Geosystemics

GEOSYSTEMICS and ENTROPY of EARTHQUAKES

A vision of our planet and a key of access

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… to NATO and the **Organisers** of this Workshop for the support and the invitation here.

Geosystemics

Projects and Funding Institutions

INGV

Project of Exchange Research Visits Italy-Albania 2012-2014

EM^{3}S

Earth Magnetic Field measurements, Modelling and Seismicity – **EM^{3}S**
Funded by: Italian Foreign Office & Ministry of Education and Science (Albania)

Project of Excellence Italy-China 2010-2012

SAGA 4 EPR Earthquake Pattern Recognition

SAGA-4-EPR: Satellite, Seafloor and Ground data Analyses for ("4") Earthquake Pattern Recognition
Funded by: Italian Foreign Office, INGV (Italy), Northeastern University (China)

DS^{3}F

European Project 2010- 2012
DS^{3}F: Deep Sea & Subseafloor Frontier
Funded by the European Commission

Outline

1. Introduction
2. Earth as a Complex system
3. Geosystemics
4. Universal Tools
5. Entropy of Earthquakes
6. Focalisation
7. Other applications
8. Conclusions
9. Selected bibliography

1. INTRODUCTION:
WORLD IS CHANGING

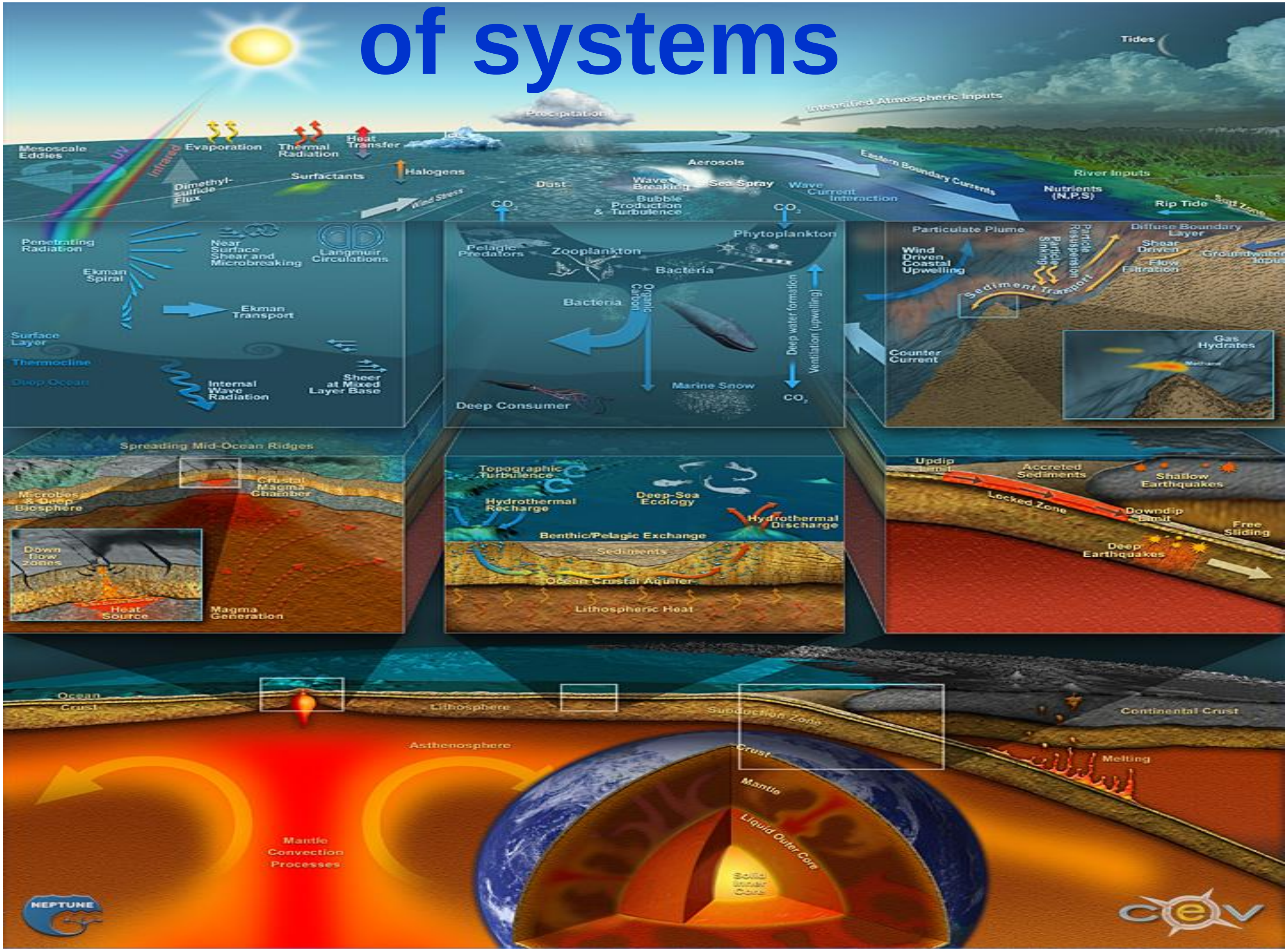
- growing population
- global warming
- pollution
- biodiversity reduction
- geohazards

& greater weakness against disasters

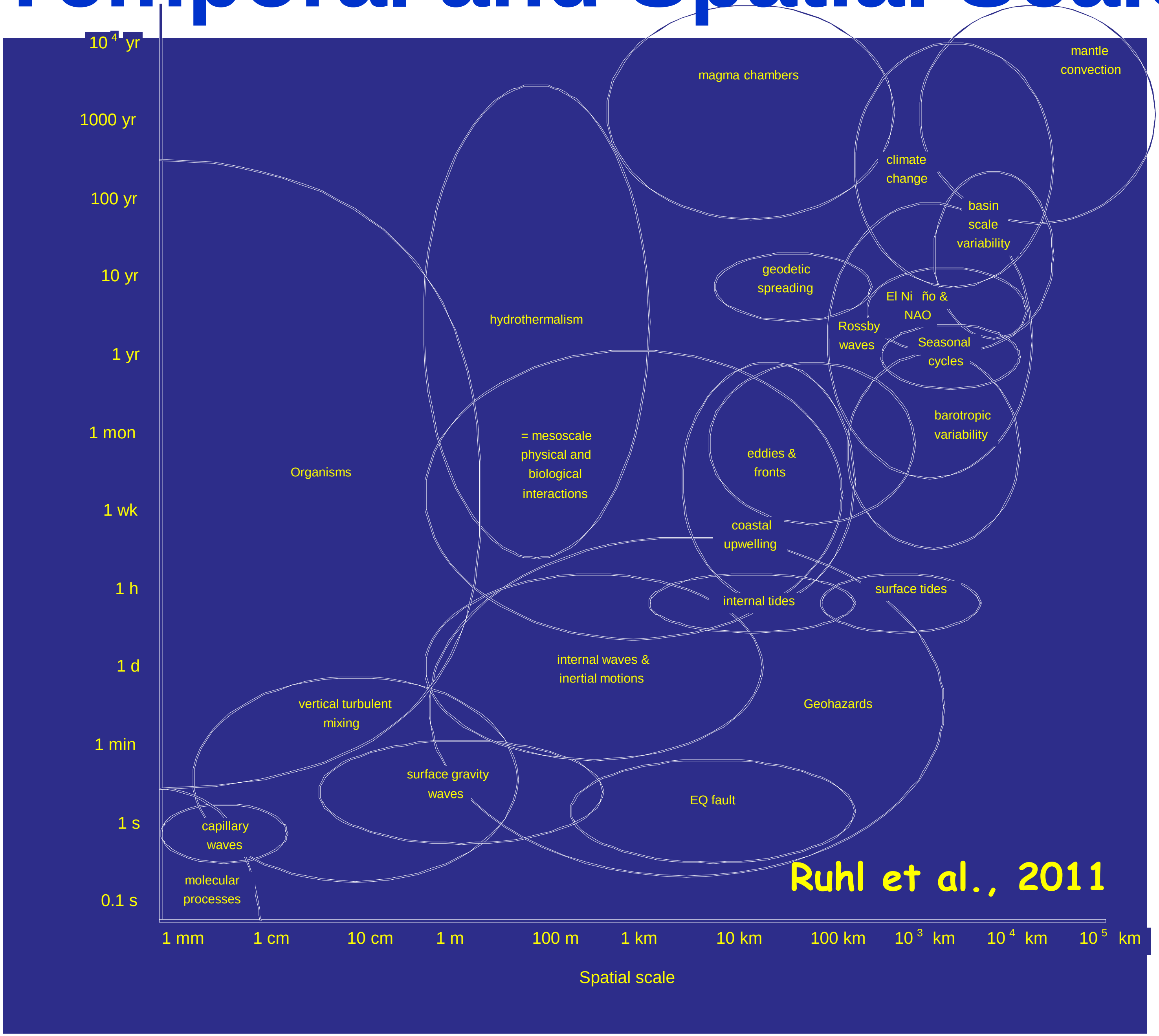
- reduction of resources

Man is both affecting and affected

EARTH: Interconnected system of systems



Temporal and Spatial Scales



Geosystemics

2. Earth as a Complex System

Points in bold from ***Baranger, 2001***

1. A complex system contains many constituents interacting nonlinearly,

2. and interdependent;

This is the specific case of our planet, composed by an enormous number of sub-systems and elements and sub-elements, placed into around 10^{12} km^3 of solid volume and much more larger volume of its oceans, coversphere, biosphere and gaseous atmosphere.

3. A complex system possesses a structure spanning several scales.

Earth phenomena range from atomic scale to thousand - km scale, from almost instant processes to billion – year timescale;

4. and it is capable of emerging behaviour. Concepts of : surprise, capability of change, self-reproduction (autopoiesis) and self-organization, mixing. For instance, Wilson cycle and cybertectonics of Earth.

5. It is characterised by an interplay between chaos and non-chaos,

This point indicates that chaos can emerge sporadically, due to some change of boundary conditions under which the phenomenon is occurring.

6. and between cooperation and competition. Positive and negative feedbacks in Earth processes (e.g. see Gaia Hypothesis)

The aim of science is not things themselves, but the ***relations between things;*** *[…] outside those relations there is no reality knowable.*

Henri Poincaré in “Science and Hypothesis”, 1905

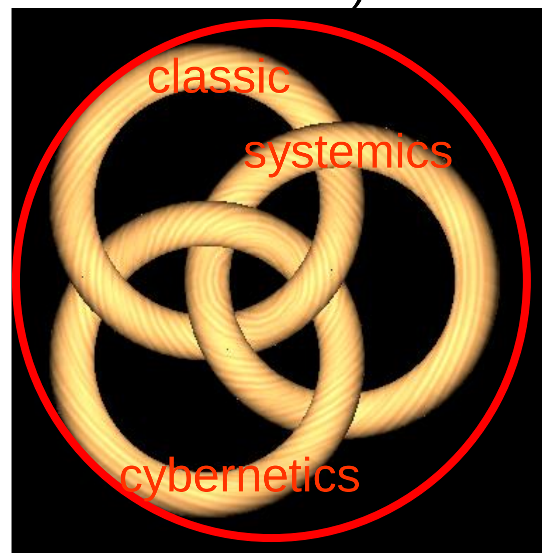
3. Geosystemics: definition

Transfer of knowledge from “classic” disciplines
MATHEMATICS, PHYSICS (GEOPHYSICS), CHEMISTRY (GEO CHEMISTRY), BIOLOGY, GEOLOGY, INFORMATICS (GEOINFORMATICS)

& more recent disciplines
SYSTEMICS[1] and CYBERNETICS[2]

to ***Geosystemics***

(trans-disciplinary approach)



Geosystemics studies Earth system from the holistic point of view, looking with particular attention at self-regulation phenomena and relations among the parts composing Earth (De Santis, WSEAS, 2009)

[1] *Systemics* is the science of complex systems studied from a holistic point of view (in their wholeness) (e.g. Klir, 1991).
[2] *Cybernetics* is the science that studies phenomena of self-regulations and communications among natural and artificial systems (Wiener, 1948).

Geosystemics: Science /1

Ask anybody what the physical world is made of, and you are likely to be told "matter and energy". Yet if we have learned anything from engineering, biology and physics, **information** is just as crucial an ingredient.

Jacob D. Bekenstein
in Scientific American (2003)

Geosystemics: Science /2

Not only **energy** and **matter** are important, but also (sometime even more) **Information**, **self-regulation**, **nonlinear coupling**, **emergent behaviour**, **irreversibility** which are decisive ingredients of Geoscience, and matter of study for ***Geosystemics***.

Geosystemics puts the emphasis on **contextuality** and **interactions** among the elements of Earth System, on the **cause-effect relationships**, on various sub-systems couplings and on both **production** and **transfer of Information** (Shannon, 1948) from a sub-system to another.

Science /3

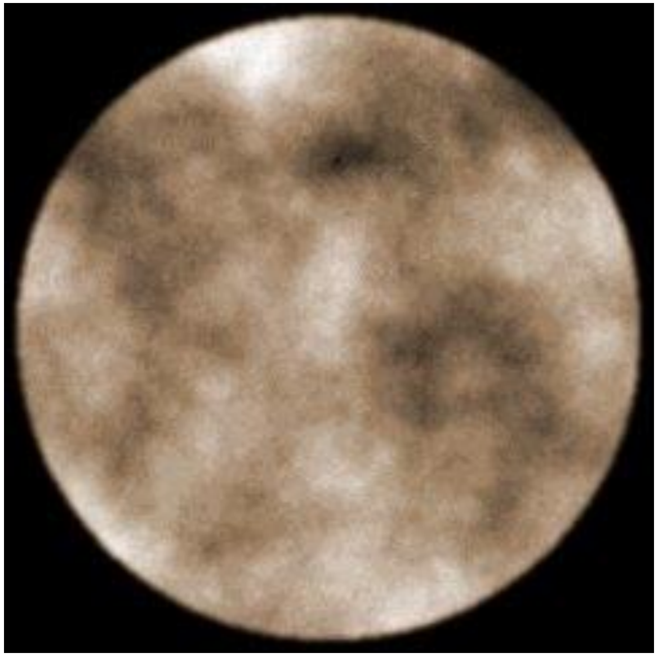
Geosystemics overcomes traditional boundaries between science, mathematics and philosophy, between harmony and diversity, invariance and variability, simplicity and complexity, symmetry and asymmetry, uniformity and diversity, order and disorder, reversibility and irreversibility, which all together characterise Earth's evolution.

Universal tools (e.g. fractal dimension, phase space, degrees of freedom, information and **entropy) + Multi-scale/parameter/platform observation** help in this challenge.

4. Universal tools
Fractal dimension

In a fractal with N=N(ε) elements with size ε covering the whole structure, the fractal dimension D is defined as:

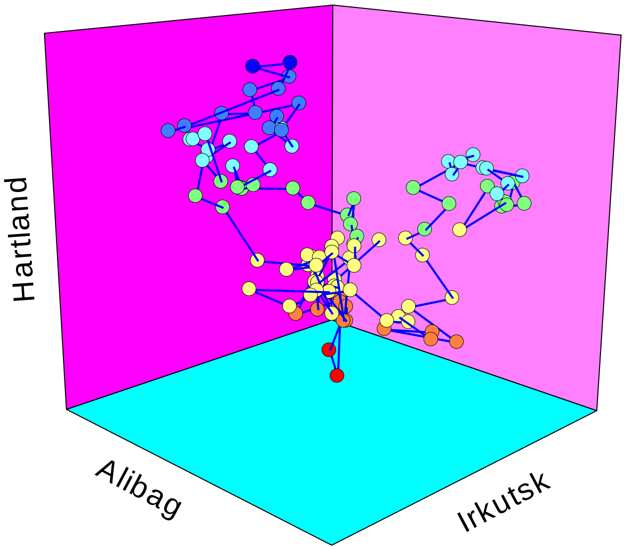
$$D = \lim_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log 1/\varepsilon}$$



This figure shows an example of fractal interpretation that has been given for the core-mantle boundary of Earth, from the study of the geomagnetic field over the last 400 years (De Santis & Barraclough, *PEPI*, 1997).

Universal tools
Phase Space

The **phase space** of a dynamical system is the ideal space where each state of the system can be represented by a single point. The minimum number *E* of phase space axes, which contain all orbits of the dynamics, defines **the degrees of freedom** of the system, i.e. the number of variables that are required to describe that system. *E* is also said **embedding dimension.**



Theorem for Reconstruction of pseudo space phase (Takens, 1981)

This figure shows an example of phase space reconstruction that has been given for the geomagnetic field in 3 observatories for the last 150 years (De Santis et al., *Fractals*, 2002).

Shannon Entropy

Claude E. Shannon

Shannon Entropy (Shannon, 1948) of a "system" characterized by N independent states and a probability distribution $p_i(t)$

$$H(t) = -\sum_{i=1}^{N} p_i(t) \cdot \log p_i(t)$$

if $p_i(t)=0$ then we impose $\log p_i(t)=0$

Some Physical Interpretations

1. Measure of **disorder**
2. Measure of the **average information content** missing to the knowledge about the state of the system;
3. Measure of **unpredictability** of the state of the system among many alternatives;
4. Measure of the **degree of dispersion** of an observable among the system's parts

Other Universal tools

Shannon Information and Entropy over a sphere

If B(t) is a physical quantity defined over a sphere, we can write it as sum of orthonormal spherical harmonics Ψ_n^m with maximum degree *N* (which defines the smallest detail of the representation), i.e.

$$B(t)=\sum_{n=1}^{N}\sum_{m=0}^{n}c_n^m(t)\psi_n^m \quad \text{then} \quad \boxed{I(t)=-H=\sum_{n=1}^{N}p_n(t)\cdot\ln p_n(t)}$$

where $p_n(t)$ is the probability to have a certain *n*-degree spherical harmonic *power* contribution instead of another (De Santis et al. 2004):

$$p_n=\frac{\langle B_n^2\rangle}{\langle B^2\rangle}=\frac{\sum_{m=0}^{n}(c_n^m)^2}{\sum_{n'=1}^{N}\sum_{m=0}^{n'}(c_{n'}^m)^2}$$

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5. Entropy of Earthquakes

> Any attack to the problem of earthquake is worth doing

> Our approach (*geosystemics*) is holistic (not against reductionism but in parallel/complementary):

- earth as a whole,
- phenomenon in its most important macroscopic features

--> Here we will see some cases

Some empirical statistical laws

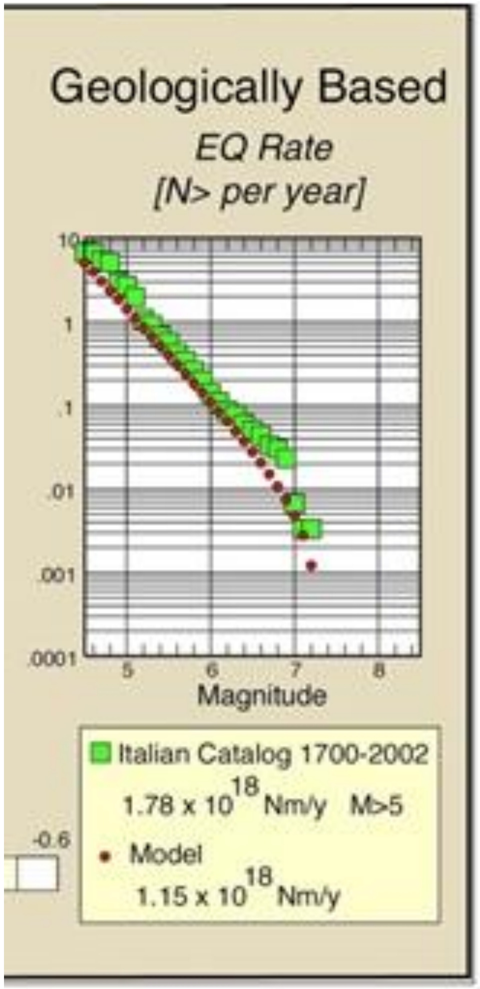
On all earthquakes:

1. Gutenberg-Richter Law (1944)

The rate of earthquakes occurrence (number of earthquakes N in a certain time interval) in a given region follows an exponential law of the magnitude M.
(small earthquakes are many more than larger ones).

$$\boxed{\log N = a - bM} \quad (b \cong 1)$$

Case of M5 in Italy: 1/year
Case of M6 in Italy : 0.1/year, i.e. 1/10 yrs.
M7 0.01/year, 1/100 yrs



Some empirical statistical laws

On the aftershocks:

2. Omori Law (1894; modified by Utsu in 1961): inverse power law of the rate n of aftershosks occurrence

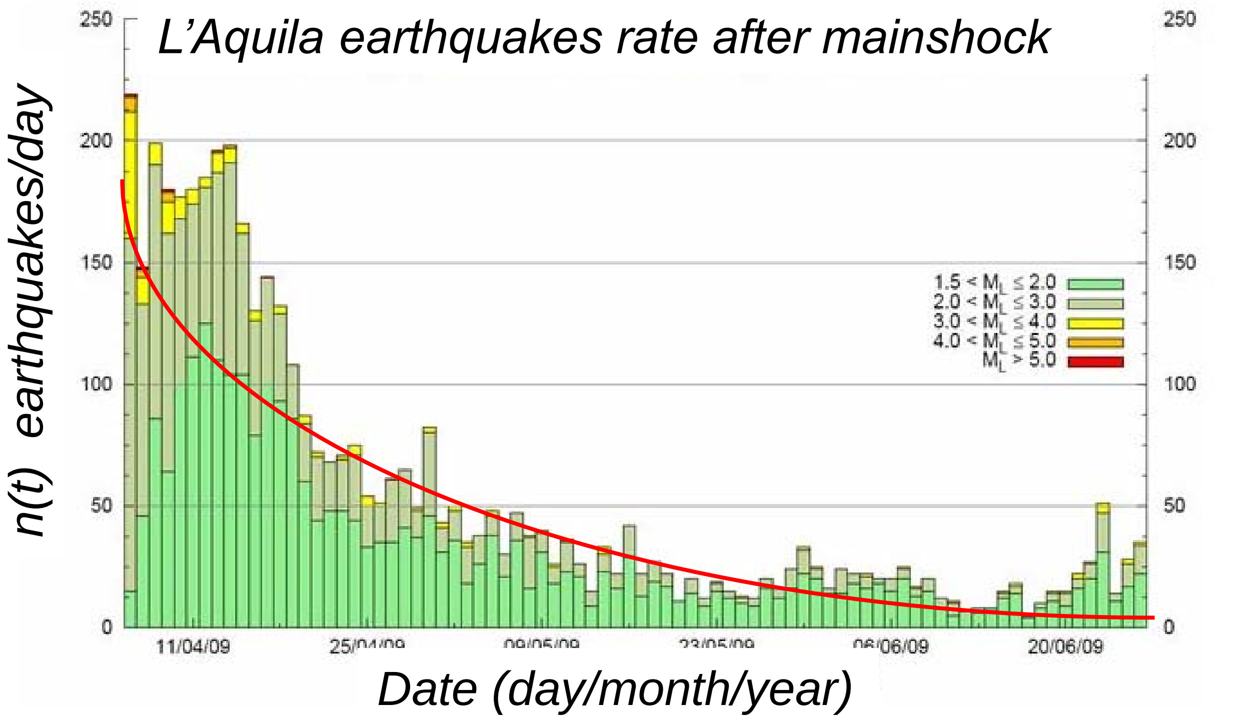
$$\boxed{n(t) = K/(c+t)^{p}}$$ with $p \cong \mathbf{1}$

3. Båth Law (1965):

$$\boxed{\Delta M = M_{main} - maxM_{after} \cong 1.2 \pm 0.2}$$

For 2009 M6.2 L'Aquila Eq.: $\Delta M = 1.0$

For 2012 M5.9 Emilia it does not fit: $\Delta M = 0.1$!!



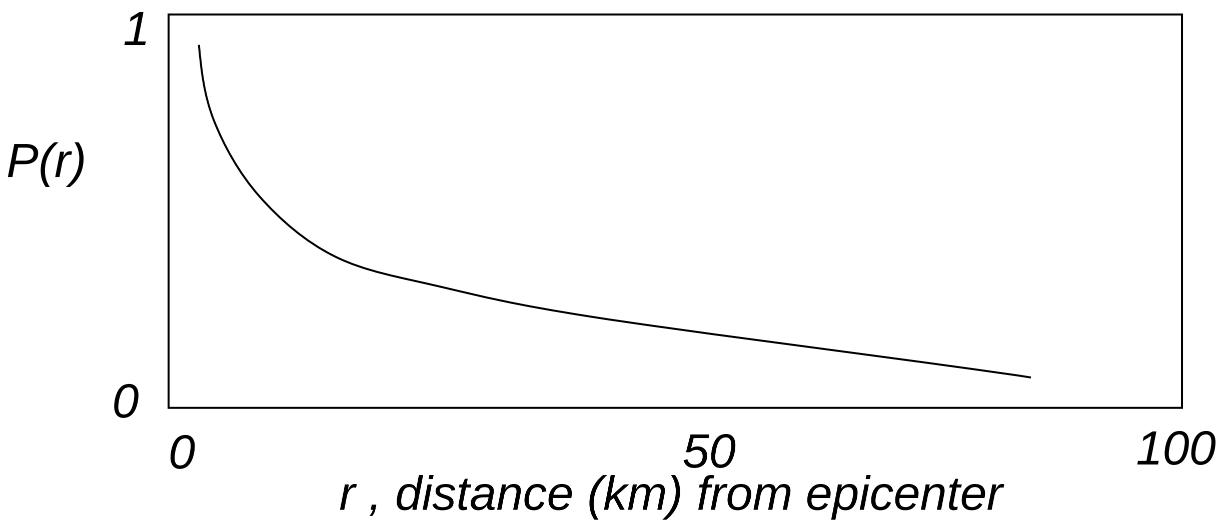
Some empirical statistical laws

On the aftershocks:

4. Felzer & Brodsky (2006): *inverse power law of the probability P of having an aftershosk at distance r from the mainshock epicenter (at least up to 100 km)*

$$\boxed{P(r) = K/r^{s}}$$

with $s \cong 1.4\text{-}1.8$



Entropy of Earthquakes

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Gutenberg-Richter Law $\log n(M) = a - bM$

$n(M)$ EQs magnitude ≥ M
a, b several interpretation

Shannon Entropy $H(t) = -\sum_{i=1}^{N} p_i(t) \cdot \log p_i(t)$

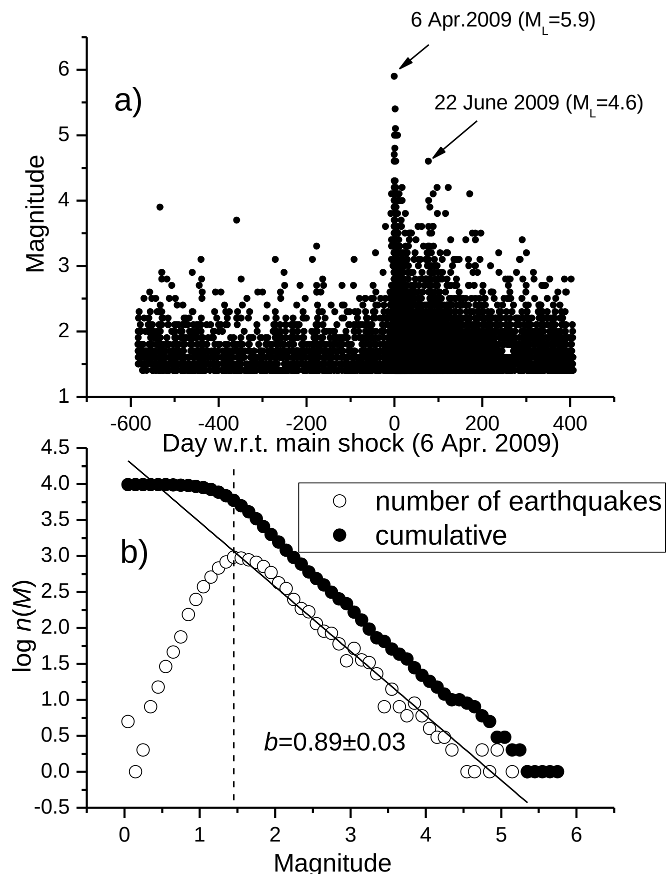
$0 \leq H \leq 1$ if we divide by $\log N$

p_i probability of the i-th level of seismicity defined by a range of magnitudes

b-value and Entropy

$$\boxed{H(t) = \log(e \cdot \log e) - \log b = k' - \log b}$$

$$b = \frac{b_{max}}{10^H} \approx \frac{1.2}{10^H}$$



So, this is a new insight into the b-value meaning!

(De Santis et al., BSSA, 2011)

Entropy of Earthquakes

Two Cases in Central Italy

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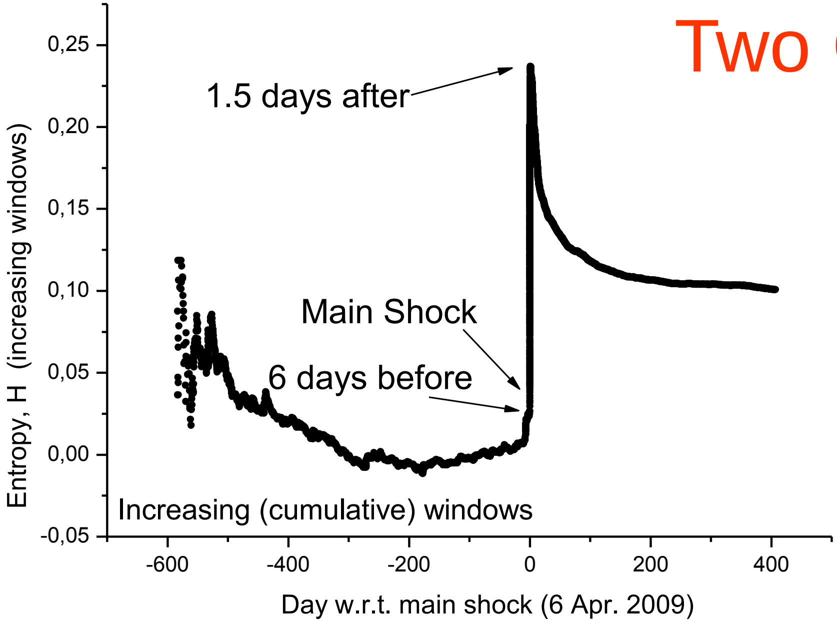
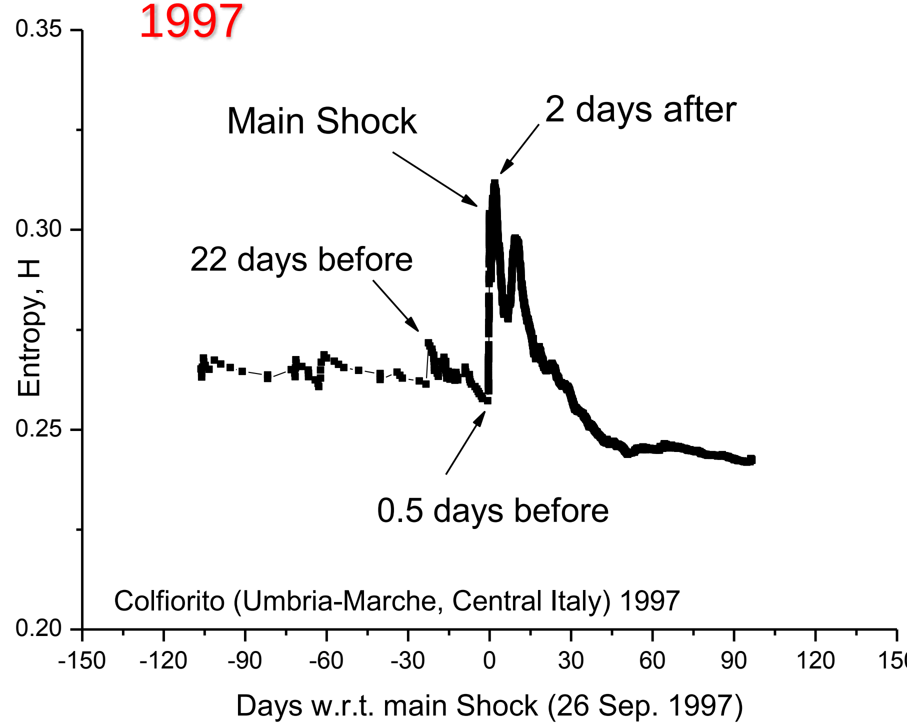


Entropy - L'Aquila sequence
Central Italy, mainshock M6.2 2009

Entropy - Colfiorito sequence, Central Italy, mainshock M6.1 1997



In general, some major features can be noticed:

- preparation phase — a generalized increase (months before main-shock)

Focalization

- concentration phase — a sudden jump from days to hours before main-shock
- diffusive phase — a decrease "after" the main-shock

(De Santis et al., BSSA, 2011)

main-shock **is not** a singularity
it is a part of a population of events

Magnetic Transfer Function Entropy

In the frequency domain the time variations of the components **X**,**Y**,**Z** of the geomagnetic field observed at Earth surface are each other coupled:

$$\mathbf{Z}(\omega) = A(\omega)\,\mathbf{X}(\omega) + B(\omega)\,\mathbf{Y}(\omega)$$

A(ω) and *B(ω)* are the Magnetic Transfer Functions which are related with the conductivity at a certain depth inversely proportional to the square root of frequency ω.

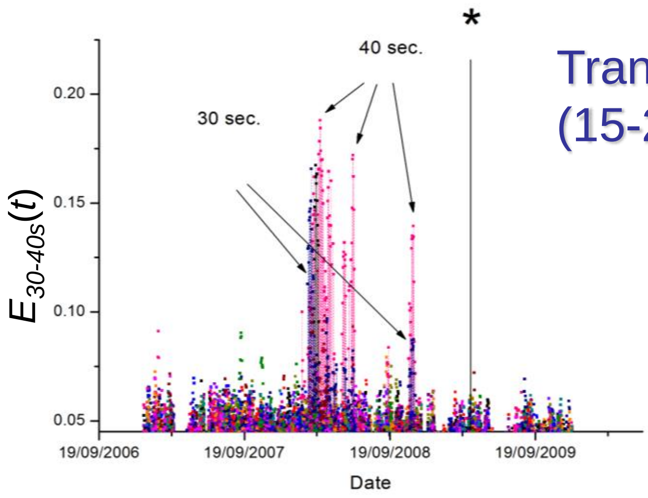
The (normalised) entropy contribution of the harmonic ω_i is given by :

$$E_i(t) = -\frac{p(\omega_i,t)\cdot\log p(\omega_i,t)}{\log N}$$

where:

$$p(\omega_i,t) = \frac{K_r^2(\omega_i,t)}{\sum_{i=1}^{N} K_r^2(\omega_i,t)}$$

K_r=real parts of *A* or *B*



Transfer Function Entropy for periods of 30-40 sec. (15-20 km depth)- L'Aquila (Central Italy), 2007-2009

Migration of fluids from below to the hypocentral zone (10km) activated the seismic sequence that culminated with the M6.3 mainshock of 6 Apr. 2009.

(Cianchini et al., NPG, 2012)

Entropy of Earthquakes: Wavelet Entropy of satellite magnetic signal

From Fourier analysis → the spectral entropy (Powell and Percival, 1979)

$$S = -\sum_i P_i \ln P_i \quad \text{where} \quad P_i = \frac{|f_i|^2}{\sum_{i'} |f_{i'}|^2} \quad \text{for frequency} \quad f_i$$

It measures how energy “concentrates” or “spreads” in frequency.

Wavelet analysis decomposes a signal $f(t)$ both in time and scale (or frequency)

$$f(t) \Longrightarrow W(s,\tau)$$

Wavelet Transform

$$S_W = -\sum p_{s,\tau} \log_2 \left(p_{s,\tau} \right)$$

Wavelet Entropy

Example 26th Dec, 2004 (Sumatra EQ, M9)

$$p_{s,\tau} = \frac{E(s,\tau)}{\sum_s E(s,\tau)}$$

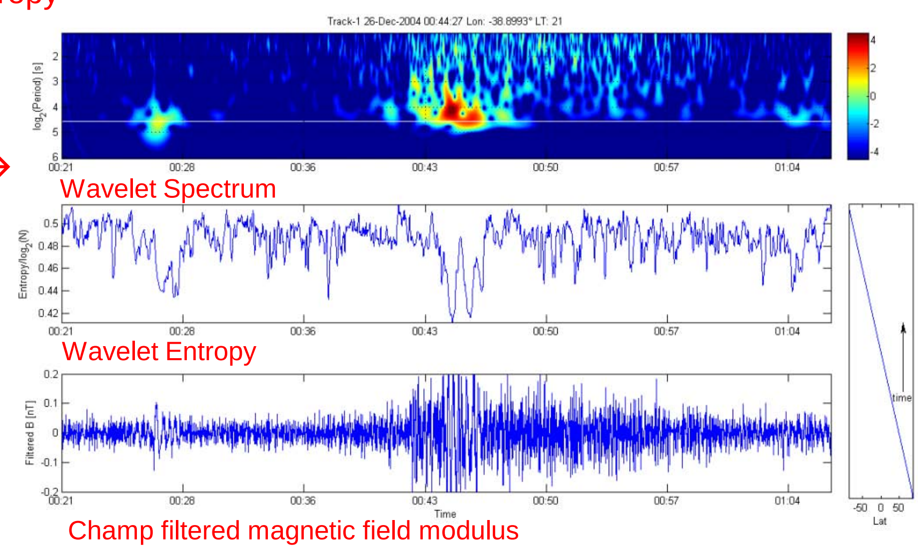
Probability

where

$$E(s,\tau) = |W(s,\tau)|^2$$

Energy

The case of magnetic signal from CHAMP satellite (in orbit 2000-2010) →



Cianchini et al., *ESA*, 2009

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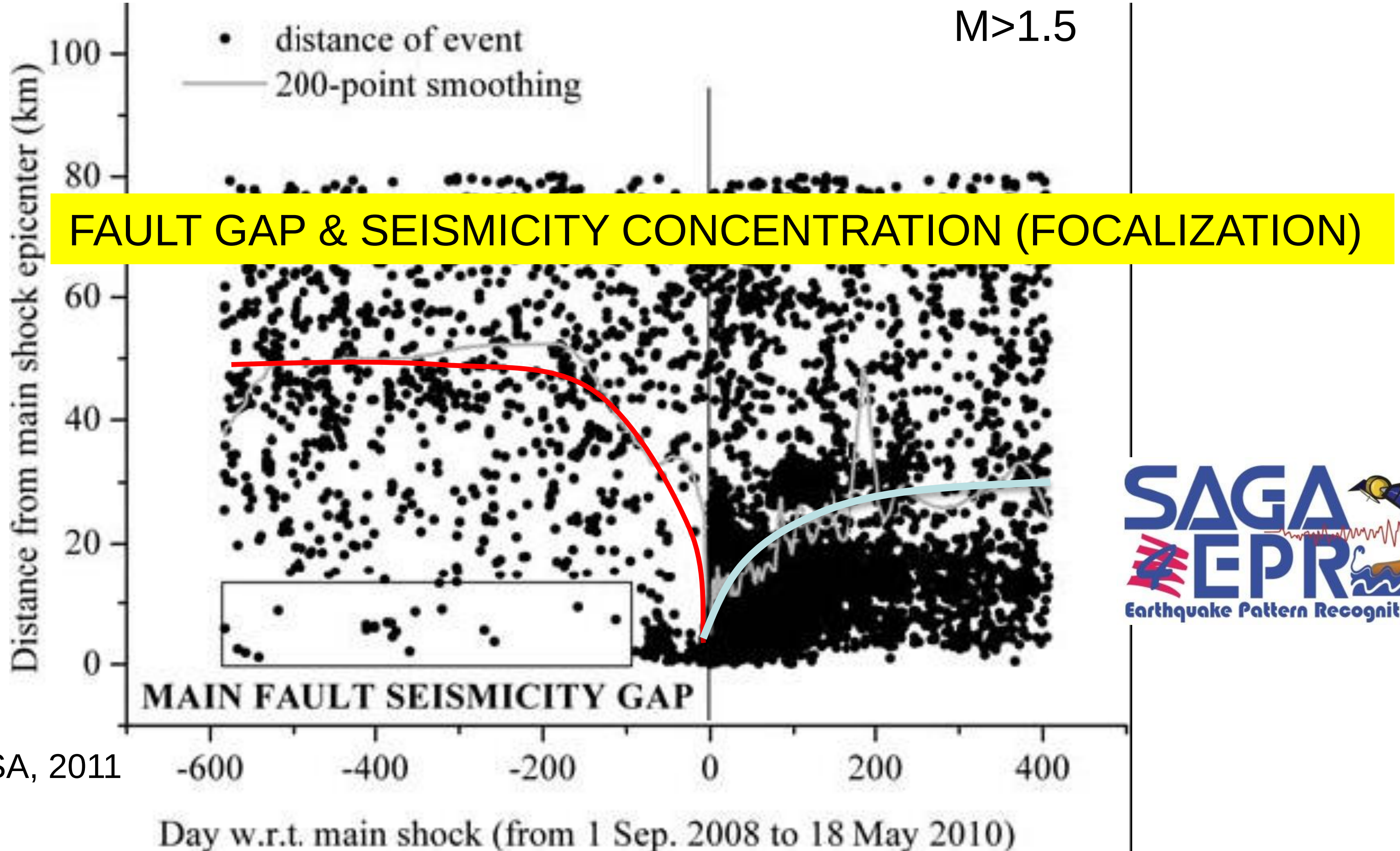
6. SPACE-TIME FOCALIZATION

THE CASES OF M6.3 L'Aquila (2009) and M5.9 Emilia (2012) EARTHQUAKES

An attempt to solve an important *conundrum* of seismology:

How does the stress at the tectonic plates transfer to an individual fault?

Lessons learnt from L'Aquila /1



De Santis et al., BSSA, 2011

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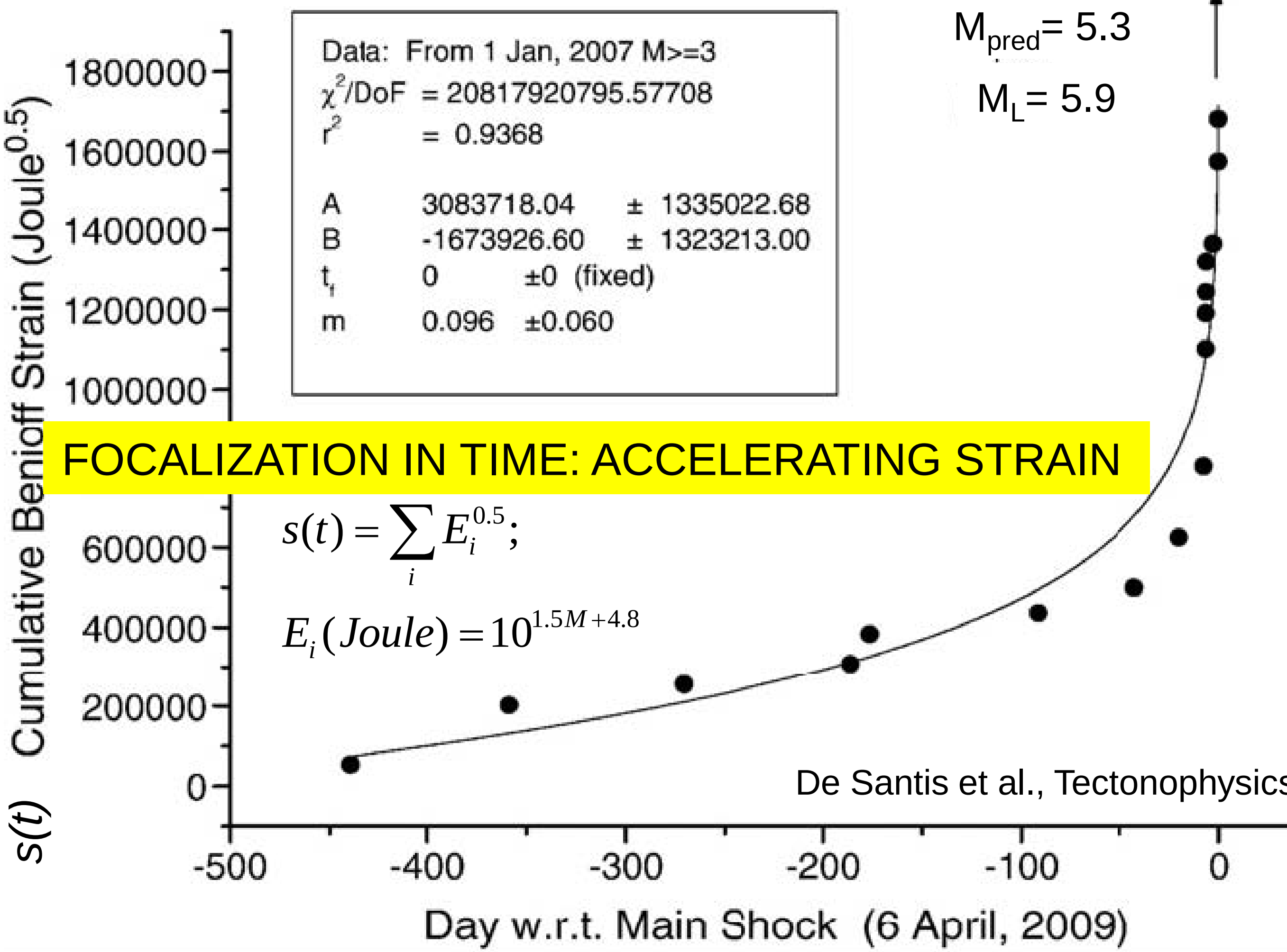
Lessons learnt from L'Aquila /2



FOCALIZATION IN TIME: ACCELERATING STRAIN

$$s(t) = \sum_i E_i^{0.5};$$

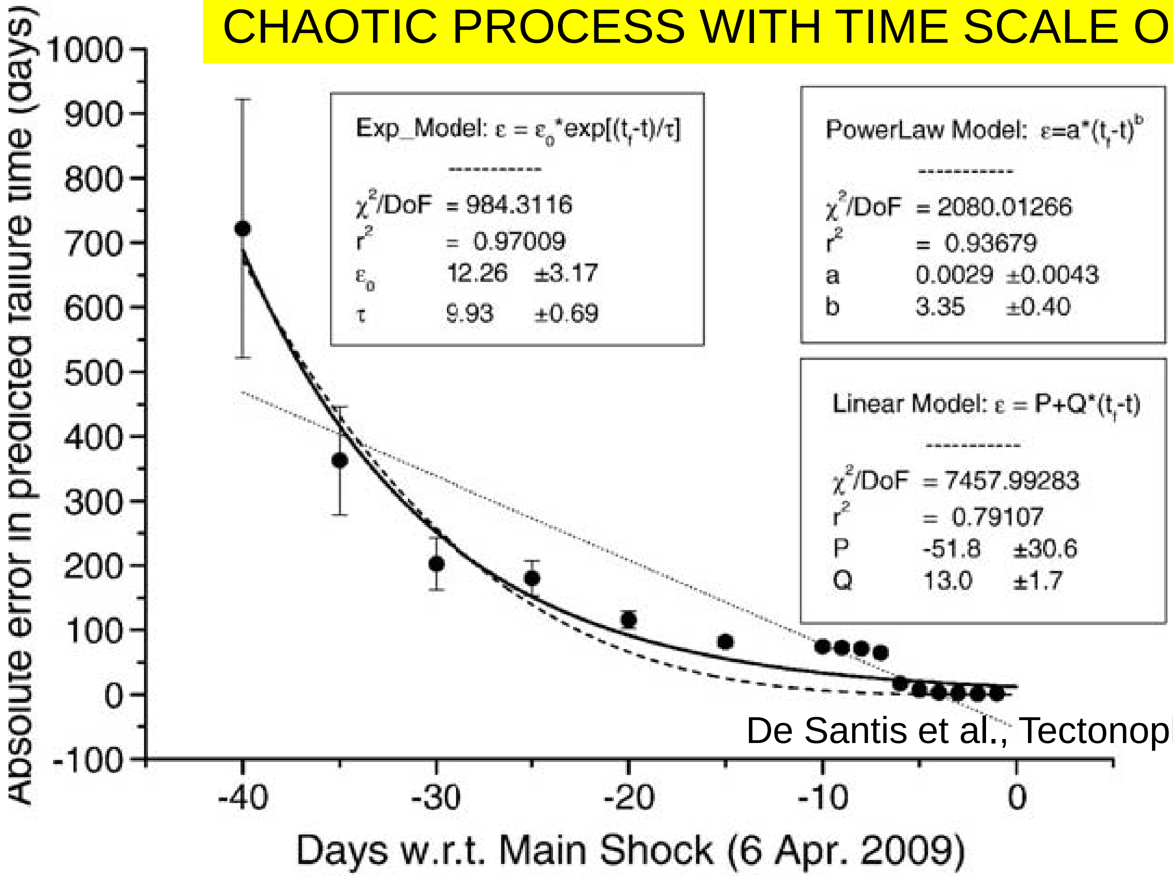
$$E_i(Joule) = 10^{1.5M+4.8}$$

De Santis et al., Tectonophysics, 2010

SAGA 4 EPR Earthquake Pattern Recognition

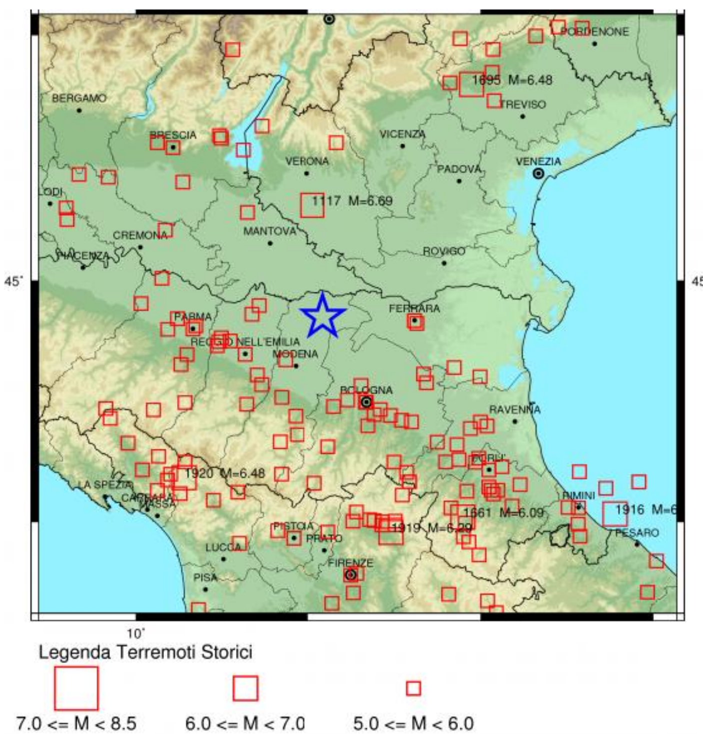
Lessons learnt from L'Aquila /3

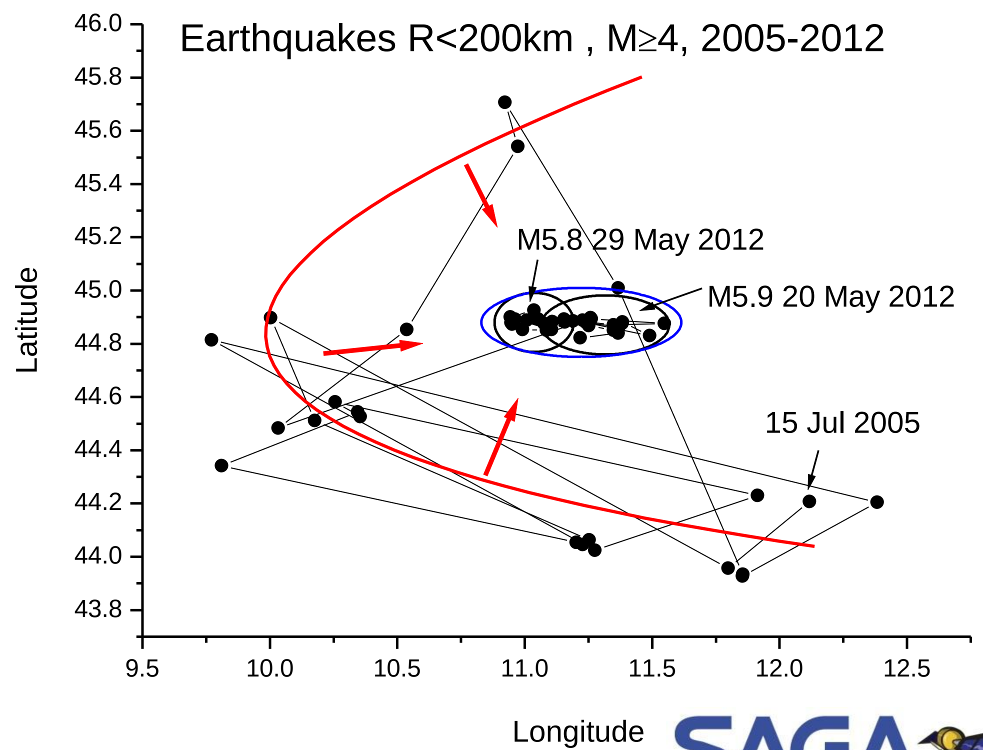
CHAOTIC PROCESS WITH TIME SCALE OF 10 DAYS



De Santis et al., Tectonophysics, 2010

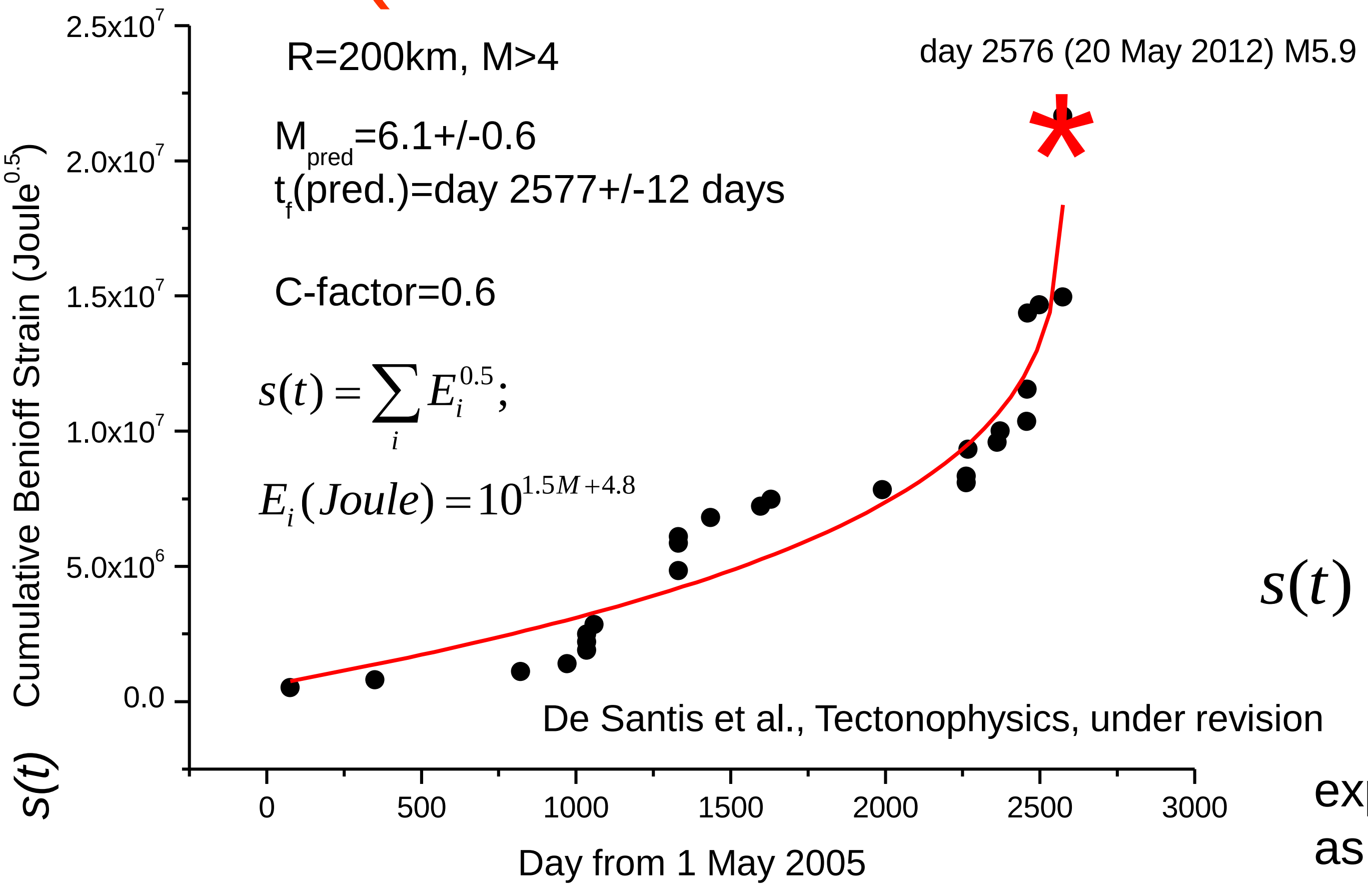
Focalization of earthquakes
Emilia 2012





A *partial* Mogi doughnut (Mogi, 1969):
1. Former seismicity at the periphery 2. the present seismicity filled the gap

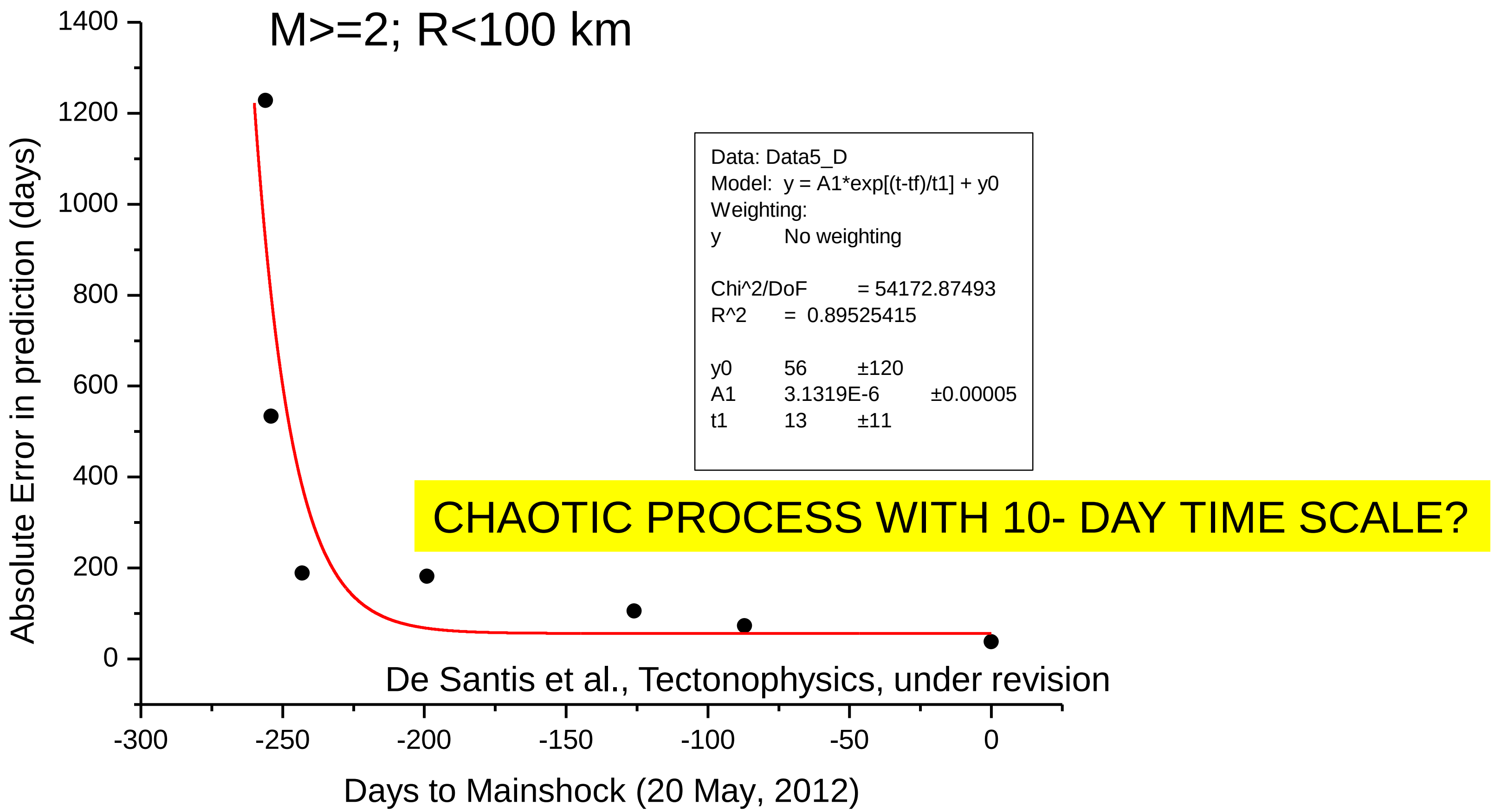
Focalization of earthquakes in time: ASR (Accelerated Strain Release)



$$s(t)=A+B(t_f-t)^m$$

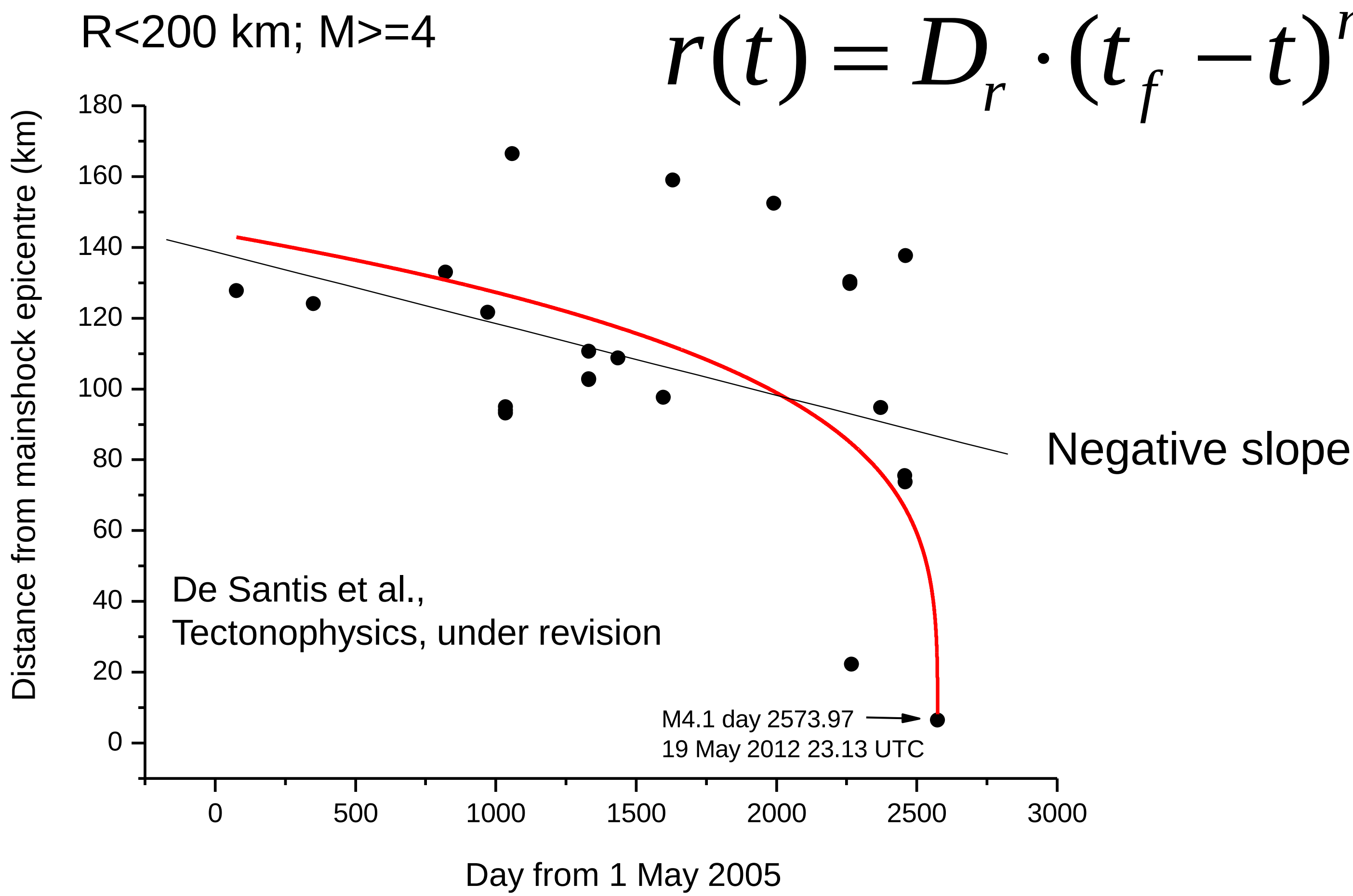
exponent m =0.25 as some theoretical critical models

Focalization of earthquakes in time: Chaos



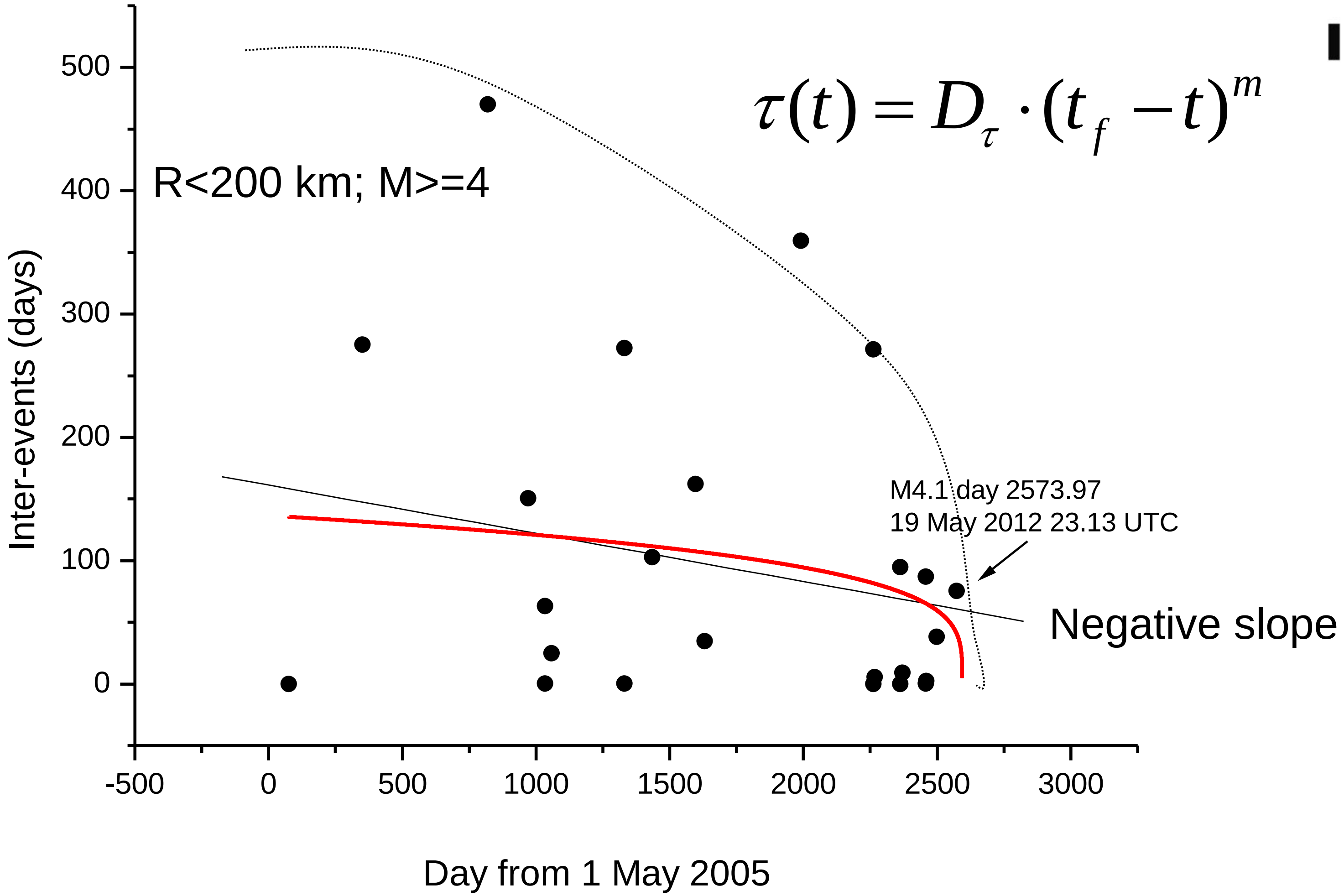
Focalization of earthquakes
Distances from epicenter

$$r(t) = D_r \cdot (t_f - t)^m$$

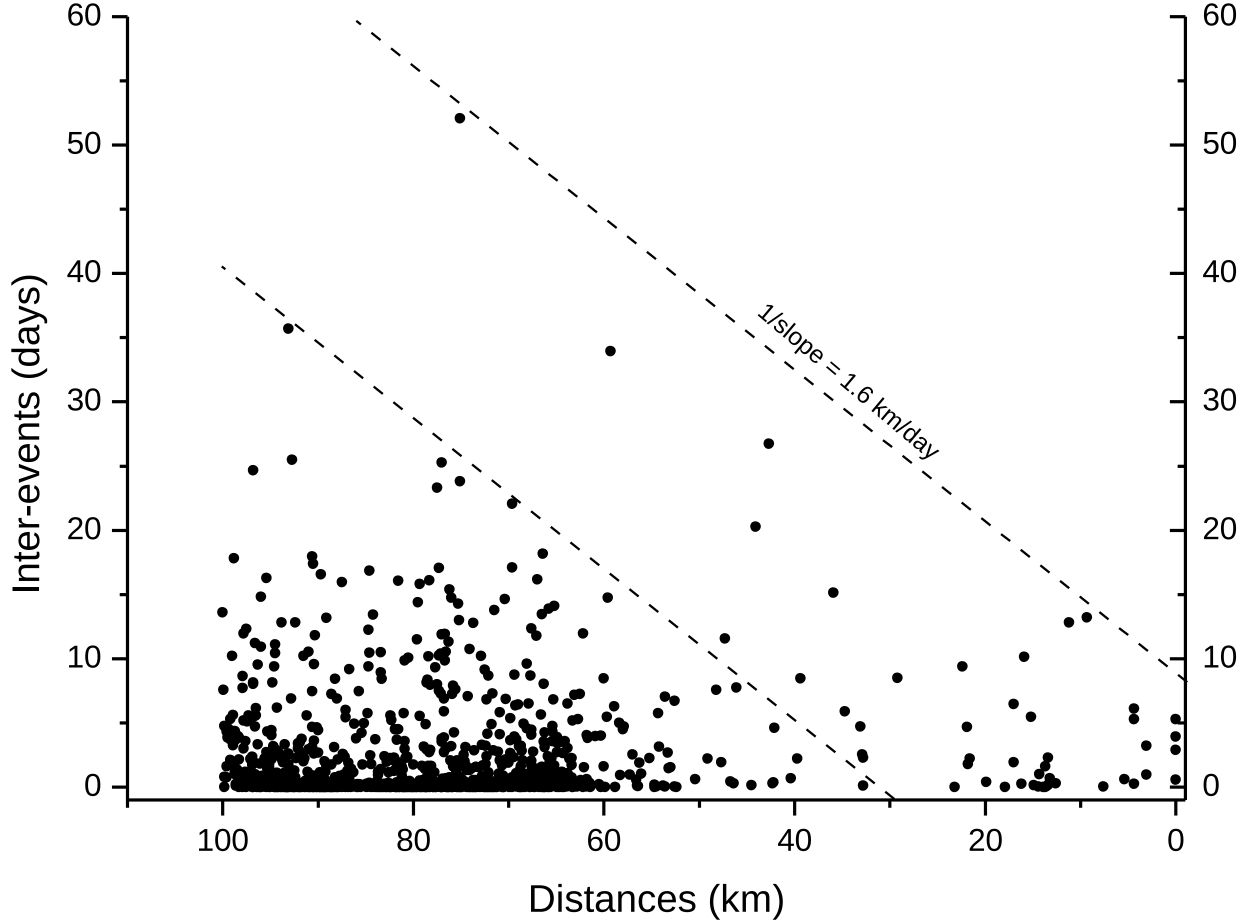


Focalization of earthquakes in time: Inter-events

$$\tau(t) = D_\tau \cdot (t_f - t)^m$$

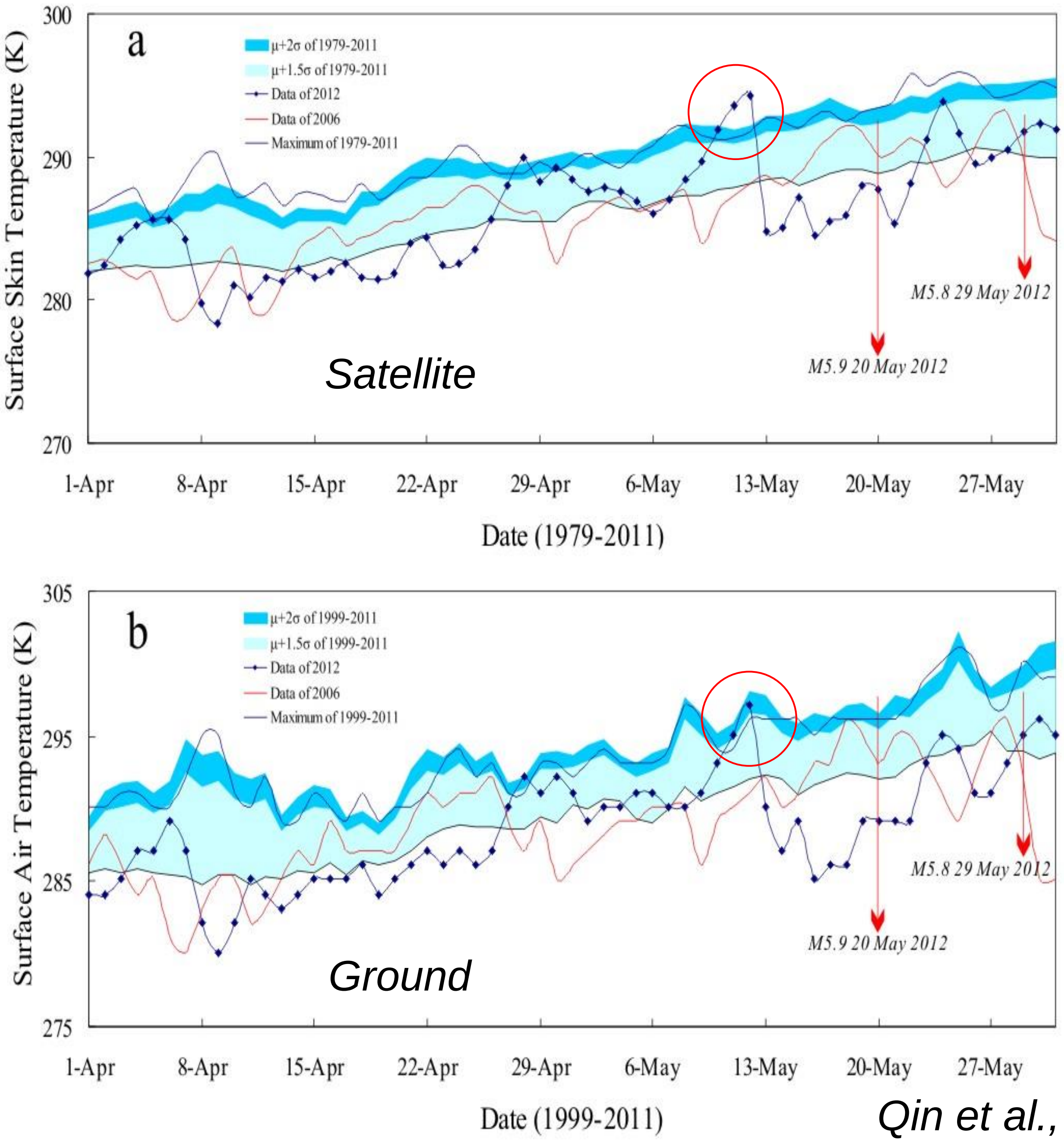


Multiscale Focalization of earthquakes in space & time:



Stress from tectonic plates to fault diffuses at the minimum velocity of 1-2 km/day?

De Santis et al., Tectonophysics, under revision



Focalization confirmed from space: IR thermal anomaly from satellite

Qin et al., Annals Geoph., 2012

Laboratory fracturing-model

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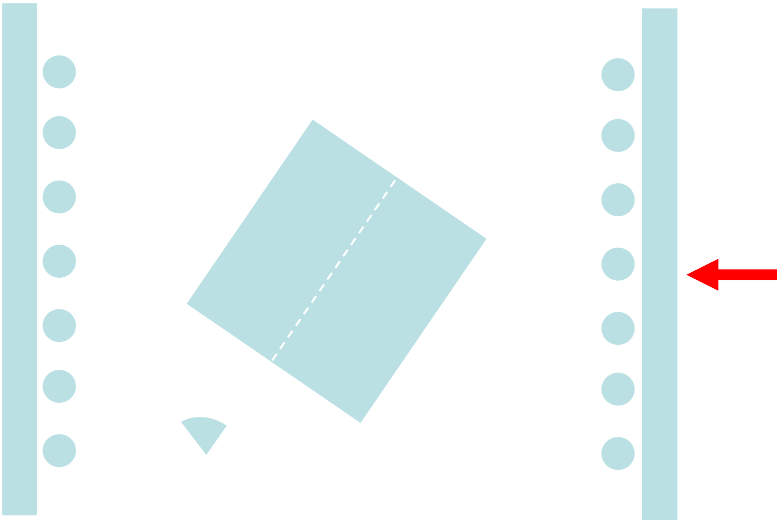
Infrared Detection Experiment of Compressed-shearing Loaded Rock

Original Settings

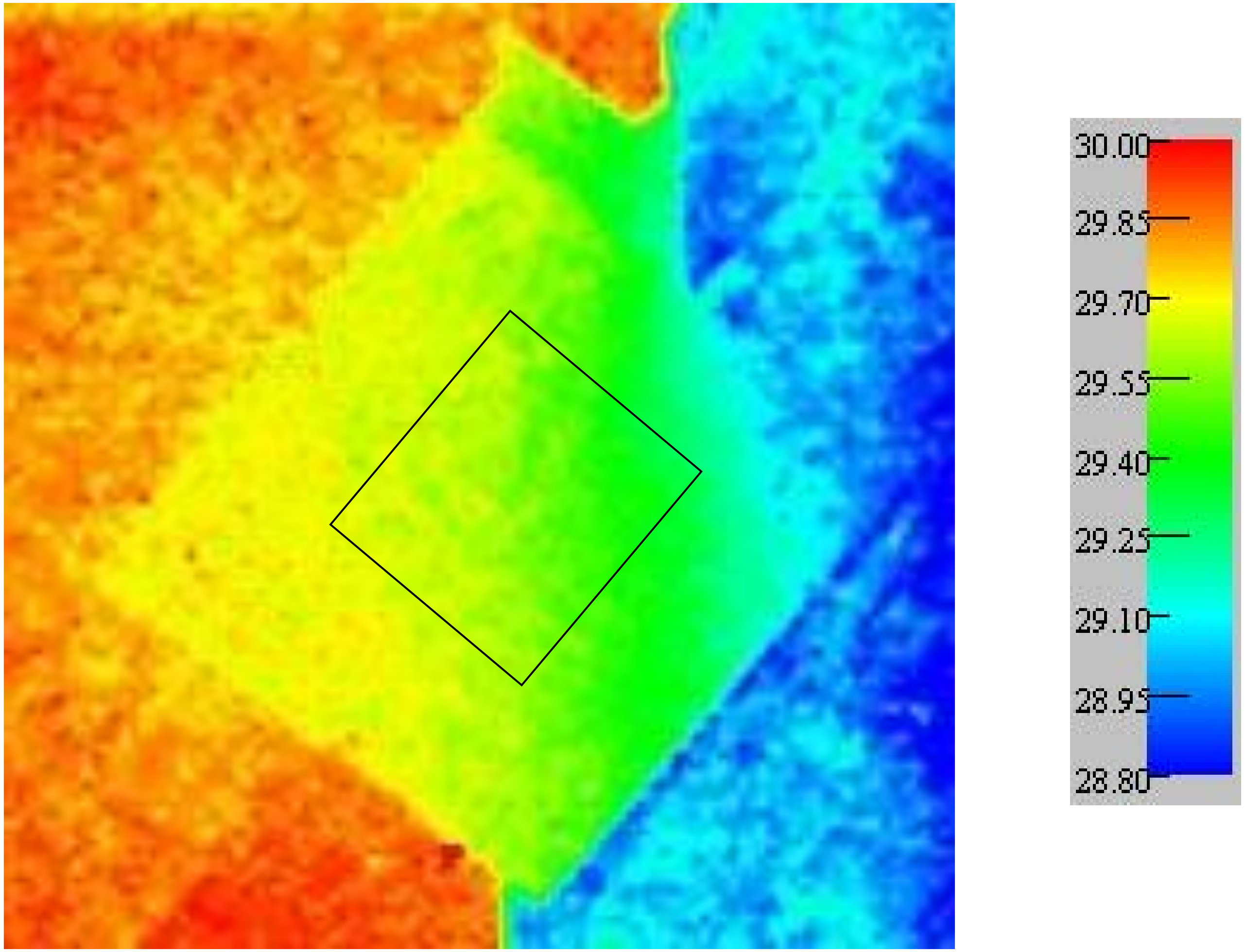


Settings rotated by 90º

Experiments made in the frame of SAGA-4-EPR by Proff Liu and Wu of NEU (China)

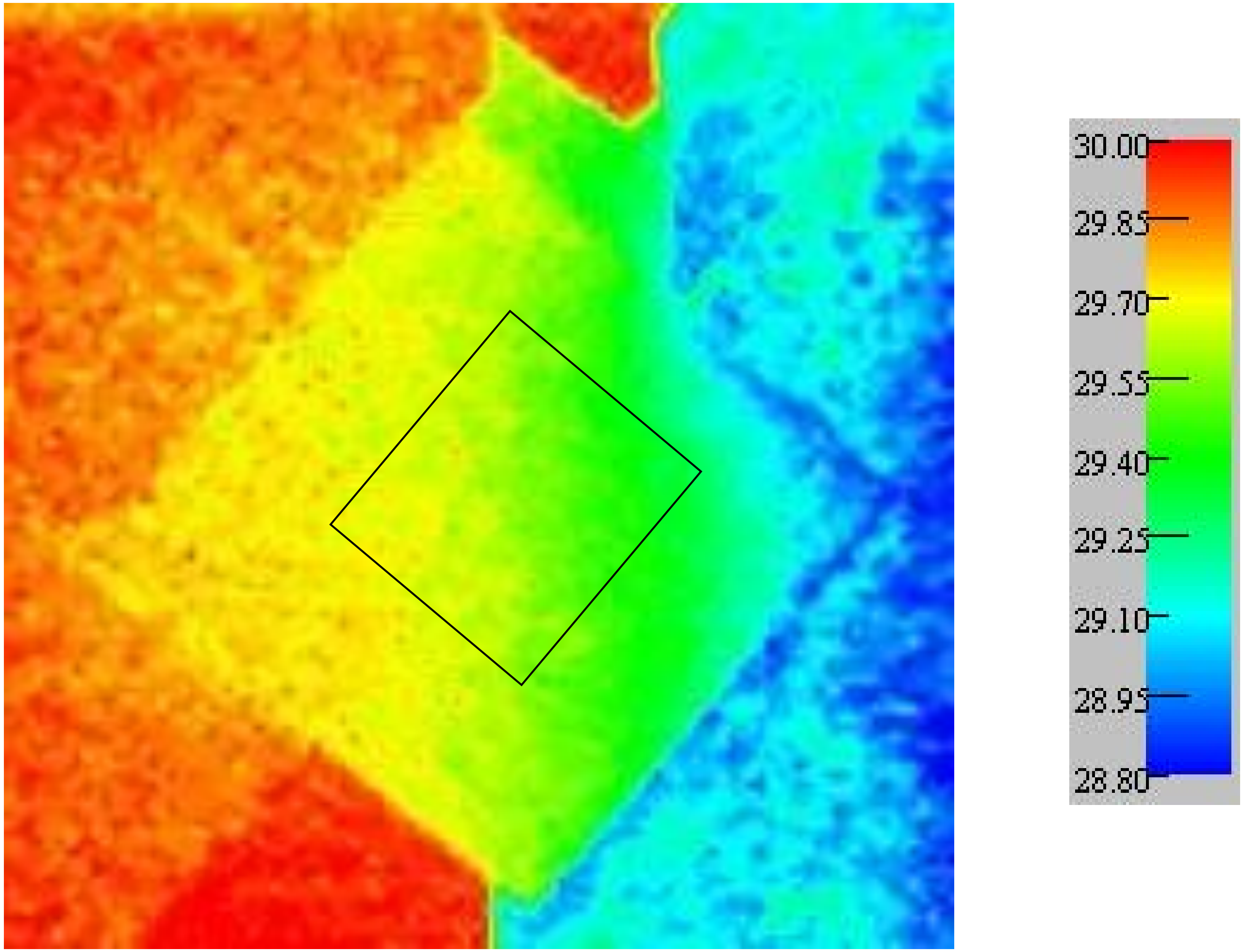
Experimental result of sample 1-9

t=001s



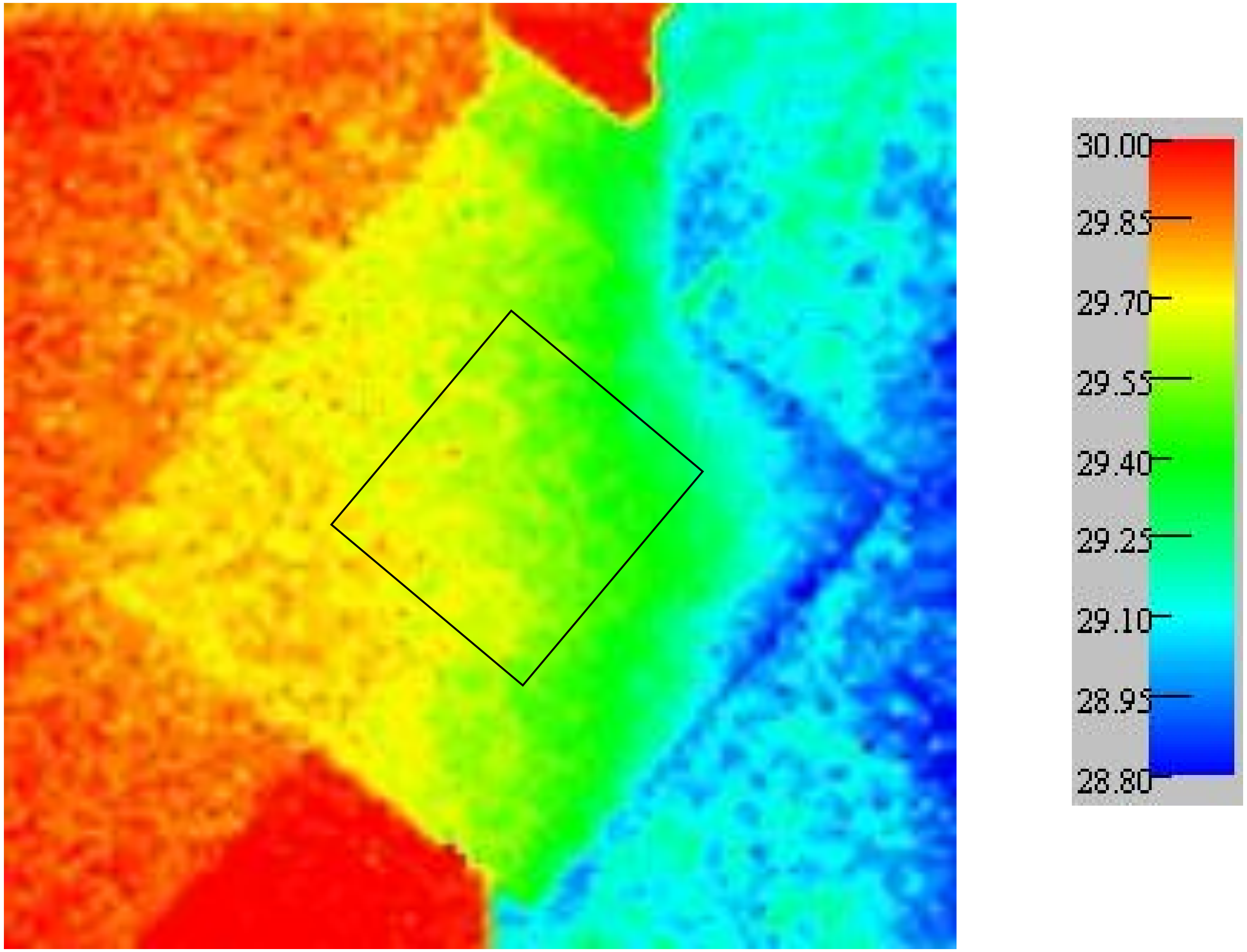
Experimental result of sample 1-9

t=040s



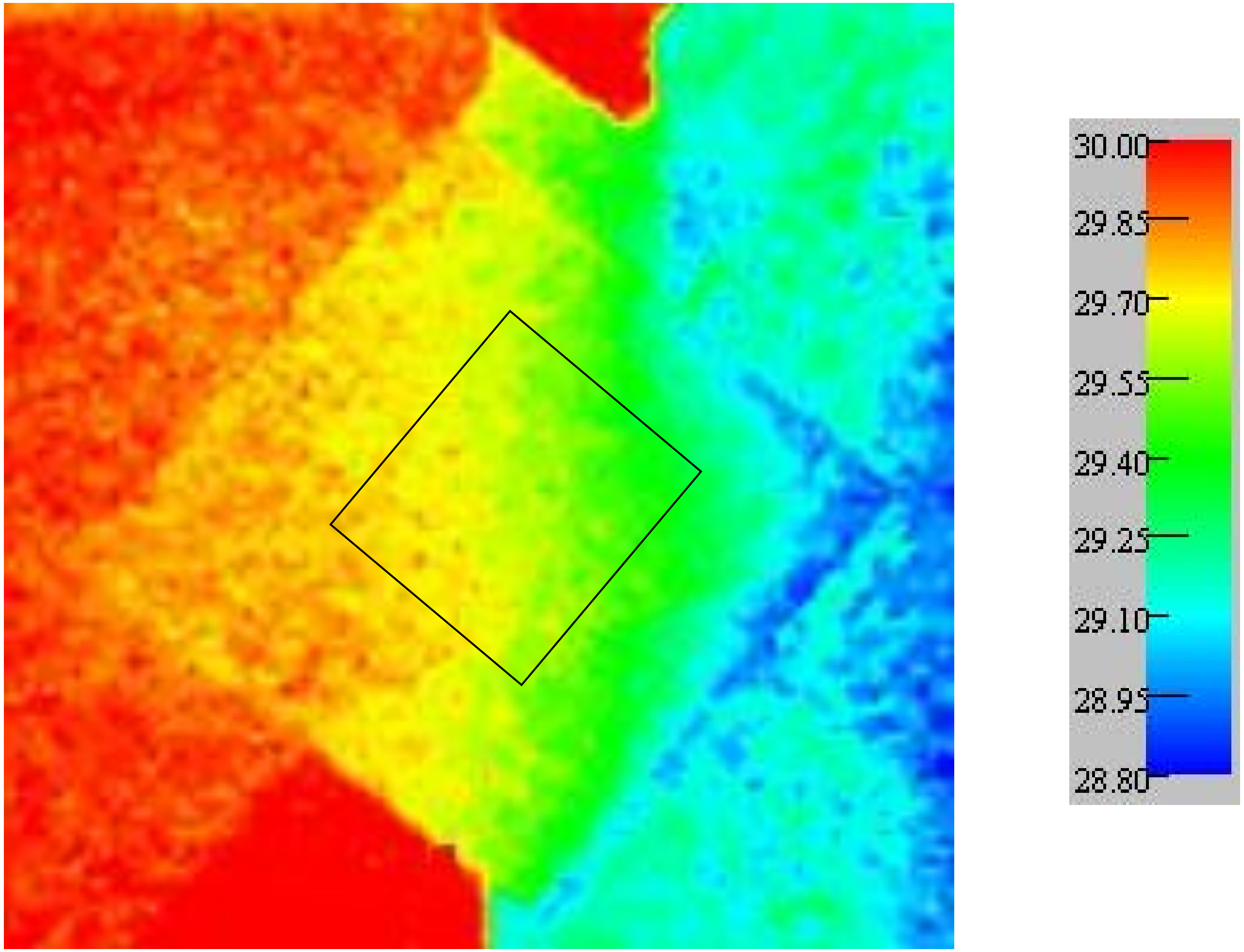
Experimental result of sample 1-9

t=080s

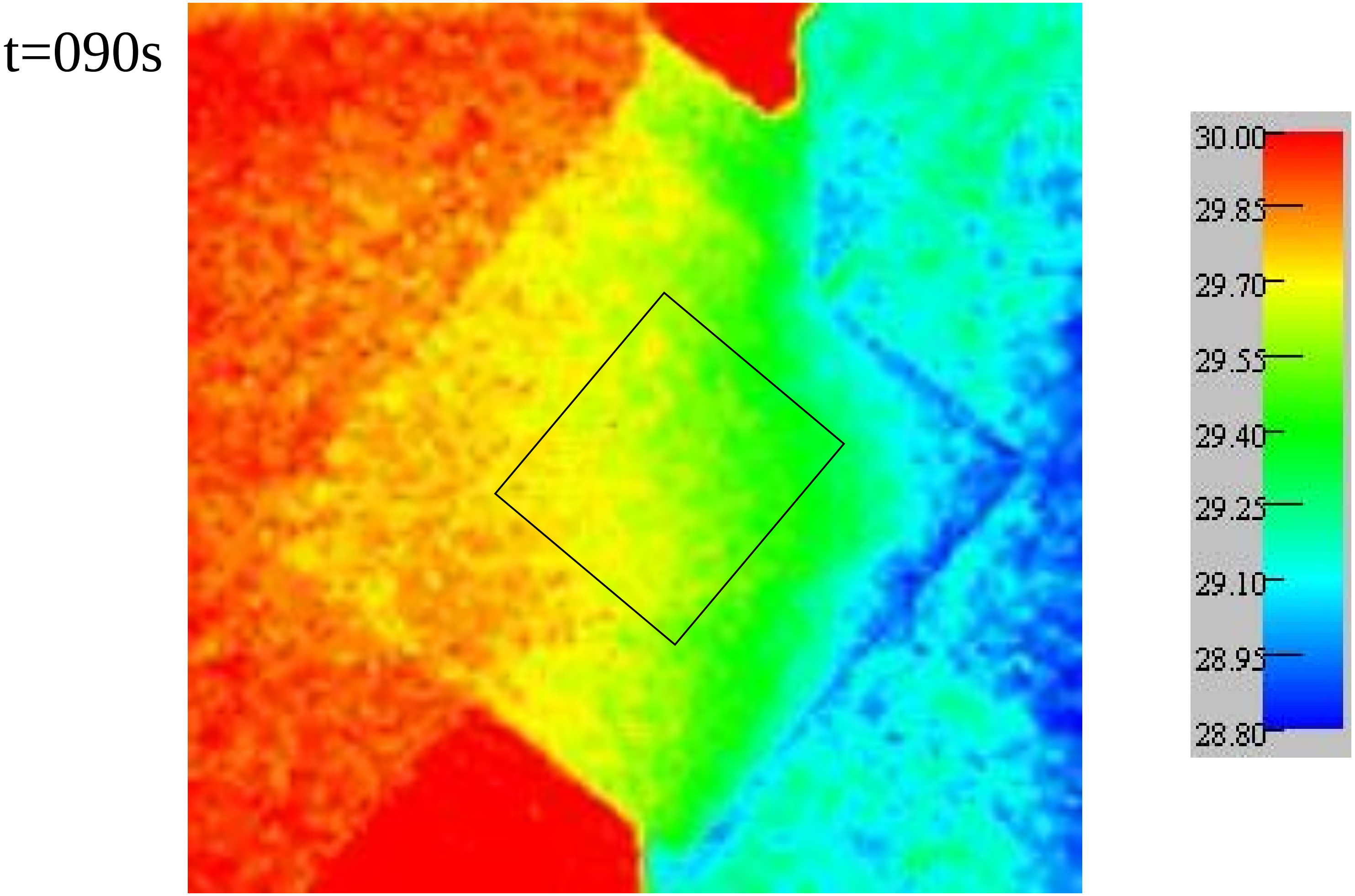


Experimental result of sample 1-9

t=086s

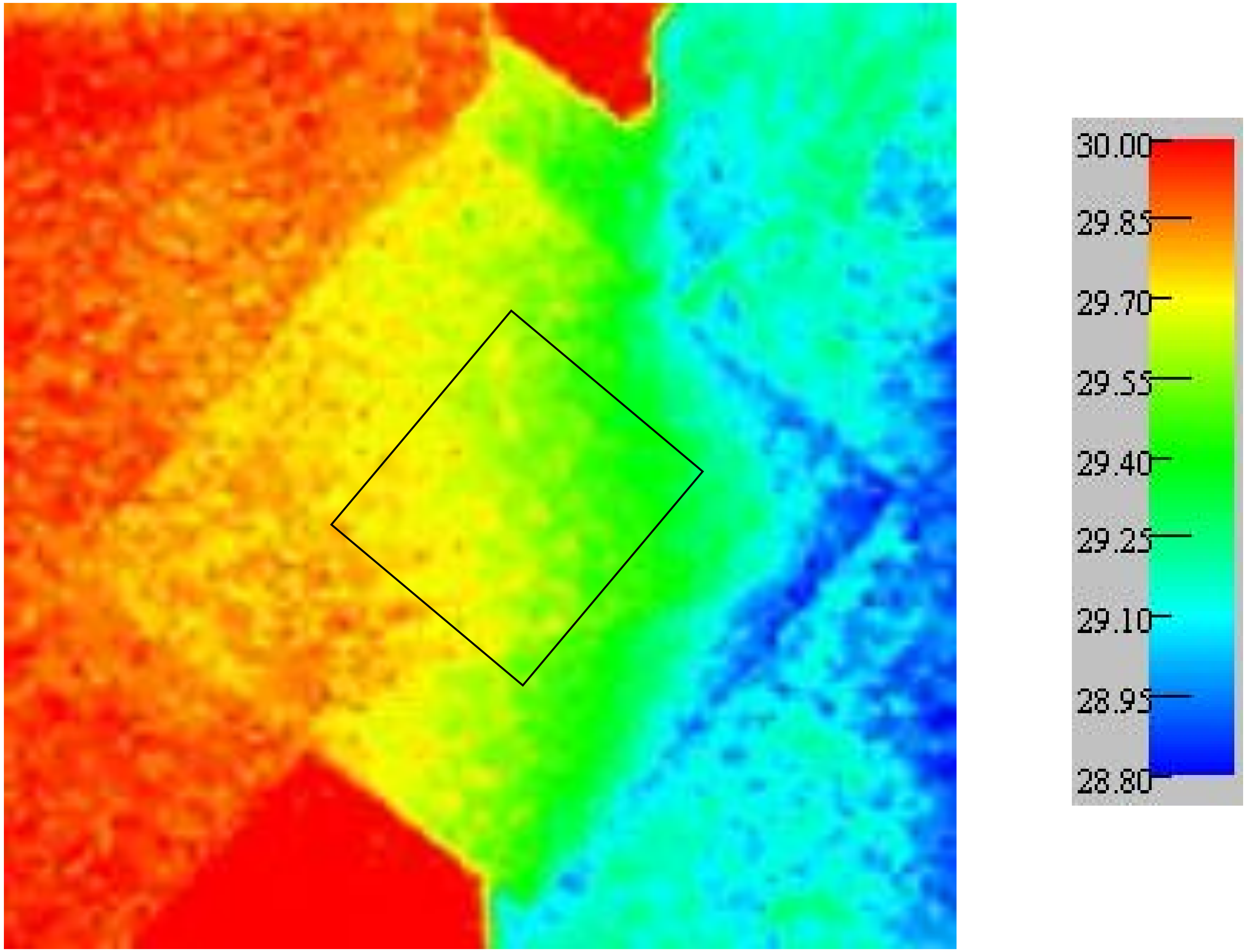


Experimental result of sample 1-9



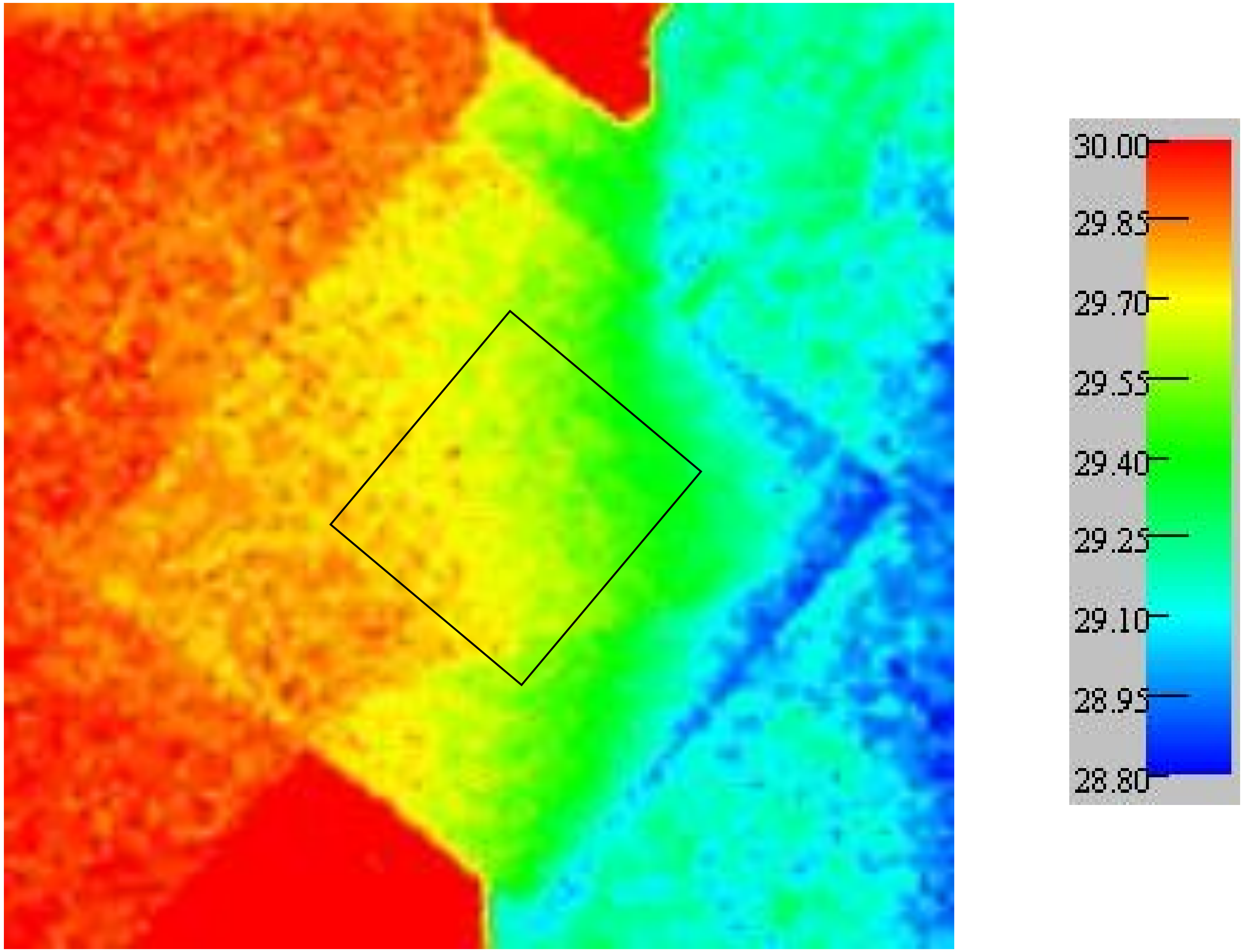
Experimental result of sample 1-9

t=095s



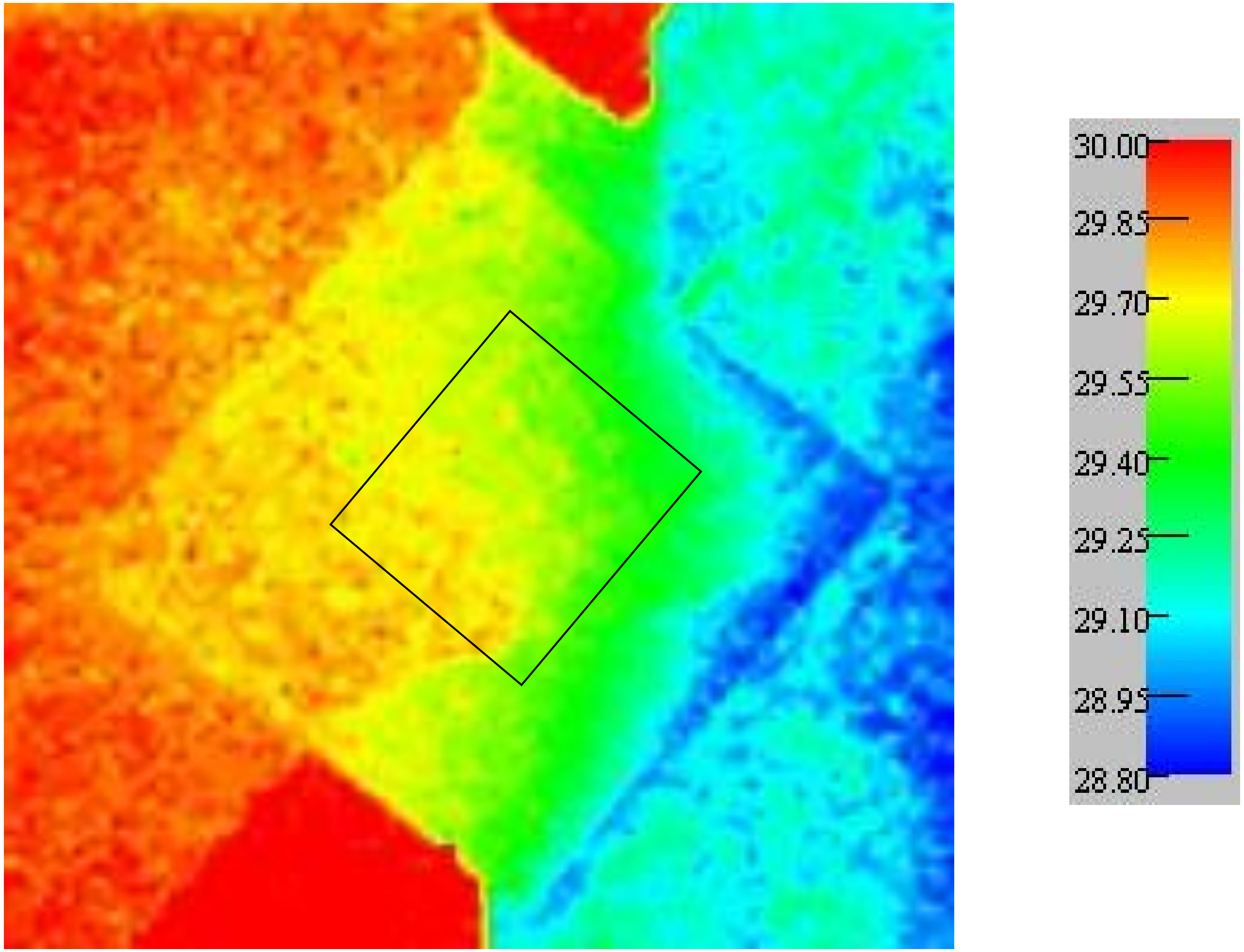
Experimental result of sample 1-9

t=100s



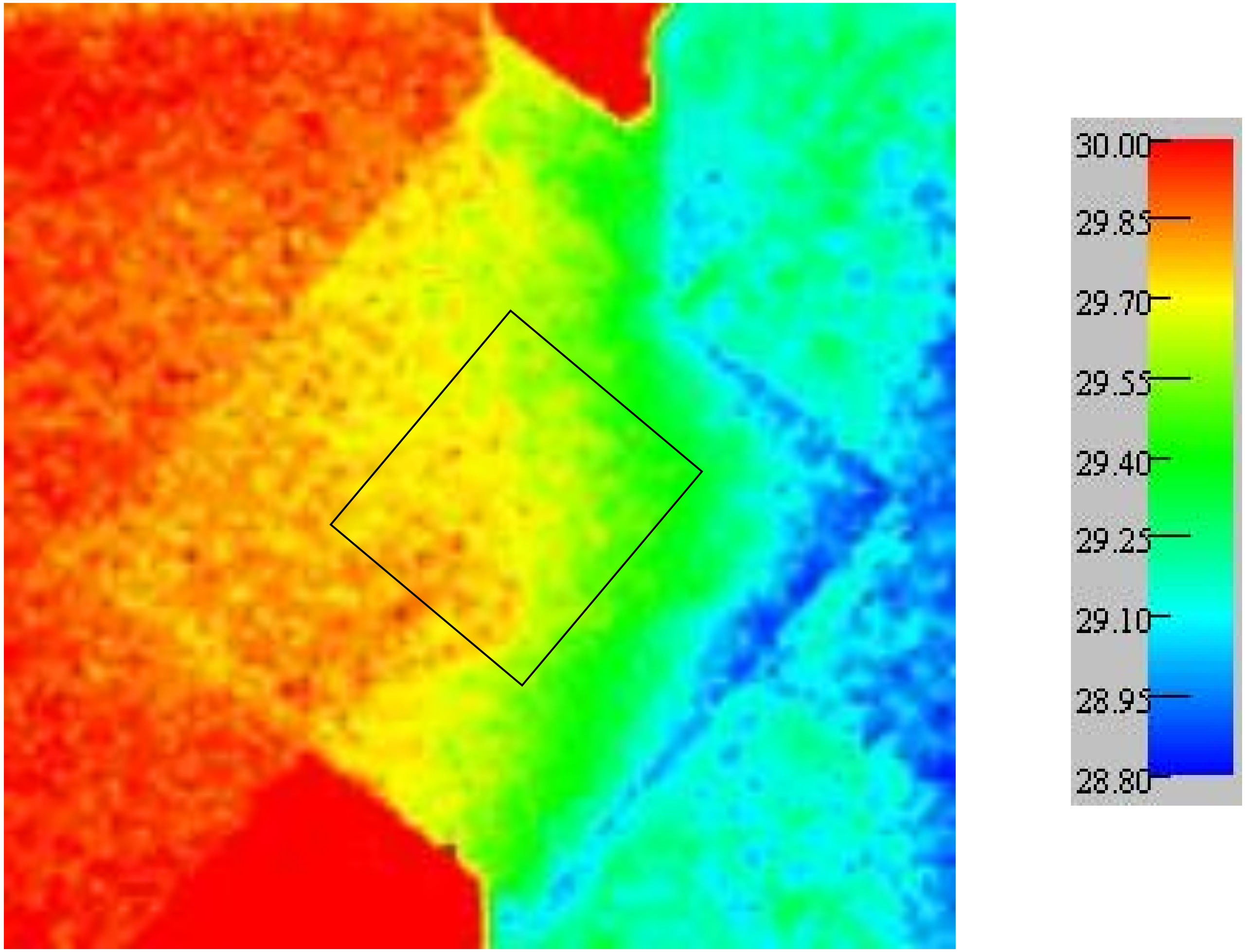
Experimental result of sample 1-9

t=106s



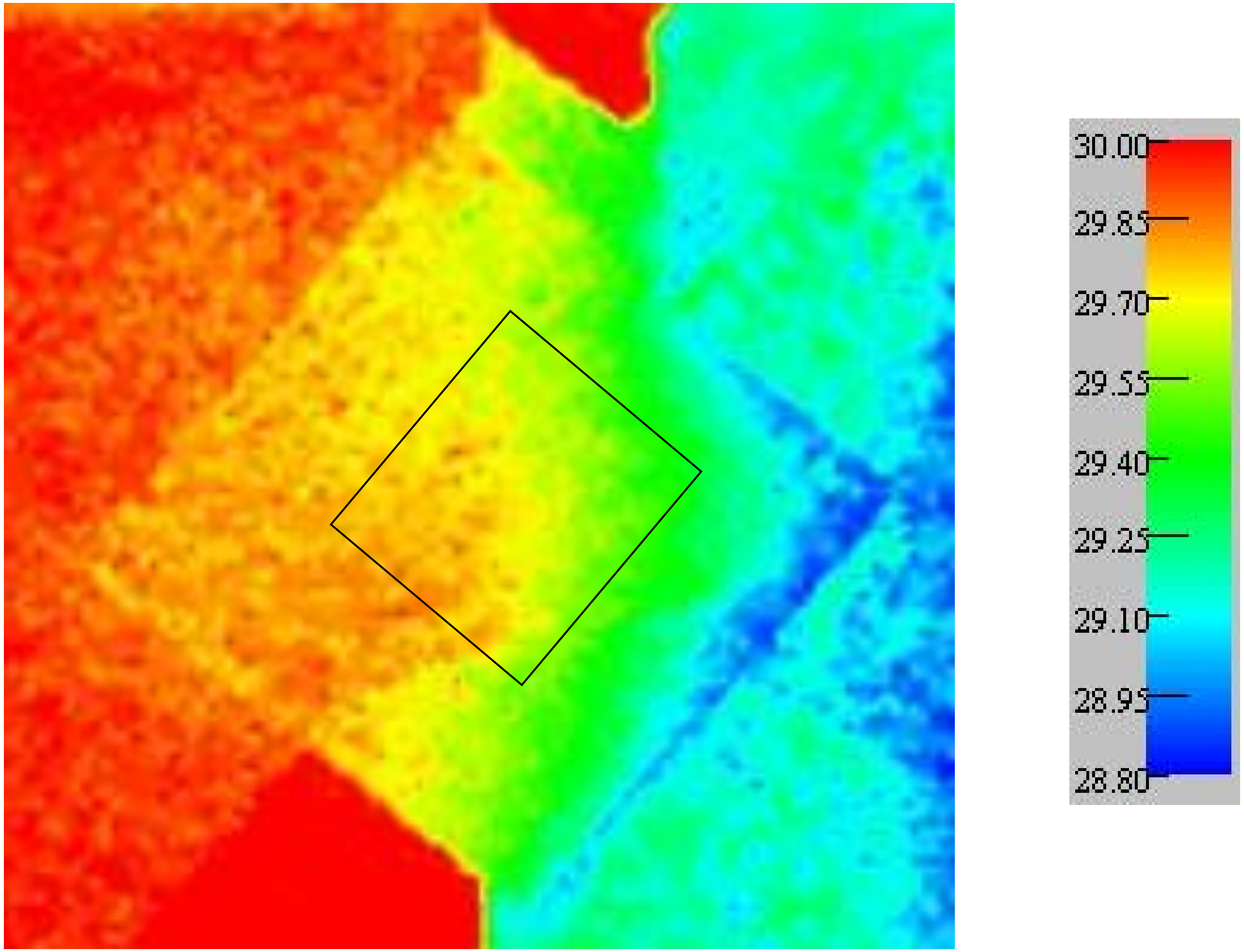
Experimental result of sample 1-9

t=108s



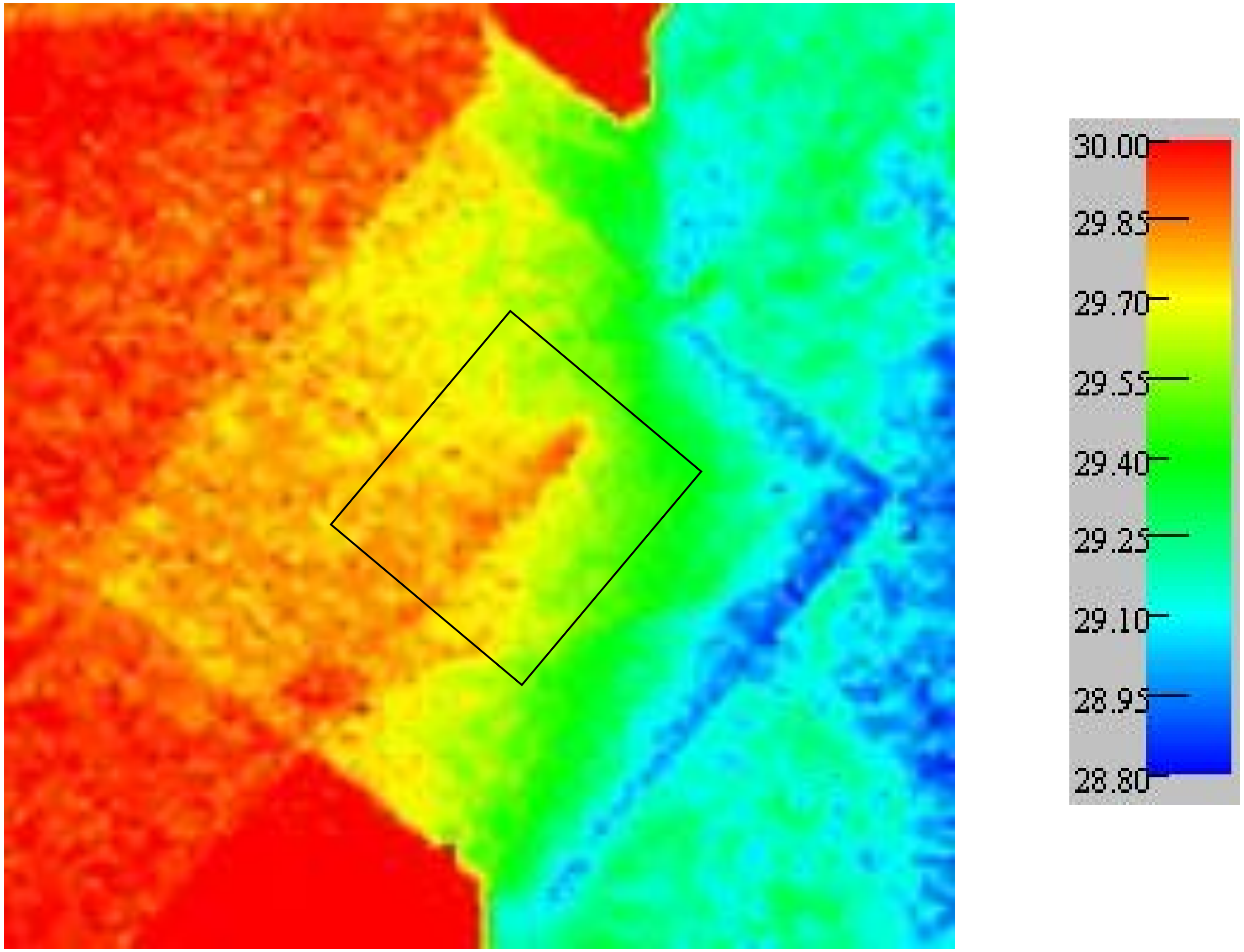
Experimental result of sample 1-9

t=109s



Experimental result of sample 1-9

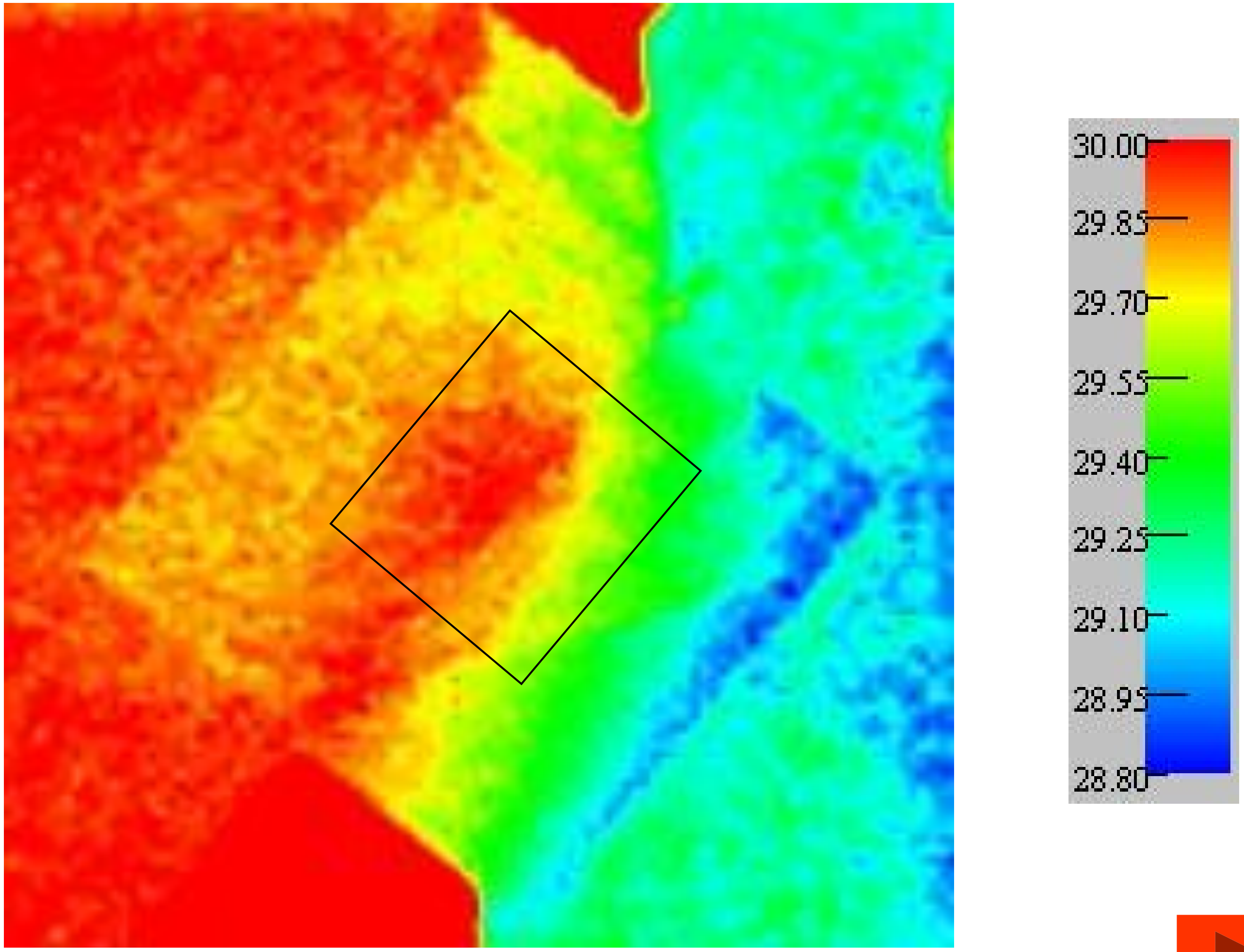
t=110s



De Santis, Geosystemics & Entropy, Samarkand (Uzbekistan), 21 May, 2013

Experimental result of a sample 1-9

t=140s



Geosystemics

Conclusions on Emilia Focalisation

•Seismicity that happened before the recent EMILIA earthquakes is compatible with a partial **Mogi doughnut** model characterized by a precursory space-time focalization process.

•The time evolution has behaved as *a critical point process* both in space and in time.

• A simple laboratory model was able to grasp some the most important features of the focalization process.

Geosystemics

7. OTHER APPLICATIONS
A *systemic* approach to investigate **Deep Seafloor**

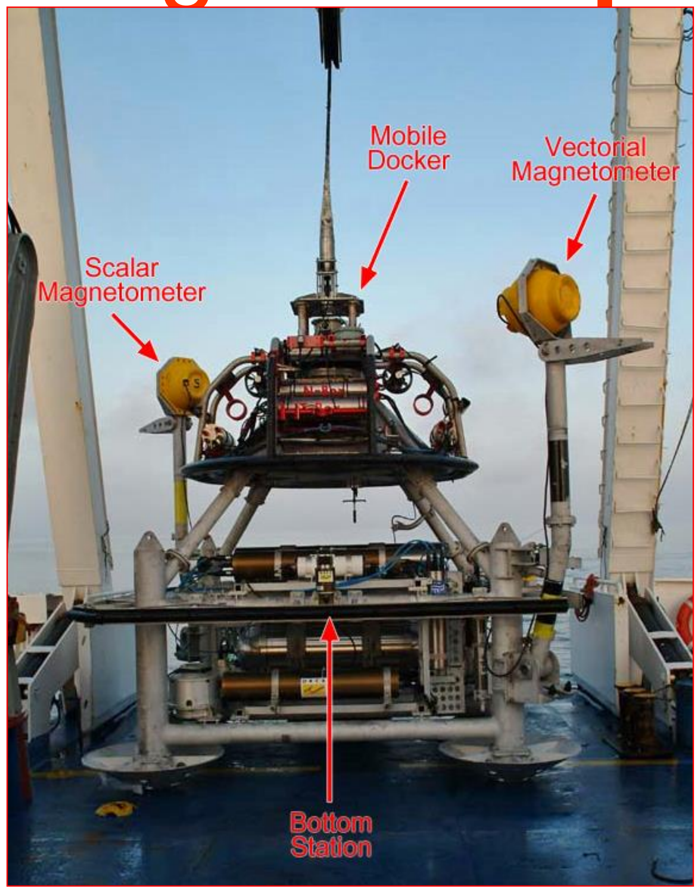
Seafloor Station deployed several times
down to **3000 m depth**
in Tyrrhenian Sea

Under the European Projects:
GEOSTAR
ORION
EMSO

DS³F

A recent effort: Deep sea and subseafloor frontier **DS3F** Project

http://www.deep-sea-frontier.eu/



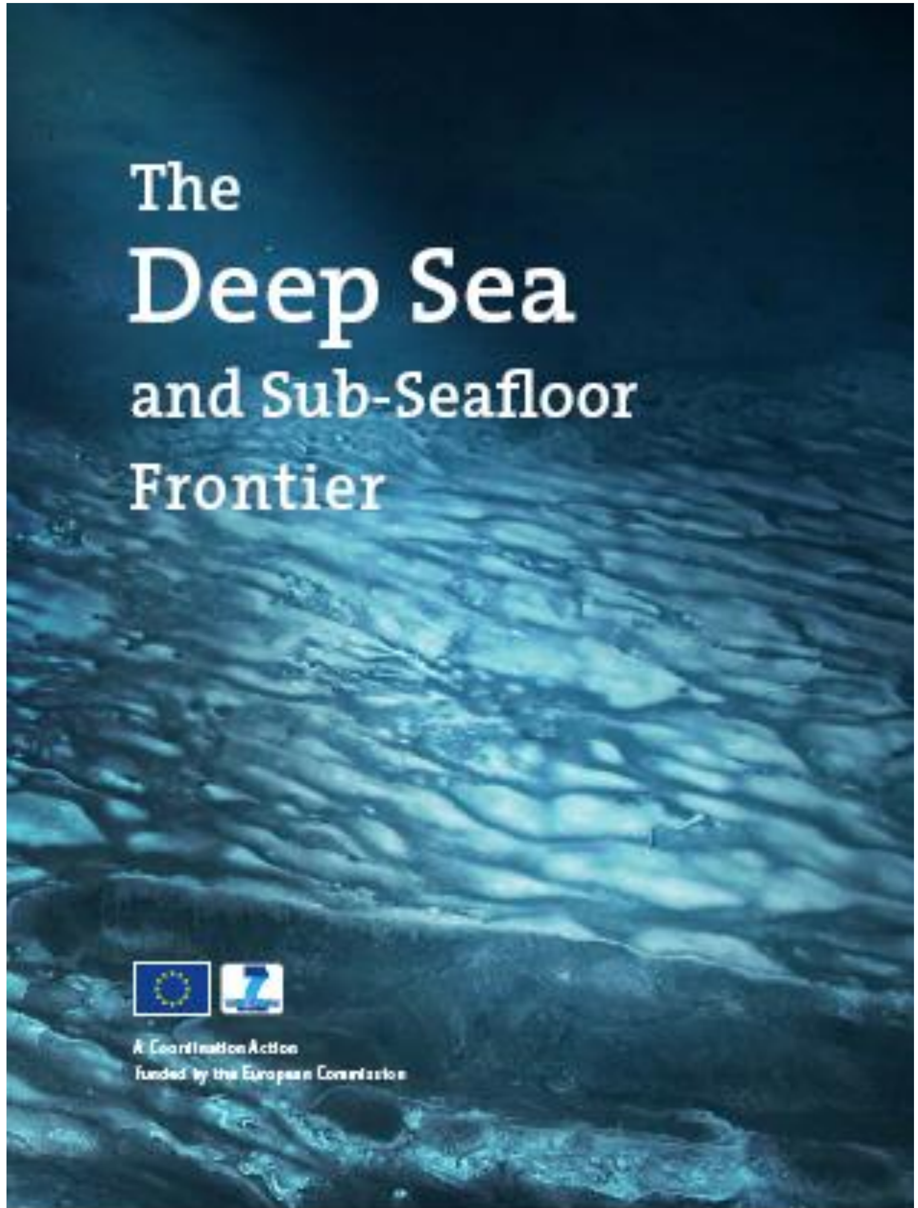
Beranzoli et al., PEPI, 1998

Instruments:

Seismometer
Magnetometers
Gravimeter
Currentmeter
…

From **Multiparameter** monitoring to **Trans-disciplinary** analysis

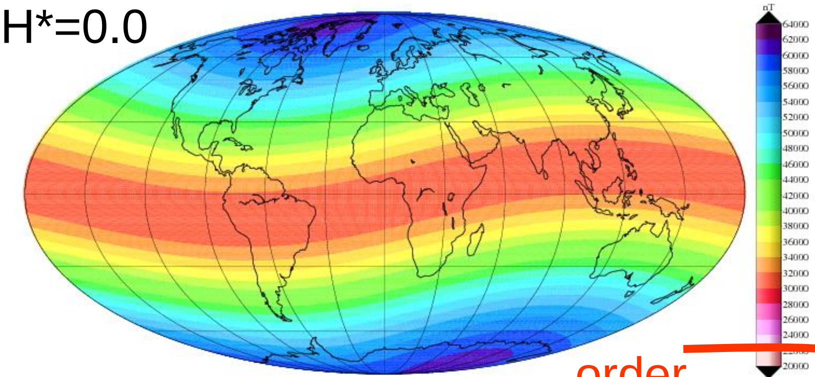
The Deep Sea White Paper



Geomagnetism

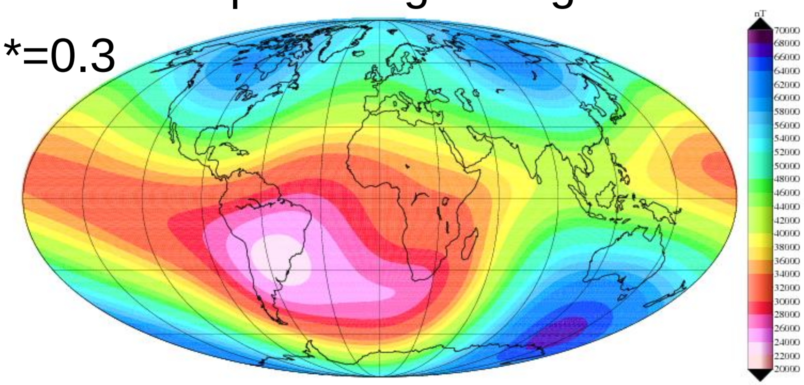
Normalised Entropy over a sphere

H*=0.0



The present geomagnetic field

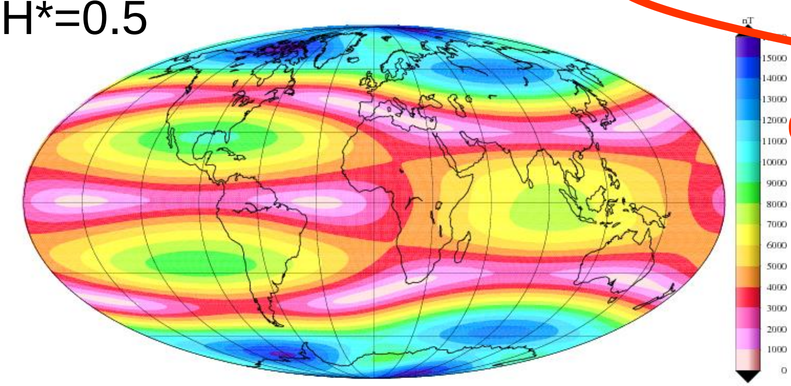
H*=0.3



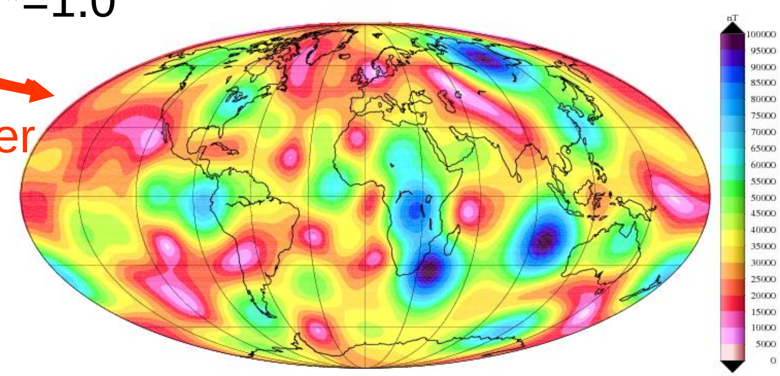
order

disorder

H*=0.5



H*=1.0



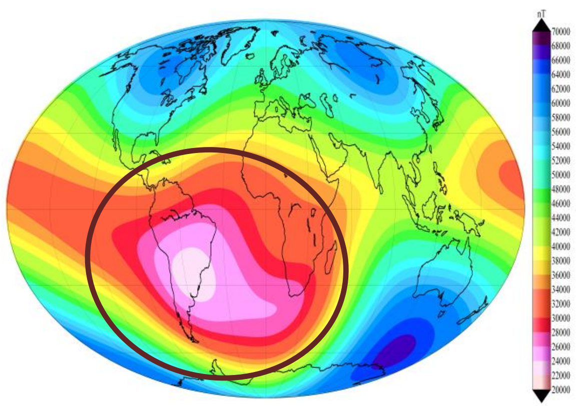
Adapted from De Santis & Qamili, 2008

Geosystemics

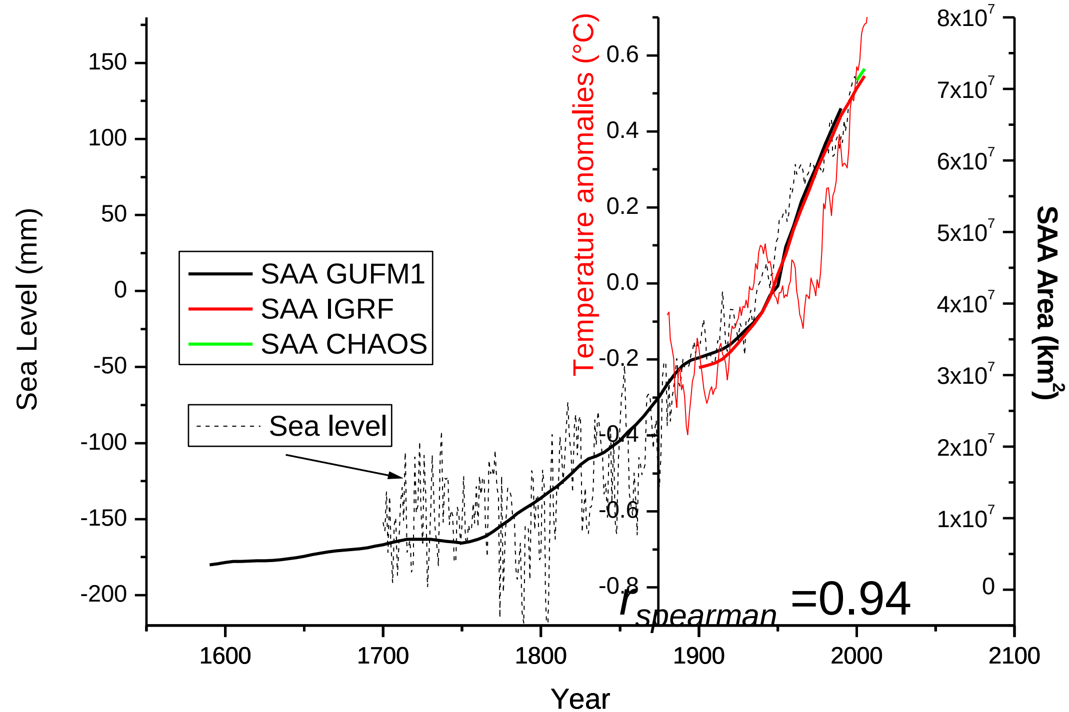
Geomagnetism and climate

SAA and mean sea level

(De Santis et al., *JASTP*, 2012)



SAA= South Atlantic Anomaly



Kullback-Leibler (1951) Relative Entropy

$$K_L(p_1, p_2) = \int p_1(s) \ln[p_1(s)/p_2(s)] ds$$

K_L =0.05-0.06 (0.20-0.40 for surrogate data)

8. Conclusions

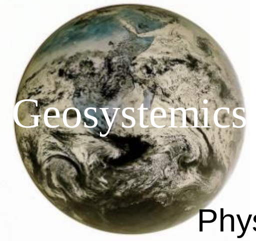
1. We defined a new systemic approach (*vision*) to Earth system study called **GEOSYSTEMICS**

where multi-platform/parameter/scale observations are fundamental to take a whole picture of our planet

2. Fundamental tools (*keys*) have been proposed, mainly based on - **Entropy and Information**

measuring the whole & the relationships among components

3. We showed an important application to Seismology (*disclosing the relationship between b-value and entropy*)
4. and then something about focalisation of the process (cases of 2009 L'Aquila and 2012 Emilia earthquakes)
5. Together with some other applications
6. Future can provide other cases of application in other fields of Earth sciences.



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