Faults and Faulting

Processes in Structural Geology & Tectonics
Ben van der Pluijm

© WW Norton+Authors, unless noted otherwise
2/2/2017 14:47
We Discuss …

Faults
• Types and Geometries
• Systems
• Fault bends
• Dimensions
• Fault Surfaces
• Fault Rocks
  • Cataclasites
  • Mylonites
  • Pseudotachylytes
  • Character with Depth
• 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: Dip-slip and Strike-slip Faults

Dip-slip faults

(a) Normal

(b) Reverse

Footwall block

Hanging-wall block

Strike-slip faults

(c) Right-lateral (or dextral)

(d) Left-lateral (or sinistral)
Fault Types: Oblique-slip Faults

Dip-slip faults
- Footwall block

Hanging-wall block
(a) Normal
(b) Reverse

Strike-slip faults
(c) Right-lateral (or dextral)
(d) Left-lateral (or sinistral)

Oblique-slip faults
(e) Left-lateral/normal
(f) Left-lateral/reverse
(g) Right-lateral/normal
(h) Right-lateral/reverse

(i) Scissor
Field Example: Normal Fault
Modern Fault Scarp: Norcia (Italy) Earthquake (10-30-2016)

A Notaro, 2014

P Galli, 2016
Field Example: Reverse (Thrust) Fault

Hoback Canyon (U-M's Camp Davis area)
Field Example: Lateral-slip (or Strike-slip) Fault

Alpine Fault
New Zealand (S Island)
Extensional and Contractional Faults

a) Starting condition
b) Extension
c) Contraction

Note horizontal length changes.

Shortening is:

\[ e = \frac{l - l_0}{l_0} = \frac{\delta l}{l_0} \]
Fault Systems

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

Whipple Mtns
Fault Systems

Normal Fault ("detachment") systems

Reverse Fault ("thrust") Systems

Lateral-slip Fault System
Field Example: Reverse or Thrust Faults

Swiss Alps
Fault Bends: Thrust Ramps and Flats

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

(b) Cross section illustrating hanging-wall and footwall flats and ramps, and ramp anticline.

“Ramp anticline”

(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

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

Minimum fault displacement defined by farthest distance between thrust outcrops in klippe and window (blue line).
Restraining and Releasing Fault Bends

Map-views of:

(a) restraining bend along a right-lateral (dextral) slip fault.

(b) releasing bend along a 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 $\sigma_1$ and faults at 30°, following Andersonian theory.
(a) Fault terminates at ground surface at A; at B, fault is cut by a pluton; at C and D, one fault cuts another; at E, fault was 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 thrust ramps merging at depth with single fault (floor thrust or “decollement”).
Fault Scaling 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:

\[ D(\text{displacement}) \approx 3\% \text{ of } L(\text{length}) \]

<table>
<thead>
<tr>
<th>TABLE 8.4</th>
<th>FIRST-ORDER RELATIONSHIPS BETWEEN FAULT PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
</tr>
<tr>
<td>Length</td>
<td>—</td>
</tr>
<tr>
<td>Displacement</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Fault Zone Width</td>
<td>$10^{-4}$</td>
</tr>
</tbody>
</table>

Row fault property equals value times column property; for example, width = 0.01 x displacement [W = 0.01 x D]. (From Scholz, 2002)
Fault Surfaces: Striations and Polish

SAFOD samples
Fault surfaces: Slickensides (polish) and Slickenlines (fibers)
Fault Rock Classification

Cataclasite

Mylonite

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

Argille scaglieose

Cataclasite
Fault gouge

Fault breccia
Pseudotachylyte

Vein-filled breccia

Mylonite

Also used: Foliated vs. Non-foliated.
Fault Rocks: Cataclasite, (Tectonic) Breccia and Gouge
Fault Rocks: Mylonites (Shear Zones)
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 Melts)

Alpine Fault (~500Ka) and Grenville Front (~1.1Ga)
Synoptic Fault Zone and Character with Depth

Changing fault character with depth (steeply dipping fault). Also, change in fault zone width and types of fault rock with depth.
Mechanics: Thrust Paradox

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

$\sigma_n = F/\text{area} = (a.m)/\text{area}$

$= 9.8 \times (2600 \times 10^5 \times 10^4 \times 5 \times 10^3)$

$/10^5 \times 10^4$

$= 127 \times 10^6$ Pa = 127 MPa

$\sigma_f = \mu \times \sigma_n$, $\mu = 0.7$

so $\sigma_i \sim 90$ MPa

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

$\sigma_n$ is stress from loading,
$\sigma_f$ is frictional resistance ($=\sigma_s$),
$\sigma_i$ is boundary load at end of thrust sheet,
$P_{H2O}$ is pore pressure
Effective Friction: Fluid Pressure Scenario

\[ \sigma_f = C + \mu (\sigma_n - P_f); \text{ fracture} \]

or

\[ \sigma_f = \mu (\sigma_n - P_f); \text{ friction} \]

So, \( \mu_{\text{effective}} = \mu \left(1 - \frac{P_f}{\sigma_n}\right) \)

\( \mu_{\text{effective}} \leq \mu; \)

Note: \( P_f < \sigma_3 \)

(a) Pushed from rear

(b) High fluid pressure at basal detachment

\( \sigma_n \) is stress from loading, \( \sigma_f \) is frictional resistance \((=\sigma_s)\), \( \sigma_l \) is boundary load at end of thrust sheet, \( P_{H2O} \) is fluid pressure \((P_f)\)
**Low Friction: Lubricant Scenario**

(a) Pushed from rear
(b) Low friction material at basal detachment

- $\sigma_n$ is stress from loading,
- $\sigma_f$ is frictional resistance,
- $\sigma_l$ is boundary load at end of thrust sheet

**Sliding block:**

- $100 \times 10 \times 5$ km
- $\rho = 2600$ kg/m$^3$

$$\sigma_n = \frac{F}{\text{area}} = 127 \text{ MPa}$$

$$\sigma_f = \mu \times \sigma_n$$

$\mu = 0.2$, so $\sigma_f \sim 25$ MPa

Strength of natural rock greater, so sliding.
Extra: Role of Gravity

Role of fluid pressure:
“Dry” sliding: dip is 35-40° (angle of repose)
“Wet” sliding: \( \lambda = \frac{P_f}{P_l} \)
\( \lambda = 1 \) (\( P_f=P_{lith} \)), dip is \( \sim 0^\circ \)
\( \lambda = 0.8 \), dip \( \sim 10^\circ \)
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.
Critical taper (angle $\phi_c$) is sum of surface slope angle ($\alpha_1$) and basal slope angle ($\beta$).

a) Stress acting on wedge, partly horizontal boundary load caused by backstop ($\sigma_{bs}$) and partly caused by gravity ($\sigma_g$).

b) If backstop moves, wedge thickens, so surface slope increases, and taper ($\phi$) eventually exceeds $\phi_c$.

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: Earthquake Impact

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Deaths</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 23, 1556</td>
<td>China, Shansi</td>
<td>830,000</td>
<td>~8</td>
</tr>
<tr>
<td>October 11, 1737</td>
<td>India, Calcutta**</td>
<td>300,000</td>
<td></td>
</tr>
<tr>
<td>January 12, 2010</td>
<td>Haiti, Port au Prince</td>
<td>300,000</td>
<td>7.0</td>
</tr>
<tr>
<td>July 27, 1976</td>
<td>China, Tangshan</td>
<td>255,000</td>
<td>7.5</td>
</tr>
<tr>
<td>August 9, 1138</td>
<td>Syria, Aleppo</td>
<td>230,000</td>
<td></td>
</tr>
<tr>
<td>December 26, 2004</td>
<td>Sumatra, Indonesia</td>
<td>225,000</td>
<td>9.1</td>
</tr>
<tr>
<td>May 22, 1927</td>
<td>China, near Xining</td>
<td>200,000</td>
<td>8.3</td>
</tr>
<tr>
<td>December 22, 856+</td>
<td>Iran, Damghan</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>December 16, 1920</td>
<td>China, Gansu</td>
<td>200,000</td>
<td>8.6</td>
</tr>
<tr>
<td>September 1, 1923</td>
<td>Japan, Kwanto/Tokyo</td>
<td>143,000</td>
<td>8.3</td>
</tr>
<tr>
<td>October 8, 2005</td>
<td>Pakistan</td>
<td>75,000</td>
<td>7.6</td>
</tr>
<tr>
<td>May 12, 2008</td>
<td>China, Sichuan</td>
<td>70,000</td>
<td>7.9</td>
</tr>
<tr>
<td>December 28, 1908</td>
<td>Italy, Messina</td>
<td>70,000</td>
<td>7.5</td>
</tr>
<tr>
<td>November 1, 1755</td>
<td>Portugal, Lisbon</td>
<td>70,000</td>
<td>8.7</td>
</tr>
<tr>
<td>May 31, 1970</td>
<td>Peru</td>
<td>66,000</td>
<td>7.8</td>
</tr>
<tr>
<td>June 20, 1990</td>
<td>Iran</td>
<td>50,000</td>
<td>7.7</td>
</tr>
<tr>
<td>August 17, 1999</td>
<td>Turkey, Izmit</td>
<td>45,000</td>
<td>7.4</td>
</tr>
<tr>
<td>March 11, 2011</td>
<td>Japan, Sendai</td>
<td>20,000</td>
<td>9.0</td>
</tr>
</tbody>
</table>
Earthquakes and (Stick-)Slip

EQ spectrum:
form seismic slip (earthquake), tremor (slow earthquakes to aseismic slip (creep))

Stick-slip behavior: elastic stress built-up and (partial) stress release (“stress drop”).

Note: EQ stress drop is 1-10MPa, which is 1/10\textsuperscript{th} of differential stress!
Structure and Society: Faults

Resources: Fossil Fuels

Resources: Mineralization

EXPLANATION
- Syntectonic basin fill
- Upper-plate sedimentary and igneous rocks
- Lower-plate metamorphic rocks
- Mylonite
- Mineralization
- Fault
- Cu-Fe-Pb-Zn-Ag-Au replacement and veins
- Ba-F veins
- Mn bedded and veins

Fault Trap
Anticline Traps
Salt Dome Trap