Seizures – Quakes of the Brain?

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What are seizures?

- Video clip

Epilepsy Background

Epilepsy is the most prevalent serious neurological disease which occurs across all age groups and genders.

Hauser WA, Annegers J F, Rocca WA. Descriptive epidemiology of epilepsy: contributions of population-based studies from Rochester, Minnesota. Mayo Clin Proc 1996; 71:576-586

Epilepsy Numbers

- 1 to 2% in industrialized countries have epilepsy
- 2.7 million in the U. S. have epilepsy.
- 5 to 10% in non-industrialized countries have epilepsy
- 60 million worldwide have epilepsy

Hauser WA, Annegers J F, Rocca WA. Descriptive epidemiology of epilepsy: contributions of population-based studies from Rochester, Minnesota. Mayo Clin Proc 1996; 71:576-586

Epilepsy Incidence

Cumulative incidence

- 1.4% by age 32
- 3.3% by age 80

Hauser WA, Hersdoffer DC. Epilepsy: Frequency, Causes and Consequences. Demos NY, 1990

Epilepsy - The People

Those directly and indirectly affected by epilepsy

- live in relative isolation
- have low self-esteem
- have low expectations

Mendez MF, CummingsJL, Denson DF. Depression in epilepsy: Significance and phenomenology, Arch Neurol 1986; 43:766-770

Olsson I, Chaplin J, Ekstedt J. Extensive rehabilitation needed for epilepsy. Different models for varying needs. Lakartidningen 1997; 94:2572-2575

Epilepsy Mortality

Up to 42,000 Americans die each year as a direct consequence of seizures.

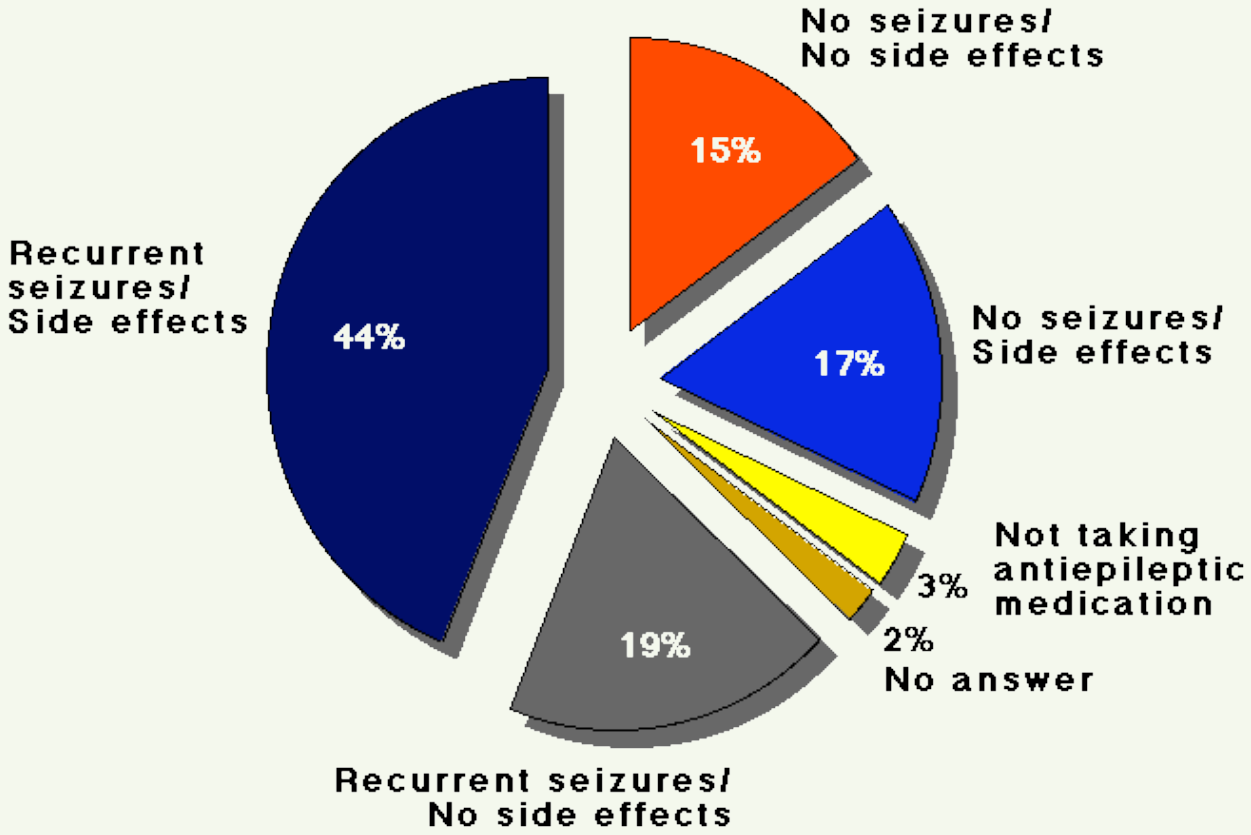
DeLorenzo RJ, Pellock JM, Towne AR, Boggs JG. Epidemiology of Status Epilepticus. J Clin Neurophysiology 1995 12:316-325

Epilepsy Costs

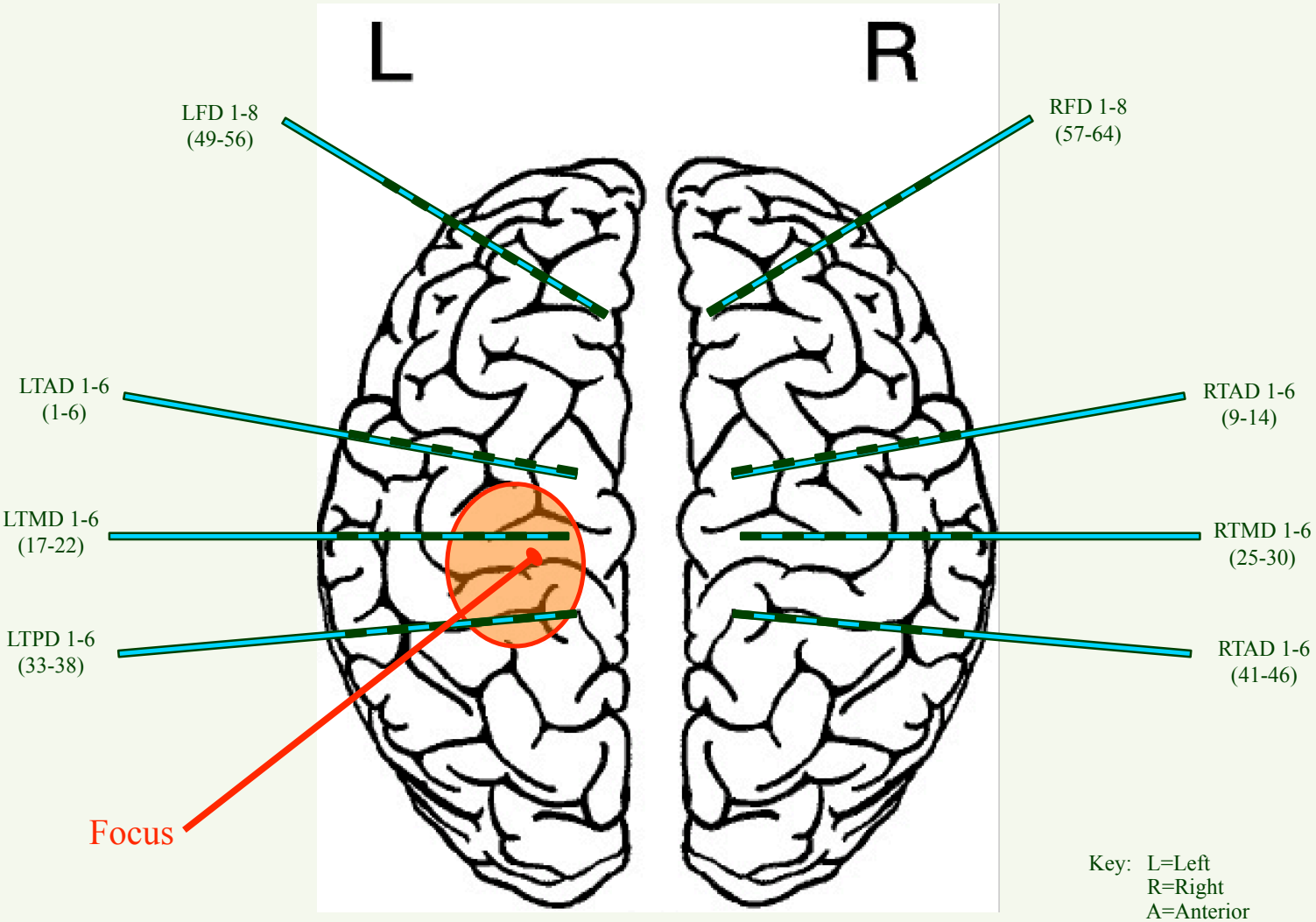
Direct and Indirect Costs total $12.5 billion annually in the United States

Epilepsy Foundation of America; 1999

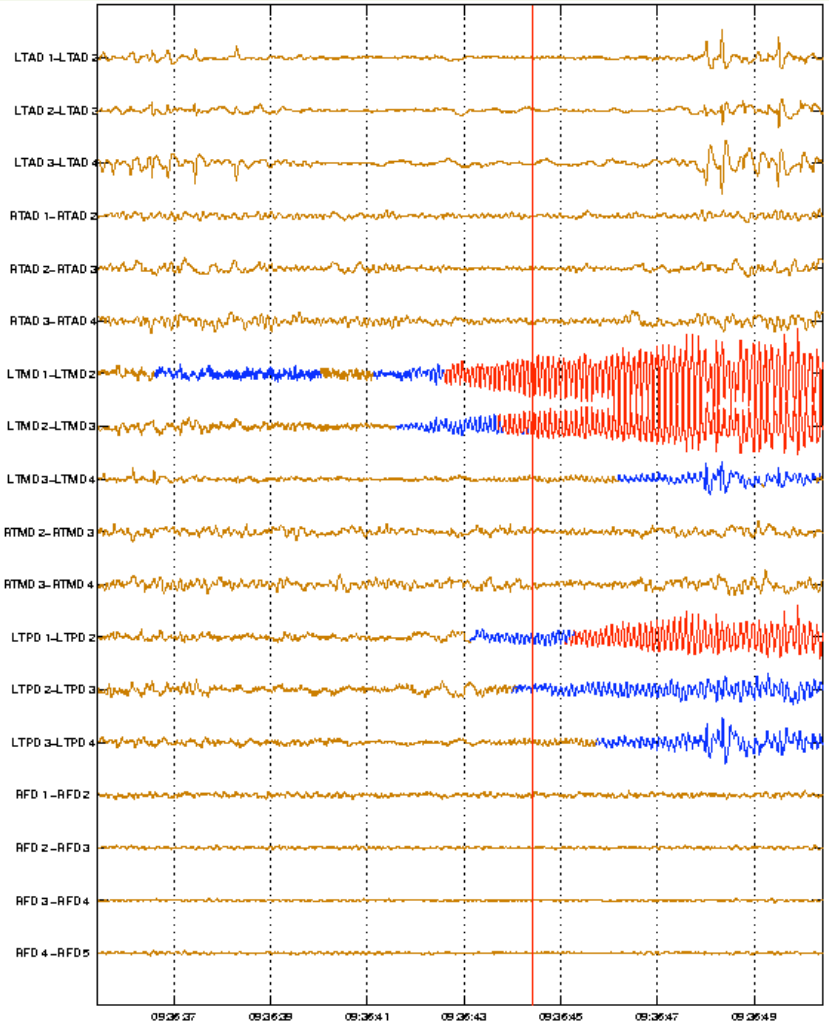
Seizures / side effects

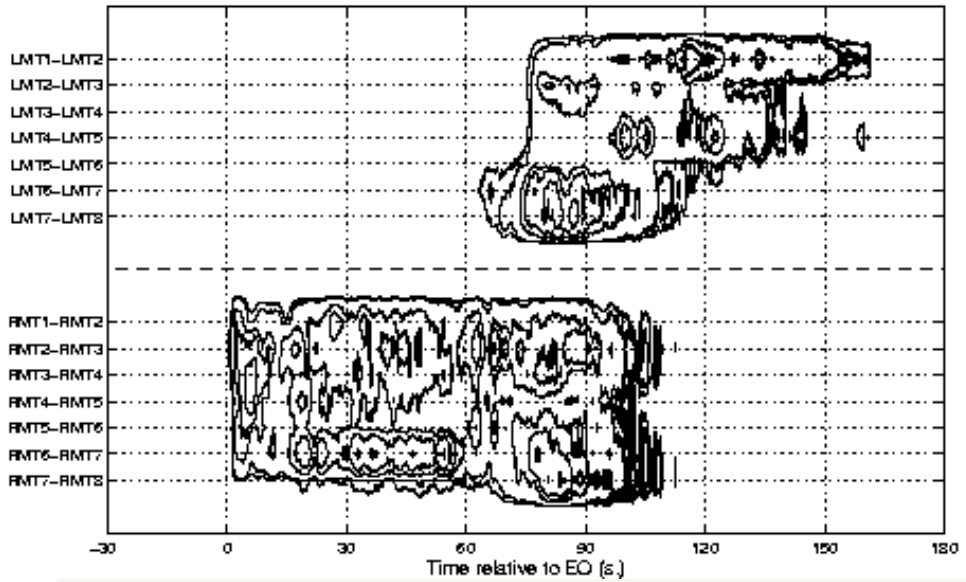


The Roper Organization, Inc. Living with Epilepsy: Report of a Roper Poll of Patients on Quality of Life, 1992


L
R
LFD 1-8
(49-56)
RFD 1-8
(57-64)
LTAD 1-6
(1-6)
RTAD 1-6
(9-14)
LTMD 1-6
(17-22)
RTMD 1-6
(25-30)
LTPD 1-6
(33-38)
RTAD 1-6
(41-46)
Focus
Depth Needle Electrodes Contact Numbering: N … 3 2 1
Key: L=Left
R=Right
A=Anterior
M=Mesial
P=Posterior
D=Depth
T=Temporal
F=Frontal

Quantifying Seizure Spread

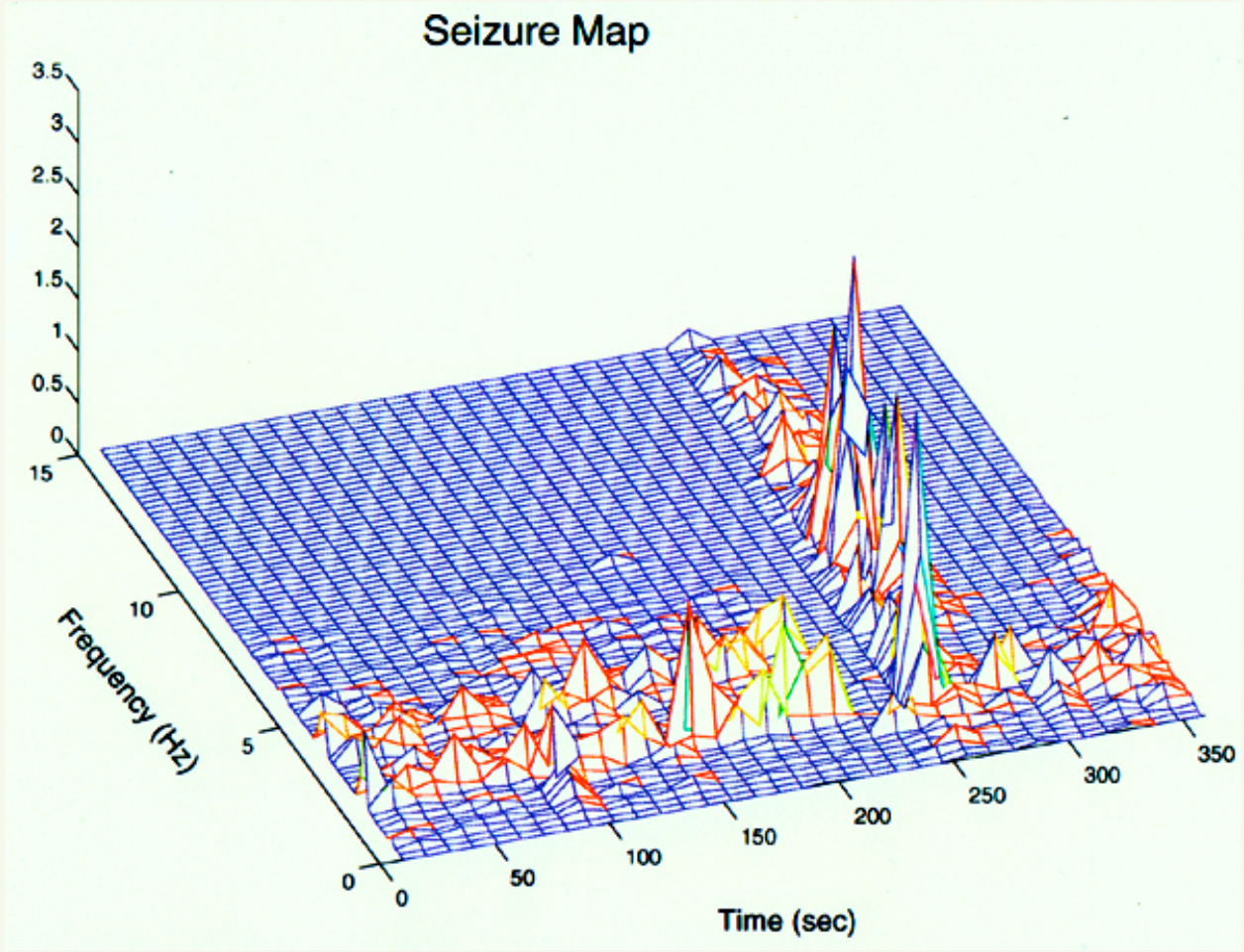




secondary gen.

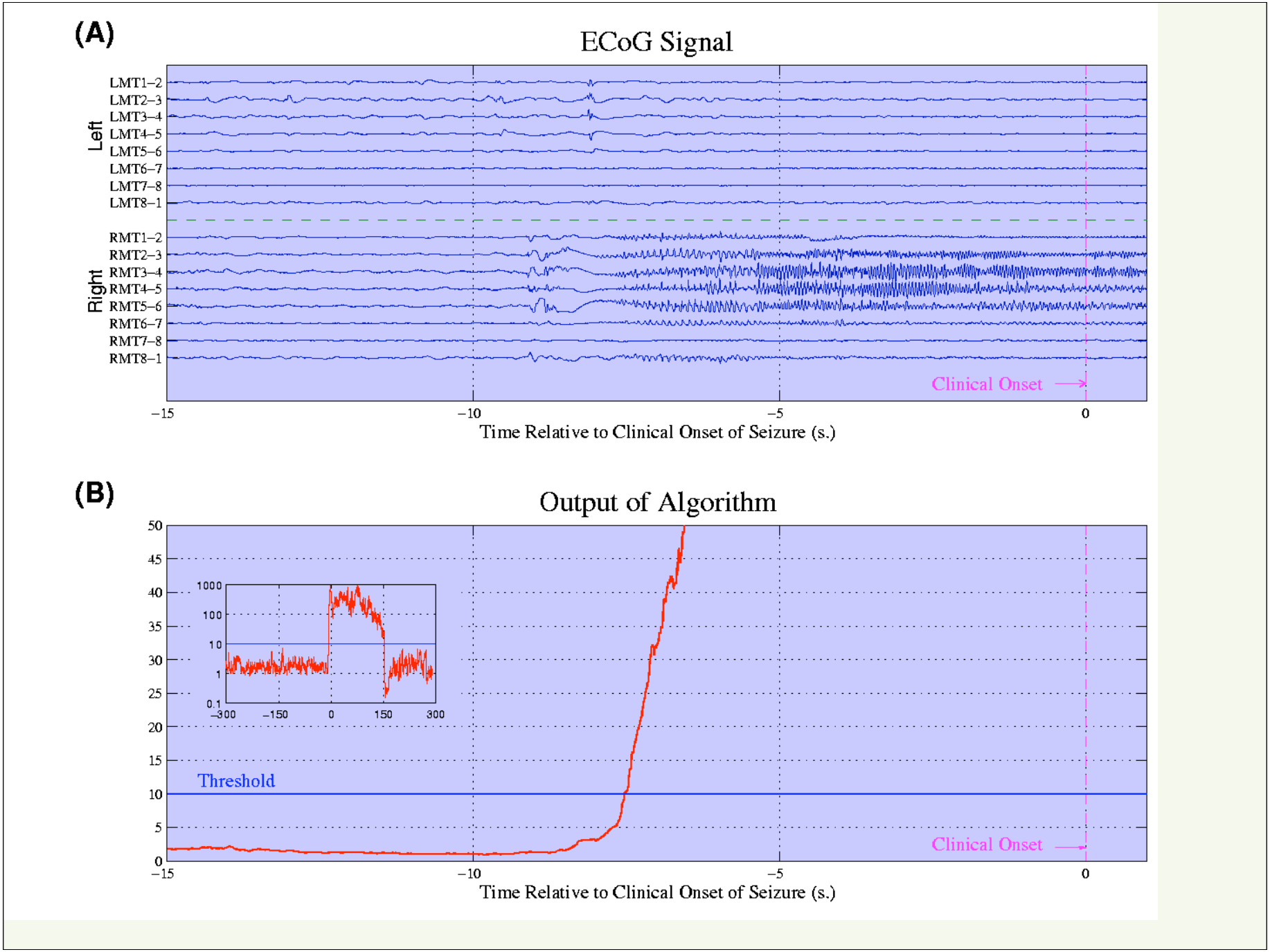
aura begins

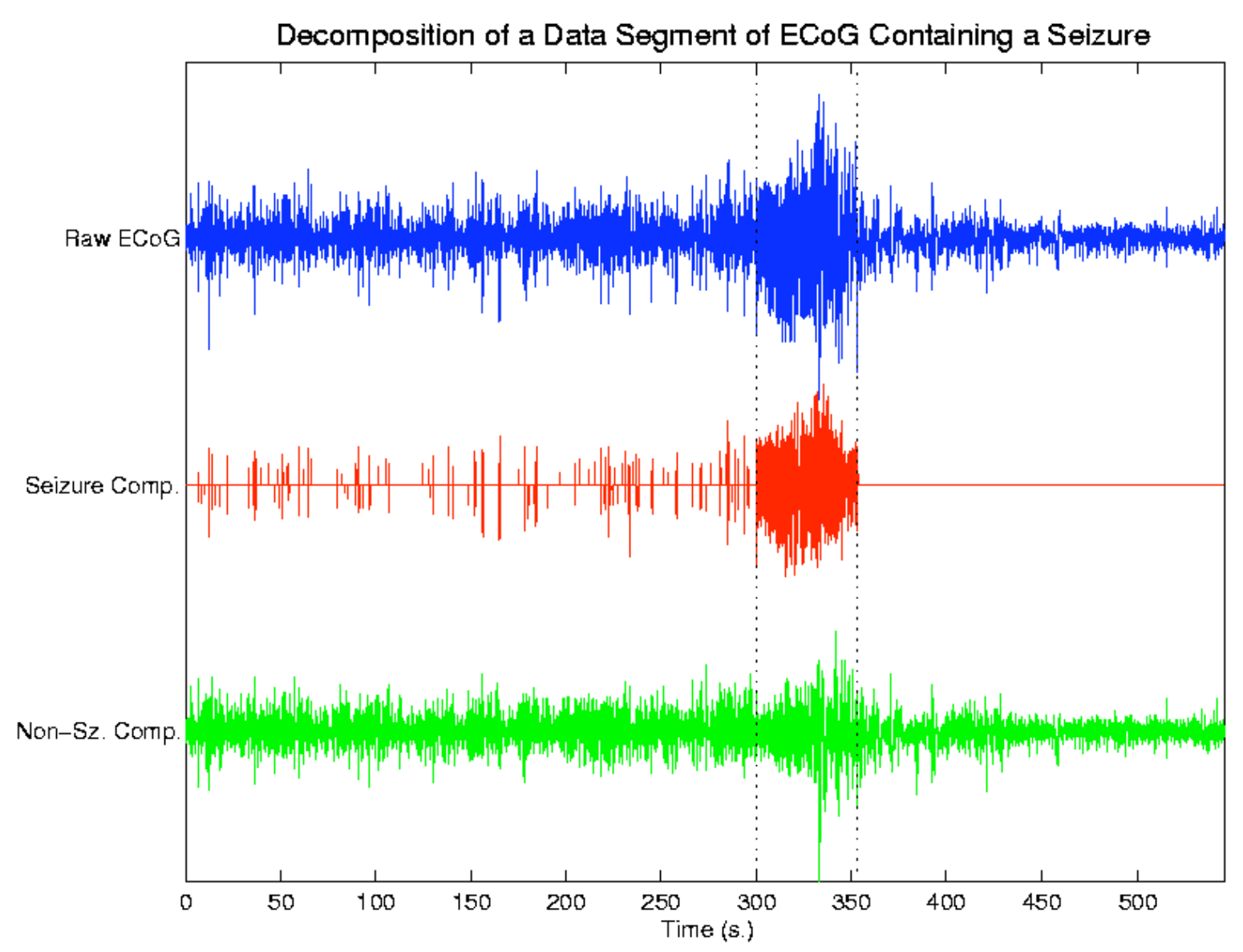
Seizure Map


Seizure Map
3.5
3
2.5
2
1.5
1
0.5
0
15
10
5
0
Frequency (Hz)
0
50
100
150
200
250
300
350
Time (sec)

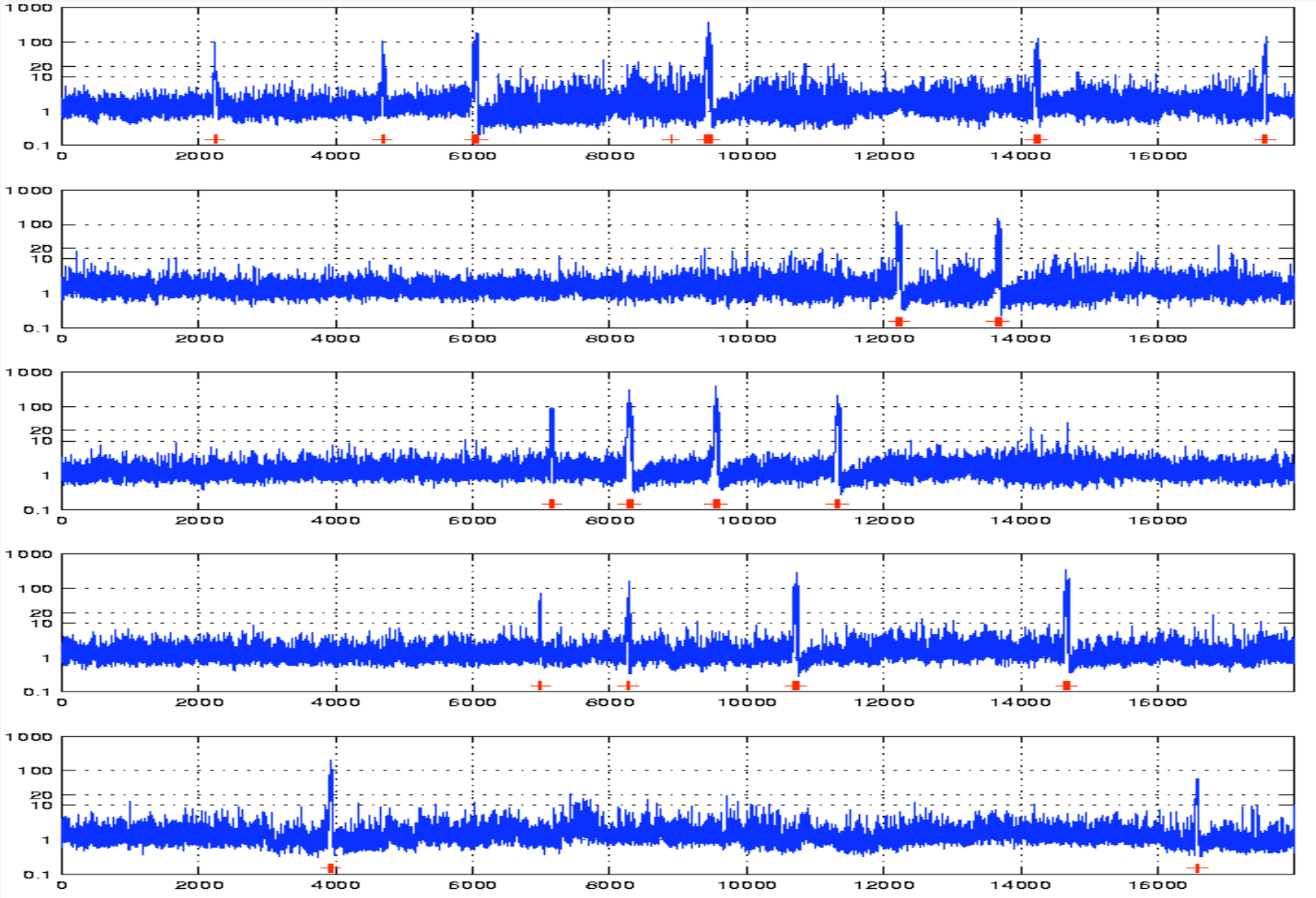
Elements of Detection Algorithm

- Decomposition (via time-frequency-energy analysis)
- Median filtering
- Normalization by background to produce a ratio
- Threshold and duration constraints
- Adaptation / Optimization


(A)
ECoG Signal
Left
LMT1–2
LMT2–3
LMT3–4
LMT4–5
LMT5–6
LMT6–7
LMT7–8
LMT8–1
Right
RMT1–2
RMT2–3
RMT3–4
RMT4–5
RMT5–6
RMT6–7
RMT7–8
RMT8–1
Clinical Onset
−15
−10
−5
0
Time Relative to Clinical Onset of Seizure (s.)
(B)
Output of Algorithm
50
45
40
35
30
25
20
15
10
5
0
1000
100
10
1
0.1
−300
−150
0
150
300
Threshold
Clinical Onset
−15
−10
−5
0
Time Relative to Clinical Onset of Seizure (s.)

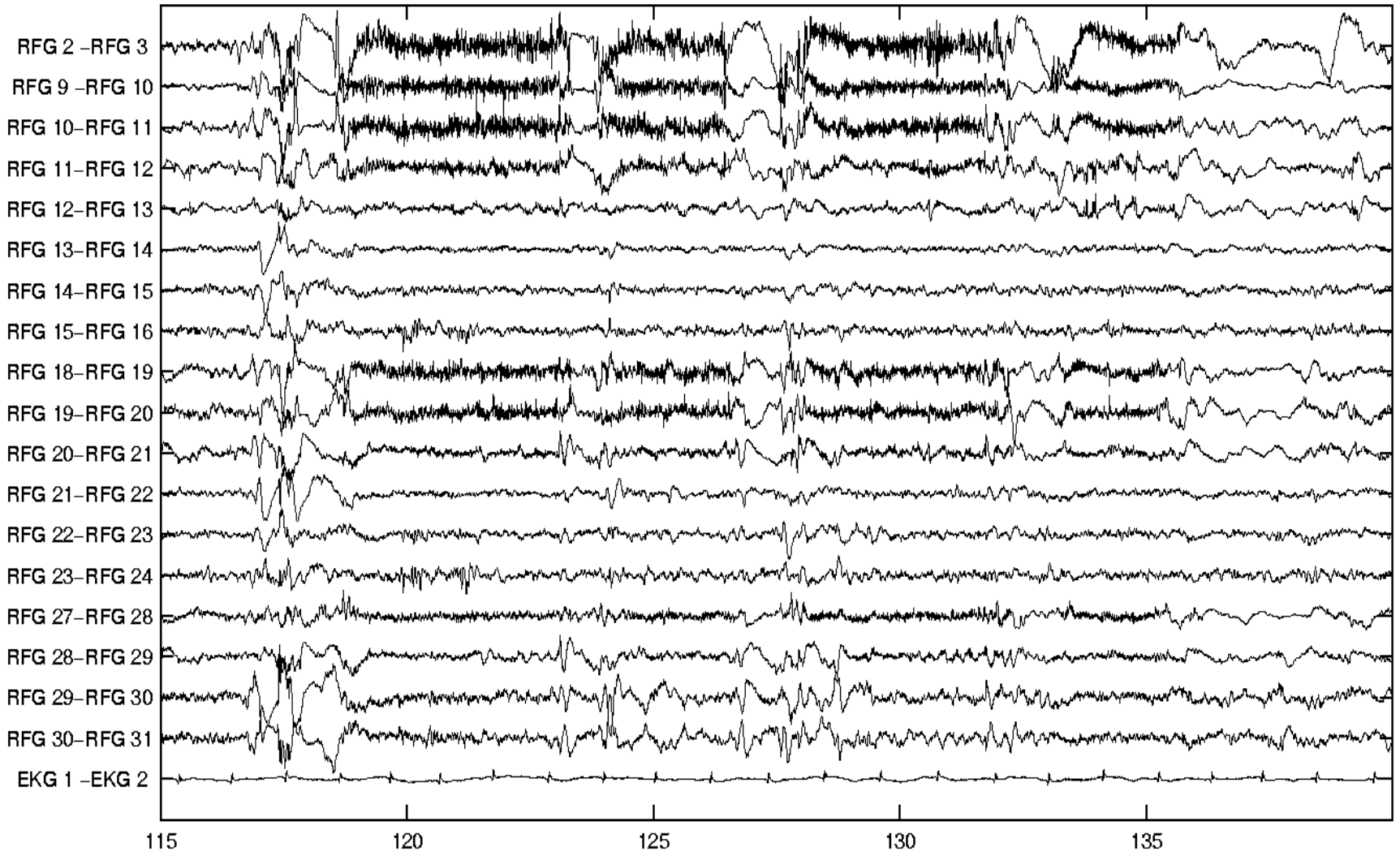

Decomposition of a Data Segment of ECoG Containing a Seizure
Raw ECoG
Seizure Comp.
Non–Sz. Comp.
0
50
100
150
200
250
300
350
400
450
500
Time (s.)

25 hours of continuous seizure monitoring



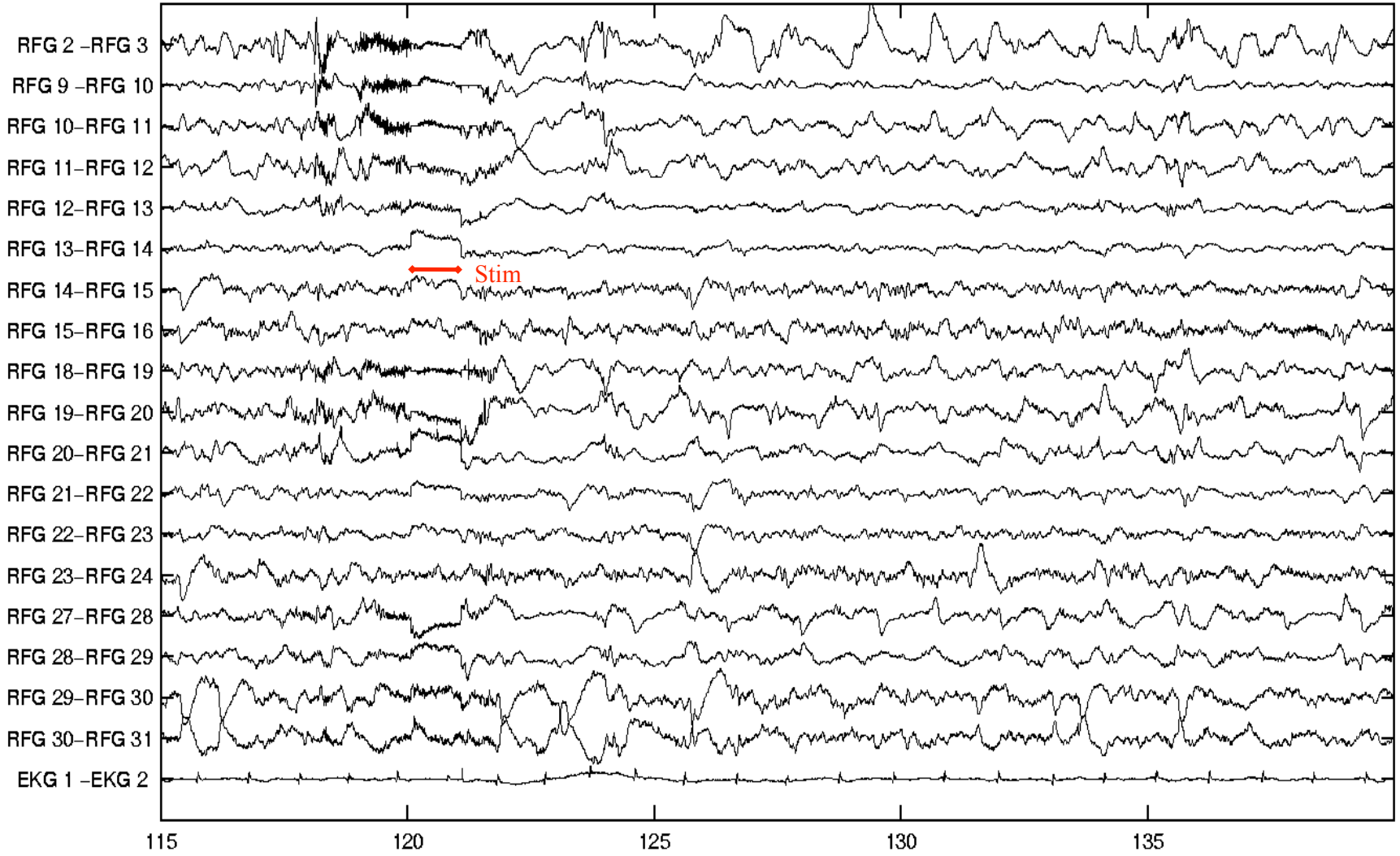
Automated “Closed-Loop” Therapy

Brain Signals Showing a Seizure (Without Stimulation)



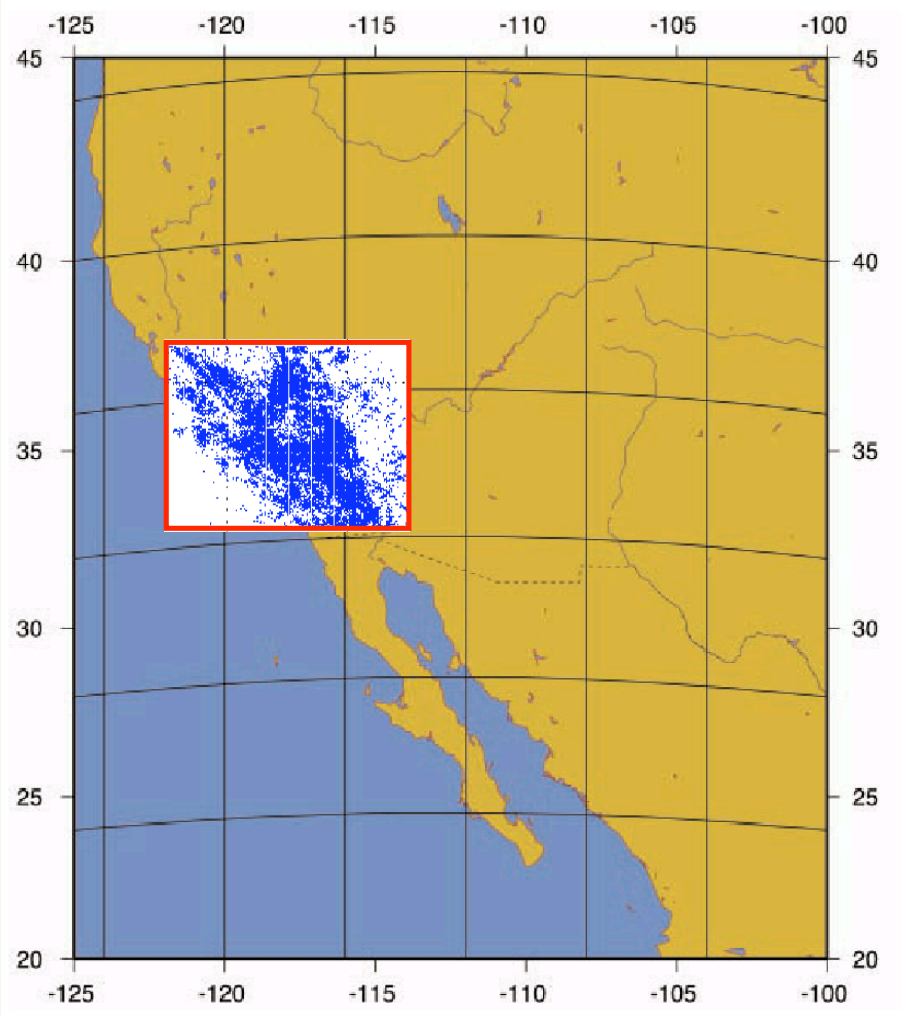
Automated “Closed-Loop” Therapy

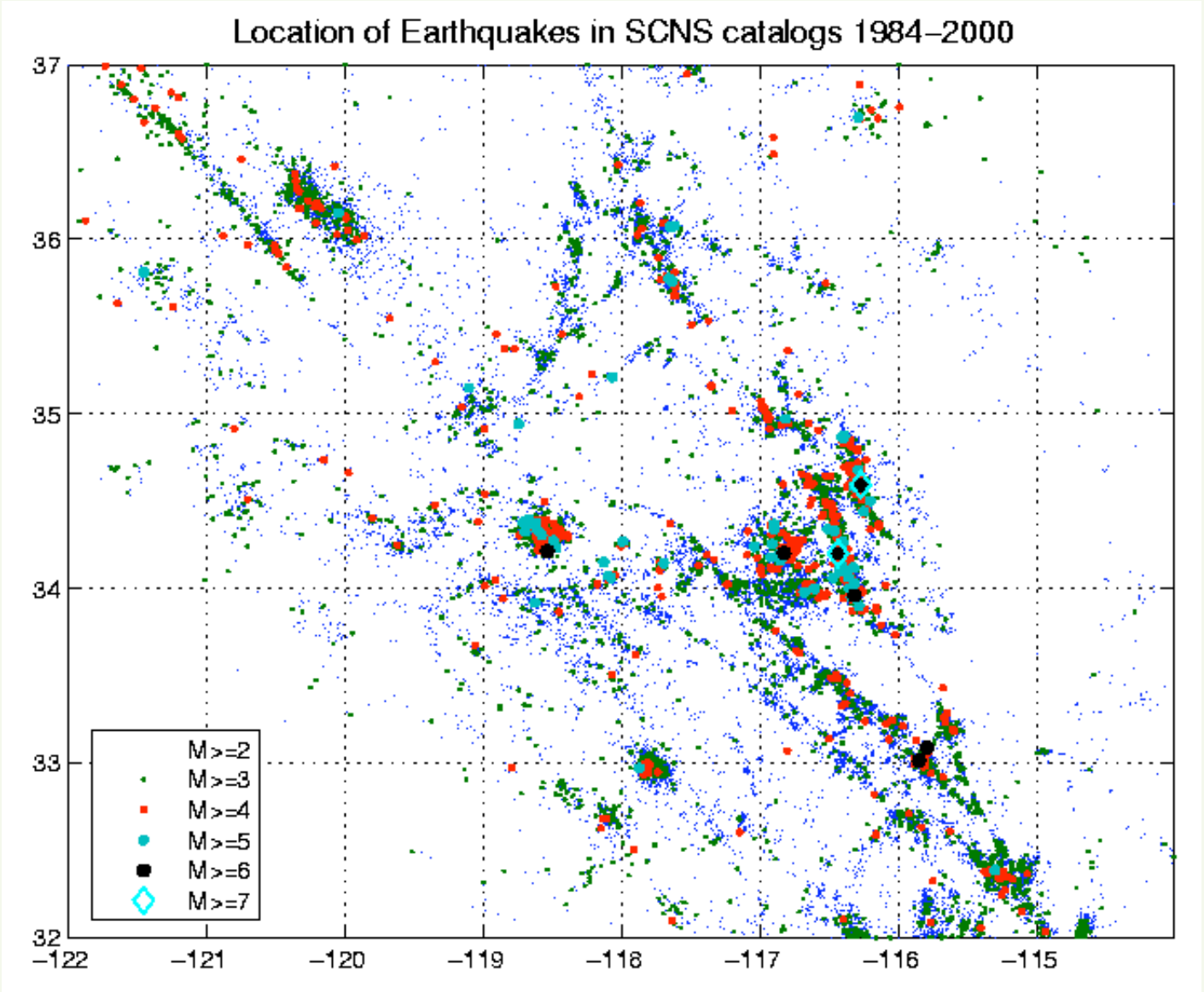
Brain Signals Showing a Seizure Aborted by Stimulation



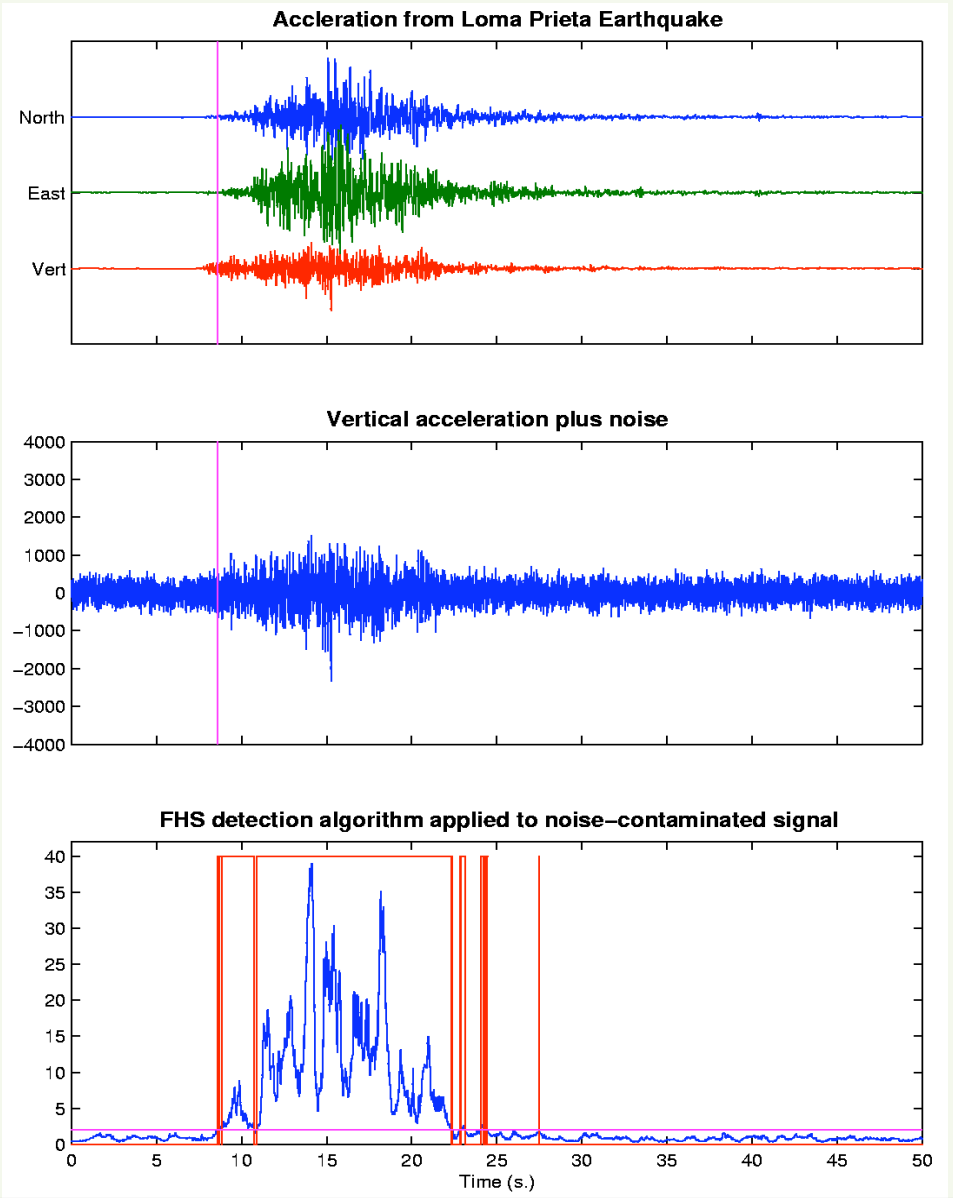
Statistical laws of seismicity

- Intermittent seismic signal and acceleration spectrum
- Gutenberg-Richter law: $\sim 1/E^{1+\beta}$ (with $\beta \approx 2/3$)
- Omori law (direct and inverse) $\sim 1/t^{p}$ (with $p \approx 1$ for large earthquakes)
- PDF of inter-event times: quasi-universal, power law regimes
- Paradox of the mean waiting time till the next event
- Productivity law $\sim E^{a}$ (with $a \approx 2/3$)
- PDF of fault lengths $\sim 1/L^{2}$
- Fractal/multifractal structure of fault networks $\zeta(q)$, $f(\alpha)$
- PDF of seismic stress sources $\sim 1/s^{2+\delta}$ (with $\delta \geq 0$)

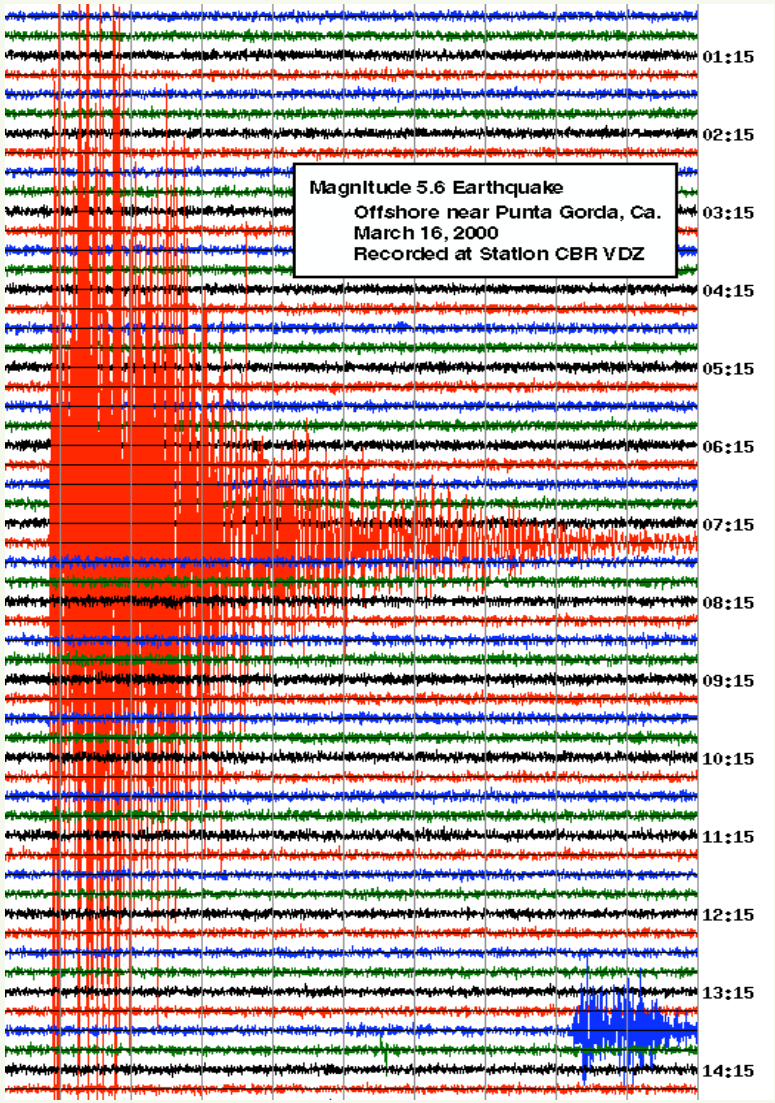

-125
-120
-115
-110
-105
-100
45
40
35
30
25
20


Location of Earthquakes in SCNS catalogs 1984–2000
37
36
35
34
33
32
−122
−121
−120
−119
−118
−117
−116
−115
M>=2
M>=3
M>=4
M>=5
M>=6
M>=7

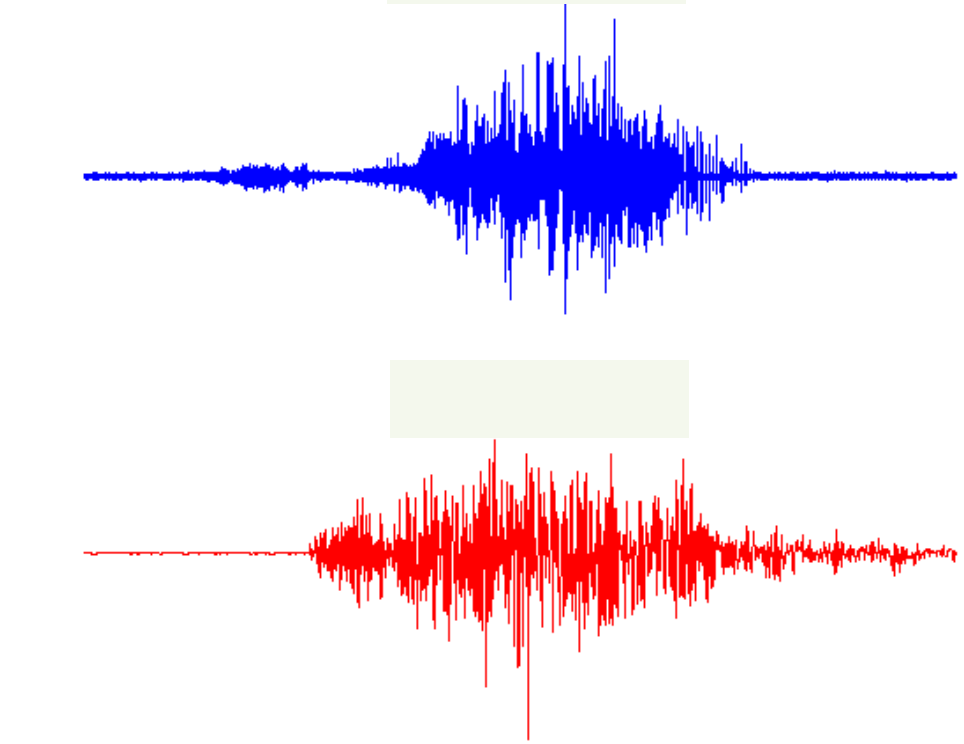
Seismic Analysis

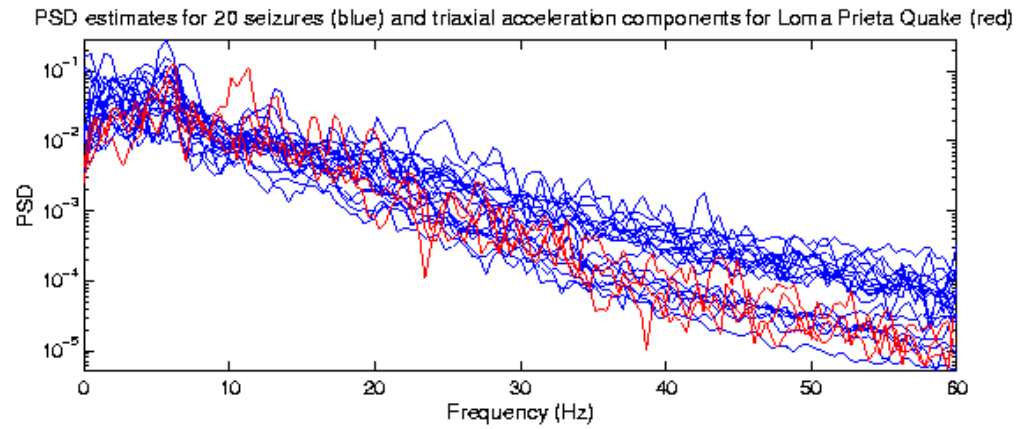


14 hr of seismic waves

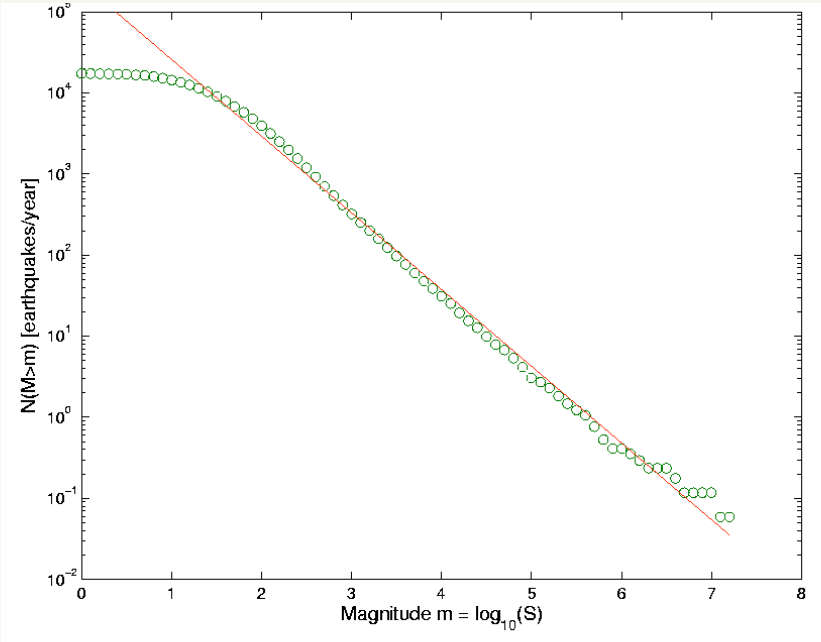


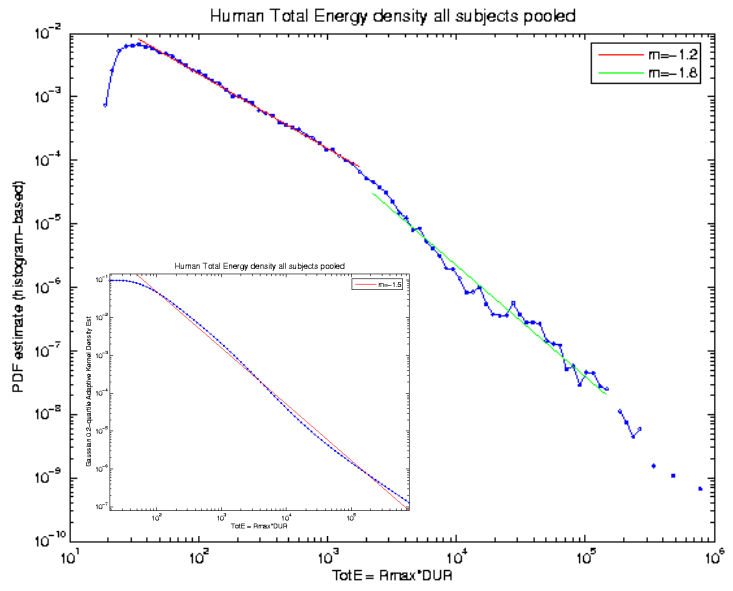
3 min of brain waves

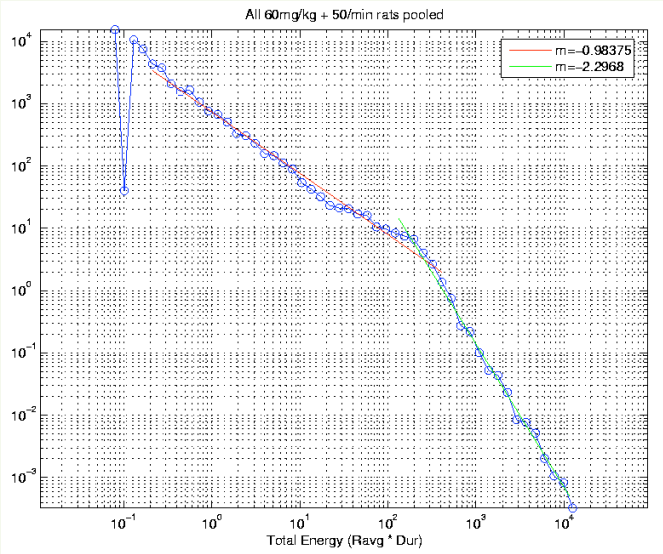


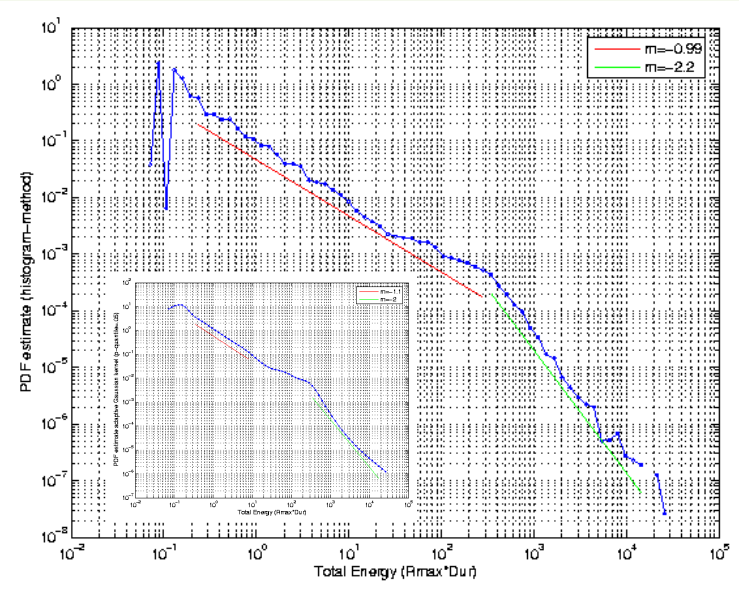

PSD estimates for 20 seizures (blue) and triaxial acceleration components for Loma Prieta Quake (red)
PSD
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
50
60
Frequency (Hz)

Gutenberg-Richter

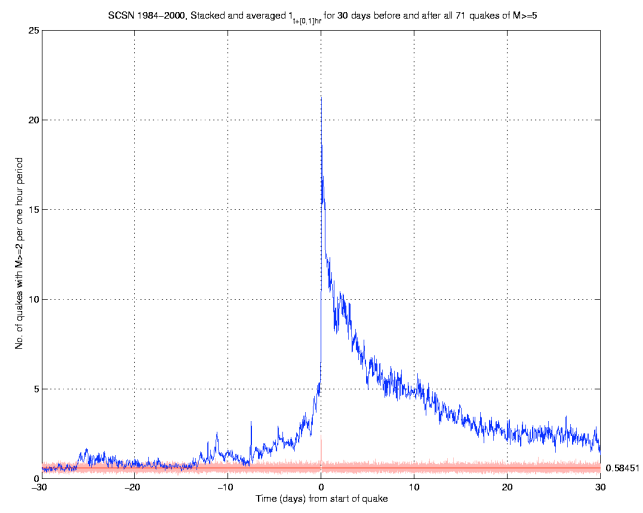


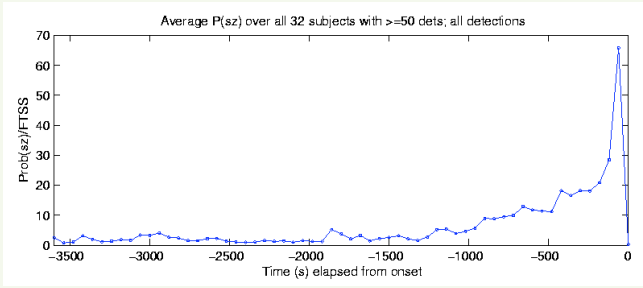


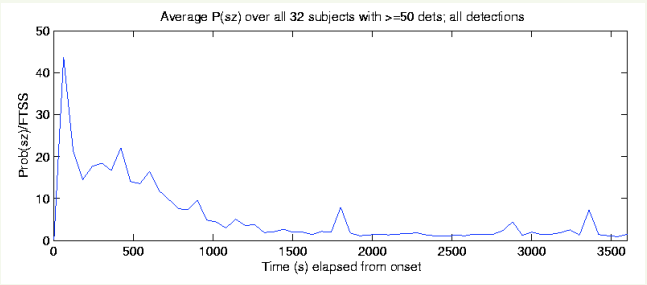


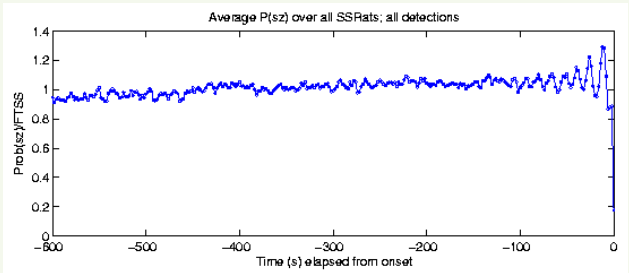


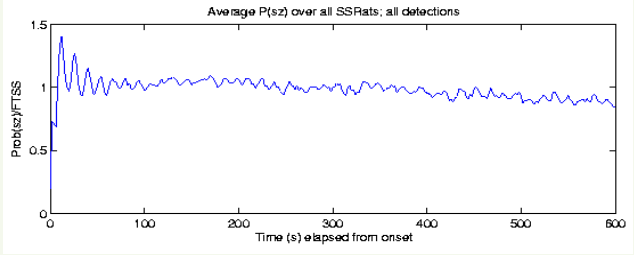
Omori and Reverse-Omori

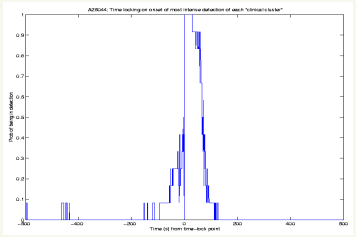


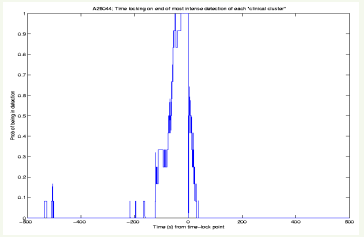


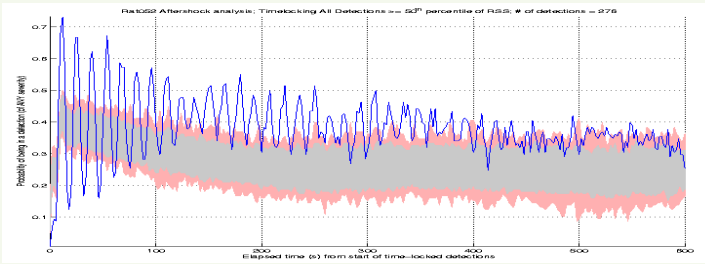








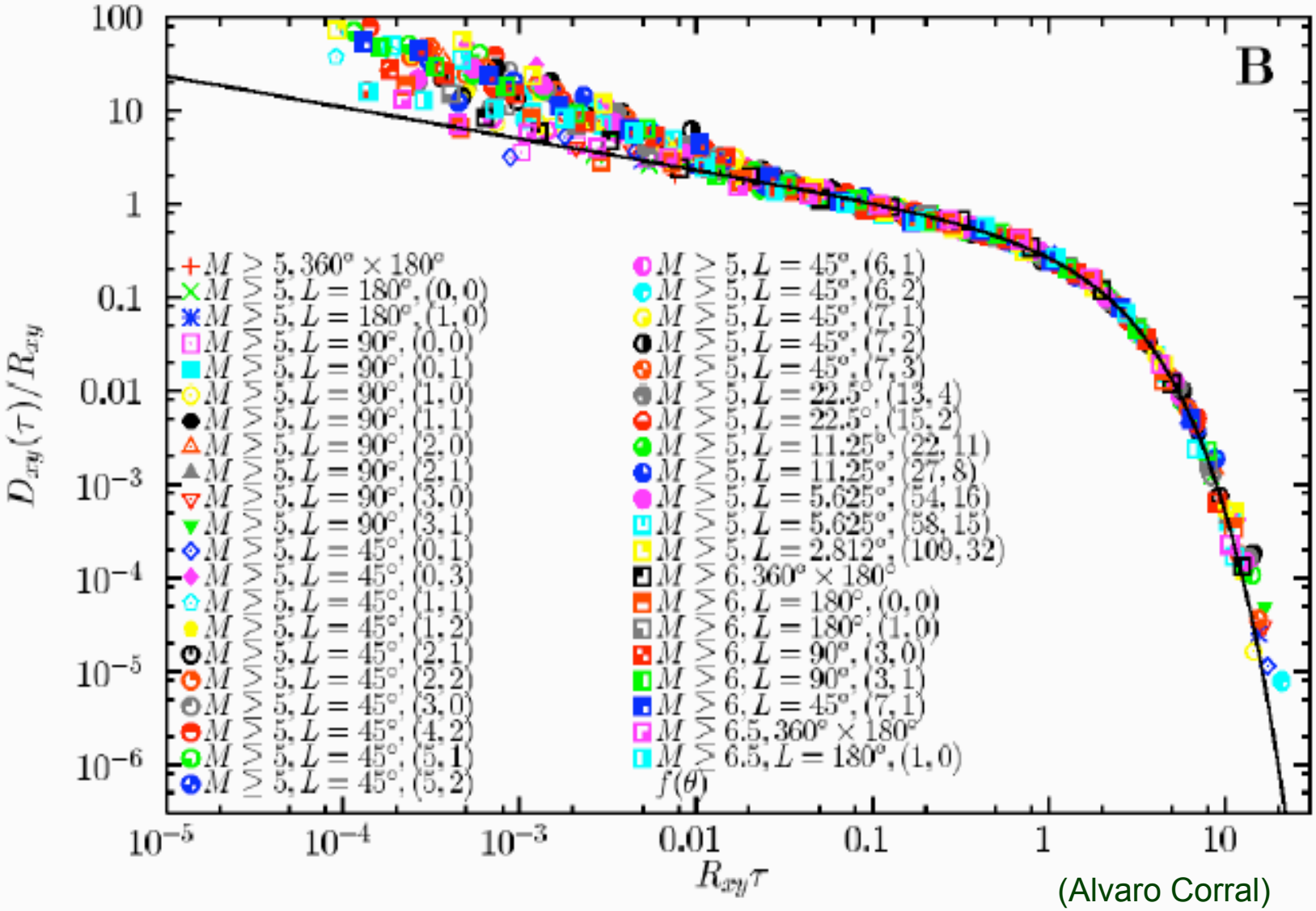




Universality

Distribution of inter-event waiting times

Changing the spatial region: stationary seismicity up to 2.8° (300 km)



(Alvaro Corral)

Distribution of inter-event waiting times

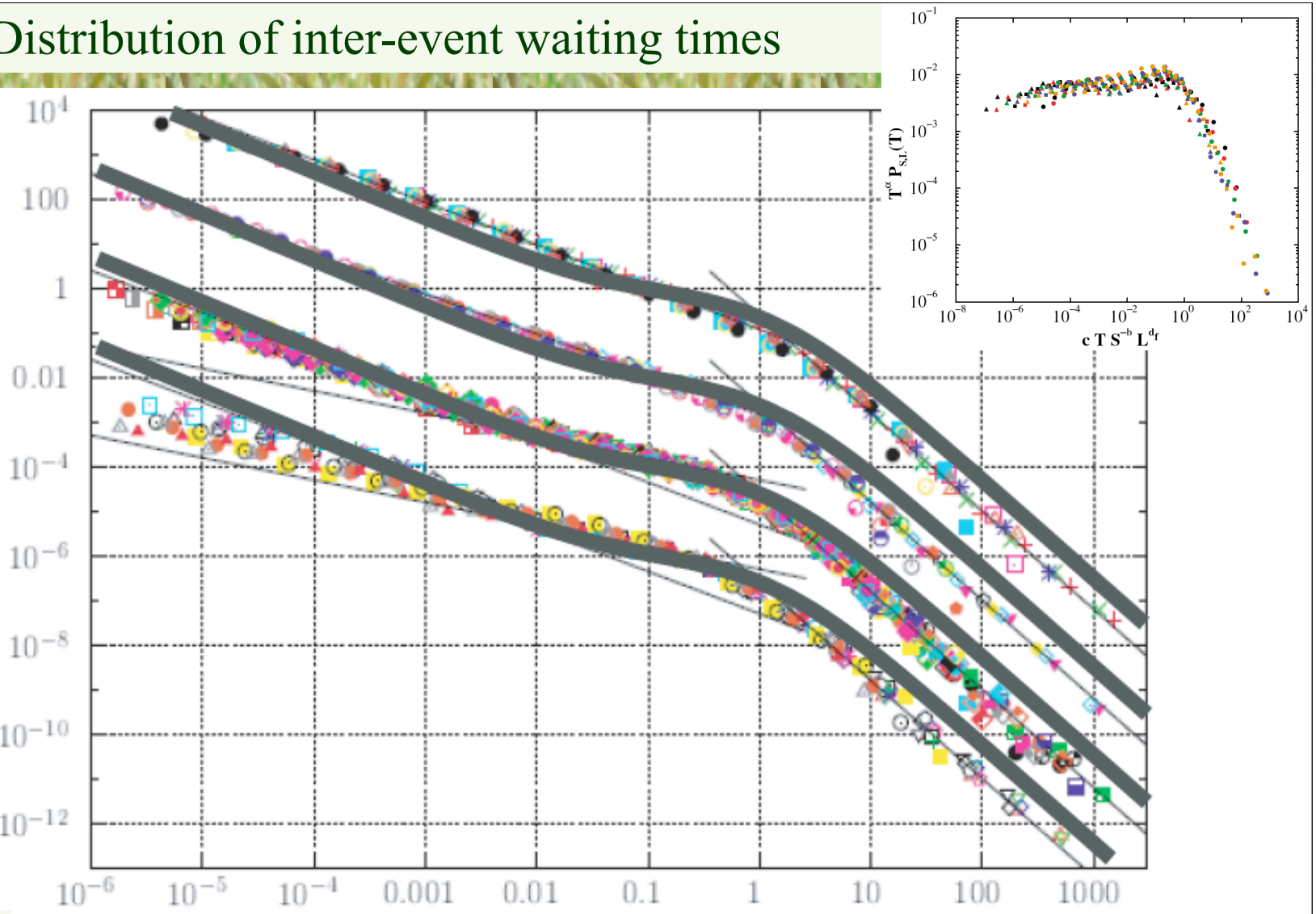
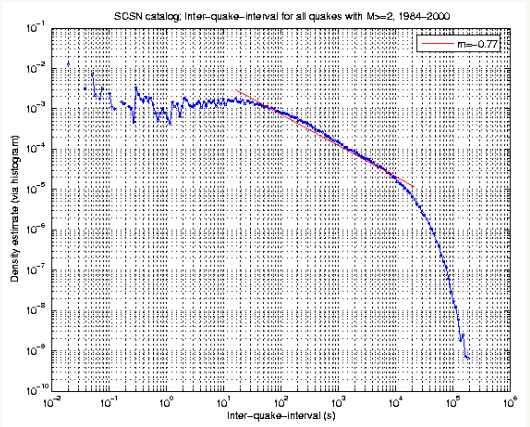
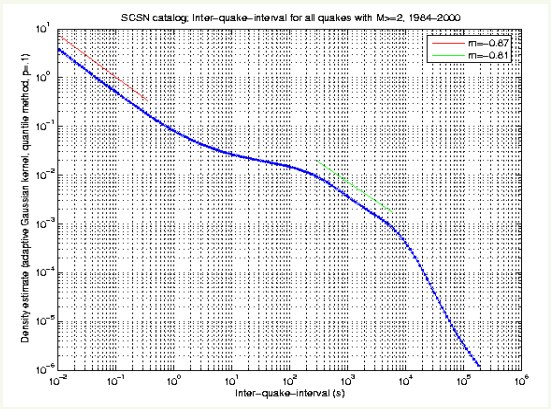
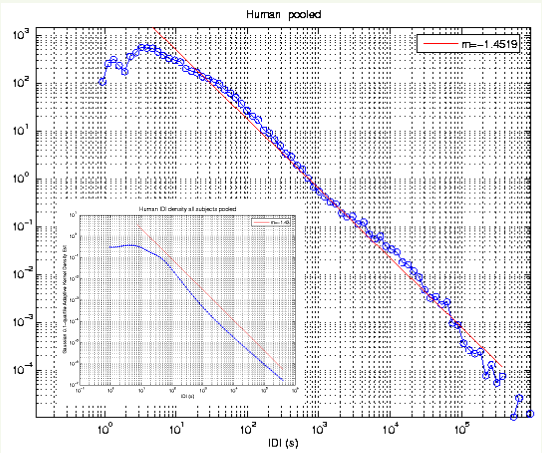


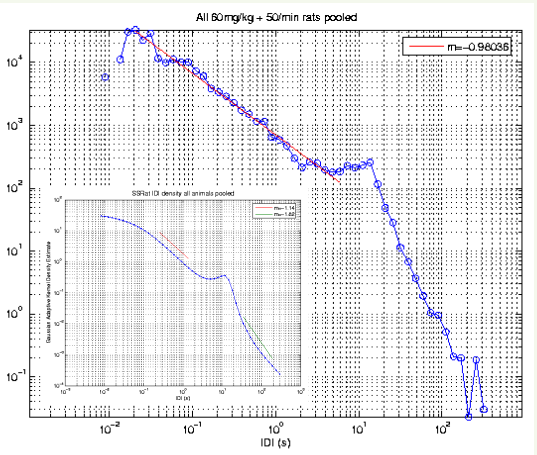
Figure 8. Empirical PDFs of the recurrence times between earthquakes over multiple regions following *Bak et al.*'s [2002] procedure obtained from Figure 2 of *Corral* [2004a], on which has been superimposed our prediction for $h(x)$ obtained with the Gamma distribution (77) for $\mathcal{E}(u)$ with $\theta = 0.03$, $n = 0.9$, $\epsilon = 0.76$, and (d_f=1.8). The curves have been translated from top to bottom by the factors 1, 10^{-2}, 10^{-4}, 10^{-6}.

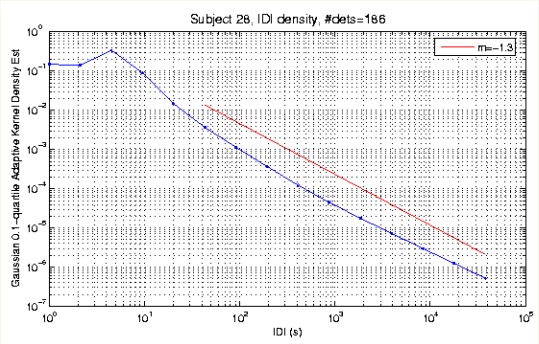
Distribution of inter-event waiting times

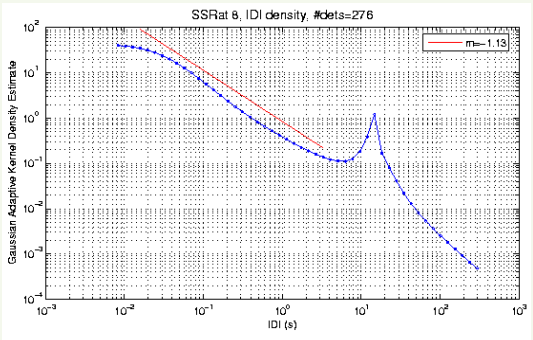






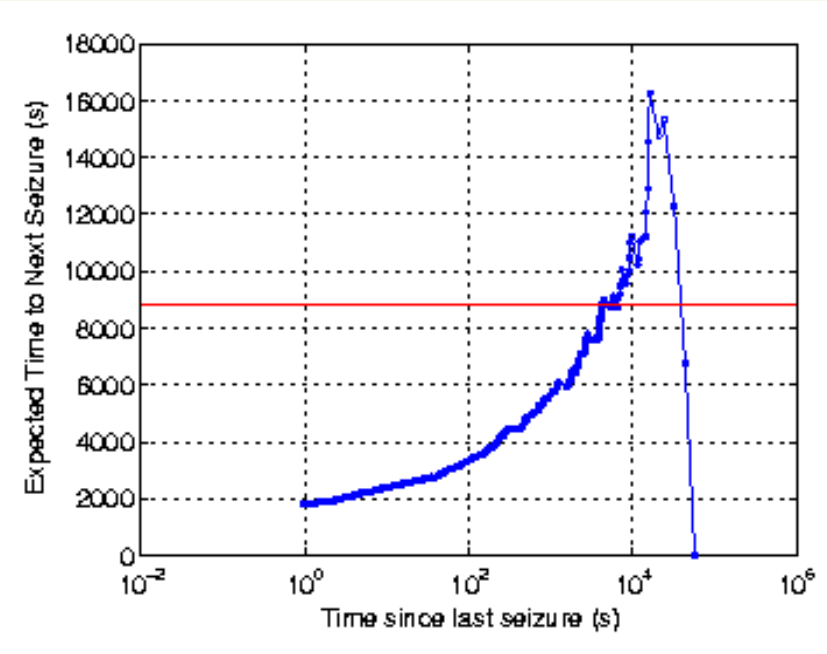


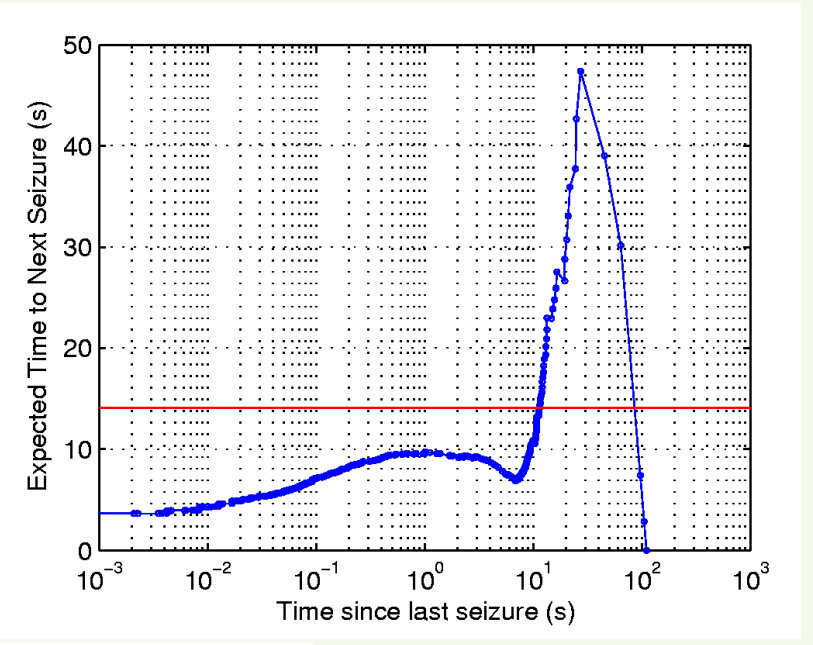


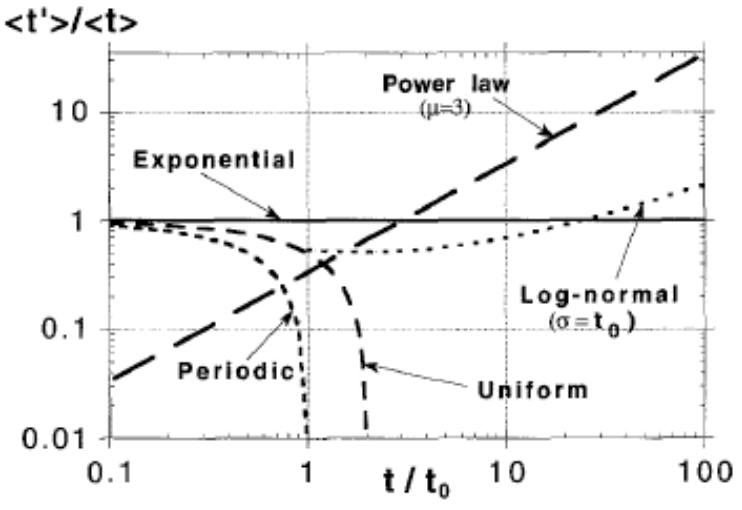


Expected Time to Next Seizure

Conditioned on Time Since Last Seizure



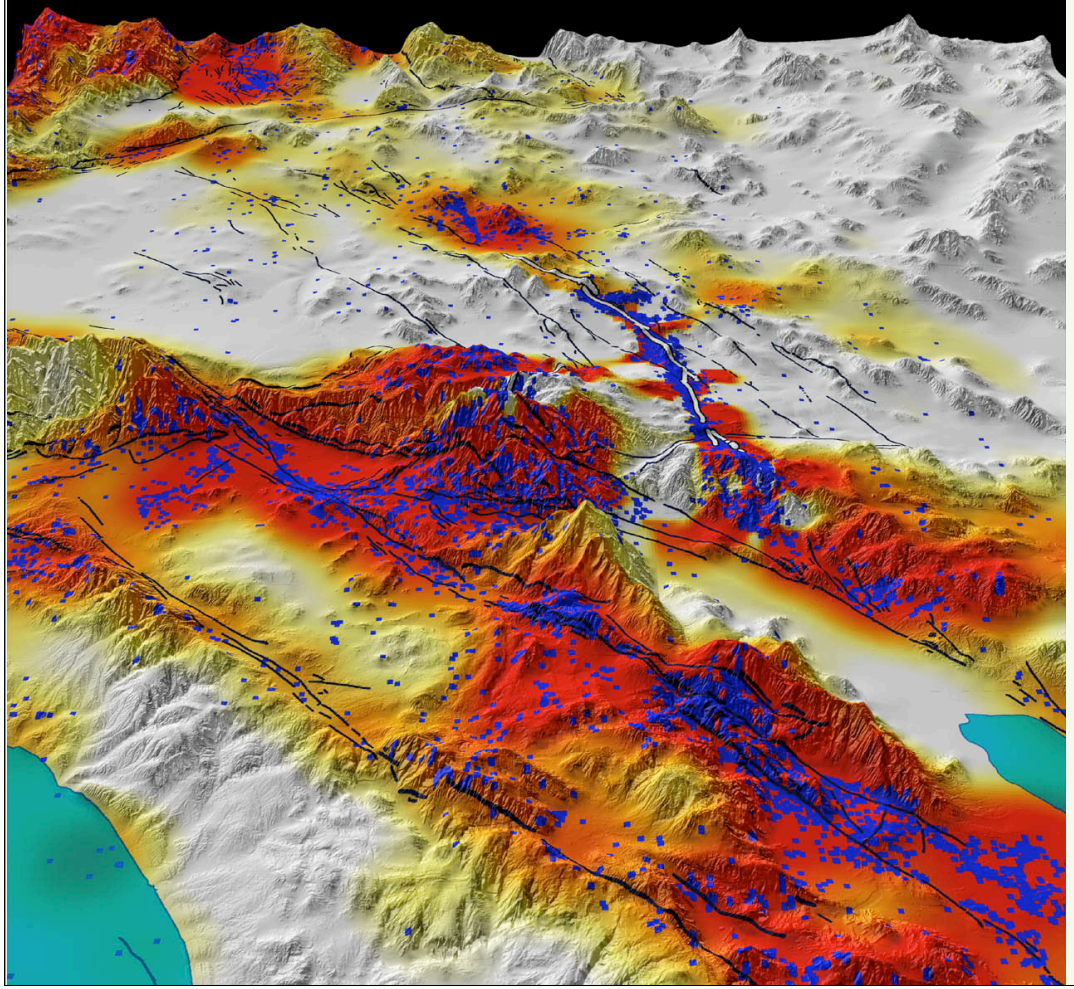


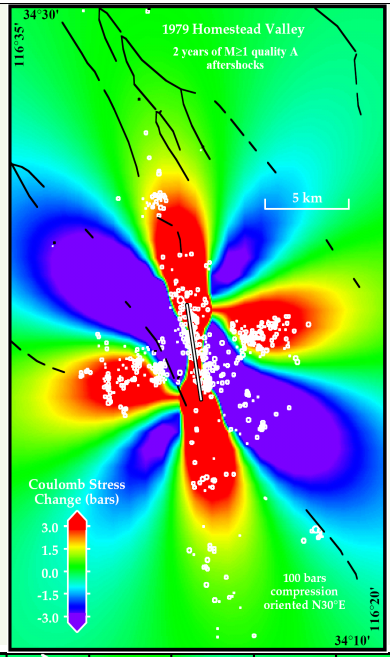


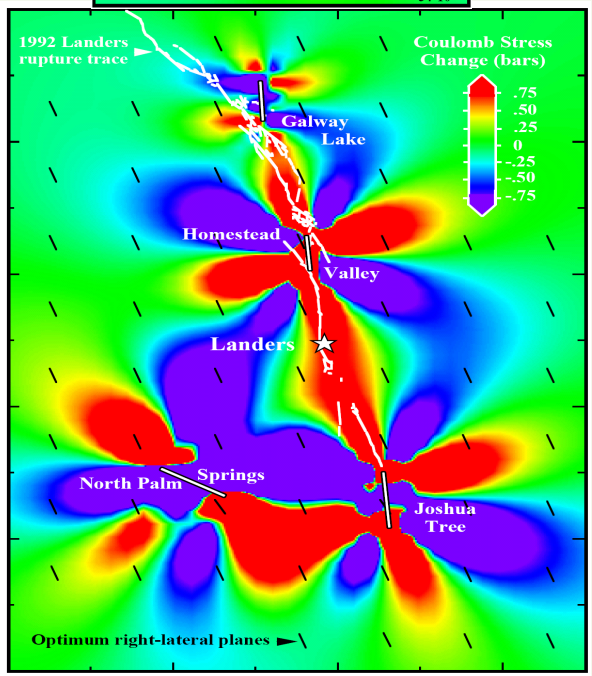
(Sornette and Knopoff, 1997)

Earthquake Conversations

Ross S. Stein
U.S. Geological Survey





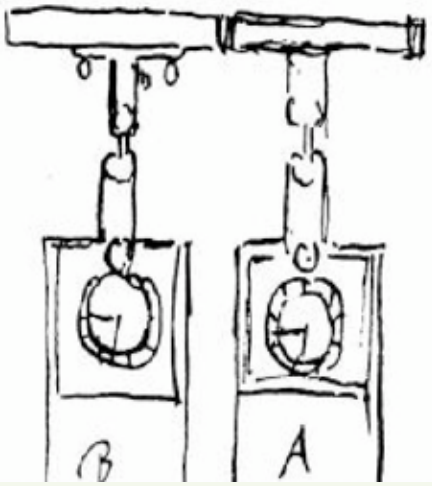


SYNCHRONISATION AND COLLECTIVE EFFECTS IN EXTENDED STOCHASTIC SYSTEMS

huygens' V.[1] clocks

1665.

[Fig. 75.][2]



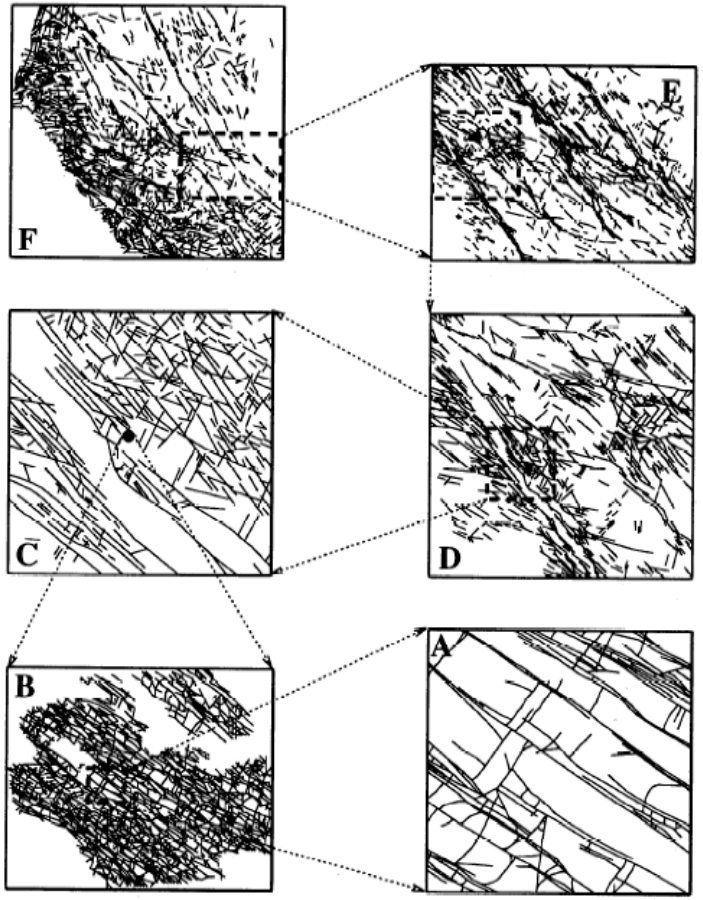
22 febr. 1665.

Diebus 4 aut 5 horologiorum duorum novorum in quibus catenulæ [Fig. 75], miram concordiam obſervaveram, ita ut ne minimo quidem exceſſu alterum ab altero ſuperaretur. ſed conſonarent ſemper reciprocationes utriusque perpendiculi. unde cum parvo ſpatio inter ſe horologia diſtarent, ſympathiæ quandam [3]) quasi alterum ab altero afficeretur ſuſpicari cœpi. ut experimentum caperem turbavi alterius penduli reditus ne ſimul incederent ſed quadrante horæ poſt vel ſemihora rurſus concordare inveni.

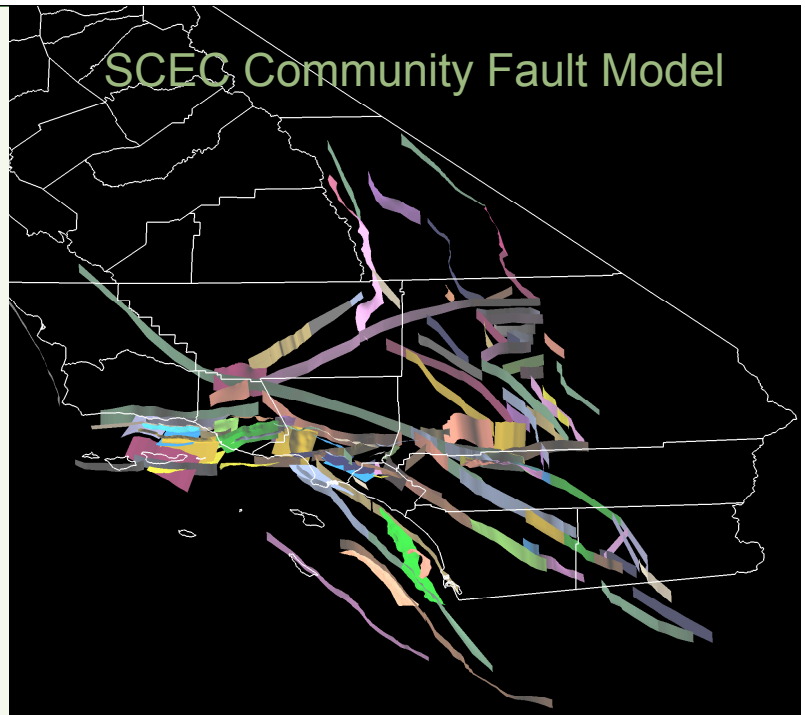
Fireflies

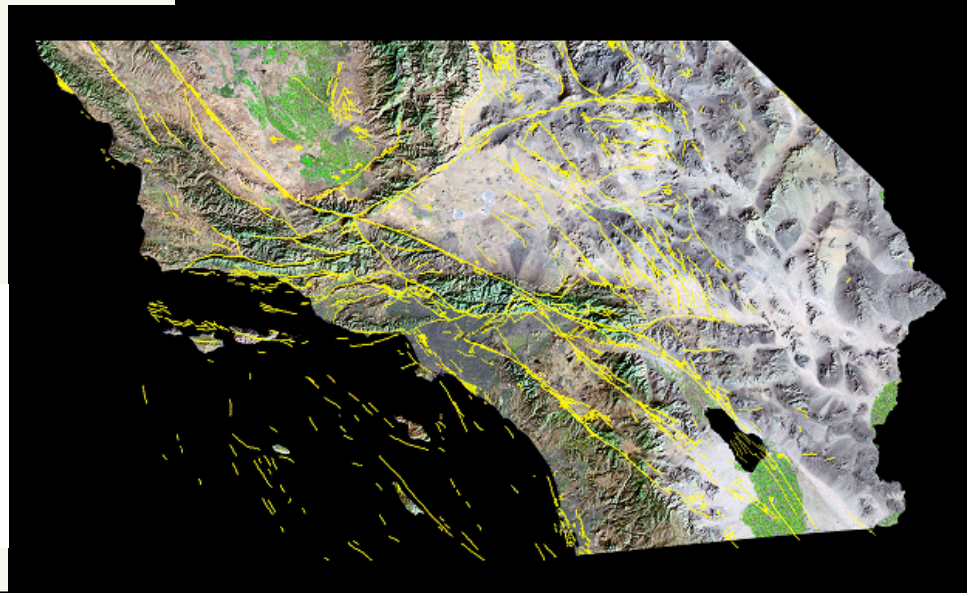
Hierarchical geometry of faulting

Ouillon, Castaing, Sornette (JGR 1996)

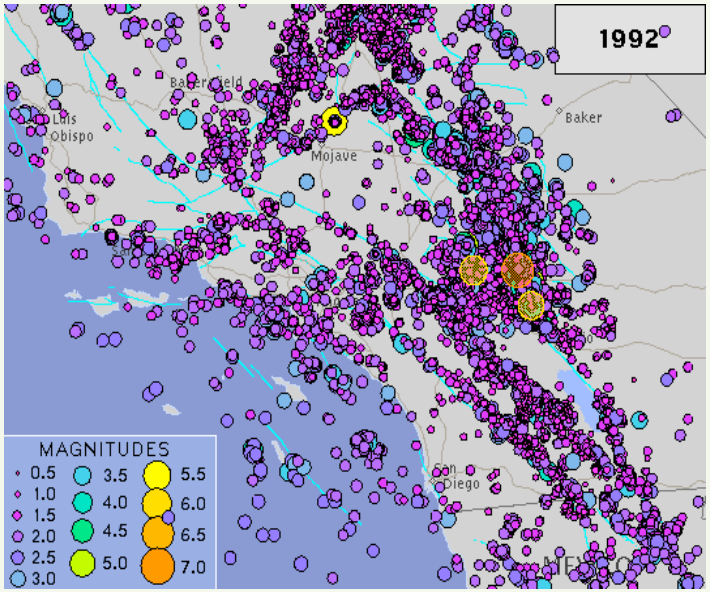


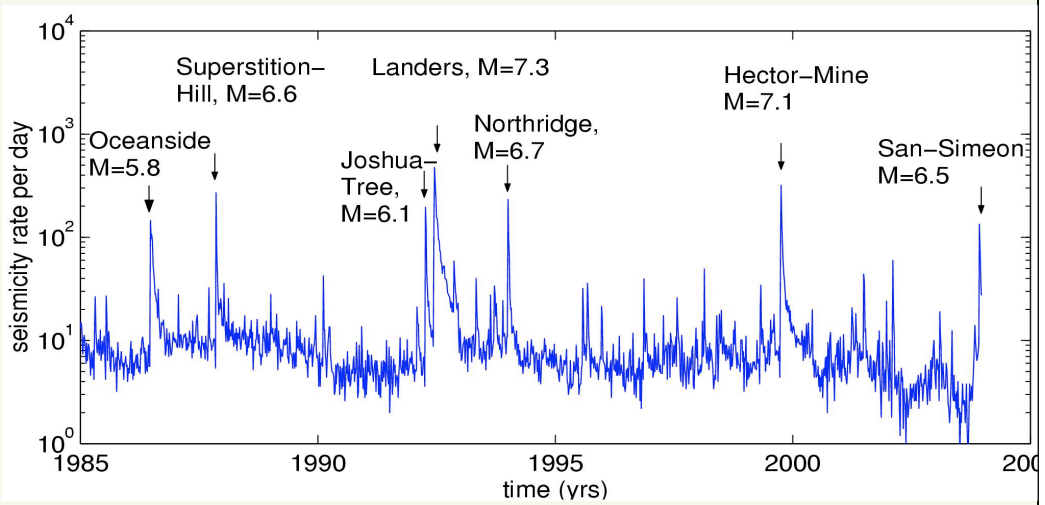
Map A: linear size=10 m, orig. scale=1:1
Map B: linear size=60 m, orig. scale=1:220
Map C: linear size=11 km, orig. scale=1:62,500
Map D: linear size=45 km, orig. scale=1:125,000
Map E: linear size=150 km, orig. scale=1:250,000
Map F: linear size=400 km, orig. scale=1:1,000,000





Spatial and temporal organization of seismicity in Californie



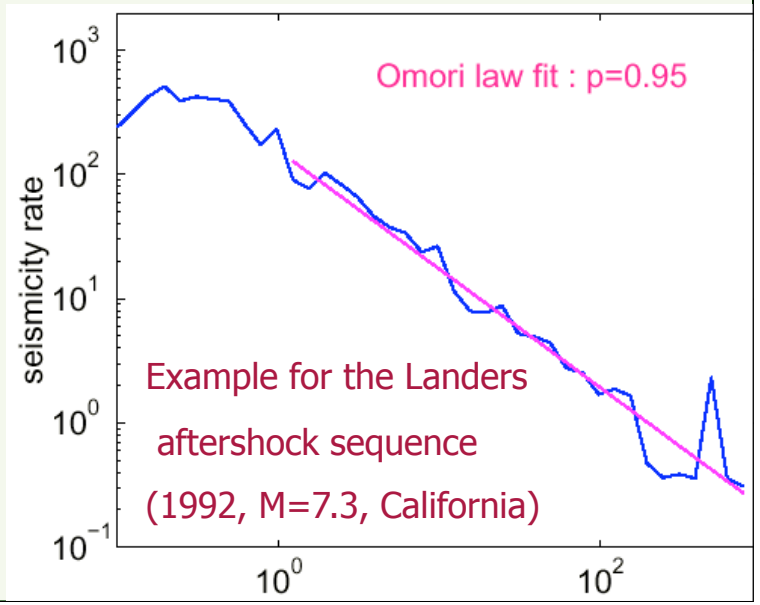


Temporal decay of the rate **N(t)** of aftershocks after a mainshock at **t=0**

$$N(t) = K/(t+c)^p$$

p is in the range [0.3, 2], often close to 1

[Omori, 1894; Utsu, 1960]



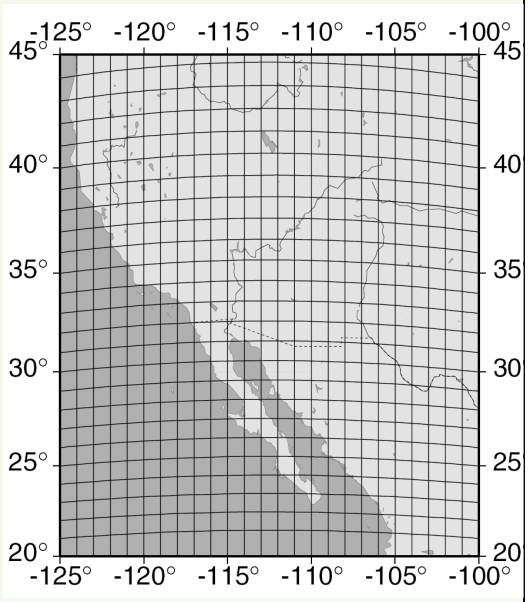
rate of seismic events of magnitude $M > m$ occurring in a cell of size $L \times L$

Monofractal view:

$$\lambda(m,L,T) = a\ 10^{-bm}\ L^{d}\ T^{-p}$$

Unified Scaling Law for Earthquakes

(Bak et al, PRL 2002; Corral, 2003; Baiesi and Paczuski, 2004)



Multifractal view ("metric"):

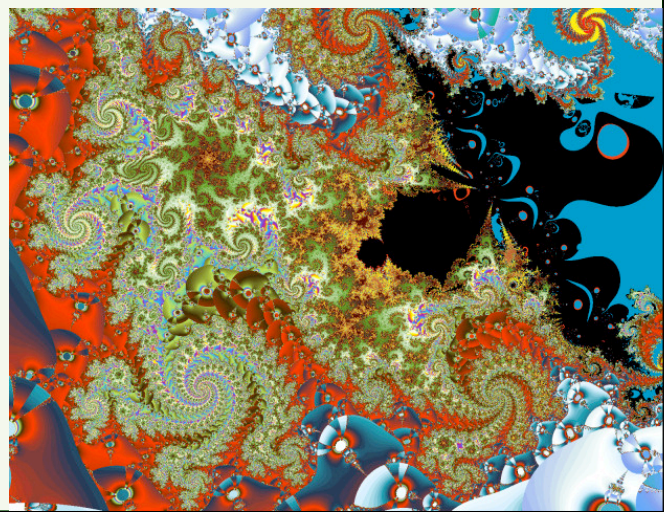
$$\lambda_i(m,L,T) = a_i\ 10^{-b_i m}\ L^{d_i}\ T^{-p_i}$$

exponents are inter-related

(Lee Skinner)

Van Gogh
View of
turbulence

Multifractal
view of
fragmentation



Thin Plate Model

Cowie et al (1993, 1995); Miltenberger et al (1995);
Sornette et al (1994); Sornette et al. (1996):

- 2D plate of tiles
- Boundaries of tiles are fault segments
- Plate Boundary conditions:
  - periodic in x
  - constant anti-plane strain at top
  - free boundary at bottom

$$\sigma_{yz}(x,y) = g(u_z(x,y) - u_z(x,y-1))$$
$$\sigma_{xz}(x,y) = g(u_z(x,y) - u_z(x-1,y))$$
$$\nabla . g(\nabla u_z(x,y)) = 0$$

Stress equilibrium
Elastic constant g

- Rupture criterion: Heterogeneous stress thresholds

Localisation

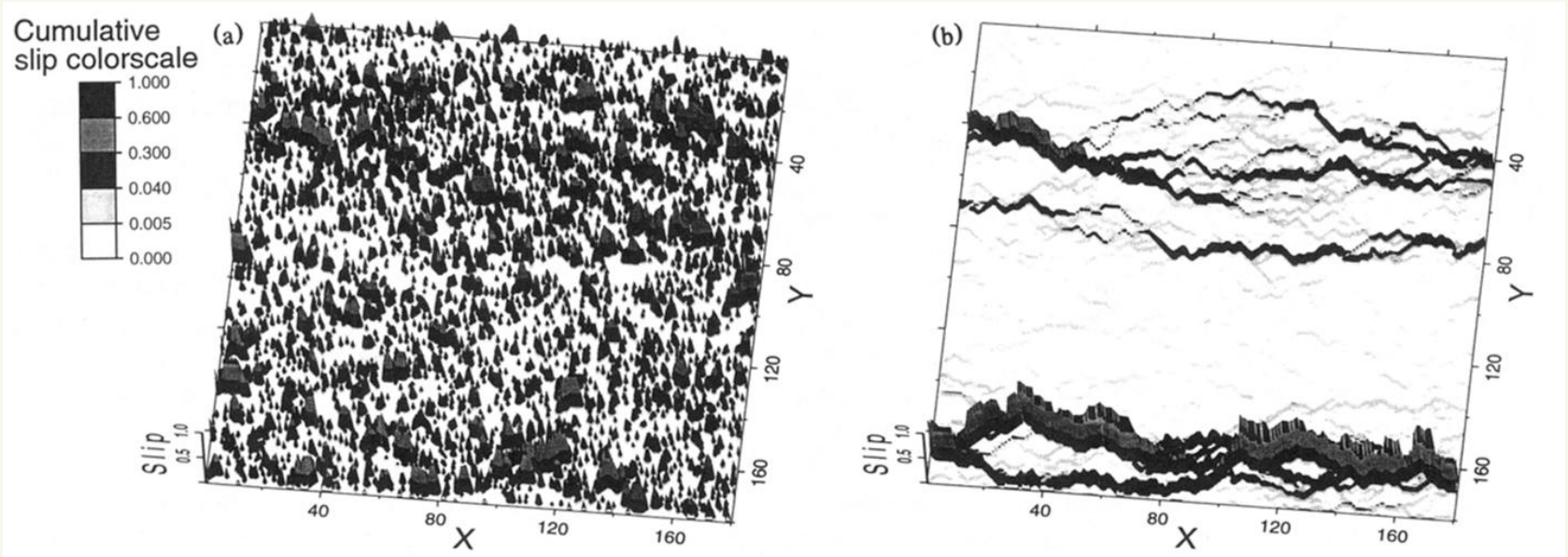
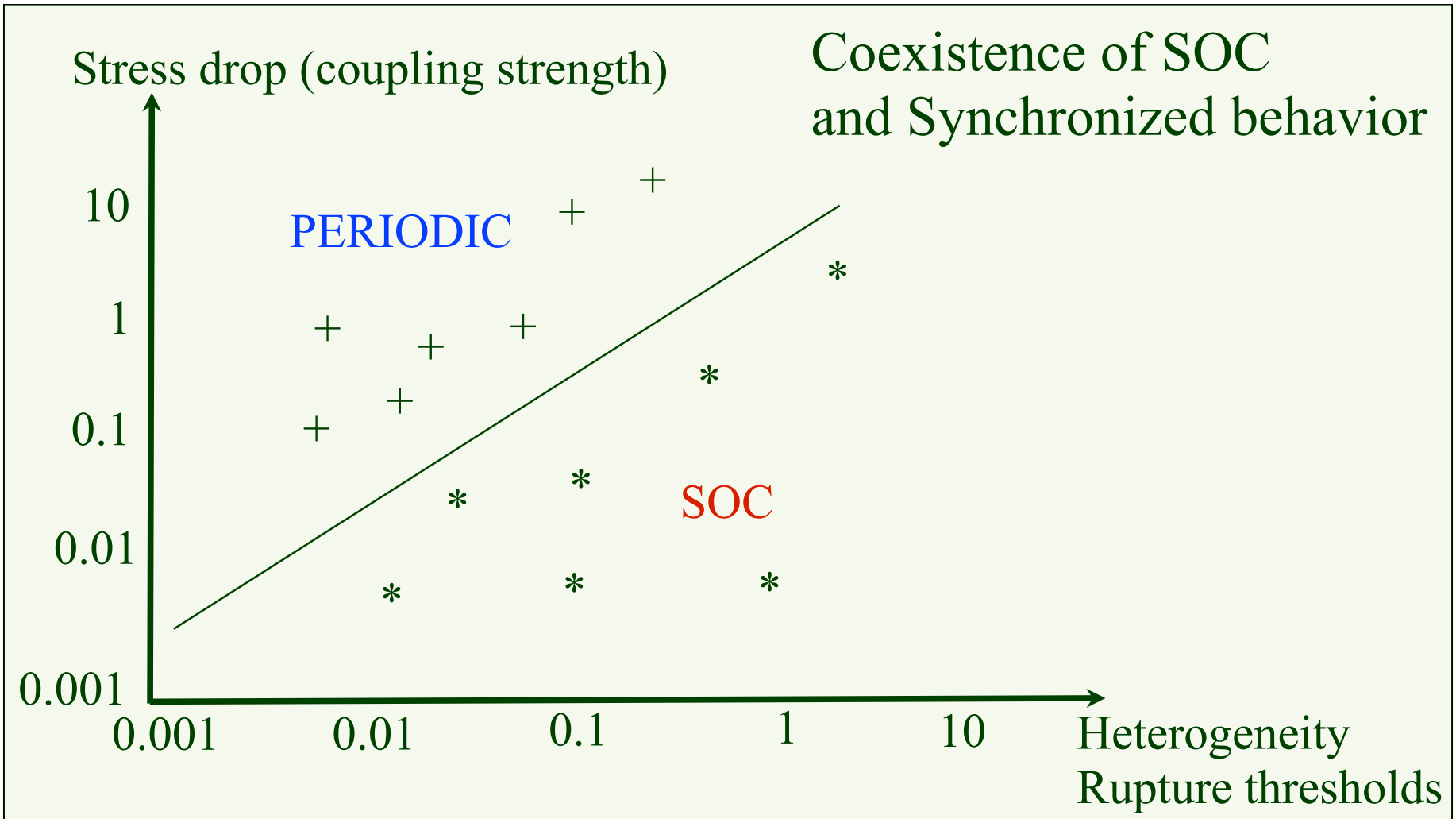


FIG. 1. Evolution of the cumulative earthquake slip, represented along the vertical axis in the white to black color code shown above the picture, at two different times: (a) early time and (b) long time, in a system of size $L=90$ by $L=90$, where $\Delta\sigma=1.9$ and $\beta=0.1$.

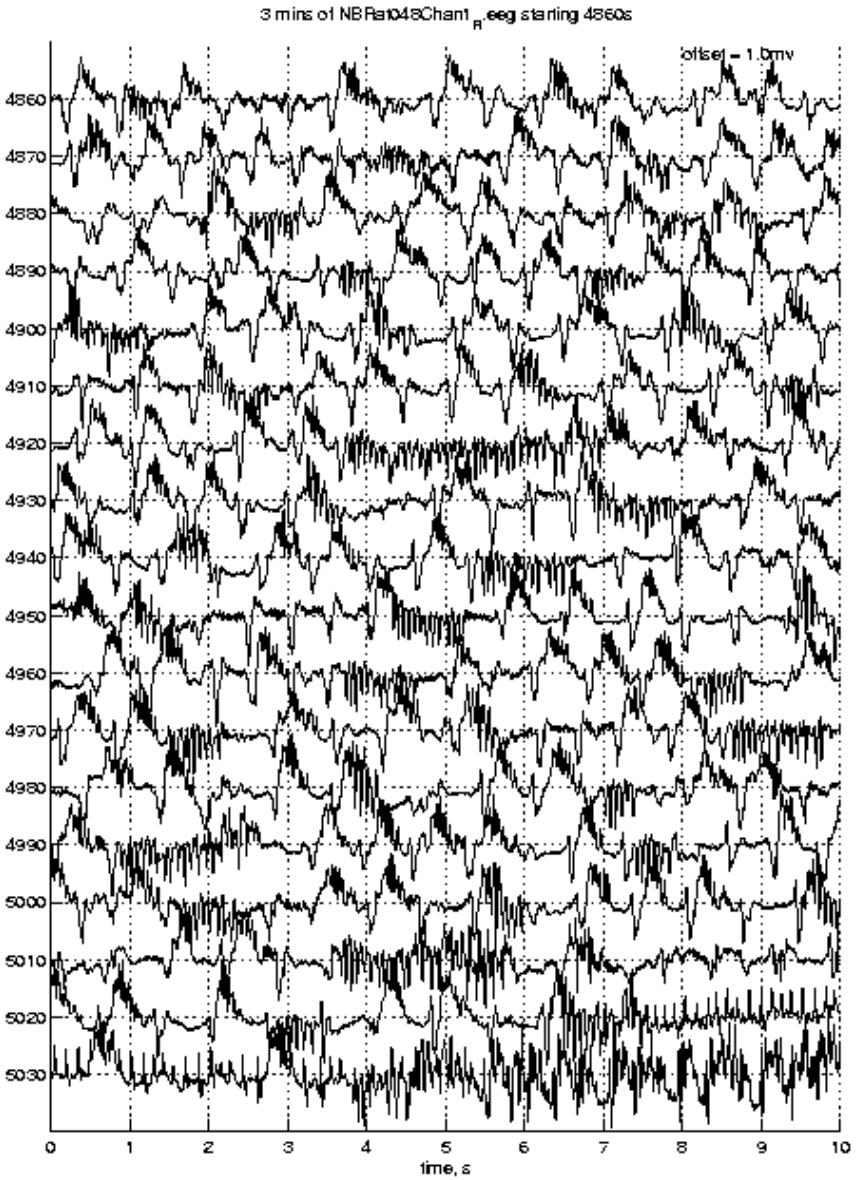
No pre-existing weak zones or material property changes (weakening)

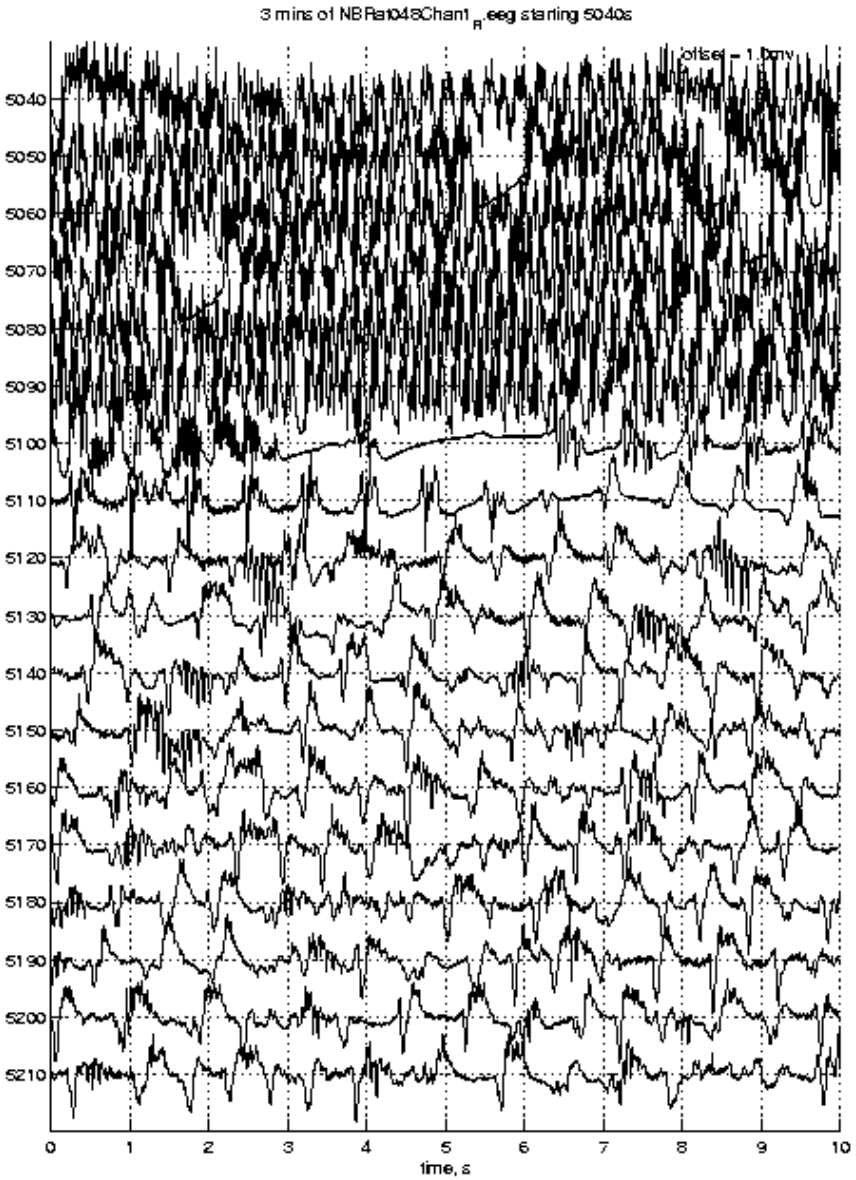
Faults as optimal structures

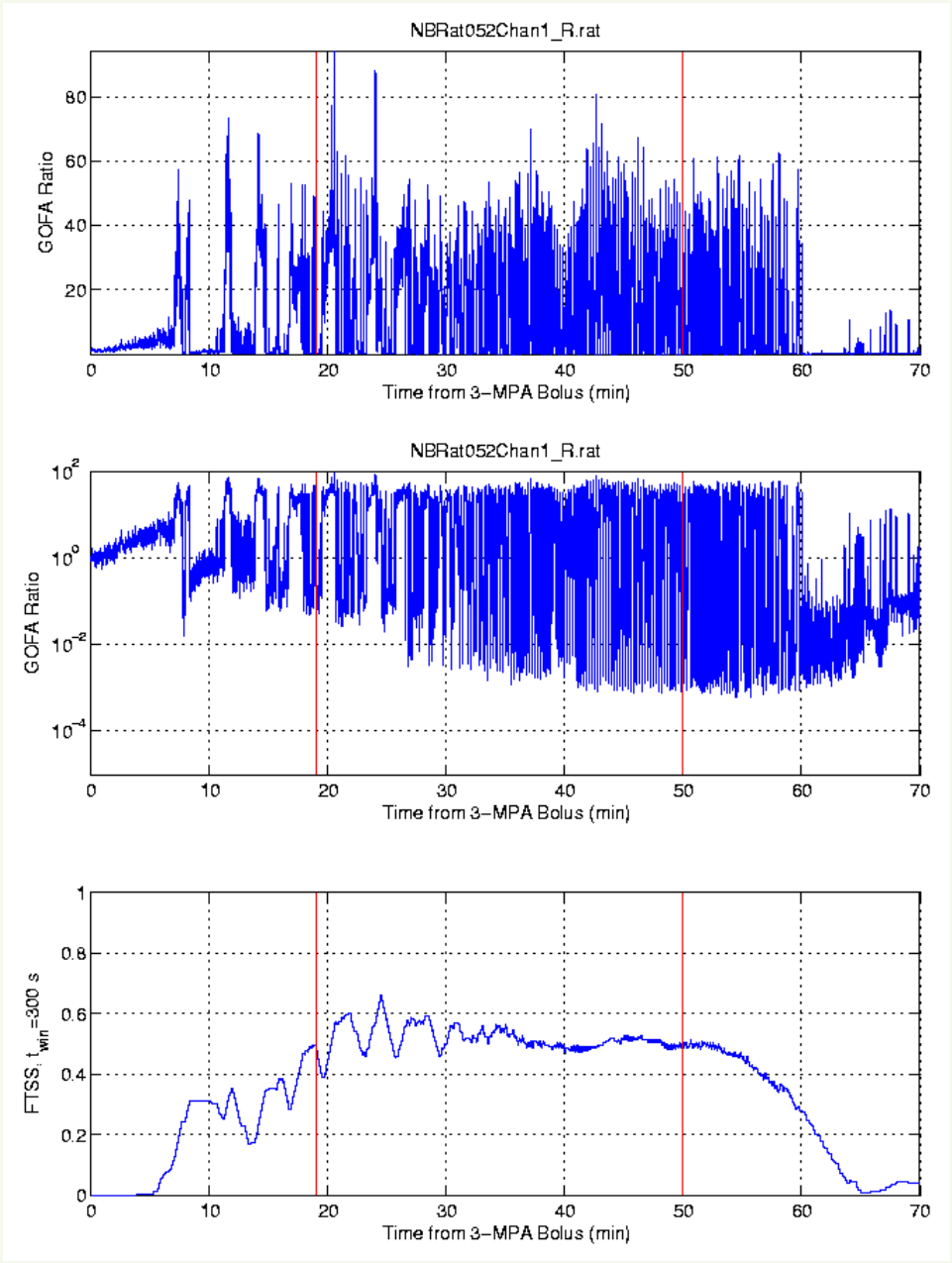
Miltenberger et al. (1993)



"Phase diagram" for the model in the space (heterogeneity, stress drop).
Crosses (+) correspond to systems which exhibit a periodic time evolution.
Stars * corresponds to systems that are self-organized critical, with a Gutenberg-Richter earthquake size distribution and fault localization whose geometry is well-described by the geometry of random directed polymers.


3 mins of NBRat048Chan1_R.eeg starting 4860s
offset = 1.0mv
4860
4870
4880
4890
4900
4910
4920
4930
4940
4950
4960
4970
4980
4990
5000
5010
5020
5030
0
1
2
3
4
5
6
7
8
9
10
time, s


3 mins of NBRat048Chan1_R.eeg starting 5040s
offset = 1 0mv
5040
5050
5060
5070
5080
5090
5100
5110
5120
5130
5140
5150
5160
5170
5180
5190
5200
5210
0
1
2
3
4
5
6
7
8
9
10
time, s


NBRat052Chan1_R.rat
GOFA Ratio
Time from 3–MPA Bolus (min)
NBRat052Chan1_R.rat
GOFA Ratio
Time from 3–MPA Bolus (min)
FTSS, t_{win}=300 s
Time from 3–MPA Bolus (min)