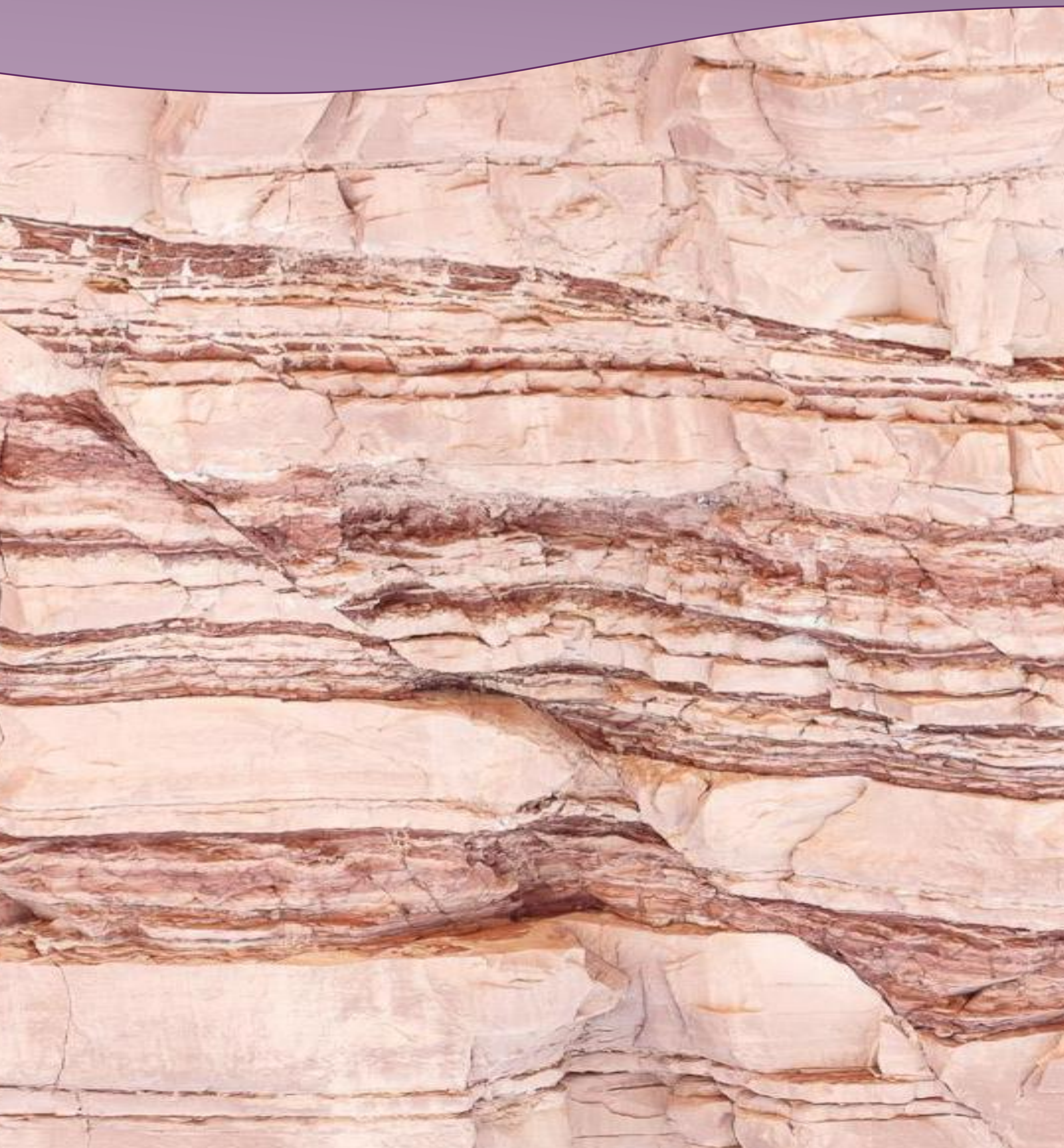
STRUCTURAL GEOLOGY

Shaas N Hamdan



STRUCTURAL ANALYSIS

Descriptive analysis	• **The characterization of geologic structures (shape & appearance)** • *Include* development of the following: 1.Precise vocabulary (jargon) 2.To describing structural orientation in 3D
Kinematic analysis	• **The determination of movement paths of rocks during transformation from the undeformed to the deformed state** • *Include*: Use of features in rocks to define direction of movement on a fault
Strain analysis	• **The development of mathematical tools for quantifying the strain in a rock** • *Includes* the search for features in rock that can be measured to define strain
Dynamic analysis	• **The development of an understanding of stress & its relation to deformation** • ***Includes***: 1.The use of tools for measuring present-day state of stress in the Earth 2.Application of techniques to interpreting state of stress for microstructures in rocks
Mechanism analysis	• **Study of processes on atomic to grain scales that allow structures to develop** • *Includes* study of fracture & flow of rocks
Tectonic analysis	• **The study of the relationship between structures & global tectonic processes** • *Includes* the study & interpretation of: 1. regional-scale (megascopic) features 2. relationships among structural geology, stratigraphy, & petrology

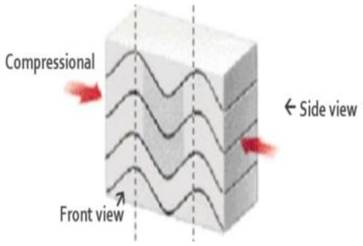
- **Structural geology** examines the present state of crustal deformation & determine the original setting, & the nature & direction of the tectonic forces that produced rock structures

STRESS & PRESSURE

- **Factors that determine the amount & type of a rock deformation (T, P, X, P_F, t, df/dt):** Temperature, Pressure, Fluids, Composition (rock type), Time, & rate of deformation

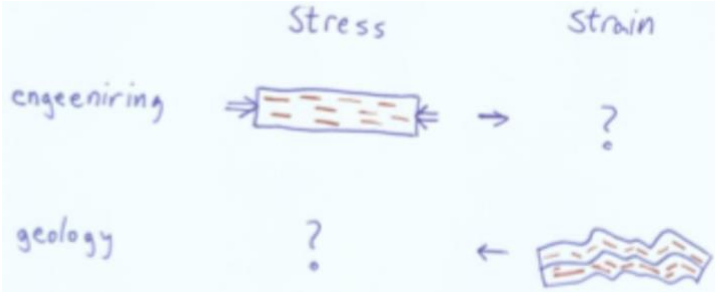
Types of stress	
Confining (Uniform, or direct)	• ***equal in all directions*** • **reduced volume without deformation** • **lead to deformation if great enough**
Differential stress	• ***aren't equal in all directions*** • **include** Tensional, Compressional, Shear

Differential Stress	
Compressive stress	• Tectonic stress, ***Squeezes rocks & shorten the distance between 2 points*** • **Produce:** Folds, reverse & thrust faults
Tensional stress	• ***Stretches rock & lengthens the distance between 2 points*** • **Produce:**elongation, fracture, normal fault
Shear stress	• **Slippage & translation of rocks,** acts as parallel forces but in opposite direction • **Produce:** Beading & Breaking

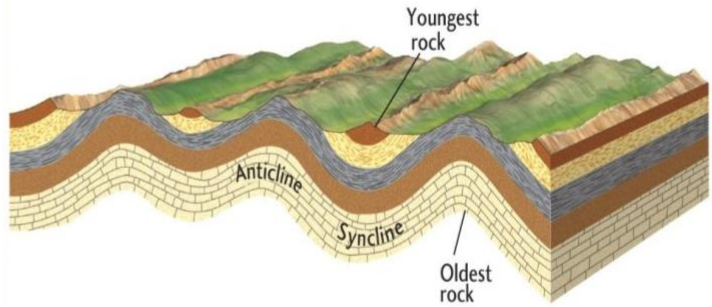


التثني غير واضح في side view لان القوة تكون عامودية عليه (وهو اتجاه ال strike) perpendicular الذي يكون به ال apparent dip angle = صفر) بينما ال front تكون القوة موازية لاتجاه الناظر حيث يكون اكبر قيمة

- **Rock deform under 3 orientations for the directed stress**
- **STRESS vs STRAIN:** strain are actually observe & directly measure but Stress are not directly measured but inferred or constrained from the strain

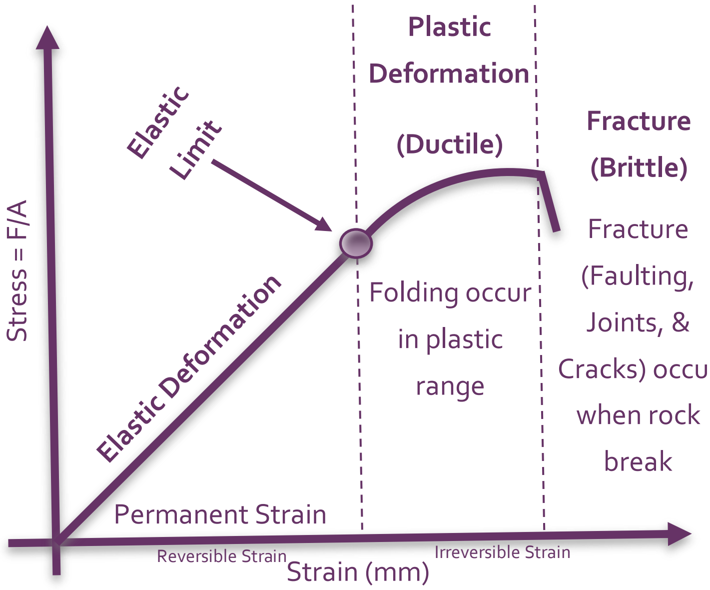


ROCK FOLDING IS INFLUENCED BY THE TYPE OF ROCK AND THE COMPRESSIVE FORCES



DEFORMATION STAGES

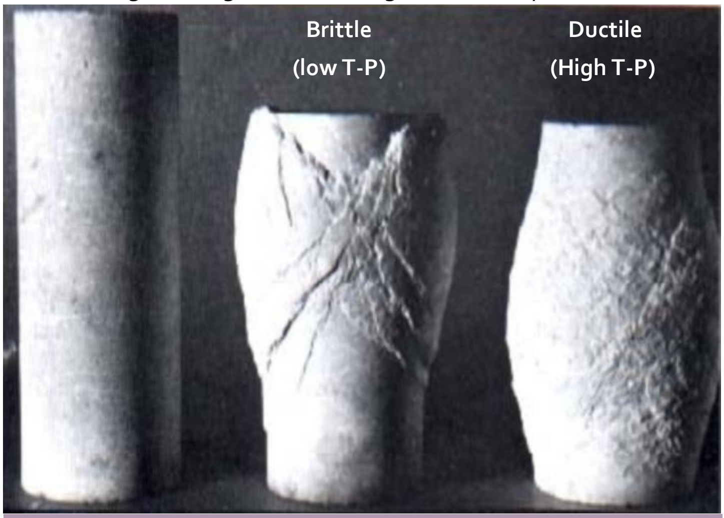
- Rocks deform under stress
- **Deformation**: changes in volume &/or shape of rock body



- **Stress**: is a force applied per unit area [N/m] of rock material, & it's a vectorial amount (magnitude + direction) $P^{\rightarrow} = F^{\rightarrow}/A$
- **Strain:** is a deformational response of rock to stress applied

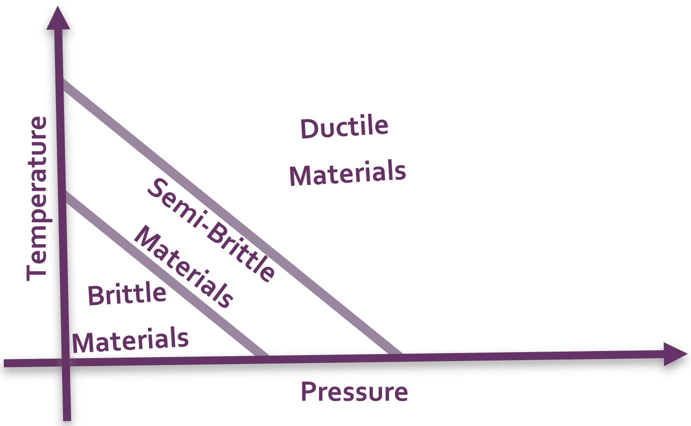
Deformation	Behavior & Examples
Elastic	Return to it's original size & shape
Plastic (bend, flow)	Breaking slowly, has a lot of 'give' (undergo smooth), include Folds, & Mylonite
Brittle (break)	Little change, then break suddenly or quickly into sharp pieces (Joints, Fault floor & breccia)

- **Deformational (or Stress) produces:** Fractures, Veins, Faulting, Folding, Rock Cleavage, Schistosity, Foliation…

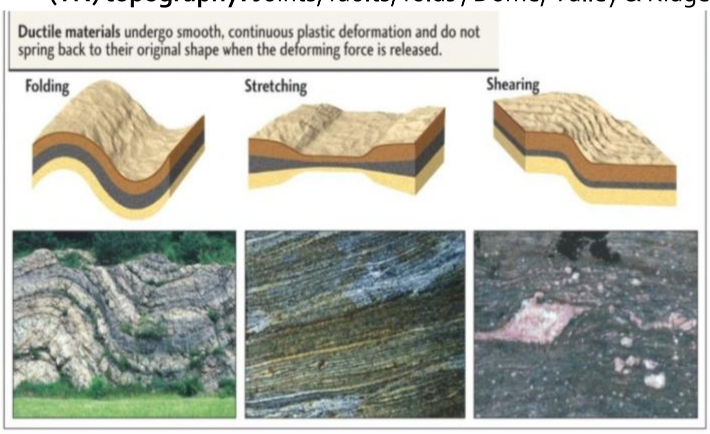


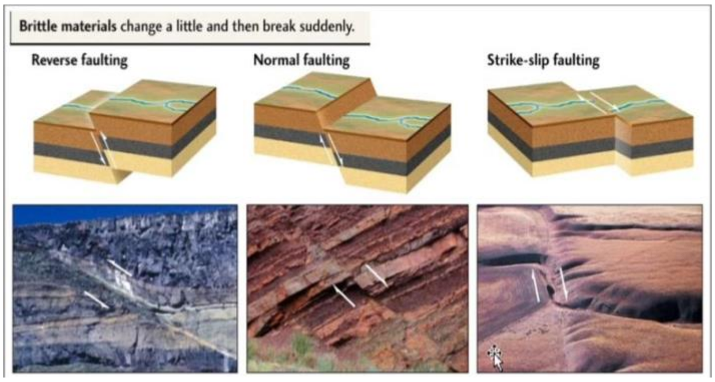
Deformation of marbles by compressive forces under confining pressures similar to shallow (middle) & deeper crust (right)
كلما تعمقنا اكثر في ال crust تزداد الضغوط الجانبية بسبب سماكة الصخور(يحدث fracturing (ما يفسر اختلاف ال deformation بين shallow و deeper crust

Materials	Behavior
Ductile (Plastic)	• Have a small region of elastic behavior & a large of ductile behavior before fracture • High T, high confining P, & low strain rate
Brittle	• Have a small or large region of elastic behavior & only a small region of ductile behavior before they fracture • Low T, low confining P, & high strain rate

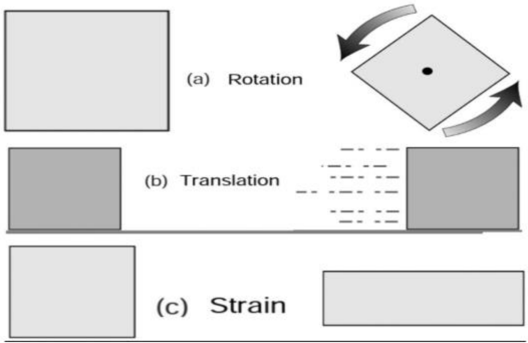


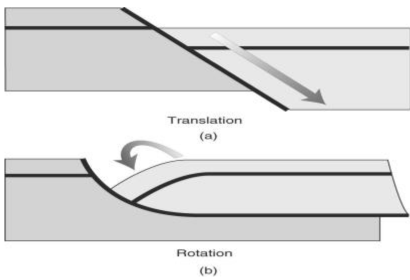
- Rocks undergo **ductile deformation** when subjected to high confining pressure & temperature near the surface & in the upper crust, & **ductile structures** form at greater depth
- **(TN) topography:** Joints, faults, folds , Dome, Valley & Ridge



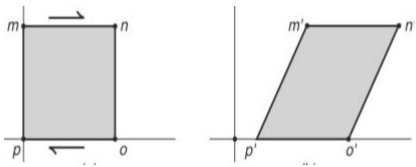


- **Components of deformation**: Rotation, Translation, Strain





Translational & rotational along a fault: a) A translated fault block, b) a rotated fault block in a hanging wall



Deformation represented as a coordinate transformation

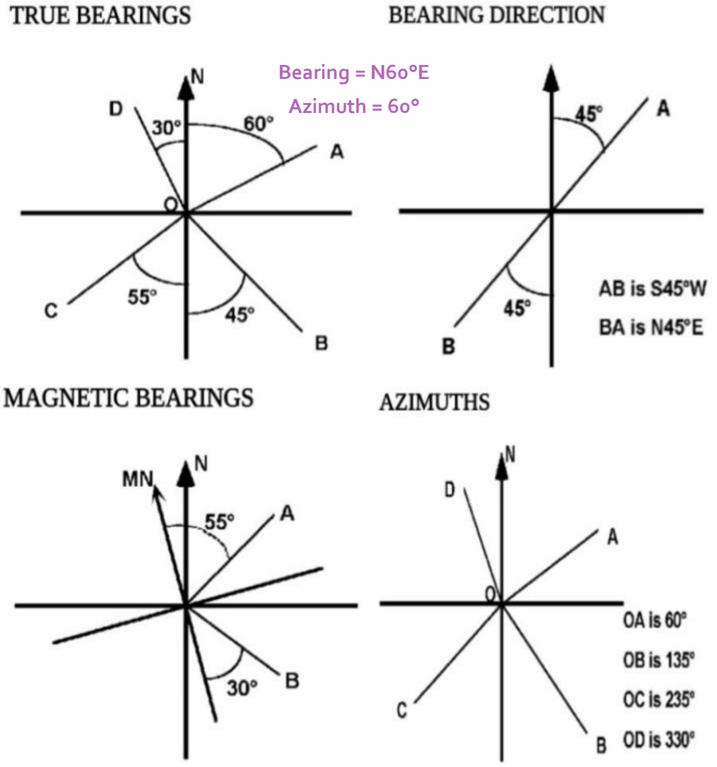
ATTITUDES & VICTORS

- **Attitude:** Orientation of a geometric element in a space
- **Attitudes of a point:** Length, width, & height
- **Attitudes of a line:** Bearing, & Azimuth
  - ➢ **Bearing** horizontal angle, **plunge** inclined angle
- **Attributes of a plane:** Strike line (Straight line on the surface, in Degrees) & Dip (angle + direction)
- **Types of Angle:**
  1. **Horizontal angle [degree, minute, second]**: measured in a horizontal plane by level instrument, Used to determine locations of points & orientations of lines
  2. **Azimuth [degree from N]:** from a reference meridian

Types of a horizontal angles	
Interior	Inside closed polygon, measured clockwise or counterclockwise with direction (e.g. 45°NS)
Deflection	Right or left from an extension of the current line to the next station (e.g. 45°L, 45°R)
Types of a Azimuth angles	
True	Based on true north
Magnetic	Based on magnetic north

- **DIRECTIONS OF LINES:** Defined by a horizontal angle between the line & a defined reference line (meridian)

Types of a line	
Inclined (from N_m)	N-S reference from earth's magnetic field
Inclined (from N_T)	N-S reference from Earth's geographic poles
Bearing	• The direction of a line **by angle** & **quadrant letters** (e.g. N45°E), **< *90°*** • **True bearings** based on true N • **Magnetic bearing** on magnetic N
Plunge	• angle of linear element with **vertical surface (vertical line)** • **Direction:** is an Azimuth of the plunge



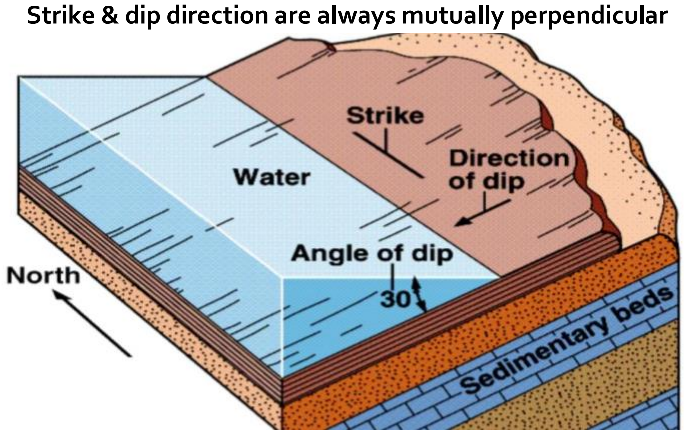
Bearing: Angle < 90° + Direction (e.g. S80°W)

Azimuth: Only Angle (0 - 360°) from N (e.g. 260°)

- **Strike:** direction of the line produced by the intersection of inclined plane with the horizontal plane (surface)
  - ➢ **Direction**: Azimuth of horizontal line in dipping plane
- **Dip**: angle between the inclined plane & the horizontal plane
  - ➢ **Direction**: Azimuth of a horizontal line that is perpendicular to the strike

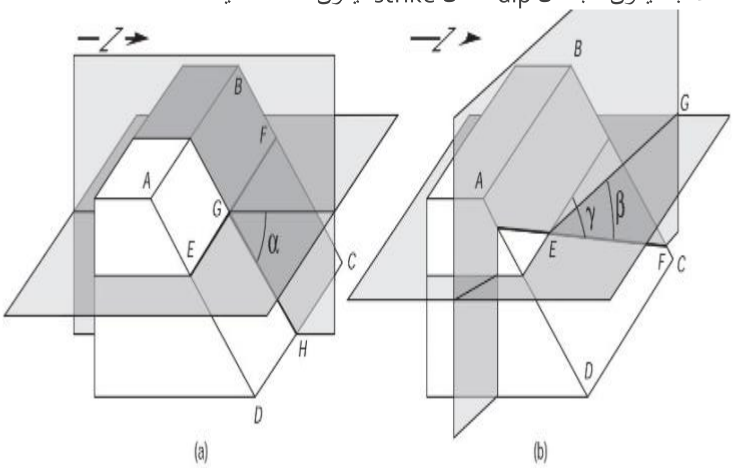
Apparent dip	Dip of a plane, imaginary vertical plane & **not perpendicular to strike,** ≤ True dip
True dip	Slope of a surface, **horizontal angle** of a plane measured in vertical plane, **perpendicular to strike**

- **Strike & dip direction are always mutually perpendicular**



e.g. Strike (Azimuth) 000, Strike (Bearing) N, Dip angle (Plunge) 30°, Dip direction (Bearing) NW → 000, N30°W

كيف نحدد اتجاه ال strike & dip ؟؟ تسير المياه في اتجاه اقصر واسهل الطرق و هذا الاتجاه يكون اتجاه ال dip اما ال strike فيكون متعامد عليه



a) **Attitude of a plane:** dip, & strike. strike of plane ABCD intersection with horizontal plane EF. GH is dip direction

b) **Attitude of a line:** plunge, & pitch. The plunge of EF is angle β (from EG in plane EF-EG) & line EG is the plunge direction. pitch (γ) angle that EF makes with strike of plane ABCD

Other terms	
Position	Location of a geometric element (outcrop)
Pitch (rake)	Angle between linear element that lies in a given plane & the strike of that plane
Trace	Intersection line between 2 non-parallel surfaces
Profile plane	Perpendicular to a geometric element (e.g. the plane perpendicular to the hinging line of a fault)
Trend	Azimuth of any feature in map view sometimes used as synonym for strike Eat Structure
Foliation	Surface occurs repeatedly in a body of rock
Lineation	Penetrative linear element (e.g. intersection in bedding cleavage or alignment of elongate grains)

GEOLOGIC STRUCTURES

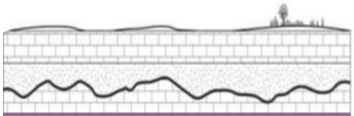
- **There are 2 types of geologic structures:**
  1. **Primary Structures (Architecture)**: formed at the time of rock origin deposition or crystallization (e.g. Unconformity, cross-Bedding, Ripples)
  2. **Secondary Structures:** formed due to tectonic activities after deposition, imparted by strain in response to stress (e.g. Fracture, Cracks, Folds, Faults, Joints)
- **Law of Original Horizontality (Conformity):** The fundamental laws of stratigraphy (by N. Steno), state that any deposition when takes place is in a horizontal fashion
  - ➢ After deposition the layers or beds are tilted by tectonic movement (except cross-bedding which are formed under fluvial "riverine" or aeolian "wind" environments)
- **Superposition law:** Strata follow one another in chronological order, but not necessarily continuous
  - ➢ Separated but aligned outcrops of the same lithologic sequence **imply stratigraphic continuity**
  - ➢ **Sharp Discontinuities in lithologic patterns occurs due to** faults, unconformities, or intrusive contacts
- Deformed areas subdivided into regions contain structural attitudes (domains), e.g. area with folded strata subdivided into regions with constant dip direction such as limbs & hinge areas of large-folds
- **The least astonishment principle**: The simplest but internally consistent interpretation is most correct

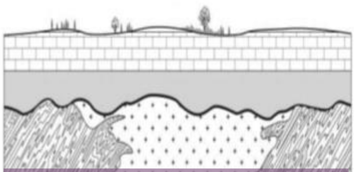
UNCONFORMITIES

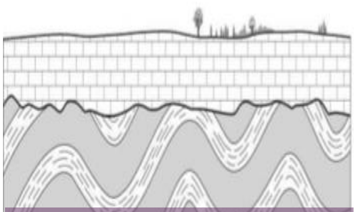
PRIMARY STRUCTURES

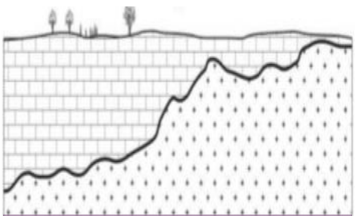
- **Unconformities**: are a significant bedding contacts which are break or gap in rock-stratigraphic record, indicate period of erosional or non-deposition
- **Reasons for Unconformities (Formation involves):** Horizontal or conformable strata are formed & break in sedimentation (deposition) due to tectonic movements, that causes uplift or subsidence & the next phase of sedimentation cycle, where new sedimentation produce another set of conformable beds
- **Is one of the most common feature in rocks & succession**
- **different from all other structures**
- **resulted due to** tectonic activity (uplift or subsidence)

Types of Unconformity	
Non-conformity	As the underlying rocks are Igneous or Metamorphic (unstratified) & overlying younger rock are sedimentary (stratified)
Disconformity	When the underlying (older) & overlying (younger) sedimentary rock strata are parallel & the contact is erosional surface
Angular unconformity	When the underlying (older) & overlying (younger) rock strata show some angle


Disconformity

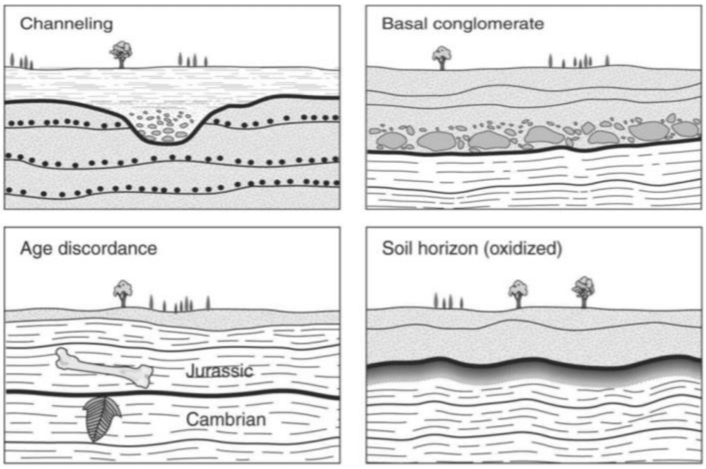

Nonconformity


Angular Unconformity


Buttress unconformity

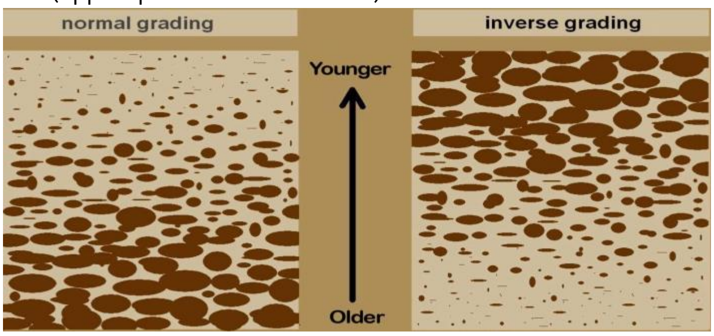
Angular unconformity: contact between layers at different angles Sediments tilted upward to angle of about 50°, then eroded. On this surface volcanic pyroclastic deposits were deposited as a flat sheet, The section of rocks has been eroding from the east, exposing tilted & flat rock layers.

Features related to Unconformities



OTHER PRIMARY STRUCTURES

- **Graded Bedding:** a layer of sediment in which particle sizes change systematically in a vertical &/or lateral direction (applicape to beds & laminae)

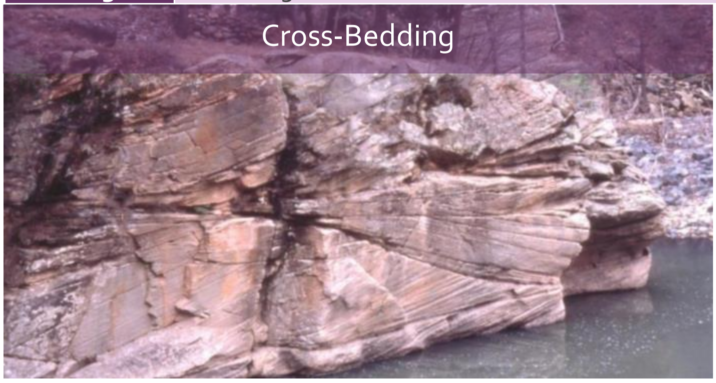


- **Current Ripples:** found at relatively low flow strengths in sands (<0.7 mm in diameter), asymmetric in cross-section

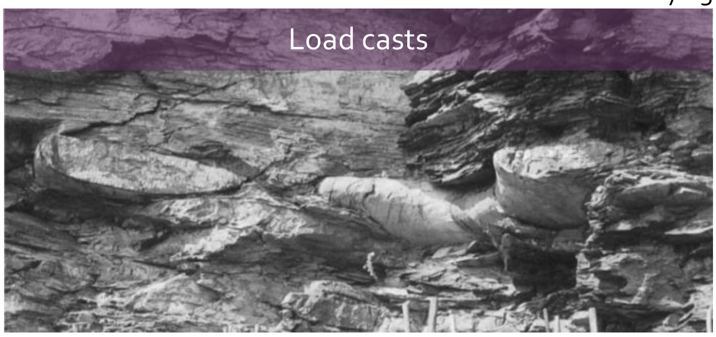
Ripple marks

- **Cross-bedding:** Sets of internal strata, beds & laminae are not oriented parallel to the bounding surfaces of the bedset. Applicable to both beds (>1 cm) and laminae (<1 cm)

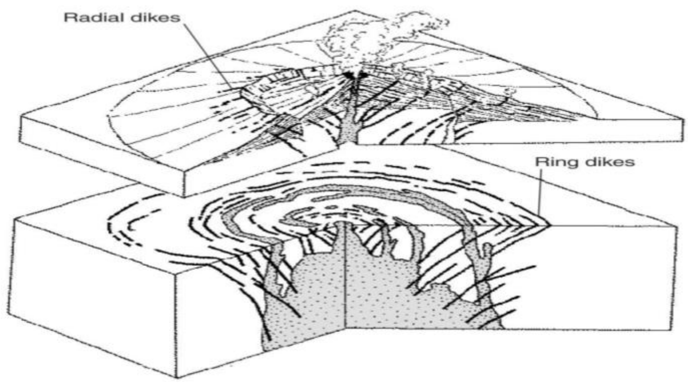
Types of Cross-stratification (cross-bedding)	
Tabular	Bounding surfaces are planar & intersecting
Trough	Bounding surfaces are curved



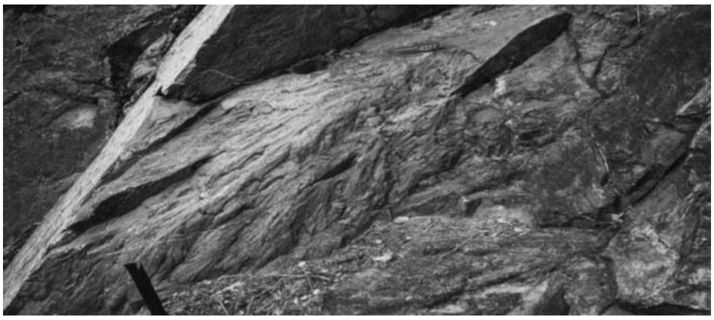
- **Flute Casts:** current-formed erosion structure
  - **bulbous cast:** formed by scouring of sediment interface, bulbous & generally points up-current
  - **Load Casts:** irraular knobs found on sandstone overlying

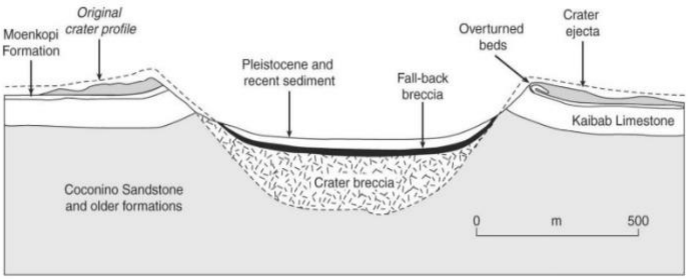


Igneous Structures	
Batholith	A Huge blob-like intrusion, composite of plutons
Dike	A sheet intrusion cross cuts stratification in a stratified sequence, or roughly vertical in unstratified sequence
Hypabyssal	Intrusion formed in the upper few km of the crust; cool relatively quickly, & generally fine grained
Laccolith	Hypabyssal intrusion concordant with strata at its base, but bows up overlying strata to dome or arc
Pluton (intrusion)	Moderate-sized blob like intrusion (several km) the term used to refer to any intrusion
Sill	sheet introns, parallels preexisting stratification in stratified sequence,&subhorizontal in unstratified
Stock	A small, bloblike intrusion (a few km in diameter)

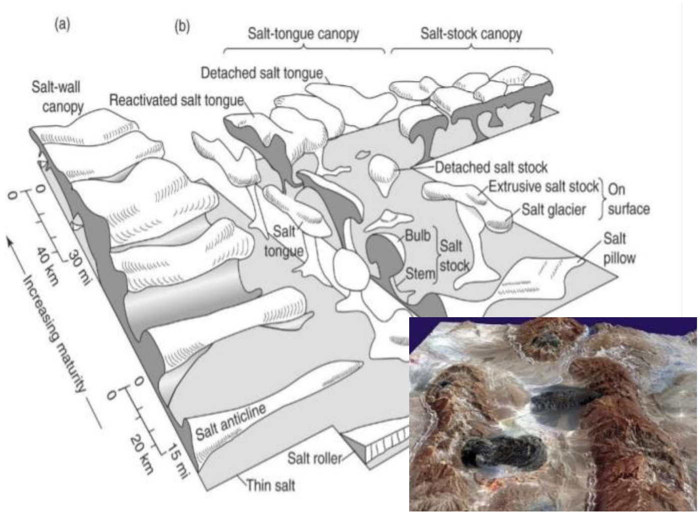


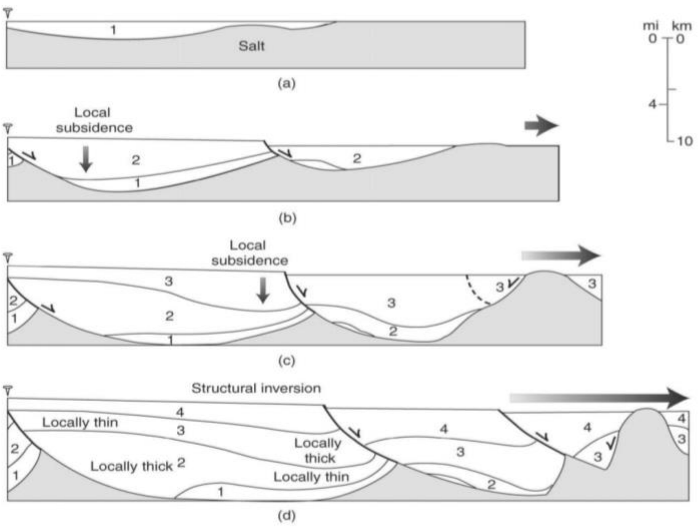
IMPACT STRUCTURES

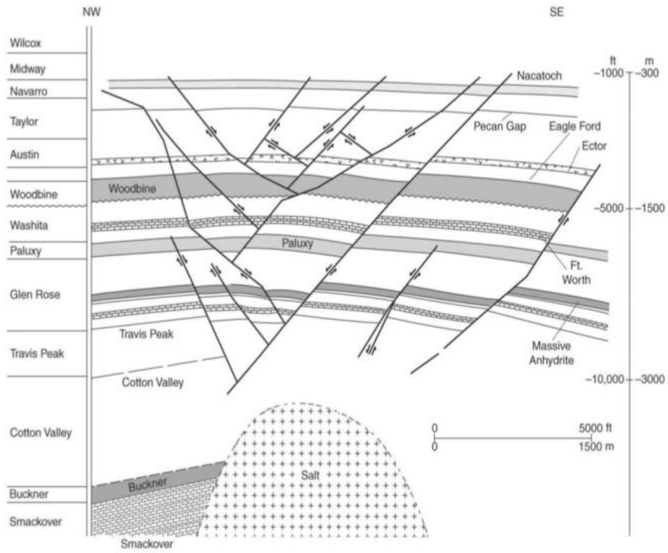




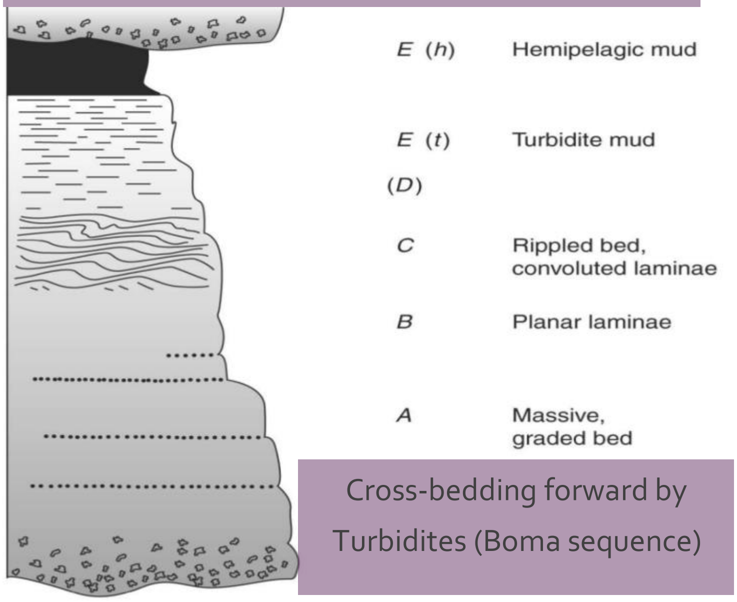
Salt structures







Salt dome



Cross-bedding forward by Turbidites (Boma sequence)

Other PRIMARY STRUCTURES

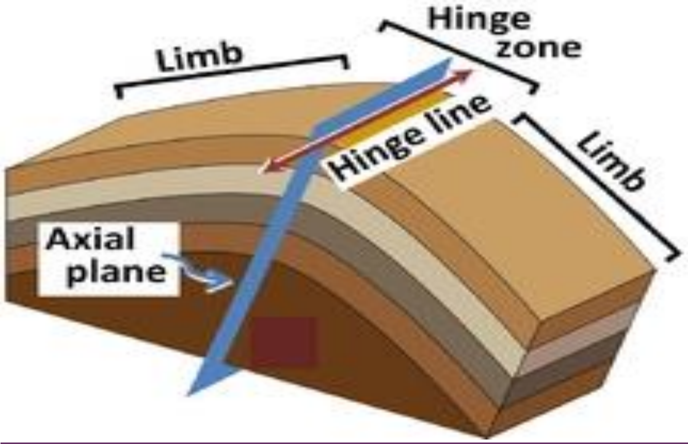
Penecontemporaneous structures

Pitted Pebbles

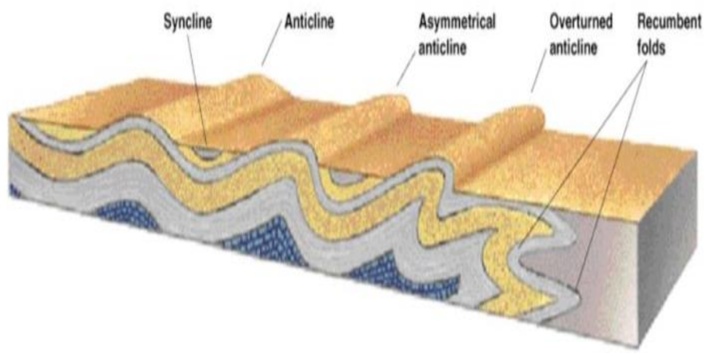
FOLDS
SECONDARY STRUCTURE

- **A fold**: is a bent structure that originally was planar
- **produced by** horizontal compression or vertical forces, as pushing in on opposite sides or up from below
- **Formed as** rocks squeezed together by compressive forces
- Inequality in stresses is the cause of all local movements

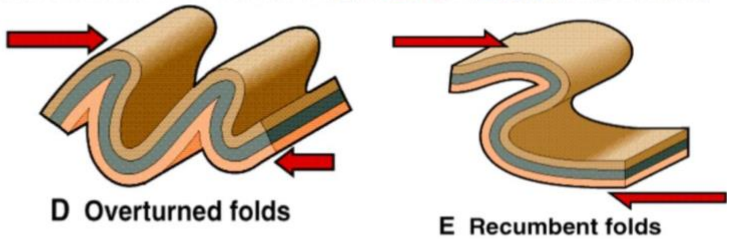
Part of Folds	
Limb (Monocline)	The two sides of a fold, one direction of dip prevails in a fold
Axis (hinge line)	A line along the points of maximum curvature of a layer of a fold, between 2 angle
Axial plane	Divides a fold into 2 symmetrical parts
Plunge	Angle of the axis with the horizontal plane
Anticline	• Concave down or convex up, upfolds or arches, the oldest beds are in the center • **Non-plunging:** if the axis is horizontal, nose in the direction of plunge • **Plunging:** if there's angle between axis of anticline & the horizontal surface
Syncline	• Concave up or convex down, downfold or trough, the youngest beds in the center • **Plunging:** nose are opposite to the plunge
Nose	intersection of a fold with a horizontal plane



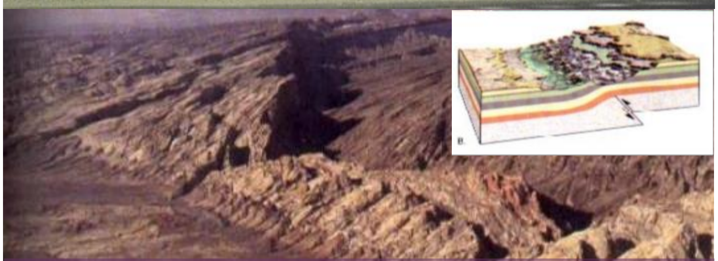
Folds types & classification		Axial plane
Symmetrical	limbs dipping symmetrically • have an equal bed width	vertical
Asymmetrical	One limb dipping more steeply • have different widths	Tilted
Overturned	if fold bushed in one direction more than the other direction	One limb tilted
Recumbent	if dip of Axial Surface 0-10 • overturned lying on its side	horizontal
Inclined	If the dip of Axial Surface 10-70°	Titled
Upright	If the dip of Axial Surface 70 -90°	Titled



الفرق بالزاوية بين syncline &anticline لعدم تساوي القوتين

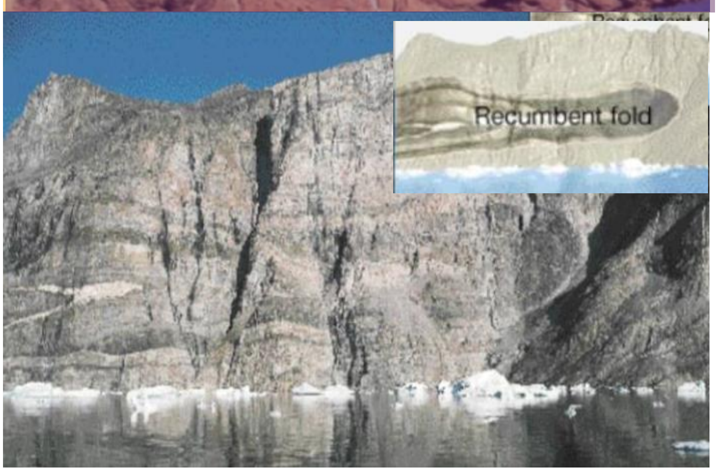


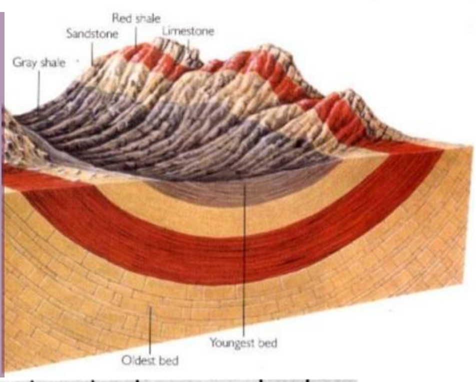
Folds of deformed sedimentary strata (The dashed-line indicates a fault also present)



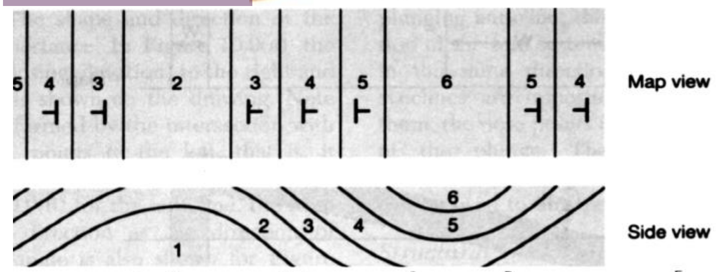
Monocline

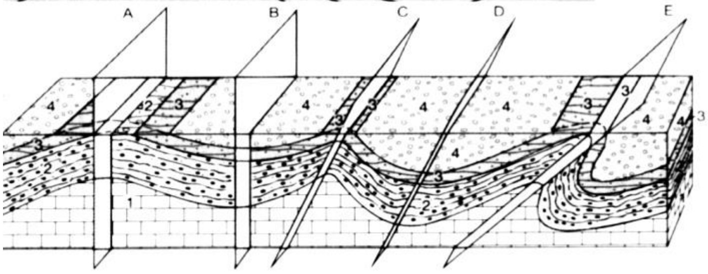
Overturned fold. One limb has been turned completely upside-down with older beds



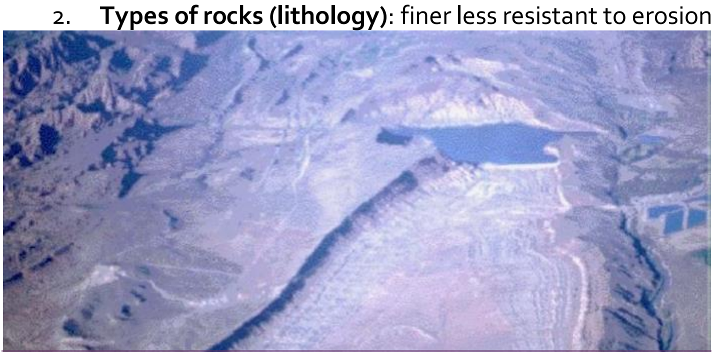


The surface of eroded remnants of a syncline & the characteristic core of younger rocks flanked on both sides by older rocks dipping toward core





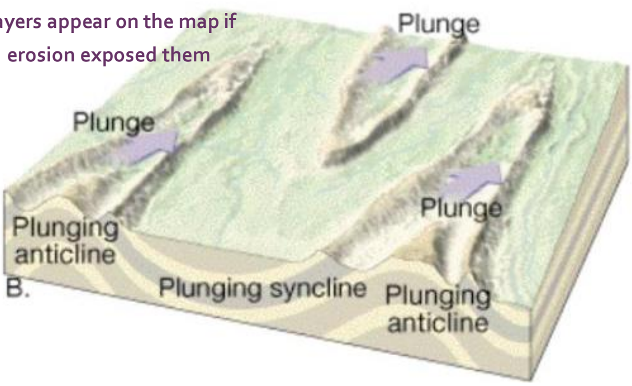
- **Width of outcrop**: distance between any 2 point, differ from one location to another due to difference in **erosional rate**
- Outcrop appear on the map if **erosion exposed them,** & appear due to interaction between **Thickness, Dip, & Slope**
- **Erosional rate controlling by**:
  1. **Slope**: nversely proportional (i.e. Gentel slope result in wider dip, & steep slope in narrow dip)
  2. **Types of rocks (lithology)**: finer less resistant to erosion

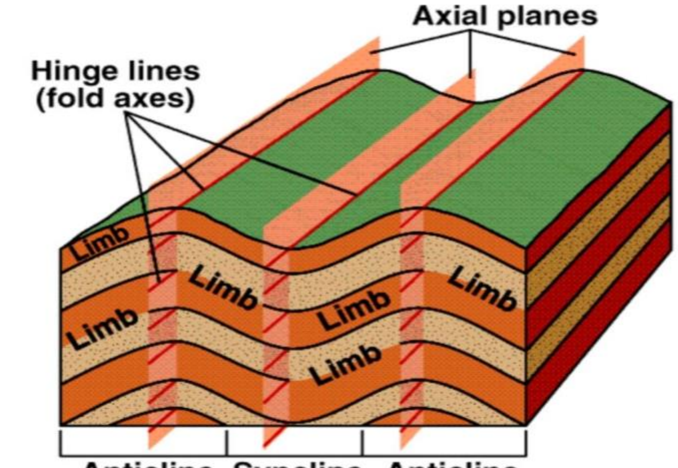


وجود البحيرة اعلى ال nose بسبب شد القوى وهو اتجاه ال maximum strain لذا تحدث joints التي تسهل عملية ال erosion، المناطق المرتفعة والمخفضة بسبب different erosional rates بسبب اختلاف types of rocks

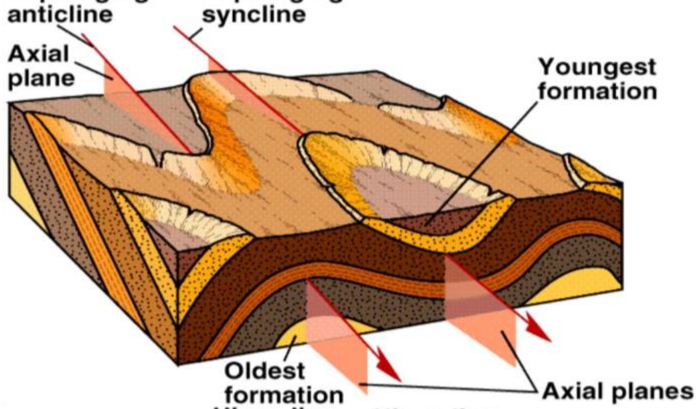
Nose: pointing in the direction of plunge & in opposite direction

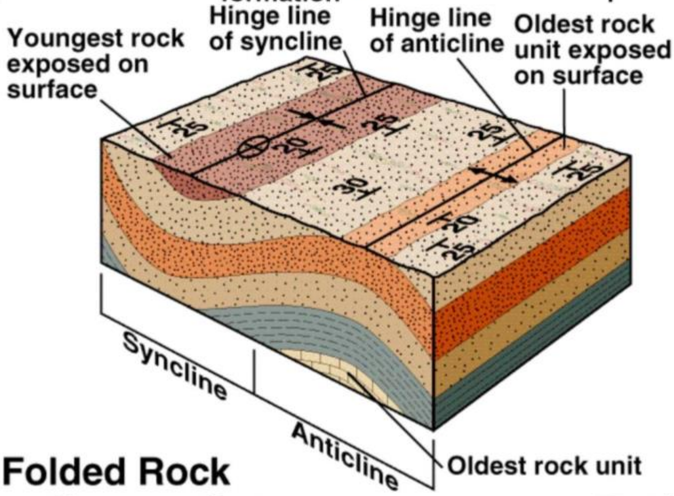
Layers appear on the map if erosion exposed them

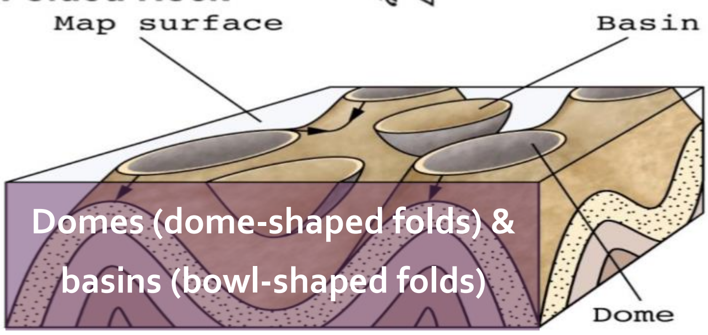




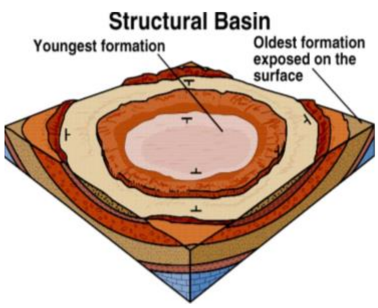
Plunging Folds

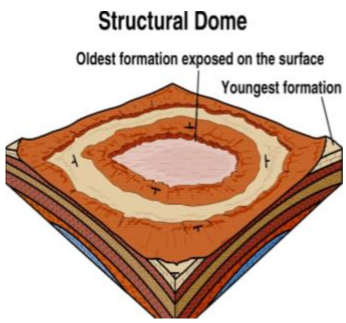




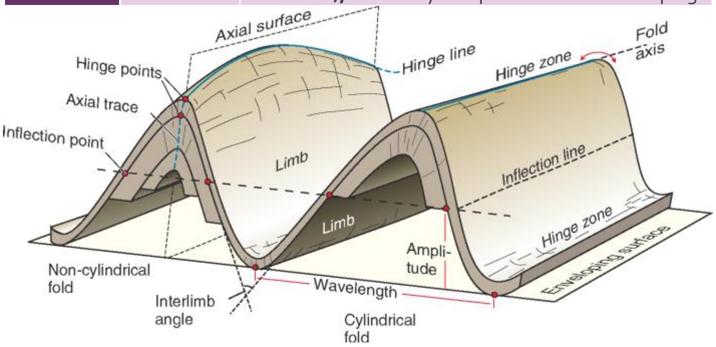


Domes (dome-shaped folds) & basins (bowl-shaped folds)





Structure	Resemble	description
Domes	Anticline	Beds dip in all directions **away from the center (oldest in center),** caused by compression & uplift
Basins	Syncline	Beds dip in all direction **toward center (youngest in center),** caused by compression & down warping



- **Engineering Concerns of Folds:** Means of Extrapolating Bed Locations, Fracturing related to folding, Favorable or non-favorable orientations of beds to engineered structure/ slope

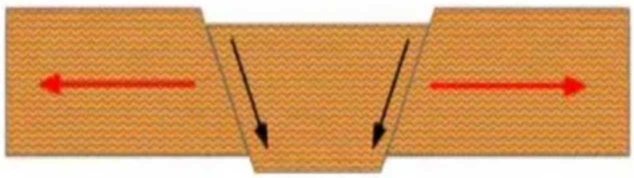
FAULTS

SECONDARY STRUCTURE

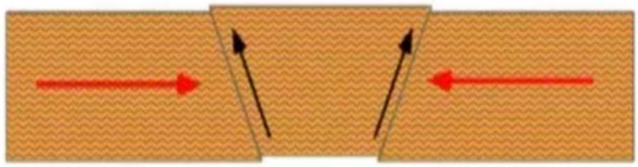
- **A faults:** is a fracture in a rock with a relative movement parallel to the fracture (break in a rock across which there is observable movement)
- **As break occurred an earthquake was generated**
- Sometimes fault die at depth & don't break surface

Fault zone	Containing of parallel or anastomosing faults
Shear zone	Zone across which 2 blocks displaced in fault, but without development of visible fractures
Footwall	The surface bounding the body of rock below a non-vertical fault), ***rises down in reverse fault & up in normal fault*** • **Footwall block:** The body of rock itself
Hangingwall	The surface bounding the body of rock above a non-vertical fault) , ***rises down in normal fault & up in reverse fault*** • **hangingwall block:** The body of rock
Cut-off line	The trace of a displaced plane on the fault • Occur in pairs **(footwall & hangingwall)**
Slip	The displacement, represented by relative slip vector (hangingwall relative to footwall)

- **Graben Fault:** produced when tensional stresses result in the subsidence of a block of rock (2 normal faults)
  - **Rift Valleys:** is a large scale Graben Fault



- **Horst Fault:** is the development of 2 reverse faults causing a block of rock to be pushed up by compressional force

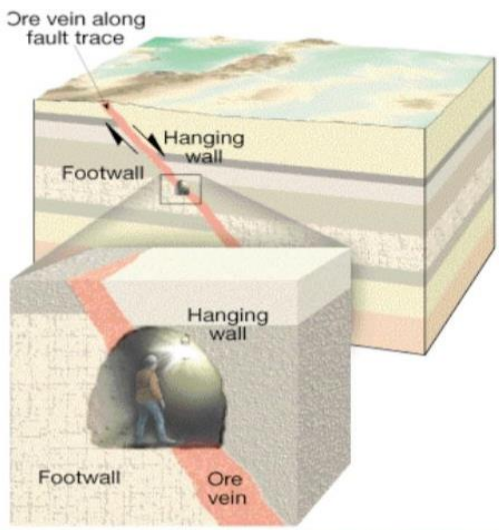



A fresh fault scarp after an earthquake

- **Evidence for faults:** change in topographic, Displacement, lineation, breccia (where no displacement), vines (craks)

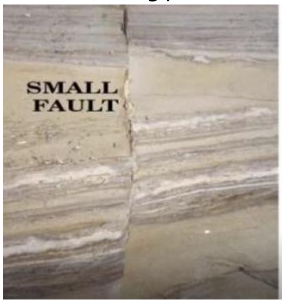

Slip lineations on a fault


Breccia, broken-up rock along

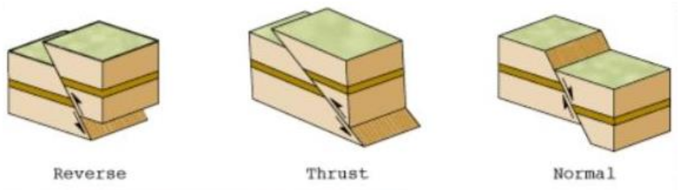


The names of hanging wall & footwall came from minerals mining along fault, who hung their lanterns on the hanging wall & walked on the footwall

- **A fault near the surface becomes mylonite at great depth**
- **Mylonite:** metamorphic rock formed by ductile deformation during intense shearing encountered with folding & faulting by cataclastic or dynamic metamorphism process
  - ➢ **Characterised by** smearing, flattening, & rotation of any porphyroblasts formed during metamorphism
- **Cataclastic metamorphism**: complete pulverisation of the parent rock so the original minerals are almost completely broken down & recrystallise as smaller grains which are tightly intergrown forming a dense hard rock
  - ➢ As a result of the shearing encountered during formation, recrystallised minerals grow preferentially along planes of foliation parallel to the direction of shear

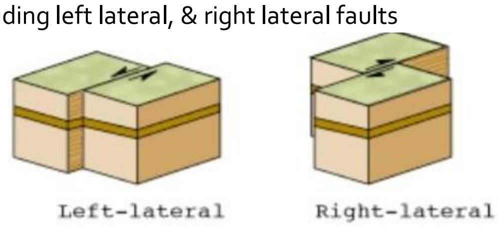


- **Types of faults:**
  1. **Dip-slip fault:** Normal, Reverse, & Thrust faults

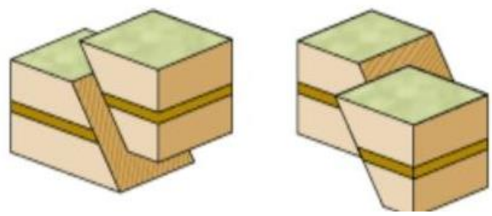


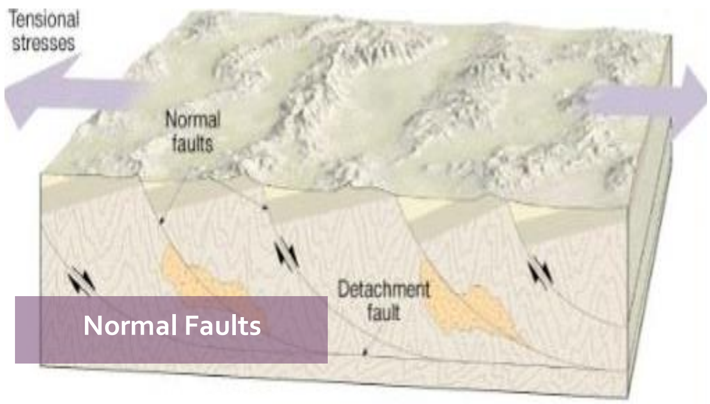
Faults	Result in	Caused by	Hanging
Normal	Extension	Tensional force	Down
Reverse	Shortening	Compressional force	Up
Thrust	Reverse fault with gentle slope (< 45°)		

  2. **Strike-slip fault**: associated with shearing forces, including left lateral, & right lateral faults

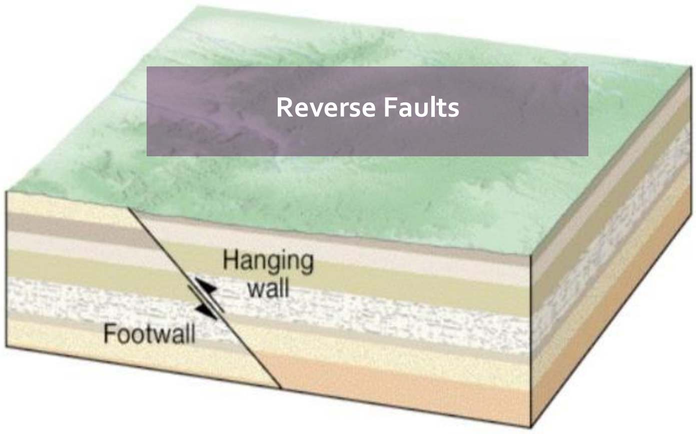


  3. **Oblique-slip (translation)**: combination of shearing & compression-tension. (strike-slip & dip-slip faults)

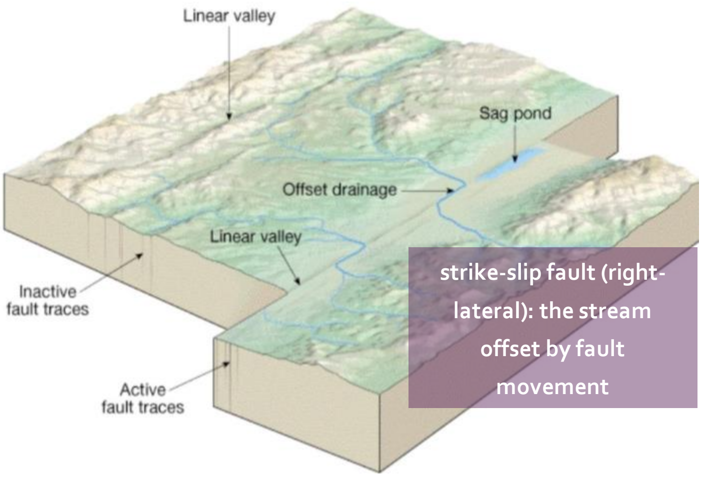




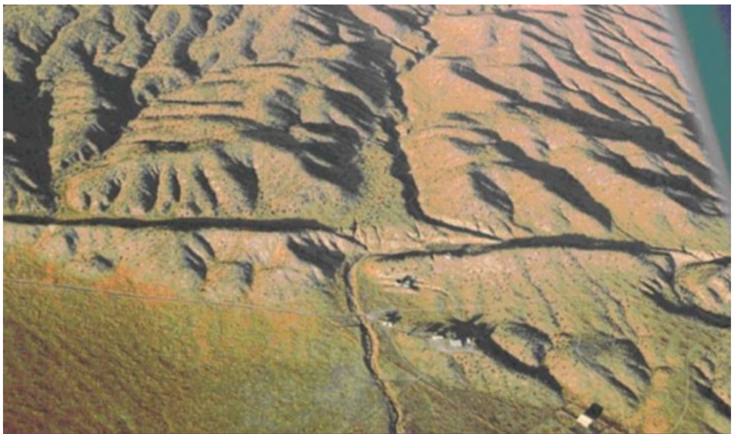
Normal faulting in the Basin & Range Province: Tensional elongated & fractured the crust, Movement along the fractures tilted the blocks producing parallel mountain ranges



Thrust fault
Dark-limestone (Cambrian) has been thrust over light-colored Jurassic sandstone, younger by some 350Ma



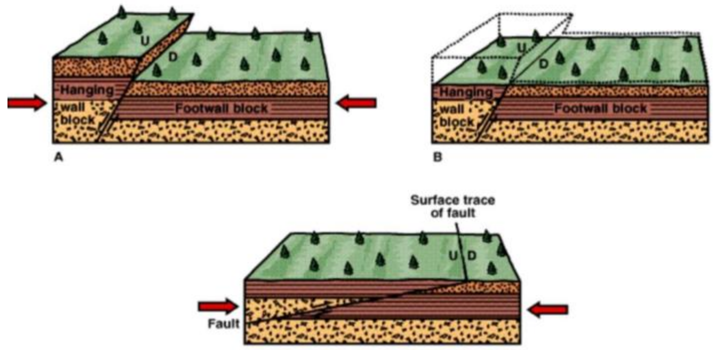
strike-slip fault (right-lateral): the stream offset by fault movement

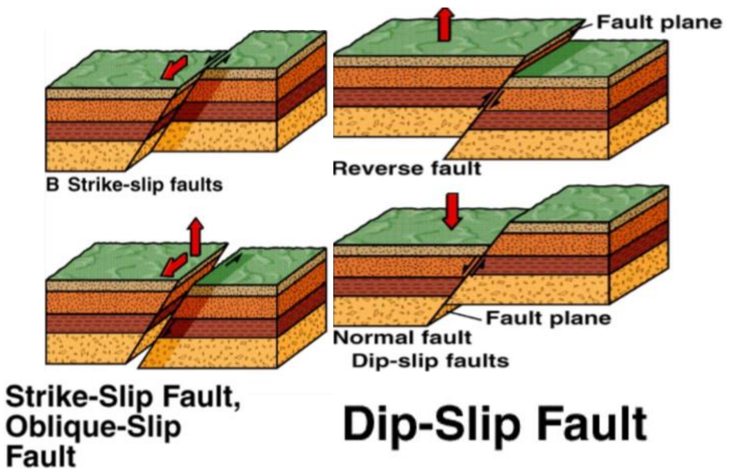


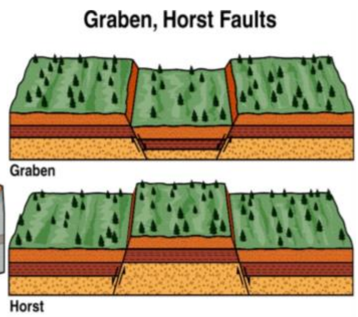
Strike-slip faults expressed by a series of straight linear ridges & troughs that can be traced for long distances. (San Andreas fault)

The San Andreas Fault system runs from the Gulf of California & enters Pacific accumulated displacement, from earthquakes & creep, exceeds 560 km over its 29Ma

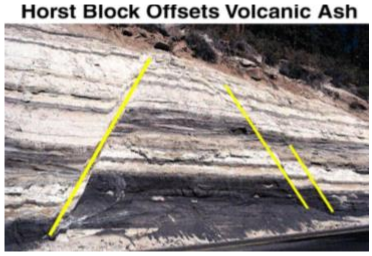
Reverse and Thrust Faults





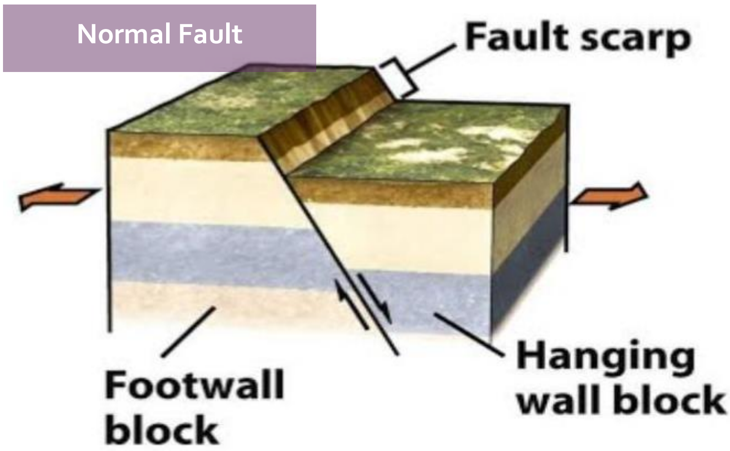


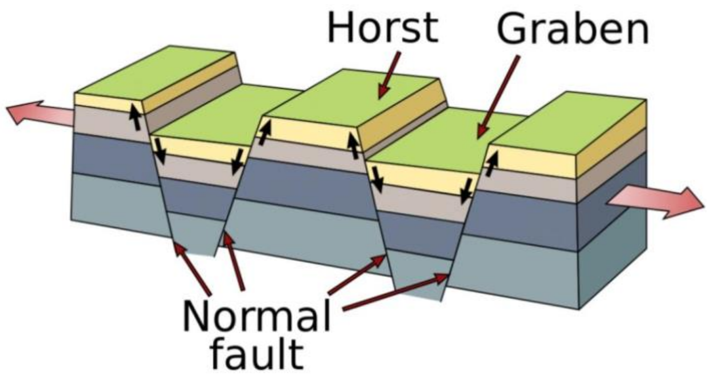
Horst Block Offsets Volcanic Ash

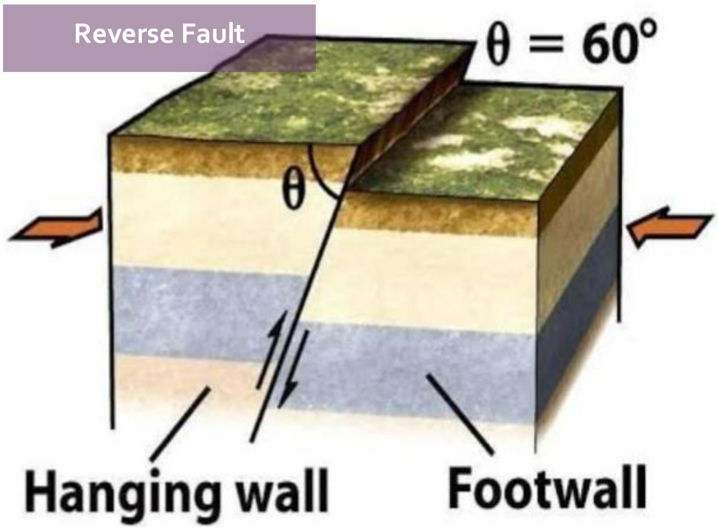


Fault in Big Horn Mountains, WY

Stream Channel Displacement

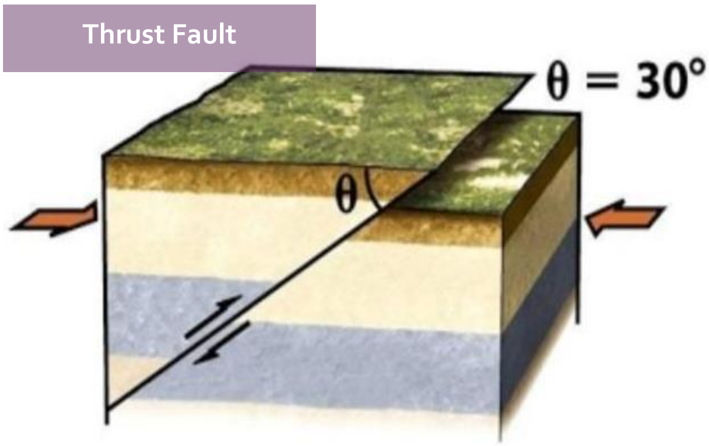

Normal Fault
Fault scarp
Footwall block
Hanging wall block


Horst
Graben
Normal fault

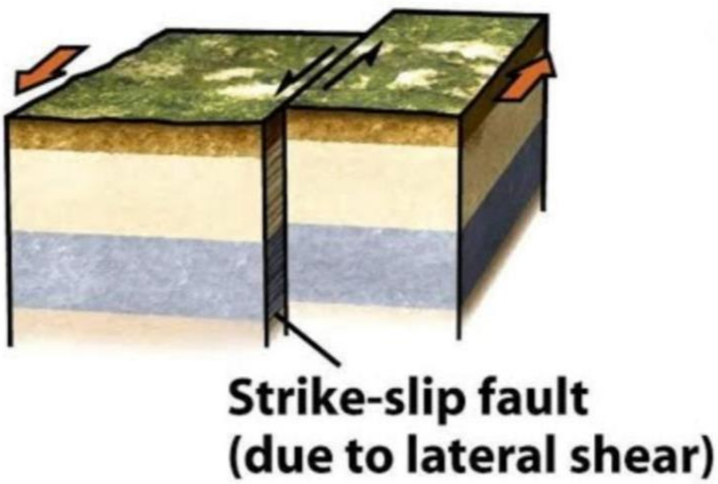

Reverse Fault
θ = 60°
θ
Hanging wall
Footwall


Normal Faults

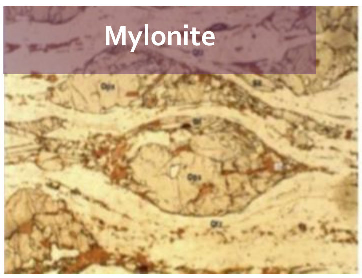

Normal Faults

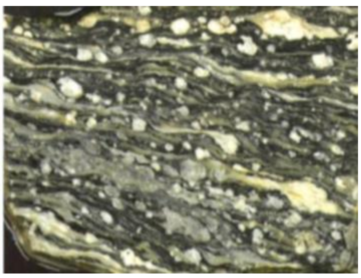

Thrust Fault
θ = 30°
θ


Horst Faults


Strike-slip fault
(due to lateral shear)


NE
Desert Pk Thrust
SW
Oe
Oe
Oc/Osp
Oc/Osp
footwall cutoff

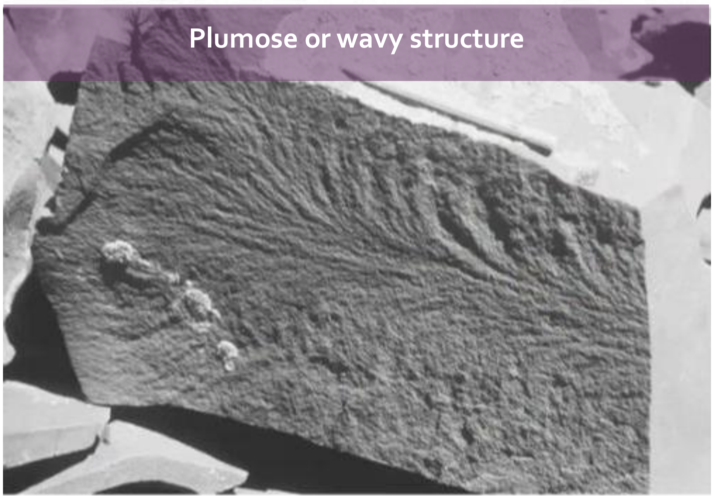


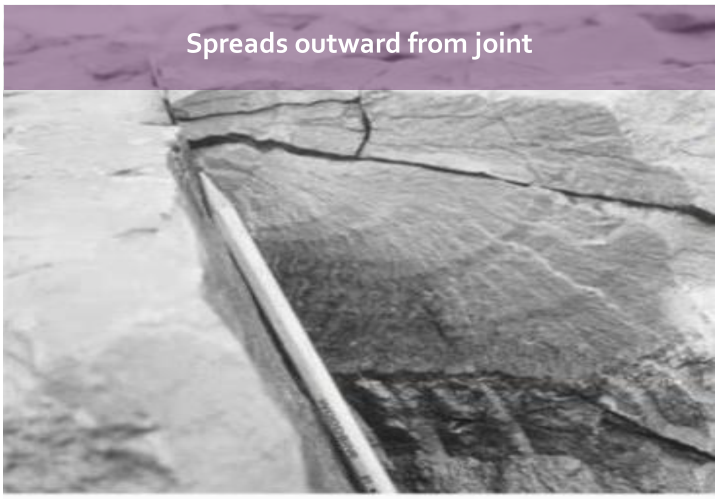


- **Engineering Concerns of Faults:** Planes of Weakness, Sources of Seismic Hazard if Active, Significant Water Courses, & Significant as Groundwater "Dams"

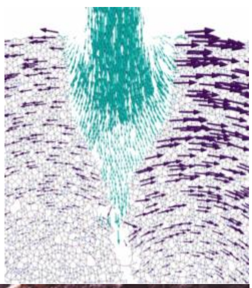
JOINTS (SECONDARY STRUCTURE)

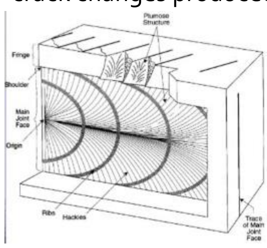
- **A joint**: is a crack in a rock along which no appreciable movement has occurred, produced when rocks are deformed by tectonic forces with some exceptions (a fracture without measurable shear displacement, cracks or tensile fractures)
- **Joint:** A natural fracture that forms by tensile loading- walls of fracture move apart slightly as joint develops
- **Form perpendicular to weakest stress, often tensile σ3**
- **Surface morphology of a joints:** ***<u>Plumose structure</u>*** (wavy structure on joint), ***<u>Spreads outward from joint origin</u>***
- **Plumose structure:** a subtle roughness on surface of joints; resembles imprint of feather. Due to inhomogeneity of rock

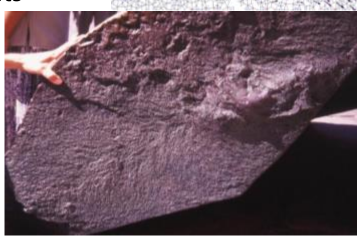


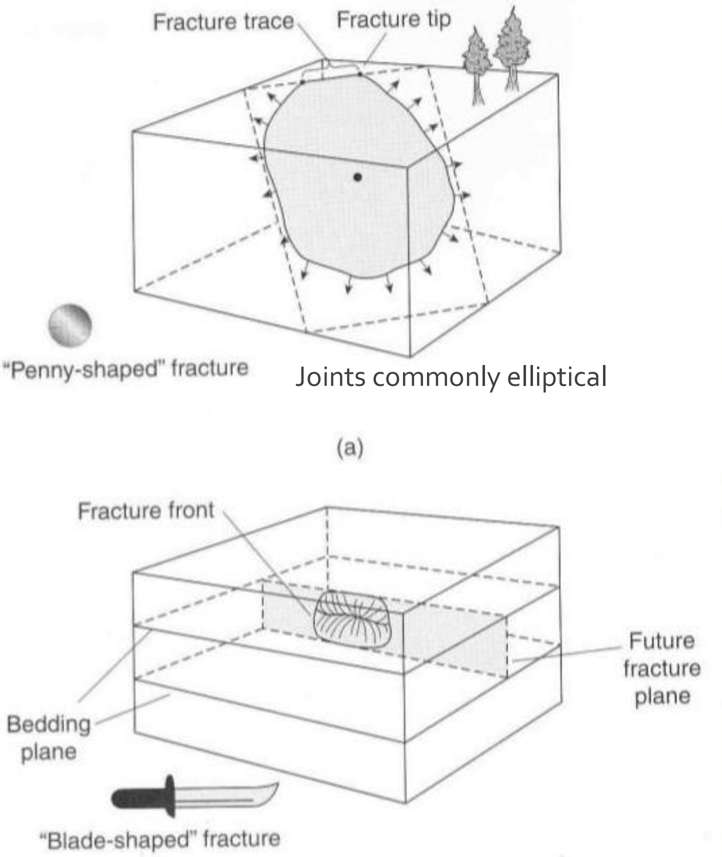


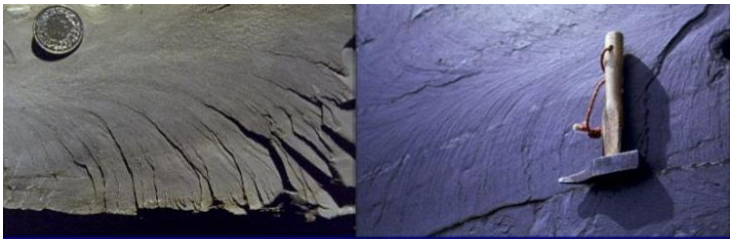
- **The formation of Plumose structure:** loading of hetrogeneous rock yield smooth fractures perpendicular to stress (real joints are not perfectly smooth), & imperfections distort the local stress field, stress field at the tip of the propagating crack changes produced joints



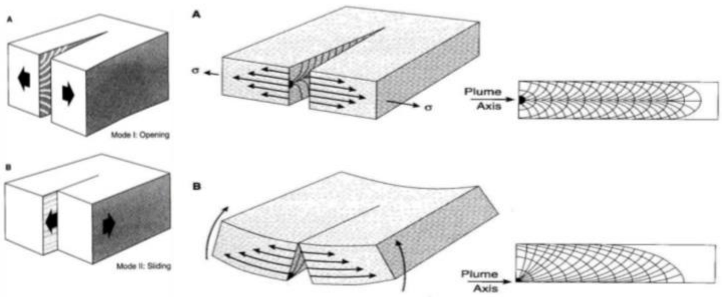






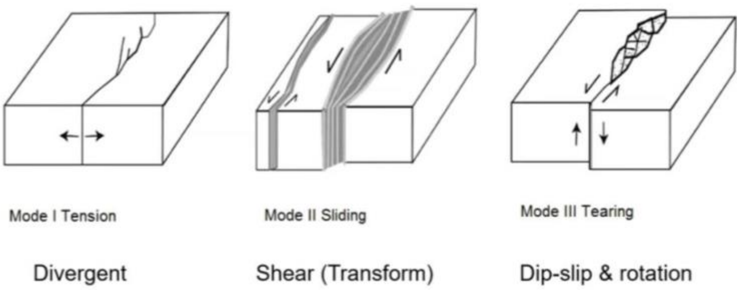


Close-up views of hackles in plumose structure
Plumose structure is more prominent away from origin due to stress concentrations at crack tips



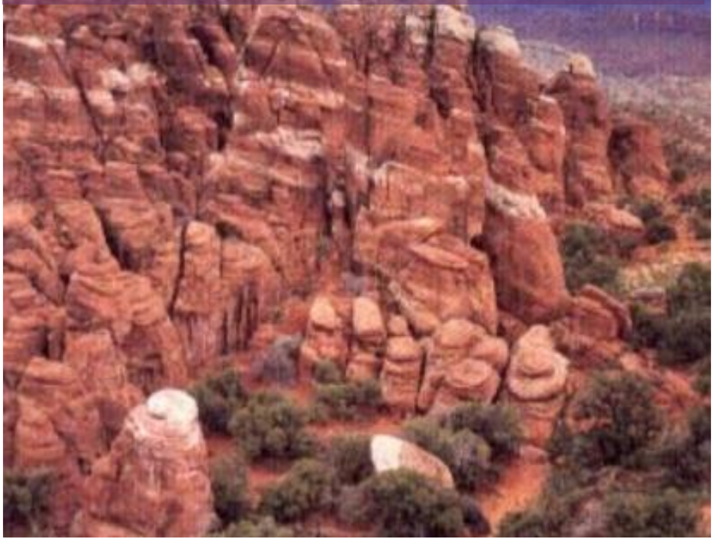
Joints of fracture : kinematics
Ribs are arrest lines-opening is not instantaneous but rhythmic, like splitting wood

- **Mods of joints:** Divergent, Shear, Dip-Slip & Rotation

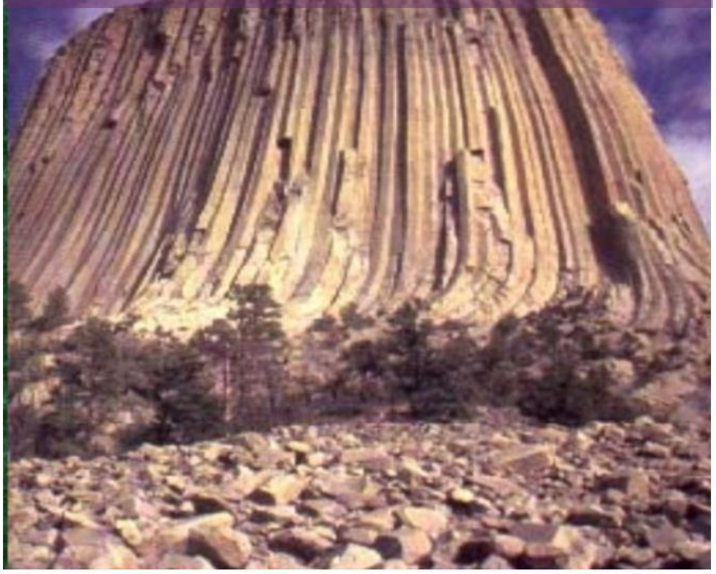


- **Types of joints**: Tectonic Joints (e.g. Eroded joints, & columnar joints), & Non-tectonic joints (sheet joints)

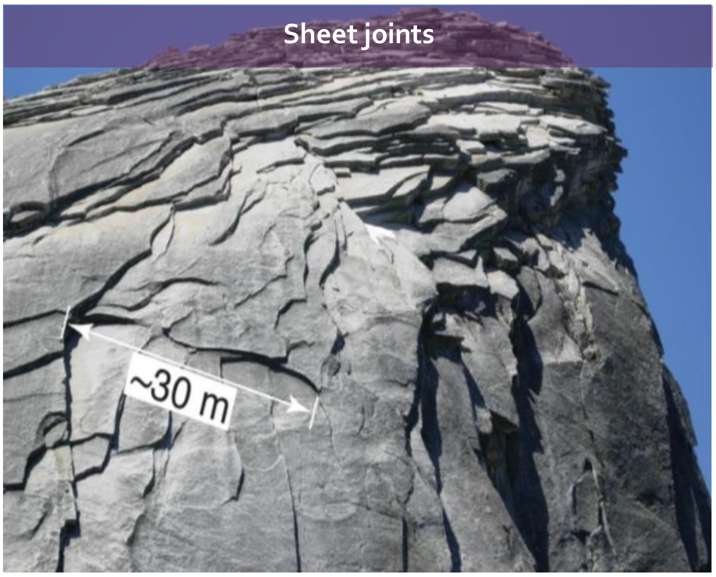
Eroded joints

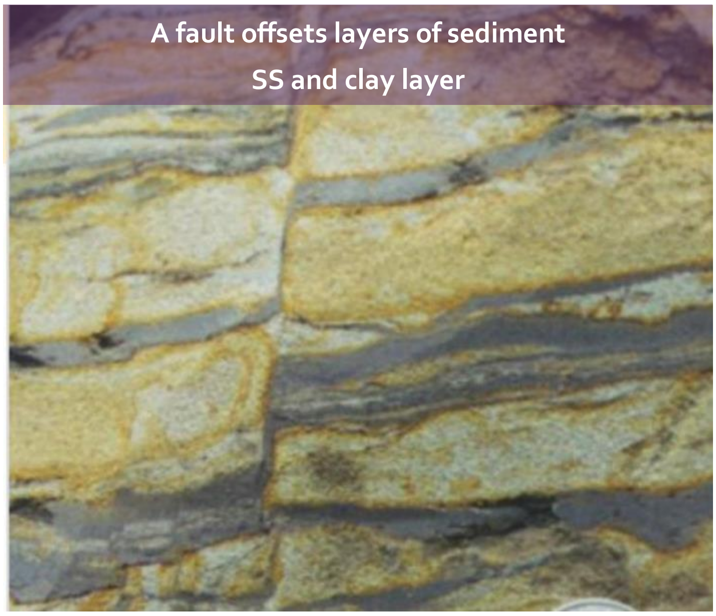


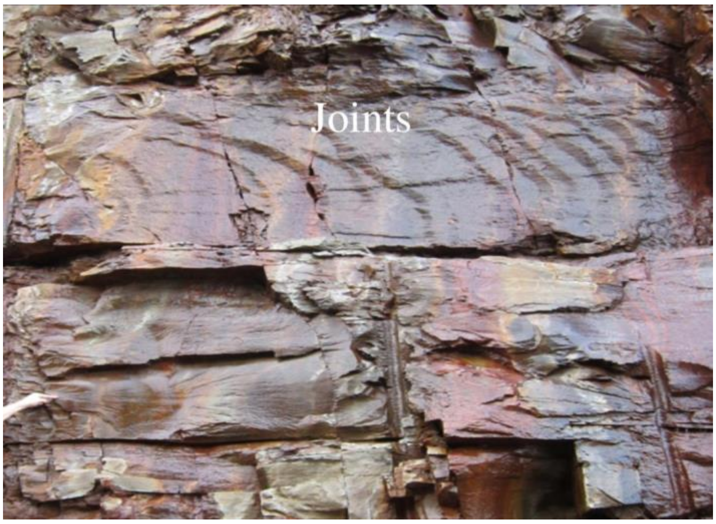
columnar joints form as igneous rocks cool & develop shrinkage fractures producing elongated columns

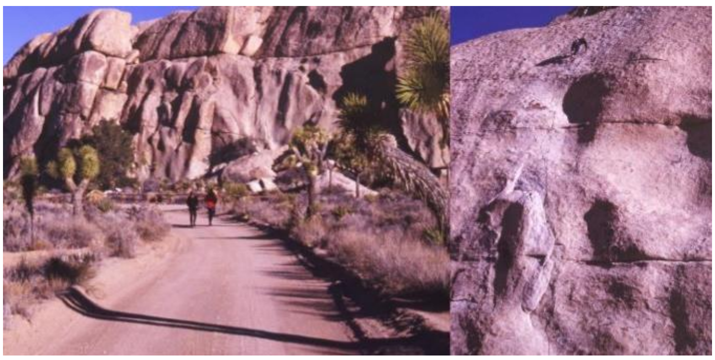


Top view of columnar





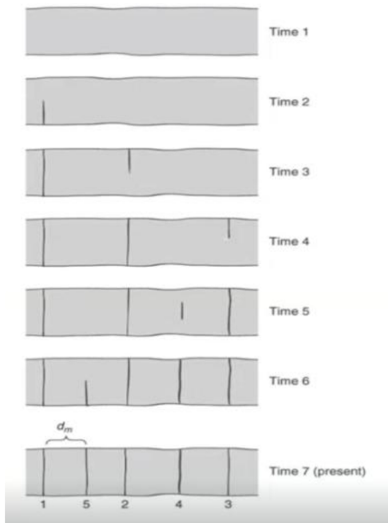




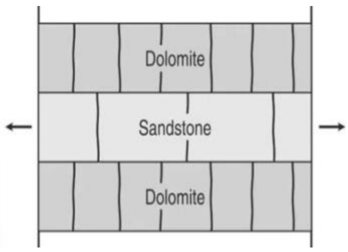
- Rock with low tensile develop more closely space joints & Rock with more tensile strain (stretching) yields more joints

Joints Vs Lithology

- Joint Spacing in sedimentary rocks
  - ➢ **Joints are mostly evenly spaced**: widely or closely spaced depending on length of time & tensile stress applied
  - ➢ **Joint spacing & bed thickness**: Closely spaced in thin bedded & Widely in thick bedded

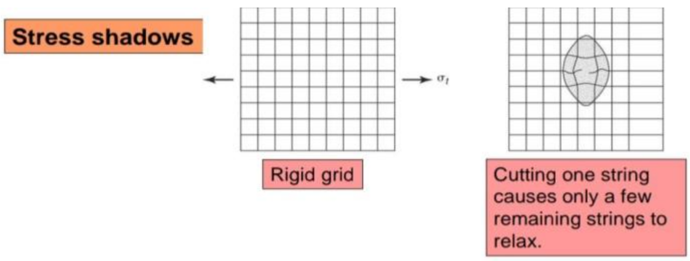


- **Joint spacing & Lithology:** Stiffness = Elastic value (Youngs modulus), Hookes law σ = E.e (e is the elongation strain)
  - ➢ Stiff dolomite fractures a few times before the sandstone fractured the first time because Dolomite stiffness >> Sandstone
    1. Stretch a block
    2. Stress in each bed controlled by Hookes law (magnitude of stress depend on E)



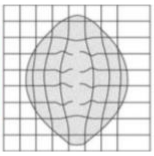
  - ➢ large E (stiffness) related to more stress, & fractured first

Joint arrays (Systematic vs Nonsystematic)



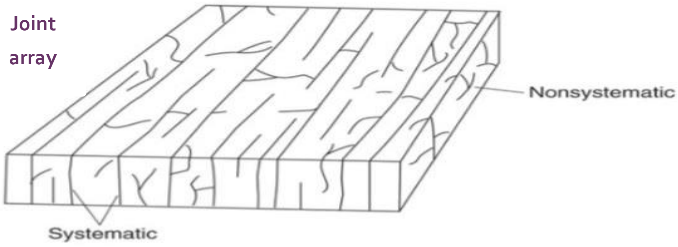
Greater length of joint has a wider stress shadow

Cutting many strings in a row causes a wide band of strings to relax – larger area affected

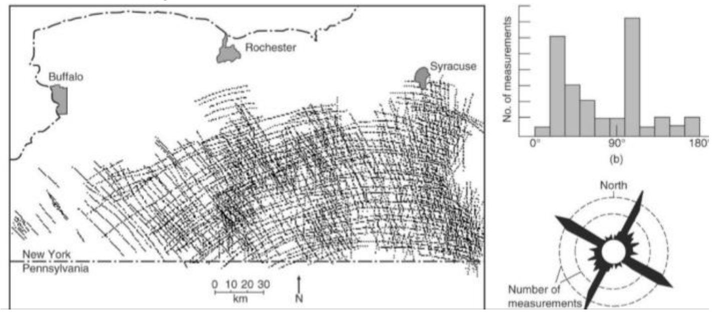


- **Systematic joints:** Planar joints, parallel or subparallel, with same average spacing
- **Nonsystematic joints:** Irregular spatial distribution, Not parallel to one another, Different average spacing

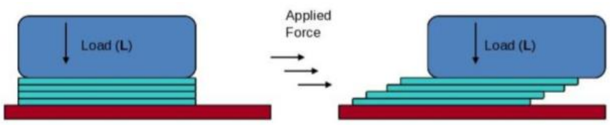
Joint array



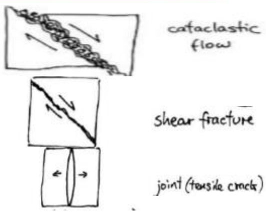
- **Systematic joints:** Planar, parallel to subparallel, Same average spacing
- **Nonsystematic joints:** Irregular spatial distribution, Not parallel to one another, Different average spacing
- **Why study joints:** Tectonics (paleostress), Geomorphology (drainage patterns)
- **Methods to study joints in the field:** Inventory (fracture density, & joint orientation: strike-dip), & Relate to tectonics



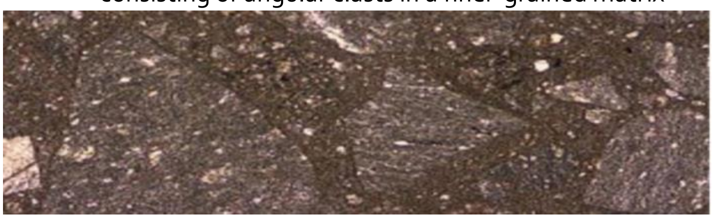
- **Categories of Brittle Deformation:**
  1. **Frictional Sliding** on preexisting fractures



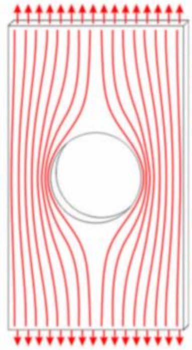
  2. **Cataclastic flow** due grain scale fracturing
  3. **Shear rupture** at acute angle to max. Principle stress
  4. **Tensile cracking** perpendicular to dir of min. Stress

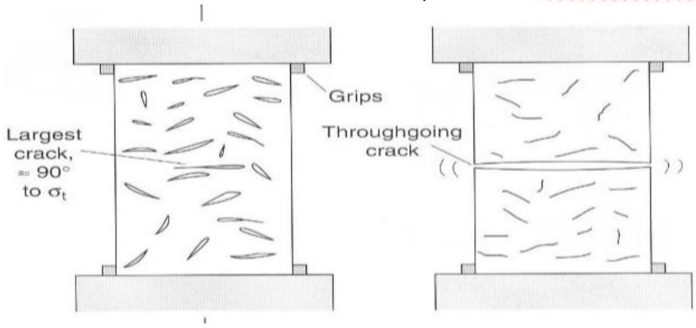


- **Cataclastic rocks:** is a metamorphic rock that wholly or partly formed by progressive fracturing
  - ➢ Rock fragments are reduced in size by crushing & grinding of existing rock, a process known as **cataclasis**
  - ➢ cataclasis process is mainly associated with fault zones
  - ➢ **Cataclasite:** cataclastic rock, formed during faulting, consisting of angular clasts in a finer-grained matrix

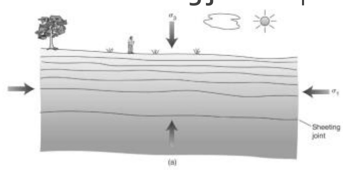


- **Stress Concentration & Griffith Cracks**
  - ➢ **A stress concentration:** is a location where stress is concentrated. An object is strongest when force is evenly distributed over its area, so a reduction in area, (e.g. crack results in a localized increase in stress)
  - ➢ **Griffith cracks:** preexisting micro-fractures & flaws in rock, weakening it. Reason rock failure < theory



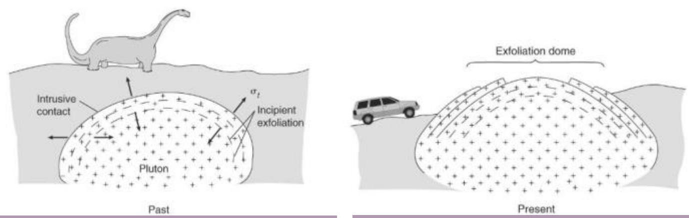


- **Origin & Interpretation of joints**
  1. **Sheeting joints:** uplift & exhumation



Sheeting joints

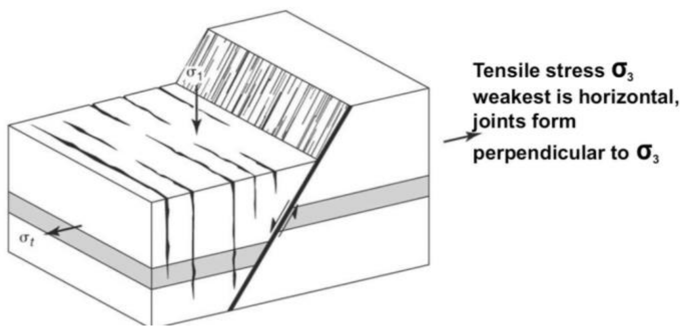
form where σ1 is horizontal & σ3 is vertical near the ground. Joints are closely placed near ground



A cooling pluton contracts more than country rock. Here, σt (tensile stress) is oriented perpendicular to the contact

After exhumation, joints form parallel to intrusive contact and creates an exfoliation dome

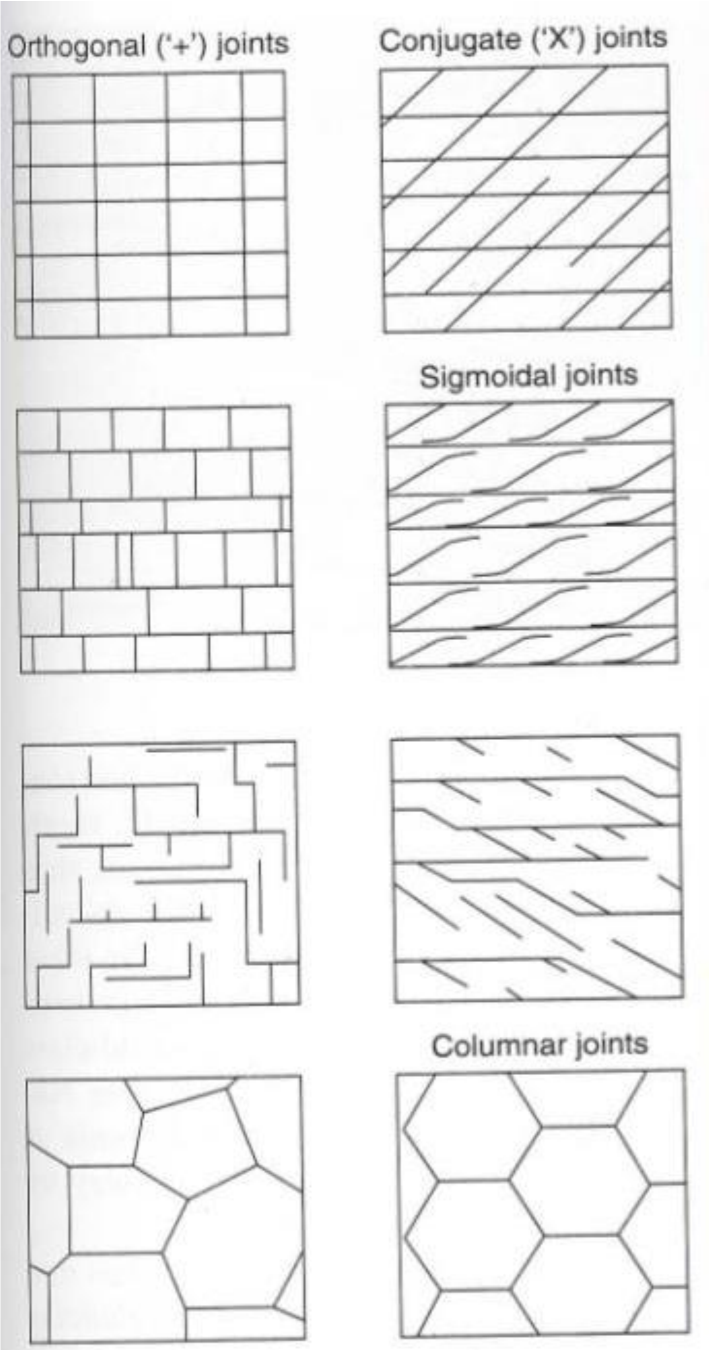
  2. **Regional divergence**



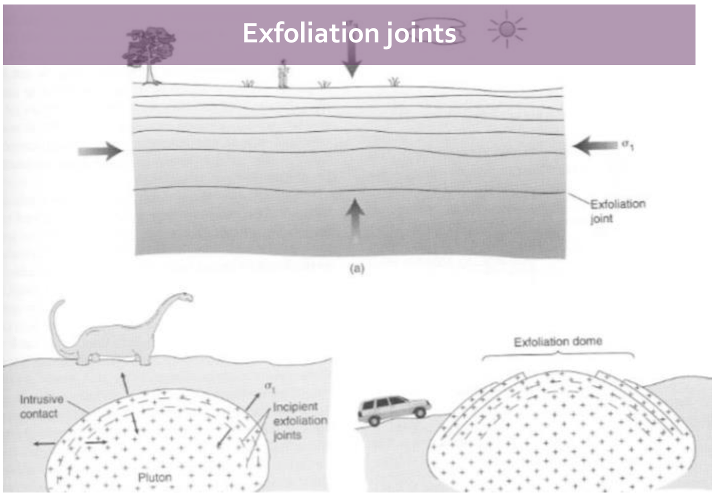
Tensile stress σ_3 weakest is horizontal, joints form perpendicular to σ_3

High pore pressures subject to divergence, weakens confining P
Formation of joints in hanging-wall block with normal faults

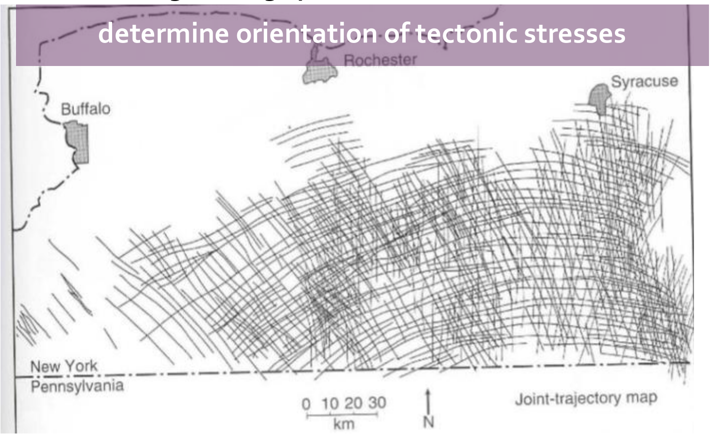
3. **Natural Hydraulic fracturing:** increases pore pressures in a pre-existing crack pushes outward (increases of tensile stress σ that allow cracks tip to developed)
   - ➢ Stress in the Earth crust are mostly compressive



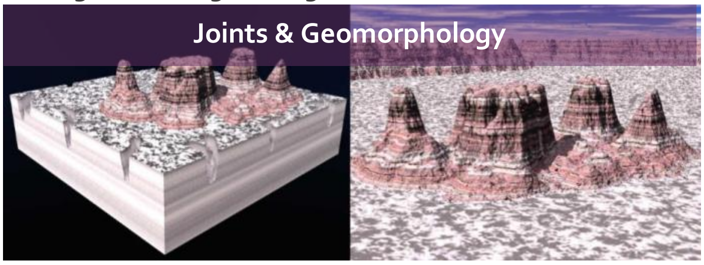
- Three competing mechanisms that contribute to joint formation during uplift and erosion:
  1. **Contraction during cooling (by thermal construction)**
  2. **Poisson effect: Exfoliation joints, Form by unloading of bedrock through erosion parallel to topography (e.g., rock expands in vertical direction & contracts in horizontal direction during unloading)**
  3. **Membrane effect: Tectonic joints, expansion due to increase in curvature of layer by tectonic stresses as opposed to Stresses induced by topography**



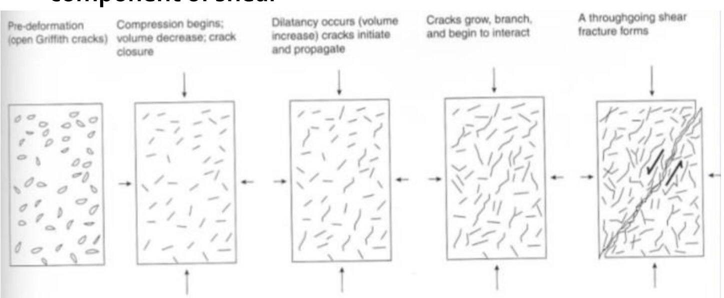
- Joints array significant
  1. **Determine orientation of tectonic stresses**
  2. **Determining the Geologic Hazards**
  3. **For engineering : place of weakness**



- **Significant engineering of Joints:** Planes of weakness

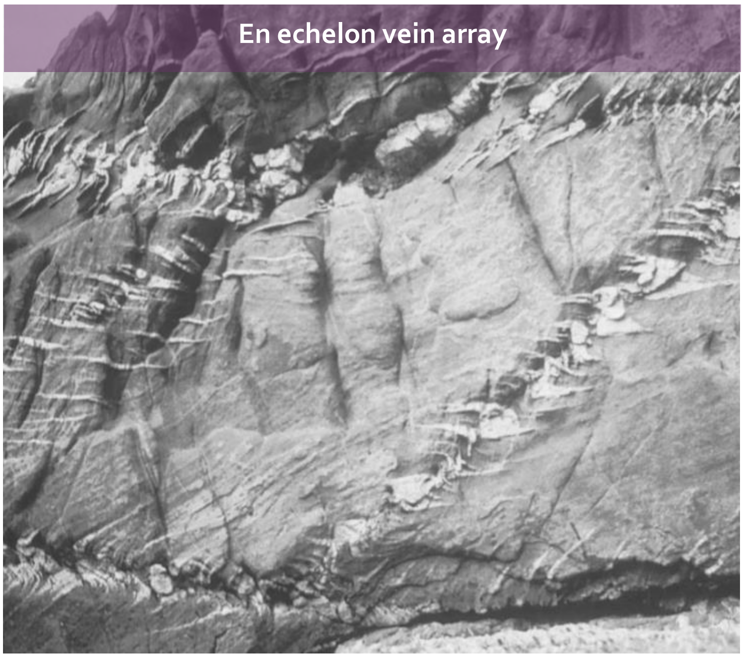


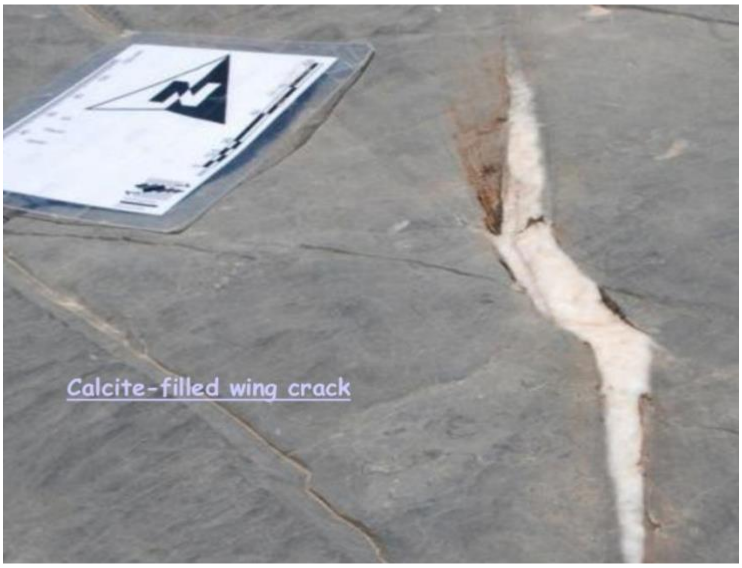
- **Shear fracture: A fracture that grows in association with a component of shear**

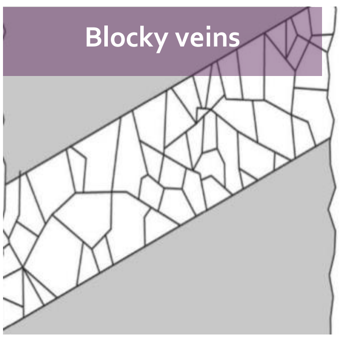


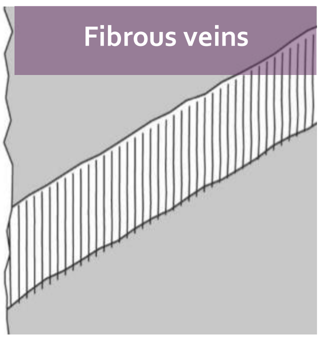
VEINS & VEIN ARRAYS

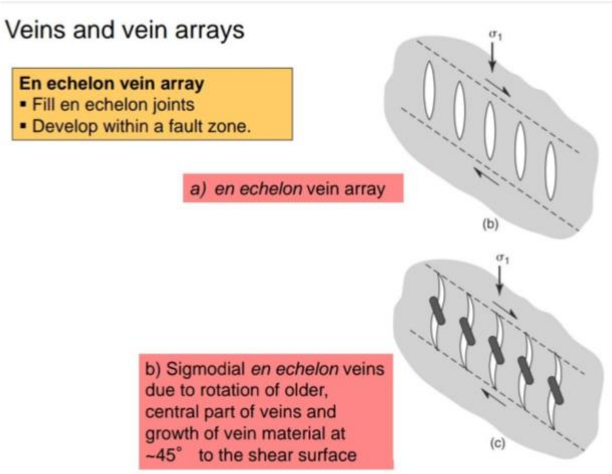
- **Vein**: A fracture filled with mineral precipitated from fluids
- Quartz or calcite are common vein fill
- Ore minerals occur as vein fill
- **Vein Array:** Groups of veins
- **Stockwork array of veins**: rock shattered & filled by mineral
- **En echelon vein array:** Fill en echelon joints, Develop within a fault zone
- **Blocky vein** fill equant, open fracture when mineral precipitated
- **Fibrous vein** crystals long relative to width

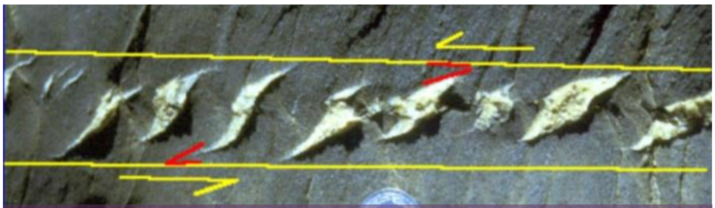






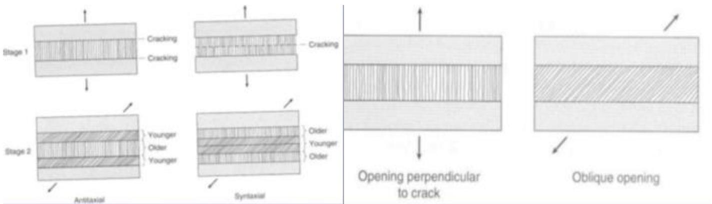






Shear fructure (tension gashes, 45° from plane of max stress

Echelon tension gashes (right to top to right from center to tips during rotation)

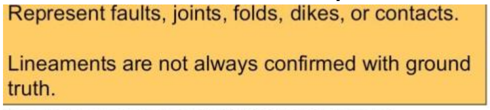


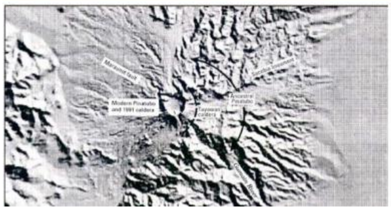
Vein filling during crack opening

- **Significance:** economic value (alteration/mineralization along fructure, veins preserve dilational separation)

LINEAMENT

- A linear feature recognized on aerial photos, topographic maps or remotely sensed images
- Defined only on a regional scale
- Aligned topography, changes in vegetation
- Represent faults, joints, folds, dikes, or contacts.
- Lineaments are not always confirmed with ground truth.

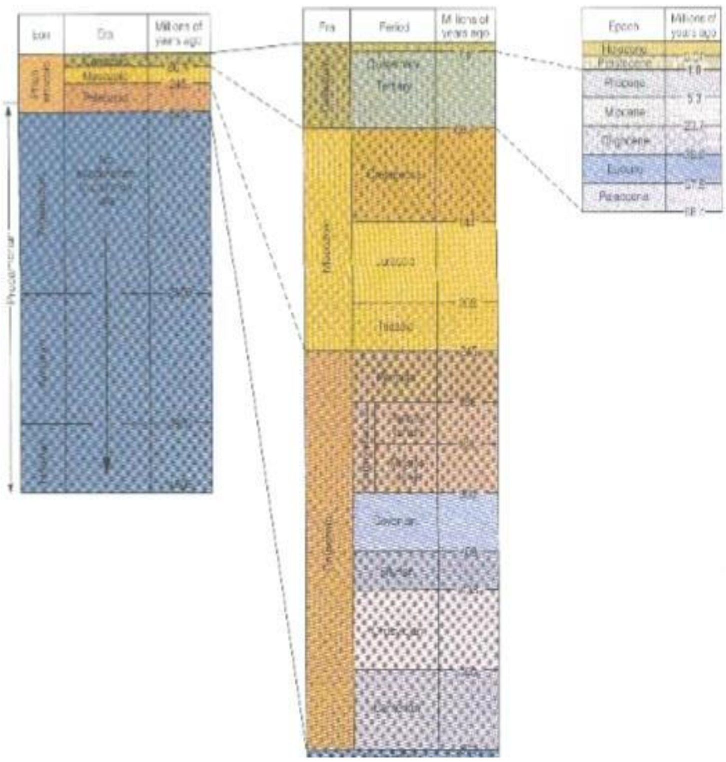




KINKS

- **Kink band:** structure formed by brittle ductile deformation

GEOLOGIC TIME



- Geologic time divided into Era, Period, Epoch based on major events (extinctions, mountain building)
- Age of the Earth (History)
    - Kelvin and a basis in heat flow (set at 20Ma)
    - Problem of fitting all of evolution in this time
    - Rutherford & the introduction radioactive decay
    - Added a head source, pushed ages back to 4.5Ga
- **Relative Time:** Principle of Superposition, Fossil Evidence, Cross Cutting Relationships, Unconformities, Alteration, cross-cutting relationships, & Fracture Termination
- **Absolute Time**: Basis on radiometric dating (Common dating tools 14C, K-Ar, Rb-Sr, & Uranium decay series)

Precambrian: Minimal fossil record

Paleozoic (Old Life): Brachiopods, Trilobites, Fish

- **Periods** based on English Geology
- **Cambrian** for Latin Wales
- **Ordovician & Silurian** for ancient Welsh Tribes
- **Devonian** for Devon
- **Carboniferous**: Coal (Mississippian&Pennsylvanian)
- **Permian** for Perm Basin in Ukraine

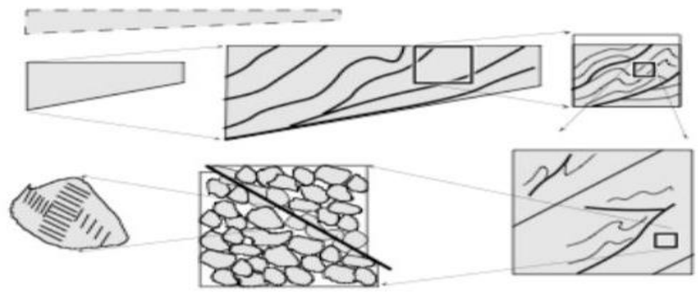
Mesozoic (Middle Life): Ammonites, Dinosaurs

- **Triassic**: distinctive 3-layer stratigraphy in Germany
- **Jurassic**: Jura Mountains in France & Switzerland
- **Cretaceous** (**Chalk**): chalk that forms Dover's cliffs

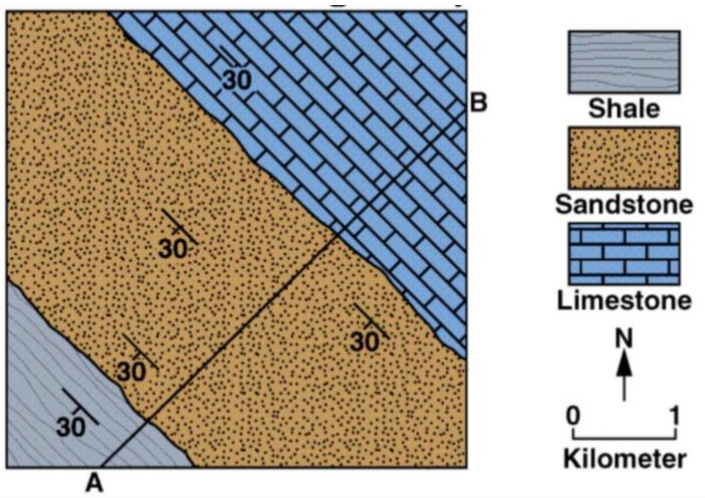
Cenozoic (Recent Life): Mammal, marine fauna (foraminifera)

- **Tertiary** (before Ice Ages) & **Quaternary** (ice ages)
- **Primary & secondary** have been long replaces
- Rocks of Washington are Tertiary & Quaternary

- **CEE 437 Structural Geology:** World Stress, Brittle & Ductile Deformation, Faults, Joints, & Folds
- **Time scales:** geological processes occur over a wide range of characteristic time scales.
- **The characteristic time scales for fault rupture:** Stresses that accumulate steadily over many years, due to relative plate motion, may be released abruptly within seconds to tens of seconds.
- **The characteristic time scales for dike intrusion**: Modern dikes eruptions (e.g., in Hawaii) have lasted between a few hours and a few days (show a movie).
- **The characteristic time scales for mylonite formation**: The physical processes that accompany the formation of metamorphic fabric are slow (e.g., dissolution & re-precipitation of minerals).
- The formation of brittle structures is discontinuous & evolves via abrupt steps, the formation of ductile fabric is more or less continuous & is governed by slow processes
- **Length scales**: deformation is occurring simultaneously at a wide range of length scales, & The different scales include: Plate, Regional, Outcrop, Hand-sample, Grain, & Crystal

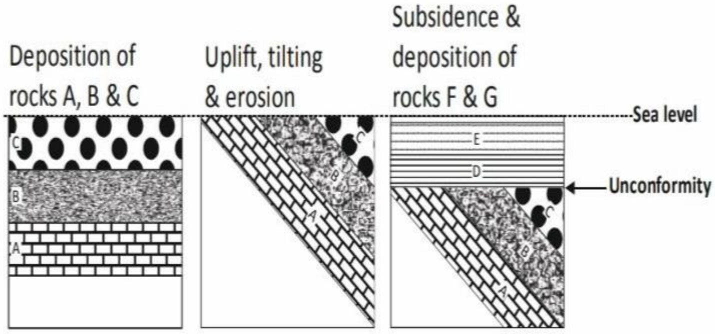


GEOLOGIC MAPS



- **Elements of a geologic map**: rock types, relative ages, geologic contacts between different rock units, geologic structures (e.g., faults), & maybe topographic contours
- **Layer-cake stratigraphy:** planar (horizontal) layers with constant thickness & continue
- **Orientation of plane**: boundaries between units or beds
- **Bed**: thin layers within the rock, each bed formed over a short period of time, & the surface of a bed formed the sediment surface at some point in the past
- **Units**: collection of adjoining bed that grouped together when have some similarity (mineralogy, palaeontology, structures) that indicate a process in their origin
    - Mappable & distinct from one another, but the contact doesn't have particularly distinct
    - Grouped together in stratigraphy as formations & members of formations
- **Outcrop patterns:** represent the intersection of 3D shape of the rock with the land surface
    - Where the rocks are flat & the land is not the boundaries will outcrop along topographic contour lines
    - **Vertical features (or plane):** straight line cut contours
    - **Horizontal layer:** follow the contour lines (parallel)
    - **Inclined layer**: intersect the contour line (intersecting with the contour lines along the straight line))
    - **Plunging folds**: not parallel in poth side of outcrops
    - **Non-Plunging folds:** parallel in poth side of outcrops
    - **Folds** forming V – shapes in valleys & ridges
- Geologists define the orientation of dipping beds using the terms **strike & dip**
    - **Strike**: azimuth (bearing on a compass) of a horizontal line on a bed (line perpendicular to steepest angle of dip) (e.g. 090 for a bed striking EW)
    - **Dip:** angle from the horizontal of the steepest gradient of the bedding surface (horizontal bed has a dip of N20E)
    - Strike & dip are measured with a compass or clinometer on an area about 10cm x 10 cm
    - Dip direction is from older to younger layers
    - True dip is a line perpendicular to the strike & is the steepest line along the plane of the bed
    - **Apparent dip** is the angle from a horizontal line that is not perpendicular to the strike

- **Dip variations** Folds & faults are the most common causes of variation in strike & dip
    - Folding & faulting , followed by subsequent erosion & deposition of a younger rock produces an unconformity
    - Unconformities are variations to the simplest case of sedimentary rocks, identifiable on maps as place where more than one younger rock is in contact with several older rocks

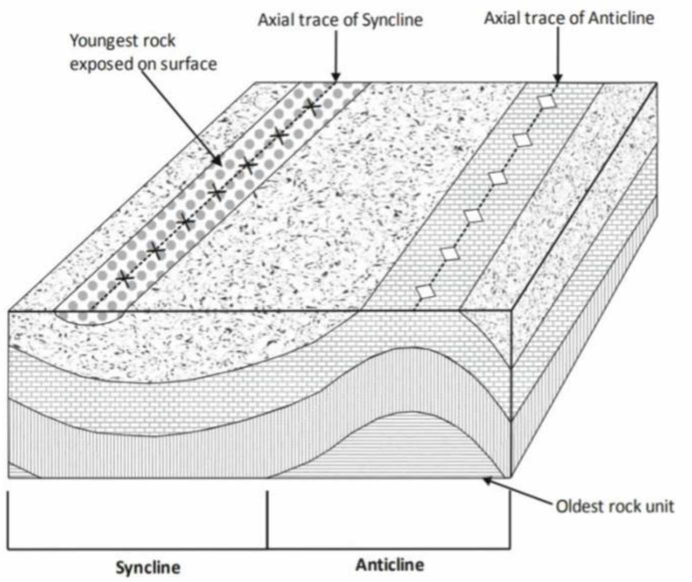


$$t = w\ x\ sin\theta = V\ x\ sin\theta$$

w =V= vertical thickness or width, θ=dip, t=True thickness

$$slope = \frac{\Delta Y}{\Delta X} = \frac{vertical\ distance\ (CI)}{horizontal\ distance\ (SI)}$$

$$True\ Dip = tan^{-1}\left(\frac{CI}{SI}\right)$$



- Faults are surfaces in the Earth across which there has been some displacement , usually by cataclasis (the deformation of rock via crushing & shearing)
    - usually narrow in proportion to their length & breadth , often planar or gently curved & exist mainly in the top 10-15km of the Earth's crust
    - Below this depth , rock deforms in a plastic fashion , without fracturing, Because faults involve displacement, one of the targets of geologists is to quantify this displacement (ideally as a vector) .
        - Horizontal offset (displacement) called **heave**
        - Vertical Horizontal offset (displacement) is **throw**
        - if horizontal beds are displaced horizontally, heave & throw are both zero
        - dipping beds with measurable heave & throw displacement could be solely horizontal, solely vertical or oblique

STEREONETS

Plotting a Plane

- An inclined plane plots alog a great circle
- The endpoint of the cyclographic trace of a plane with a non-zero dip are at diametrically opposed pointson the primitive circle, these points define the line of strike for the plane

EXAMPLE to drown a plane with 60° Strike & 50° Dip

Step 1: Lay tracing paper over stereonet

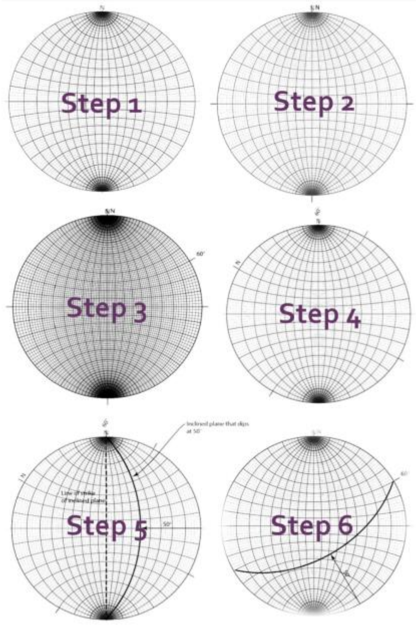
Step 2: trace primitive circle with a compass (label 0°, 90°, 180°, 270°, & N at 0)

Step 3: Plot a strike mark (60°) on primitive circle

Step 4: rotate tracing to placing the strike mark at N

Step 5: Draw the plane of the dip (50°)

Step 6: Remove stereonet to see the results, Visualize the results, & check to see if they make sense



Plotting a Line

- **A line lies at the intersecon of 2 planes:**
    1. **A vertical plane (magenta)** with a strike that matches the trend of the line
    2. **An inclined plane (violet)** with a dip that matches the plunge of the line & that dips in the direction line plunges

EXAMPLE to drown a line with 60° trend & 50° plunge

Step 1: Lay tracing paper over stereonet

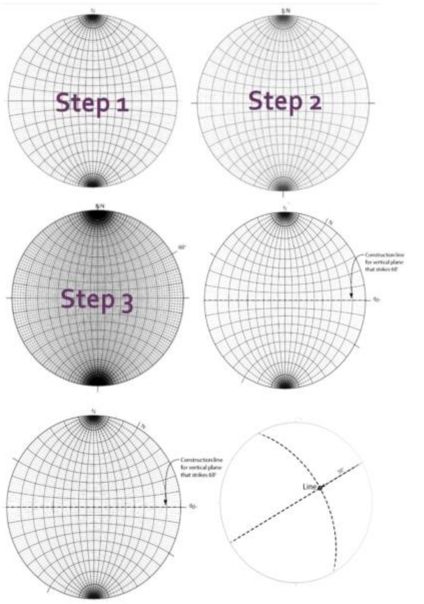
Step 2: trace primitive circle with a compass (label 0°, 90°, 180°, 270°, & N at 0)

Step 3: Plot a trend mark (60°) on primitive circle

Step 4: rotate tracing to placing the trend mark at small circle that projects as a straight line (i.e., the equatorial line)

Step 5: Mark off the plunge (50°), counting from the primitive circle towards the center of the plot (The line of interest is at the intersecon of the vercal pink plane and the plunging violet plane)

Step 6: Remove the stereonet to see the results



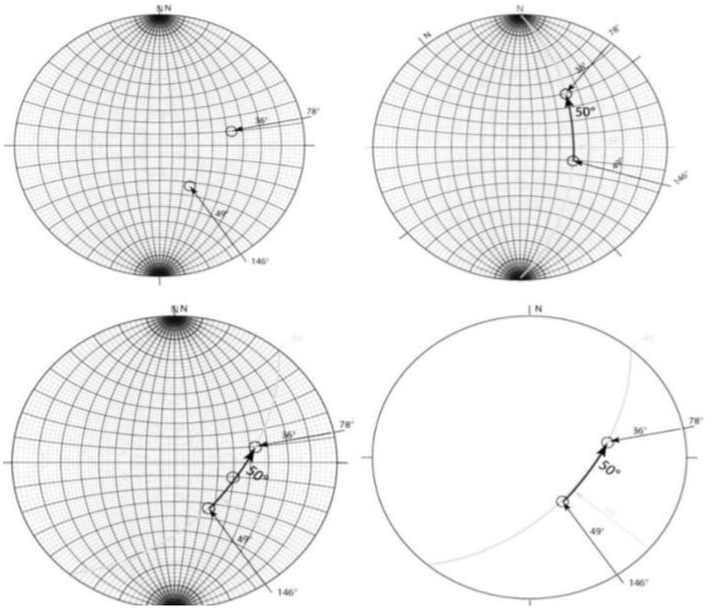
Measuring the angle between two lines

- The angle between the lines is measured along the cyclographic trace of the plane that contains the lines
- The procedure is exactly analogous to measuring the angle between two lines with a protractor

Example find the angle between 2 lines one trends 78° & plunges 36°; & the other trends 146° & plunges 49°

Step 1: Plot the lines

Step 2: Find the plane that contains both lines (Rotate the tracing paper such that both lines lie on a single great circle & measure the angle along the great circle between the 2 lines. Here = angle 50° & the common plane (green) dips 50°)

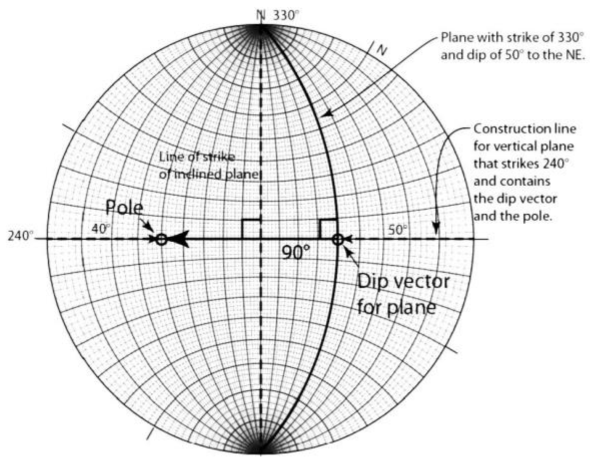


Plotting the Pole to a Plane

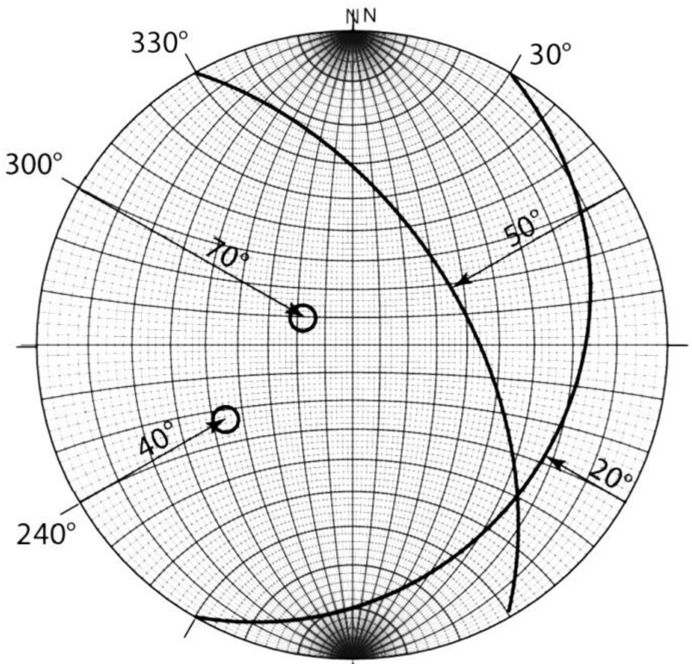
- The pole to a plane is a line that plotted like any other line
- The pole to a plane of interest lies in a vertical plane perpendicular to the plane of interest
- The pole also makes a 90° angle (as measured in the vertical plane) with respect to the "dip vector" of the plane of interest

Example Consider a plane of interest that strikes 330° & dips 50° to the NE, its pole can be found by simple calculations.

- ➢ The pole trends 240° & plunges 40°
- ➢ The pole to a plane lies in a vertical plane perpendicular to the plane of interest
- ➢ The pole also makes a 90° angle (as measured in the vertical plane) with respect to the "dip vector" of the plane of interest



Measuring the angle between two planes



Measure angle between poles in a plane containing the poles

- Rotate the tracing to find the common plane that contains the 2 poles
- The angle between the planes is measured in the plane containing the poles
- The angle determined graphically is 43° (measured to the nearest degree)