Possible cause of “weak” faults

- Preexisting fracture

![Preexisting fracture diagram](image1)

- Clay $\Rightarrow$ low $\mu$

![Clay low $\mu$ diagram](image2)

- Pore fluid

![Pore fluid diagram](image3)
How to get quantitative graphs? Make assumption!

Zoback et al example.

Assume $\sigma_c$ constant. $\tau_{\text{fault}} = c_0$.

Given $\beta, c_0, \sigma_r$ get $\alpha$.

Question: In far field, $\sigma_{12} = c_F$.

On fault $\sigma_{12} = c_0$.

$\frac{\partial \sigma_{12}}{\partial x_1} > 0$ -- How can this be?

Another approach: Assume $\sigma_r \equiv c_0$, find $\sigma_r$ given $\alpha$.

Fig. 6_4

Fig. 6_5
Pore fluid pressure model of fault weakening

>`Cross section`

**Fault zone highly permeable**

\[
\text{Darcy flow} \approx \text{heat flow} \\
\text{Permeability} \approx \text{conductivity} \\
p \approx T
\]

**Given source of water**

High permeability $\Rightarrow$ high $p$

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**Fig. 6_6**

**Fig. 6_7**
Question:
- What are implications for stress direction in the fault zone?
- Is low $\Delta \sigma$ in the fault zone consistent with large $\Delta \sigma$ outside?

![Diagram](image.png)

**Stress Rotation, after Zoback et al, 1987**

The principal stress directions are observed to rotate in the vicinity of the San Andreas fault (SAF). In the far-field (e.g., Nevada), the maximum compressive stress is oriented at an angle to the fault trace $\beta \sim 55^\circ$. But in the near field, this angle, now called $\alpha$, is close to $85^\circ$. (Note that this is the same as the angle between the least compressive stress and the normal to the fault plane, the angle conventionally used in Mohr circle analysis.)

Assume that in the far-field stress has $\sigma_1 = -68$ MPa, $\sigma_{II}$ (assumed vertical and lithostatic) $= -136$ MPa, and $\sigma_{III} = -204$ MPa. (What style of faulting would this cause?)

Assume that the fault has strength $C_0$, so that $\sigma_{12}$ becomes smaller approaching the fault. (How could this happen, given Newton's second law?).

Also assume that the normal stress across the fault maintains its far-field value ($\sigma_{22}$ in the coordinate system fixed to the fault, as shown in the diagram). Assume that $\sigma_c$ remains the same. (Does this agree with the style of faulting and the folding near the SAF?)

Then, from a Mohr's circle construction, it is straightforward to obtain a relation between $\alpha$ and $\beta$. 
The coefficients of friction, $\mu$, for a wide variety of rocks, are comparable, in the range $0.6 \text{–} 0.9$. The only rocks with low coefficients of friction are clays, which are not stable at the high pressures and temperatures characteristic of fault zones at depths of $\sim 10$ km where earthquakes nucleate.
Note: the Navier-Coulomb failure law, $|\tau| = \mu|\sigma| + \sigma_0$, is also sometimes written

$$|\tau| = \mu|\sigma| + S_0.$$  

For rocks, $S_0 \sim 0.1 - 4$ kbars (10 - 400 MPa). How does this "breaking strength compare with the "frictional stress?"

Plot stress predicted for the initiation of faulting as a function of depth, assuming that $\sigma$ is the lithostatic stress. (Recall that the "lithostatic stress gradient ~ 1 kbar/3 km.)
So, if Byerlee's law is correct, and if the stress in the lithosphere is not too far from lithostatic, the shear stress on faults should be ~5 kbar at 15 km depth and about 250 kbar at 700 km depth.

How can we test this prediction?

- Model stresses associated with holding up mountains (e.g., Himalayas > 1.5 kbar)
- Stress drops associated with earthquakes (usually ~ 3-300 bars, very rarely > 1 kbar)
- Work available from convection (dynamic "engine," <~1 kbar)
- Heat flow in fault zones (frictional heating rate ~ \( \tau v \Rightarrow \tau \sim 100 \) bars)
Big discrepancies here - a frontier region of geodynamics.

Important factor - the role of **pore fluid pressure** in faults.

Empirical results: For a pore fluid pressure \( p \), the Navier-Coulomb failure law becomes:

\[
|\tau| = \mu|\sigma+p| + S_0
\]

(Note that because compressive pressure is positive, while compressive normal stress \( \sigma \) is negative, the pressure decreases the amplitude of the "effective normal stress" \( |\sigma+p| \).)

Graphically:

![Graphical representation](image)

**Fig. 6_13**

A qualitative explanation of the effect of pore fluid pressure is that the fluid helps to "support" some of the normal stress that is otherwise carried by solid grains. Consider a simple model of a continuum made up of dry sand. Let \( f_A \) represent the fraction of a surface area that is made up of solid grain contacts. Then for a macroscopic normal stress \( \sigma \), the average (microscopic) normal stress at the solid grain contacts is \( \sigma/f_A \), since the pore space in between can support no normal tractions. (Of course, in places the actual value will be much larger than the average value.) If Admonton's law applies to the
contacts, then the microscopic shear traction needed to cause failure is $\mu \sigma/f_A$, and the macroscopic shear traction is $\tau=\mu \sigma$.

If pore fluid pressure is now introduced, the pore fluid will support some of the macroscopic normal stress, leading to a decrease to the normal stress at the grain contacts.

![Diagram showing stress on grains with and without pore fluid pressure]

Fig. 6_14

Adding pore fluid pressure effectively "stretches" the $\sigma_n$ axis, giving, effectively, a lower coefficient of friction (except that angles no longer work out!)
An alternative explanation for deep earthquakes is that the failure envelope bends over at large $\sigma_n$.

Finally, let's consider a medium that is anisotropic – perhaps one which has a preexisting fracture at an angle $\theta$ to the least principal stress. (For a preexisting fracture, the strength $S_0 = 0$.) Then if the double angle $2\theta$ is within the region shown, the rock will fail along the preexisting fracture.
Fig. 6.17