Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 21. Brittle Structures

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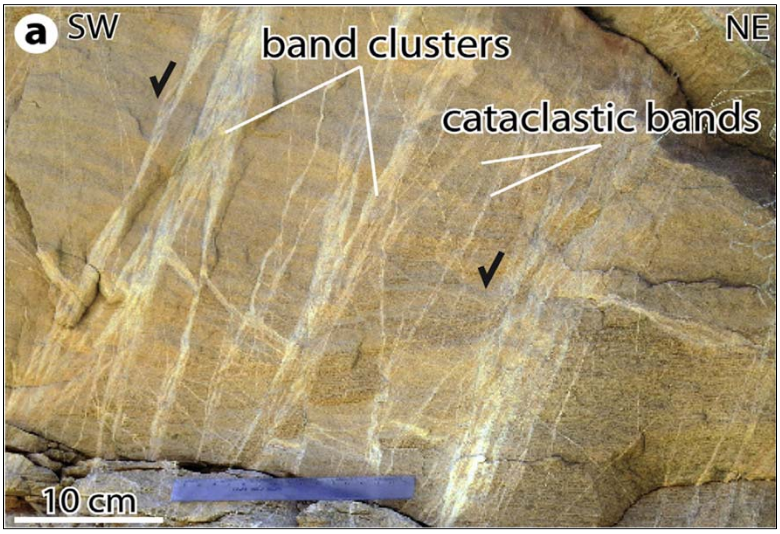
Experimental Rock Deformation Laboratory

Brittle Deformation

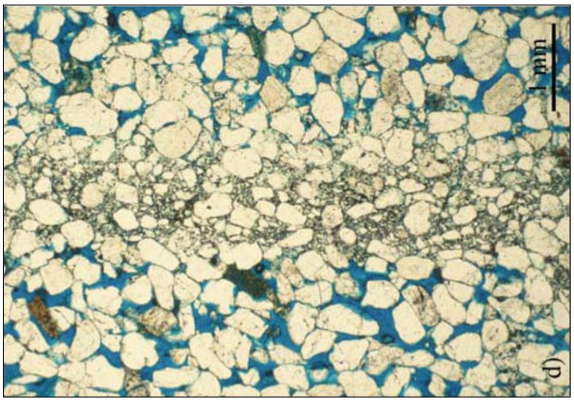
- Combination of brittle fracture and frictional sliding of grains
- Activated when the shear / tensile strength of the rock is exceeded
- A mechanism of low temperature
- No internal distortion of crystal/lattice structures
- Pressure sensitive deformation
- Commonly observed in upper crust
- Characterized by Fracturing at any scale

Compaction Band

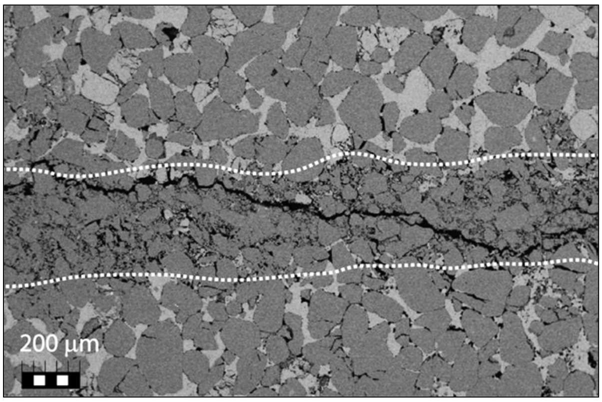


Ballas et al., 2015

Compaction Band

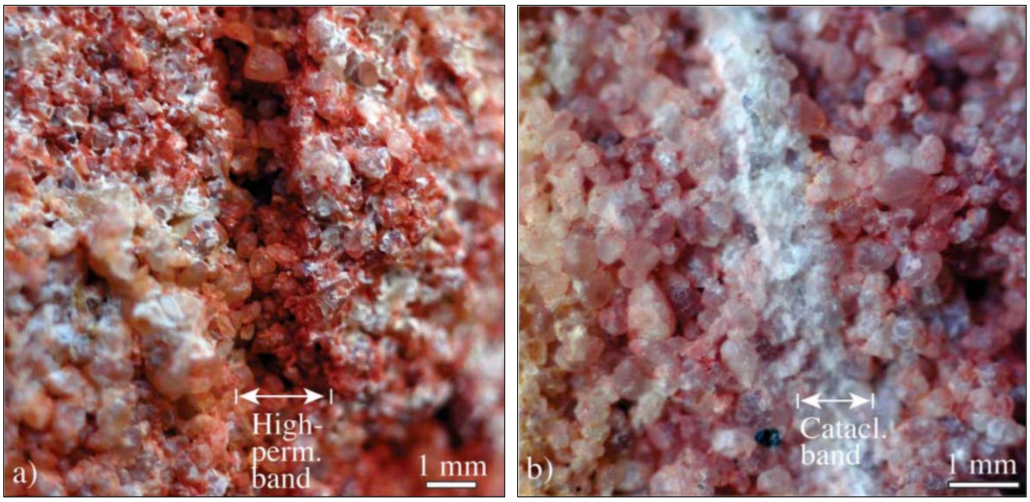


Fossen et al., 2014



Skurtveit et al., 2014

Compaction Band



Fossen et al., 2007

Brittle Failure Criteria

- During brittle fracturing, rocks can deform either by creating new fractures or by can deform along pre-existing fractures. In both cases friction plays an important role.
- Brittle fracturing is commonly described with the **Mohr-Coulomb criterion**.

$$\tau_c = S + \mu(\sigma_n - P_f)$$

τ_c = critical shear stress for fracturing
S = cohesion of the material
μ = co-efficient of friction
σ_n = normal stress acting on the fracture surface
P_f = pore fluid pressure

- If the there is any pre-existing fracture in the rock, the rock has no cohesion and S = 0 (*Amontons Law*).

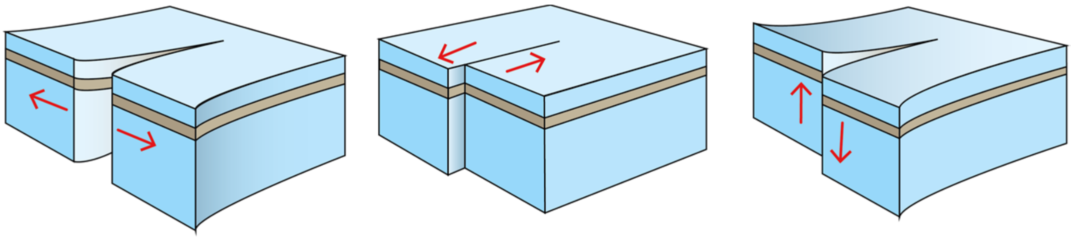
Note: The Mohr-Coulomb criterion describes only a critical state of stress, at which fracturing occurs. It does not place a relationship between stress and strain and is therefore not a constitutive relationship of rheology (flow law)

Types of Fractures

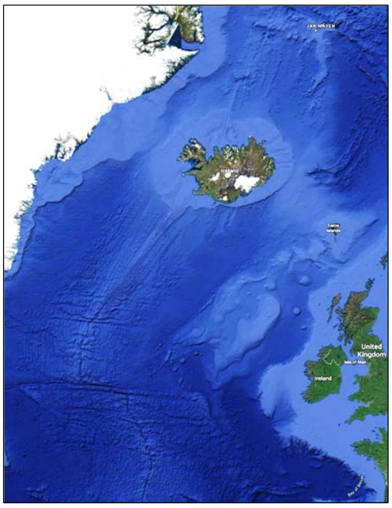
Mode I: Opening mode (a tensile stress acting normal to the plane of the crack)

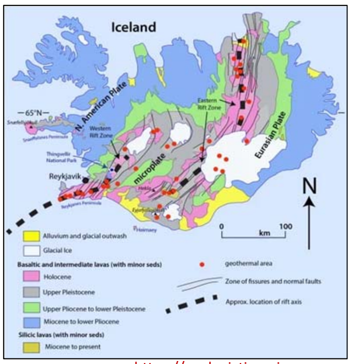
Mode II: Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front)

Mode III: Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front)



Mode I Fractures

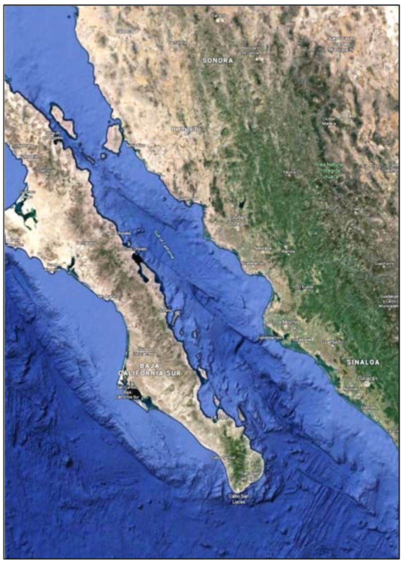


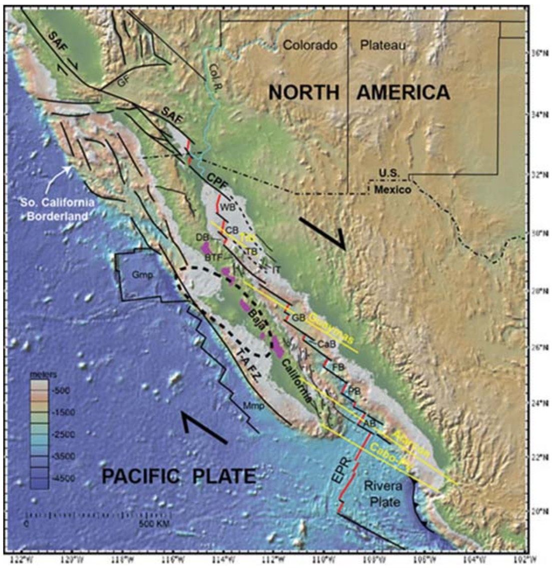


https://geologictimepics.com

Iceland's rift valley in Thingvelir, marks the crest of the Mid-Atlantic Ridge

Mode II Fractures





http://geoprisms.org

Some typical Mode I structures

Joints

Veins and dikes

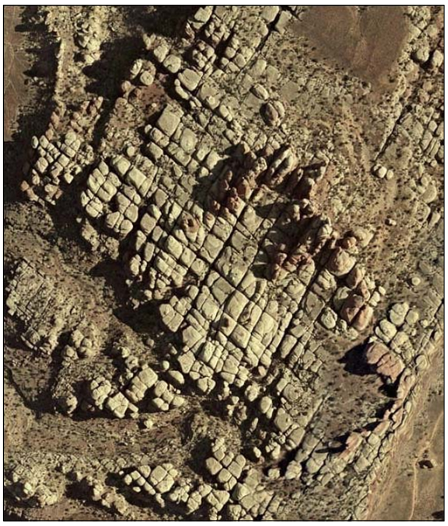
Boudinage and Pinch-and-Swell (*ductile*)

Joints

- Joints (Mode-I fractures) are planes of separation on which no or undetectable shear displacement has taken place. The two **walls** maintain tiny opening (*aperture*) and typically remain in tight (matching) contact.
- Joints from due to
  - regional tectonics (i.e. the compressive stresses in front of a mountain belt),
  - folding (due to curvature of bedding),
  - faulting, or
  - internal stress release during uplift or cooling.
- The growth of Joints is controlled by the thickness of the deforming rock. Apertures can be open (resulting in permeability enhancement) or occluded by mineral cement (resulting in permeability reduction). A joint with a large aperture (> few mm) is a **fissure**.
- If present in sufficient number, open joints may provide adequate porosity and permeability in an otherwise impermeable rock - > a productive **fractured reservoir**.

Set of Joints

http://whattherockstellus.blogspot.com



https://structuralgeo.files.wordpress.com

Set of Joints

Photograph: Santanu Misra

Veins and Dikes

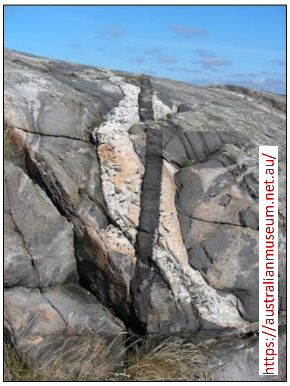
A dike (also dyke), is a sheet of rock that is formed in a fracture of a pre-existing rock body.

Dikes can be either magmatic or sedimentary in origin.

Magmatic dikes form when magma flows into a crack then solidifies as a sheet intrusion, either cutting across layers of rock or through a contiguous mass of rock.

Clastic dikes are formed when sediment fills a pre-existing crack

diabase dike intrusions

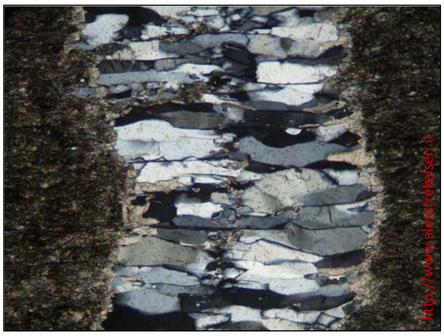


An igneous intrusion cut by a pegmatite dyke, which in turn is cut by a dolerite dyke (Koster Islands in Sweden)

Veins and Dikes

Veins in rocks are practically the same as dikes; yet a distinction is sometimes made that dikes are narrow, often straight-walled and run for considerable distances, while veins are irregular, discontinuous and of limited extent.

Extension fractures



Quartz vein in shale; width of the image: 2mm

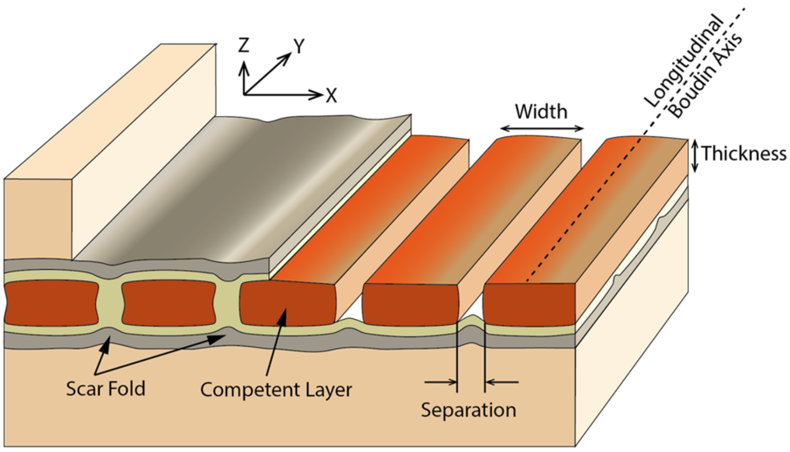
Boudinage

Marble with pelitic boudinaged layers
[Width of the image: ~ 50cm]

Boudinaged allanite crystal.
Width of the image: 7mm

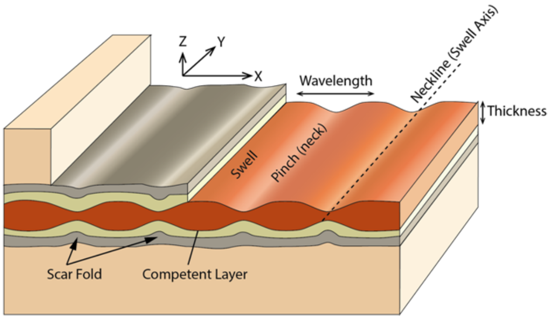
Boudinage

- Stretching, necking and eventually segmentation of a layered body surrounded by a less competent (i.e., more deformable) matrix develops side by side, sausage-shaped bodies, the ***boudins***. A structure found in low grade metamorphic rocks.



Pinch-and-swell Structure

- At higher grades, and sometimes in unconsolidated rocks, the competent layers have generally not broken through; narrow, thinned necks separate and alternate with boudins of relatively still, thick layers. The resulting structure is called ***pinch-and-swell***.



- After separation, the disconnected layer segments display lens- or pillow-shaped forms. Extreme stretching reduces necks to very thin and long selvage of the layer connecting variably shaped swells.

https://www.unil.ch

Some typical Mode II structures

Faults

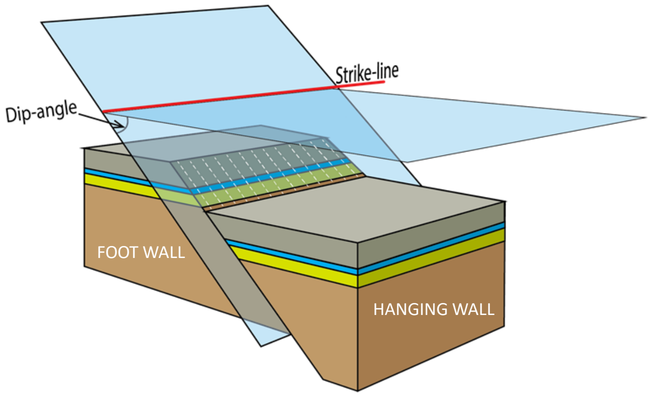
Basics and Definitions

- **Faults** are defined when two adjacent blocks of rock have moved past each other in response to induced stresses. The notion of localized movement leads to two genetically different classes of faults reflecting the two basic responses of rocks to stress: **brittle** and **ductile** (and **Brittle-ductile**).

- **Brittle Faults** are fracture discontinuity along which the rocks on either side have moved past each other in a direction parallel to the fracture plane. A low PT feature.

- **Ductile Faults** (commonly known as **Shear Zones/Ductile Shear Zones**) are narrow zones of localized but continuous ductile displacement between two blocks without developing any fractures at the scale of observation. A high PT feature.

Brittle Faults: Terminologies

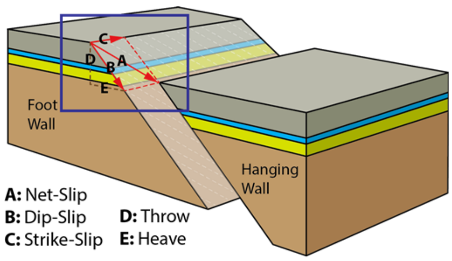


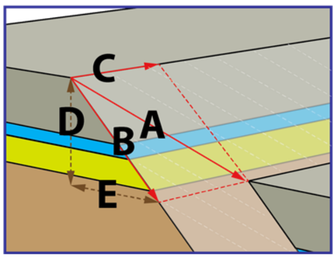
- In outcrop scales, faults generally appear as straight planes. In general, fault surfaces are curved in large scale (seen in 3D seismic data). The fault corrugations thereby identified are attributed to the linkage of fault-segments through time.

- The rock immediately above and below a non-vertical fault or shear zone is referred to as the **hanging wall** and the **foot wall** of the fault, respectively.

- Fault dip > 45° **high angle faults**
  Fault dip < 45° **low angle faults**.

Basic Terminologies of Brittle Faults





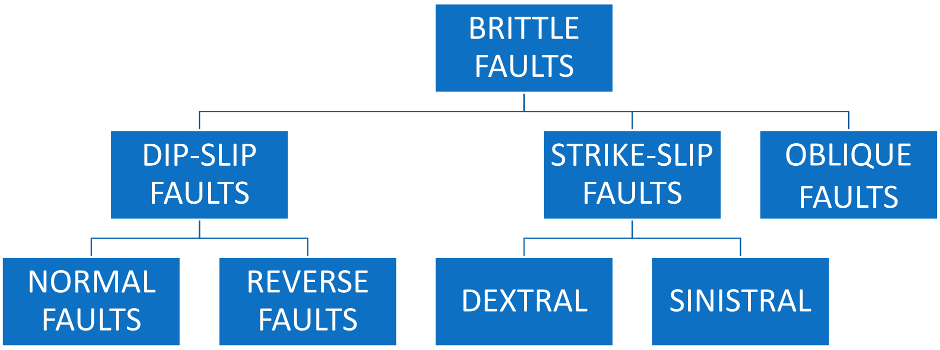
- **Net-slip** (**A**) is the direction of movement of the hanging wall relative to the footwall. Its length provides the amount of displacement on the fault, which generally is the addition of several movements.

- The components of the net-slip along dip and strike directions are **Dip-slip** (**B**) and **Strike-slip** (**C**), respectively.

- The offset shown by a planar feature in a vertical cross section perpendicular to the fault is called the **dip separation**. The vertical component of the dip separation is the **throw** (**D**) and the horizontal component (perpendicular to the fault strike) is the **heave**. (**E**).

Note: the dip separation is not equivalent to the dip slip

Basic Classification of Brittle Faults



Basic Classification of Brittle Faults

NORMAL FAULT

A **normal fault** is a high angle, dip slip fault on which the hanging-wall has moved down relative to the footwall. A normal fault brings younger rocks over older ones. Because of the separation of geological horizons that results from normal faulting, such faults are also termed **extension faults**.

⇧ **DIP SLIP FAULT** ⇩

REVERSE FAULT

A **reverse fault** is a dip slip fault on which the hanging-wall has moved up and over the footwall. Consequently, old rocks are brought over younger ones. A **thrust fault** is a low-angle reverse fault.

STRIKE SLIP FAULT

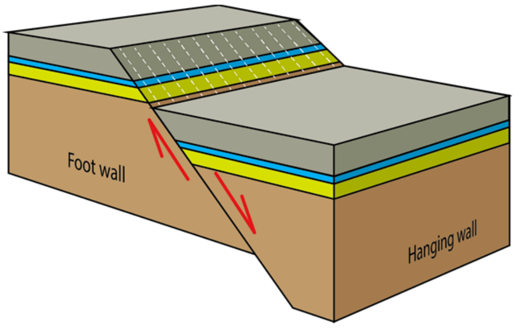
Strike slip faults usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane. Large strike slip faults are also referred to as **transcurrent faults** and **wrench faults**.

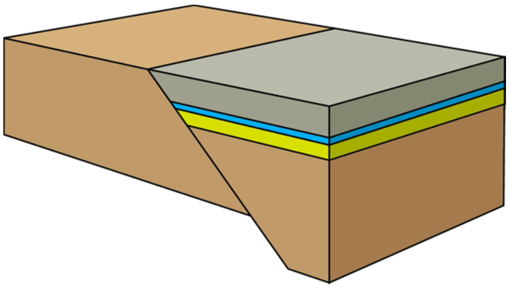
OBLIQUE FAULT

Combination of strike slip fault with normal or reverse fault.

Normal Faults

A **normal fault** is a high angle, dip slip fault on which the hanging-wall has moved down relative to the footwall. A normal fault develops in extensional regimes and brings younger rocks over older ones. Because of the separation of geological horizons that results from normal faulting, such faults are also termed **extension faults**.



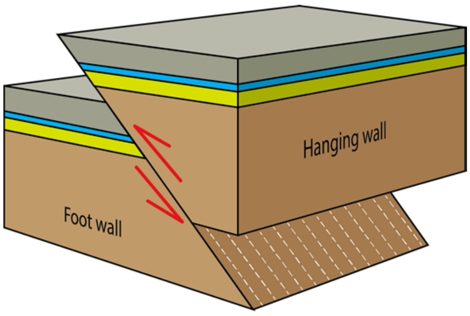


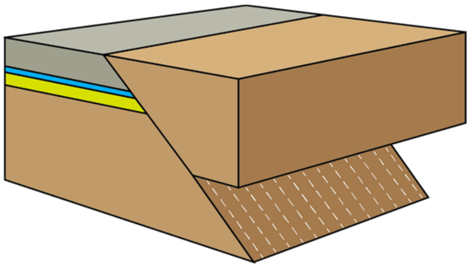
Normal Faults

Normal fault in La Herradura Formation, Morro Solar, Peru. The light layer of rock shows the displacement. A second normal fault is at the right. [Photo: Miguel Vera León]

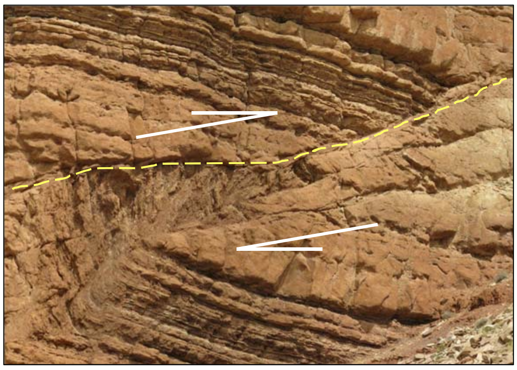
Reverse Faults

A **reverse fault** is a dip slip fault on which the hanging-wall has moved up and over the footwall. Consequently, old rocks are brought over younger ones. A **thrust fault** is a low-angle reverse fault. Reverse faults are produced in compressional regimes.





Reverse Faults

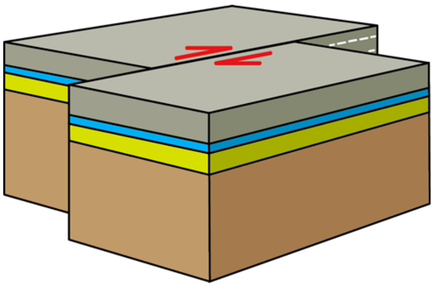


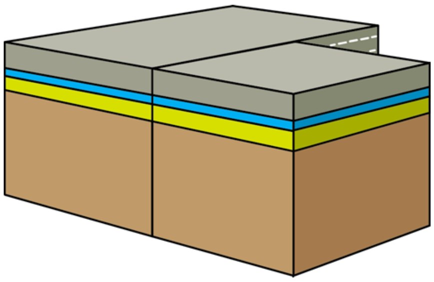
[Photo: Ron Schott, Twitter]

Photograph: Fossen, 2005

Strike-slip Faults - Dextral

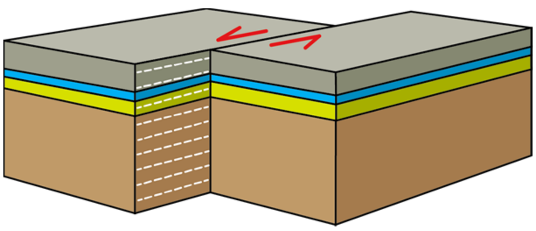
Strike slip faults usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane.

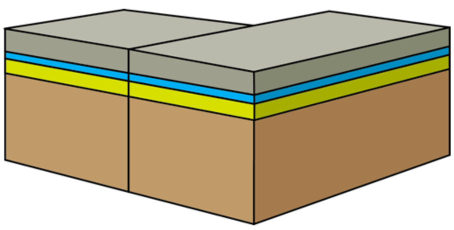




Strike-slip Faults - Sinistral

Strike slip faults usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane.

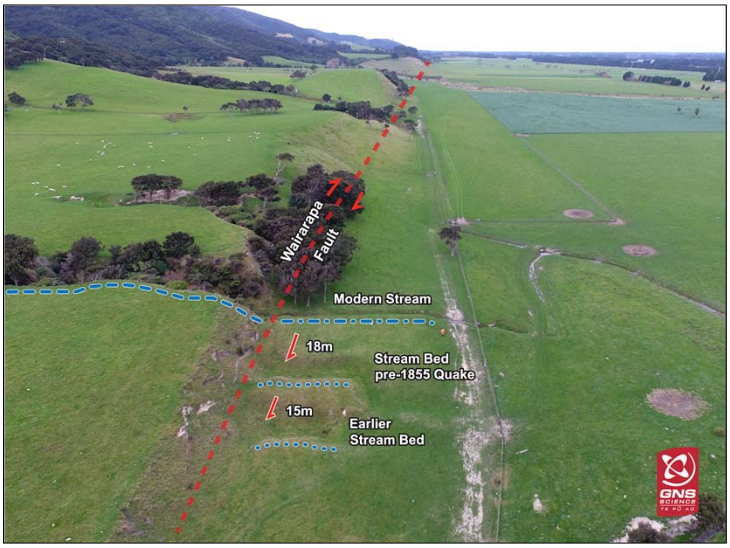




Strike-slip Faults - Sinistral

Small offset from a single earthquake in California (M 6.9 strike-slip event in 1979). [Photograph: Cavit, D, U.S. Geological Survey]

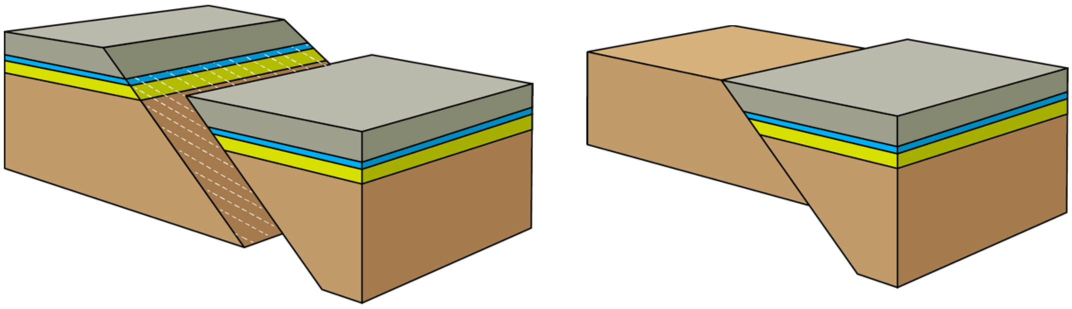
Strike-slip Faults - Dextral



The Wairarapa Fault (near Wellington) is one of New Zealand's large active faults. It was responsible for the massive magnitude 8.2 earthquake that violently shook the lower North Island in 1855 in New Zealand's largest historically recorded 'quake. [Photograph from GNS Science, New Zealand]

Oblique Faults

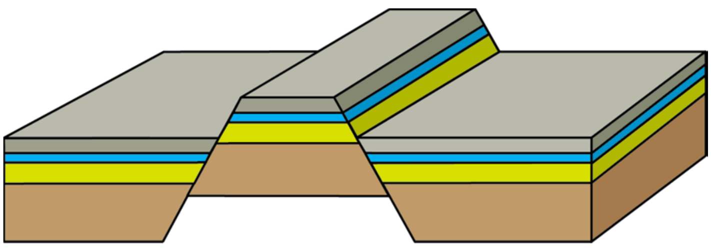
Combination of strike slip fault with normal or reverse fault.



This illustration is with normal-slip components, an oblique fault with reverse slip component is also possible.

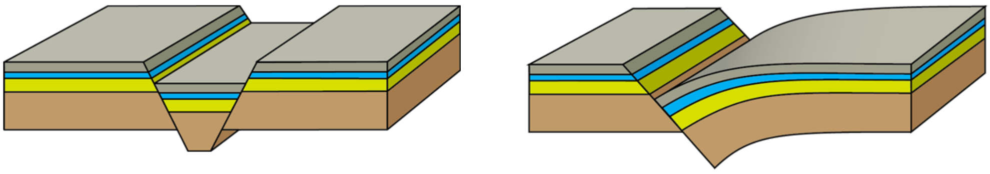
More on Normal Faults

- Normal faults dipping away from each other create an upthrown block called a **horst**.



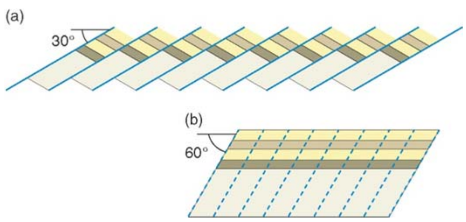
More on Normal Faults

- Normal faults dipping toward each other create a downthrown block known as a **graben**. A one sided graben is known as **half-graben**.



Normal Faults: Domino Model

- Sections through a rifted portion of the upper crust typically show a series of rotated fault blocks arranged more or less like domino bricks or overturned books in a partly filled bookshelf. This analogy has given rise to the name bookshelf tectonics or the (rigid) domino model.



(a) Schematic illustration of rigid domino-style fault blocks. (b) Such fault blocks can be restored by rigid rotation until layering is horizontal. In this case we have applied 30° rotation and displacement removal.

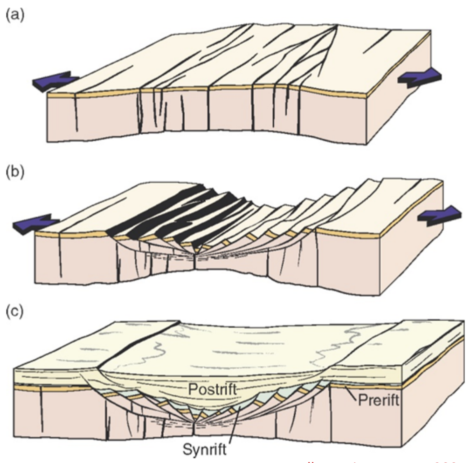


Illustration: Fossen, 2005

Next Lecture

Basic Structures and related terminologies
(Fault, Fold and Shear Zones)