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H4.SMR/1150 - 19

Fifth Workshop on Non-Linear Dynamics
and Earthquake Prediction

4 - 22 October 1999

Criticality, Complexity and Collective Behavior of Earthquakes and Faults

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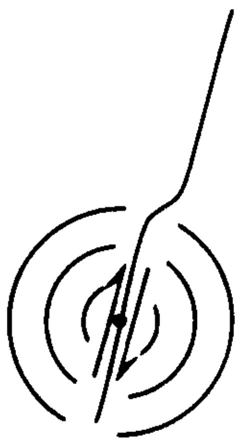
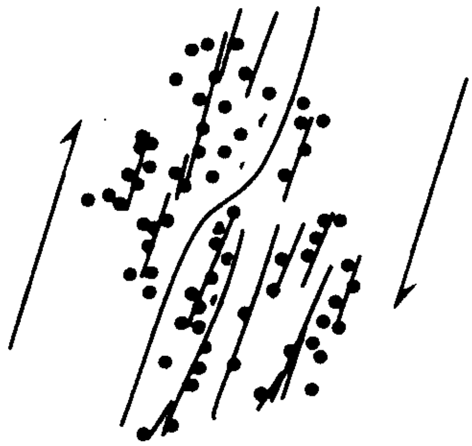
Physics of Earthquakes

Individual Events

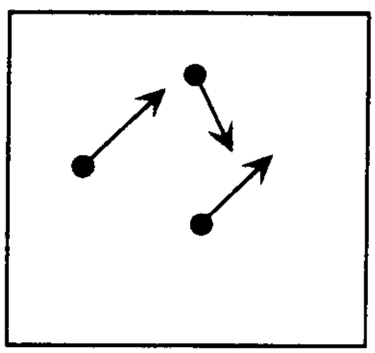


Collective Behavior



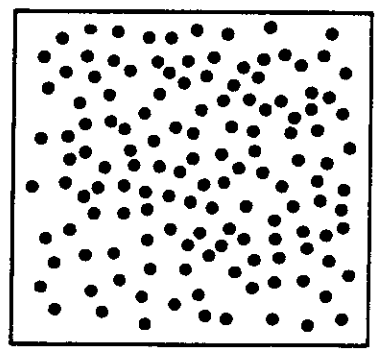
Gas Analogy

Mechanics



$$\sum \vec{F} = \frac{d}{dt}(m\vec{v})$$

Statistical Mechanics



$$PV = \underbrace{Nk}_{R}T$$

Earthquake phenomenology is abundant with power law distributions. Examples include:

* Frequency-size statistics of earthquakes

density: $\phi(M_0) \propto M_0^{-1-\beta}$; cumulative: $N(M_0) \propto M_0^{-\beta}$; $\beta \sim 2/3$
$\mathrm{Log}(M_0) \propto 3/2\, M$
Gutenberg-Richter relation: $N(M) = a - bM$ with $b \sim 1$

* Frequency-size statistics of faults
cumulative: $N(L) \propto L^{-\eta}$; $\eta \sim 1\text{-}3$

* Aftershock decay rates
Modified Omori's law: $\Delta N/\Delta t = k\,(t + c)^{-1}$

* High frequency radiation (e.g., Aki, 1967)
$\Omega(\omega) \propto \omega^{-\gamma}$; $\gamma \sim 1\text{-}2$

* Fault Roughness (e.g., Brown, 1995)
$G(k) \propto k^{-\alpha}$; $\alpha \sim 1\text{-}2$

* Slip vs. fault length for single events and cumulative offset (e.g., Scholz, 1990)
$u \propto L^{\delta}$; $\delta \sim 1\text{-}2$

* Slip-rate (tectonic) vs. fault length (Wesnousky, 1999)
$\Delta u/\Delta t \propto L^{\varepsilon}$; $\varepsilon \sim 1\text{-}2$

* Spatial patterns of fractures & hypocenters, and rotations of focal mechanisms (e.g., Kagan, Physica D, '94).

Possible General mechanisms:

I. *The equation of motion for a continuum solid*

$$\tau_{ij,j} + f_i = \rho\, \ddot{u}_i$$

is scale-independent

This suggests naively that deformation processes in solids should produce self-similar (fractal) patterns manifested in power law statistics.

But length scales associated with rheology, existing structures, and interaction of dynamic processes with these can produce deviations from self-similarity.

An example at small spatial scale is a transition from stable creep to dynamic instability, at a nucleation size whose dimensions depend on frictional and elastic parameters [e.g., Dieterich, Tectonophysics, 92; Rice, JGR, 93].

This transition defines a minimum earthquake size, and it fueled hopes to observe the precursory deformation associated with the nucleation process.

But high resolution geodetic measurements [Johnston et al., Tectonophysics, 87] and the existence of very small earthquakes (e.g., M = –1 on the SAF) indicate that, even on major faults, the nucleation zone is too small to produce detectable surface signals.

Dieterich (1992)

As suggested by eq. 29, the numerical results demonstrate that instabilities can nucleate when $A - B > 0$ (velocity strengthening), given sufficient perturbation of stress above the steady-state friction. Qualitatively, the simulations with $A - B > 0$ are similar to those with $A - B < 0$, including the development of a sub-patch with dimensions that scale by eq. 15 using $\xi = 0.4B$. However, if the fault is rate-strengthening, and if the initial stress is not sufficiently high relative to the steady-state friction, then accelerating slip terminates and the condition for instability is not reached.

Figure 4 illustrates results of models with uniform initial θ, uniform normal stress and random initial shear stress, distributed uniformly between

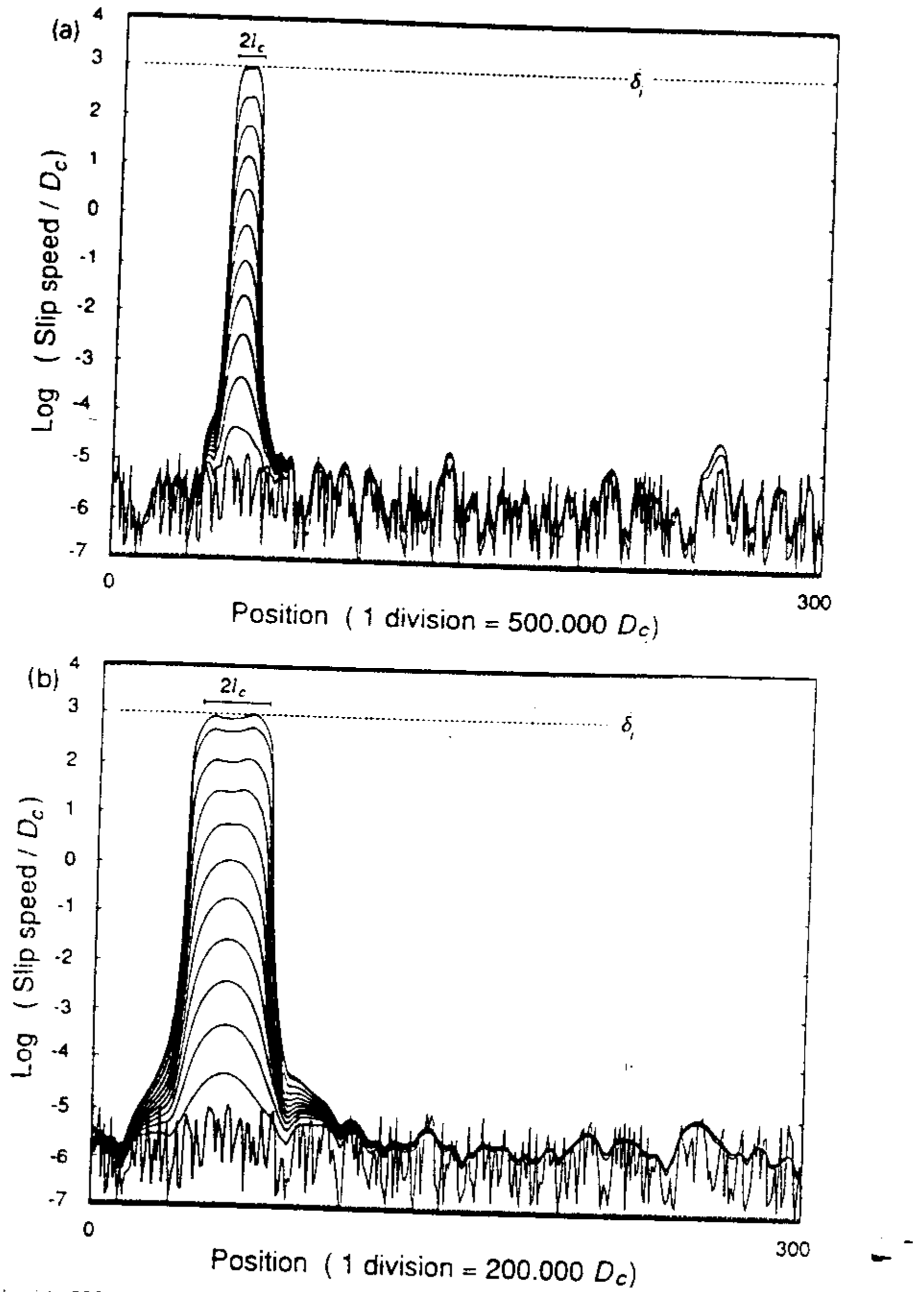
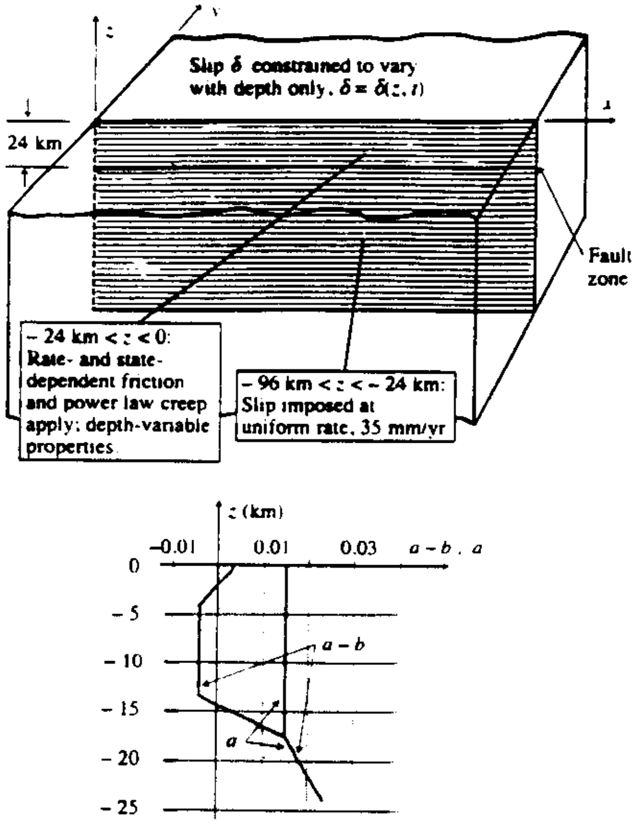
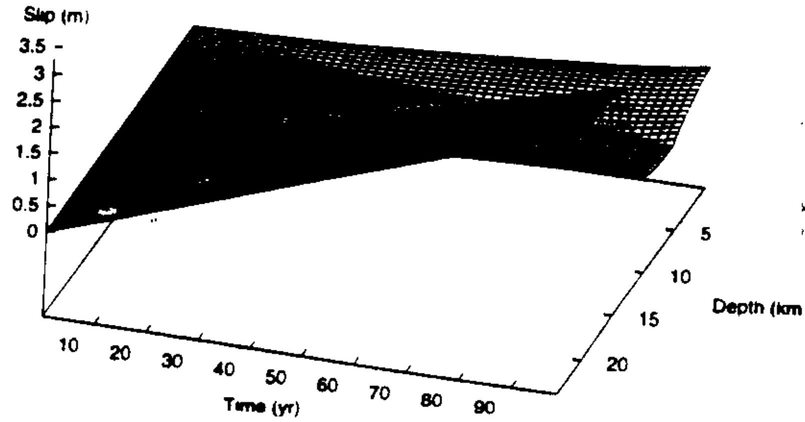


Fig. 4. Numerical model with 300 nodes and randomized initial shear stress. Parameters for the calculations are: $A = 0.004$, $B = 0.006$, $\theta = 10^9$ s, $G = 10^4\sigma$, $\dot{\tau} = 0$, and initial shear stress from $(\mu_0' + 0.06)\sigma$ to $(\mu_0' + 0.08)\sigma$. The logarithm of slip speed for faults with different values of D_c is indicated.

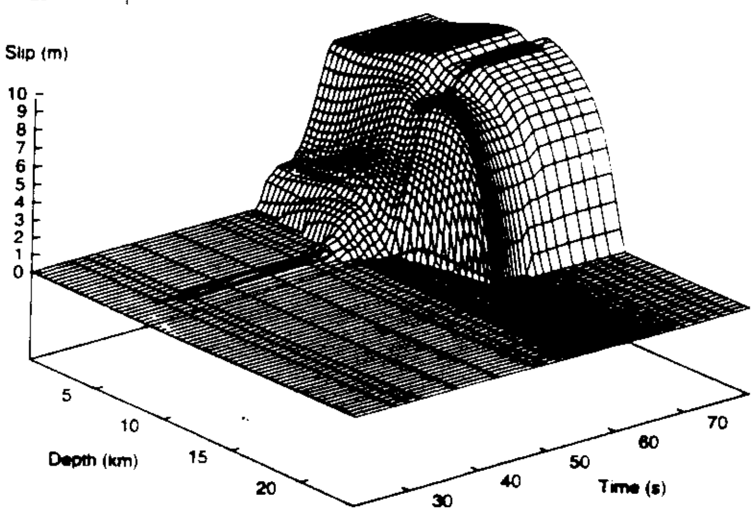
$\tau = (\mu_0'$ -
the mag
for the s
0.004, B
non-unif
also non
As wi
dimensic
heteroge
eq. 15

Ben-Zion and Rice
JGR, 1997

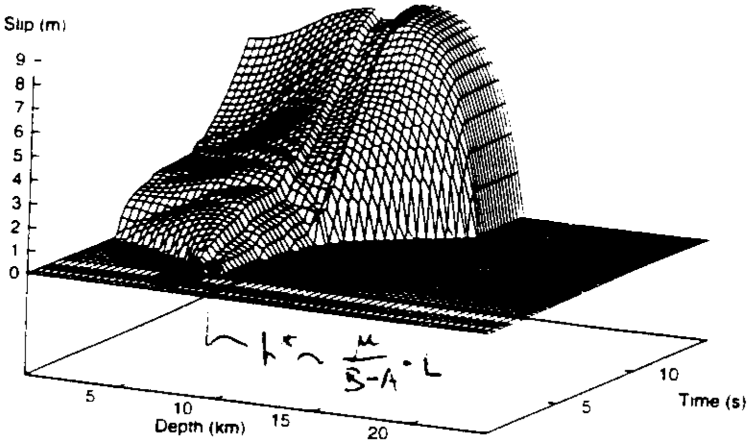




...g stable deformation in dynamic simulation with the "slip" version of the ...n. The creep model process is disabled, p is hydrostatic, and $h = h^*/4$.

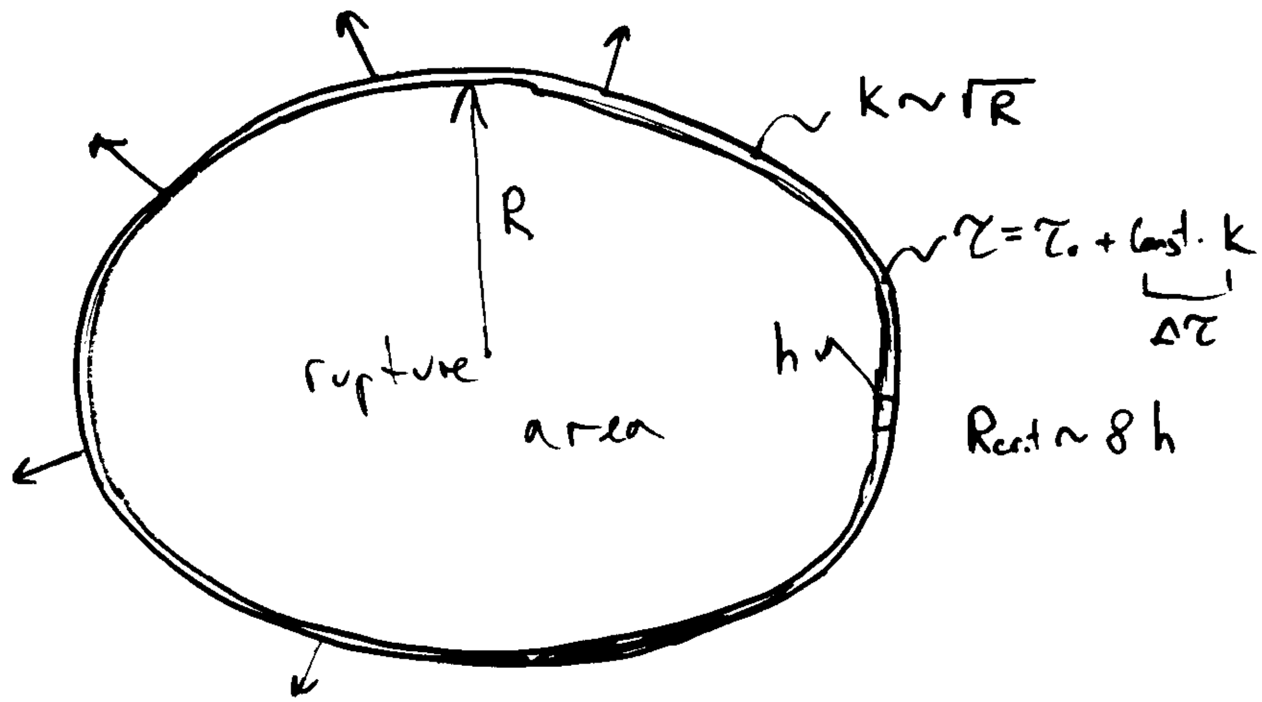


...gure 3a. A dynamic slip event in the model leading to Figure 2. Slip distribution is relative to a given ...ue chosen by the plotting program. The dynamic instability is preceded by a smoothly growing nucleation ...ase. The apparent abrupt initiation of the nucleation phase and apparent low final slip in the center are ...tting artifacts.



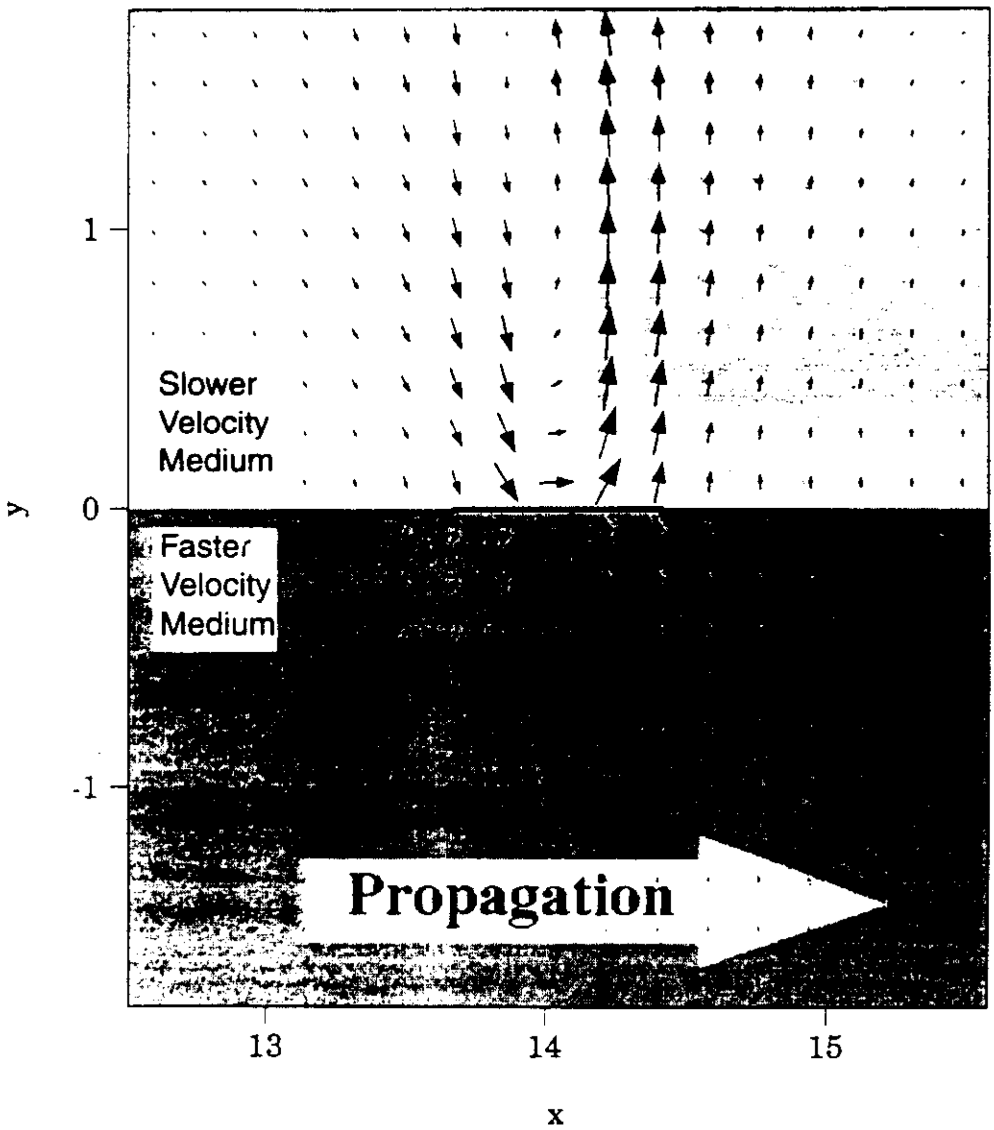
...igure 3b. Last 15 s of the model earthquake. The rupture propagates from the nucleation phase to the free ...urface and is then reflected downward. Variations of final slip, visible clearly in the shallow zone, are ...ssociated with dynamic waves.

A large size example of a transition breaking self-similarity is produced by the scaling of stress concentration in elastic solids with rupture dimension.



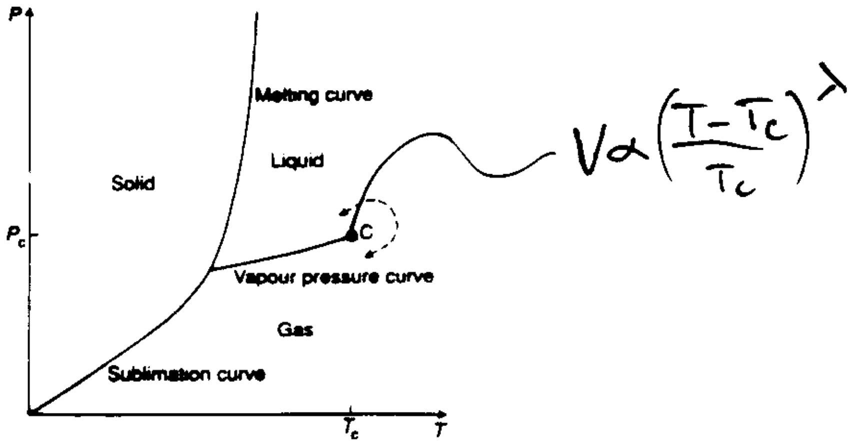
When the rupture reaches a critical size, generating stress transfer to the edge that is comparable to the average stress drop, it may become a "runaway" event terminating the power law regime of earthquake statistics [Ben-Zion and Rice, JGR, 93].

A third example, related to existing structures, is transition from a smooth crack-like rupture mode in homogeneous media to a narrow wrinkle-like mode on a fault separating different elastic solids (e.g., Andrews and Ben-Zion, JGR, 97).



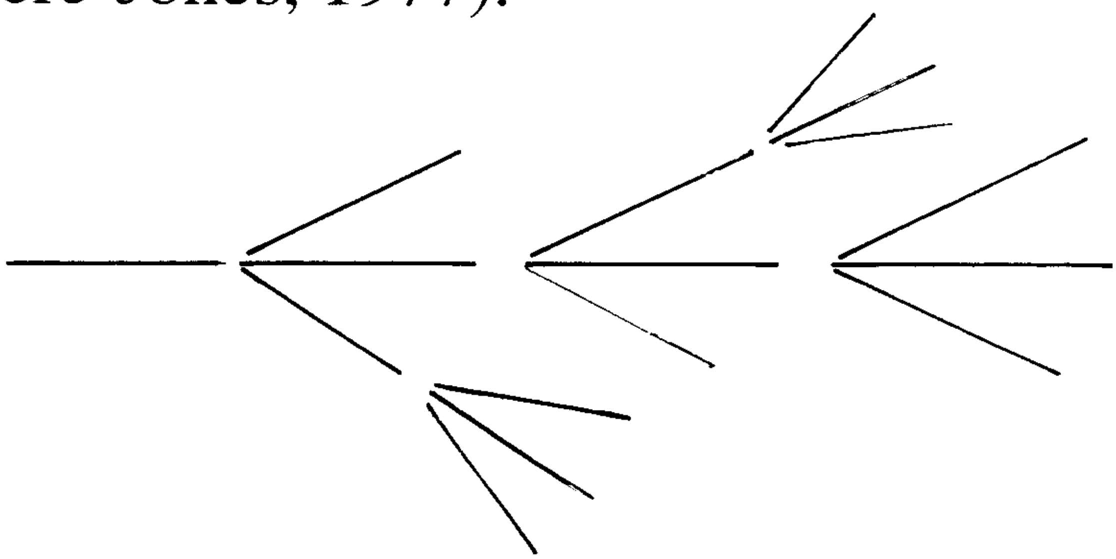
On a planar fault in homogeneous solid, there is no coupling between slip and normal traction. On the other hand, if there is a material contrast across the fault, slip can change the normal traction. Thus, fault zone material interfaces provide a natural setting for dynamic interaction between slip and normal stress variations. The existence of a material contrast may be viewed as a critical boundary between different dynamic regimes, since a host of dynamic rupture phenomena emerge, or deteriorate, as model parameters cross this phase-space boundary.

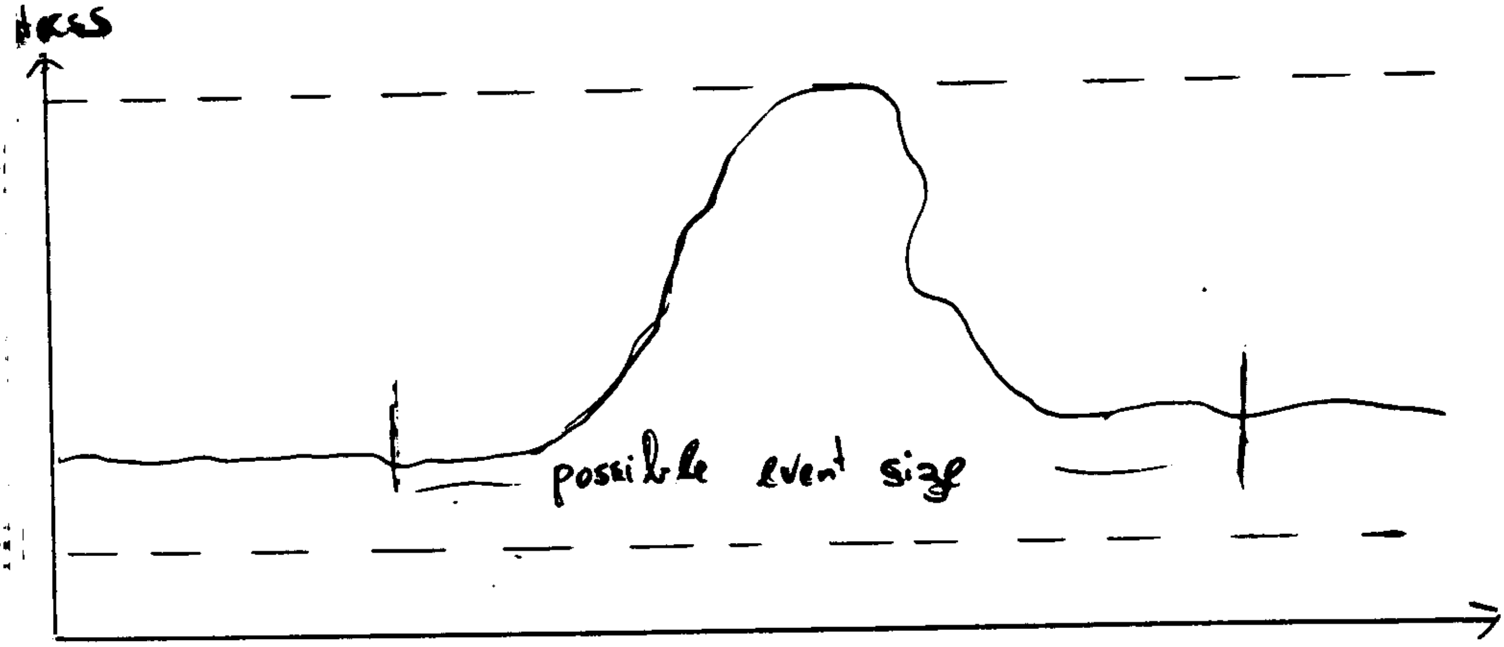
II. *proximity to critical points of phase transition.*

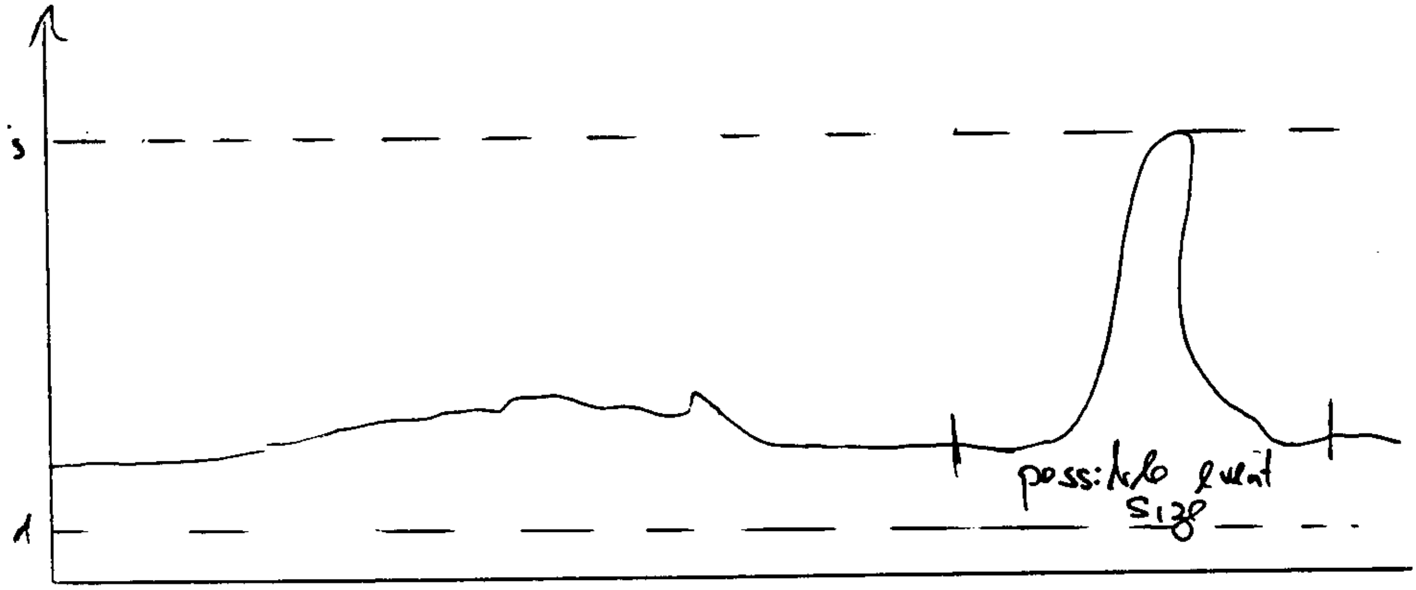


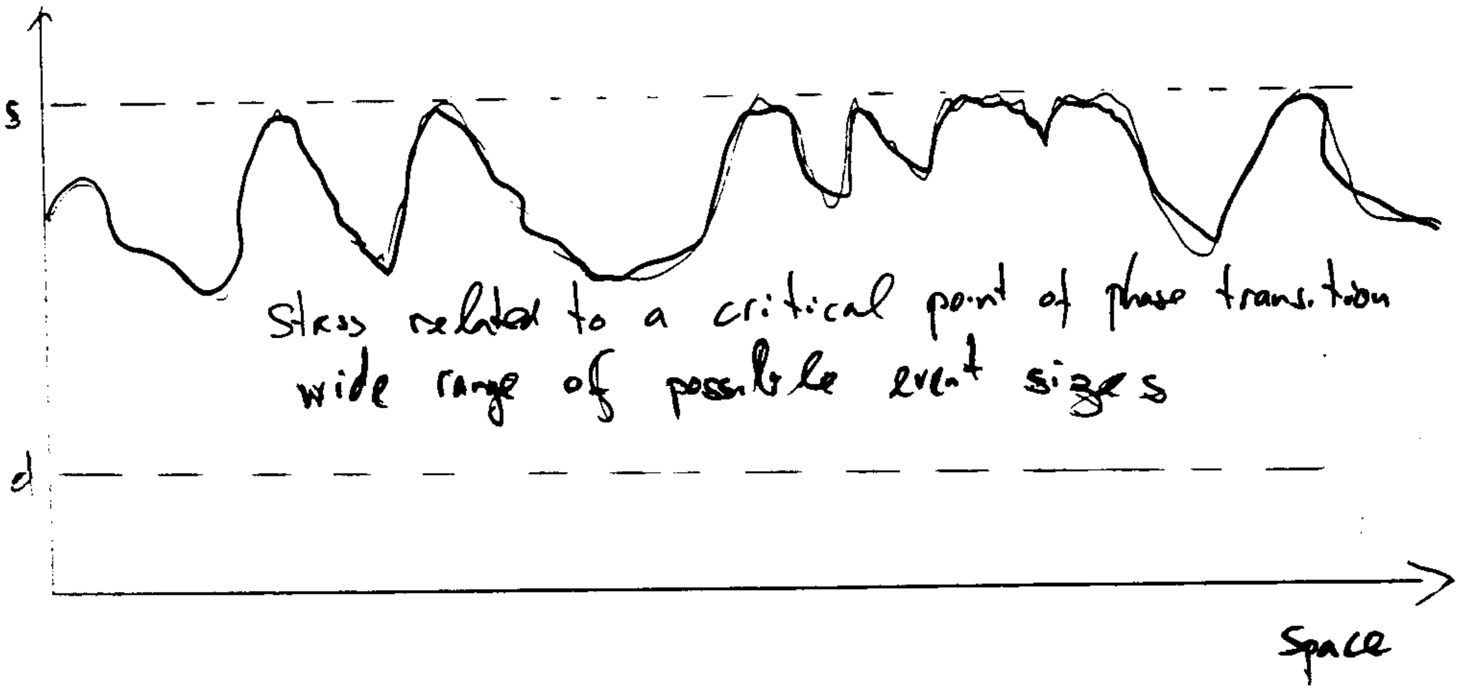
At critical points, associated with special value(s) of tuning parameter(s), phase transition is second order and several phases can co-exist. Statistics near critical points follow power law relations.

Critical Stochastic Branching (e.g., Vere-Jones, 1977).




possible event size

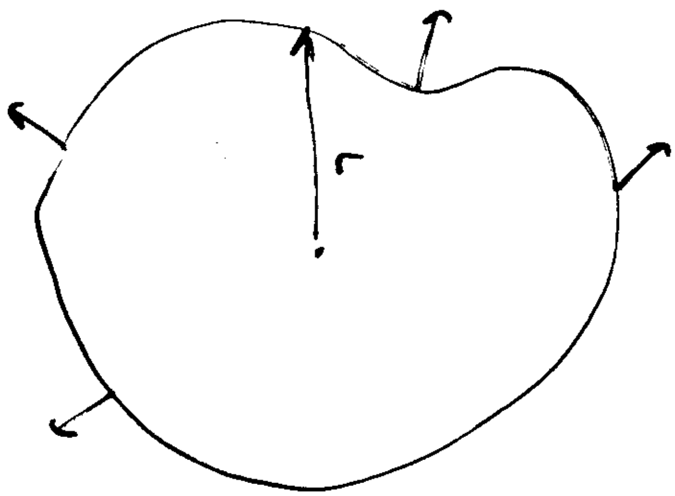

s
possible event size
d


s
stress related to a critical point of phase transition
wide range of possible event sizes
d
space

Self Organized Criticality: Stationary critical behavior without tuning parameter, i.e., in all or most relevant parameter space (Bak et al., 1988; Sornette & Sornette, 1989).

Large Relevant parameter space

Small Relevant parameter space



$r \to \infty$

$r \to 0$

Bak et al. (1988); Sornette & Sornette (1989)
Ito & Matsuzaki (1990); Horowitz & Ruina (1989)
Carlson & Langer (1989); Shaw et al. (1992)
Myers et al. (1996); Shaw (1997)

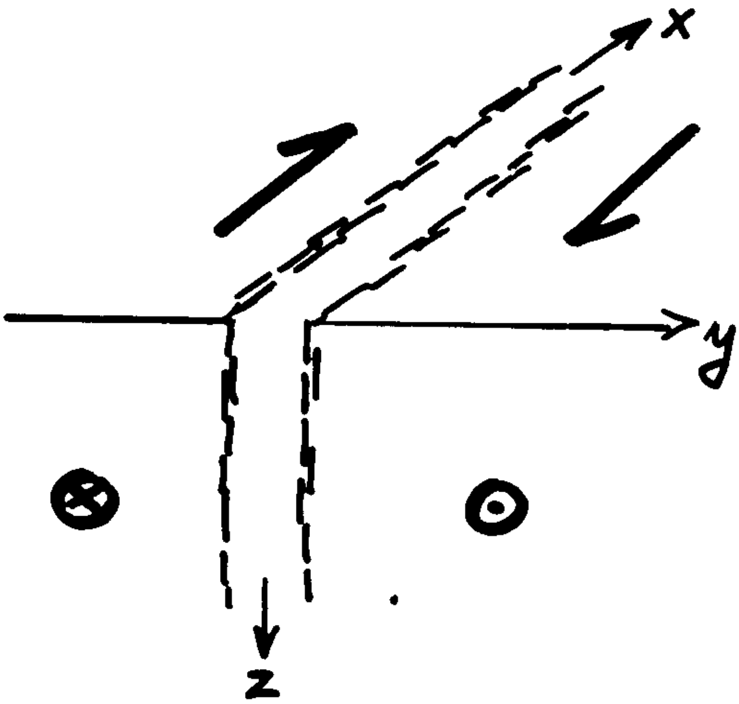
Rice (1993); Ben-Zion & Rice (1993, 1995, 1…
Lomnitz-Adler (1993); Rundle & Klein (…
Cochard & Madariaga (1996); Fisher et al. (…
Dahmen et al. (1998); Shaw & Rice (199…

Dynamic slip complexity on a homogeneous fault with many degrees of freedom (Carlson and Langer, 1989; Horowitz and Ruina, 1989).

Deterministic Chaos: dynamic complexity in a low dimensional system. (applications to E/Qs: Huang and Turcotte, 1990; McCloskey, 1993).

MODELING A SINGLE FAULT ZONE ①

(Ben-Zion, Rice
J. Phys. Res 98, 14109)

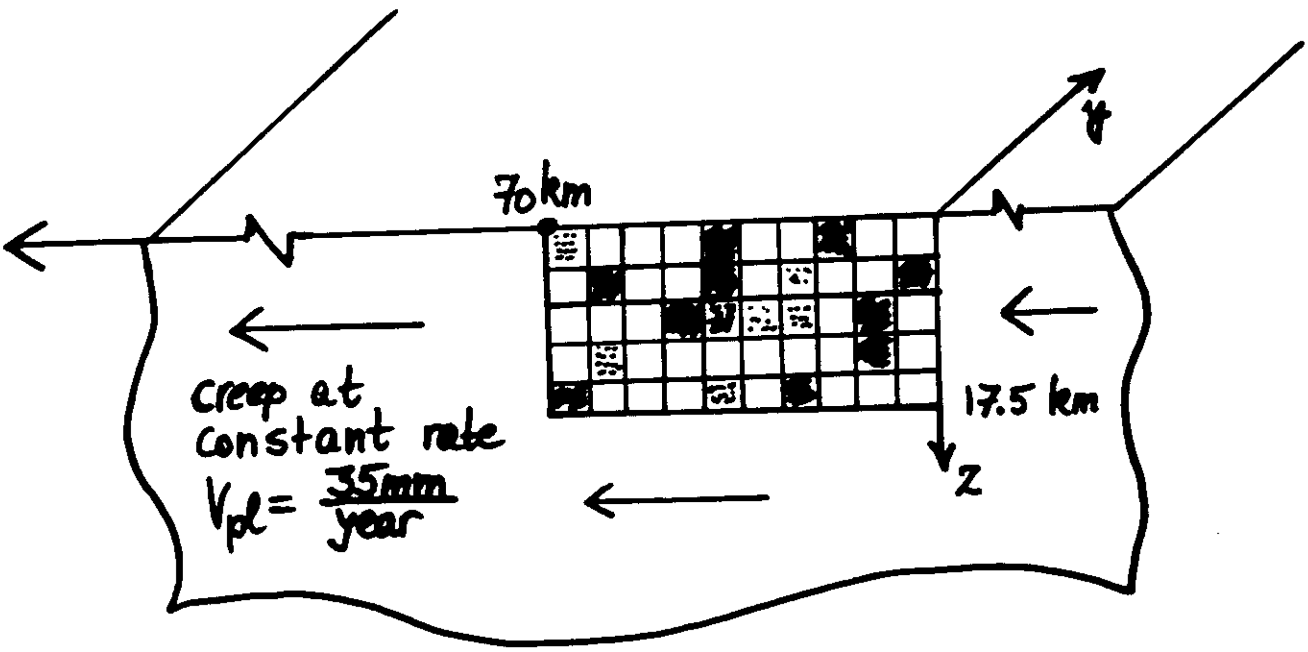


← 3 dim FAULT

mapped onto

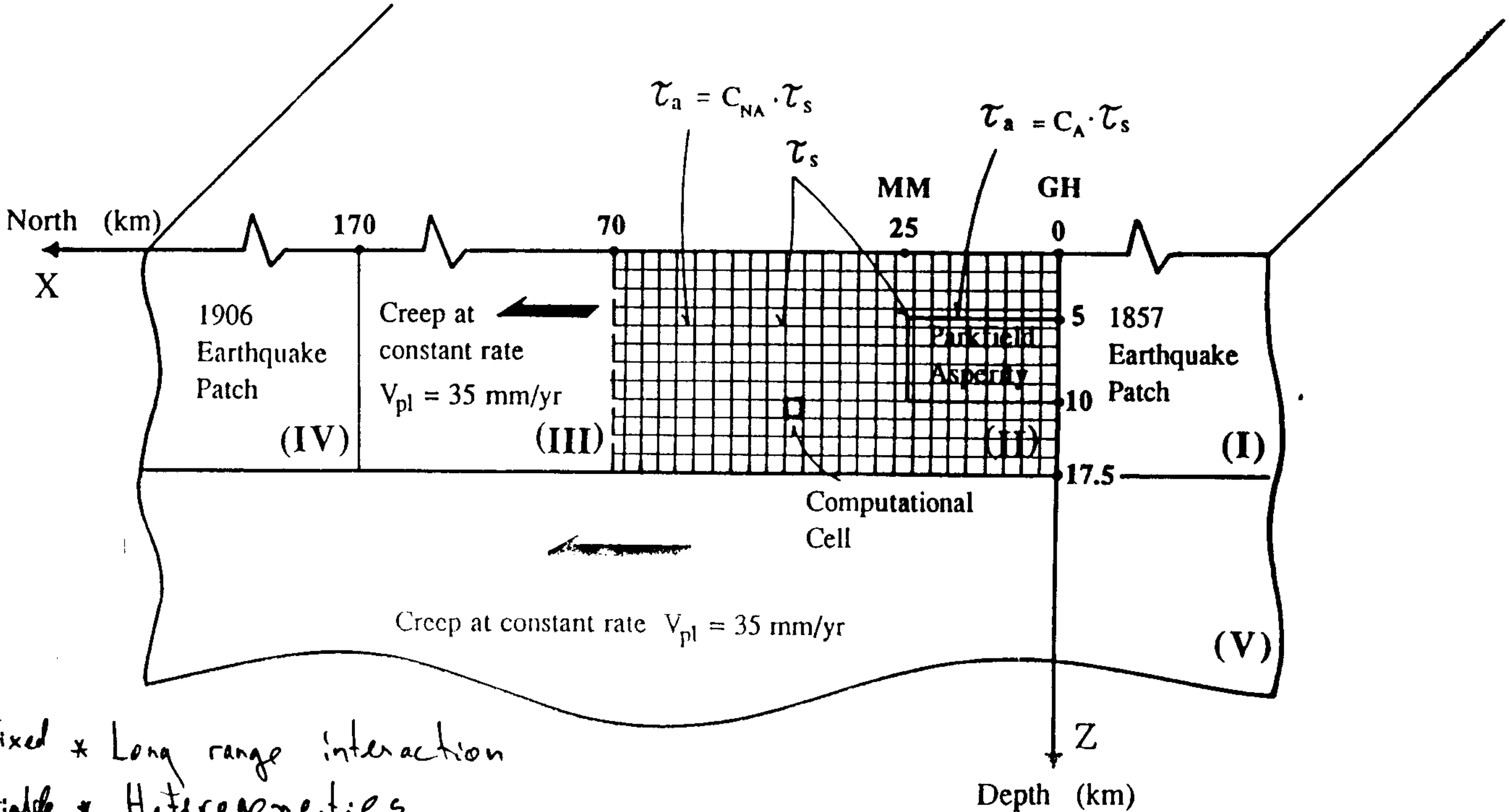
2 dim FAULT embedded in 3 dim elastic halfspace

↓



FOCUS ON LARGE SCALE PROCESSES ONLY!

(JGR, '93, '95, '96)



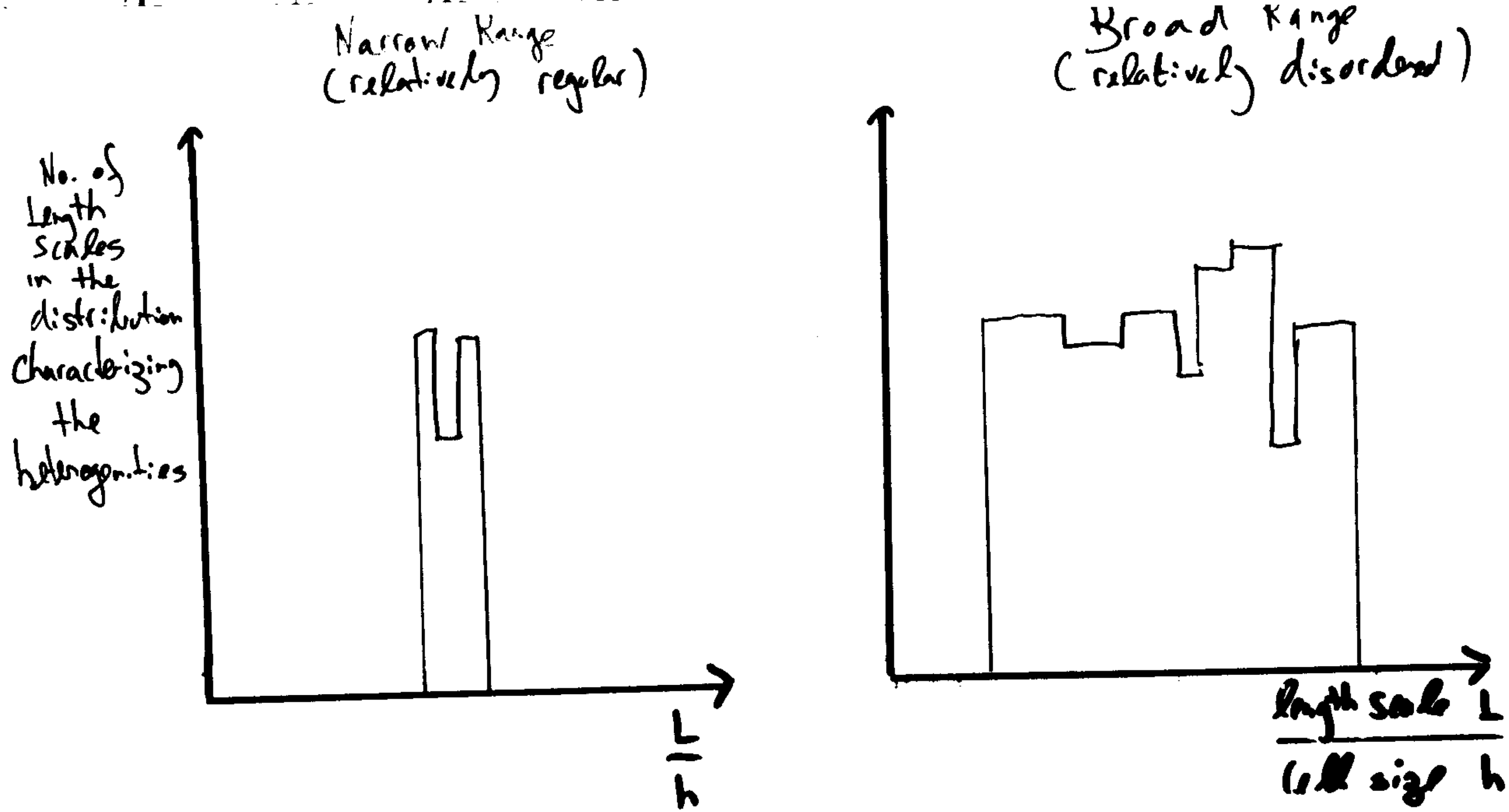
Fixed * Long range interaction

Variable * Heterogeneities

Fixed * Reasonable rheology (friction, creep)

Fixed * Realistic boundary conditions

Figure


Narrow Range (relatively regular)
Broad Range (relatively disordered)
No. of Length scales in the distribution characterizing the heterogeneities
L/h
length scale L / cell size h

FS Statistics for relatively Regular fault systems with NROSS

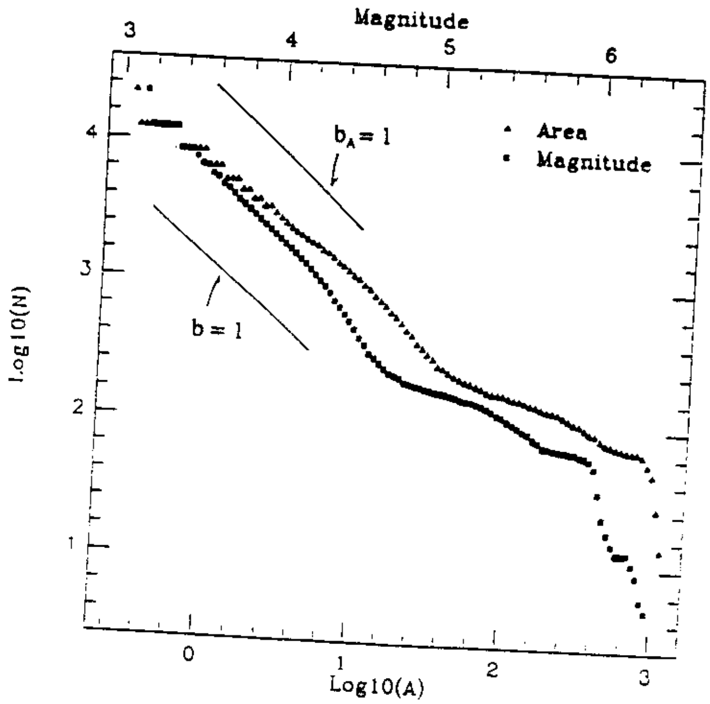


Figure 6a. Cumulative frequency-size (FS) statistics of earthquake magnitude (squares) and rupture area (triangles) during 150 analysis yr in the computational grid for the stress drop distribution case 1 of text (i.e., like Figure 2a but without random fluctuations). Units of rupture area are km^2.

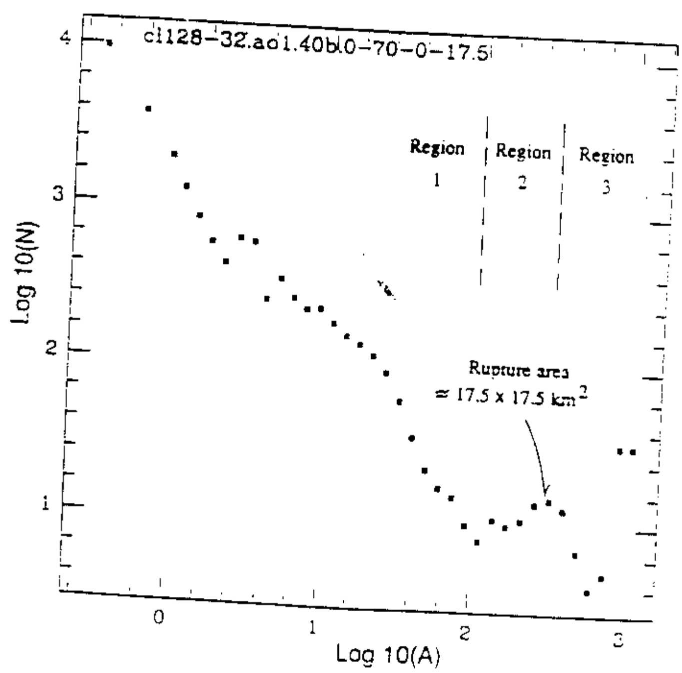
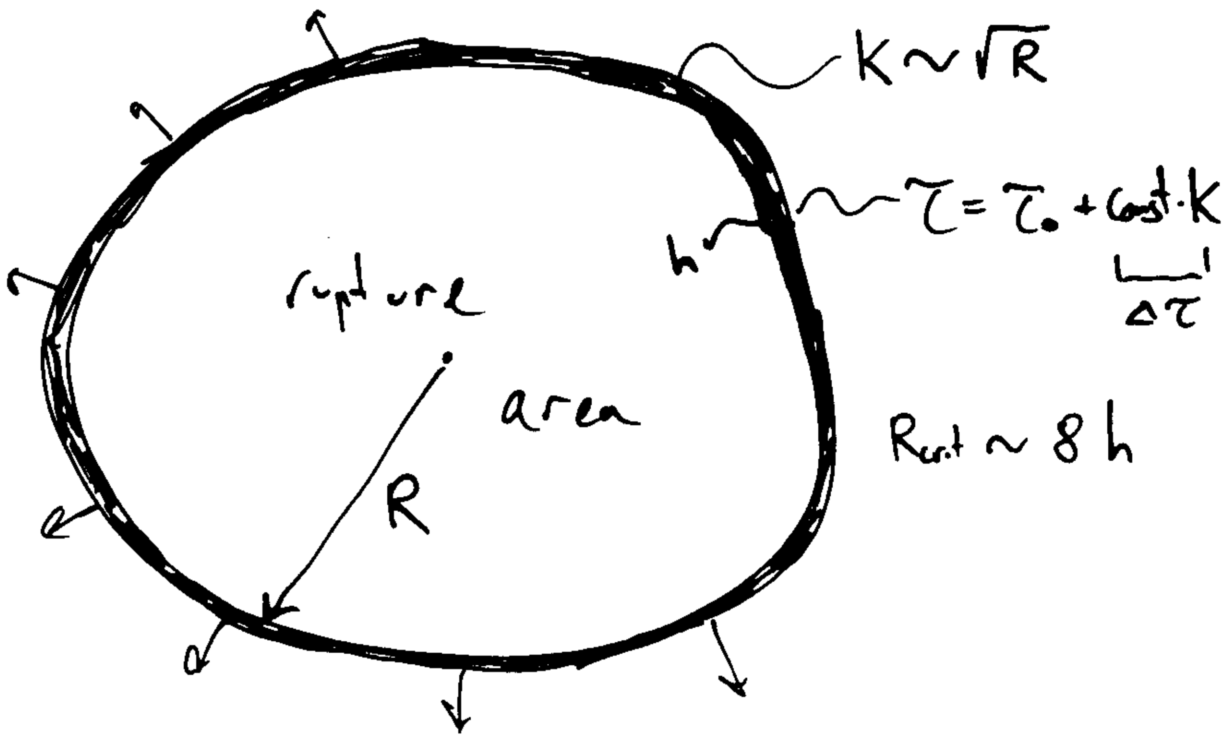


Figure 6b. Same as (a) for noncumulative FS statistics of rupture area.

A large size example of a transition breaking self-similarity is produced by the scaling of stress concentration in elastic solids with rupture dimension.



When the rupture reaches a critical size, generating stress transfer to the edge that is comparable to the average stress drop, it may become a "runaway" event terminating the power law regime of earthquake statistics [Ben-Zion and Rice, JGR, 93].

FS statistics for highly disordered fault systems with WROSS

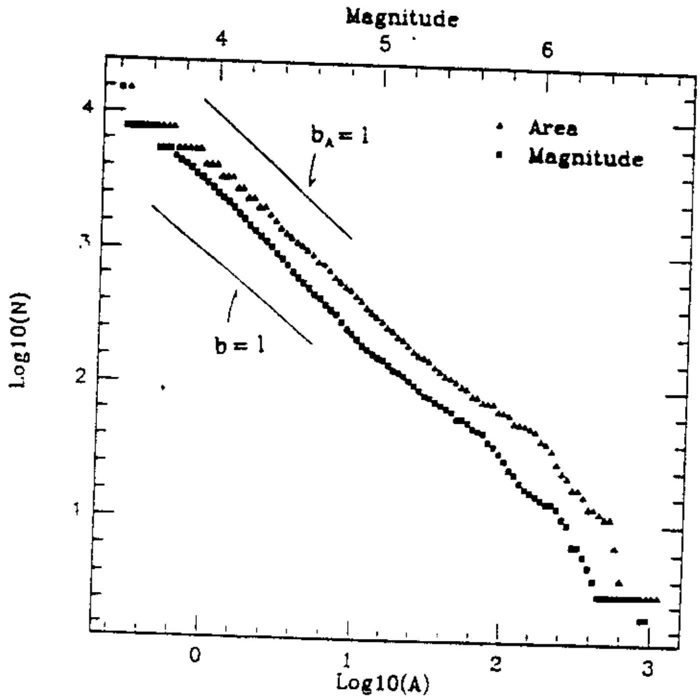


Figure 8a. Cumulative FS statistics of earthquake magnitude and rupture area during 150 analysis yr in the computational grid for the stress drop distribution representing weak segements of variable size with strong boundaries, case 5 of text (Figure 2c).

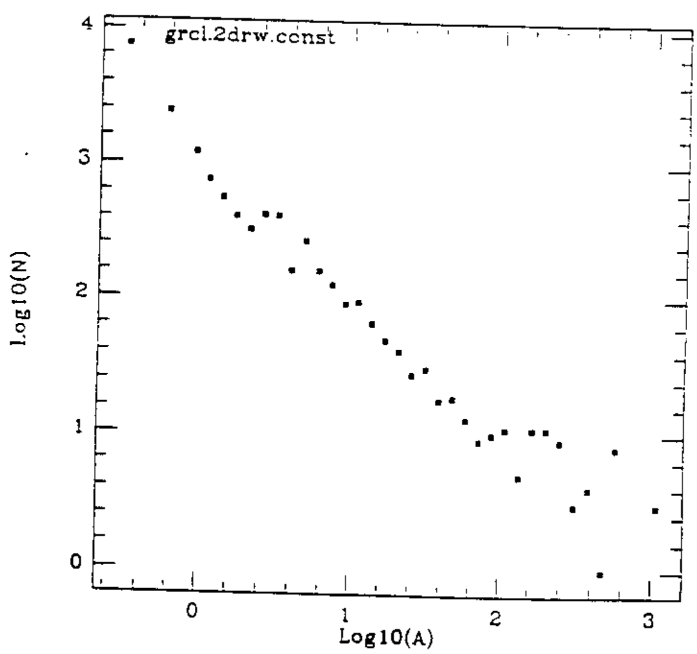
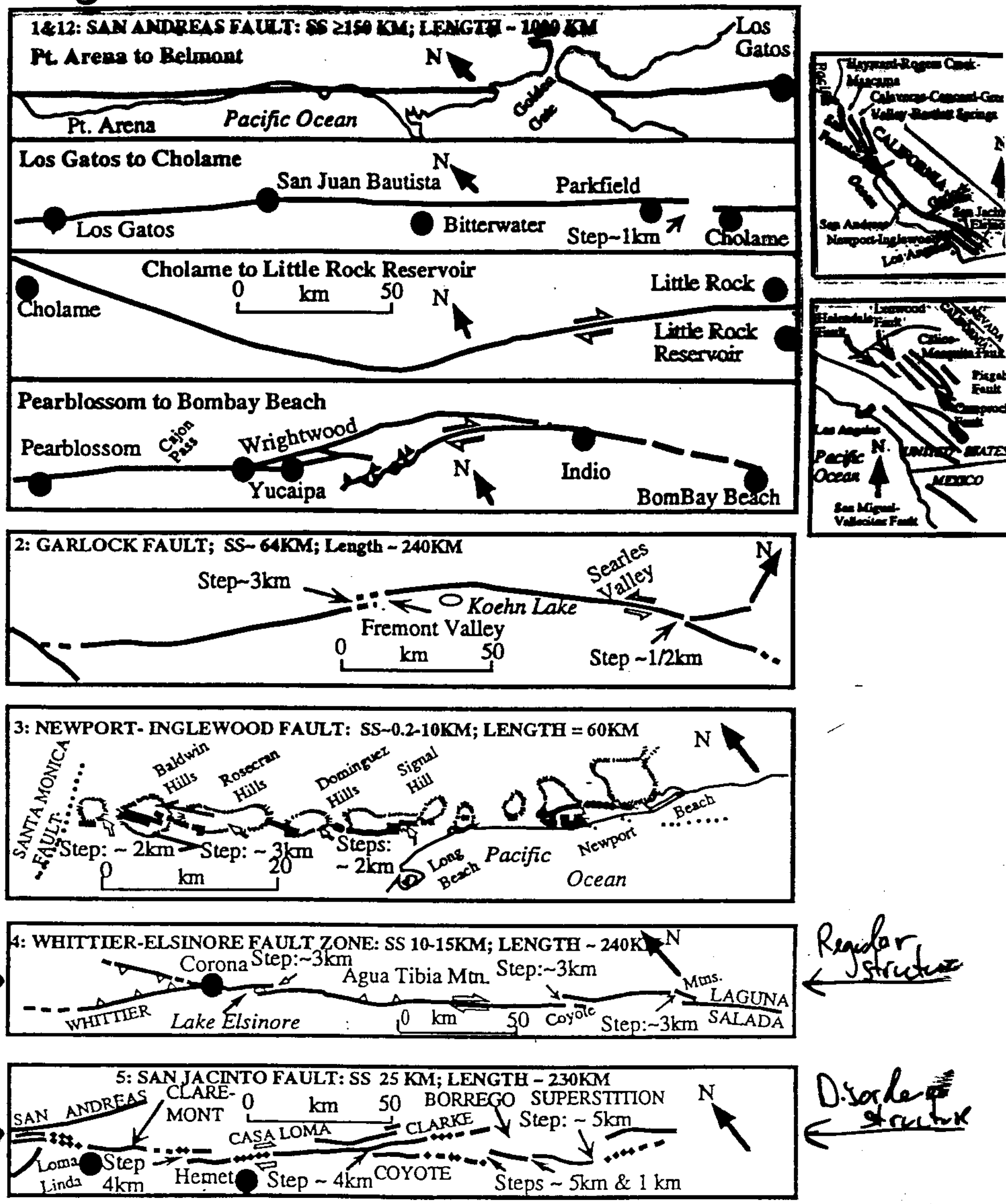


Figure 8b. Same as (a) for noncumulative FS statistics of rupture area.

Wesnousky, 1994



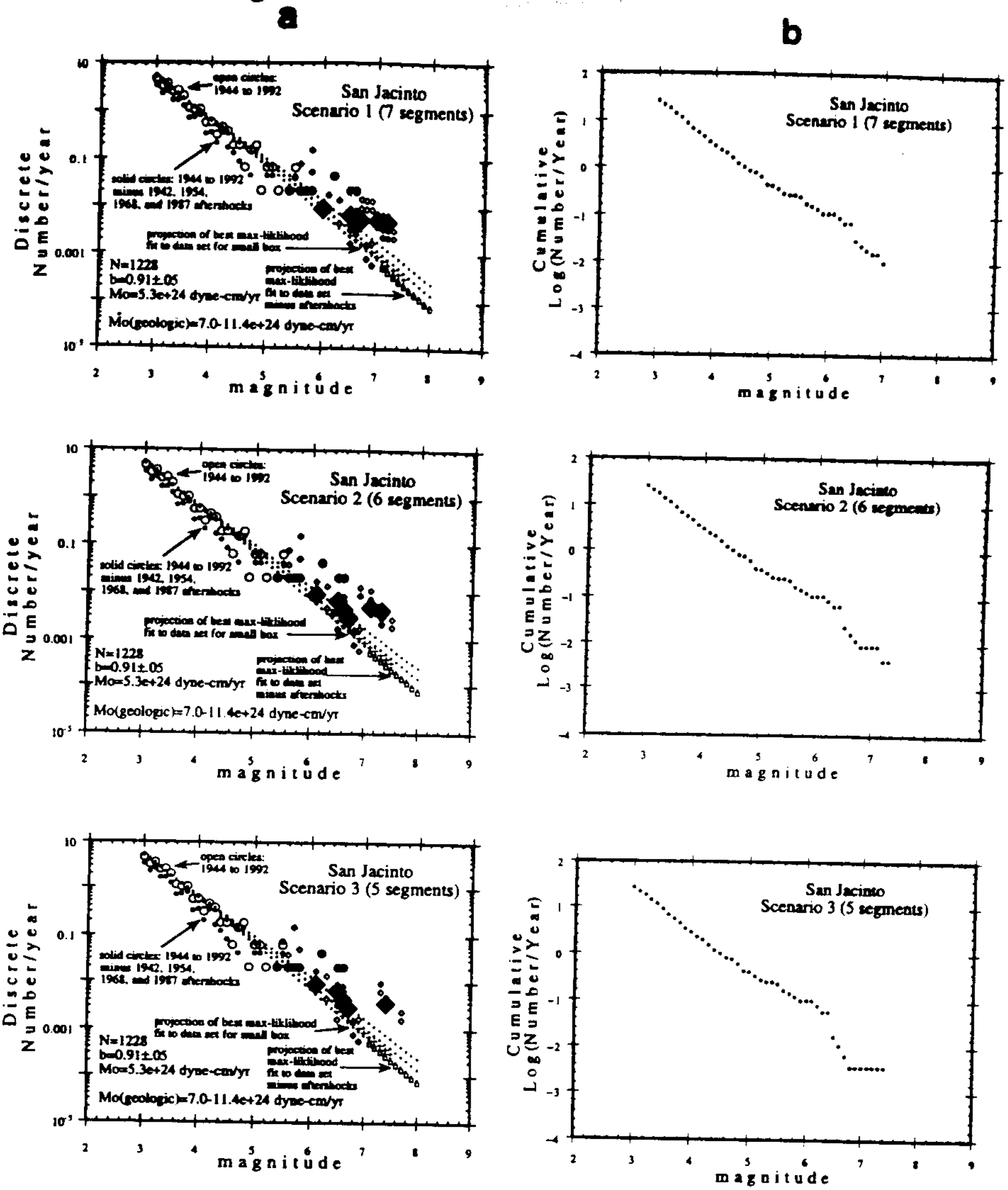
NoSS

Regular Structure

Disorder structure

Fig A

Wesnousky (1994), San Jacinto



Wesnousky (1994), Whittier-Elsinore

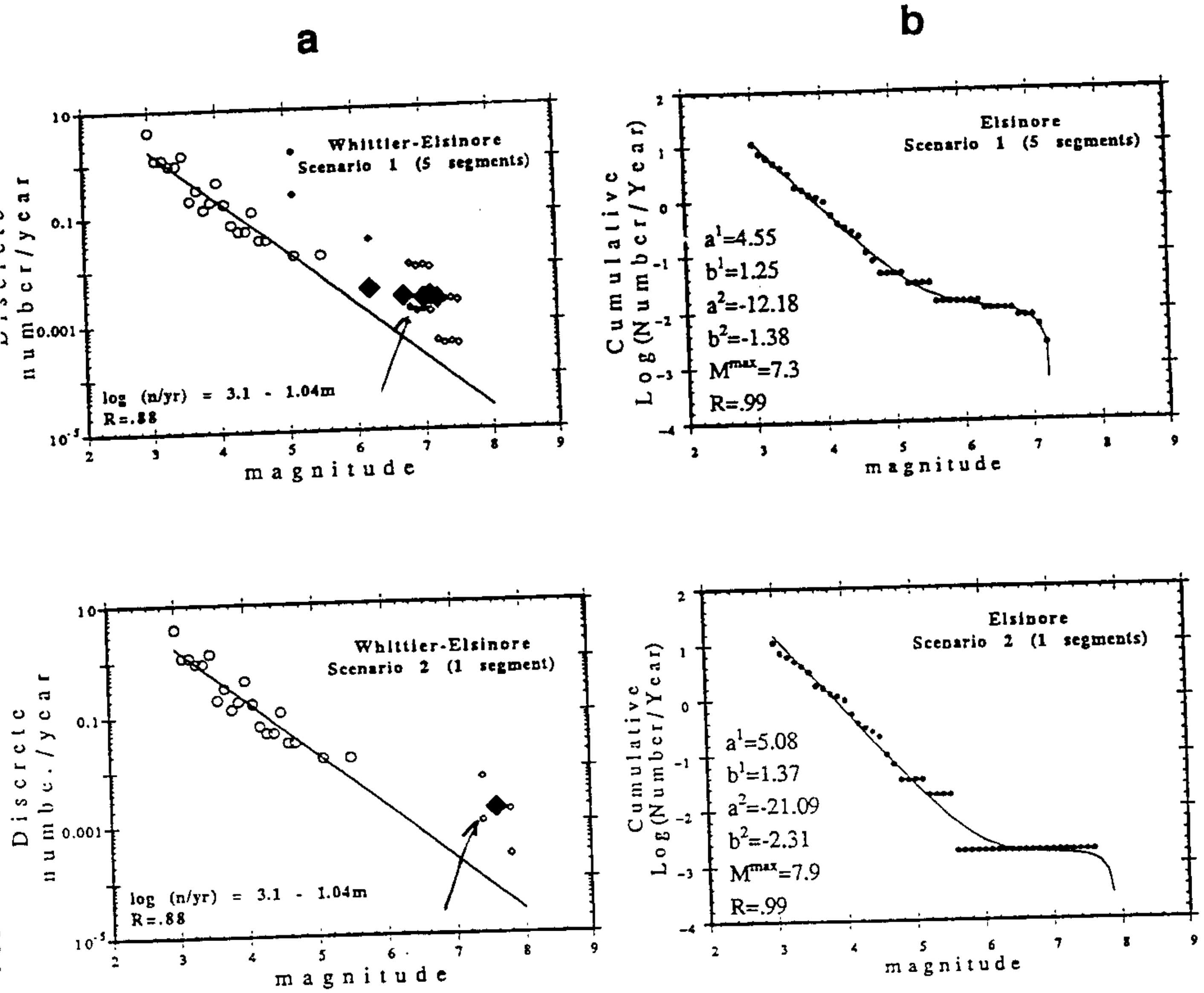
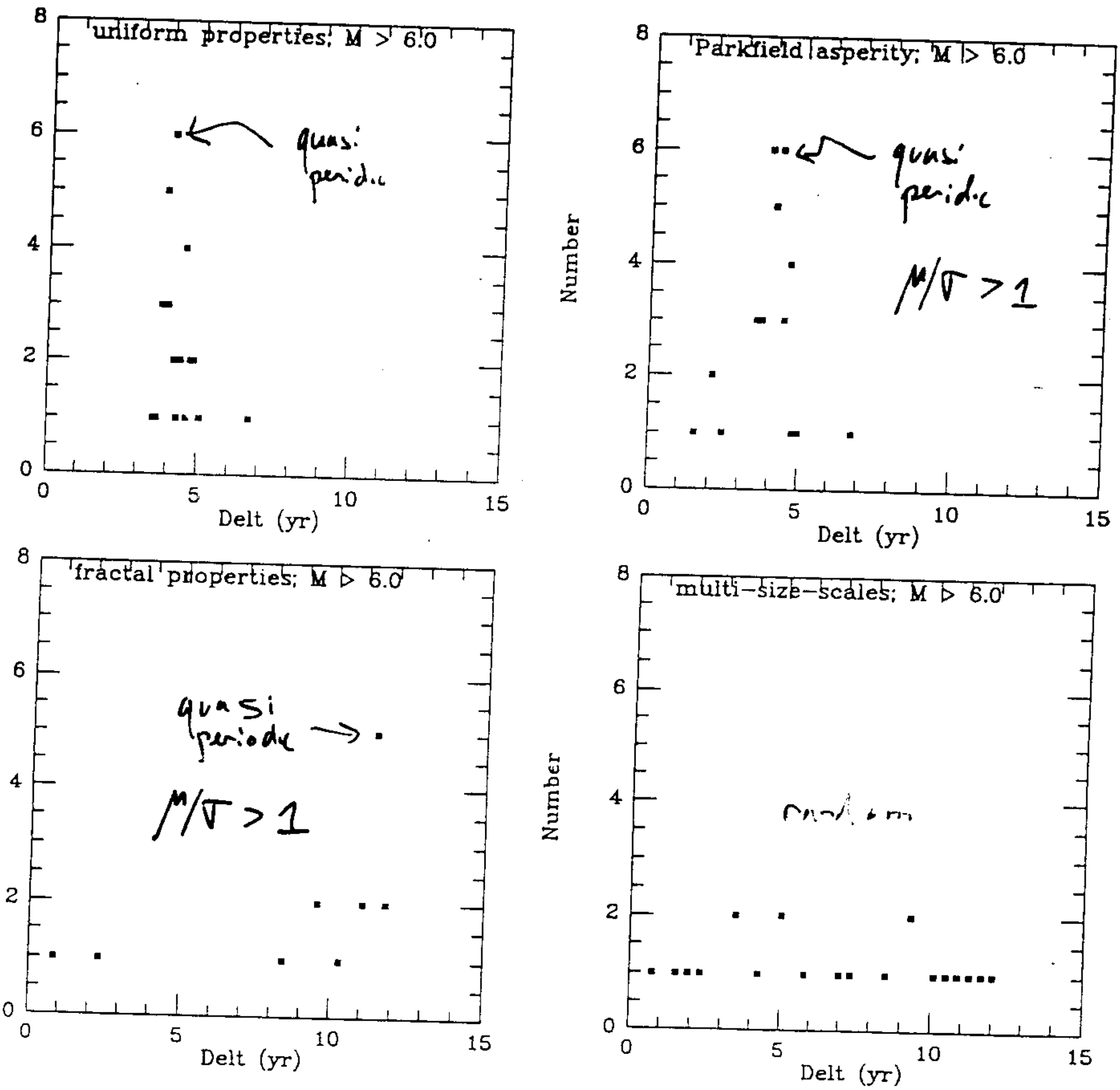


Figure 7

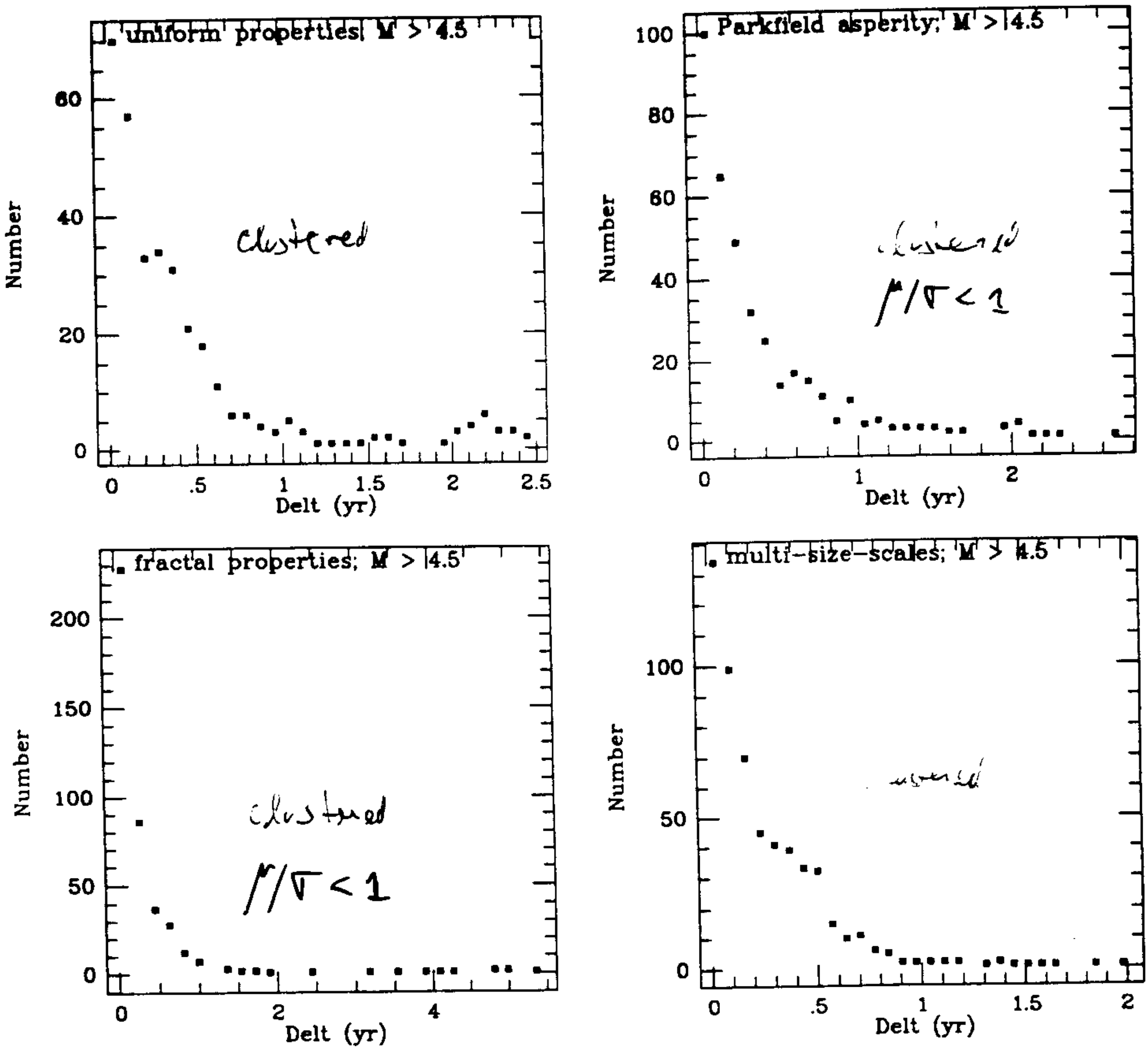
Temporal Statistics

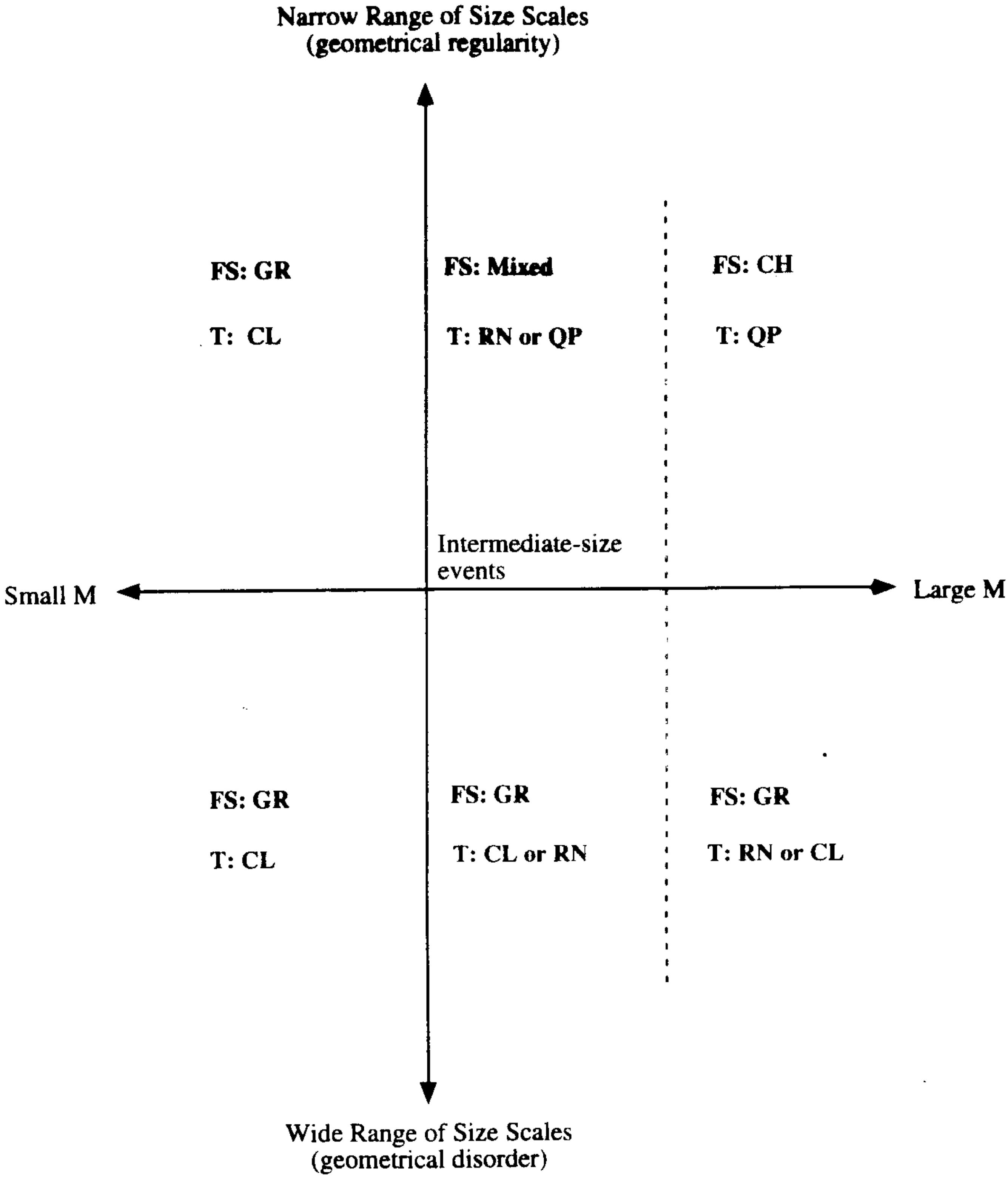
$M \geq 6.0$



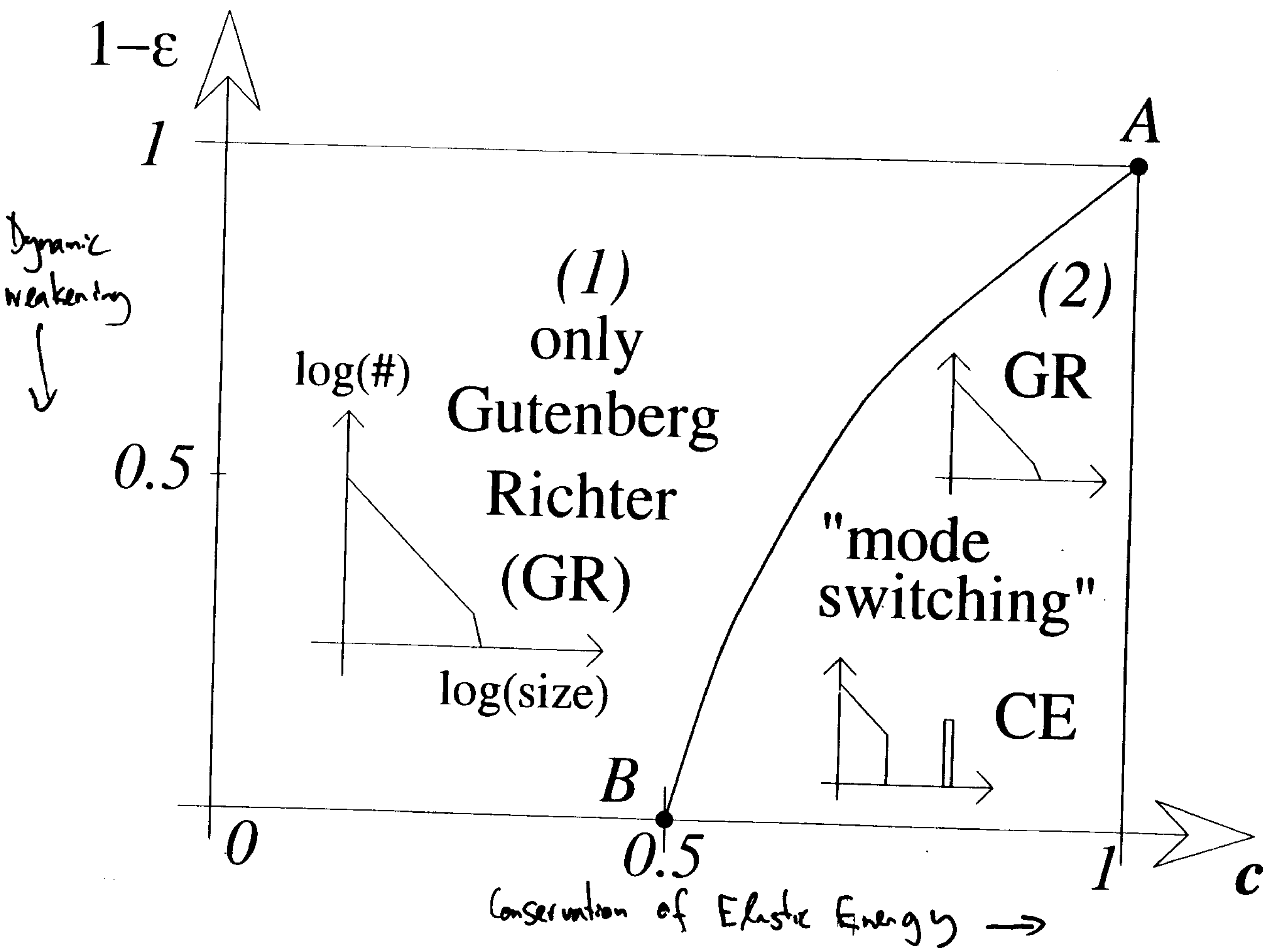
Temporal Clusters

$M \geq 4.5$




Narrow Range of Size Scales
(geometrical regularity)
FS: GR
T: CL
FS: Mixed
T: RN or QP
FS: CH
T: QP
Intermediate-size
events
Small M
Large M
FS: GR
T: CL
FS: GR
T: CL or RN
FS: GR
T: RN or CL
Wide Range of Size Scales
(geometrical disorder)

(PRE, 1998)


1−ε
1
0.5
0
Dynamic weakening
(1)
only
Gutenberg
Richter
(GR)
log(#)
log(size)
(2)
GR
"mode
switching"
CE
A
B
0.5
1
c
Conservation of Elastic Energy →

Relevance of

Plain

Criticality

vs.

Self Organized

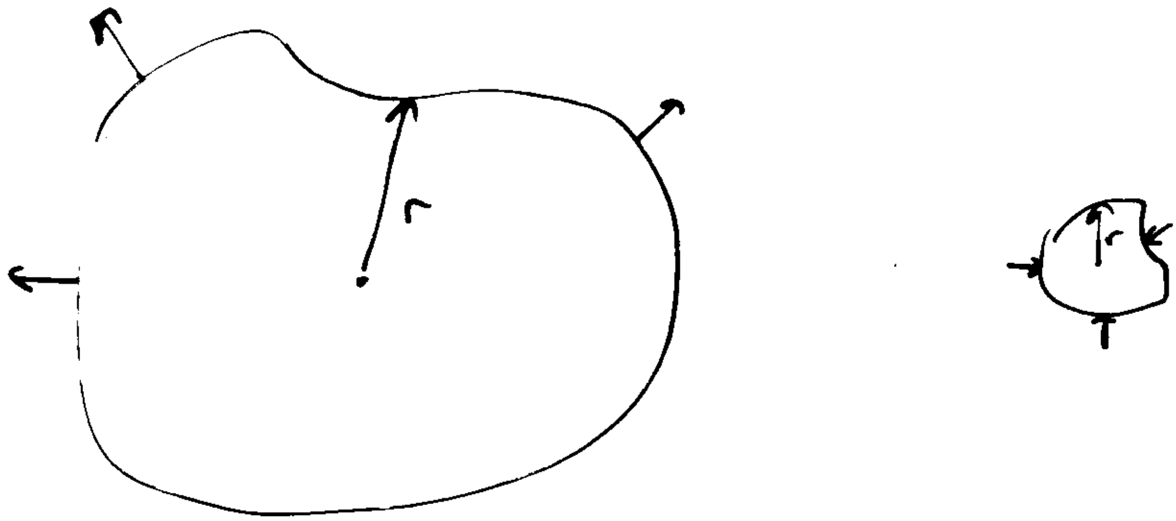
Criticality (SOC)

Debate ?

Tuning parameters, if they exist, provide crucial information on the dynamics we want to understand!

Self Organized Criticality: Stationary critical behavior without tuning parameter, i.e., in all or most relevant parameter space (Bak et al., 1988; Sornette & Sornette, 1989).

Large Relevant parameter space | Small Relevant parameter space



r → ∞ | r → 0

Bak et al. (1988); Sornette & Sornette (1989)
Ito & Matsuzaki (1990); Carlson & Langer (89)
Horowitz & Ruina (1989); Shaw et al. (1992)
Myers et al. (1996); Shaw (1997)

Rice (1993); Ben-Zion & Rice (1993, 1995, …
Lomnitz-Adler (1993); Olami et al. (1992
Rundle & Klein (1993); Cochard & Madaria…
Fisher et al. (1997); Dahmen et al (199…
Shaw & Rice (1998)

Dynamic slip complexity on a homogeneous fault with many degrees of freedom (Carlson and Langer, 1989; Horowitz and Ruina, 1989).

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Ben-Zion and Rice
(JGR, 1997)

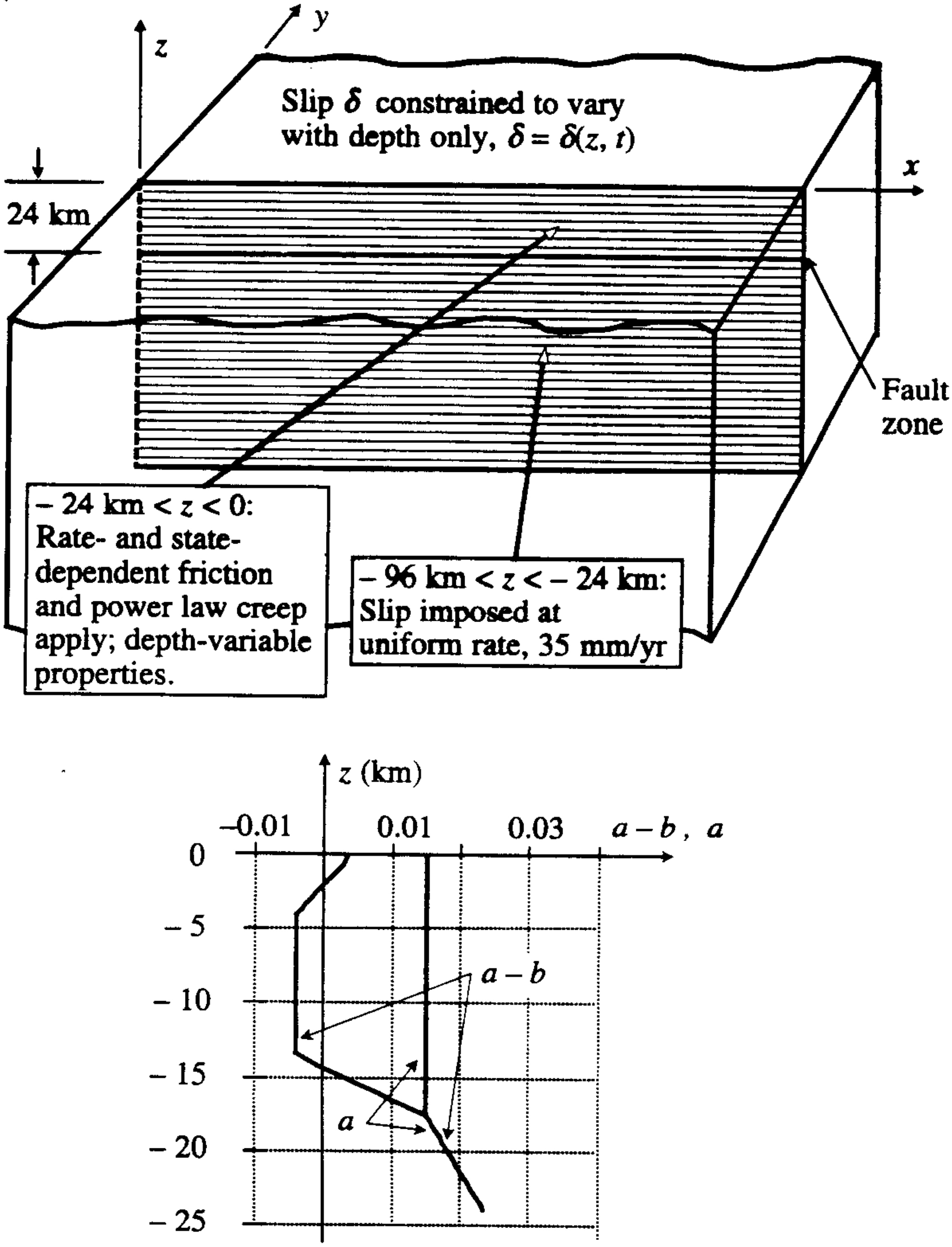
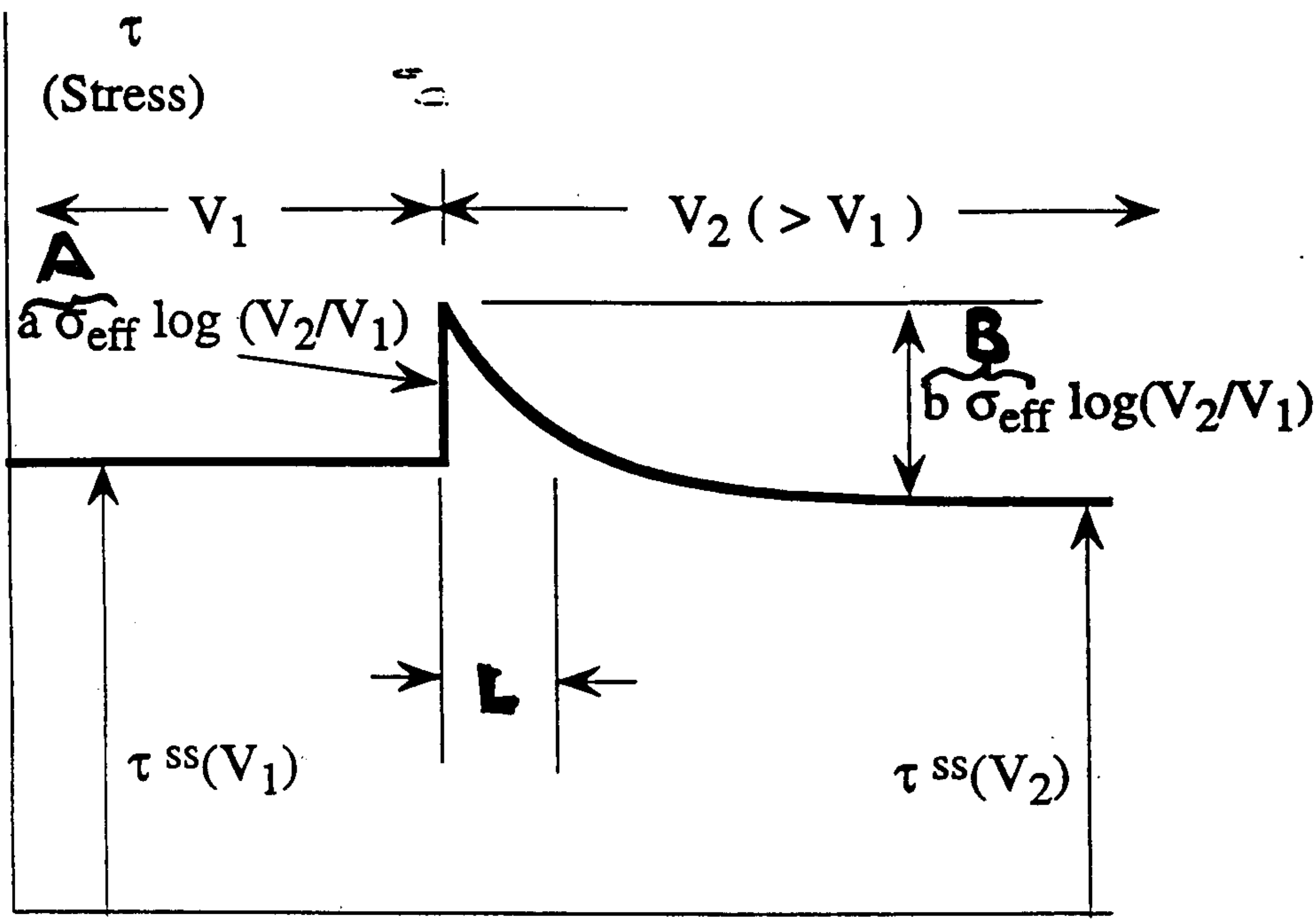


Figure 1.

Rate- and State- dependent friction
(Dieterich, Ruina, Rice ...)

Response to a sudden increase in slip speed V
(at fixed effective normal stress, $\sigma_{eff} = \sigma_n - p$)



δ (Slip)

$\tau = \tau_{ss}(V_2) + e^{-\delta/L}[\tau_{ss}(V_1) - \tau_{ss}(V_2) + A \ln$

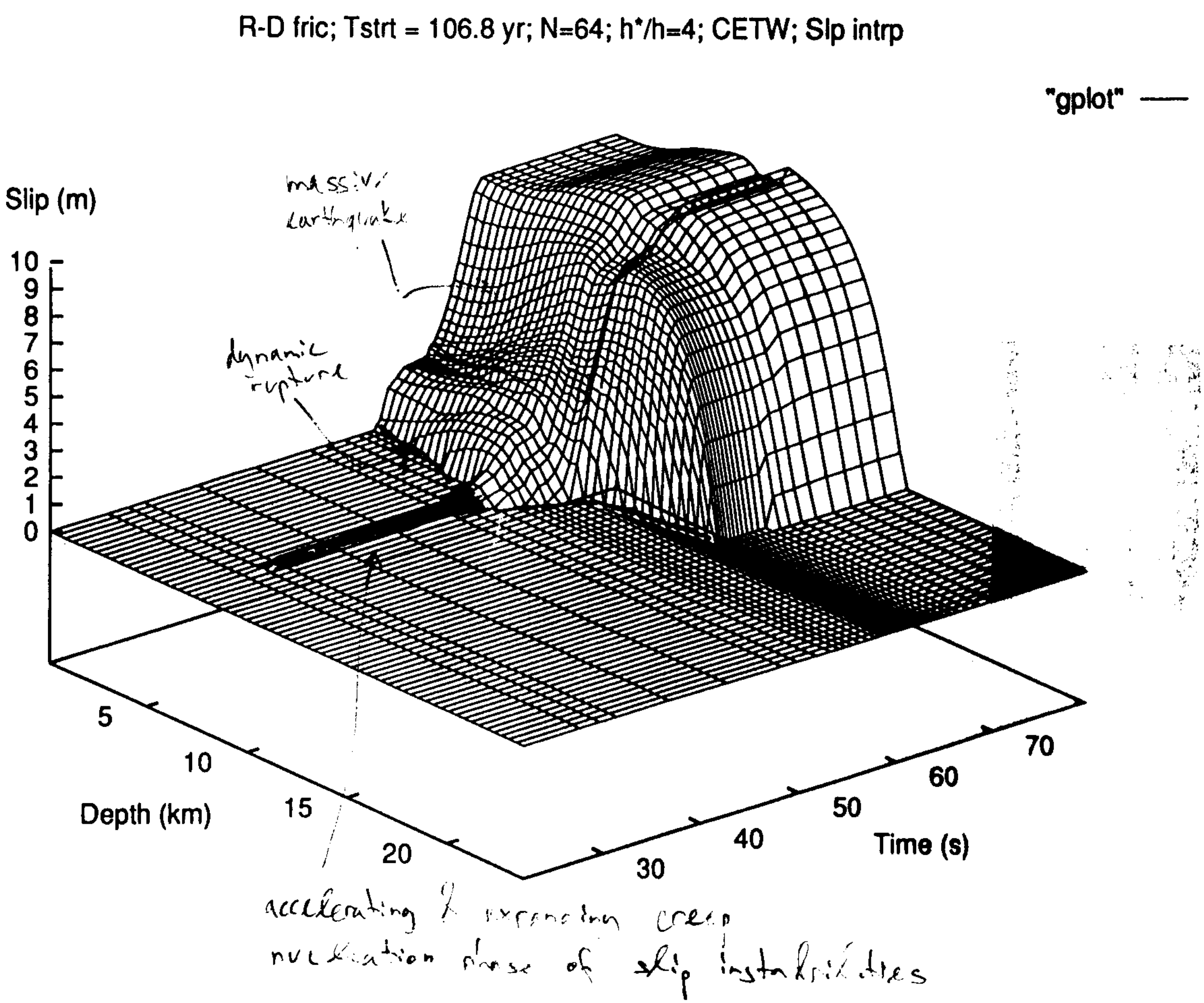
$\delta = V_2 t$ measured from time of velocity jump to V_2

$$(V\partial\tau/\partial V)_{inst} = A$$

$$\tau_{ss}(V) = \tau_0 - (B-A)\log(V/V_0)$$

$h^* = 2L\mu/\pi(B-A)$ ≡ nucleation size (Rice, 93)

$h << h^*$ ⟹ Smooth fault in elastic continuum


R-D fric; Tstrt = 106.8 yr; N=64; h*/h=4; CETW; Slp intrp
"gplot"
Slip (m)
10
9
8
7
6
5
4
3
2
1
0
Depth (km)
5
10
15
20
Time (s)
30
40
50
60
70
massive earthquake
dynamic rupture
accelerating & expanding creep
nucleation phase of slip instabilities

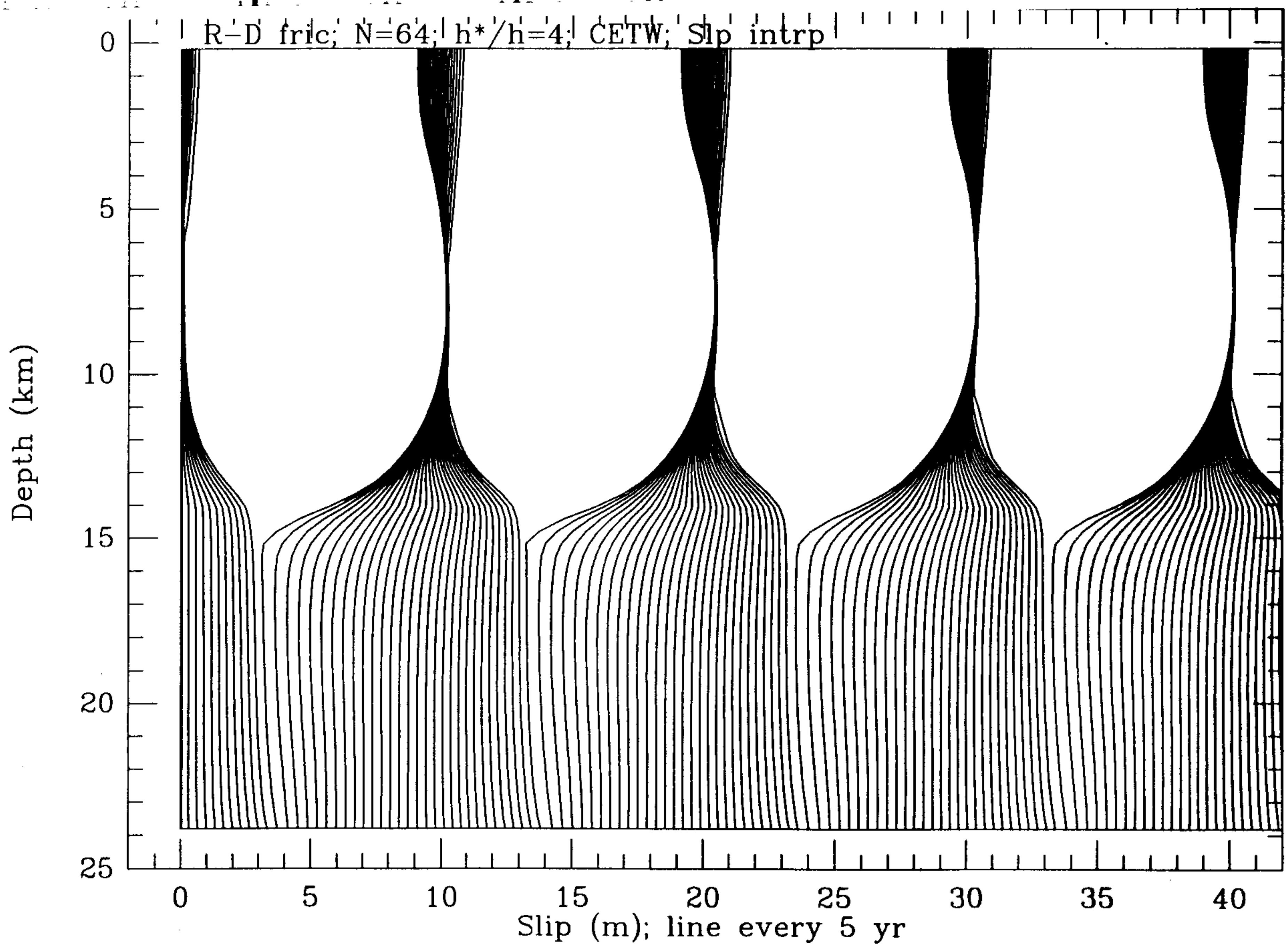

R-D fric; N=64; h*/h=4; CETW; Slp intrp
Depth (km)
0
5
10
15
20
25
0
5
10
15
20
25
30
35
40
Slip (m); line every 5 yr

Figure 4.

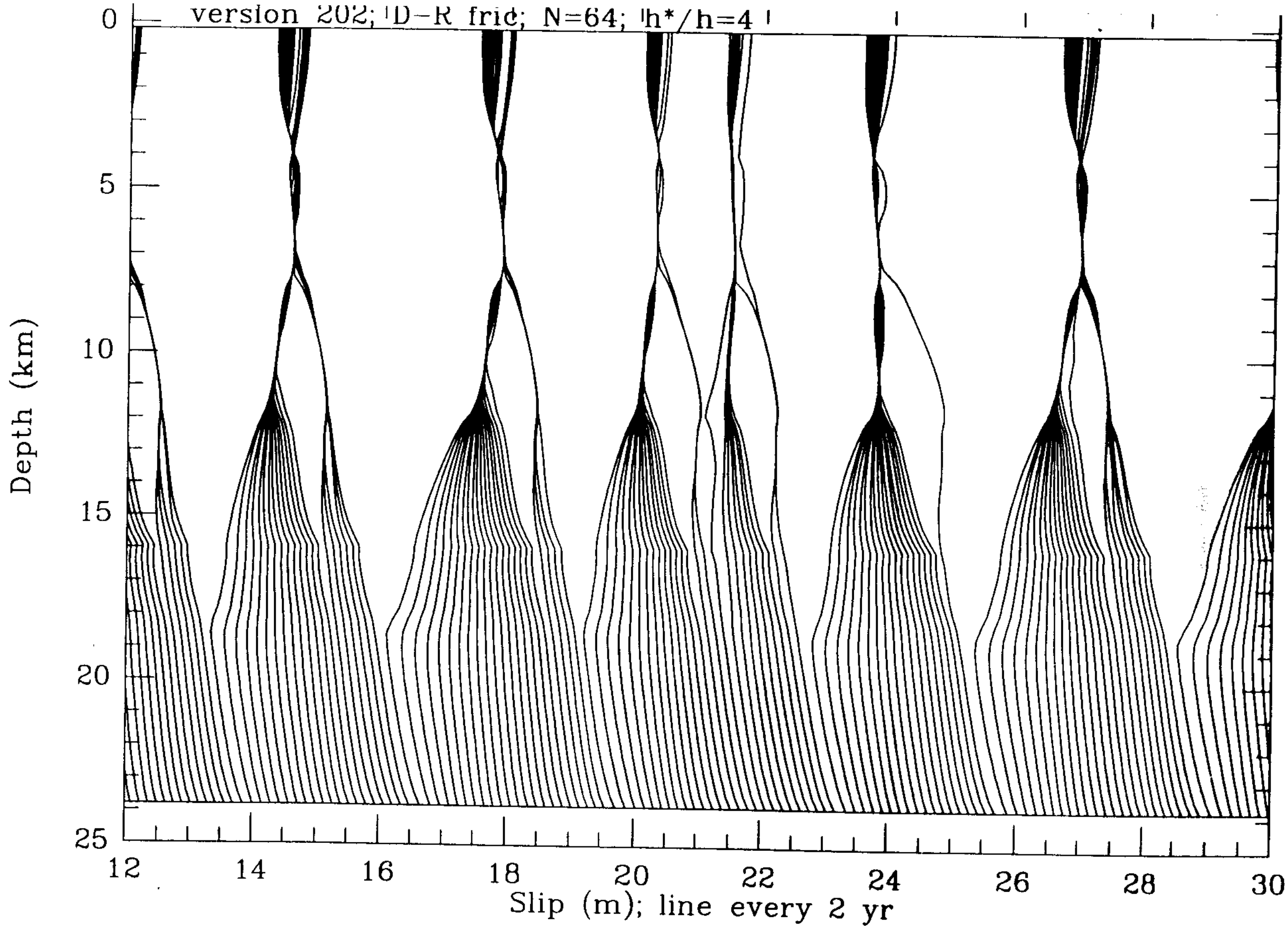

version 202; D-R fric; N=64; h*/h=4
Depth (km)
0
5
10
15
20
25
12
14
16
18
20
22
24
26
28
30
Slip (m); line every 2 yr

Figure 7.

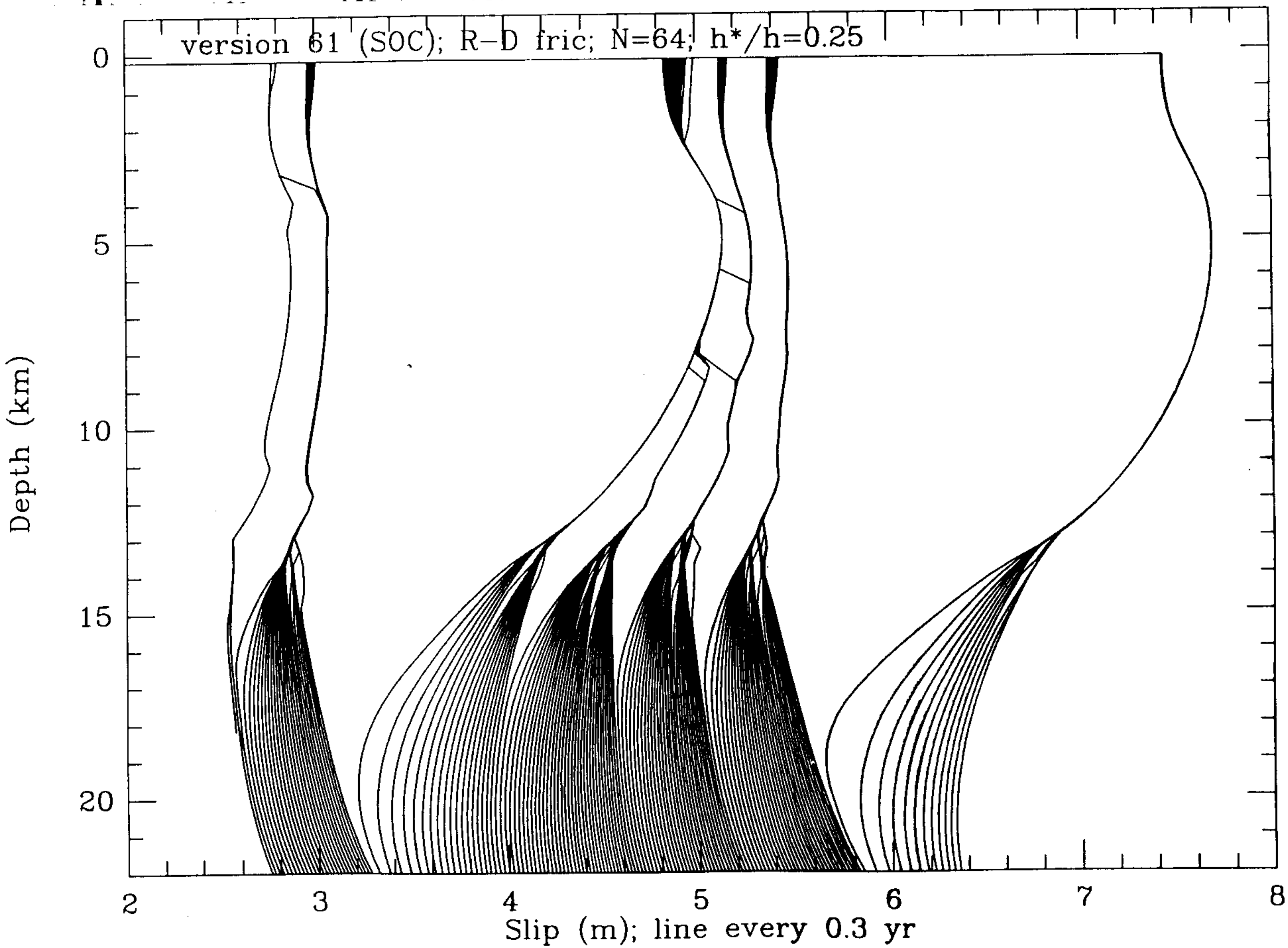

version 61 (SOC); R–D fric; N=64; h*/h=0.25
Depth (km)
0
5
10
15
20
2
3
4
5
6
7
8
Slip (m); line every 0.3 yr

Figure 11.

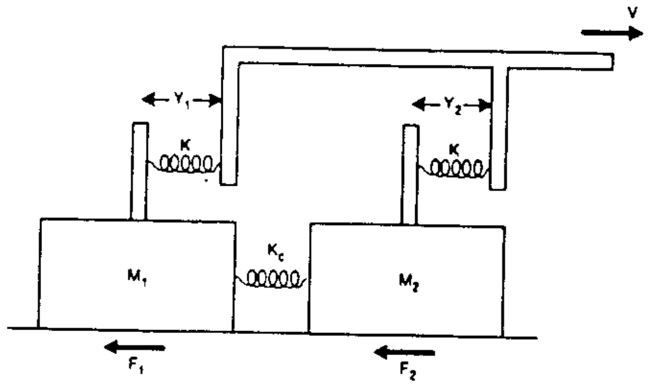


Figure 1. The double-block model (after Huang & Turcotte 1990 a b).

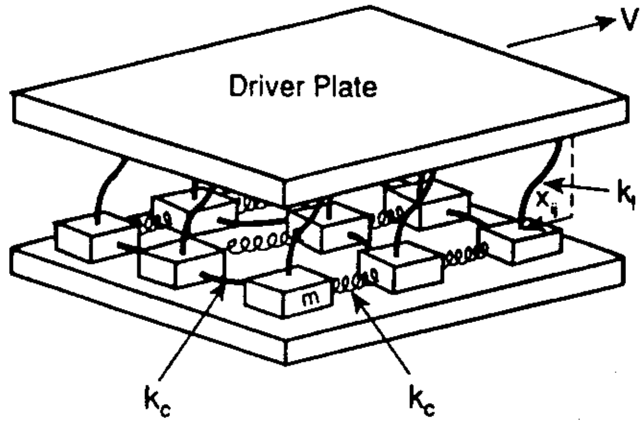


Figure 3. The cellular automaton (after Olami *et al.* 1991).

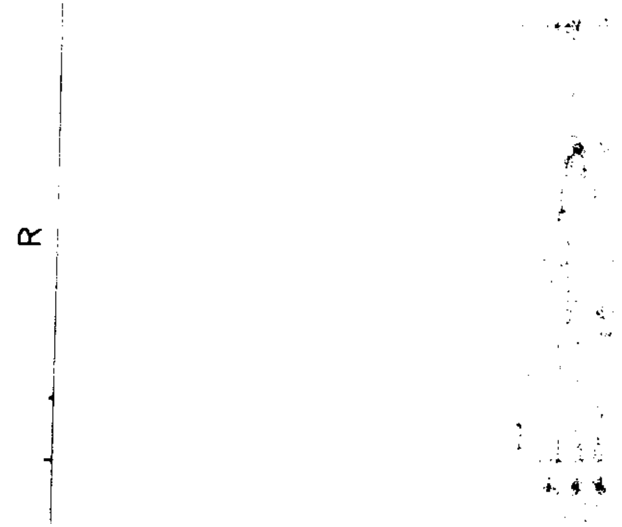


Figure 17. Predictability as a function of threshold magnitude f data from the DNAG catalogue. The dotted line indicates t corresponding one-displacement autocorrelation coefficients.

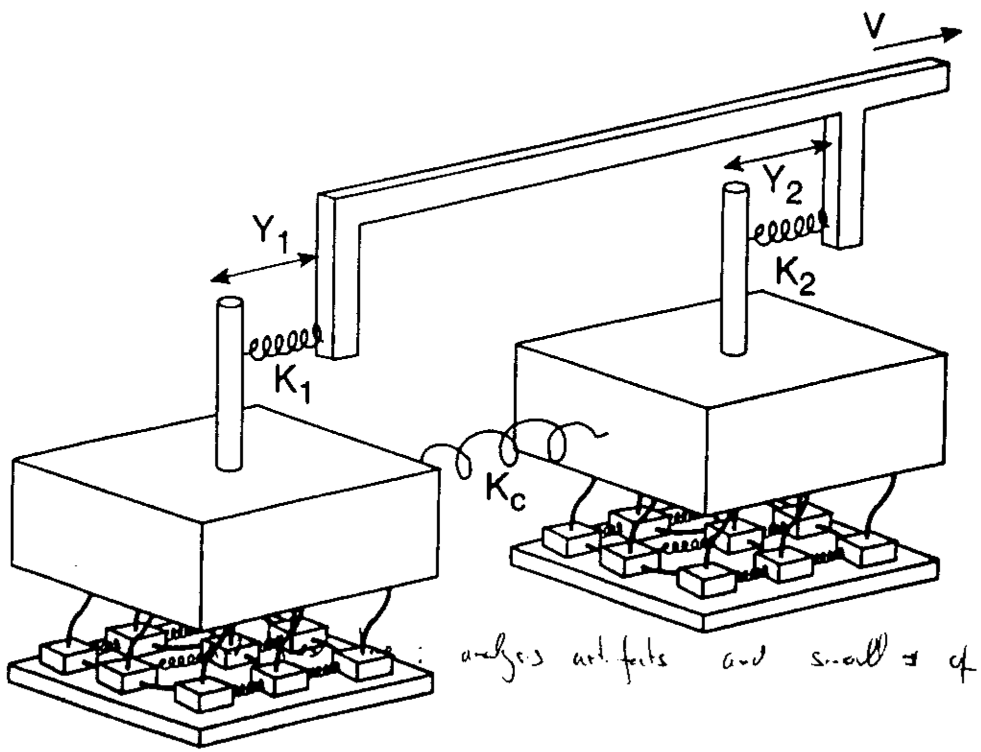


Figure 12. A schematic diagram of the hierarchical model.

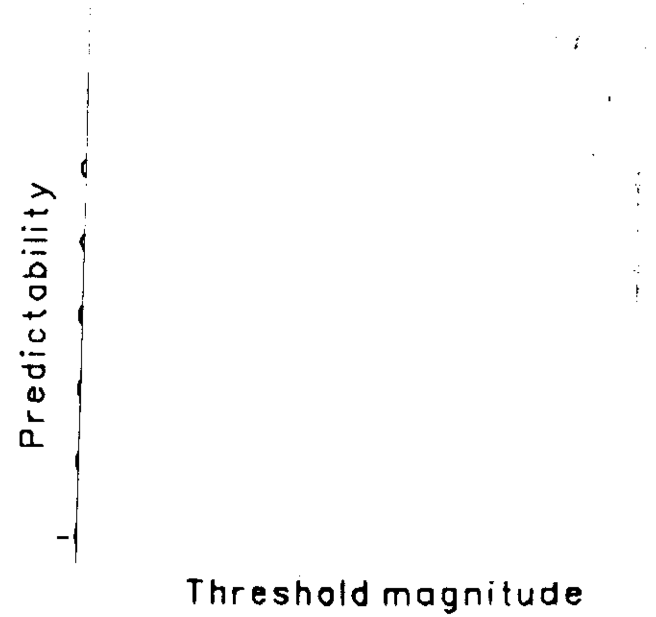


Figure 16. Predictability of data from the hierarchical model as a function of magnitude. The improvement of predictability for more energetic events is due to the increasing representation in the data sets of the low-dimensional seismicity.

Conclusions:

Claims for (1) generic criticality in earthquake dynamics, (2) generic inherential complexity in earthquake dynamics, and (3) general applicability of Chaos to earthquakes are Unjustified

Approach to
and retreat from
Criticality

(Intermittent Criticality)

Time evolution in models with tuning parameters not at critical values:

* Cyclical (non-repeating) establishment and destruction of long range correlations of stress

* Approach to and retreat from criticality

* Definition of an earthquake cycle on spatially extended heterogeneous fault system

* Application to hazard assessment and prediction

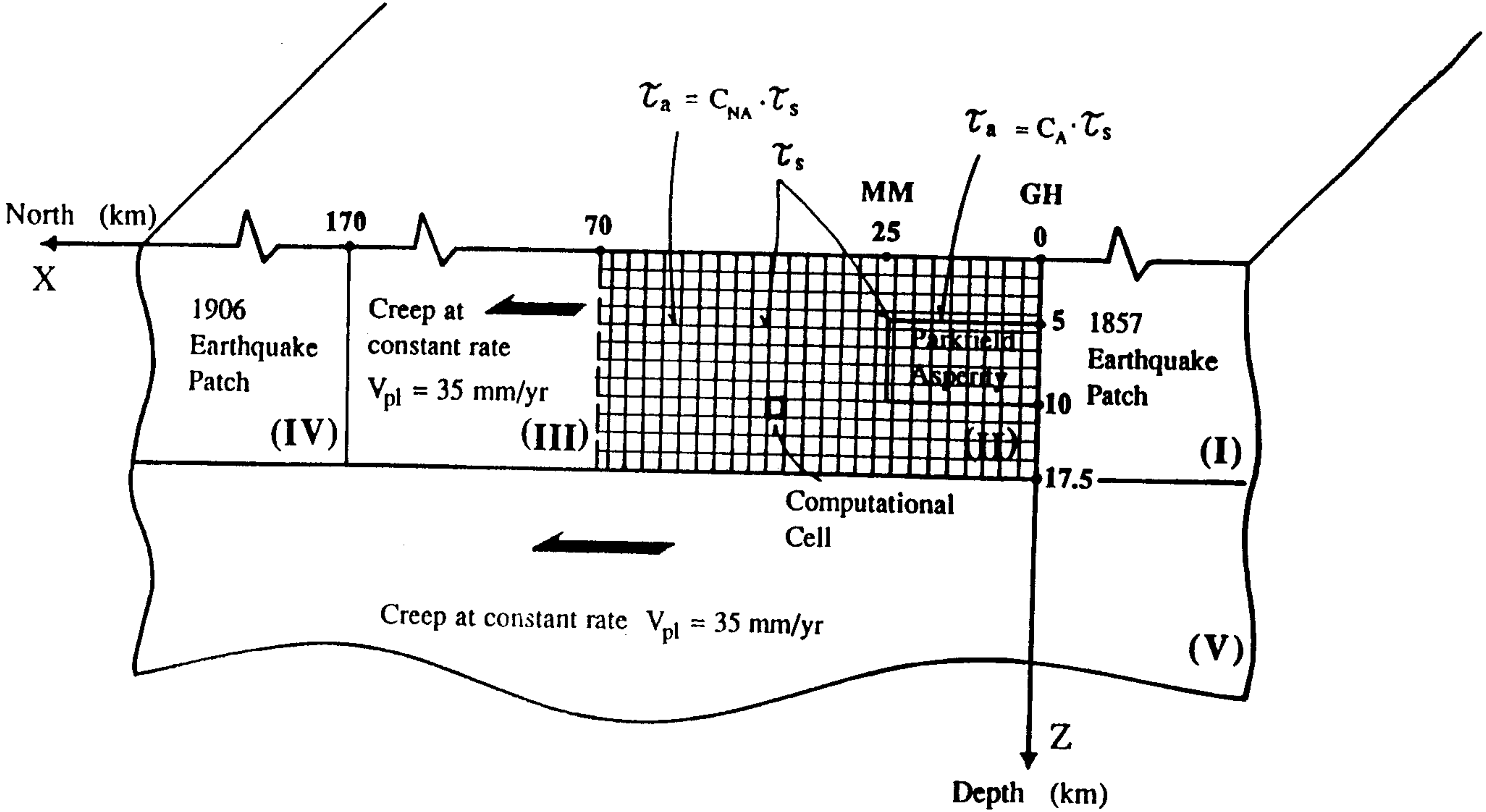
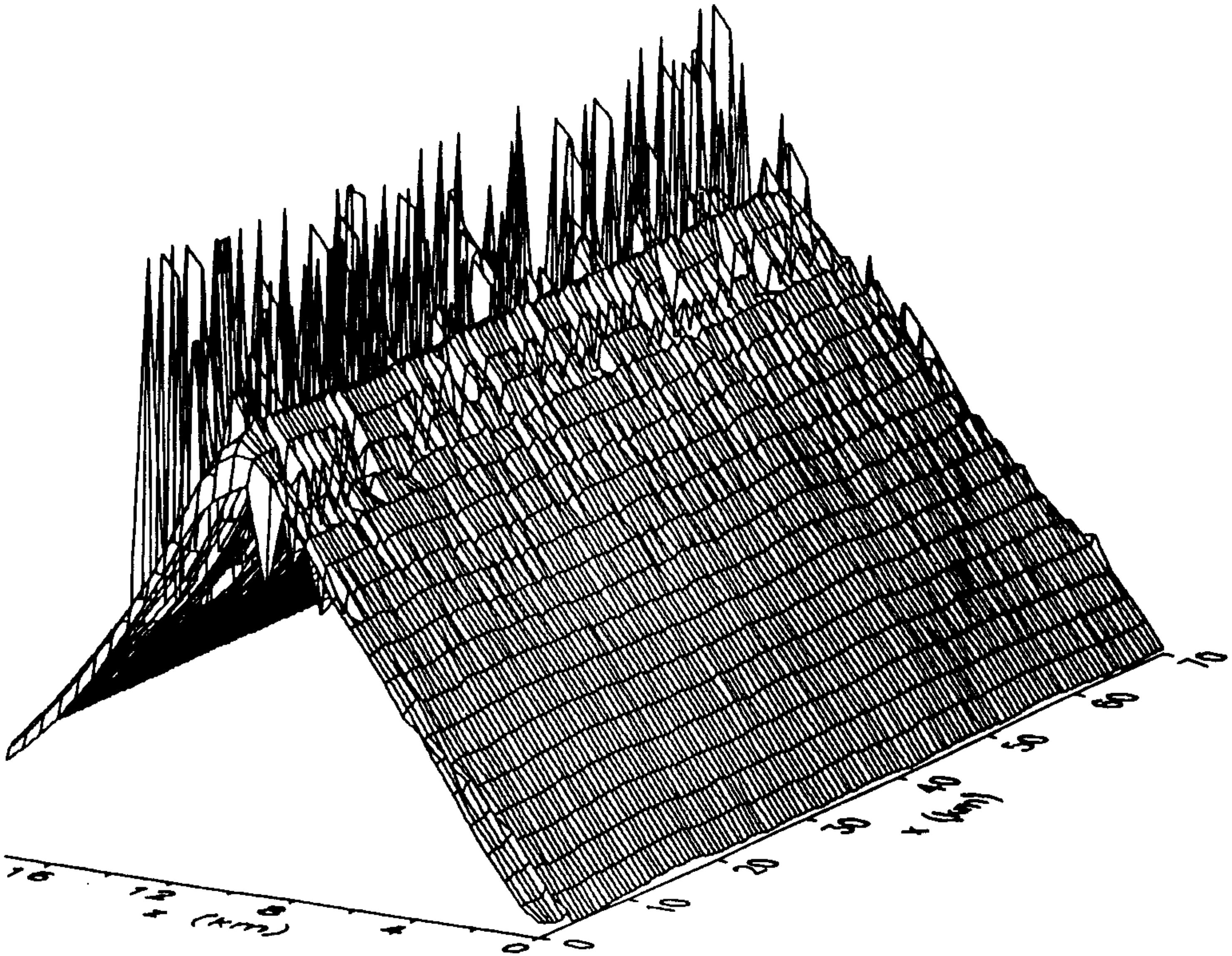
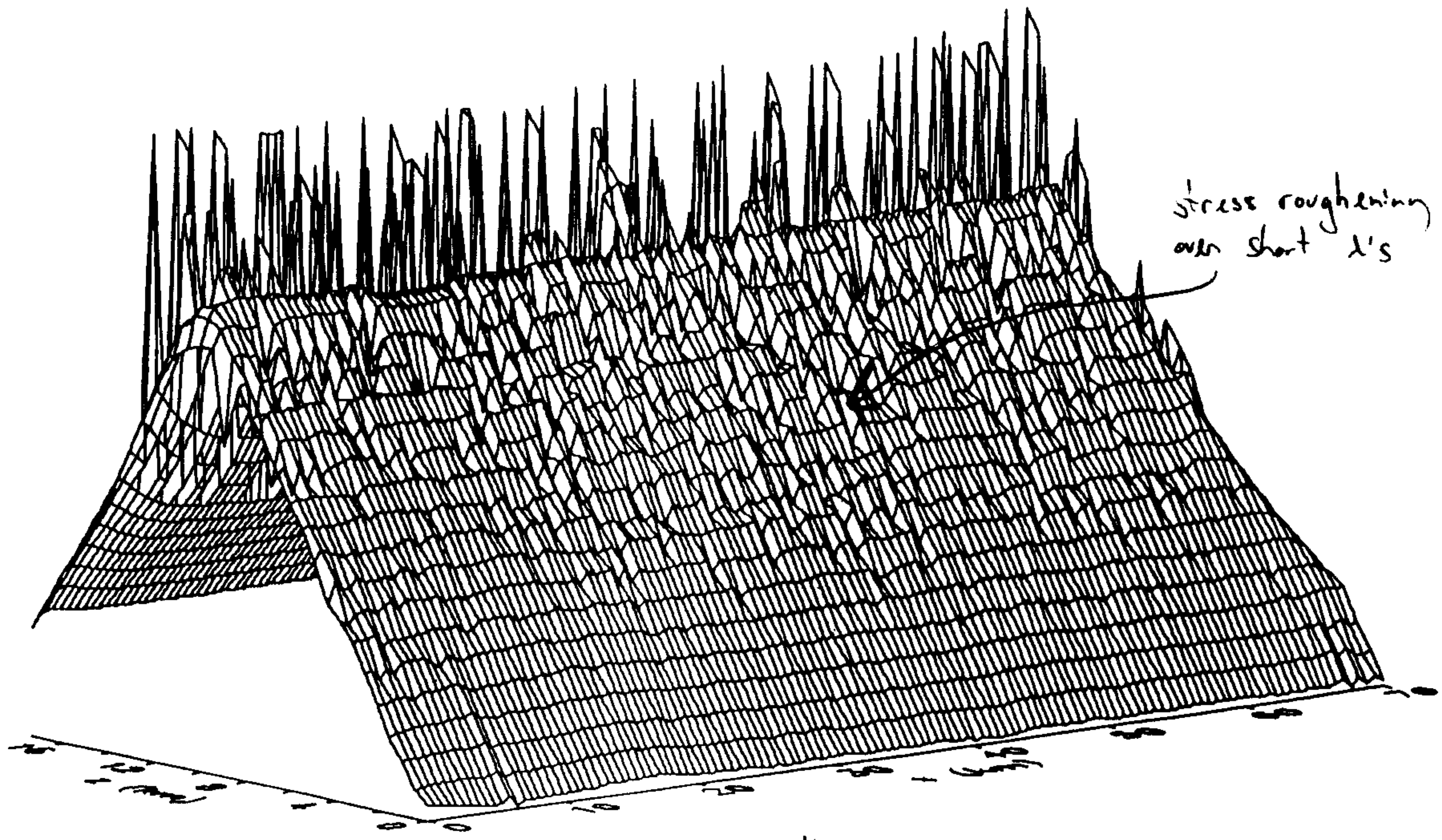

τa = CNA·τs
τs
τa = CA·τs
MM
GH
North (km)
X
170
70
25
0
5
10
17.5
1906
Earthquake
Patch
(IV)
Creep at
constant rate
Vpl = 35 mm/yr
(III)
Parkfield
Asperity
(II)
1857
Earthquake
Patch
(I)
Computational
Cell
Creep at constant rate Vpl = 35 mm/yr
(V)
Z
Depth (km)

Figure 2

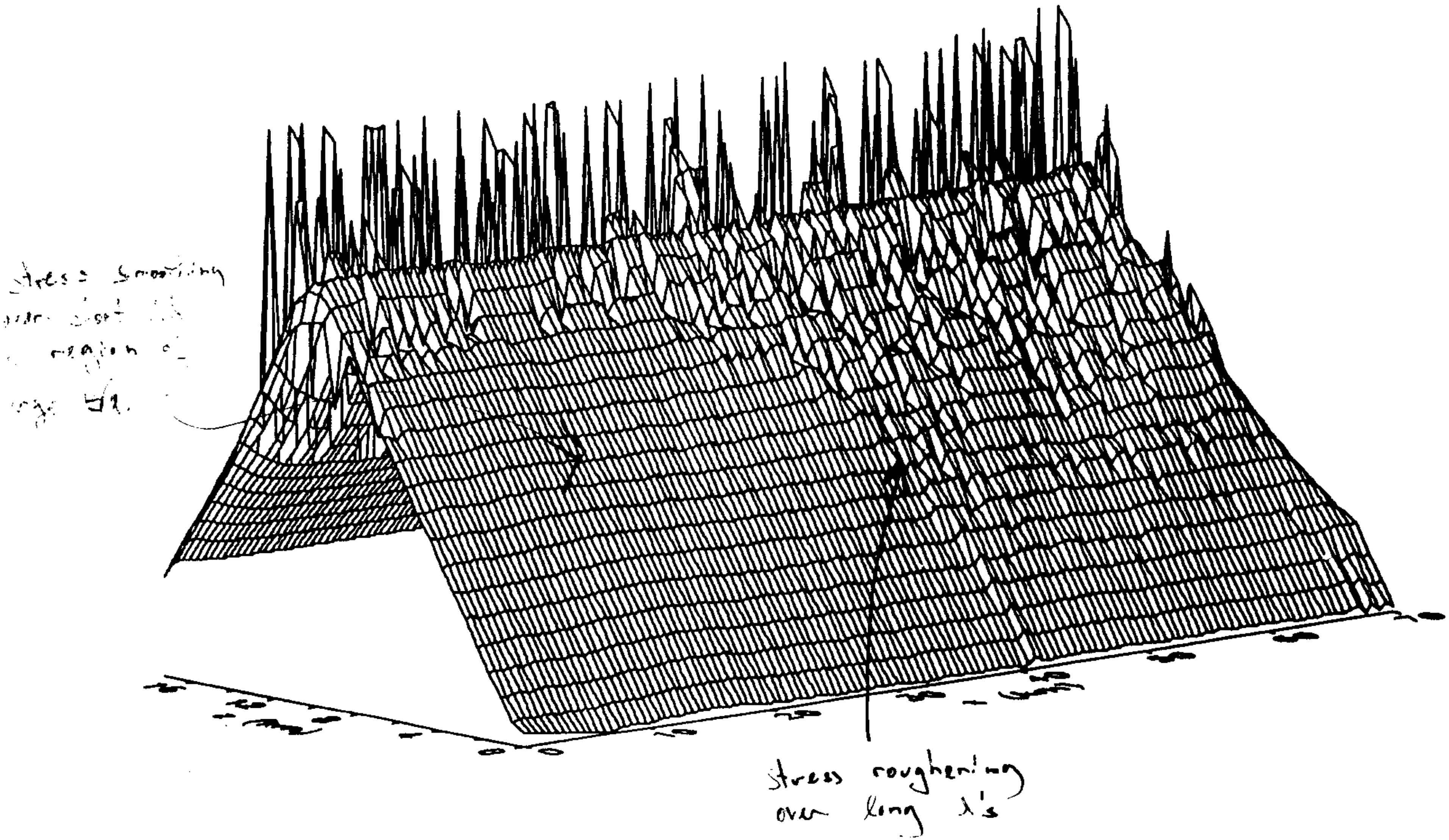
stress.frac at t=180 yr

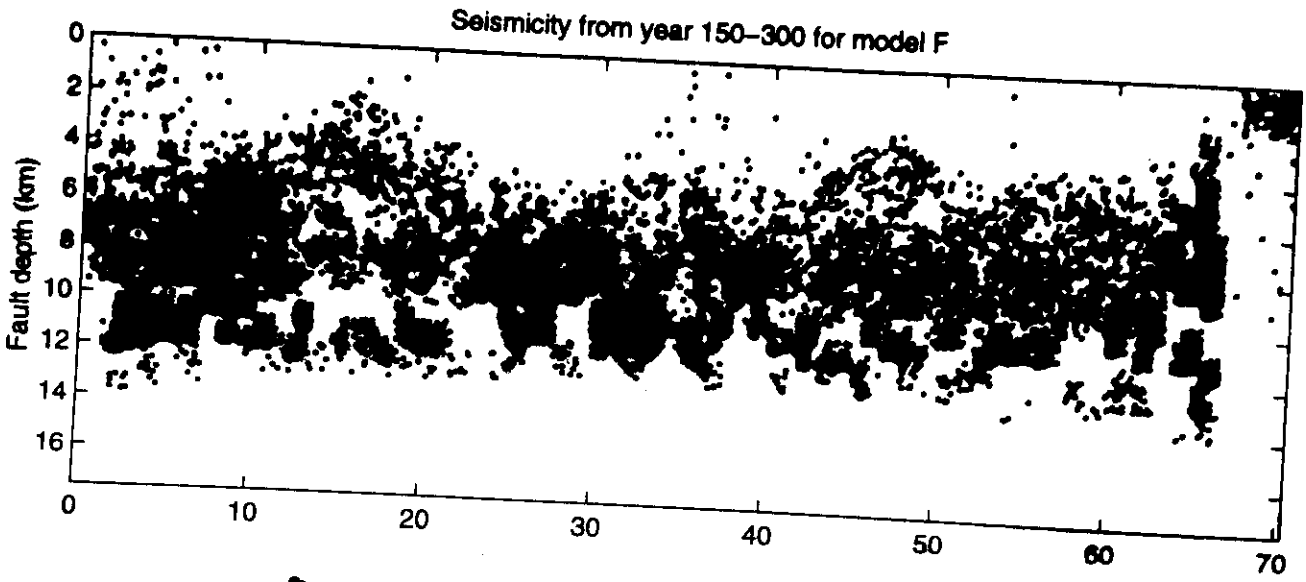


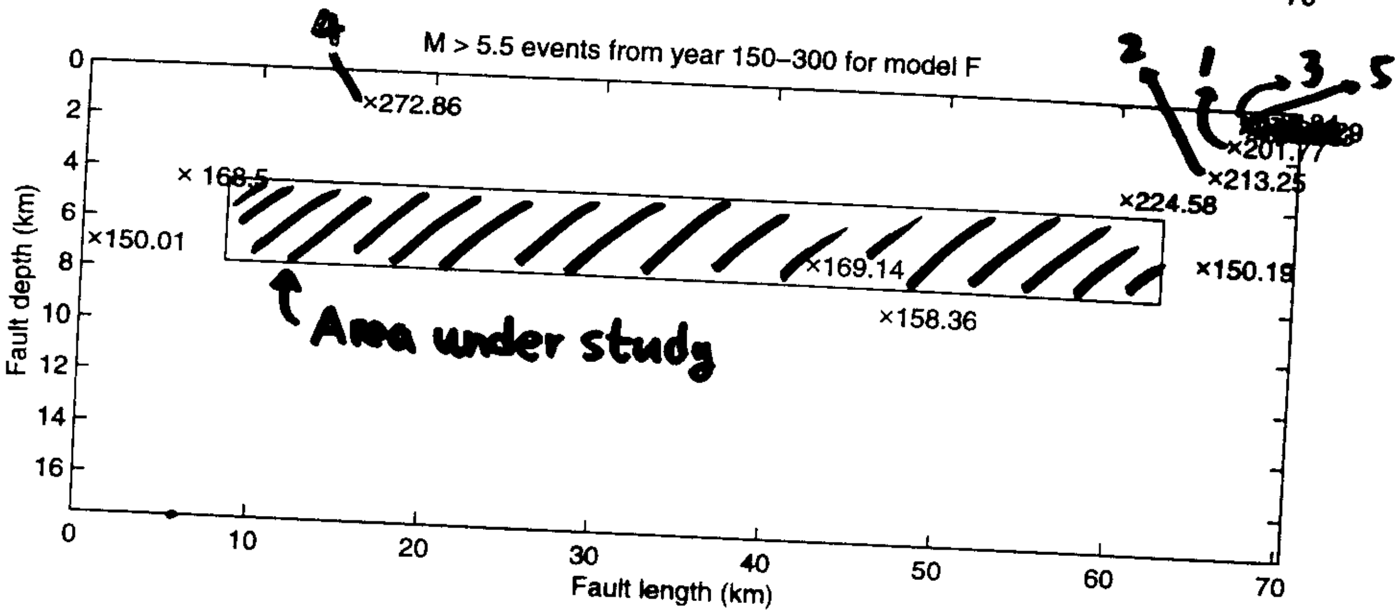
stress before an M=6 event, frac

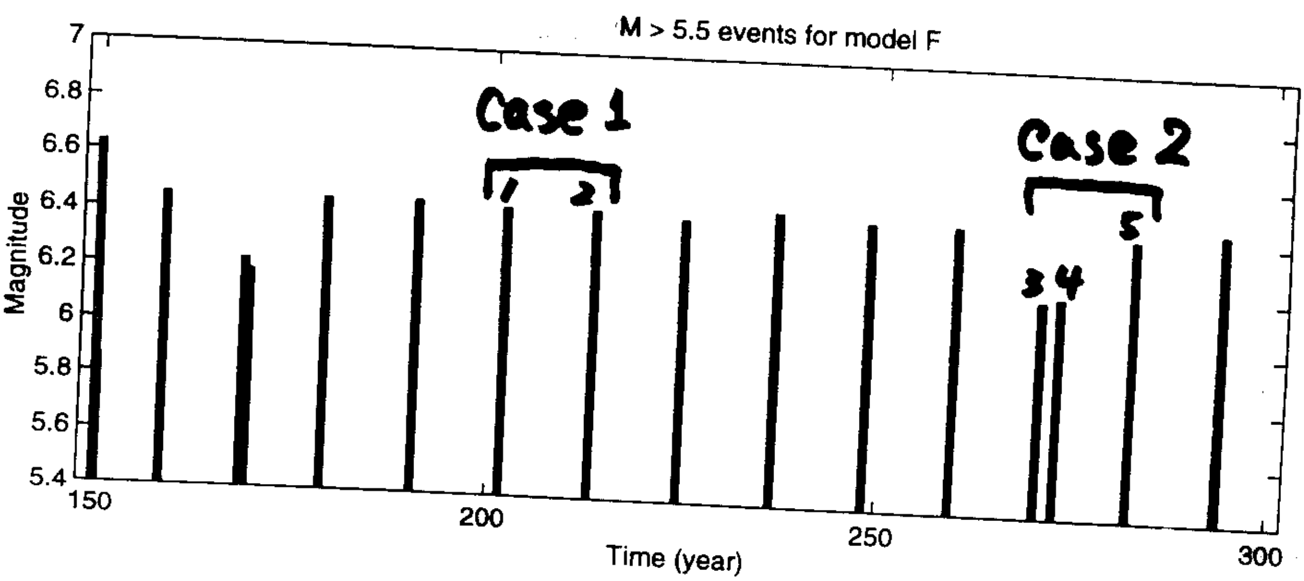


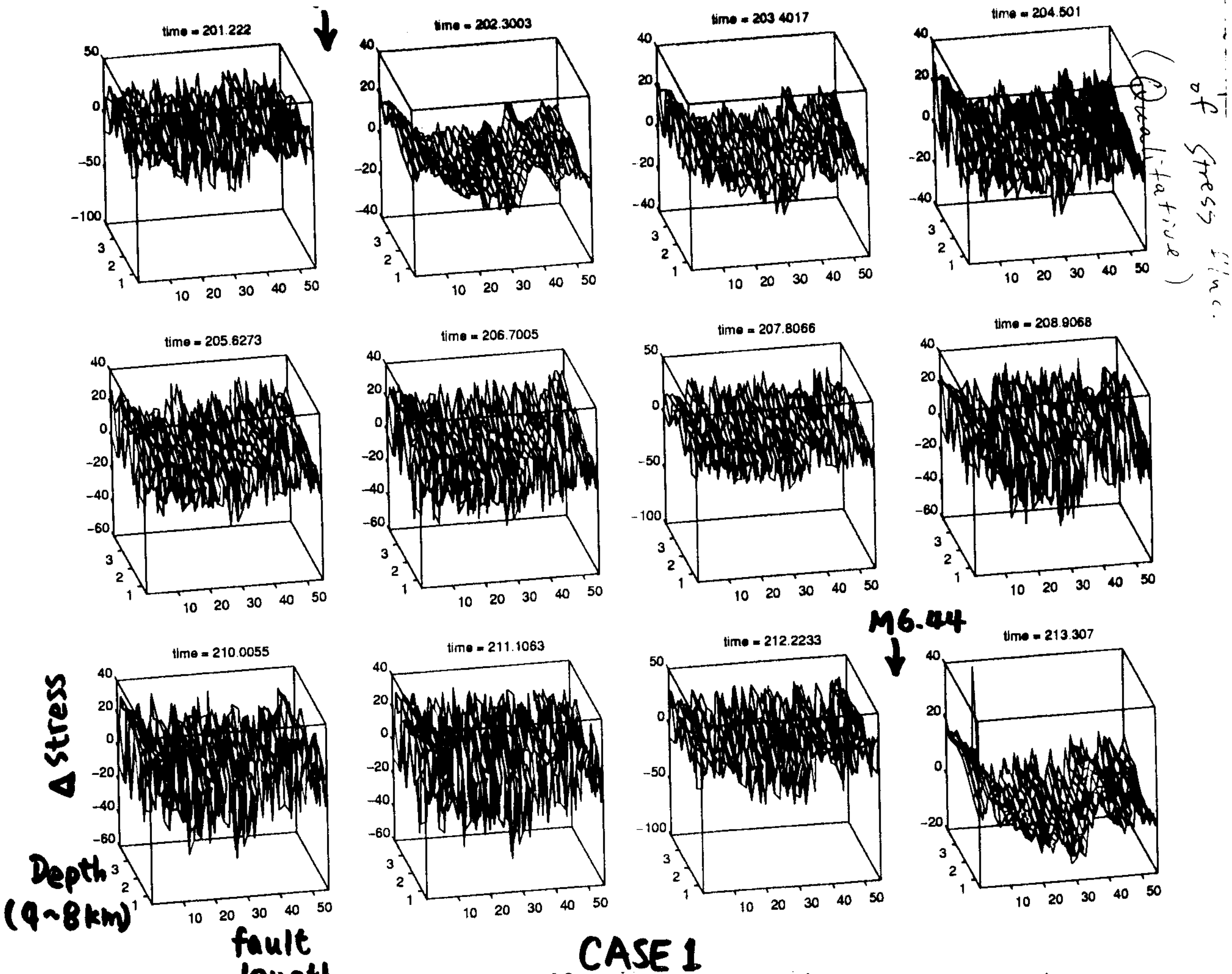
stress after an M=6 event, frac




Seismicity from year 150–300 for model F
Fault depth (km)
0
2
4
6
8
10
12
14
16
0
10
20
30
40
50
60
70


M > 5.5 events from year 150–300 for model F
Fault depth (km)
Fault length (km)
×272.86
× 168.5
×150.01
×169.14
×158.36
×201.77
×213.25
×224.58
×150.19
4
2
1
3
5
Area under study
0
2
4
6
8
10
12
14
16
0
10
20
30
40
50
60
70


M > 5.5 events for model F
Magnitude
Time (year)
Case 1
1
2
Case 2
3
4
5
7
6.8
6.6
6.4
6.2
6
5.8
5.6
5.4
150
200
250
300


of stress func.
(Qualitative)
time = 201.222
time = 202.3003
time = 203 4017
time = 204.501
time = 205.6273
time = 206.7005
time = 207.8066
time = 208.9068
time = 210.0055
time = 211.1063
time = 212.2233
time = 213.307
M6.44
Δ stress
Depth (4~8 km)
fault length

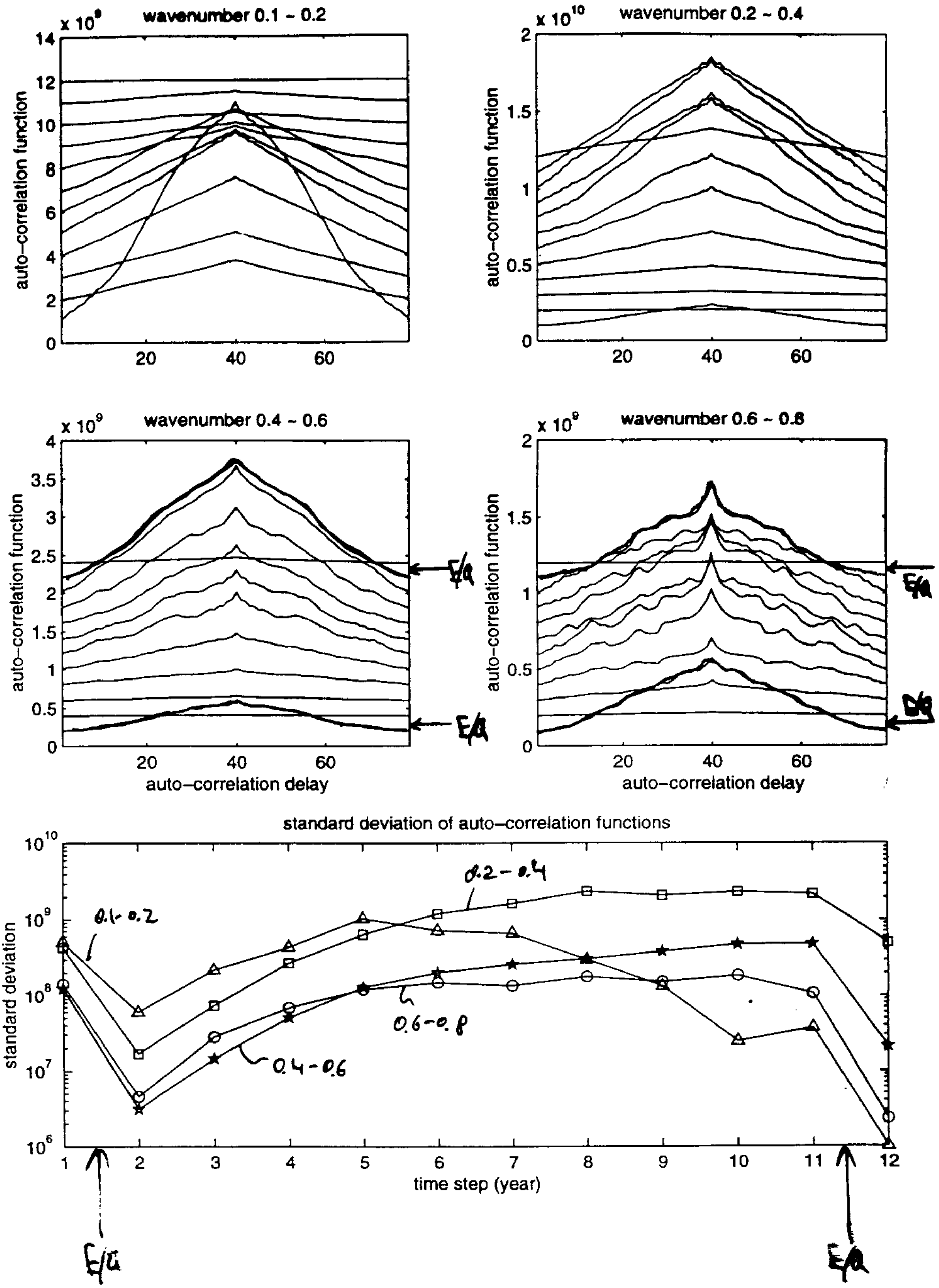
CASE 1

Analysis Steps(for each 3-months time interval):

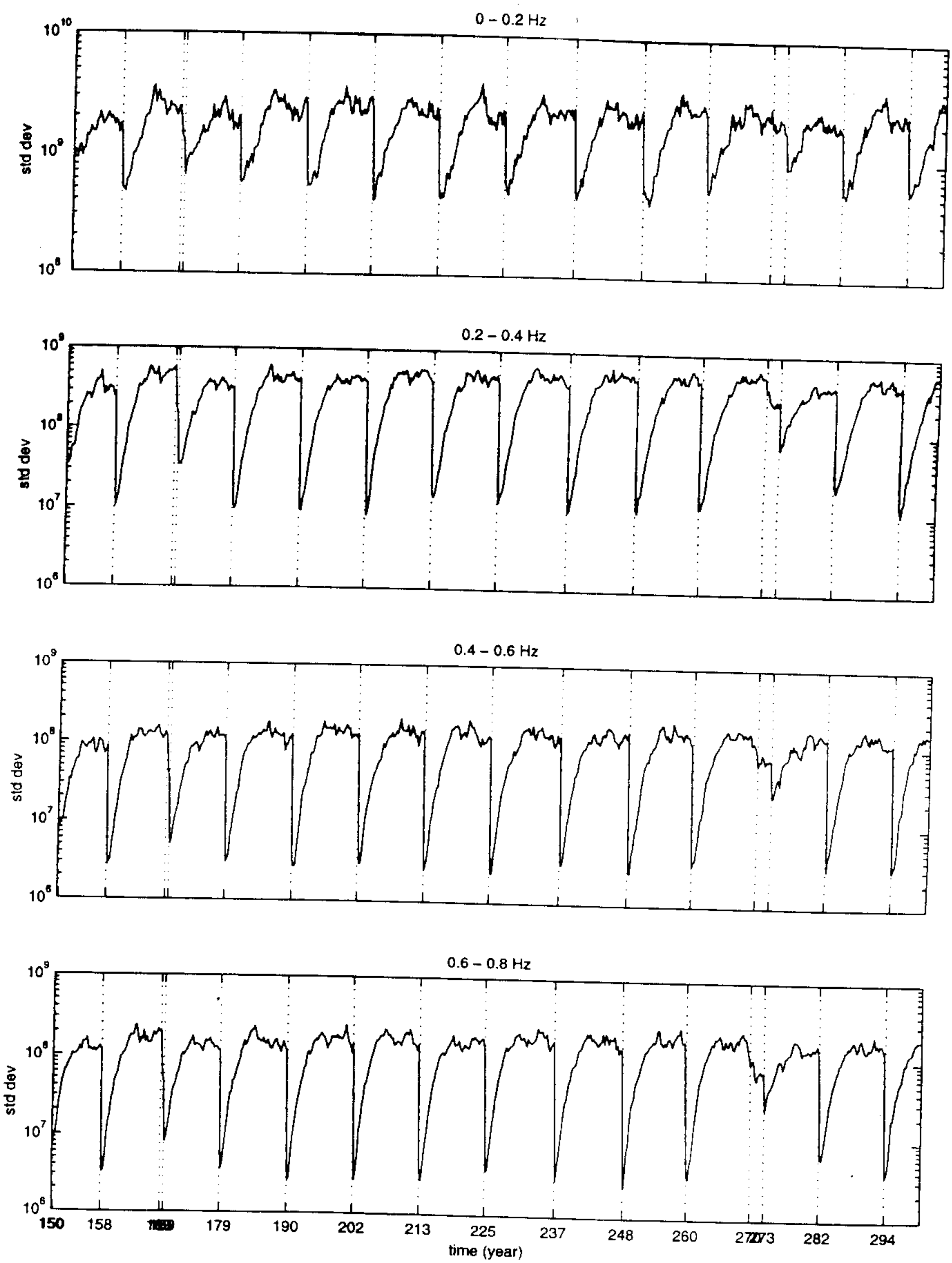
1) Transform the stress data to spectral-space domains using the Empirical Mode Decomposition method (Huang et al., Proc. R. Soc. Lond. A, 1998)

2) Compute the auto-correlation coefficients of stress at different wavenumber intervals as a function of space offset.

3) Calculate the standard deviations of the auto-correlation functions, and use these as estimates for the width of the stress correlations.



wavenumber 0.1 ~ 0.2
x 10^9
auto-correlation function
wavenumber 0.2 ~ 0.4
x 10^10
wavenumber 0.4 ~ 0.6
wavenumber 0.6 ~ 0.8
auto-correlation delay
standard deviation of auto-correlation functions
standard deviation
time step (year)
0.1-0.2
0.2-0.4
0.4-0.6
0.6-0.8
E/a



0 – 0.2 Hz
0.2 – 0.4 Hz
0.4 – 0.6 Hz
0.6 – 0.8 Hz
std dev
time (year)
150
158
179
190
202
213
225
237
248
260
273
282
294

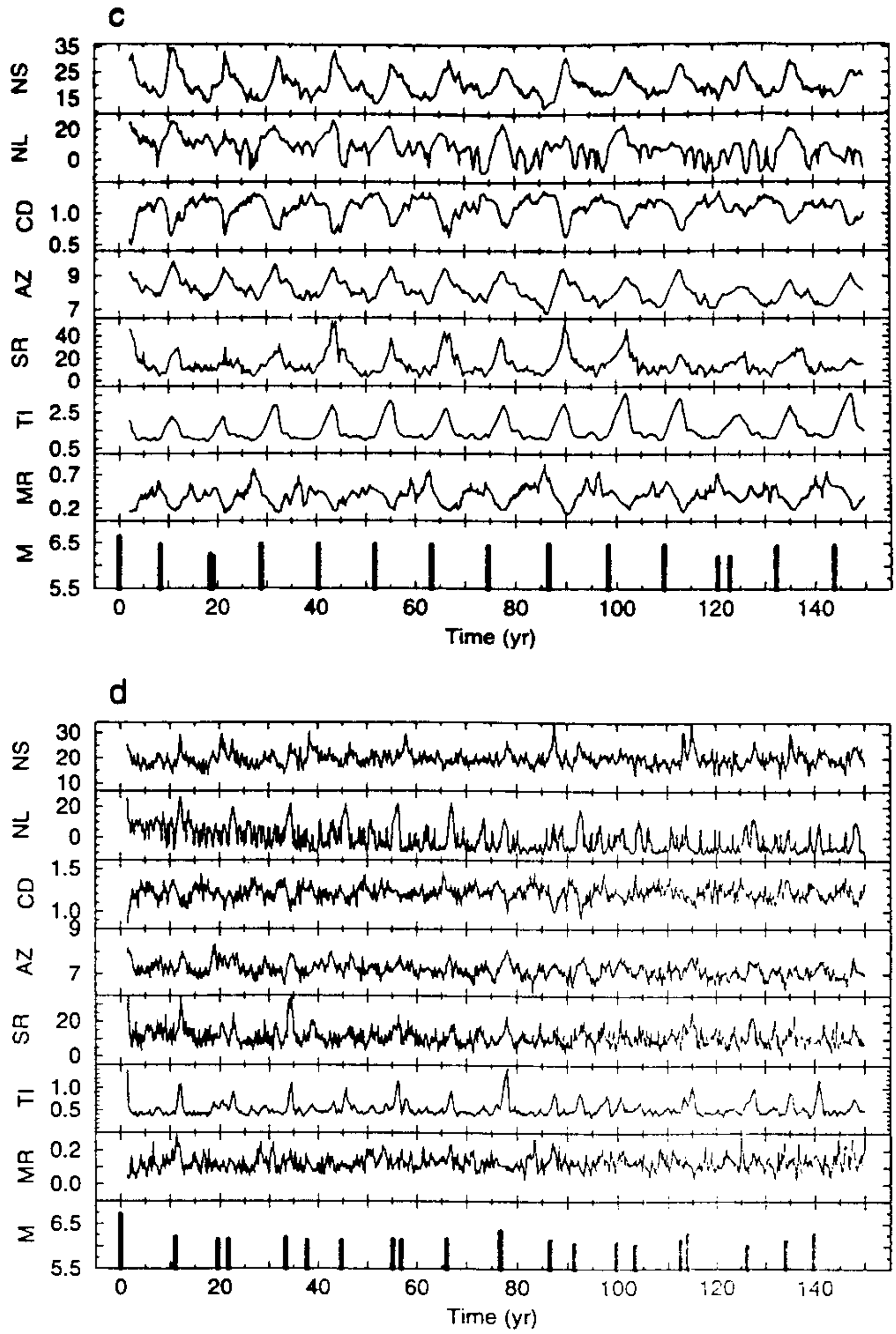


Figure 2. (continued)

kept as low as practically possible, with the range $-1 \leq \Delta \leq 2$ marking the largest deviations occasionally allowed in this study. As an example, $N^{large} = 30$ in model A, but $n^{max} = 28$ for the parameter *SR* and $n^{min} = 31$ for the parameter *AZ*.

5.2. Reliability of the Threshold Levels, *s*

Applications to real catalogs will have to include practical adjustments of the empirical threshold levels *s*. This subject is not studied extensively here, but it is possible to check how realistic the threshold levels used above are. For the sake of clarity, subscripts of *s* will be used in this section to mark the thresholds for different parameters, such as s_{NS}, s_{NL}, etc.

As an example, the group *CD* values define range widths, which increase from 0.67 for model M, to 0.70 in models U and A, and to 0.87 in model F (see Figure 2). In contrast, the width of the range from 100 randomly simulated sets, with 100 points per set (to be comparable with the groups here), using techniques described by *Eneva* [1996], is 0.30 to 0.37 in the various models. Thus in this case the width of the range covered by the group values is more than twice larger than the

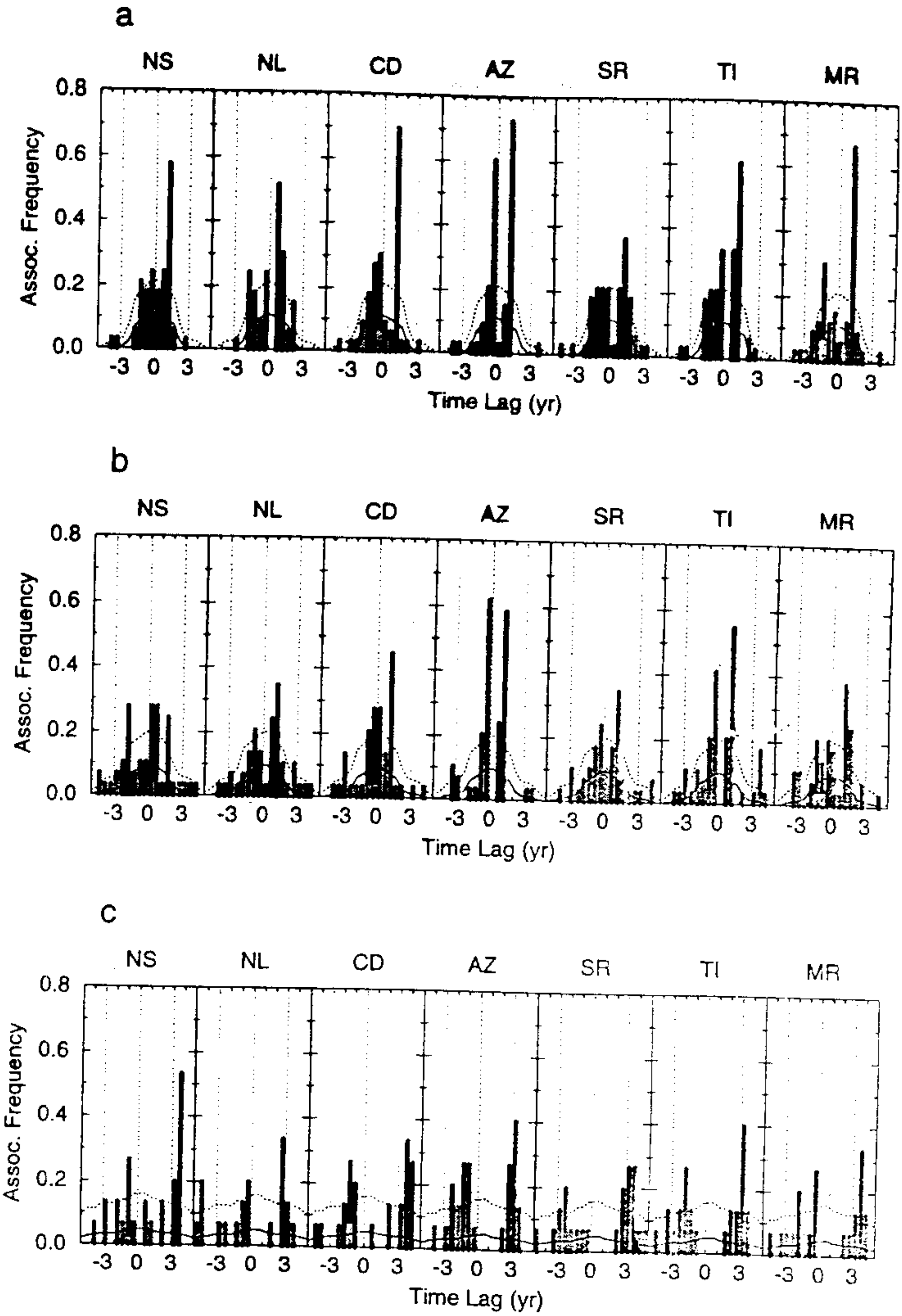


Figure 4. Association plots for (a) model U, (b) model A, (c) model F, and (d) model M. Frames from left to right of each plot show association frequencies between $M \geq 6$ events and local extrema in the seven parameter times series as marked; heavily and lightly shaded bars denote association with local maxima and minima, respectively. Average association distributions and those values +2 standard deviations from 1000 simulations of corresponding random time series are shown with solid and dashed lines, respectively.

frames) and "first" aftereffects at positive time lags (right halves of the frames). For any parameter, the designations "last" and "first" are used to choose from several precursory or aftereffect extrema associated with a given large event only the ones that are the closest in time to its occurrence. Although significant aftereffects are observed for all models and most parameters, the additional analysis done below focuses only on precursors.

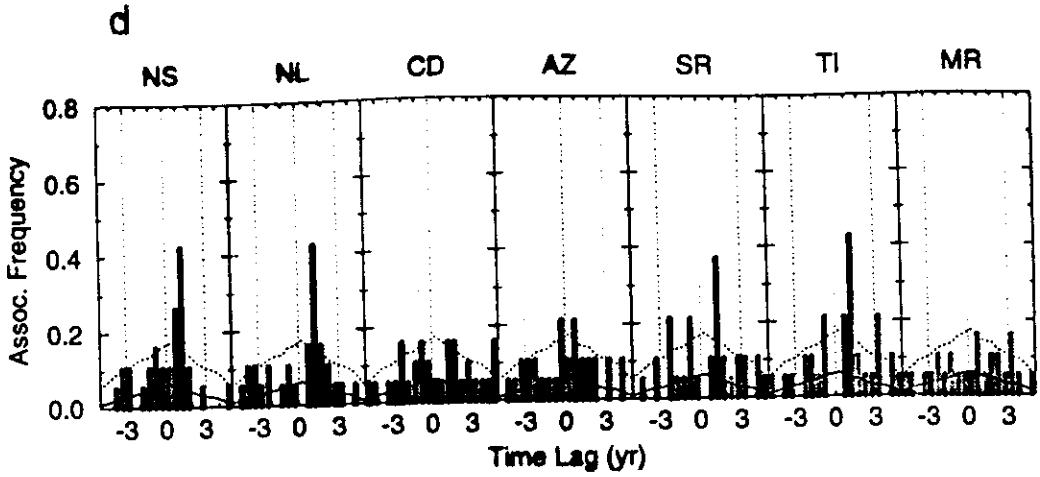


Figure 4. (continued)

In view of the high negative correlation (r_s = −0.94) established for the *NS* and *CD* time series in model F, one may expect the respective association plots in Figure 4c to be similar. However, the association plots are based on comparison between the time series of large events and the time series of local extrema (as opposed to the entire time series used in the evaluation of the interparameter correlations). This difference is apparently sufficient to cause the observed differences in the details of the *NS* and *CD* association plots, although the overall predictability of the large events would be almost the same (~80%) if either of these two parameters is used.

precursors are observed. The significance in this case is such that the probability of the simulated random association frequencies being larger than the observed frequencies for the same time lags is smaller than 5%. This test identifies precursors with the required confidence for all parameters and models, with the exception of three parameters (*NS*, *NL*, and *MR*) in model M. However, the results from this test, too, should not be taken in isolation, as in some cases "sharp" precursory anomalies (significant associations for distinct time lags) may be absent, but a cluster of association frequencies at several adjacent time intervals may be of interest (e.g., *NS* in Figure

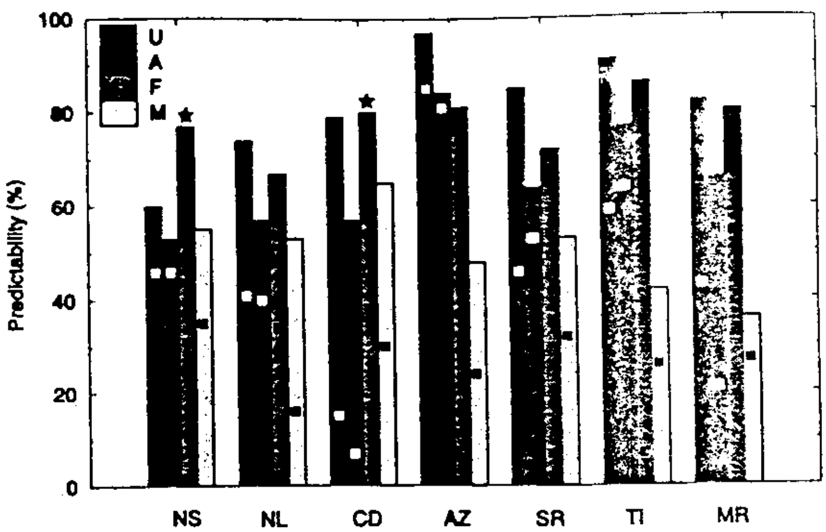


Figure 5. Predictability and trends in the four models. Results for the different models are shown with different shadings as in legend. Predictability is given as percentage of $M \geq 6$ events preceded by a local extremum in any of the seven parameters indicated along the horizontal axis. The types of local extrema depicted are as follows: *NS* maxima for model A and minima for all other models; *NL*, *AZ*, *SR*, and *TI* minima for all models; *CD* and *MR* maxima for all models. The portion of large events below the square in each bar is preceded by decreasing trends, and above the square by increasing trends (squares are solid or open only for contrast with the background shading). Stars mark redundant parameters with high interparameter correlation (see text).

so far. Most significant are the predictabilities that are larger than 50% in Figure 5. This is because a local extremum in the

models represent cases of mature, relatively regular, fault

Prediction

Current understanding of earthquake complexity and nucleation process indicate that prediction of individual events is very unlikely.

But it is still possible that the self-organization of stress and seismicity generate informative statistical measures for intermediate-term prediction of large events.

This is supported by, e.g.,

patterns recognition analysis of observed (e.g., Keilis-Borok & Kossobokov, 90) and synthetic (e.g., Pepke et al., 94; Eneva and Ben-Zion, 97) catalogs

time-to-failure analysis of Benioff strain (e.g., Bufe & Varnes, 93; Sornette & Sammis; Bowman et al., 98)

cyclical (non-repeating) establishment and destruction of long range correlation of stress (e.g., Ben-Zion & Li, 98; Sammis & Smith, 98).

Caution: Must improve the rigor of hypothesis testing and data analysis (e.g., Kagan, Geller, Mulargia, Jackson, Eneva, Michael)

Perspectives on the Field of Physics of Earthquakes

Yehuda Ben-Zion, Charles Sammis, and Tom Henyey
University of Southern California

This article reports on the state of physics governing the behavior of earthquakes and faults, based on discussions held during a workshop of the Southern California Earthquake Center (SCEC) suggested by Tom Henyey and convened by Yehuda Ben-Zion and Charles Sammis at Snowbird, Utah, June 21–23, 1998. The objective of the workshop was to assess the current state of understanding of earthquake processes including event nucleation, propagation and arrest of ruptures, spatiotemporal seismicity patterns, interactions between faults, and evolution of fault systems. A better understanding of the earthquake process should enable scientists to develop seismic hazard assessment tools based upon improved estimates of the locations and sizes of future earthquakes and the time-dependent probabilities of their occurrence. It will allow incorporation of realistic simulations of dynamic rupture and wave propagation into hazard models so that time histories of strong ground-shaking from scenario earthquakes needed in performance-based seismic design of structures can be synthesized. There are many approaches to such problems, including continuum mechanics, statistical physics, laboratory experiments, and field observations. By bringing together experts in the various disciplines, we hoped to compare results and identify key problems for future research. A total of fifty-three scientists representing universities, the USGS, national laboratories, and government agencies participated in the workshop.

In a series of long review talks, Yehuda Ben-Zion began with brief outlines of laboratory studies, fracture mechanics, damage rheology, granular mechanics, and statistical physics approaches. He commented that while a unified framework for earthquake physics does not exist, a good common reference may be the equations of motion for a continuum solid. These equations are scale-independent, suggesting that deformation processes should produce self-similar patterns manifested in power law statistics. Such patterns are abundant in earthquake phenomenology. However, length scales associated with rheology, existing structures, etc. can produce important deviations from self-similarity. Ben-Zion gave two examples. The first is a transition from stable creep to dynamic instability at a nucleation size whose dimensions depend on frictional and elastic parameters. This transition, defining a minimum earthquake size, fueled hopes to observe the precursory deformation associated with the nucleation process. However, high resolution geodetic measurements and the existence of $M = -1$ events on the San Andreas Fault (SAF) indicate that, even on major faults, the nucleation zone is too small to produce detectable surface signals. The second, a larger example of a transition-breaking self-similarity, stems from the scaling of stress concentration in continuum solids with rupture dimension, which can produce a critical event size terminating the power law regime of frequency-size earthquake statistics. Returning to power laws, Ben-Zion reviewed the suggestion that these may result from proximity of dynamic variables to critical points of phase transitions. He recalled that while classical critical points are associated with specific values of "tuning parameters", self-organized criticality (SOC) involves a stationary critical behavior for a wide range of parameters. He noted that detailed experimental and theoretical works do not support the assertion that SOC describes earthquake dynamics. He also pointed out that early claims for generic inertial-dynamic complexity on a smooth homogeneous fault have not been supported by later studies and that recent results indicate that inertial-dynamic complexity, like criticality, occurs only for narrow ranges of tuning parameters. The identification of the effective tuning parameters (*e.g.*, geometric disorder and dynamic weakening) and associated critical values are important subjects of continuing theoretical and observational research.

Moving to details of individual ruptures, Ben-Zion commented that challenging problems in this area are proper understanding of the energy partition at a rupture front and the trajectory (including branching) of dynamic ruptures. Classical theory for a homogeneous solid and recent lab experiments indicate a transition from smooth rupture to rough crack surfaces and branching at rupture speeds lower than those commonly inferred for earthquakes. This is compatible with strongly disordered structures of immature fault systems but not with long straight fault traces characterizing mature fault zones and long straight ruptures in such systems. A possible explanation for the latter may stem from dynamic reduction of normal stress that accompanies slip on a material interface. This provides a dynamic mechanism for trapping ruptures in fault zones with well developed interfaces and also for producing a self-healing slip pulse associated with short rise times and small amounts of frictional heat. Ben-Zion noted that progress in understanding realistic dynamic phenomena will require lab measurements of branching processes and friction at high slip velocity for various rupture conditions, and rupture and friction experiments with dissimilar materials. Direct seismological observations will provide important input by improving estimates of static and dynamic stress drops and of rupture velocity and dimensions. This in turn involves obtaining high-resolution velocity models, especially for fault zone structures.

Jim Rice reviewed the status of continuum mechanics modeling of the earthquake process. He noted that rigorous models for which a continuum limit exists are limited by the size of the earthquake nucleation zone that scales with the characteristic slip distance associated with frictional weakening and by the required small time steps associated with rapid weakening of evolving fields. Models that incorporate nucleation zones based on the submillimeter slip weakening distances found in the lab are not yet practical. Rice pointed out that the broad distribution of event sizes observed in nature is not a generic outcome in continuum fault models. Such a behavior sometimes occurs for certain ranges of model parameters and can be enhanced by tuning the velocity-weakening friction laws. However, we still lack a systematic understanding of these conditions. Event populations with power law statistics are never seen in a continuum model with a single weakening mechanism but appear to be generic in inherently discrete models in which a continuum limit does not exist or was not obtained due to oversized cells. On the other hand, broad event statistics can be produced using a continuum model which incorporates a pair of weakening mechanisms, one of which nucleates at small scales and produces a very small stress drop and one which nucleates at scales on the order of the crustal seismogenic depth and involves a nearly full stress drop. The reasons for this are not fully understood, but it is very unlikely that such parameter choices are realistic. As noted by Ben-Zion, the existence of small events (observed down to $M = -1$ on the SAF) require nucleation zones with dimensions far smaller than the seismogenic depth.

Other issues in continuum earthquake models raised by Rice involve (a) the extension of rate and state-dependent (RSD) friction to high slip velocities which operate during an earthquake, (b) the rupture of strongly heterogeneous faults which break through geometric complexities and fault networks, (c) the role of strong heterogeneity and/or dissimilarities of fault properties across a fault plane in producing a short-duration slip pulse and associated phenomena, (d) how one earthquake contributes to another through stress transfer and how this differs between mature highly slipped faults and immature faults with little total slip, and (e) studies of branching of dynamic rupture. Finally, Rice raised three general questions: (1) Why is the stress level low (≤ 200 bars) along high-slip plate-bounding faults where the large earthquakes occur but high (consistent with lab friction) in the more stable crust where large earthquakes rarely occur? (2) Is the rheology at the base of the seismogenic zone controlled by hot frictional sliding on the fault plane, which satisfies RSD friction and exhibits velocity strengthening, or by a high-temperature creep mechanism? (3) Does dilatancy or strong velocity strengthening stabilize shallow fault rupture?

Daniel Fisher discussed the earthquake source from the perspective of statistical physics. He began by raising the question of whether the Gutenberg-Richter power law frequency-size relation is due to the distribution and geometry of faults, and therefore reflects some aspect of the long-time geological history, or whether it arises from the dynamics of failure on individual fault systems. He proposed to focus on individual fault systems because they are simpler and more easily modeled and to explore the roles of (a) long-range elasticity, (b) dimension of the system, (c) heterogeneities, (d) stress waves, (e) friction laws, and (f) history. The goal of a statistical physics approach is to understand the types of possible earthquake statistics, and "shapes" and dynamics of ruptures. Shapes of earthquakes, Fisher explained, deal with the question of whether the rupture is cracklike or pulselike, whether it is connected or islandlike, irregular, compact, or fractal. The shape of an earthquake determines how it scales—that is, how the slip, area, moment, and duration scale with effective diameter. If a wide range of power law scaling exists, then "universal" explanations may exist. The hope is that these explanations are robust in the sense that they depend on only a few features such as dimension or range of forces and are independent of most detail. Equilibrium systems that involve stable phases and critical points are fairly well understood analytically, while nonequilibrium systems, to which earthquakes belong, are not. Although there have been many computer simulations for nonequilibrium systems, they do not provide at present an adequate theoretical understanding.

Fisher outlined a strategy to understand the origins and robustness of scaling relations in seismicity. This begins by writing the effective equations of motion, which may be statistical but which depend on length scale. Then the renormalization group technique is used to study the system scale by scale to see how large-scale features are affected by small-scale ones. The strategy is to start with simplistic models or "caricatures" of the real system and then add features of the physics one at a time to see if a given feature is irrelevant and doesn't affect the scaling laws or is relevant and changes the scaling laws (and the universality class), or even destroys scaling altogether. The goal is to discover what is important and what is not in understanding the observed scaling relations. Fisher then gave several examples of this procedure based on a model of a single fault system with heterogeneous properties.

Tom Rockwell reviewed contributions from paleoseismicity. He focused on the extensive trenching of active faults in southern California to date prehistoric events. An exciting result is the tendency for large events in a given region to cluster in time. In the eastern Mojave, all the trenched faults show a major event in the past 2,000 years, with another peak of activity between 4,500 and 6,500 years ago, another between 8,000 and 10,000 years ago, and a weak peak between 14,000 and 16,000 years ago. Similarly, the faults in the Salton trough show clustering of large events at approximately 1,200, 1,350, 1,500, 1,675, and 1,925 years before present.

Greg Beroza presented seismic observations of the source process, including the imaging of heterogeneous slip and the Coulomb stress changes which foreshocks produce at the hypocenters of large events. He discussed the rather surprising result that many foreshocks, which occur immediately before the mainshock, actually reduce the Coulomb stress at the hypocenter, moving it further from failure. Beroza showed observations of repeating microearthquakes and discussed their use for inferring time-dependent properties of faults. He also discussed the possibility that observed seismograms contain signatures of dynamic breakouts from earthquake nucleation zones that scale with the final event size.

Jim Dieterich discussed the laboratory contribution to our understanding of source physics. He reviewed basic rate- and state-dependent friction theory and recent direct experimental observation of asperities on transparent sliding surfaces which support the physical interpretation of rate and state parameters in terms of the density, size, and lifetime of surface asperities. He then showed how RSD friction theory can be used to calculate changes in the rate of regional seismicity following a stress change. In particular, he showed that RSD friction can lead to Omori's observational law, in which the rate of aftershocks decreases as the inverse of time since the mainshock.

Charlie Sammis discussed prospects for earthquake prediction. He pointed out that although prediction was not a reputable pursuit in the early 1960's, the subsequent discoveries of plate tectonics and laboratory precursors have provided a physical basis which legitimize prediction research. Plate tectonics tells where earthquakes are likely to occur and why, and thus offers a "prediction" of location which is better than the base level null hypothesis of a random distribution in space. Recent calculations of the change in Coulomb stress associated with large events offer the promise of even better spatial predictions.

Temporal prediction has been more of a problem. Physical precursors observed in the laboratory before failure of a rock specimen have not been observed consistently in the field. Temporal predictions based on "recurrence intervals" seem ill-conceived based on careful paleoseismic studies at Pallet Creek on the SAF. Although the average recurrence interval is 134 years, as expected from plate tectonic strain rates, individual intervals scatter widely about this average, ranging from 44 to 332 years. Like the seismic patterns discussed by Rockwell in an earlier talk, large events on the Mojave section of the SAF seem to come in clusters of two or three events, separated by less than 100 years, with longer cluster intervals on the order of 200 to 300 years. The notion of a regular "recurrence interval" has also been rebuffed by the notable absence of the cyclic Parkfield earthquake which is now more than ten years overdue.

The observed lack of periodicity has led many to conclude that regional seismicity, like weather, is chaotic and inherently unpredictable. Some have argued that the crust is in a continuous state of SOC, which implies that a small earthquake at any time can potentially cascade into a major event. Sammis argued, like Ben-Zion, that the crust is not in a state of continuous SOC. Evidence includes recent documentation of regional "stress shadows" following large events and observations of clustering of intermediate events before large earthquakes. He proposed that the largest earthquakes in a region perturb it away from the critical state and that methods of statistical physics can be used to monitor the return of the region toward criticality and the next large event. He presented examples of the approach and retreat from the critical state in simple cellular automatons with loss and/or structural complexity, and he showed examples of the power law increase in seismic energy release preceding large events. He concluded that statistical physics suggests new precursors to look for in the quest for temporal prediction.

In a series of short presentations, Steve Wesnousky began by discussing evidence that fault distributions in California, New Zealand, and Japan evolve in a manner where smaller faults coalesce into longer faults, which, in turn, accommodate a greater portion of the slip budget. Jim Brune summarized results of analog modeling of rupture dynamics using foam rubber blocks, which include dynamic fault separation and strong asymmetry of shaking for dipping faults. In a second talk, Brune reported on results from the distribution of precarious rocks at a distance of 15 km from the San Andreas Fault, placing constraints on ground motion at these locations from great San Andreas earthquakes for the last several thousand years.

Andrea Donnellan discussed GPS observations from the Los Angeles basin indicating significant aseismic deformation, compatible with RSD friction on faults, in the year following the Northridge earthquake. Yehuda Bock presented data from a few continuous GPS stations and a long baseline strainmeter in the southern California region showing significant aseismic deformation, again compatible with RSD friction, for more than 0.5 years after the 1992 Landers earthquake.

Andy Michael pointed out that independent inversions of seismic data for fault zone velocity structures generally agree among themselves and correlate with initiation and arrest locations of mainshock ruptures. Ruth Harris discussed calculations of dynamic rupture in 3D models that quantify the ability of earthquakes to propagate across fault stepovers and produce multisegment events. Bill Ellsworth discussed seismological efforts to constrain friction on a fault during an earthquake rupture. He noted that although several recent studies gave estimates of slip weakening distances *in situ*, these should be regarded only as rough upper bounds.

Jean Carlson compared theoretical studies based on single slider block, Burridge-Knopoff array, and 3D continuum elastic model, concluding that, in some cases, the lack of spatiotemporal complexity in the continuum model may be attributed to computational limitations. Raul Madariaga discussed calculations of dynamic rupture on a planar fault based on a 3D finite-difference model, which show that rupture propagation under heterogeneous stress conditions is far less efficient than in the homogeneous case, raising the interesting possibility that the stress field on natural faults is maintained close to a critical level of heterogeneity, generating slip complexities.

Bill Klein summarized results from a cellular automaton model that included long-range interactions. Simulation and theory show that this system is in metastable equilibrium and that the model has a spinodal critical point. Didier Sornette presented experimental, numerical, and theoretical results suggesting that rupture in heterogeneous media with long-range elasticity may be a genuine critical phenomenon. Don Turcotte presented a simple mechanism for SOC based on collision probabilities between clusters in a forest-fire model. John Rundle proposed a "pattern dynamics approach" for finding space-time patterns in earthquake populations similar to methods now used in the forecasting of El Niño climate events. He demonstrated these ideas using a simulated earthquake catalog that yielded approximately 70% accuracy six months in advance.

In summary, earthquake physics is an active and fertile field that applies cutting-edge research in continuum mechanics, materials science, and statistical physics to interpret an increasingly rich collection of seismological and field observations. Because of the strong spatial heterogeneity and variety of temporal processes, both of which exist over an extraordinarily wide range of scales, earthquakes have become the premier natural testing ground for modern models of nonequilibrium, spatially extended dissipative systems. The intellectual goal is a deeper understanding of the complexity of individual earthquakes and the spatiotemporal distribution of regional seismicity. The practical goal is a more accurate assessment of earthquake hazard and the possible development of a forecasting strategy.

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