Natural time analysis of Seismicity: Recent Results

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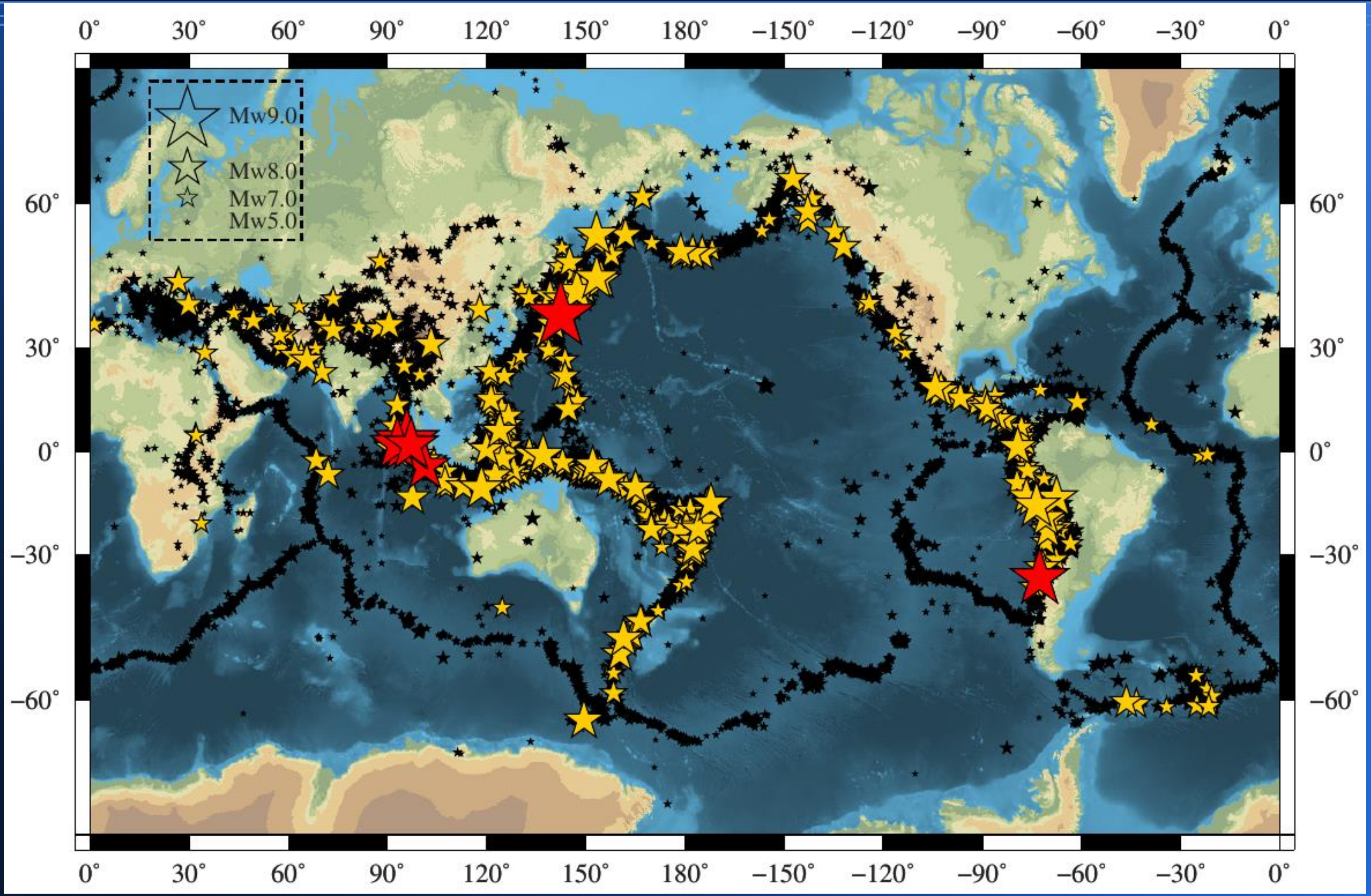
OUTLINE

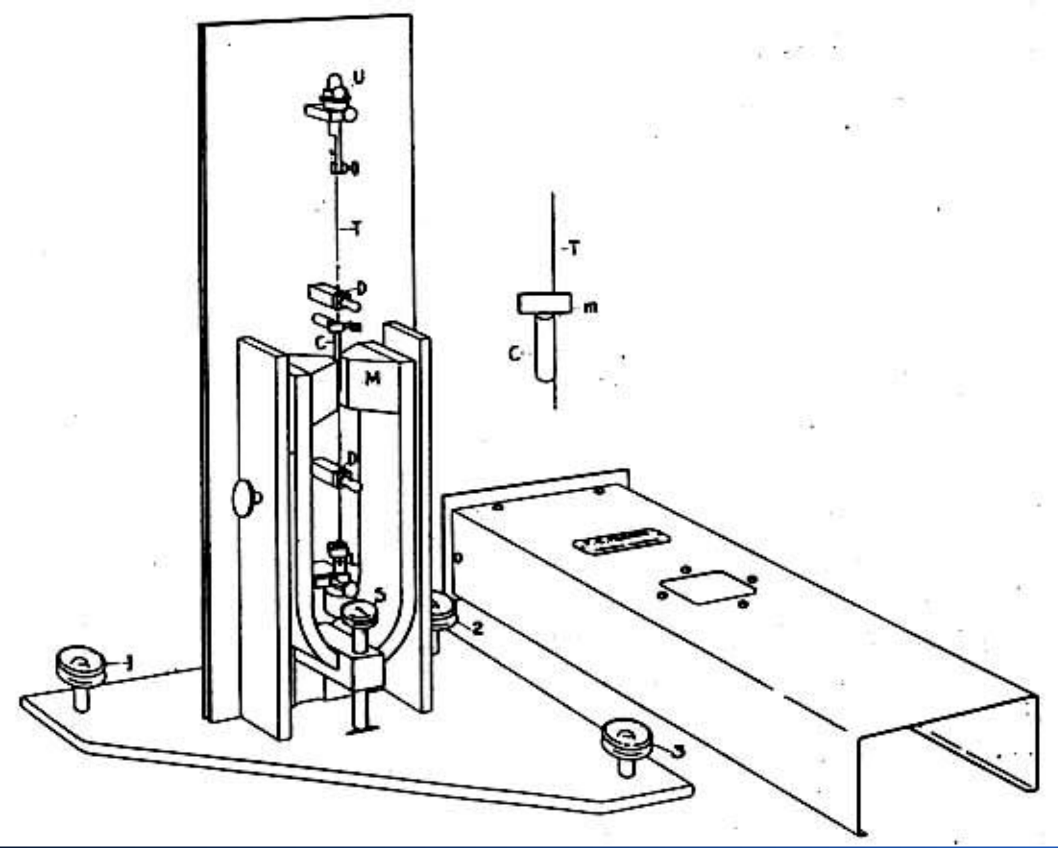
- The Gutenberg-Richter (GR) law of seismicity
- Derivation of the GR law on the basis of Tsallis non-additive entropy statistical mechanics
- Natural time analysis background
- Introduction of the order parameter κ_1 for seismicity
- The long term behaviour of κ_1 for seismic active areas and the GR law
- Study of the order parameter fluctuations before major earthquakes

The Gutenberg-Richter (GR) law of seismicity



N.V.S., S.-R. G. Christopoulos, and E.S. Skordas (2015) Minima of the fluctuations of the order parameter of global seismicity, *Chaos*, **25**, 063110.

The Gutenberg-Richter (GR) law of seismicity



Anderson, J. A., and H. O. Wood (1925) Description and theory of the torsion seismometer, *Bull. Seismol. Soc. Am.* **15**, 1–72.

The Gutenberg-Richter (GR) law of seismicity

Bulletin of the Seismological Society of America

VOL. 25 JANUARY, 1935 No. 1

AN INSTRUMENTAL EARTHQUAKE MAGNITUDE SCALE*

BY CHARLES F. RICHTER

In the course of historical or statistical study of earthquakes in any given region it is frequently desirable to have a scale for rating these shocks in terms of their original energy, independently of the effects which may be produced at any particular point of observation. On the suggestion of Mr. H. O. Wood, it is here proposed to refer to such a scale as a "magnitude" scale. This terminology is offered in distinction from the name "intensity" scale, now in general use for such scales as the Rossi-Forel and Mercalli-Cancani scales, which refer primarily to the local intensity of shock manifestation.

C. F. Richter (1935) *Bull. Seism. Soc. Am.* **25,** 1-32.

The Gutenberg-Richter (GR) law of seismicity

The procedure may be interpreted to give a definition of the magnitude scale number being used, as follows: *The magnitude of any shock is taken as the logarithm of the maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer* ($T_0 = 0.8$ *sec.*, $V = 2800$, $h = 0.8$) *would register that shock at an epicentral distance of 100 kilometers.*

SUMMARY

1. Comparison of the maximum amplitudes recorded at different epicentral distances by the torsion seismometers of the Southern California group makes it possible to rate earthquakes in this region in terms of a magnitude scale. The magnitude assigned is characteristic of the shock as a whole; it thus differs from the intensity, which varies from point to point of the affected area.

2. The magnitude of a shock is defined as the logarithm of the calculated maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer ($T_0 = 0.8$, $V = 2{,}800$, $h = 0.8$) would register that shock at an epicentral distance of 100 kilometers.

C. F. Richter (1935) *Bull. Seism. Soc. Am.* **25,** 1-32.

The Gutenberg-Richter (GR) law of seismicity

FREQUENCY OF EARTHQUAKES IN CALIFORNIA*

By B. GUTENBERG and C. F. RICHTER

ESTIMATES of the frequency of destructive shocks in California have usually been based on the very imperfect historical record. The present note attempts to revise these estimates by statistical comparison of earthquake frequency in California with that of the world as a whole.

Listing is complete for magnitude 4 and higher; for magnitude 3.5, various estimates indicate that the count is roughly 20 per cent too small. Supposing

$$\log N = a + b\,(8 - M) \tag{1}$$

a least-squares solution gives

$$a = -2.04 \pm 0.09, \qquad b = 0.88 \pm 0.03 \tag{2}$$

B. Gutenberg and C.F.Richter (1944) *Bull. Seismol. Soc. Am.* **34**, 185–188.

The GR law of seismicity $N(>M)=10^{a-bM}$

Considering that the seismic energy E released during an earthquake is related [39] to the magnitude through

$$E \propto 10^{c\mathrm{M}}, \tag{6.3}$$

where c is around 1.5, Eq. (6.2) turns to the distribution of Eq. (2.98), i.e.,

$$P(E) \propto E^{-\gamma} \tag{6.4}$$

for the earthquake energies E, where

$$\gamma = 1 + b/1.5. \tag{6.5}$$

39. Kanamori, H.: Quantification of earthquakes. Nature **271**, 411–414 (1978)

Derivation of the GR law on the basis of Tsallis non-additive entropy statistical mechanics

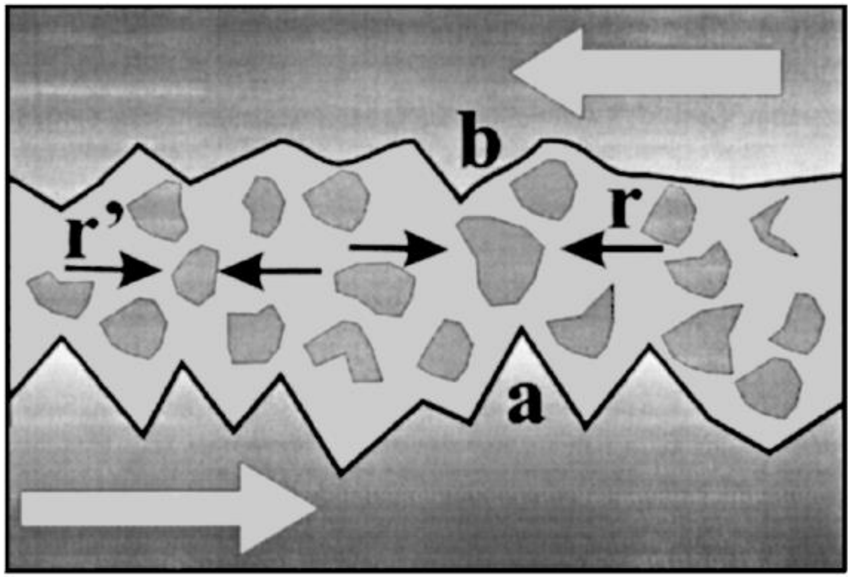


FIG. 1. An illustration of the relative motion of two irregular faults in the presence of material filling the space between them. Observe that this material may play the role of bearings or also of particles that hinder the relative motion of the plates as seen in the figure between points *a* and *b*.

The fault motion can be hindered not only by the overlapping of two irregularities of the profiles, but also by the eventual relative position of several fragments as illustrated in the figure between the points "a" and "b." Stress in the resulting structure accumulates until a displacement of one of the asperities, due to the displacement of the hindering fragment, or even its breakage in the point of contact with the fragment leads to a relative displacement of the fault planes of the order of the size of the hindering fragment "r."

O. Sotolongo-Costa and A. Posadas, (2004) Fragment-asperity interaction model for earthquakes *Phys. Rev. Lett.* **92**, 048501.

Derivation of the GR law on the basis of Tsallis non-additive entropy statistical mechanics

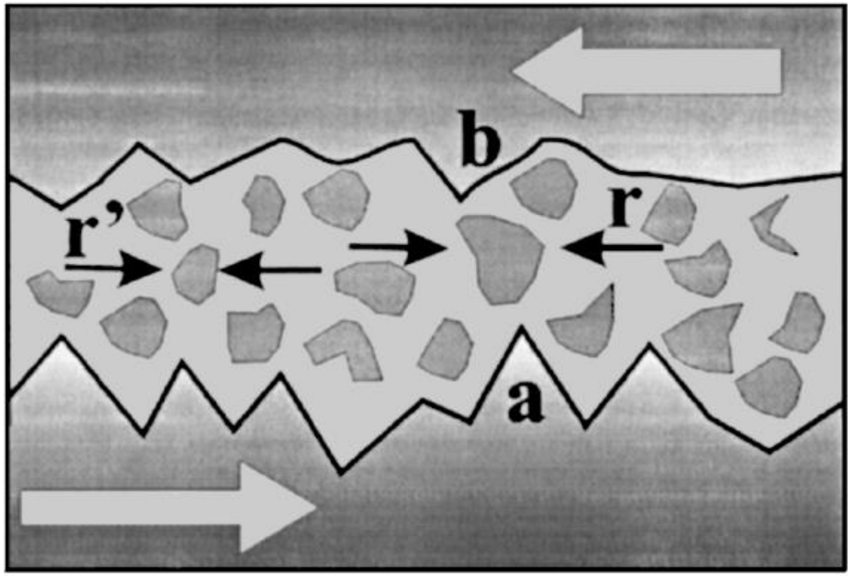


FIG. 1. An illustration of the relative motion of two irregular faults in the presence of material filling the space between them. Observe that this material may play the role of bearings or also of particles that hinder the relative motion of the plates as seen in the figure between points *a* and *b*.

As large fragments are more difficult to release than small ones, Sotolongo-Costa and Posadas assume the earthquake energy "ε" to be proportional to r, so that the energy distribution of earthquakes generated by this mechanism can reflect the size distribution of the fragments between plates.

Then, they apply the maximum entropy principle for the Tsallis entropy:

$$S_q = k\frac{1 - \int p^q(\sigma)d\sigma}{q-1}$$

for the distribution *p(σ)* finding a fragment of relative surface *σ*.

O. Sotolongo-Costa and A. Posadas, (2004) Fragment-asperity interaction model for earthquakes *Phys. Rev. Lett.* **92**, 048501.

Derivation of the GR law on the basis of Tsallis non-additive entropy statistical mechanics

Then, the application of the maximum entropy principle under the constraints

$$\int_0^\infty p(\sigma)d\sigma = 1,$$

and

$$\int_0^\infty \sigma p^q(\sigma)d\sigma = \langle\langle\sigma\rangle\rangle_q.$$

leads to

$$p(\sigma)d\sigma = \frac{(2-q)^{1/(2-q)}d\sigma}{[1+(q-1)(2-q)^{(q-1)/(2-q)}\sigma]^{1/(q-1)}}$$

for the area distribution of the fragments of the fault plates.

Since the released relative energy ε was assumed proportional to the linear dimension r of the fragments and σ scales with r^2, the energy distribution function of earthquakes due to this mechanism can be obtained, which when assuming m∝log(ε) leads to

$$\log(N(>m)) = \log N + \left(\frac{(2-q)}{1-q}\right) \times \log[1 + a(q-1) \times (2-q)^{(1-q)/(q-2)} \times 10^{2m}].$$

O. Sotolongo-Costa and A. Posadas, (2004) Fragment-asperity interaction model for earthquakes *Phys. Rev. Lett.* **92**, 048501.

Derivation of the GR law on the basis of Tsallis non-additive entropy statistical mechanics

Later, Silva et al. (2006) revisited the same problem and applied the maximum entropy principle under the following constraints that make use of the escort distriburion $P_q(\sigma)$

$$\int_0^\infty p(\sigma)d\sigma = 1,$$, $$\sigma_q = \langle\sigma\rangle_q = \int_0^\infty \sigma P_q(\sigma)d\sigma$$ and $$P_q = \frac{p^q(\sigma)}{\int_0^\infty p^q(\sigma)d\sigma}$$

this led to $$p(\sigma) = \left[1 - \frac{(1-q)}{(2-q)}(\sigma - \sigma_q)\right]^{1/(1-q)}$$

for the area distribution of the fragments of the fault plates.

Then, assuming for the energy $\varepsilon \propto r^3$, Silva et al. (2006) obtained the energy distribution function $p(\varepsilon)$ for the earthquakes and by considering the relationship $m = \ln(\varepsilon)/3$:

$$\log\left(\frac{N_{>m}}{N}\right) = \left(\frac{2-q}{1-q}\right)\log\left[1 - \left(\frac{1-q}{2-q}\right)\frac{10^{2m}}{a^{2/3}}\right]$$

R. Silva, G. S. França, C. S. Vilar, and J. S. Alcaniz (2006) Nonextensive models for earthquakes *Phys. Rev. E* **73**, 026102.

Derivation of the GR law on the basis of Tsallis non-additive entropy statistical mechanics

$$\log\left(\frac{N_{>m}}{N}\right) = \left(\frac{2-q}{1-q}\right)\log\left[1-\left(\frac{1-q}{2-q}\right)\frac{10^{2m}}{a^{2/3}}\right]$$

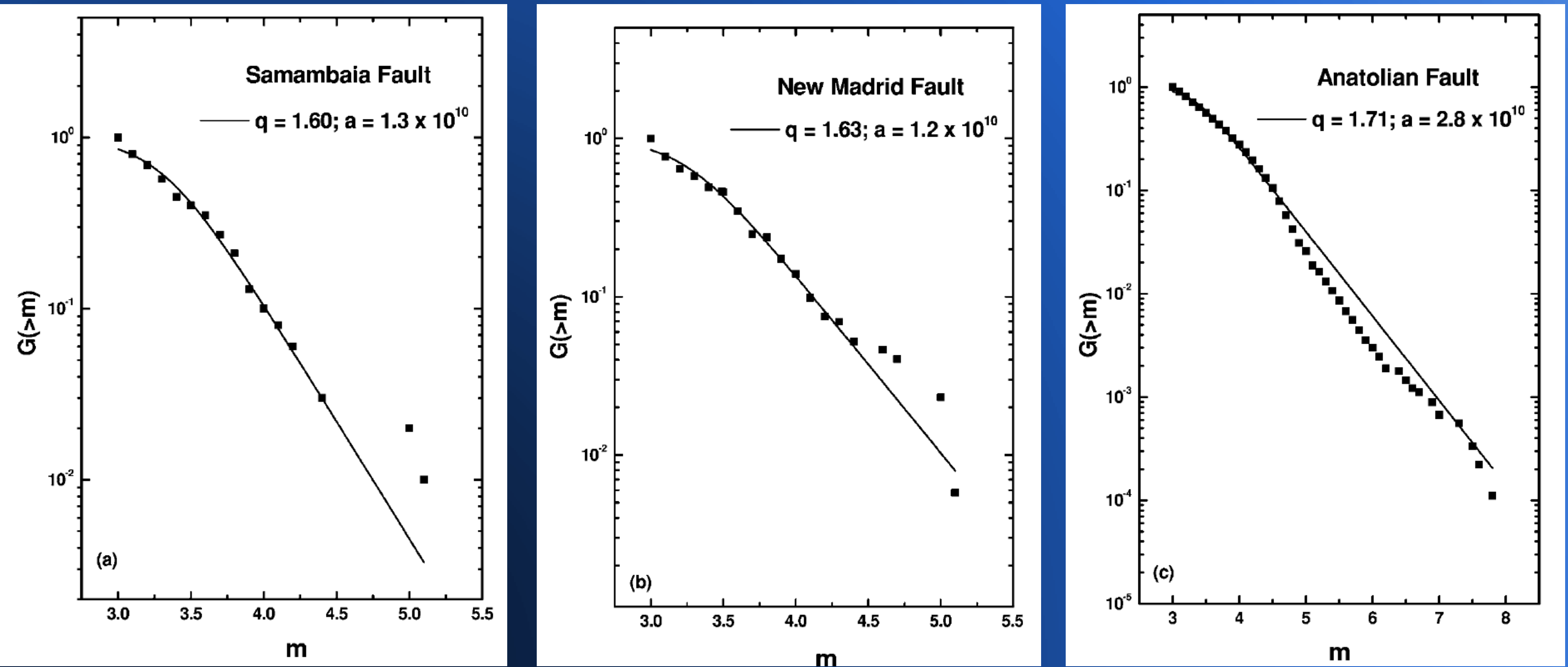
The above equation incorporates the characteristics of nonextensivity into the distribution of earthquakes by magnitude, and the GR law can be deduced as its particular case when considering a significant magnitude threshold. Then, it reduces to the GR law with*

$$b = 2(2 - q)/(q - 1).$$

Thus, it can be alternatively termed as a generalized GR law.

*N.V.S., E. S. Skordas, and P. A. Varotsos (2010) Nonextensivity and natural time: The case of seismicity, *Phys. Rev. E* **82**, 021110.

Derivation of the GR law on the basis of Tsallis non-additive entropy statistical mechanics



Brazil U.S.A. Turkey

R. Silva, G. S. França, C. S. Vilar, and J. S. Alcaniz (2006) Nonextensive models for earthquakes *Phys. Rev. E* **73**, 026102.

NATURAL TIME ($\chi\rho\acute{o}\nu o\varsigma$)

It was suggested by P. Varotsos, N. Sarlis and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001). For a recent review see P. Varotsos, N. Sarlis and E. Skordas "Natural Time Analysis: The New View of Time" Springer-Verlag (2011).

Ion current fluctuations in membrane channels

exhibit properties described by the "uniform" distribution which is completely different from those of SES (critical dynamics)

Phys.Rev.E **66**, 011902 (2002)

Analysis of electrocardiograms in natural time:

The **sudden cardiac death** individuals are distinguished from the truly healthy ones as well as from patients.

Phys. Rev. E **70**, 011106 (2004);*Phys. Rev. E* **71**, 011110 (2005);*Appl. Phys. Lett.* **91**, 064106(2007); *EPL* **87**, 18003 (2009); *EPL* **109**, 18002 (2015)

The **entropy** S changes to S- **under time reversal**.

*Phys.Rev.E***71**, 032102 (2005) and its change can be used for predicting the avalanches in the OFC model Tectonophysics **513**, 49 (2011)

Discrimination of SES activities (strongest memory) **from noise** emitted from nearby artificial sources

*Phys.Rev.E***67**, 021109 (2003); *CHAOS* **19**, 023114(2009); **20** 033111 (2010); *Tectonophysics* **503,** 189-194 (2011)**.**

Physics of Earthquakes:

- Universal curve
- Order parameter
- which exhibits characteristic fluctuations before mainshocks
- Identify correlations between earthquake magnitudes
- Studying the seismicity after an SES activity, we can determine **the time-window of the impending mainshock** with good accuracy of a few hours to a few days.
- Predict the magnitude of aftershocks

Similar looking signals that are emitted from systems **with different dynamics** can be distinguished.

Modern techniques of statistical physics, e.g., Hurst Analysis, Wavelet transform, Detrended Fluctuation Analysis (DFA) etc. should be better made in natural time.

Phys. Rev. E **68**, 031106 (2003)

- High **Tc-superconductors**

(Small changes in the magnetic field can result in large rearrangements of fluxing the sample, known as flux avalanches)

- **Rice piles**

(**S**elf **O**rganized **C**riticality)

Phys.Rev.B **73**, 054504 (2006); *EPL* **96**, 28006 (2011)

- **Critical Systems** in general

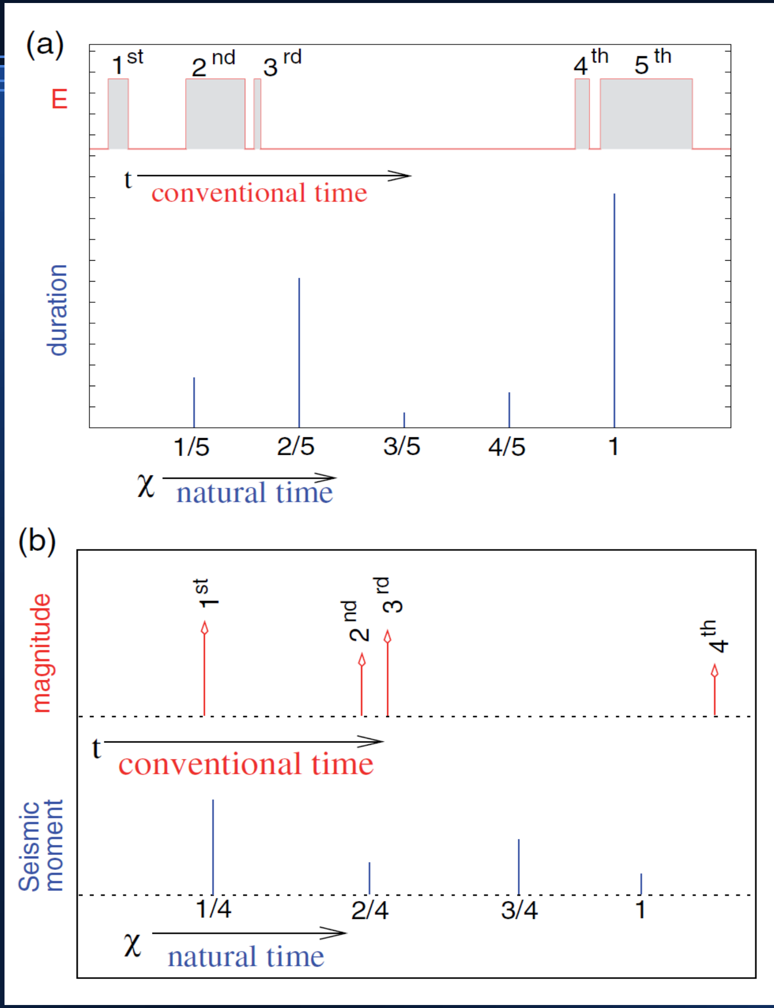
Proc. Natl. Acad. Sci. USA **108,** 11361-11364 (2011)

Applications to the physics of earthquakes:

Practica Athens Acad. **76**, 294-321 (2001); *Acta Geophys. Pol.* **50**,337-354 (2002)

- **Order parameter (OP)** *Phys. Rev. E* **72** , 041103 (2005)
- **Universal curve** *Phys. Rev. E* **72** , 041103 (2005);**82**, 021110 (2010), *EPL* **100** 39002 (2012)
- **This OP:** (1) exhibits **characteristic fluctuations before mainshocks** *EPL* **91**, 59001(2010); **96** 59002 (2011); **99** 59001 (2012), *Nat. Hazards Earth Syst. Sci.* **12**, 3473–3481(2012), *Tectonophysics* **589**, 116-125(2013); *Proc. Natl. Acad. Sci. USA* **110**, 13734–13738(2013); *Pure Appl. Geophys.*, DOI: 10.1007/s00024-014-0930-8 (2014); *J. Geophys. Res.* Space Physics **119**, 9192–9206 (2014);*Proc. Natl. Acad. Sci. USA* **112**, 986–989 (2015); *Scientific Reports* **8**, 9206 (2018) (2) **identifies correlations** between earthquake magnitudes *Phys. Rev. E* **74**, 051118 (2006); **80**, 022102 (2009);**82**, 021110(2010); **84**, 022101 (2011), *CHAOS* **22**, 023123 (2012)
- Studying the seismicity after an SES activity, we can determine **the time window of the impending mainshock** with good accuracy of a few days to one week. *Practica Athens Acad.* **76**, 294-321 (2001); *Acta Geophys. Pol.* **50**, 337-354 (2002); *Phys. Rev. E* **72**, 041103 (2005); **73**, 031114 (2006); **74**, 021123 (2006), *J. Appl. Phys.* **103**, 014906 (2008), *Proc. Jpn Acad. Ser. B* **84**, 331-343 (2008), *J. Geophys. Res.* **114** B02310 (2009); *EPL* **92**, 29002 (2010); *Proc. Jpn. Acad. Ser. B* **89**, 438-445(2013); *J. Asian Earth Sci.* **80** **,** 161–164 (2014); *Earthq. Sci.* **28** , 215-222 (2015); *Earthq. Sci.* **30,** 183-191 (2017); **30,** 209-218 (2017)
- Prediction of aftershock magnitudes: *Phys. Rev. E* **85,** 051136 (2012); *Complexity* **2017**, 6853892 (2017)

Introduction to Natural Time Analysis (NTA)



P. Varotsos, N. Sarlis, and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001)

Let us assume a time series comprising N events. In NTA, the first event is `placed' on the horizontal axis at χ_1=1/N, the second at χ_2=2/N etc. In general, the event that occurred k-th in order is placed at χ_k=k/N

We call χ_k=k/N natural time.

For each event k, we consider a quantity Q_k which is, in general, proportional to the released energy E_k.

In NTA, we study the evolution of the pair (χ_k,Q_k).

In order to study the evolution of the pairs (χ_k, Q_k) in natural time analysis, we define the normalized energy release:

$$p_k = Q_k / \sum_{n=1}^{N} Q_n$$

- Since p_k are positive and sum up to unity they can be considered as probabilities. Thus,

$$\Phi(\omega) = \langle \exp(i\omega\chi) \rangle = \sum_{n=1}^{N} p_n \exp(i\omega\chi_n)$$

or $\Pi(\omega)=|\Phi(\omega)|^2$

may be considered as characteristic functions for the distribution of p_k in the sense of Probability Theory.

P. Varotsos, N. Sarlis, and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001)

The variance κ_1 of natural time

Since characteristic functions provide information on the distribution when $\omega \rightarrow 0$, we study $\Pi(\omega)$ in this limit:

As $\omega \rightarrow 0$, $\Pi(\omega) \approx 1 - \kappa_1 \omega^2$

where

$$\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2 = \sum (\chi_k)^2 p_k - \left(\sum \chi_k p_k\right)^2$$

is the variance of natural time.

P. Varotsos, N. Sarlis, and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001)

Important properties of κ_1

*The quantity κ_1, or equivalently the quantity $\Pi(\omega)=|\Phi(\omega)|^2$ for $\omega\rightarrow 0$, has been proposed as an *order parameter (OP)* for seismicity.
[P. Varotsos et al. *Phys. Rev. E* **72**, 041103 (2005)]

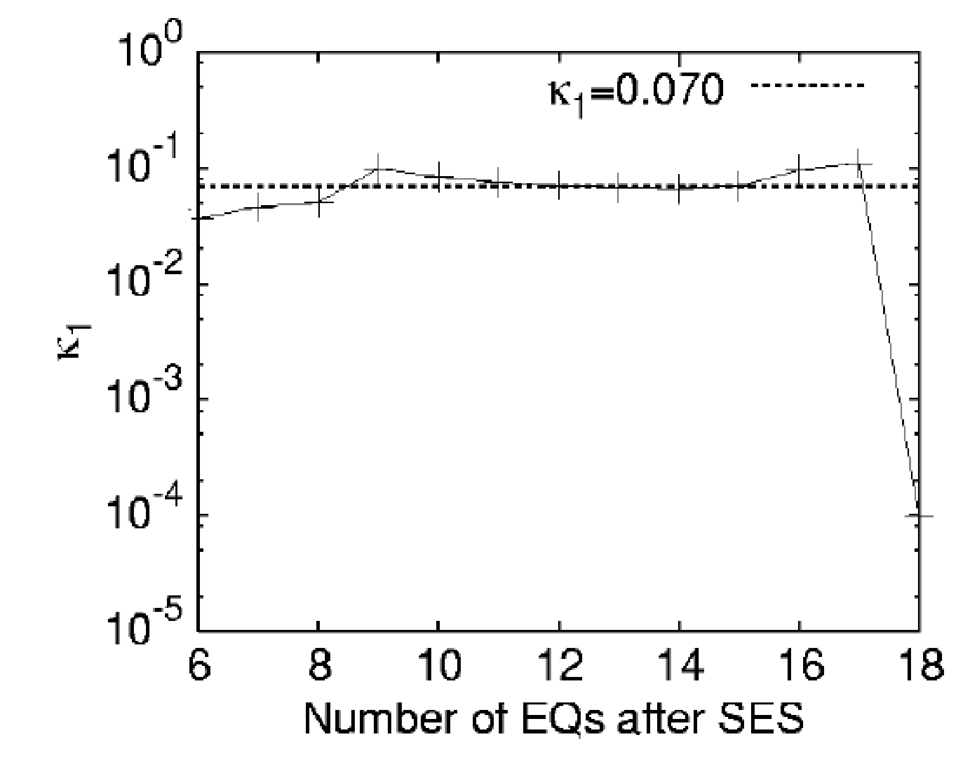
*For systems at criticality the following condition holds κ_1=0.070
[P. Varotsos et al. *Proc. Nat. Acad. Sci. USA* **108,** 11361-11364 (2011) **]**

Definition of the order parameter (OP)

According to L.D. Landau and E.M. Lifshitz (*Statistical Physics 3rd Edition Part 1,* Pergamon Press, Oxford 1980, see p.449):

"To describe quantitatively the change in the structure of the body when it passes through the phase transition point, we can define a quantity η, called the *order parameter,* in such a way that it takes non-zero (positive or negative) values in the unsymmetrical phase and is zero in the symmetrical phase."

Why κ_1 behaves like an OP for seismicity?



The value of κ_1 after the Seismic Electric Signal on April 18, 1995 until the M6.6 Kozani-Grevena EQ on May 13, 1995 (labelled 18).

Phys. Rev. E, **72** (2005) 041103

- κ_1 is non-zero before the occurence of a strong earthquake (EQ) (like magnetization M is non-zero below the Curie temperature in the unsymmetrical phase)
- κ_1 becomes zero upon the occurrence of a strong EQ (like M is zero above the Curie temperature in the symmetrical phase)

Similarity in the fluctuations of the order parameter for correlated systems

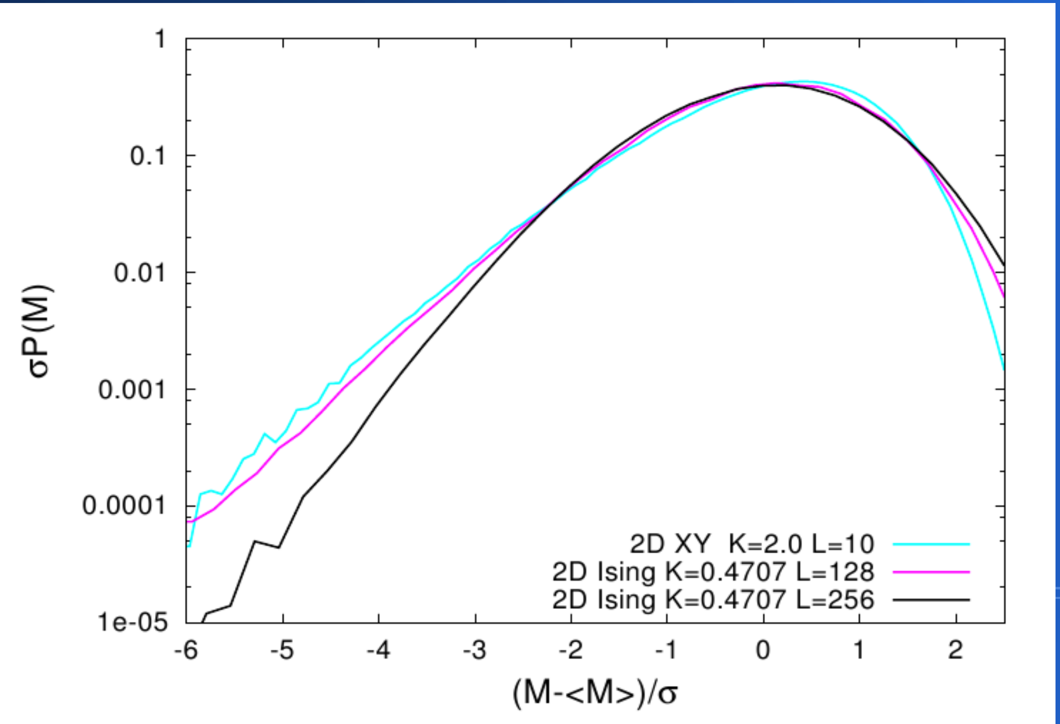
Bramwell, Holdsworth and Pinton (BHP) [*Nature* **396,** 552(1998)] in an experiment of a closed turbulent flow, found that the (scaled) probability distribution function (pdf) of the power fluctuations has the same functional form as that of the magnetization M of the finite-size 2D (two-dimensional) XY equilibrium model in the critical region below the Kosterlitz-Thouless transition temperature (Magnetic ordering is then described by the *order parameter* M).

The scaled pdf, denoted by P(m), is defined by introducing the reduced magnetization $m=(M-\langle M\rangle)/\sigma$, where $\langle M\rangle$ denotes the mean and σ the standard deviation. For both systems, BHP found that while the high end ($m>0$) of the distribution has a Gaussian shape, a distinctive exponential tail appears towards the low end ($m<0$) of the distribution.

For systems with a second-order phase transition, the scaled pdf of the order parameter in the critical regime depends [B. Zheng and S. Trimper, Phys. Rev. Lett. 87, 188901 2001] on $K=1/T$ and the length L through a scaling variable

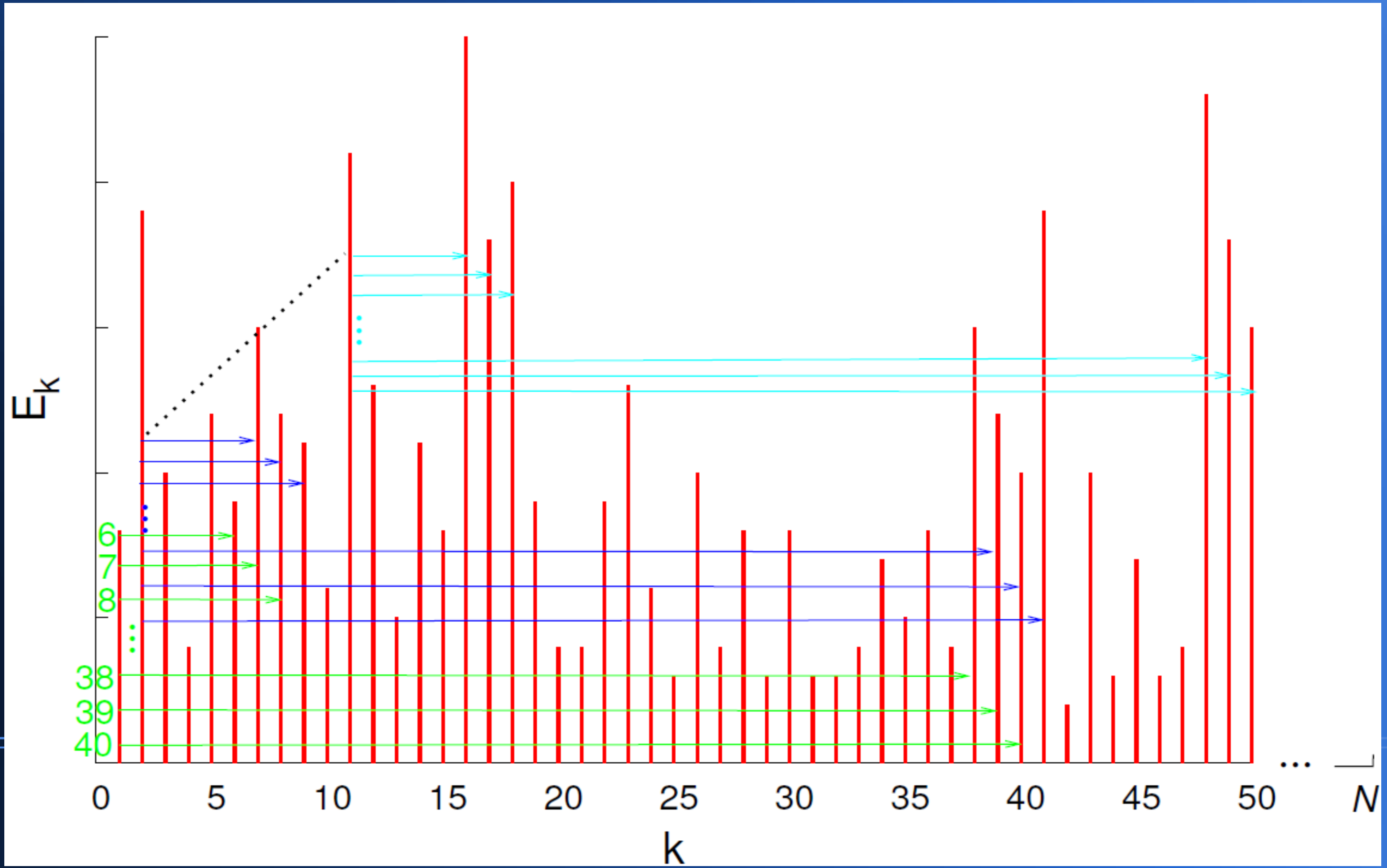
$$s=L^{1/\nu}(K-K_c)/K_c,$$

where $K_c=1/T_c$ and T_c denotes the critical temperature. The quantity s^ν provides the ratio of the lattice size and the correlation length at K. In the figure, we include numerical results of the 2D Ising model for $s=8.72$ $L=128$, $K=0.4707$ and $s=17.44$ $L=256$, $K=0.4707$. These s values were intentionally selected because for $s\geq 8.72$[B. Zheng, Phys. Rev. E 67, 026114 2003], the scaled pdfs for the 2D Ising model and of a number of other critical models i.e., 2D XY, 2D Ising, 3D Ising, 2D three-state Potts share the same form up to a constant factor of s.



Construction of the probability density function of the OP κ_1 of *seismicity*

We consider sliding windows of 6 to 40 events and estimate κ_1 for each earthquake (EQ) in the EQ catalog



This way we construct the probability distribution (pdf) P(κ$_1$) which changes once we randomly 'shuffle' the catalog

Phys. Rev. E **74**, 021123 (2006)

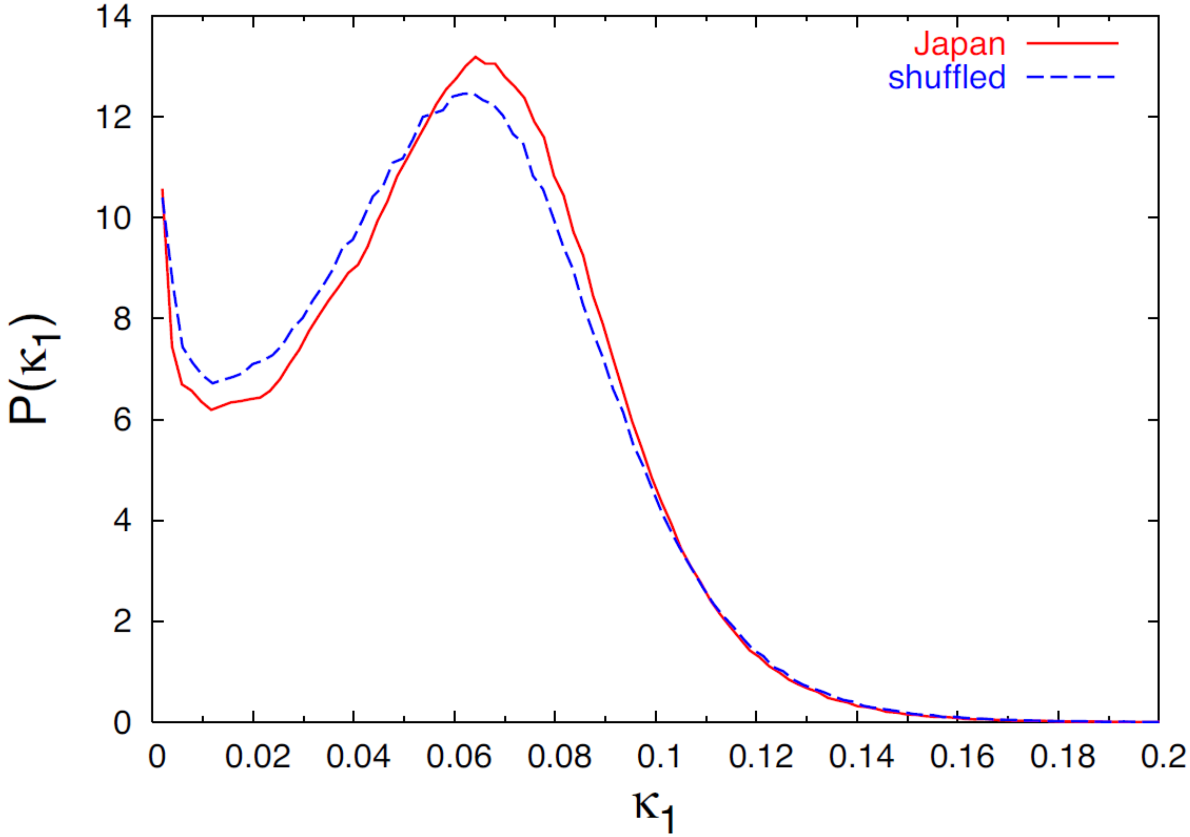
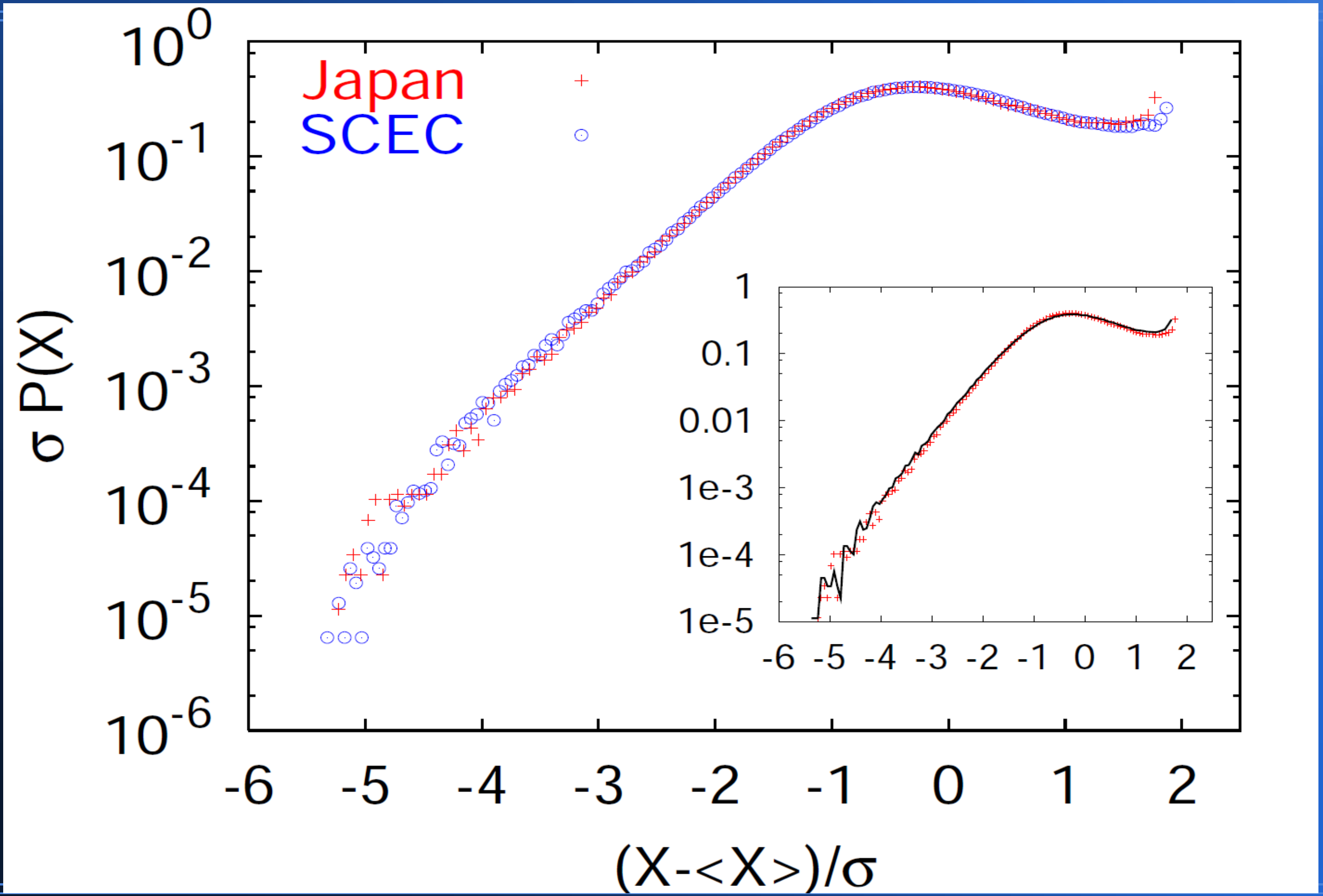


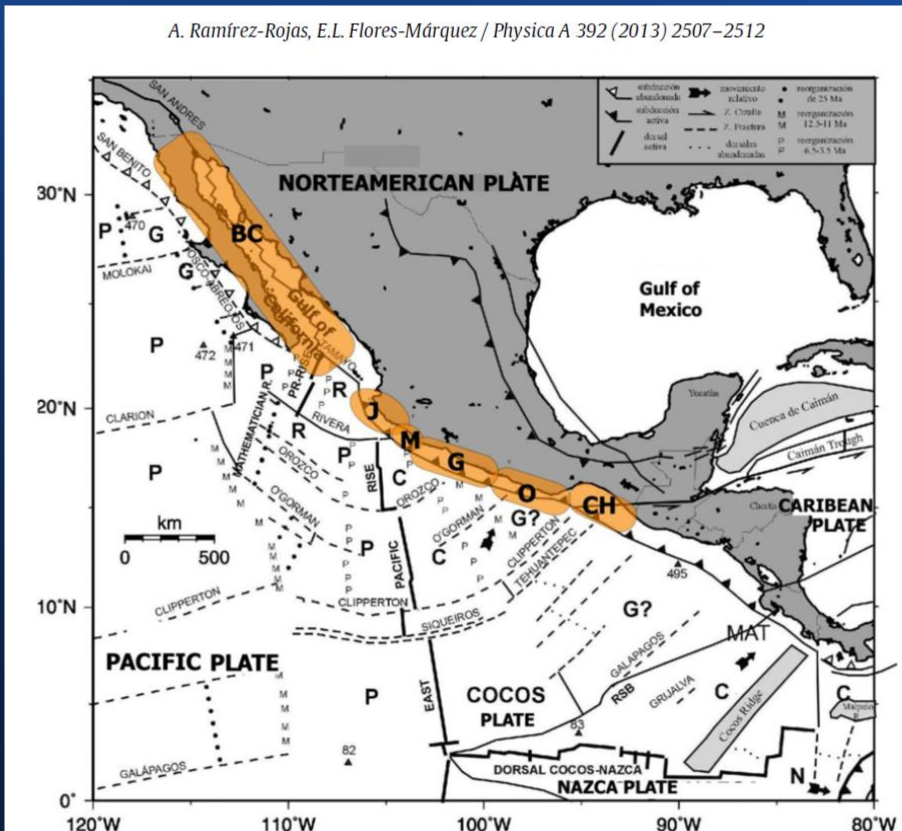
FIG. 5. (Color online) The PDF's of κ_1 when using either the actual seismic catalog of Japan (solid red line) treated in Ref. [17] or the same data in random order (dashed blue line).

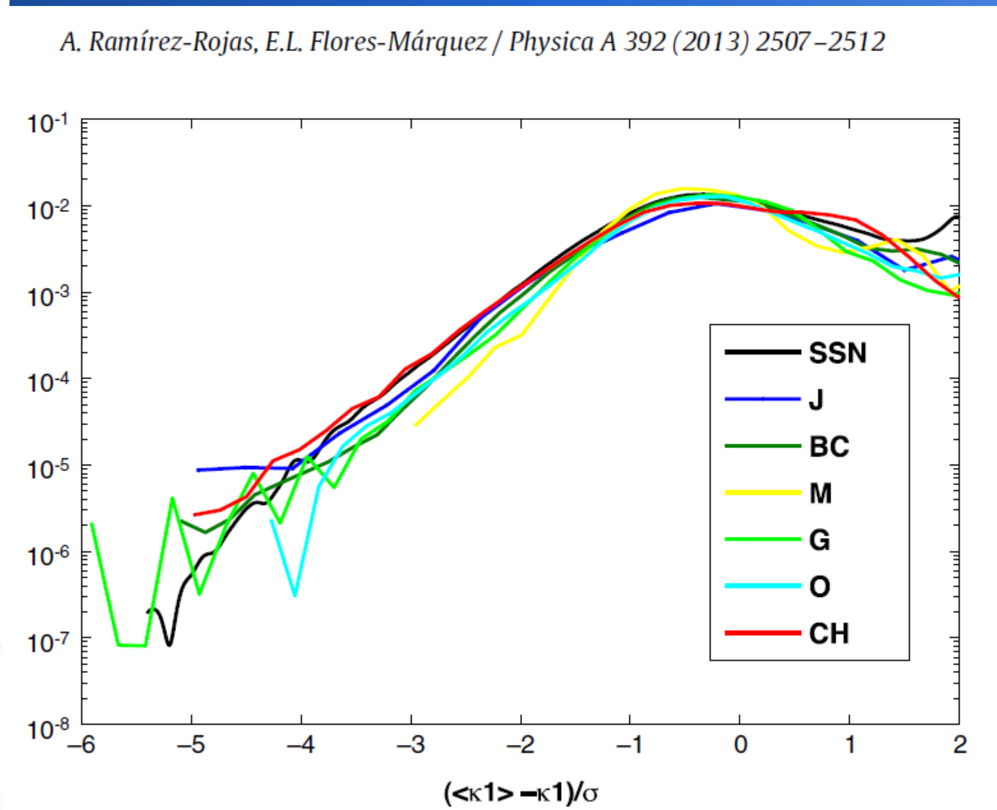
The scaled pdf however is universal for various regional seismicities



Phys. Rev. E **74**, 021123 (2006)

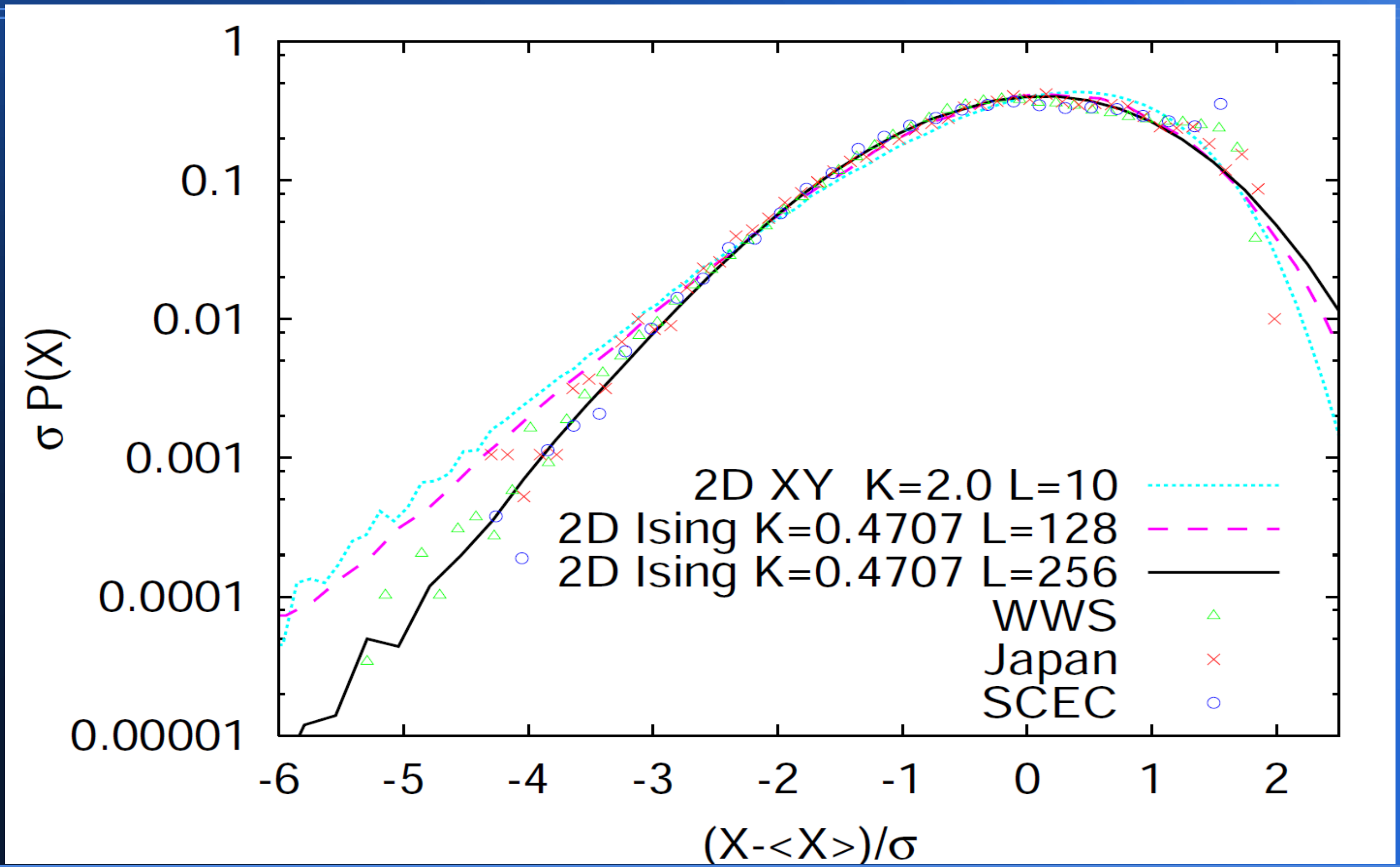
The scaled pdf however is universal for various regional seismicities





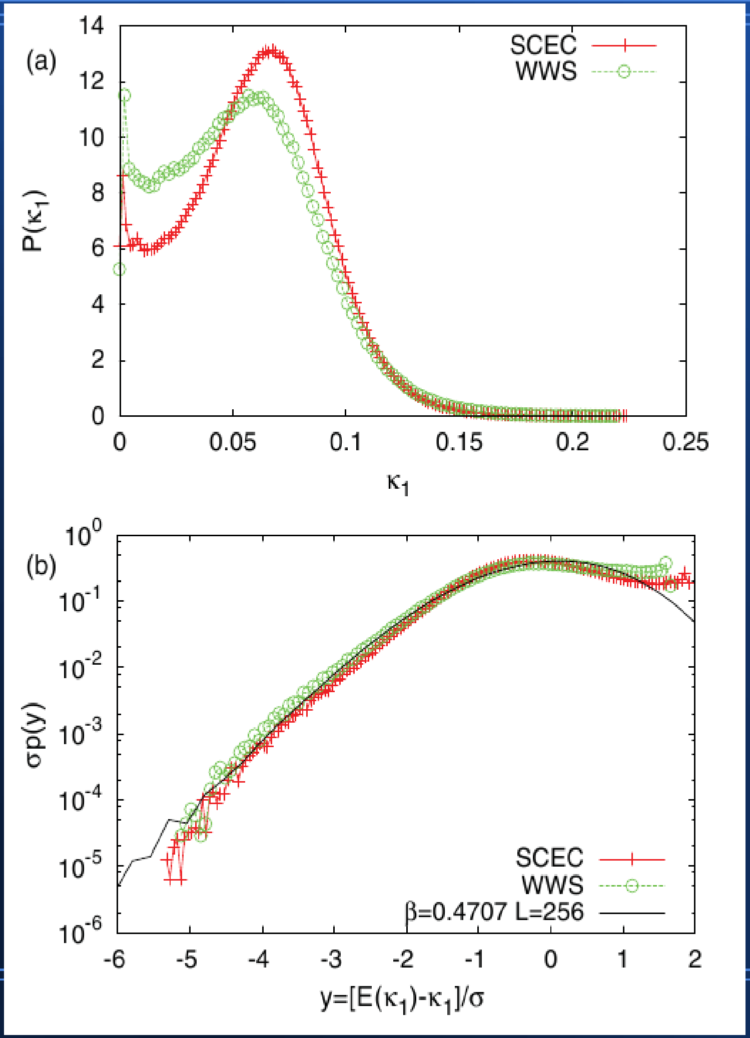
Physica A **392**, 2507-2512 (2013)

and collapses on that of other critical phenomena



Phys. Rev. E **74**, 021123 (2006)

the same behavior is also observed for the global seismicity when considering the most accurate global seismicity catalogs



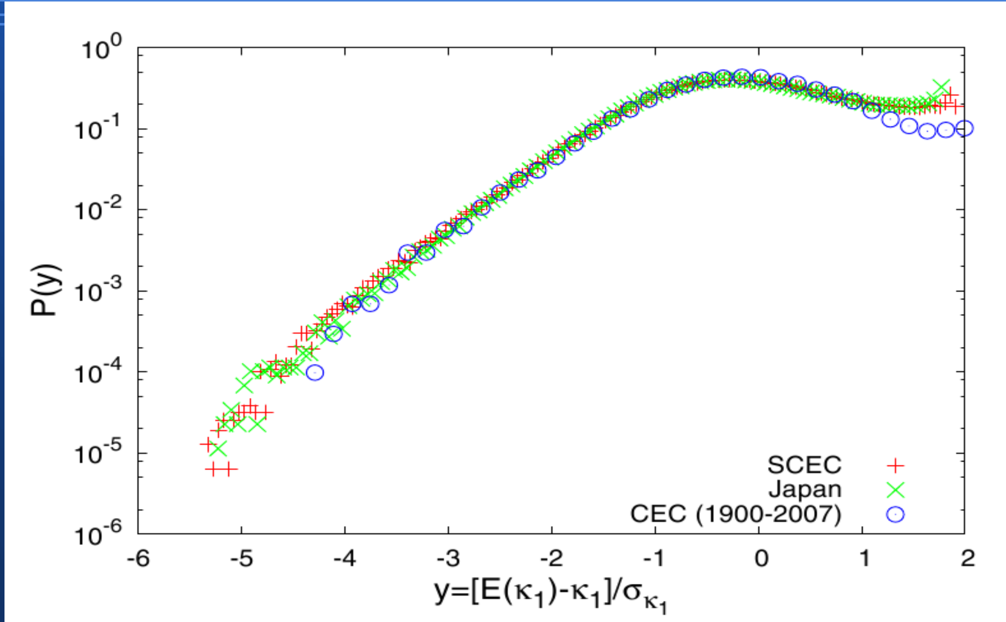


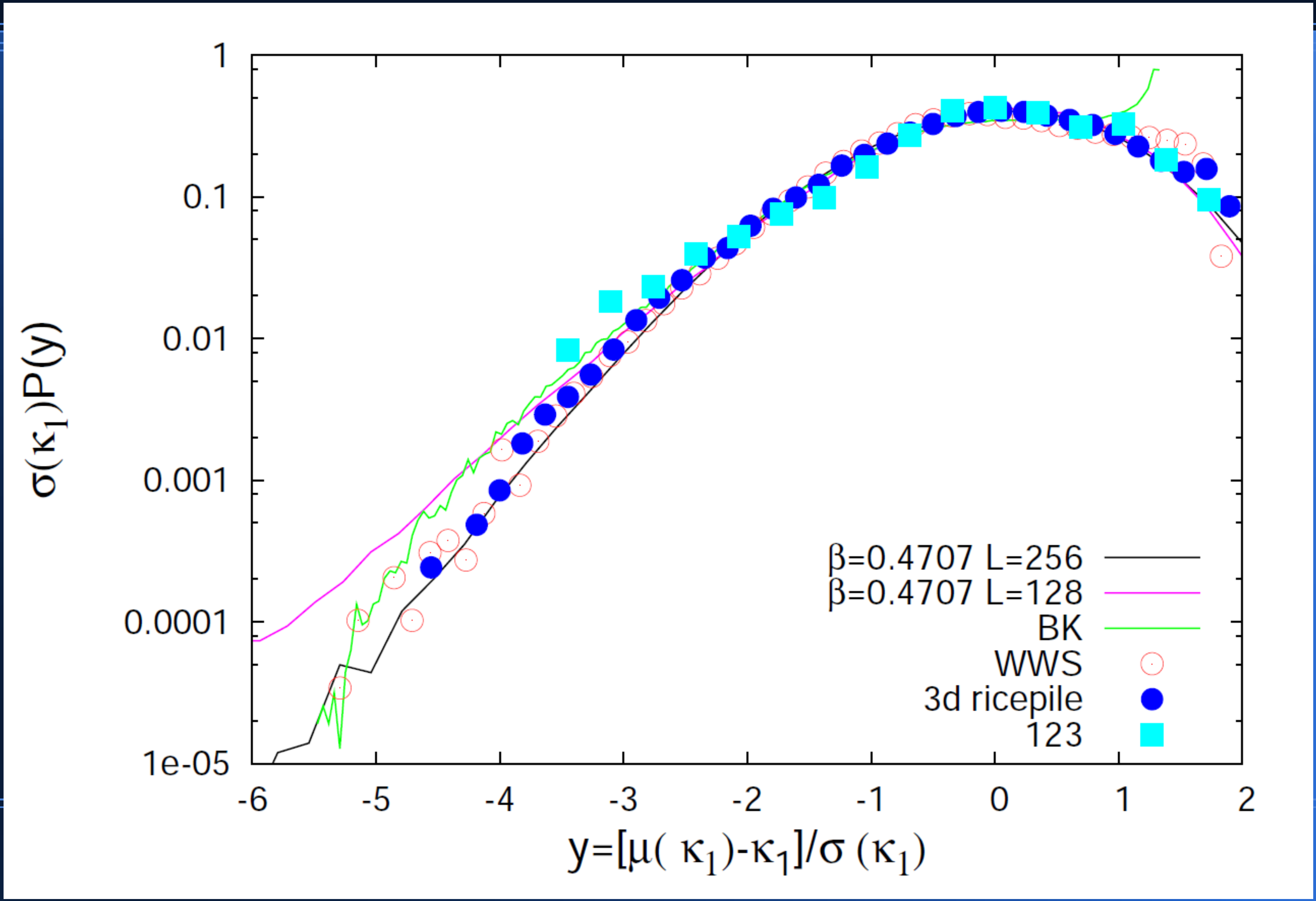
FIG. 2. The scaled probability density function of κ_1 for SCEC, Japan and Centennial Earthquake Catalog (CEC 1900–2007).

Chaos **22**, 023123 (2012)

and pertains down to the AE in Etna Bassalt [F.Vallianatos, G. Michas, P. Benson and P. Sammonds, *Physica A* **392**, 5172-5178 (2013)]

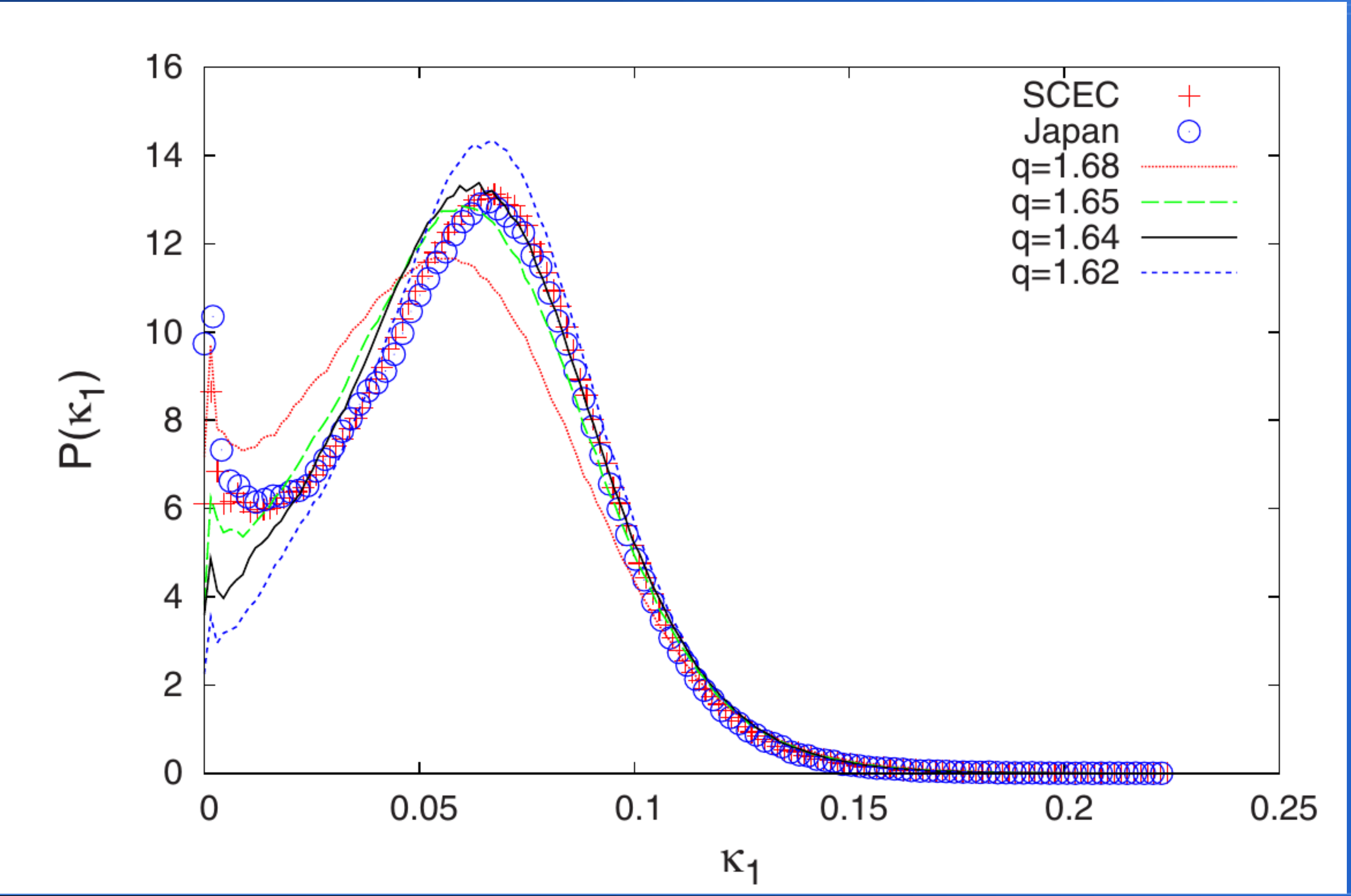
Similarity of fluctuations in systems exhibiting Self-Organized Criticality

EPL **96** (2011) 28006



The long term behaviour of κ_1 for seismicity, the GR law and the generalized GR law which is based on Tsallis non-additive entropy

PRE **82** (2010) 021110

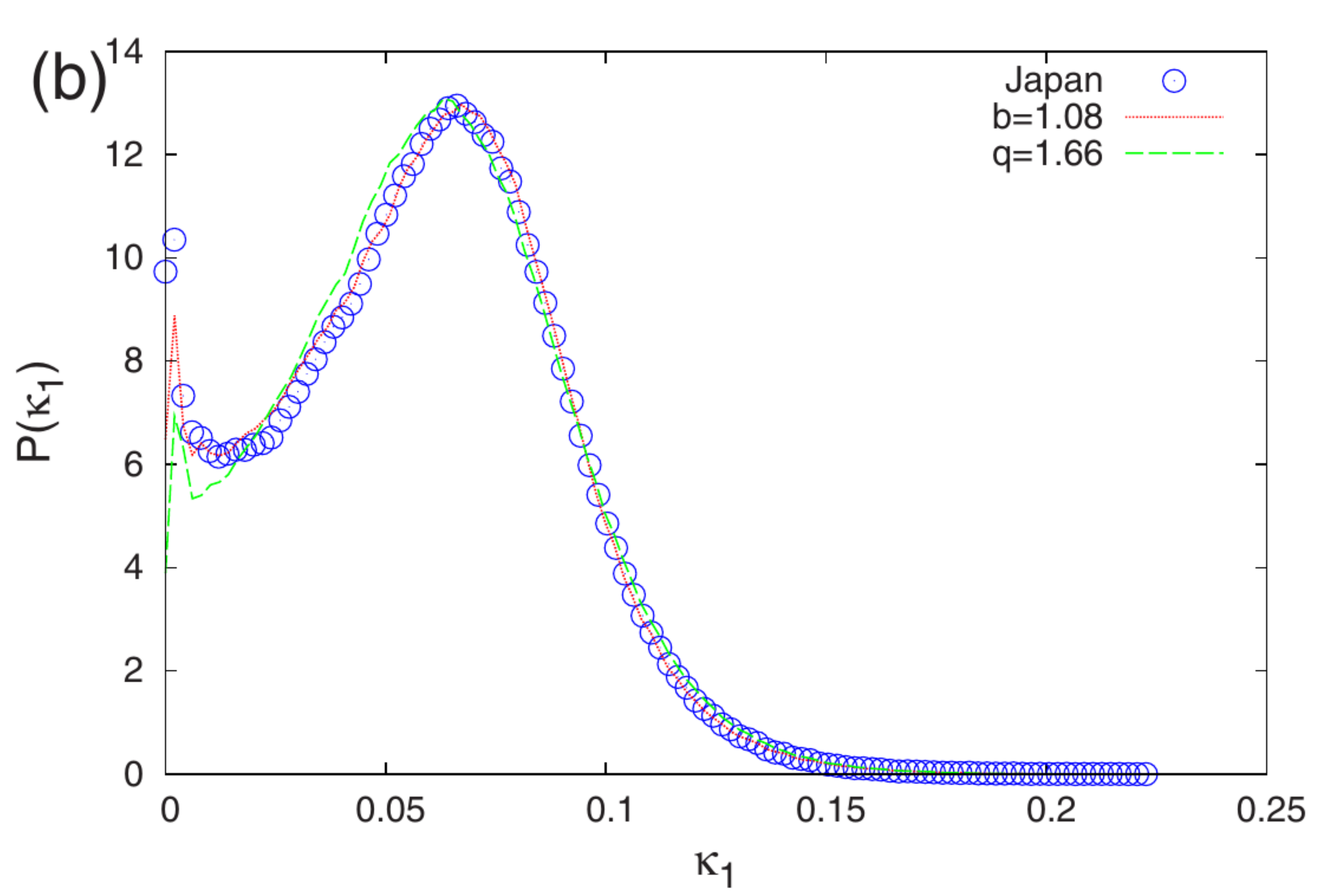


Results for Southern California and Japan

- (no temporal correlations between earthquake magnitudes)

The long term behaviour of κ_1 for seismicity, the GR law and the generalized GR law which is based on Tsallis non-additive entropy

PRE **82** (2010) 021110

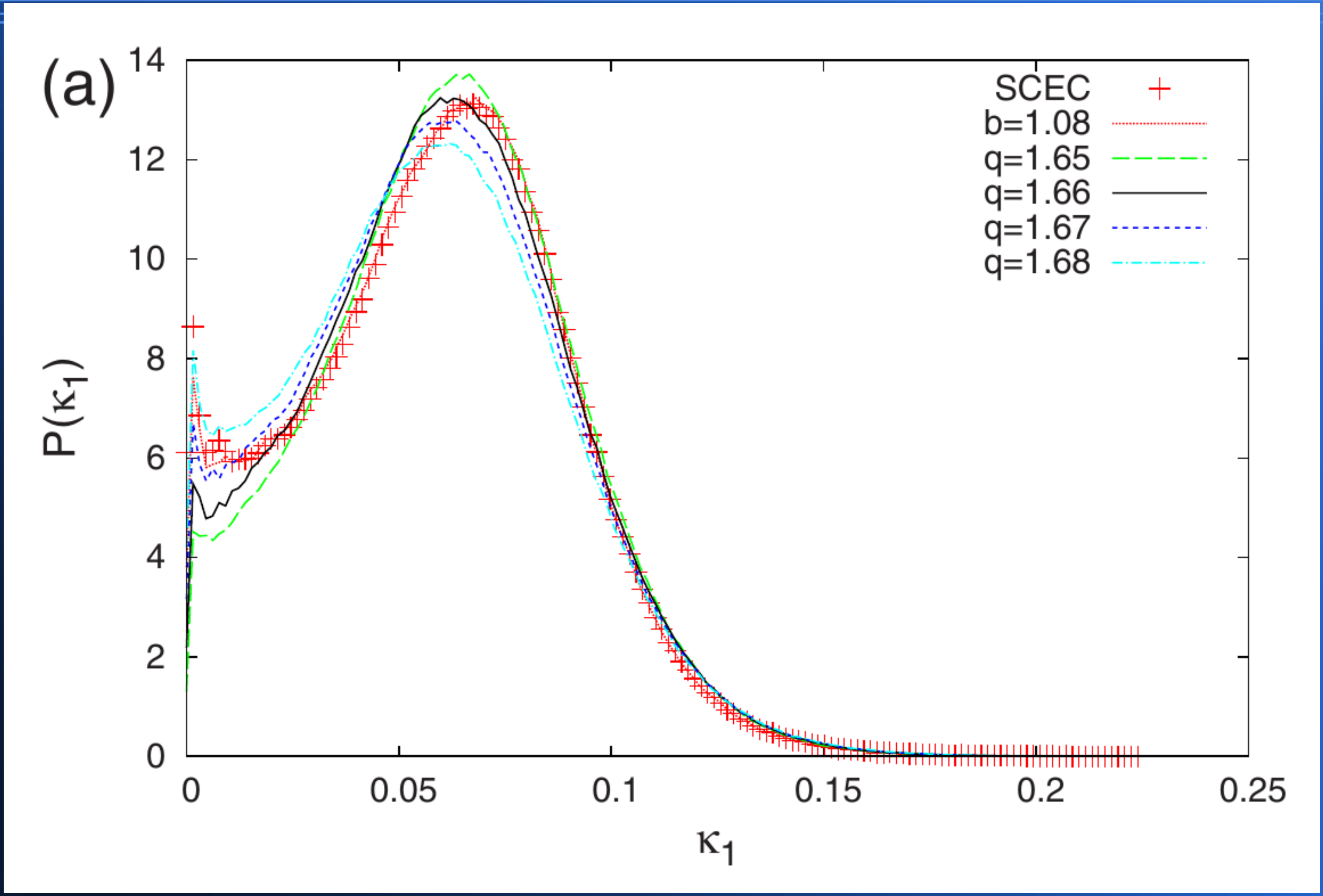


Results for Japan

- (WITH the observed temporal correlations between magnitudes)

The long term behaviour of κ_1 for seismicity, the GR law and the generalized GR law which is based on Tsallis non-additive entropy

PRE **82** (2010) 021110



Results for Southern California

- (WITH the observed temporal correlations between magnitudes)

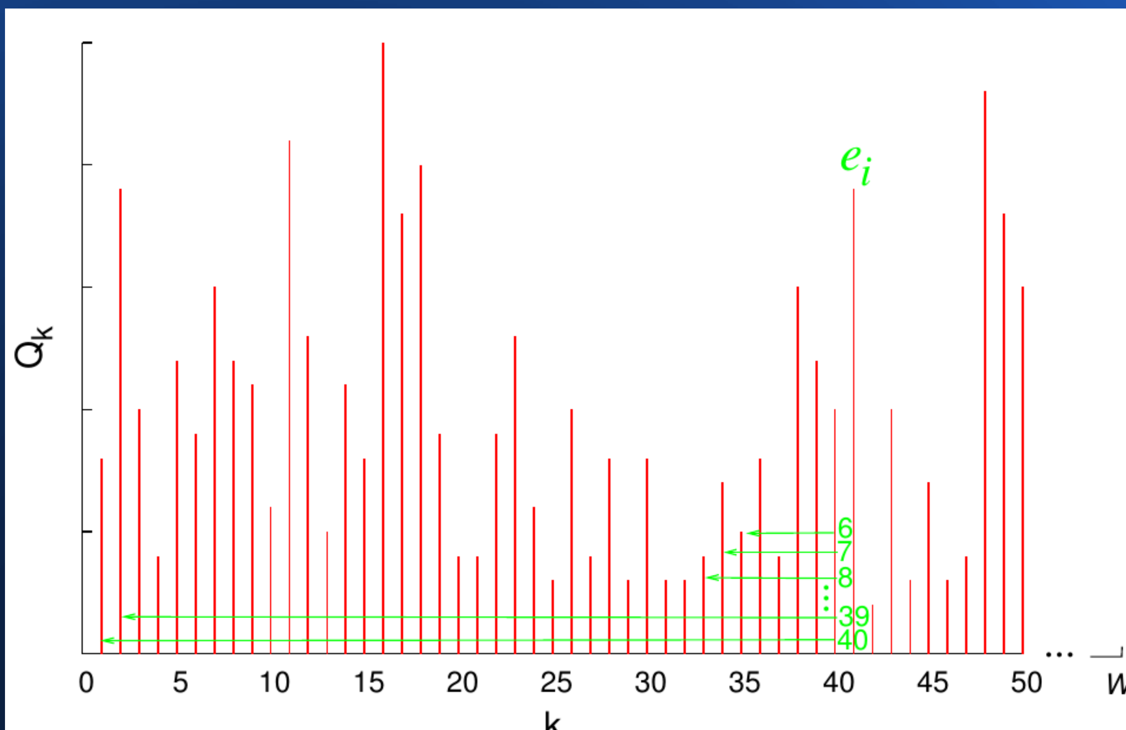
The long term behaviour of κ_1 for seismicity, the GR law and the generalized GR law which is based on Tsallis non-additive entropy

These results show that the nonextensive parameter *q* does not capture the effect of long-range temporal correlations between the magnitudes of successive earthquakes.

PRE **82** (2010) 021110

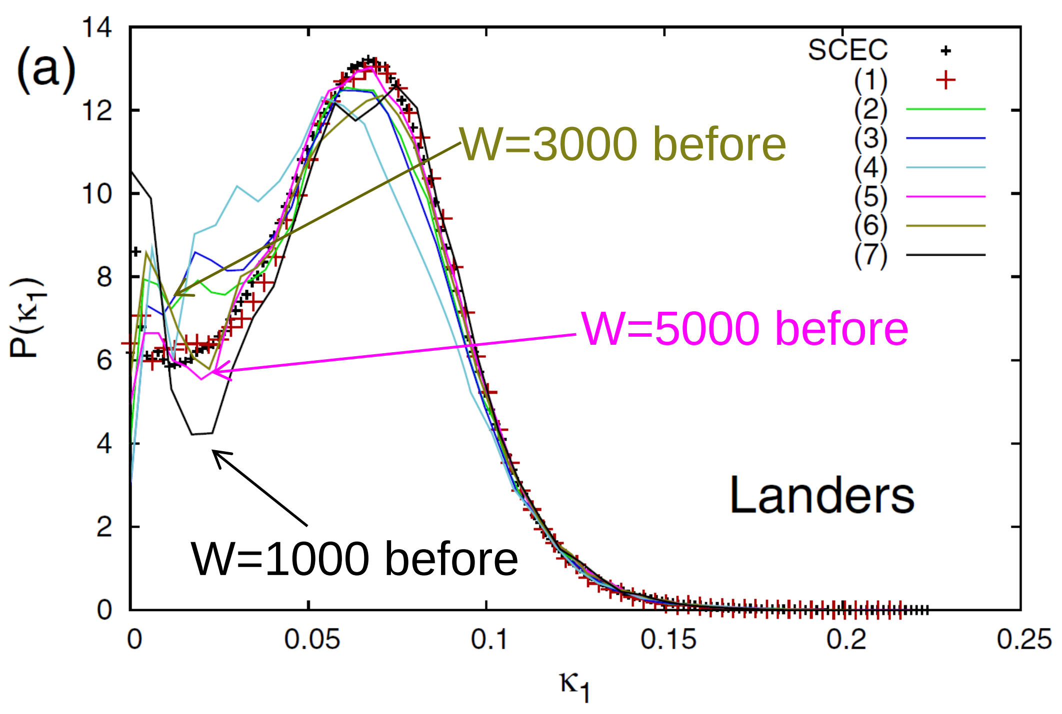
Study of the order parameter fluctuations before major earthquakes

Natural time analysis of seismological catalog excerpts



We calculate for each EQ e_i (i=41 in the present example) the κ_1 values using the previous 6 to 40 consecutive EQs (in the opposite direction to that in A) and assign these κ_1 values to e_i . Selecting now the κ_1 values related with e_i *for* $i=i_0, i_0-1, \ldots, i_0-W-1$, we can get a picture of how the OP of seismicity κ_1 behaves before an EQ that takes place at *i.*

Natural time analysis of seismological catalog excerpts



Such a picture can be obtained by studying the probability density function $P(\kappa_1)$ of the such obtained (κ_1-values') ensembles.

New result!

The variability of κ_1,
$\beta \equiv \sigma(\kappa_1)/\mu(\kappa_1)$,
when using various natural
time windows *ending just
before* a main shock,
exhibits an *increase*
when approaching a main shock.

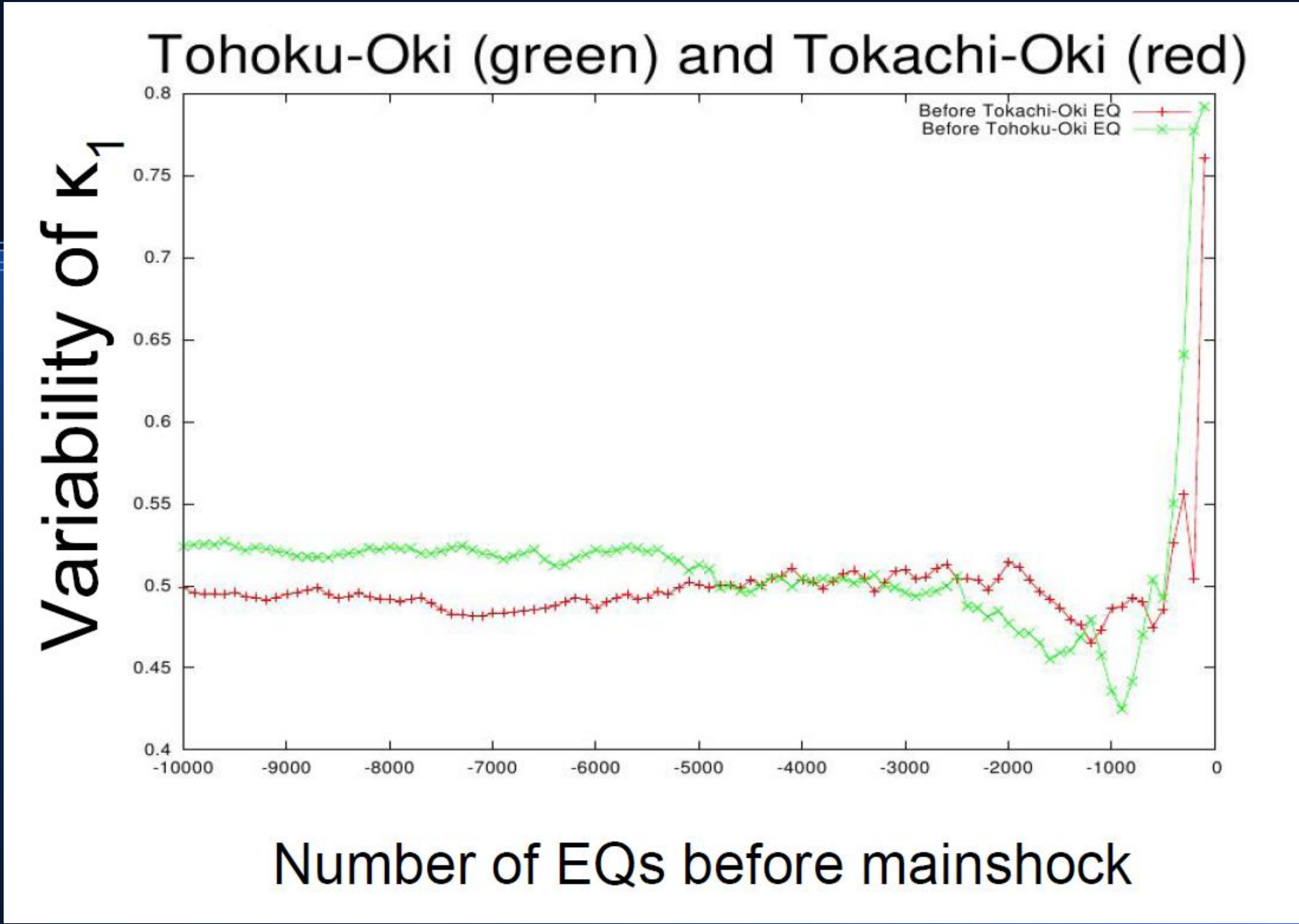


Fig. A6, taken from the book "*EARTHQUAKE PREDICTION BY SEISMIC ELECTRIC SIGNALS: The success of the VAN method over thirty years*" by Dr Mary Lazaridou-Varotsos published in 2013 by *Springer-Verlag*

A Letters Journal Exploring the Frontiers of Physics

December 2011

EPL, 96 (2011) 59002
doi: 10.1209/0295-5075/96/59002

www.epljournal.org

Scale-specific order parameter fluctuations of seismicity in natural time before mainshocks

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received 13 September 2011; accepted in final form 17 October 2011
published online 16 November 2011

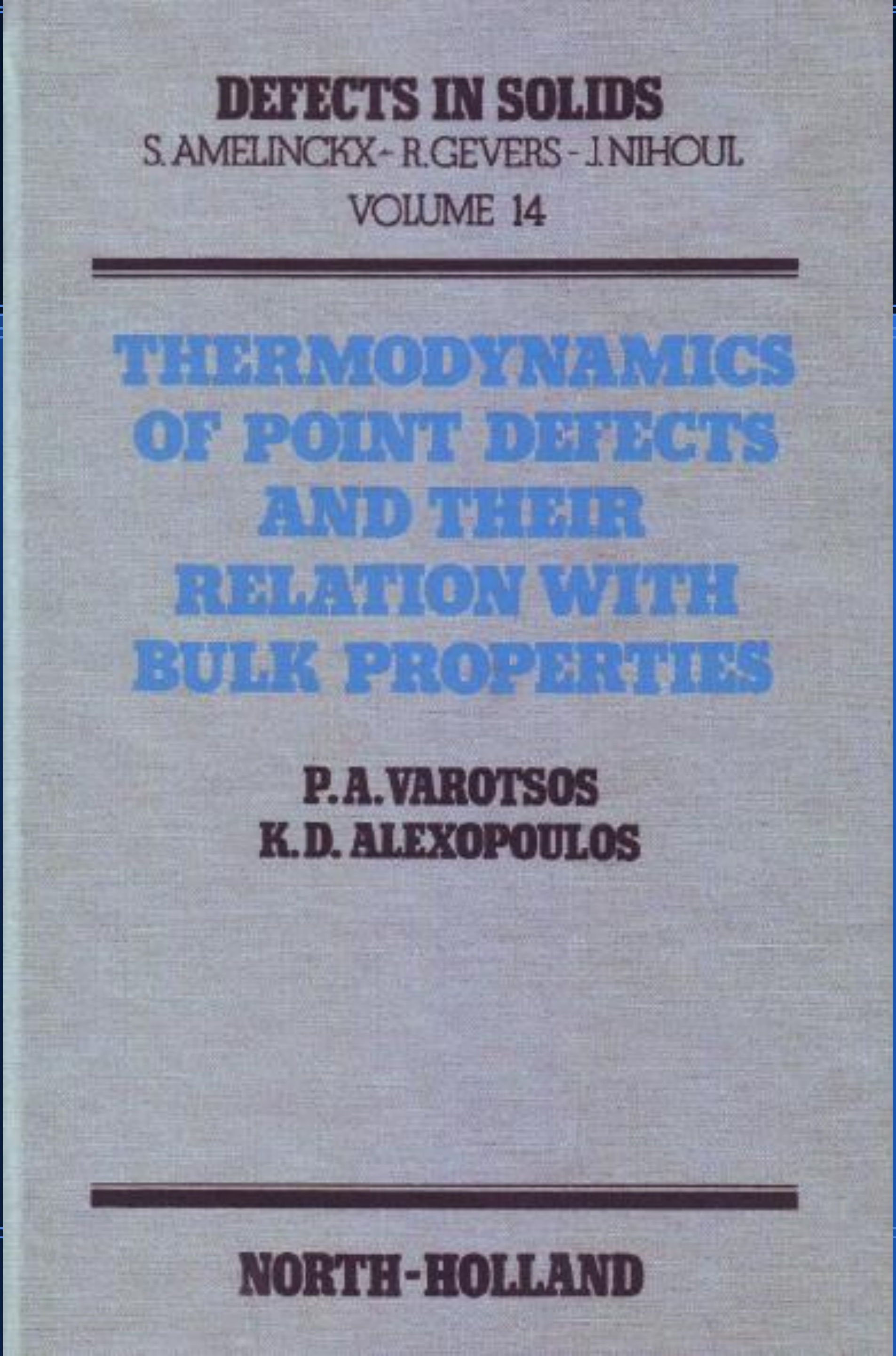
PACS 91.30.Ab – Theory and modeling, computational seismology
PACS 89.75.Da – Systems obeying scaling laws
PACS 95.75.Wx – Time series analysis, time variability

Abstract – We have previously shown that the probability distribution of the order parameter κ_1 of seismicity in natural time turns to be bimodal when approaching a mainshock. This reflects that, for various natural time window lengths ending at a given mainshock, the fluctuations of κ_1 considerably increase for smaller lengths, *i.e.*, upon approaching a mainshock. Here, as a second step, we investigate the order parameter fluctuations, but when considering a natural time window of a fixed-length sliding through a seismic catalog. We find that when this length becomes comparable with the lead time of Seismic Electric Signals activities (*i.e.*, of the order of a few months), the fluctuations exhibit a global minimum before the strongest mainshock. Thus, the approach of the latter is characterized by *two* distinct features of the order parameter fluctuations that complement each other.

Seismic Electric Signal Activities

Seismic Electric Signals (SES) activities are series of low frequency electric signals that precede earthquakes **(with an average lead time of a few months)** reported from measurements in Greece in the 80’s.
Almost 35 years ago, it has been suggested that SES activities arise from a cooperative orientation of electric dipoles formed due to defects when the stress in the focal area reaches a *critical* value.

Cooperativity is a hallmark of criticality.


DEFECTS IN SOLIDS
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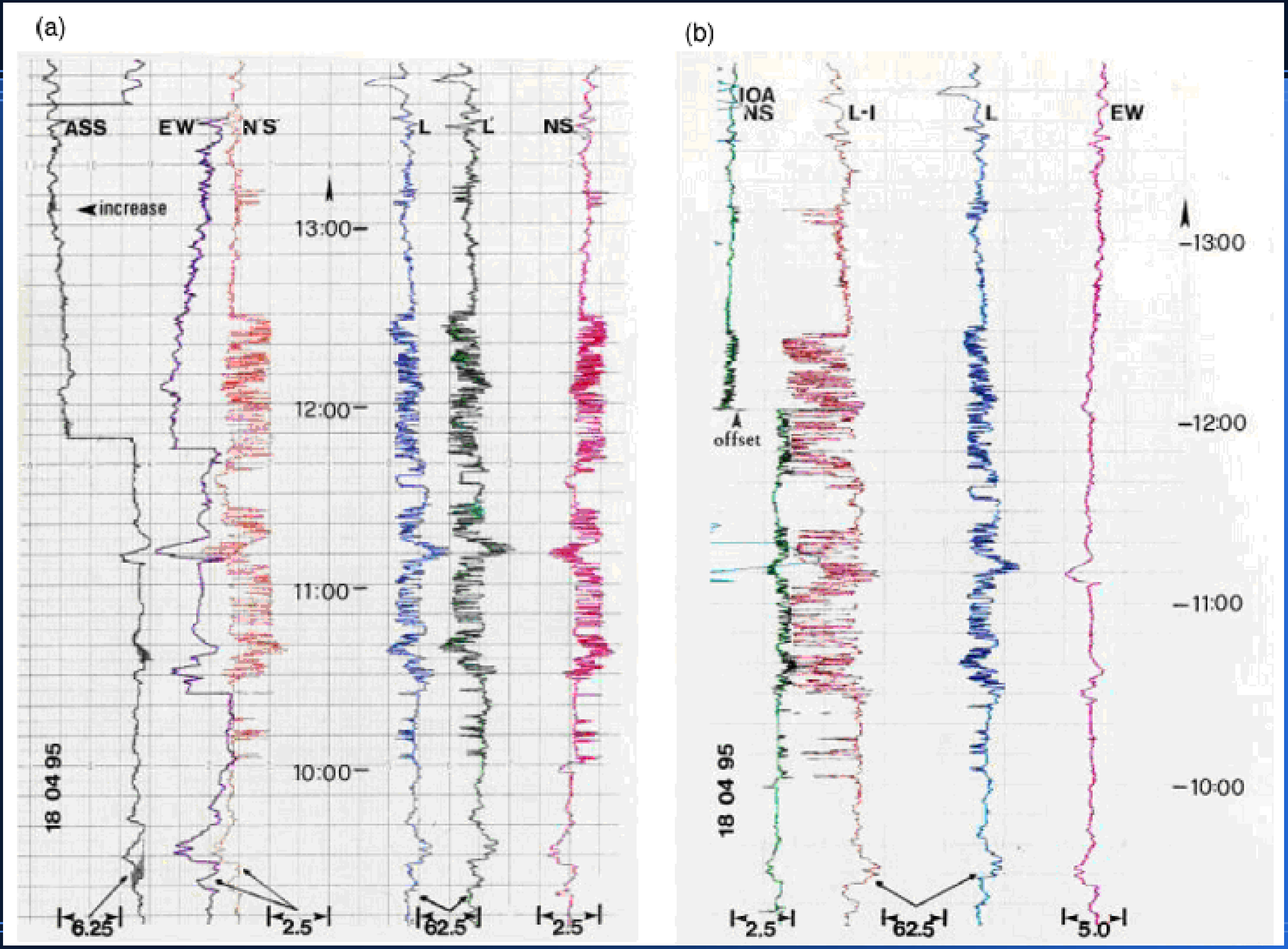
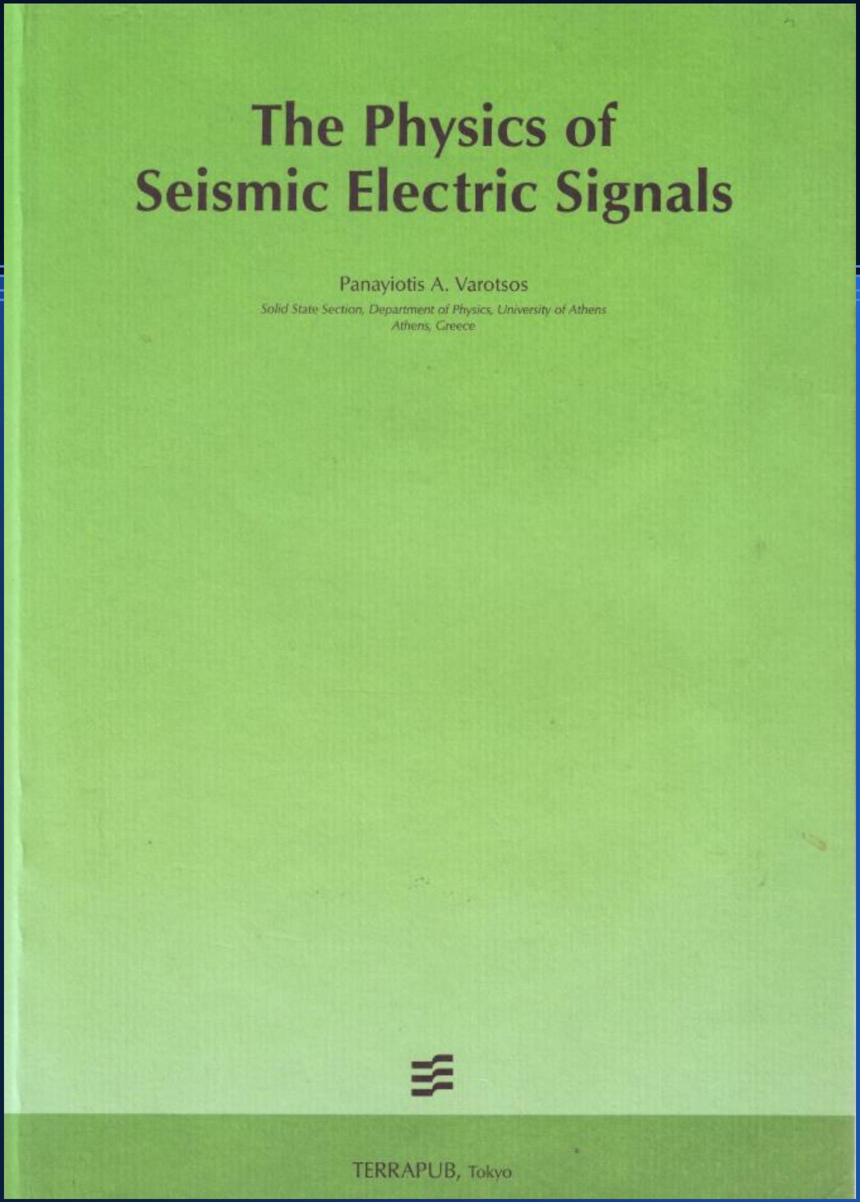
VOLUME 14
THERMODYNAMICS OF POINT DEFECTS AND THEIR RELATION WITH BULK PROPERTIES
P. A. VAROTSOS
K. D. ALEXOPOULOS
NORTH-HOLLAND

1986

An SES activity example from 1995

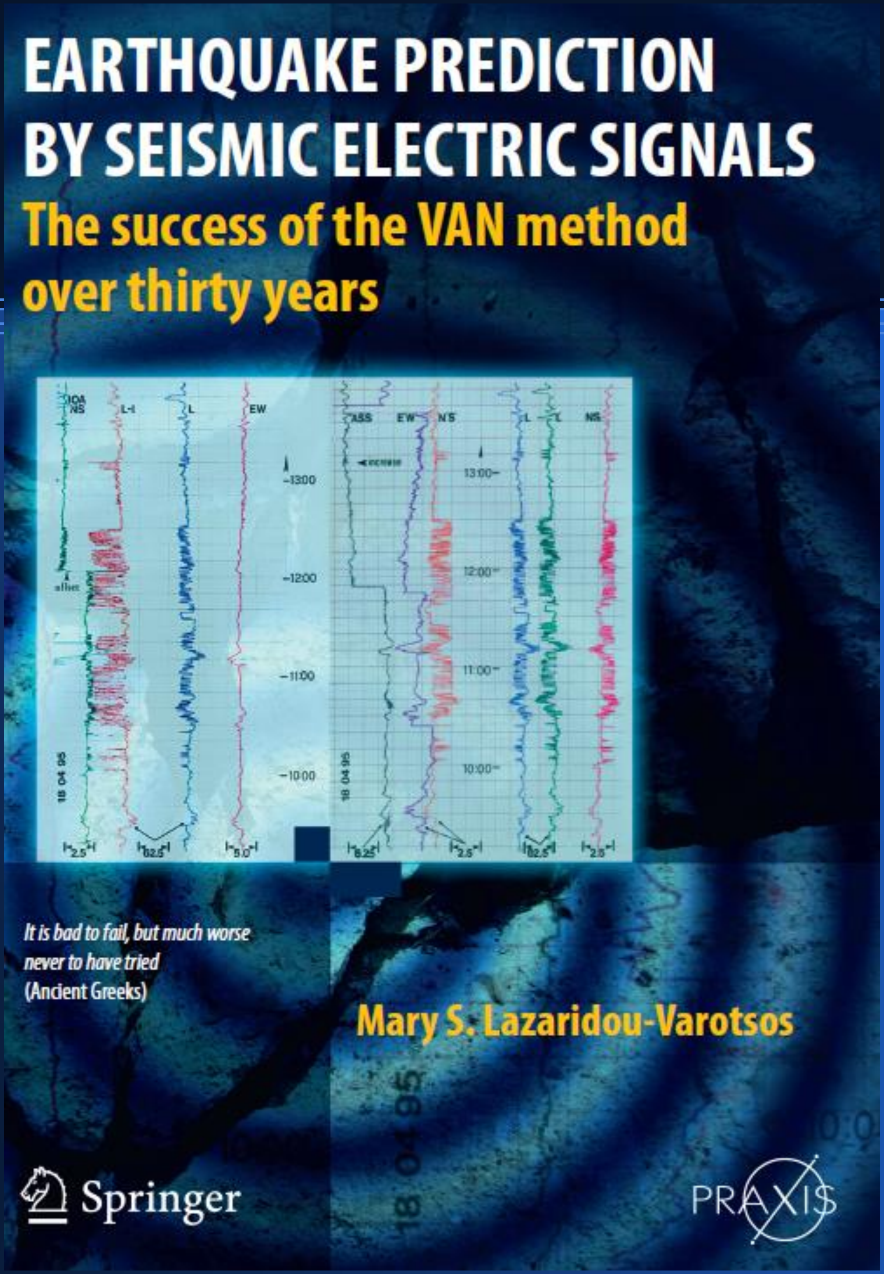


recorded almost one month before an M6.6 earthquake



2005

The cover of the book entitled “Physics of Seismic Electric Signals” by P. Varotsos released in 2005 by the Japanese Publishing House *TerraPub* in Tokyo.



2013

The cover of the book entitled “Earthquake prediction by Seismic Electric Signals” by Mary S. Lazaridou-Varotsos released in 2013 by Springer

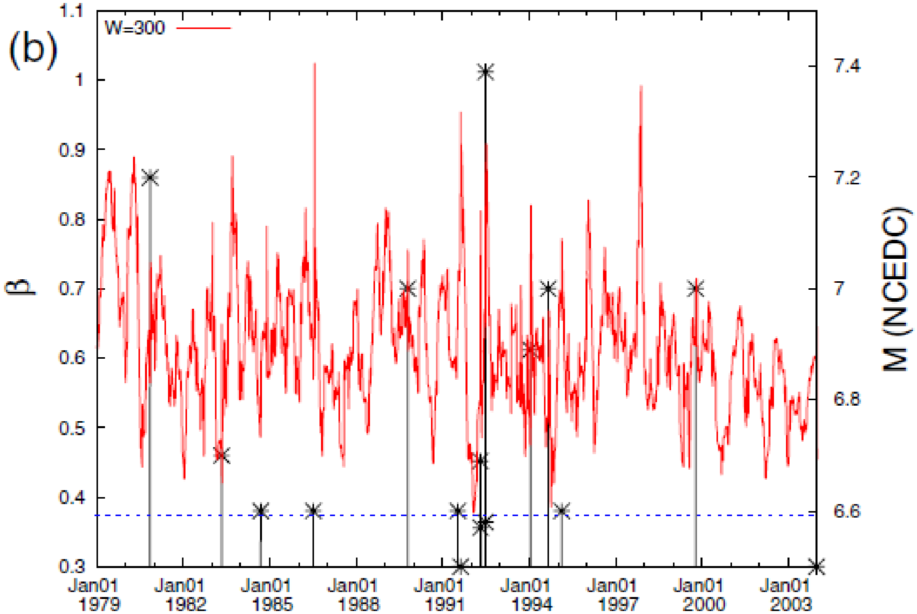
New result!

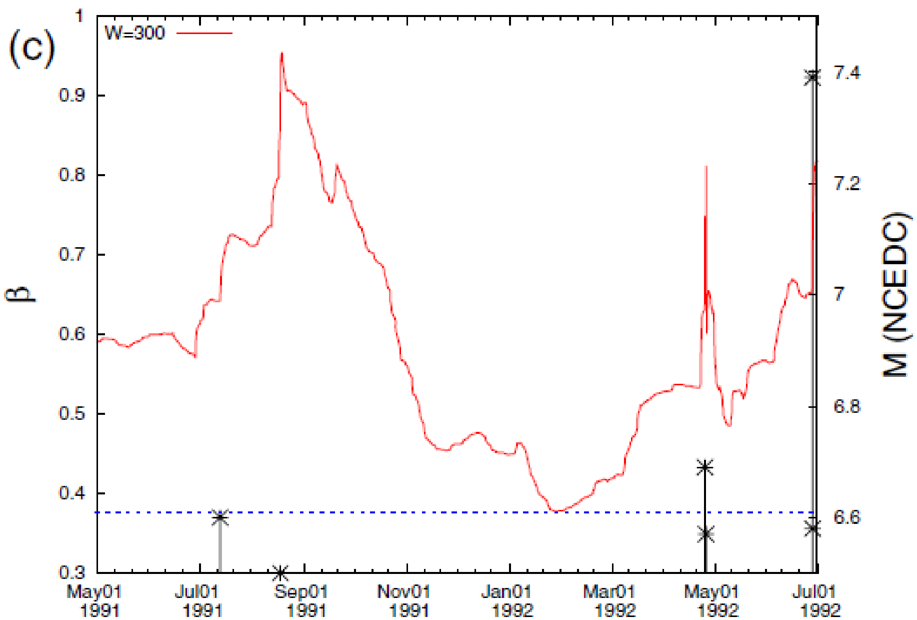
The variability of κ_1,

$$\beta \equiv \sigma(\kappa_1)/\mu(\kappa_1),$$

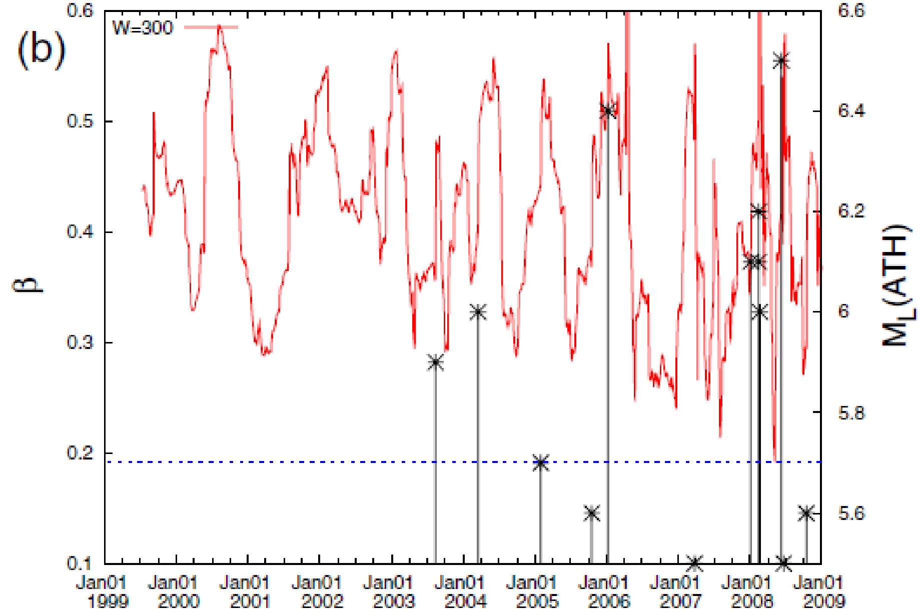
calculated for the specific scale W=300, which corresponds to the average lead time of Seismic Electric Signals, exhibits the deepest minimum before the strongest mainshock.

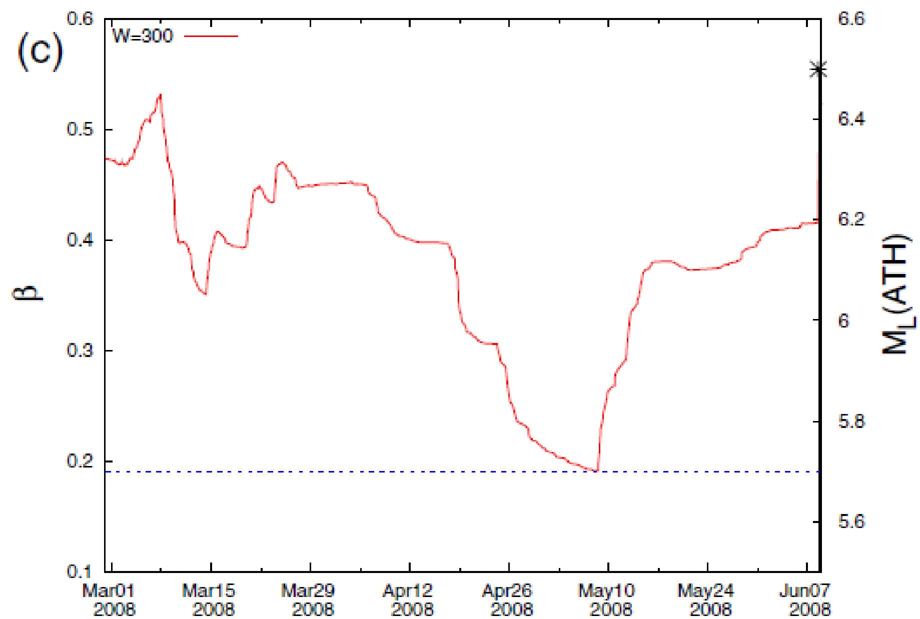
California





Greece





New result!

The variability of the OP κ_1,

$$\beta \equiv \sigma(\kappa_1)/\mu(\kappa_1),$$

calculated for scales comparable to the average lead time of Seismic Electric Signals, exhibits characteristic minima a few months before strong earthquakes.

Minimum of the order parameter fluctuations of seismicity before major earthquakes in Japan

Nicholas V. Sarlis[a], Efthimios S. Skordas[a], Panayiotis A. Varotsos[a], Toshiyasu Nagao[b], Masashi Kamogawa[c], Haruo Tanaka[d], and Seiya Uyeda[e,1]

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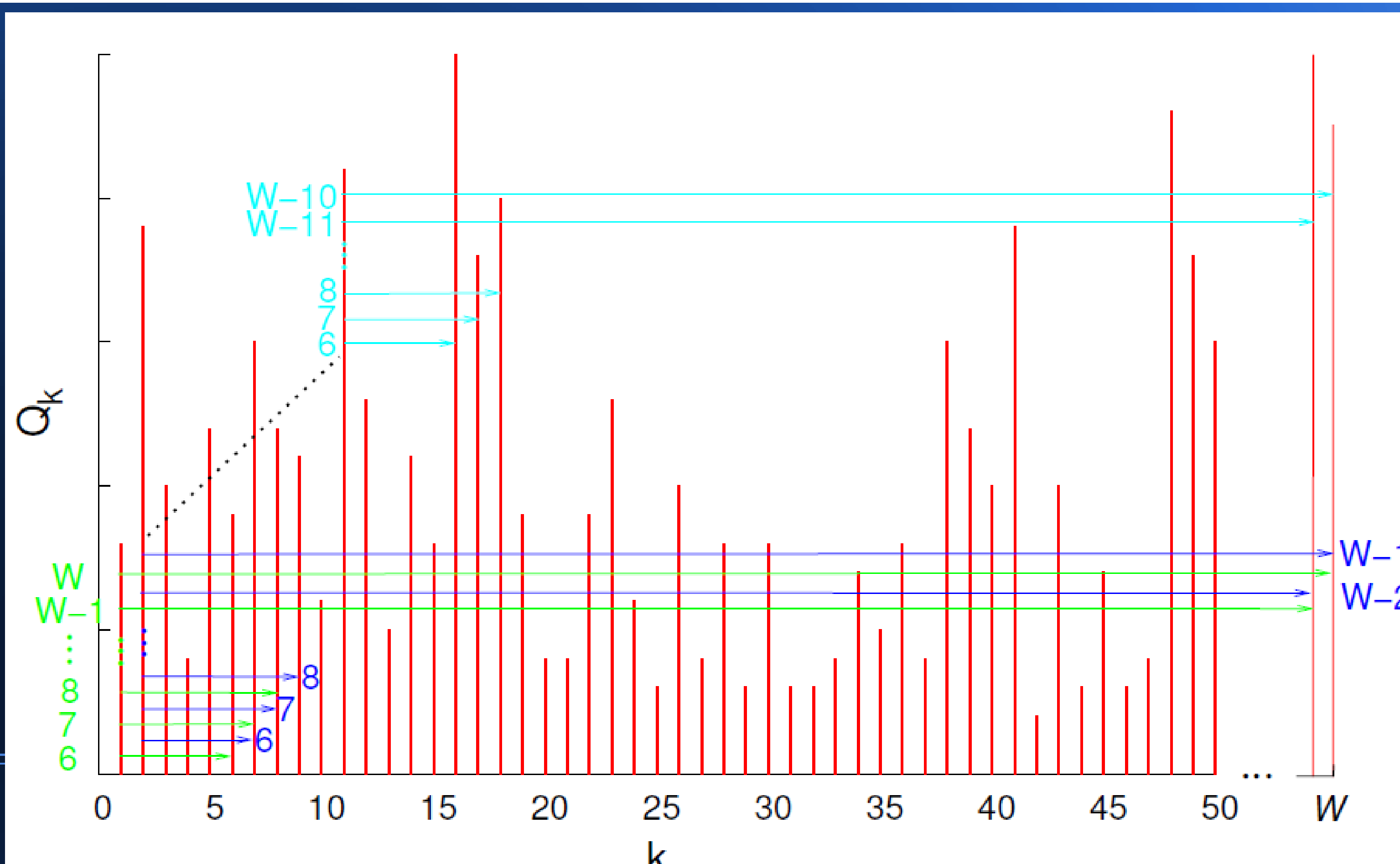
Contributed by Seiya Uyeda, July 11, 2013 (sent for review May 18, 2013)



Proc. Natl. Acad. Sci. U.S.A. **110**, 13734-13738 (2013)

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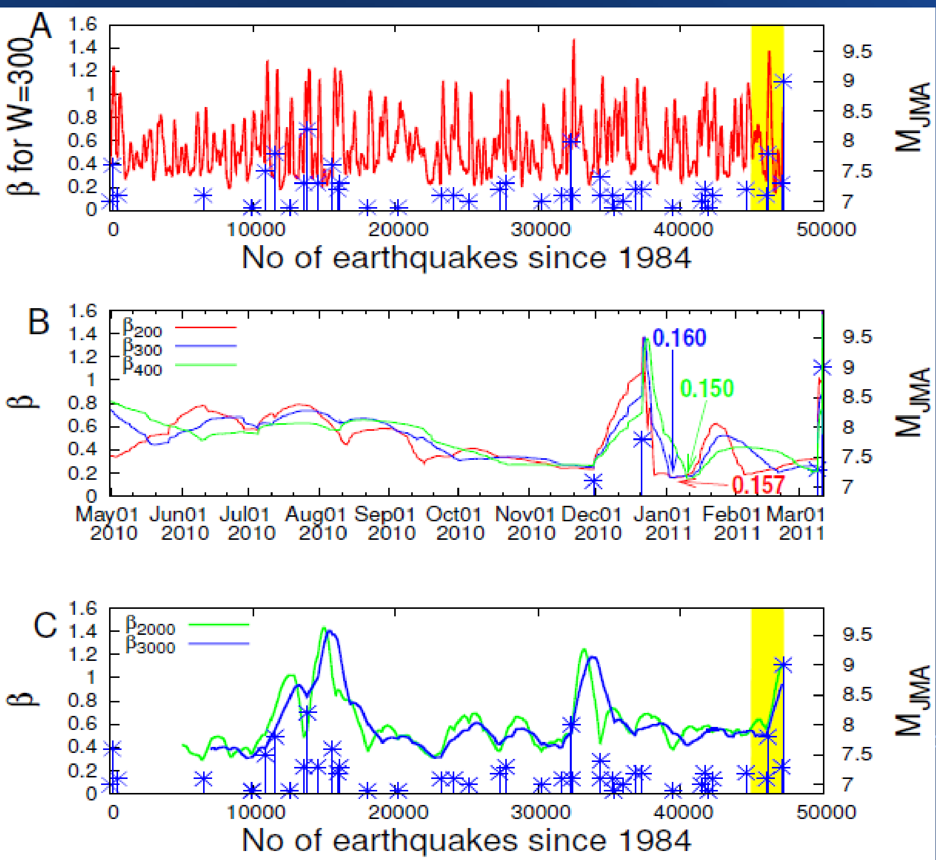
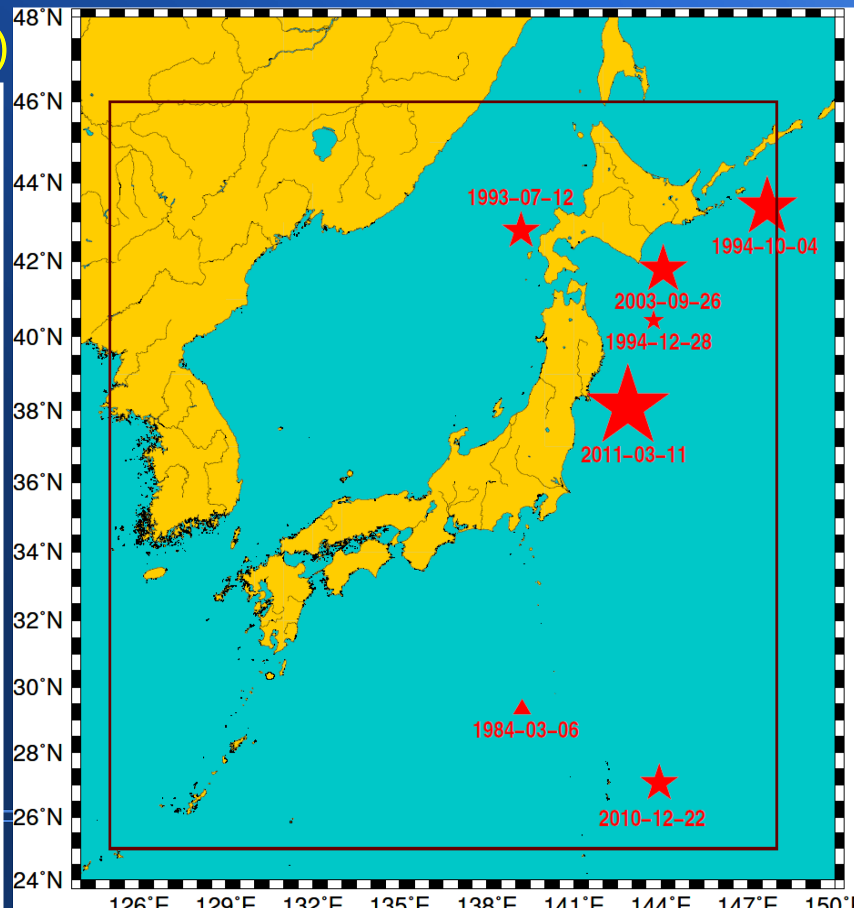
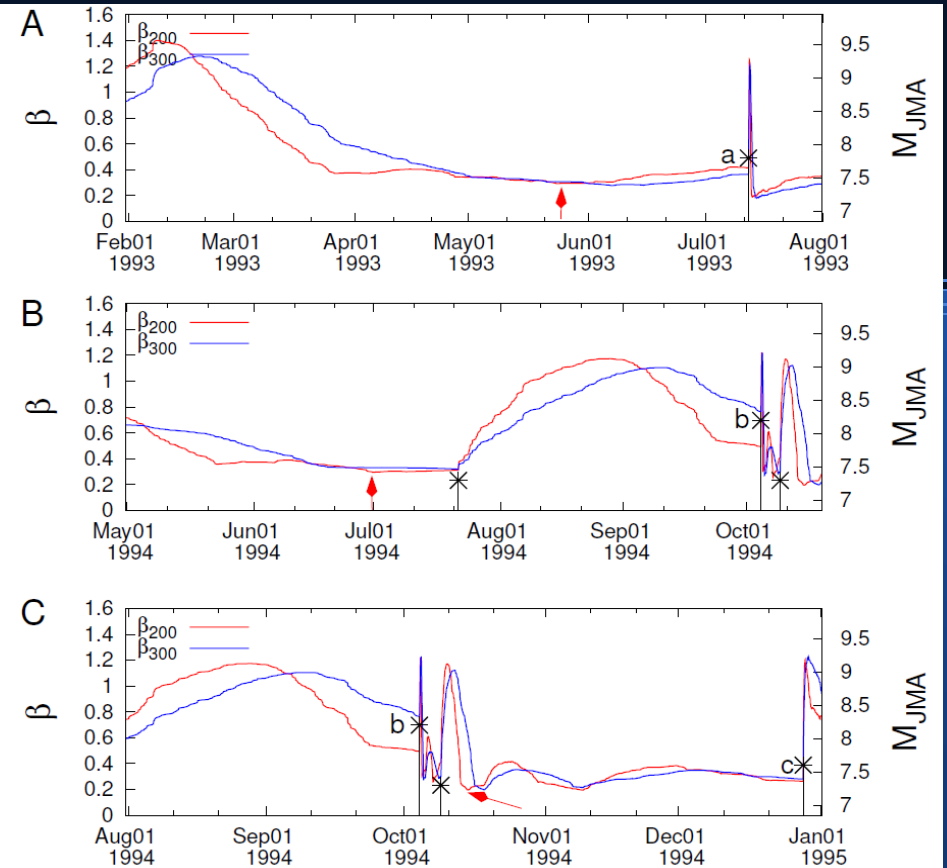
1/1/1984 - M9 Tohoku EQ (11 March 2011)





Proc. Natl. Acad. Sci. U.S.A. **110, 13734-13738 (2013)**



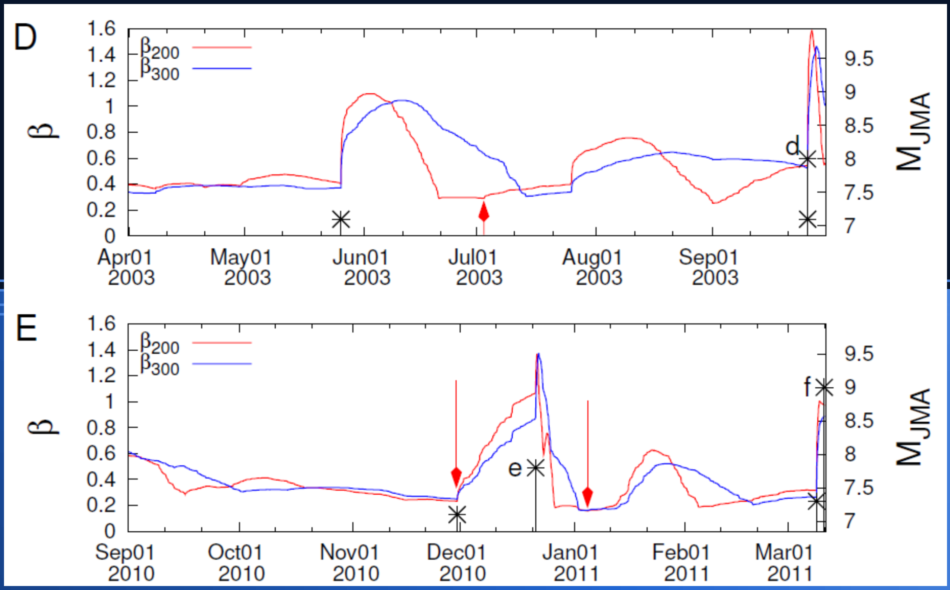


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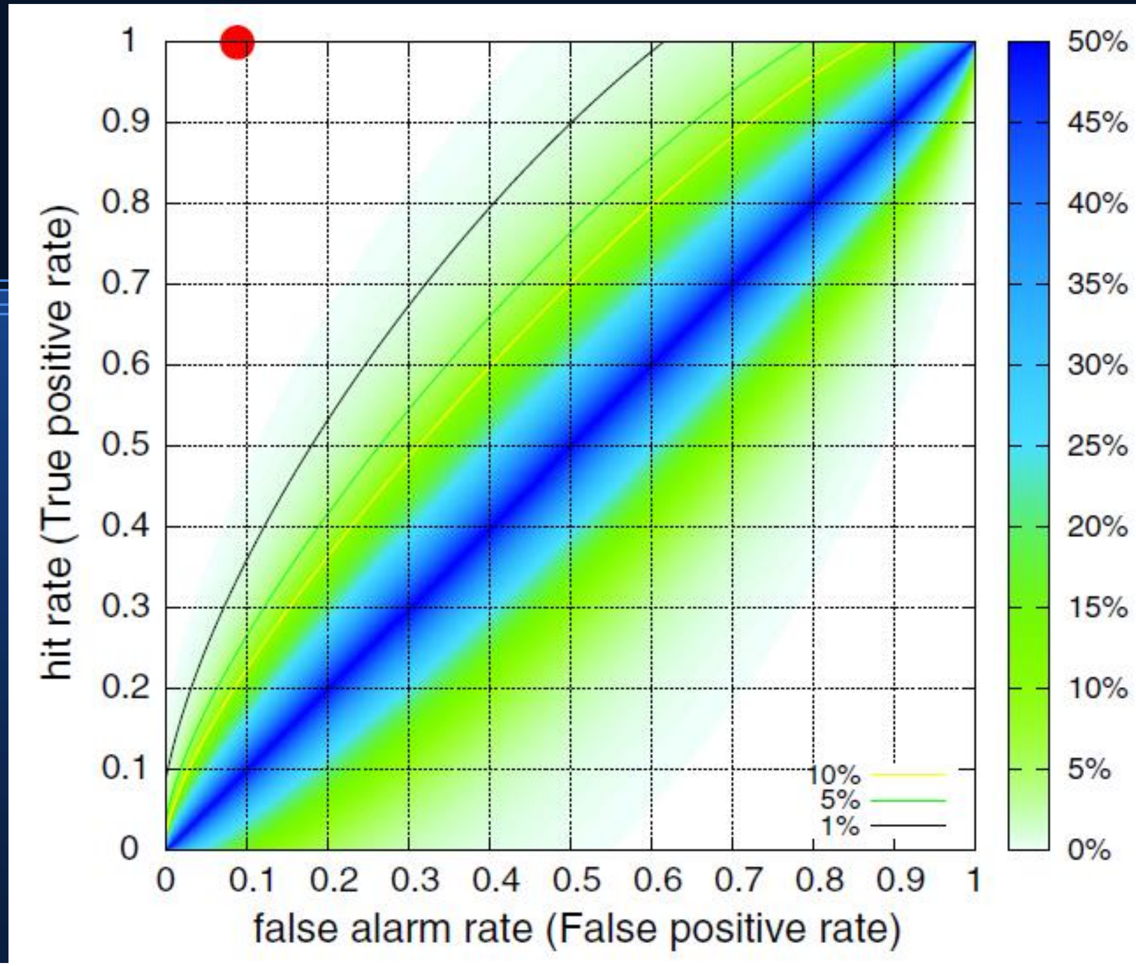
Table 1. All shallow EQs with magnitude 7.6 or larger since January 1, 1984 until M9 Tohoku EQ within the area $N_{25}^{46}\, E_{125}^{148}$

Label	EQ date	EQ name	Lat., °N	Long., °E	M	$\beta_{200,\min}$	$\beta_{300,\min}$	$\beta_{300,\min}/\beta_{200,\min}$	Δt_{200}
a	1993-07-12	Southwest-Off Hokkaido EQ	42.78	139.18	7.8	0.293 (1993-05-23)	0.278 (1993-06-07)	0.95	2
b	1994-10-04	East-Off Hokkaido EQ	43.38	147.67	8.2	0.295 (1994-06-30)	0.319 (1994-07-22)	1.08	3
c	1994-12-28	Far-Off Sanriku EQ	40.43	143.75	7.6	0.196 (1994-10-15)	0.197 (1994-10-19)	1.01	2–3
d	2003-09-26	Off Tokachi EQ	41.78	144.08	8.0	0.289 (2003-07-03)	0.306 (2003-07-14)	1.06	3
e	2010-12-22	Near Chichi-jima EQ	27.05	143.94	7.8	0.232 (2010-11-30)	0.248 (2010-11-30)	1.07	1
f	2011-03-11	Tohoku EQ	38.10	142.86	9.0	0.157 (2011-01-05)	0.160 (2011-01-05)	1.02	2

The symbols $\beta_{W,\min}$ are the minima of the κ_1 variability that preceded these EQs along with their dates. Δt_{200} is the difference in months between the dates of $\beta_{200,\min}$ and EQ. Lat., latitude; Long., longitude.

Pure Appl. Geophys.,
DOI: 10.1007/s00024-014-0930-8 (2014)



Receiver operating characteristics diagram for $P = 6$ and $Q = 103$ in which the *red circle* corresponds to the results obtained by SARLIS *et al*. (2013). This *circle* is far away from the *blue* diagonal that corresponds to random predictions. The colored contours present the p value to obtain by chance an ROC point based on k-ellipses (SARLIS and CHRISTOPOULOS 2014); the k-ellipses with p =10, 5, and 1 % are also shown

Thank you!