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H4.SMR/1330-28

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

15 - 27 October 2001

The Dynamical Influence of Fluids on Seismicity and Faulting

Stephen A. Miller

Geophysics Institute
ETH-Zurich, Switzerland

Lecture I: The dynamical influence of fluids on seismicity and faulting

- Rock and fluid mechanics
- Dislocations and brittle faulting
- Stress transfer models
- The hydraulics of fault zones
- Coupling fluid flow to large scale tectonics
- Earthquakes as a coupled shear stress, high pore pressure dynamical system
- The properties of large model earthquakes

Lecture II: Earthquake scaling and the strength of seismogenic faults

- Earthquake scaling: Small earthquakes
- Earthquake scaling: Large earthquakes
- Pore pressure as a fundamental scaling parameter
- Application of result to global earthquake catalogs
- Can pore pressures be inferred from earthquake rupture properties

Lecture III: Neotectonics and earthquake generation along complex fault systems

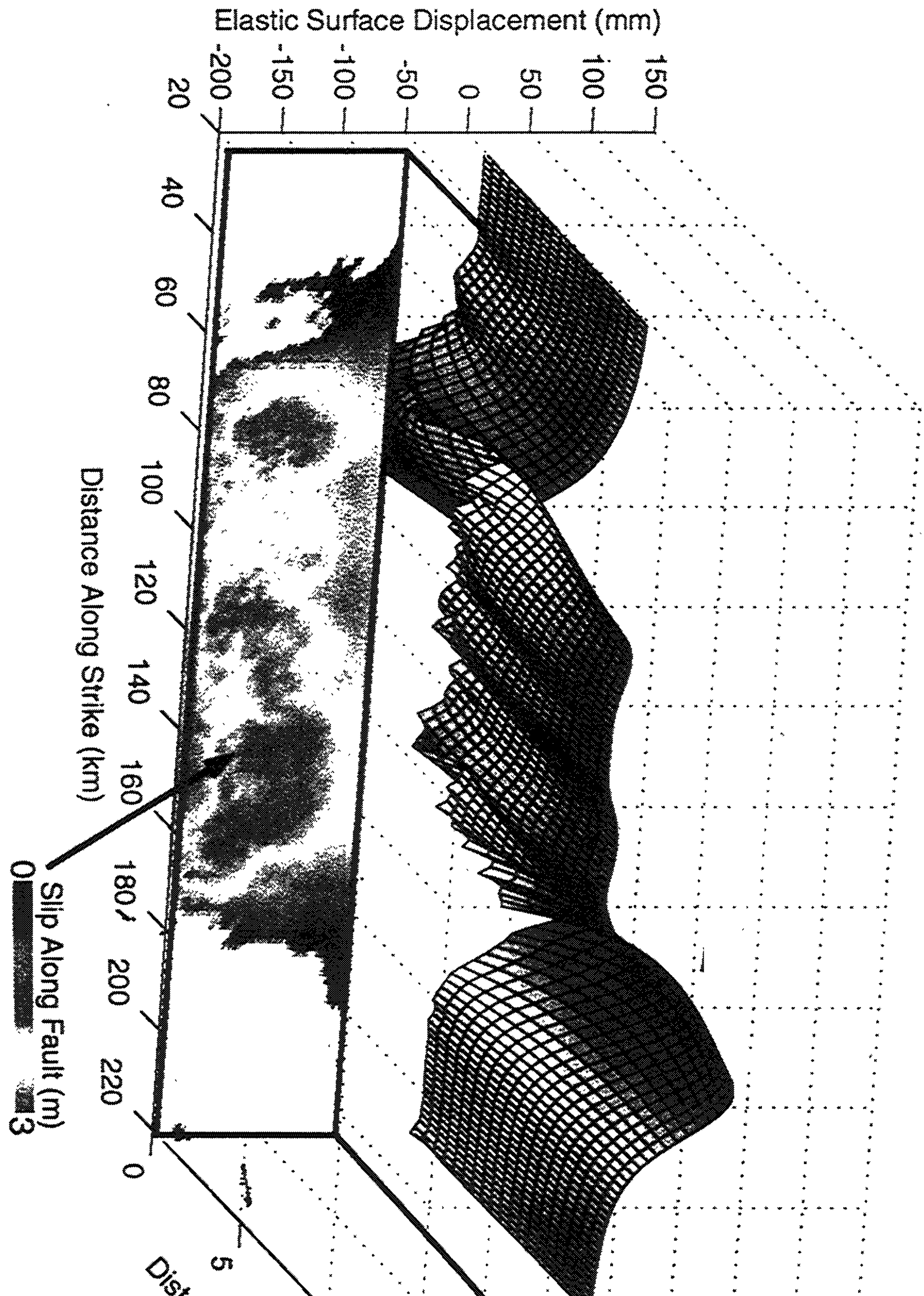
- The North Anatolian Fault Zone
- The San Andreas Fault System
- Building a forward model of the earthquake process
- Fault Interaction

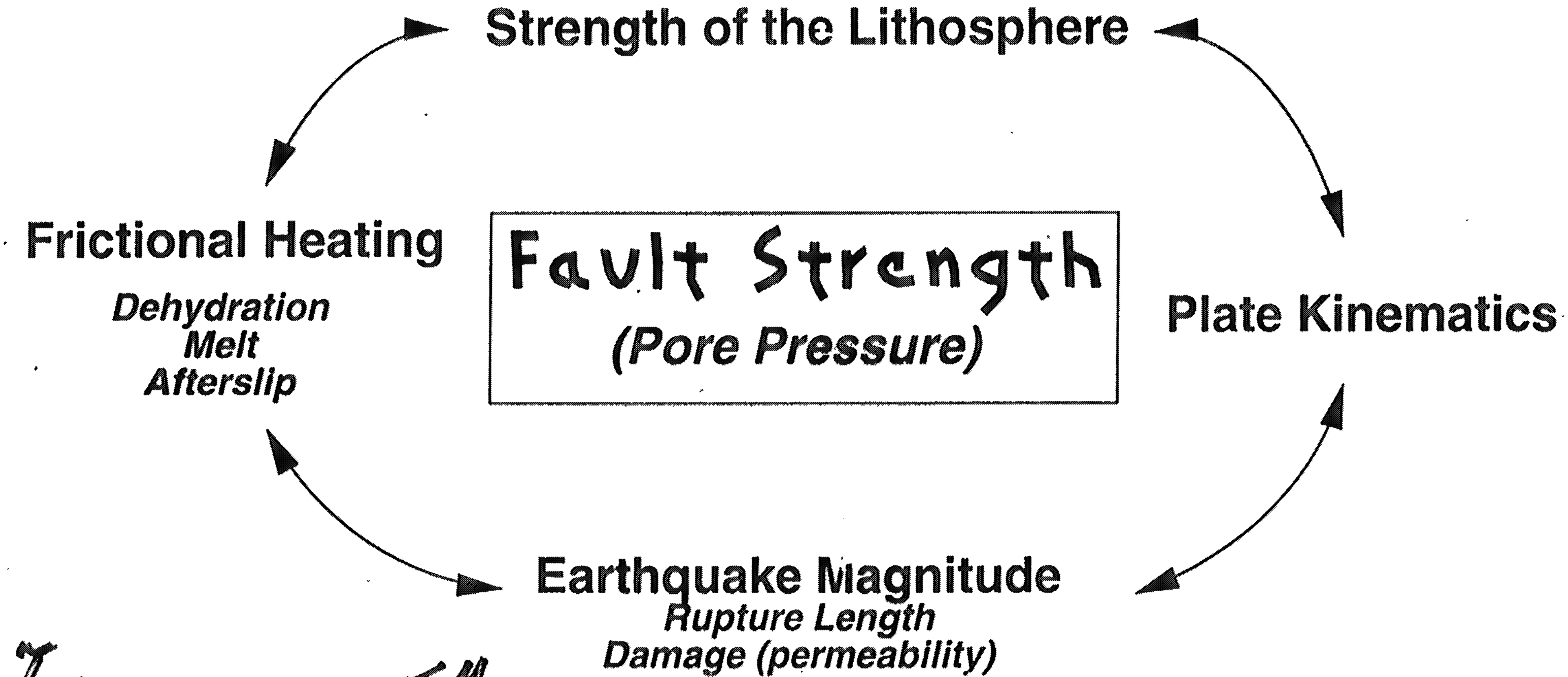
The Model

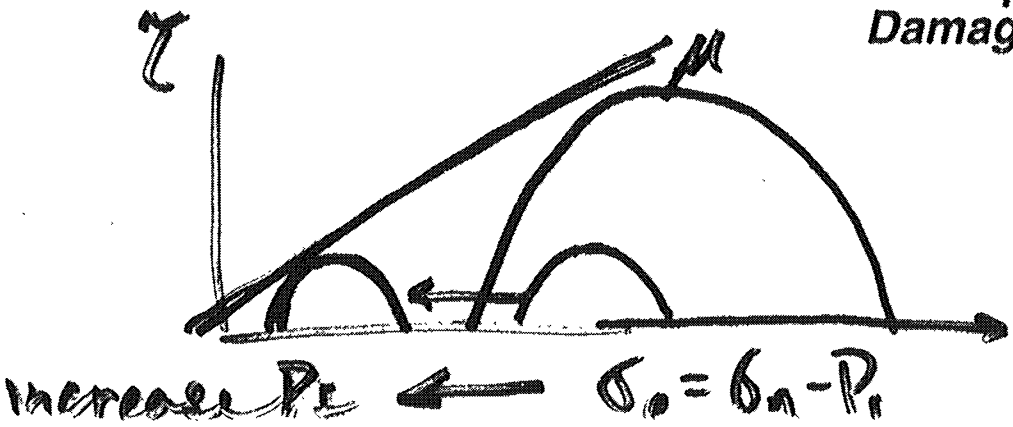
- Fault-valve behavior and fault zone architecture
- Permeability as a toggle-switch
- Coupling fault zone pore pressures to large-scale tectonic loading
- Stress space disorder
- Physical space disorder
- Slip weakening friction
- Surface displacements in response to slip
- Long-term fault behavior

1. Stress Drop
2. Average Slip vs. Rupture Length
3. Comparison with earthquake catalogs

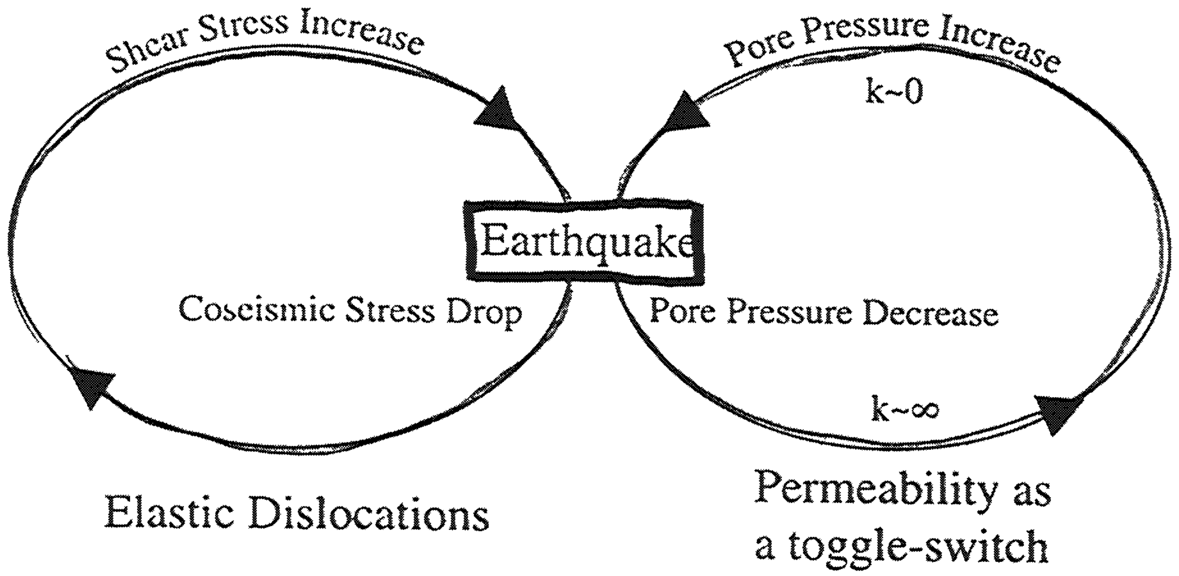
- Generalizing the model to any geometry

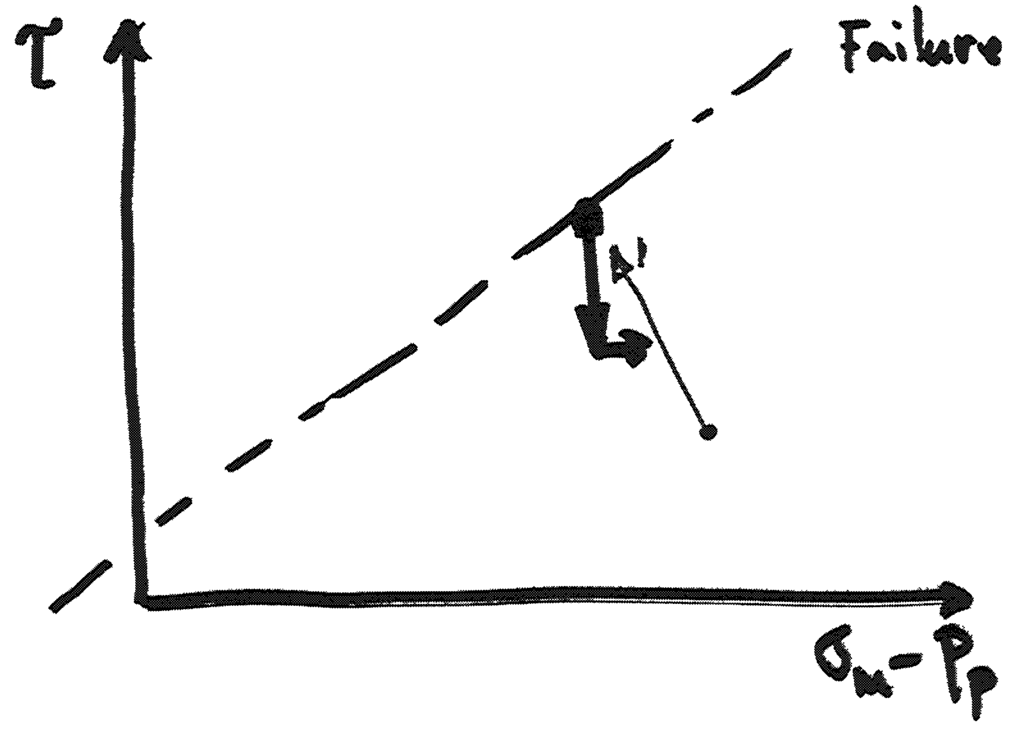

Elastic Surface Displacement (mm)
-200
-150
-100
-50
0
50
100
150
20
40
60
80
100
120
140
160
180
200
220
Distance Along Strike (km)
Slip Along Fault (m)
0
3
0
5
10
15
Distance From Fault (km)


Strength of the Lithosphere
Frictional Heating
Dehydration
Melt
Afterslip
Fault Strength
(Pore Pressure)
Plate Kinematics
Earthquake Magnitude
Rupture Length
Damage (permeability)


τ
μ
increase Pf ←
σ0 = σn − Pf

Fault Valve Model (Sibson, 1992)





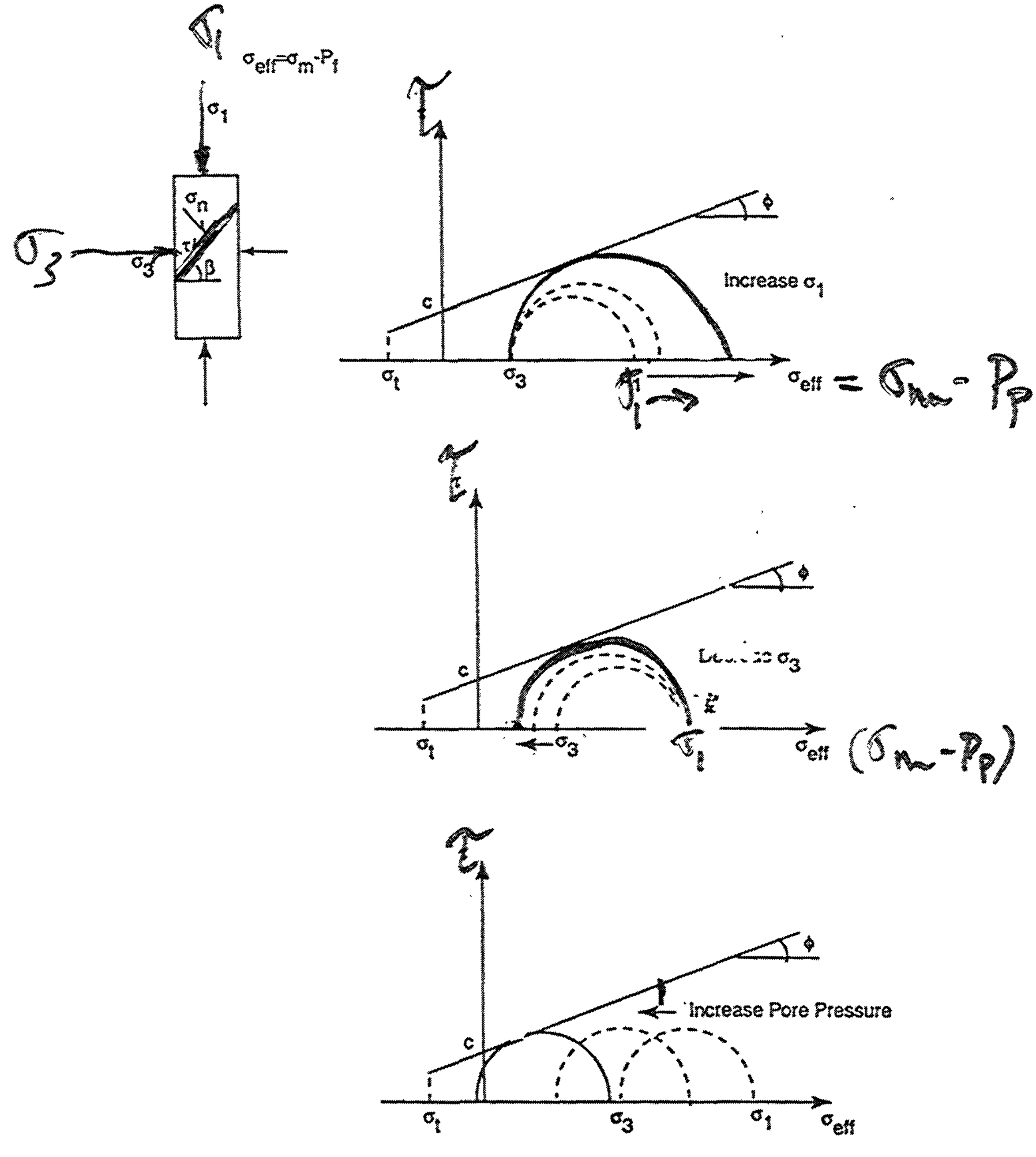
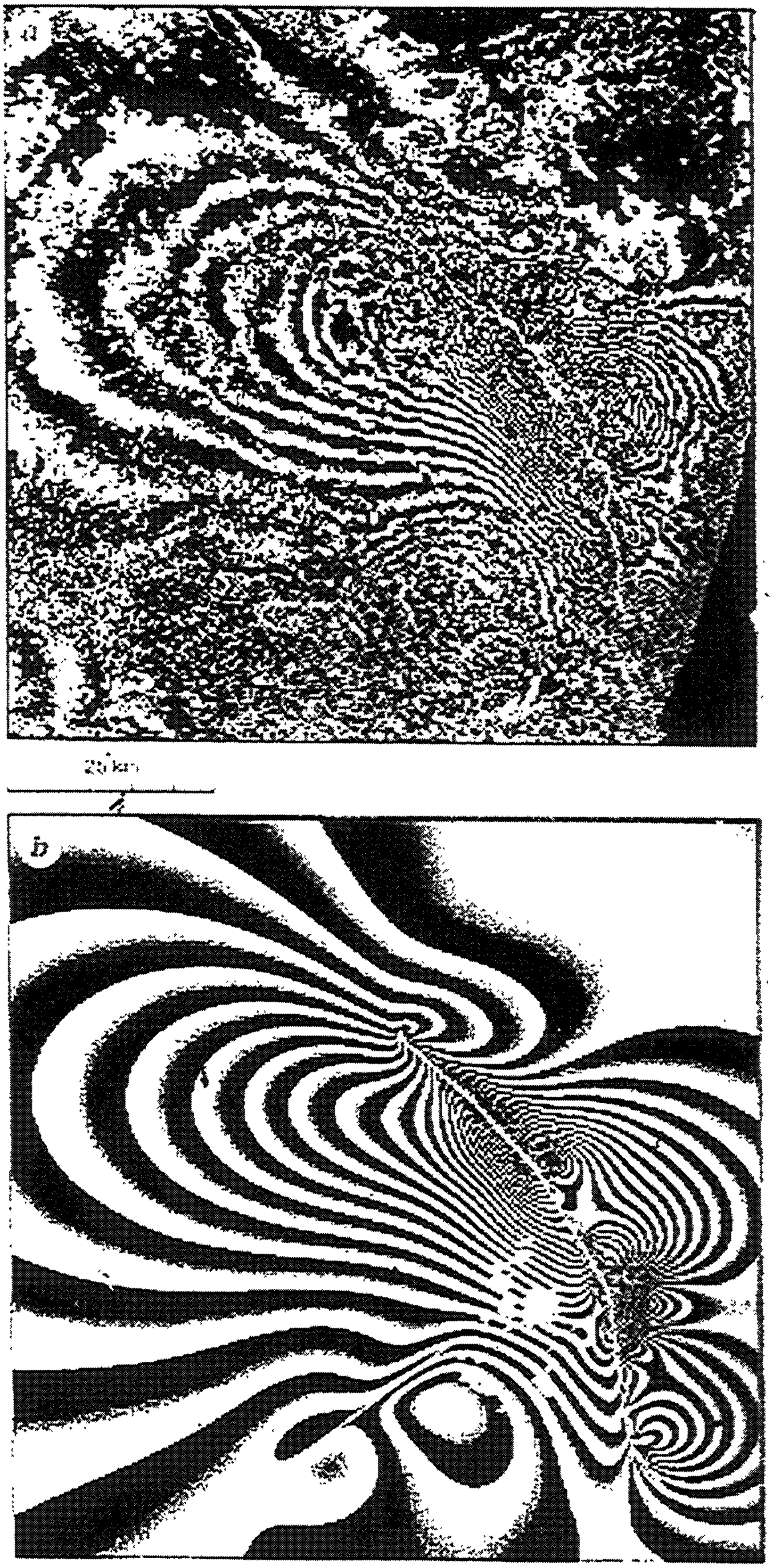


Figure 3.11: The influence of fluids on rock strength

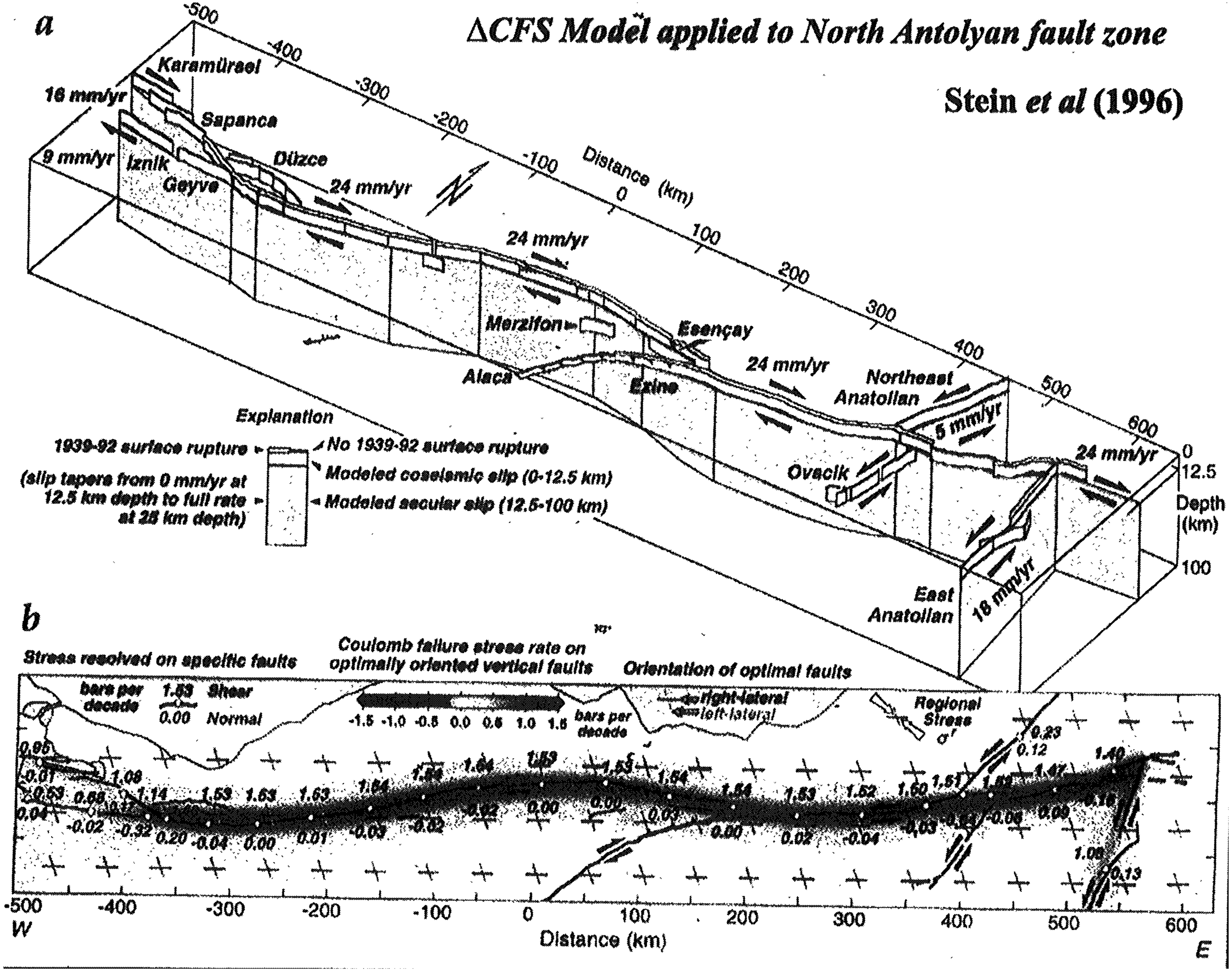
Using Elasticity Theory to Monitor Analyze Earth Deformations



Massonnet et al (1993)

ΔCFS Model applied to North Antolyan fault zone

Stein *et al* (1996)



8

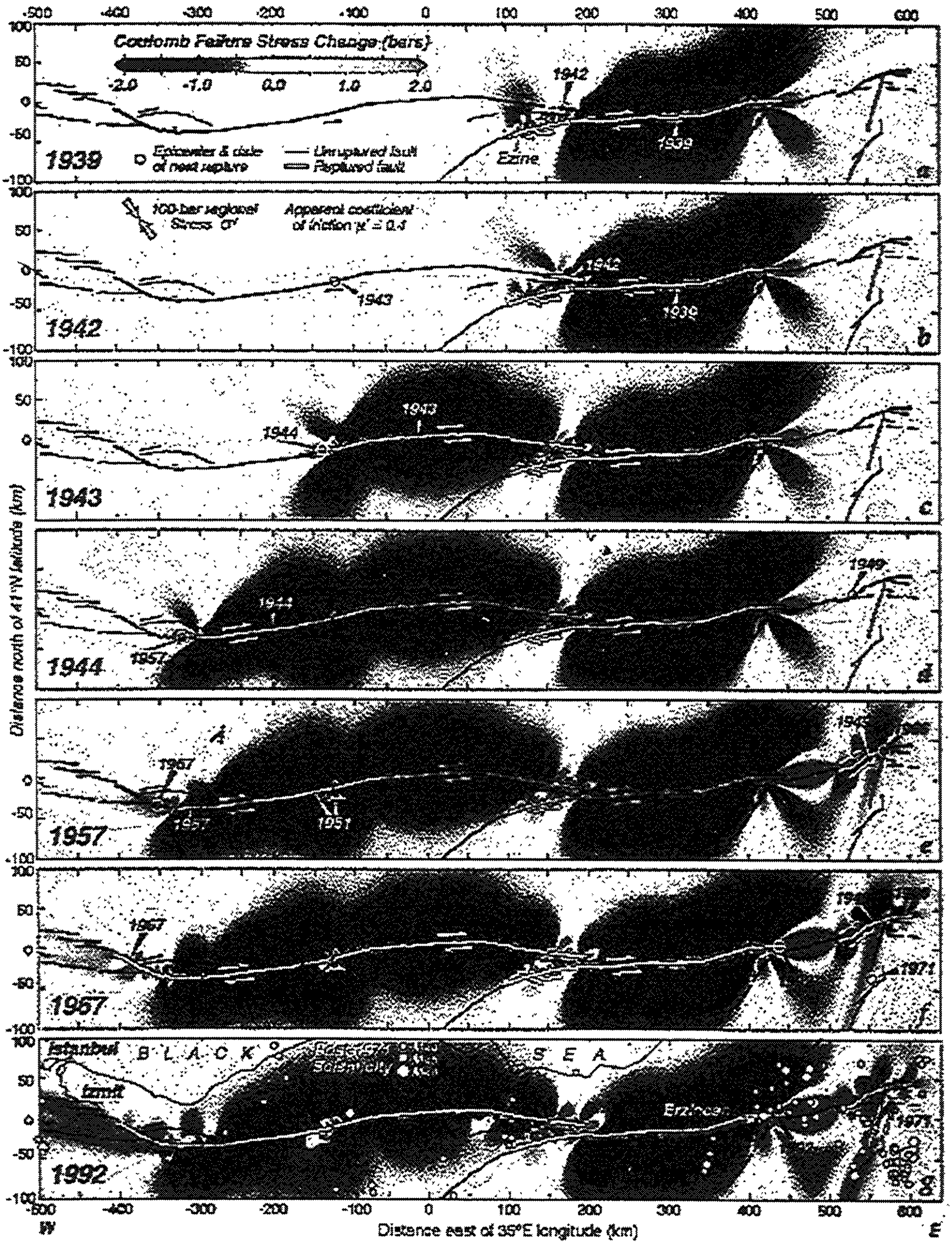
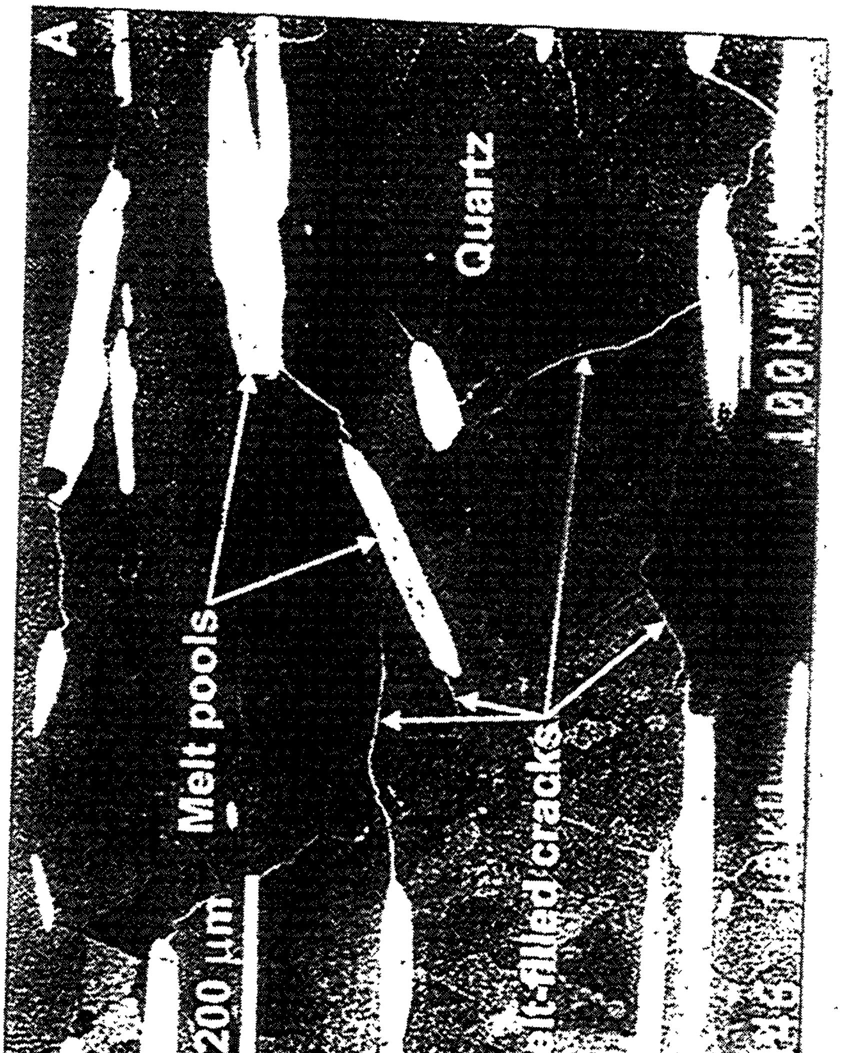
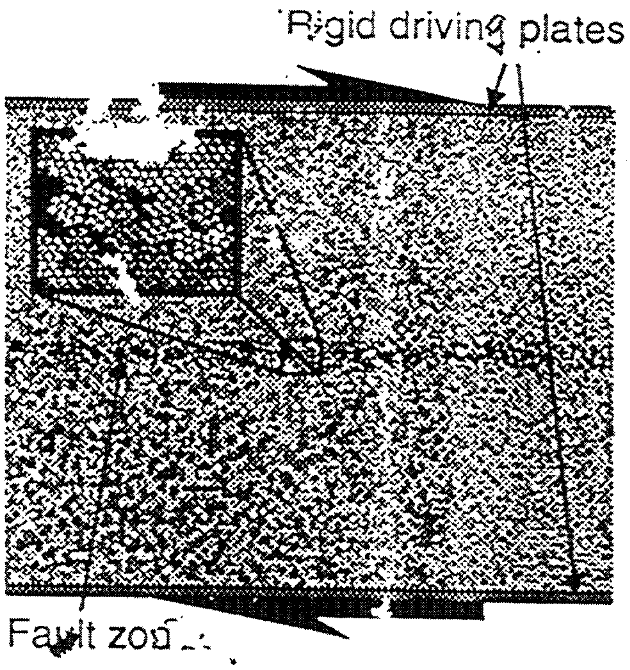


Figure 4 17 Oct 96 Stein et al.

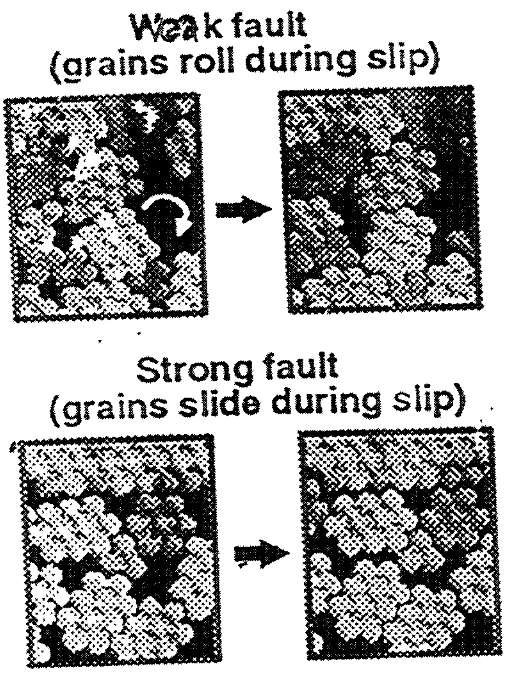


Connolly et. al. (97)

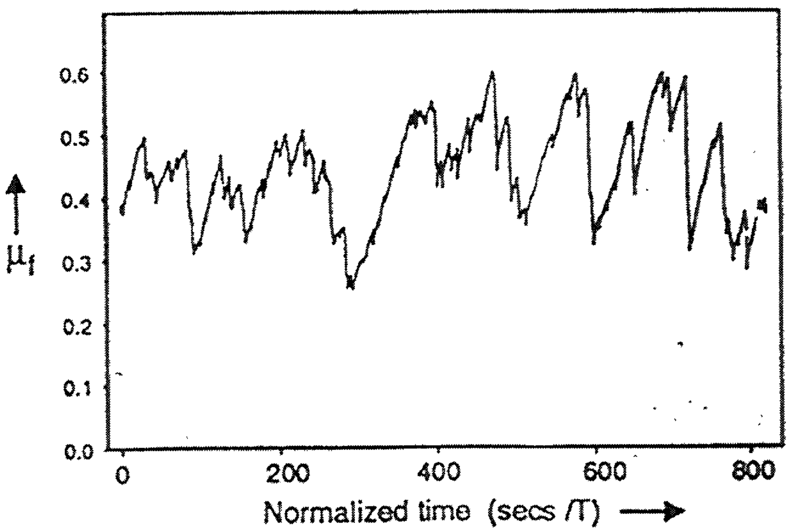


Rigid driving plates
Fault zo

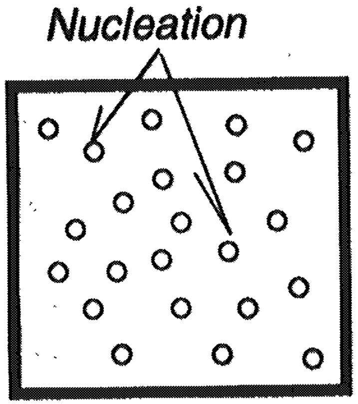
Place & Mora



Weak fault
(grains roll during slip)
Strong fault
(grains slide during slip)



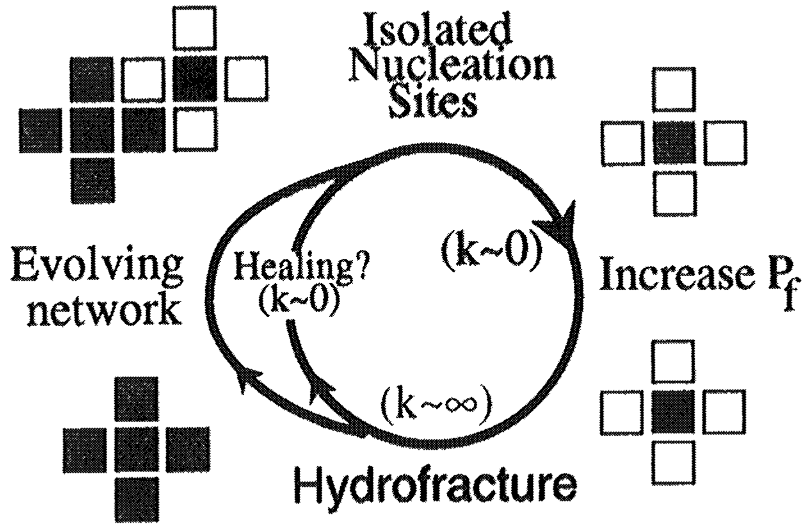
0.6
0.5
0.4
0.3
0.2
0.1
0.0
μ_f
0
200
400
600
800
Normalized time (secs /T)



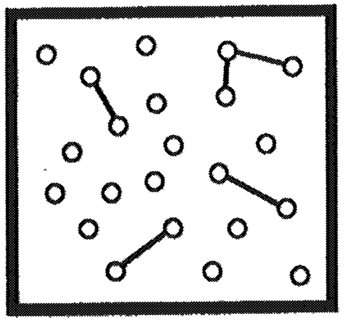
SOURCE
Dehydration/Melting
Plastic Pore Closure

$$\left.\frac{\Delta P}{\Delta t}\right|_{no\ flow} = \frac{\dot{\Gamma}-\dot{\phi}}{\phi(\beta_\phi+\beta_f)}$$

Conceptual Model

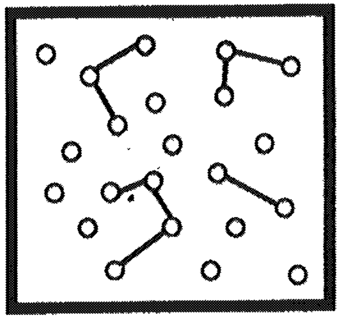


Connectivity

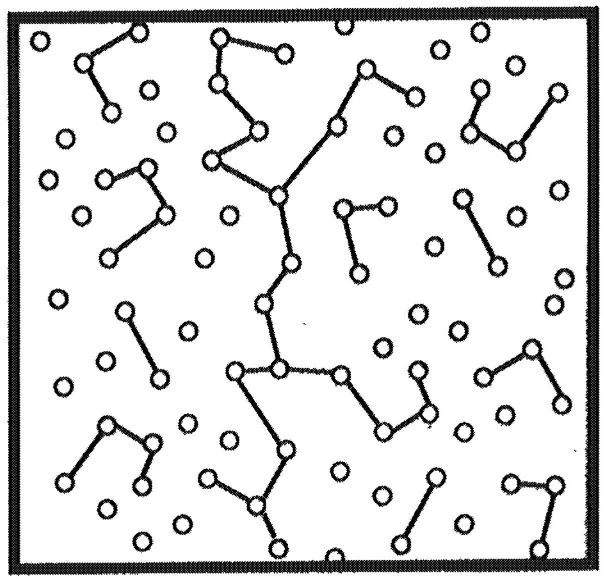


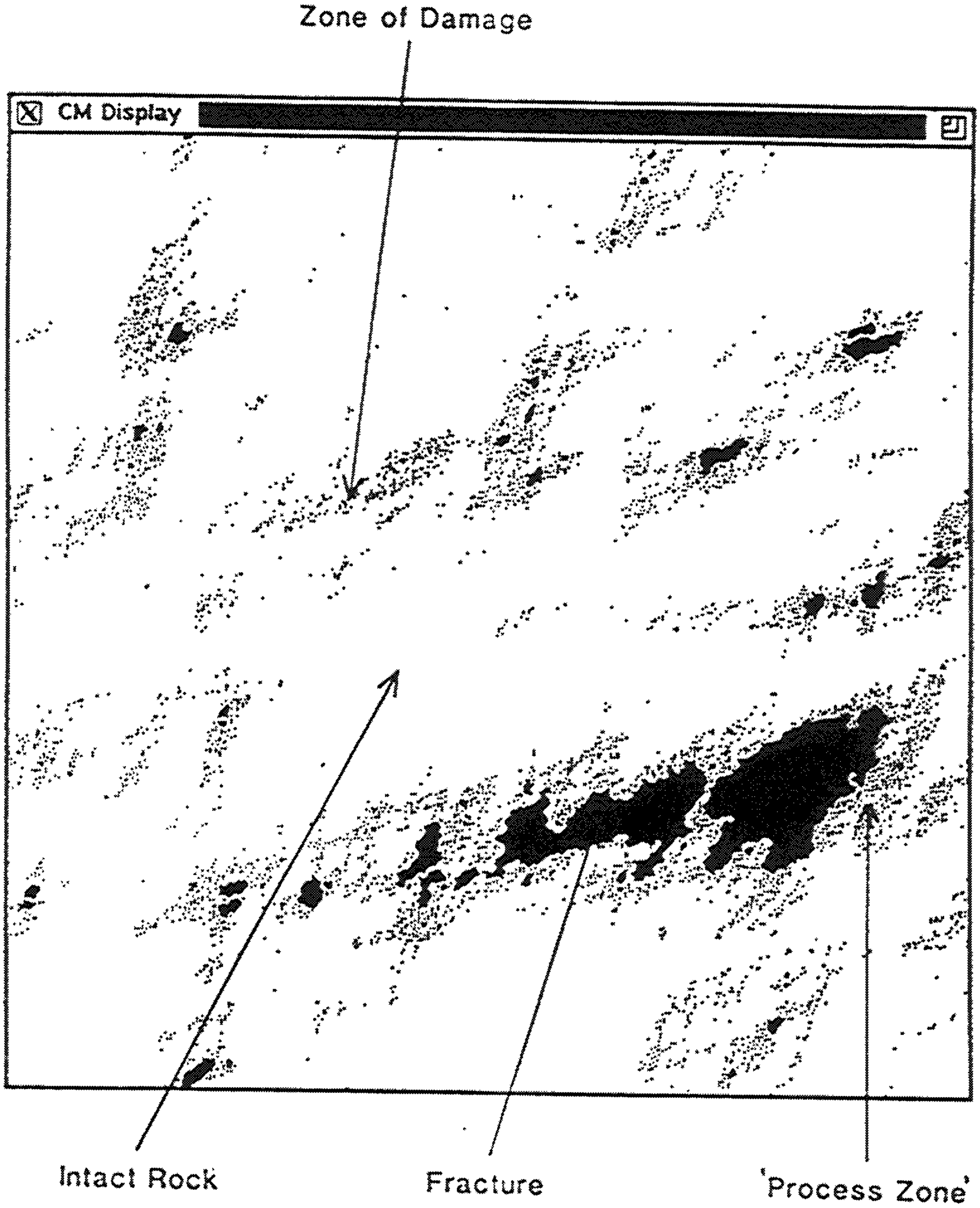
$$\bar{P} = \frac{\Sigma(\phi\beta)_i P_i}{\Sigma(\phi\beta)_i}$$

Growth



Coalescence





Henderson et.al (1997)

Diffusion Equation with Source Term

$$\frac{\partial P_f}{\partial t} = \frac{1}{\phi(\beta_\phi + \beta_f)}\left[\frac{k}{v}\nabla^2 P_f - (\dot{\phi}_{plastic} - \dot{\Gamma})\right] \quad (1)$$

where

- ϕ is porosity
- β_ϕ and β_f are the pore and fluid compressibility
- ν is the viscosity
- ρ is the fluid density
- k is the intrinsic permeability of the matrix.
- $\dot{\phi}_{plastic} - \dot{\Gamma}$ is a source term

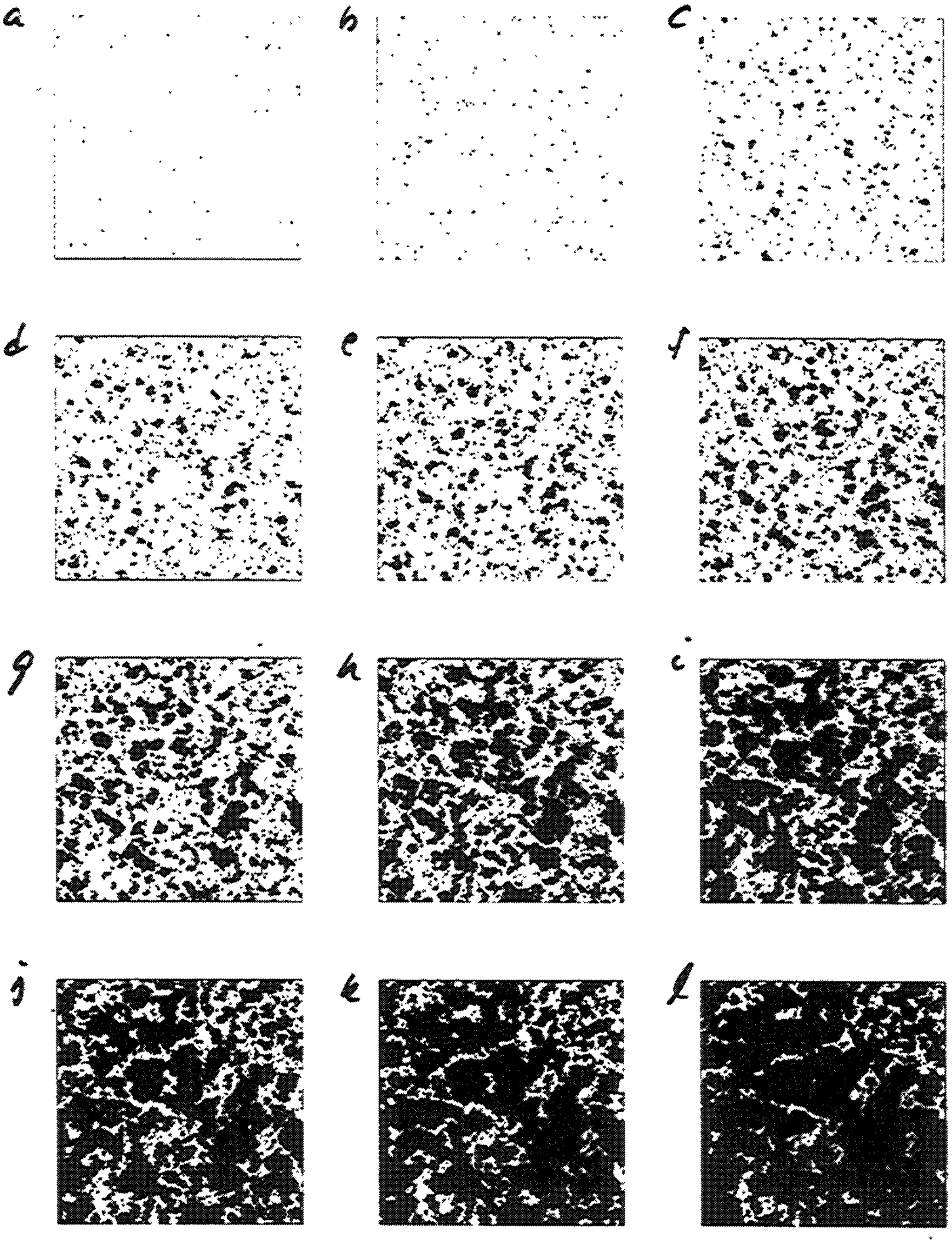
For an impermeable matrix ($k \sim 0$)

$$\frac{\partial P_f}{\partial t}\Big|_{noflow} = \frac{(\dot{\Gamma} - \dot{\phi})_i}{\phi_i \beta_i} \quad (2)$$

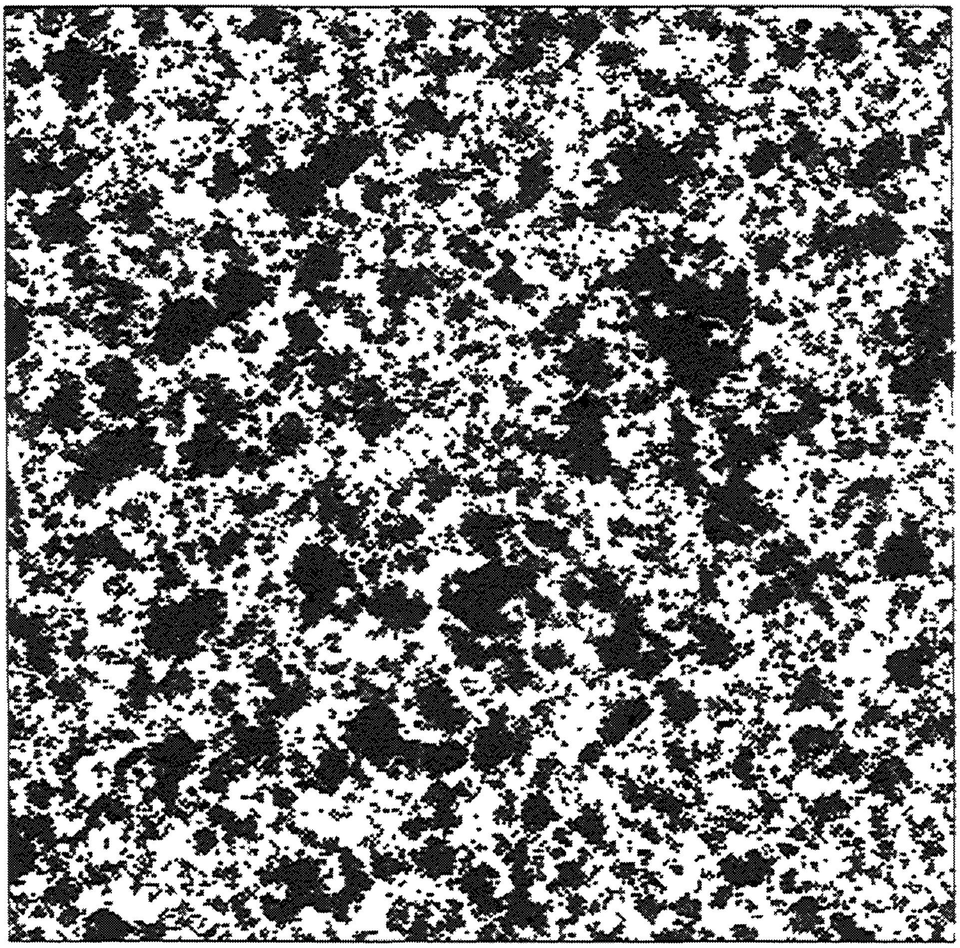
At failure (hydrofracture), fluid pressures equilibrate with nearest neighbor cells. The equilibrium pressure (by conserving fluid mass and ignoring gravity, is:

$$\overline{P} = \frac{\Sigma_{i=1}^{m}(\phi\beta)_i P_i}{\Sigma_{i=1}^{m}(\phi\beta)_i} \quad (3)$$

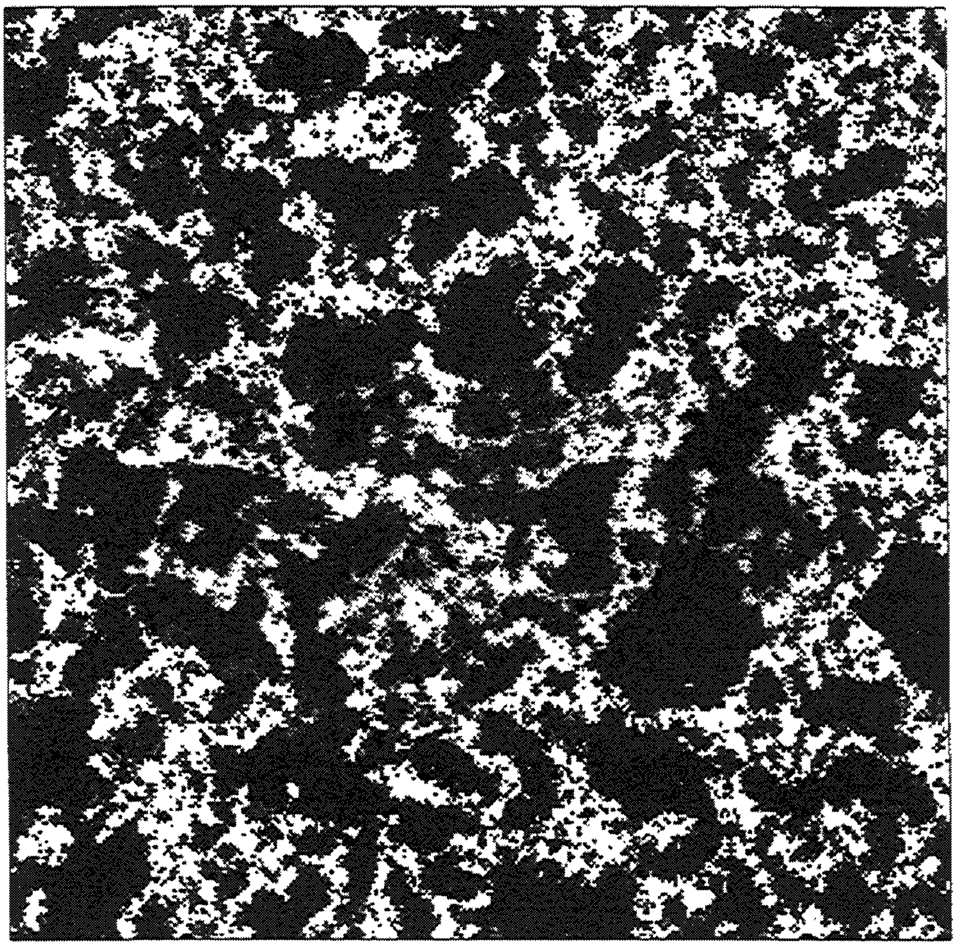
where $\overline{P}$ is the average pressures of affected cells.

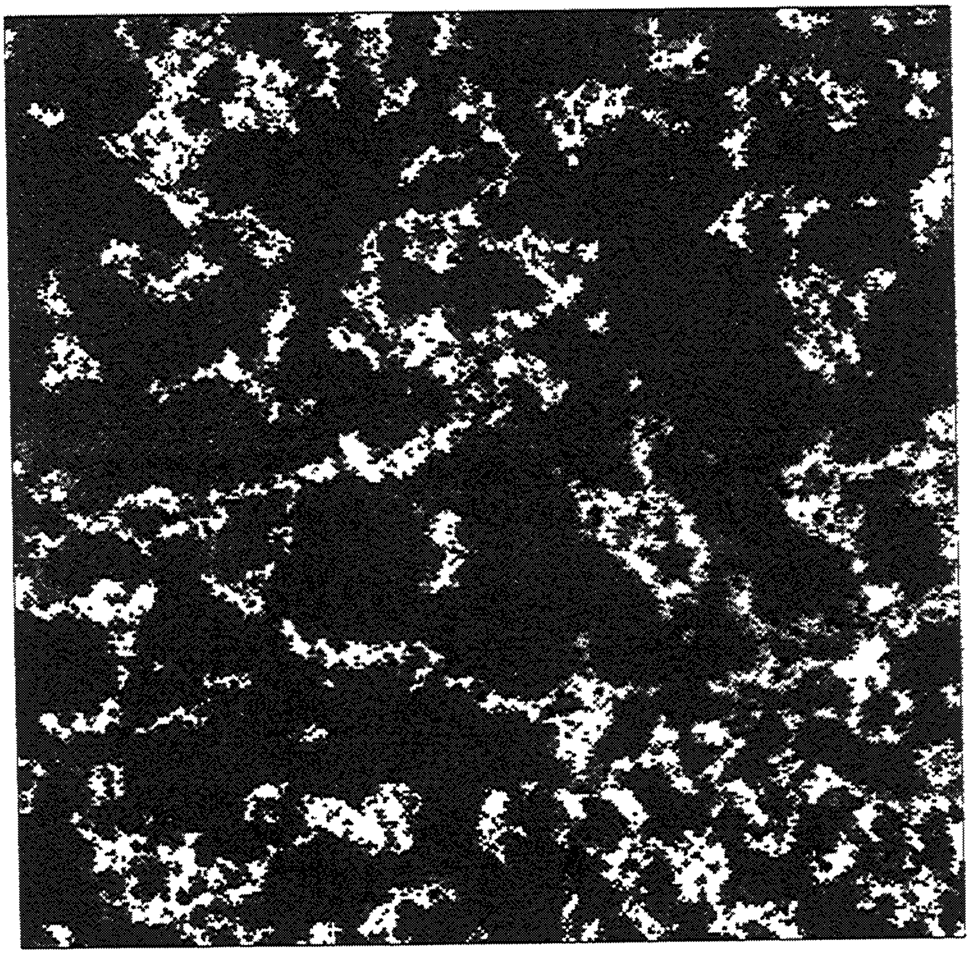


Black = Incipient Failure Miller & Nur (2000)

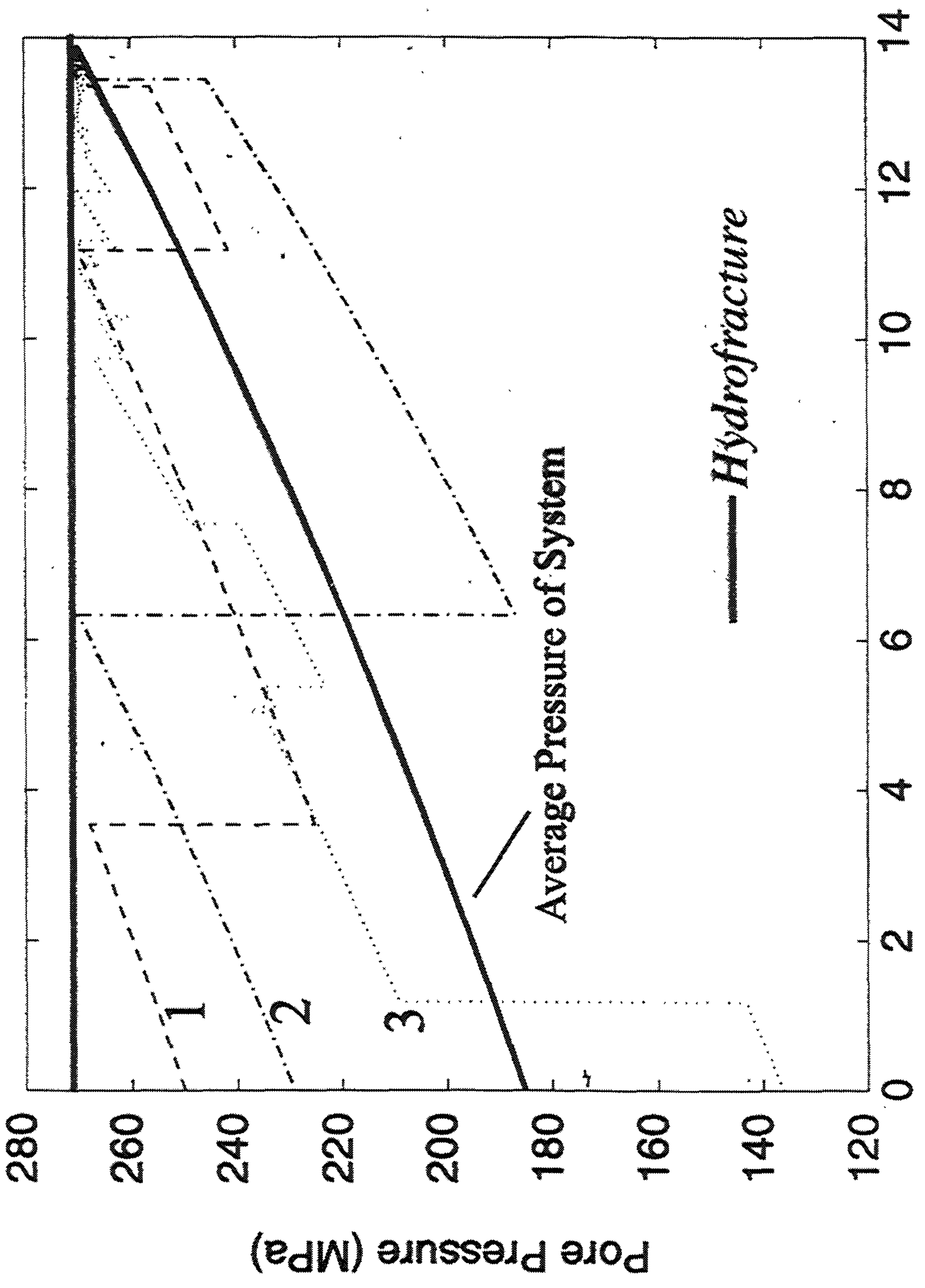


Cells at failure Condition

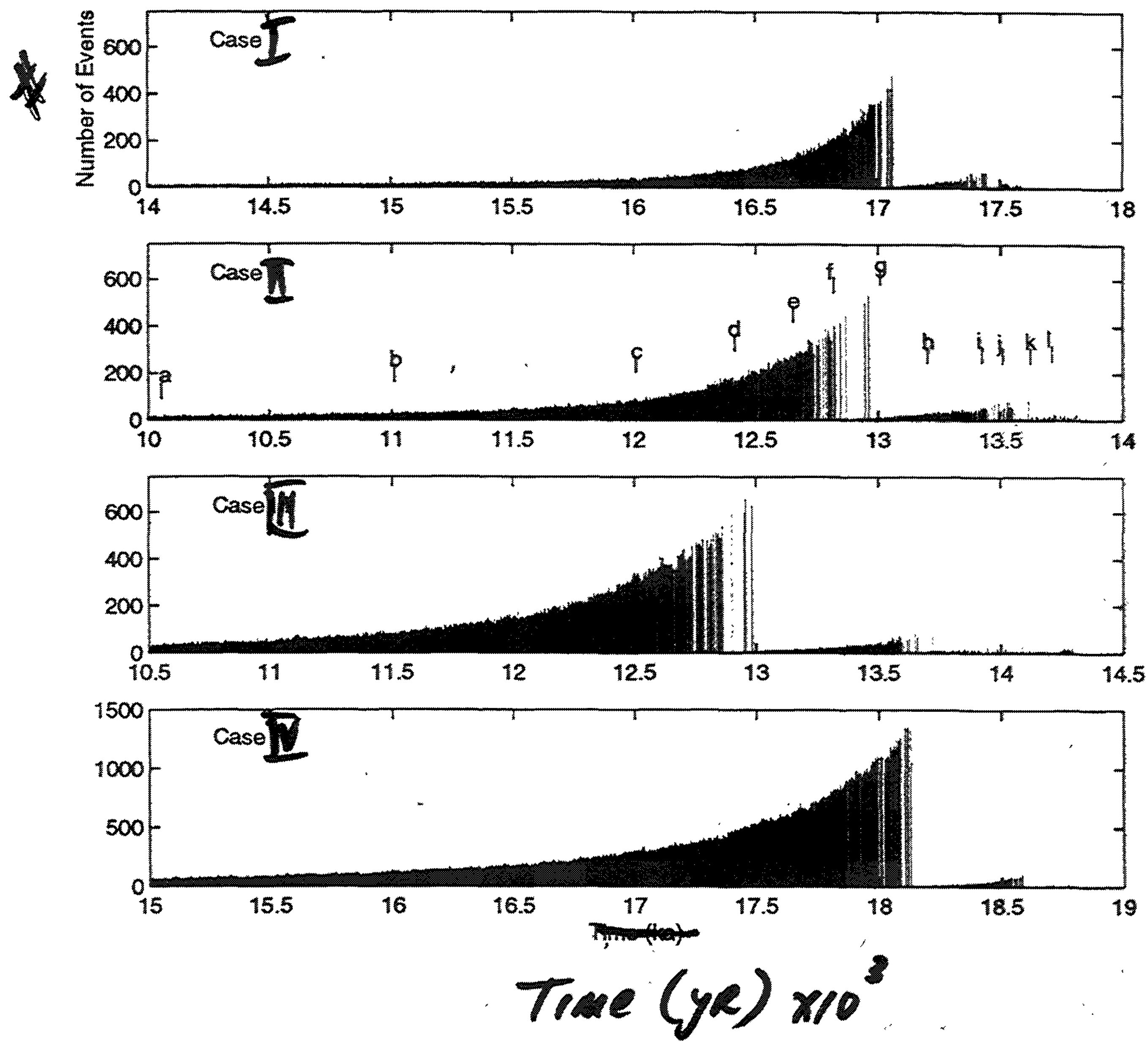




Pore pressure paths of arbirtrary cells and system pressure

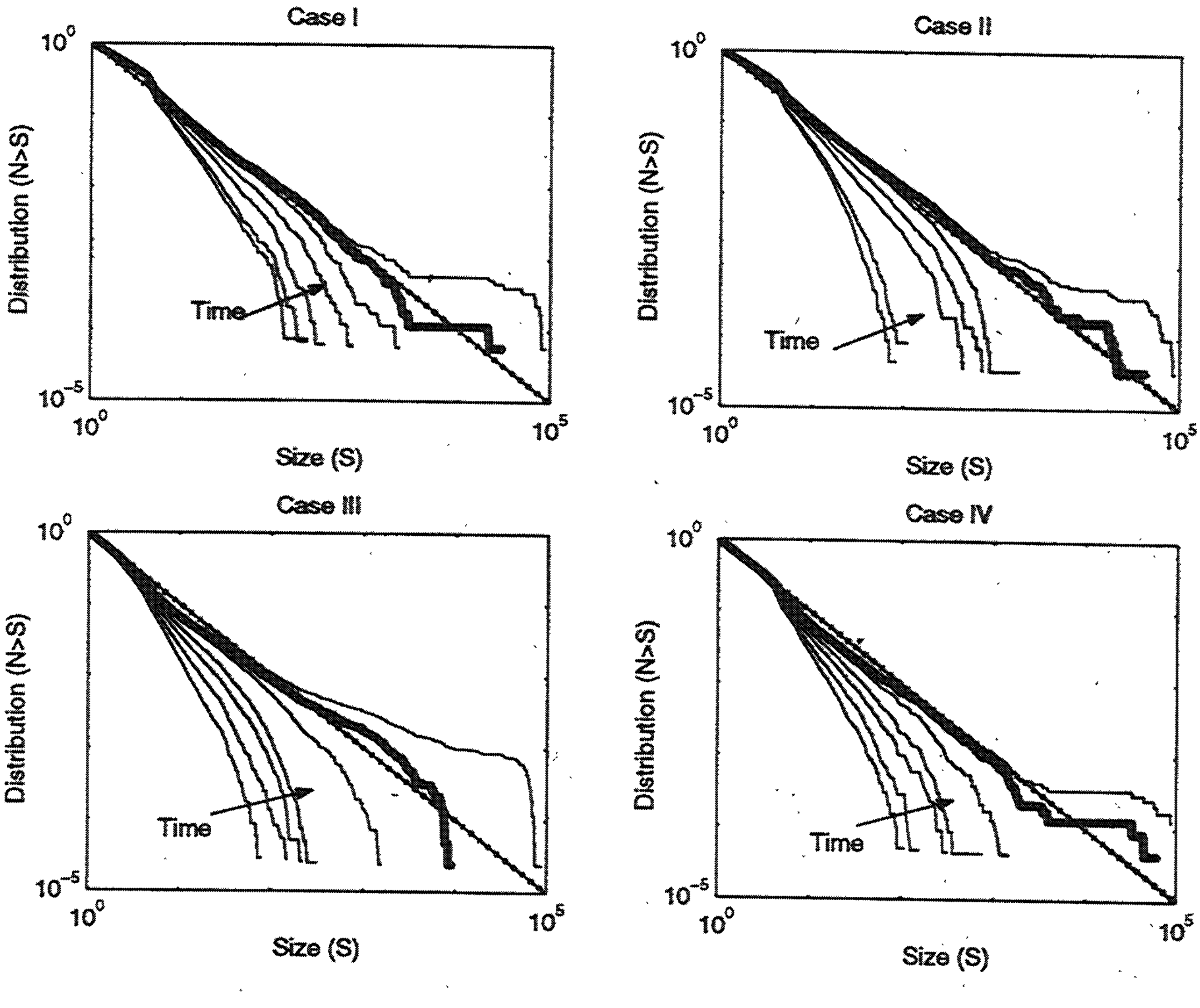


TIMELINE of NUMBER of EVENTS



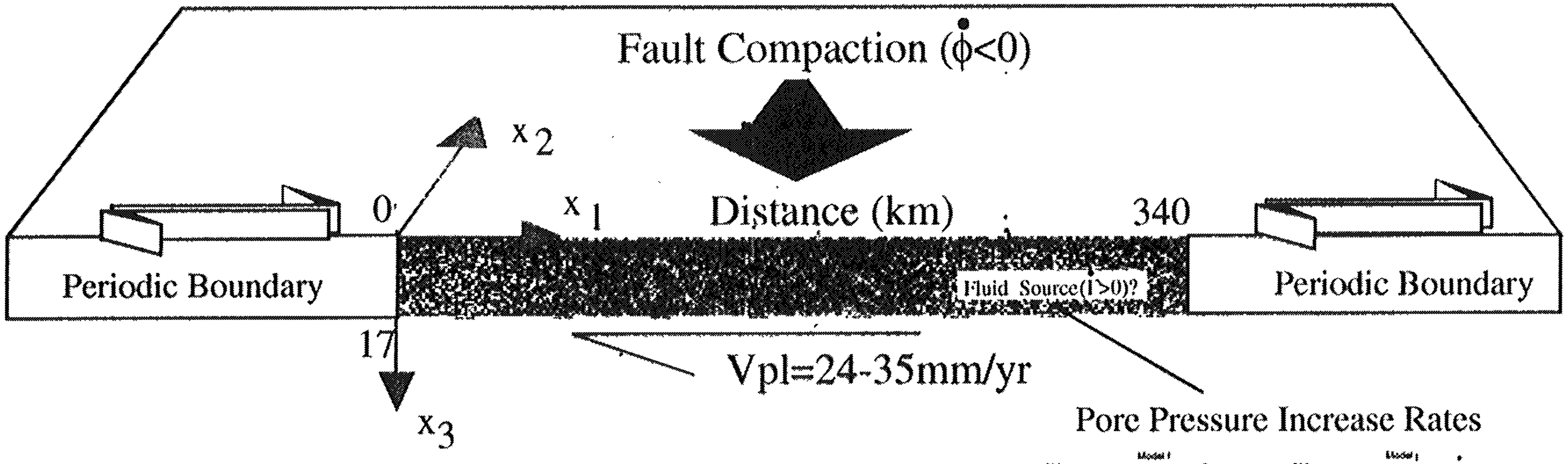
Miller & Nur (2000 EPSL)

CLUSTER SIZE DISTRIBUTION AT CRITICAL STATE

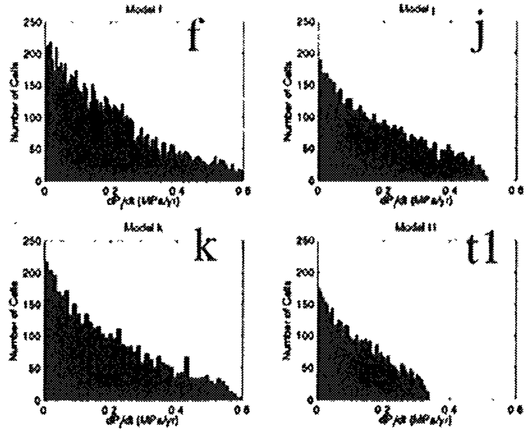


Miller & Nur (EPSL, 2000)

The Model

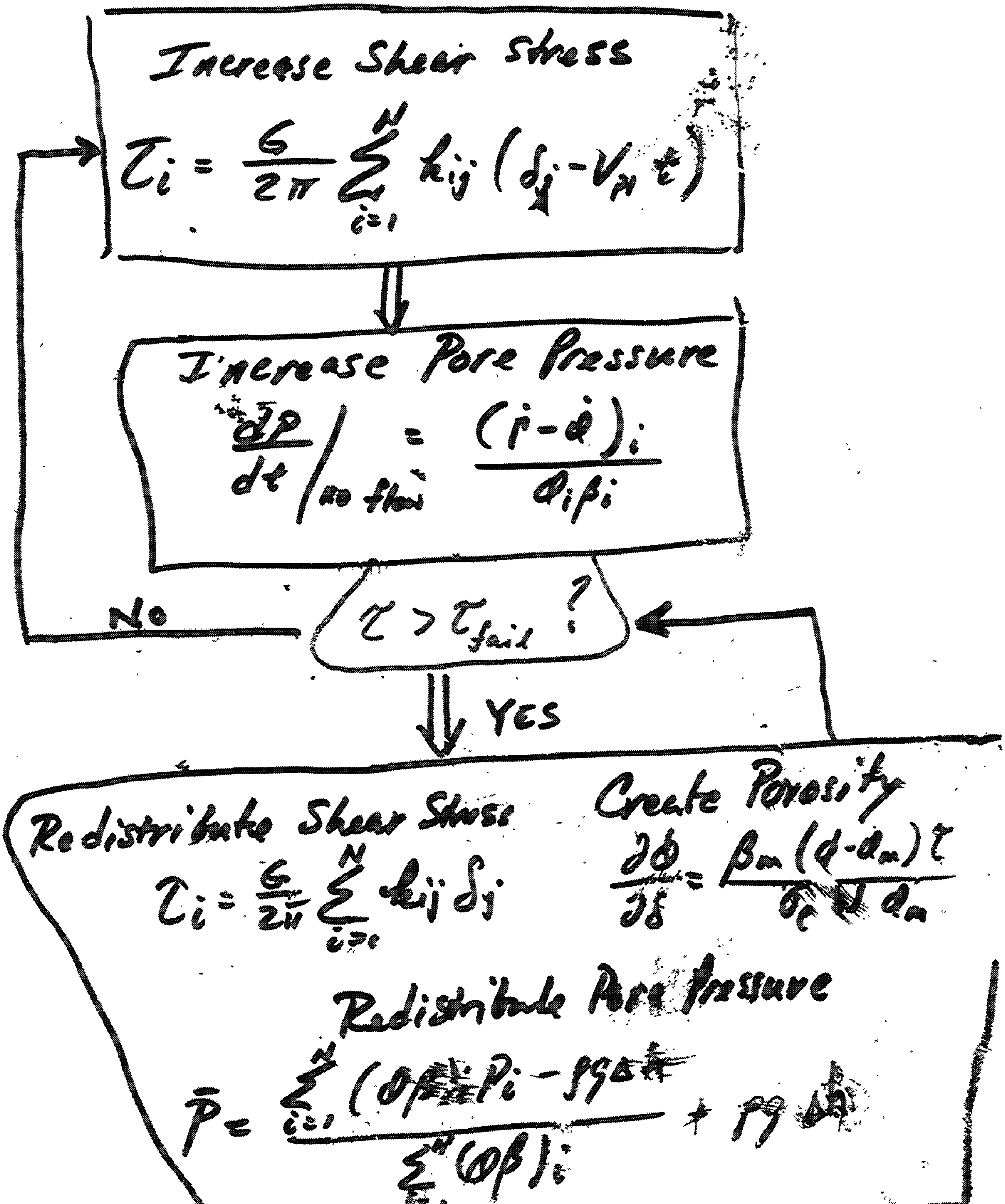


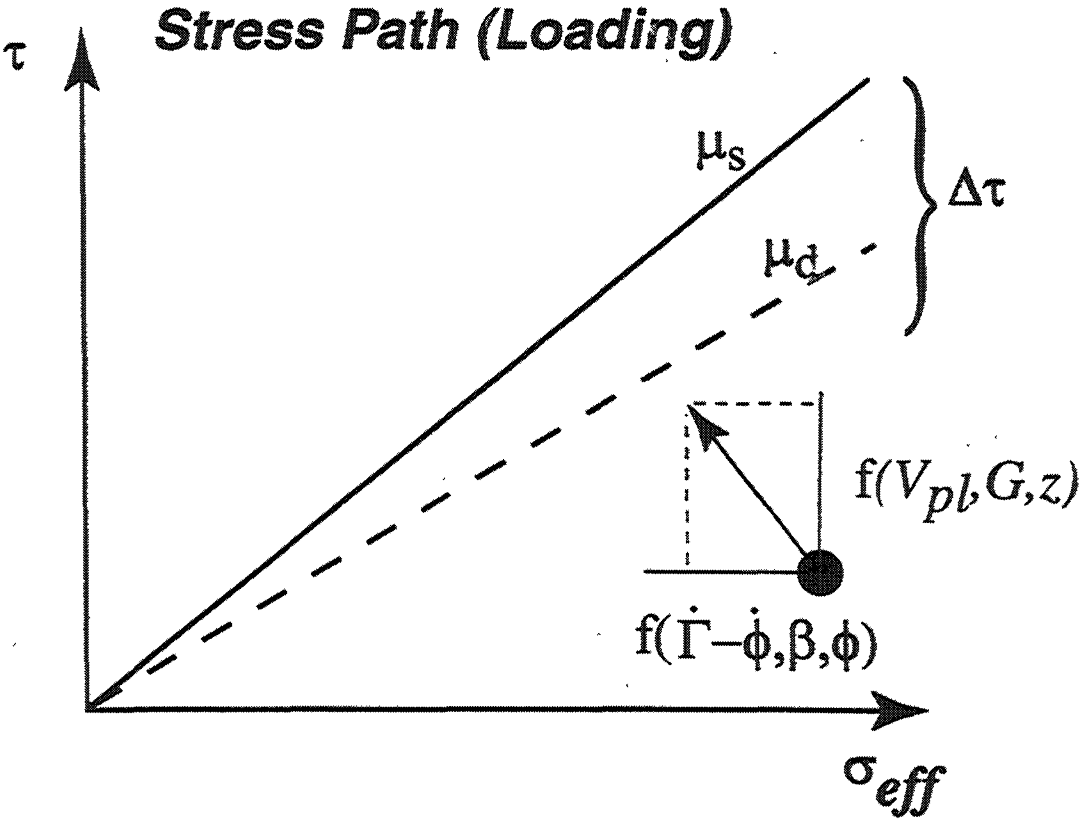
Model	Vpl (mm/yr)	μs	μd	Δσ (%)
f	35	0.6	0.3	80
j	35	0.6	0.5	25
k	35	0.6	0.4	40
T1	24	0.6	0.5	25

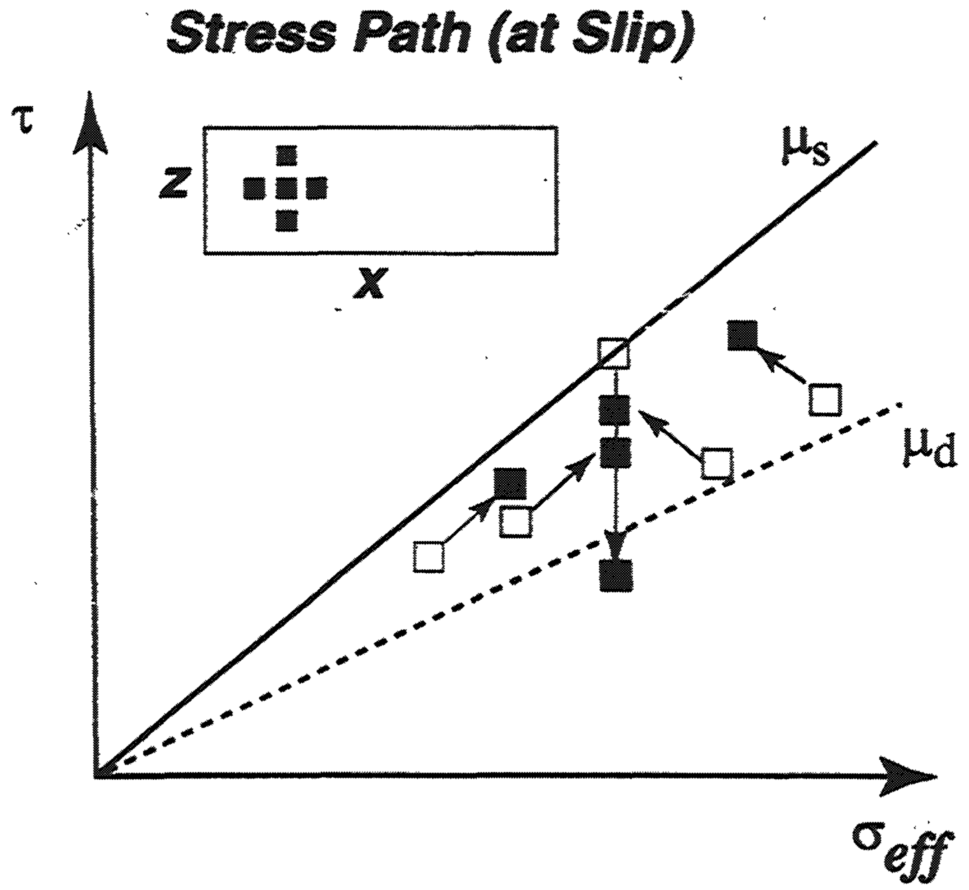


Miller, et.al. JGR 1999

MODEL ALGORITHM

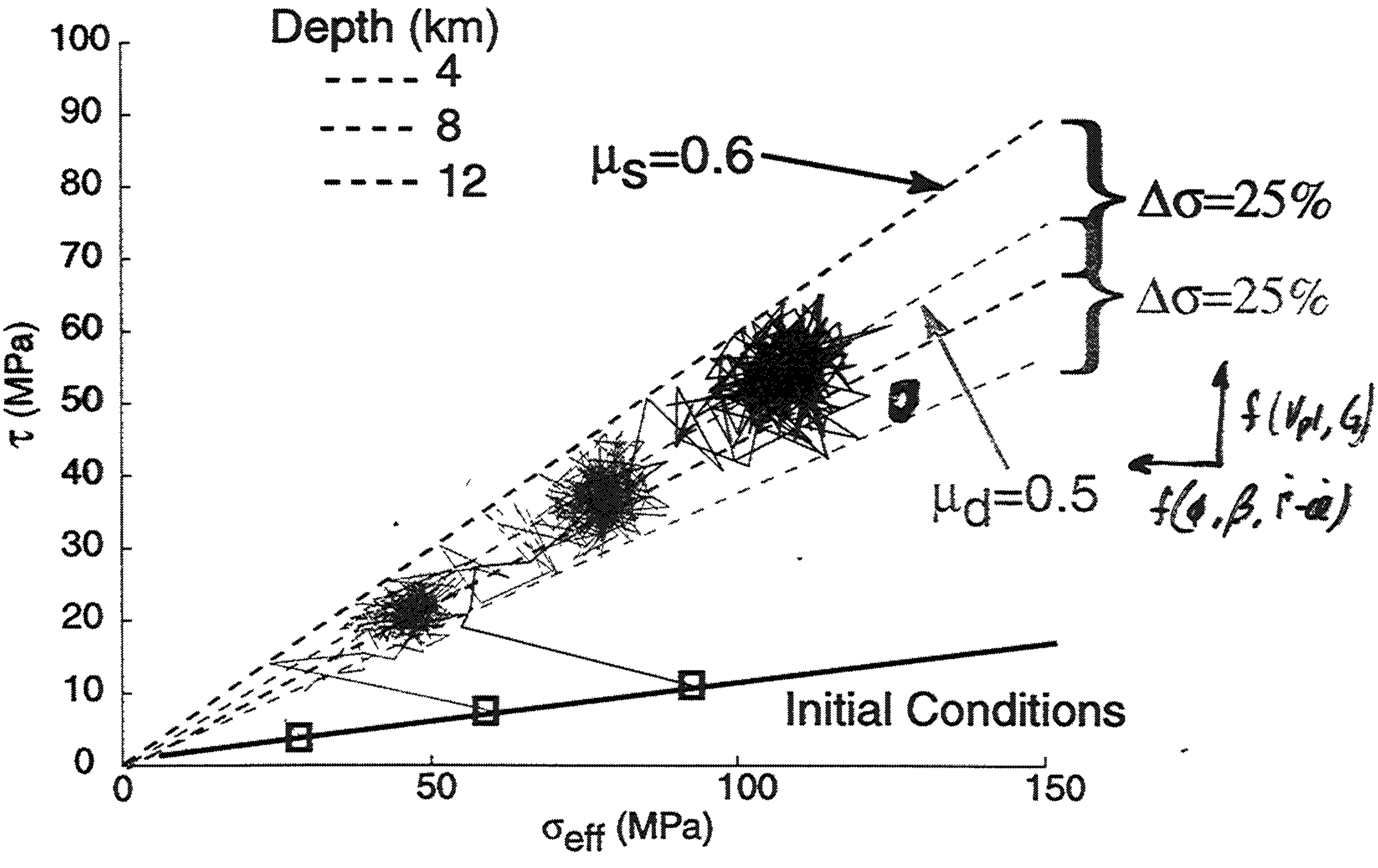


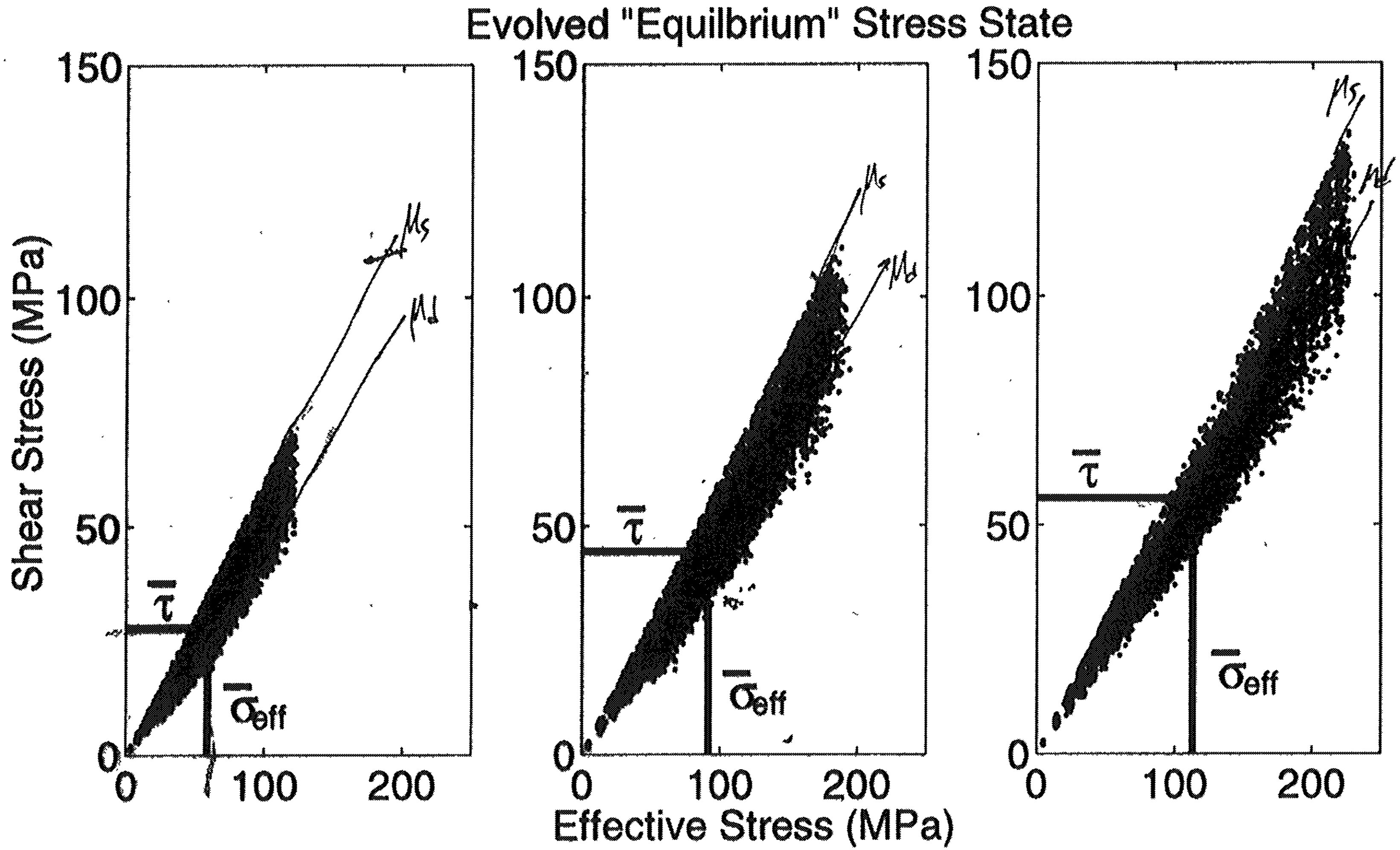

Stress Path (Loading)
τ
μs
Δτ
μd
f(Vpl,G,z)
f(Γ̇−φ̇,β,φ)
σeff


Stress Path (at Slip)
τ
z
x
μs
μd
σeff

General Result: Model Finds Dynamic Equilibrium

$f(Vp, \dot{\Gamma} - \dot{\phi}, \Delta\sigma, \mu)$

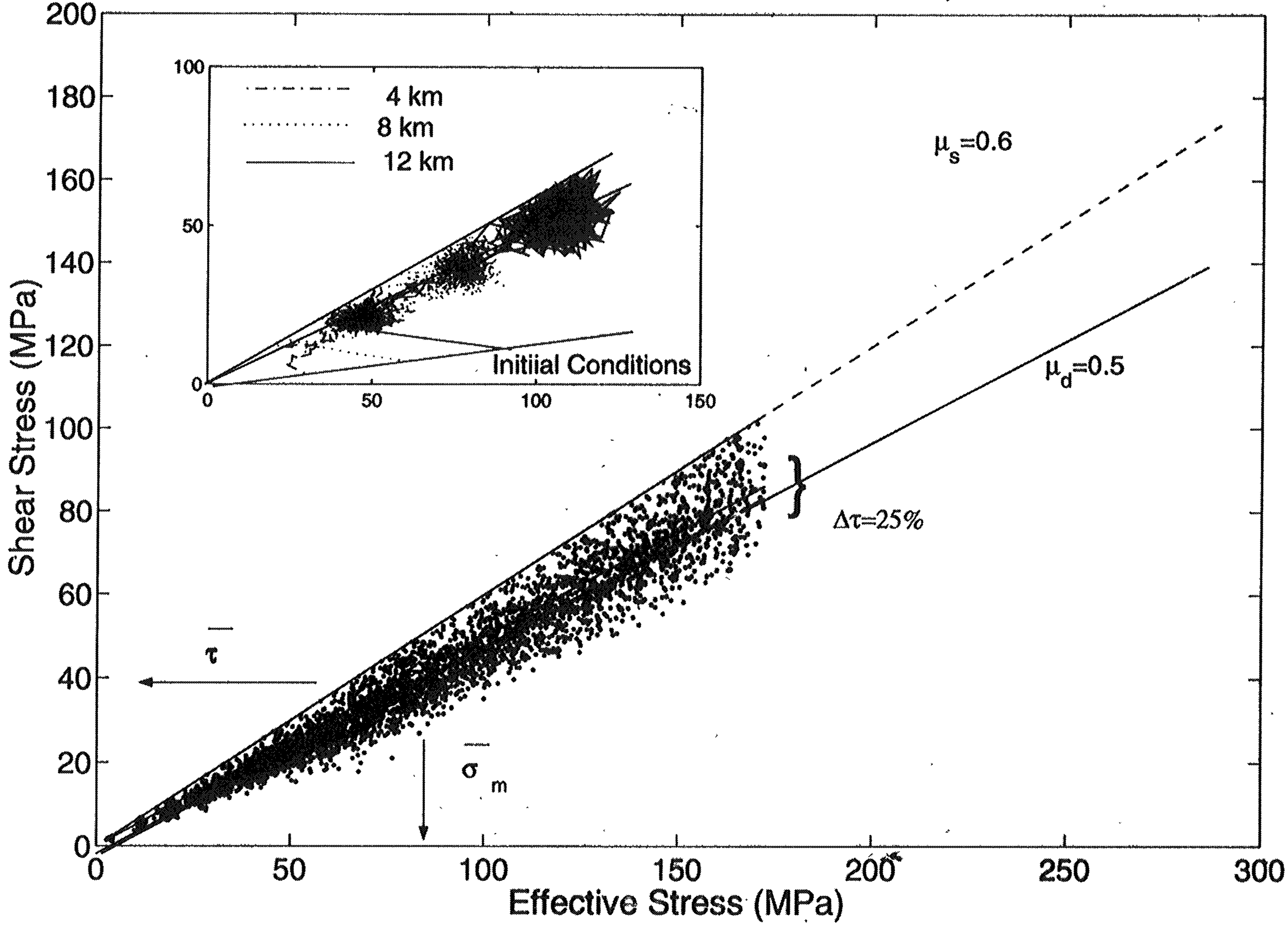


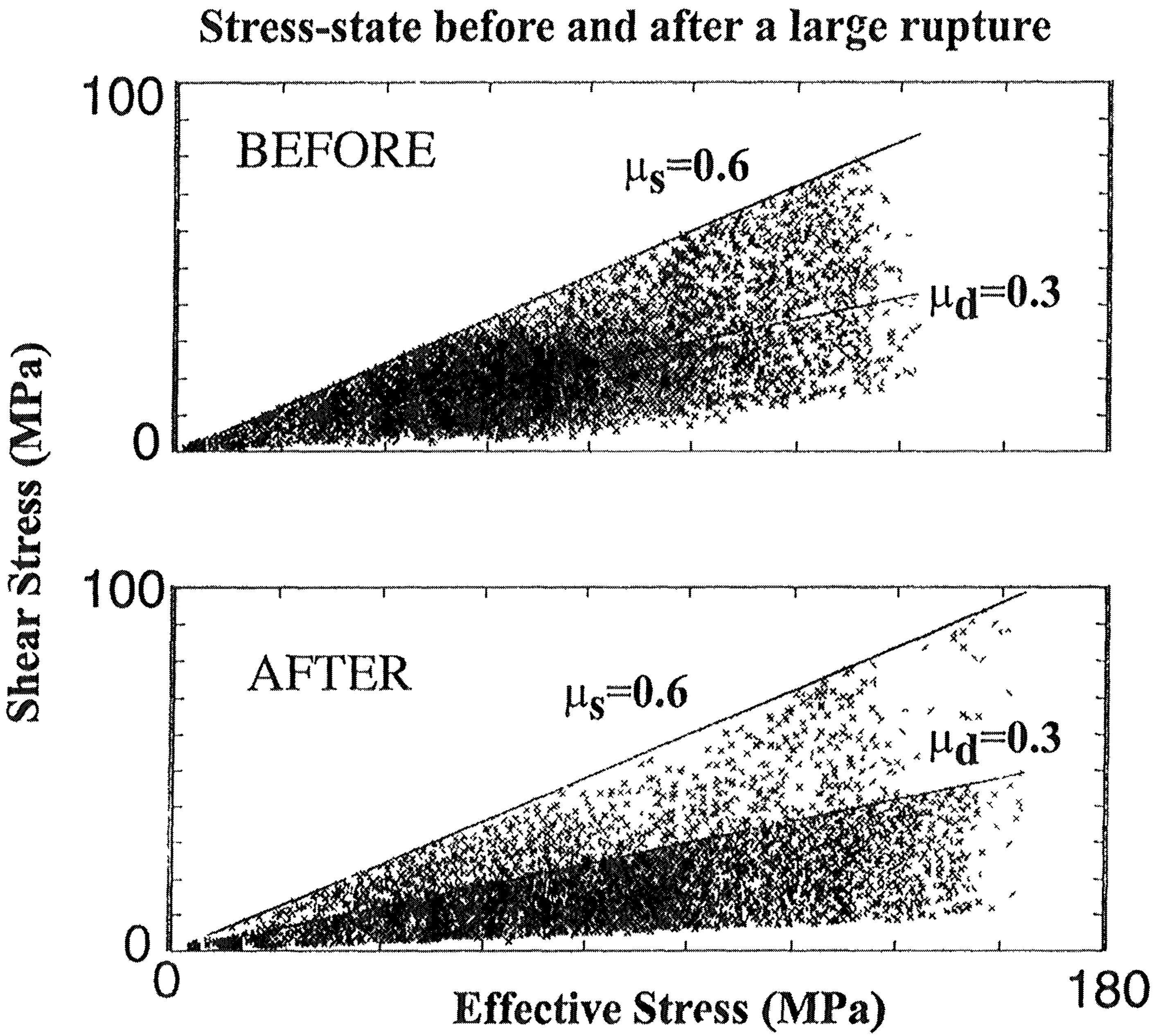


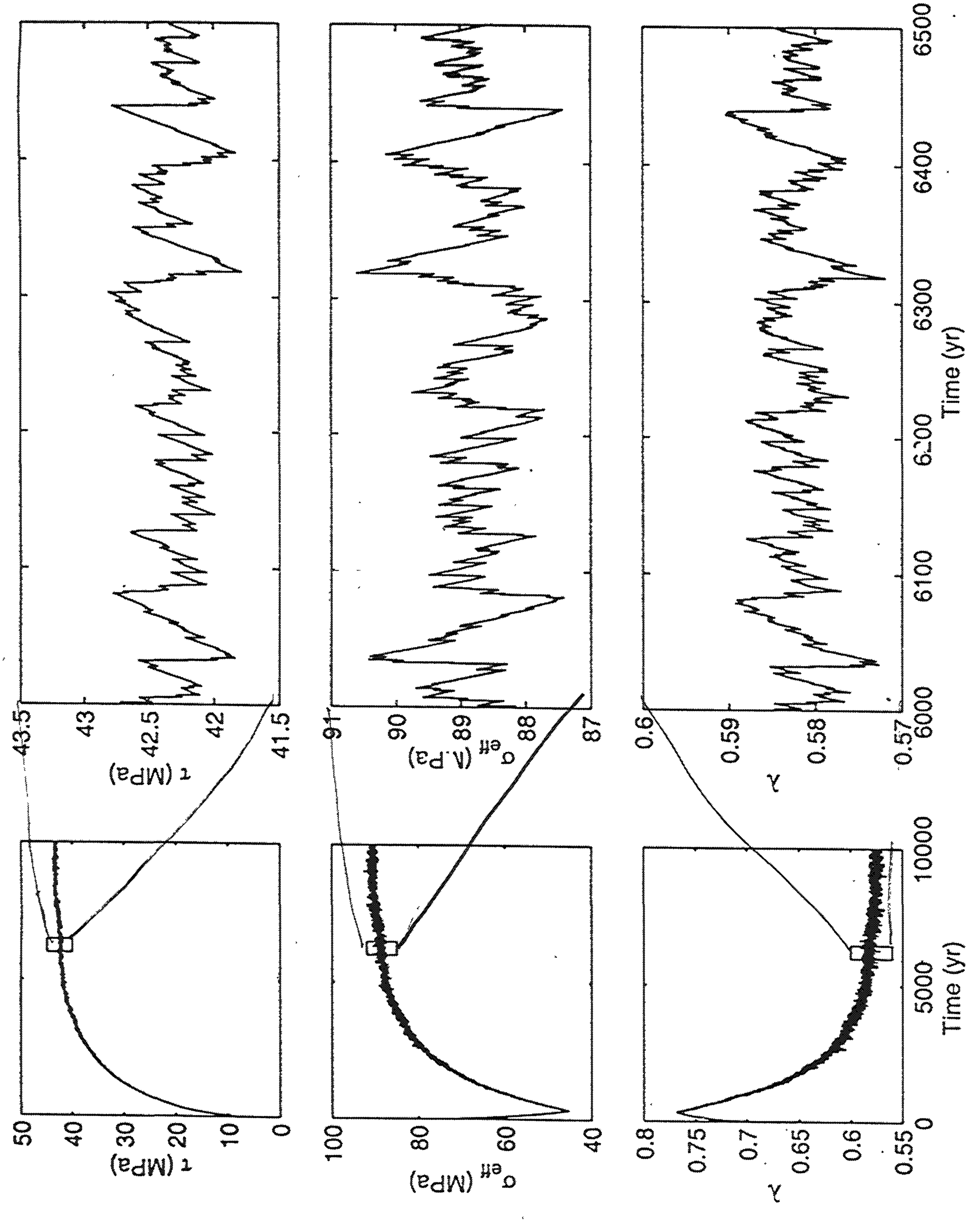
$$\overline{\Delta\tau_d} = (C_1\mu_s - \mu_d)\,\bar{\sigma}_e = (C_1\mu_s - \mu_d)\,\rho g\,\bar{z}\,(1-\lambda)$$

$$\bar{z} \to \tfrac{1}{2}W \Rightarrow \overline{\Delta\tau_d} = \tfrac{1}{2}(C_1\mu_s - \mu_d)\,\rho_r g\,W(1-\lambda)$$

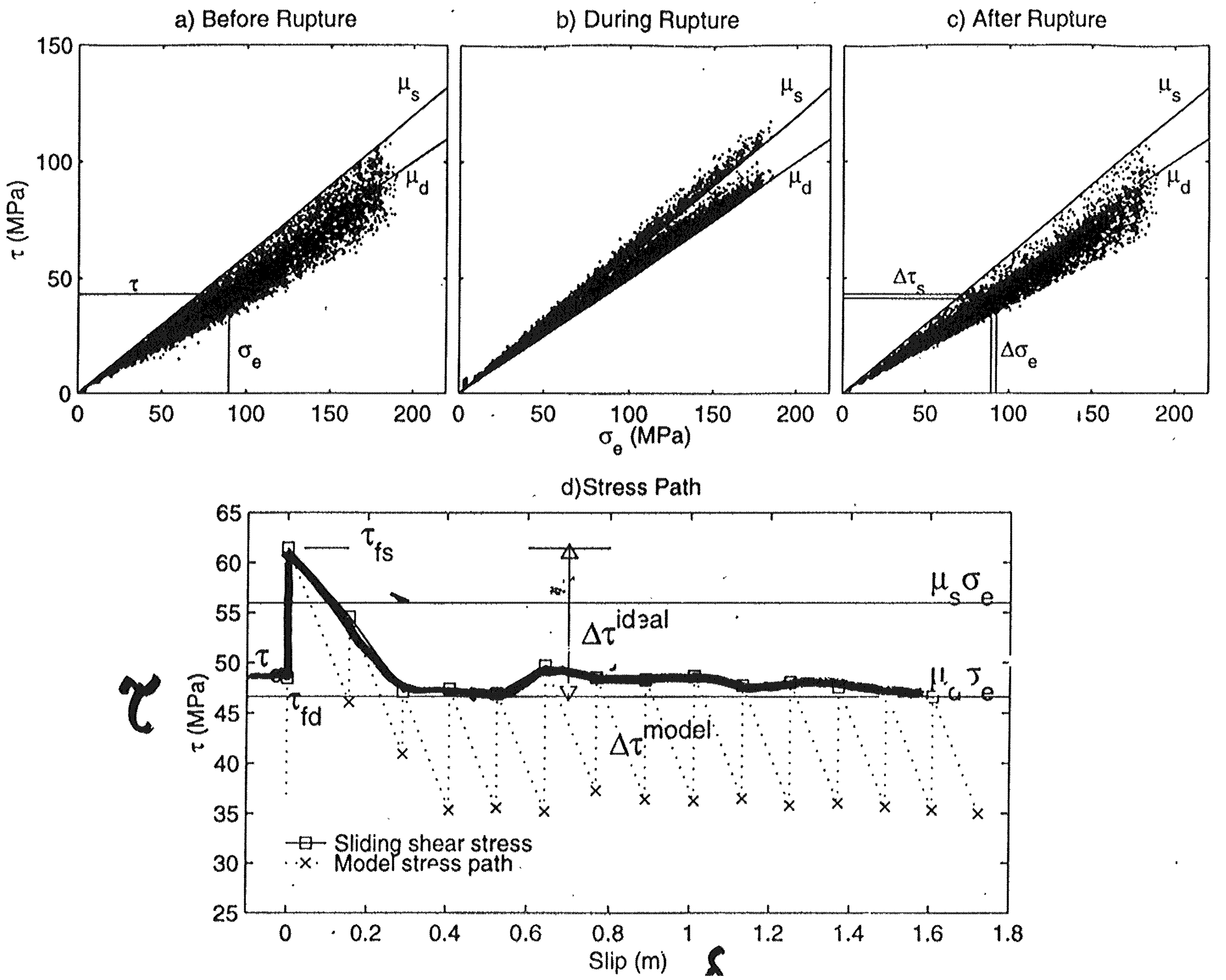
Stress Paths & Dynamic Equilibrium



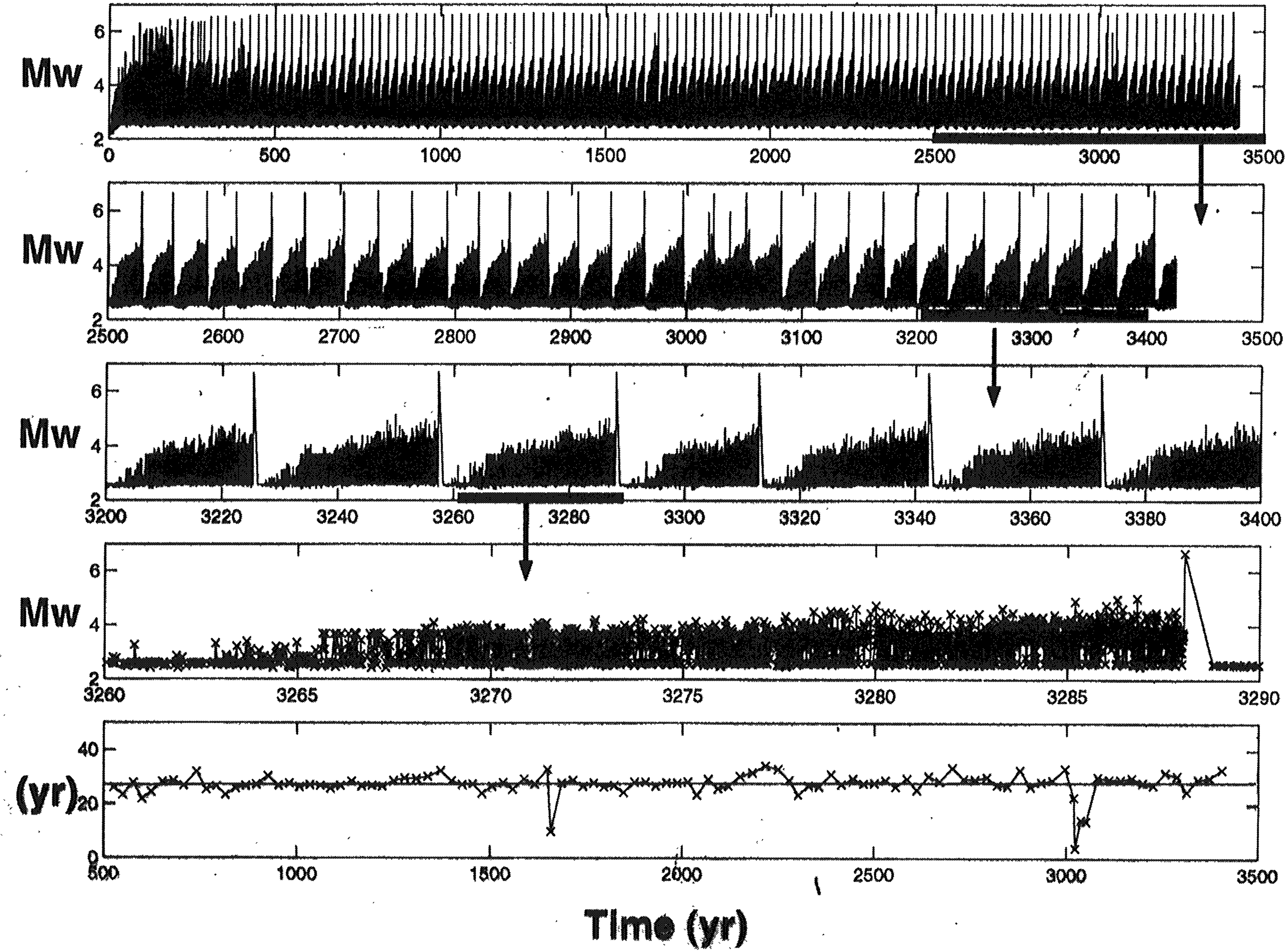

Stress-state before and after a large rupture
BEFORE
μs=0.6
μd=0.3
AFTER
μs=0.6
μd=0.3
100
0
100
0
0
180
Shear Stress (MPa)
Effective Stress (MPa)

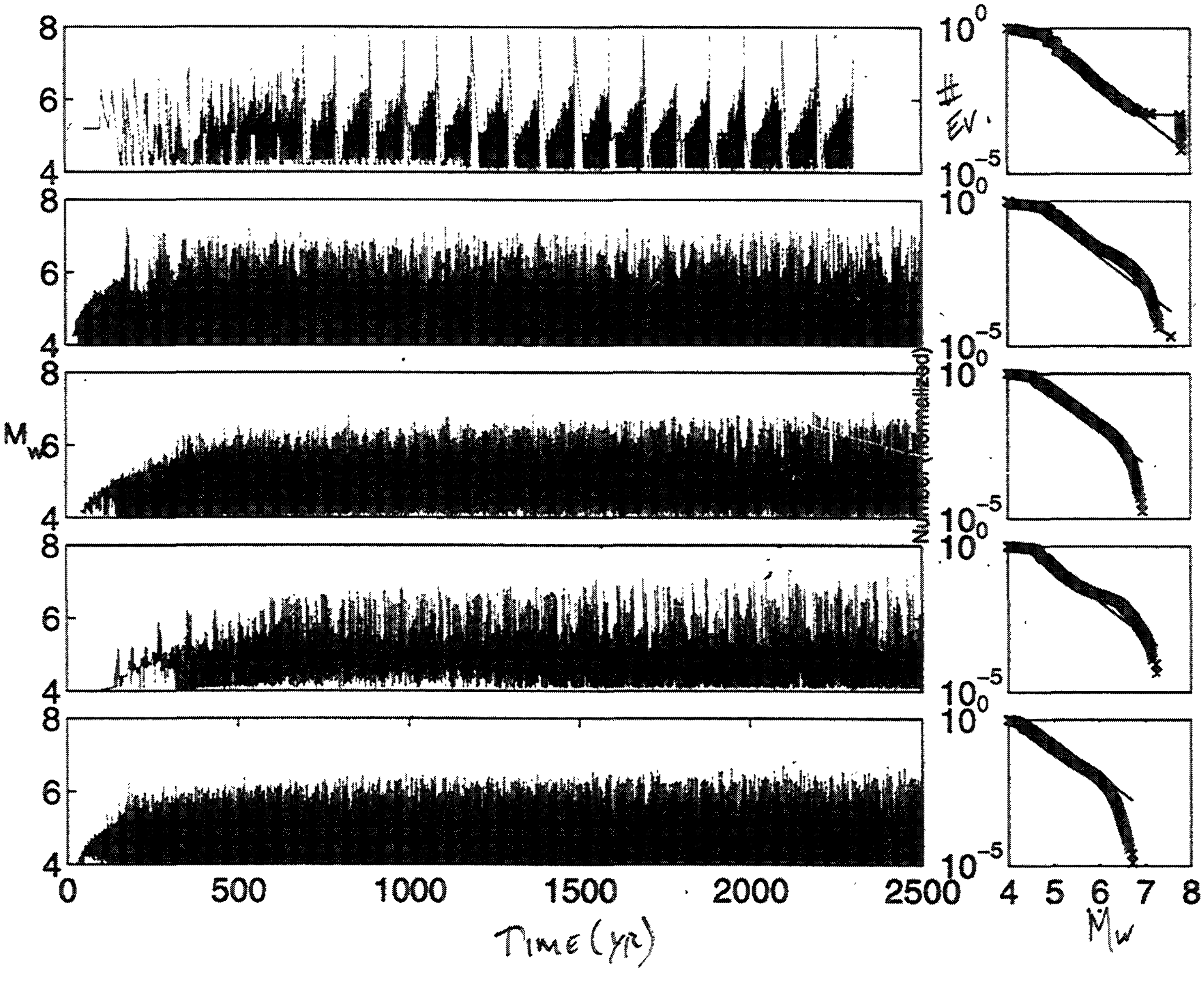


τ (MPa)
σeff (MPa)
λ
Time (yr)

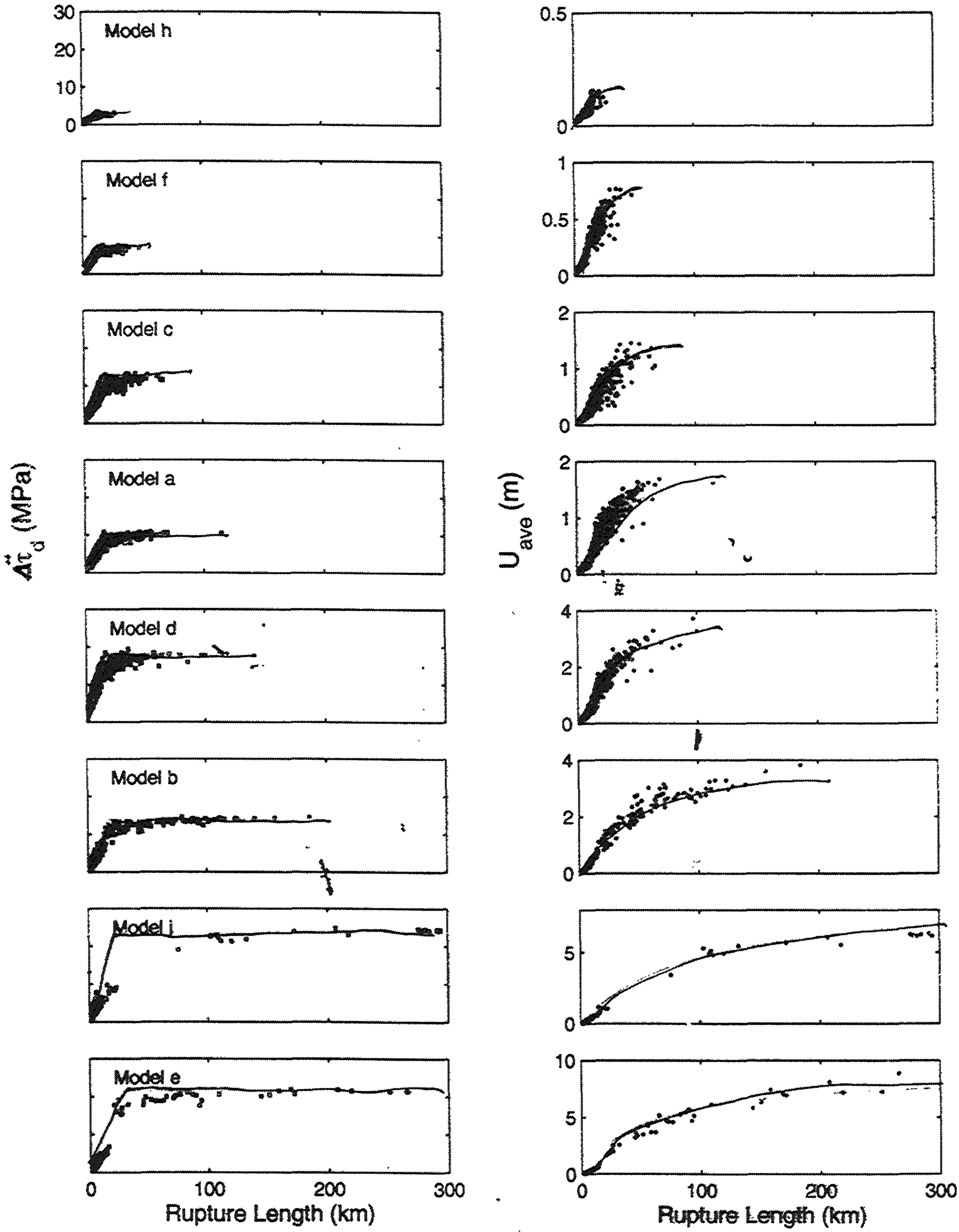

a) Before Rupture
b) During Rupture
c) After Rupture
τ (MPa)
σe (MPa)
μs
μd
τ
σe
Δτs
Δσe
150
100
50
0
0
50
100
150
200
d)Stress Path
τ (MPa)
Slip (m)
τfs
τfd
μsσe
Δτideal
Δτmodel
Sliding shear stress
Model stress path
65
60
55
50
45
40
35
30
25
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

Repeat Times and the Earthquake Cycle

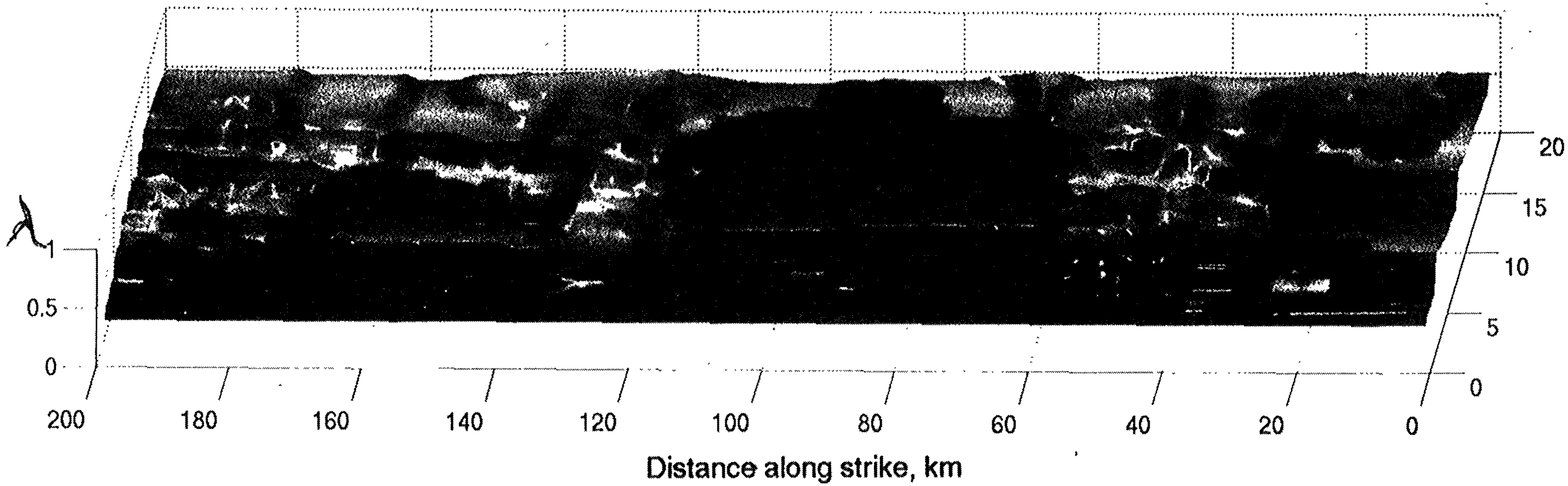


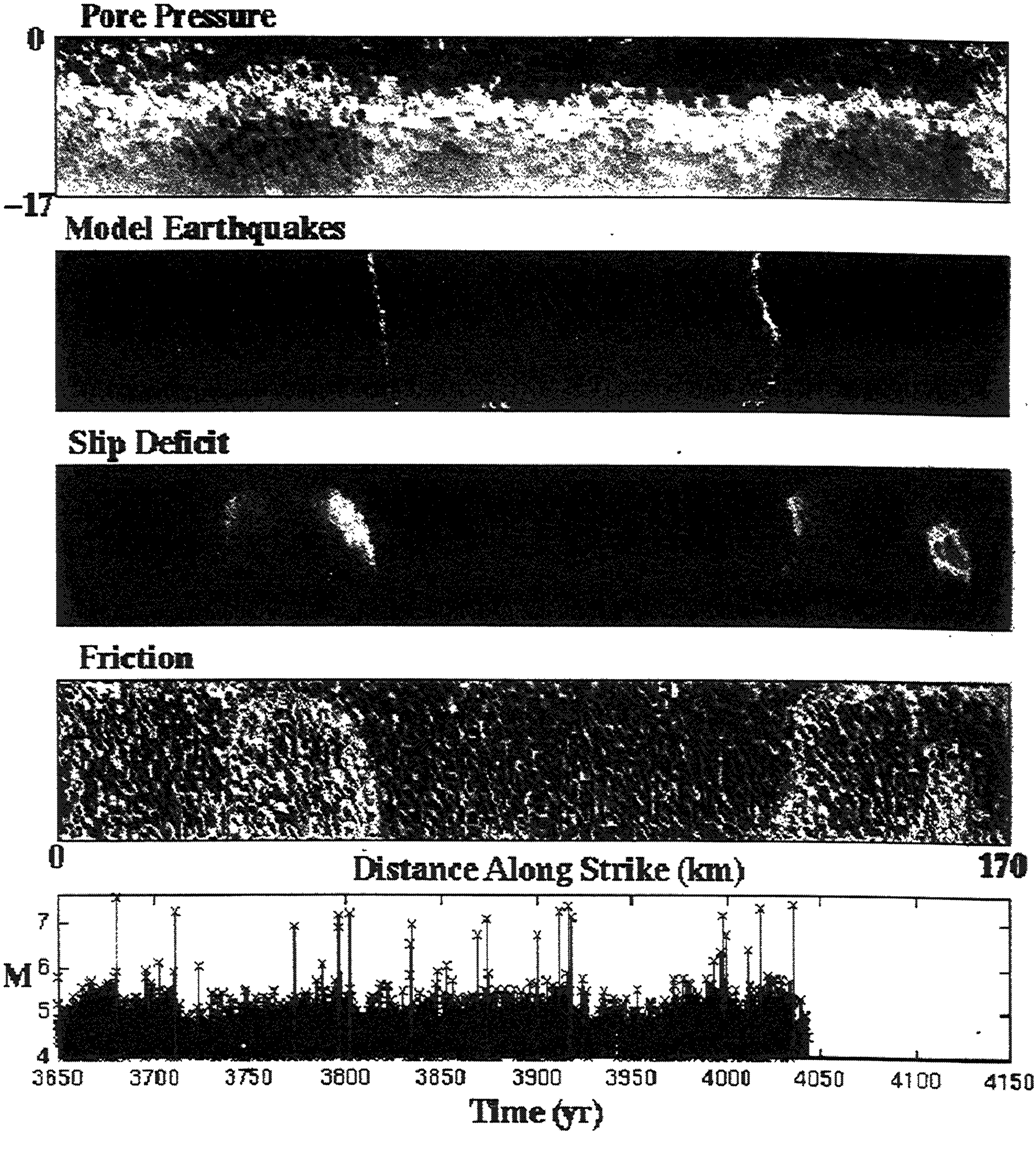


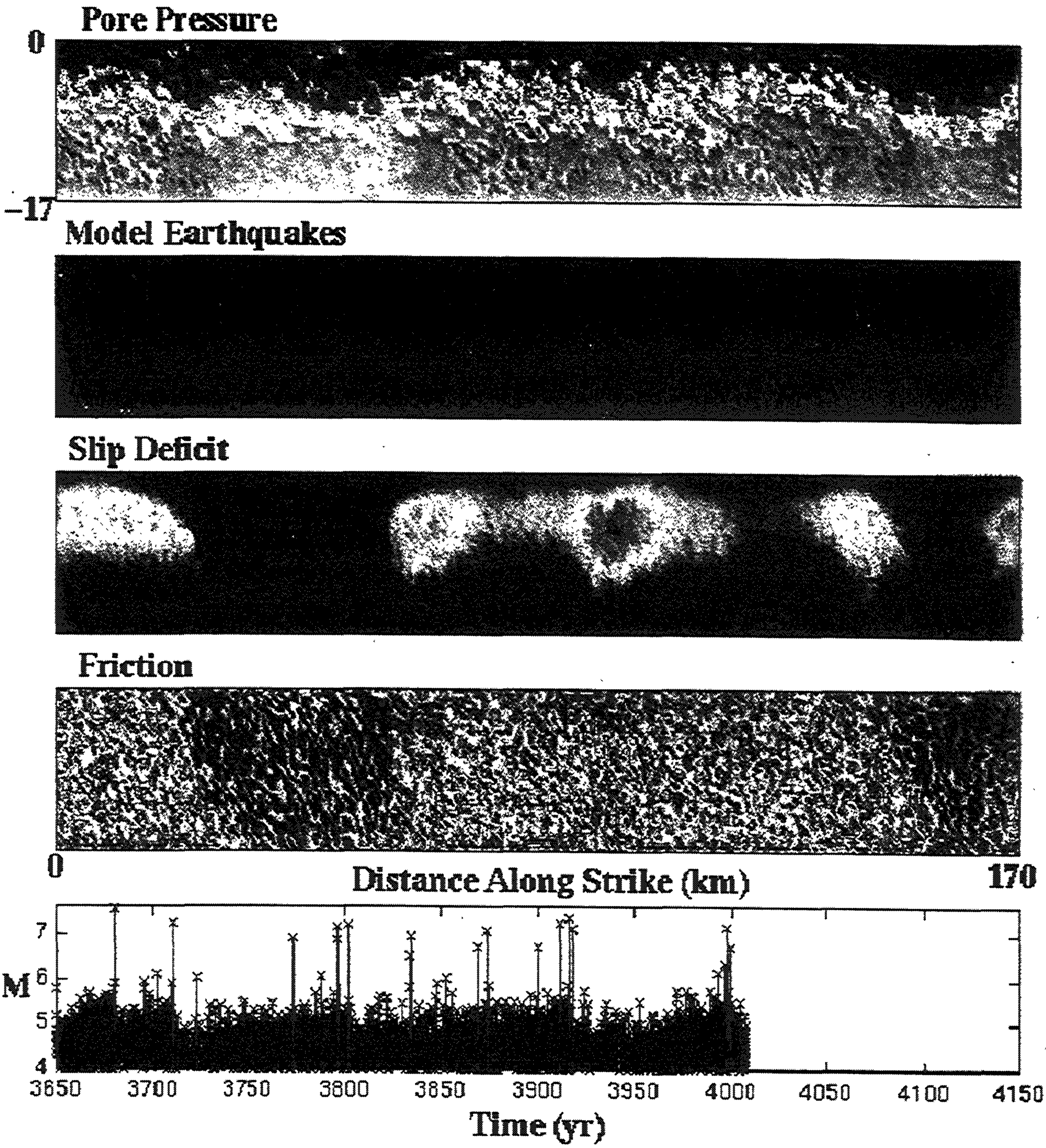
8
6
4
M_w
0
500
1000
1500
2000
2500
TIME (YR)
10^0
10^-5
EV.
Number (normalized)
4
5
6
7
8
M_w


Model h
Model f
Model c
Model a
Model d
Model b
Model j
Model e
Δτ_d (MPa)
U_ave (m)
Rupture Length (km)
Rupture Length (km)

PORE PRESSURE ALONG FAULT




Pore Pressure
0
−17
Model Earthquakes
Slip Deficit
Friction
0
Distance Along Strike (km)
170
7
M 6
5
4
3650
3700
3750
3800
3850
3900
3950
4000
4050
4100
4150
Time (yr)


Pore Pressure
0
-17
Model Earthquakes
Slip Deficit
Friction
0
Distance Along Strike (km)
170
M
7
6
5
4
3650
3700
3750
3800
3850
3900
3950
4000
4050
4100
4150
Time (yr)

Comparison of Moment-Rupture Area with Historical Strike-Slip Catalog

(*Wells and Coppersmith, '94*)