GEOLOGY
A2 Level

Interpreting the Geological Record

Topic G2: Rock Deformation

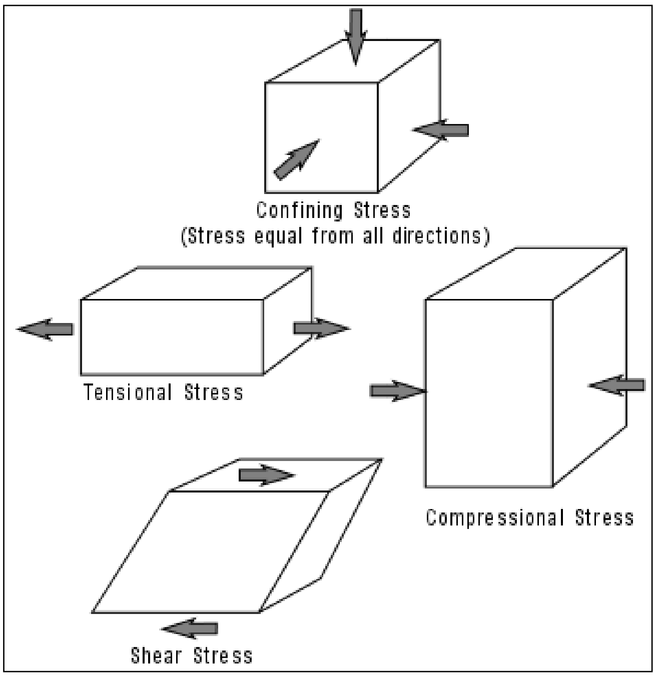
A. Prickett
Whitmore High School

Key Idea 1: Geological structures are formed when rock material undergoes deformation

How do rocks deform?

a) The nature of rock deformation is determined by the **competence** of the **parent rock** and **conditions** during deformation (*temperature*, *confining pressure* and *strain rate*)

Rock deformation results when rocks undergo permanent strain in response to applied tectonic stresses. **Stress** is the force applied per unit area and therefore has units of Force/area (like g/cm^2). Pressure is a stress where the forces act equally from all directions. If stress is not equal from all directions, then we say that the stress is a differential stress. Three kinds of differential stress occur:

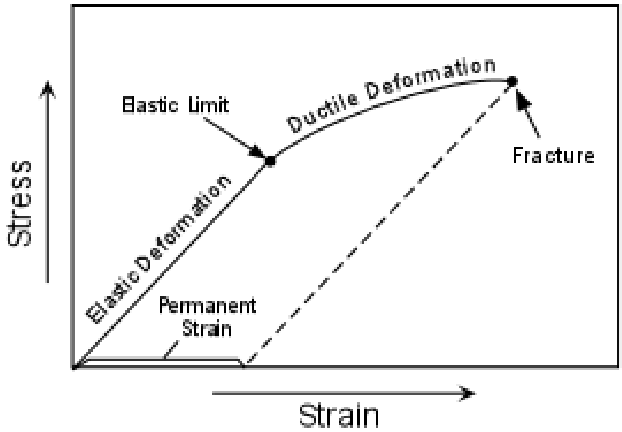


1. ***Tensional stress (or extensional stress)***, which stretches rock.
2. ***Compressional stress***, which squeezes rock.
3. ***Shear stress***, which results in slippage.

When rocks deform they are said to **strain**. A strain is a change in size, shape, or volume of a material.

Stages of Deformation

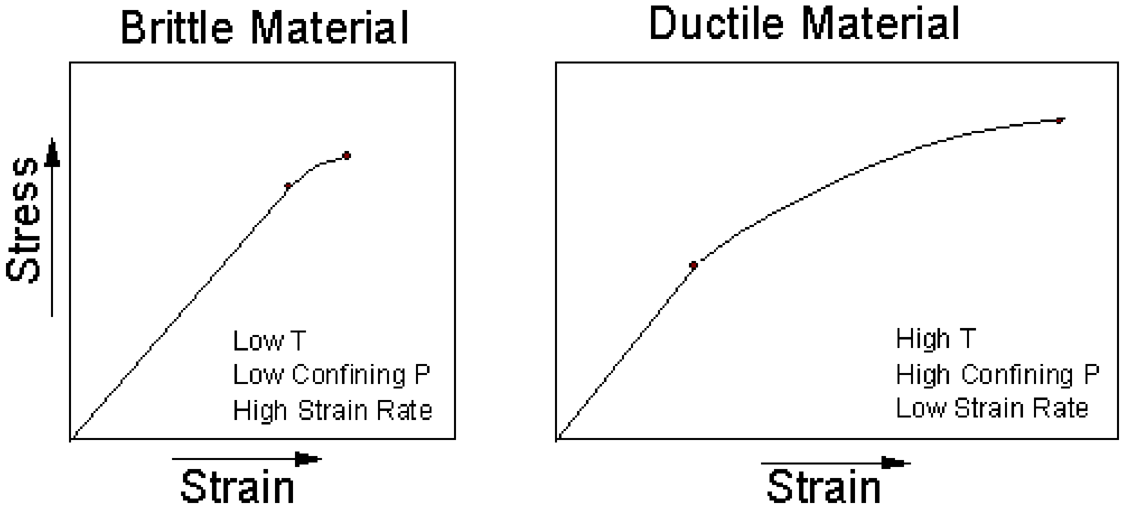
When a rock is subjected to increasing stress it passes through 3 successive stages of deformation:



- **Elastic Deformation** -- where the strain is reversible.
- **Ductile Deformation** -- where the strain is irreversible.
- **Fracture** - irreversible strain where the material breaks.

We can divide materials into two classes that depend on their relative behaviour under stress:

- Brittle materials have a small or large region of elastic behaviour but only a small region of ductile behaviour before they fracture.
- Ductile materials have a small region of elastic behaviour and a large region of ductile behaviour before they fracture.



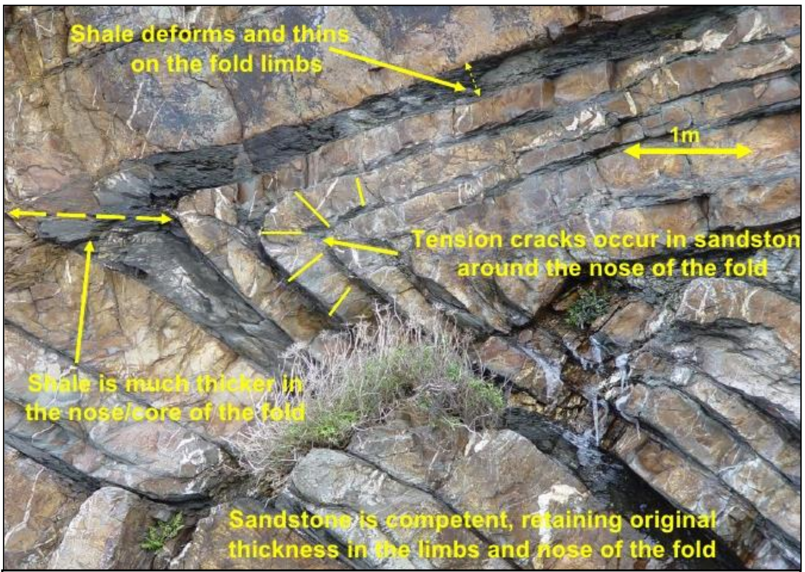
<u>Factors affecting the type of Deformation</u>

How a rock behaves will depend on several factors? Among them are:

- **Temperature** - At high temperature molecules and their bonds can stretch and move, thus materials will behave in more ductile manner. At low Temperature, materials are brittle. Temperatures increase with depth inside the crust (geotherm), as a result rocks are more likely to behave in a ductile way at depth and a brittle way near the surface.
- **Confining Pressure** - At high confining pressure materials are less likely to fracture because the pressure of the surroundings tends to hinder the formation of fractures. At low confining stress, material will be brittle and tend to fracture sooner. As a result, rocks are more likely to deform near the surface where confining stresses are lower. Rocks are more likely to be ductile at higher confining pressures.
- **Strain rate** - At high strain rates material tends to fracture. At low strain rates more time is available for individual atoms to move and therefore ductile behaviour is favoured. So the lower the strain rate the more likely that ductile behaviour is.

Finally, the **composition** of the material (rock) will determine the way in which it behaves. Some minerals, like quartz, olivine, and feldspars are very brittle. Others, like clay minerals, micas, and calcite are more ductile. This is due to the chemical bond types that hold them together. Thus, the mineralogical composition of the rock will be a factor in determining the deformational behaviour of the rock. Another aspect is presence or absence of water. Water appears to weaken the chemical bonds and forms films around mineral grains along which slippage can take place. Thus wet rock tends to behave in ductile manner, while dry rocks tend to behave in brittle manner.

When sequences made up of different rock layers like sandstone and shale are compressed, these rocks deform in different ways. **Sandstone** is usually a stronger **competent** rock and is more likely to hold its structure and then fracture during deformation, whereas **shale** in **incompetent**. This means the shale is usually more ductile and clay particles within in are more likely to flow during deformation.



Folded shale and sandstone beds at Millook Haven in Cornwall

Folding

b) **Fold characteristics**; amplitude, wavelength, inter-limb angle, (open, tight, isoclinal), axial plane attitude (upright, inclined, overturned, recumbent) and plunging folds.

Folding occurs when tectonic stresses exceed the **yield strength** of the rock layers.

There are a number of standard terms used to identify the characteristic features of geological folds:

- Fold limbs
- Hinge
- Axial plane
- Axial plane trace

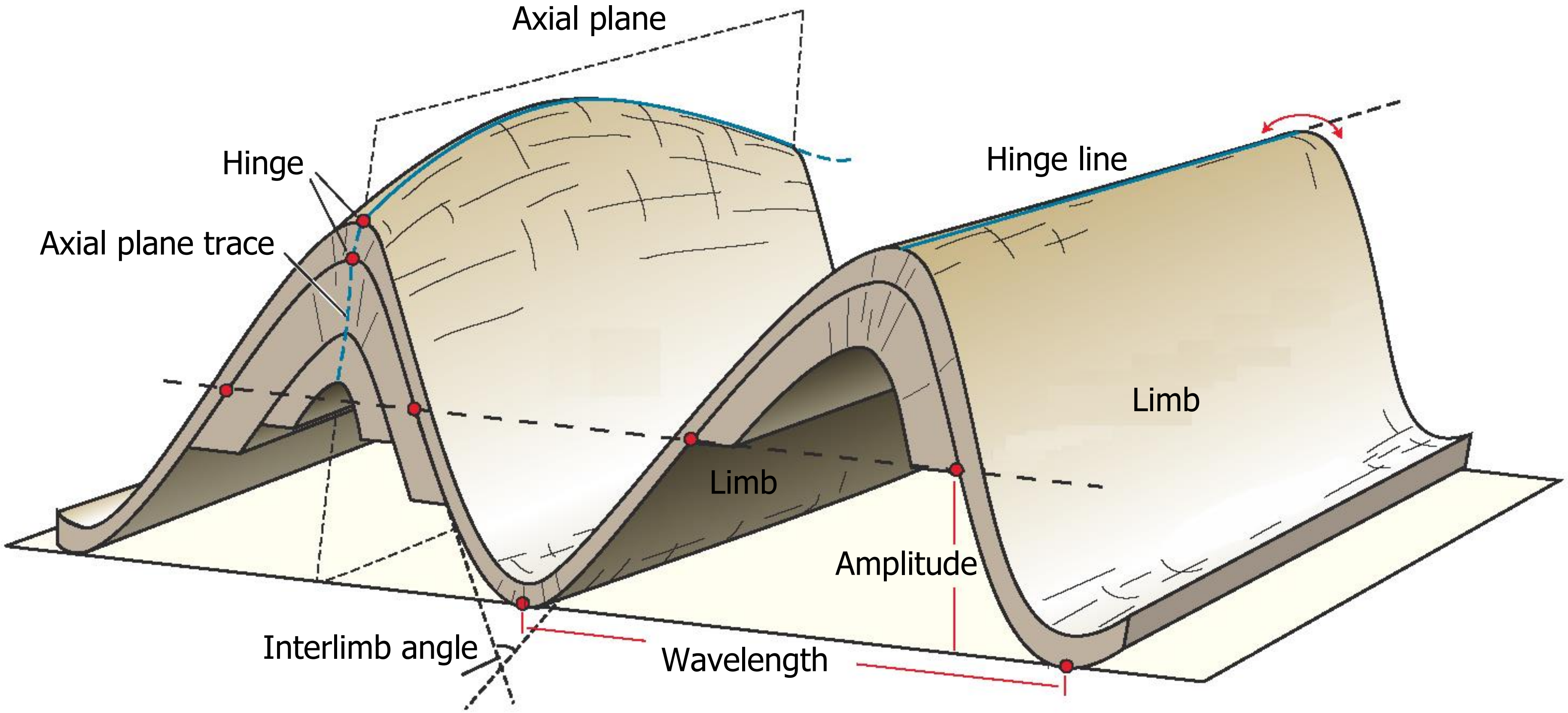
You should be able to **recognise** each of these in photographs, maps or block diagrams of fold structures

And also terms used to measure various elements of folds:

- Interlimb angle
- Wavelength
- Amplitude
- Plunge

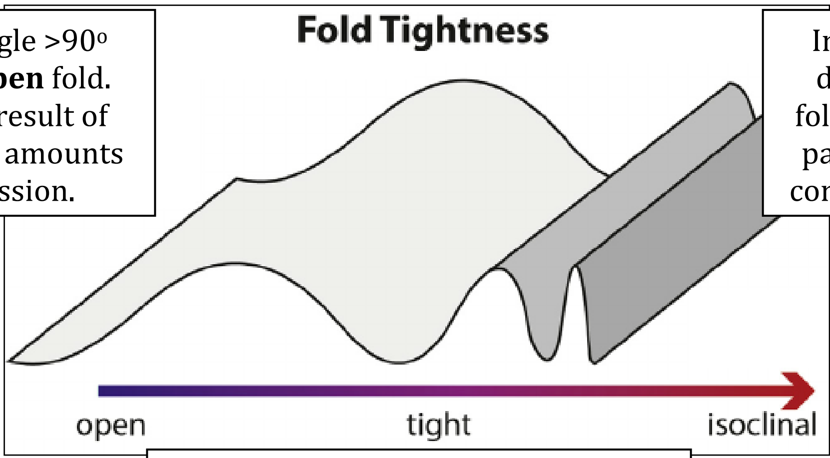
You should be able to **measure** each of these on diagrams, maps or from photographs of folding

Fold Terminology



* Based on the interlimb angle there are three main categories that all folds can be placed into:

Interlimb angle >90º defines an **open** fold. Usually as a result of relatively low amounts of compression.

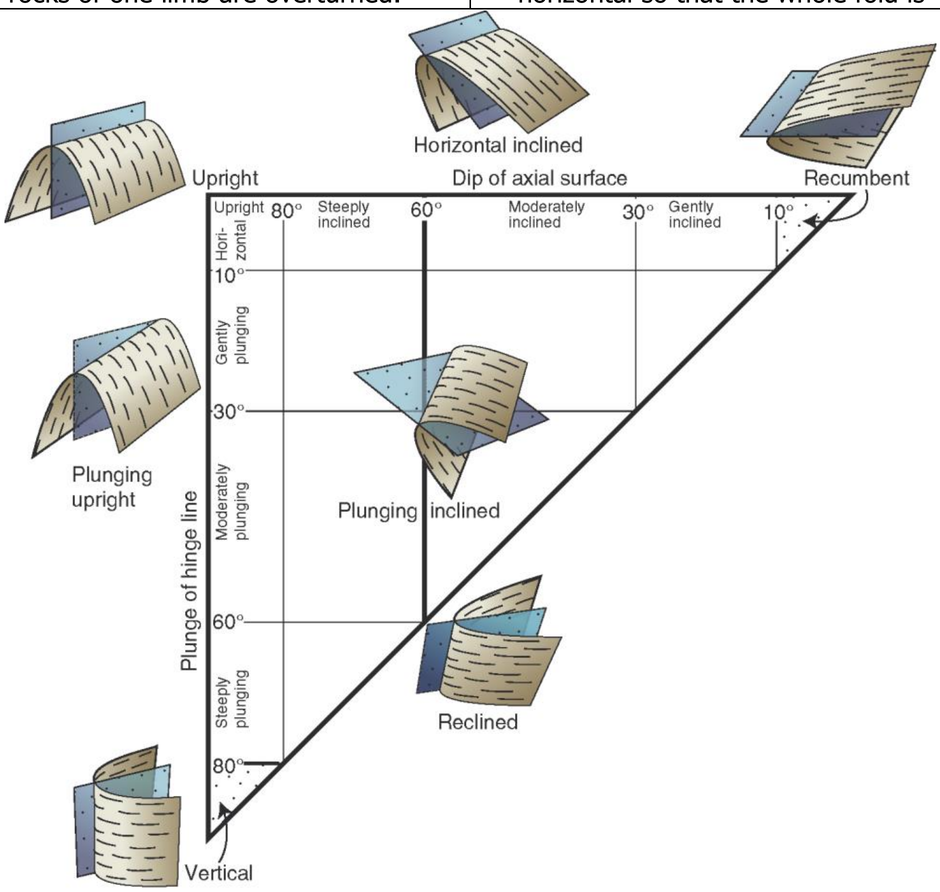


Interlimb angle of 0º defines an **isoclinal** fold. The fold limbs are parallel. From intense compressional stresses.

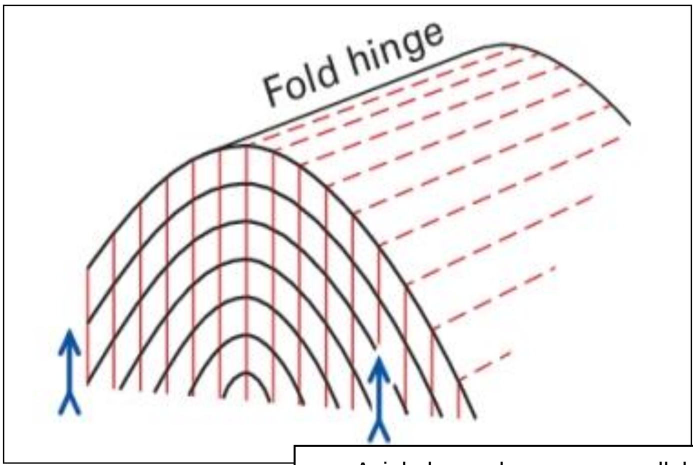
Interlimb angle <90º defines a **tight** fold. Usually as a result of quite large amounts of compression.

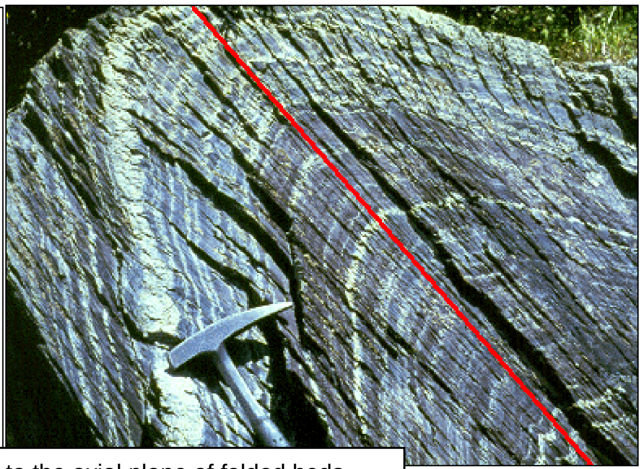
* Finally, the attitude (orientation) of the axial plane of a fold will define its type as well:

<u>Upright folds</u> These are defined by having a vertical and non-plunging axial plane.	<u>Inclined folds</u> Have a dipping axial plane surface, but the axial plane trace (hinge line) may be plunging.
<u>Overturned folds</u> This is where the axial plane is inclined to a point where the rocks of one limb are overturned.	<u>Recumbent folds</u> These occur where the axial plane surface is horizontal so that the whole fold is 'lying down'.



When rock layers are folded, those on the surface of the bed at the hinge of the fold will undergo more tension than those at the base of the bed (which will actually be compressed). This result of this tension or stretching of the rock near the surface will be the formation of **axial planar cleavage** (cracks formed roughly parallel to the axial plane of the fold).

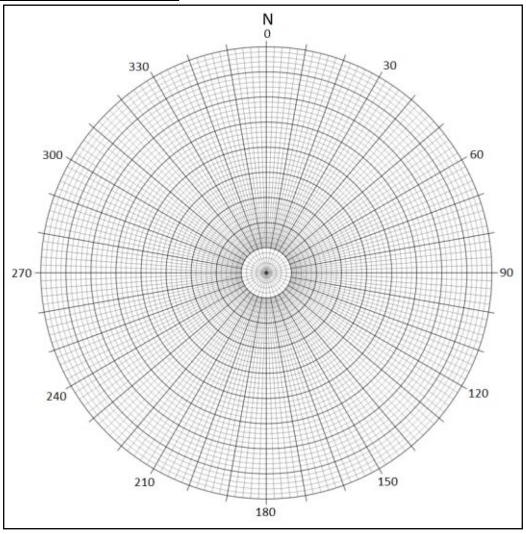




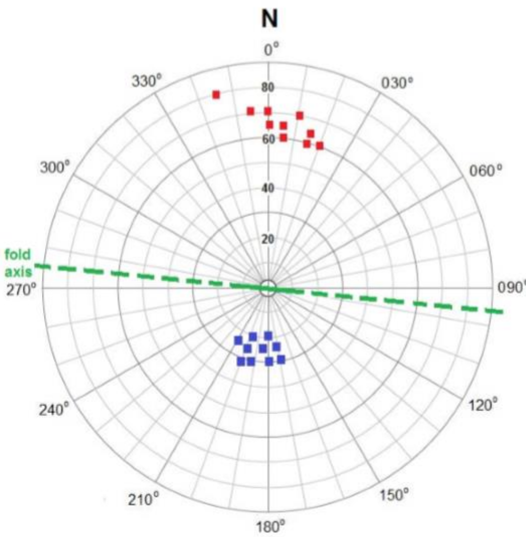
Axial planar cleavage – parallel to the axial plane of folded beds

<u>Plotting dip and strike data on a Polar Equal Area Stereonet</u>

A polar stereonet is a graph (similar to a rose diagram) on to which a variety of geological data can be plotted and analysed. It gives a visual display of trends and amounts but has a drawback for folded strata. If this method is used to plot dip directions on either side of a fold or series of folds, the type of fold (antiform or synform) will not be obvious. Although the dip directions of the limbs are shown, there is no indication as to whether the limbs are dipping towards or away from each other unless further annotation is given.



Azimuth/Dip angle (°)	Azimuth/Dip angle (°)
North dipping limb	South dipping limb
000/71	169/30
001/65	171/24
005/65	179/30
007/60	180/19
011/70	185/24
015/60	193/30
016/64	198/20
020/60	199/26
345/80	200/32
353/72	210/25



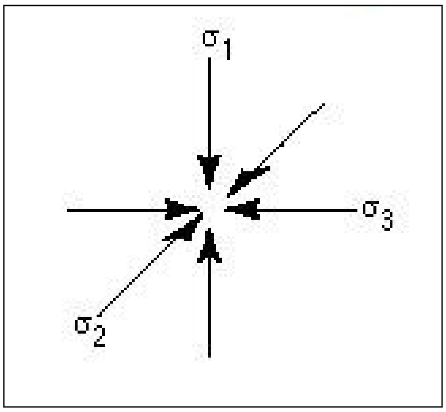
Faulting

c) Fault type is determined by the orientation of the principal stresses. Technical terms to describe fault elements: slickensides, fault gouge, fault breccia.

<u>Principal Stresses</u>

The type of faulting that rocks undergo is defined by the principal stresses exerted on the rocks. Remember that **stress** (shown as σ or ρ) is a force applied to a rock per unit area. **Strain** is the resulting change in shape of a rock as a result of applied stresses.

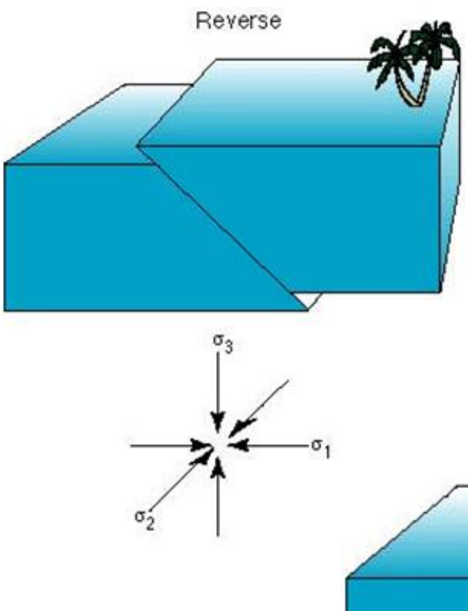
The three principal stress directions are at 90° to one another and are recorded as maximum (σ or ρ max), Intermediate (σ or ρ int) and minimum (σ or ρ min).

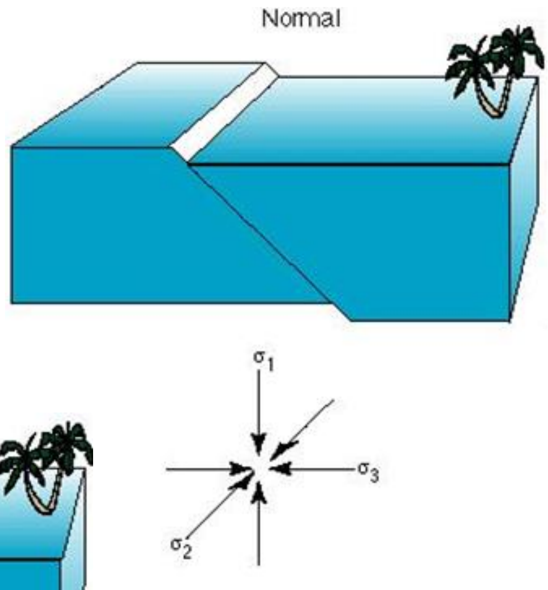


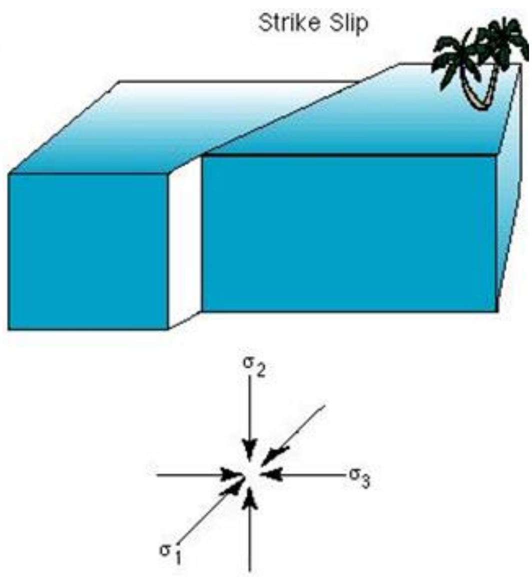
The Maximum stress direction refers to the maximum compression. Whereas, the minimum stress direction refers to the greatest tensional stress.

So in effect we are referring to only the **compressional** stresses applied to rocks.

<u>Principal Stresses for each major fault type</u>

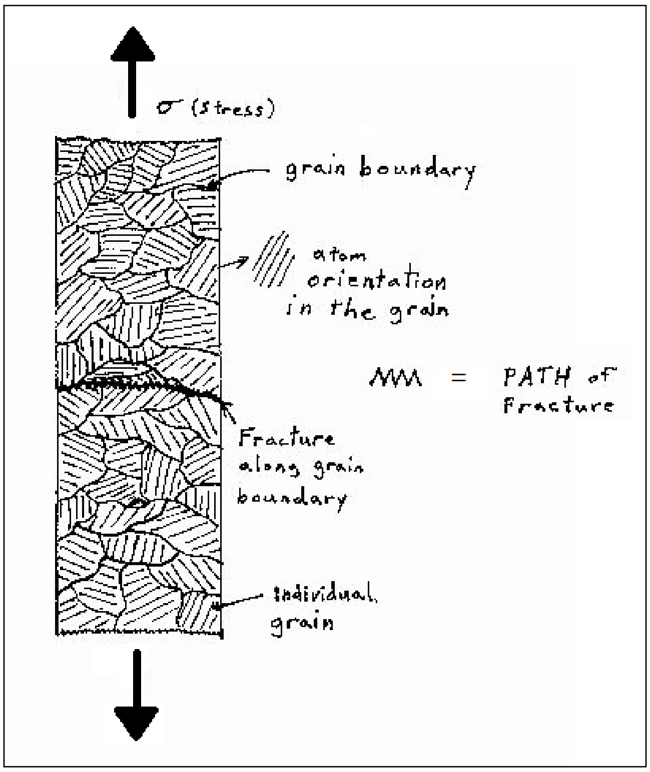






Annotate these to explain the differences.

Due to applied stresses rocks will actually break/fracture due to a process known as **intergranular fracture**. As stresses increase so the bonds between mineral grains are weakened.

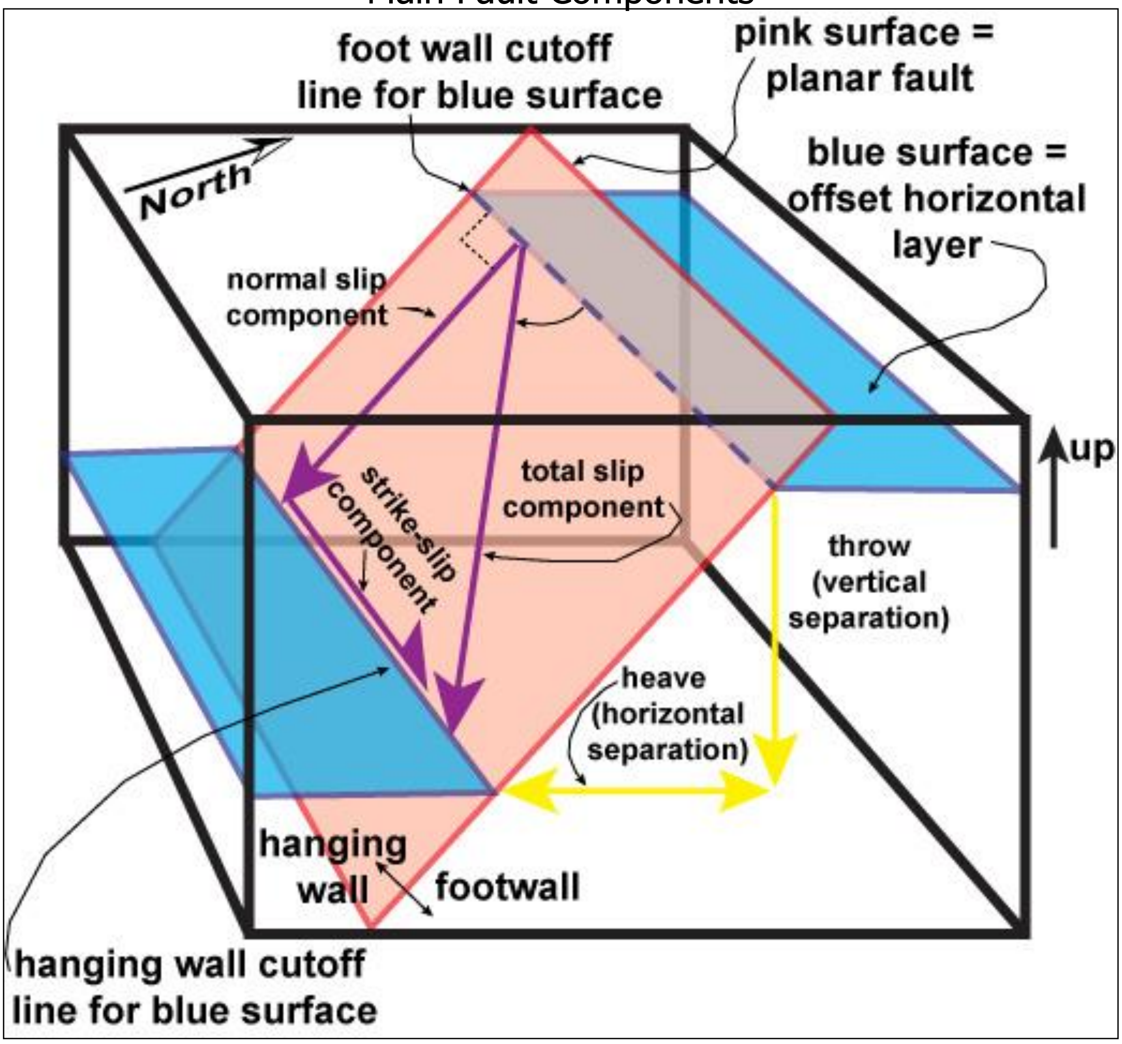


<u>Key fault terminology</u>

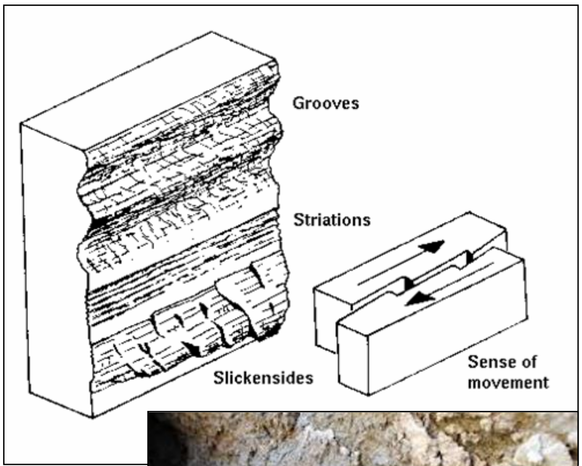
There are a number of key terms used to describe either elements of the structure of a fault or the rocks and features produced as a result of faulting:

* Fault plane	* Hanging wall
* Footwall	* Upthrow
* Downthrow	* Displacement
* Throw	* Heave
* Slickensides	* Fault breccia
* Fault gouge	* Mylonite

Main Fault Components

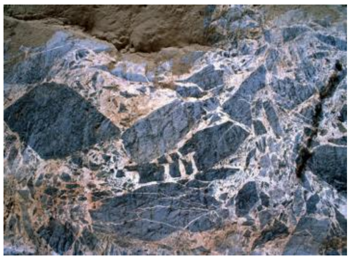


Slickensides form when one surface of rock slides over another (along a fault plane), thus developing scrape marks. These are linear grooves and ridges parallel to the direction of fault movement. They record the last direction of movement only and are bi-directional. Evidence of previous movements can be destroyed (scraped away).
Slickensided surfaces are often coated with a layer of minerals produced by the breakdown of the original rock, or from mineral rich water flowing along the fault plane.



Finally, there are three distinct rocks types (we have dealt with previously when studying dynamic metamorphism) that form due to intense pressure along or near to fault planes.

- Fault Breccia - At shallow levels in the crust, **brittle** deformation dominates and is characterised by **competent** rocks (such as sandstone and limestone) which are shattered to form **fault breccia**. This occurs along fault planes where shearing of the rocks has occurred. This often creates an easy path for groundwater to flow, causing mineralisation (calcite and quartz are common) along the fault plane cementing the fault breccia together.



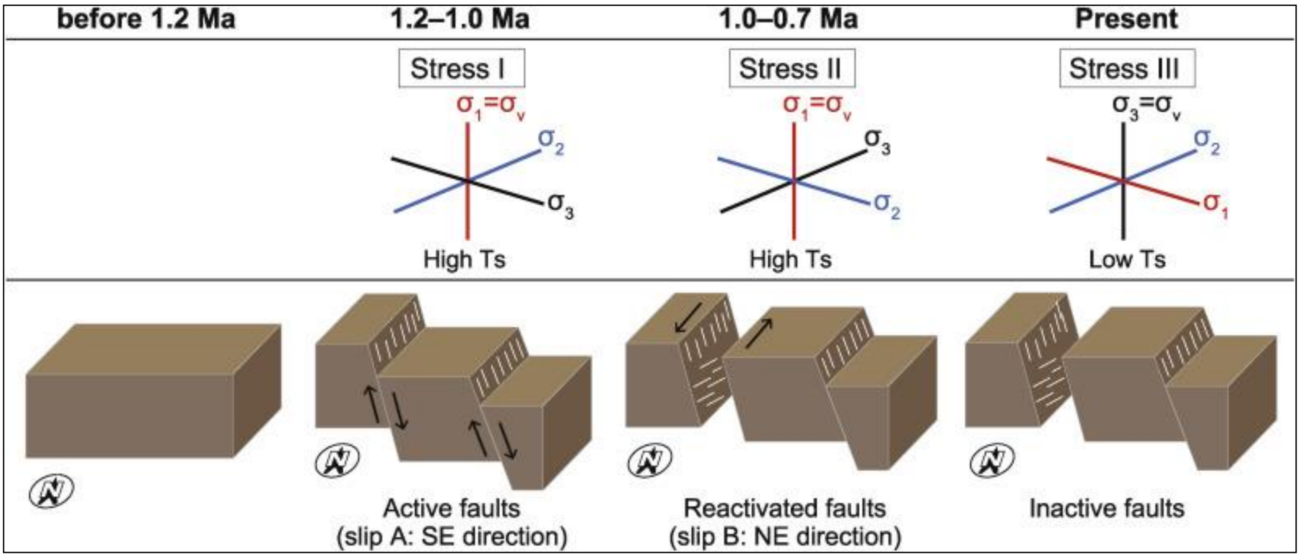
- Fault Gouge – However, **brittle** deformation of **incompetent** rocks (such as shale or clay) will form **fault gouge** (sometimes known as rock flour). This is a fine mixture of clay minerals and silt particles which have flowed along the fault plane under pressure.

- Mylonite – During intense, prolonged shearing at deeper levels in the crust, **ductile** deformation will occur along a fault plane. Individual crystals within the rock become separated and the whole rock becomes more and more fine-grained, often developing a crude foliation. This rock formation through intense 'flowing' is known as **mylonite**.

Structural reactivation

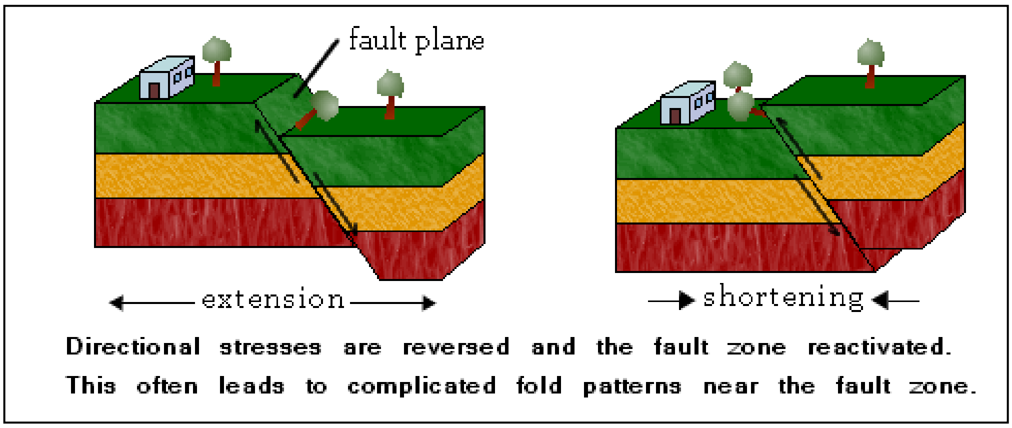
d) Earlier-formed faults can be reactivated during later tectonism; folds may be refolded. Structural inversion: reactivation of normal faults in compression or reverse faults/thrusts in extension.

Reactivated faults form when movement along formerly inactive faults can help to alleviate strain within the crust or upper mantle.



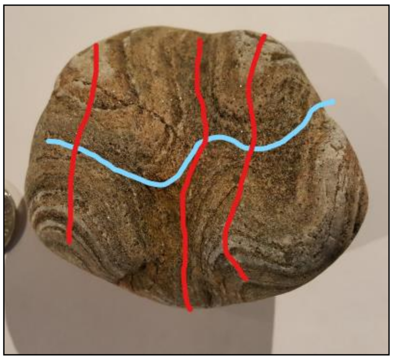
Faults can also be inverted or changed as the stresses change. These **fault inversions** occur when an existing fault is subject to changing forces:

Normal faults are suddenly compressed (squeezed) see below and reverse faults are suddenly extended (stretched)



Reactivated faults will have slickensides which only record the last direction of movement as all previous evidence will be destroyed.

Rocks can also become **refolded** after many millions of years if they are subject to near periods of compressional stresses. If these stresses are from different directions, then unusual rocks like the one to the right can be formed with different folds preserved within them.



Structures on geological maps

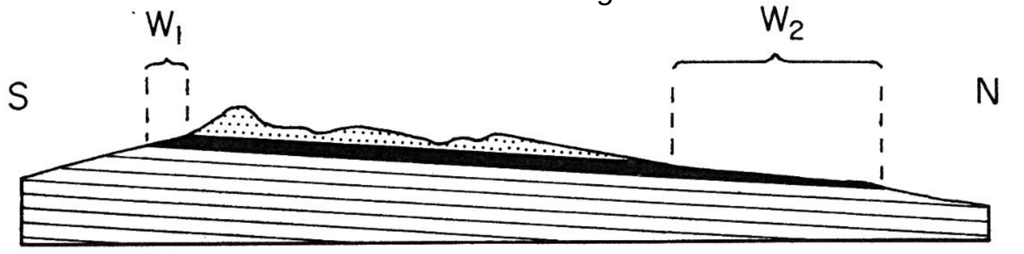
e) The nature of outcrop patterns formed by the intersection of geological structures with a topographic surface are displayed on geological maps.

Outcrop thickness

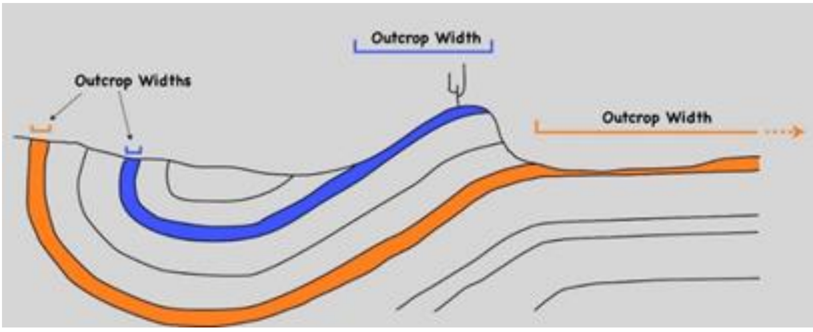
This can vary based on the angle of dip or the topography of the area:

1) The width of the outcrop will vary depending on the shape of the landscape (topography).

Cross-section through a hill.

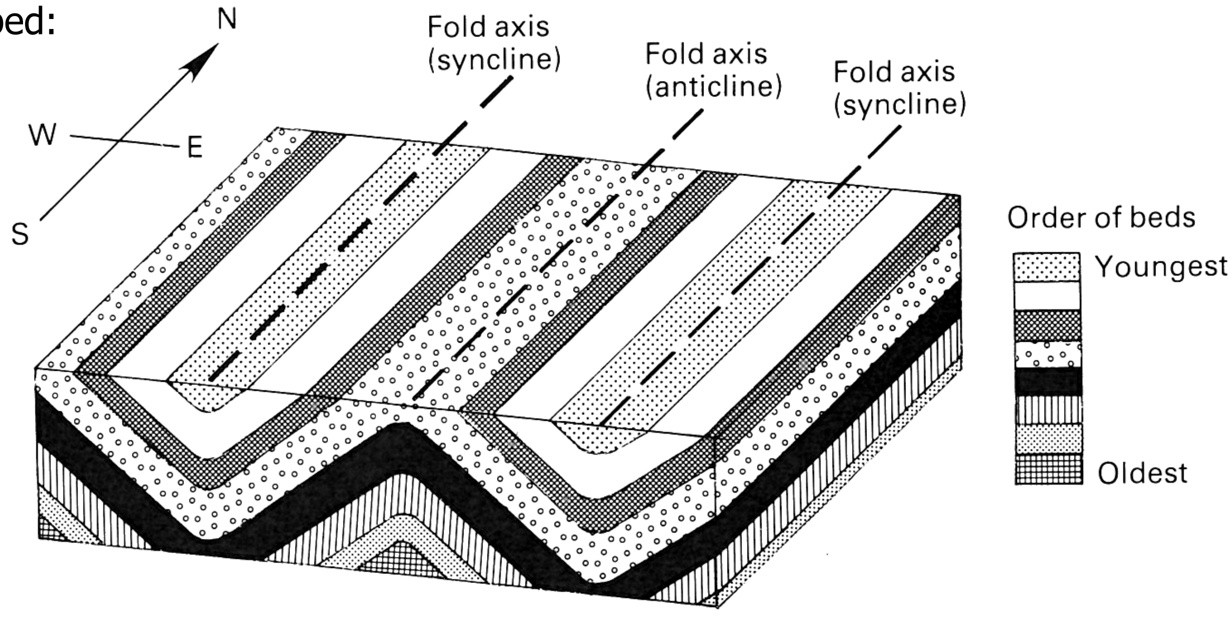


2) The angle of dip can also have an effect on the width of outcrop.



Folds

Folds can be identified by looking for repeating beds either side of a central bed:

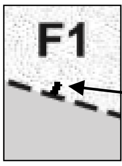


Faults

To identify fault type and orientation a number of clues need to be looked for. Faults are marked on geological maps with a dashed or thick black line. Their outcrop pattern depends on the angle of dip of the **fault plane**:

The downthrown side of a fault (only dip-slip faults) can be determined by:

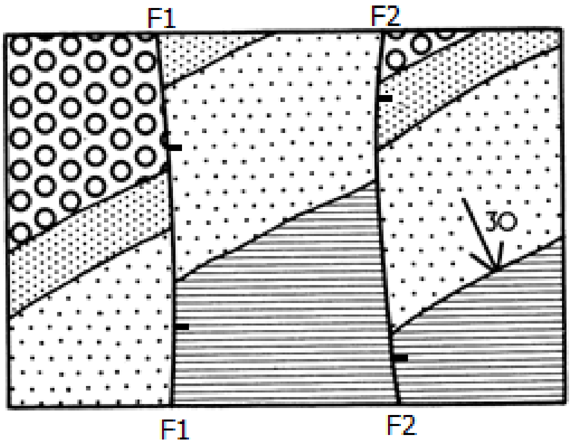
- A small tick on the fault line on the map (check the key).
- The younger rock will outcrop on the downthrown side of the fault.



* Fault F2 must downthrow to the E

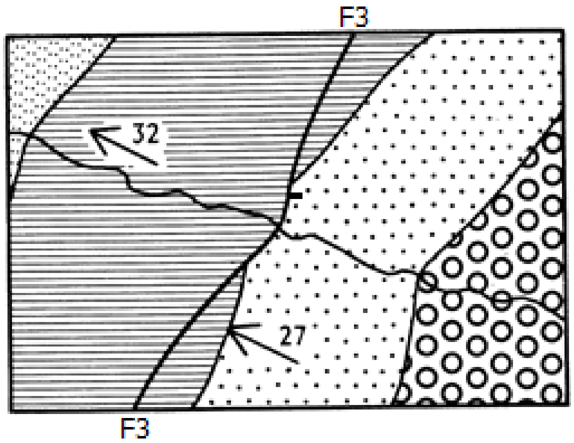
* Fault F1 must have younger rock to the NE

Examples:



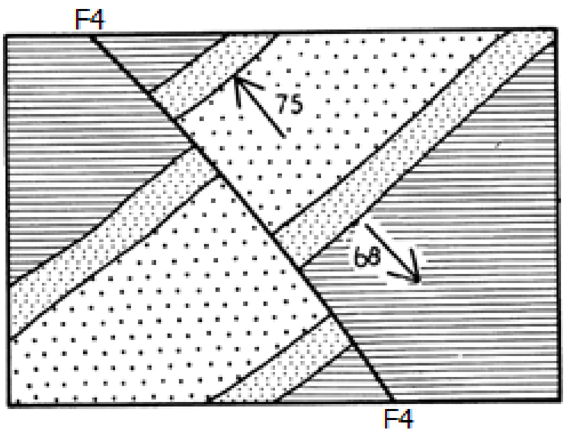
Both faults dip steeply to the East

Fault types: **Normal**
Reason: Both fault plane dip and downthrow are in the same direction.



The fault dips at 30° to the West

Fault type: **Reverse**
Reason: The fault plane dips in the opposite direction to the downthrow.



The fault is vertical

Fault type: **Strike slip**
Reasons: The fault plane is vertical and the beds are clearly displaced horizontally. The axial plane trace of the antiform is also laterally displaced. Beds could be slid back into position.

Calculating the dimensions and orientation of beds

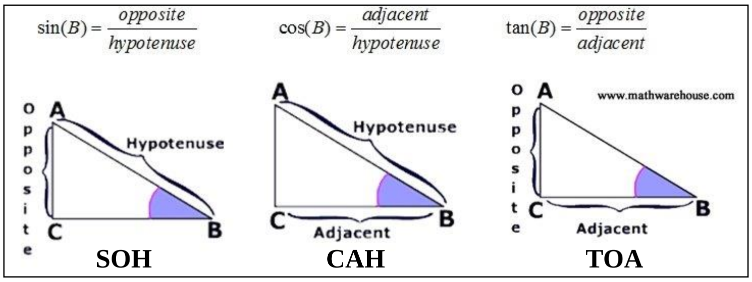
The diagram below is a cross section through a dipping bed where:

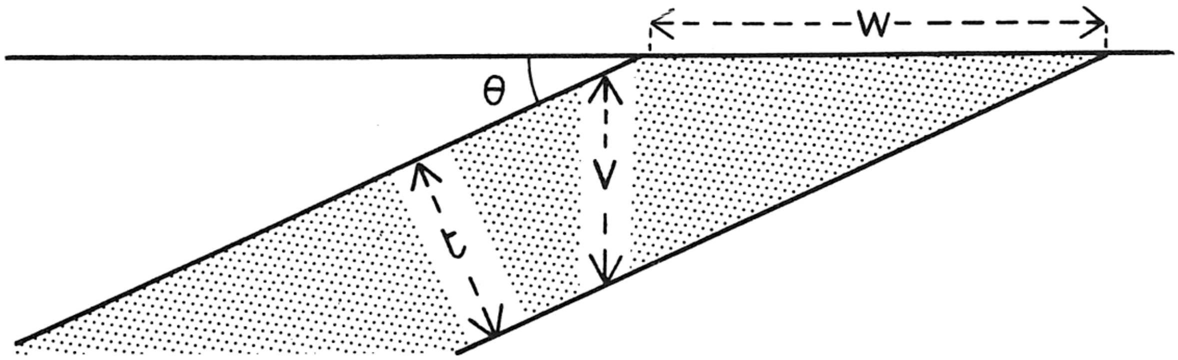
W is the outcrop width

t is the true thickness of the bed

V is the vertical thickness of the bed

θ is the angle of dip





Show how you can use trigonometry to work out the value for each of the four variables using the other variables. (Remember **SOHCAHTOA**)

W =

t =

V =

θ =