Faults and Faulting

Earth Structure (2019)
(Processes in Structural Geology &Tectonics)

© Ben van der Pluijm
1/31/2019 16:25

Rock Stories: Fault

A fault is a surface or zone in rocks on which slip (displacement) occurred. We distinguish dip-slip (normal, reverse), strike-slip (lateral) and their combinations, based on relative displacements of fault blocks on opposing sides.

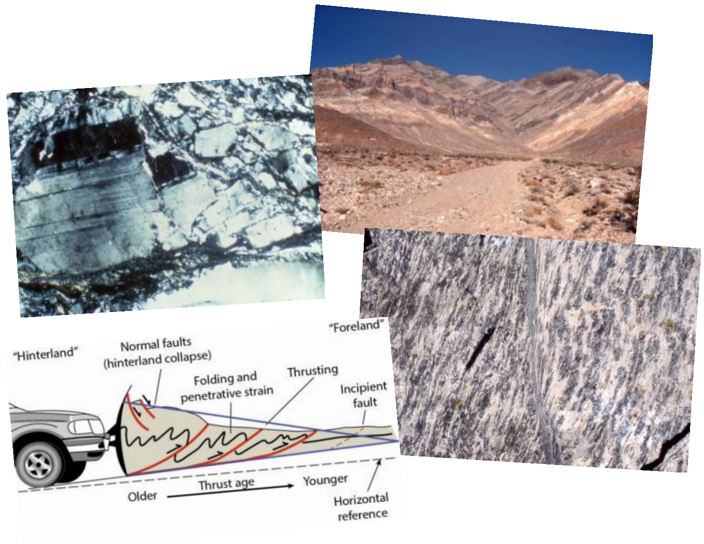
Faults occur on many scales and control the regional arrangement of rock units. They create surface topography and govern landscape evolution. Faults control the distribution of resources (like, oil, ore bodies) and rock permeability, which, in turn, controls subsurface fluids.

Regional faulting can cause devastating earthquakes and tsunamis.

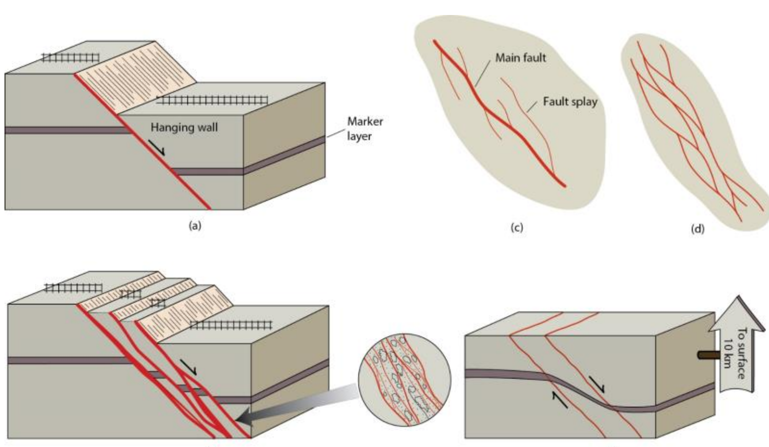
Lewis Thrust, Canada; Eocene reverse fault placing L Carboniferous carbonate on U Cretaceous shale. Regional (top) and fault rock at contact (left).

We Discuss …

Faults
- Types and Geometries
- Fault Systems
- Fault bends
- Dimensions
- Fault Surfaces
- Fault Rocks (with depth)
  - Cataclasites
  - Mylonites
  - Pseudotachylytes
- More on Mechanics of (Reverse) Faulting
  - Thrust Paradox
  - Thrust Wedges
- Structure and Society
  - Earthquakes
  - Resources

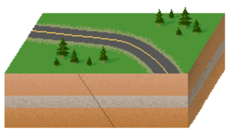


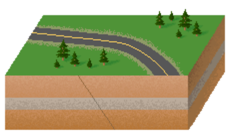
Faults, Fault Zones and Shear Zones



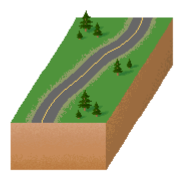
a) Fault.
b) Fault zone, with cataclastic deformation.
c) Principal fault and fault splays.
d) Anastomosing faults.
e) Shear zone.

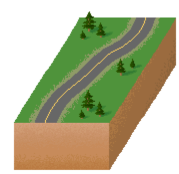
Fault Types and Characterization



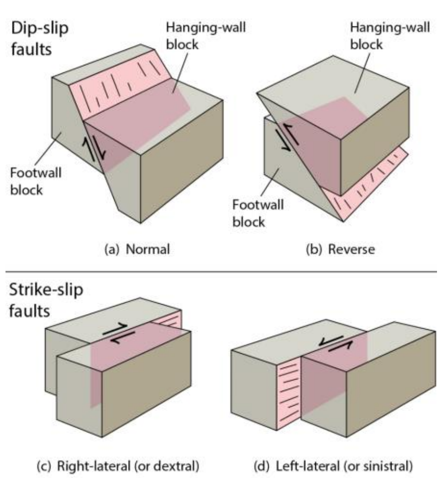


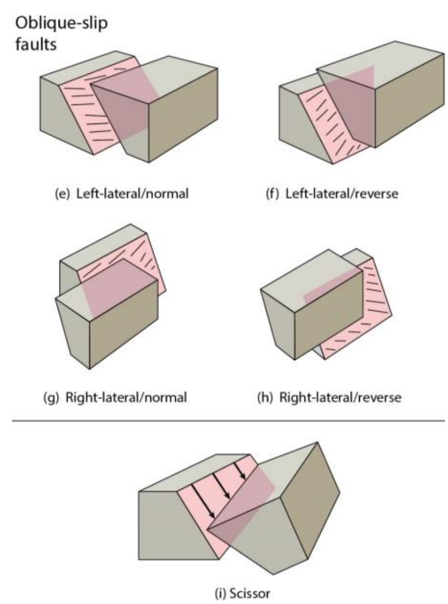
Type	Displacement	Geometry	Kinematics
Dip-slip	Normal (down-dip)	High-angle Low-angle	Horst-graben Detachment
	Reverse (up-dip)	High-angle Low-angle	Accretionary Duplex
Strike-slip	Right-lateral (dextral)	Vertical	Transcurrent Transfer
	Left-lateral (sinistral)	Vertical	Transcurrent Transfer



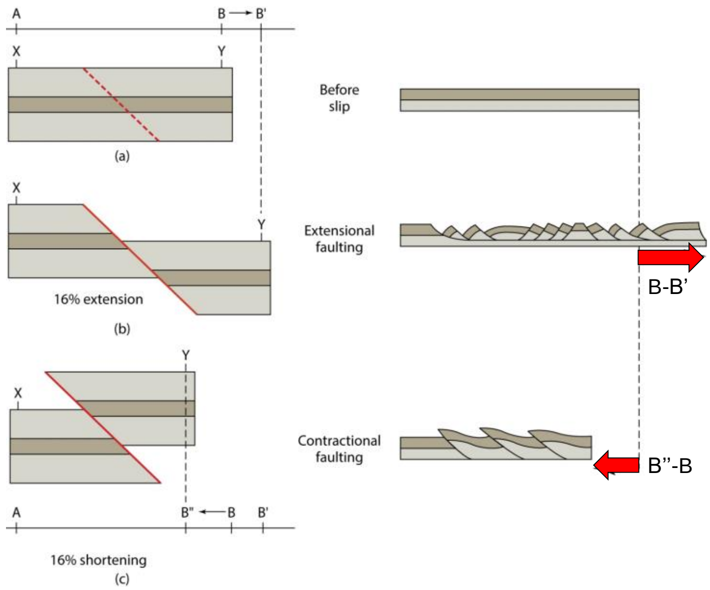


Fault Types: Oblique-slip Faults





Extensional and Contractional Faults

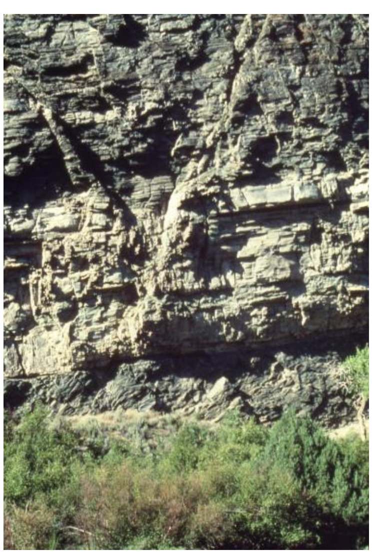


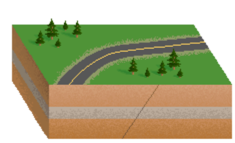
a) Starting condition
b) Extension
c) Contraction

Horizontal length change. Shortening strain (e) is:

$$e = \frac{l - l_o}{l_o} = \frac{\delta l}{l_o}$$

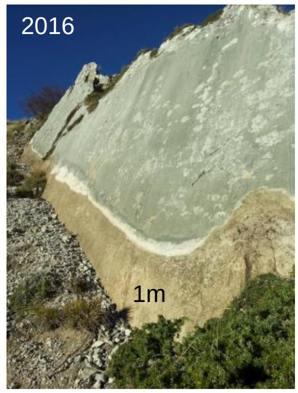
Normal Faults



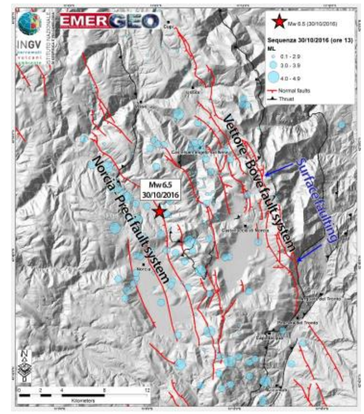


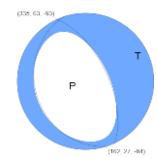
Modern Fault Scarp: Norcia (Italy) Earthquake (10-30-2016)

A Notaro, 2014

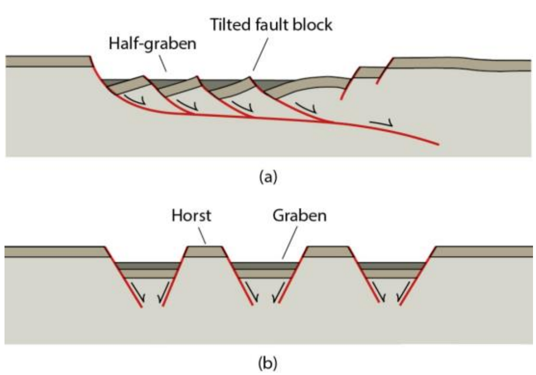


P Galli, 2016



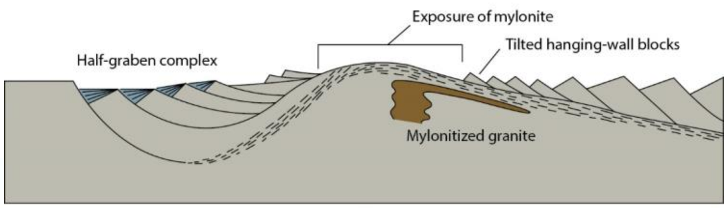


Normal Fault Systems



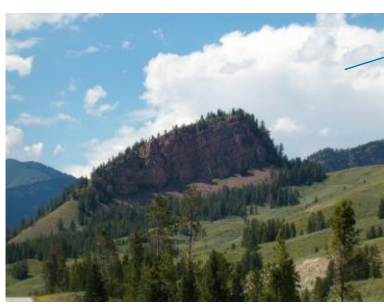
Normal Fault ("detachment") systems
(a) low-angle
(b) high-angle

Example: Low-angle Normal Fault ("detachment")

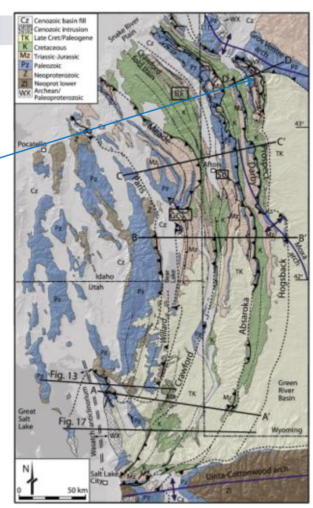


Whipple Mtns

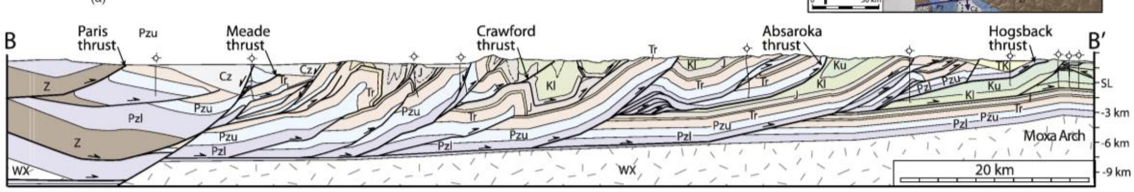
Reverse (Thrust) Faults



Battle Mnt, Hoback Canyon (U-M's Camp Davis area)



Yonkee and Weil, 2015

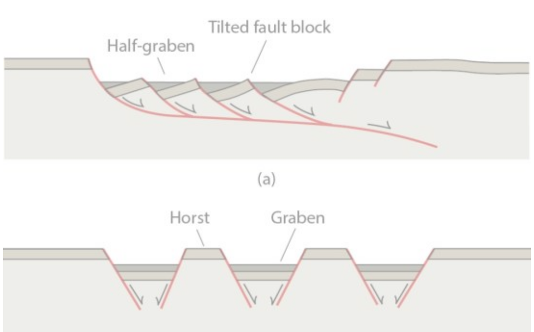


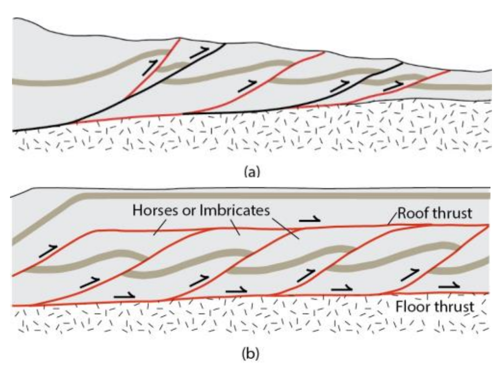
Low-angle Reverse (or Thrust) Faults




Glarner (or Glarus) Thrust, Swiss Alps

Reverse Fault Systems

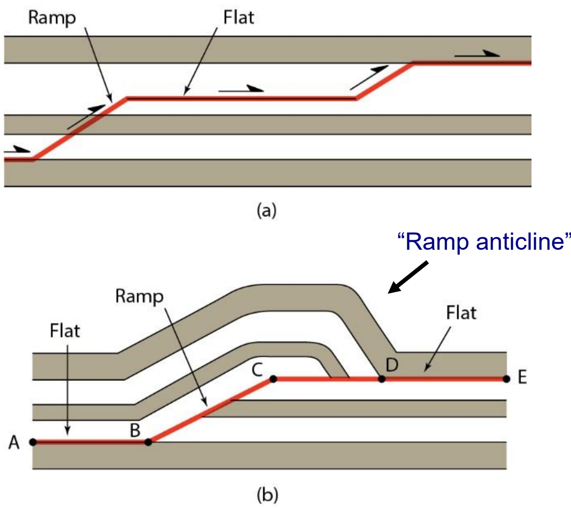




Normal Fault ("detachment") systems
(a) low-angle
(b) high-angle

Reverse Fault ("thrust") Systems
(a) wedge
(b) duplex

Fault Bends: Thrust Ramps and Flats



(a) Cross section with future ramps and flats along thrust fault.

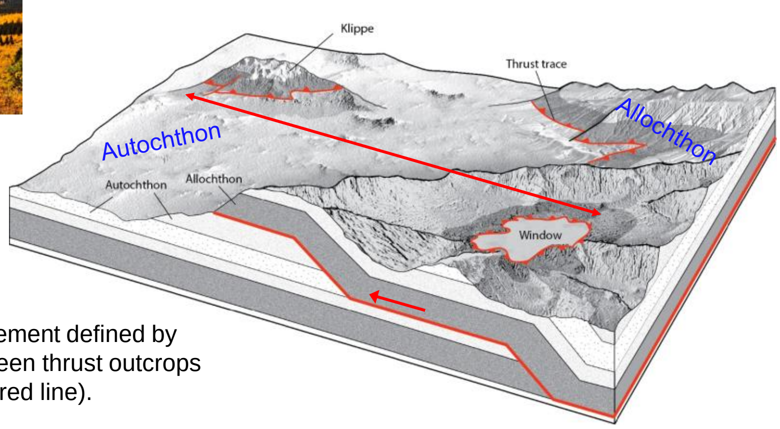
(b) Cross section illustrating hanging-wall and footwall flats and ramps, and ramp anticline. (see also Folds and Folding …)

(Segment AB is hangingwall flat on footwall flat. Segment BC is hanging-wall flat on footwall ramp. Segment CD is hangingwall ramp on footwall flat, and segment DE is hanging-wall flat on footwall flat.)

(Erosional) Klippe and Window

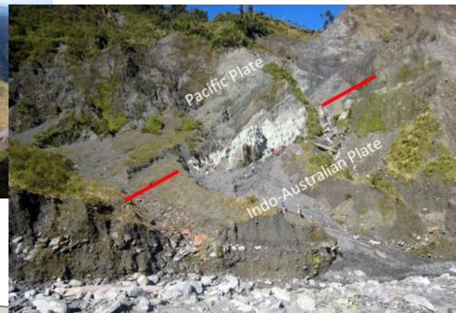
Chief Mtn, MT
PreC on Cret

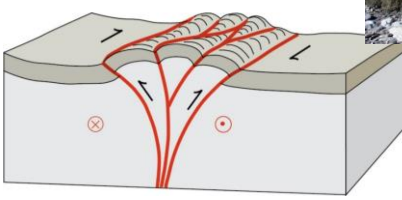
Klippe, window, allochthon and autochthon in thrust-faulted region.



Minimum fault displacement defined by farthest distance between thrust outcrops in klippe and window (red line).

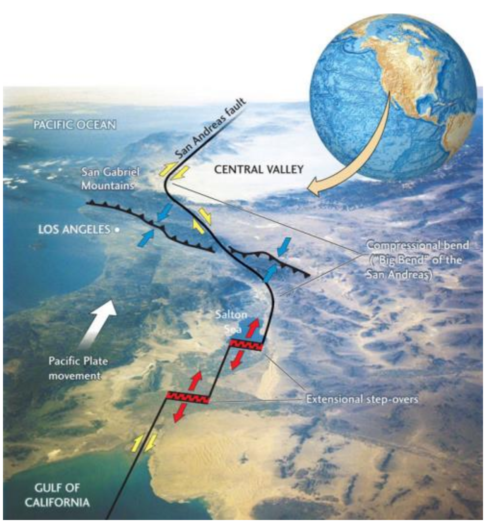
Lateral-slip (or Strike-slip) Faults

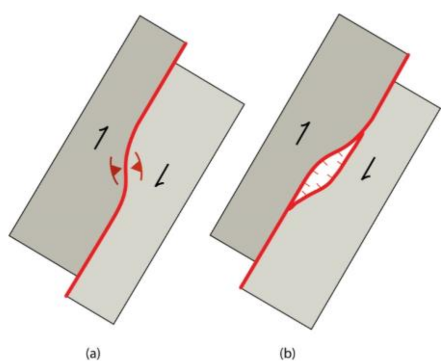




Alpine (“LotR”) Fault
New Zealand (S Island)

Strike-slip Faults: Restraining and Releasing Bends





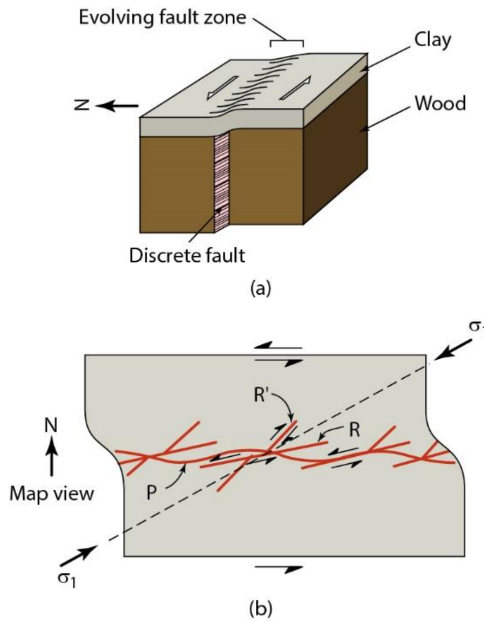
Map-views of:
(a) restraining bend along right-lateral (dextral) slip fault.
(b) releasing bend along right-lateral (dextral) slip fault.

Subsidiary Faults

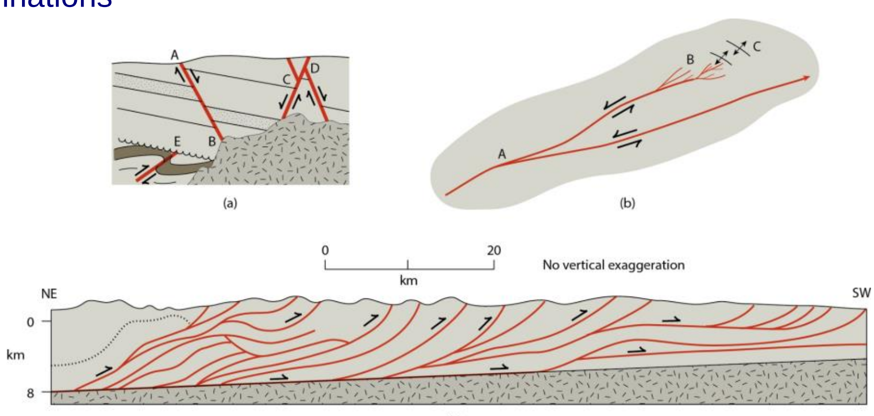
R-, R′-, and P-shears

(a) Clay deforms when underlying blocks of wood slide past one another.
(b) Top surface of clay layer, with orientation of Riedel (R), conjugate Riedel (R′), and P-shears.

Note that acute bisector of R- and R′-shears is parallel to σ_1 and faults at ~30º, following Andersonian theory.

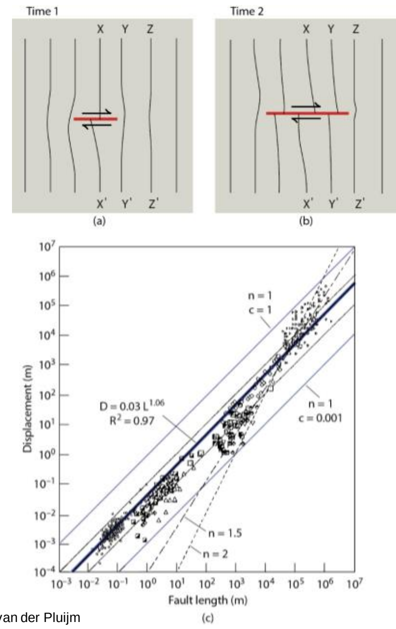


Fault Terminations



(a) Fault terminates at surface at A; at B, fault is cut by pluton; at C and D, one fault cuts another; at E, fault eroded at unconformity.
(b) Termination of fault by merging with another fault (at A), by horsetailing (at B) and dying out into zone of distributed deformation (at C).
(c) Series of thrusts merging at depth with single fault (floor thrust or "decollement").

Fault Size and Self-similarity



Displacement on fault increases as fault grows (i.e., fault length increases)

Measures of maximum displacement and fault length gives empirical relationship:

D(isplacement) is ~3% of L(ength)

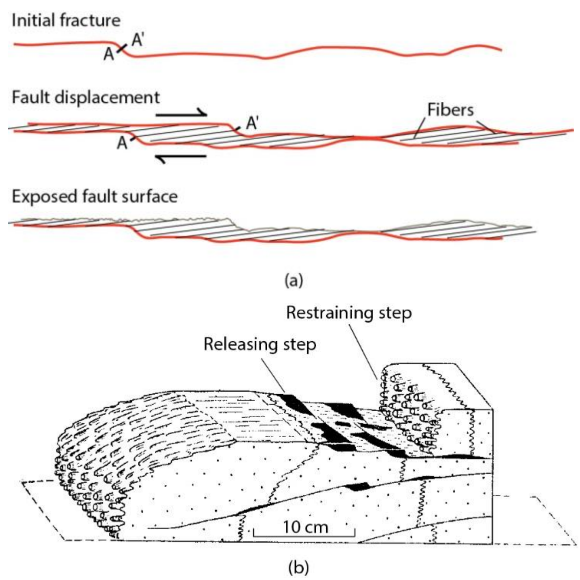
	Length	Displacement	Fault Zone Width
Length	—	10^{2}	10^{4}
Displacement	10^{-2}	—	10^{2}
Fault Zone Width	10^{-4}	10^{-2}	—

Row fault property equals value times column property; for example, width = 0.01 × displacement ($W = 0.01 \times D$). *(From Scholz, 2002)*

Fault Surfaces: Striations and Polish

San Andreas Fault Observatory at depth (SAFOD)

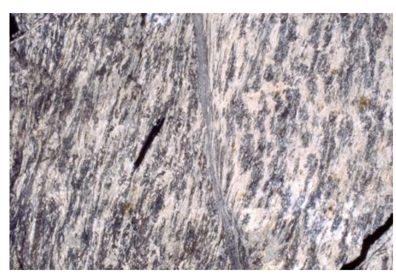
Fault surfaces: Slickensides (polish) and Slickenlines (fibers)



Fault Rock Classification

Frictional Regime: Cataclasite

Plastic Regime: Mylonite

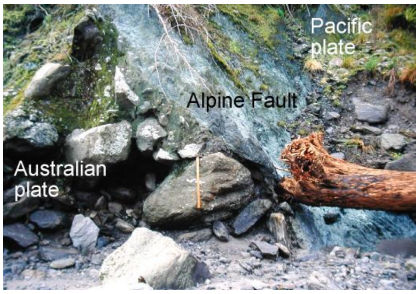


Descriptions of fault rock classes by hand-specimen appearance and degree of cohesion:

Cataclasite	Fault breccia	Vein-filled breccia
Fault gouge	Pseudotachylyte	**Mylonite**

Also used: Foliated vs. Non-foliated.

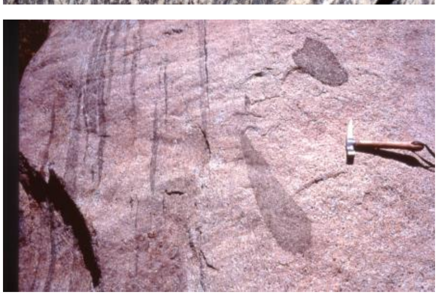
Fault Rocks: Cataclasite, (Tectonic) Breccia and Gouge



Breccia

Gouge

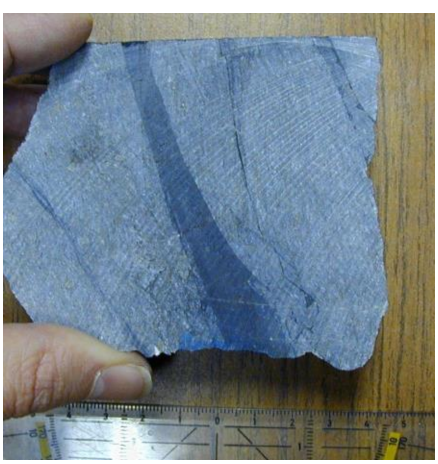
Fault Rocks: Mylonites ("Ductile" Shear Zones)



Extra: Types of Mylonites

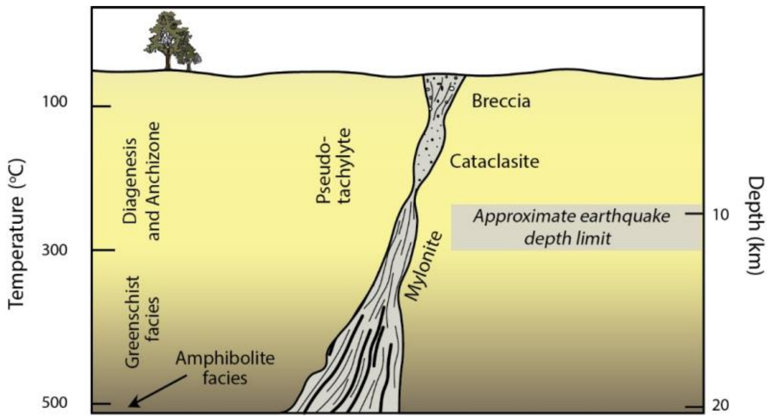
Blastomylonite	Mylonite that contains relatively large grains that grew during mylonitization (e.g., from metamorphic reactions or secondary grain growth).
Clastomylonite	Mylonite that contains relatively large grains or aggregates that remain after mylonitization reduced the grain size of most of the host rock (e.g., relatively undeformed feldspar grains or clumps of mafic minerals).
Phyllonite	Mica-rich mylonite.
Protomylonite	Mylonite in which the proportion of matrix is <50% (i.e., rocks in which only a minor portion of the minerals underwent grain-size reduction).
Ultramylonite	Mylonite in which the proportion of matrix is 90–100% (i.e., rocks in which mylonitization was nearly complete).

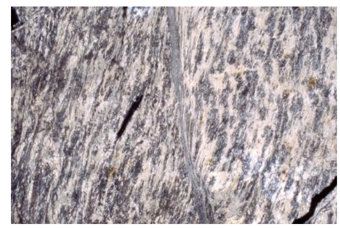
Fault Rocks: Pseudotachylyte (Friction Melt)



Alpine Fault (~500Ka) and Grenville Front (~1.1Ga)

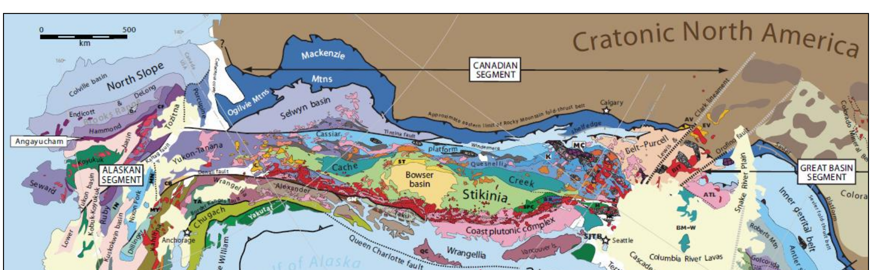
Synoptic Fault Zone and Character with Depth

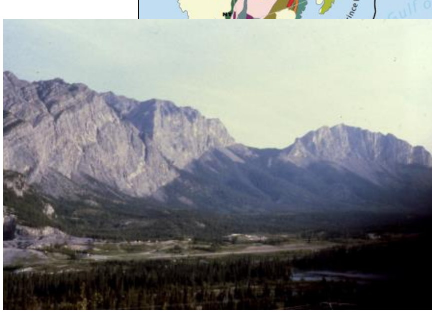


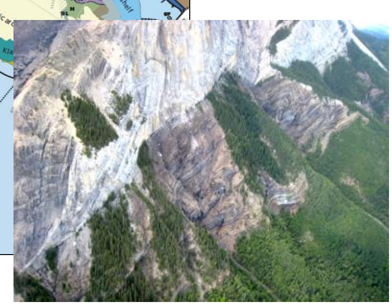


Changing fault character and fault rocks with depth (steeply dipping fault).
Note change in fault zone width.

More on Fault Mechanics …







Canadian Rockies

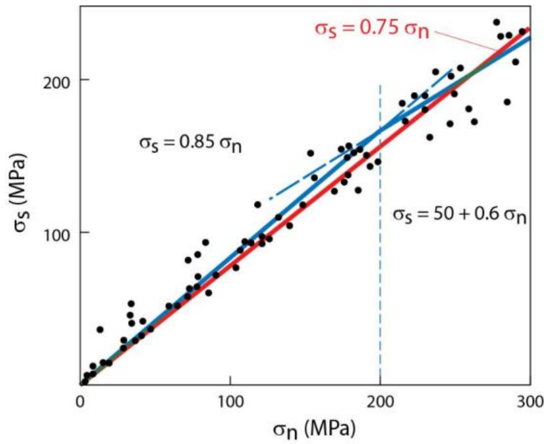
Frictional Sliding Criterion

Recall:

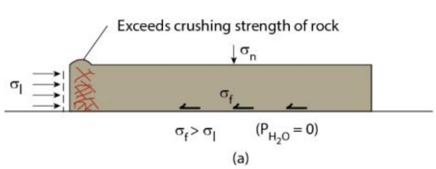
σ_s / σ_n = constant = μ

= coefficient of friction

μ = **~0.75**



Mechanics: Thrust Paradox



σ_n is stress from loading,
σ_f is frictional resistance ($=\sigma_s$),
σ_l is boundary load at end of thrust sheet,
P_{H2O} is pore pressure.

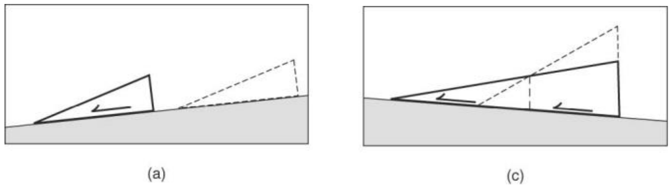
Sliding block:
100(w) x 10(l) x 5(h) km
block; ρ = 2600 kg/m^3

σ_n = F/area = (a.m)/area
= 9.8 x (2600x1E5x1E4x5E3) /1E5x1E4
= 127 x 10E6 Pa = 127 MPa

$\sigma_f = \mu$ x σ_n , **μ = 0.75**
so σ_l ~95 MPa

Compressive strength of natural rock on same order, so fracturing at front instead of sliding

Gravity Sliding



Sliding down (a) and up (c) a tilted slope. Downslope is representative for landslides (dry and wet), BUT most thrust belts have a bottom sloping up.

Dry and Wet:

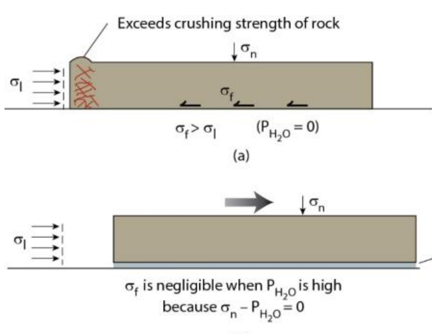
"Dry" sliding: dip is 35-40º (angle of repose)

"Wet" sliding: $\lambda = P_f/P_l$

$\lambda = 1$ (P_f=P_{lith}), dip is ~0º

$\lambda = 0.8$, dip ~10º

Effective Friction: Fluid Pressure Scenario



(a) Pushed from rear.

(b) High fluid pressure at base;

σ_n is stress from loading, σ_f is frictional resistance (=σ_s), σ_l is boundary load at end of thrust sheet, P_{H2O} is fluid pressure (P_f).

$\sigma_f = C + \mu (\sigma_n - P_f)$; fracture

or

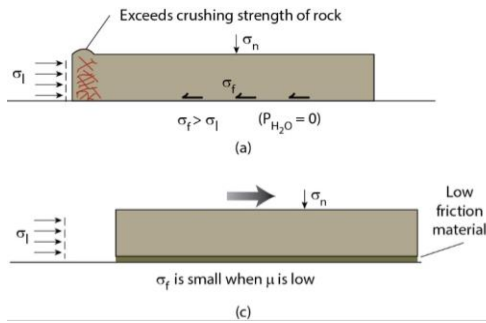
$\sigma_f = \mu (\sigma_n - P_f)$; friction

So, $\mu_{effective} = \mu (1 - P_f/\sigma_n)$

$\mu_{effective} \leq \mu$;

Note: $P_f < \sigma_3$

Low Friction: Lubricant Scenario



(a) Pushed from rear.
(b) Low friction material at base;
σ_n is stress from loading, σ_f is frictional resistance, σ_l is boundary load at end of thrust sheet.

Sliding block:
100 x 10 x 5 km
ρ = 2600 kg/m^3

σ_n = F/area = 127 MPa
$\sigma_f = \mu \times \sigma_n$

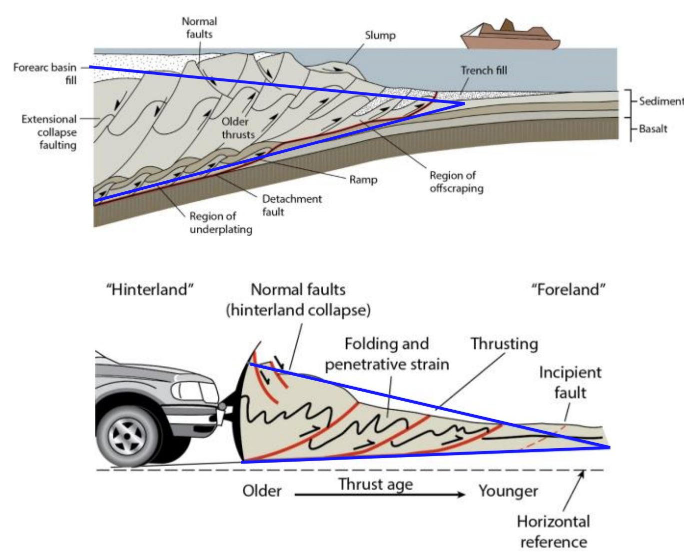
μ **= 0.2**, so σ_f ~25 MPa

Strength of natural rock greater, so sliding

Mechanics: Thrust Wedges

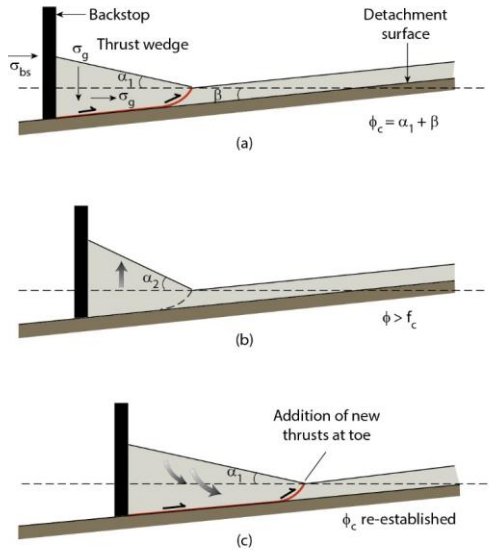
Plow analogy:
Wedge of snow or sand extends with continued shortening; thrusts initiate from hinterland to foreland.

As thrusts add material at toe of wedge, hinterland portions develop penetrative strain, normal faults and slumps.



Thrust Wedge Mechanics: Critical Taper Theory

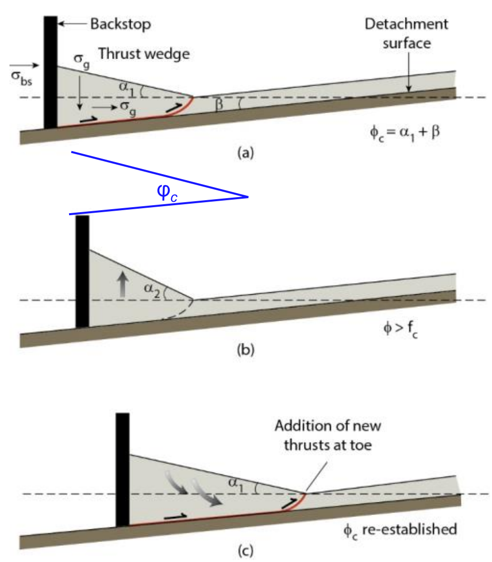
Arlo Weil's snow service



Thrust Wedge Mechanics: Critical Taper Theory

Critical taper (angle φ_c) is sum of surface slope angle (α_1) and basal slope angle (β).

a) Stress acting on wedge, partly horizontal boundary load caused by backstop (σ_{bs}) and partly caused by gravity (σ_g).
b) If backstop moves, wedge thickens, so surface slope increases, and taper (φ) eventually exceeds φ_c.
c) Wedge slides toward foreland and new material is added to toe, and extension of wedge occurs so that surface slope decreases.

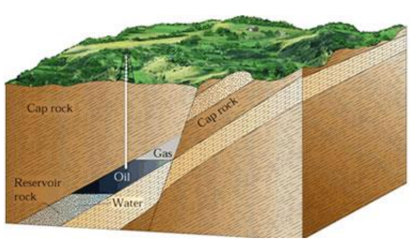


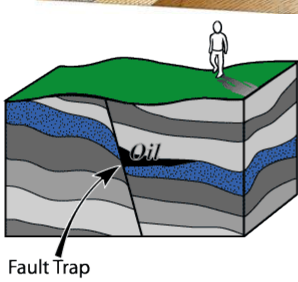
Structure and Society: Earthquakes

Date	Location	Deaths	Magnitude
January 23, 1556	China, Shansi	830,000	~8
October 11, 1737	India, Calcutta**	300,000	
January 12, 2010	Haiti, Port au Prince	300,000	7.0
July 27, 1976	China, Tangshan	255,000	7.5
August 9, 1138	Syria, Aleppo	230,000	
December 26, 2004	Sumatra, Indonesia	225,000	9.1
May 22, 1927	China, near Xining	200,000	8.3
December 22, 856+	Iran,Damghan	200,000	
December 16, 1920	China,Gansu	200,000	8.6
September 1, 1923	Japan, Kwanto/Tokyo	143,000	8.3
October 8, 2005	Pakistan	75,000	7.6
May 12, 2008	China, Sichuan	70,000	7.9
December 28, 1908	Italy, Messina	70,000	7.5
November 1, 1755	Portugal, Lisbon	70,000	8.7
June 20, 1990	Iran	50,000	7.7
August 17, 1999	Turkey, Izmit	45,000	7.4
March 11, 2011	Japan, Sendai	20,000	9.0

Structure and Society: Resources

Resources: Fossil Fuels





Resources: Mineralization