Faults and fluid flow

M.Geo.239
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Faults and fluid flow

- A large part of the deformation of the brittle crust is accommodated in discrete zones called faults
- Today's menu:
- Part 1: Fault structure, permeability and the effects of faults on fluid flow:
    - Faults are very important for crustal fluid flow: they can provide pathways for fluid transport between shallow and deep levels of the crust and at the same time often form barriers to lateral fluid flow
    - Many if not most hydrothermal systems and associated thermal anomalies and ore deposits are located in faults
- Part 2: The effects of fluid flow and pressure on faulting and deformation:
    - Fluid flow and pressure play a major role in deformation processes in faults and earthquakes, fluids can affect the strength of faults and the crust directly through fluid pressure and indirectly by mineral transformations and dissolution/ precipitation

Processes influencing fault permeability

- Faults are so important for fluid flow because their permeability and structure is very different from the host rock
- Processes that control the fluid flow properties of faults in the brittle crust (up to ~12 km depth):
    - Particulate flow: deformation bands and clay smear
    - Fracturing and brecciation, damage zones
    - Cataclasis: grain crushing
    - Cementation: clay mineral formation and transformation

Particulate flow

- Lithologies of host rocks get incorporated into fault zones
- Clay smear has received the most attention -> clay = low permeability
- Strong effect on fault zone permeability and the trapping of hydrocarbons
- However, permeable formations also get smeared into the fault zone
- -> low permeability for flow perpendicular to the fault zone, high permeability parallel to the fault zone

Example of clay smear along a normal fault in the lower Rhine embayment
Bense et al. (2004) NJG

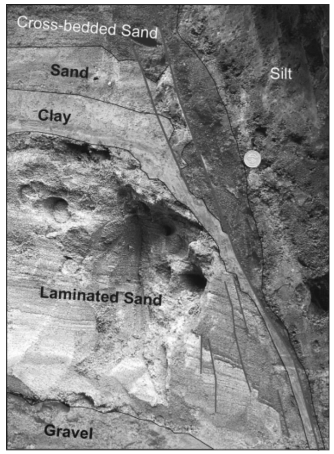
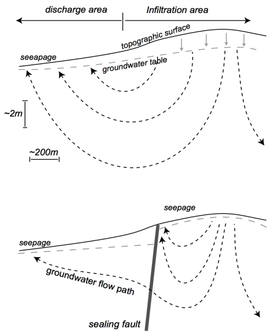
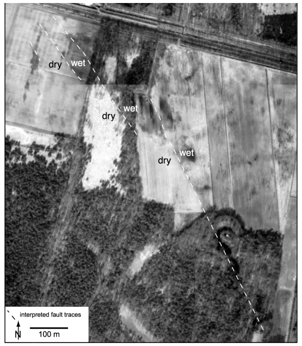


Fig. 3. Clay smear in unconsolidated sediments in a trenched outcrop over a secondary fault in the Roer Valley Rift System. The coin has a diameter of ~2 cm.

Faults & groundwater flow

- Effect of clay smear on groundwater flow patterns -> reduction of permeability
- Faults are often barriers to lateral groundwater flow

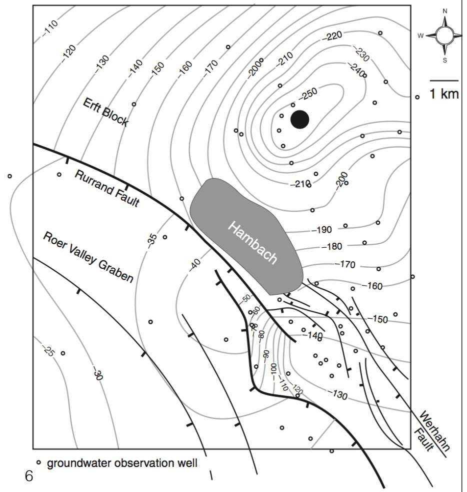




Bense et al. (2003) NJG

Faults as barriers to shallow groundwater flow

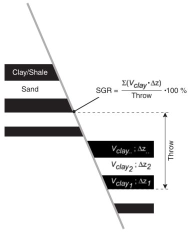
- High differences in hydraulic head across fault zones means that these fault zones are relatively impermeable

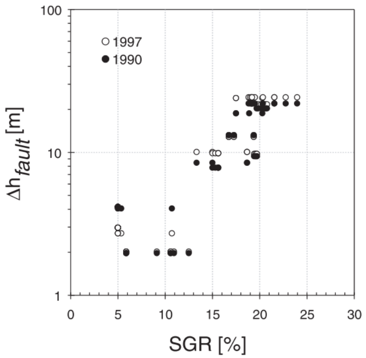


Hydraulic gradients across normal faults
Bense & van Balen (2004) Basin Research

Shale gouge ratio

- The difference in hydraulic head across fault zones is correlated with the shale gouge ratio (SGR) -> SGR is a good first order predictor of fault permeability
- Shale gouge ratio: measure of how much clay is incorporated in the fault zone
- =cumulative thickness of clay that was at one stag next to a point in the fault plane





Shale gouge ratio vs hydraulic head difference across normal faults
Bense & van Balen (2004) Basin Research

Faults as barriers and conduits?

- Field evidence for dual conduit and barrier behaviour in faults
- High hydraulic head gradients suggest faults are barriers to groundwater flow
- However, leakage of saline water suggests fault transmits groundwater

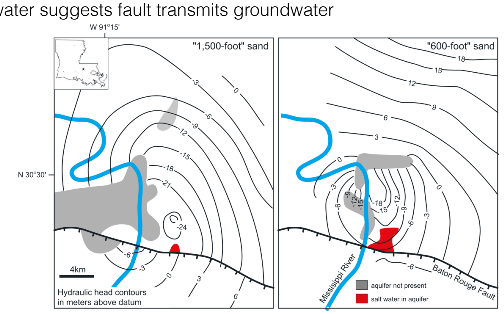


Figure 1. Hydraulic heads in the "1,500-feet sand" and the "600-foot sand" close to the Baton Rouge fault in Louisiana (redrawn after *Whiteman* [1979]). North of the fault salt water is invading these aquifers presumably as a result of pumping for municipal water supply. The high hydraulic head gradient over the fault suggests that the fault is impeding groundwater flow. However, isotope data provide evidence [e.g., *Stoessel and Prochaska*, 2006] that the origin of the salt water, now at shallow depth, is far below these aquifers and has migrated upward along the fault zone to invade the shallow aquifer system.

Bense & Person (2006) WRR

Faults as barriers and conduits?

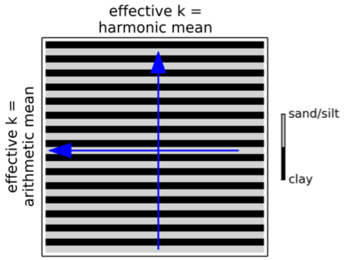
- Effective permeability parallel and across the fault zone can be calculated using the arithmetic and harmonic mean of the permeability of the individual lithologies
- Permeability of sand/silt in fault: function of porosity and grain size/specific surface, can be calculated using the Kozeny-Carman equation
- Permeability of clays: use empirical equations for porosity vs permeability
- See your lecture notes on sediment permeability
- Result: generally ~3 orders of magnitude difference in permeability parallel and perpendicular to the fault

For flow parallel to layers, effective K = arithmetic mean:

$$K_e = \frac{\sum K\Delta x}{\sum \Delta x}$$

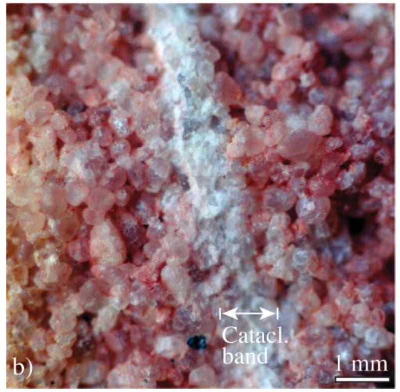
For flow perpendicular to layers, effective K = harmonic mean:

$$K_e = \frac{\sum \Delta x}{\sum \frac{\Delta x}{K}}$$



Fault permeability in lithified rocks: Cataclasis

- Permeability reduction in fault cores due to cataclasis
- =crushing of grains in faults produces a very fine grained “rock flour”
- Occurs in lithified sediments, crystalline rocks or coarse sands
- and in unlithified rocks at greater depths (~several 100s of m)



Example of cataclasic deformation band in the Nubian sandstone
 Fossen et al. (2007) Jrnl Geol. Soc.

Cataclasis

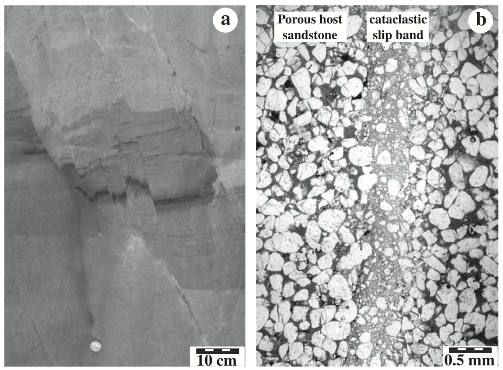


Figure 3. (a) Cataclastic slip bands in the Nubian sandstones observed in outcrop. The thin ferromagnesian stripes (dark) provide the offset marker (a few millimeters to decimeter) for each band. (b) Microstructure of a cataclastic slip band (thin section microphotograph). The quartz grains appear white and the injected epoxy resin filling pores is dark. In the cataclastic band the grain size and the porosity are drastically reduced compared to the host sandstone.

Example of cataclasis in sandstones in a fault in the Suez rift
Du Bernard (2002) JGR

Fault gouge clays

- Fault gouge contains clays from incorporation of host rock (clay smear)
- However, over the last 2 decades more and more evidence for formation of authigenic clays in fault zones due to interaction of rocks in the fault zone with fluids
- Authigenic clays tend to form at temperatures of 60-180 degr. C, main controls -> host rock and fluid composition
- Examples:
  - Dissolution of K-Feldspar to form illite
  - Smectite from acidic volcanic rocks
- Relatively poorly studied so far.
- Nonetheless, very important for permeability and fluid flow (clay = low permeability)
- And very important for fault friction and earthquakes

Fault gouge clays

- Recently discovered clay gouge in the San Andreas fault: saponite (= part of smectite group clays)
- Result of fluid-assisted reaction between feldspar in host rock and serpentenite in the fault rock
- Potential cause for the anomalous low strength of the San Andreas fault

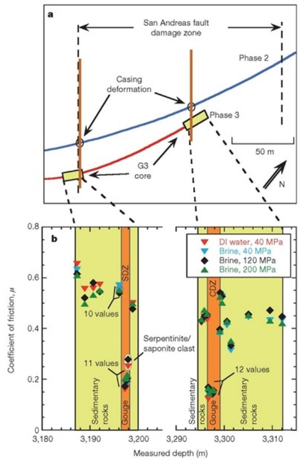
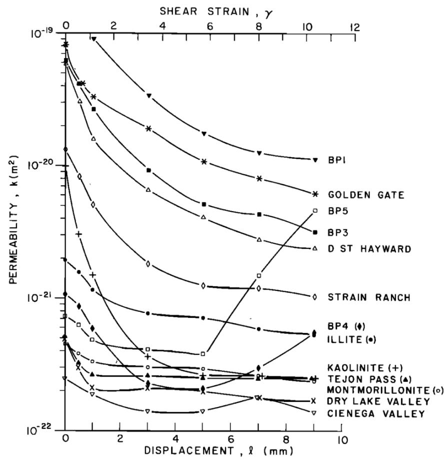


Figure 1 | Location and strengths of SAFOD core samples. a, Map view of SAF damage zone and SAFOD boreholes from phase 2 (blue) (indicating actively deforming casing) and phase 3 Hole G (red) with location of recovered core (yellow) at approximately 2.7 km vertical depth. Active deformation zones are shown in orange. **b,** Frictional strength of core samples plotted versus measured depth along Hole G (at sliding rate $V = 1.15\ \mu m\ s^{-1}$). Active fault traces SDZ (3,196.4–3,198.1 m measured depth) and CDZ (3,296.6–3,299.1 m) have notably low strength. A few samples were tested with deionized (DI) water. Extrapolation to SAF plate rate reduces shear zone strength to $\mu \approx 0.15$.

Lockner et al. (2011) Nature

Fault gouge

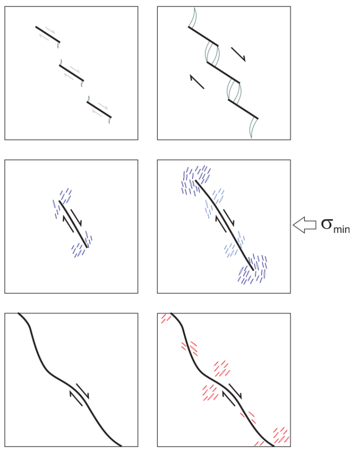
- Increasing shear displacement decreases permeability
- Decrease is stronger for relatively high permeability gouge
- -> lower limit for fault gouge permeability at high displacement rates?
- cause for reduction in permeability: grain crushing and rotation



Permeability fault gouge, San Andreas fault
Morrow et al. (1984) JGR

Fault permeability in lithified rocks:Fracturing and brecciation

- Mechanisms of fracturing around active faults
  - Linking up of fractures during fault initiation
  - Damage zone at fault tip during fracture propagation
  - Extensional and shear fractures around irregular faults



Faulkner et al. (2010) Jrnl. Struct. Geol.

Fracturing and brecciation

- Fractures & damage zone around a low offset normal fault

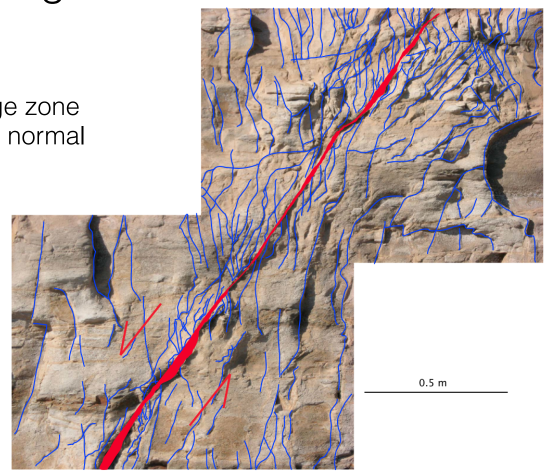
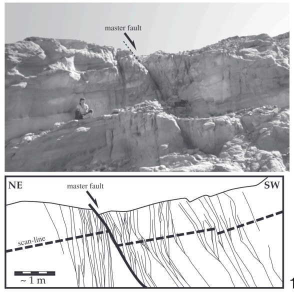


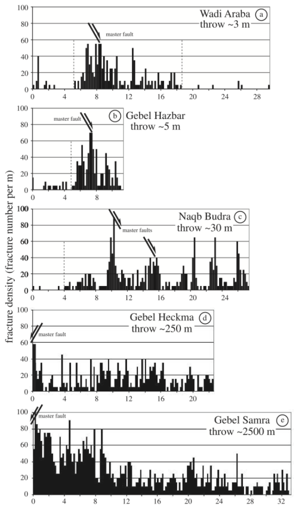
Figure 2. Low Tide Fault. The fault core is red, and the fractures surrounding the fault are blue. Fractures are nearly vertical away from the fault and rotate with proximity to the fault.

Savage & Brodsky (2011) JGR

Damage zone scaling

- However, relation is not always simple
- Example of fracture density vs distance to main fault/slip surface for faults with different values of offset in the Suez rift:

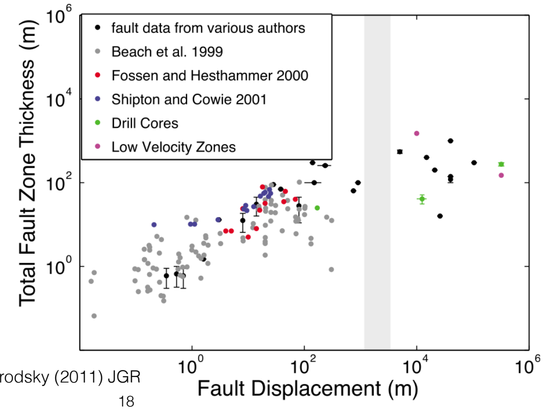




 Du Bernard et al. (2002) JGR

Damage zone scaling

- Thickness of damage zone increases with fault displacement, but may level off around ~150 m



Savage & Brodsky (2011) JGR

Evolution of faults & fractures

- Example of the formation of a fault in a laboratory shear experiment on a granite
- Dots in the top panel show micro-seismic events in a granite block that delineate where fracturing takes place
- First fracturing is diffuse (panels a-c), but then concentrates on a single slip surface, the new fault (panels d-f)

Lockner and Beeler (2002) USGS

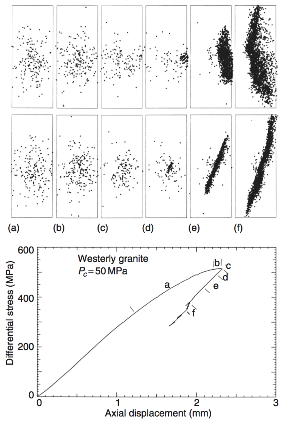
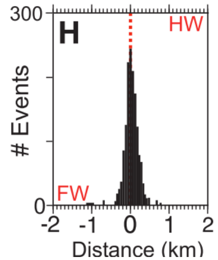
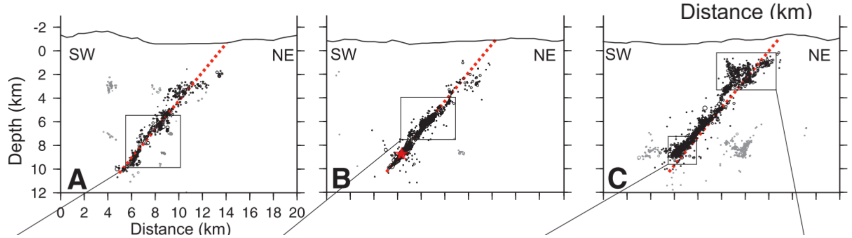


FIGURE 3 Acoustic emission (AE) hypocentral locations during fault formation of initially intact Westerly granite. Time progresses from left to right. Middle: Figures view sample along strike of eventual fault plane which appears as diagonal feature in (e) and (f). Top: Same AE events viewed perpendicular to strike. Bottom: Accompanying stress–displacement curve indicates segments of the experiment from which acoustic emission plots are made. Fault nucleation occurs in (d).

Fault zone structure from earthquake data

- The structure of fault zones can also be deduced from seismic data
- High resolution dataset of aftershocks of the MW6.1 l'Aquila normal fault earthquake in 2006, 19000 events
- Main event and aftershocks cluster on the main fault plane
- Distribution of aftershocks decreases exponentially with distance from the fault core
- -> the earthquake damage zone exhibits the same behaviour as the fault damage zone in outcrop studies

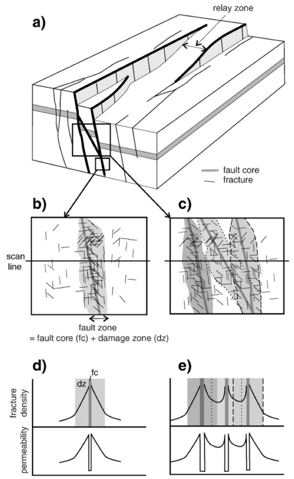




Distribution of aftershocks of the MW6.1 l'Aquila earthquake in 2006. Valoroso et al. (2014) Geology

Models of fault structure

- Permeability enhancement:
    - incorporation of permeable rocks in fault zone
    - fracturing
- Permeability reduction:
    - clay smear
    - cataclasis
    - formation of clay minerals
    - cementation
- Permeability reduction in fault core, permeability enhancement in fault damage zone



Bense et al. (2013) Earth Sc. Rev.

Fault zone structure

- Permeability profile across Nojima fault zone (Kobe 1995 earthquake)
- 3 orders of magnitude difference in permeability between clay-bearing fault gouge and damage zone

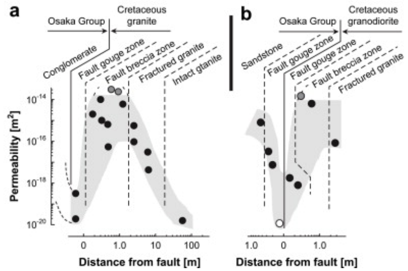


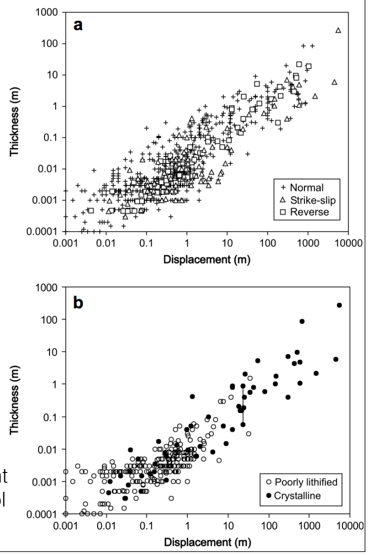
Fig. 9.
Permeability structure of the Nojima fault at Funaki (a) and Hirabayashi (b). Permeability at P_e = 90 MPa is plotted as a function of distance from the fault trace. The permeabilities of the samples marked by a gray circle were greater than 10^{-14} m^2, and the permeability of the sample marked by an open circle was less than 10^{-20} m^2.

Mizoguchi et al. (2008) Jrnl Struct. Geol.

Fault zone structure

- Similar to the fault damage zone, the fault core (ie, the low-permeable part) also gets thicker with increasing displacement
- The relation between the fault core thickness and displacement holds for different types of faults (normal, reverse, strike-slip) and different lithologies (unconsolidated, lithified)

Fault core thickness vs displacement
Childs et al. (2009) Jrnl. Struct. Geol



Fault zone structure

- However, some very large displacement faults display very small fault core thicknesses
- Example: the Glarus thrust fault in the Alps

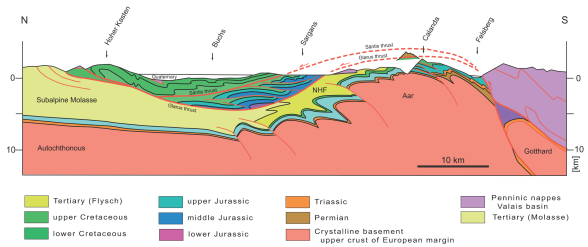


Fig. 2.1-5a: Profile through the Helvetic nappes of the eastern Swiss Alps. The Helvetic nappes were displaced along the Glarus thrust over a distance of around 50 km. But the rocks above and below the Glarus thrust were also intricately deformed as is evident from the fold and thrust structures. The Säntis thrust displaced the uppermost part, the Cretaceous strata, of the Helvetic nappes an additional 10 km to the north. Deeper down, the crystalline basement rocks of the Aar massif were shortened and now form an anticlinal upwarp. From: Pfiffner (2005).

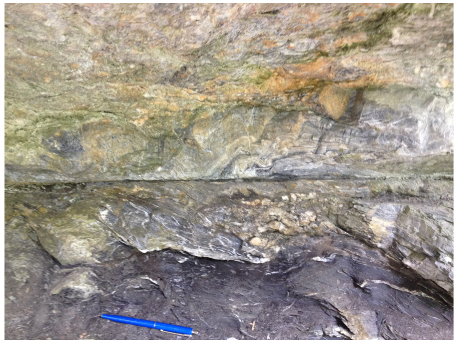
Fault zone structure

- However, some very large displacement faults display very small fault core thicknesses
- Example: the Glarus thrust fault in the Alps

Glarus thrust fault in the Swiss Alps

Fault zone structure

- However, some very large displacement faults display very small fault core thicknesses
- Example: the Glarus thrust fault in the Alps. A single ~ mm thick fault core accommodated 50 km of slip during the Cenozoic



Summary part 1

- Fault structure:
  - Shallow faults in unconsolidated sediments: Rotation and incorporation of permeable and impermeable sediments (clay smear) into fault zone
  - Consolidated sediments, crystalline rocks:
    - Damage zone: fractures or deformation bands. density decreases exponentially with increasing distance from fault core
    - Fault core: one or several slip surface with low permeability due to cataclasis and clay mineral formation/transformation
- Overall: high permeability parallel to fault, low permeability perpendicular to fault. Magnitude poorly constrained, but in most cases at least 3 orders of magnitude
- Dual conduit-barrier behaviour of faults can be observed in shallow hydrogeology, groundwater flow patterns and hydraulic heads
- + many more examples for hydrothermal systems, hot springs, etc. stay tuned for next week's lecture

Part 2

- Faults affect fluid flow
- However, how did faults and fractures get there in the first place?
- However, how did faults & fractures get there in the first place?
- Next lecture: Effects of fluid flow & pressure on deformation
  - Deformation and pore pressure
  - Brief overview of fluids & deformation case studies