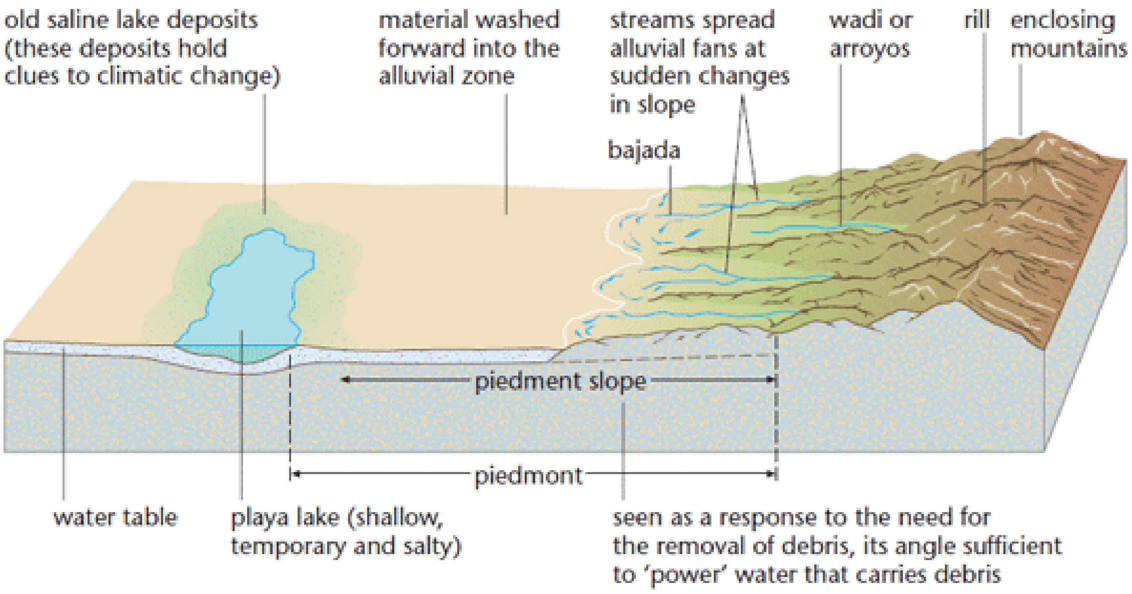


Fig. 73. water landforms

There are two features that can help differentiate between a pediment and bajada. First, pediments will likely have common exposures of bedrock sticking up through a thin veneer of sediment while bajadas will not have these exposures. Second, the major drainages of bajadas can be traced back to a few steep narrow canyons that are the source of the material deposited on the surface of the bajada. Pediments will not have these source canyons and erosion will be removing sediment from the entire surface

playa, **(Spanish: shore or beach),** flat-bottom depression found in interior desert basins and adjacent to coasts within arid and semiarid regions, periodically covered by water that slowly filtrates into the ground water system or evaporates into the atmosphere, causing the deposition of salt, sand, and mud

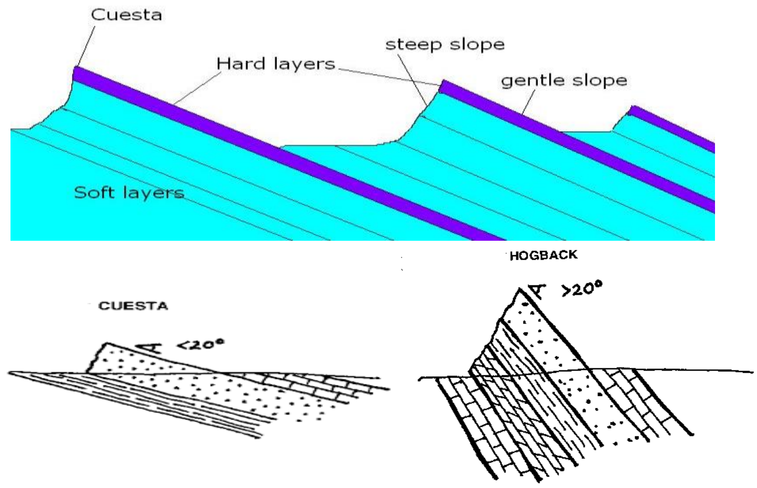


Fig. 74. Cuesta and Hogback

Hogback is a long narrow ridge or series of hills with a narrow crest and steep slopes of nearly equal inclination on both flanks. Typically, this term is restricted to a ridge created by the differential erosion of outcropping, steeply dipping (greater than 20°),

Cuestas are similar formations with dip slopes of less than 20 degrees; escarpment slopes of cuestas are much steeper than the dip slopes.

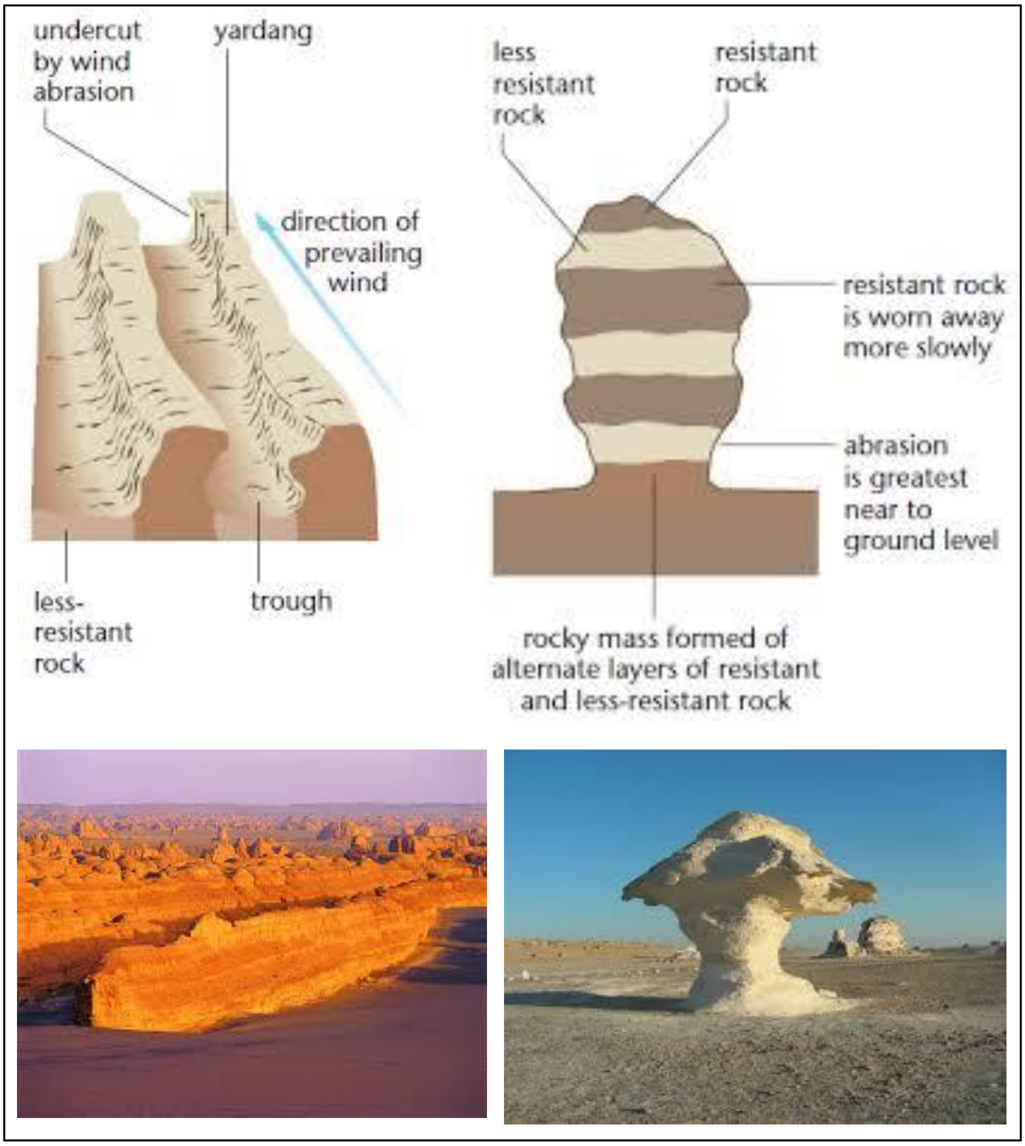


Fig. 75. Yardang, Zeugen and Yardang

Zeugen

Mushroom-shaped rock that has been eroded by the abrasive action of windblown sand. The undercutting effect is concentrated near ground level, where sand movement is greatest, and is enhanced in areas of near-horizontal strata when the lowest bed is relatively weak Streams

A Yardang

It is a streamlined hill carved from bedrock or any consolidated or semiconsolidated material by the dual action of wind abrasion, dust and sand, and deflation. Yardangs become elongated features typically three or more times longer than wide, and when viewed from above, resemble the hull of a boat. Facing the wind is a steep, blunt face that gradually gets lower and narrower toward the lee end. [2] Yardangs are formed by wind erosion, typically of an originally flat surface formed from areas of harder and softer material. The soft material is eroded and removed by the wind, and the harder material remains. The resulting pattern of yardangs is therefore a combination of the original rock distribution, and the fluid mechanics of the air flow and resulting pattern of erosion.

Alluvial land forms

Streams are channeled flows of any amount of water. Although streams hold only a small percentage of the Earth's water at any given time, the energy of streams has done much to sculpt the landscape. Stream energy is controlled by channel size and slope.

1. **Gradient**: The steepness of land over which a stream flows. As a stream flows down a slope, its potential energy converts to kinetic energy. The steeper the gradient, the faster the stream flows.
2. **Base level**: The lowest level to which a stream can erode its channel. Oceans are considered the ultimate base level because they are the final destination of streams. More often, local base levels like lakes, dams, or stream junctions control stream flow.
3. **Cross section**: The area of water in a cross-sectional slice of a stream. For a flat stream, cross section is calculated by multiplying depth by width. For a semi-circular stream, it is calculated using stream radius: $(1/2)\pi r^2$.
4. **Discharge**: The volume of water that flows past a certain point in a stream over a measured time interval. Discharge is calculated by multiplying the cross section of the stream by the velocity of the stream.

Stream Flow and Transport

1. **Water can flow within a stream in two ways:**
    1. **Laminar flow**: In slow-moving streams, water flows in parallel paths.
    2. **Turbulent flow**: In fast-moving streams and in rough stream channels, water swirls around as it moves down a gradient.
2. **Capacity**: The amount of sediment a stream can carry past a certain point in a given time.
3. **Competence**: A measure of how strong a stream is, based on the biggest size of an object the stream can move.
4. **Saltation**: Skipping and bouncing of particles on the bottom of a stream caused by water flow pushing the particles.
5. **Load**: The material a stream carries. There are several types:
    1. **Bed load**: Heavy objects dragged along a stream bottom.
    2. **Suspended load**: Fine particles carried suspended in a stream's moving water.
    3. **Dissolved load**: Material (salt, carbonate, or other ions) dissolved in the stream water.
6. **Graded stream**: A stream with a slope and channel that have adjusted enough over time so that the stream has just enough energy to carry its load, but no excess energy so that it erodes its banks.

Stream Settings

1. Alluvial fan: A gently sloping blanket of alluvium, or sediment deposited by a stream, where it exits a gully onto a flatter surface

2. **Flood plain**: A plain surrounding a stream. Streams periodically overflow their banks or move laterally across surrounding flood plains, leaving layers of sediments in their wake.
3. **Delta**: The mouth of a stream, where the stream slows due to a gentler gradient and deposits much of its sediments as it moves to base level.
4. **Tributary**: A small stream that flows into a larger stream.
5. Drainage system:
6. **Stream Shapes and Patterns**

There are several types of streams and drainage patterns, which are dictated by landforms and also shape those landforms. Whereas glaciers carve flat-bottomed, U-shaped valleys, streams carve sharp canyons, or V-shaped valleys.

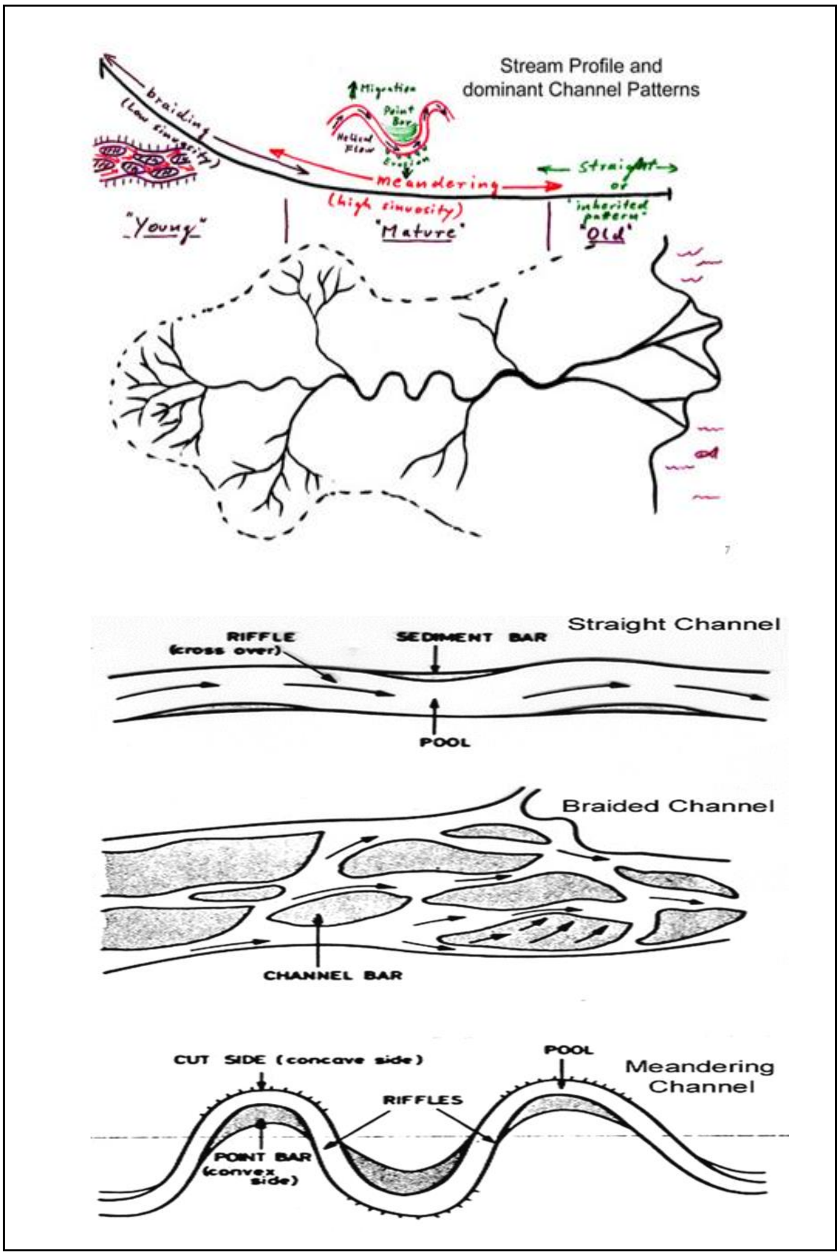


Fig. 76. Streams are channeled

1. **Braided stream**: A stream that divides into smaller streams. When a stream gradient decreases, its flow slows, causing the stream to branch into smaller subchannels. Braided streams are common on alluvial fans and glacial outwash plains.
2. **Meandering stream**: A stream that carves a path sideways and forms wide loops, called meanders, as it flows downstream. Often, when water in a stream flows over a bump, ripples are created that deflect water toward one side of the stream and carve into the side. This sideways flow creates a bend in the channel, and water flowing out of this bend then deflects toward the opposite side of the stream, carving a bend there.
    1. **Point bar**: Sediment deposited in the inner curves of a meandering stream. The stream moves slowest in these inner curves, so the stream drops sediment here.
    2. **Oxbow lake**: A lake that splits off from a meandering stream when erosion carves a straight channel that cuts off the flow into one of the stream's meanders.

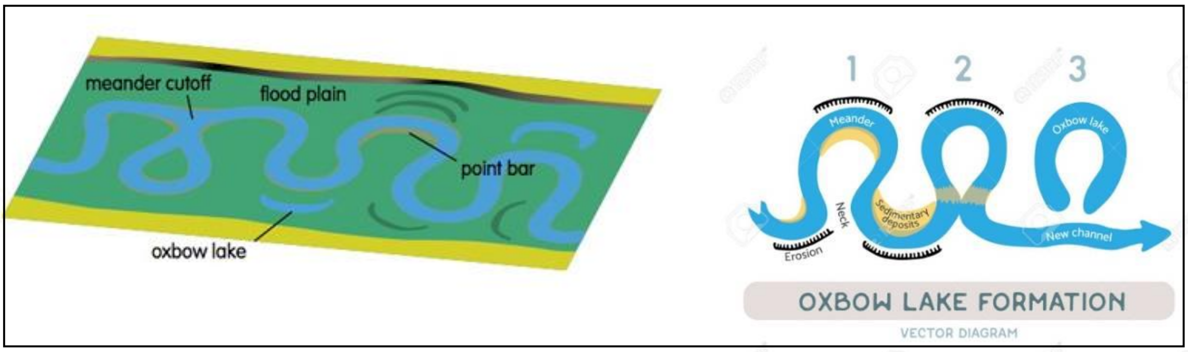


Fig. 77. Oxbow lake formation

3. **Streams can follow several different drainage patterns:**
    1. **Dendritic drainage**: Several substreams branch out from a main stream in a treelike **pattern.**
    2. **Radial drainage**: Streams run in all directions from a central high point.
    3. **Rectangular drainage**: Streams make right-angled turns, following rectangular fracture patterns in the bedrock over which they flow.
    4. **Trellis drainage**: Tributaries flow perpendicular to the main channel, following parallel beds of weak strata. Trellis drainage often occurs in tilted or folded rocks (Fig. 78).

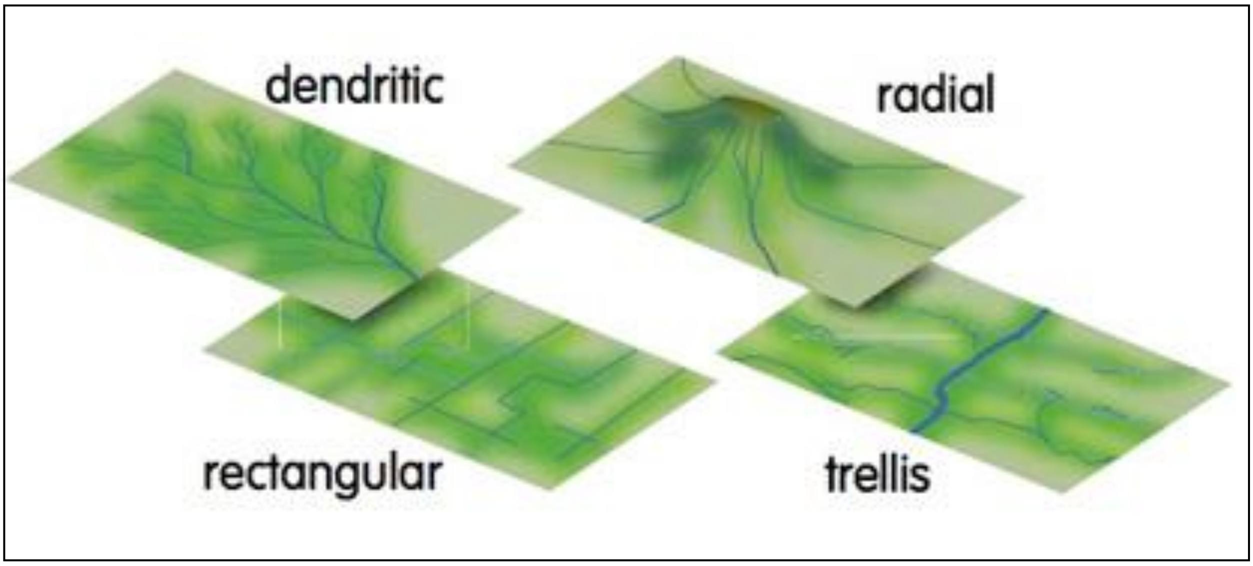


Fig. 78. Drainage pattern

Flood plain environments are composed of a mosaic of different landform features including cutbanks, pointbars, natural levees and oxbow lakes

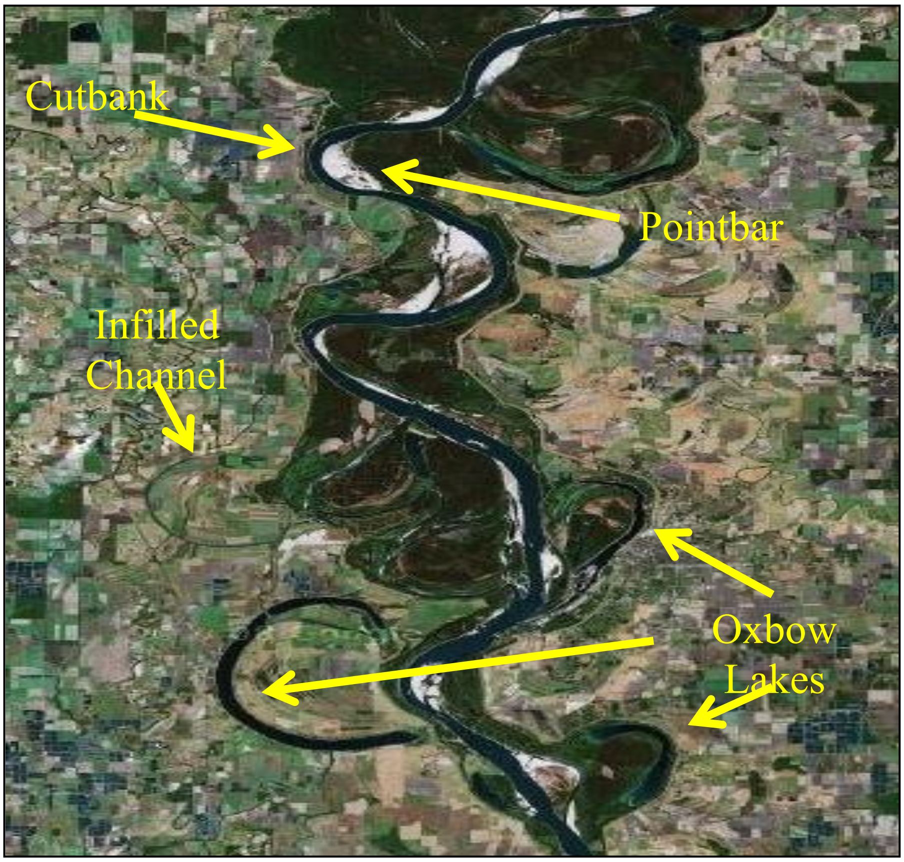


Fig. 79. cutbanks, pointbars, natural levees and oxbow lakes

- ***Cutbanks*** form along the outer convex margin of meander bends. Cutbanks , unlike most floodplain landforms are actually erosional features formed by the lateral movement of the channel across the flood plain. Flood plain sediments are eroded from the cutbank and deposited on pointbar surfaces.
- ***Pointbars*** are concave, depositional landforms that form opposite of the eroding cutbanks, and they develop in concert with the laterally migrating river channel. Pointbars are typically composed of sands, gravel, silts, and clay deposits, that form arcuate, meander-scroll ridges.
- ***Natural levees*** are depositional landforms formed from the vertical accumulation of sediments deposited during flood events. Natural levees form topographically higher surfaces adjacent to the river channel, that generally consist of stratified, well-sorted sands, silts, and clays. Natural levees deposits are thickest and coarsest close to the channel and they become progressively thinner, and finer with increasing distance from the channel.
- ***Oxbow lakes*** or infilled channels form when a meander bend is cut off from the main river and abandoned in the floodplain. Abandoned meanders can occur in various stages from flooded oxbow lakes to being completely infilled with sediment deposits.

Potholes

Potholes are cylindrical holes drilled into the bed of a river that vary in depth & diameter from a few centimetres to several metres. They're found in the upper course of a river where it has enough potential energy to erode vertically and its flow is turbulent. In the upper course of a river, its load is large and mainly transported by traction along the river bed. When flowing water encounters bedload, it is forced over it and downcuts behind the bedload in swirling *eddy currents*. These currents erode the river's bed and create small depressions in it.

The creation of eddy (swirl) currents as a result of bedload in a river.

As these depressions deepen, pebbles can become trapped in them. As a result of the eddy currents, the pebbles drill into the depressions making them more circular, wider & deeper. Pebbles will only be able to erode a river's bed though if the rock the pebble's made of is stronger than the rock the river bed is made of.

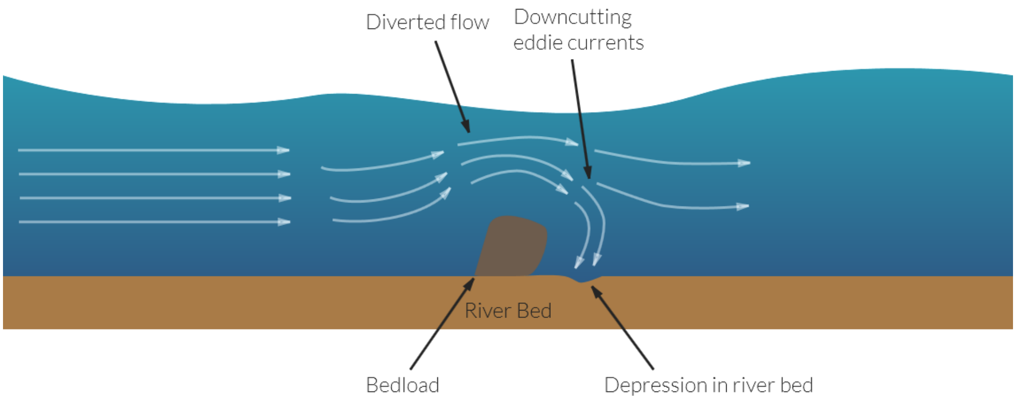


Fig. 80. A pothole that has formed along the River Clyde.

V-Shaped Valleys

V-Shaped valleys are found in the upper course of the river and are a result of both erosion by the river and weathering. V-Shaped valleys are deep river valleys with steep sides that look like a letter V when a cross section of them is taken, hence the name. They're found in the upper course because this is where the river has the greatest gravitational potential energy and so the greatest potential to erode vertically. It does so during periods of high discharge. When the river's discharge is high, it is able to transport its large bedload by traction eroding the river's bed and valley by corrosion, deepening it. Not much lateral erosion takes place so the channel and valley remains relatively narrow.

As the channel and valley deepens the sides of the valley are exposed and become susceptible to weathering. The valley's sides also undergo mass movements resulting in large volumes of material falling into the river's channel, adding to its erosive power and causing the valley sides to take up a V shape. The steepness of the valley sides and whether the valley actually looks like a V is dependent on the climate, vegetation and rock structure among things. In cold, wet climates, freeze thaw weathering is abundant and rainwater can act as a lubricant, aiding mass movements. Vegetation can impede mass movements because it will help bind the soil. If the valley is composed of hard rock the valley sides will be very steep because they won't be weathered easily.

Waterfalls (Geological)

Waterfalls develop when a change of lithology (rock type) takes place along the river's course resulting in differential erosion. When the rock type of the river's channel changes from a resistant rock to a less resistant one (e.g. granite to limestone), the river erodes the less resistant rock faster producing a sudden drop in the gradient of the river with the resistant rock being higher up than the less resistant rock. As the river flows over the resistant rock, it falls onto the less resistant rock, eroding it and creating a greater height difference between the two rock types, producing the waterfall.

When water flows over the waterfall it creates a plunge pool at its base and the splashback from the falling water undercuts the resistant rock. The unsupported rock is known as the cap rock and it eventually collapses into the plunge pool causing the waterfall to retreat upstream. Over thousands of years, the repeated collapse of the cap rock and retreat of the waterfall produces a *gorge of recession*.

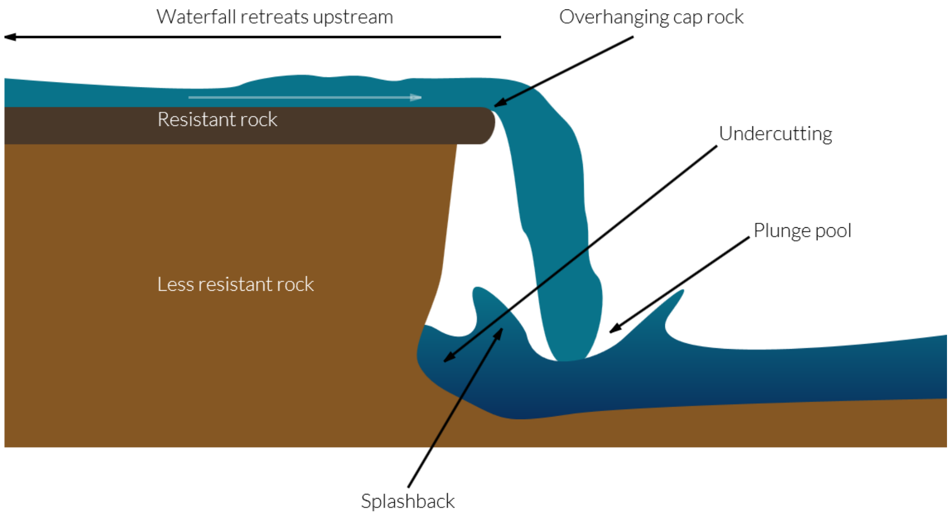


Fig. 81. A pothole that has formed along the River Clyde.

Rapids

Rapids are sections of a river where the gradient of the river bed is relatively steep resulting in an increase in the river's turbulence and velocity. They form where the gradient of the river is steep and the bed is composed mainly of hard rocks.

Meanders

Meanders are bends in a river that form as a river's sinuosity increases. The sinuosity of a river is a measurement of how much a river varies from a straight line. It's a ratio between the channel length and displacement (straight line distance) between two points in the river's course:

$$\text{Sinuosity} = \text{Channel Length} / \text{Displacement}$$

A sinuosity of 1 means that the channel is perfectly straight. A sinuosity greater than 1 means that the river meanders.

Meanders develop when alternating riffles & pools form along a river channel. A riffle is a a shallow section of a channel while a pool is a deep section. These riffles and pools develop at equal points along the river channel with each pool being about 5× the length of the channel (Fig. 82).

In a pool, the channel is more efficient while at a riffle, the channel is less efficient. This causes the flow of the river to become irregular and the maximum flow is concentrated on one side of the river. This increases erosion on one side of the river and increases deposition on the other causing the river's channel to appear to bend. Erosion is greatest on the outside bend and deposition is greatest on the inside bend.

The alternating riffles & pools have another affect, they increase the turbulence of the river and produce a special type of flow known as *helicoidal* flow. This is a corkscrew like movement which spirals from one side of the channel to another between pools. The helicoidal flow erodes the pools along the channel and increases deposition on the next inside bend after a pool.

Characteristics

A cross section of a meander would show that on the outside bend, the channel is very deep and concave (Figs. 83 &84). This is because the outside bend is where the river flows fastest and is most energetic, so lots of erosion by hydraulic action and corrasion takes place. *River cliffs* form on the outside bend as the river erodes laterally. The inside bend is shallower with a gentle *slip-off slope* made of sand or shingle that is brought across from the outside bend by the helicoidal flow of the river. The river flows much slower on the inside bend so some deposition takes place, contribution to the slip-off slope.

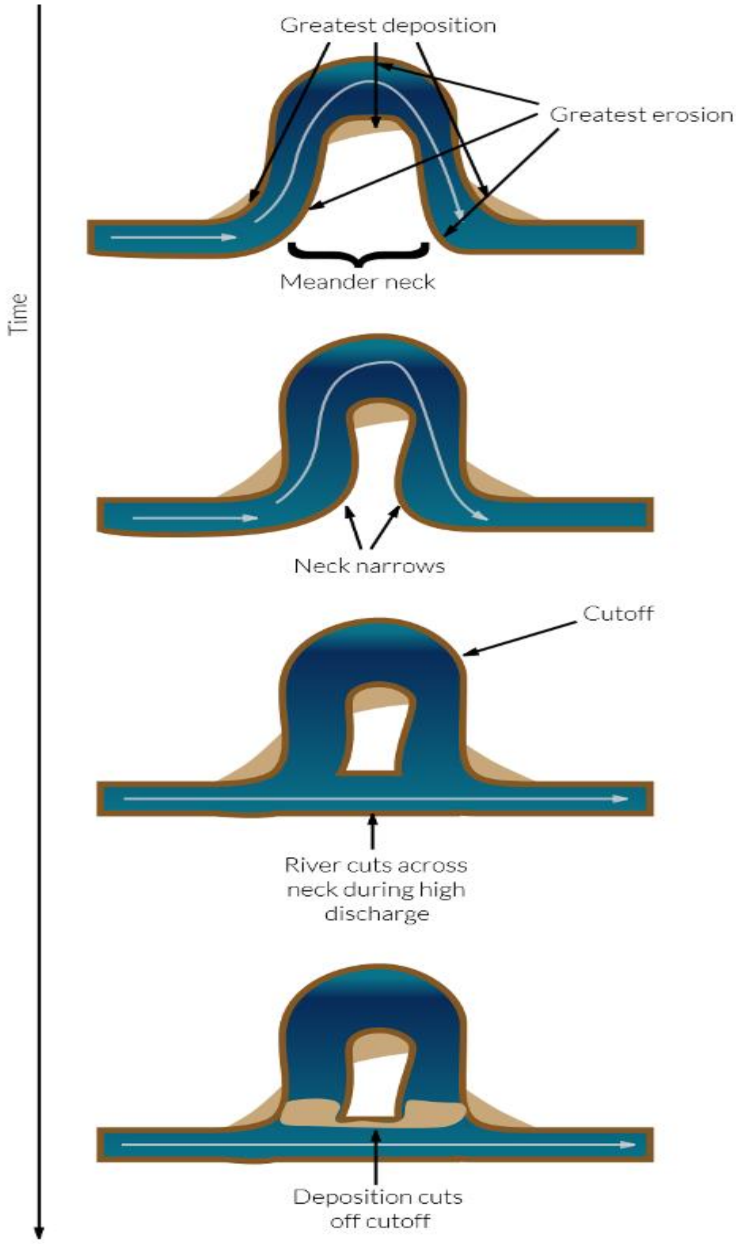


Fig. 82. Development of meanders

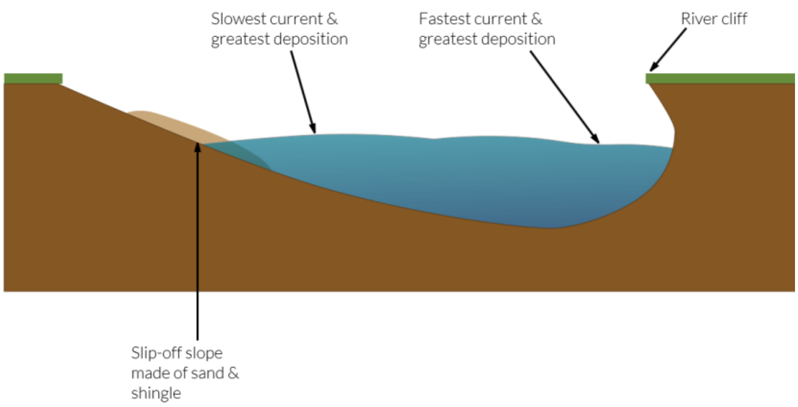


Fig. 83. Development of meanders

Fig. 84. A cross section of a meander

A river cliff on a meander that has had rocks placed near it to slow down erosion.

Oxbow Lakes

Oxbow lakes are an evolution of meanders that undergo extensive deposition and erosion. As strong erosion takes place on the outside bend of a meander while deposition takes place on the inisde bend. As a result, the neck of a meander narrows. During extremely high discharge (e.g., a flood), it's more efficient for a river to flow accross the neck of a meander rather than around it. When discharge returns to normal levels, the river continues follow this new course. The meander is left connected to the channel as a *cutoff*. Deposition eventually separates the cutoff from the main channel leaving behind an *oxbow lake*. With its main source of water disconnected, the lake eventually dries up leaving behind a *meander scar*.

Braided Channels

A braided channel is a type of channel that is divided into smaller sub-channels by small, temporary islands called *eyots*. Braided channels develop in rivers with a lot of sedimentary load, a steep gradient and where the discharge of the river changes regularly. When the volume of load exceeds the river's capacity or the discharge of the river drops, the river is forced to deposit its load in the channel and islands of sediment (eyots) form.

Fig. 85. A heavily braided section of the Tagliamento’s channel in Italy.

Floodplains

Floodplains are large, flat expanses of land that form on either side of a river. The floodplain is the area that a river floods onto when it’s experiencing high discharge. When a river floods, its efficiency decreases rapidly because of an increase in friction, reducing the river’s velocity and forcing it to deposit its load. The load is deposited across the floodplain as *alluvium*. The alluvium is very fertile so floodplains are often used as farmland.

The width of a floodplain is determined by the sinuosity of the river and how much meander migration takes place. If there’s a lot of meander migration, the area that the river floods on will change and the floodplain will become wider.

Levees

Levees are natural embankments produced, ironically, when a river floods. When a river floods, it deposits its load over the flood plain due to a dramatic drop in the river’s velocity as friction increases greatly. The largest & heaviest load is deposited first and closest to the river bank, often on the very edge, forming raised mounds. The finer material is deposited further away from the banks causing the mounds to appear to taper off. Repeated floods cause the mounds to build up and form levees.

Levees aren’t permanent structures. Once the river’s discharge exceeds its bankfull discharge[1], the levees can be burst by the high pressure of the water. Levees increase the height of the river’s channel though, so the bankfull discharge is increased and it becomes more difficult for the river to flood.

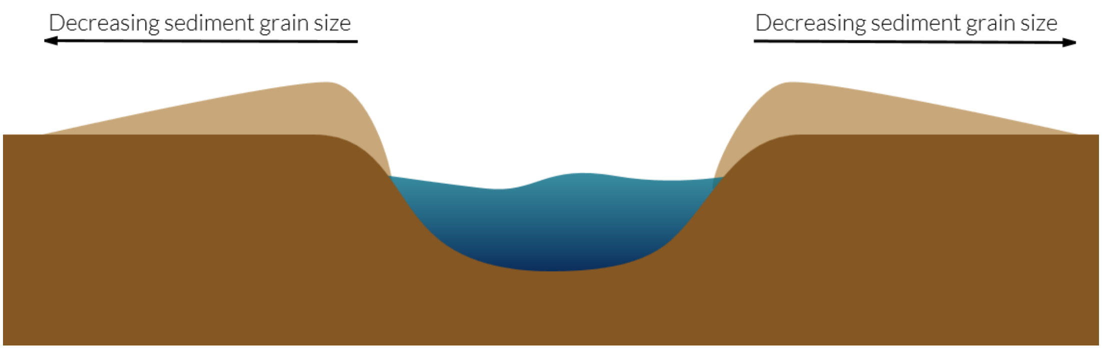


Fig. 86. Levees

River Terraces

River terraces are older remnant flood plain surfaces that are higher in elevation than the modern flood plain (Fig. 87). They may occur on one or both sides of the valley. Terraces are formed when the river channel cuts down into the flood plain and laterally erodes the alluvial valley, carving a new river channel and flood plain entrenched within the older flood plain surfaces. Down cutting can occur because of hydrologic or sedimentary changes in the headwaters or valley gradient changes caused by a retreating sea-level and lowered or extended base-level. Terraces can also form from tectonics and valley uplifting. Terraces are generally isolated from the more recent river processes and may only flood during 100 or 500 year flood events. River terraces are often archeological hot spots because they contain artifacts from historic colonies that used the river and flood plain.

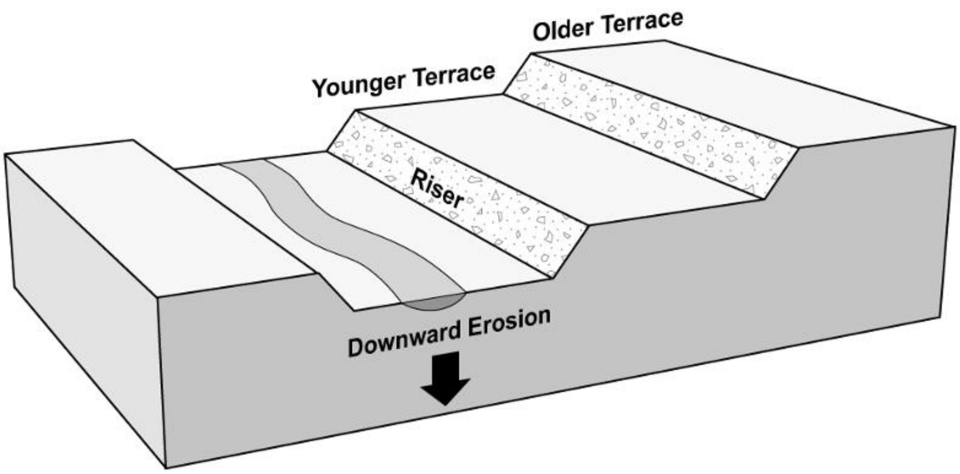


Fig. 87. River terraces

Deltas

Deltas are depositional landforms found at the mouth of a river where the river meets a body of water with a lower velocity than the river (e.g. a lake or the sea). For a delta to develop, the body of water needs to be relatively quiet with a low tidal range so that deposited sediment isn't washed away and has time to accumulate (Fig. 88).

When a river meets a stationary body of water, its velocity falls causing any material being transported by the river to be deposited. Deltas are made up of three sediment beds that have been sorted by the size of the sediment. The bottom most bed, the *bottomset* bed, is composed primarily of clay and some other fine grained sediments. Clay is the main constituent because when clay meets salt water a process called flocculation takes place where clay & salt particles clump together (flocculate) due to an electrostatic charge developing between the particles. This makes the clay particles sink due to their increased weight producing the bottomset bed. The bottomset bed stretches a fair distance from the mouth of the river as the fine sediments can be transported a reasonable distance from the river's mouth.

The foreset bed lies on top of the bottomset bed. The foreset bed is composed of coarser sediments that are deposited due to a fall in the river's velocity and aren't transported very far into the stationary body of water that the river flows into. The foreset bed makes up the majority of the delta and is dipped towards deep water in the direction that the river is flowing in.

The topset bed is, as the name suggests, the topmost bed of the delta. It too is composed of coarse sediment but, unlike the foreset bed, the topset bed doesn't dip, it's horizontally bedded.

Deltas can take on many different shapes. The three primary shapes of delta are *cuspate*, *arcuate* and *bird's foot*.

Arcuate deltas (e.g. The Nile Delta, Egypt) are shaped like a triangle (which is where the term delta comes from, the Greek letter delta Δ) and form when a river meets a sea with alternating current directions that shape the delta so that it looks like a triangle.
Cuspate deltas (e.g. Ebro Delta, Spain) are vaguely shaped like a V with curved sides. Cuspate deltas form when a river flows into a sea with waves that hit it head on, spreading the deposited sediment out.
Bird's foot deltas (e.g. The Mississippi Delta) are shaped like (as the name suggests) a bird's foot. They extend reasonably far into a body of water and form when the river's current is stronger than the sea's waves. Bird's foot

deltas are uncommon because there are very few areas where a sea's waves are weaker than a river's current.

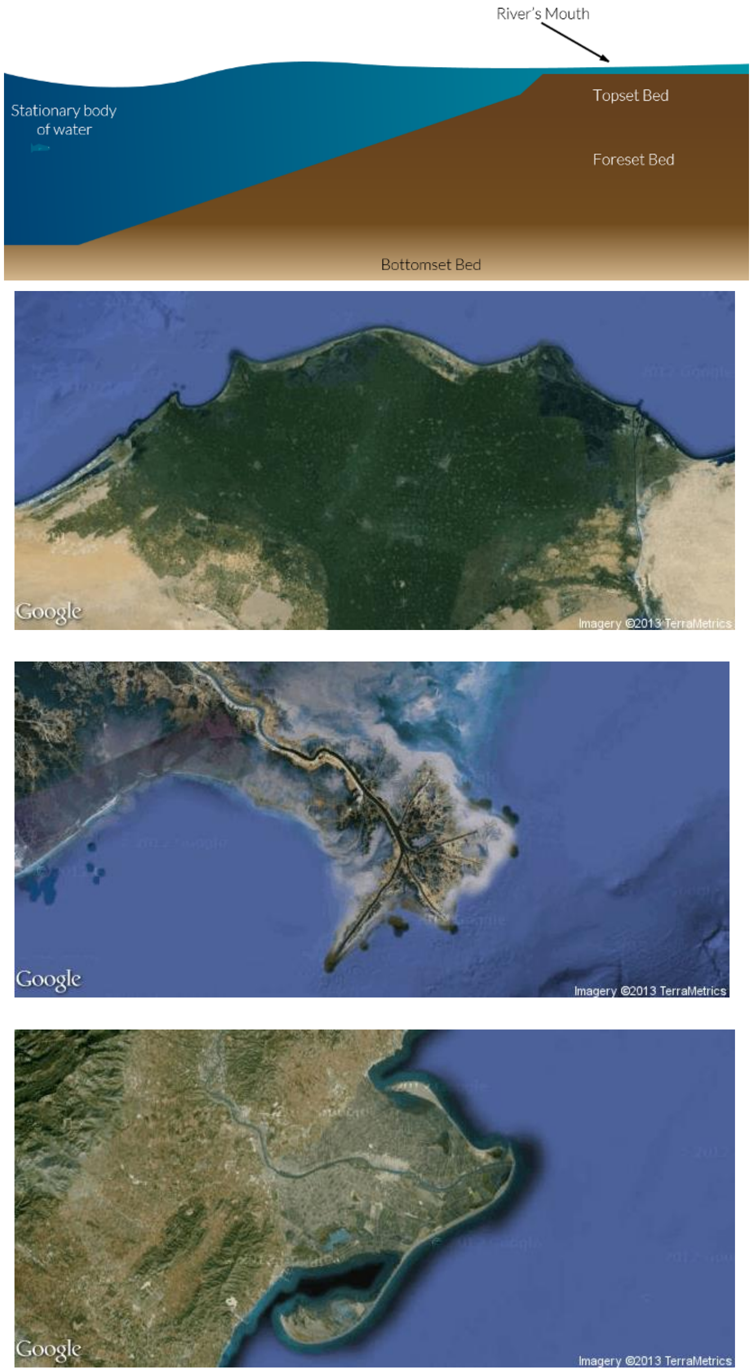


Fig. 88. Different forms of delta