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Similarity and Difference in sequences of solar flares, earthquakes, and starquakes

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Introduction and motivation

- Impulsive energy release occurs in many natural systems. Some examples are earthquakes, solar and stellar flares, “neutron-star-quakes”, gamma-ray bursts, current disruptions in plasma devices, etc.
- Some similarities exist in the statistical properties of these phenomena, e.g. power law distributions of released energy and inter-event times

- Is there a common (“universal”) physical mechanism giving rise to these processes?
- This idea has been considered in particular for earthquakes and solar flares (e.g. the Self Organized Criticality paradigm proposed by Bak et al., 1987, 1988)
- The presence of universality in earthquake and solar flare occurrence has been more recently suggested on the basis of the analogies found in the statistical properties of the temporal sequences of the two phenomena (de Arcangelis et al. 2006)

Introduction and motivation

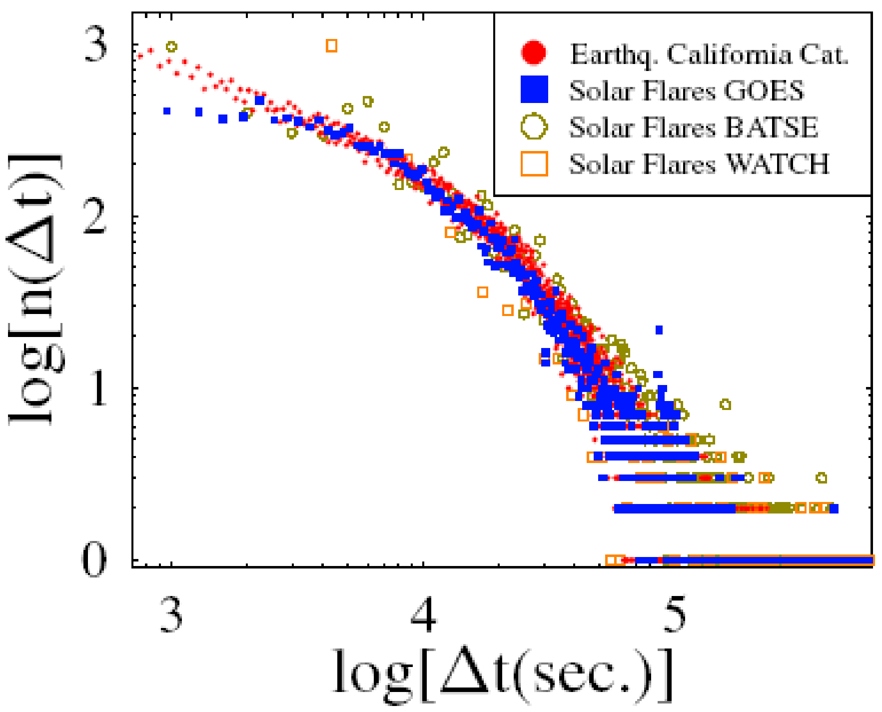


FIG. 1 (color online). The number distribution $n(\Delta t)$ of intertimes Δt between consecutive events in solar flare and earthquake catalogs. Solar data refer to x-ray observations in three different energy ranges covering different periods of the solar cycle: soft x-ray data in the 1.5–2.4 and 3.1–24.8 keV ranges from the GOES catalog (■); hard x-ray (>25 keV) from the BATSE catalog (○); intermediate x-ray (10–30 keV) from the WATCH catalog (□). Earthquake intertimes data are from the California catalog for events with magnitude $M \geq 2$ (●).

Introduction and motivation

- In this work we reconsider the question of “universality” in earthquakes and solar flares analyzing the statistical properties of the sequences of events available from the SCSN earthquake catalog and in the GOES flare catalog

- An important technical issue in studies of probability distributions is the binning method. In order to reduce the ambiguities related to the choice of binning we decided to work with cumulative distributions

Earthquakes

- Sudden energy release events in the Earth crust.

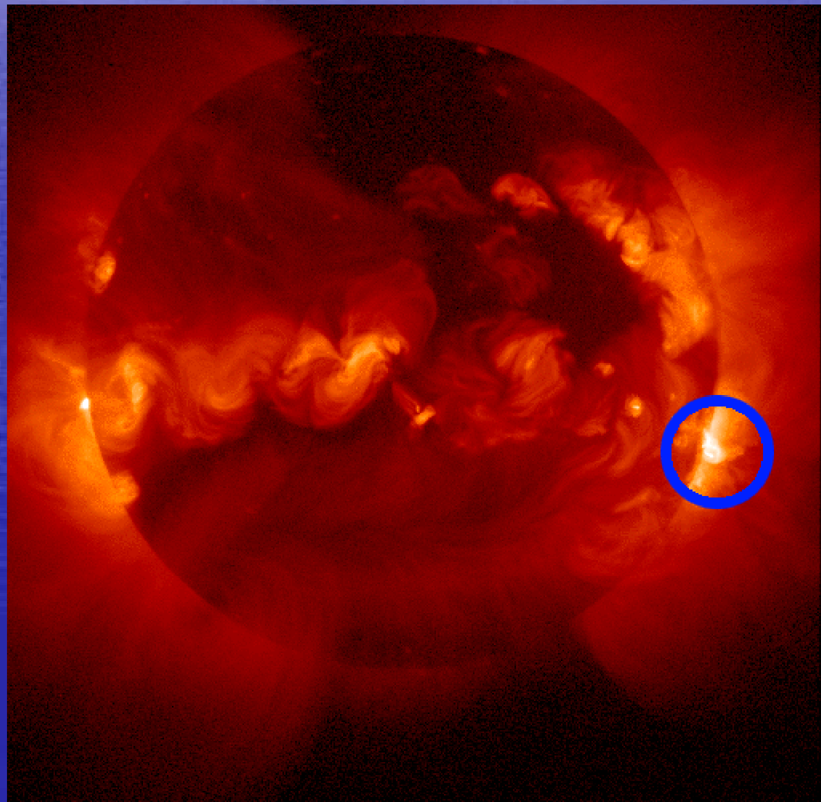
  - A coherent phenomenology on seismic events, which we evidence from their consequences, is lacking. Apparently, earthquakes occur through frictional sliding along the boundaries of highly stressed hierarchies of blocks of different sizes (from grains of rock about 10^{-3} m to tectonic plates up to 10^{7} m in linear dimension) that form the lithosphere of the Earth (*Keilis-Borok 1990*).
  - $E = 10^{2} \div 10^{18}$ J (i.e., $M = -2 \div 9$)
  - Earthquakes occur prevalently in seismic regions, i.e. in fault zones.

November 14, 2001, Kokoxili Earthquake along the Kunlun fault in Tibet (Xinhua/China News Agency)

Solar flares

- Sudden energy release events in the solar atmosphere
- Emission observed in a wide frequency range of the E.M. spectrum, from radio waves up to X-rays and γ-rays

- Solar flares are due to the conversion of magnetic energy (accumulated in the solar atmosphere as a consequence of turbulent convective motions) into accelerated particles, heating, plasma flows.
- $E = 10^{17} \div 10^{26}$ J
- Flares occur prevalently in magnetic activity regions



Soft X-ray image of the solar corona (Yohkoh spacecraft)

Data

Earthquake catalog

- Southern California Seismic Network (SCSN) catalog
- Period 1986-2005
- Over 350000 events. About 87000 with $M \geq 2$.

Solar flare catalog

- Compiled from observations of the Geostationary Operational Environmental Satellites (GOES) in the soft X-ray band 1.5-12.4 keV
- Period 1975-2006. Three solar cycles (1975-1986, 1986-1996, 1996-2006).
- Flares classified according to the peak burst intensity I_p in the above band

  B class if $I_p < 10^{-3}$

  C class if $10^{-3} < I_p < 10^{-2}$

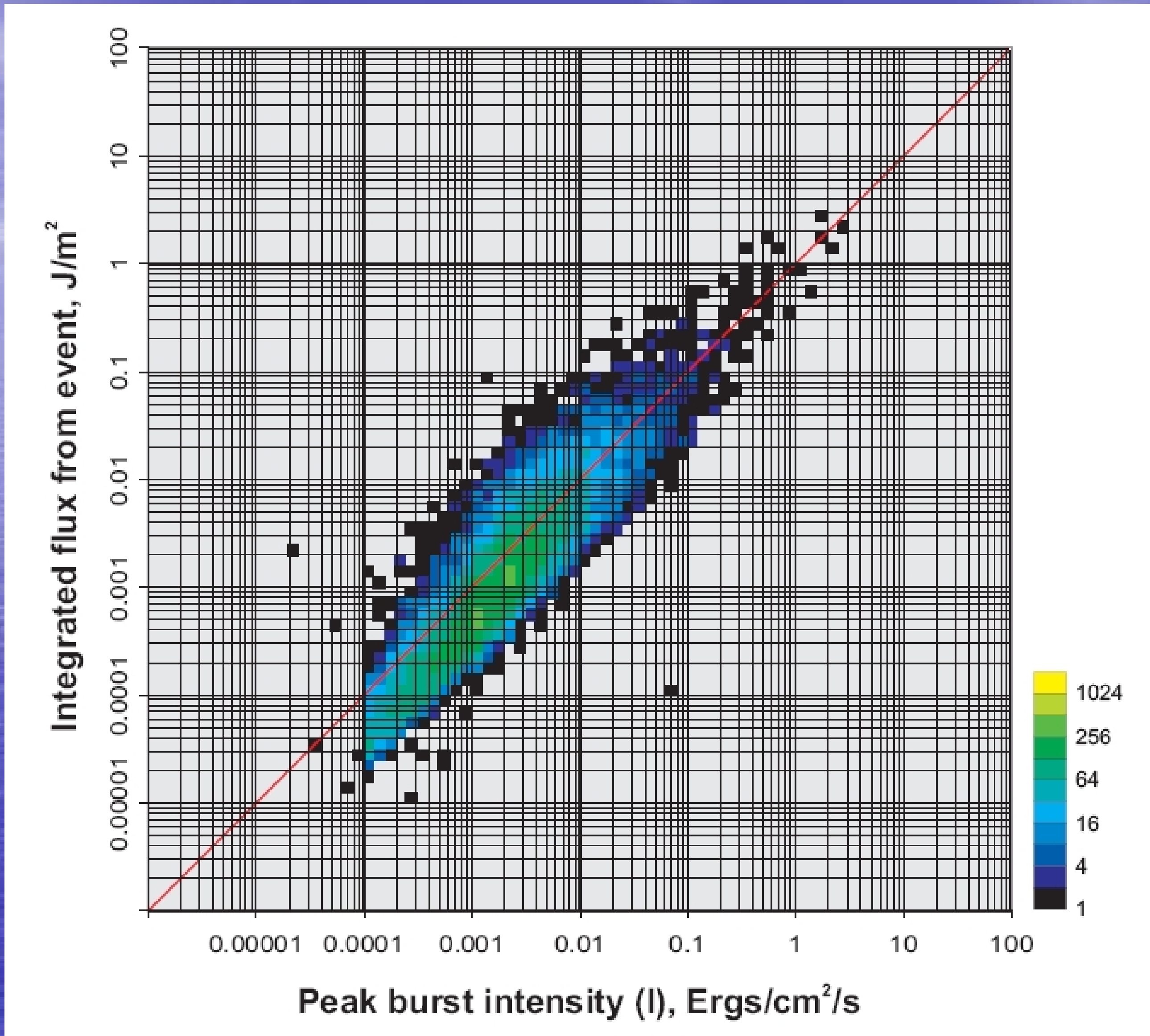
  M class if $10^{-2} < I_p < 10^{-1}$

  X class if $I_p > 10^{-1}$

  (Values of I_p given in erg s^{-1} cm^{-2})

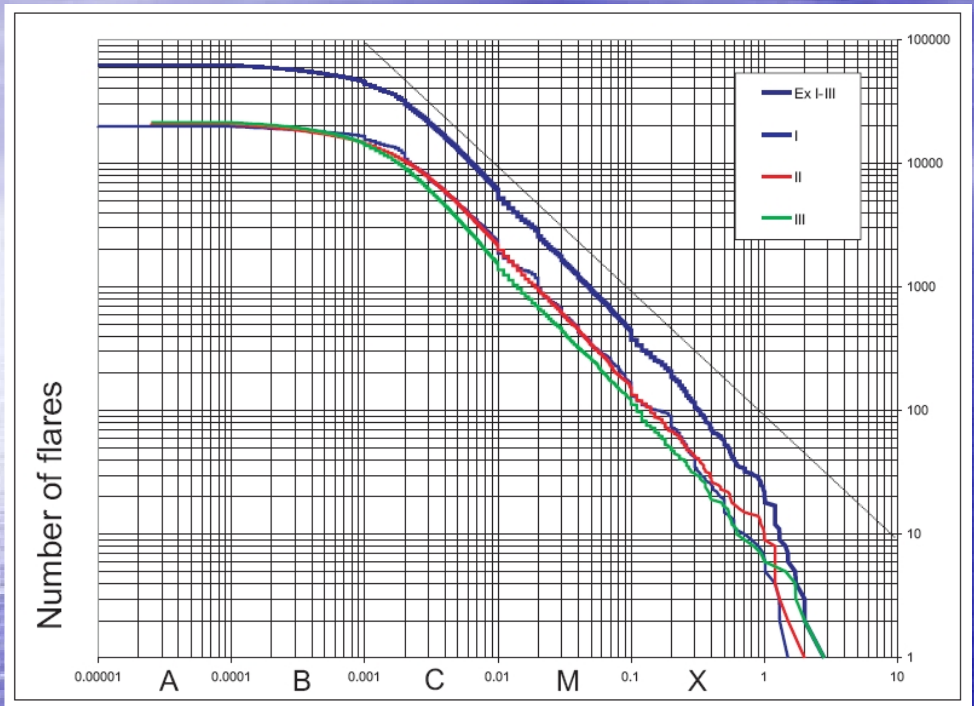
  For example a C4.6 class means that $I_p = 4.6 \times 10^{-3}$ erg s^{-1} cm^{-2}
- Over 62000 events. About 32000 of class ≥ C2

Flare peak burst intensity vs. integrated flux

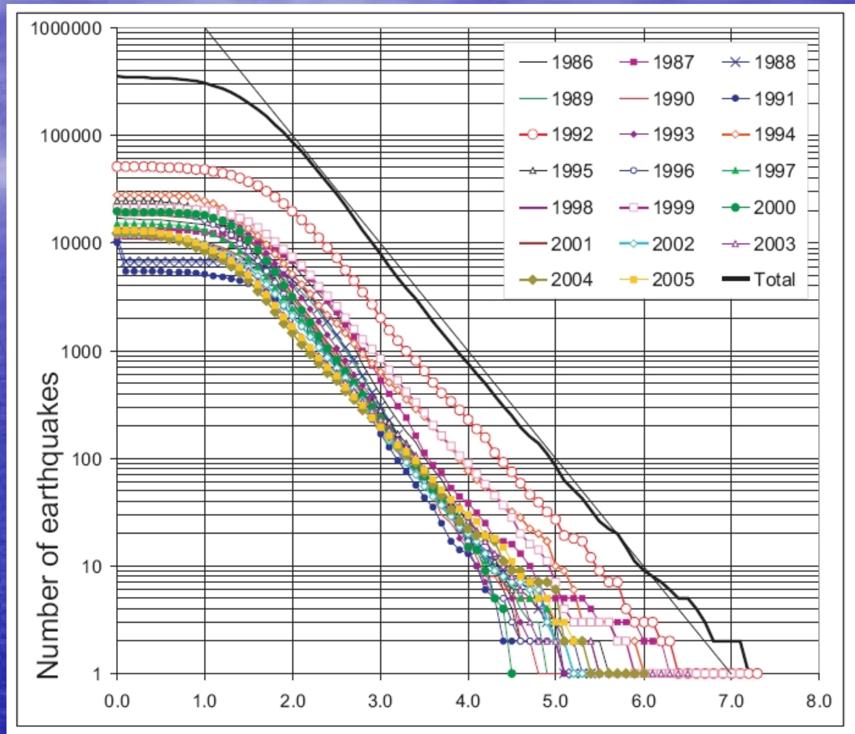


Gutenberg-Richter plots

Solar flares



Earthquakes

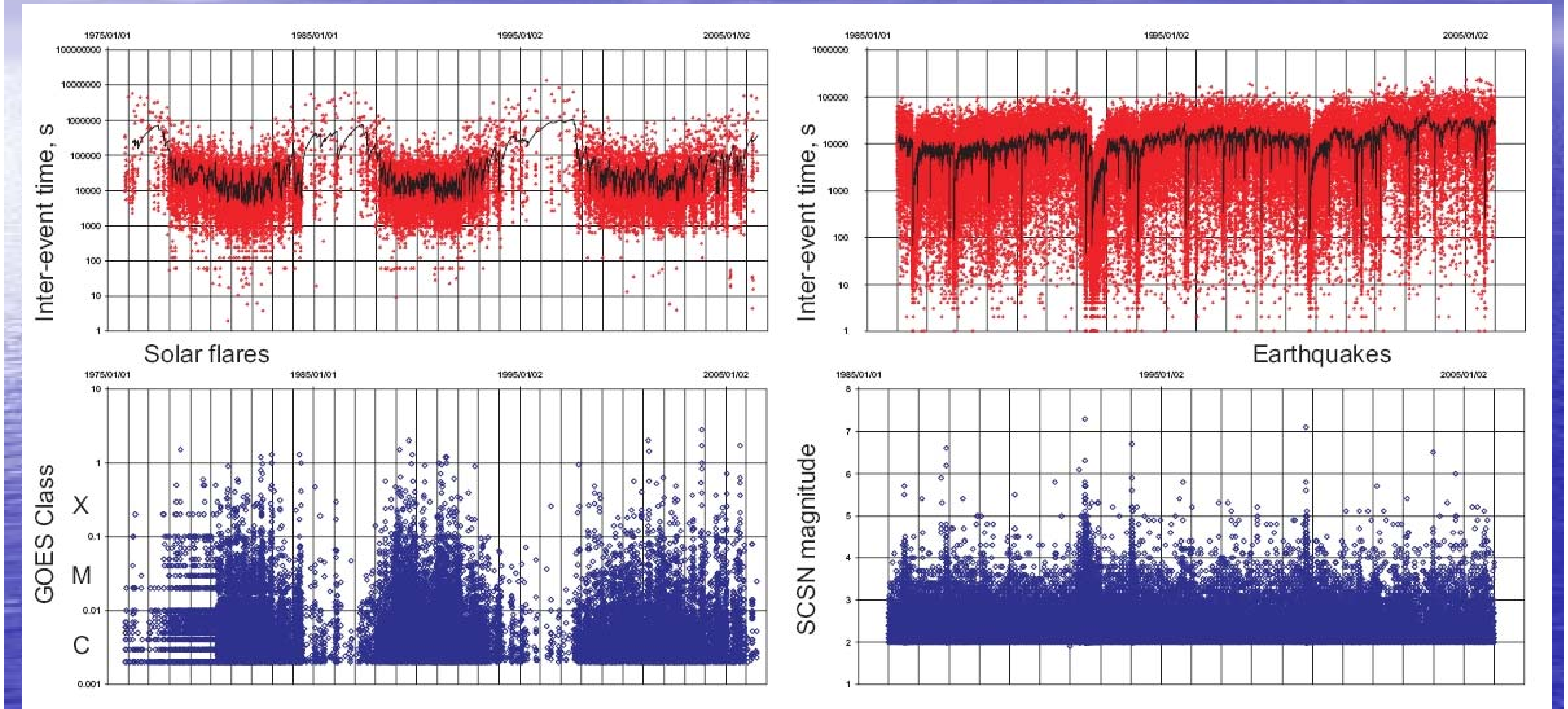


- Lower breakpoints of the power law linearity around C2 class for flares and M2 magnitude for earthquakes, suggest incompleteness of the catalogs below these values
- These cut-offs were considered in the rest of our analysis

Inter-event times and event magnitude vs. time

Solar flares

Earthquakes

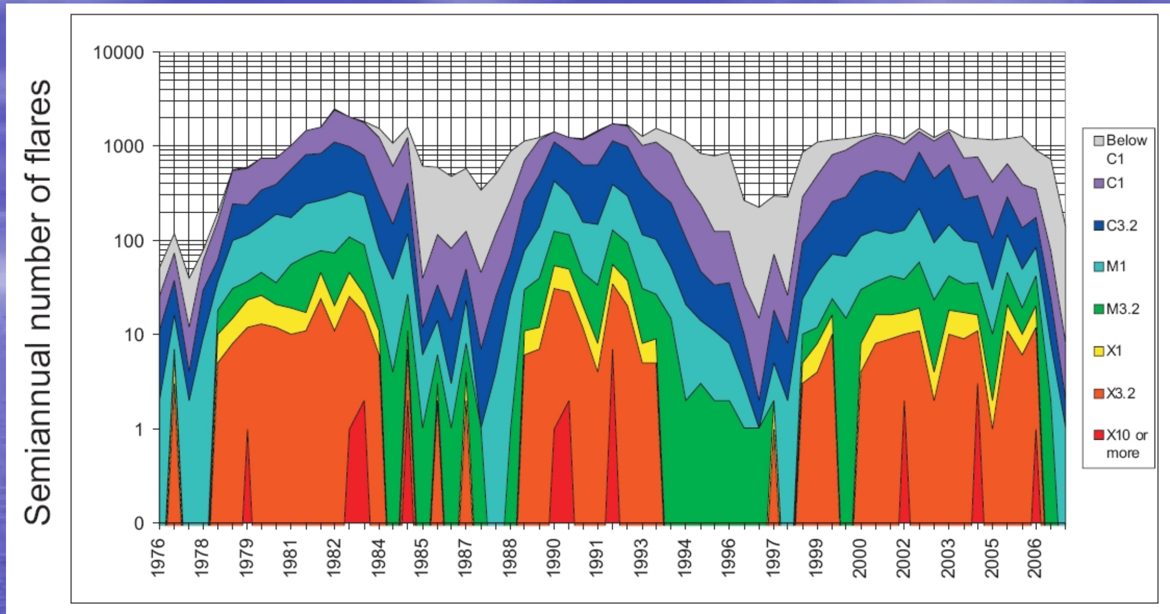


GOES class vs. time

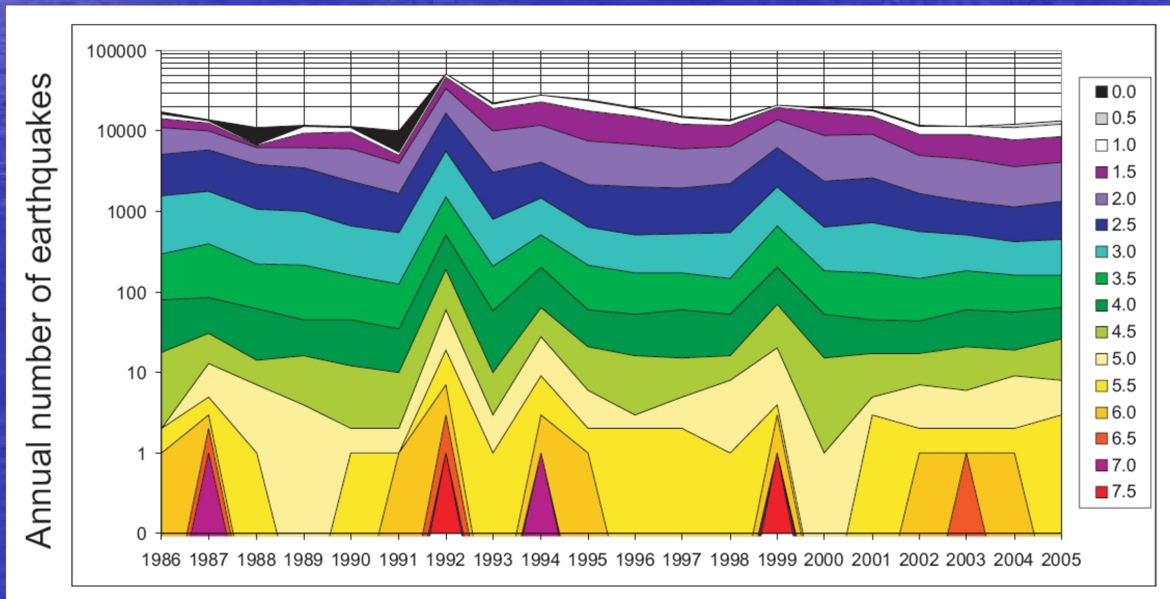
Magnitude vs. time

Magnitude frequencies vs. time

Solar flares



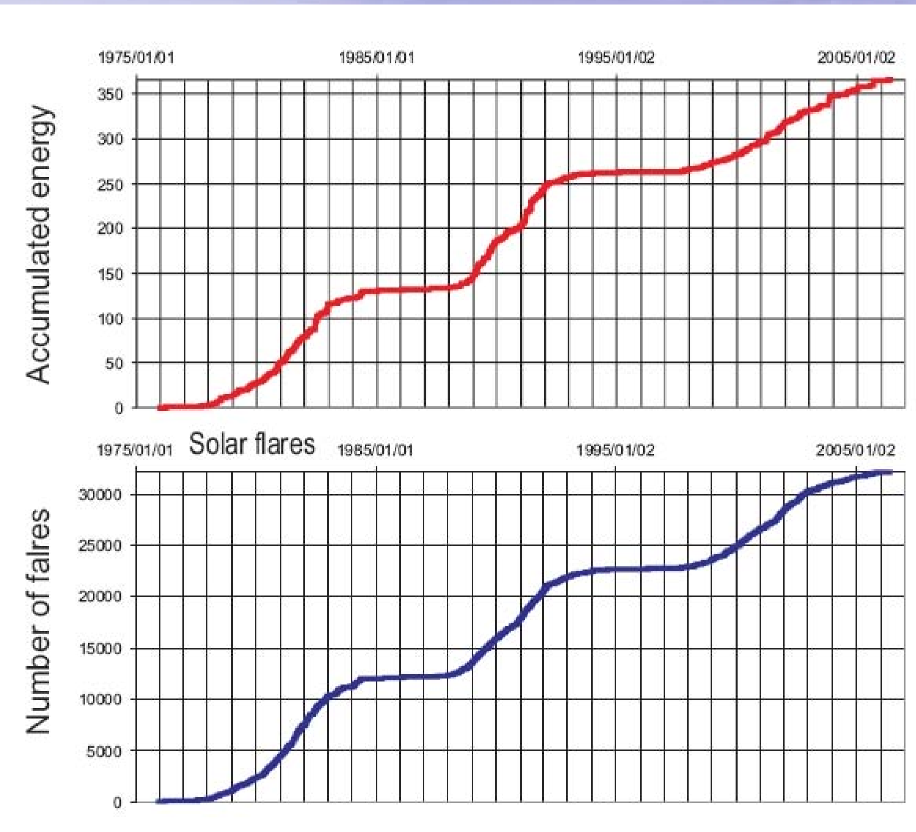
Earthquakes

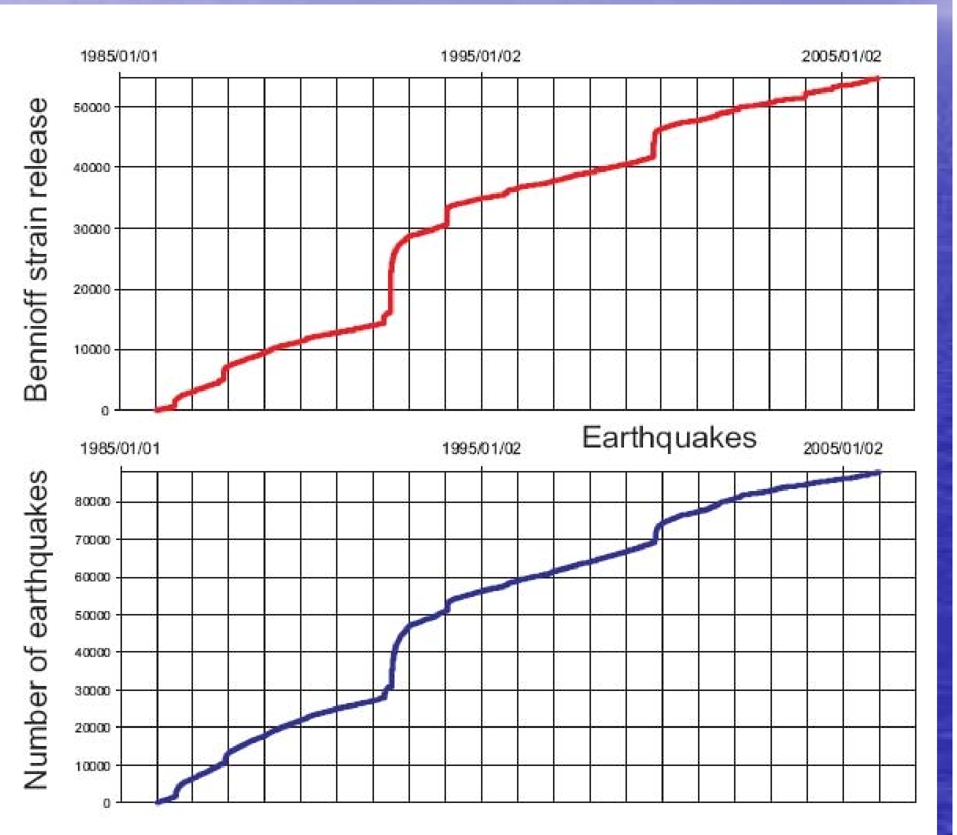


Accumulated number and energy vs. time

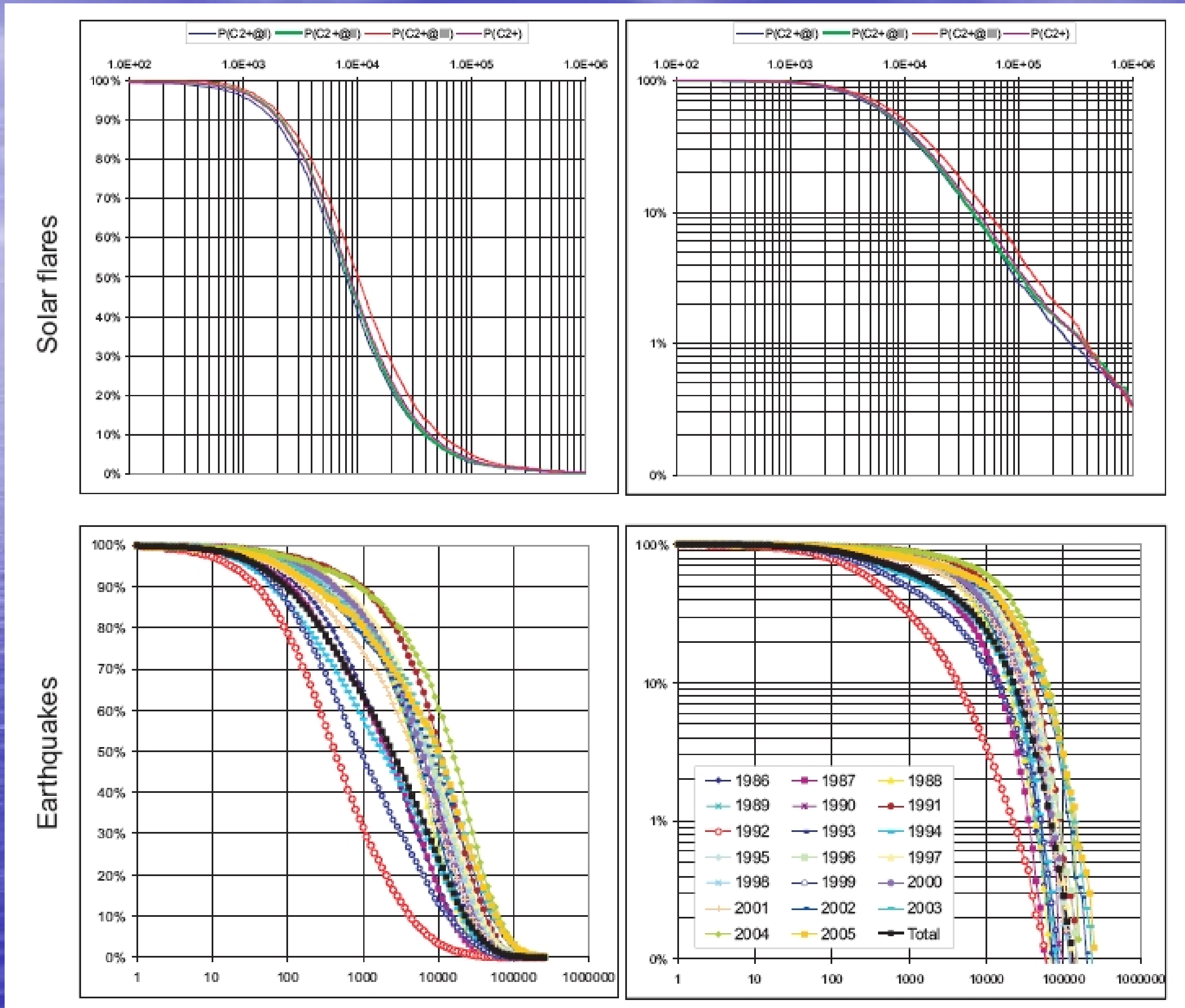
Solar flares

Earthquakes

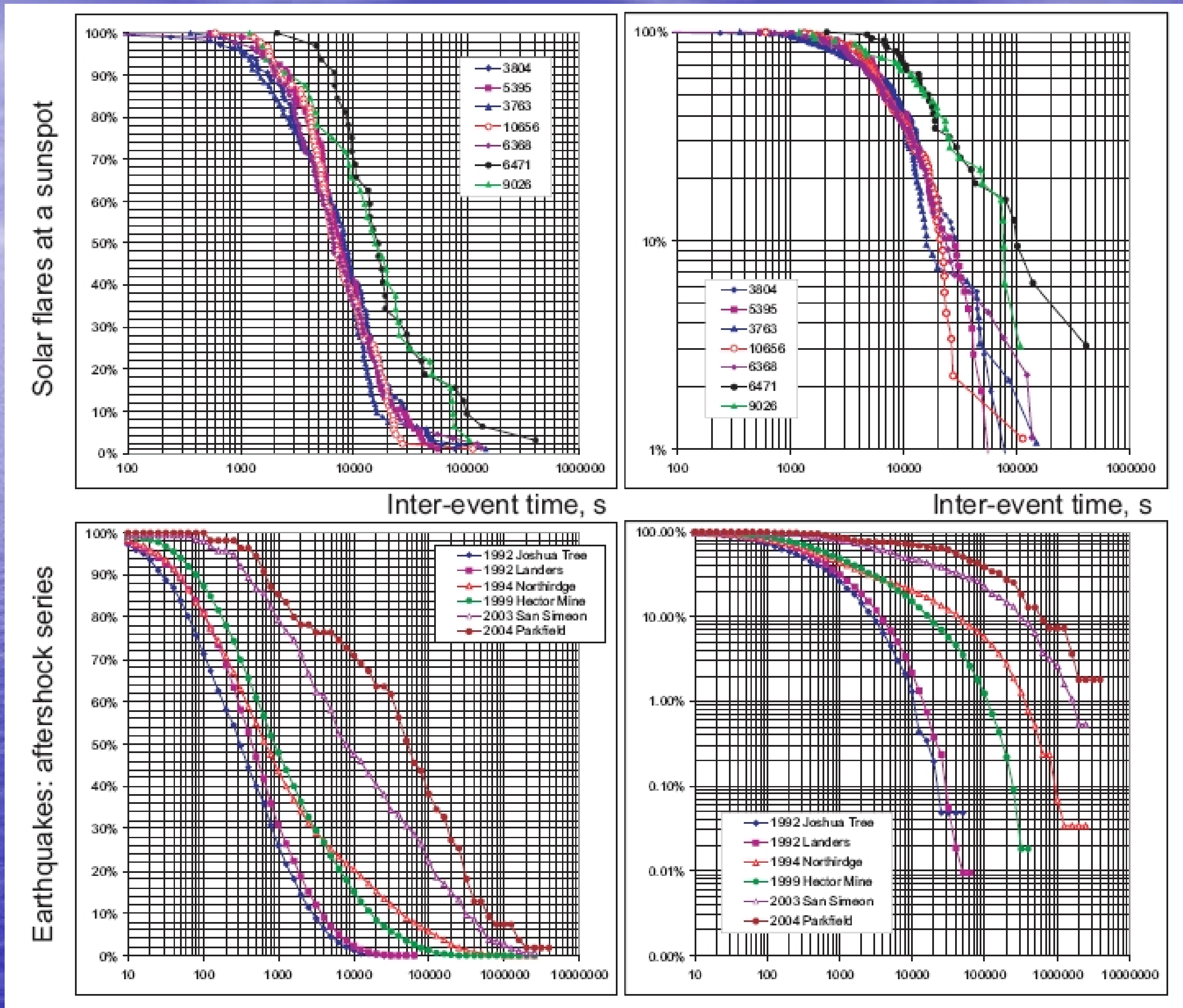




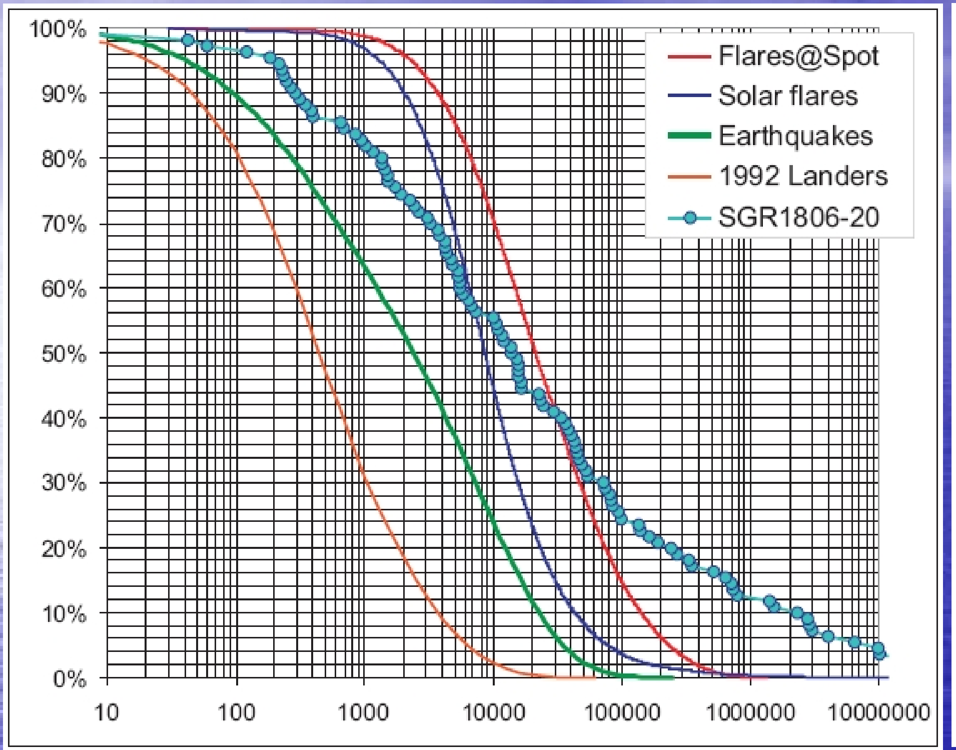
Inter-event time distributions

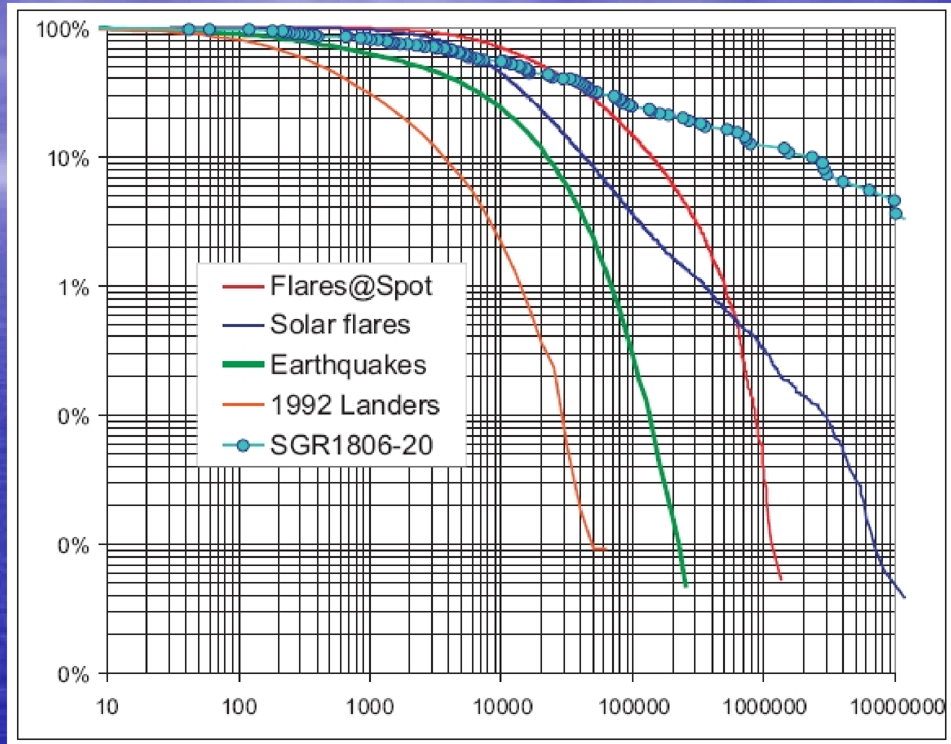


Inter-event time distributions in activity spots



Inter-event time distributions



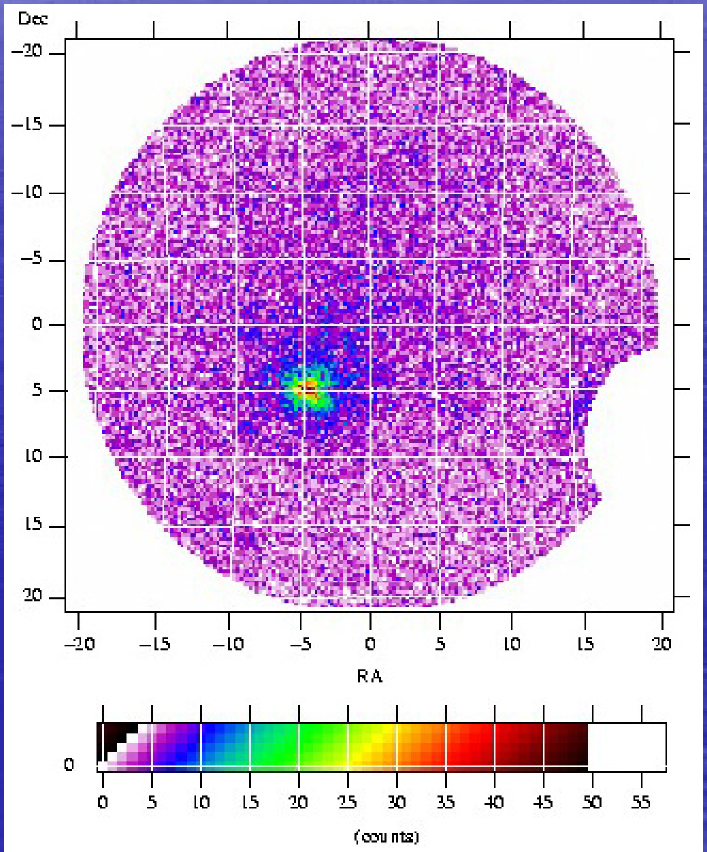


- The inter-event time distribution of soft γ-rays flashes produced by star-quakes on the neutron star 1806-20 is also shown (light blue circles). Energy released in a single event up to 10^{46} erg. (Kossobokov et al. 2000).

SGR1806-20 sequence

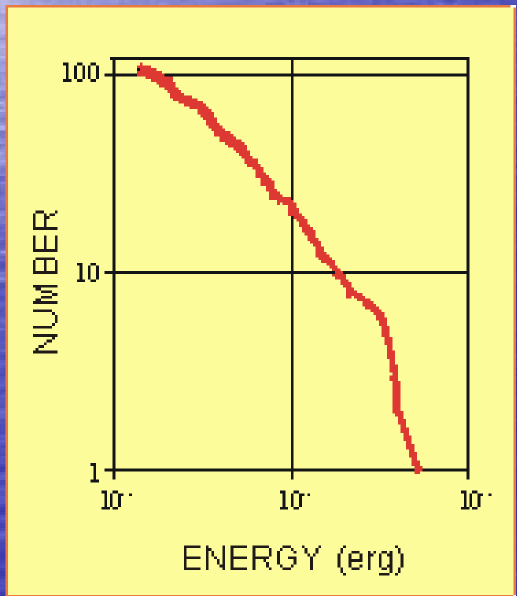
Soft-Gamma-Repeater 1806-20 is the source in Sagittarius, from which more than a hundred X-ray pulsations have been detected. Its location on the sky (1806-20 refer to celestial coordinates: 18 degrees 06 minutes right ascension, -20 degrees declination) is near the Galactic center, which is 25,000 light years away.

The energy of one burst varies from $1.4 \cdot 10^{40}$ erg to $5.3 \cdot 10^{41}$ erg (the largest earthquakes release about 10^{26} erg).



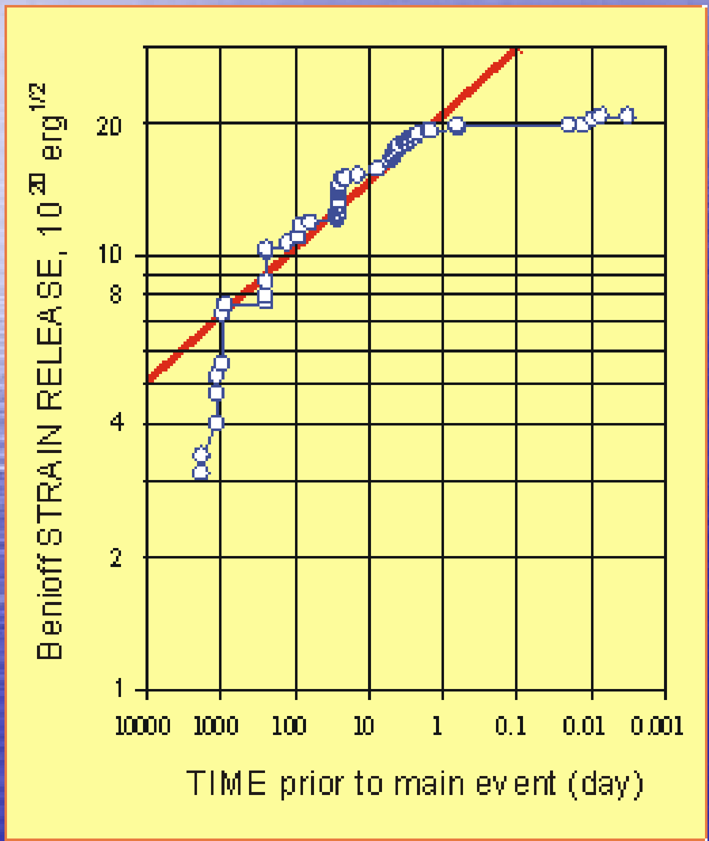
Common general features

A fundamental property of multiple fracturing is the power-law distribution of energy $\log_{10} N(E) = a + b \cdot \log_{10} E$



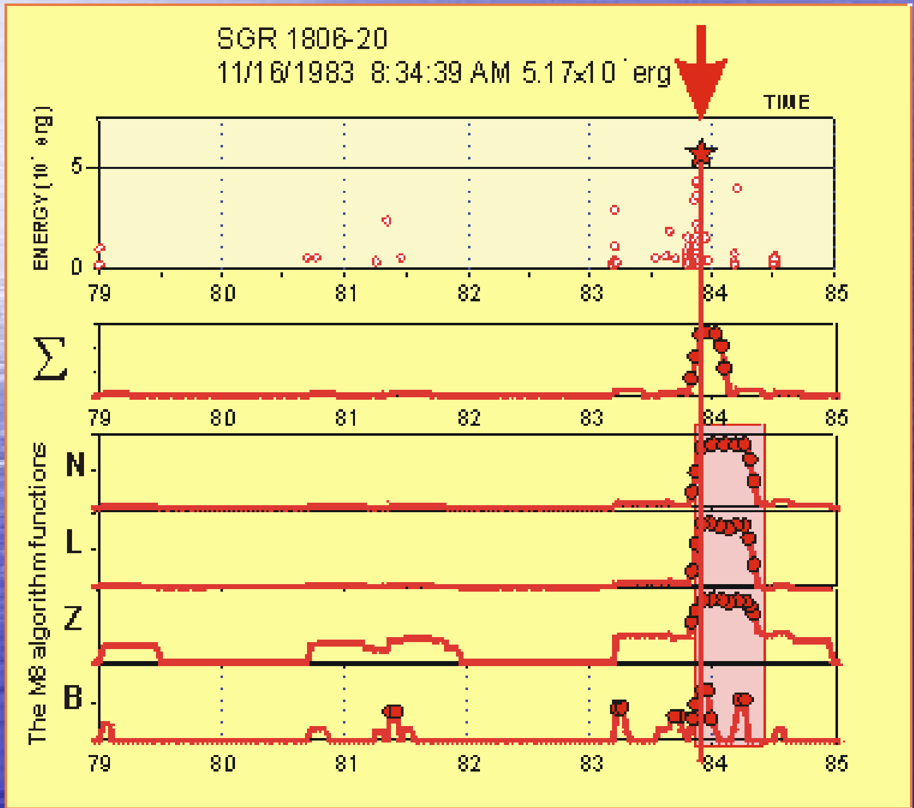
(Gutenberg-Richter relation)

Symptoms of transition to the main rupture



- Escalation of fracturing lasting nearly 1000 days and culminated with the largest starquake on November 16
- The power-law increase of activity, e.g. Benioff strain release ε(t), with a possible trace of the four log-periodic oscillations.

Seismic premonitory patterns



- Pattern $\Sigma \sim E^{2/3}$

  Keilis-Borok & Malinovskaya, 1964

- Pattern B

  Keilis-Borok, Knopoff & Rotwain, 1980

- M8 algorithm

  Keilis-Borok & Kossobokov, 1990

Similarity of starquakes and earthquakes

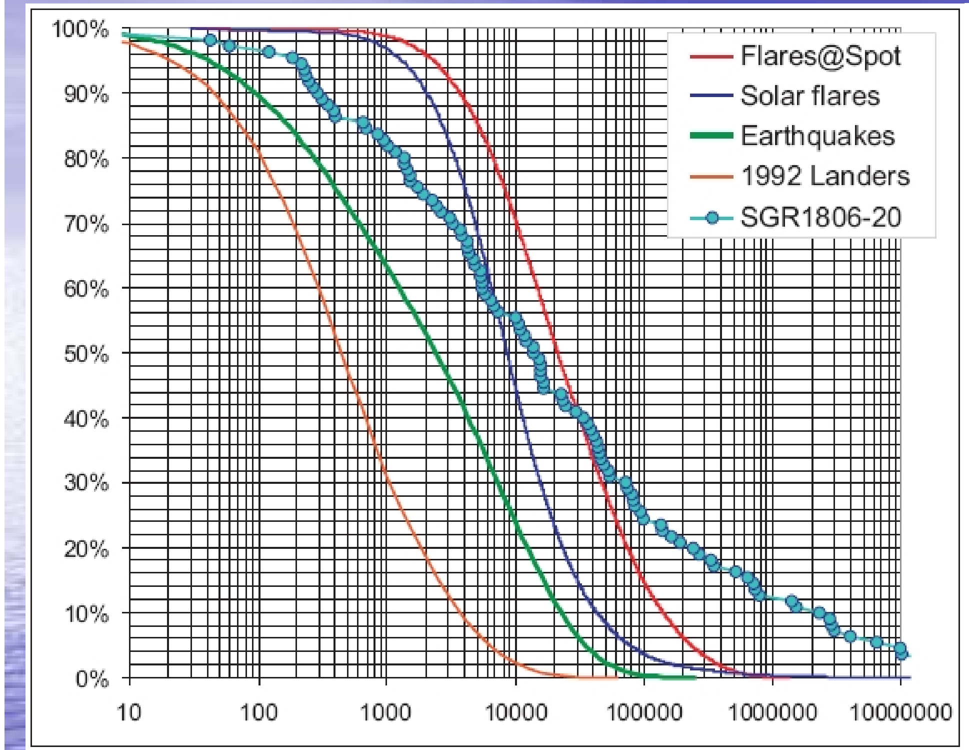
Qualitative so far

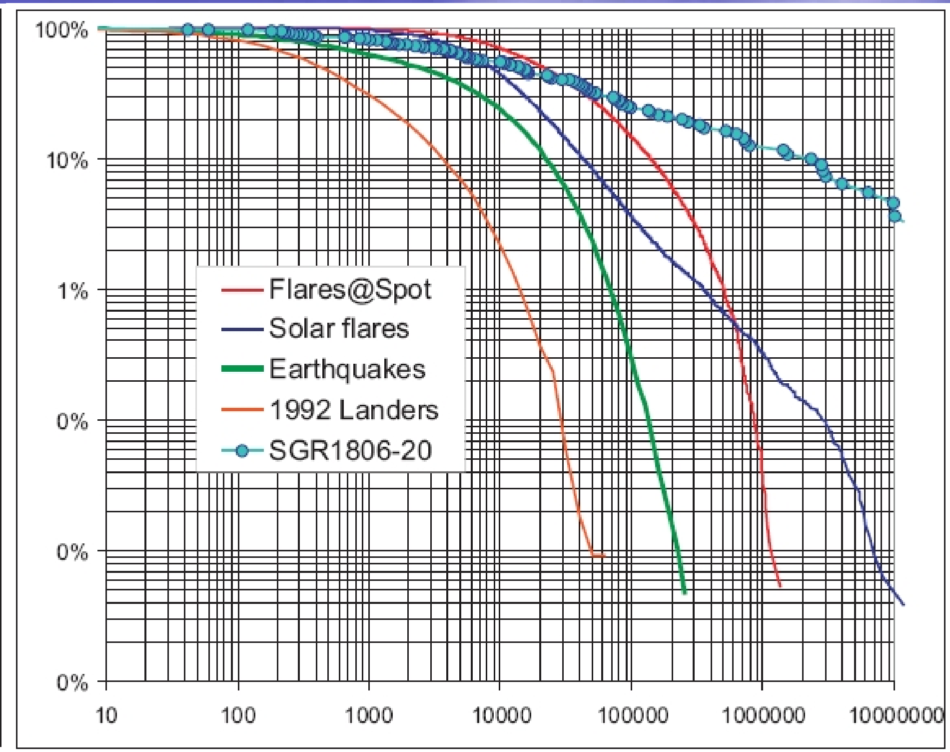
- Gutenberg-Richter relation
- Premonitory changes
- Decay of "aftershocks"
  - Omori power-law

Starquakes evidence drastic expansion of the Realm of Multiple Fracturing previously observed from the lithosphere of the Earth to laboratory samples

Kossobokov, Keilis-Borok & Cheng, 2000

Inter-event time distributions





- The distributions show significant differences
- We calculated the minimum values of K-S statistic for all the couples of distributions over all rescaling fits of the type $P'(\Delta t)=P(C\,\Delta t^{\alpha})$, with C and α fitting constants

The K-S statistic

The two sample Kolmogoroff-Smirnoff statistic $\lambda_{K\text{-}S}$ is defined as

$$\lambda_{K\text{-}S}(D,n,m) = [nm/(n+m)]^{1/2} D$$

where $D = \max |P_{1,n}(\Delta t) - P_{2,m}(\Delta t)|$ is the maximum value of the absolute difference between the cumulative distributions $P_{1,n}(\Delta t)$ and $P_{2,m}(\Delta t)$ of the two samples, whose sizes are n and m respectively.

This test has the advantage of making no assumptions about the distribution of data. Moreover, it is widely accepted to be one of the most useful and general nonparametric methods for comparing two samples, as it is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples.

Inter-event time distributions:

The Kolmogoroff-Smirnoff two-sample criterion

	Flares	Flares at spot	SCSN	Landers	SGR1806-20
Flares	32076	3.435	8.648	2.071	0.636
Flares at spot	100 %	18878	5.898	1.669	0.434
SCSN	100 %	100 %	87688	3.726	1.435
Landers	99.96%	99.26%	100 %	10706	0.47
SGR1806-20	19.13%	0.92%	96.77%	2.24%	110

- The results indicate that the distributions cannot be rescaled onto the same curve (confidence level > 99%)
- Only the association of the starquake distribution (by far the smallest sample, 111 events) with all flares, flares at an activity spot, and Landers event cannot be rejected

Conclusions

- The statistics of inter-event times between earthquakes and solar flares show different scaling.
- Even the same phenomenon when observed in different periods or at different spots of activity show different scaling. This difference were found in our analysis both for earthquakes and solar flares
- In particular, the observed inter-event time distributions of different phenomena show a wide spectrum of scaling and cannot be rescaled onto a single curve
- Even if some statistical analogies are present (e.g. power laws of different characteristics), which could be related to common characteristics of impulsive energy release processes in critical nonlinear systems, our results do not support the presence of "universality"

Farewell remarks

И.М.Гельфанд
ДВА АРХЕТИПА В ПСИХОЛОГИИ ЧЕЛОВЕЧЕСТВА
1989 Лекция при вручении премии INAMORI FOUNDATION
(Киото, Япония)

I would like to recall what was said as a casual remark before. Mathematics is an area in which two types of thinking collide - artistic and precise, logical; and this unique alloy makes mathematics an area, which occupies a special place in human culture. Perhaps the only music can compete with it.

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7. Liability of mathematicians.

I would like to say a few words about the moral responsibility of mathematicians.

Mathematics is one of the highest achievements of the human spirit and at the same time, a very accurate and adequate language, without which the physics and many other fields would have been impossible. And the first side of liability of mathematicians is of using the experience and achievements of mathematics, especially mathematics of XX century, to expand significantly an opportunity for creating adequate languages in other branches of science. First and foremost, to help in identifying the structures and, if possible, to develop an adequate language for living systems - various areas of biology, economics, psychology, etc.

I am an optimist and I believe that nowadays in this not much advanced direction much will be done, especially in the times of computers, which are slowly but inevitably will change the psychology of mathematicians, forcing them to recall non-formalizable living systems.

…

И.М.Гельфанд
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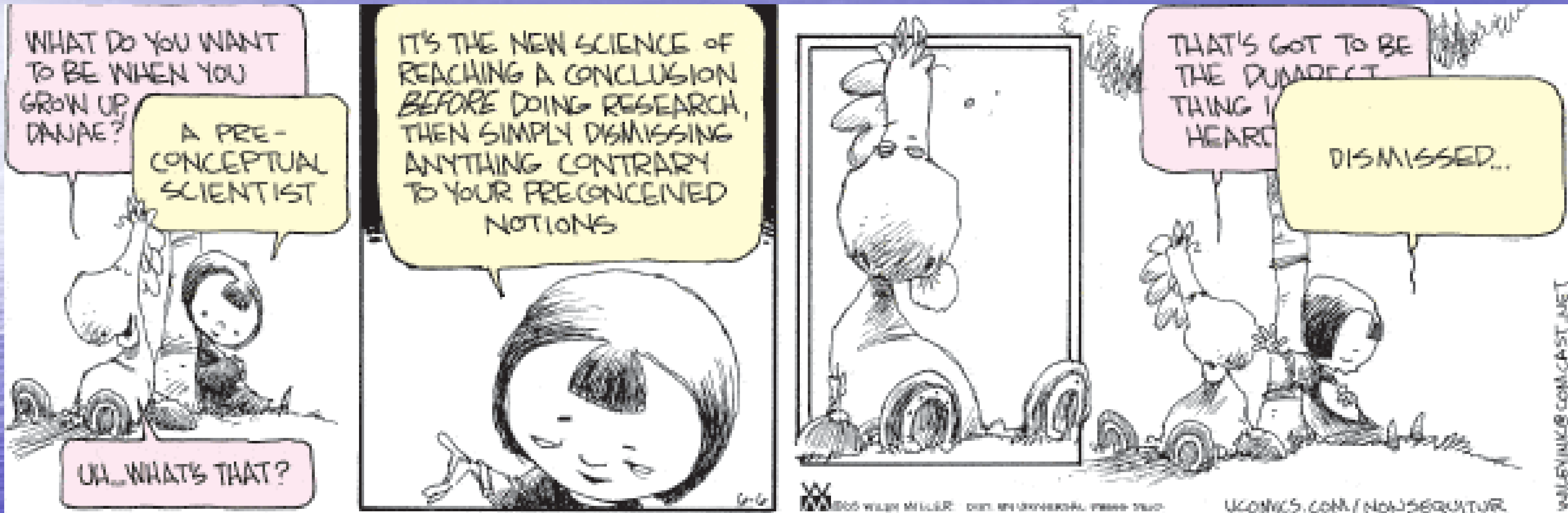
…

But perhaps even more responsibility, as I have said, is to counter the unwise and dangerous use of precise mathematical and logical systems outside their applicability. Despite the fact that I gave this little room here, I see it as an important issue, which should be dealt with in a separate dedicated report. For who but mathematicians can help preventing abuse of mathematics in our technocratic age.


WHAT DO YOU WANT TO BE WHEN YOU GROW UP, DANAE?
A PRE-CONCEPTUAL SCIENTIST
UH...WHAT'S THAT?
IT'S THE NEW SCIENCE OF REACHING A CONCLUSION BEFORE DOING RESEARCH, THEN SIMPLY DISMISSING ANYTHING CONTRARY TO YOUR PRECONCEIVED NOTIONS
THAT'S GOT TO BE
DISMISSED...
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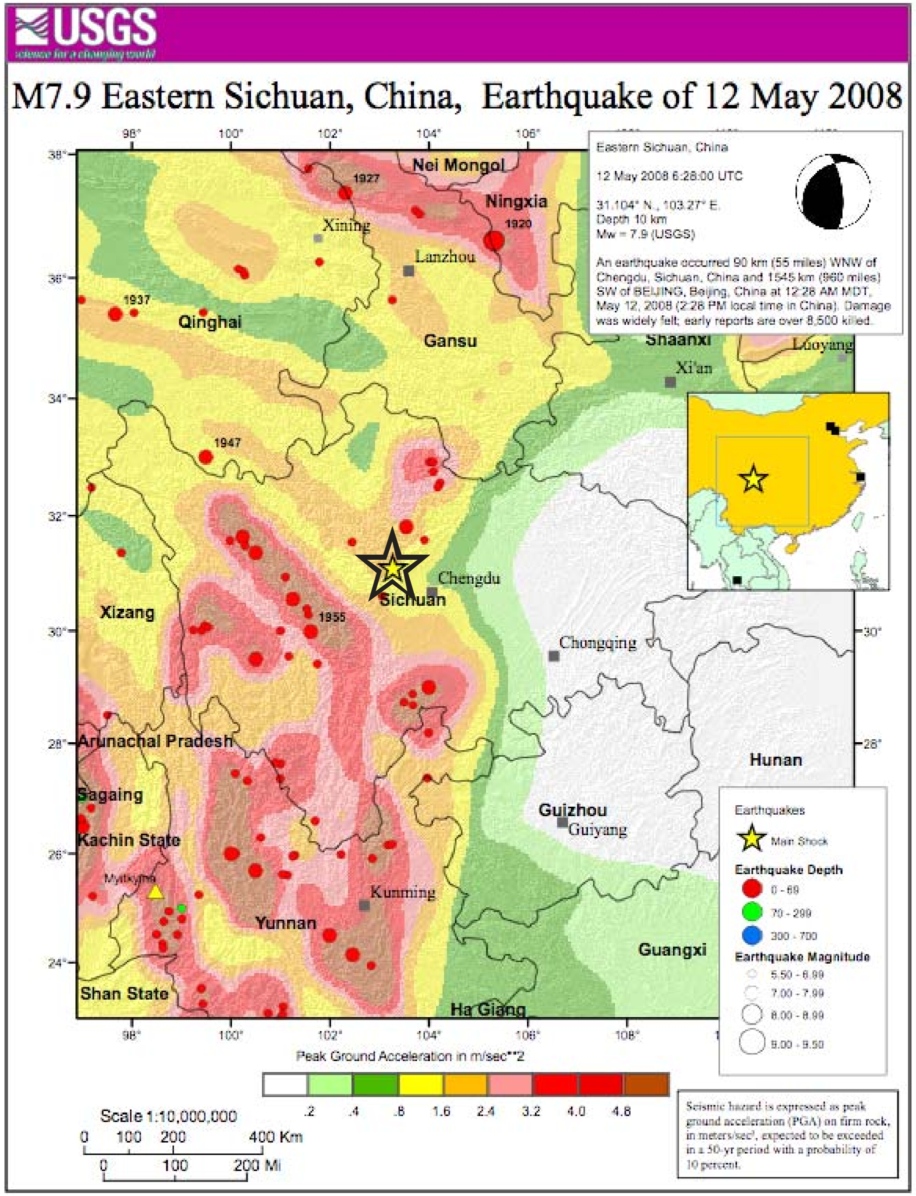

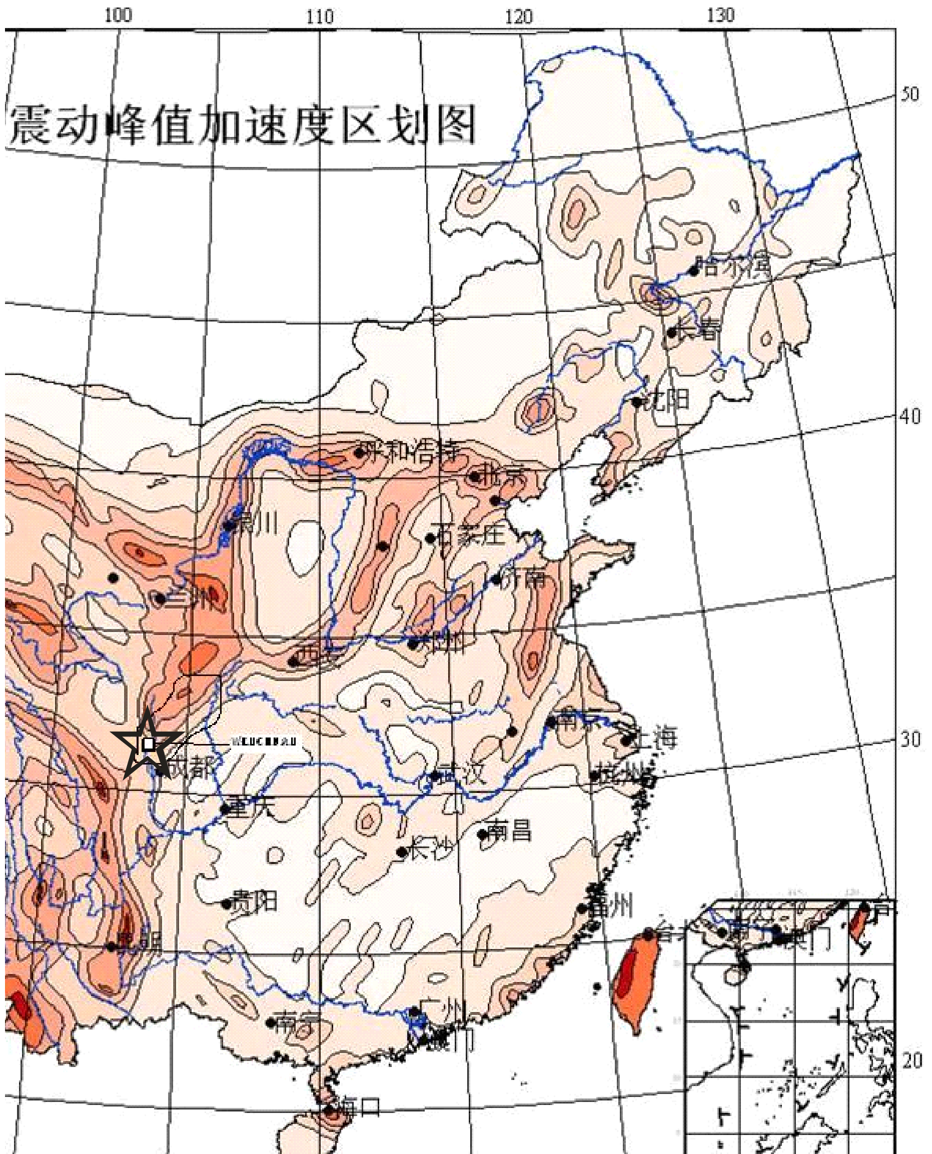

Chinese National Seismic Design Map


AFP

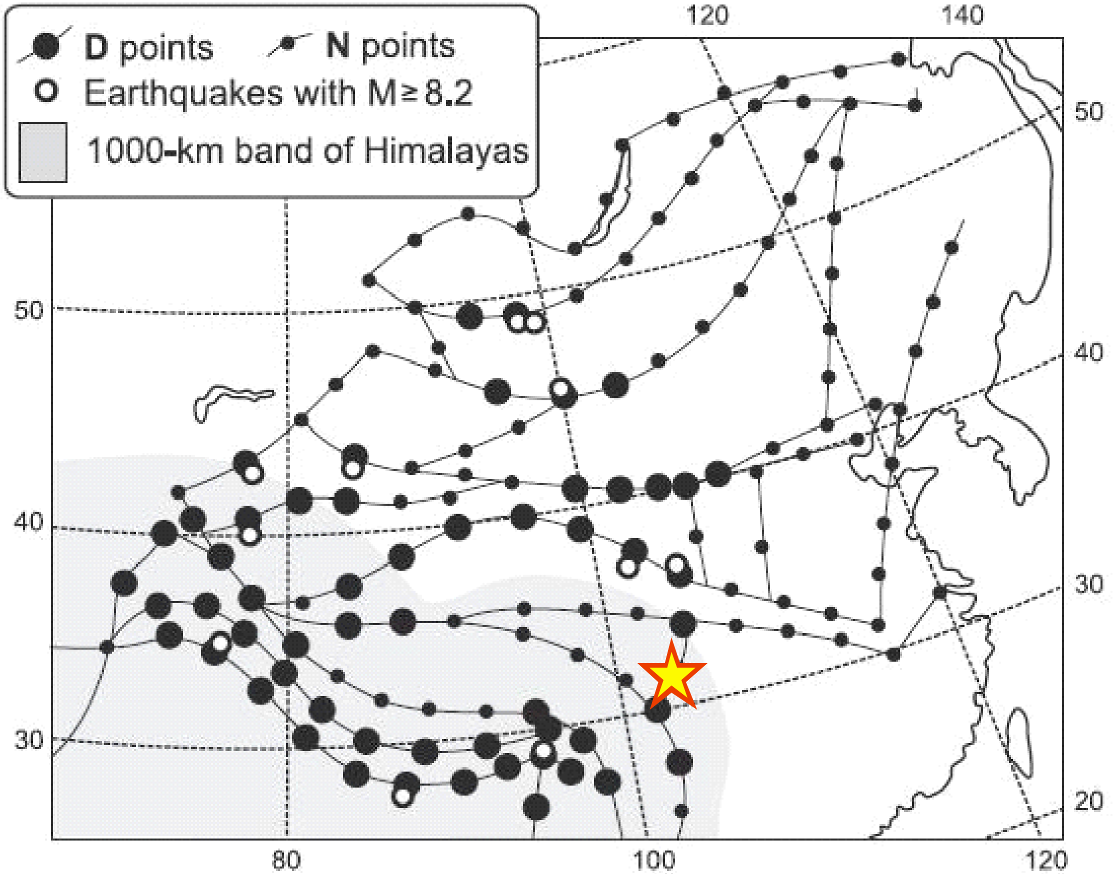

Fig. 6.14. Earthquake-prone segments in the Transasian seismic belt outside its Alpine zone ($M \geq 8.2$): Composite recognition by hyperplanes in $H_{\max} \times H_{\min}$ [Kos84]. The reduced decision rule for the Alpine belt works within 1000-km distances from Himalayas (shaded grey) [GK84], i.e. $\Delta H \geq 6,5$ km there

Кособоков В.Г. Общие свойства мест сильнейших землетрясений (с M ≥ 8,2) внеальпийской зоны Трансазиатского сейсмического пояса. *Логические и вычислительные методы в сейсмологии.* М.: Наука, 1984, 69-71. (*Вычислительная сейсмология, Выпуск 17*).


Thank you !