

NIGERIA MARITIME UNIVERSITY

Okerenkoko, Warri South-West, Delta State

Department of Marine Geology

MGY 201

Physical Geology

Lecture Note

Introduction to Physical Geology · Plate Tectonics
Surface Processes · Geological Structures

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Course information

This note covers four parts of MGY 201: an introduction to physical geology, plate tectonics, the surface processes that shape the land and the coast, and geological structures. Earth's internal structure, rocks and the rock cycle, earthquakes, volcanism and geologic time are covered in the other part of the course.

Item	Detail
Course	MGY 201: Physical Geology
Level	200 level, first semester, 2026/2027 session
Department	Marine Geology
Institution	Nigeria Maritime University, Okerenkoko, Warri South-West, Delta State
Lecturer	Dr. Daniel Tuoyo Amiwero
Part covered by this note	Introduction, plate tectonics, surface processes and geological structures

Learning outcomes

At the end of this part of the course, you should be able to:

1. Define physical geology, name its main branches and explain how solar energy, gravity and Earth's internal heat drive geological processes.
2. Summarise the evidence for continental drift and seafloor spreading, and explain the theory of plate tectonics and its driving forces.
3. Describe divergent, convergent and transform plate boundaries and their features, and relate plate tectonics to the geology of Nigeria and the Gulf of Guinea.
4. Explain mechanical and chemical weathering, soil formation and mass wasting, with Nigerian examples.
5. Describe how rivers, groundwater, waves, wind and ice erode, transport and deposit sediment.
6. Apply simple equations for spreading rate, stream discharge, slope stability, groundwater flow and apparent dip.
7. Recognise folds, faults, joints and unconformities, and describe their origin and practical importance.
8. Relate surface processes and structures to the Niger Delta and the Nigerian coast.

Why physical geology matters to a marine geologist

Every grain of sand on a Nigerian beach began as a mineral in a rock far inland. Weathering freed it, rivers carried it, and waves and currents placed it on the shore or the shelf. The Niger Delta, the coastal lagoons and the continental shelf are the end of that journey. The Gulf of Guinea itself opened when Africa and South America drifted apart. A marine geologist who understands plate tectonics, surface processes and structures can read how the basin formed, where its sediment came from, how it moved, and how it was later folded or faulted.

Section 1: Introduction to physical geology

Geology is the science of the Earth: what it is made of, how it works, and how it has changed through time. Physical geology studies the materials of the Earth and the processes that act on and beneath its surface today. Its partner, historical geology, uses those materials and processes to reconstruct the Earth's past.

1.1 The branches of geology

Geology draws on chemistry, physics, biology and mathematics. It has grown into many specialised branches, several of which you will meet in this programme.

Branch	What it studies
Mineralogy	The composition, structure and properties of minerals
Petrology	The origin, composition and texture of rocks
Structural geology	The deformation of rocks: folds, faults and joints
Geomorphology	Landforms and the processes that shape them
Sedimentology	Sediments, their transport and deposition
Stratigraphy	Layered rocks, their order and their correlation
Geophysics	The Earth's physical properties: gravity, magnetism, seismic waves
Geochemistry	The chemistry of the Earth's materials
Hydrogeology	Groundwater and its movement
Engineering geology	Geology applied to construction and ground hazards
Economic geology	Mineral, energy and water resources
Marine geology	The geology of the ocean floor and coasts

1.2 The Earth as a system

The Earth is a set of interacting parts, or spheres:

- **Geosphere:** the solid Earth, from the crust to the core.
- **Hydrosphere:** all water: oceans, rivers, lakes, groundwater and ice.
- **Atmosphere:** the layer of gases around the Earth.
- **Biosphere:** all living things.

Two energy sources drive the system. **Solar energy** powers the atmosphere and the hydrosphere: it evaporates water, drives winds and waves, and so powers weathering and erosion. **Earth's internal heat**, left from the planet's formation and produced by radioactive decay, drives plate motion, mountain building, earthquakes and volcanism. **Gravity** acts on both, pulling rock, water and ice downhill.

This note follows that division. Section 2 explains **plate tectonics**, the theory that links Earth's internal heat to the movement of the outer shell. Sections 3 to 7 cover the **surface processes** powered mainly by the Sun and gravity. Section 8 covers the **geological structures** produced when internal forces deform rocks.

1.3 Uniformitarianism

In the late 18th century James Hutton argued that the processes we see today, such as erosion by rivers and deposition in the sea, also acted in the past and, given enough time, could build and destroy whole landscapes. Charles Lyell later popularised this idea as **uniformitarianism**, often summarised as "the present is the key to the past".

Modern geologists accept that the same physical and chemical laws have always applied, but rates and intensities have varied. Rare, sudden events such as large floods, landslides and meteorite impacts also shape the Earth. The principle still guides interpretation: to understand an ancient delta in the rock record, study the modern Niger Delta.

1.4 How geologists work

Geology is a field science. Geologists observe outcrops, cores and landforms; record measurements; form a hypothesis; and test it with further observations, laboratory analyses and maps. When a hypothesis survives repeated testing it may become a theory, such as plate tectonics. Because the geological record is incomplete, good practice is to keep several working hypotheses open until the evidence rules some out.

1.5 Geology and society

Geology underpins much of the Nigerian economy and daily life:

- **Resources:** crude oil and gas from the Niger Delta, solid minerals such as tin, gold, limestone, barite and iron ore, and groundwater for most households.
- **Hazards:** floods along the Niger and Benue, gully erosion in the south-east, coastal erosion along the Lagos and Ondo coasts, and slope failures on road cuts.
- **Engineering:** foundations, roads, bridges, dams, jetties and dredged channels all depend on ground conditions.
- **Environment:** pollution of soils, rivers and groundwater, and the effects of sea-level rise on the delta.

1.6 Key points of Section 1

- Physical geology studies Earth materials and present-day processes.
- Solar energy and gravity drive surface processes; internal heat drives deformation and volcanism.
- Uniformitarianism lets us read the past from processes we can observe today.

Section 2: Plate tectonics

Plate tectonics is the unifying theory of geology. It states that the Earth's rigid outer shell is broken into large plates that move slowly over a weaker layer beneath. Most earthquakes, volcanoes, mountain belts and ocean basins form where plates meet. The theory also explains how the Gulf of Guinea opened and why the Niger Delta and the Benue Trough exist.

2.1 From continental drift to plate tectonics

In 1915 the German scientist Alfred Wegener published his hypothesis of **continental drift**. He proposed that the continents had once formed a single supercontinent, **Pangaea**, which later broke apart. His evidence was:

- **The fit of the continents.** The coastlines of South America and Africa fit together like puzzle pieces. The fit is even better when the edges of the continental shelves, rather than the present coastlines, are matched.
- **Fossils.** Fossils of the same freshwater and land animals, such as the small reptile *Mesosaurus*, and of the same plants, the *Glossopteris* flora, occur on continents now separated by wide oceans. These organisms could not have crossed an ocean.
- **Rocks and mountain belts.** Rock types, ages and mountain belts on one side of the Atlantic continue on the other when the continents are brought together.
- **Ancient climates.** Glacial deposits of late Palaeozoic age occur in Africa, India, South America and Australia, regions now far apart and partly tropical. They make sense only if the continents were once grouped near the South Pole.

Most geologists rejected the idea because Wegener could not explain what force moved the continents. Evidence from the ocean floor, gathered mainly after the Second World War, revived it:

- **Mid-ocean ridges:** a continuous chain of submarine mountains, more than 60,000 km long, with a central rift valley, high heat flow and shallow earthquakes.
- **Deep-sea trenches:** long, narrow troughs, more than 10 km deep in places, associated with deep earthquakes and chains of volcanoes.
- **Young ocean floor:** no ocean crust is older than about 200 million years, far younger than the continents.
- **Magnetic stripes:** bands of rock magnetised in normal and reversed directions run parallel to the ridges, mirrored on each side (Section 2.5).

In 1962 Harry Hess proposed **seafloor spreading**: new ocean crust forms at mid-ocean ridges and moves away on both sides. In 1963 Fred Vine and Drummond Matthews showed that the magnetic stripes record this spreading. By the late 1960s these ideas had been combined into the theory of plate tectonics.

2.2 Lithosphere and asthenosphere

Plate tectonics divides the outer Earth by **strength**, not by composition:

- The **lithosphere** is the rigid outer layer, made of the crust and the uppermost mantle. It is about 100 km thick on average: thin at mid-ocean ridges, and up to 200 km or more beneath old continents.
- The **asthenosphere** lies below it and extends to a depth of a few hundred kilometres. It is hot and weak, and a small fraction may be molten, so it can flow slowly. The plates move over it.

The crust on top of the lithosphere is of two kinds:

Property	Oceanic crust	Continental crust
Typical thickness	About 7 km	About 35 km; up to 70 km under mountains
Composition	Basalt and gabbro (mafic)	Granite-like rocks on average (felsic)

Property	Oceanic crust	Continental crust
Density	About 3.0 g/cm^3	About 2.7 g/cm^3
Maximum age	About 200 million years	Up to about 4 billion years

Because oceanic lithosphere is denser, it sinks back into the mantle where plates converge. Continental lithosphere is too buoyant to sink far, which is why the continents preserve very old rocks.

2.3 The plates

The lithosphere is divided into about seven large plates (the Pacific, North American, South American, Eurasian, African, Antarctic and Indo-Australian plates) and a number of smaller ones, such as the Nazca, Cocos, Caribbean, Philippine Sea, Arabian and Scotia plates. Most plates carry both oceanic and continental lithosphere.

Plates move at a few centimetres per year, about as fast as fingernails grow. The Atlantic widens by roughly 2 to 4 cm each year; parts of the East Pacific Rise spread more than 10 cm per year.

Nigeria lies well inside the **African Plate**, far from any active plate boundary. This is why the country has few earthquakes, although small tremors do occur, such as those felt in parts of Abuja in 2018.

2.4 Plate boundaries

Plates interact along three types of boundary (Figure 2.1).

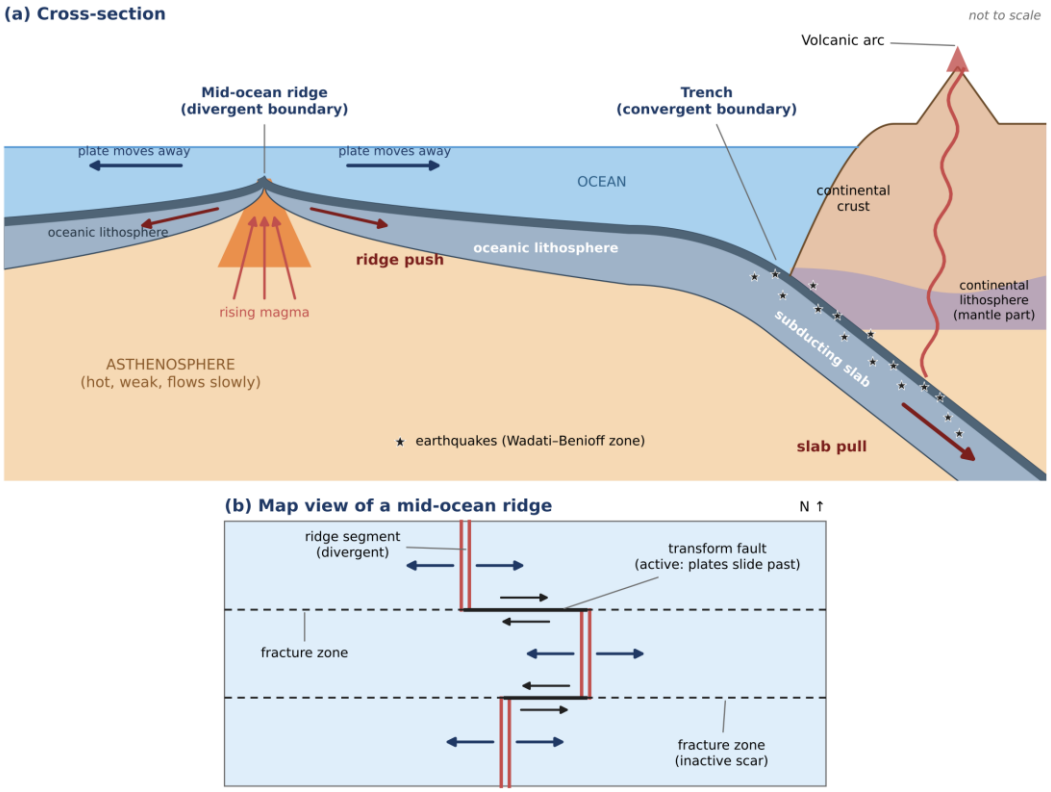


Figure 2.1. Plate boundaries. (a) Cross-section showing a divergent boundary at a mid-ocean ridge and a convergent boundary where oceanic lithosphere is subducted beneath a continent. (b) Map view of a ridge offset by transform faults.

Divergent boundaries form where plates move apart under tension. Magma rises from the mantle to fill the gap and creates new lithosphere.

- In the oceans they form **mid-ocean ridges**, such as the Mid-Atlantic Ridge, with basaltic volcanism and shallow earthquakes.
- On continents they form **rift valleys**, such as the East African Rift. If rifting continues, the continent splits and a new ocean opens, as the Red Sea is doing today.

Convergent boundaries form where plates move towards each other. They are the sites of the largest earthquakes and of explosive volcanoes.

- **Ocean–continent:** the denser oceanic plate is **subducted** beneath the continent, forming a deep-sea **trench** and a chain of volcanoes on the continent, as in the Andes.
- **Ocean–ocean:** one oceanic plate is subducted beneath another, forming a trench and a curved chain of volcanic islands called an **island arc**, as in Japan and the Mariana Islands.
- **Continent–continent:** when an ocean between two continents closes completely, neither continent sinks. The crust is thickened, folded and thrust into high mountains, as in the Himalaya, where India has collided with Asia.

Earthquakes at subduction zones occur along a sloping band that follows the descending plate down to about 700 km. This is the **Wadati–Benioff zone**.

Transform boundaries form where plates slide past each other horizontally, under shear. Lithosphere is neither created nor destroyed. Most transform faults offset segments of mid-ocean ridges (Figure 2.1b). Some cross continents, such as the San Andreas Fault in California. In the equatorial Atlantic, long transform faults and their inactive extensions, called **fracture zones**, such as the Romanche and Chain fracture zones, run towards the Gulf of Guinea.

Boundary	Plate motion	Stress	Main features	Examples
Divergent	Apart	Tension	Mid-ocean ridges, rift valleys, basaltic volcanism, shallow earthquakes	Mid-Atlantic Ridge, East African Rift, Red Sea
Convergent	Together	Compression	Trenches, volcanic arcs, island arcs, fold mountains, deep earthquakes	Andes, Japan, Himalaya
Transform	Side by side	Shear	Strike-slip faults, offset ridges, shallow earthquakes	San Andreas Fault, Romanche Fracture Zone

2.5 Seafloor spreading and palaeomagnetism

When basaltic lava cools at a mid-ocean ridge, its magnetite grains record the direction of the Earth's magnetic field at that time. The Earth's field has reversed its polarity many times: compasses would have pointed south during **reversed** periods. As new crust forms and moves away from the ridge on both sides, it carries a record of these reversals as parallel bands of normally and reversedly magnetised rock. The pattern on one side of the ridge is a mirror image of the pattern on the other (Figure 2.2).

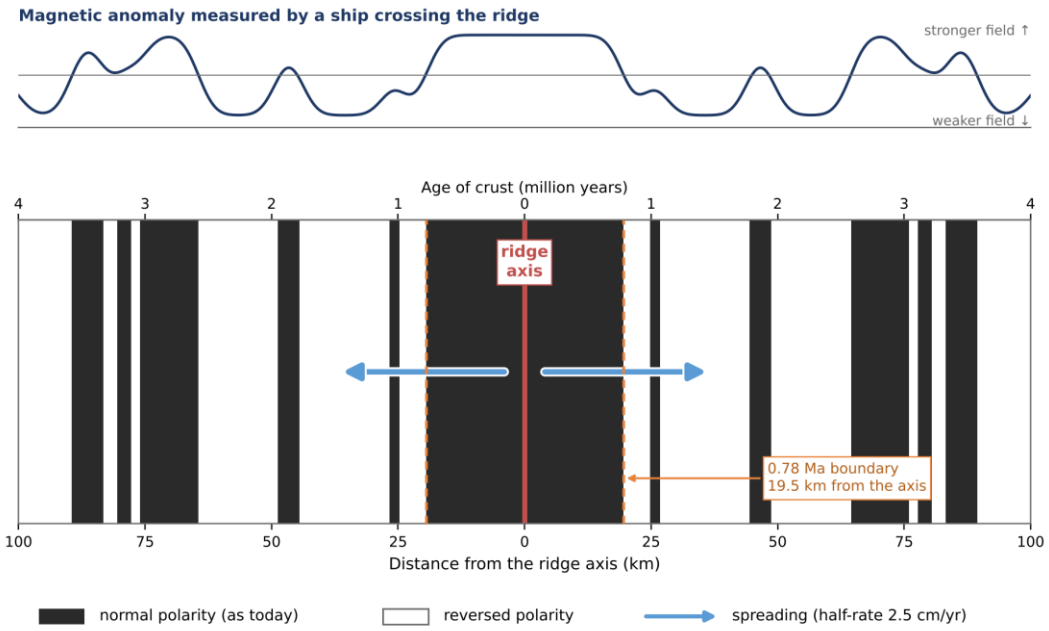


Figure 2.2. Magnetic stripes on the ocean floor. New crust forms at the ridge and records the magnetic field as it cools; the stripes are symmetrical about the ridge and grow older away from it.

Because the ages of the reversals are known from dated lava flows on land, the stripes give the age of the ocean floor and the rate of spreading. The spreading rate (v) is the distance (d) from the ridge axis to a stripe of known age, divided by that age (t):

$$v = \frac{d}{t}$$

A useful conversion is that 1 km per million years equals 1 mm per year.

Worked example. The most recent reversal, the Brunhes–Matuyama boundary, is about 0.78 million years old. At one ridge it lies 19.5 km from the axis.

$$v = \frac{19.5\ \text{km}}{0.78\ \text{Myr}} = 25\ \text{km/Myr} = 25\ \text{mm/yr} = 2.5\ \text{cm/yr}$$

This is the rate on one side of the ridge, the **half-spreading rate**. The two plates are separating at twice this rate, 5 cm per year.

Other evidence confirms seafloor spreading. Deep-sea drilling shows that sediments on the ocean floor get thicker and older away from the ridges. Heat flow is highest at the ridges. Lines of volcanic islands over **hot spots**, such as the Hawaiian–Emperor chain, become older in the direction of plate motion.

2.6 What drives the plates?

The ultimate energy source is the Earth's internal heat. Three forces act on the plates:

- **Slab pull:** the cold, dense edge of a subducting plate sinks into the mantle and pulls the rest of the plate after it. This is thought to be the strongest force, which is why plates attached to long subduction zones, such as the Pacific Plate, move fastest.
- **Ridge push:** newly formed lithosphere at a ridge stands high and slides down and away from the ridge under gravity.

- **Mantle convection:** slow movement of hot mantle rock rising and cooler rock sinking. It carries heat out of the Earth and is linked to the motion of the plates, but how much it drives them directly is still debated.

2.7 The Wilson cycle

J. Tuzo Wilson recognised that ocean basins open and close in a repeating cycle, now called the **Wilson cycle**:

1. **Continental rifting:** a continent stretches and splits along a rift valley (East African Rift).
2. **Young ocean:** a narrow sea floored by new oceanic crust forms (Red Sea, Gulf of Aden).
3. **Mature ocean:** the ocean widens, with a mid-ocean ridge and passive margins on both sides (Atlantic Ocean).
4. **Closing ocean:** subduction begins at the margins and the ocean shrinks (Pacific Ocean).
5. **Collision:** the ocean closes and the continents collide to form a mountain belt (Himalaya).

The cycle explains why ancient mountain belts often mark the sites of former oceans.

2.8 Plate tectonics and the geology of Nigeria

The geology of Nigeria records two major plate tectonic events:

- **The Pan-African orogeny (about 600 million years ago).** Nigeria lies in a belt of rocks that was deformed, metamorphosed and intruded by granites when the West African Craton collided with the region to its east during the assembly of the supercontinent Gondwana. The Nigerian basement complex, with its gneisses, schist belts and Older Granites, is the product of this collision.
- **The break-up of Gondwana (Cretaceous, from about 130 million years ago).** As Africa and South America separated, the South Atlantic opened from the south, and the equatorial Atlantic opened along long transform faults. The **Benue Trough** formed as a rift basin at this time. In a widely cited model, Burke, Dessauvagie and Whiteman (1971) interpreted the Gulf of Guinea region as a rift **triple junction**: two arms opened into oceans, while the third, the Benue Trough, stopped spreading and became a sediment-filled **failed arm** (Figure 2.3).

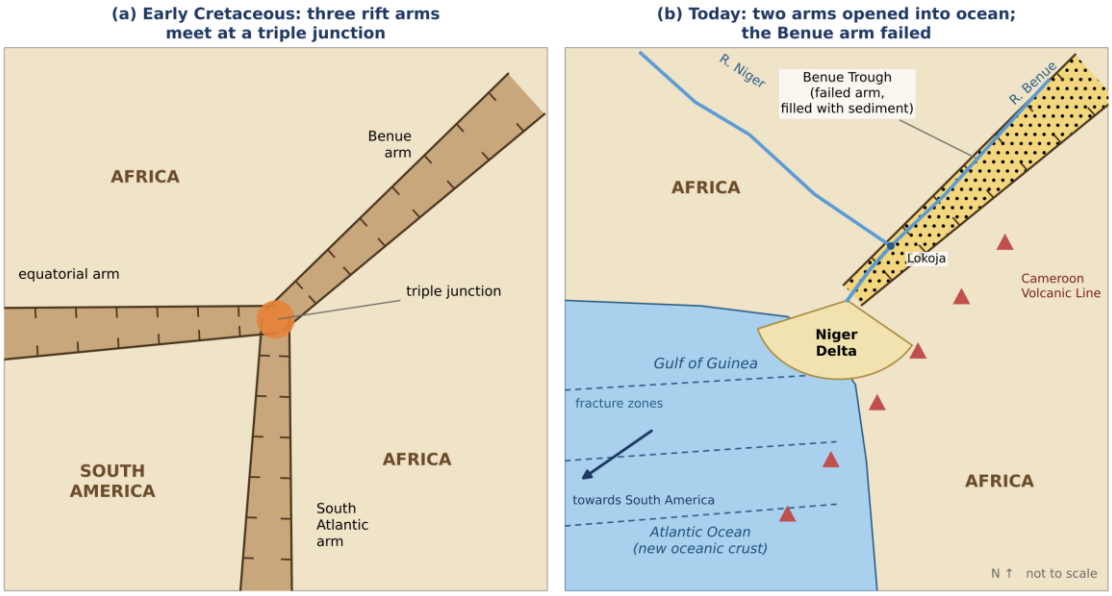


Figure 2.3. A simplified model of the triple junction in the Gulf of Guinea, after Burke, Dessauvagie and Whiteman (1971). Two rift arms opened into the Atlantic; the third, the Benue Trough, failed and filled with sediment. The Niger Delta has built out over the junction.

Later events followed from this setting. In the Santonian (Late Cretaceous), compression folded and uplifted the sediments of the Benue Trough to form the Abakaliki Anticlinorium (Section 8.3). From the early Tertiary onwards, the Niger and Benue rivers carried huge volumes of sediment to the junction, building the **Niger Delta** out over the young oceanic crust of the Gulf of Guinea. The weight of this sediment and its movement towards the sea created the growth faults that trap much of Nigeria's oil and gas (Section 8.4).

The **Cameroon Volcanic Line**, a chain of volcanoes that runs from islands in the Gulf of Guinea through Mount Cameroon into the Nigeria–Cameroon border region, is another expression of plate processes beneath this region. Its origin is still debated.

2.9 Key points of Section 2

- The lithosphere is broken into rigid plates that move over the weak asthenosphere at a few centimetres per year.
- Plates move apart at divergent boundaries, together at convergent boundaries, and past each other at transform boundaries.
- Magnetic stripes, the age of the ocean floor and hot-spot chains confirm seafloor spreading; spreading rate equals distance divided by age.
- Nigeria's basement formed in the Pan-African collision; the Benue Trough, the Gulf of Guinea and the Niger Delta formed during and after the break-up of Gondwana.

Section 3: Weathering and soils

Surface processes break down rocks, move the fragments and lay them down as sediment. They are powered by the Sun, which drives the movement of water and air, and by gravity. This section introduces the water cycle that links them and the first step in the chain, weathering.

3.1 The hydrologic cycle

Water moves continuously between the oceans, the atmosphere and the land (Figure 3.1). Water evaporates from the sea and from land, and plants release water by **transpiration**. The vapour condenses into clouds and falls as **precipitation**. On land, part of it soaks into the ground (**infiltration**) to become groundwater, part flows over the surface as **runoff** into streams, and part returns to the air. Rivers and groundwater eventually carry it back to the sea.

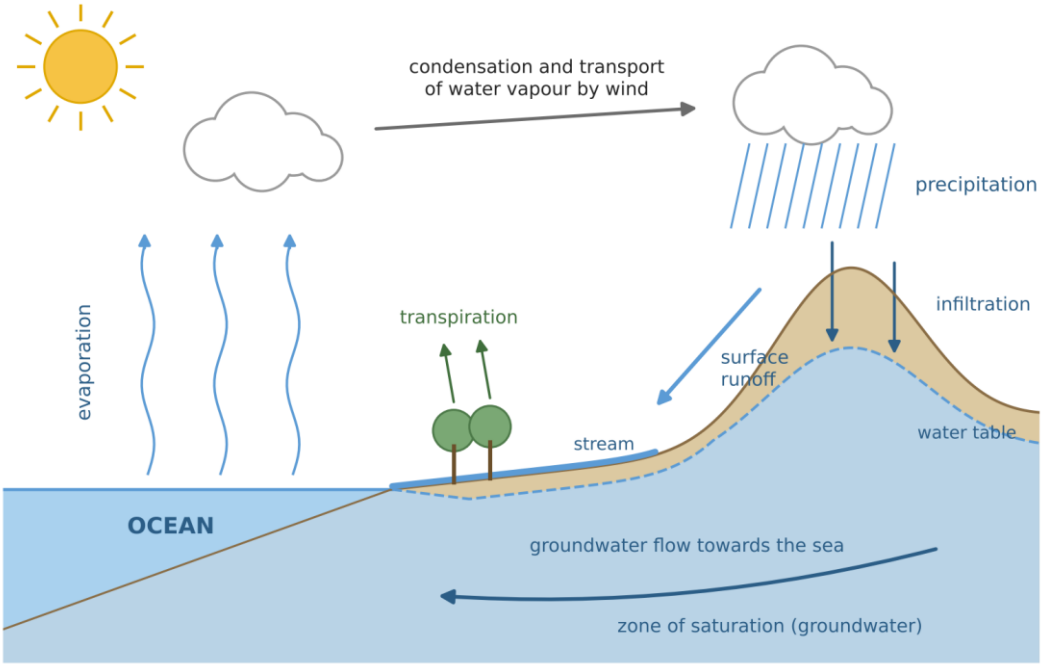


Figure 3.1. The hydrologic cycle. Arrows show the main transfers of water between the ocean, the atmosphere and the land.

About 97% of the Earth's water is in the oceans, about 2% is locked in ice, and about 1% is groundwater. Lakes, rivers, soil moisture and the atmosphere together hold less than 0.1%. Yet that small, fast-moving fraction does most of the geological work on land.

3.2 Weathering and erosion

Weathering is the physical breakdown and chemical decomposition of rock at or near the Earth's surface, in place. **Erosion** is the removal and transport of the weathered material by water, wind, ice or gravity. Weathering prepares rock for erosion: it turns hard bedrock into loose fragments and dissolved ions.

There are two kinds of weathering, which usually act together:

- **Mechanical (physical) weathering** breaks rock into smaller pieces without changing its minerals.
- **Chemical weathering** changes the minerals into new ones or dissolves them.

3.3 Mechanical weathering

Frost wedging. Water expands by about 9% when it freezes. Repeated freezing in cracks pries rock apart. It is important in cold climates and high mountains, but not in Nigeria.

Unloading and exfoliation. Rock that formed deep underground expands as the overlying rock is eroded away. It cracks into curved sheets parallel to the surface, which peel off like the layers

of an onion. This process forms the rounded granite domes and inselbergs of the Nigerian basement, such as Olumo Rock (Abeokuta), Zuma Rock (near Abuja) and the Idanre Hills.

Thermal expansion. Daily heating and cooling expand and contract the surface of a rock. On its own its effect is debated, but it helps break rock in hot deserts, especially where moisture is present.

Salt crystal growth. Salt crystals growing from evaporating water in pores and cracks can break rock apart. It is common along coasts and in dry regions, and it damages concrete and building stone near the sea.

Biological activity. Roots grow into cracks and widen them. Burrowing animals bring fresh material to the surface.

Mechanical weathering greatly increases the surface area on which chemical weathering can act. A cube of side a has a surface area of $6a^2$. If it is cut into n^3 smaller cubes, each of side a/n, the total surface area becomes:

$$A = n^3 \times 6\left(\frac{a}{n}\right)^2 = n \times 6a^2$$

Worked example. A 1 cm cube has a surface area of 6 cm^2. Cut into 8 cubes of 0.5 cm ($n = 2$), the area doubles to 12 cm^2. Cut into 1,000 cubes of 1 mm ($n = 10$), it rises to 60 cm^2. Fine-grained or highly fractured rock therefore weathers chemically much faster.

3.4 Chemical weathering

Water is the key agent of chemical weathering, especially when it is slightly acidic. Rainwater dissolves carbon dioxide from the air and from the soil to form carbonic acid:

$$\mathrm{CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-}$$

Four main processes follow.

Dissolution. Some minerals dissolve completely. Halite dissolves in pure water. Calcite, the main mineral of limestone, dissolves in carbonic acid:

$$\mathrm{CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2\,HCO_3^-}$$

This reaction forms caves and sinkholes in limestone regions (Section 6.6).

Hydrolysis. Hydrogen ions replace the cations in silicate minerals, breaking them down to clay minerals. This is the most important weathering reaction for the common silicates. Potassium feldspar weathers to kaolinite:

$$\mathrm{2\,KAlSi_3O_8 + 2\,H^+ + 9\,H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2\,K^+ + 4\,H_4SiO_4}$$

The potassium and silica are carried away in solution. The kaolinite remains as clay. This is how the granites and gneisses of the Nigerian basement weather to sandy clay and kaolin.

Oxidation. Iron released from minerals such as olivine, pyroxene and biotite combines with oxygen to form red and brown iron oxides and hydroxides:

$$\mathrm{4\,Fe^{2+} + O_2 + 4\,H_2O \rightarrow 2\,Fe_2O_3 + 8\,H^+}$$

Haematite (Fe_2O_3) gives tropical soils and laterites their red colour; goethite ($FeO(OH)$) gives yellow and brown colours.

Hydration. Water is taken into a mineral's structure. Anhydrite becomes gypsum:

$$CaSO_4 + 2\,H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

3.5 Which minerals weather fastest?

S. S. Goldich showed in 1938 that the common silicates weather in roughly the reverse of the order in which they crystallise from magma (Figure 3.2). Minerals that form at high temperatures, such as olivine and calcium-rich plagioclase, are least stable at the cool, wet Earth's surface and weather first. Quartz, which forms last and at the lowest temperature, is the most resistant.

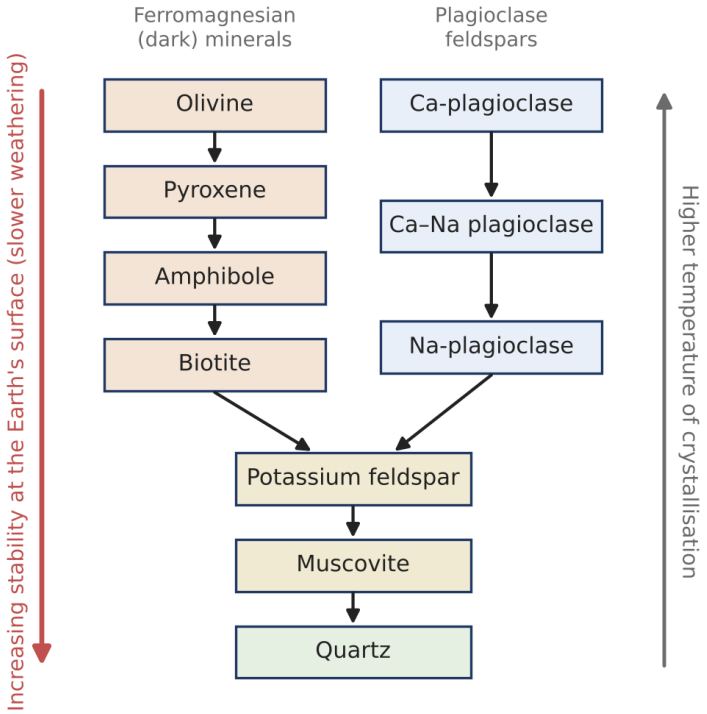


Figure 3.2. The Goldich weathering series. Minerals at the top weather fastest; quartz at the bottom is the most stable at the Earth's surface.

This explains why beach and river sands, including most sands of the Niger Delta, are rich in quartz: the less stable minerals have been weathered away on the journey from the source rock.

3.6 Controls on the rate of weathering

- **Rock type and mineralogy:** limestone dissolves; quartzite resists. Rocks rich in olivine and pyroxene weather faster than granite.
- **Fractures and joints:** they let water in and increase surface area (Section 8.5).
- **Climate:** chemical weathering is fastest where it is hot and wet. In southern Nigeria, weathered profiles over basement rocks can be tens of metres thick. Mechanical weathering dominates in cold or dry climates.
- **Topography and vegetation:** steep slopes remove weathered material quickly; vegetation supplies organic acids and holds soil in place.
- **Time:** the longer rock is exposed, the deeper the weathering.

When neighbouring rocks weather at different rates, the result is **differential weathering**. Resistant granite domes stand above surrounding plains of more easily weathered gneiss, producing the inselberg landscapes of south-western and north-central Nigeria.

3.7 Soils

Regolith is the layer of loose weathered material over bedrock. **Soil** is the upper part of the regolith that contains organic matter and supports plant growth. Five factors control soil formation: parent material, climate, organisms, relief (slope) and time.

A mature soil develops layers called **horizons** (Figure 3.3):

- **O horizon:** leaf litter and humus at the surface.
- **A horizon (topsoil):** dark mix of mineral grains and humus; most biological activity.
- **E horizon:** a pale zone from which water has washed out clay, iron and aluminium (**eluviation**). Not present in all soils.
- **B horizon (subsoil):** the zone where washed-down clay and iron oxides accumulate (**illuviation**).
- **C horizon:** partly weathered parent rock.
- **R:** unweathered bedrock.

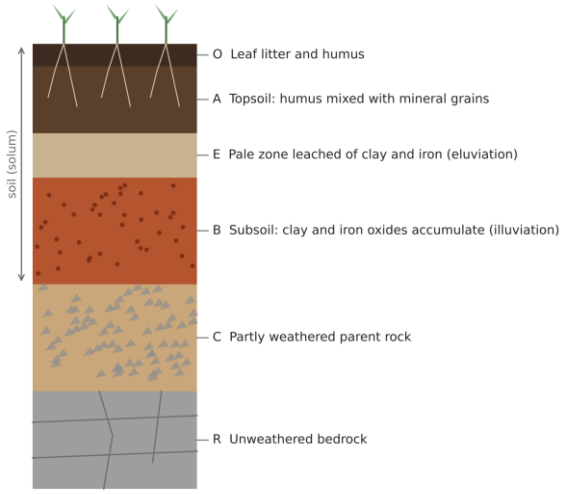


Figure 3.3. An idealised soil profile with its horizons.

Laterites. In the hot, wet tropics, intense leaching removes silica, calcium, sodium and potassium, and leaves iron and aluminium oxides behind. The result is **laterite**: a red, iron-rich soil that can harden into an ironstone crust (ferricrete) when exposed and dried. Laterite is widely used in Nigeria as road base and fill. Where the parent rock is rich in aluminium and leaching is extreme, **bauxite**, the ore of aluminium, forms.

Soil erosion. Where vegetation is removed, rain splash and runoff strip the soil. Erosion begins as thin **sheet erosion**, cuts small channels called **rills**, and can grow into deep **gullies**. The gully systems of south-eastern Nigeria, such as those around Agulu and Nanka in Anambra State, have formed in deeply weathered, poorly consolidated sandy formations. They destroy farmland, roads and homes.

3.8 Key points of Section 3

- Weathering breaks rock down in place; erosion carries the products away.

- Mechanical weathering increases surface area; chemical weathering changes minerals, mainly by hydrolysis, oxidation and dissolution.
- In the humid tropics chemical weathering dominates and produces deep, red, lateritic soils.

Section 4: Mass wasting

Mass wasting is the downslope movement of rock, regolith and soil under the direct pull of gravity. It ranges from imperceptible creep to catastrophic rock avalanches. Mass wasting moves weathered material from slopes into streams, which then carry it away.

4.1 What controls slope stability

Every slope is a balance between forces that drive material downhill and forces that resist movement. Gravity provides the driving force. Friction and cohesion between grains provide the resistance.

The **factor of safety** compares the two:

$$F = \frac{\text{resisting forces}}{\text{driving forces}}$$

A slope with $F > 1$ is stable; failure occurs when F falls to 1 or below. For a long slope in dry, cohesionless material such as sand, the factor of safety reduces to:

$$F = \frac{\tan\phi}{\tan\beta}$$

Here ϕ is the **angle of internal friction** of the material and β is the slope angle. For dry sand, ϕ is close to the **angle of repose**, the steepest angle at which loose material stands, usually about 30° to 37°.

Worked example. A dry sand slope has $\phi = 35°$ and a slope angle $\beta = 30°$.

$$F = \frac{\tan 35°}{\tan 30°} = \frac{0.700}{0.577} = 1.21$$

The slope is stable. If it is steepened to 35°, F falls to 1.0 and the slope is on the point of failure.

Factors that reduce stability:

- **Water.** Rain fills pore spaces and raises **pore water pressure**, which pushes grains apart and reduces friction. Most landslides happen during or after heavy rain. (A little water helps cohesion, which is why damp sand holds a steeper slope than dry or saturated sand.)
- **Oversteepening.** Rivers undercut their banks, waves undercut cliffs, and road cuts and excavations steepen slopes.
- **Removal of vegetation.** Roots bind soil and plants remove water. Clearing land for farming or building reduces stability.
- **Weak layers.** Clay beds, weathered zones and joints dipping out of a slope provide surfaces along which failure can occur.
- **Triggers.** Heavy rainfall, earthquakes, vibration from blasting or traffic, and added load from buildings or fill.

4.2 Types of mass movement

Mass movements are classified by the material involved (rock, debris or earth), the type of movement (fall, slide or flow), and the speed (Figure 4.1).

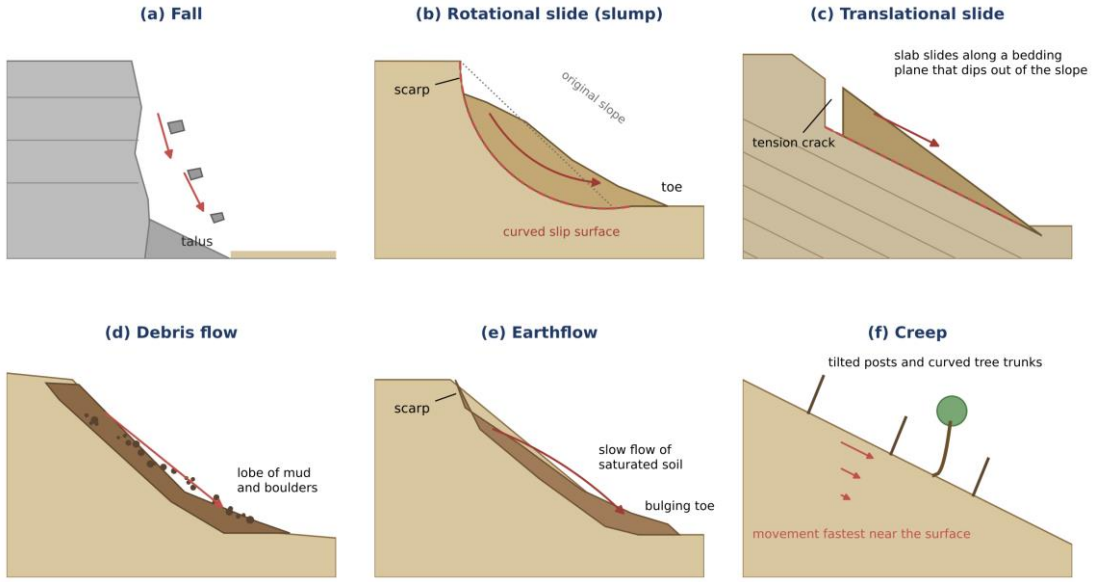


Figure 4.1. The main types of mass movement, shown in cross-section.

- **Fall:** blocks of rock break from a cliff and fall freely, collecting as **talus** (scree) at the base. Common on steep road cuts and sea cliffs.
- **Slide:** material moves as a coherent mass along a surface of failure.
  - **Rotational slide (slump):** movement on a curved, spoon-shaped surface. The block rotates backwards, leaving a scarp at the top and a bulging toe. Common in thick clay and weathered soils, and on riverbanks.
  - **Translational slide:** movement along a planar surface such as a bedding plane or joint that dips out of the slope.
- **Flow:** material moves as a viscous fluid.
  - **Debris flow and mudflow:** fast-moving mixtures of water, mud and rock that follow valleys after intense rain.
  - **Earthflow:** slower flow of saturated fine-grained soil on hillslopes.
- **Creep:** very slow downslope movement of soil, a few millimetres to centimetres per year. It is revealed by tilted fences, poles, walls and trees with curved trunks.

4.3 Mass wasting in Nigeria and its control

Nigeria's mass movement problems are mostly linked to deep tropical weathering and intense rainfall:

- **Gully erosion and slope failure** in the south-east, where gully walls in loose sands repeatedly slump and collapse, enlarging the gullies.
- **Riverbank failure** along the Niger, the Benue and the creeks of the Niger Delta, where banks of soft silt and clay are undercut by currents and boat wash.
- **Failures of road cuts** in weathered basement rocks and sedimentary formations.

Engineering geologists reduce the risk by improving drainage, regrading slopes to gentler angles, building retaining walls, planting vegetation, and keeping buildings away from unstable slopes and gully heads.

4.4 Key points of Section 4

- Mass wasting is downslope movement under gravity; water is the main trigger.
- The factor of safety compares resisting and driving forces; failure occurs when it falls to 1.
- Movements are classified as falls, slides, flows and creep.

Section 5: Running water

Rivers are the most important agents of erosion on land. They carry most of the sediment that reaches the sea, and they build floodplains and deltas. The Niger, which flows about 4,200 km from the Guinea Highlands to the Gulf of Guinea, and its main tributary the Benue, which joins it at Lokoja, have built the Niger Delta.

5.1 Drainage basins and drainage patterns

A **drainage basin** (catchment) is the area of land that supplies water to a stream and its tributaries. It is separated from neighbouring basins by a **divide**, a line of high ground. Small streams join to form larger ones. In the Strahler system of **stream order**, the smallest headwater streams are first order; two first-order streams join to form a second-order stream, and so on.

The layout of streams in a basin, its **drainage pattern**, reflects the underlying geology (Figure 5.1):

- **Dendritic:** tree-like branching on rocks of uniform resistance, such as flat-lying sediments or massive granite. The most common pattern.
- **Radial:** streams flow outward from a central high point, such as a volcano or dome.
- **Rectangular:** streams follow right-angled joints or faults, with sharp bends.
- **Trellis:** long parallel main streams in the valleys of folded rocks, joined at right angles by short tributaries.

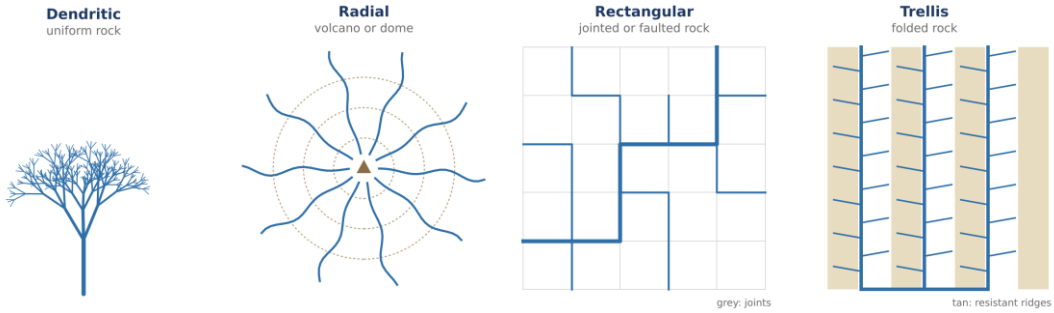


Figure 5.1. The four main drainage patterns and the geology that produces them.

5.2 Streamflow

Water in a channel flows faster in the middle and near the surface, and slower along the bed and banks, where friction is greatest. Most river flow is **turbulent**, with eddies that lift sediment from the bed.

The amount of water a stream carries is its **discharge**, Q: the volume passing a point per unit time, in cubic metres per second (m^3/s).

$$Q = A \times v = w \times d \times v$$

Here A is the cross-sectional area of the channel, w is its width, d its average depth and v the average velocity.

Worked example. A channel is 20 m wide and 2 m deep on average, and the water flows at 1.5 m/s.

$$Q = 20 \times 2 \times 1.5 = 60 \text{ m}^3/\text{s}$$

If the discharge stays the same where the channel narrows to 15 m at the same depth, the velocity must rise to $60/(15 \times 2) = 2$ m/s.

Downstream, discharge, width, depth and velocity generally increase, while the **gradient** (the slope of the channel) decreases. Large lowland rivers flow faster than many people expect because their deep, smooth channels lose less energy to friction.

5.3 Erosion, transport and deposition

A stream carries its **load** in three ways:

- **Dissolved load:** ions in solution from chemical weathering and groundwater.
- **Suspended load:** fine silt and clay kept up by turbulence. It makes rivers like the Niger brown in the rainy season.
- **Bed load:** sand and gravel that roll, slide or bounce (**saltation**) along the bed.

Competence is the largest particle a stream can move; it rises sharply with velocity. **Capacity** is the total load it can carry; it rises with discharge.

The relationship between grain size and the velocity needed to erode, transport and deposit sediment is shown by the **Hjulström diagram** (Figure 5.2). Two features are important:

1. Fine sand (about 0.1 to 0.5 mm) is the easiest sediment to erode.
2. Clay and fine silt need higher velocities to erode than sand, because the tiny particles stick together (cohesion) and form a smooth bed. Once lifted, however, they stay in suspension even in very slow water.

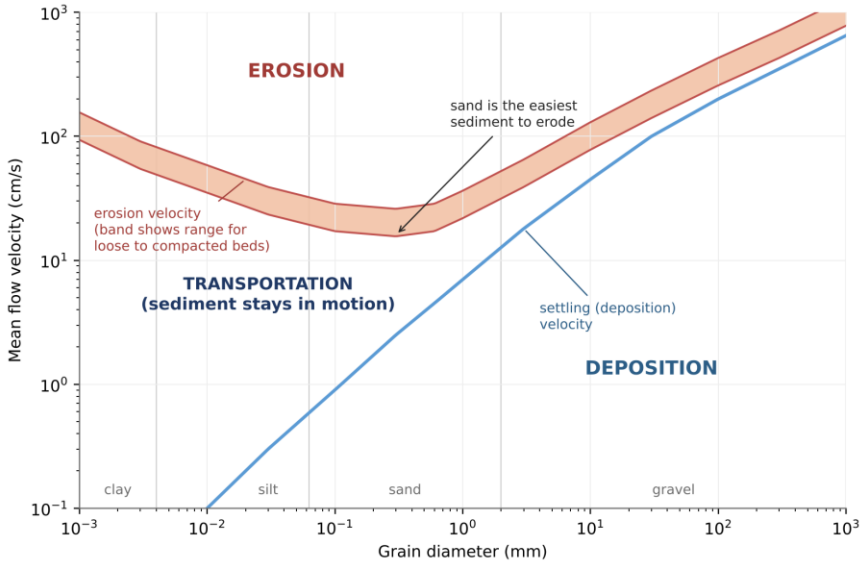


Figure 5.2. A simplified Hjulström diagram, after Hjulström (1935). Both axes are logarithmic; the curves are approximate.

5.4 Base level and the graded stream

Base level is the lowest level to which a stream can erode its channel. **Sea level** is the ultimate base level. Lakes, reservoirs and bands of resistant rock act as **local** base levels.

A stream adjusts its gradient, channel and load so that, over time, it just carries the sediment supplied to it, neither eroding nor depositing overall. Such a stream is **graded**. If base level falls, for example when sea level drops during an ice age, the stream cuts down and forms valleys and terraces. If base level rises, the stream deposits sediment and builds up its valley. The valleys cut across the Nigerian continental shelf during low sea levels of the last glacial period were later flooded and filled as the sea rose.

5.5 Channel types and floodplains

- **Straight channels** are rare and short; they usually follow faults or joints.
- **Meandering channels** wind in loops across a wide floodplain. They are typical of low-gradient rivers carrying mainly fine sediment.
- **Braided channels** split into many interlacing channels around bars of sand and gravel. They form where the load is coarse and abundant and discharge varies widely.

In a **meander**, the fastest water swings to the outside of each bend, eroding the **cut bank**. On the inside of the bend, slower water deposits sand as a **point bar** (Figure 5.3). The meander therefore migrates sideways and downstream. When two bends erode towards each other, the river cuts through the narrow **neck**, abandoning the loop as a crescent-shaped **oxbow lake**.

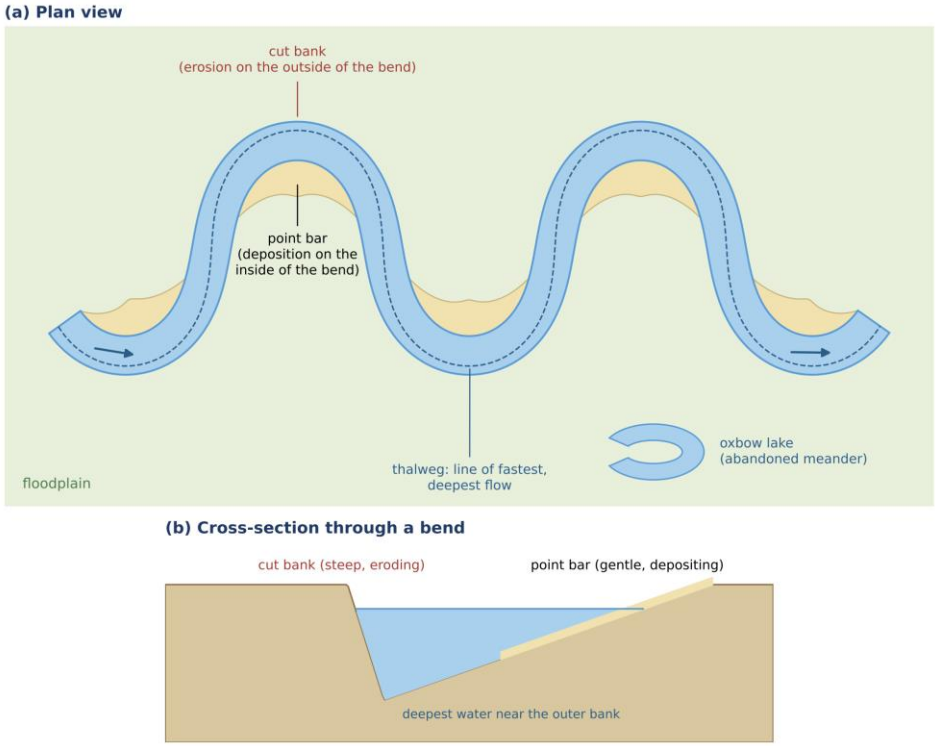


Figure 5.3. Features of a meandering river, in plan view and in cross-section through a bend.

When a river overflows its banks, the water slows as it spreads out. The coarsest sediment is dropped at the edge of the channel, building ridges called **natural levees**. Finer silt and clay settle farther away in **backswamps**. The flat land built by repeated flooding is the **floodplain**. The great floods of 2012 and 2022 along the Niger and Benue spread over these floodplains, affecting millions of people.

5.6 Deltas

Where a river enters a standing body of water, its velocity drops and it deposits its load as a **delta**. The river divides into **distributaries** that spread sediment across the delta. A delta has three parts:

- **Delta plain:** the low-lying land with distributary channels, levees, swamps and, near the sea, tidal creeks and mangroves.
- **Delta front:** the shallow zone where the river meets the sea, with mouth bars and beaches.
- **Prodelta:** the deeper, gently sloping zone where fine mud settles.

The shape of a delta depends on the balance between three processes: the supply of sediment by the river, the reworking of sediment by waves, and the redistribution of sediment by tides (Figure 5.4).

- **River-dominated deltas** build long, finger-like distributaries into the sea. The Mississippi is the classic example.
- **Wave-dominated deltas** have smooth, arcuate shorelines of beach ridges, because waves spread sediment along the coast. The São Francisco (Brazil) is an example.
- **Tide-dominated deltas** have funnel-shaped estuaries and elongate sand bars aligned with tidal currents. The Ganges–Brahmaputra is an example.

The **Niger Delta** lies between the wave- and tide-dominated end members. Waves build a smooth, arcuate shoreline of sandy barrier islands, while tides cut a dense network of creeks and estuaries behind them, fringed by mangroves. Okerenkoko itself sits within this tidal creek network of the western delta.

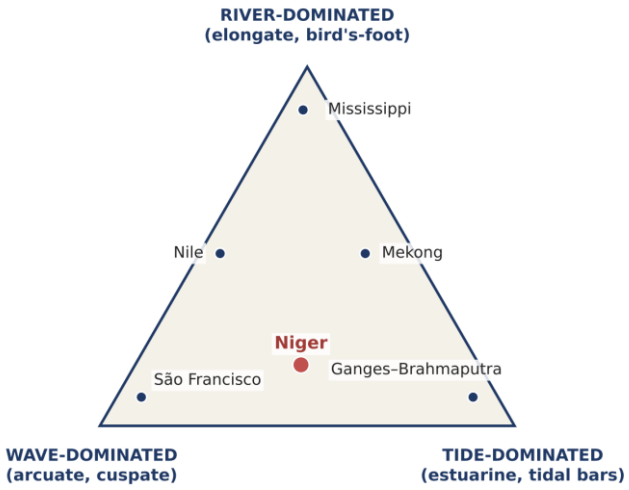


Figure 5.4. Classification of deltas by the dominant process, after Galloway (1975). The Niger Delta plots between the wave- and tide-dominated end members.

5.7 Key points of Section 5

- Discharge equals cross-sectional area times velocity.
- Sand is the easiest sediment to erode; clay is hard to erode but easy to keep in suspension.
- Meanders erode their cut banks and build point bars; deltas form where rivers meet the sea.
- The Niger Delta is shaped by both waves and tides.

Section 6: Groundwater

Groundwater is the water held in the pores and fractures of soil and rock below the surface. It is the largest store of liquid fresh water on land and the main source of drinking water for most Nigerians.

6.1 Where groundwater occurs

Below the surface are two zones:

- The **zone of aeration** (unsaturated zone), where pores hold both air and water.
- The **zone of saturation**, where all pores are filled with water. The water in this zone is **groundwater**.

The top of the zone of saturation is the **water table**. It roughly follows the shape of the land surface, standing higher under hills and lower under valleys, but with gentler slopes. Where the water table meets the surface, it feeds rivers, lakes, springs and swamps.

6.2 Porosity and permeability

Porosity is the percentage of a rock or sediment's total volume that is open space:

$$n = \frac{V_v}{V_t} \times 100$$

Here n is porosity (%), V_v is the volume of voids and V_t is the total volume.

Permeability is the ability of a material to transmit water. It depends on the size of the pores and how well they are connected, not just on how many there are.

Material	Typical porosity (%)	Permeability
Gravel	25 to 40	Very high
Sand	25 to 50	High
Silt	35 to 50	Low to moderate
Clay	40 to 70	Very low
Sandstone	5 to 30	Moderate
Limestone (karstic)	5 to 50	Variable, can be very high
Fractured granite	0 to 10	Low to moderate, along fractures

Clay shows why the two properties differ: it has high porosity but its pores are so tiny that water barely moves through it.

6.3 Aquifers and aquitards

An **aquifer** is a body of rock or sediment that stores and transmits enough water to supply wells and springs. Sand, gravel, sandstone, fractured rock and karstic limestone make good aquifers. An **aquitard** is a layer of low permeability, such as clay or shale, that slows groundwater flow.

- An **unconfined aquifer** has the water table as its upper surface and is recharged directly from above.
- A **confined aquifer** is sealed above and below by aquitards. Its water is under pressure. If a well is drilled into it, the water rises above the top of the aquifer to a level called the **potentiometric surface**. Such a well is **artesian**. If the potentiometric surface lies above the ground, the well flows without pumping (Figure 6.1).
- A **perched water table** sits on a small, local aquitard above the main water table.

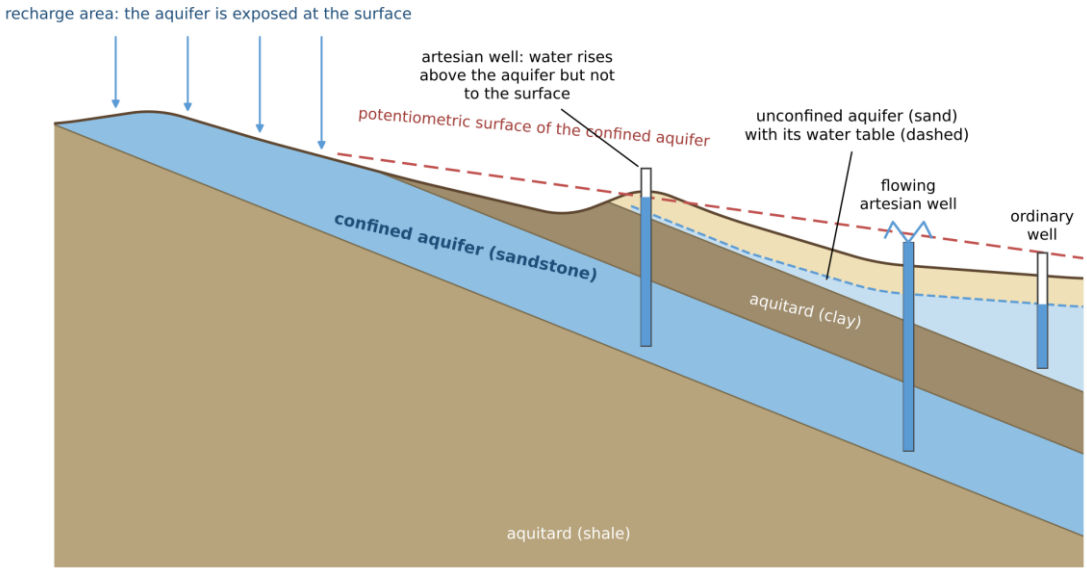


Figure 6.1. Unconfined and confined aquifers, with an ordinary well, an artesian well, a flowing artesian well and a spring.

6.4 Groundwater flow and Darcy's law

Groundwater moves slowly from areas of high water table (recharge areas) to areas of low water table (discharge areas). The rate of flow through a body of sediment is given by **Darcy's law**:

$$Q = KA\frac{\Delta h}{L}$$

Here Q is the discharge (m^3/day), K is the **hydraulic conductivity** (m/day), A is the cross-sectional area of flow (m^2), Δh is the difference in hydraulic head (m) between two points and L is the distance between them (m). The ratio $\Delta h/L$ is the **hydraulic gradient**, i.

The average speed at which water actually moves through the pores is the **seepage velocity**:

$$v_s = \frac{Ki}{n_e}$$

where n_e is the effective porosity expressed as a decimal.

Worked example. A sand aquifer has $K = 10$ m/day and an effective porosity of 0.25. Two wells 400 m apart have water levels that differ by 2 m. The aquifer cross-section is 100 m^2.

$$i = \frac{2}{400} = 0.005 \qquad Q = 10 \times 100 \times 0.005 = 5 \text{ m}^3/\text{day}$$

$$v_s = \frac{10 \times 0.005}{0.25} = 0.2 \text{ m/day}$$

At this speed, water takes about 2,000 days, more than five years, to travel the 400 m between the wells. This is why polluted groundwater is so slow to clean up.

6.5 Springs, wells and the effects of pumping

A **spring** forms where the water table meets the land surface, often where an aquifer rests on an aquitard on a hillside. A **well** is a hole drilled or dug below the water table. Pumping lowers the water table around the well into a **cone of depression**. Where many boreholes are closely

spaced, their cones overlap and the water table falls over a wide area. Overpumping can dry up shallow wells, cause the ground to subside, and, near the coast, draw seawater into the aquifer.

6.6 Karst

Where groundwater dissolves limestone (Section 3.4), it enlarges joints into **caves** and passages. Collapse of cave roofs and dissolution at the surface form **sinkholes**. Landscapes dominated by these features are called **karst**. Karst aquifers can yield large volumes of water, but pollutants travel through them quickly with little filtering.

6.7 Groundwater in Nigeria

- **Sedimentary basins** hold the best aquifers. In the Niger Delta, the sands and gravels of the Benin Formation form a thick, highly productive aquifer. The Chad, Sokoto and Benue basins also contain important sandstone aquifers, some of them confined.
- **Basement complex** areas, which cover about half the country, have little primary porosity. Groundwater is found in the weathered zone (regolith) and in fractures. Yields are low, and boreholes must be sited carefully using geophysics.

6.8 Key points of Section 6

- The water table is the top of the zone of saturation.
- Porosity is storage; permeability is the ability to transmit water.
- Darcy's law relates flow to hydraulic conductivity, area and hydraulic gradient.
- Sedimentary basins hold Nigeria's best aquifers; basement areas depend on weathered and fractured rock.

Section 7: Coasts, wind and glaciers

Rivers deliver sediment to the coast, where waves, tides and currents take over. In dry regions wind, and in cold regions ice, are also powerful agents of erosion and deposition. This section covers all three, with most attention on the coast.

7.1 Waves

Most sea waves are generated by wind blowing over the water surface. A wave is described by its **height** (H, crest to trough), **wavelength** (L, crest to crest) and **period** (T, the time between crests). The size of a wave depends on wind speed, how long the wind blows, and the **fetch**, the distance of open water over which it blows. The long swells that reach the Nigerian coast are generated by storms far to the south in the South Atlantic.

In deep water, water particles move in circular orbits that shrink with depth. Below a depth of about half the wavelength, called **wave base**, the water is almost undisturbed:

$$\text{wave base} \approx \frac{L}{2}$$

When a wave enters water shallower than wave base, its orbits touch the seabed. The wave slows, its wavelength shortens, and its height increases until it becomes too steep and **breaks**. The **surf zone** is where breaking waves expend their energy, moving sand and eroding the shore.

Waves approaching the shore at an angle bend as the part in shallower water slows first. This **wave refraction** concentrates wave energy on headlands, which erode, and spreads it in bays, where sand accumulates.

7.2 Longshore currents and longshore drift

Most waves reach the beach at an angle. The **swash** runs up the beach in the direction of the waves, but the **backwash** runs straight back down the slope under gravity. Sand grains therefore move along the beach in a zigzag path (Figure 7.1). This **beach drift**, together with the **longshore current** that flows parallel to the shore in the surf zone, moves large volumes of sand along the coast. The combined process is **longshore drift**.

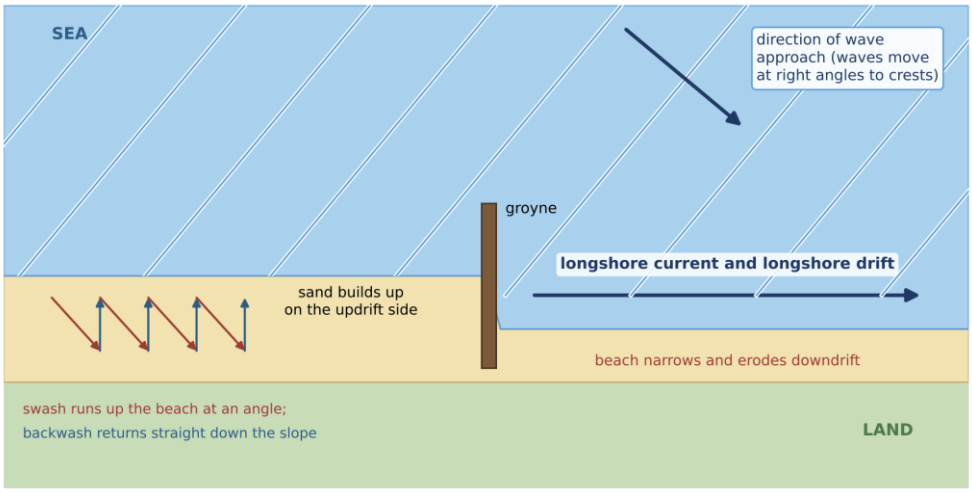


Figure 7.1. Longshore drift. Waves approach the beach at an angle; sand moves along the shore in a zigzag path and builds up against the updrift side of a groyne.

Structures that block longshore drift trap sand on their updrift side and starve the beach downdrift. Along the Lagos coast, longshore drift moves sand from west to east. The harbour moles built at the entrance to Lagos Harbour in the early 20th century trapped sand to the west (Lighthouse Beach), while the beaches to the east, including Bar Beach on Victoria Island, suffered severe erosion. The Eko Atlantic sea wall and land reclamation are a later response to the same problem.

7.3 Coastal landforms

Erosional landforms form where wave energy is high and the coast is rocky: wave-cut cliffs, wave-cut platforms, sea caves, sea arches and sea stacks.

Depositional landforms form where sediment supply is high:

- **Beaches:** accumulations of sand or gravel in the zone of wave action.
- **Spits:** ridges of sand extending from the land across the mouth of a bay, built by longshore drift.
- **Barrier islands:** long, narrow sand islands parallel to the coast, separated from the mainland by a **lagoon**. The Lagos Lagoon and the Lekki coast lie behind such a barrier system.
- **Tidal flats and mangrove swamps:** muddy areas exposed at low tide, common in the Niger Delta.

The Nigerian coastline, about 850 km long, is usually divided into four zones from west to east: the **barrier–lagoon coast** (from the Benin Republic border to east of Lagos), the **transgressive mud coast** of Ondo State (around Ayetoro), the **arcuate Niger Delta coast**, and the **strand coast** east of the delta towards Calabar. Coastal erosion is a serious problem in several places, especially around Ayetoro and along parts of the delta, where subsidence, reduced river sediment supply and rising sea level combine.

7.4 Tides and sea level

Tides are the regular rise and fall of sea level caused mainly by the Moon's gravity, with a smaller contribution from the Sun. Most coasts, including Nigeria's, have two high and two low tides each day. Tidal currents flood and drain the estuaries and creeks of the Niger Delta, carrying sediment and salt water far inland.

Sea level changes over time. During the last glacial maximum, about 20,000 years ago, so much water was locked in ice sheets that sea level stood about 120 m lower than today. The Nigerian continental shelf was then dry land crossed by river valleys. As the ice melted, the sea rose and flooded the shelf. Sea level is rising again today, threatening low-lying coasts such as the Niger Delta.

7.5 Wind

Wind is an important agent where vegetation is sparse and sediment is dry, as in the deserts and semi-arid lands to the north of Nigeria.

Wind erosion works in two ways:

- **Deflation:** wind lifts and removes loose sand and dust, lowering the land surface and leaving behind a surface of pebbles called **desert pavement**.
- **Abrasion:** wind-blown sand sandblasts rock surfaces, shaping stones into faceted **ventifacts** and carving streamlined ridges called **yardangs**.

Wind transport. Sand moves close to the ground by saltation. Dust is carried high in suspension and can travel thousands of kilometres. The **Harmattan** haze that covers Nigeria in the dry season is dust lifted from the Sahara, much of it from the Bodélé Depression in Chad.

Wind deposits. Sand accumulates as **dunes**, which have a gentle windward slope and a steeper **slip face** on the downwind side. Common types are crescent-shaped **barchan** dunes (limited sand, steady wind), **transverse** dunes (abundant sand, ridges at right angles to the wind), **longitudinal** or seif dunes (ridges parallel to the wind) and **star** dunes (variable winds). Old, vegetated dunes occur in parts of north-eastern Nigeria. Fine wind-blown dust deposits are called **loess**.

7.6 Glaciers

A **glacier** is a thick mass of ice that forms on land from compacted and recrystallised snow and flows slowly under its own weight. **Valley glaciers** occupy mountain valleys; **ice sheets** cover large parts of continents, as in Antarctica and Greenland today.

Glaciers erode by **plucking** (lifting blocks of fractured bedrock) and **abrasion** (grinding the bed with rock debris held in the ice). Glacial erosion produces U-shaped valleys, bowl-shaped **cirques**, sharp ridges (arêtes) and peaks (horns), and **fjords** where glacial valleys are flooded by the sea.

Glaciers deposit **till**, an unsorted mixture of clay to boulders, in ridges called **moraines** and in streamlined hills called **drumlins**. Meltwater streams deposit sorted sand and gravel as **outwash**.

There are no glaciers in Nigeria today, but glaciation still matters to Nigerian geology. The growth and melting of ice sheets controlled the rise and fall of sea level that shaped the Niger Delta and the continental shelf. Ancient glacial deposits are also found in the rock record of other parts of Africa.

7.7 Key points of Section 7

- Wave base is about half the wavelength; waves break in shallow water and do most coastal work in the surf zone.
- Longshore drift moves sand along the coast; structures that block it cause erosion downdrift.
- Wind erodes by deflation and abrasion and builds dunes and loess.
- Glaciers erode U-shaped valleys and deposit till; ice ages control global sea level.

Section 8: Geological structures

Rocks are not only weathered and eroded; they are also bent, broken and tilted by forces inside the Earth. The resulting features are called **geological structures**. They control the shape of the landscape, the location of oil, gas, minerals and groundwater, and the safety of engineering works.

8.1 Stress, strain and how rocks deform

Stress is force per unit area acting on a rock. There are three types:

- **Compression:** squeezes rock together and shortens it.
- **Tension:** pulls rock apart and lengthens it.
- **Shear:** pushes one part of a rock past another.

Strain is the change in shape or size that results from stress. Rocks deform in three ways:

- **Elastic deformation:** the rock returns to its original shape when the stress is removed.
- **Ductile (plastic) deformation:** the rock bends or flows permanently without breaking, producing folds.
- **Brittle deformation:** the rock breaks, producing joints and faults.

Whether a rock behaves in a ductile or a brittle way depends on **temperature** and **confining pressure** (both increase with depth and favour ductile behaviour), the **rate of strain** (slow strain favours ductile behaviour), and the **rock type** (shale and salt are more ductile than quartzite and granite). Rocks near the surface tend to break; rocks deep in the crust tend to fold.

8.2 Describing the attitude of rocks: strike and dip

The orientation of a planar surface, such as a bedding plane, joint or fault, is described by its strike and dip (Figure 8.1).

- **Strike** is the compass direction of a horizontal line on the plane.

- **Dip** is the angle between the plane and the horizontal, measured at right angles to the strike, together with the direction in which the plane slopes downward.

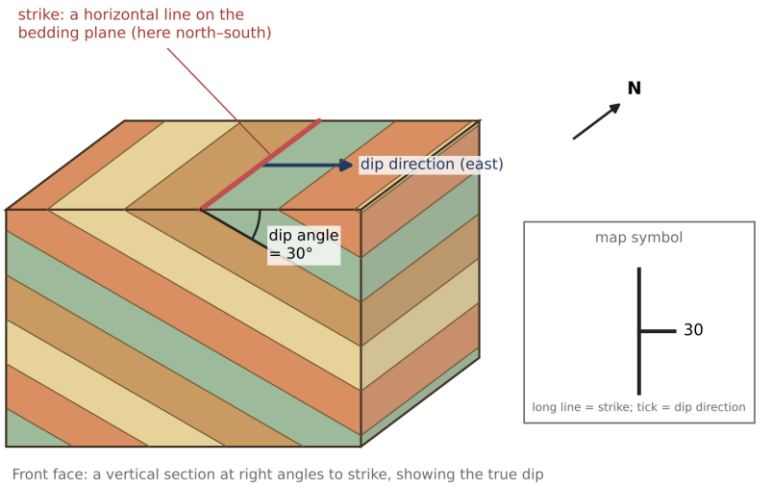


Figure 8.1. Strike and dip of a tilted bed. Strike is the direction of a horizontal line on the bed; dip is measured at right angles to strike, downward from the horizontal.

Strike and dip are measured in the field with a compass-clinometer. They can be written, for example, as 045°/30° SE: strike towards 045° (north-east), dip of 30° towards the south-east. On geological maps they are shown by a T-shaped symbol: the long line shows strike, the short tick shows the dip direction, and the number gives the dip angle.

The **true dip** is measured at right angles to strike. In a cross-section or quarry face cut at any other angle, the bed appears to dip less steeply. This **apparent dip** (α) is given by:

$$\tan\alpha = \tan\delta \times \sin\beta$$

where δ is the true dip and β is the angle between the strike and the line of the section.

Worked example. A sandstone bed has a true dip of 30°. A road cut runs at 40° to the strike.

$$\tan\alpha = \tan 30° \times \sin 40° = 0.577 \times 0.643 = 0.371 \qquad \alpha = 20.4°$$

The bed appears to dip at only about 20° in the road cut.

8.3 Folds

Folds are bends in layered rocks, produced by ductile deformation, usually under compression. Their parts are shown in Figure 8.2:

- **Limbs:** the two sides of the fold.
- **Hinge:** the line of maximum curvature where the limbs meet.
- **Axial plane (axial surface):** the surface that divides the fold as symmetrically as possible and contains the hinge lines of successive layers.
- **Plunge:** the angle at which the hinge line dips, if it is not horizontal.

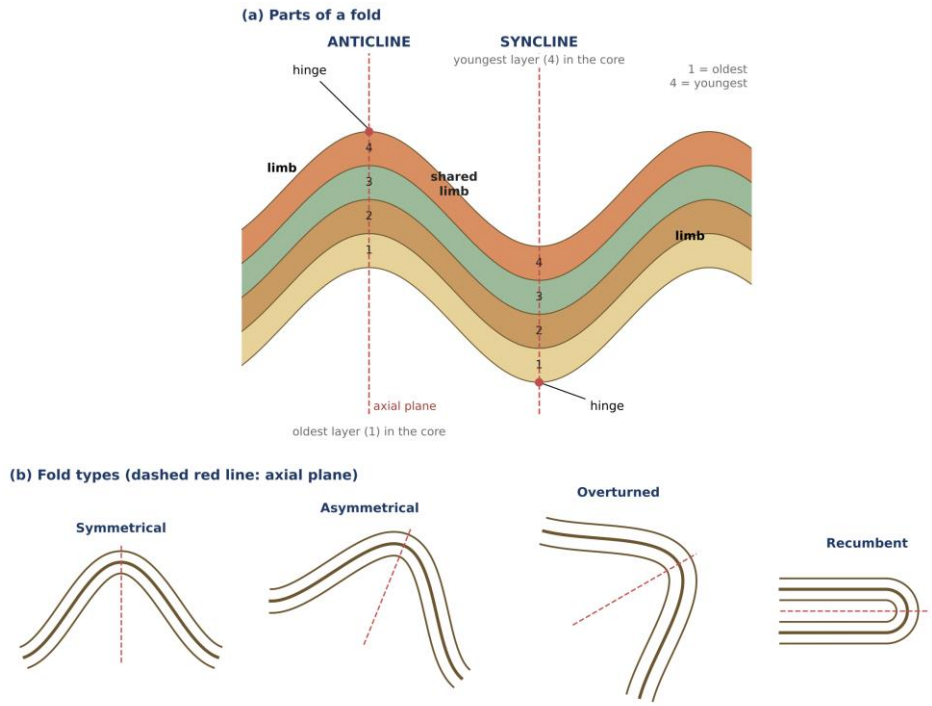


Figure 8.2. The parts of a fold, shown on an anticline and a syncline in cross-section. Numbers 1 to 4 show the layers from oldest to youngest.

Folds are named by their shape:

- An **anticline** is arched upward, with the **oldest** rocks in its core.
- A **syncline** is folded downward, with the **youngest** rocks in its core.
- A **monocline** is a single step-like bend in otherwise flat-lying layers.
- A **dome** and a **basin** are circular or oval structures in which layers dip outward from, or inward towards, a central point.

They are also described by the attitude of the axial plane and limbs: **symmetrical** (limbs dip equally), **asymmetrical** (one limb steeper), **overturned** (one limb tilted past vertical, so both limbs dip the same way), **recumbent** (axial plane nearly horizontal) and **isoclinal** (limbs parallel).

On a geological map, an eroded anticline shows a repeat of beds with the oldest in the centre; a syncline shows the youngest in the centre. In Nigeria, the **Abakaliki Anticlinorium** in the Benue Trough is a large belt of folds formed during compression in the Late Cretaceous. Anticlines are classic traps for oil and gas, because petroleum rises to the crest beneath an impermeable cap rock.

8.4 Faults

A **fault** is a fracture along which the rocks on either side have moved relative to each other. The movement can be millimetres or hundreds of kilometres. Sudden movement on a fault causes an earthquake.

For an inclined fault, the block above the fault plane is the **hanging wall** and the block below is the **footwall**. Faults are classified by the direction of movement (Figure 8.3):

- **Normal fault:** the hanging wall moves **down** relative to the footwall. Caused by **tension**; the crust is lengthened. Blocks dropped down between two normal faults form a **graben**; blocks left standing high form a **horst**.
- **Reverse fault:** the hanging wall moves **up** relative to the footwall. Caused by **compression**; the crust is shortened.
- **Thrust fault:** a reverse fault with a low dip, less than about 45°, along which older rocks may be pushed over younger rocks.
- **Strike-slip fault:** movement is horizontal, parallel to the strike of the fault, caused by **shear**. It is **dextral** (right-lateral) if the far block appears to move to the right when viewed across the fault, and **sinistral** (left-lateral) if it moves to the left.
- **Oblique-slip fault:** movement has both dip-slip and strike-slip components.

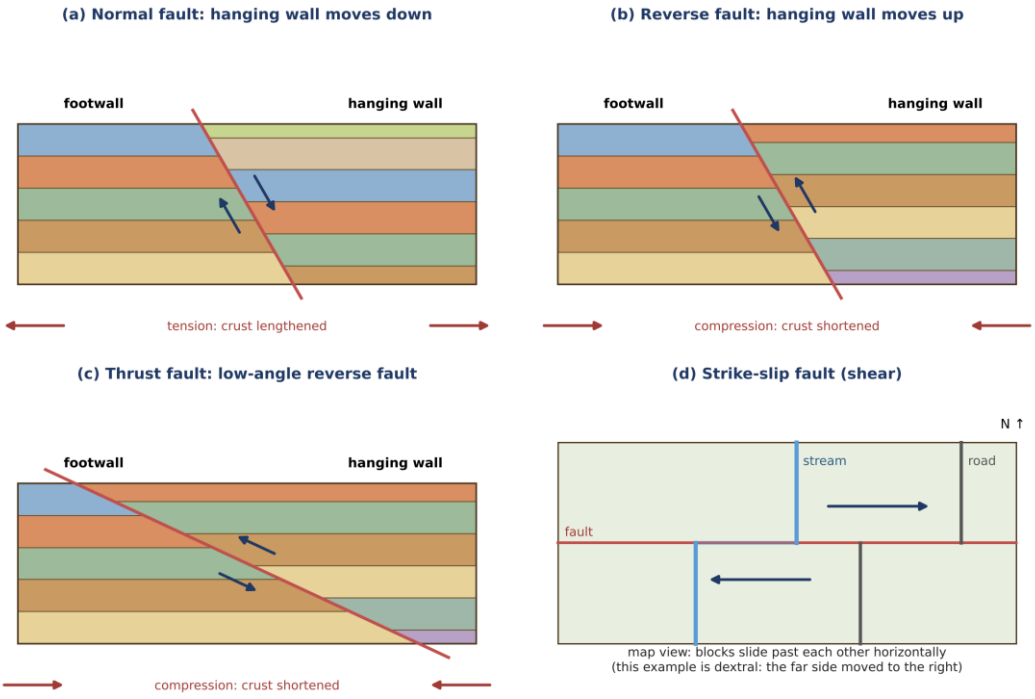


Figure 8.3. The main types of fault. Normal, reverse and thrust faults are shown in cross-section; the strike-slip fault is shown in map view.

Fault zones often contain crushed rock: angular **fault breccia**, fine clay-rich **fault gouge**, and, at depth, finely sheared **mylonite**. Polished, grooved surfaces called **slickensides** show the direction of movement.

Nigerian examples include:

- **Growth faults** of the Niger Delta: normal faults that moved while sediment was being deposited, so beds are thicker on the downthrown side. They curve and flatten with depth, and the rollover anticlines beside them trap much of the delta's oil and gas.
- The **Ifewara fault zone** in south-western Nigeria, a major shear zone in the basement complex.
- The rift faults of the **Benue Trough**, which formed as the African and South American plates separated in the Cretaceous (Section 2.8).

8.5 Joints

Joints are fractures along which there has been no noticeable movement. They are the most common structures in rocks. They form by:

- **Cooling and contraction** of igneous rocks, such as the six-sided **columnar joints** in basalt.
- **Unloading**, which produces sheet joints parallel to the surface in granite (Section 3.3).
- **Tectonic stress**, which produces sets of parallel joints, often in two or more directions.

Joints matter because they let water into rock, speeding up weathering. In basement areas they provide most of the groundwater. They also control the stability of rock slopes, quarry faces and tunnels, and guide the flow of mineralising fluids that form veins.

8.6 Unconformities

An **unconformity** is a buried surface of erosion or non-deposition that separates younger rocks from older ones. It represents a gap in the geological record, sometimes of millions of years. There are three main types (Figure 8.4):

- **Angular unconformity:** tilted or folded older layers are eroded and covered by younger, flat-lying layers. It records deposition, deformation, uplift, erosion and renewed deposition.
- **Disconformity:** the layers above and below are parallel, but an eroded, often uneven surface separates them.
- **Nonconformity:** sedimentary rocks rest on eroded igneous or metamorphic rocks. In Nigeria, the Cretaceous sediments of the Benue Trough and the coastal basins rest on the Precambrian basement complex along a nonconformity.

A fourth type, the **paraconformity**, has parallel layers and no visible erosion surface; it can be recognised only from fossils or dating.

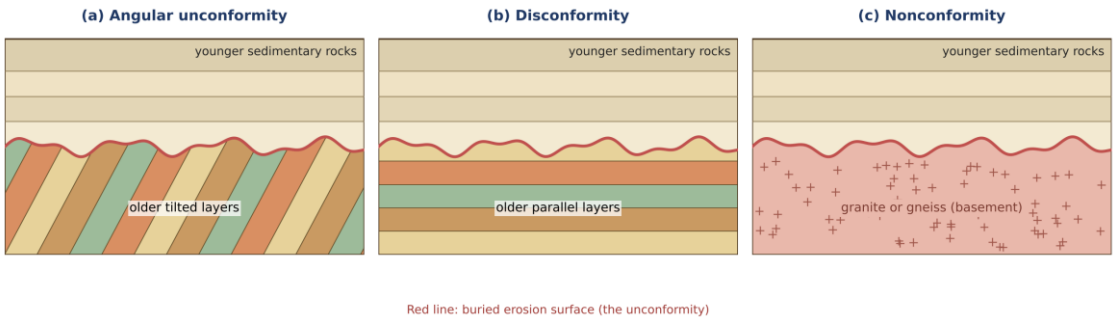


Figure 8.4. The three main types of unconformity, shown in cross-section. The wavy line marks the surface of erosion.

8.7 Why structures matter

- **Petroleum:** anticlines, fault traps and unconformities form traps for oil and gas.
- **Minerals:** faults and joints guide hydrothermal fluids that form ore veins, such as the lead–zinc veins of the Benue Trough.
- **Groundwater:** fractured rock is the main aquifer in basement areas.
- **Engineering:** faults, joints and dipping beds control the stability of slopes, dam foundations and tunnels.
- **Hazards:** active faults generate earthquakes.

8.8 Key points of Section 8

- Rocks deform elastically, ductilely or brittlely, depending on temperature, pressure, strain rate and rock type.
- Strike and dip describe the orientation of planes; apparent dip is always less than true dip.
- Anticlines have the oldest rocks in their cores; synclines have the youngest.
- Normal faults record tension, reverse and thrust faults record compression, and strike-slip faults record shear.
- Unconformities are gaps in the geological record.

Summary, review questions and glossary

Summary

Topic	Main ideas	Nigerian examples
Introduction	Earth system; solar energy, gravity and internal heat; uniformitarianism	Geology in resources, hazards and engineering
Plate tectonics	Continental drift; lithosphere and asthenosphere; divergent, convergent and transform boundaries; magnetic stripes and spreading rate; driving forces; Wilson cycle	Pan-African basement; Benue Trough failed arm; opening of the Gulf of Guinea; Niger Delta
Weathering and soils	Mechanical and chemical weathering; Goldich series; soil horizons; laterite	Inselbergs; deep tropical weathering; gullies of the south-east
Mass wasting	Factor of safety; falls, slides, flows and creep	Gully wall collapse; riverbank failure
Running water	Discharge; load; Hjulström diagram; meanders; deltas	Niger and Benue; Niger Delta
Groundwater	Porosity, permeability; aquifers; Darcy's law; karst	Benin Formation aquifer; basement aquifers
Coasts, wind, glaciers	Waves; longshore drift; coastal landforms; dunes; glacial landforms and sea level	Lagos coast erosion; Harmattan dust
Structures	Stress and strain; strike and dip; folds; faults; joints; unconformities	Abakaliki Anticlinorium; Niger Delta growth faults

Summary of key equations

Quantity	Equation	Section
Spreading rate	$v = \frac{d}{t}$	2.5
Surface area after splitting a cube into n^3 pieces	$A = n \times 6a^2$	3.3
Factor of safety	$F = \frac{\text{resisting forces}}{\text{driving forces}}$	4.1

Quantity	Equation	Section
Infinite slope in dry sand	$F = \frac{\tan\phi}{\tan\beta}$	4.1
Stream discharge	$Q = A \times v = w \times d \times v$	5.2
Porosity	$n = \frac{V_v}{V_t} \times 100$	6.2
Darcy's law	$Q = KA\frac{\Delta h}{L}$	6.4
Seepage velocity	$v_s = \frac{Ki}{n_e}$	6.4
Wave base	wave base $\approx L/2$	7.1
Apparent dip	$\tan\alpha = \tan\delta \times \sin\beta$	8.2

Review questions

Part A: Short answers

1. Distinguish between physical geology and historical geology.
2. Name the four spheres of the Earth system and the two main energy sources that drive geological processes.
3. Explain the principle of uniformitarianism and its limitations.
4. List four lines of evidence that Wegener used for continental drift, and explain why most geologists rejected his hypothesis at the time.
5. Distinguish between the lithosphere and the asthenosphere, and between oceanic and continental crust.
6. Describe the three types of plate boundary and give one example of each.
7. Explain how magnetic stripes on the ocean floor support the theory of seafloor spreading.
8. Compare ocean–continent, ocean–ocean and continent–continent convergence, giving one example of each.
9. Explain slab pull and ridge push. Which is thought to be the stronger force, and why?
10. What is a failed rift arm? Explain the origin of the Benue Trough and the Niger Delta in terms of plate tectonics.
11. Distinguish between weathering and erosion.
12. Explain how exfoliation forms the granite domes of south-western Nigeria.
13. Write the equation for the hydrolysis of potassium feldspar and name the clay mineral formed.
14. Why are tropical soils often red? Explain the formation of laterite.
15. List four factors that reduce the stability of a slope.
16. Distinguish between a rotational slide, a debris flow and creep.
17. Use the Hjulström diagram to explain why clay is harder to erode than fine sand.
18. Explain the formation of an oxbow lake.
19. Describe the three end-member types of delta and explain where the Niger Delta plots.

20. Distinguish between porosity and permeability, and between confined and unconfined aquifers.
21. Explain how longshore drift and the Lagos harbour moles have affected Bar Beach.
22. Distinguish between ductile and brittle deformation and state the factors that control them.
23. How can you tell an anticline from a syncline on a geological map?
24. Distinguish between normal, reverse and strike-slip faults, and name the type of stress that forms each.
25. What is a nonconformity? Give a Nigerian example.

Part B: Calculations

26. A magnetic stripe formed 3.58 million years ago lies 71.6 km from the axis of a mid-ocean ridge. Calculate the half-spreading rate in km per million years and in cm per year, and the full spreading rate. How long would it take this ocean to widen by 1,000 km at the full rate?
27. A 2 cm cube of rock is broken into 1 mm cubes. By what factor does its surface area increase? Calculate the new total surface area.
28. A dry sand slope has an angle of internal friction of 33°. Calculate the factor of safety at slope angles of 25° and 33°. At what angle will the slope fail?
29. A river channel is 45 m wide and 3.2 m deep, and the average velocity is 1.2 m/s. Calculate the discharge. If the discharge doubles during a flood with no change in width or velocity, what is the new depth?
30. A sample of sand has a total volume of 500 cm^3 and a void volume of 160 cm^3. Calculate its porosity.
31. A gravel aquifer has a hydraulic conductivity of 80 m/day and an effective porosity of 0.30. The water table falls 5 m over a distance of 1 km, and the aquifer cross-section is 2,500 m^2. Calculate the hydraulic gradient, the discharge and the seepage velocity.
32. A wave has a wavelength of 120 m. At what depth will it begin to touch the seabed?
33. A limestone bed has a true dip of 45°. Calculate the apparent dip in a quarry face that makes an angle of 30° with the strike.

Part C: Essay questions

34. Describe the evidence for plate tectonics and explain how the theory accounts for the distribution of earthquakes, volcanoes and mountain belts.
35. Describe the processes of mechanical and chemical weathering and explain why chemical weathering dominates in southern Nigeria.
36. Discuss the causes of gully erosion and mass wasting in south-eastern Nigeria and suggest measures to control them.
37. Describe how a river erodes, transports and deposits sediment from its source to its delta, using the Niger as an example.
38. Discuss the causes of coastal erosion along the Nigerian coastline and the engineering responses to it.
39. Describe the main types of folds, faults and unconformities, and explain their importance in the search for petroleum in the Niger Delta.

Glossary

Term	Meaning
Angle of repose	The steepest angle at which loose material remains stable
Anticline	An upward-arching fold with the oldest rocks in its core
Aquifer	A body of rock or sediment that stores and transmits useful amounts of groundwater
Aquitard	A layer of low permeability that slows groundwater flow
Artesian well	A well in a confined aquifer in which water rises above the top of the aquifer
Asthenosphere	The weak, slowly flowing layer of the upper mantle beneath the lithosphere
Base level	The lowest level to which a stream can erode
Cone of depression	The lowering of the water table around a pumped well
Continental drift	Wegener's hypothesis that the continents have moved relative to one another
Convergent boundary	A plate boundary where plates move towards each other
Delta	A body of sediment deposited where a river enters standing water
Dip	The angle between a plane and the horizontal, measured at right angles to strike
Discharge	The volume of water passing a point in a stream per unit time
Divergent boundary	A plate boundary where plates move apart and new lithosphere forms
Erosion	The removal and transport of weathered material
Exfoliation	The peeling of curved sheets of rock from a surface, mainly due to unloading
Factor of safety	The ratio of resisting to driving forces on a slope
Failed arm	A rift arm of a triple junction that stops spreading and fills with sediment
Fault	A fracture along which rocks have moved
Fold	A bend in layered rock produced by ductile deformation
Fracture zone	The inactive extension of a transform fault beyond the ridge segments it offsets
Hot spot	A long-lived centre of volcanism thought to lie above a rising plume of hot mantle
Hydrolysis	Chemical weathering in which hydrogen ions replace cations in a mineral
Joint	A fracture along which there has been no noticeable movement
Laterite	A red, iron- and aluminium-rich tropical soil formed by intense leaching
Lithosphere	The rigid outer layer of the Earth, made of the crust and the uppermost mantle
Longshore drift	The movement of sediment along a coast by waves approaching at an angle
Mass wasting	The downslope movement of rock and soil under gravity
Mid-ocean ridge	A submarine mountain chain where seafloor spreading creates new oceanic crust
Palaeomagnetism	The record of the Earth's past magnetic field preserved in rocks

Term	Meaning
Permeability	The ability of a material to transmit fluids
Plate tectonics	The theory that the lithosphere is divided into plates that move over the asthenosphere
Point bar	A deposit of sand on the inside of a meander bend
Porosity	The percentage of a material's volume that is open space
Regolith	The layer of loose weathered material above bedrock
Seafloor spreading	The formation of new oceanic crust at mid-ocean ridges and its movement away on both sides
Strike	The direction of a horizontal line on an inclined plane
Subduction	The sinking of one lithospheric plate beneath another into the mantle
Syncline	A downward fold with the youngest rocks in its core
Transform fault	A plate boundary where plates slide horizontally past each other
Trench	A deep, narrow trough in the ocean floor where a plate is subducted
Triple junction	A point where three plate boundaries or rift arms meet
Unconformity	A buried surface of erosion or non-deposition representing a gap in the record
Water table	The top of the zone of saturation
Wave base	The depth, about half the wavelength, below which waves do not disturb the water
Weathering	The breakdown and decomposition of rock at or near the Earth's surface
Wilson cycle	The repeated opening and closing of ocean basins

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