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WORKSHOP
GLOBAL GEOPHYSICAL INFORMATICS WITH APPLICATIONS TO RESEARCH IN EARTHQUAKE PREDICTIONS AND REDUCTION OF SEISMIC RISK

(15 November - 16 December 1988)

LABORATORY CONSTRAINTS ON PHYSICAL MODELS
THE PHYSICS OF FRACTURE

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TIME SCALES

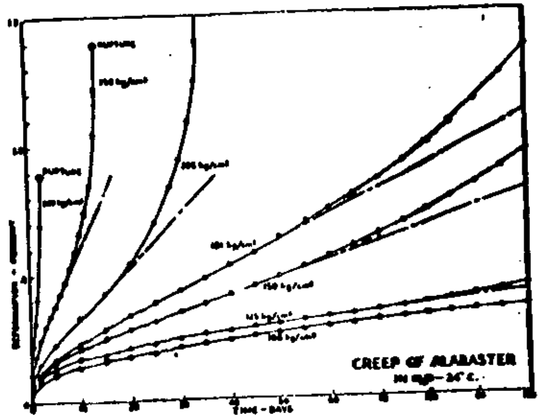
NON-ELASTIC

T ≳ 10 min	T → months–yrs	T ~ 100–500 yrs
ELASTIC	AFTERSHOCKS	PLATE TECTONICS

$= \frac{L_{FRACTURE}}{V_{ELASTIC}}$

(FORESHOCKS
SEISMIC GAPS)

CREEP, NON-LINEAR VISCOSITY



Chemical Kinetics
Activation Process
Stress Corrosion
(role of H_2O) → $t_f = t_0 e^{-E/kT}$. $E = \sigma \Delta V$

a large number of references:

Glass : Preston et al, Nature 156, 1946
J. App. Phys. 17, 1946

Metals : Zhurkov, Int J Fract Mech, 1, 1965
Rock (?) : Griggs, Bull. G.S.A. 51, 1940
Plastics, Ionic Solids : Zhurkov, loc. cit.
Metals : Cherepanov, Mech of Brittle Fract (McGraw-Hill 1979).

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(8)
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TABLE 1.—*Properties of alabaster in wet creep tests at different stresses*

(Gypsum in each experiment subject to constant load, in the presence of its own saturated aqueous solution, at [illegible])

Compressive stress ($\sigma_1 - \sigma_3$ in kg/cm²) σ	Steady-state velocity (millionths per day) v_s	Deformation before fracture (per cent) S	Duration of test (to fracture) (days) t_f	Equivalent viscosity (poises) × 10¹⁶ ?
300	2000	.53	2.45	.42
250	440	1.49	13.88	1.60
205	219*	2.1*	48*	2.04
181	100	3.0	133	5.11
165	77.0	3.3	285	6.04
150	66.5	>1.05	>110	6.36
125	24.5	3.3	308	14.4
103	~~7.0~~ 7.6	~~>7.1~~ >6.1	~~>140~~ 7/[illegible]	~~41.0 (?)~~ [illegible]

* Average of three duplicate tests.

Properties of same gypsum when dry:
Strength (short-time) = 520 kg/cm²
Deformation before fracture = 35% (primarily elastic)
Equivalent viscosity = > 5. × 10¹⁶ at 420 kg/cm²

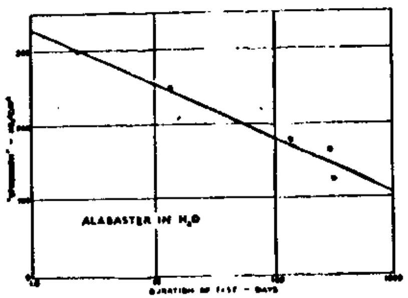
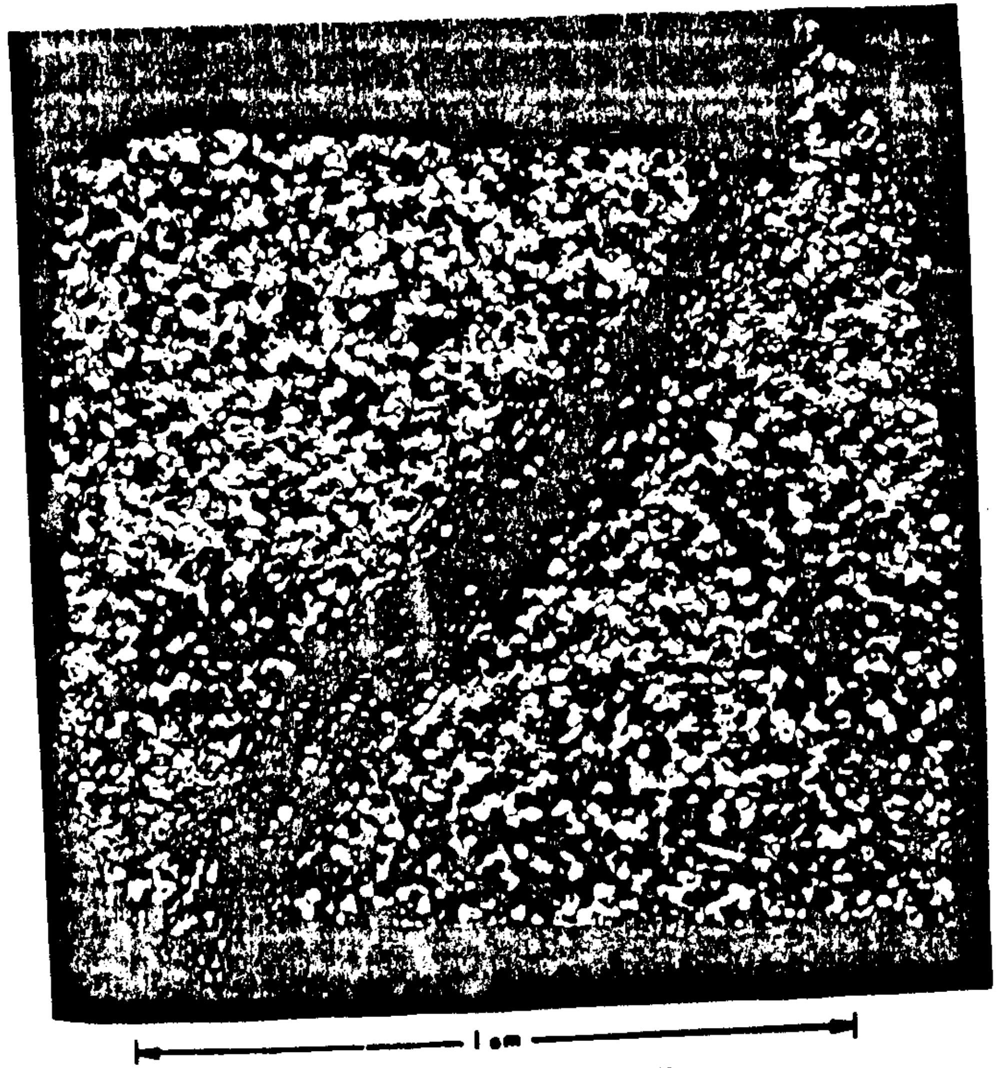


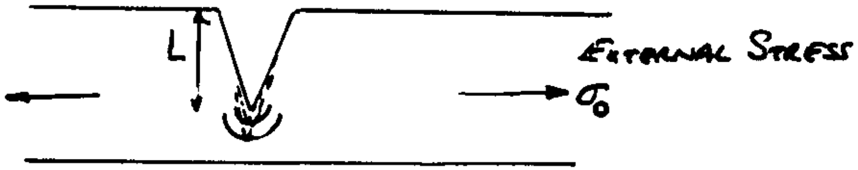
FIGURE 10.—*Strength of alabaster as a function of duration of test*

Data from experiments of Figure 9.



ST. PETER SAND 48-65 MESH

Compacted at 500°C., 5 kb confining pressure, 1 kb interstitial water pressure, then compressed 40 per cent. Temperature and fluid pressures kept constant. Thick copper jacket did not rupture despite shear offset at ends.

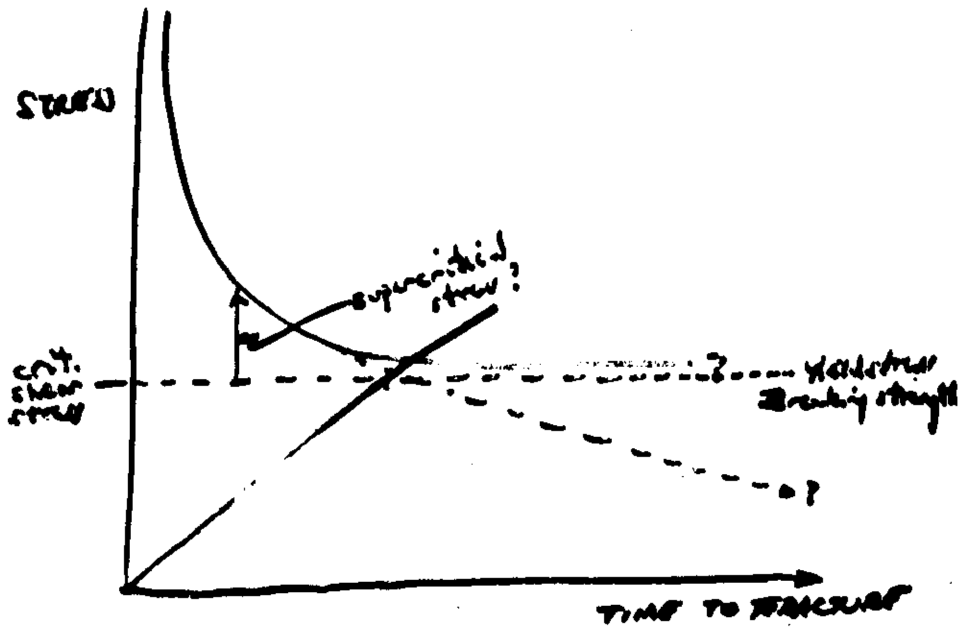


- $V = \frac{dL}{dt} \sim e^{\sigma_0 \sqrt{L}/kT \times \text{const}}$

activation process!

- Process much <u>accelerated</u>
  in presence of water

IN ROCKS
SOLUTION & RECRYSTALLIZATION



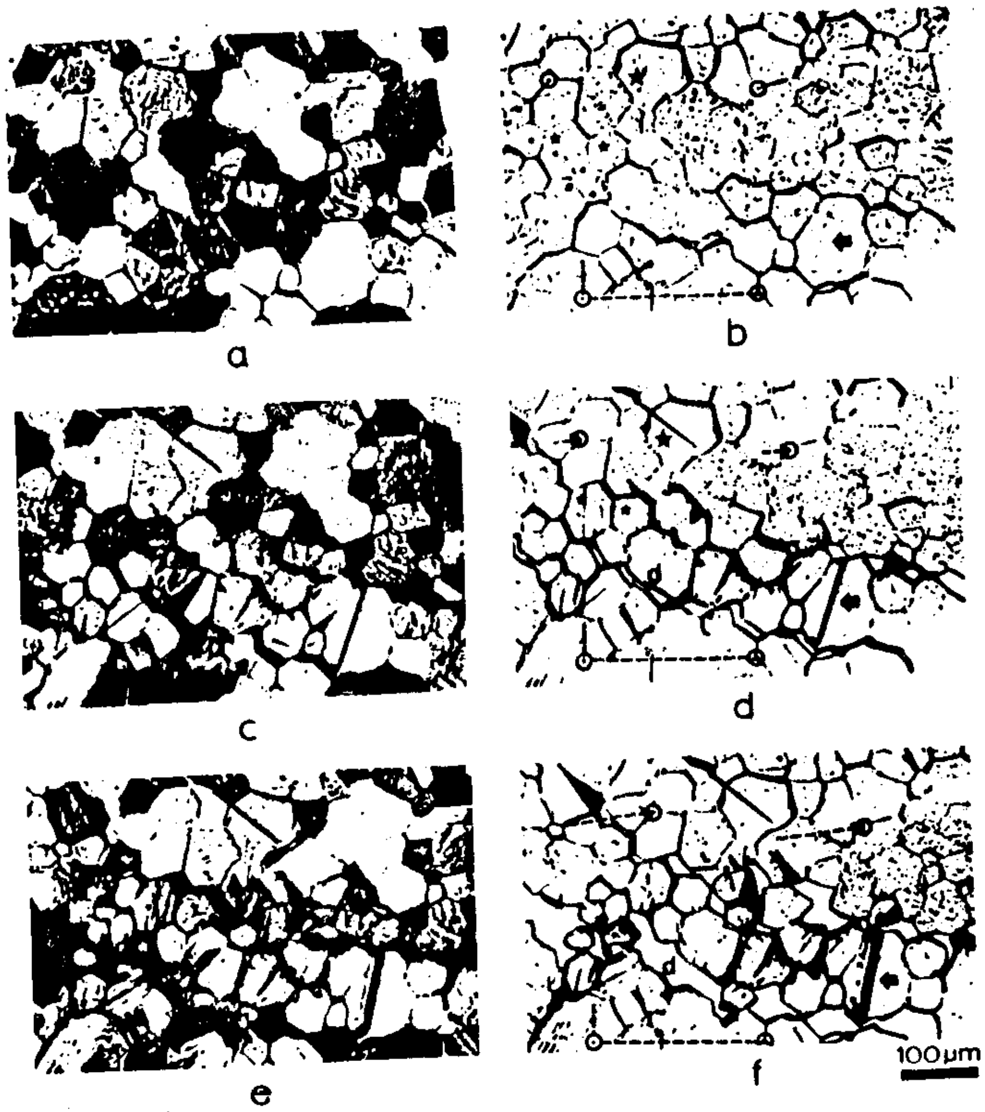
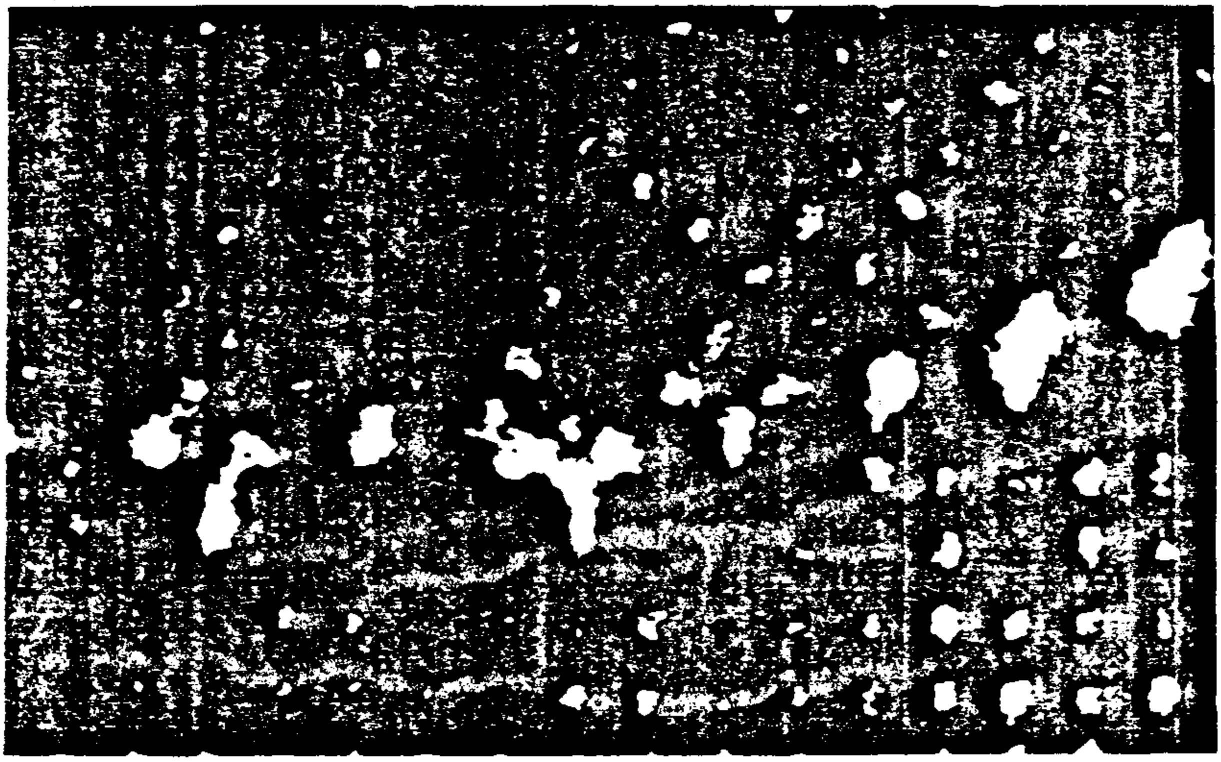


Figure 4. Cracking and twinning in sodium nitrate in dextral shear zone. Intergranular crack propagation and twin inception near small stars in b and d; twin widening at stubby arrow; microfracture dilation at d and elsewhere. Sample thickness is about 30 µm.

The Role of Water.

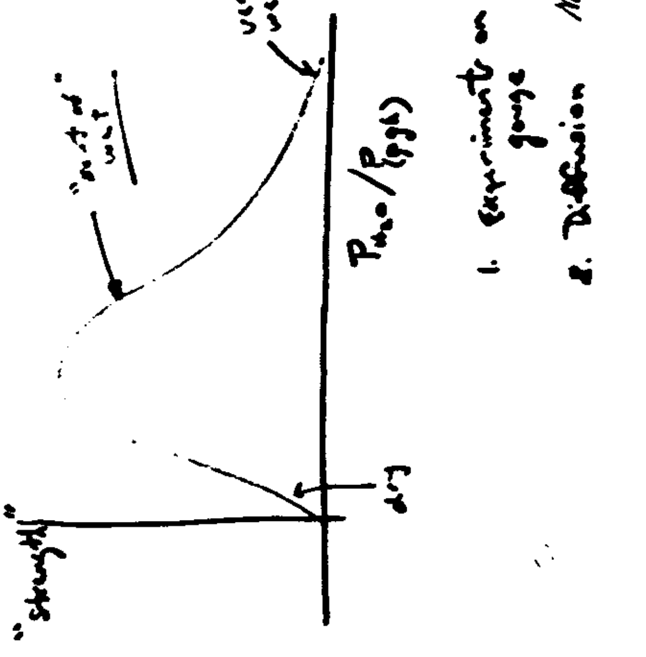
1. Why does wet sand have cohesive strength?

surface tension

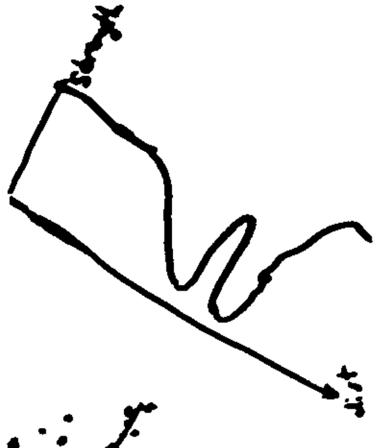


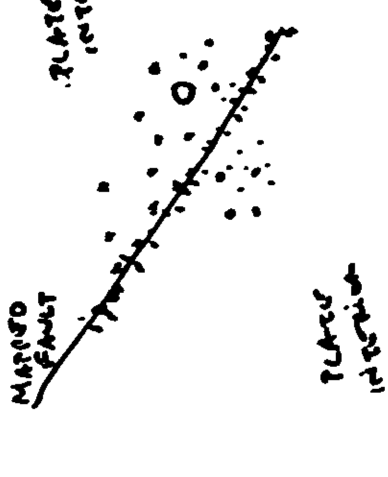
K. L. Merkle, Argonne National Laboratory

Faceted NiO boundary: *The white areas represent the areas between atom columns and show the relatively wide spaces at the grain boundary. The segment of the 38° boundary on the left is asymmetric with the grain boundary parallel to a (100) plane in the lower half of the bicrystal. The segment on the right is approximately symmetric.*



1. Experiments on gouge
2. Diffusion   mylonite





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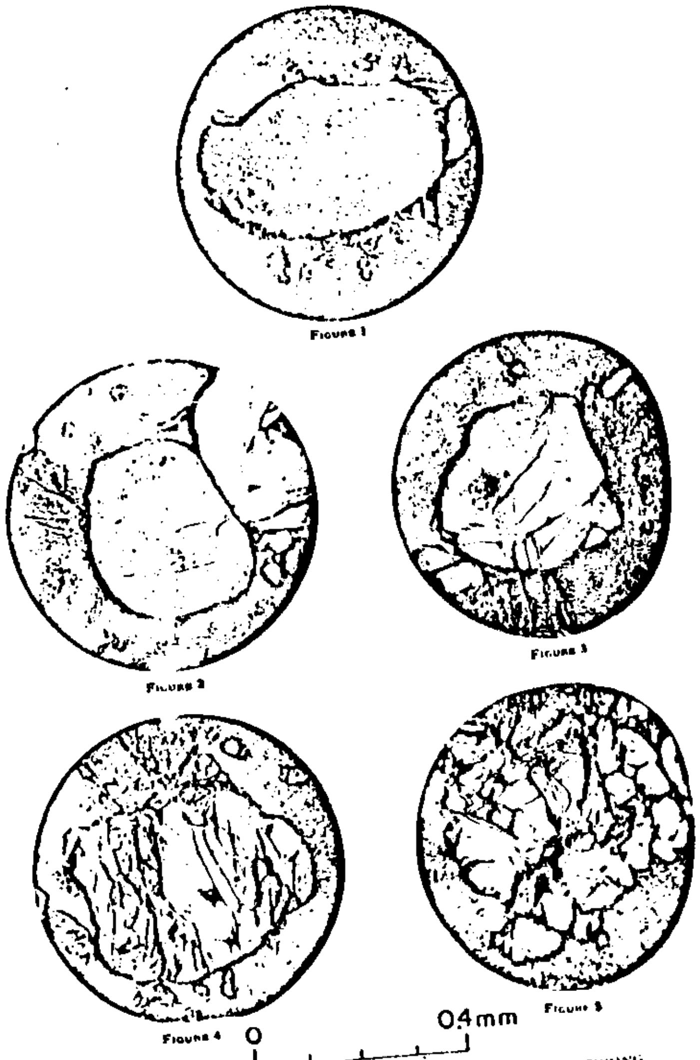
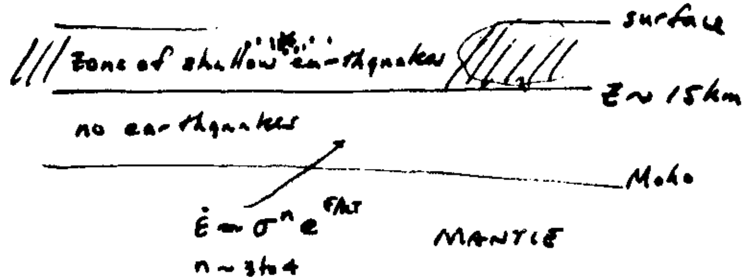
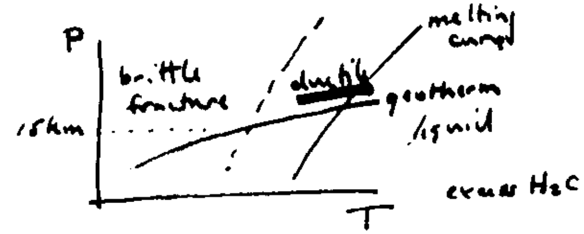


ST. PETER SAND SHOWING VARIOUS INTENSITIES OF FRACTURING

Is the viscosity of the earth everywhere of the same nature?





(Brace)
& Byerlee

What is the yield strength of a barrier to be used, if the strength depends on geometry?

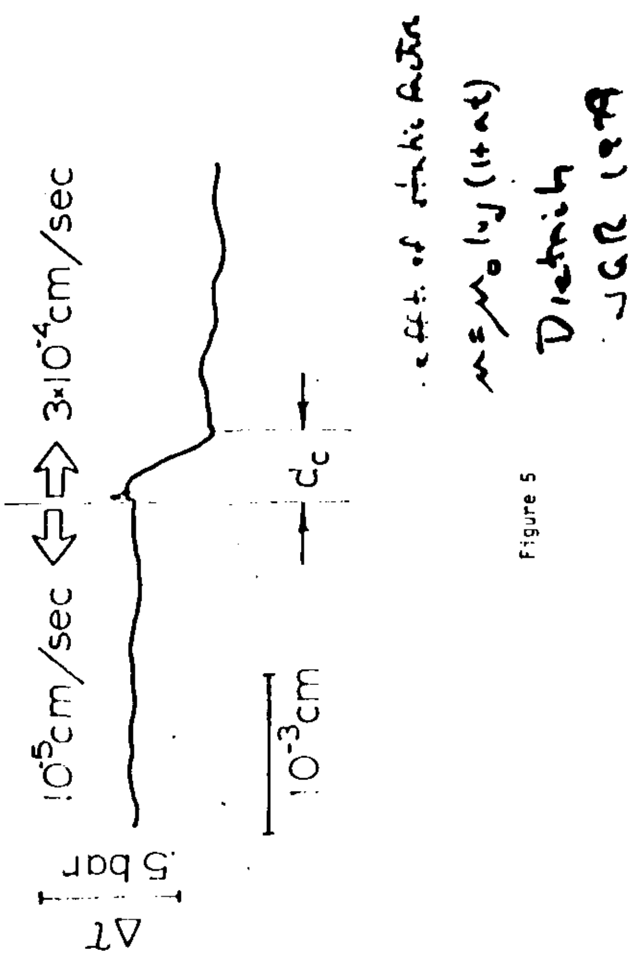
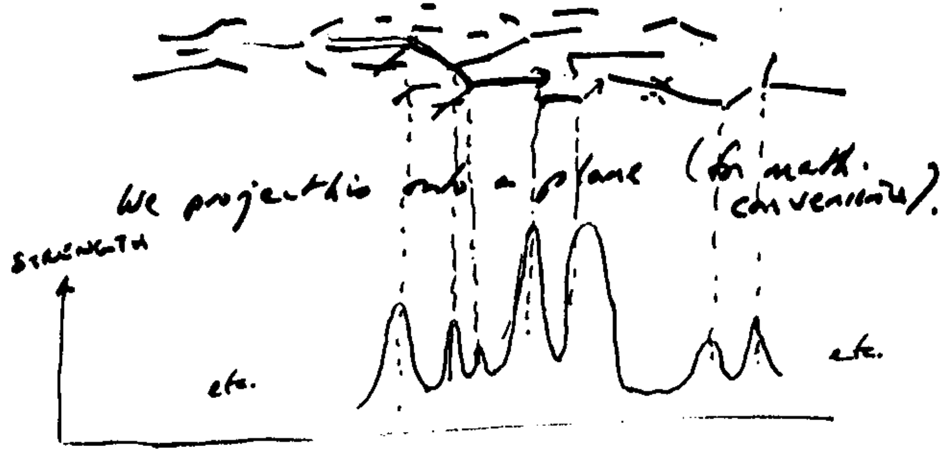
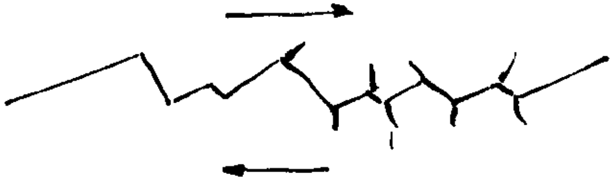


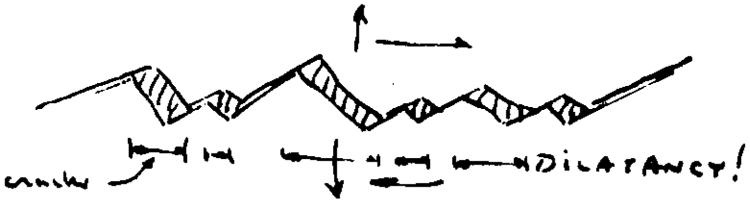
Figure 5



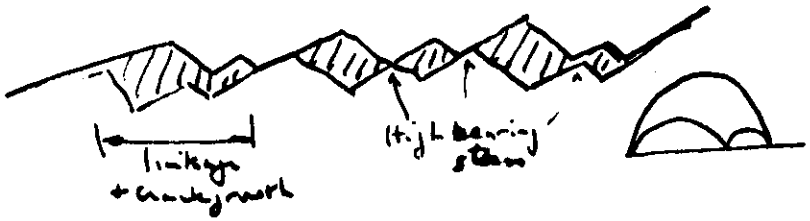
Consider an irregular crack surface which we model as a sawtooth. We subject the elastic medium to a shear stress.



In order that lateral motion take place, one crack surface must "ride" upward over the other. Thus transverse motion must take place

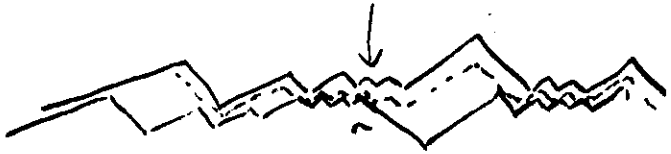


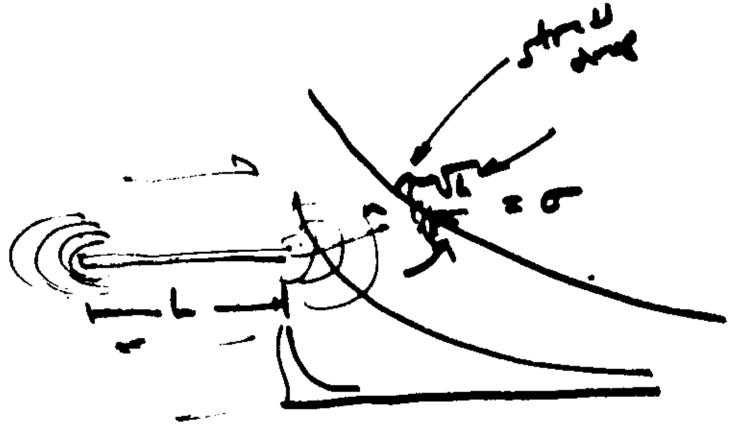
When sliding becomes too large, cracks begin to link up.

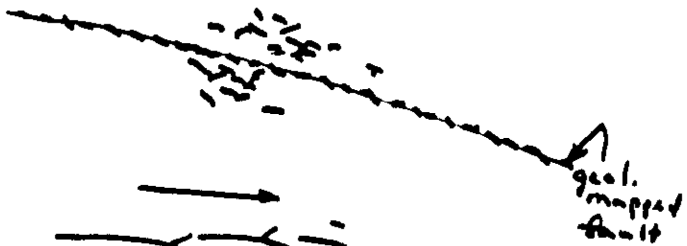


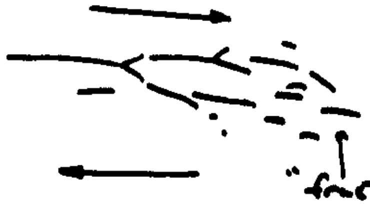
What keeps a crack "open"?

Healing!



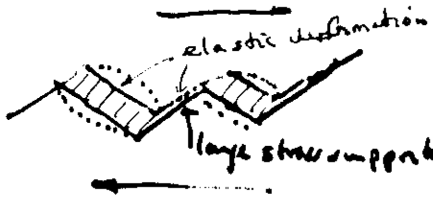






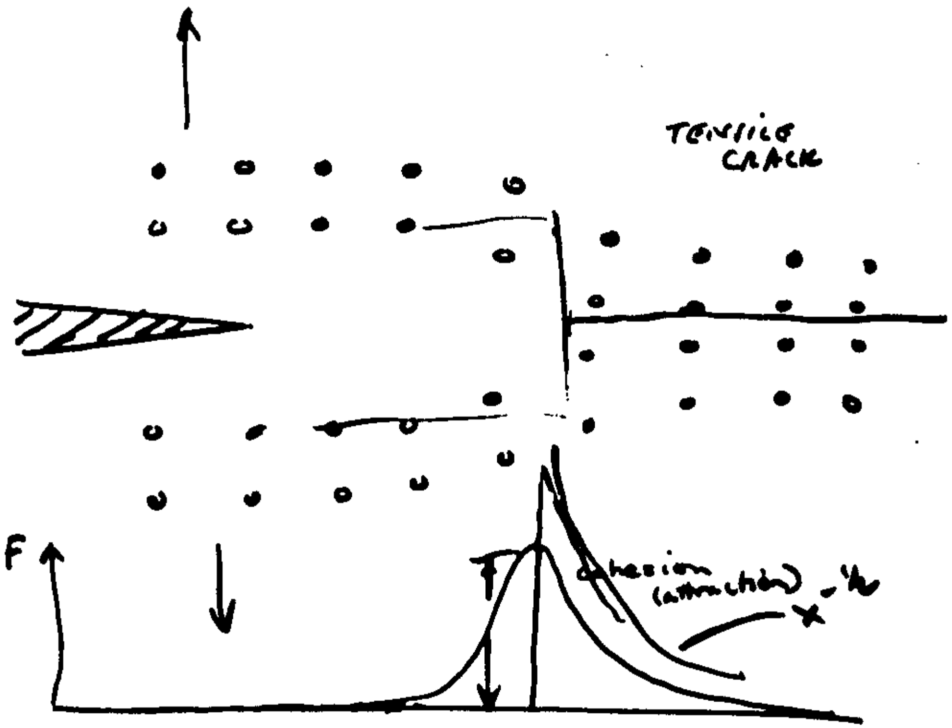
$\frac{1 \cdot C}{x^p}$

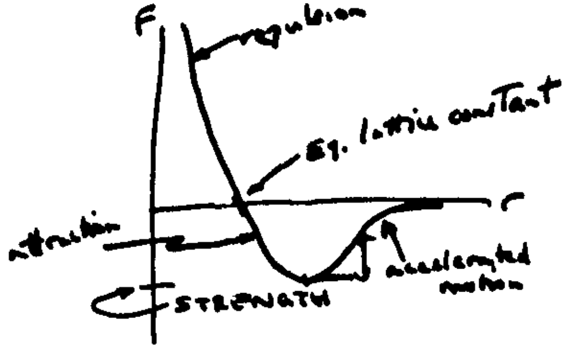
linkage of cracks
(keep cracks open for a while?)

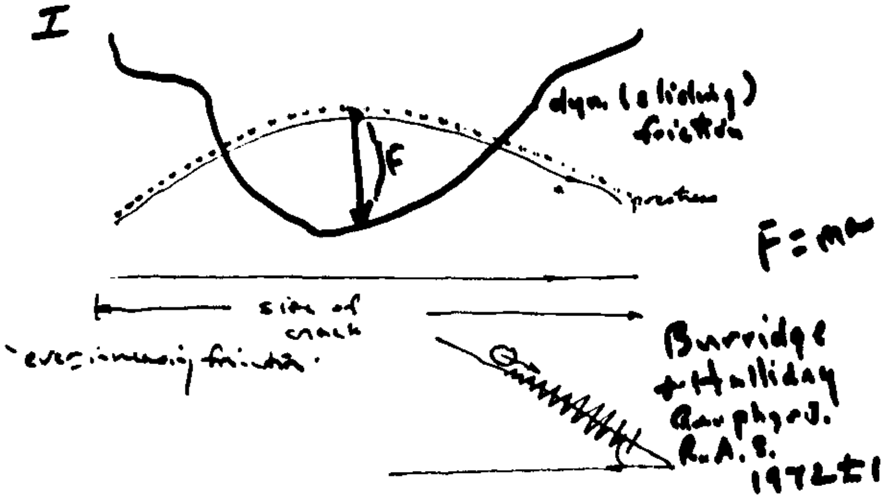


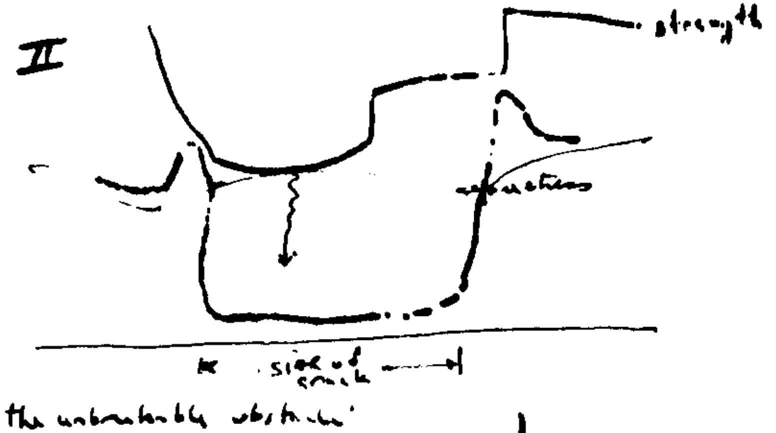
(role of water in recrystallization)

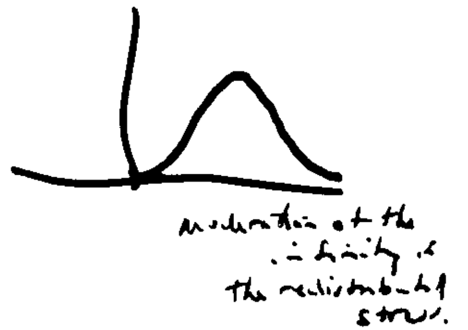
what are angles of the saw-teeth?
how high are the saw-teeth?
(wavelength)

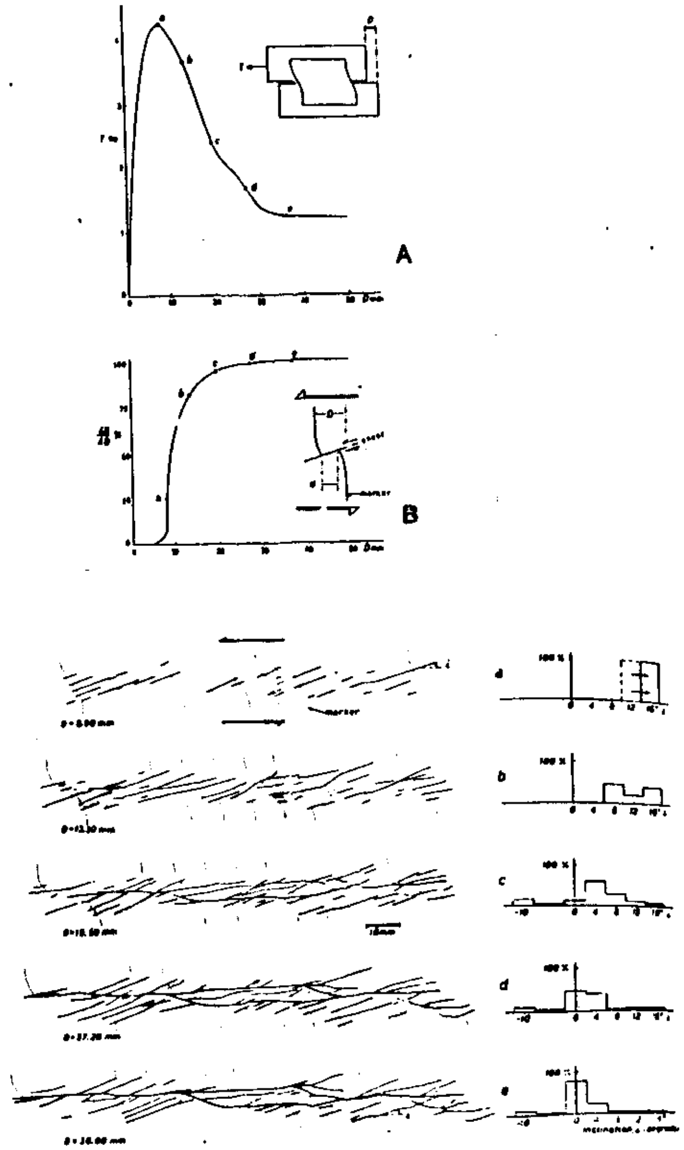




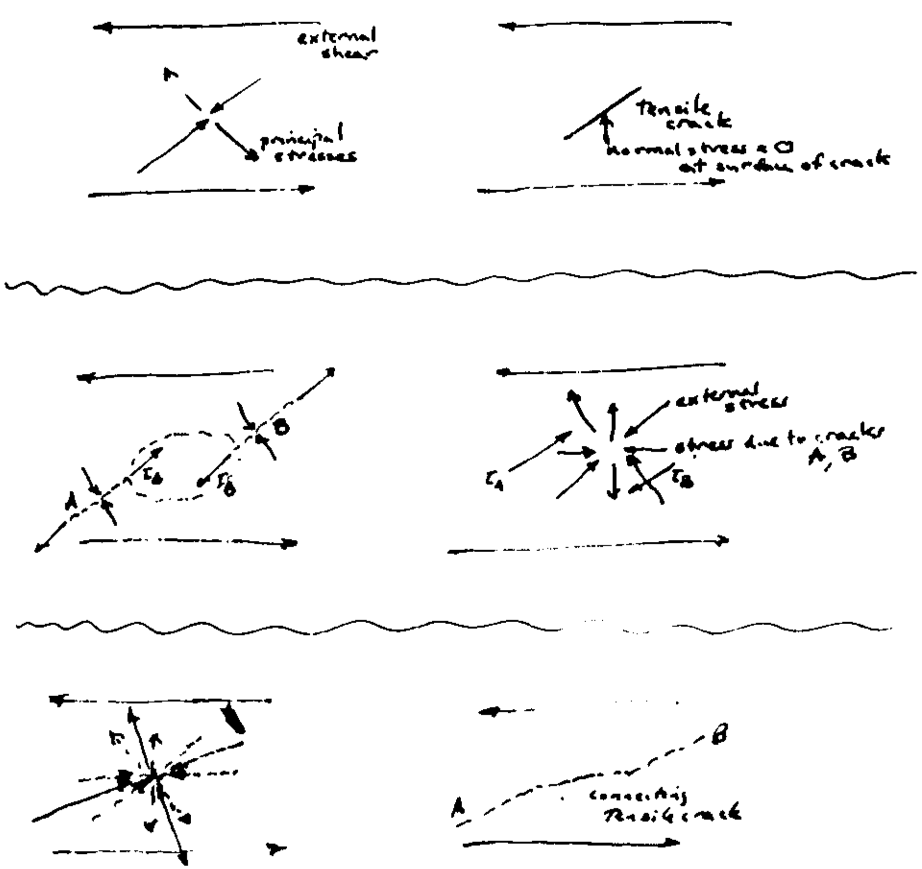

I
dyn. (sliding) friction
F
F=ma
size of crack
Burridge + Halliday Geophys J. R.A.S. 1972 #1


II
strength
size of crack
"the unbreakable obstacle"



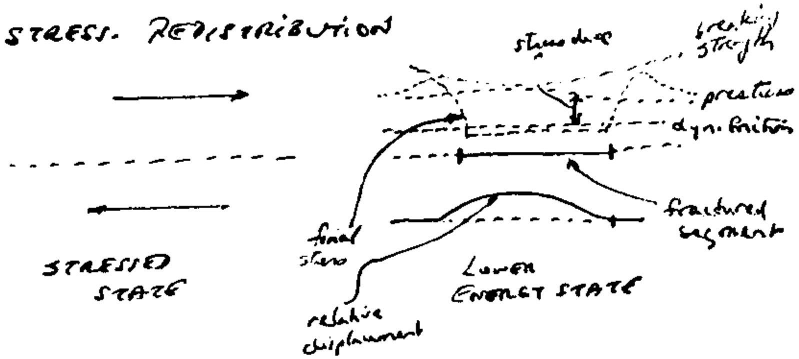

A
B
marker

Tcholenko

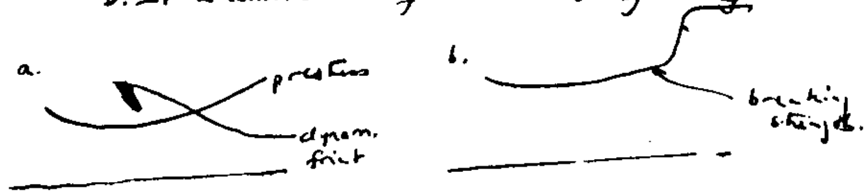


PHYSICS OF FRACTURE (simplified version)

1. A FRACTURE IN A PRESTRESSED SOLID LEADS TO A STRESS-REDISTRIBUTION



2. A fracture stops because
   a. It enters a region where the stress drop becomes negative
   b. It encounters a region of very large strength



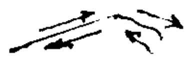
I personally believe that model b) is the mechanism (the barrier or asperity model).

3. CREEP IS AN IMPORTANT ACCOMPANIMENT TO THE EARTHQUAKE EVENT

This process must involve some sort of (non-linear) rheology. THE TIME INTERVAL BETWEEN AFTERSHOCKS IS TOO SHORT TO BE ACCOUNTED FOR BY PLATE TECTONICS. PRE- AND POST- SHOCK CREEP IS OBSERVED IN THE FIELD.

An attack on the basic assumption
(that we know how to project geometry onto
a planar stress distribution)
requires that:

- 1. We study the <u>three-dimensional</u> nature of faulting.



  a. Importance of higher-order multipolar sources.

  b. HEALING

Other horrible problems:

- 2. Coupling of dynamical rupture with quasistatic rupture

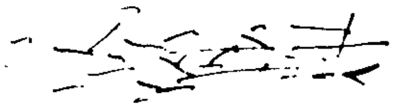
- 3. Coupling of fluid diffusion with fracture (stress diffusion)

  ... and vice-versa.

  - a. Fluid flow in conduits of irregular shape

  - b. Fluid flow (and stress diffusion) in tortuous geometries

⇓



≡ TORTUOSITY

Some Additional Problems & Reminders

1. Statistics: Not only useful to delineate major trends, but also extremely important to give estimates of accuracy of determinations

   examples: Seismic Risk Maps. of recurrence times

   Extreme value statistics

2. Dilatancy: Where does the extra volume go?
   (where does the matter go?)
   Role of the surface of the earth.

3. Elasticity: During the process of opening up (diagonal) cracks, the "grains" deform elastically

4. What is the nature of friction?
   The formation of GOUGE (mylonite)

5. Based on what we know at this point, can we construct a model in which

   a. Small eqs. occur off (away from) (geologically mapped) faults

   b. Large eqs. only occur on mapped faults

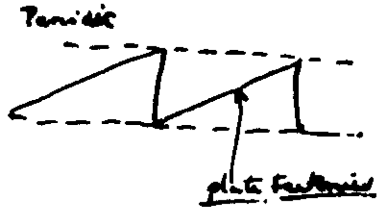
   c. Aftershocks occur.

6. What is influence of healing?
   what is nature of healing?

7. what is role of water?

ANY THEORETICAL MODEL MUST SATISFY.

If Earthquakes are
perfectly periodic
or (Poisson) random
we do not have to bother to construct complex models for their occurrence.



⇒

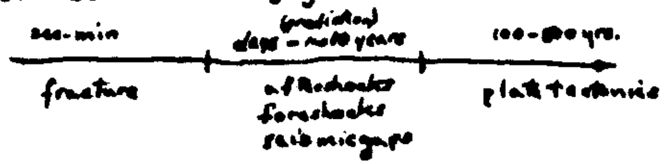
If earthquakes are CLUSTERED

INTERACTION: we must develop an interactive model.

⇒ Stress redistribution due to fracture

But stresses are redistributed elastically
TOO FAST!
We cannot account for aftershocks

3 timescales of changing stress



We need a time delays RHEOLOGY

⇒ Creep (non-elastic) processes provide time delays

⇒ plus geometrical constraints
FAULTING!

Large earthquakes (especially) must take into account
finite size of faults

CONSTRAINTS THUS FAR

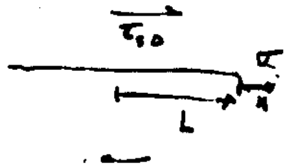
1. PLATE TECTONICS
2. NON-ELASTIC CREEP RHEOLOGY
3. BRITTLE (ELASTIC) FRACTURE
4. GEOMETRY OF FRACTURE SIZES & ORIENTATIONS

Summary of Lecture 2

1. Three time scales of seismic phenomena
   - a. To analyze seismograms in a given period range, we should have a good model of the source in that period range
   - b. What causes the time delays in aftershocks?

2. Creep phenomena in laboratory expts.
   - a. Water saturated rocks creep before they break.
   - b. Accelerated creep prior to fracture
   - c. Time delays to fracture decrease with increasing external stress $t_F \sim e^{-(\sigma_{ext}/T)\,\mathrm{const}}$

3. Increasing fracture (earthquake) size of foreshocks prior to Main Shock.
   - a. Explanation of seismic gaps & doughnuts
   - b. Stress redistribution upon fracture



end on

$\sigma \sim \frac{\tau_{SD}\sqrt{L}}{\sqrt{x}}$ short range

$\sim \tau_{SD}\frac{L^2}{x^2}$ long range

broadside

$\sigma \sim -\tau_{SD}$

   - c. Crack Fusion!

4. Anisotropy, multiple fractures in large shock
   - a. Solution in water of polycrystalline rocks & recrystallization

5. Low Viscosity zone in lower crust (long-dist trans. of stress?)
   - a. Ductility (plasticity) of lower crust: brittle-ductile transition

2