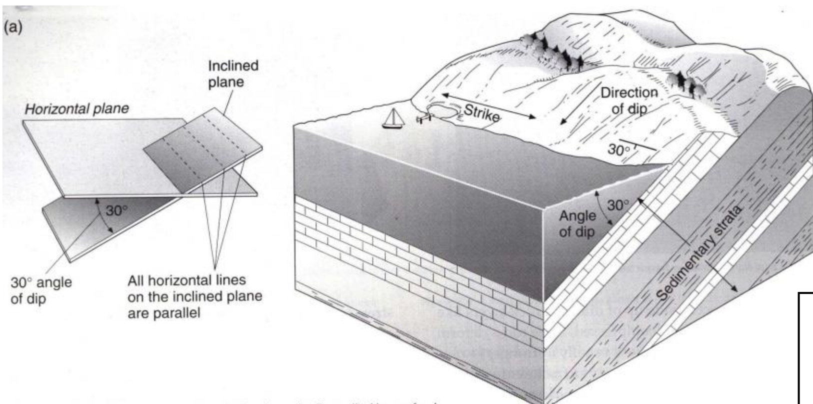
Tectonic processes: folding, faulting, deformation, earthquakes

- Result from the movements of lithospheric plates
- Plate movements generate forces within and between the plates
- These forces can **deform** the rocks
  - bending → **FOLDS**
  - breaking → **FAULTS** but note there are other ways of deforming rocks



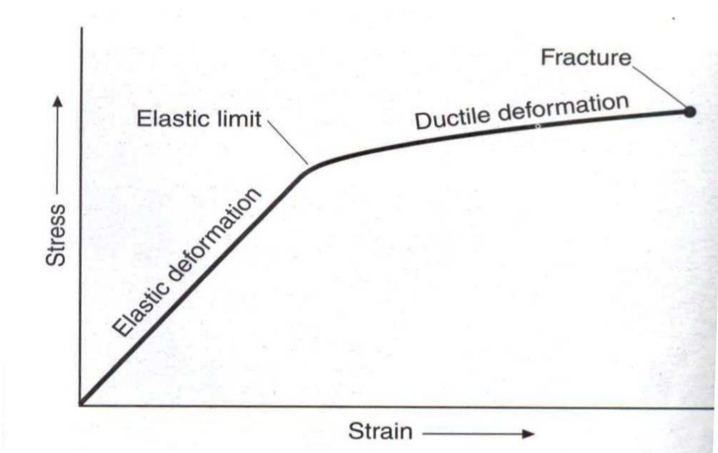
Dip – angle a layer makes to the horizontal

Strike – direction of a horizontal line along the surface of a layer, at right angles to the dip.

stress = force/area within a solid in newtons/sq metre (N/m^2)

- **tensile stress** *or*
- **compressive stress** *or*
- **shear stress**

The result of stress is **strain** = change in length, area, volume or angle per original dimension



- At the elastic limit, the rock begins to show ductile or plastic deformation
- The material begins to flow like plasticine
- The changes are permanent when the stress ends, so bent materials remain bent .

Real rocks often suffer from at least two stresses:

- Confining stresses due to the weight of rock above, which increase with depth of burial
- Stresses from tectonic processes – tensional, compressional, shear

Laboratory experiments on marble cylinders under different *confining stresses*, representing greater depths, show:

- a rock can show brittle deformation/fracture at shallow depths
- but can be ductile/bend and flow at greater depths.

Real rocks: the conditions controlling deformation are complex. Four main factors interact:

- temperature
- pressure/confining stress
- time & strain rate
- rock composition.

Temperature

- increases with depth. The geothermal gradient varies from 5°C to 75°C per km. (*Why?)*
- at higher temperatures, rocks are more likely to show ductile deformation - bending and flowing.

Pressure/Confining stress

- Confining stress is uniform stress caused by the mass of the rocks above.
- So rocks are easier to deform near the surface where the confining stresses are lower.
- Rocks tend to fracture under low confining stresses.
- Rocks are more likely to be ductile at higher confining stresses.

Time and strain rate

- The length of time a stress is applied.
- *Strain rate* is the rate at which a material deforms.
- Some rock materials show ductile deformation over longer periods; but are brittle when the same stress is applied suddenly.
- The lower the strain rate, the higher the chance of ductile deformation.

Rock composition

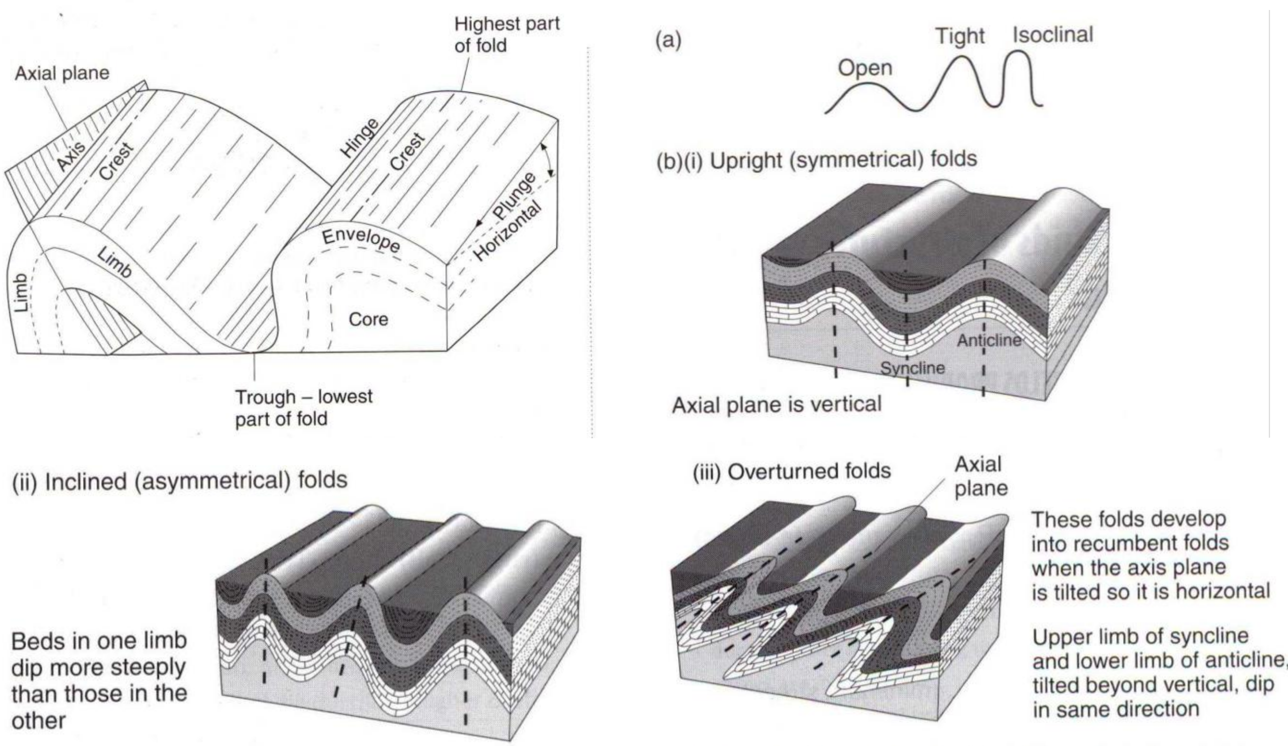
- The mineral content and the water content of the rock.
- Minerals such as calcite and mica are usually ductile.
- Minerals such as quartz, olivine and garnet are more brittle.
- Wet rocks are more likely to show ductile deformation than dry rocks (water coating the grains may reduce friction between grains).

Consider a sedimentary sequence such as alternating sandstones and shales.

- **Competence** is the term to describe the relative rheological properties of adjacent rocks.
  (Rheology is the study of deformation and flow in materials.)
- Sandstone is usually a stronger **competent** rock, but shale is **incompetent.**
- Sandstone is more likely to fracture, whereas shale is usually more ductile and so flows more easily.

Summary

- ductile flow gives folds
- brittle fracture gives faults
- but there can be intermediate situations



Faulting and Jointing

When a rock layer or a sequence of layers is subjected to too much stress, it may fracture. There are two main types of fracture:

- A **joint**: a break where there is no visible movement of the rocks *parallel* to the plane of the fracture. Scale: can be mm, cm, but rarely > 1m.
- A **fault**: a fracture in rocks where there is a displacement of one side relative to the other. At the moment of fracture, there is a release of energy, partly as shockwaves - earthquakes!

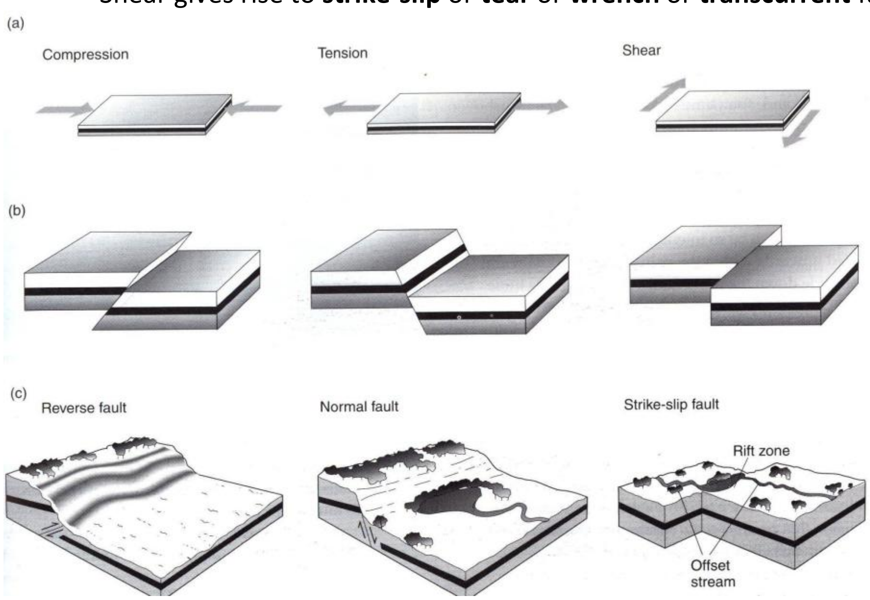
Types of joint:

- due to shrinkage on cooling
  - e.g. columnar jointing in basalts as they solidify
- due to shrinkage on dewatering
  - e.g. mudcracks, sandstones, limestones
- due to release of stress
  - e.g. unloading of granites, leading to tors or exfoliation (onion-skin peeling of granite intrusion)

Faults

The three types of stress give rise to different types of fault.

- Tension gives rise to **normal** faults. Common on the smaller scale
- Compression gives rise to **reverse** faults Less common on the smaller scale
- Shear gives rise to **strike-slip** or **tear** or **wrench** or **transcurrent** faults Least common on the smaller scale

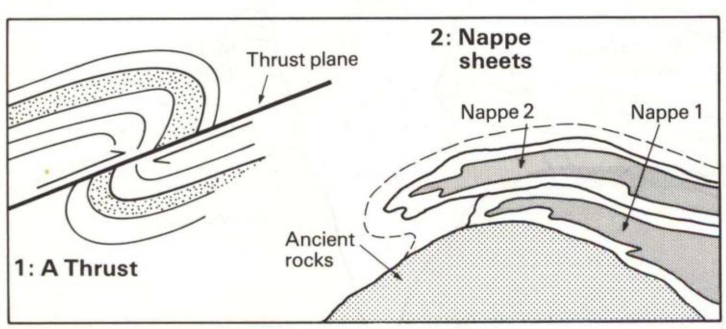


Normal fault: The movement is called dip slip, i.e. the rock above the fault plane slips down the dip of the fault plane. The angle of the fault plane is called dip and is usually steep, over 45° and often ranges 60° up to 90° (vertical).

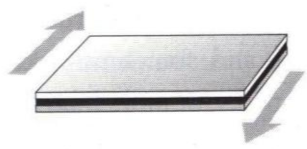
Reverse fault: The movement is still called dip slip, but this time in reverse so the relative movement of rocks above the fault plane is upwards. The angle of the fault plane is still called the dip and is variable, usually in range 35° to 90°, and often 45°.

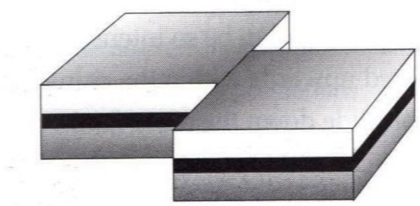
Thrust faults

- If the compression forces are very intense, as in the collision of tectonic plates, thrust faults can develop from reverse faults.
- These are large scale features with dip generally less than 35° and often less than 15° - sometimes called low-angle thrusts
- Sometimes the thrust fault develops from an overfold, which fractures under stress.
- Thrusts can stack up to greatly thicken the crust, in some areas to great thicknesses.



Shear





Strike-slip fault

Strike-slip fault:
The two blocks of rock appear to have slid past each other sideways in opposite directions. The relative movement is horizontal, at right angles to the dip of the fault plane, which is usually vertical!

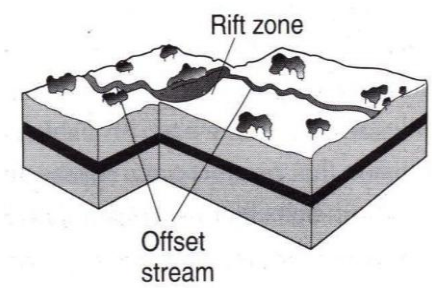
To describe the direction of relative movement, consider a person is facing the fault:

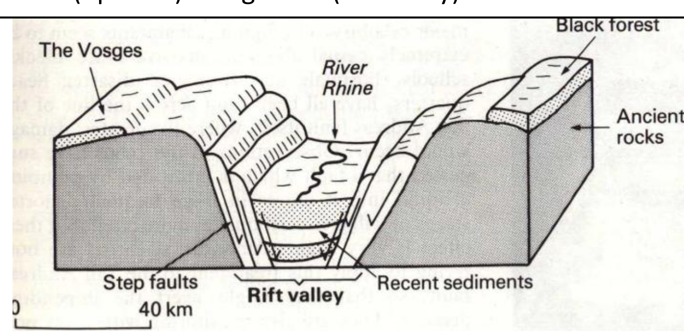
(i) A right lateral or dextral fault has moved rocks to the right on the opposite side of the fault.

(ii) A left lateral or sinistral fault has moved rocks to the right on the opposite side of the fault.

Faults in the landscape

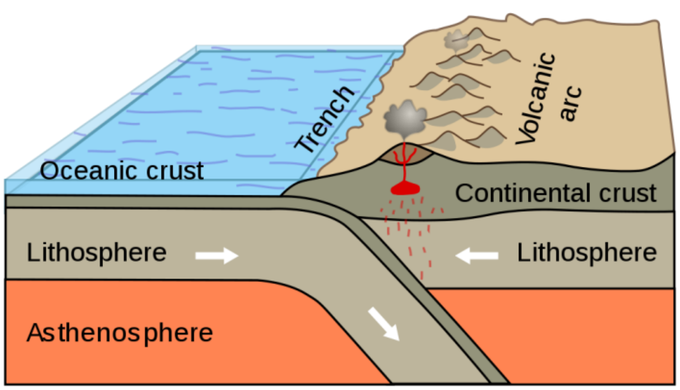
- Normal faults can give rift valley/graben, for example the Rhine Rift Valley, East African Rift Valley, and the Midland Valley of Scotland
- Several close parallel ones form a **fault zone**
- **Fault breccias**: crushed rocks along the fault, usually small angular fragments and fine clays
- **Slickensides:** evidence of grooves, scratches, rock polishing on the fault-plane. Sometimes the direction of movement can be felt by the hand as smoother/rougher direction, apparently!
- Horst (uplifted) and graben (rift valley) structures

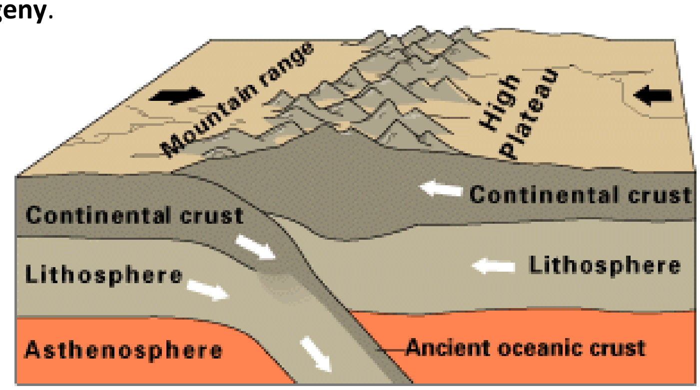




FOLD MOUNTAINS:

- Deformation on a grand scale! E.g. Scottish Highlands
- Result of collisions between moving plates .
- Two plates collide at a destructive plate margin, causing enormous compressional stress.
- Result: a mountain belt, often called fold mountains.
- The event is a mountain-building episode or **orogeny**.





Continental-continental convergence

In British Isles: Caledonian – Scottish Highlands (~400 Ma BP); Variscan – SW England (380-280 Ma BP); Alpine – North and South Downs (50 Ma BP) .
Thrust faulting extends over tens of km, even over 100 km where older rocks thrust up and over younger ones!

In an orogeny:

- **Near the surface** cooler rocks behave in a brittle manner, often producing reverse faults, and less often large-scale thrust faulting.
- Such thrust faulting can extend over tens of kilometres, even rarely over 100 km.
- Thrust faulting can push older rocks up and over younger ones!
- **Deep below** in hotter, more ductile zones, intense folding can occur giving tight isoclinals folds, accompanied by metamorphism.
- If the compression is very intense, the folds can be forced up within the mountain chain and slide down over the flanks to give enormous over-folds called **nappes**.
- Some parts of the nappe are recumbent and some parts inverted. Finding inverted layers can provide evidence of huge nappe structures.
- Recall the Glen Orchy fieldtrip; and in Alps these may be visible on cliffs.
- The metamorphic processes may give a cleavage to the rocks (eg slaty cleavage)
- Folds and cleavage can be used to study the structures and determine whether they are inverted or not.
- Scotland: the Tay nappe and the high grade metamorphism in the Moine Thrust Zone accompanied suggest that the scale of the fold mountains were like the Alps and Himalayas today!

Large strike-slip faults: where two plates or plate fragments are sliding by each other resulting in **shear stresses**. The faults resulting are termed strike-slip or wrench or tear. Examples: San Andreas and Great Glen faults

EARTHQUAKES

- British Isles: 400 each **year**; whole Earth: 1000 every **day,** 80% of which occur in the subduction zones of the Pacific Ocean. Vast majority are mild, but every year over 40 are of moderate strength or higher.
- Involve vibrations of the ground caused by sudden movements as stored energy is released suddenly.
- Analogy: try snapping a stout stick and feel the shockwaves!
- Rocks deform under stress, storing energy under strain and/or by changing shape.
- If they fracture, the energy is released all at once.
- Existing faults can also store energy and then release it as they slip suddenly, reactivating the fault.

Energy Release:

- Stored energy is released when frictional forces between rocks on either side of the fault are insufficient to maintain the rocks in their existing positions.
- The strain is released by fracture or fault movement as a series of jolts.
- This is called **'elastic rebound'** as the rocks stretch and then spring back to their original shape in a new position.

Comparing Earthquakes:

- **Richter Scale** as used in the media. The Richter Local Magnitude Scale (M_L) was devised in 1935 by Dr Charles Richter of the California Institute of Technology.
- Scale from 0 upwards and shows the 'size' or magnitude of the earthquake from the amplitude of the wave measured by an instrument called a **seismometer**.
- The scale records the energy released at the **focus** of the earthquake.
- The scale is logarithmic to base 10, so that an earthquake of magnitude 5.0 has a shaking amplitude **10 times larger** than one of magnitude 4.0.
- But the energy released increases by **30 -35 times** for each integer interval.

Seismic Waves:

- The surface waves cause the most damage.
- But the waves that travel through the body of the Earth give us the evidence of the Earth's deep interior.
- So let's look at:
    - L – waves (Love waves & Rayleigh waves)
    - S – waves (Shear waves)
    - P – waves (Compression waves)

  which all travel at different speeds, and in different ways.

Figure 2.6 *Types of earthquake waves and their properties*

Earthquake wave	Other names	Mode of propagation	Properties
Surface waves	Love, L-waves Rayleigh waves	Lateral and elliptical movement of the surface	Large amplitude, long wavelength, responsible for rolling 'ground motion' that causes most destruction
Primary waves (body waves)	P-waves, push, pressure, compression/ dilatation, longitudinal waves	Compressions and dilatations of particles in direction of wave travel	Faster of the body waves; velocity depends upon density and incompressibility; travel through solids but more slowly through liquids
Secondary waves (body waves)	S-waves, shear transverse waves,	Movement of particles by shear at right angles to wave travel direction	Slower of the body waves; travel through solids only; not transmitted by liquids