united nations
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international atomic
energy agency

the
abdus salam
international centre for theoretical physics

H4.SMR/1519-47

"Seventh Workshop on Non-Linear Dynamics and Earthquake Prediction"

29 September - 11 October 2003

PHYSICS OF FORESHOCKS AND AFTERSHOCKS

Are Large Earthquakes Predictable?

Leon Knopoff

University of California, L.A.

Dangers

1. Statistics

   What are uncertainties in ~~statistical~~ fits.

   Goodness of fit

2. Models:

   What goes on in fast time is important

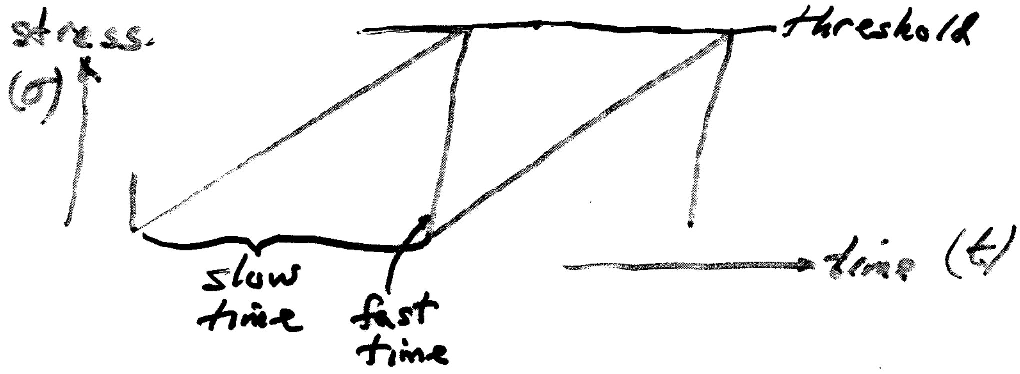
   Are random processes important?

We learned:

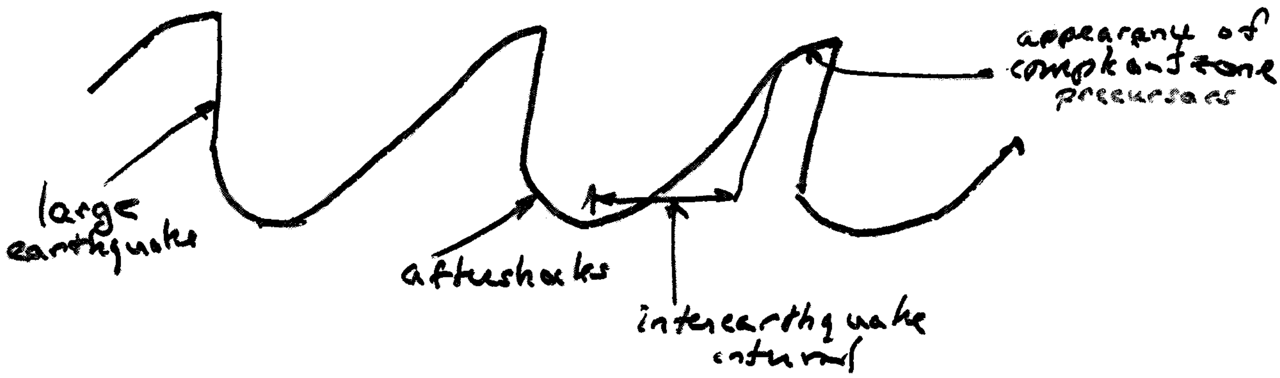
1. Two types of aftershocks
2. Two types of mainshocks ... perhaps three
3. There is an annoying interface among scales

   Multiple scales

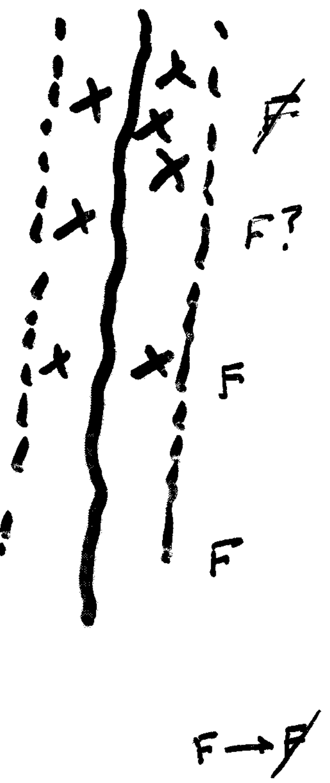
   Coarse graining
4. Organization in space
5. Organization in time
6. Organization in space time



1. Earthquakes are fractures in fast time
   What stops a crack?
   Healing. How fast do cracks heal
2. Inhomogeneities (Geometry) How impt.?
3. Dynamics of fast time

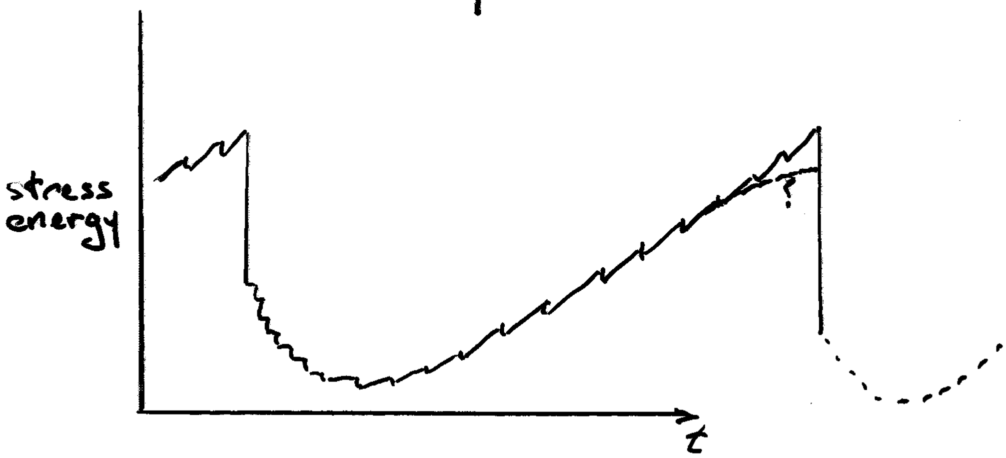


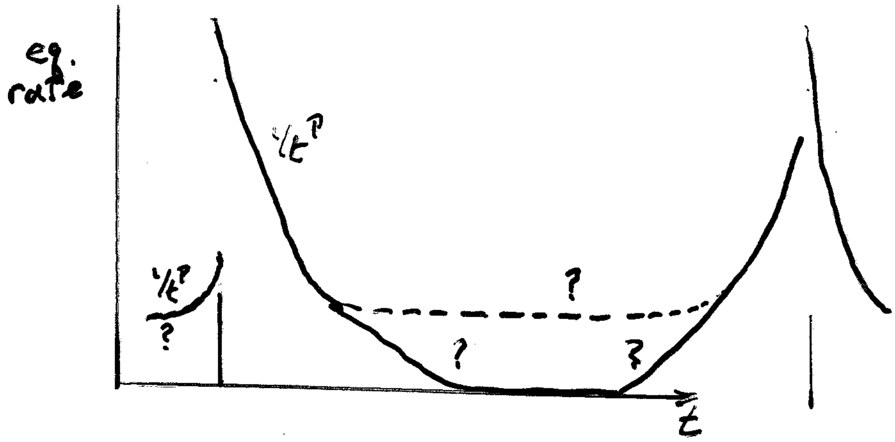
time ↓	Main Fault	Compliant Zone
interearthquake interval	locked	heterogeneous bonded
appearance of compliant zone	locked	partial debonding via small fractures (mainly)
large earthquake	rapid sliding on irregular surface	fragmentation of already heterogeneous region
aftershocks	rapid healing of main fault ... relocking	relaxation of stress in fragmented region. continued fragmentation
interearthquake interval	locked	rebonding, cessation of aftershocks



Large eq.

	Mainshocks	Aftershocks
dir. of organization	→ ?	←
triggering	plate tectonics	single (large?) eq.
faulting	activity on many faults	assoc. with single fault
stress	tectonic stress rate > relaxation rate	relaxation rate > tectonic rate
eq. rate	steady state (?) or increasing	rapid decay
spatial distrib.	diffuse	clustered (localized)





FACTS ABOUT AFTERSHOCKS

1. They satisfy the Gutenberg-Richter law,

$$N \sim 10^{-bM} \Rightarrow N \sim E^{-2b/3}, \qquad b \sim 1.0$$

2. They satisfy the Omori law,

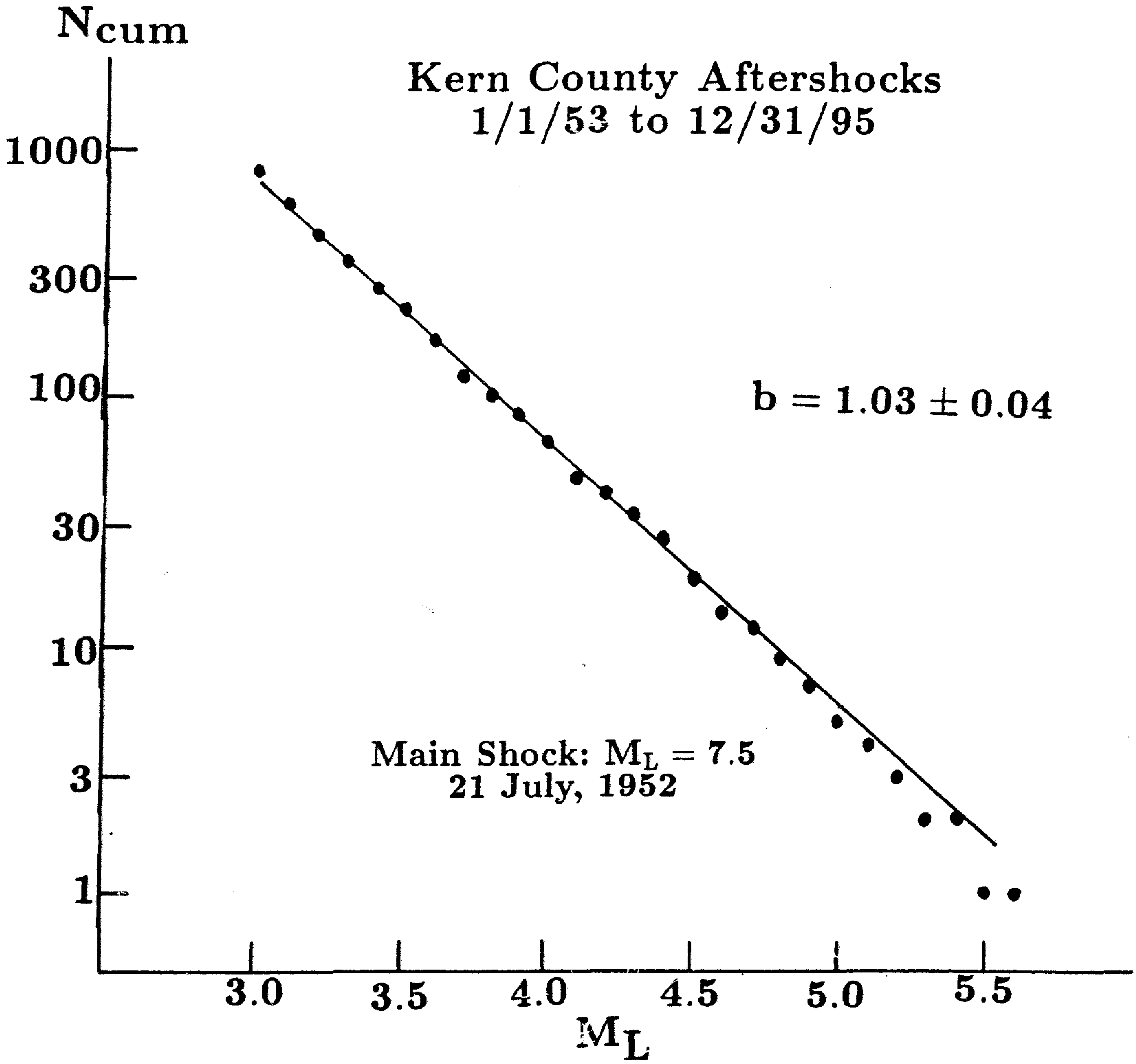
$$\dot{N} \sim t^{-p}, \qquad p \sim 1.0$$

3. Most small aftershocks occur in zone of reduced stress

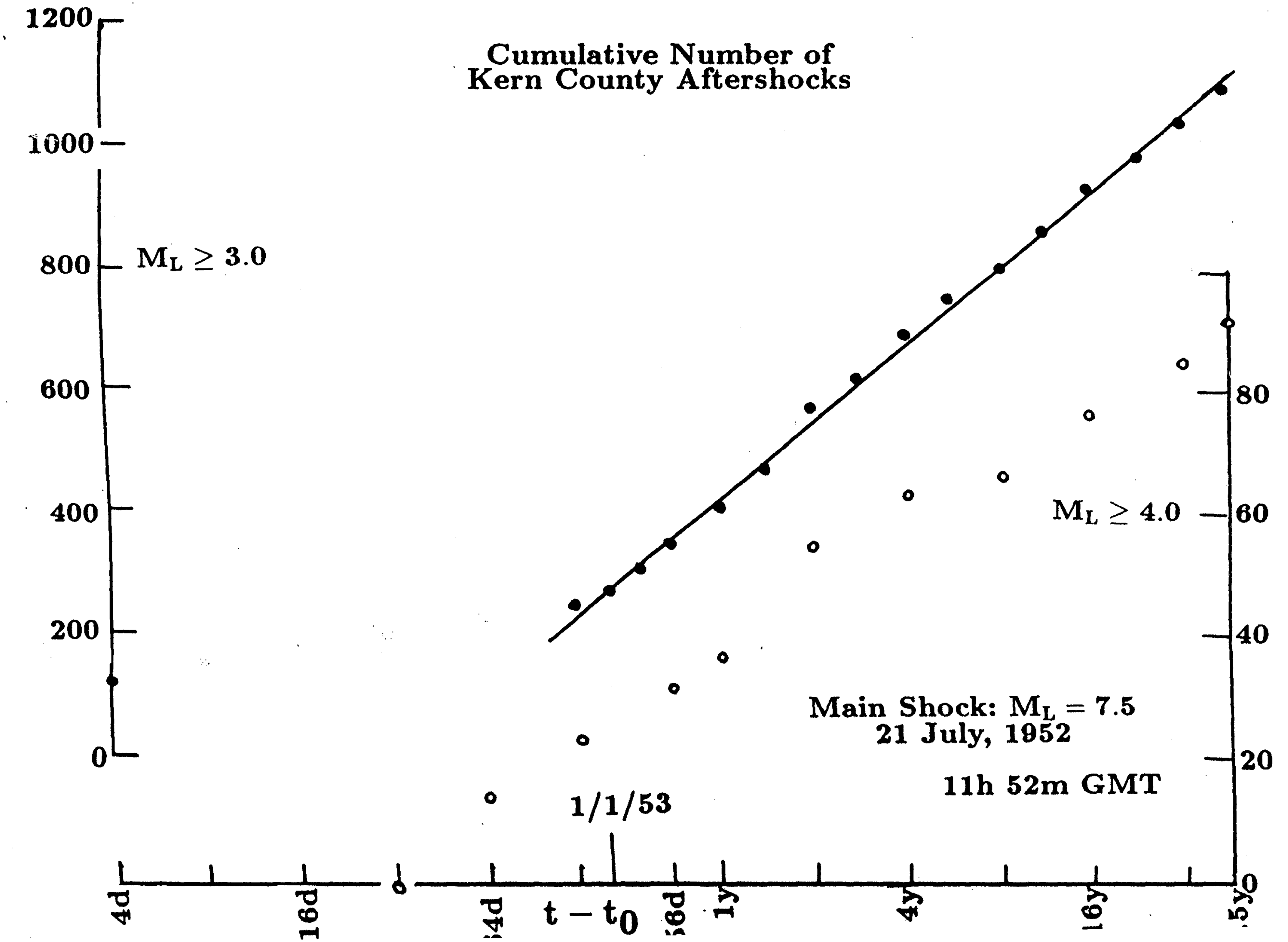
4. Most larger aftershocks occur near the time of the main shock rupture

5. Most small aftershocks may persist for years, large ones for a few months.

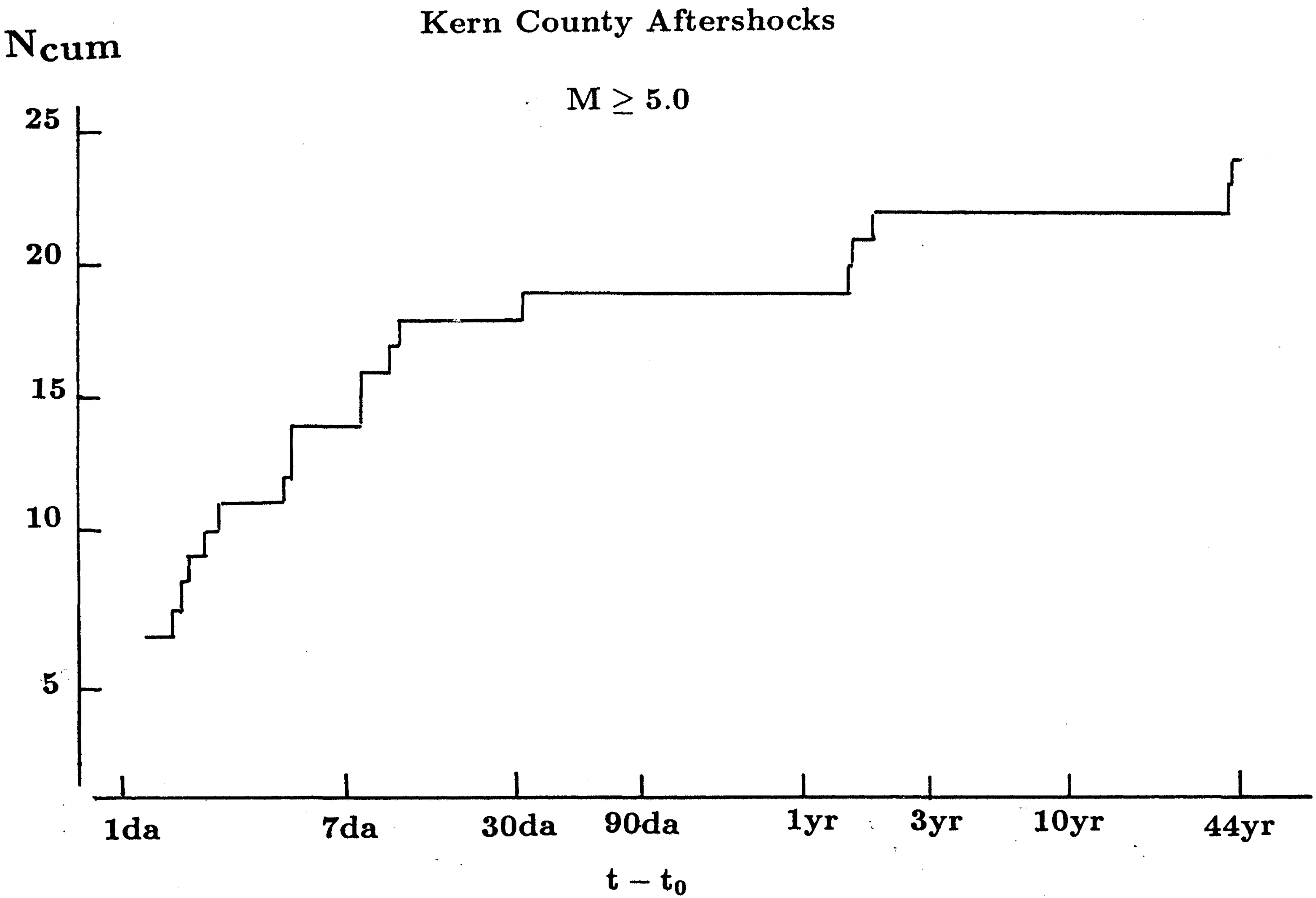
6. Some small long-range aftershocks to distances of the order of 1000 km after Landers M = 7.3 (June, 1992).



Ncum
Kern County Aftershocks
1/1/53 to 12/31/95
1000
300
100
30
10
3
1
b = 1.03 ± 0.04
Main Shock: ML = 7.5
21 July, 1952
3.0
3.5
4.0
4.5
5.0
5.5
ML



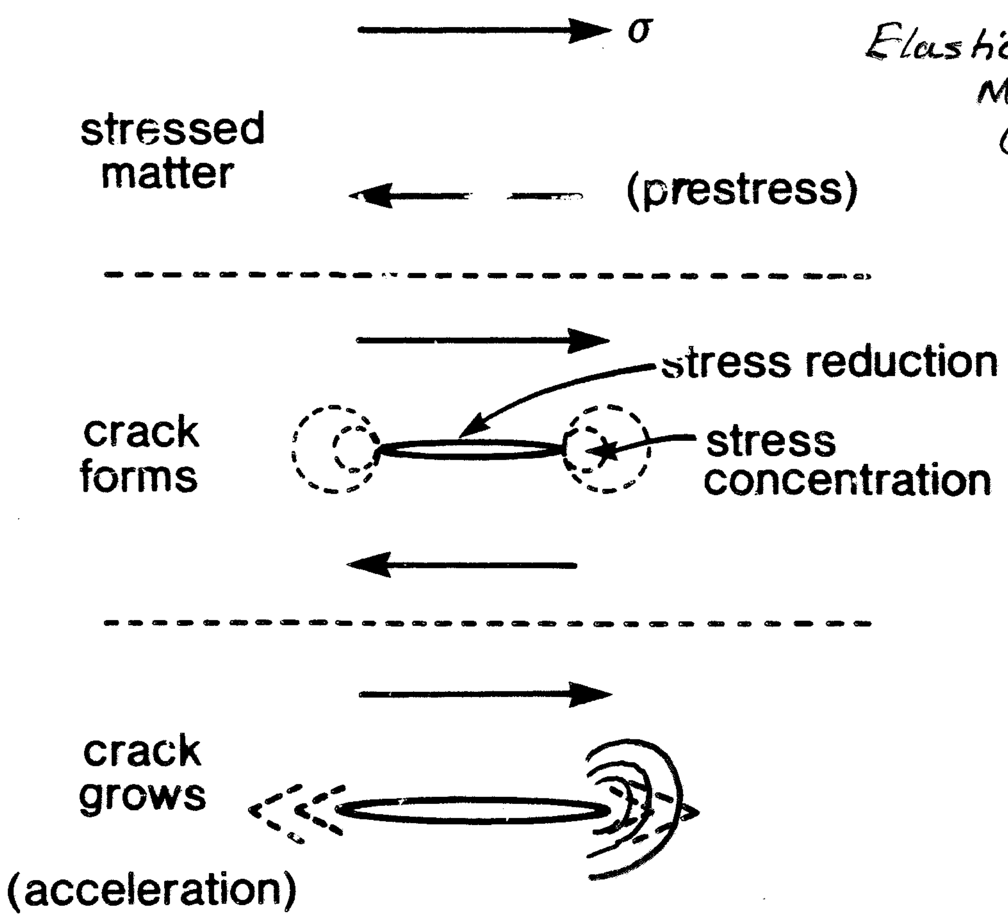
Cumulative Number of
Kern County Aftershocks
1200
1000
800
600
400
200
0
$M_L \geq 3.0$
$M_L \geq 4.0$
80
60
40
20
0
Main Shock: $M_L = 7.5$
21 July, 1952
11h 52m GMT
1/1/53
4d
16d
1y
4y
16y
$t - t_0$



Kern County Aftershocks
M ≥ 5.0
Ncum
25
20
15
10
5
1da
7da
30da
90da
1yr
3yr
10yr
44yr
t – t0

WHAT IS AN EARTHQUAKE?

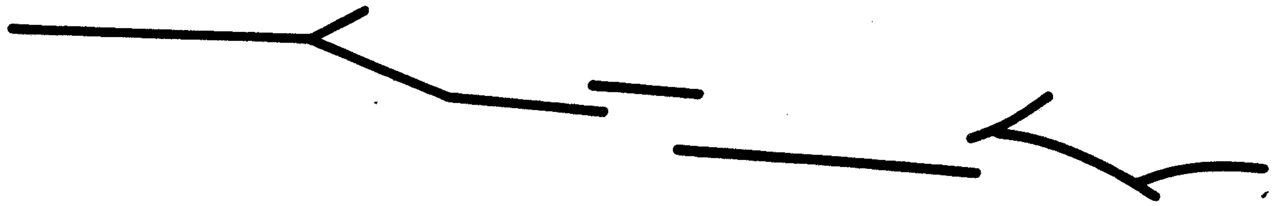
Elastic Rebound Model (H.F. Reid, 1908)



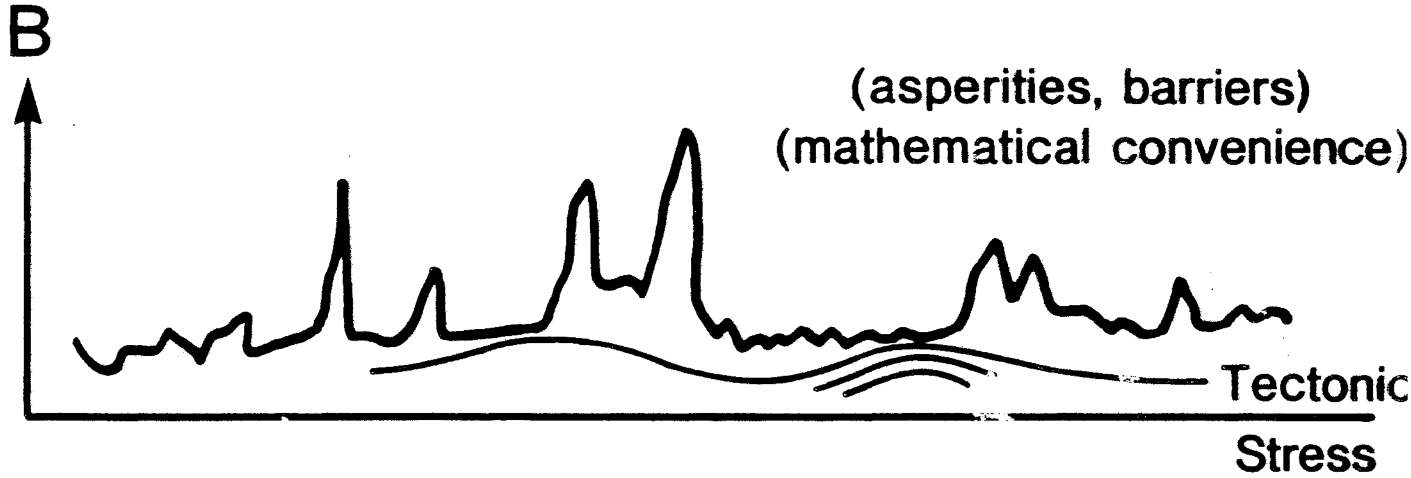
slip $u = \frac{\sigma L}{\mu}$

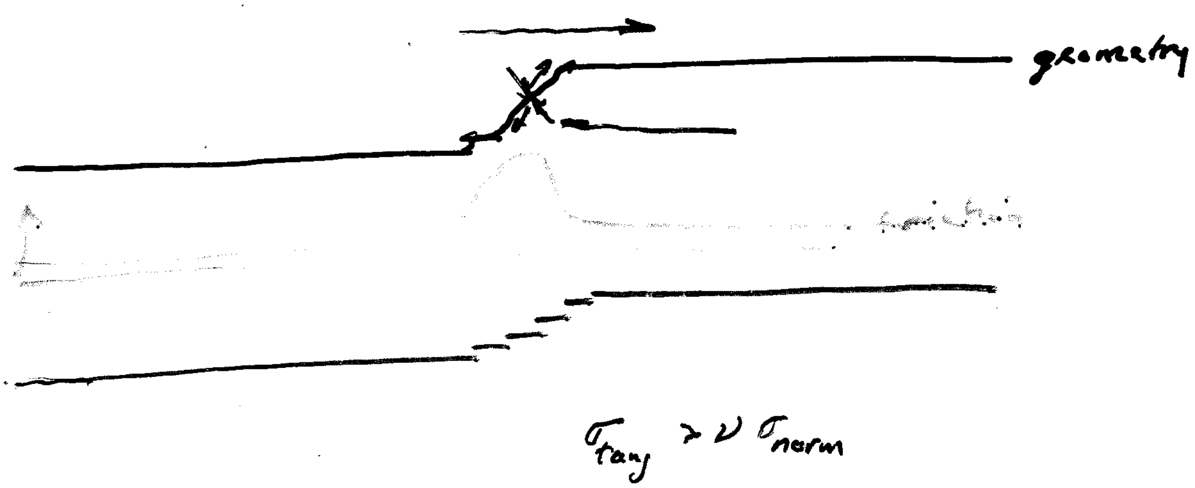
conservative stress transfer in antiplane cracking

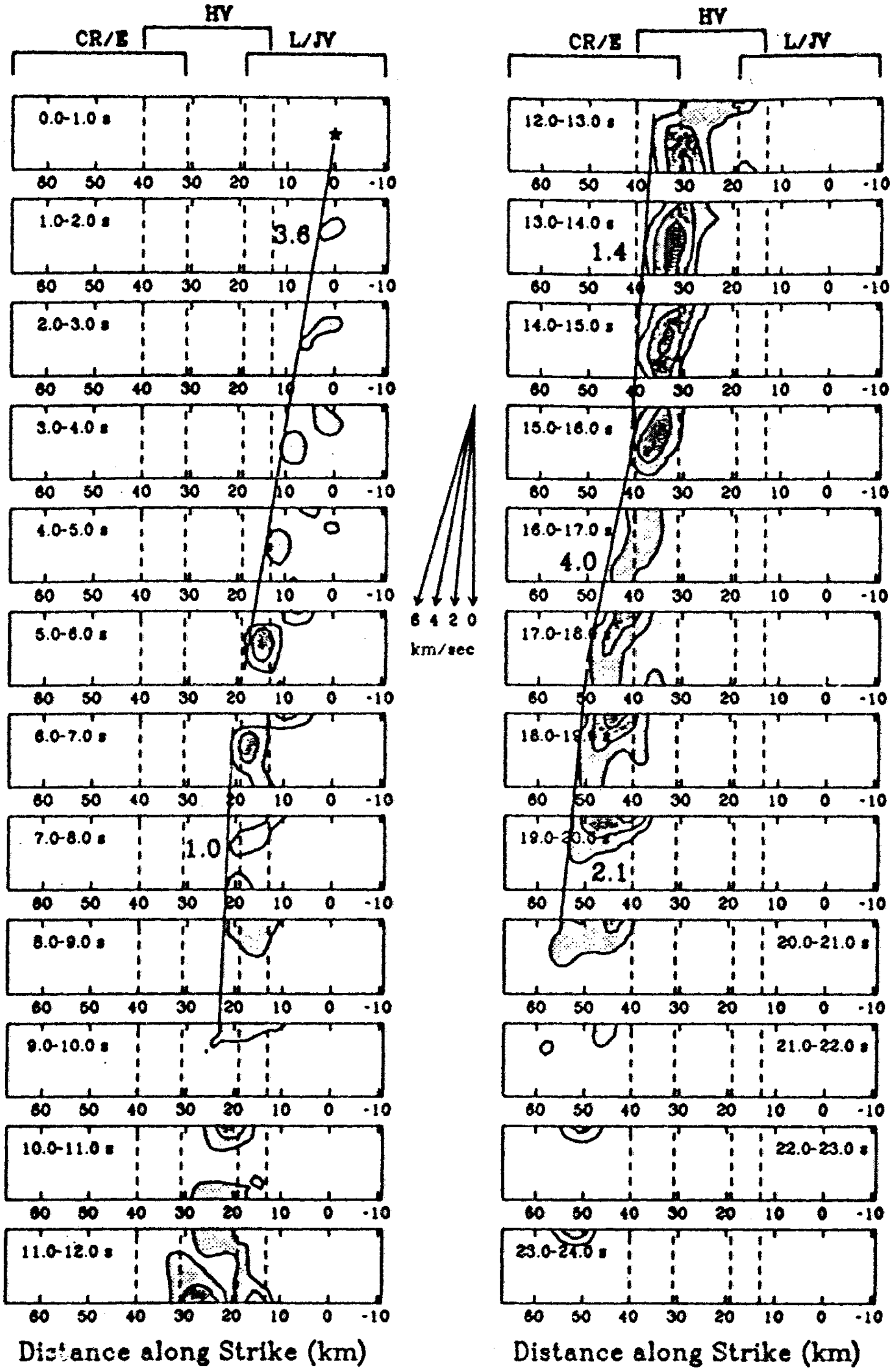
Geometry of Faulting



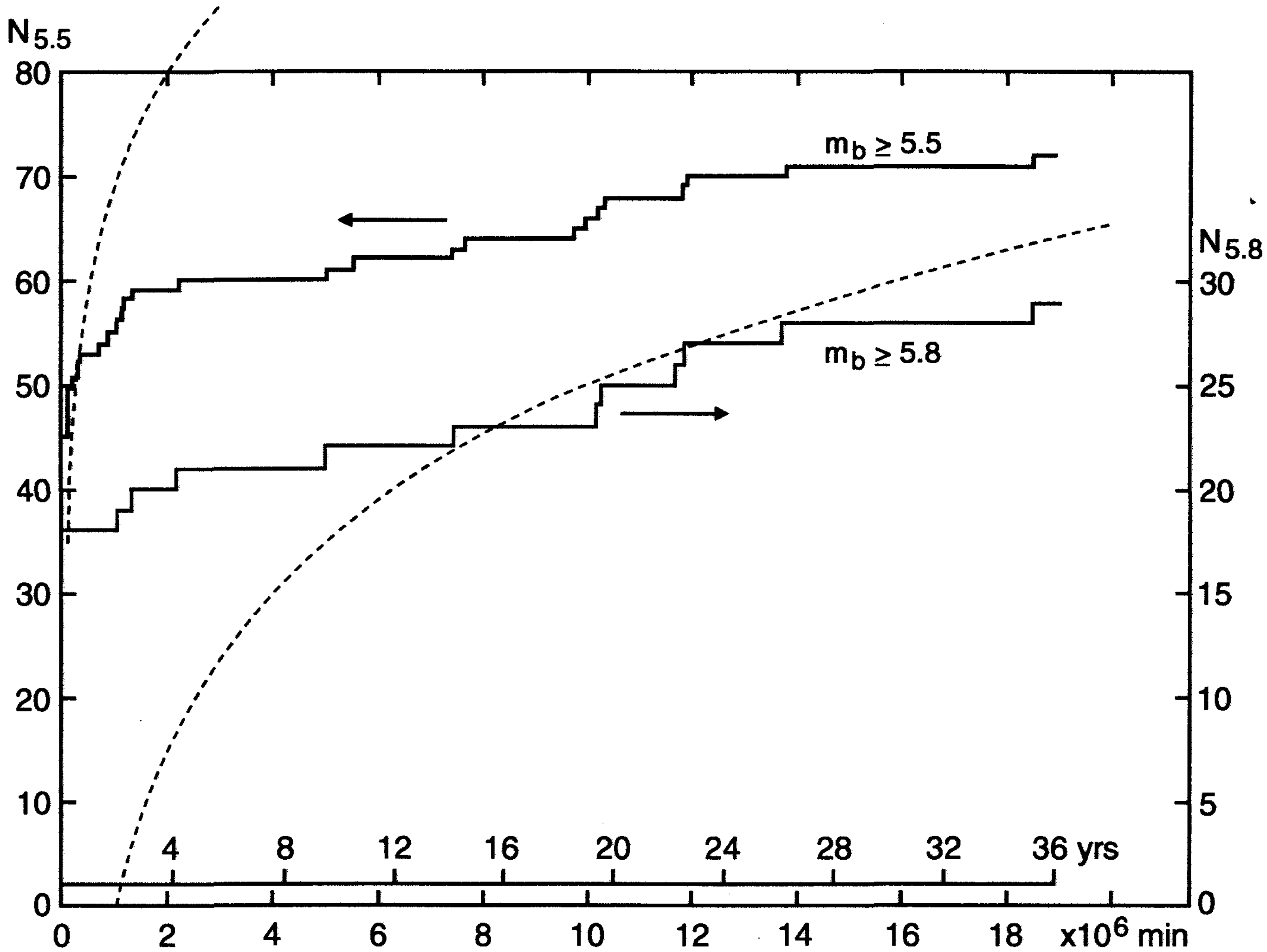
1 Dimensional Representation





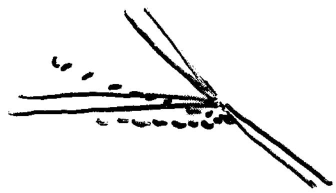


Wald and Heaton 1994



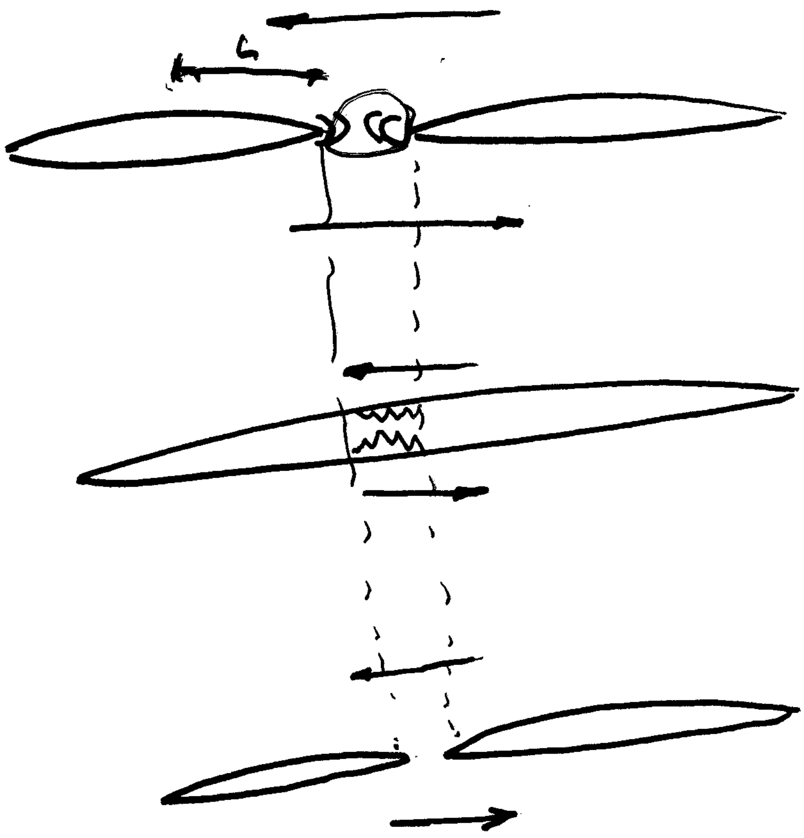
N5.5
80
70
60
50
40
30
20
10
0
mb ≥ 5.5
mb ≥ 5.8
N5.8
30
25
20
15
10
5
0
4
8
12
16
20
24
28
32
36 yrs
0
2
4
6
8
10
12
14
16
18
x10^6 min

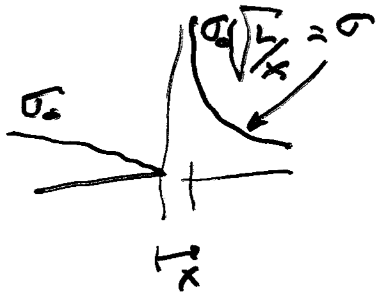
LK-061



$$\frac{dL}{dt} = V = K^n \text{ or } e^{+K/kT}$$

$$K = \sigma\sqrt{L}$$





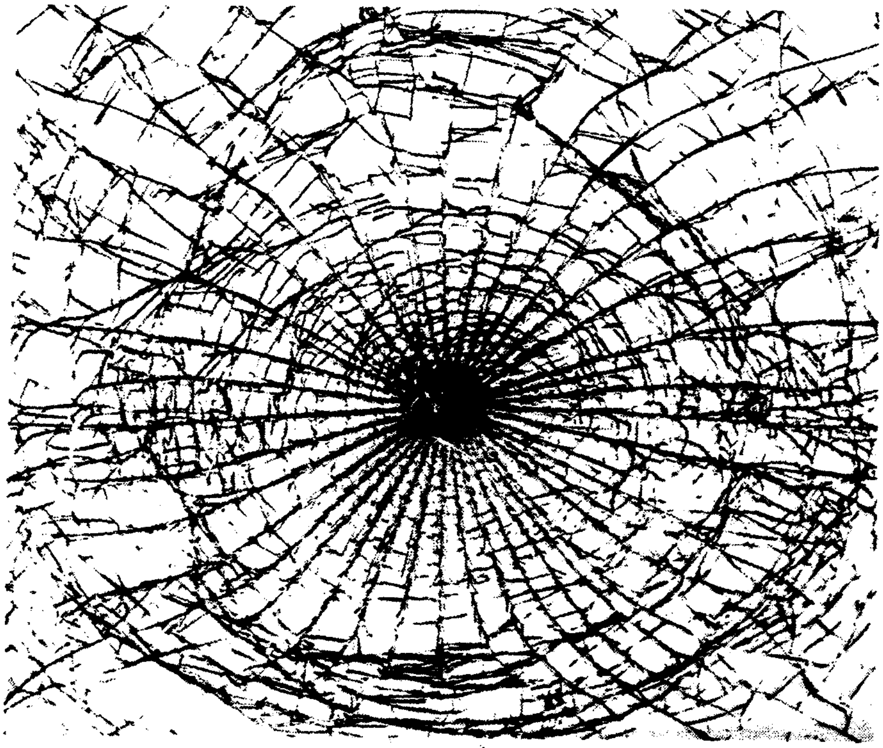


Fig. 3—Typical fracture of conventional 2.5 mm laminated windshield

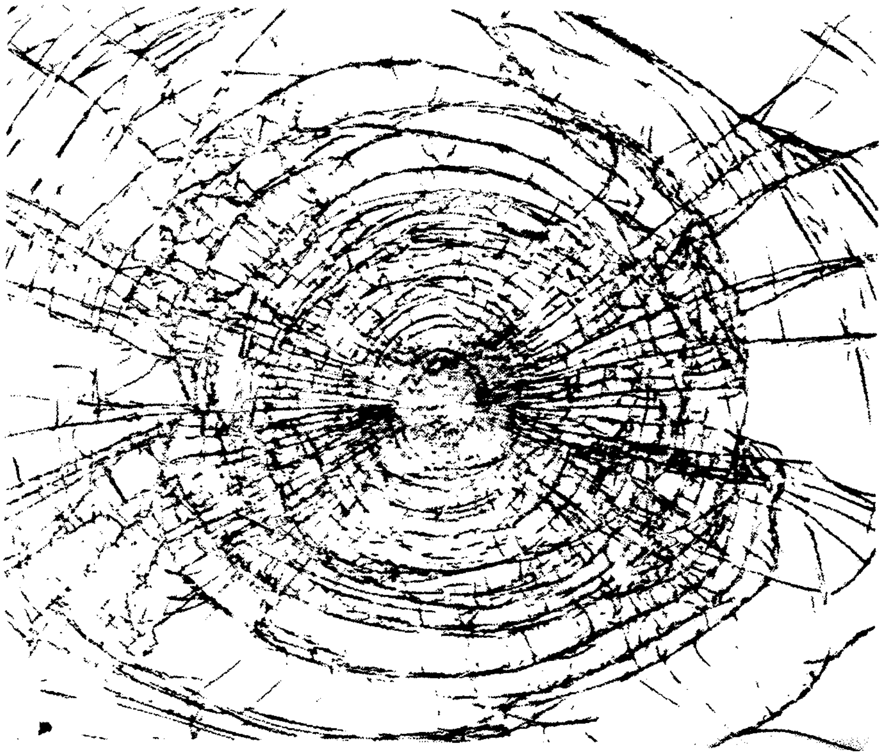
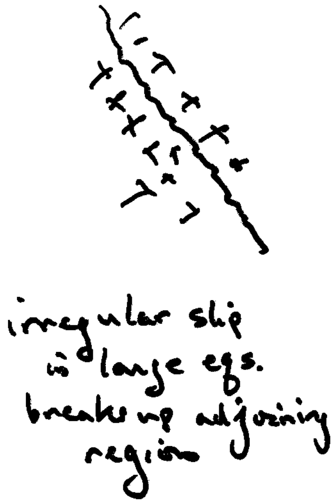
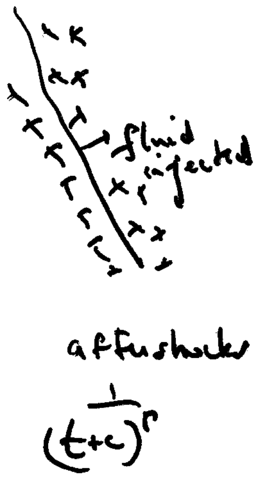
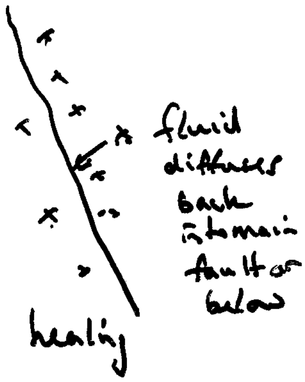
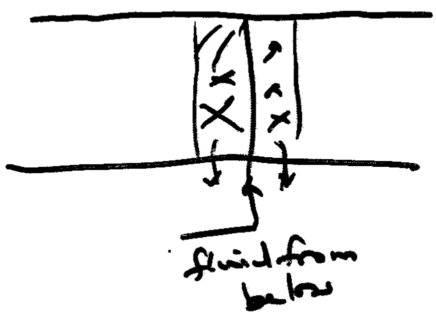


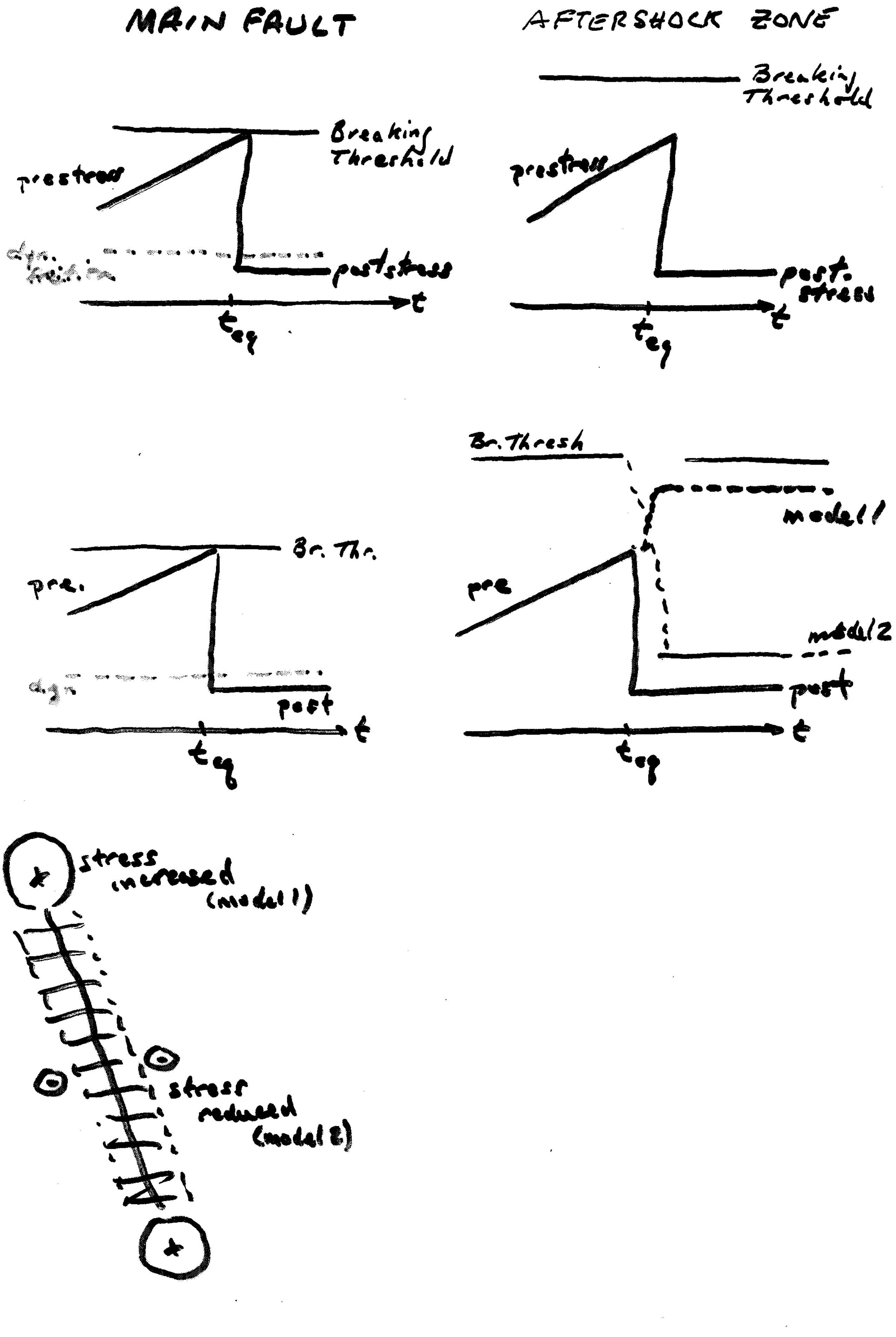
Fig. 4—Typical fracture of conventional 3 mm laminated windshield

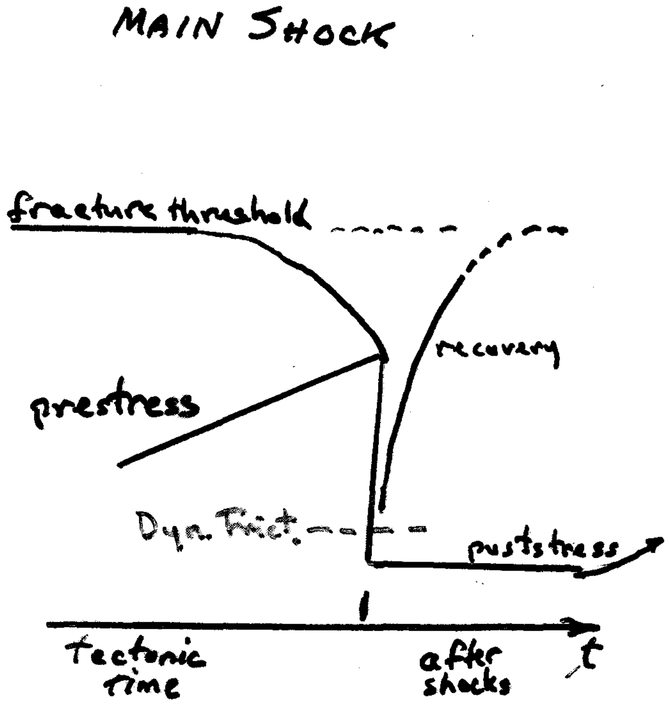

irregular slip
in large eqs.
breaks up adjoining
region

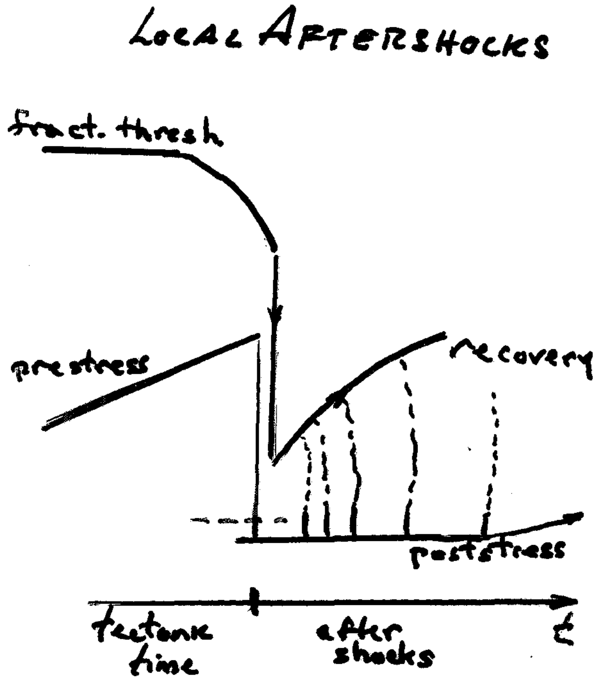

fluid
injected
aftershocks
$\frac{1}{(t+c)^p}$

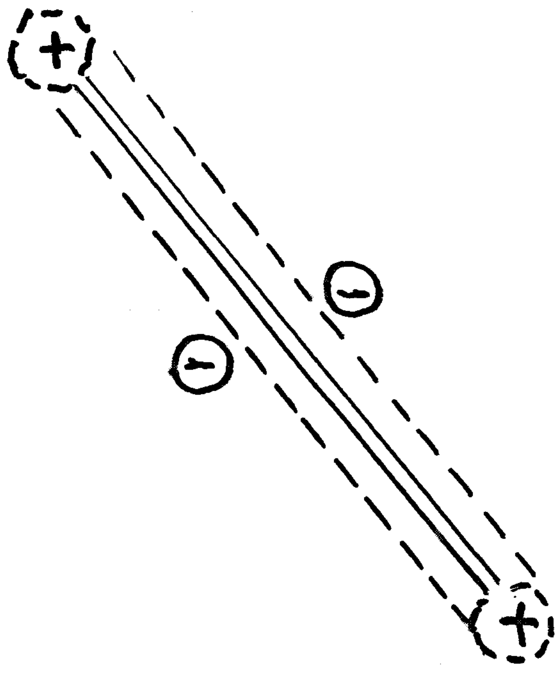

fluid
diffuses
back
into main
fault or
below
healing

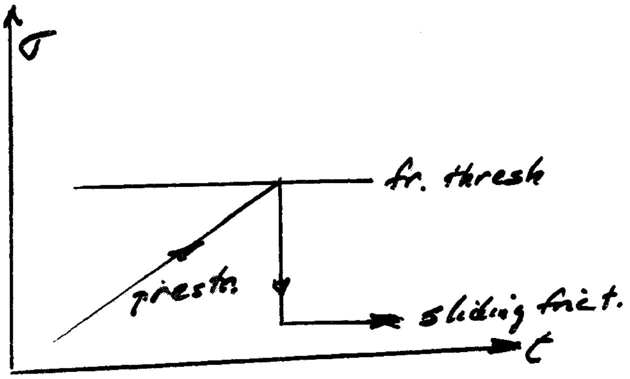

fluid from
below

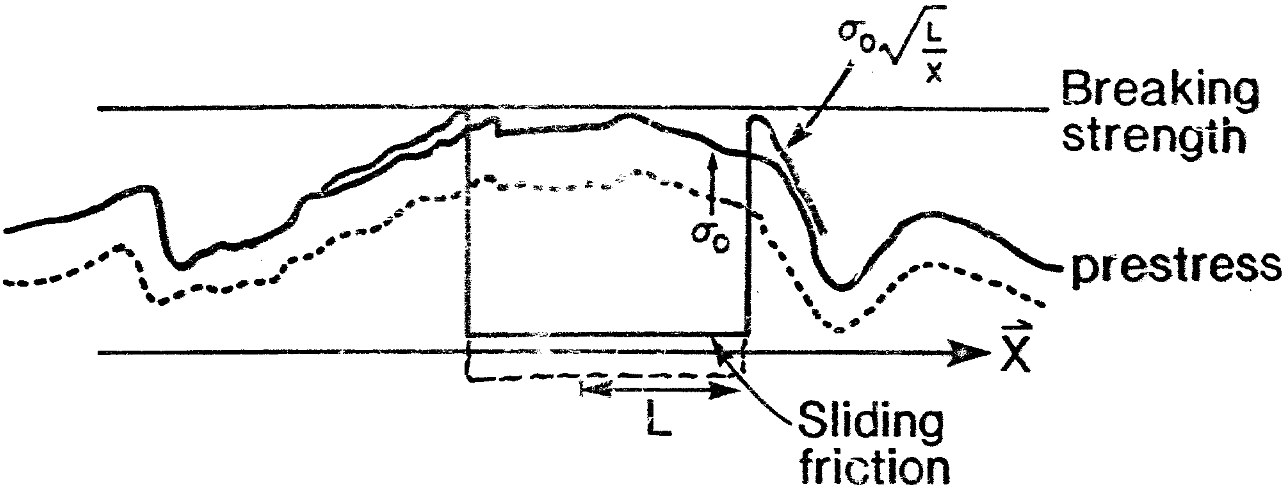

MAIN FAULT
AFTERSHOCK ZONE
Breaking Threshold
prestress
poststress
t
t_{eq}
Breaking Threshold
prestress
post. stress
t
t_{eq}
Br. Thr.
pre.
post
t
t_{eq}
Br. Thresh
model 1
pre
model 2
post
t
t_{eq}
stress increased (model 1)
stress reduced (model 2)

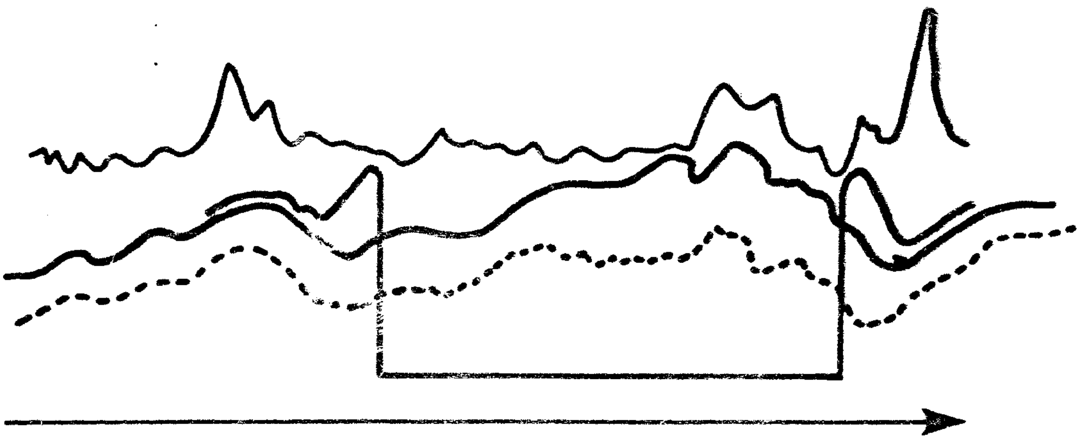

MAIN SHOCK
fracture threshold
recovery
prestress
Dyn. Frict.
poststress
tectonic time
after shocks
t


LOCAL AFTERSHOCKS
fract. thresh.
prestress
recovery
poststress
tectonic time
after shocks
t



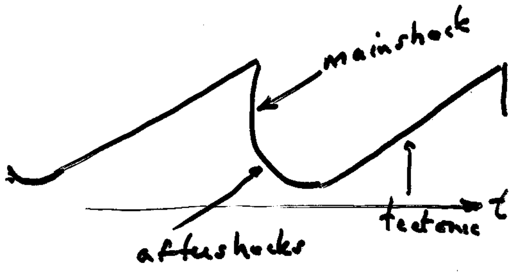


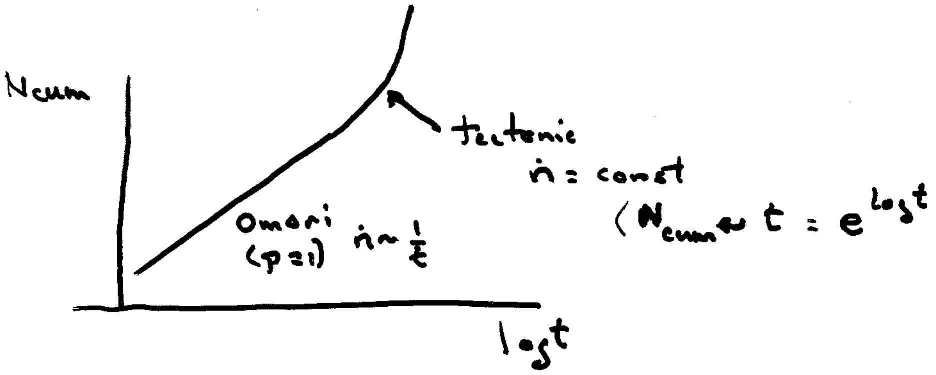


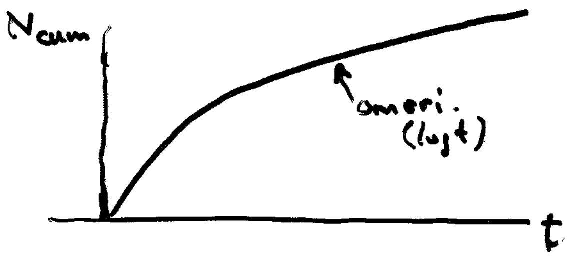


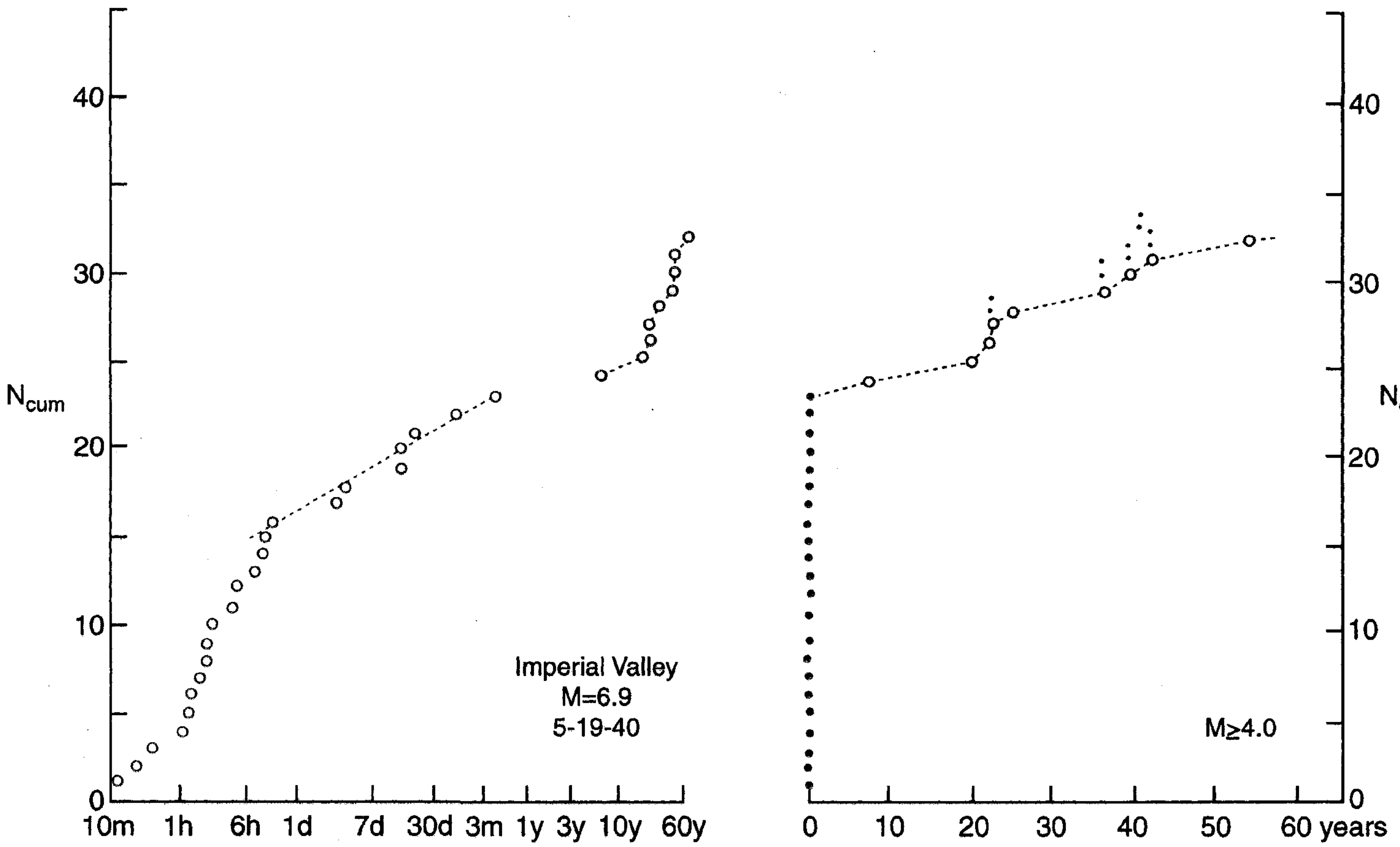
What stops the growth of a crack:
Stress Redistribution ⇒ interactive:

When do aftershock series end?

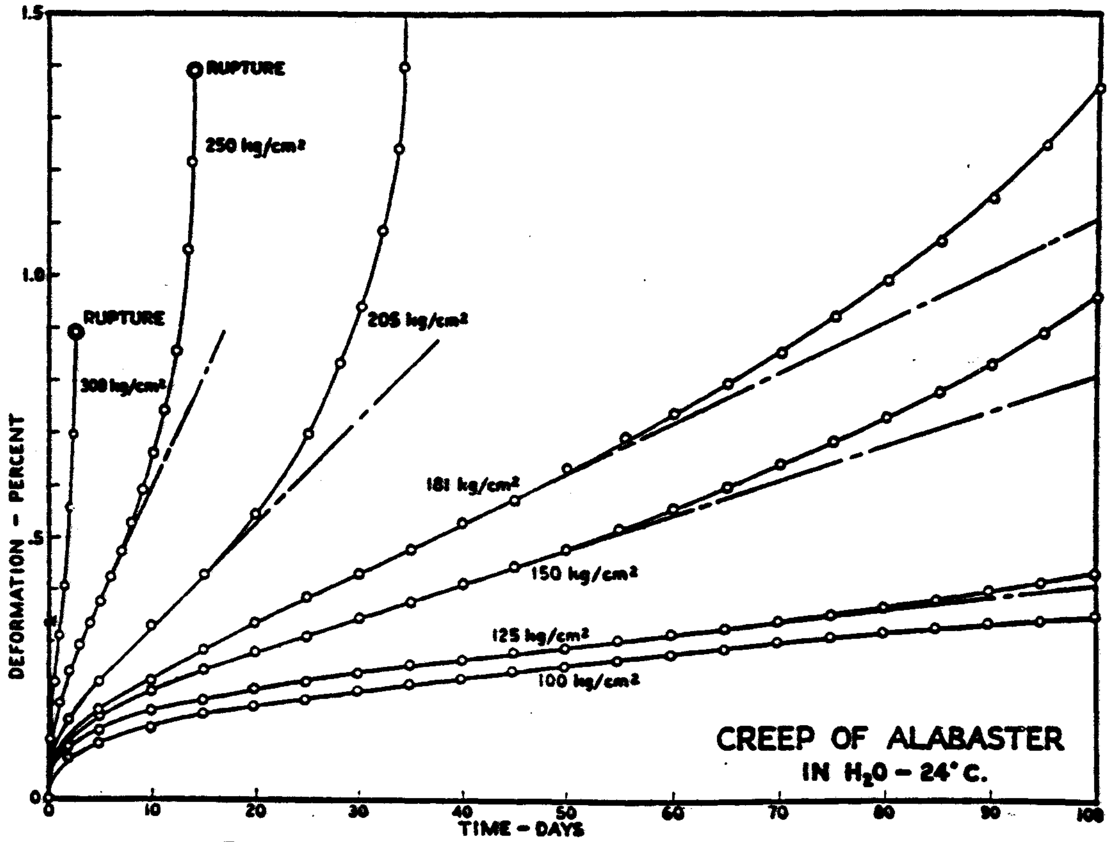






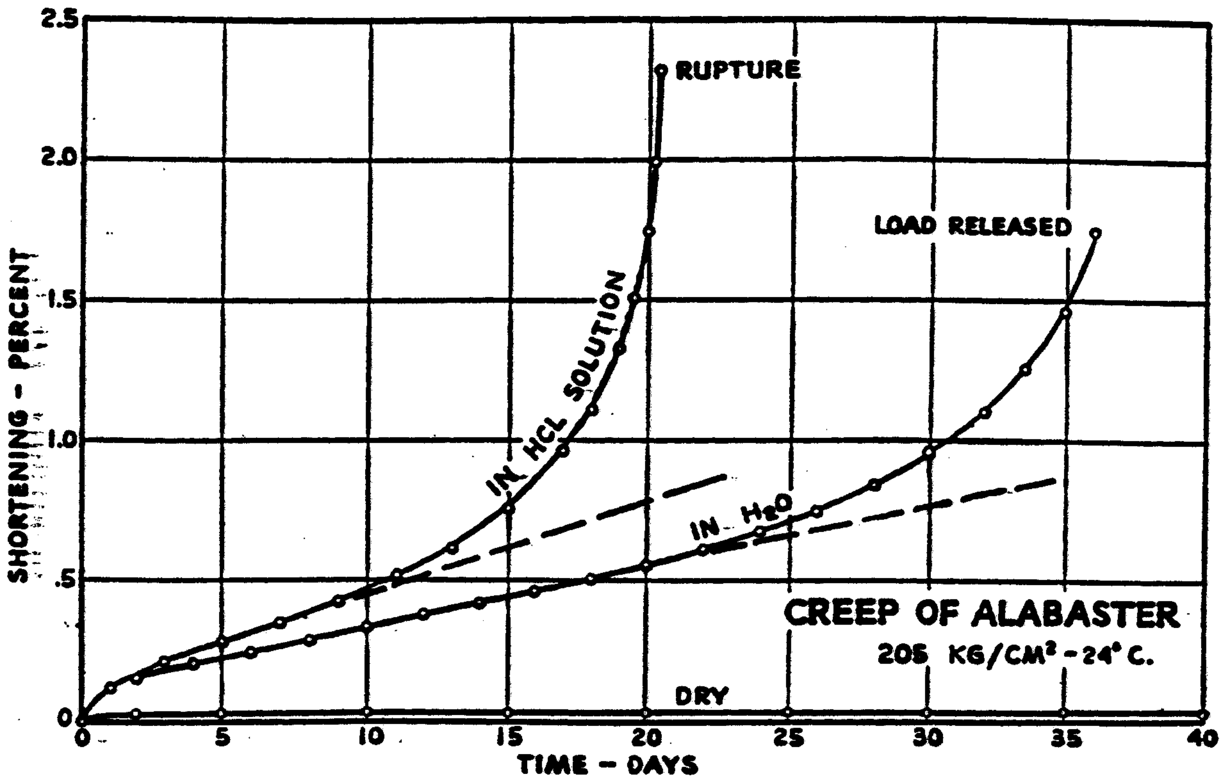


$\dot{n} \sim \frac{1}{t}$

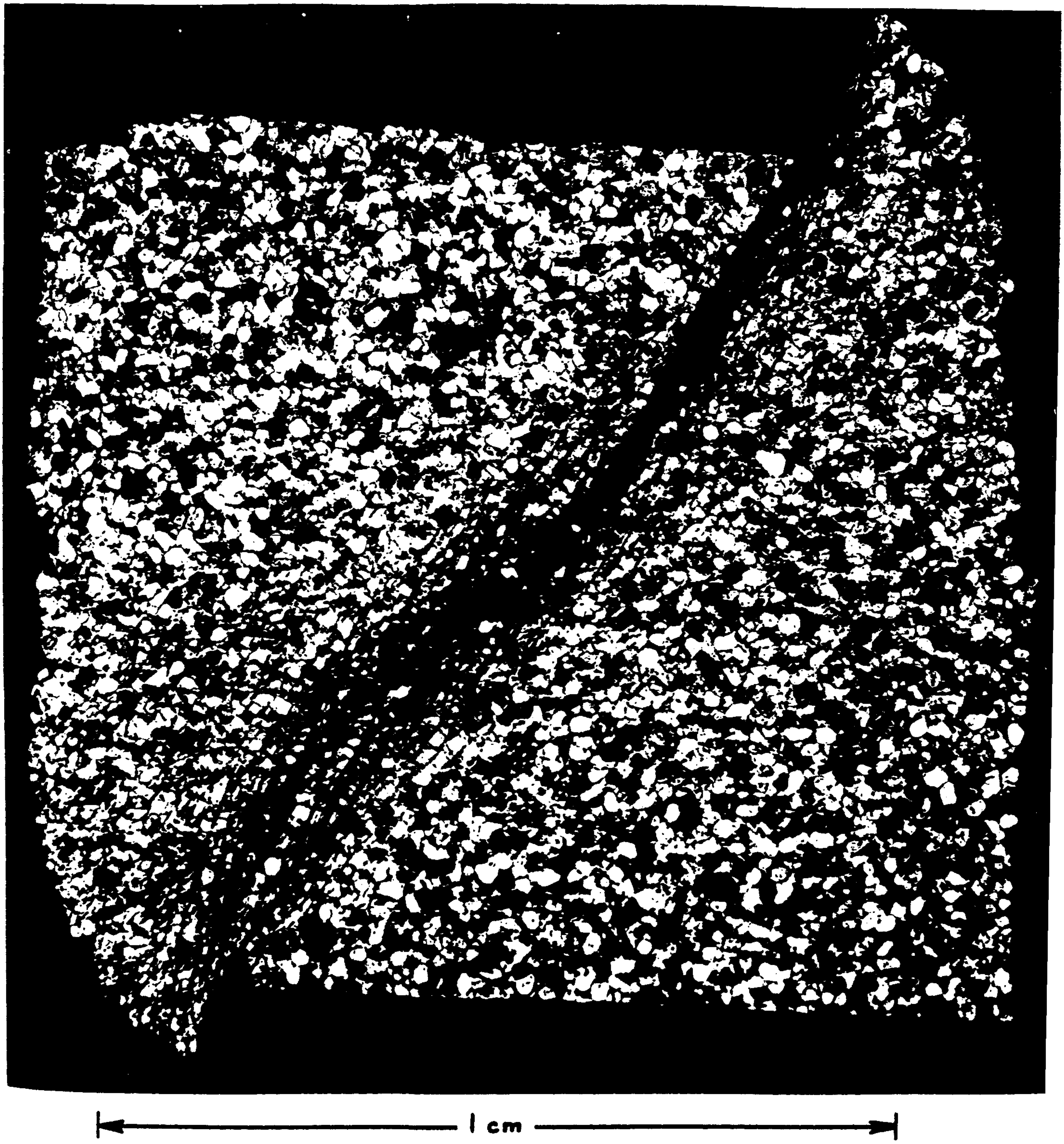


$t_f = t_0 e^{-E/kT}$, $E = \sigma \cdot V$ ⇒ Chemical Kinetics
Activation Process
Stress Corrosion
(process accel by H_2O, T

Glass: Preston et al, Nature 156, 1946
J. App Phys. 17 1946
Metals: Zhurkov, Int. J. Fract. Mech. 1, 1965
Cherepanov, Mech. of Britt. Fract. 1978
Rocks: Griggs, Bull. G.S.A. 51 1940
Plastics; Ionic Solids: Zhurkov, loc. cit.

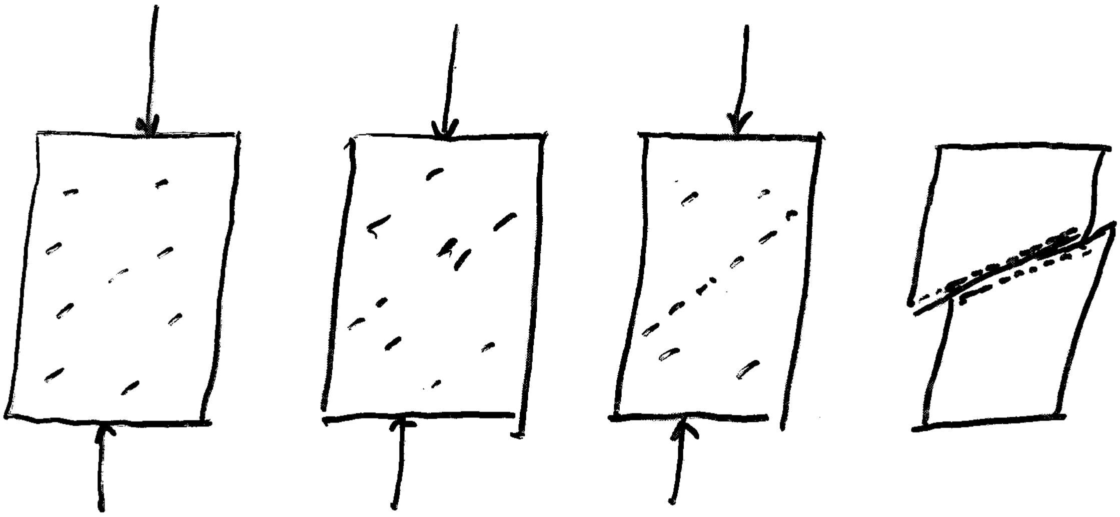


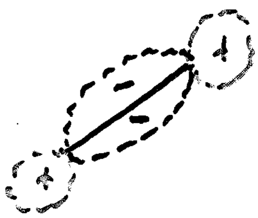
RUPTURE
LOAD RELEASED
IN HCL SOLUTION
IN H_2O
DRY
CREEP OF ALABASTER
205 KG/CM² - 24° C.
SHORTENING - PERCENT
TIME - DAYS
2.5
2.0
1.5
1.0
.5
0
5
10
15
20
25
30
35
40

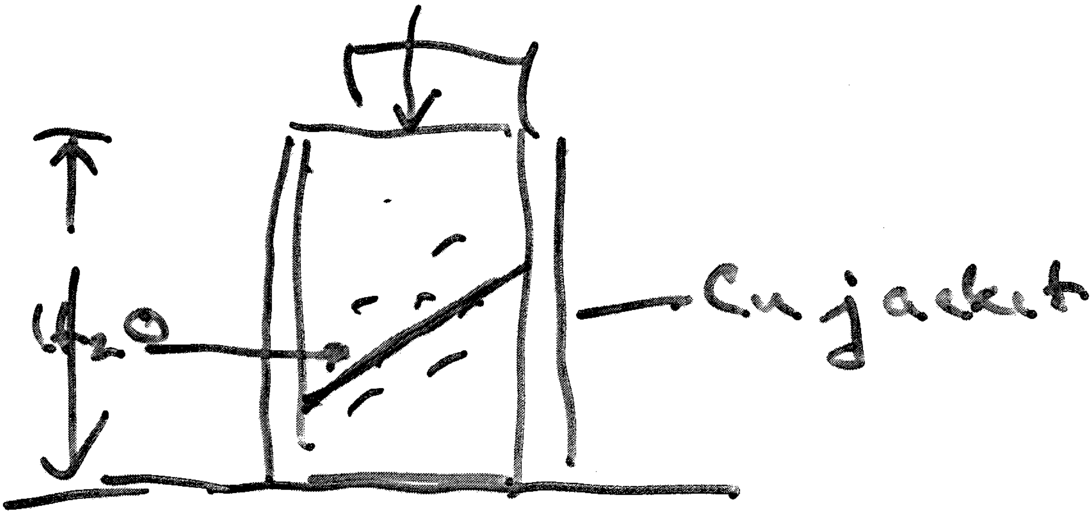


ST. PETER SAND 48–65 MESH

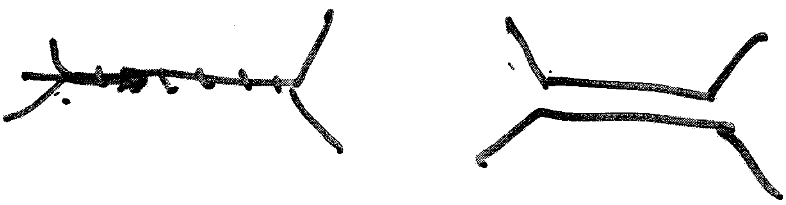
Compacted at 500°C., 5 kb confining pressure, 1 kb interstitial water pressure, then compressed 40 per cen
perature and fluid pressures kept constant. Thick copper jacket did not rupture despite shear offset at end

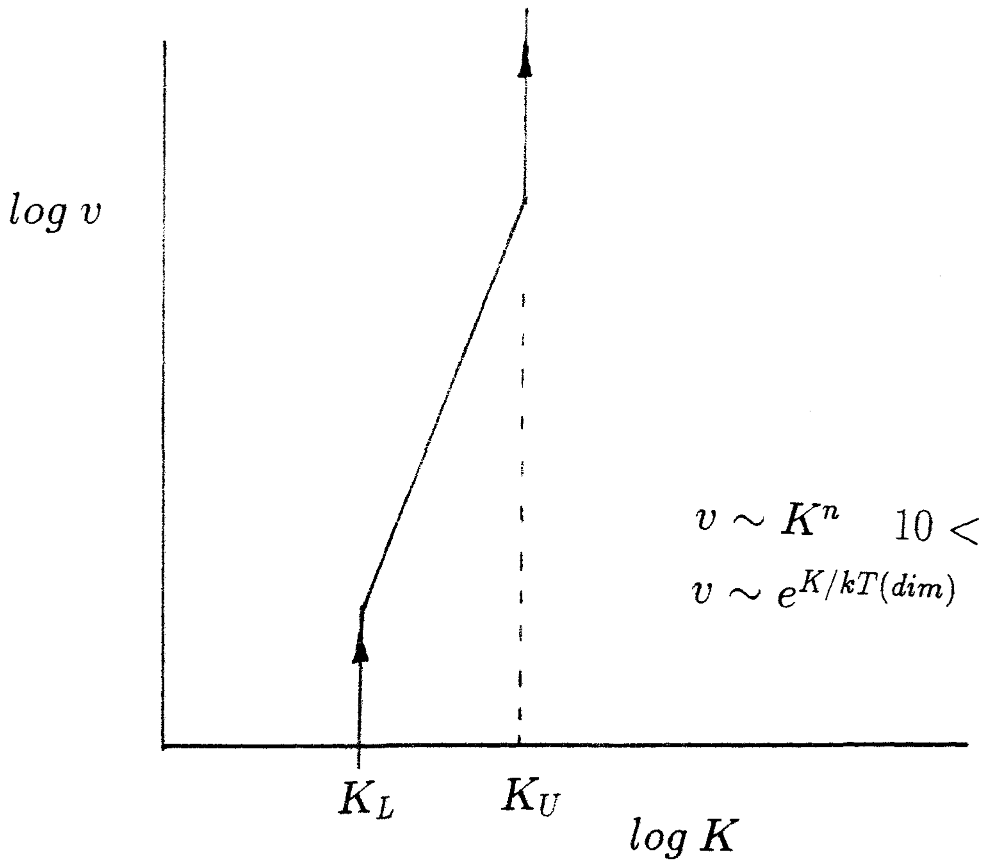






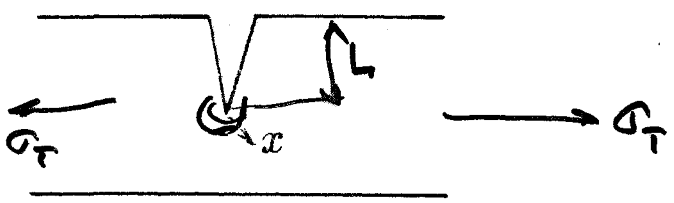
H_2O dissolves SiO_2





$v \sim K^n \quad 10 < n < 160$

$v \sim e^{K/kT(dim)}$



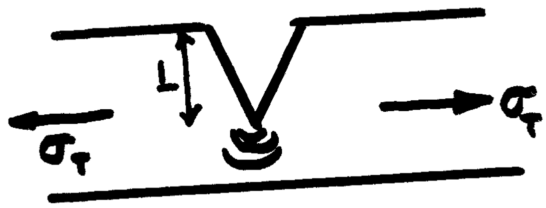
$\sigma(x) \sim \underline{\sigma_T \sqrt{L}} / \sqrt{x}$

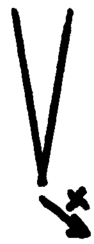
$v = \frac{dL}{dt} = K^n = (\sigma_T \sqrt{L})^n$ (e.g.)

$K \sim \sigma_T \sqrt{L}$

stress intensity factor

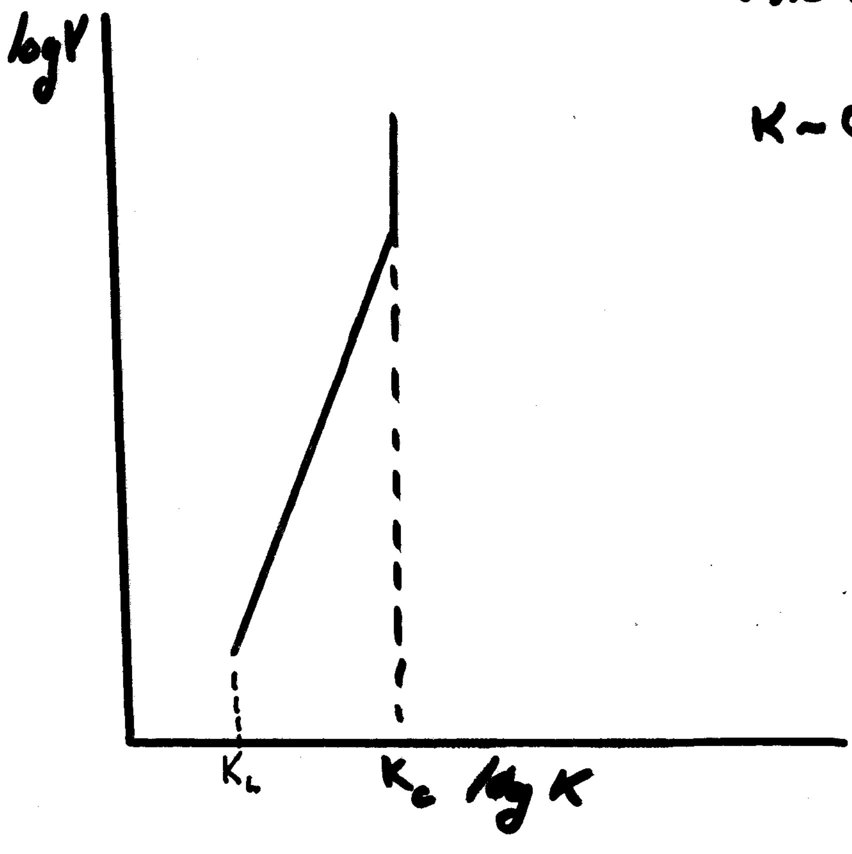
Activation Process (Chem. kinetics)
Velocity weakening
Subcritical Crack Growth
(stress corrosion)





$$\sigma(x) \sim \sigma_T \frac{\sqrt{L}}{\sqrt{x}}$$

$$K \sim \sigma_T \sqrt{L}$$

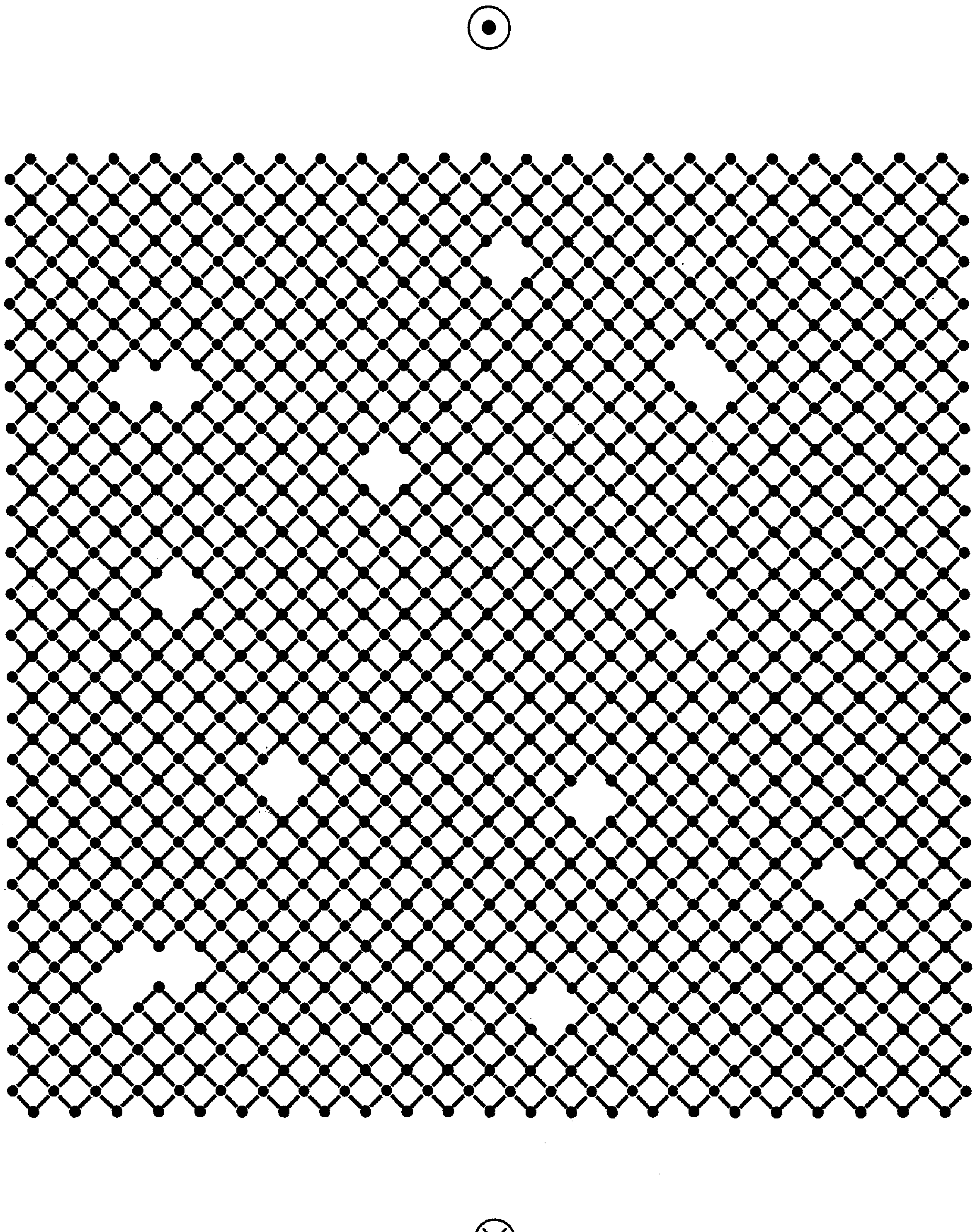


$$V = \frac{dL}{dt} \approx \frac{K^n}{e^{K/kT}} \qquad 10 < n < 160$$

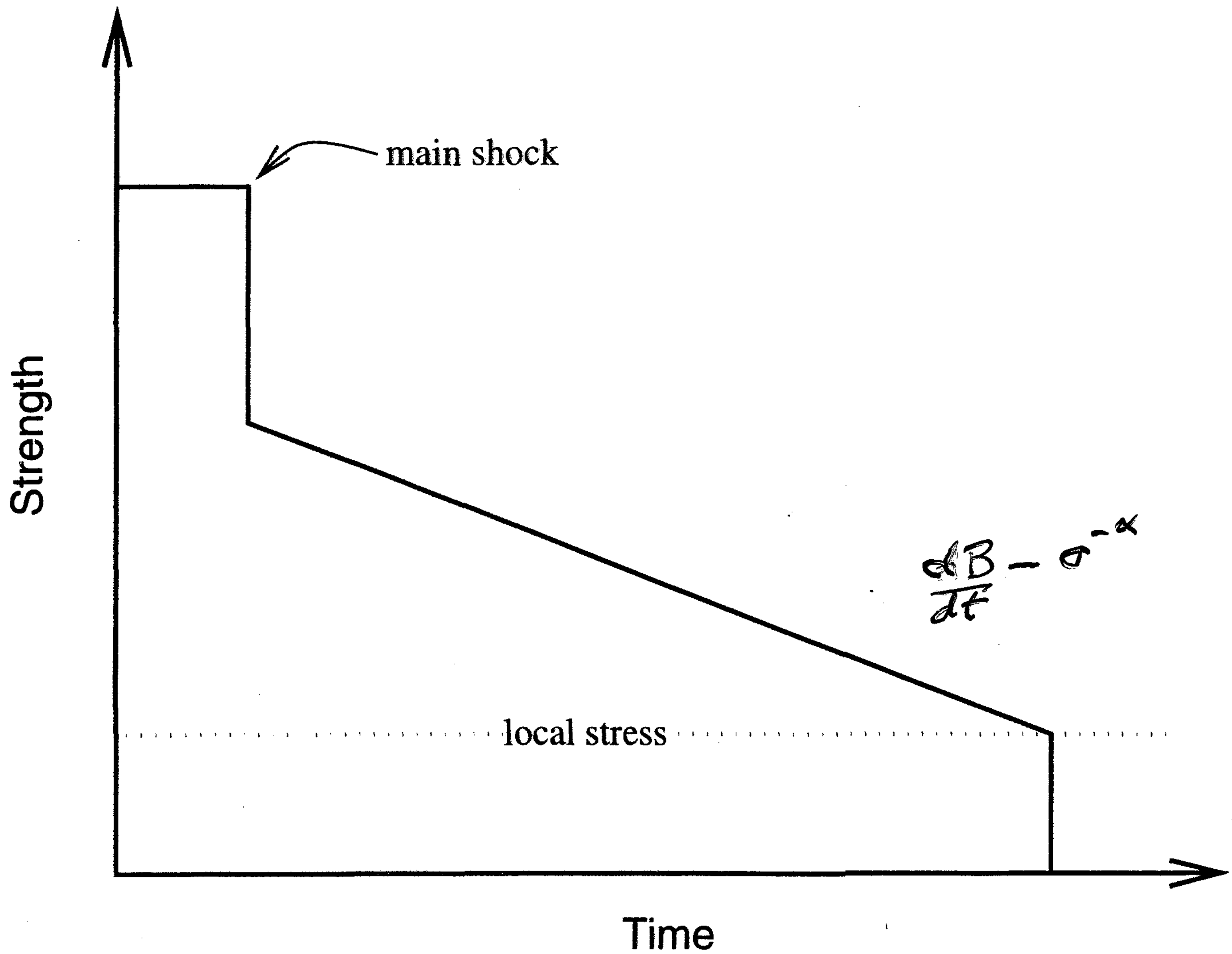
$$(\lambda+2\mu)\nabla\nabla\cdot\vec{u}-\mu\nabla\times\nabla\times\vec{u}=\rho\frac{\partial^2\vec{u}}{\partial t^2}$$

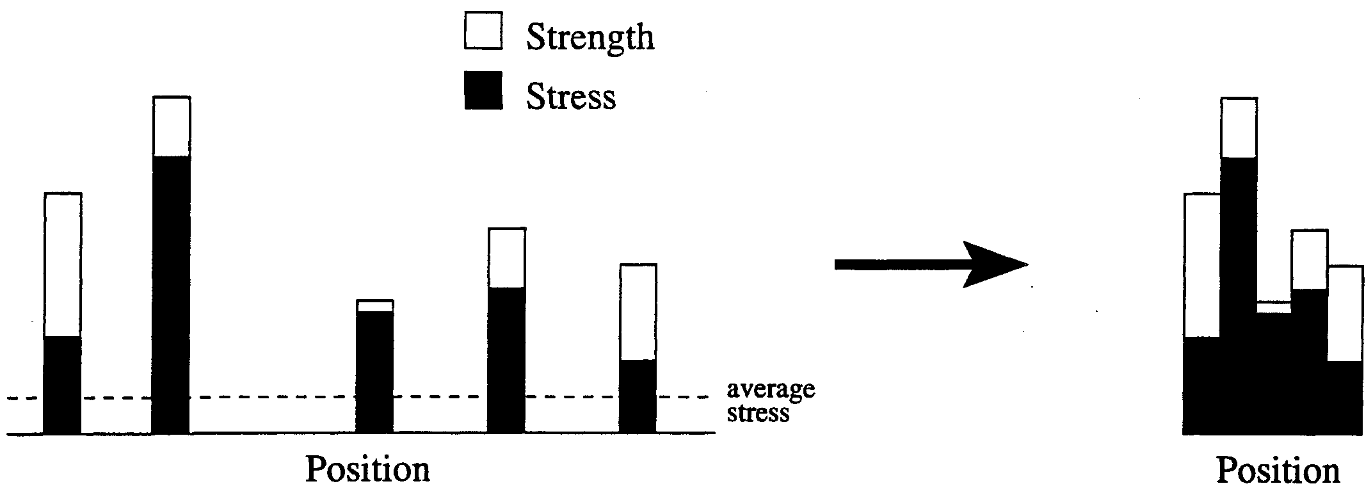
$$\mu\nabla^2 u_z=\rho\frac{\partial^2 u_z}{\partial t^2}$$

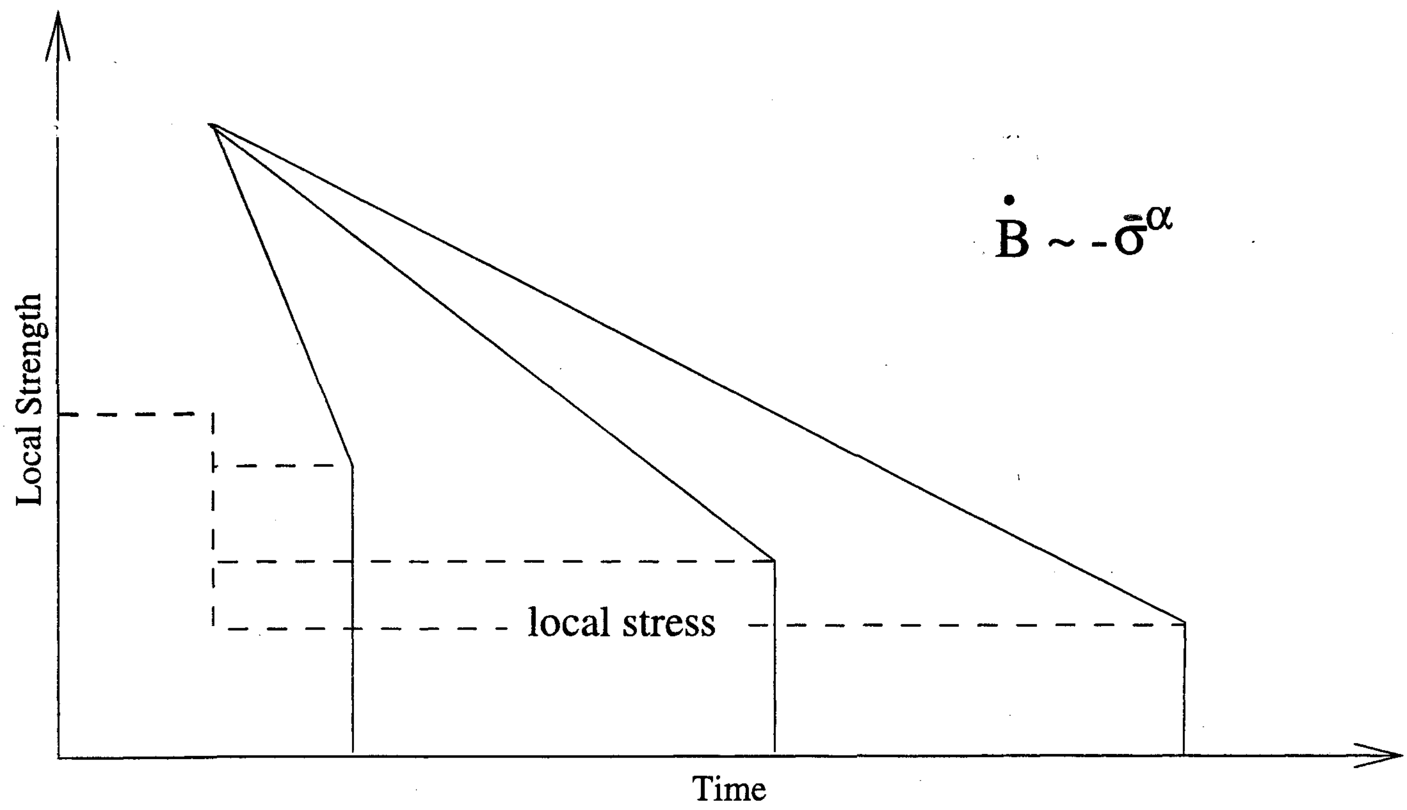
$$\mu\nabla^2 u_z=0$$

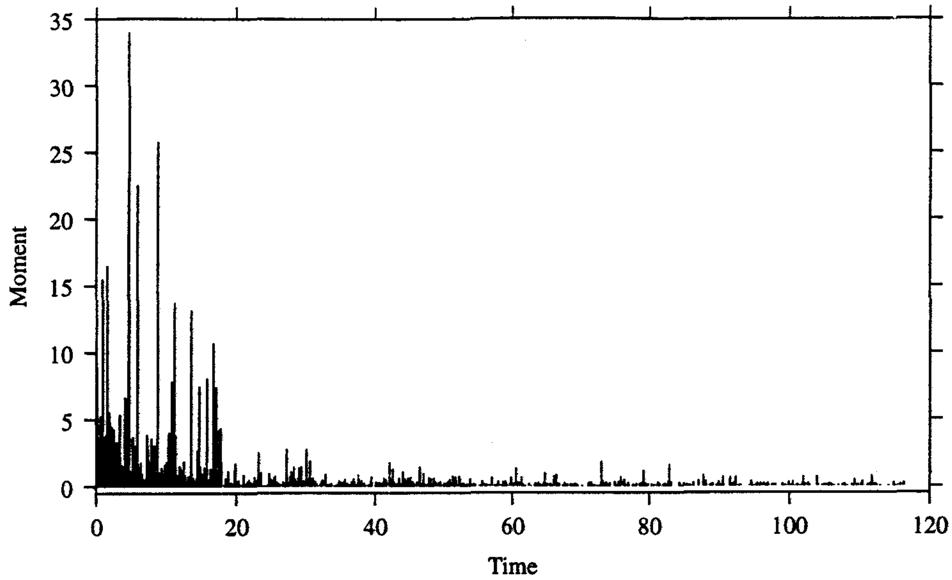


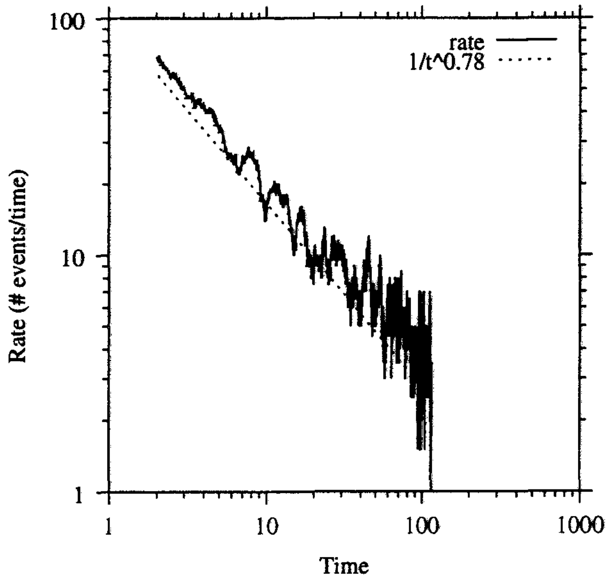
Material Strength As A Function Of Time



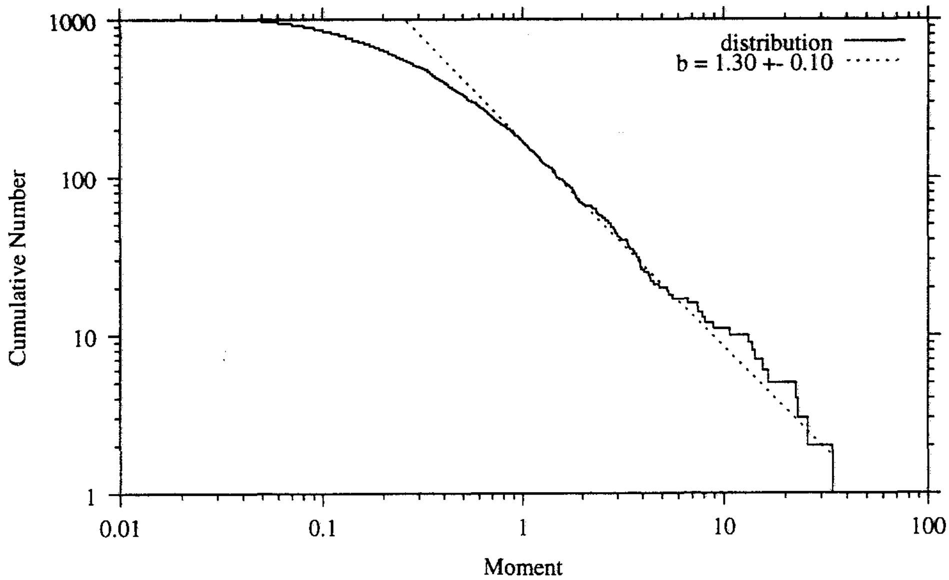

Strength
Stress
average stress
Position
Position

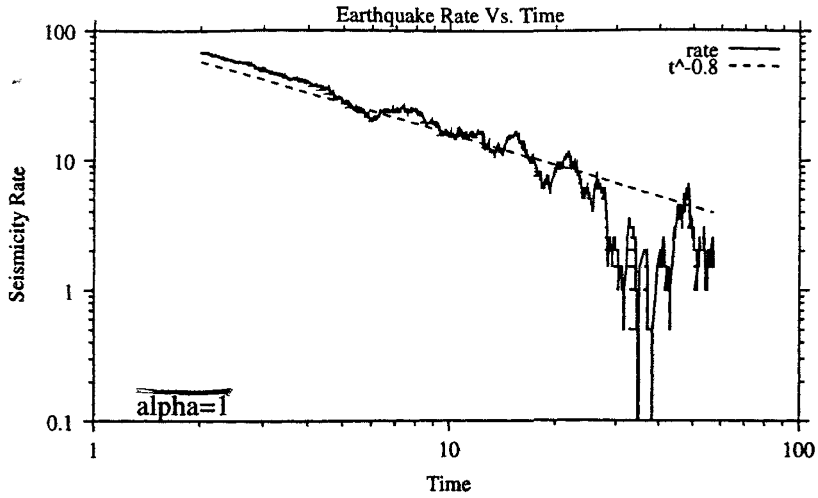

$\dot{B} \sim -\sigma^{\alpha}$
Local Strength
local stress
Time

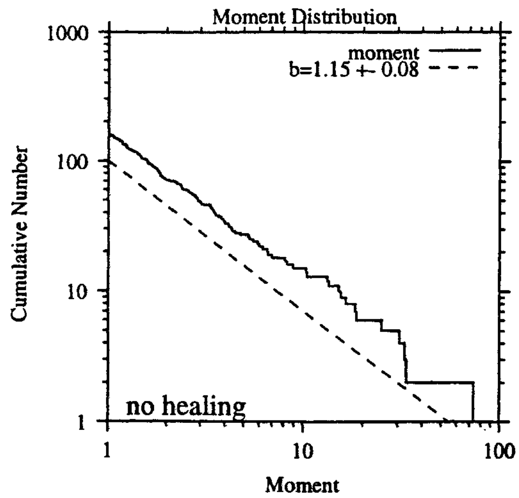


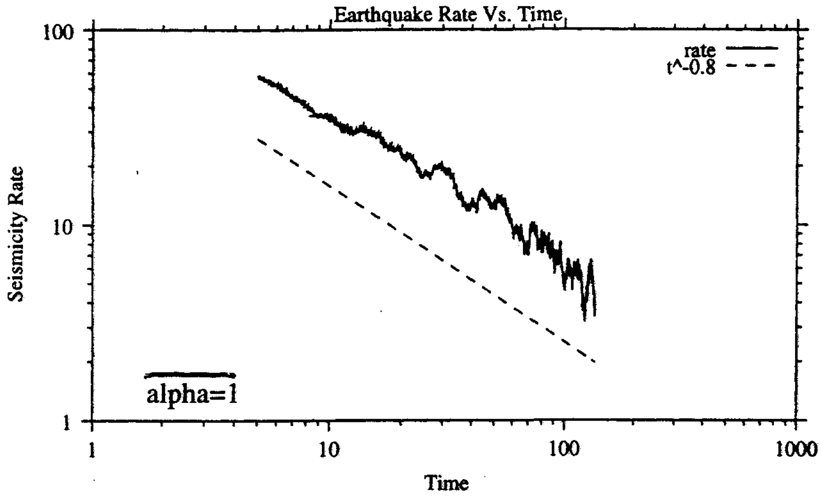


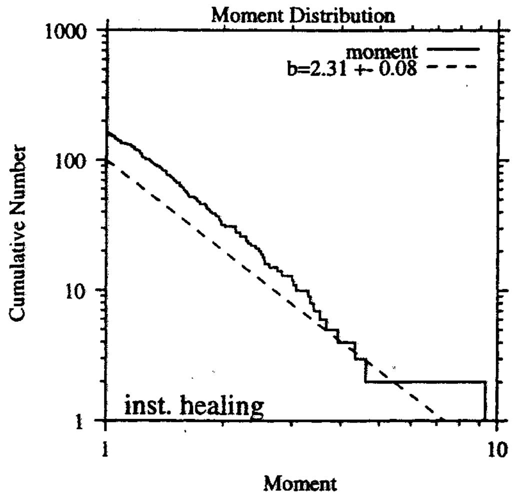
alpha=1
r=0.9
48x48 lattice

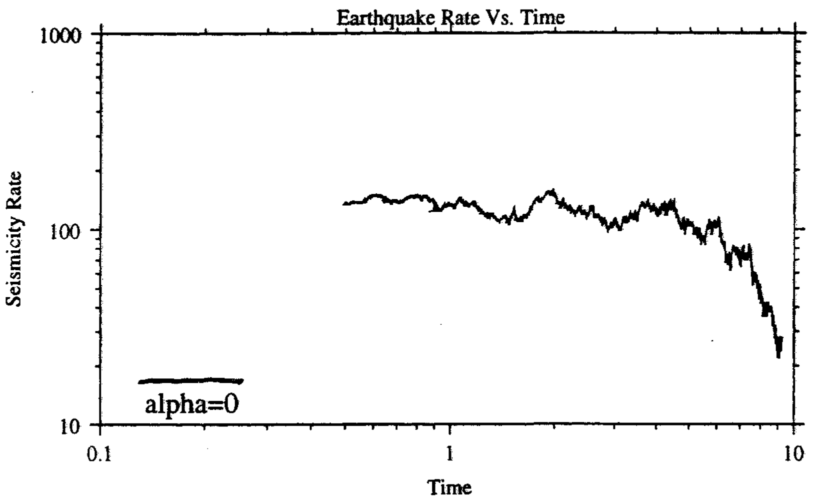


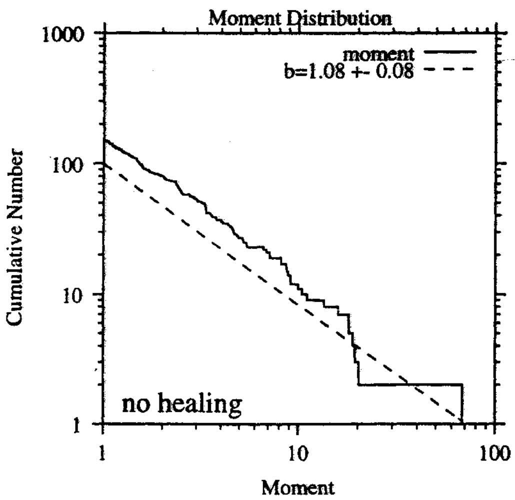

Earthquake Rate Vs. Time
rate
t^-0.8
Seismicity Rate
100
10
1
0.1
1
10
100
Time
alpha=1

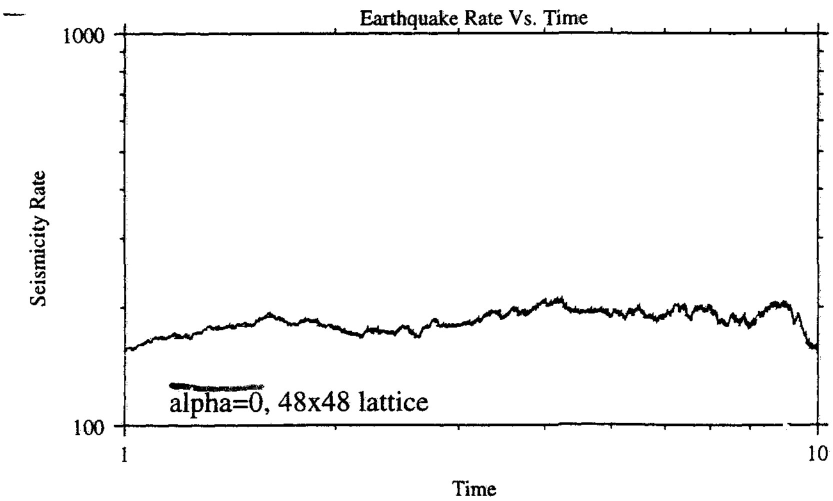

Moment Distribution
moment
b=1.15 +- 0.08
Cumulative Number
1000
100
10
1
1
10
100
Moment
no healing

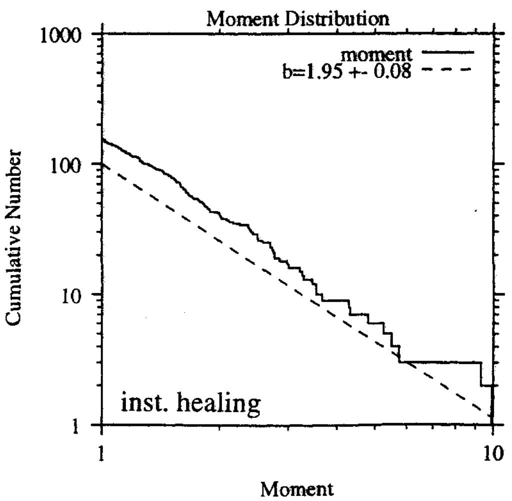

Earthquake Rate Vs. Time
rate
t^-0.8
Seismicity Rate
100
10
1
1
10
100
1000
Time
alpha=1

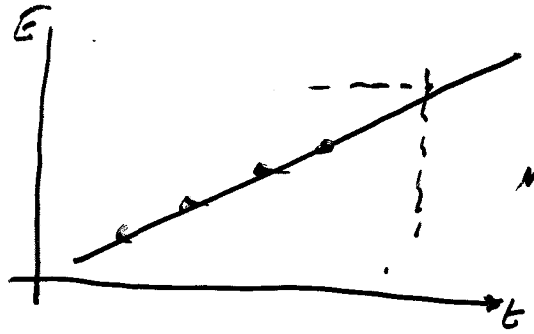

Moment Distribution
moment
b=2.31 +- 0.08
Cumulative Number
1000
100
10
1
1
10
Moment
inst. healing


Earthquake Rate Vs. Time
Seismicity Rate
1000
100
10
0.1
1
10
Time
alpha=0

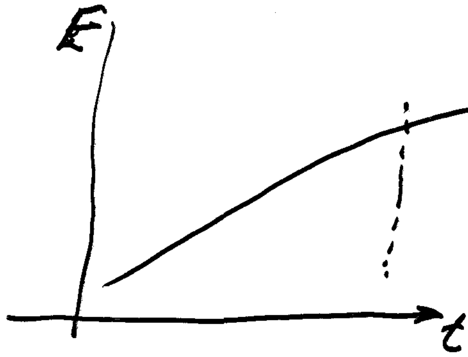

Moment Distribution
moment
b=1.08 +- 0.08
Cumulative Number
1000
100
10
1
1
10
100
Moment
no healing


Earthquake Rate Vs. Time
Seismicity Rate
1000
100
1
10
Time
alpha=0, 48x48 lattice

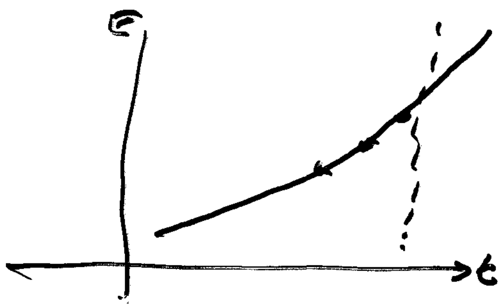

Moment Distribution
moment
b=1.95 +- 0.08
Cumulative Number
1000
100
10
1
1
10
Moment
inst. healing



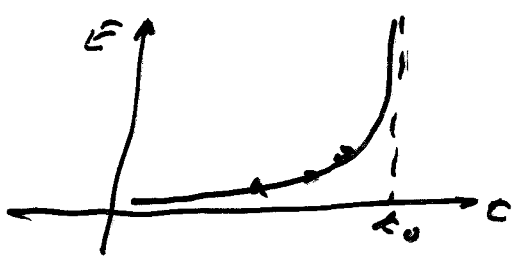
no



No



No



Yes

$$\frac{1}{(t_0 - t)^p}$$

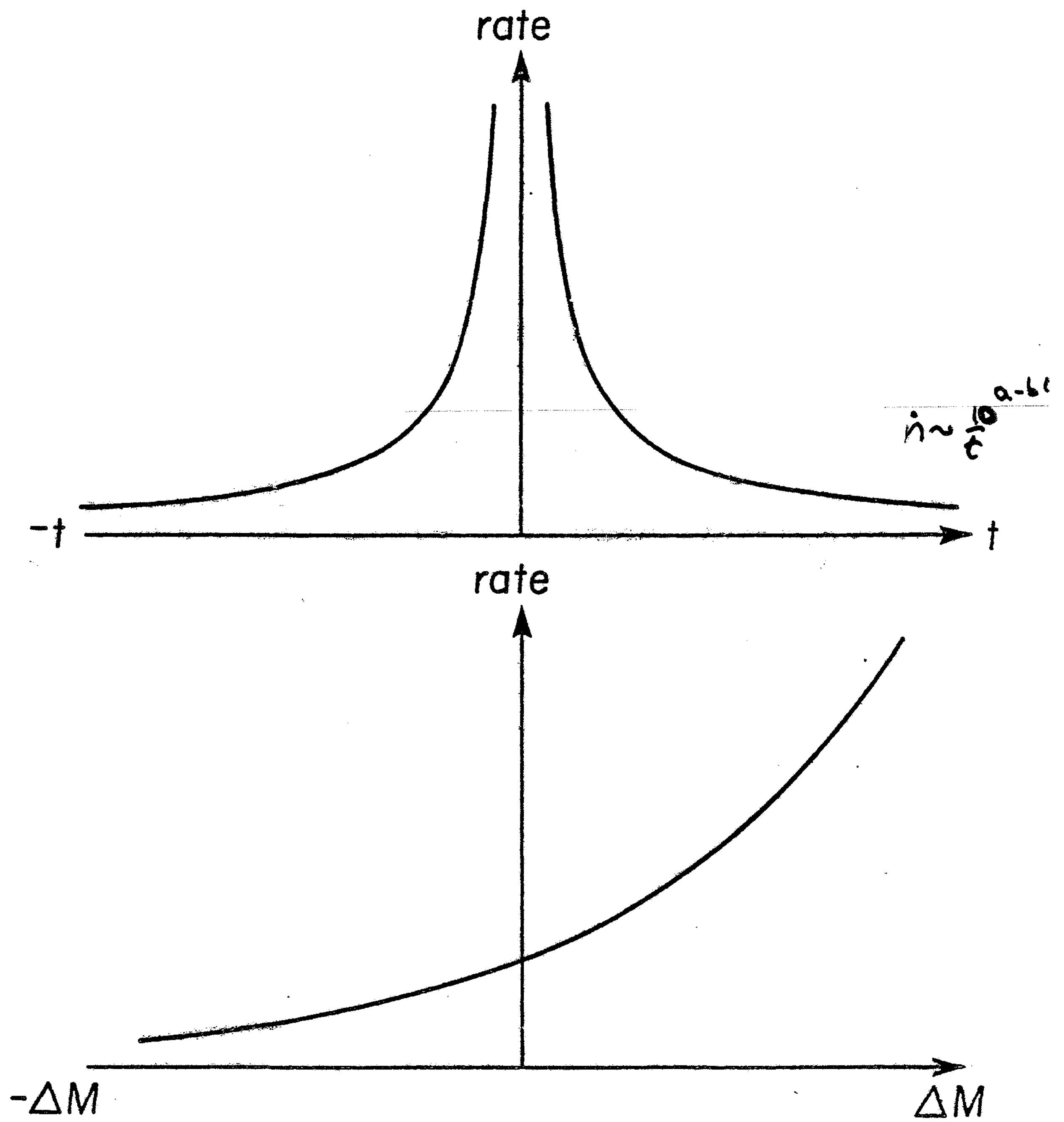


Fig. 1

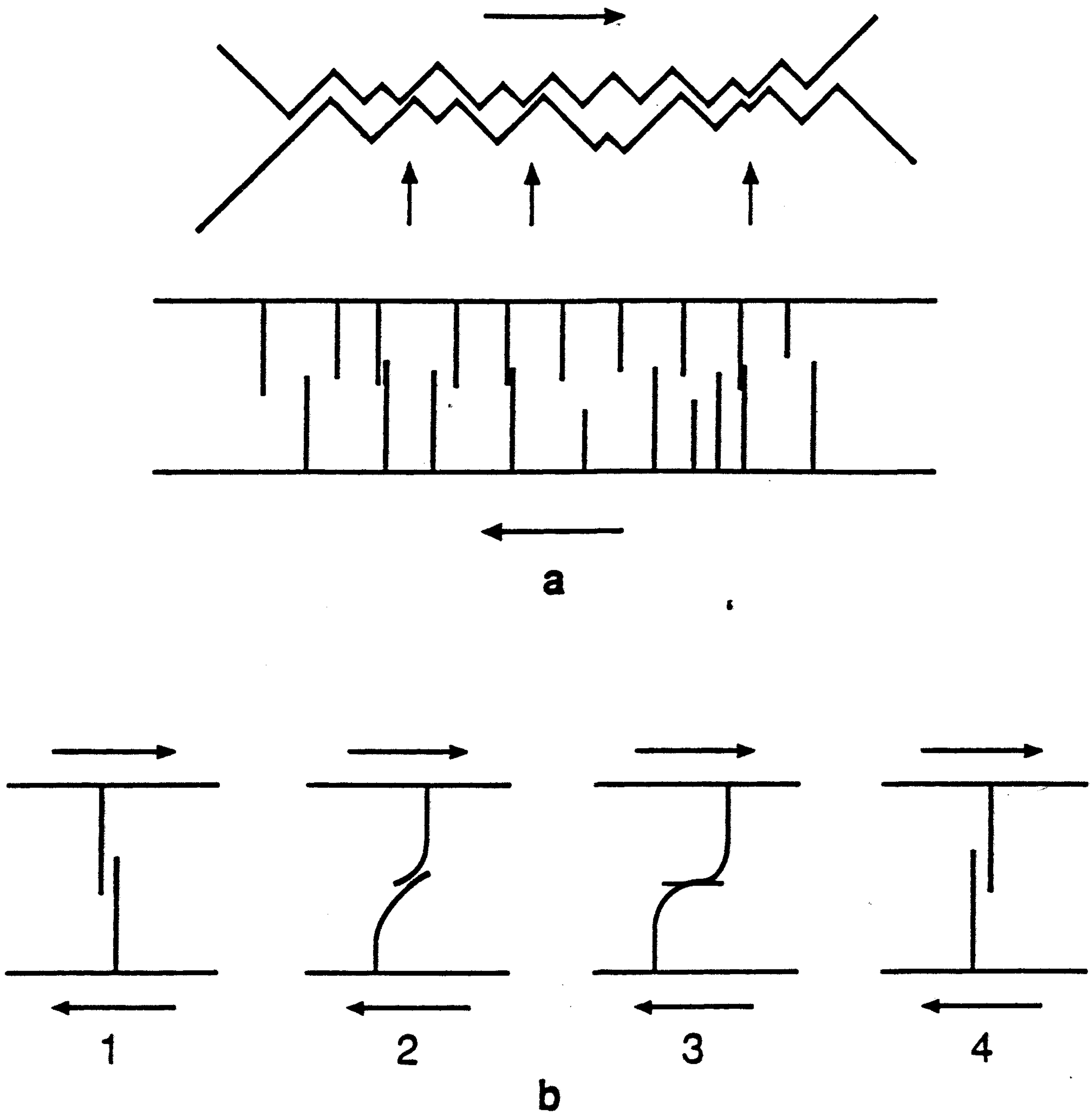
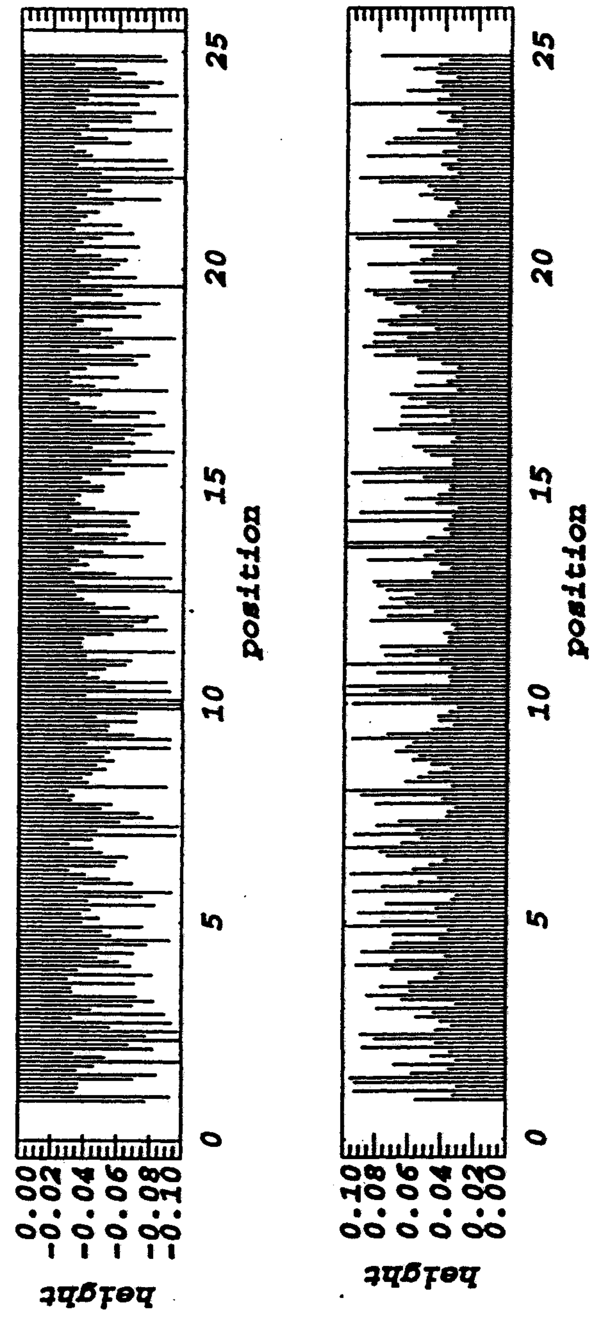


Figure 2. a) Representation of two rough surfaces in contact by a set of vanes. b) Illustration of the process from deformation to rupture and acceleration of two opposite vanes in contact. Transition from stage 3 to 4 is rapid.


height
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
0
5
10
15
20
25
position
height
0.10
0.08
0.06
0.04
0.02
0.00
0
5
10
15
20
25
position

89

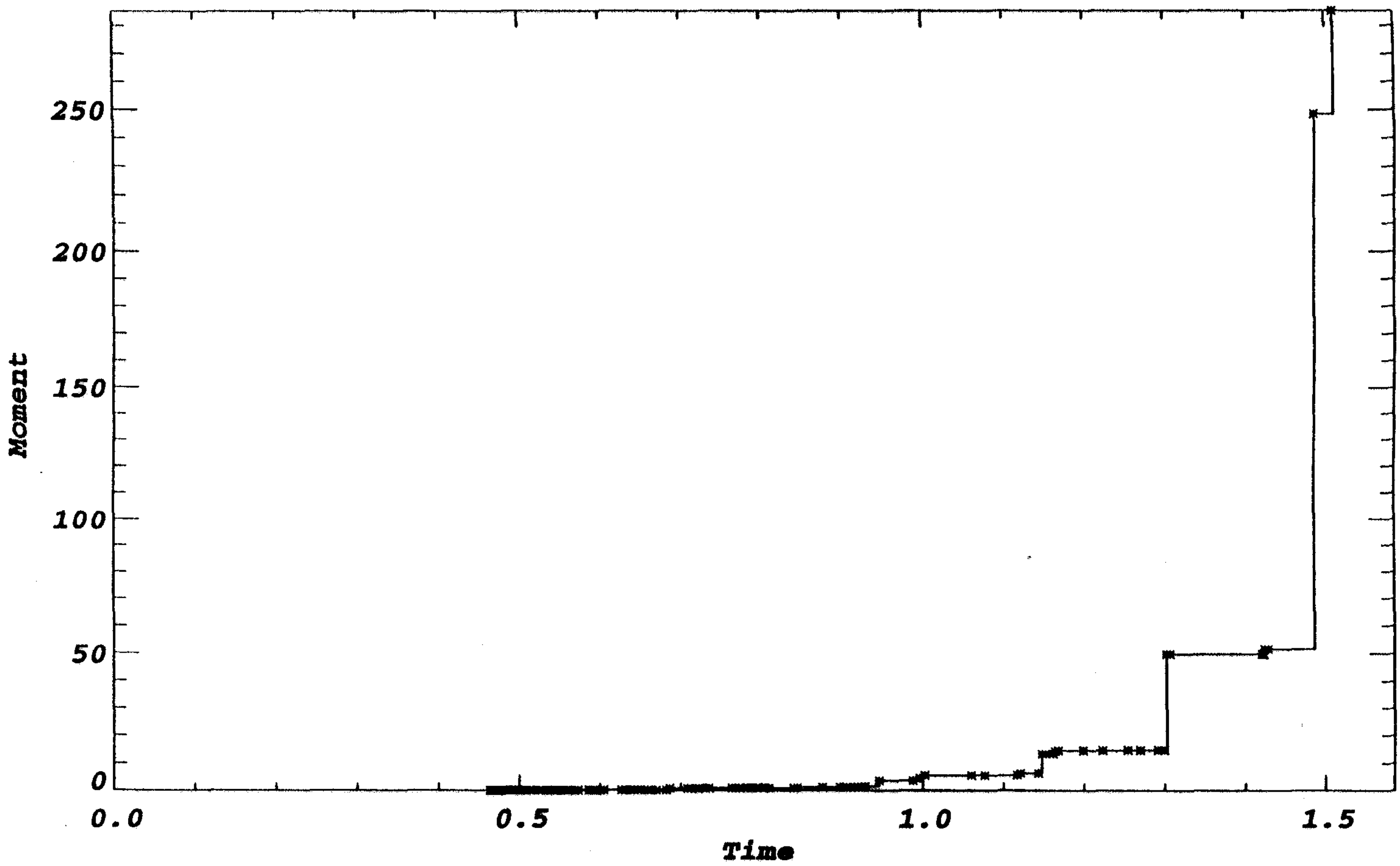
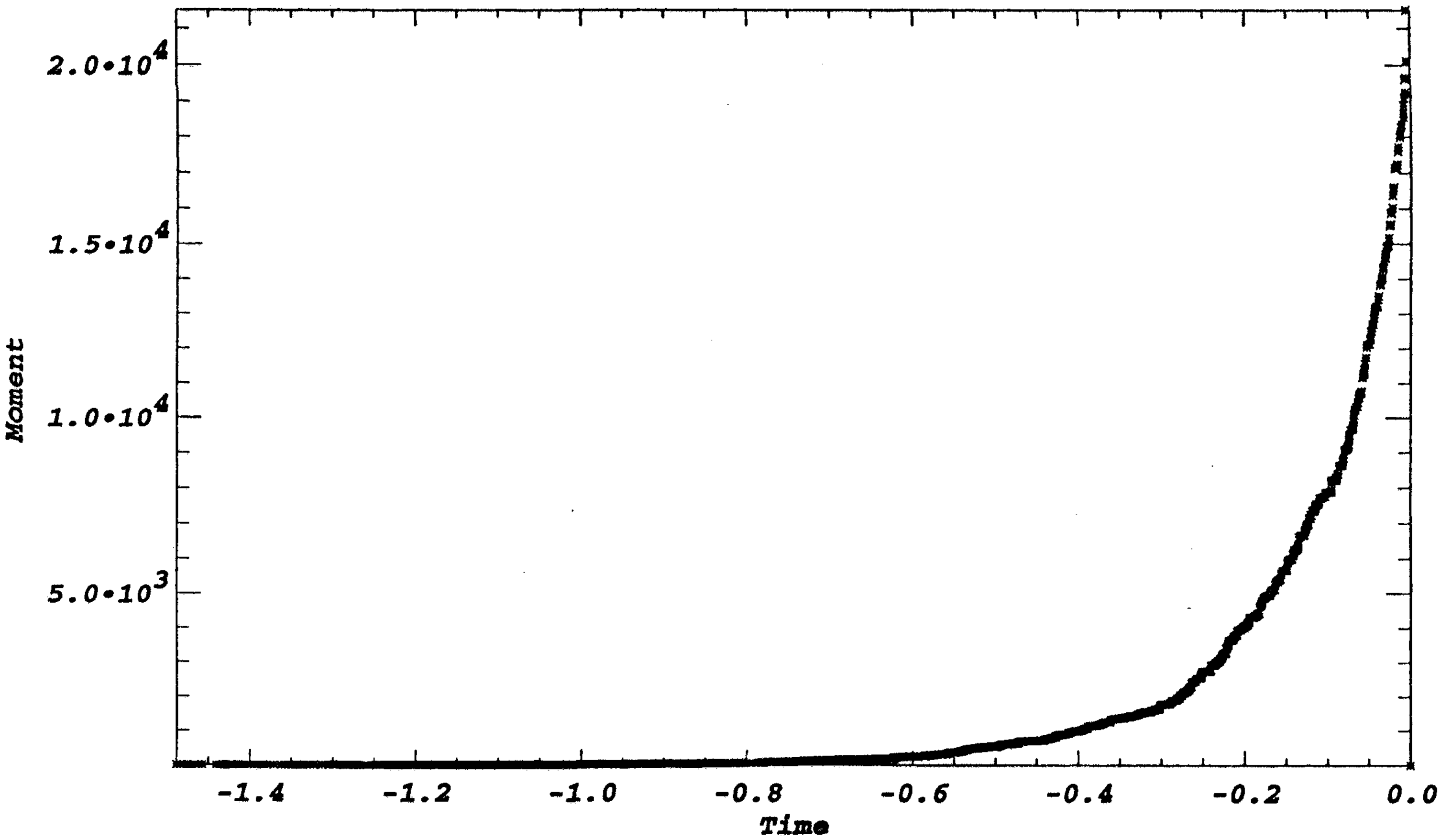
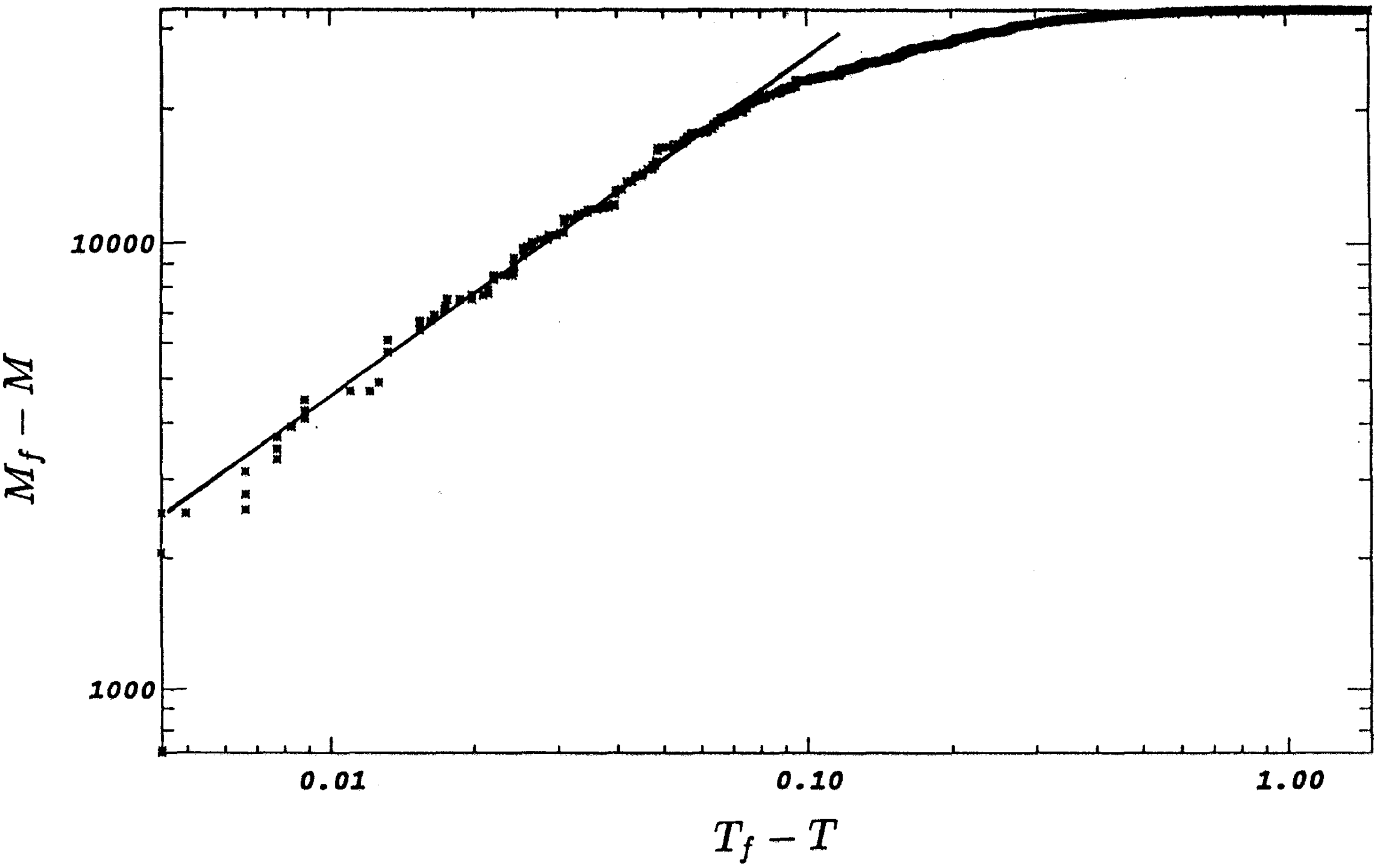


Figure 5. Moment release in the asperity before complete failure. The breakout event has a much larger moment release and is not shown in the plot.


2.0•10^4
1.5•10^4
1.0•10^4
5.0•10^3
Moment
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
Time



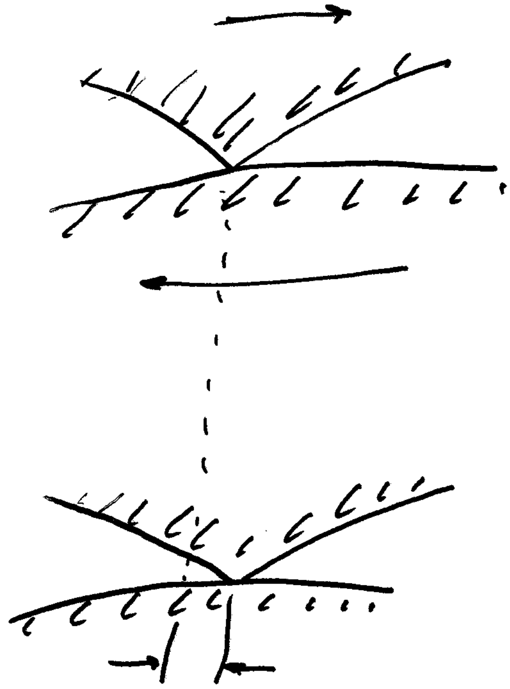
$$M_f - M = (t_f - t)^q$$

$$q \sim 0.6$$

$$\frac{dM}{dt} \sim (t_f - t)^{q-1}$$

Finite size effect

52



Can one distinguish between
continuous creep and repetitive
small earthquakes?

Aftershocks (near)

STAGE 1.

Stress waves radiated by main shock (fracture) shatter an already weakened (old shatter zone) material, forming cracks

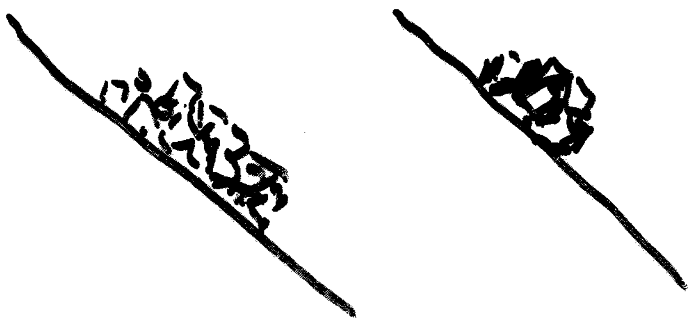
Water injected from main shock

STAGE 2.

Contacts between grains lose strength by subcritical crack growth in accelerated process, culminating in aftershock.

STAGE 3.

Crack remain open in shattered zone so that more aftershocks can occur



Aftershocks:

b-value ⇒ rate of decay of strength under stress corrosion

p-value ⇒ cracks remain open

Conclusions

1. Aftershocks in region of (average) reduced stress occur on zones of shattered material in a poorly cemented heterogeneous structure in a compliant zone.
2. Fluids, probably derived from the rapidly healing main event play an important role in the aftershock process because of stress corrosion weakening and subcritical crack growth.
3. The Omori law arises because healing in aftershock ruptures is slow. Crack-coupling effects are important.
4. There are minimal (No!) long-range spatial stress correlations.
5. Aftershock sequences ultimately terminate or have exceedingly low rates and are superseded by mainshock precursors.
6. Distant ($\Delta > 5$ km) aftershocks occur on regions that were already in a state of decay under stress corrosion. The large stress change in the main event triggers an accelerated decay. This is also the cause of the rapid extinction of aftershocks with $M \gtrsim 5$.
7. Foreshocks may also arise because of failure of cracks to heal. Unsutured cracks cause strength weakening in high compliant domains
8. Foreshocks may accumulate to a critical (predictive) threshold characterized by an infinite rate of moment release.
9. Prediction is only possible if linear elasticity is accompanied by nonlinear, time-dependent behavior.