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abdus salam
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H4.SMR/1150 - 13

Fifth Workshop on Non-Linear Dynamics
and Earthquake Prediction

4 - 22 October 1999

Contemporary Models of the Earthquake Process

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Lecture I: The Simplicity of Generating Complexity

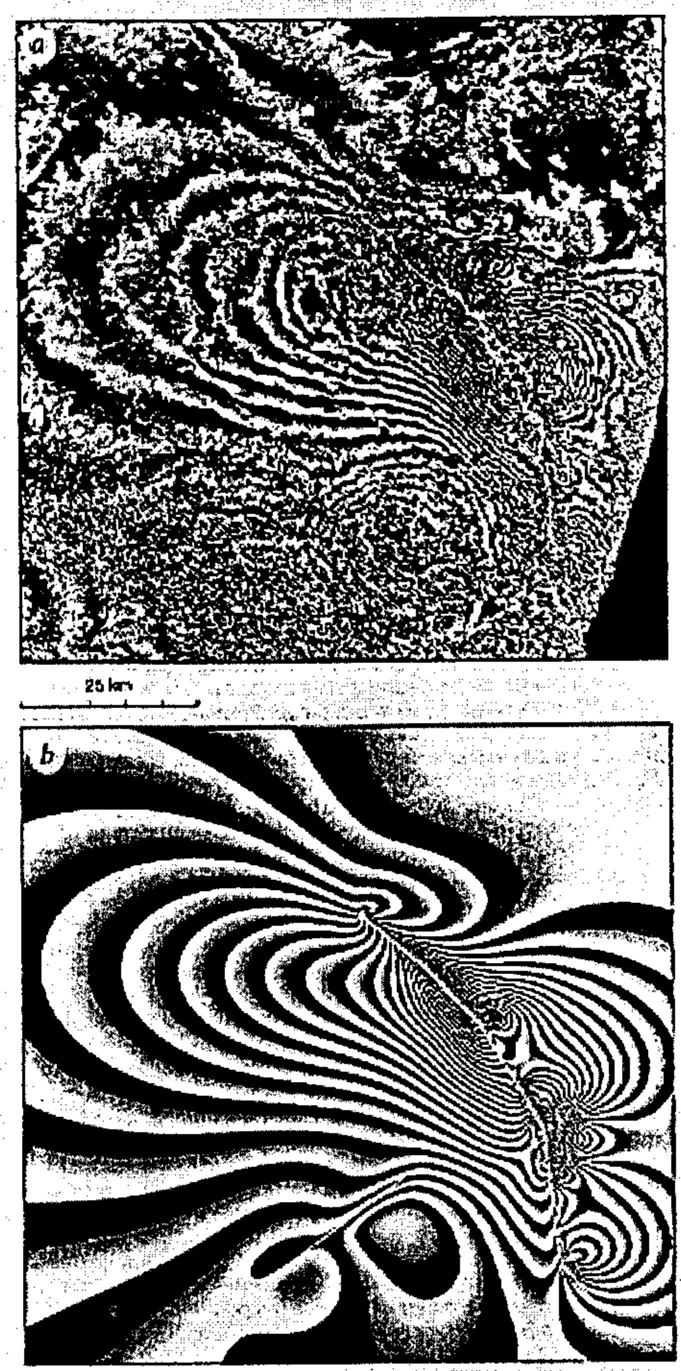
- Generating Power Laws
- Simple Examples of Complex Patterns
- Self-Organized Criticality (SOC)
- Earthquake Models of Complexity
- A CA Model Using Permeability as a Toggle Switch
- Application of the CA Model to Dehydration Reactions

Lecture II: Contemporary Models of the Earthquake Proces

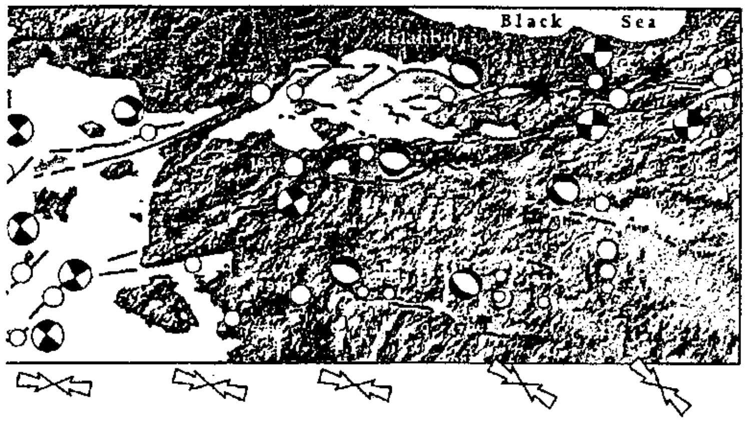
- **Dislocations and Brittle Faulting**
- **Stress Transfer Models (Incluing NAFZ in Turkey)**
- **Coupling Fluid Flow to Large Scale Tectonics**
- **Behavior of a 3-D Fluid-Controlled Earthquake Model**

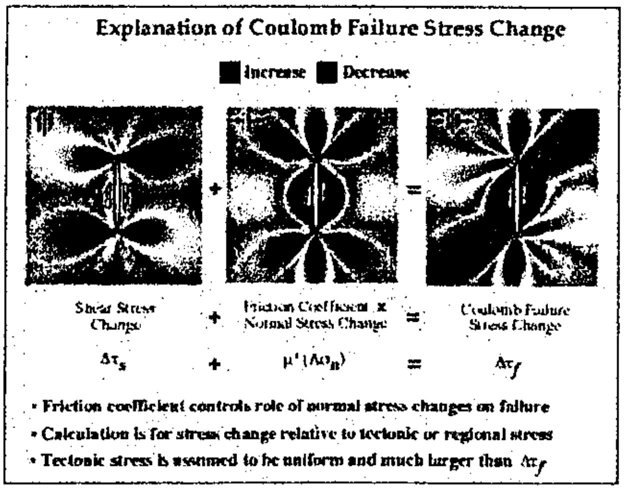
Lecture III: Properties of Large Ruptures and Surface Deformation Field

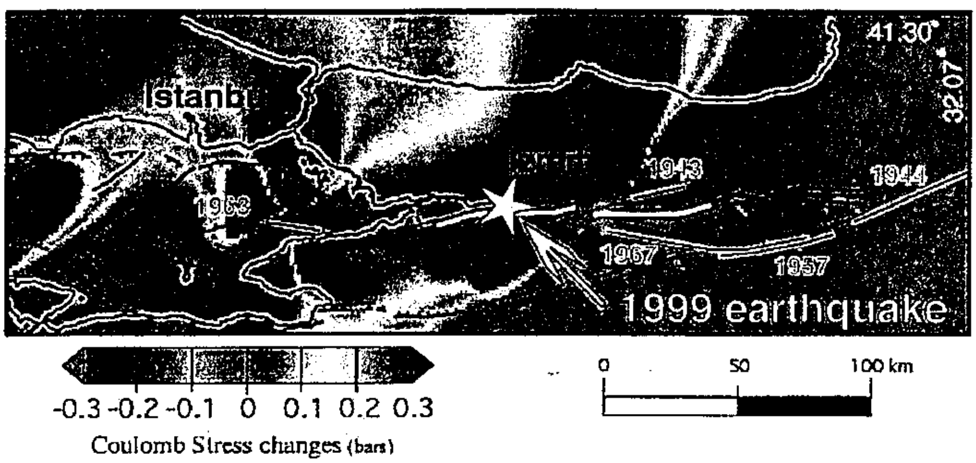
- Review of Some Rupture Models
- Complex Slip of Earthquakes
- General Strain Fields Around Elastic Dislocations
- The Properties of Large Ruptures (e.g. slip, rise time, moment release)
- Comparisons with Earhtquake Catalogs
- The Surface Deformation Field



et al
Massonnet (1996)

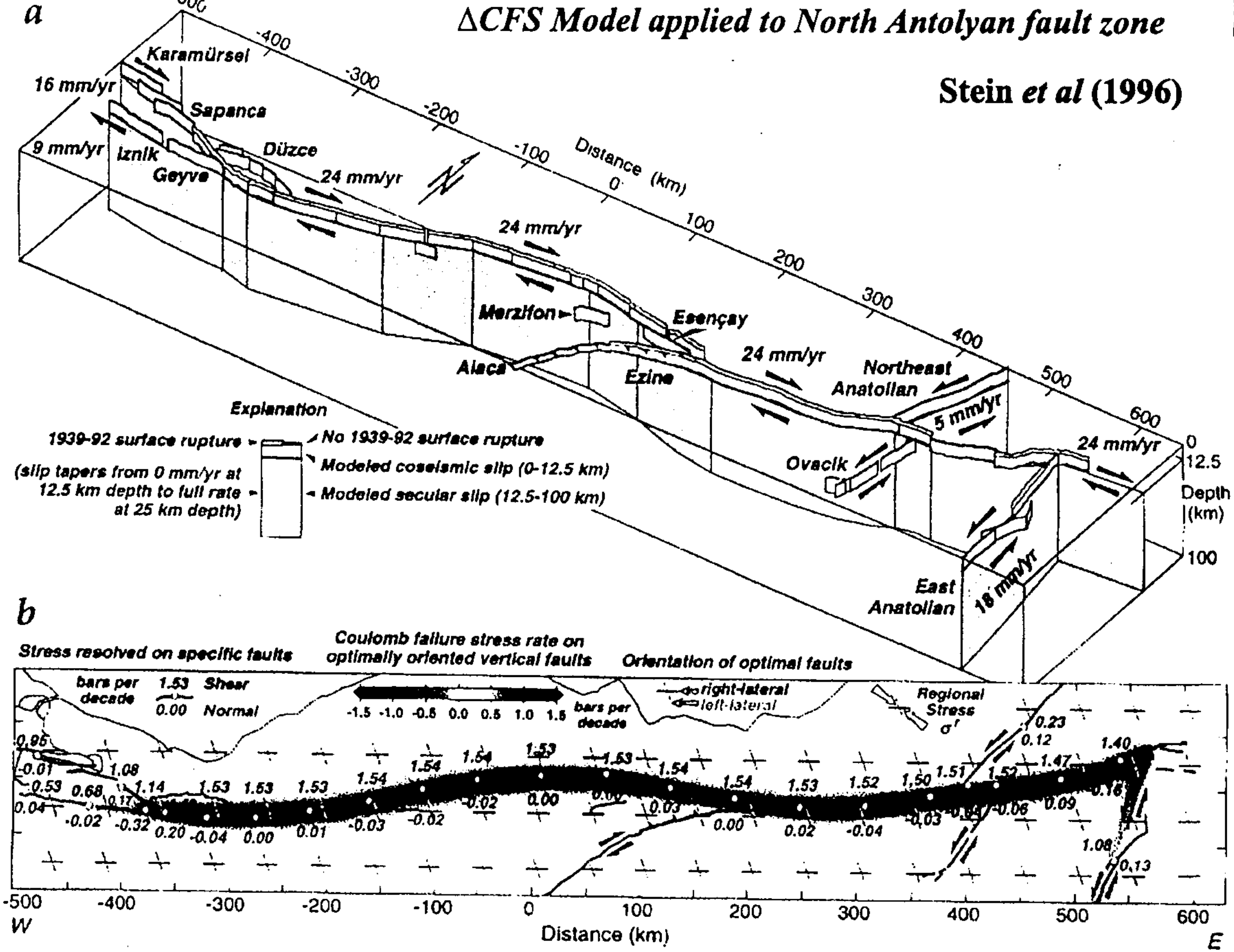

Black Sea
Istanbul


Explanation of Coulomb Failure Stress Change
Increase Decrease
Shear Stress Change
+
Friction Coefficient x Normal Stress Change
=
Coulomb Failure Stress Change
Δτs + μ'(Δσn) = Δτf
• Friction coefficient controls role of normal stress changes on failure
• Calculation is for stress change relative to tectonic or regional stress
• Tectonic stress is assumed to be uniform and much larger than Δτf


41.30°
32.07°
1963
1943
1944
1967
1957
1999 earthquake
-0.3 -0.2 -0.1 0 0.1 0.2 0.3
Coulomb Stress changes (bars)
0
50
100 km

ΔCFS Model applied to North Antolyan fault zone

Stein *et al* (1996)



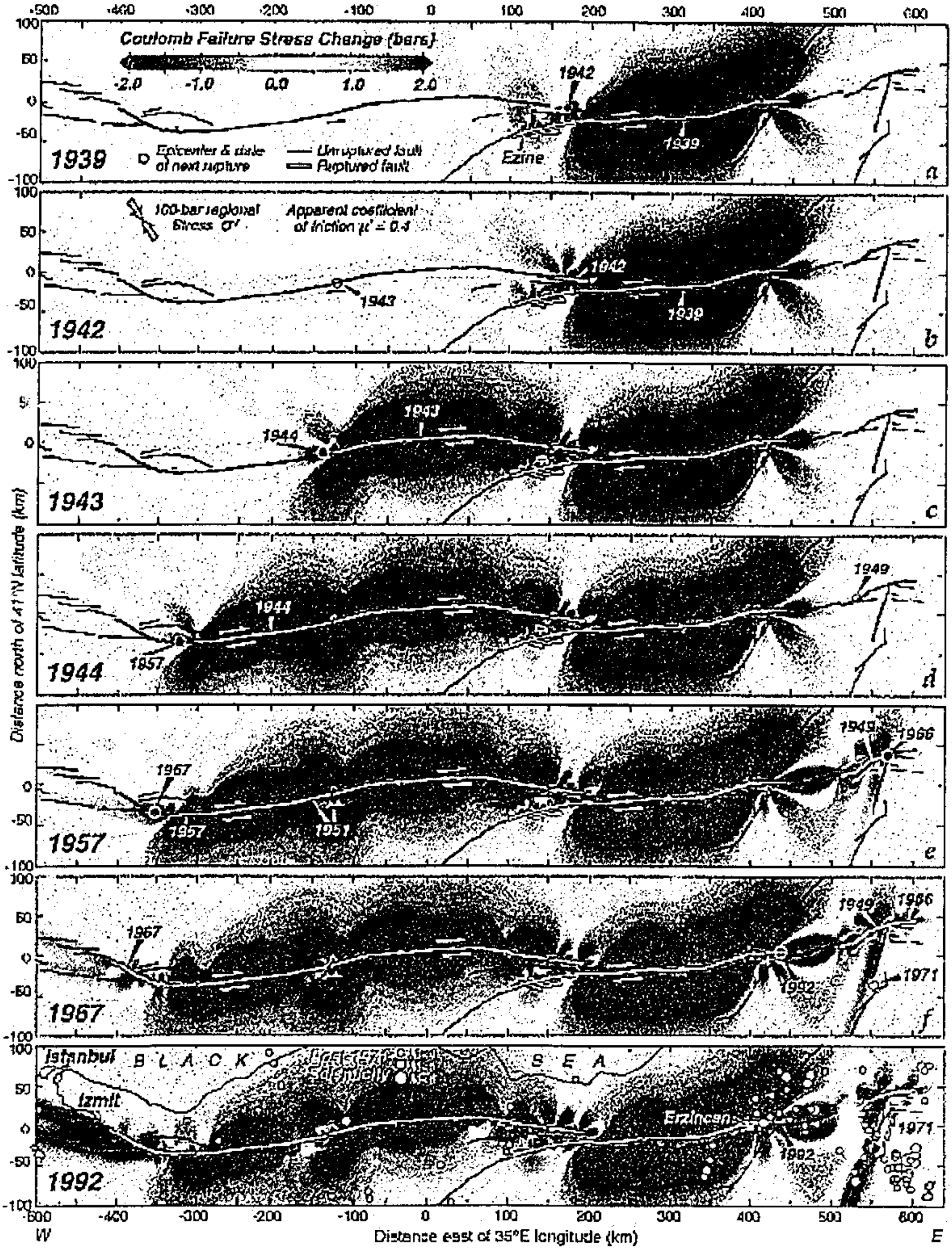
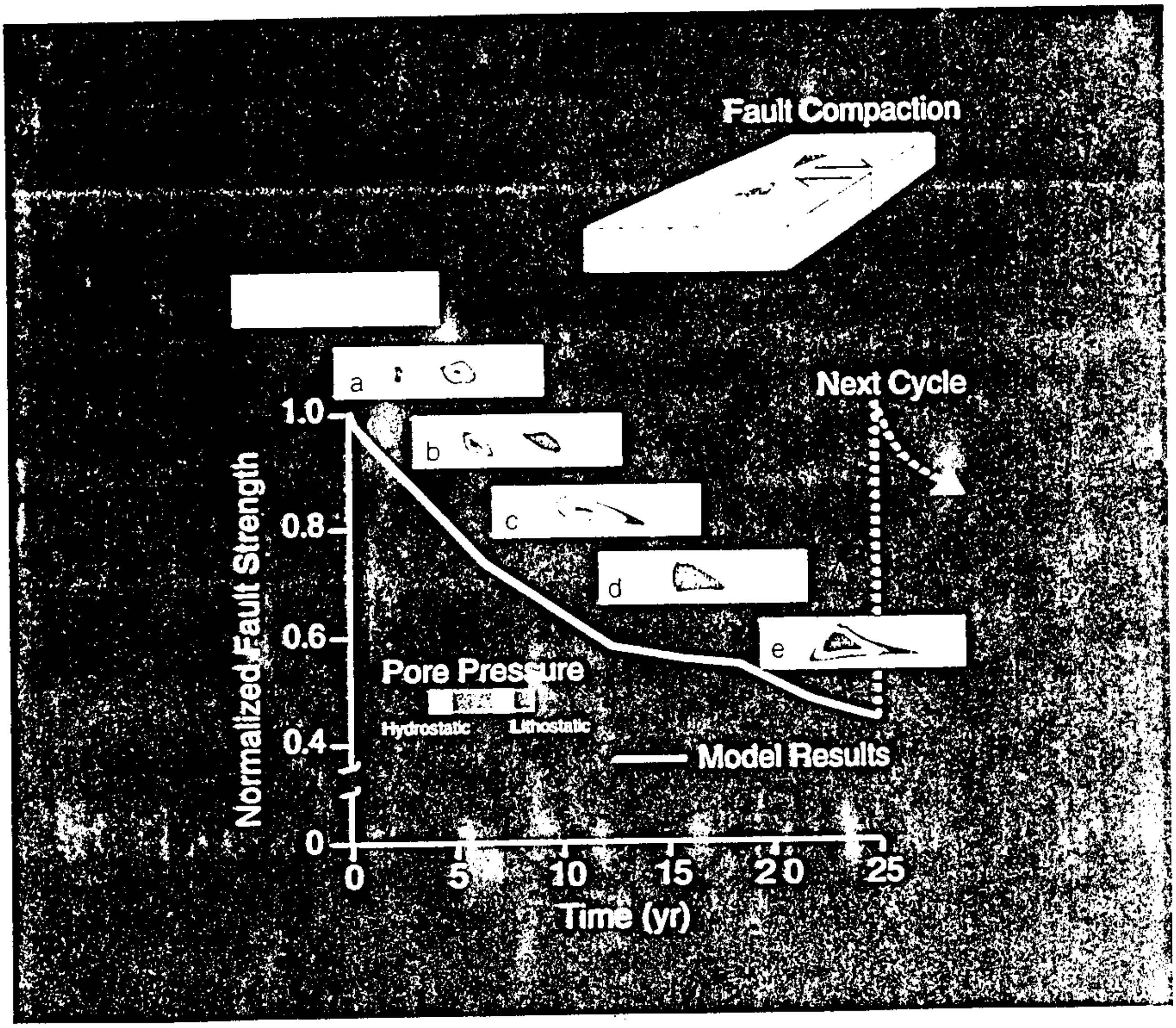


Figure 4 17 Oct 96 Stein et al.

Geophysical
Research
Letters



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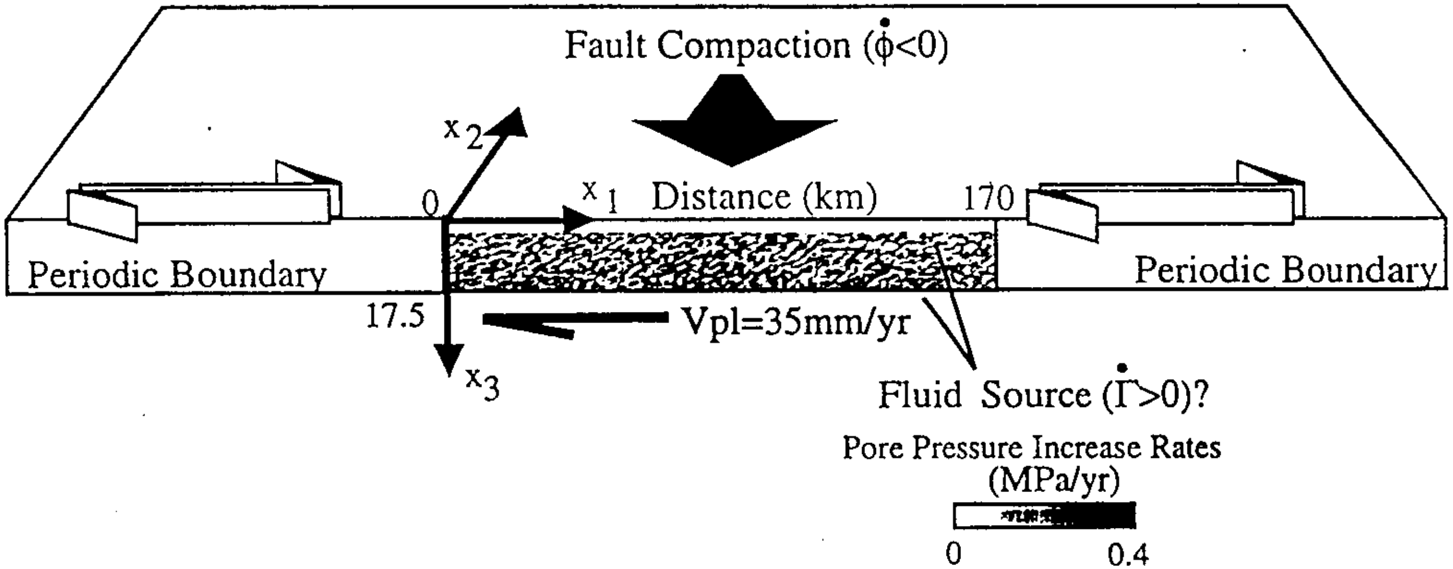
AMERICAN GEOPHYSICAL UNION

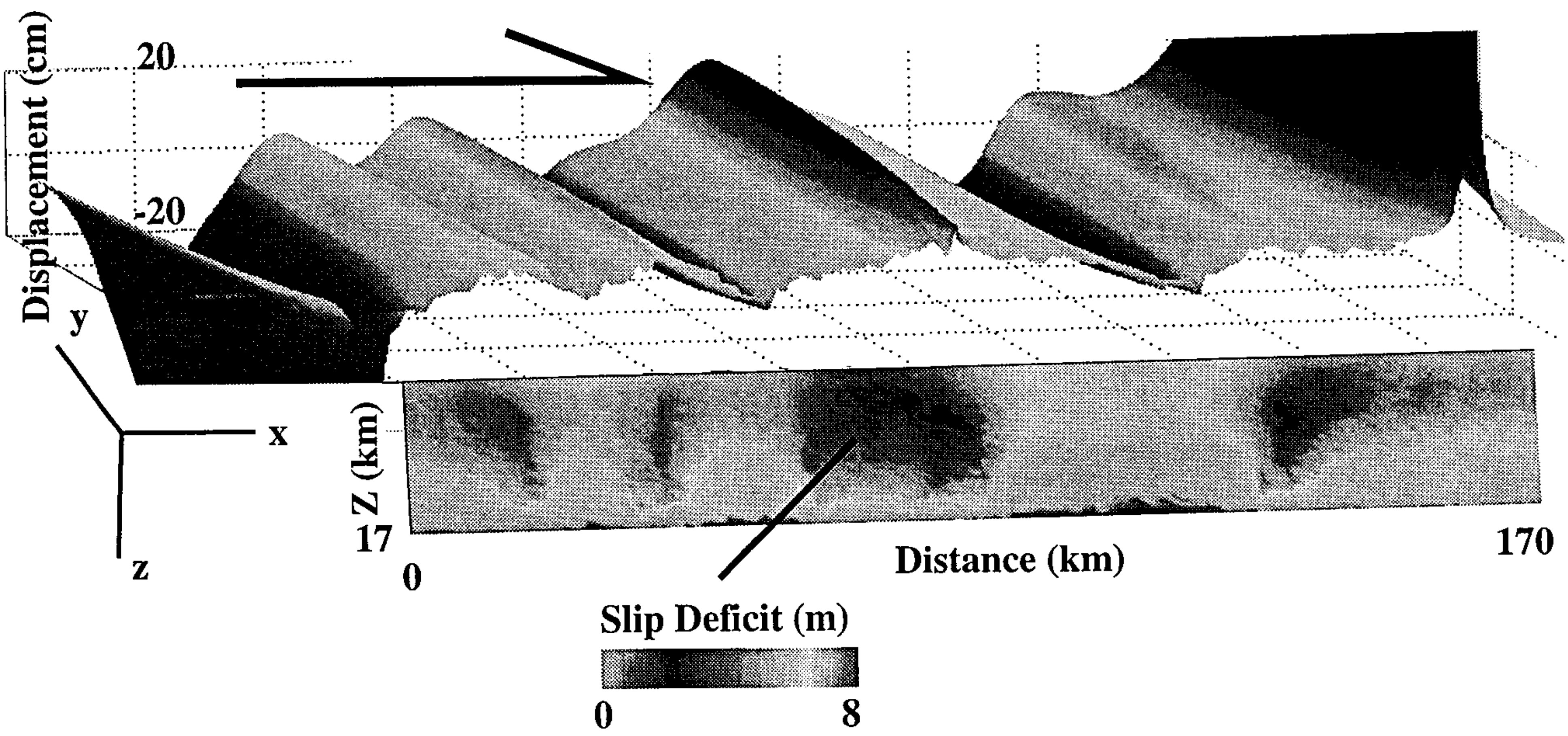
The Model

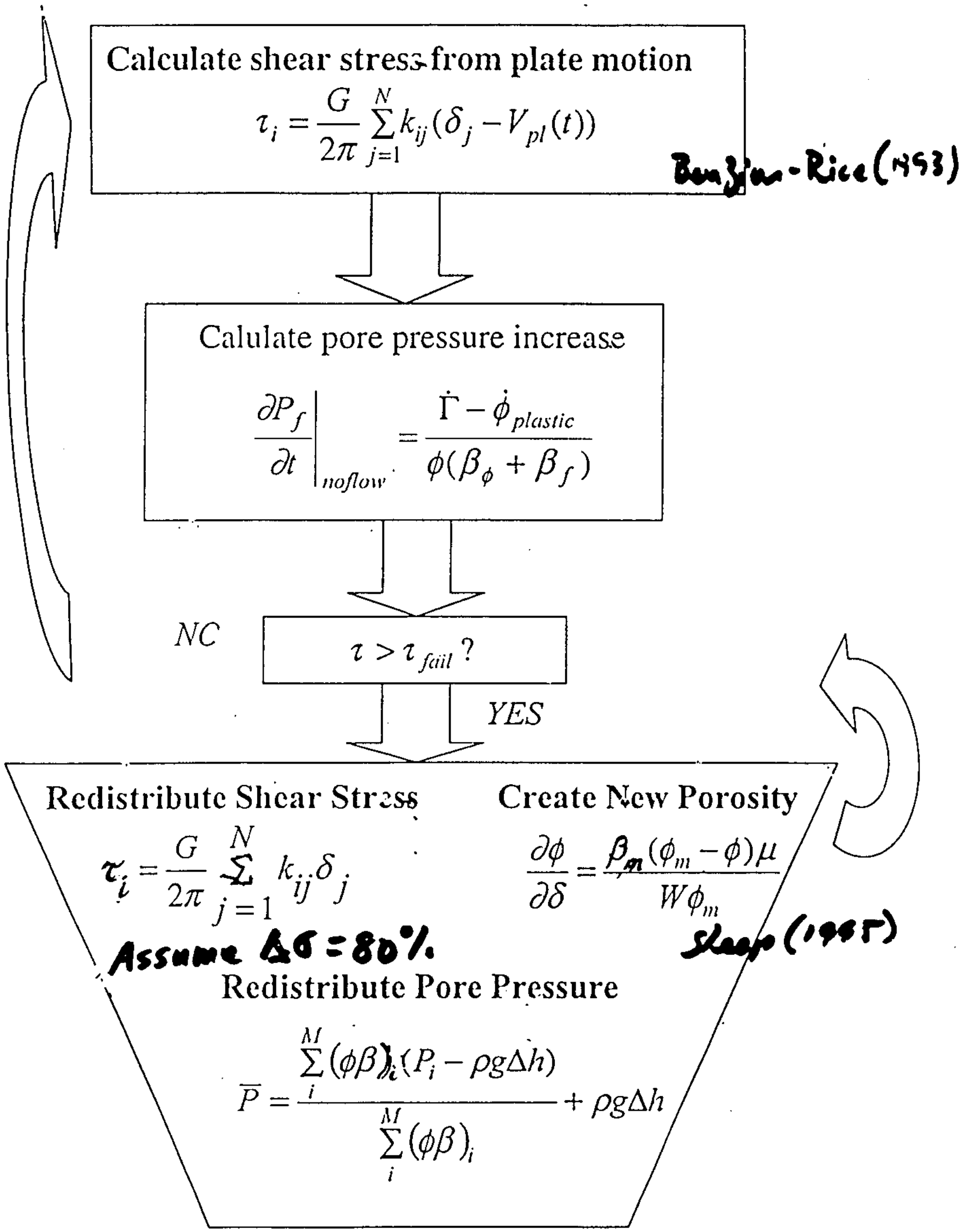


Miller et. al. (JGR 99)

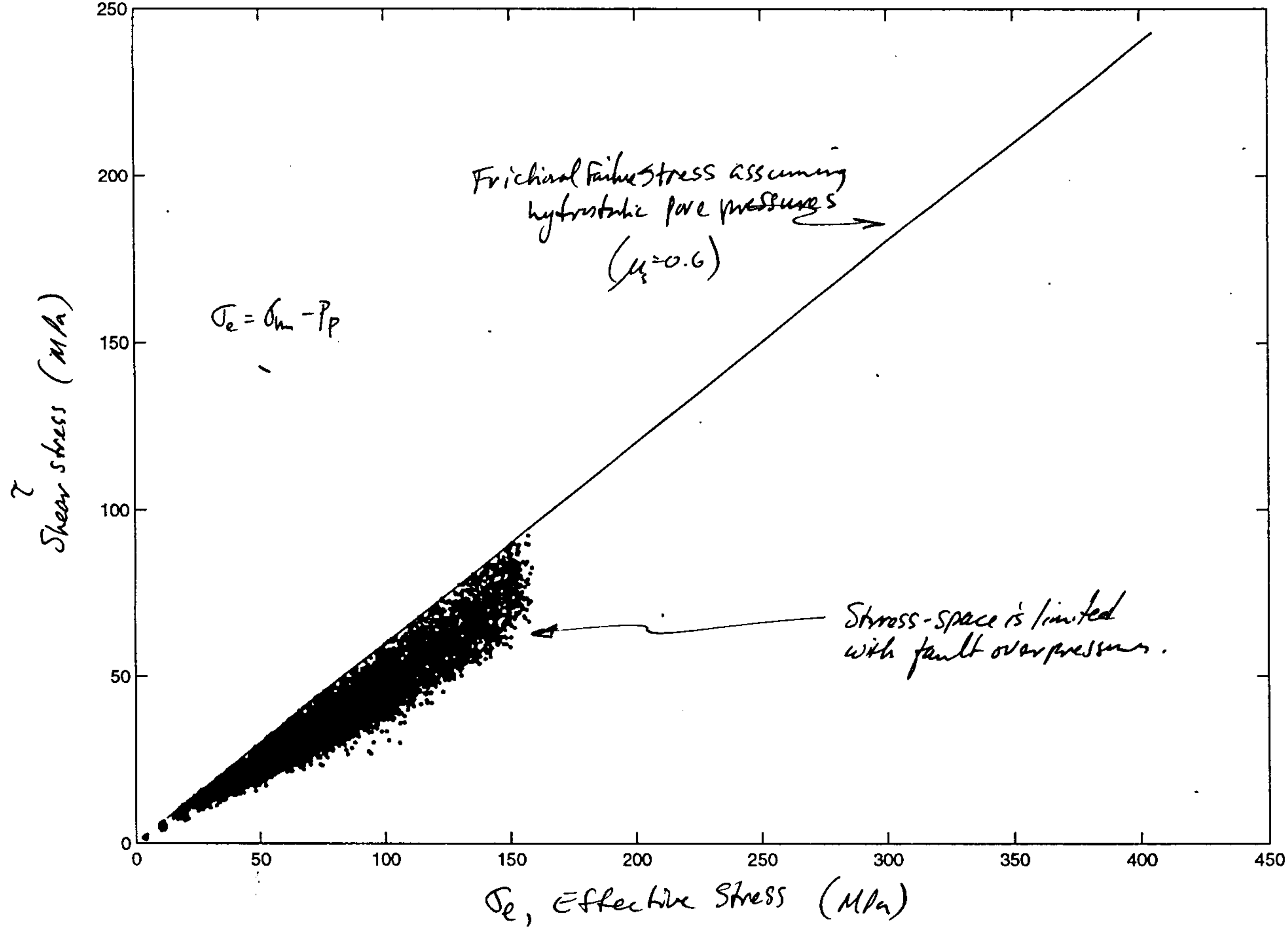
(Elastic) Surface Diplacements in Response to Slip Deficit

Model Results at 4000 years

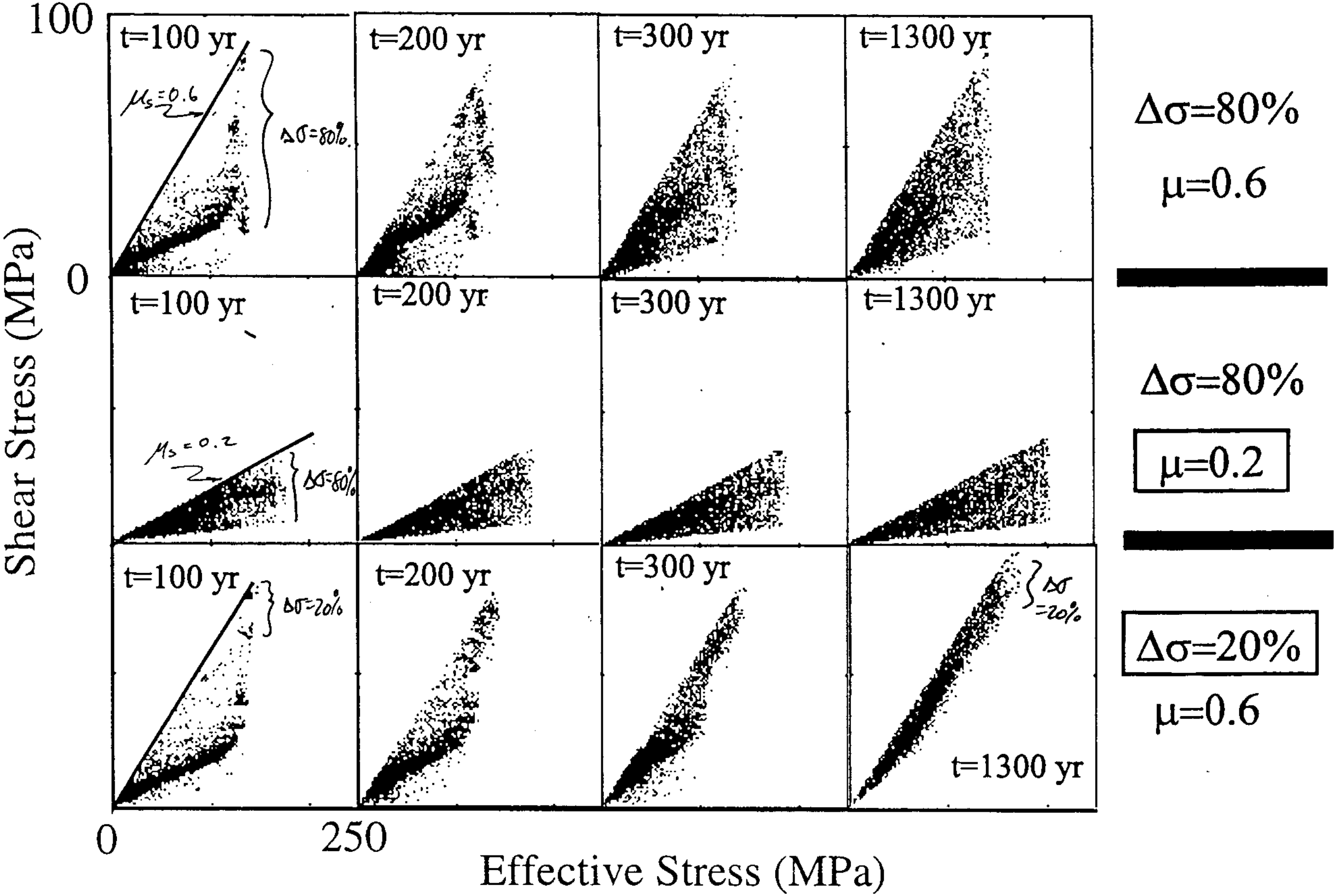


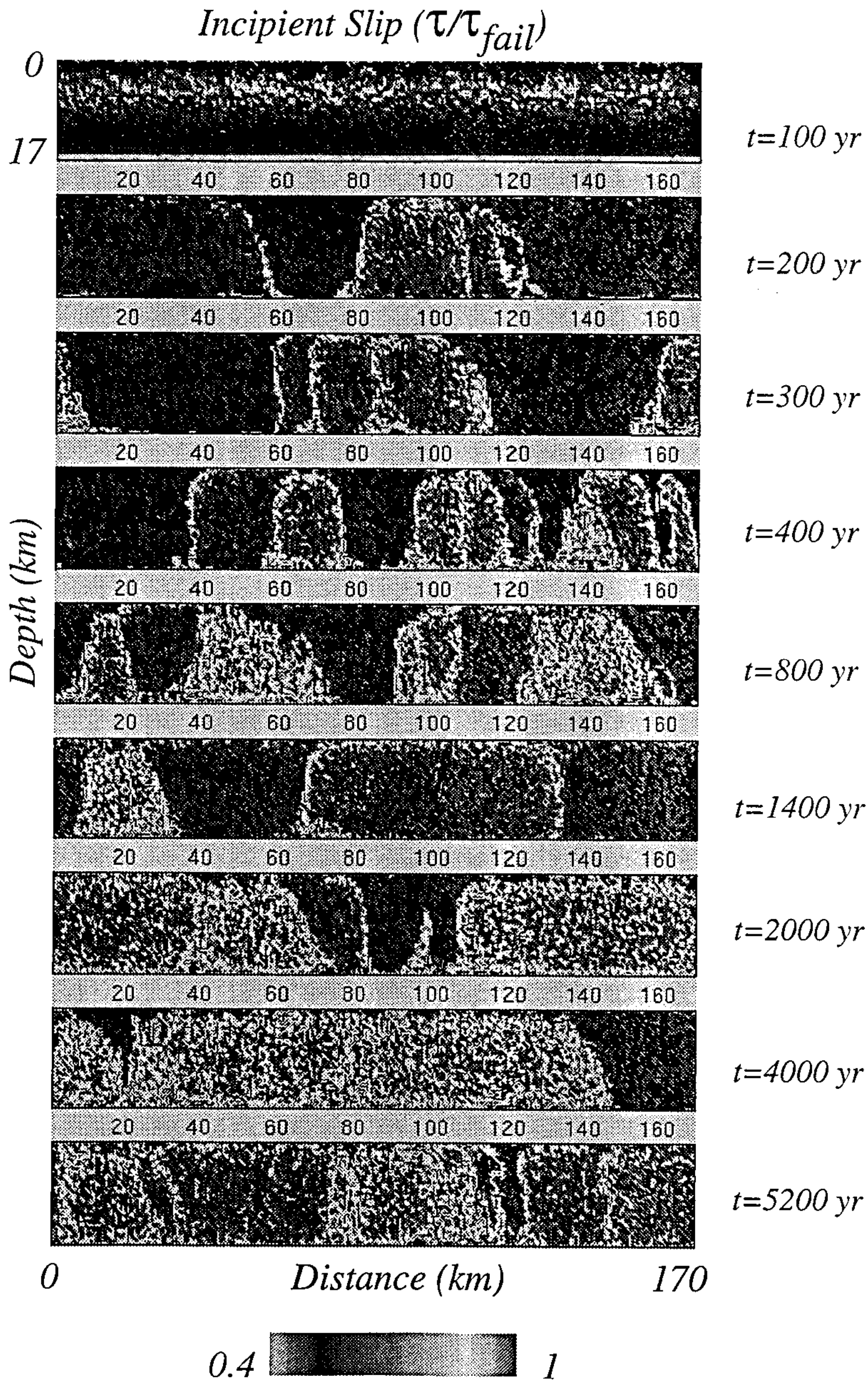

Calculate shear stress from plate motion
$\tau_i = \frac{G}{2\pi} \sum_{j=1}^{N} k_{ij} (\delta_j - V_{pl}(t))$
Ben-Zion-Rice (1993)
Calulate pore pressure increase
$\left.\frac{\partial P_f}{\partial t}\right|_{noflow} = \frac{\dot{\Gamma} - \dot{\phi}_{plastic}}{\phi(\beta_\phi + \beta_f)}$
NC
$\tau > \tau_{fail}$?
YES
Redistribute Shear Stress
$\tau_i = \frac{G}{2\pi} \sum_{j=1}^{N} k_{ij} \delta_j$
Create New Porosity
$\frac{\partial \phi}{\partial \delta} = \frac{\beta_m (\phi_m - \phi) \mu}{W \phi_m}$
Sleep (1995)
Assume Δσ=80%
Redistribute Pore Pressure
$\overline{P} = \frac{\sum_i^M (\phi\beta)_i (P_i - \rho g \Delta h)}{\sum_i^M (\phi\beta)_i} + \rho g \Delta h$

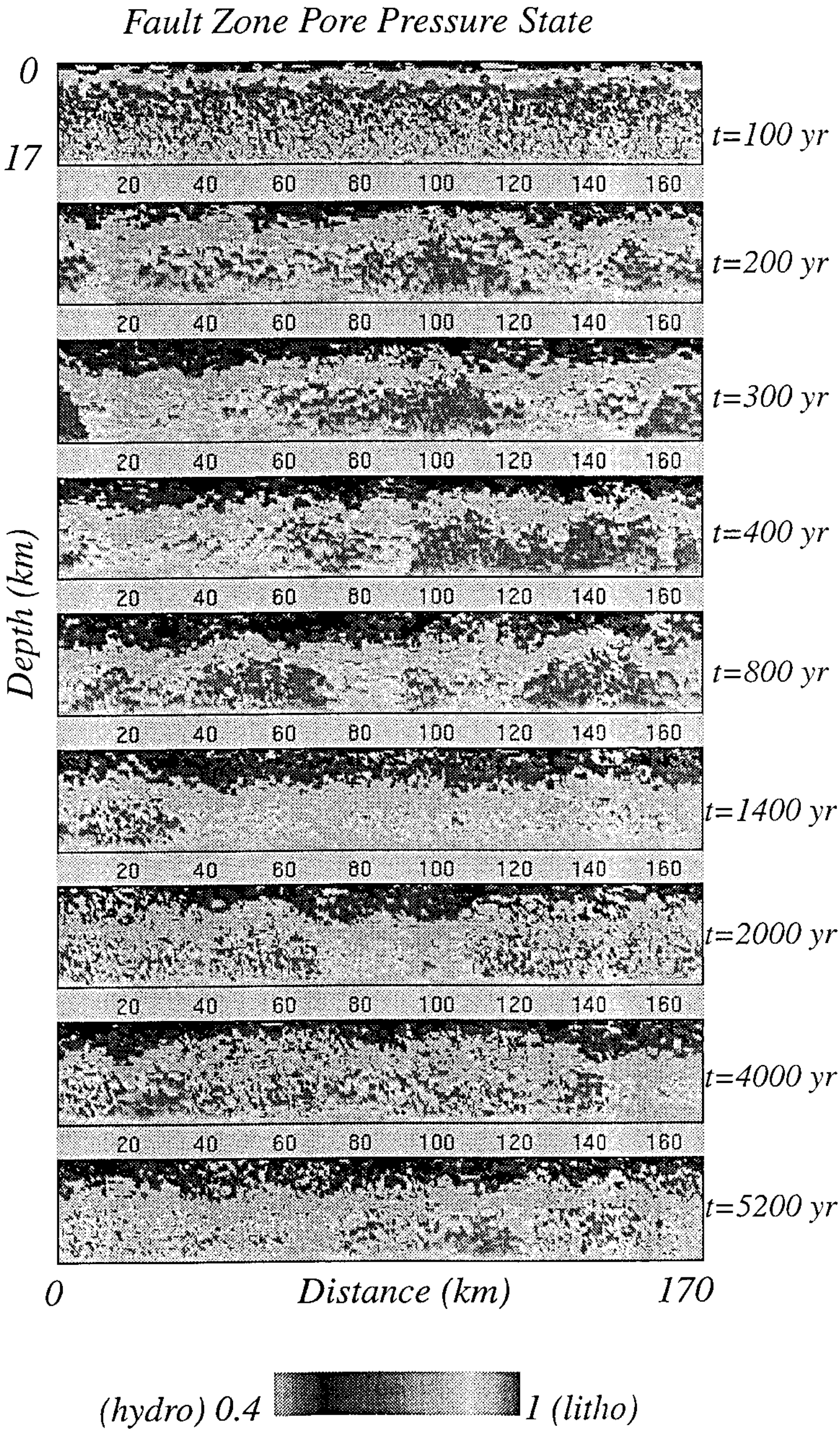
Fault Weakness

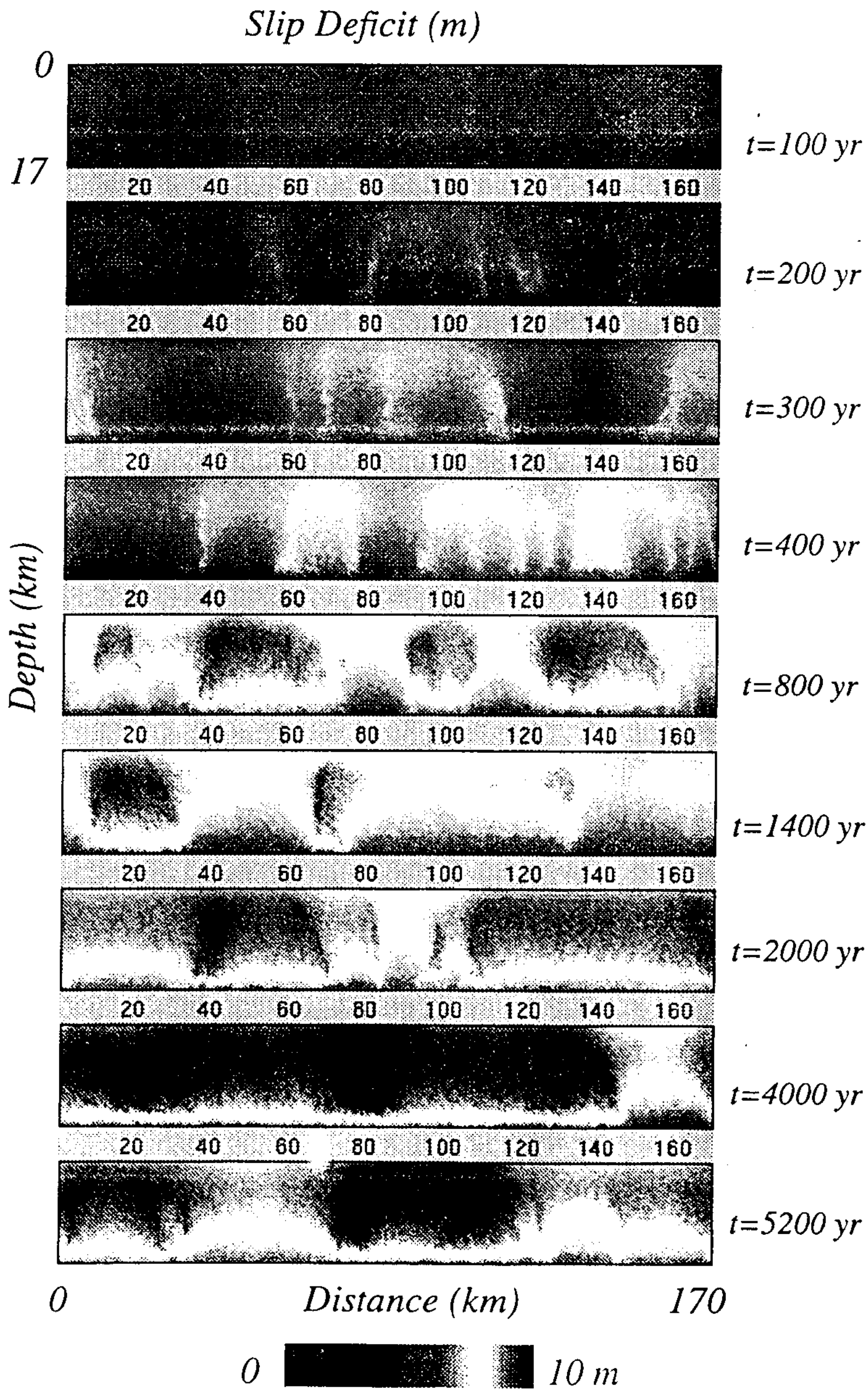


Stress State Evolution in Mohr-space for Different Cases

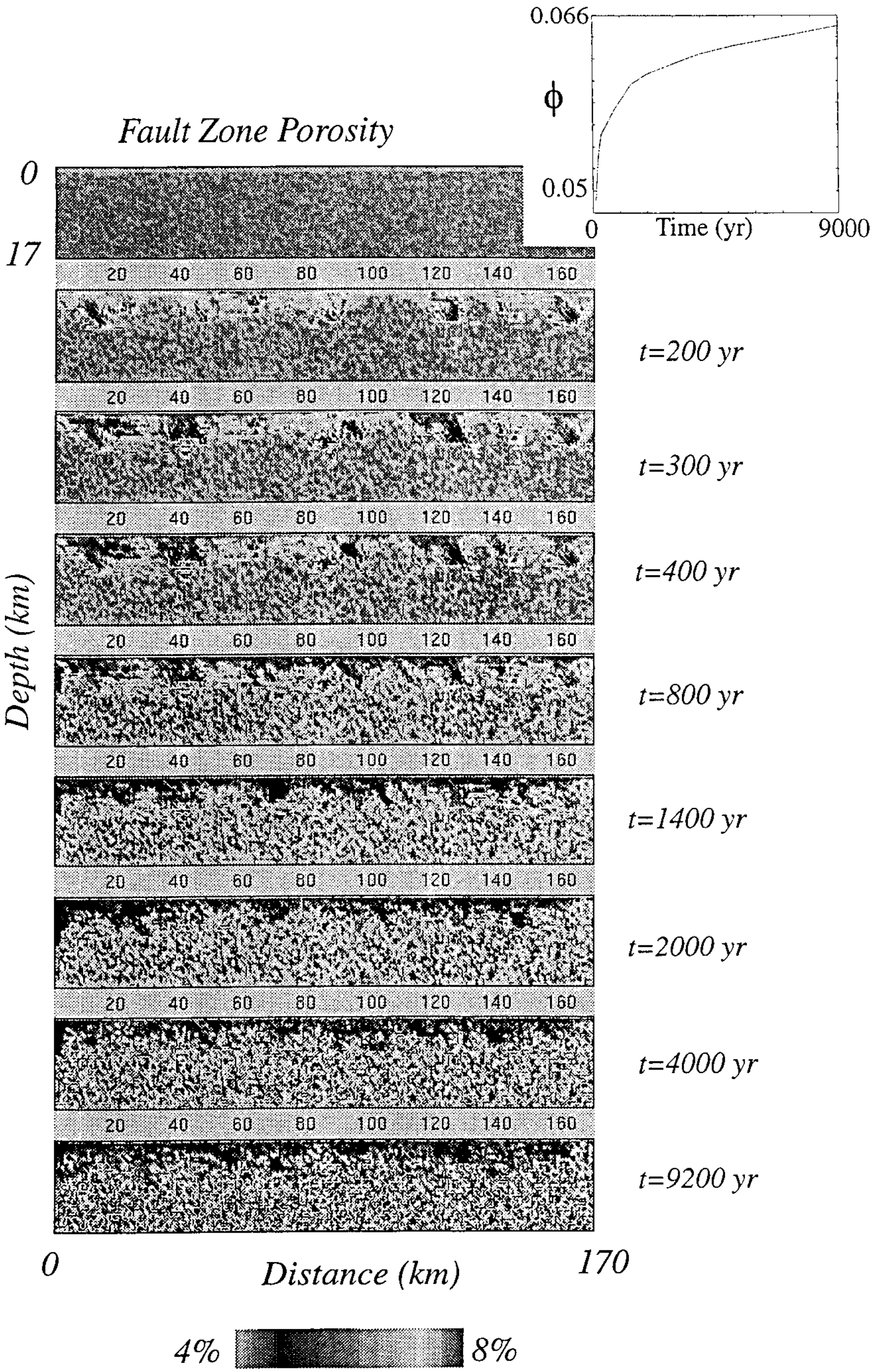


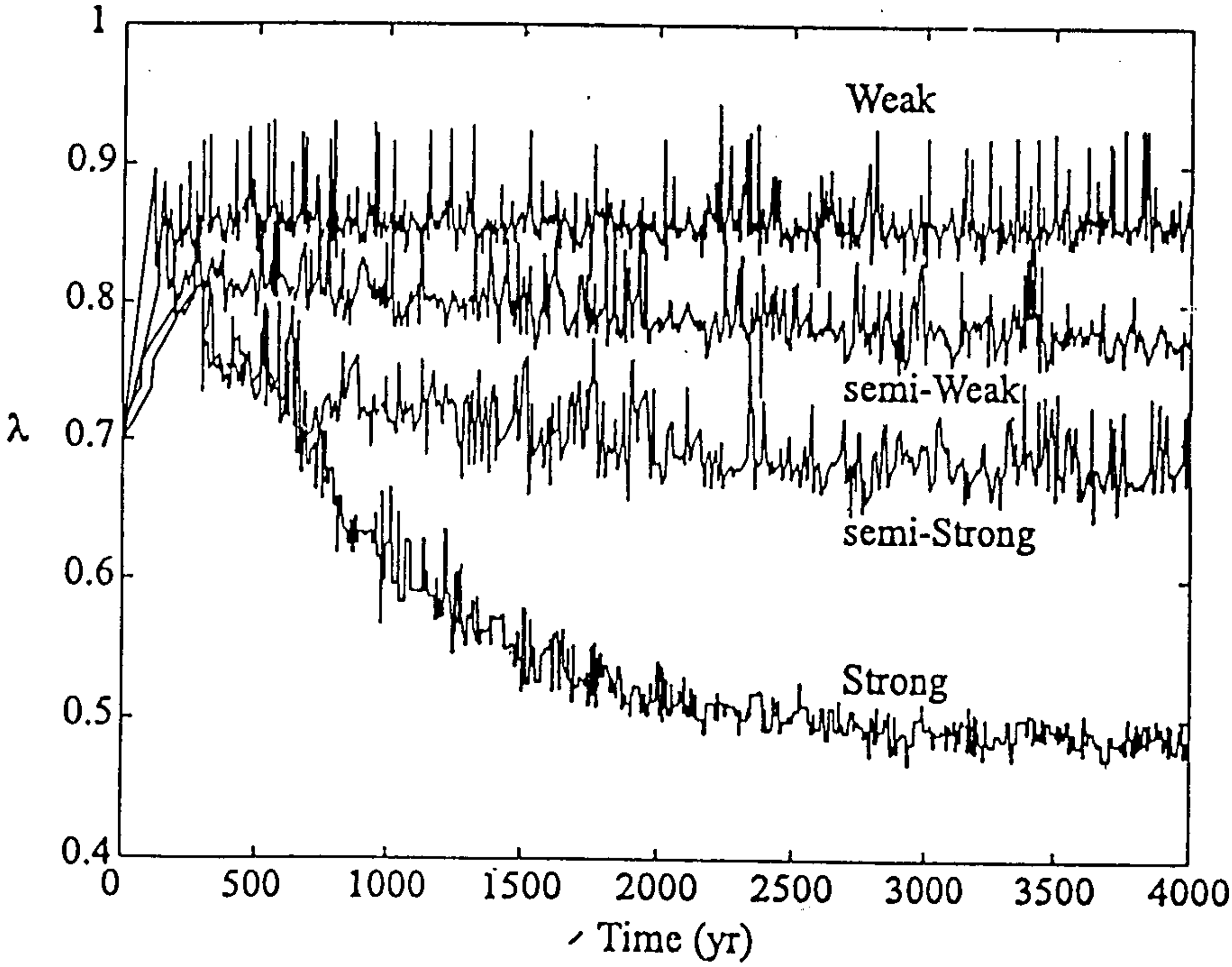

Incipient Slip (τ/τ_{fail})
0
17
Depth (km)
t=100 yr
t=200 yr
t=300 yr
t=400 yr
t=800 yr
t=1400 yr
t=2000 yr
t=4000 yr
t=5200 yr
20 40 60 80 100 120 140 160
0
Distance (km)
170
0.4
1


Fault Zone Pore Pressure State
0
17
Depth (km)
20 40 60 80 100 120 140 160
t=100 yr
t=200 yr
t=300 yr
t=400 yr
t=800 yr
t=1400 yr
t=2000 yr
t=4000 yr
t=5200 yr
0
Distance (km)
170
(hydro) 0.4
1 (litho)



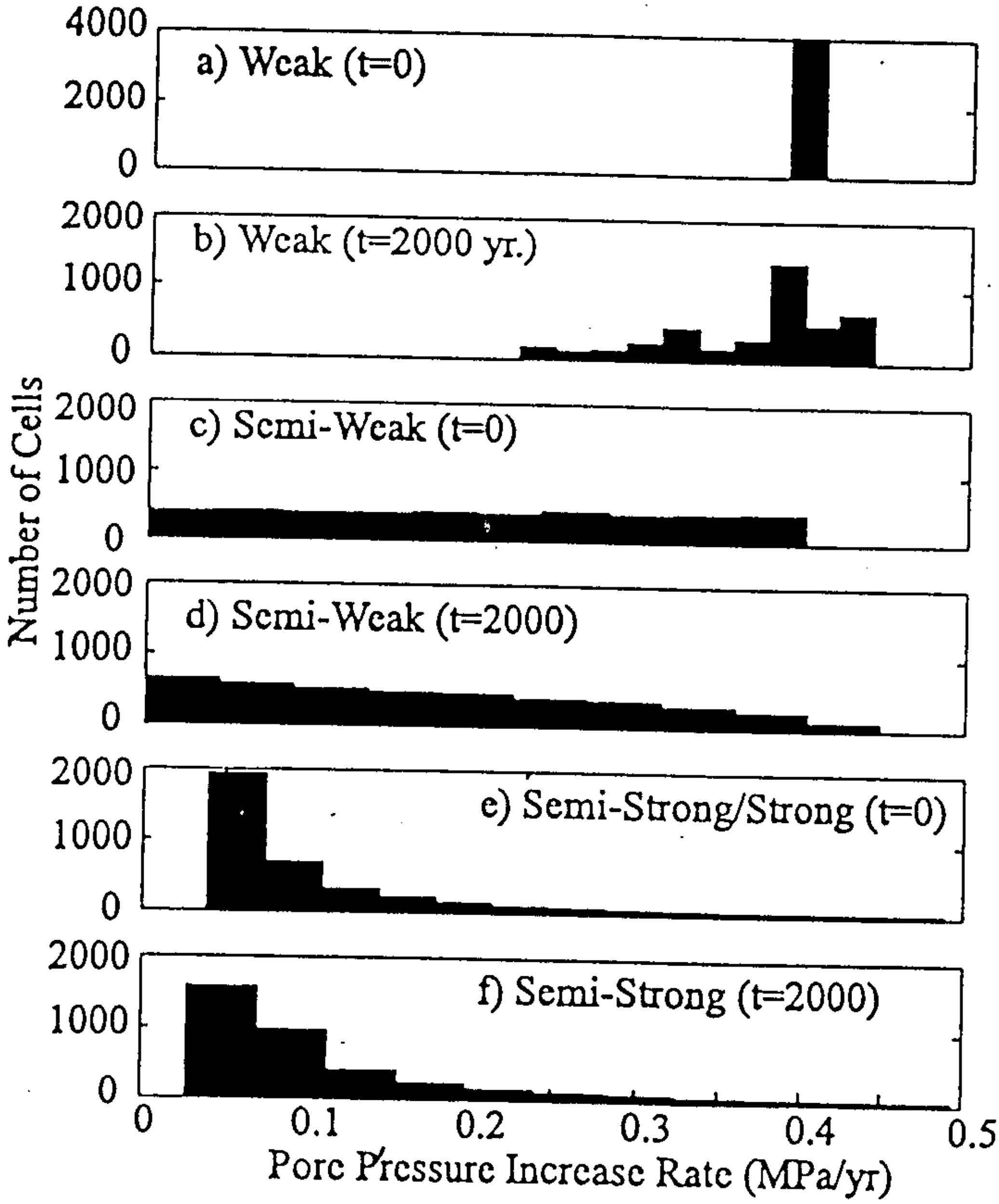
Slip Deficit (m)
0
17
Depth (km)
t=100 yr
t=200 yr
t=300 yr
t=400 yr
t=800 yr
t=1400 yr
t=2000 yr
t=4000 yr
t=5200 yr
20 40 60 80 100 120 140 160
0
Distance (km)
170
0
10 m


Fault Zone Porosity
0.066
ϕ
0.05
0
Time (yr)
9000
0
17
Depth (km)
20 40 60 80 100 120 140 160
t=200 yr
t=300 yr
t=400 yr
t=800 yr
t=1400 yr
t=2000 yr
t=4000 yr
t=9200 yr
0
Distance (km)
170
4%
8%



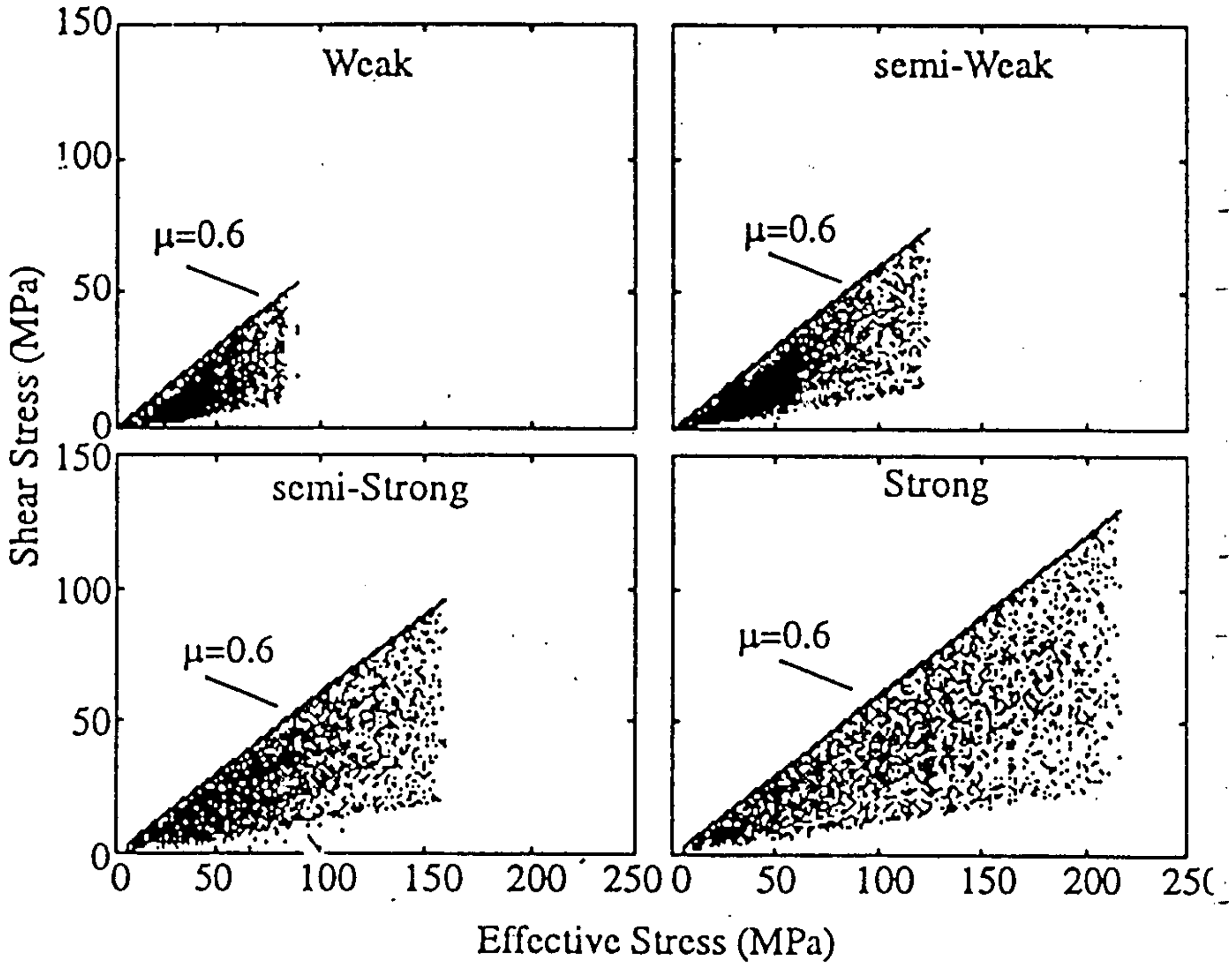
Miller et al (99)

INPUT TO MODEL: RATE of PORE PRESSURE INCREASE



Miller et al (99)

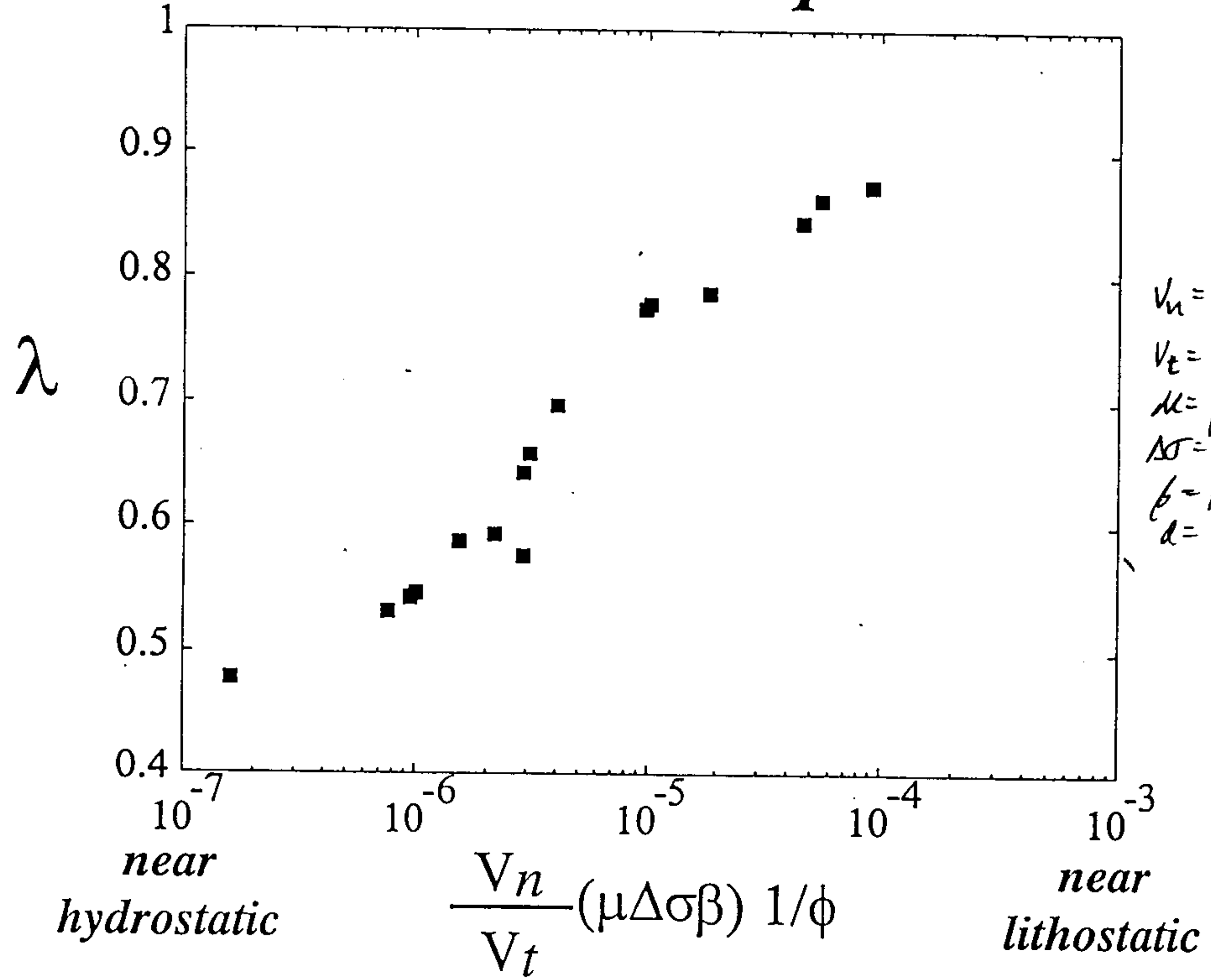
LONG-TERM EQUILIBRIUM IS MAXIMUM STRESS-SPACE DISORDER



Miller et. al (99)

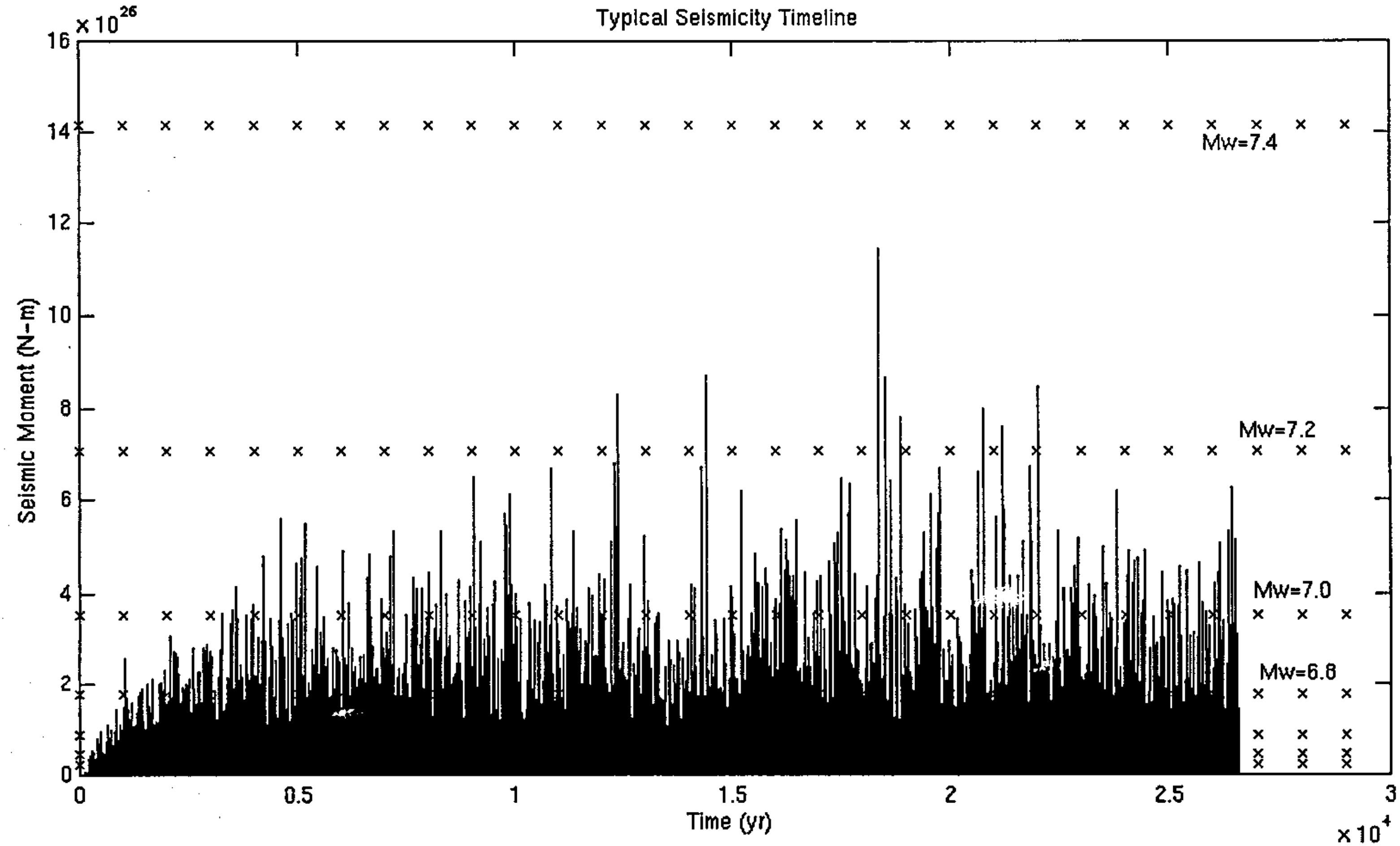
NON-DIMENSIONALIZING THE PROBLEM

Fault Zone Overpressure

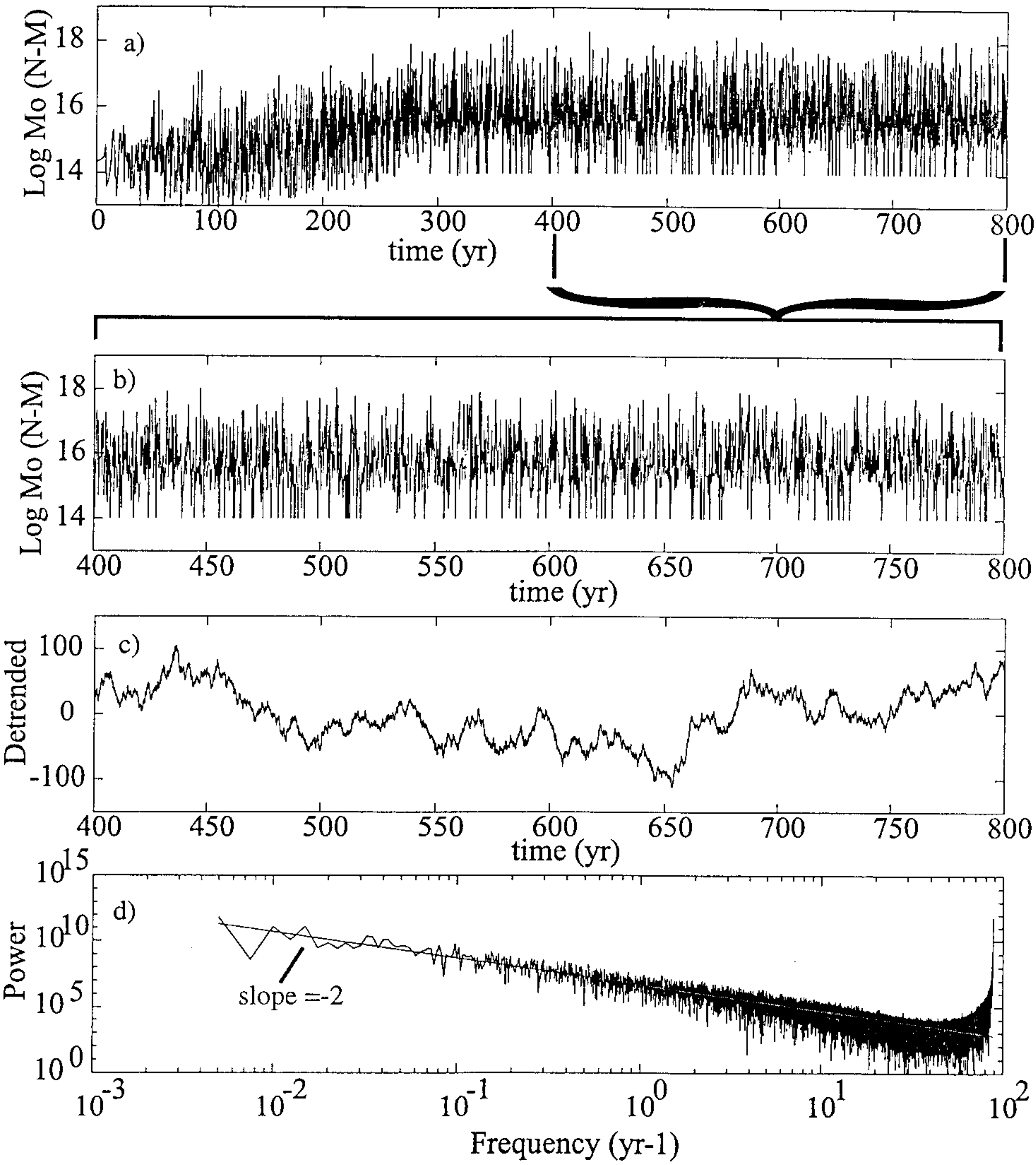


V_n = Fault-Normal velocity
V_t = Fault-tangential velocity
μ = friction coefficient
$\Delta\sigma$ = stress drop
β = pore compressibility
ϕ = porosity

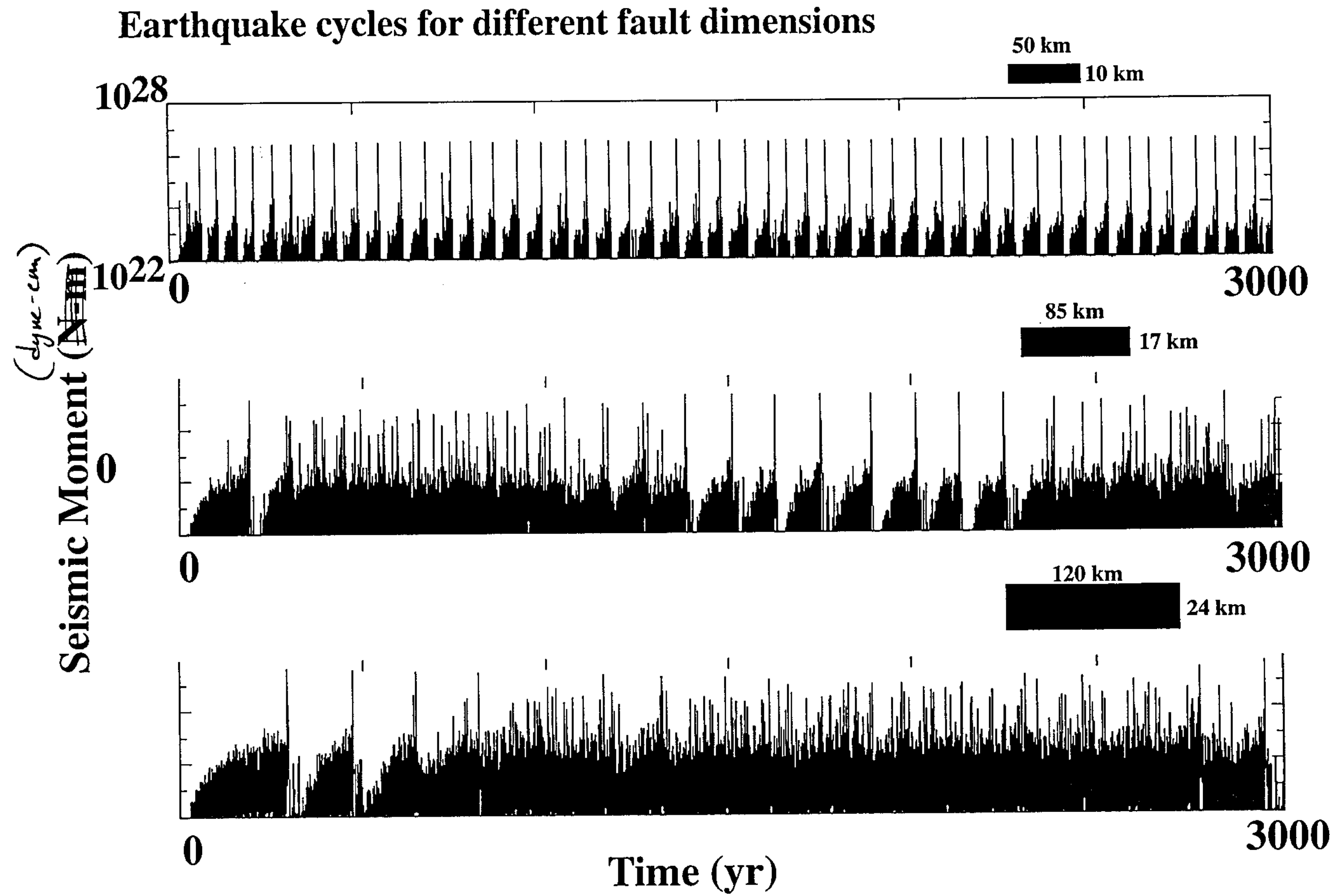
Miller & Podladchikov. (in prep.)


Typical Seismicity Timeline
× 10^26
16
14
12
10
8
6
4
2
0
Seismic Moment (N-m)
Mw=7.4
Mw=7.2
Mw=7.0
Mw=6.8
0
0.5
1
1.5
2
2.5
3
Time (yr)
× 10^4

Static Friction Only = Random Moment Release



Miller et al. (JGR 1999)



Earthquake cycles for different fault dimensions
50 km
10 km
10^{28}
10^{22}
0
3000
85 km
17 km
0
0
3000
120 km
24 km
0
3000
Seismic Moment (N-m)
(dyne-cm)
Time (yr)

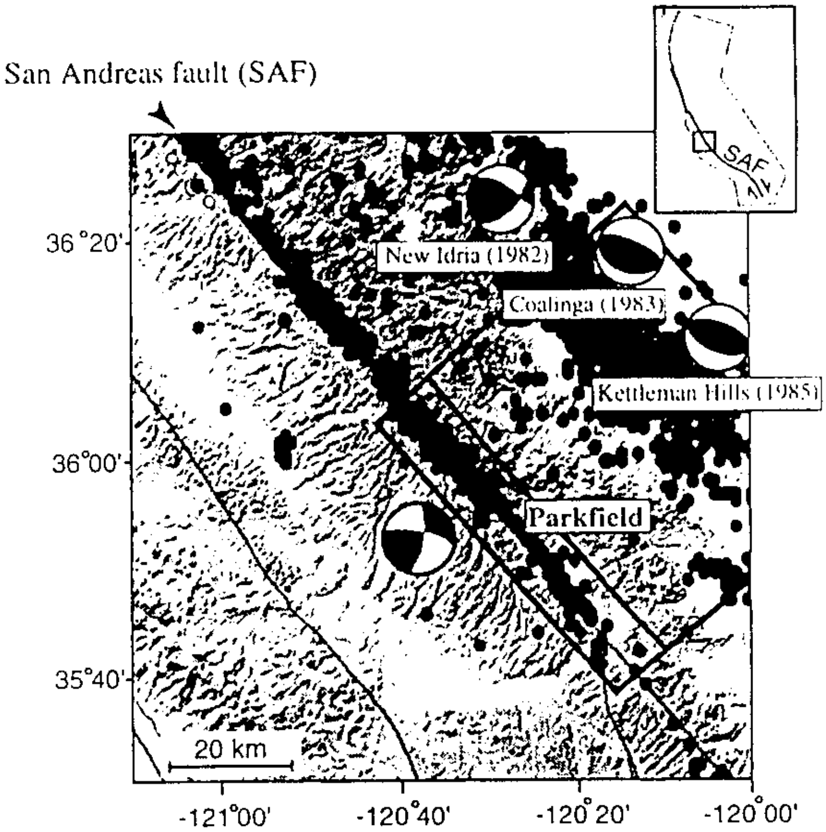


FIG. 1 Map of the study area (courtesy of US Geological Survey, USGS) with the epicentre (circles) of all events ($M \geqslant 2.5$) from January 1969 to October 1995 (data provided by the NCEDC). Concentrated epicentres mark the San Andreas fault, and the New Idria, Coalinga and Kettleman Hills regions are shown by the epicentres to the northeast. The beach balls show strike slip earthquake focal mechanisms along the San Andreas fault, and thrust fault focal mechanisms in the Coalinga region[14]. For results presented in this Letter, the region is separated into Coalinga–Kettleman Hills (CK), and 60 km along strike, centred around Parkfield (denoted by boxes).

of the geodetic data[8,16]. Changes in fault-

Miller (Nature, '96)

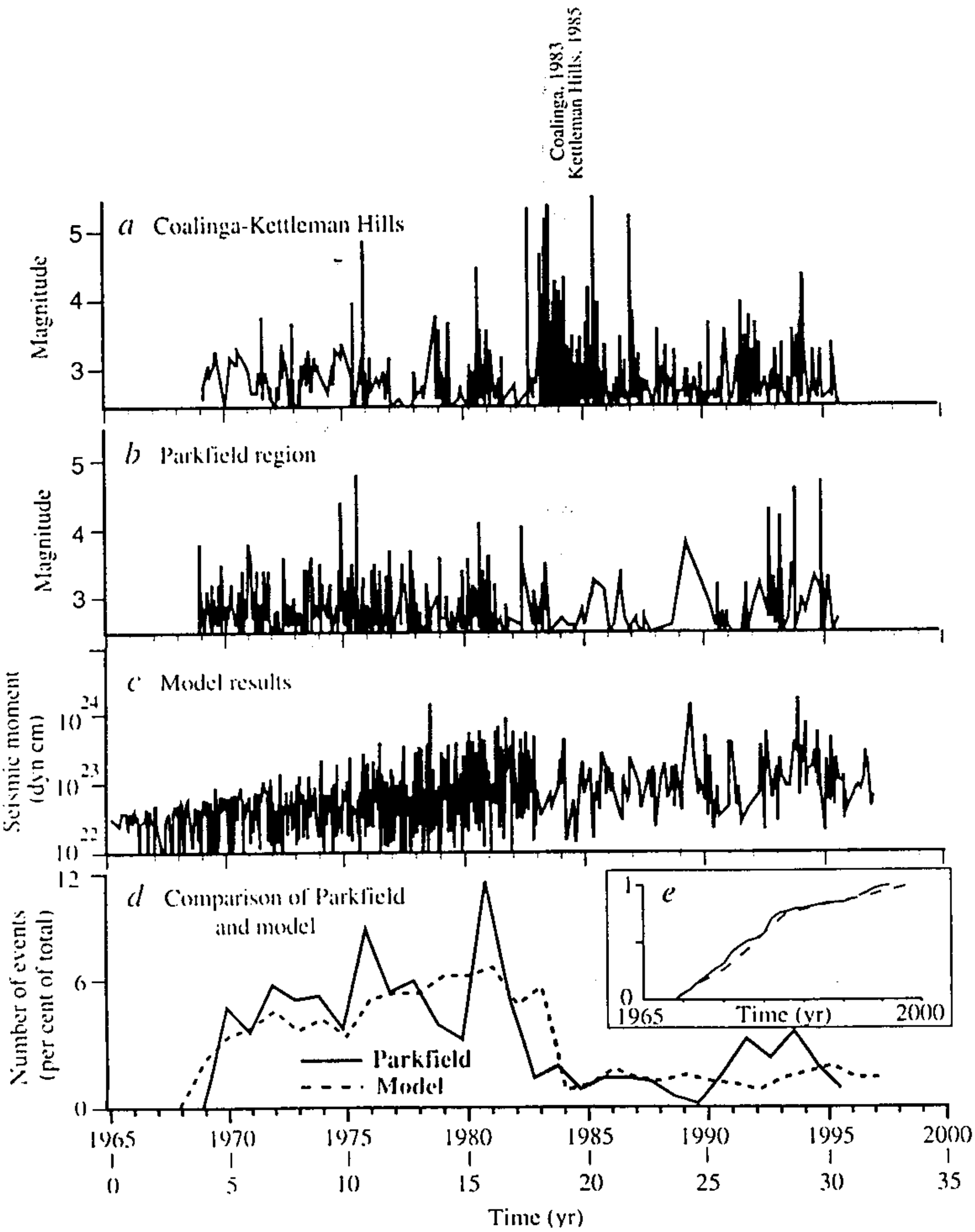
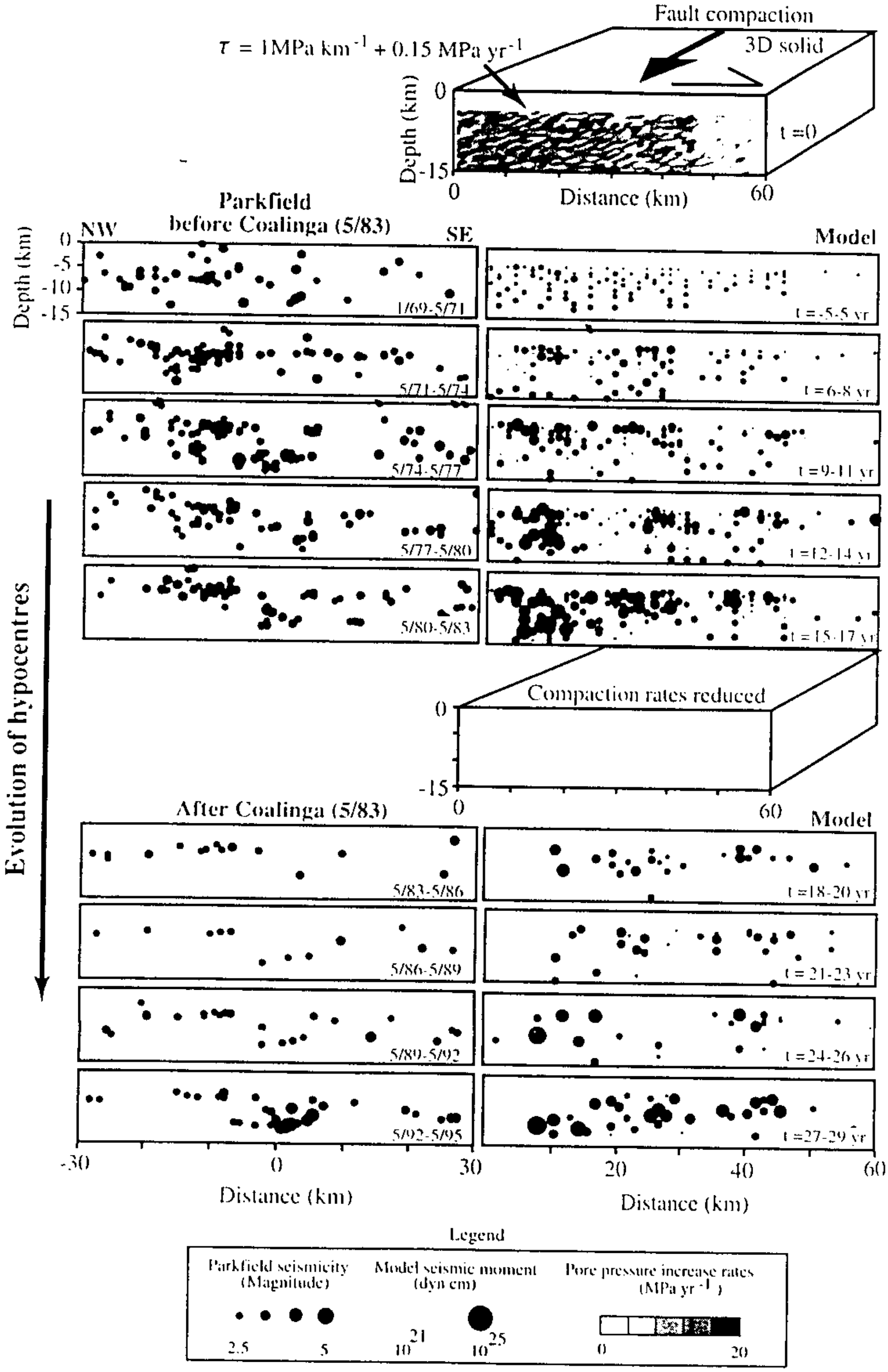


FIG. 2 Time history of seismicity for Coalinga–Kettleman Hills (*a*), Parkfield (*b*) and model results (*c*). A comparison of Parkfield seismicity and model results is shown in *d* as a percentage of the total number of events for Parkfield (478 events) and in the model (657 events). A comparison of the cumulative number of events (derived by integrating the distribution in *d*) is shown in *e*. The spatial distribution of records in *b and* c are compared in Figs 3 and 4.

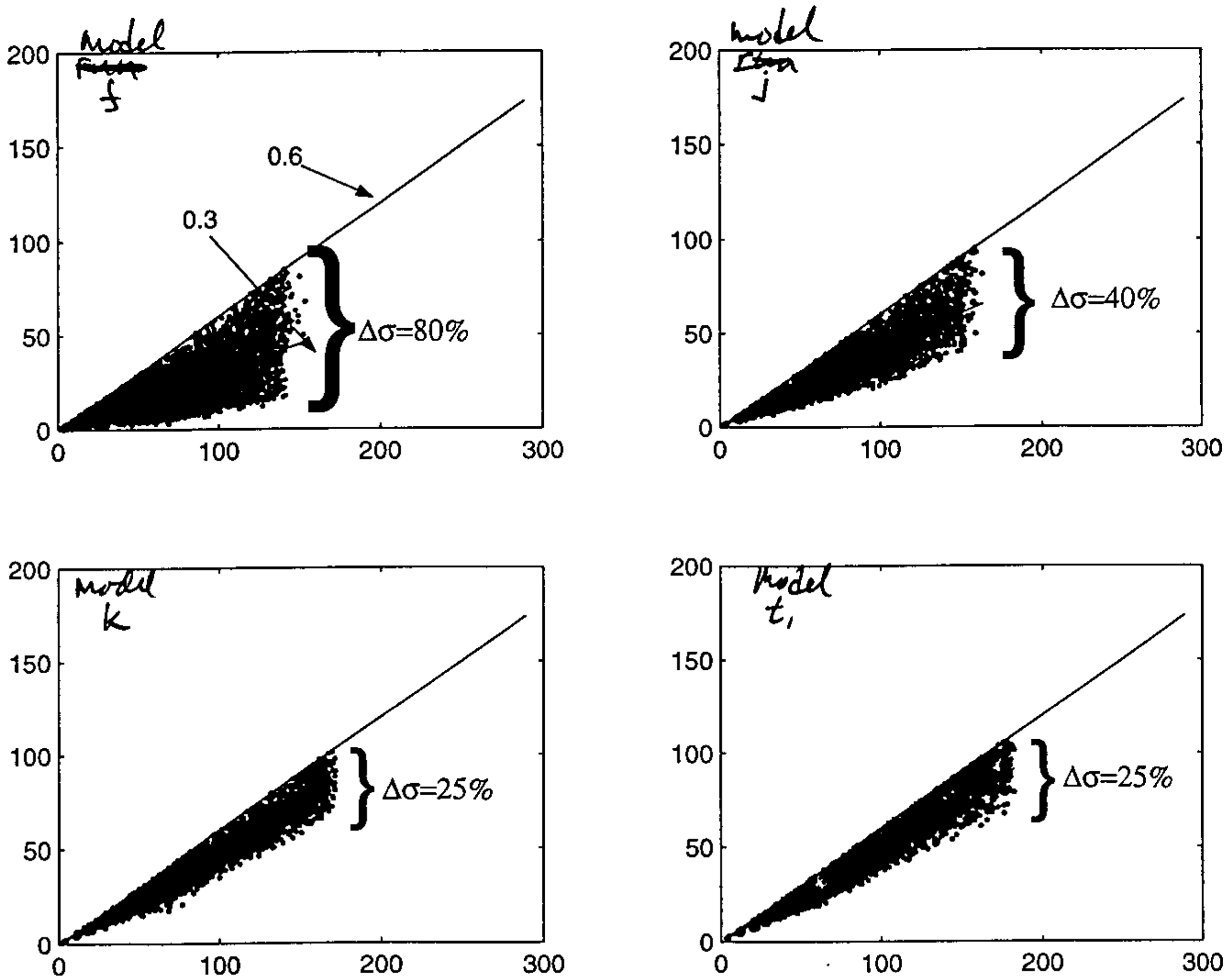
A comparison

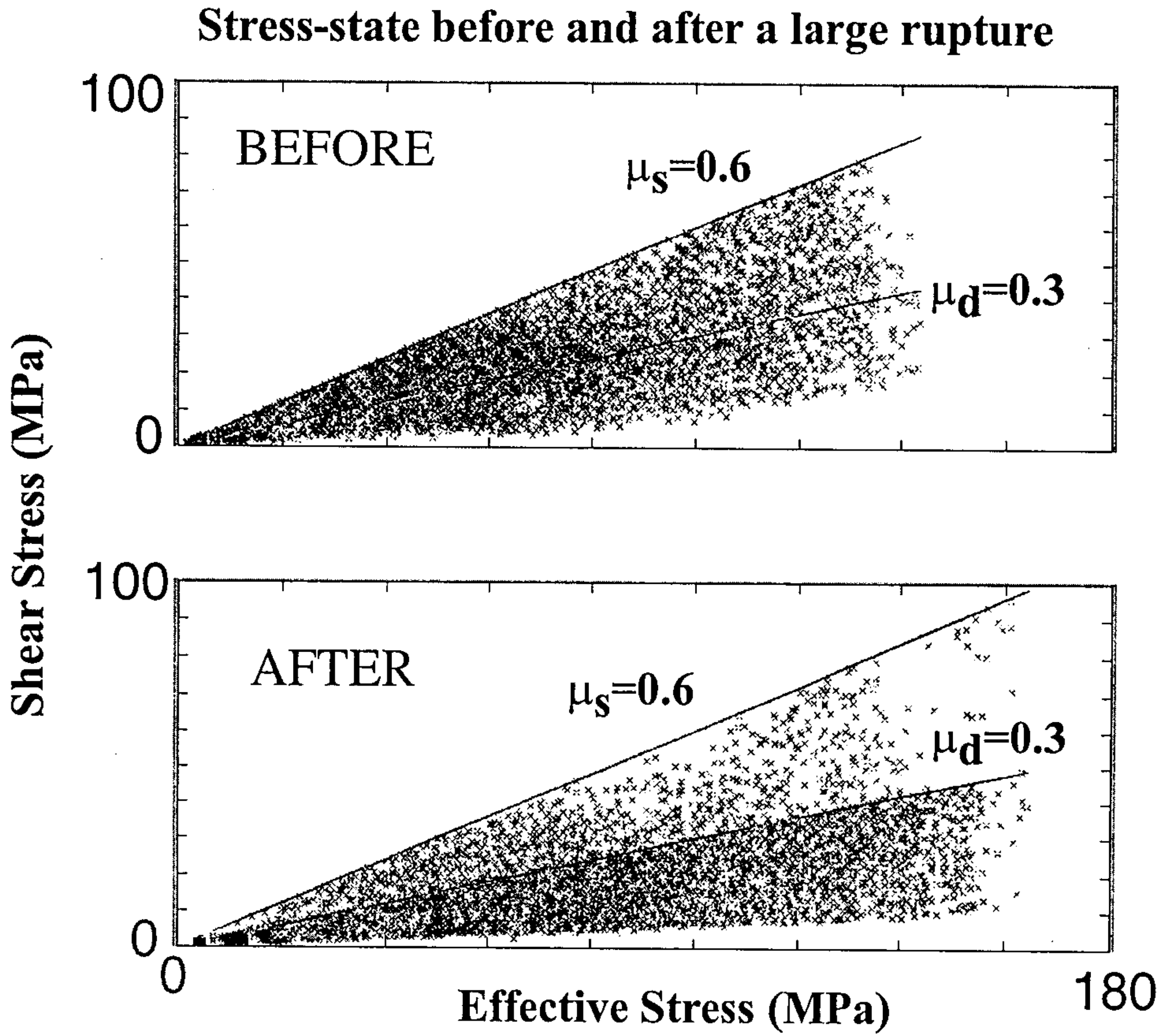
Miller (Nature, 96)

s around
ocentres
9 to May
pocentre
e three-
pressure
e model
sociated
nd Park-
owed by
1990. In
clusters,
es were
ng. The
ollowed
compar-
e in Fig.



STRESS - STATES PRECEEDING LARGE RUPTURES




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)

"Slip-Weakening" Model of Friction