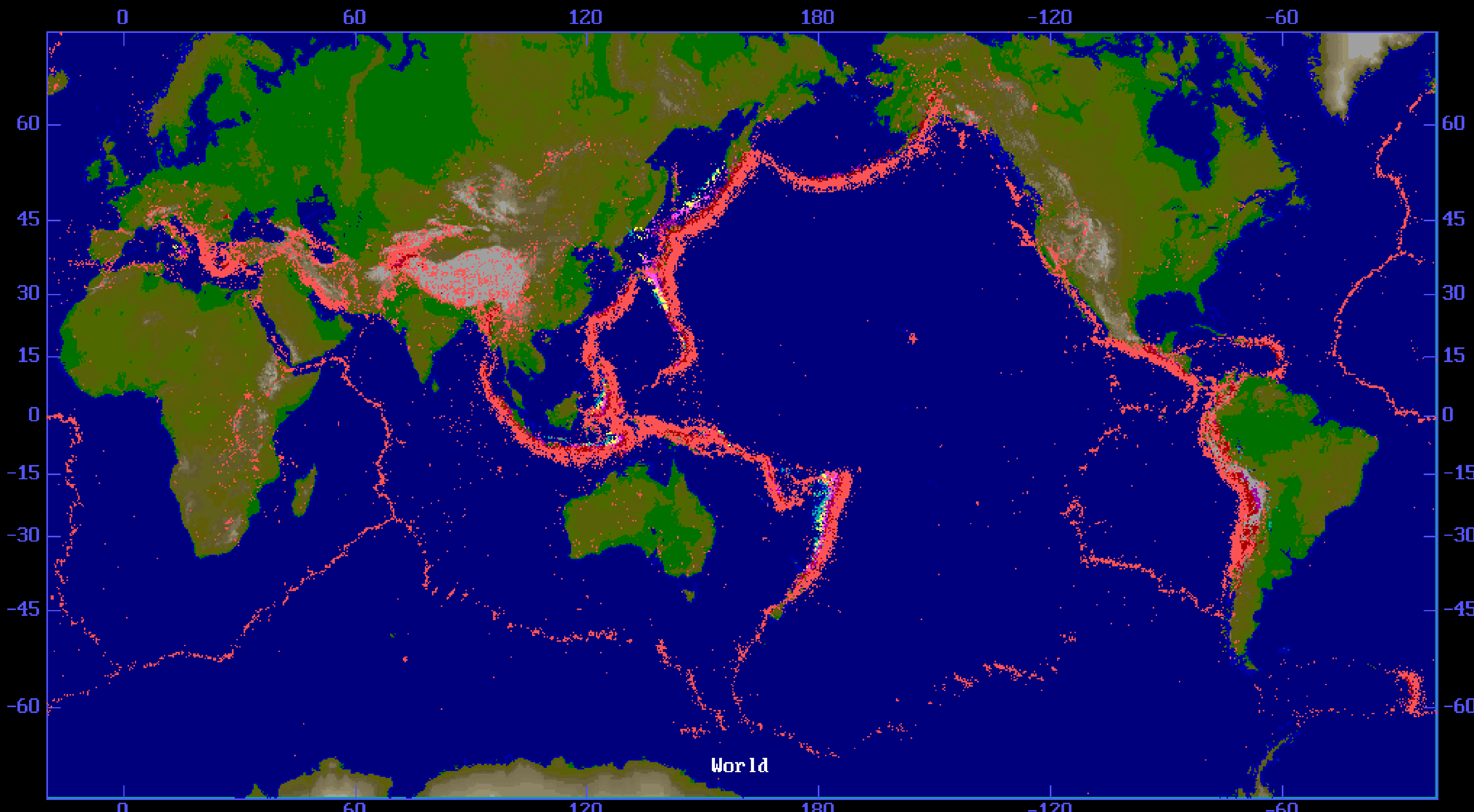
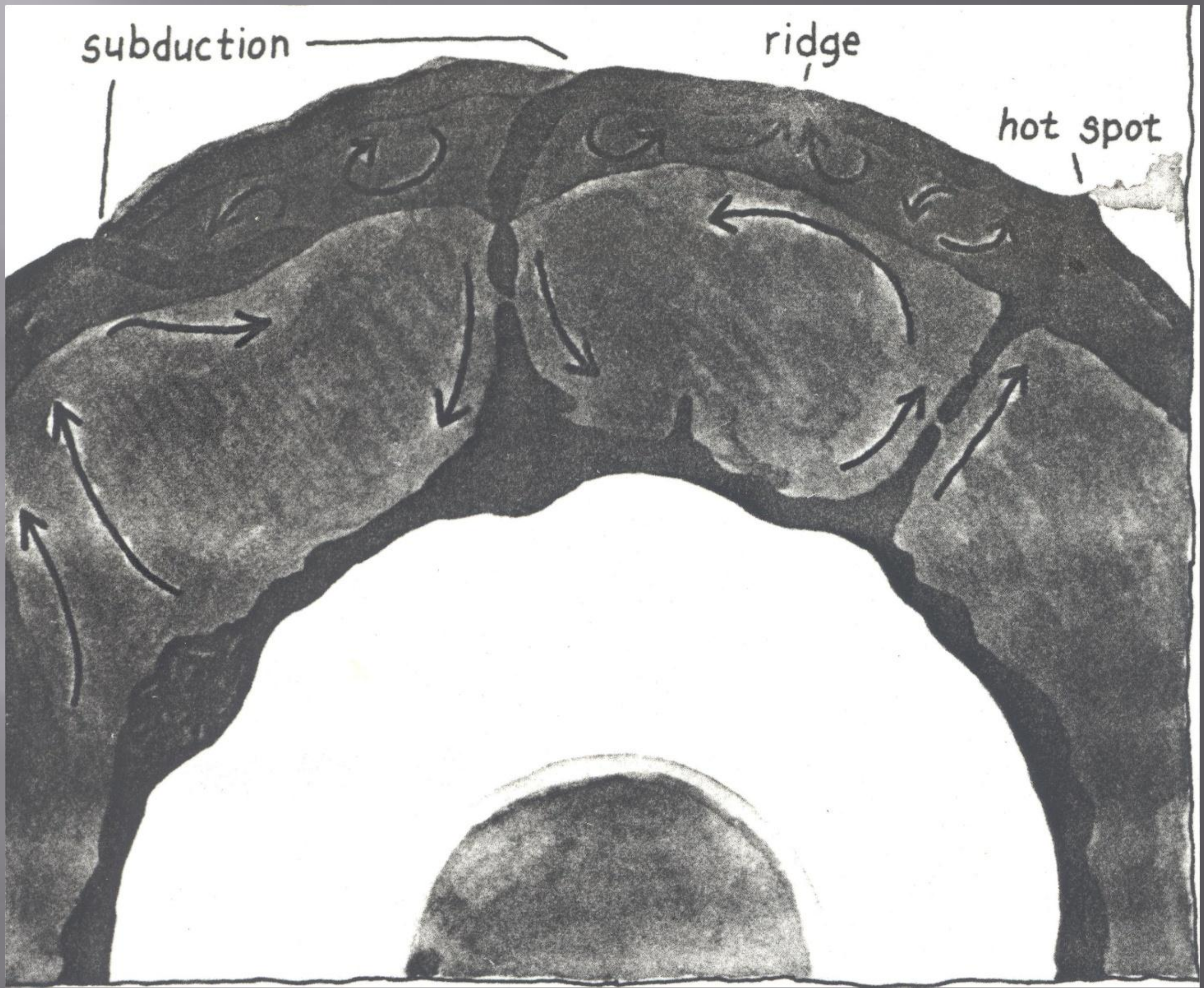
LA CORTEZA TERRESTRE COMO UN SISTEMA COMPLEJO CRÍTICAMENTE AUTOORGANIZADO

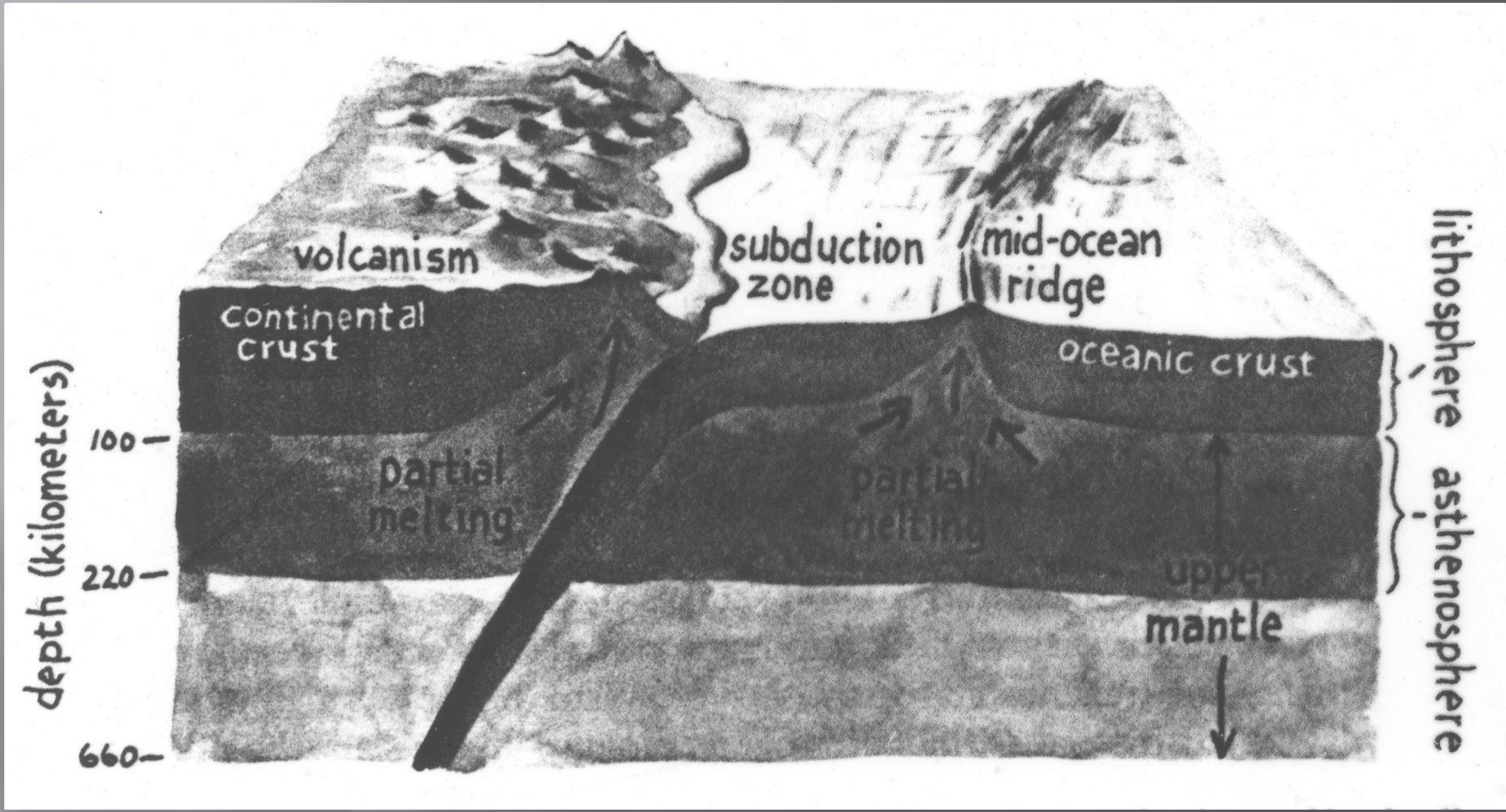
F. Angulo Brown

ESFM-IPN

Where earthquakes occur?



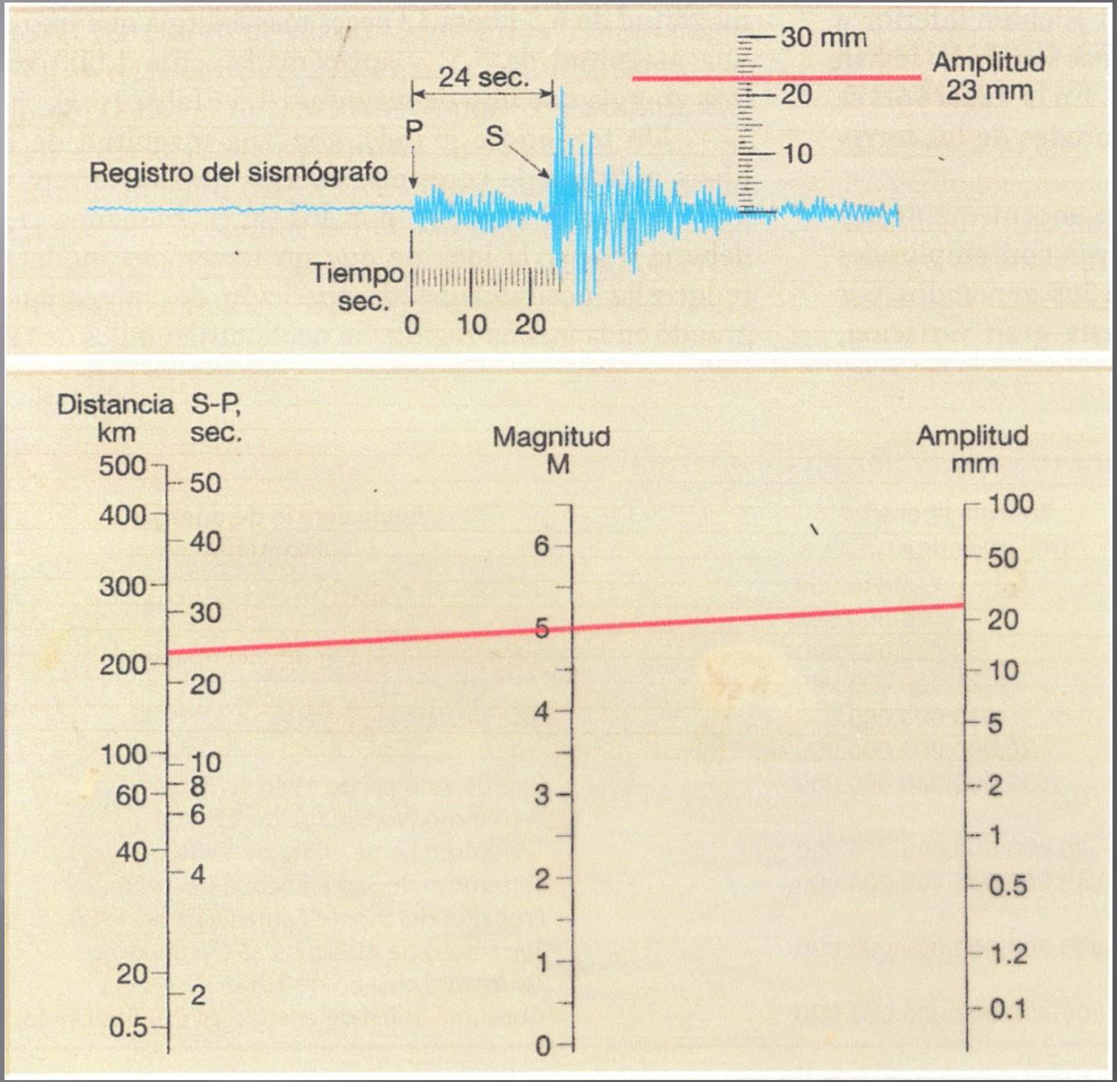

subduction
ridge
hot spot



volcanism
subduction zone
mid-ocean ridge
continental crust
oceanic crust
partial melting
partial melting
upper mantle
lithosphere
asthenosphere
depth (kilometers)
100
220
660


Mapa
Satélite
Híbrido
Imágenes ©2010 TerraMetrics - Términos de uso


Mapa
Satélite
Híbrido
Imágenes ©2010 TerraMetrics - Términos de uso


30 mm
Amplitud
23 mm
24 sec.
20
P
S
10
Registro del sismógrafo
Tiempo
sec.
0
10
20
Distancia
km
S-P,
sec.
Magnitud
M
Amplitud
mm
500
400
300
200
100
60
40
20
0.5
50
40
30
20
10
8
6
4
2
6
5
4
3
2
1
0
100
50
20
10
5
2
1
0.5
1.2
0.1

Relaciones empíricas de la sismología

Ley de Omori (1894)

La razón de ocurrencia de las réplicas de un sismo de magnitud grande o intermedia decrece de acuerdo a esta ley empírica. Donde α varía entre 0.9 y 1.8, t_r es el tiempo de ocurrencia del sismo que provoca las réplicas y el factor A(m) decrece monótonamente con la magnitud M.

$$\frac{dn}{dt} = A(M)(t - t_r)^{-\alpha(M)}$$

Ley de Gutenberg-Richter (1944)

Relación empírica para la densidad de frecuencias de la magnitud local por unidad de tiempo $\dot{N}$ es la frecuencia, por unidad de tiempo, de sismos de magnitud mayor o igual a M.

$$\log \dot{N}(M) = a - bM$$

Relación de Utsu y Seki (1954)

Relación entre el logaritmo del área de réplicas (S en km^2) y la magnitud M.

$$\log S = 1.02M - 4.01$$

Relaciones empíricas de la sismología, cont.

Relación de magnitud y energía (1956)

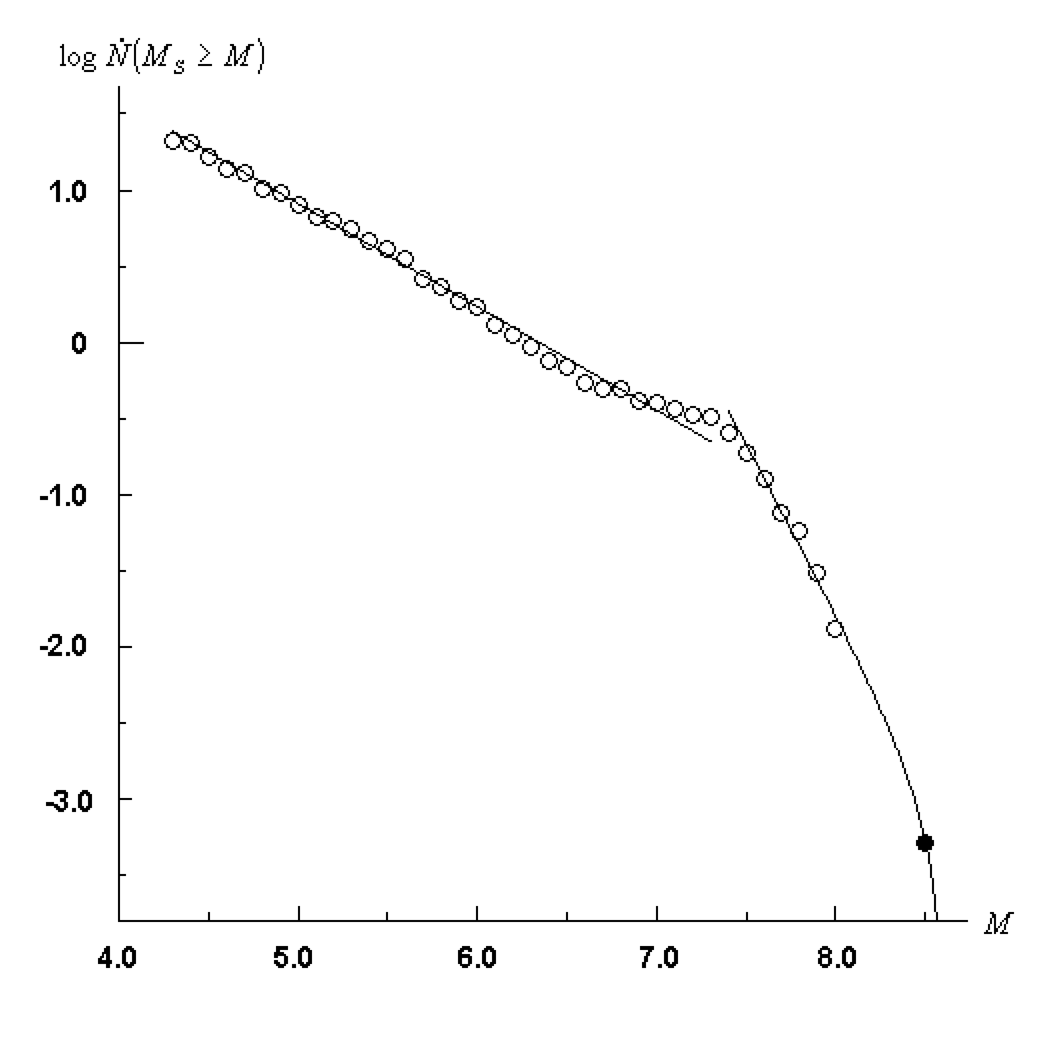
La relación entre la magnitud de ondas superficiales Ms y la energía total de las ondas sísmicas fue propuesta por Gutenberg y Richter.

$$\log_{10} E = 1.5 M_S + 11.8$$

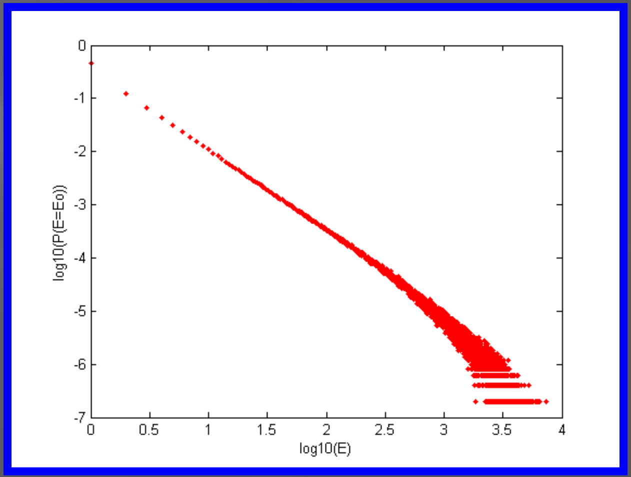
Relación de Tsubokawa (1969)

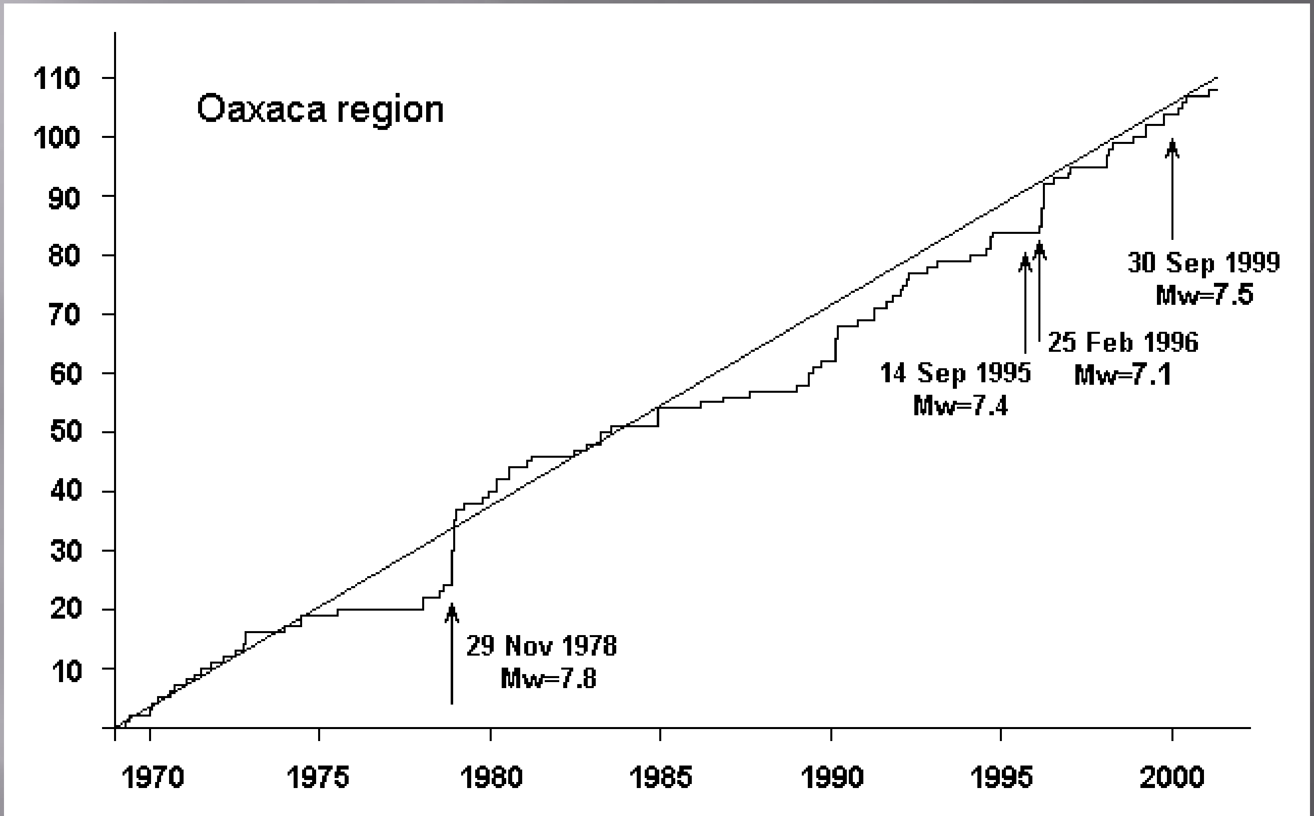
Intento para correlacionar el tiempo de duración de la anomalía precursora con la magnitud del sismo, T es el tiempo (en días) de la duración de la deformación anómala del terreno y la Ms es la magnitud del sismo.

$$\log T = 0.79 M_S - 1.88$$

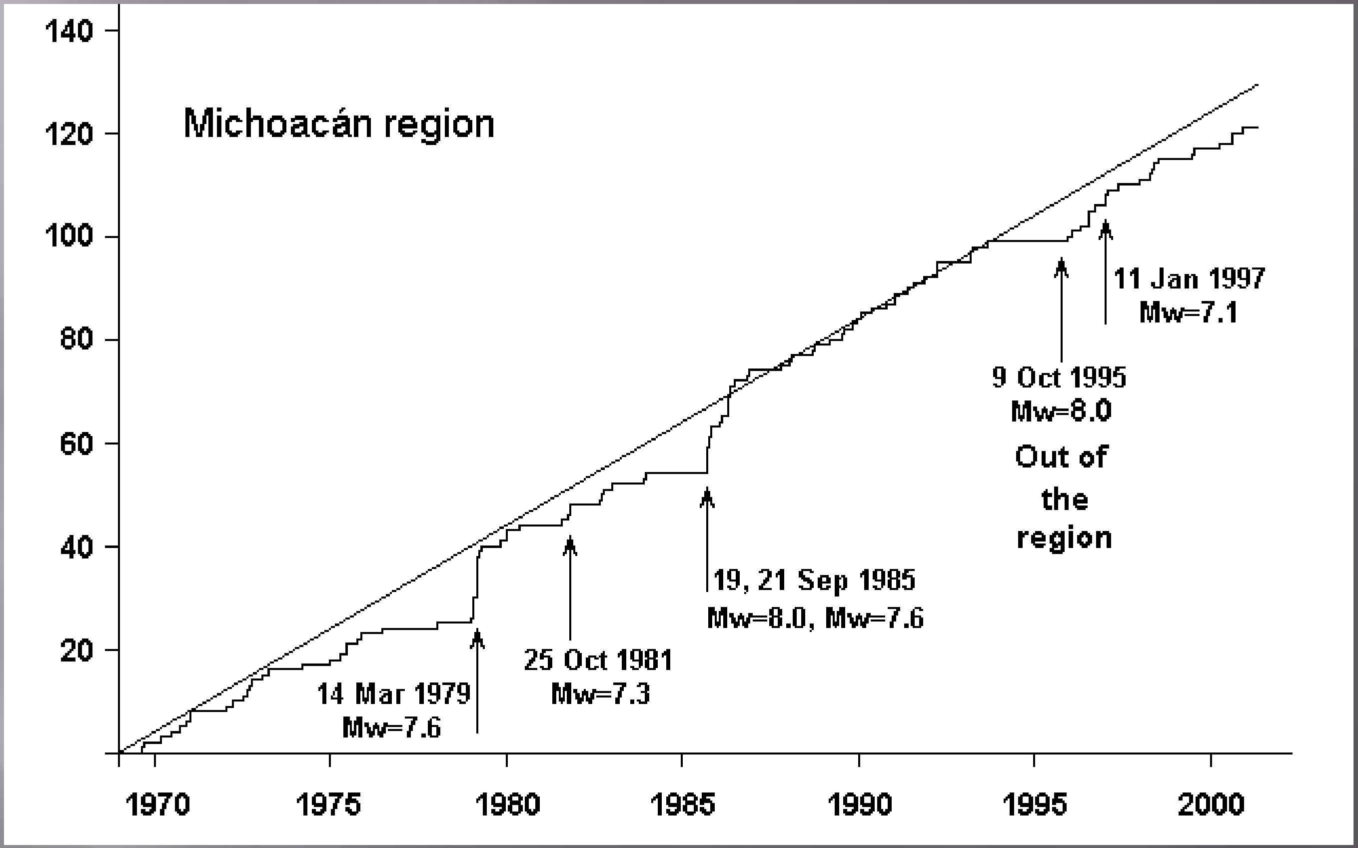


Logarithm of the frequency against the time and adjusted Gutenberg-Richter relationships. The black point with M=8.5 is an adjusted value.

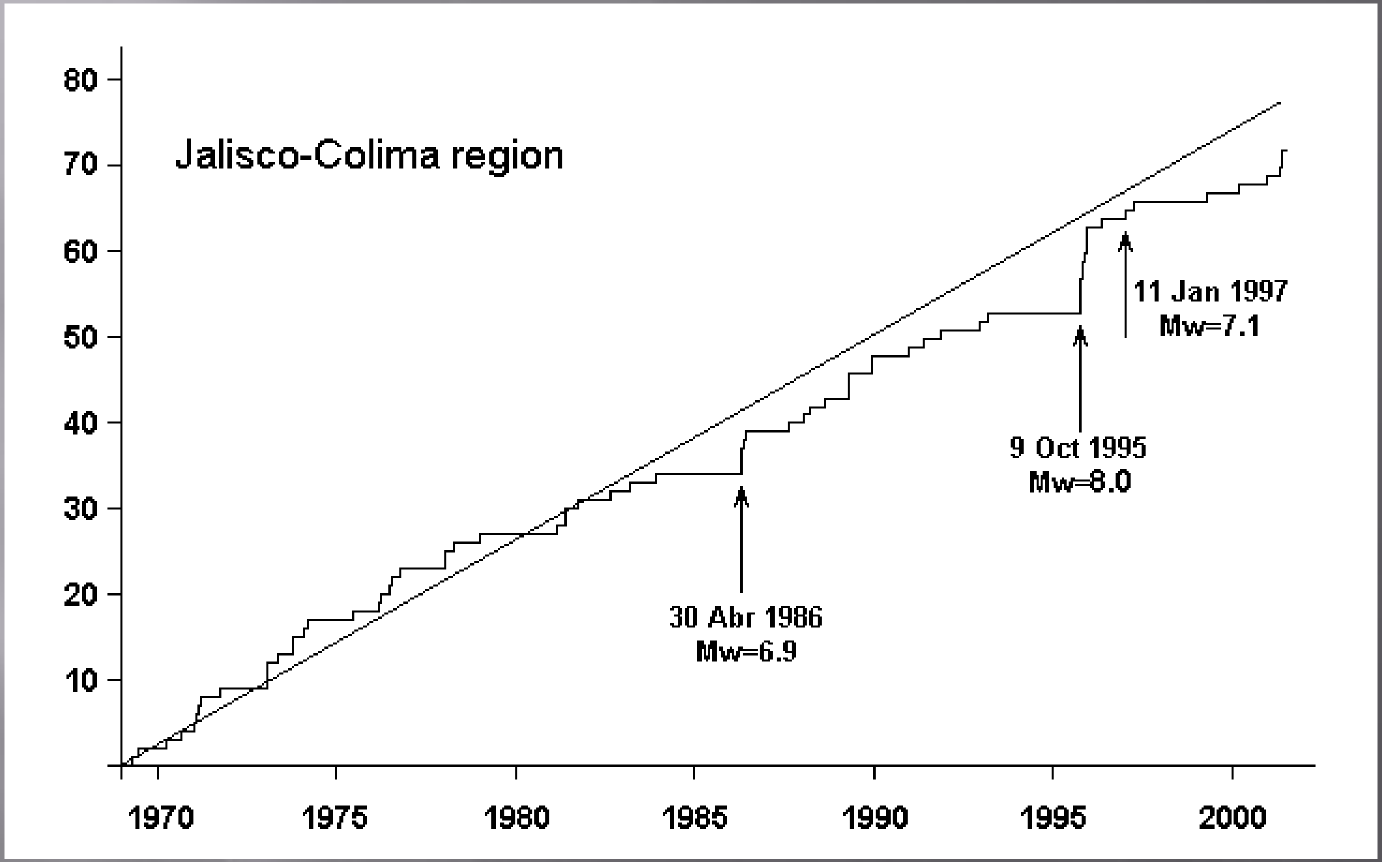




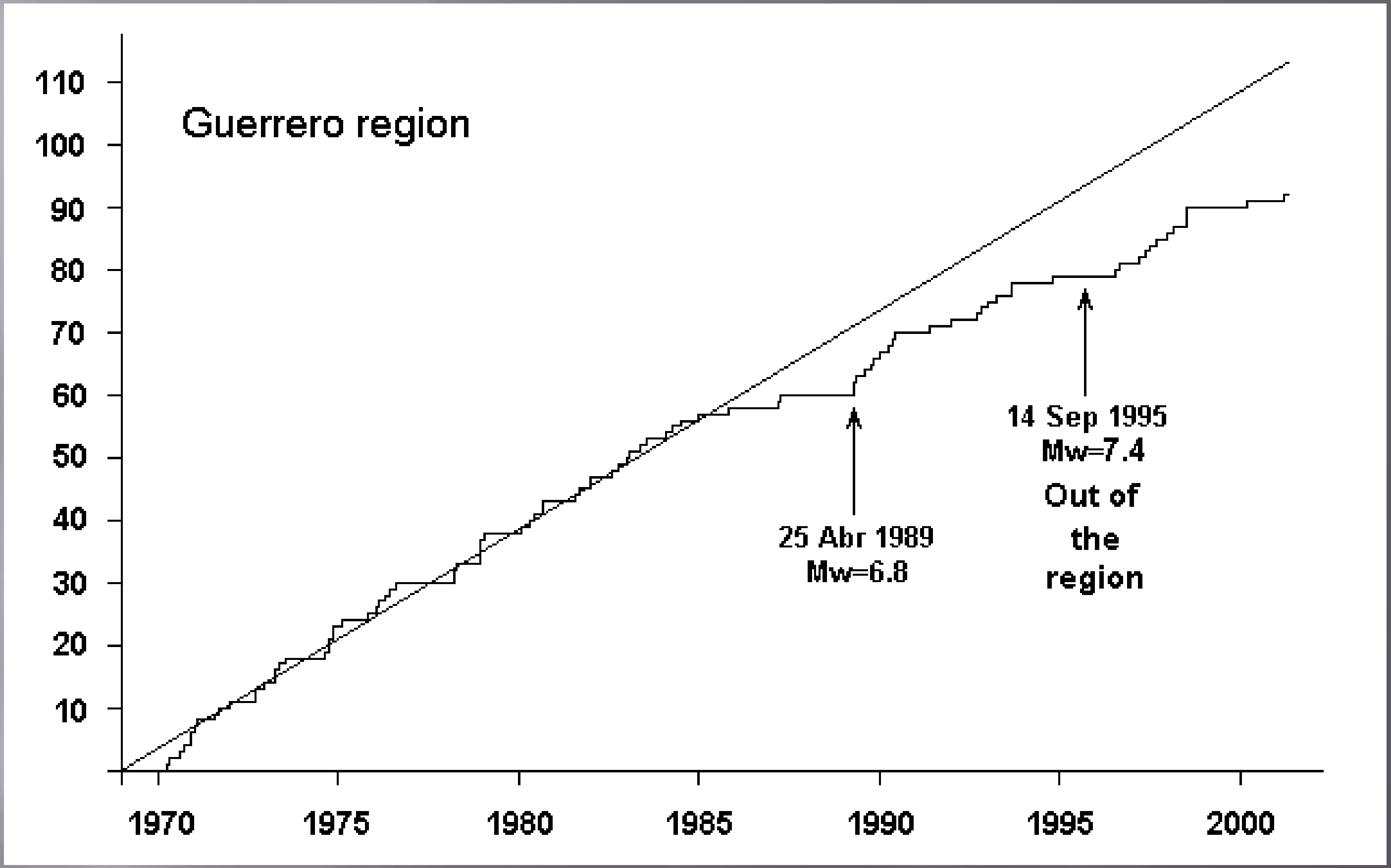
Earthquake number against time Ms ≥ 4.3, Oaxaca region. The earthquakes depth is less or equal to 60 km, and they are located between 15.0 - 17.5°N, and 95.5 - 98.0°W, since January, 1, 1969 to June, 30, 2001. The number of events is 108 and the average annual frequency is 3.4 earthquakes per year.



Earthquake number against time Ms ≥ 4.3, Michoacan region. The earthquakes depth is less or equal to 60 km, and they are located between 16.5 - 19.5°N, and 101.0 – 103.5°W, since January, 1, 1969 to June, 30, 2001. The number of events is 122 and the average annual frequency is 4.0 earthquakes per year.

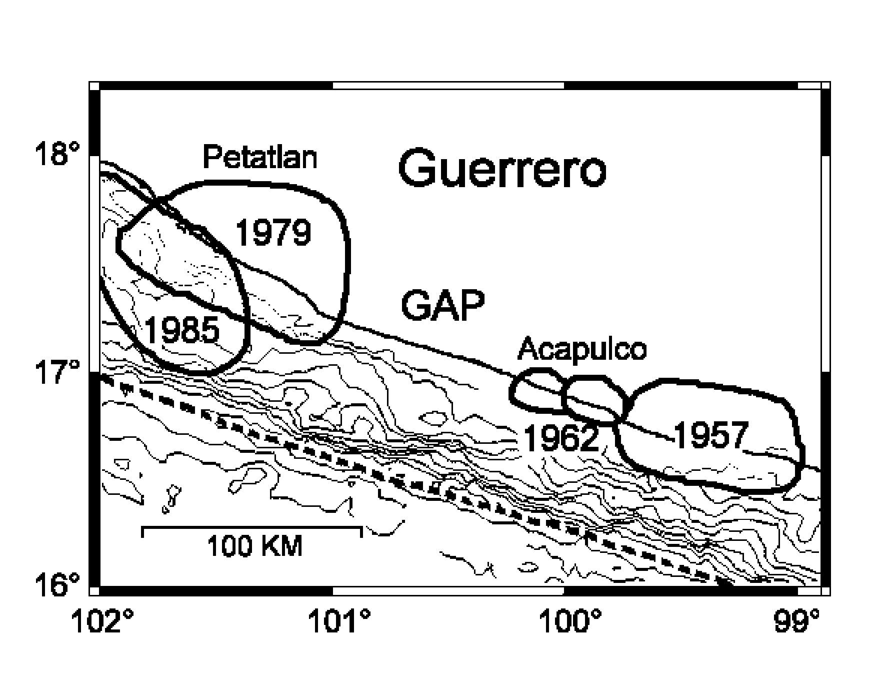


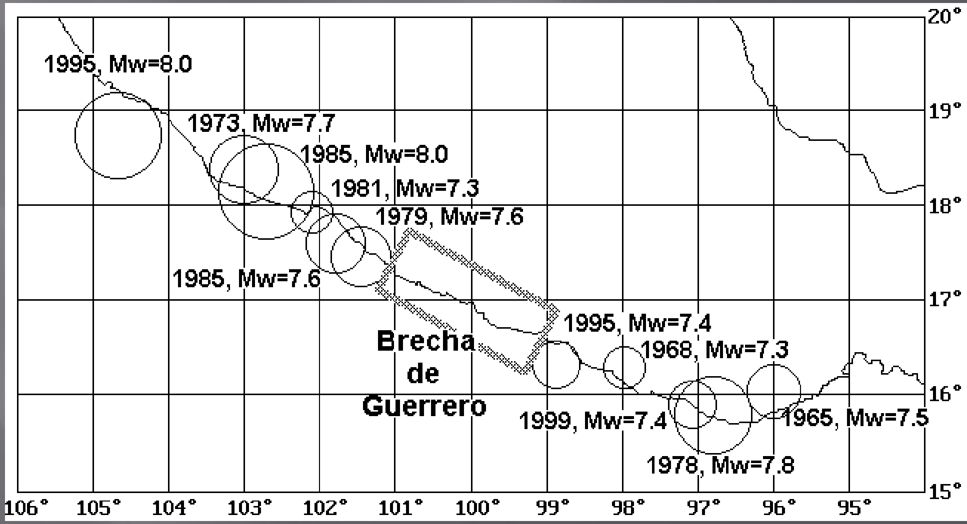
Earthquake number against time Ms ≥ 4.3, Jalisco-Colima region. The earthquakes depth is less or equal to 60 km, and they are located between 17.8 - 19.8°N, and 103.0 – 105.8°W, since January, 1, 1969 to June, 30, 2001. The number of events is 72 and the average annual frequency is 2.4 earthquakes per year.

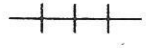


Earthquake number against time Ms ≥ 4.3, Guerrero region. The earthquakes depth is less or equal to 60 km, and they are located between 16.1 - 17.8°N, and 99.3 – 101.1°W, since January, 1, 1969 to June, 30, 2001. The number of events is 92 and the average annual frequency is 3.5 earthquakes per year.

The Guerrero gap

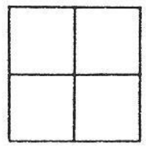






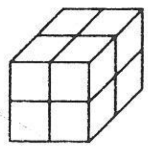
1–D N parts, scaled by ratio $r = 1/N$

$N\,r^1 = 1$



2–D N parts, scaled by ratio $r = 1/N^{1/2}$

$N\,r^2 = 1$



3–D N parts, scaled by ratio $r = 1/N^{1/3}$

$N\,r^3 = 1$

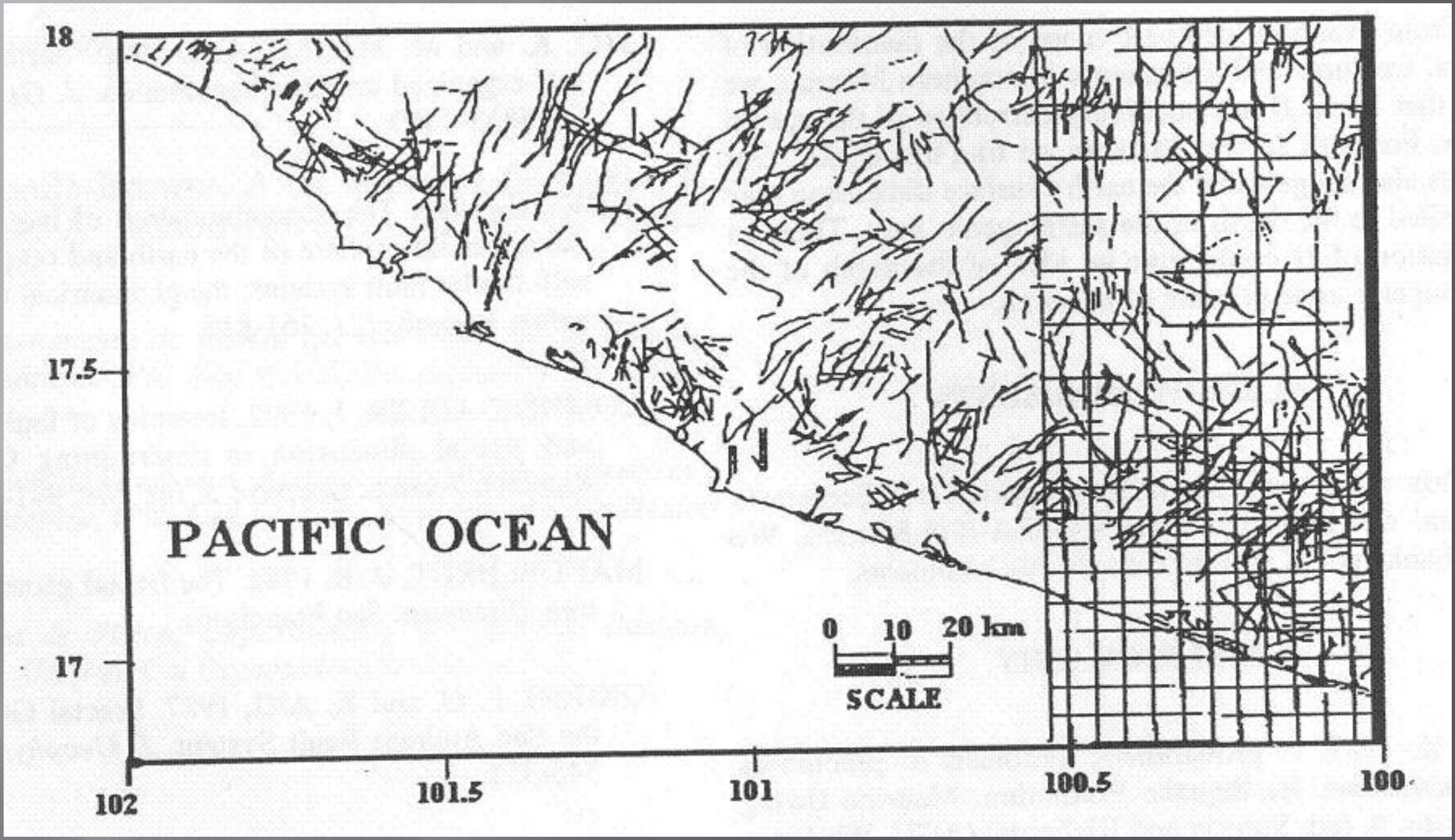
GENERALIZE

for an object of N parts, each scaled down by a ratio r from the whole

$$N\,r^D = 1$$

defines the fractal (similarity) dimension D

$$D = \frac{\log N}{\log 1/r}$$



18
17.5
17
PACIFIC OCEAN
0 10 20 km
SCALE
102
101.5
101
100.5
100

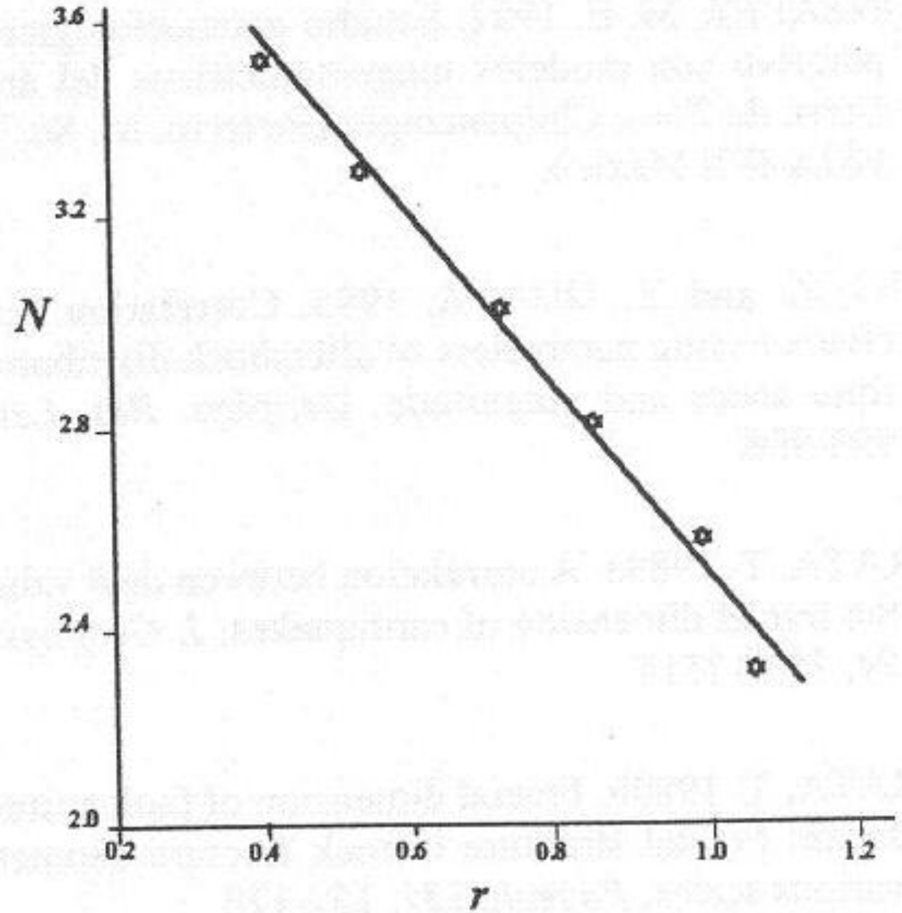


Fig. 3. Double-log graph of *N* versus *r* a slope $D \approx -1.64$. The box lengths used were 2.5, 5.0, 7.5, 10.0 and 12.5 km.

directamente. Los datos de la fuerza constituyen una serie de tiempo $F(t_i)$ para $i = 1,2,...,n$, donde n es el número de datos, se dice que ocurrió un deslizamiento al tiempo t_i cuando $F(t_i) < F(t_{i-1})$ y se define la amplitud de deslizamiento como $A(t_i) = F(t_i) - F(t_{i-1})$.

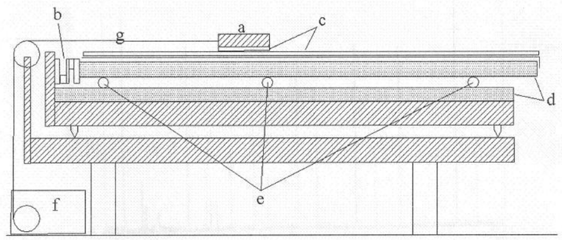


Figura 1. Diagrama experimental para el sistema bloque-resorte. a) bloque de aluminio, b) sensor de fuerza, c) lija, d) placas de vidrio, e) balines de acero, f) moto reductor y g) cuerda de nylon.

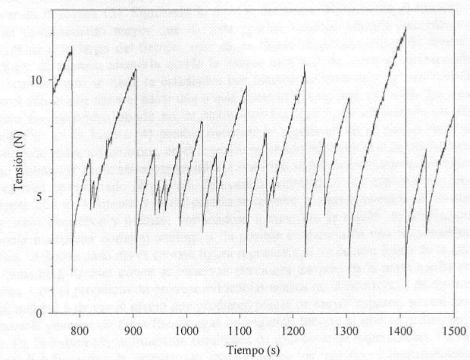
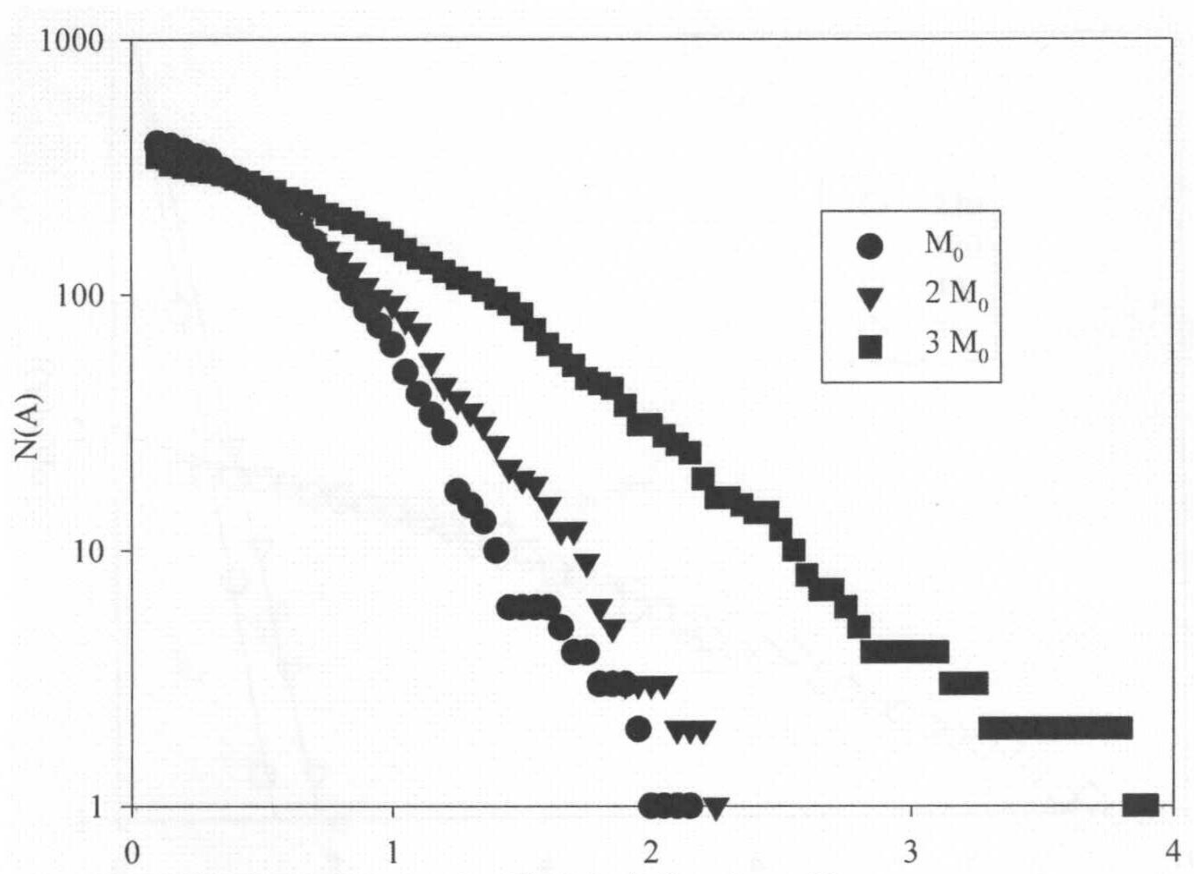


Figura 2. Gráfica de la fuerza sobre la celda de carga en función del tiempo para una lija de calibre 220.


1000
100
10
1
N(A)
0
1
2
3
4
M_0
$2\ M_0$
$3\ M_0$

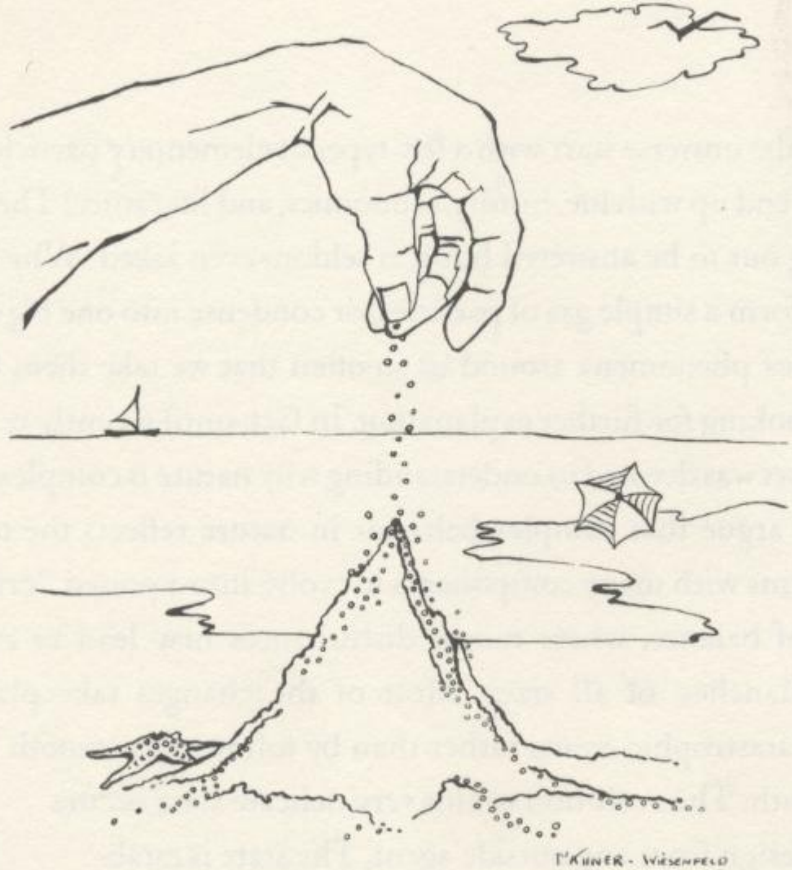
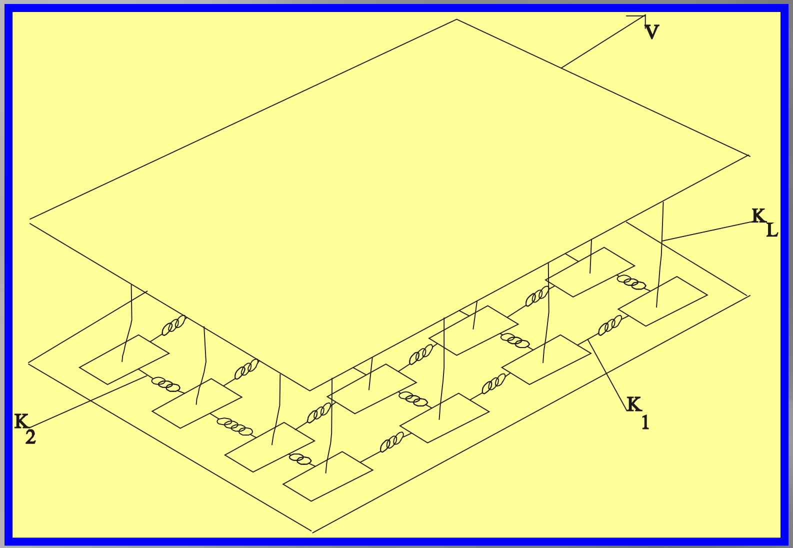


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

The spring-block model. Olami, Feder and Christensen (OFC) model.



The total force exerted by the springs on a given block (i,j)

$$F_{i,j} = K_1\left[2x_{i,j} - x_{i-1,j} - x_{i+1,j}\right] + K_2\left[2x_{i,j} - x_{i,j-1} - x_{i,j+1}\right] + K_L x_{i,j}$$

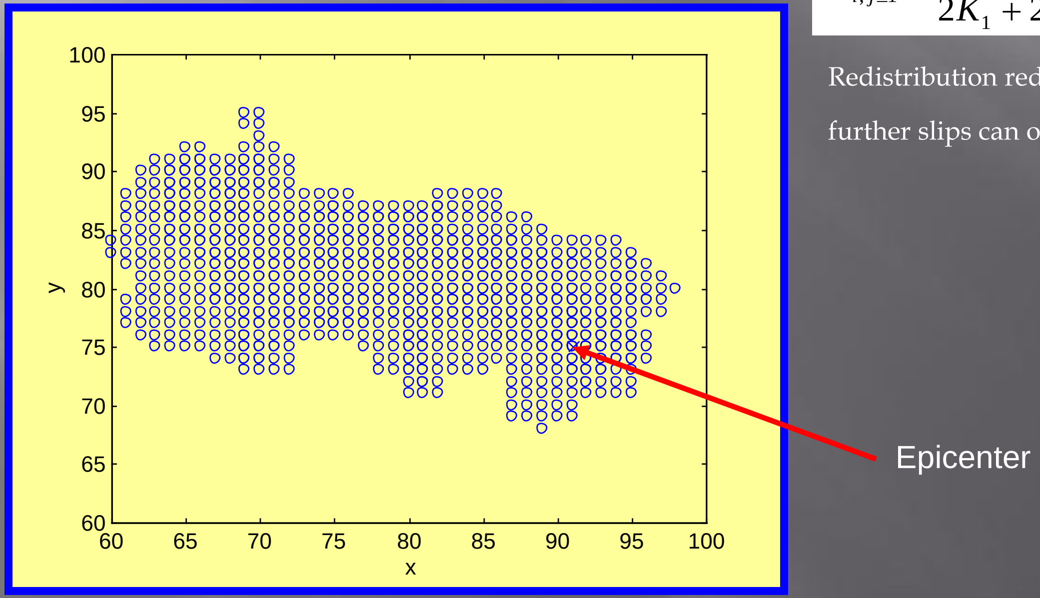
The redistribution of forces after local slip at position *(i, j)* due to the force on one of the blocks is larger than the maximal static friction

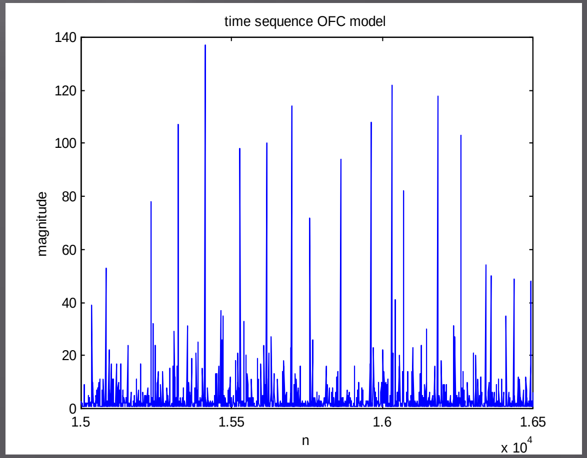
$$F_{i\pm1,j} \to F_{i\pm1,j} + \delta F_{i\pm1,j}$$
$$F_{i,j\pm1} \to F_{i,j\pm1} + \delta F_{i,j\pm1}$$
$$F_{i,j} \to 0$$

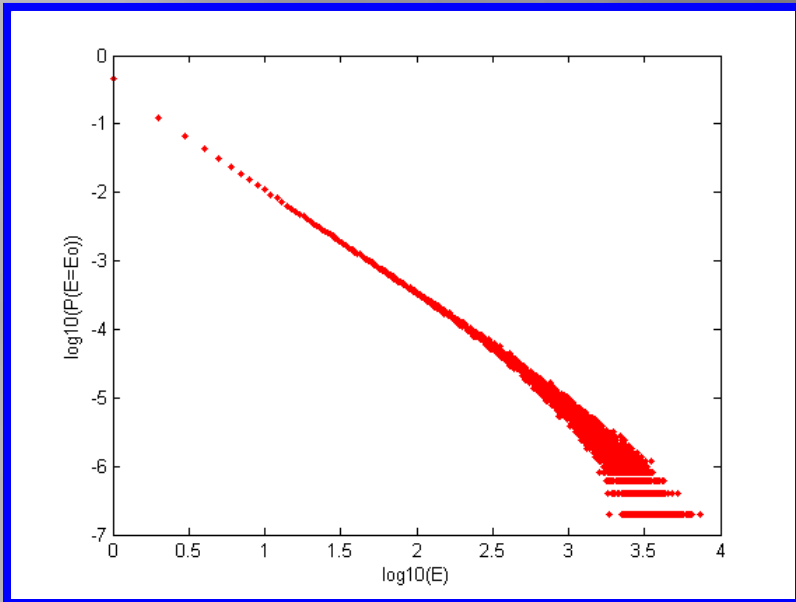
the increments in the force on the nearest-neighbor block

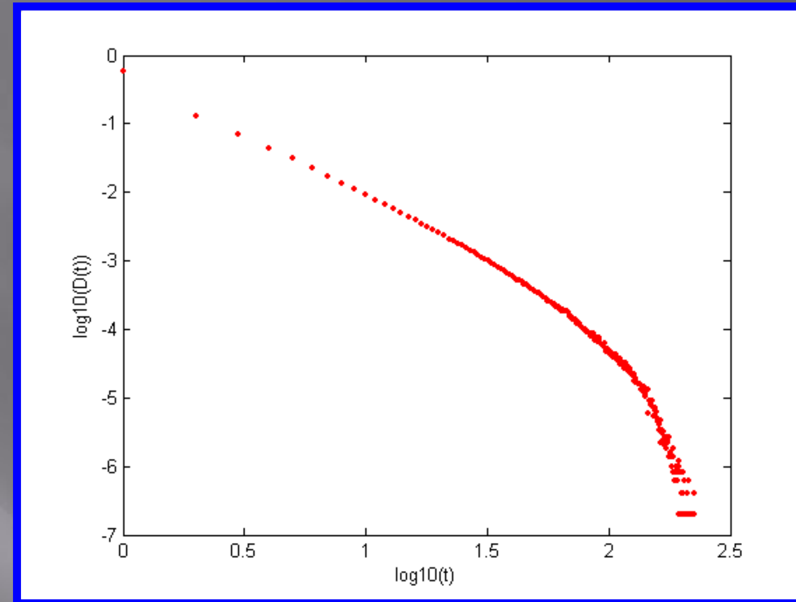
$$\delta F_{i\pm1,j} = \frac{K_1}{2K_1 + 2K_2 + K_L} F_{i,j} = \gamma_1 F_{i,j},$$
$$\delta F_{i,j\pm1} = \frac{K_2}{2K_1 + 2K_2 + K_L} F_{i,j} = \gamma_2 F_{i,j},$$

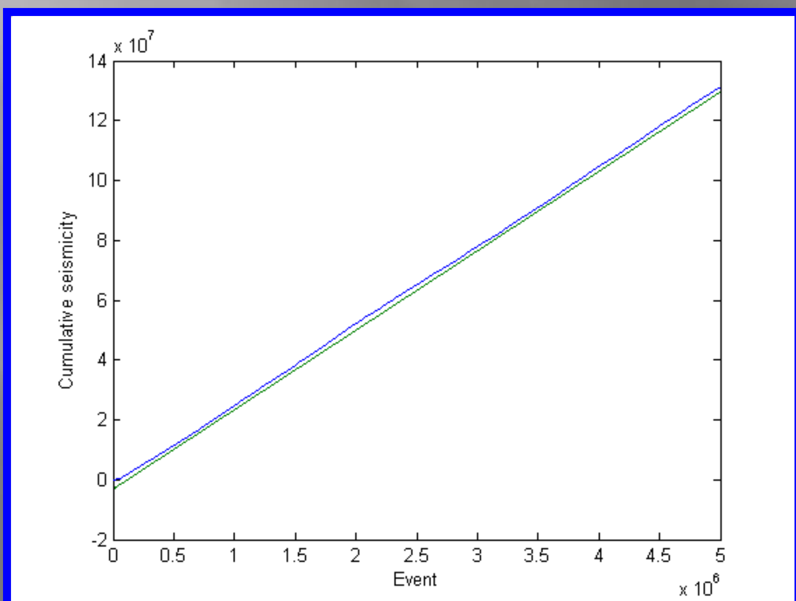
Redistribution redefines the forces in the nearest-neighbor blocks, and further slips can occur, causing a chain reaction (synthetic earthquake).







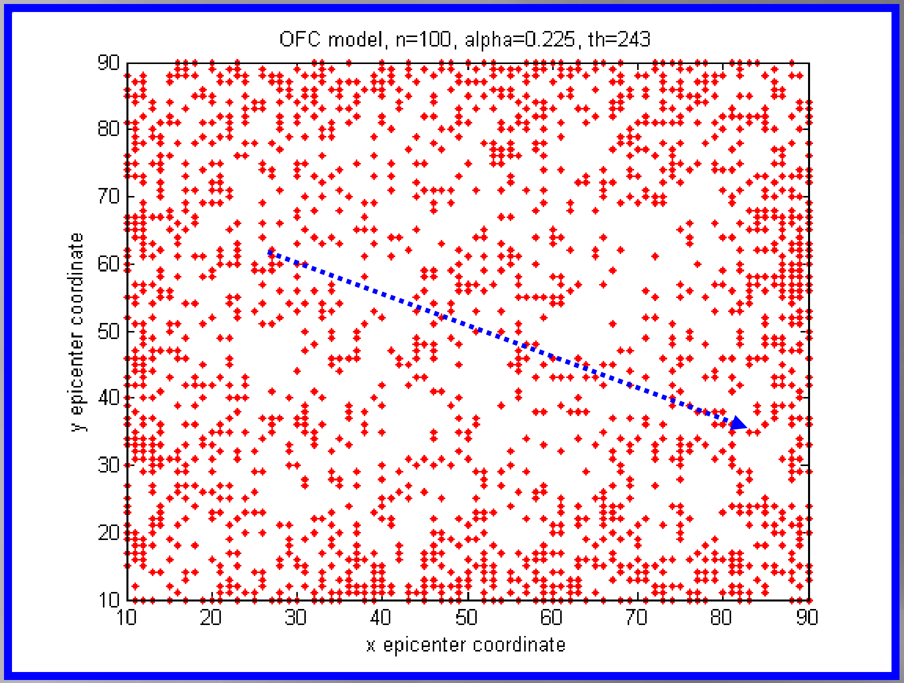


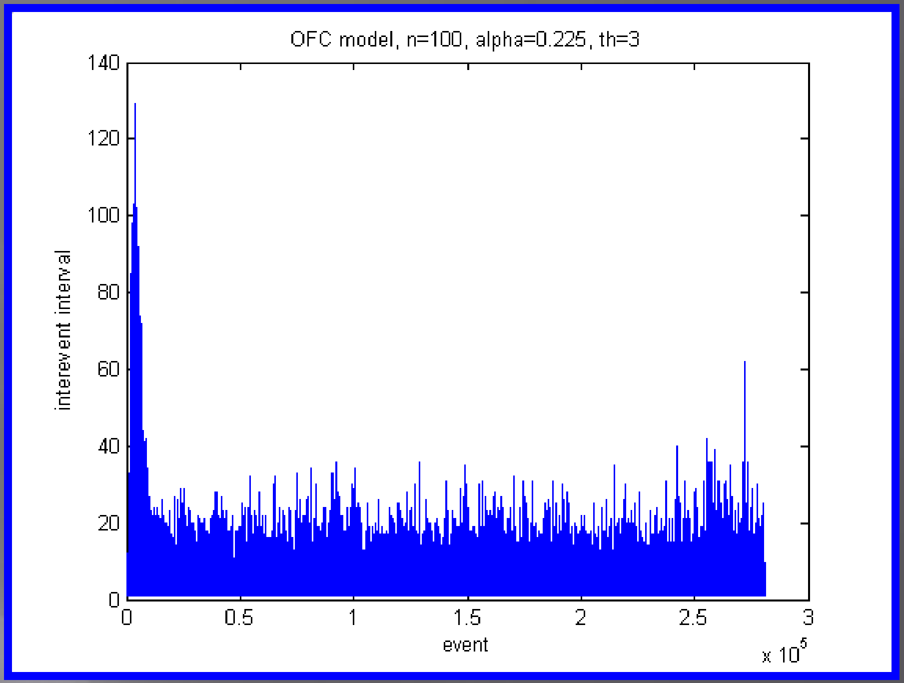


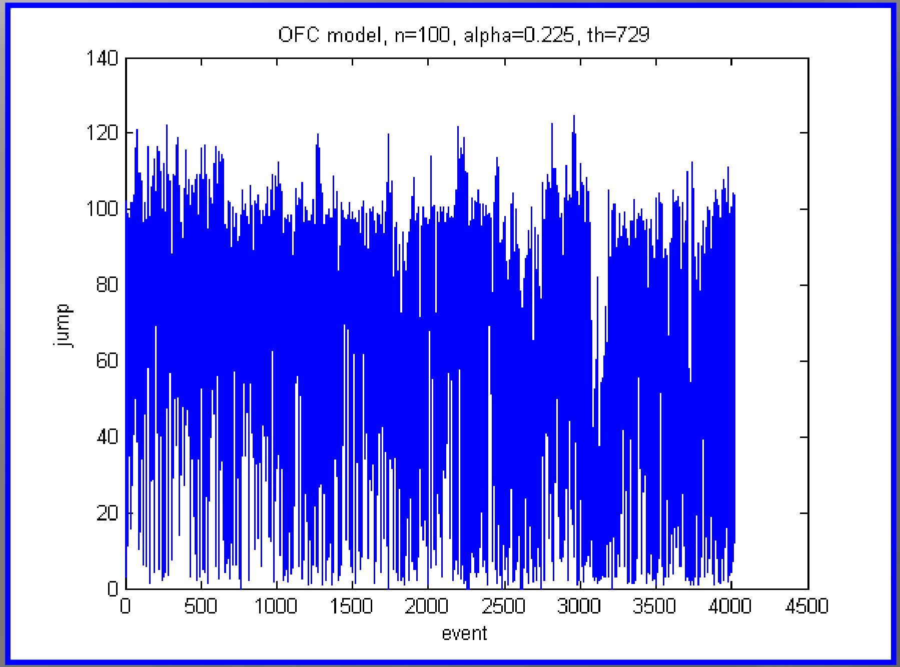
Distribution of synthetic earthquake magnitude and duration times in a 100x100 system with open boundary conditions, 5 x 10^6 events, and cumulative synthetic seismicity. The structure of the stair-shaped plots can be seen when we plot less events. The fitting with a straight line seems to be excellent.


cumulative seismicity
time (arbitrary units)
0
2
4
6
8
10
12
14
0
1
2
3
4
5

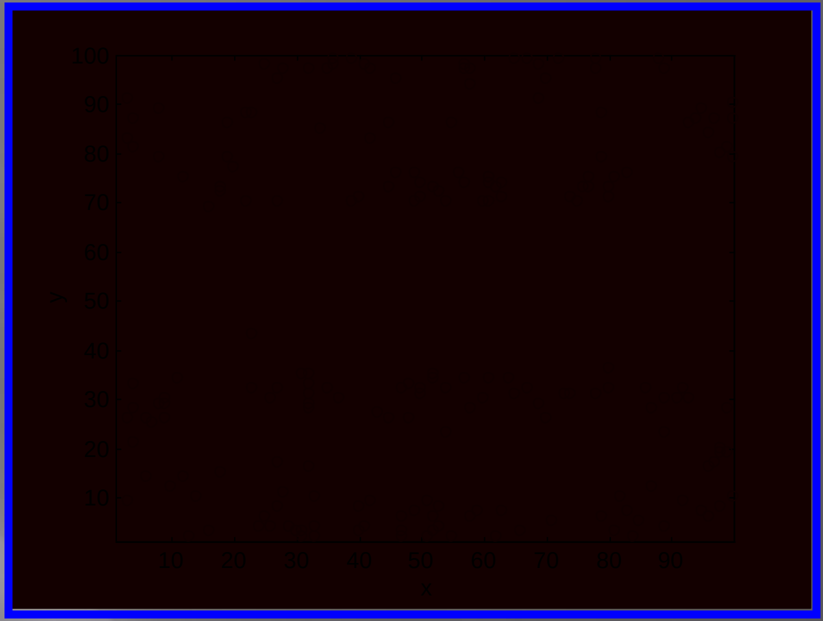

slope m
n, 50000 steps
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
0
20
40
60
80
100
120



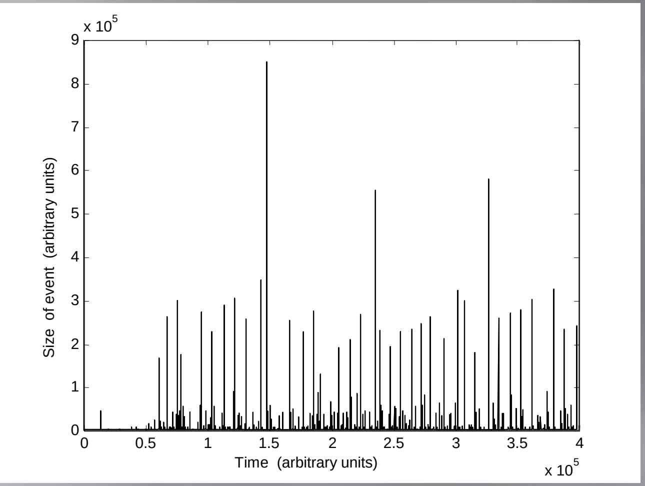




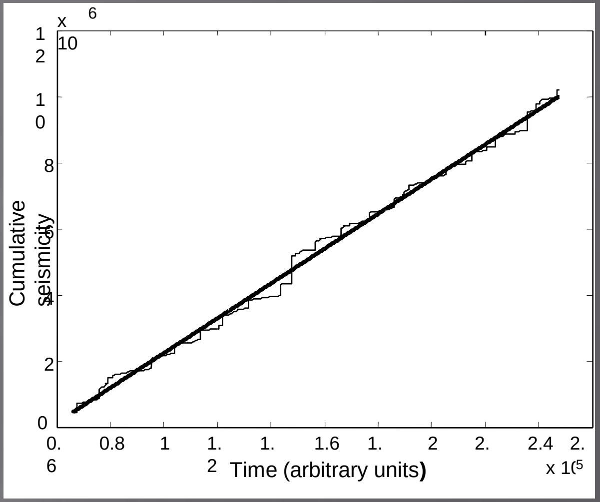
Time series of recurrence times and distance between epicenters for different thresholds



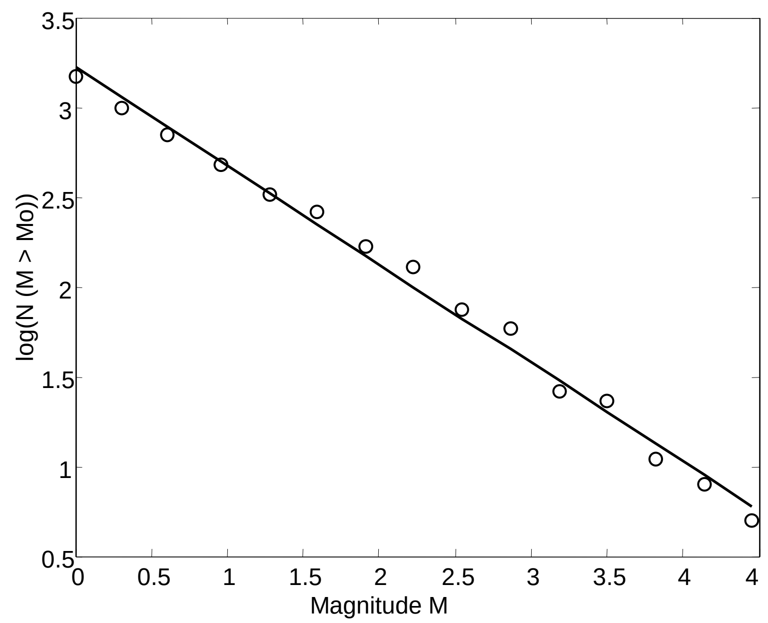
The earthquake epicenters for three regions with different γ-values, the central region with γ = *0.10* and two lateral regions with γ = *0.245*, 10,000 events, most epicenters concentrate in the region with γ = *0.10,* but when we do a cutoff to eliminate the seisms with less magnitude, we find that the events of great magnitude tend to concentrate in the regions with great γ-values. It was obtained when we take away the events less than 1/16 of the event with maximum magnitude.



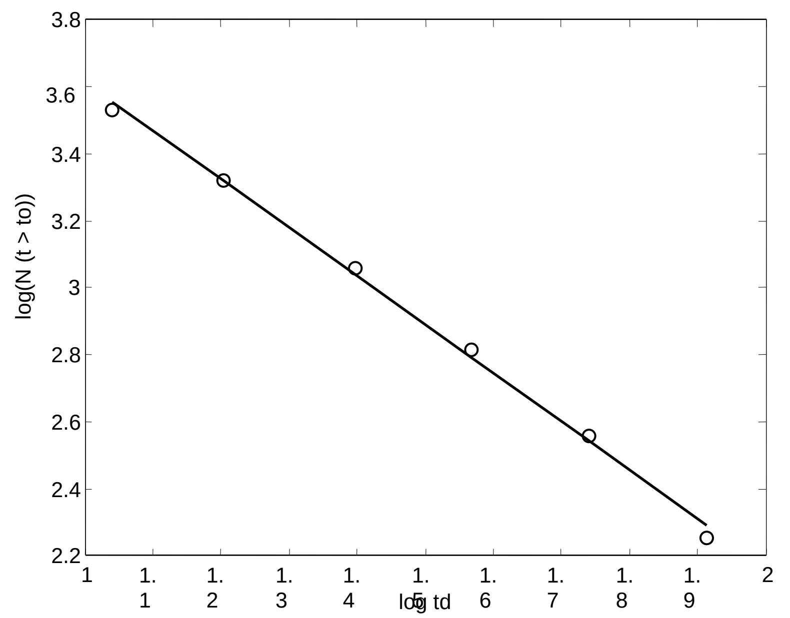
A sequence of synthetic earthquakes obtained with the third model, eighth order.



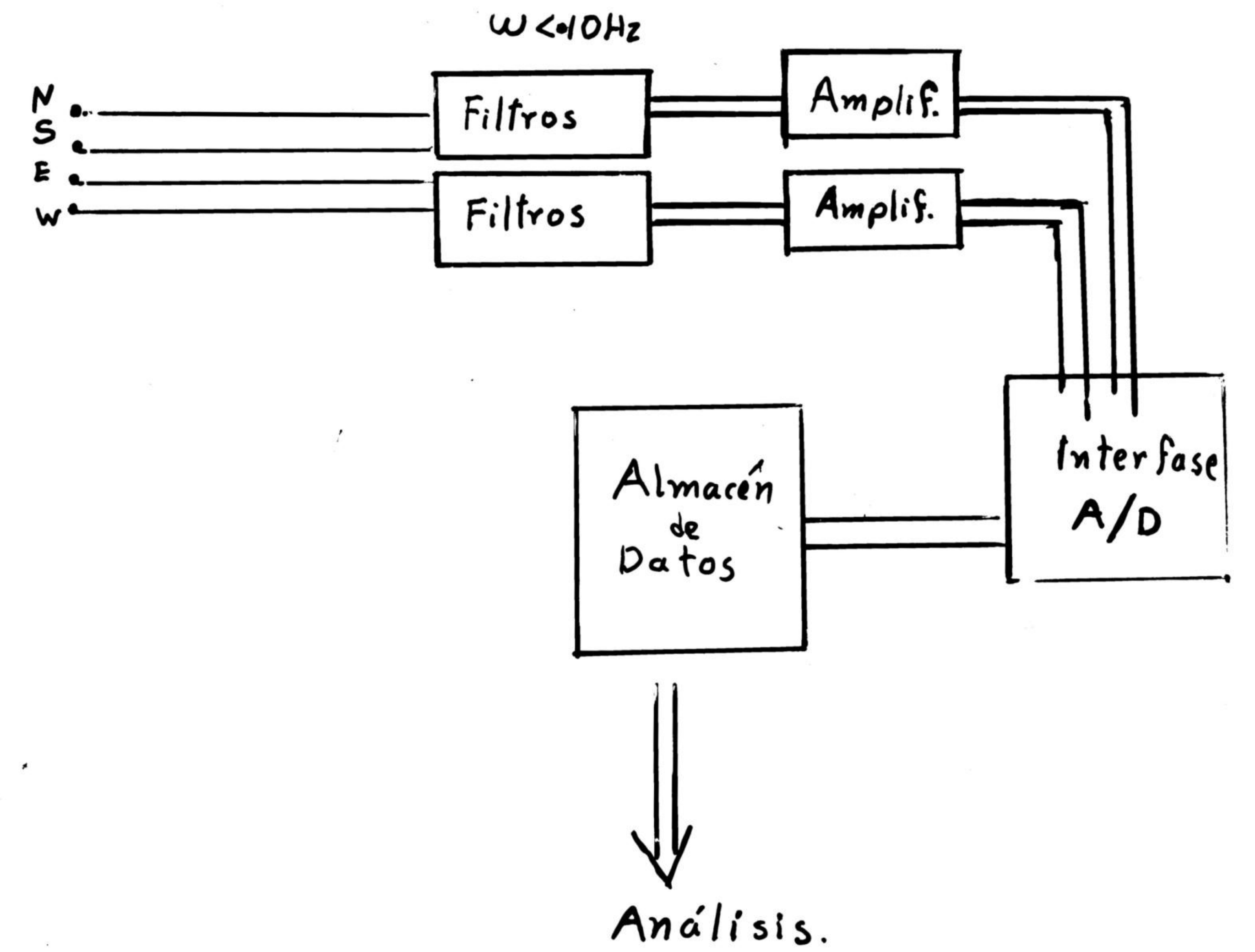
Cumulative seismicity, first fractal model, sixth order.

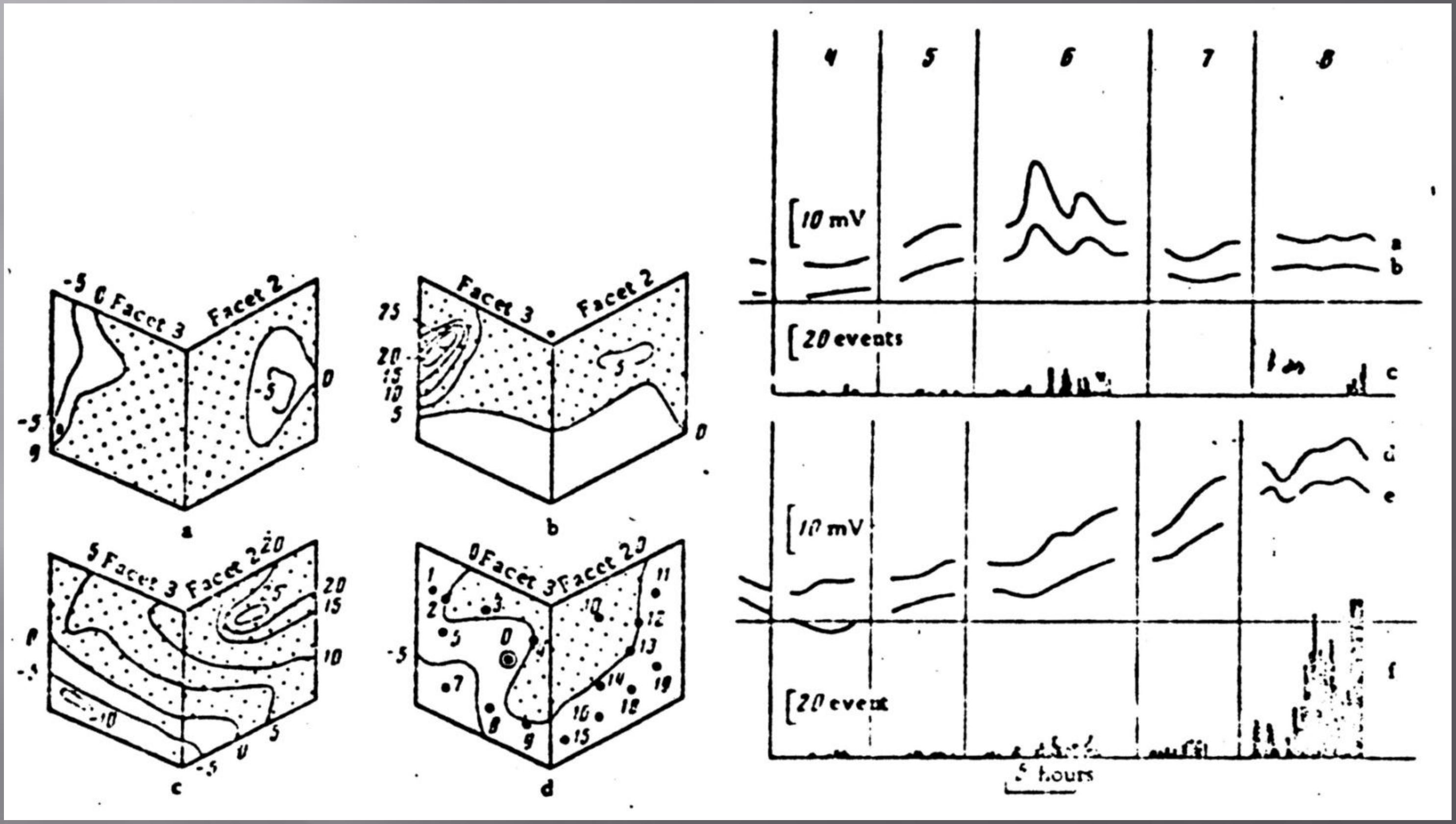


Statistical distribution of the frequency logarithm and the magnitude for a synthetic seismicity pattern obtained with the second model, sixth order.

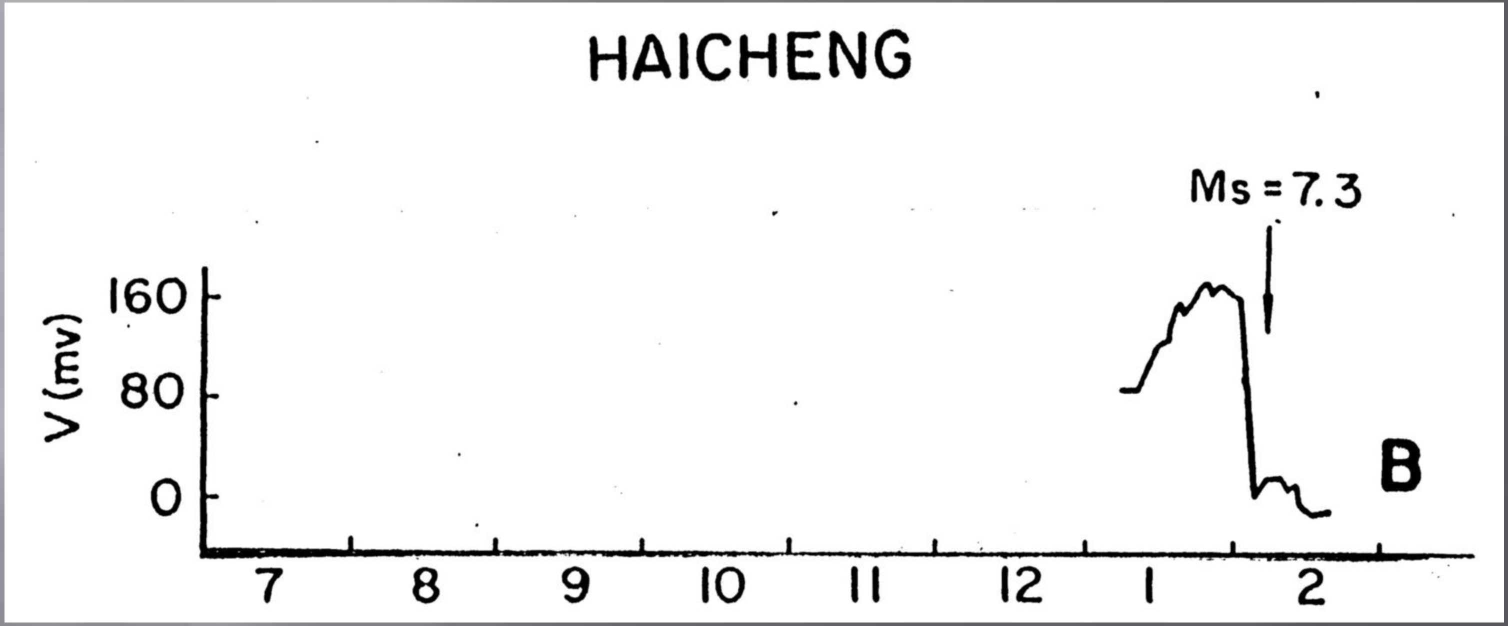


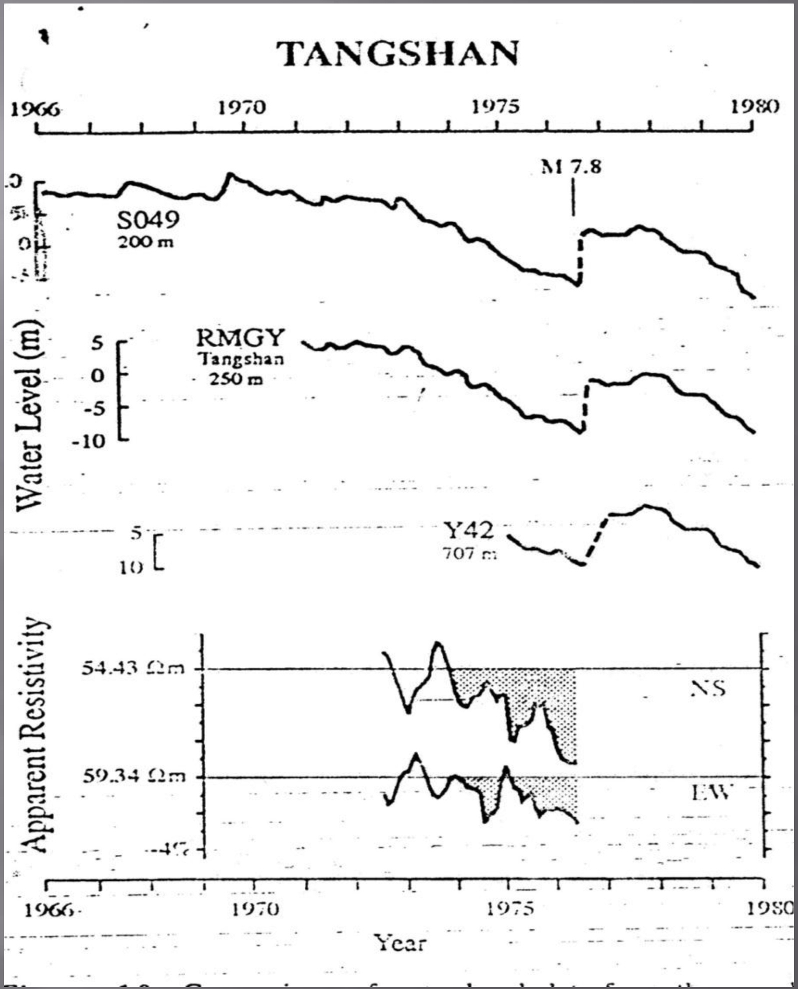
Power law for the statistical distribution of the events duration, third model, seventh order.


ω <0.10Hz
N
S
E
W
Filtros
Filtros
Amplif.
Amplif.
Interfase
A/D
Almacén
de
Datos
Análisis.



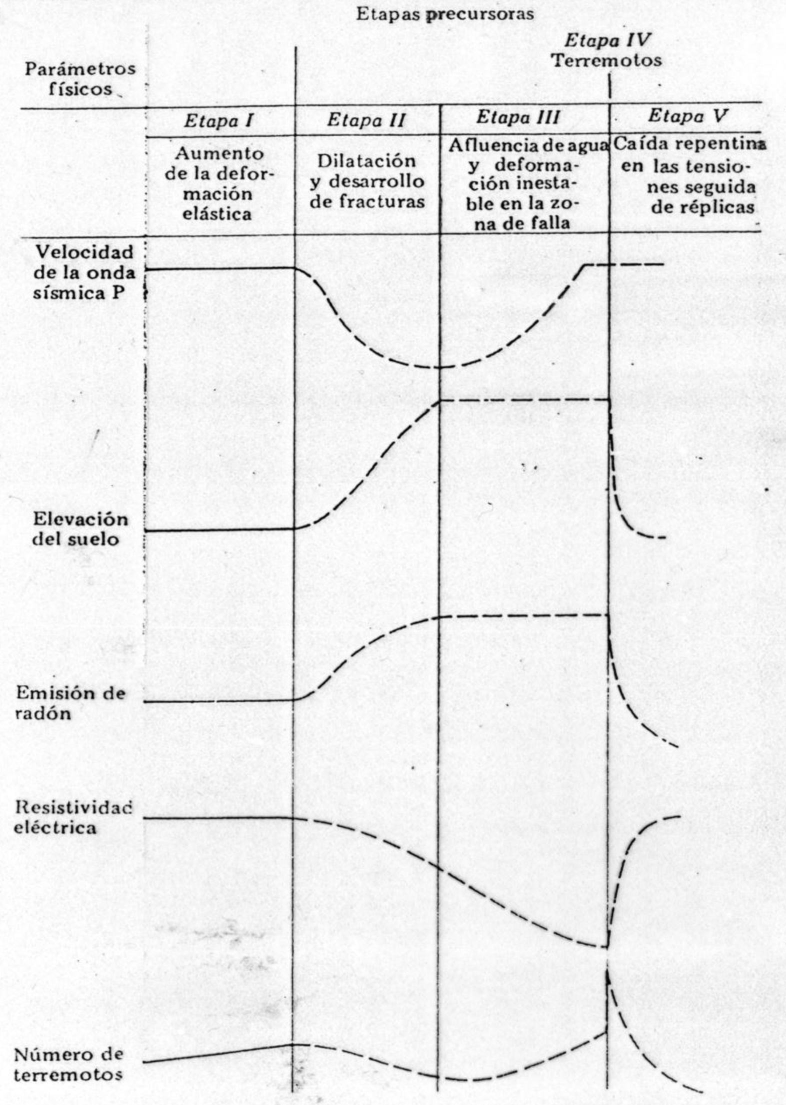
Facet 3
Facet 2
a
b
c
d
10 mV
20 events
20 event
a
b
c
d
e
f
5 hours

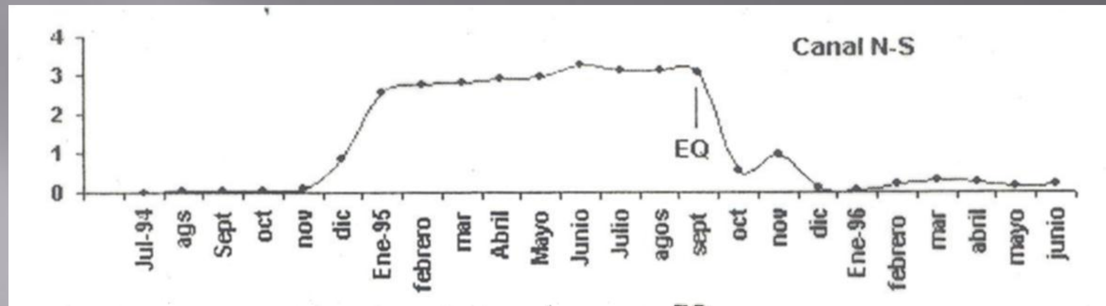

HAICHENG
Ms = 7.3
V (mv)
160
80
0
B
7
8
9
10
11
12
1
2

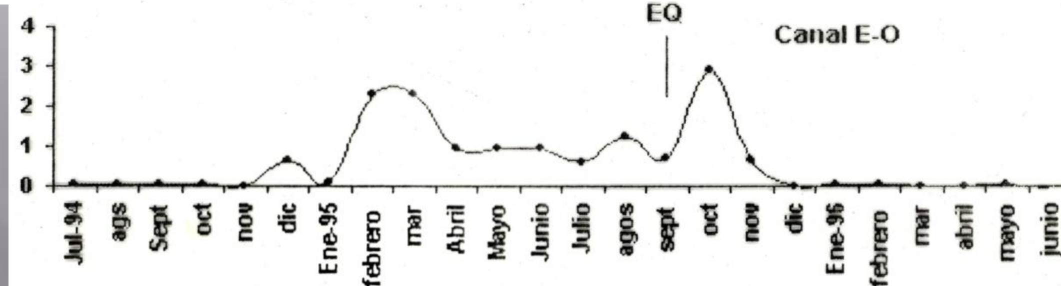


TANGSHAN
1966
1970
1975
1980
M 7.8
S049
200 m
Water Level (m)
RMGY
Tangshan
250 m
5
0
-5
-10
Y42
707 m
5
10
Apparent Resistivity
54.43 Ωm
NS
59.34 Ωm
EW
1966
1970
1975
1980
Year

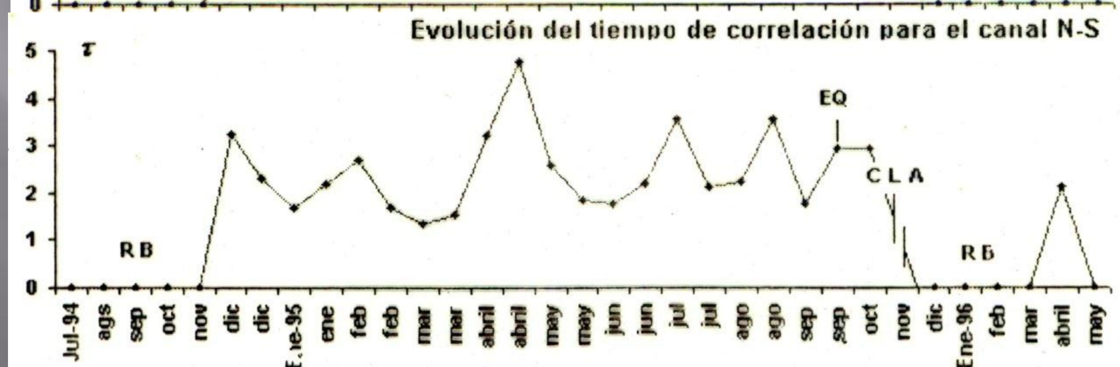
CUADRO 2. INDICIOS FÍSICOS PARA LA PREDICCIÓN SÍSMICA

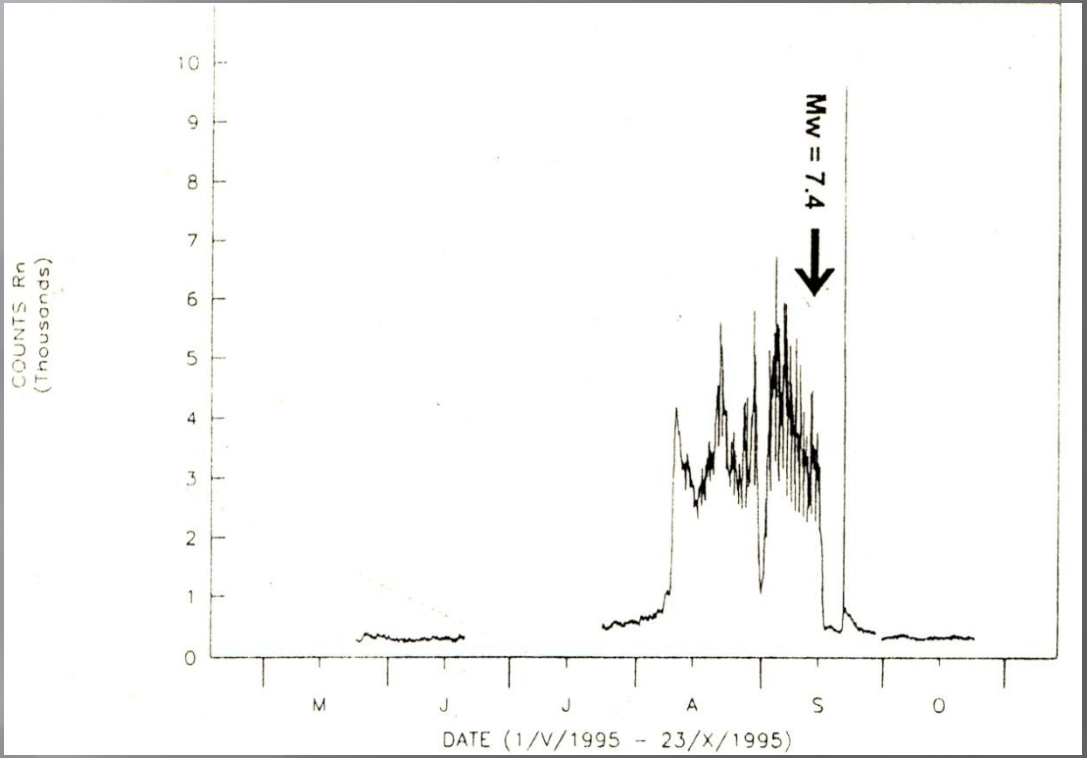



Canal N-S
EQ
0 1 2 3 4
Jul-94 ags Sept oct nov dic Ene-95 febrero mar Abril Mayo Junio Julio agos sept oct nov dic Ene-96 febrero mar abril mayo junio


Canal E-O
EQ
0 1 2 3 4
Jul-94 ags Sept oct nov dic Ene-95 febrero mar Abril Mayo Junio Julio agos sept oct nov dic Ene-96 febrero mar abril mayo junio


Evolución del tiempo de correlación del canal E-O
τ
0 1 2 3 4 5
EQ
CLA
RB
RB


Evolución del tiempo de correlación para el canal N-S
τ
0 1 2 3 4 5
EQ
CLA
RB
RB
Jul-94 ags sep oct nov dic dic Ene-95 ene feb feb mar mar abril abril may may jun jun jul jul ago ago sep sep oct nov dic Ene-96 feb mar abril may


COUNTS Rn
(Thousands)
Mw = 7.4
M
J
J
A
S
O
DATE (1/V/1995 - 23/X/1995)

Análisis: Correlaciones

Detrended Fluctuation Analysis (DFA)

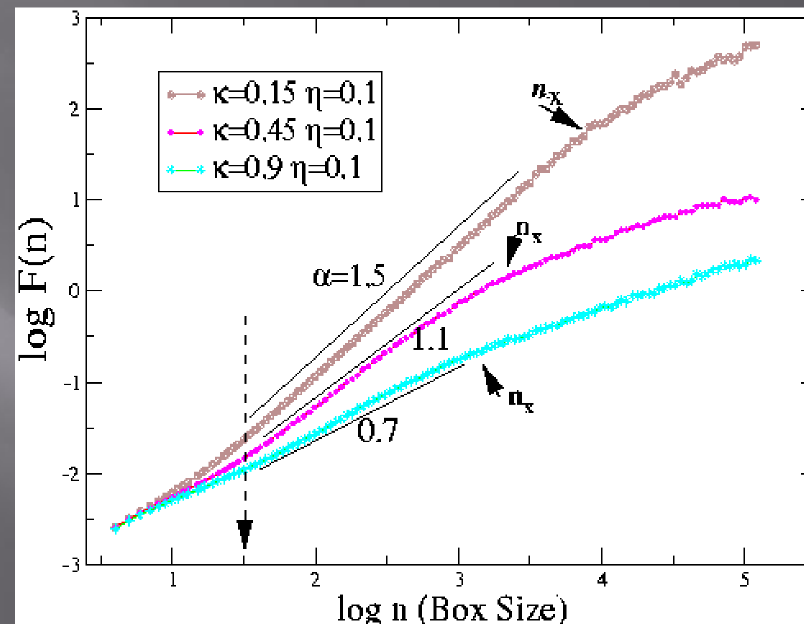
- Integración de la señal original
- División de la señal integrada en cajas de tamaño *n* y ajuste lineal a los puntos experimentales
- Calculo de Desviación Estándard de las fluctuaciones

$$F(n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[y(k) - y_n(k)]^2}$$

n es el tamaño de la caja

$$F(n) \sim n^{\alpha}$$

- *F(n)* es la Desviación Estándar de las fluctuaciones como función del tamaño de la caja (*n*)

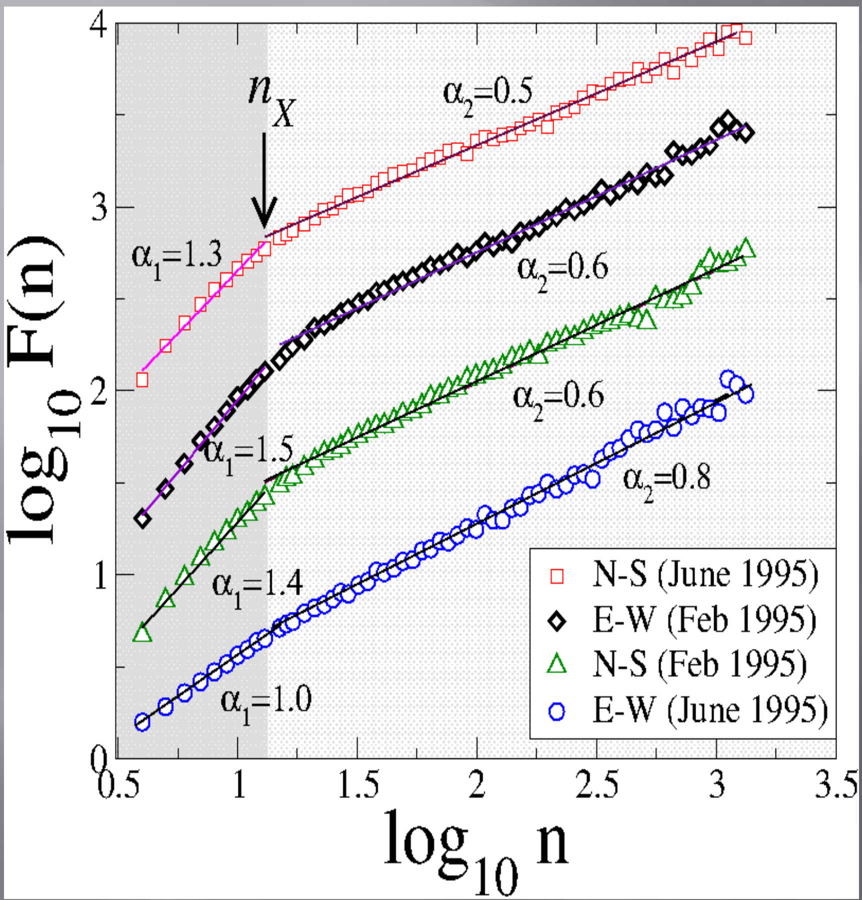


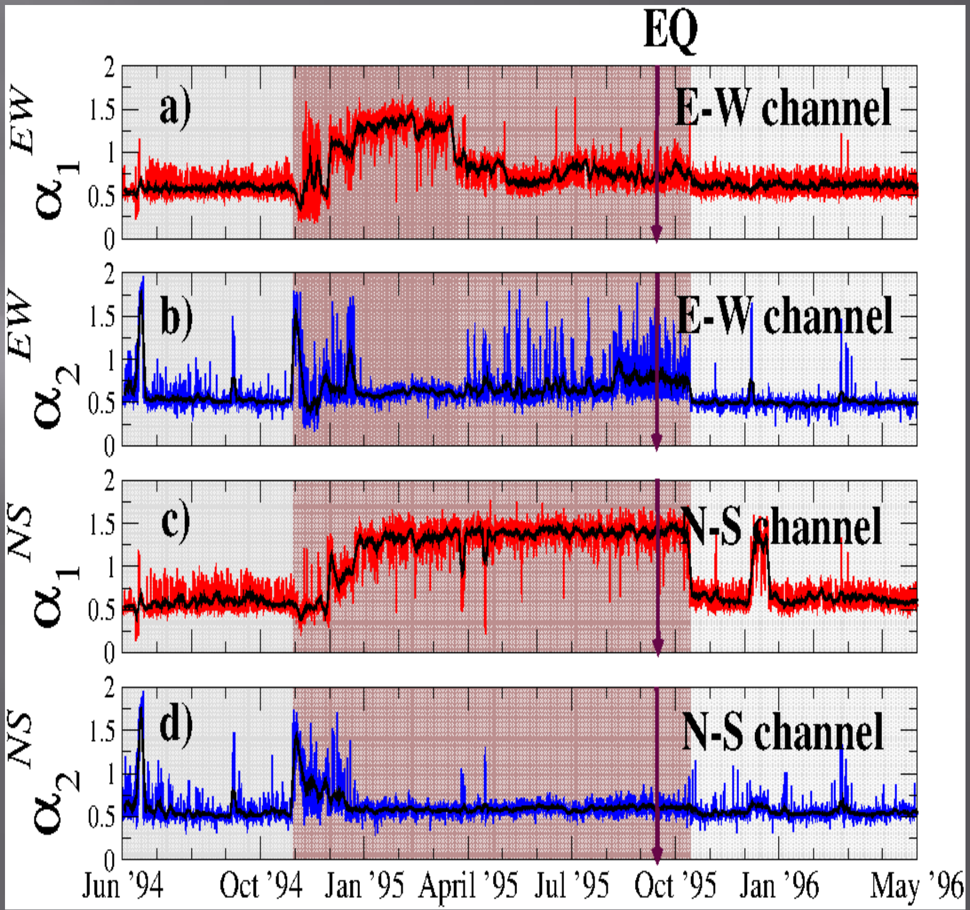
$\alpha = 0.5$ White Noise (Uncorrelated)

$\alpha = 1$ *1/f* Noise (Long-range Correlated)

$\alpha = 1.5$ Brownian Motion (Short Correlated)

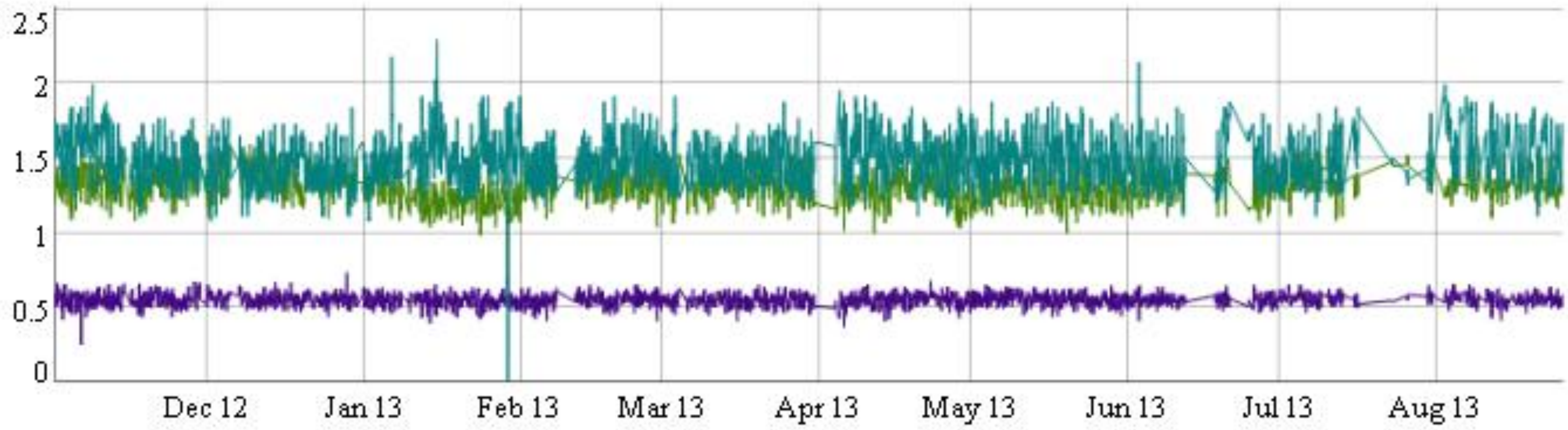
Resultados: Sismo, sept. 15 1995



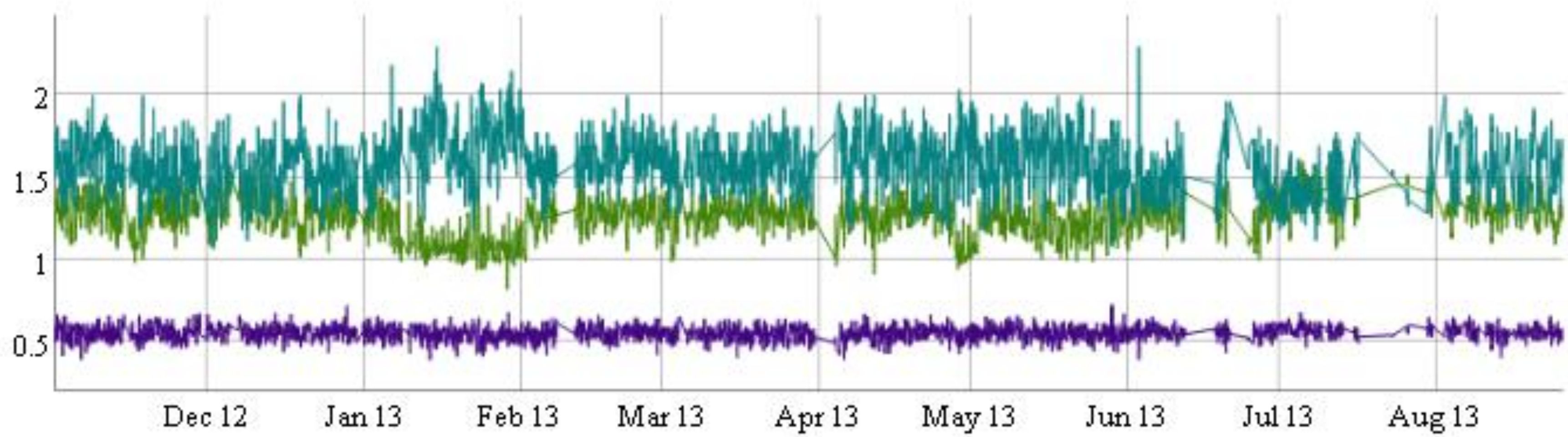


Mediciones recientes

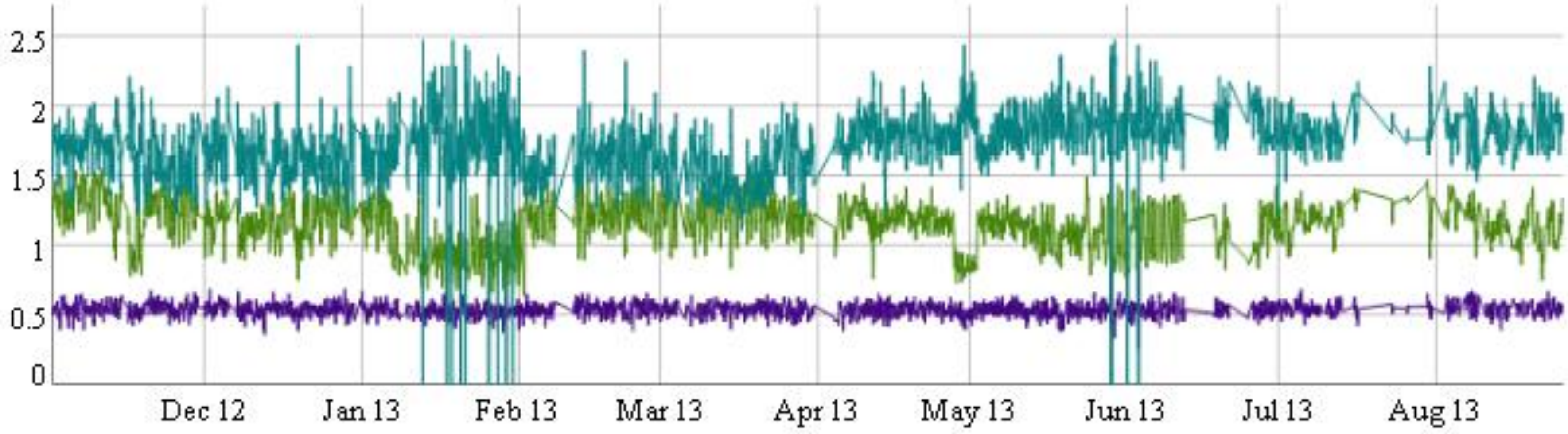
CANAL N-S (LARGE)



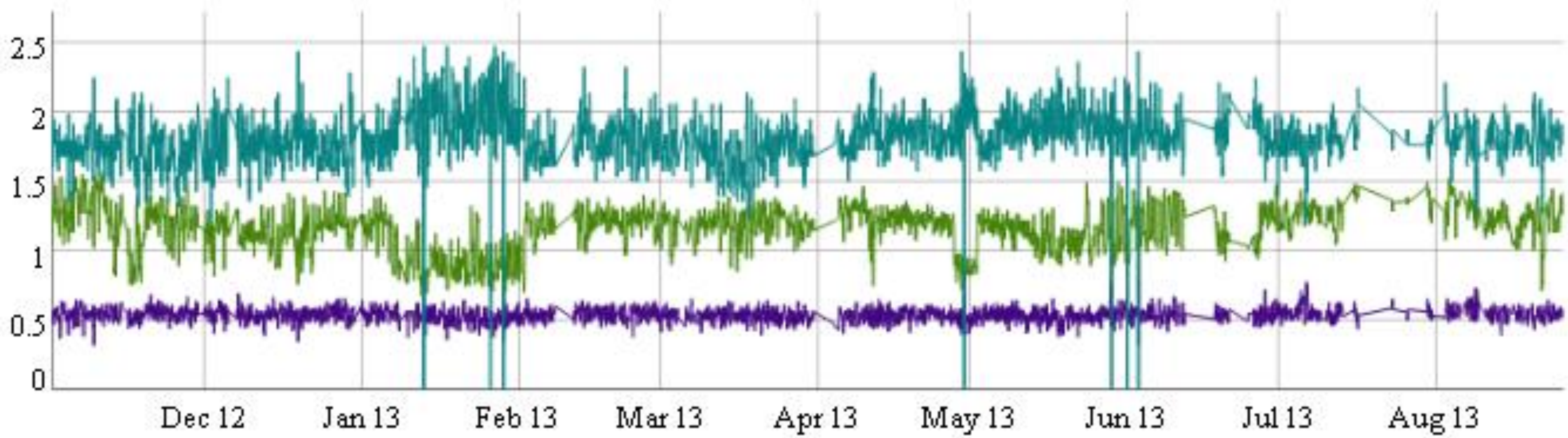
CANAL N-S (SHORT)



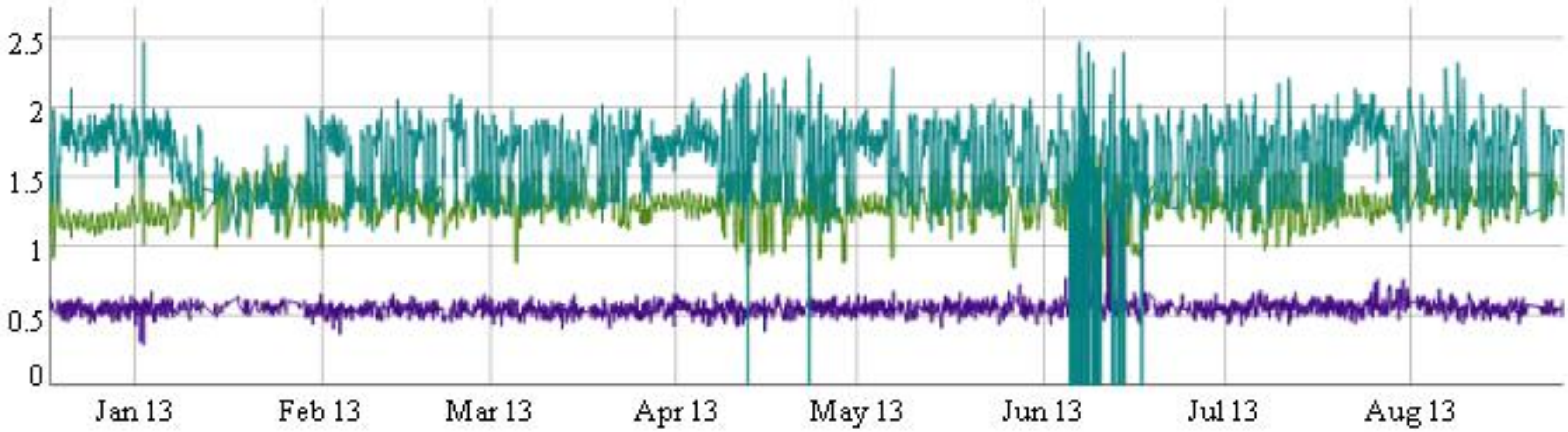
CANAL E-W (LARGE)



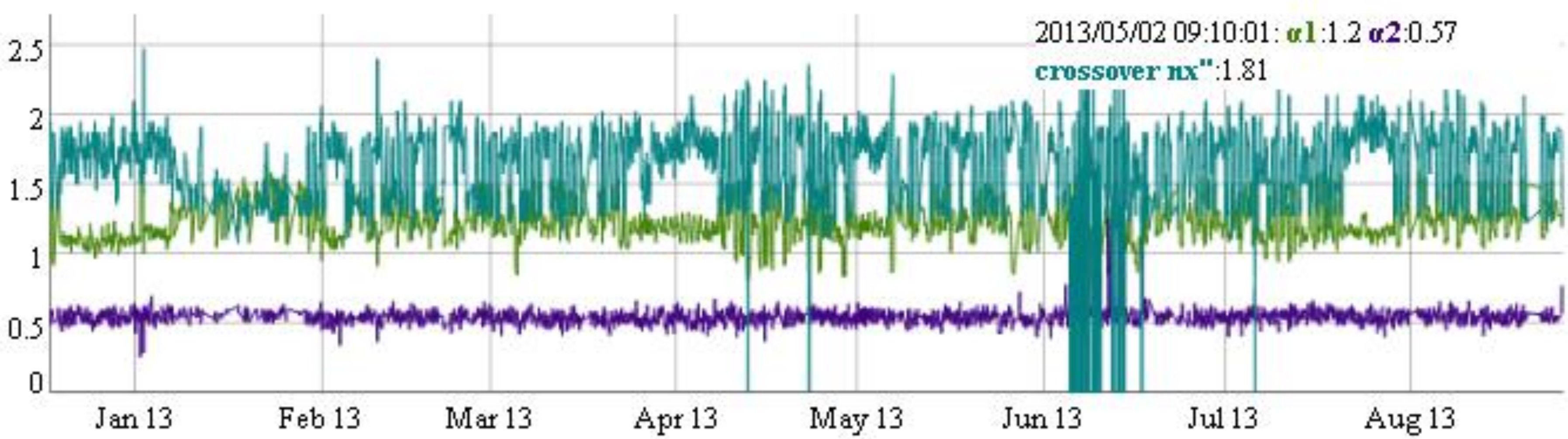
CANAL E-W (SHORT)



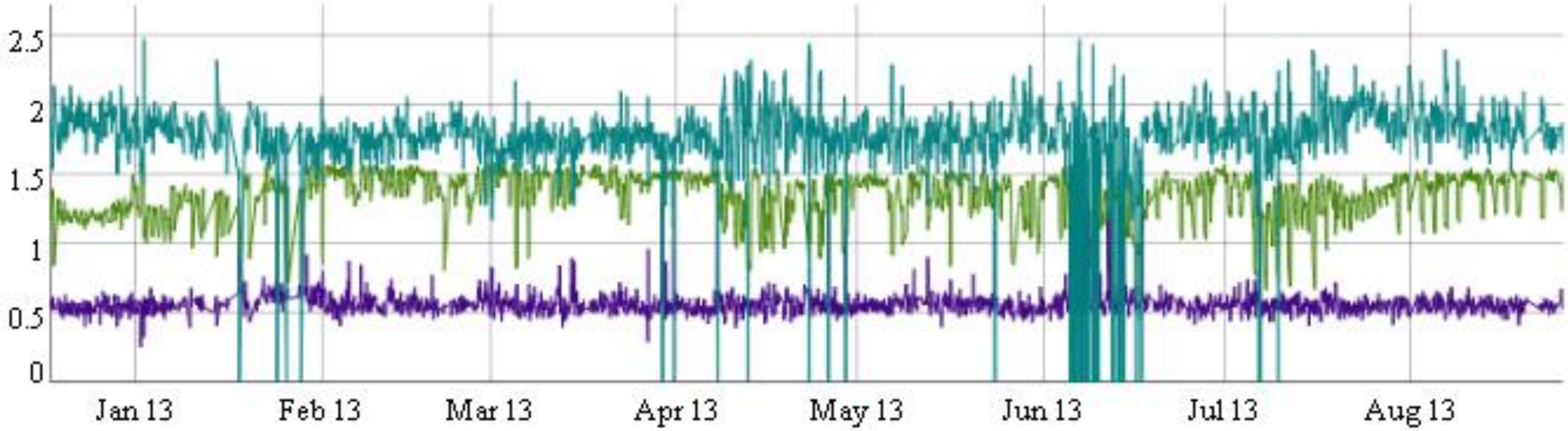
CANAL N-S (LARGE)



CANAL N-S (SHORT)



CANAL E-W (LARGE)



CANAL E-W (SHORT)