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FORECASTING THE M6.9 KYTHERA EARTHQUAKE OF 8 JANUARY 2006:

A STEP FORWARD IN EARTHQUAKE PREDICTION?

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BACKGROUND

- If seismicity is viewed as a sequence of cycles culminating in some kind of critical point, then **it is expected that an increase (acceleration) of seismic activity and long range correlation between events will precede large earthquakes.**
- The acceleration assumes the form $$\frac{\mathrm{d}\sum\Omega(t)}{\mathrm{d}\,t} = k\left(t_c - t\right)^{-\alpha} \quad \Rightarrow \quad \sum\Omega(t) = K + A(t_c - t)^n \qquad (1)$$

where $\log\Omega = cM + d$, t_c is the time at which a critical state is attained), $A < 0$, $n < 1$ and $K = \sum\Omega$ @ $t = t_c$.

IMPLEMENTATION

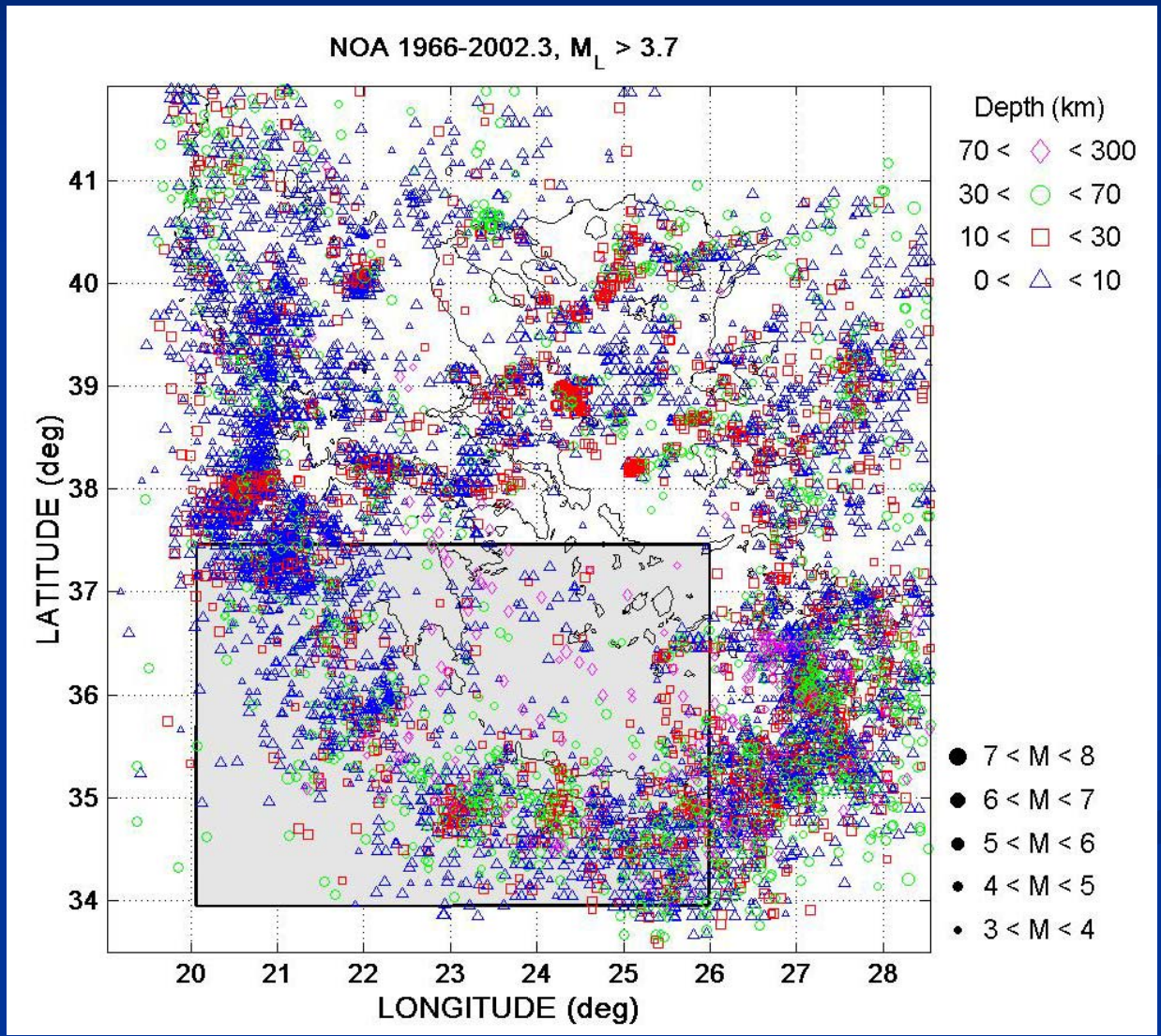
- Ω is the cumulative Benioff strain $$\varepsilon(t) = \sum_{i=1}^{N(t)} \sqrt{E_i(t)}$$ where

  $E_i(t)$: the energy of the i^{th} event s.t. $\log_{10}E_i(t) = 4.8 + 1.5M_S$.
- $N(t)$: the total number of events at time t
- Power-law behaviour tested with the Curvature $$C = (\text{Power law fit RMS})/(\text{Linear fit RMS})$$
- C < 1, if power-law a good approximation

- ✓ Compute (1) using all earthquakes within concentric circular areas
- ✓ Find radius at which C is minimum.
- ✓ Do this on a regular grid and construct maps of curvature, critical exponent, critical time and predicted magnitude to study.

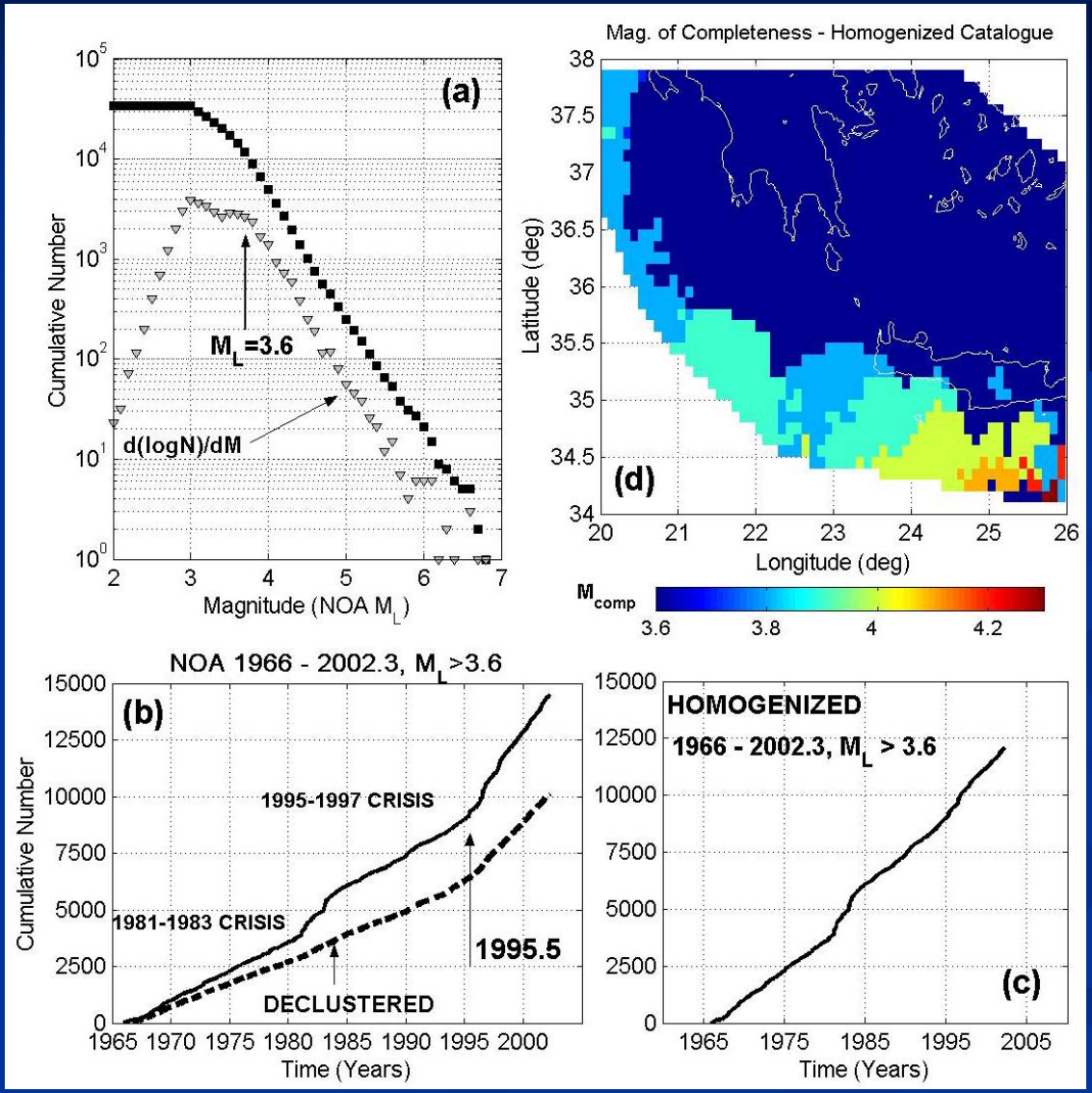
THE DATA

☞ **The most detailed (but not most accurate) catalogue of Greek seismicity is compiled by the Geodynamic Institute of NOA, containing over 55000 events.**



DATA REDUCTION I

Magnitude of Completeness is M_L= 3.6



Rate change detected in Magnitude Reporting as of 1995.5, using method of Reasenberg, (1985)

Detailed study of study area shows that magnitude of completeness is M_L= 3.9 - 4

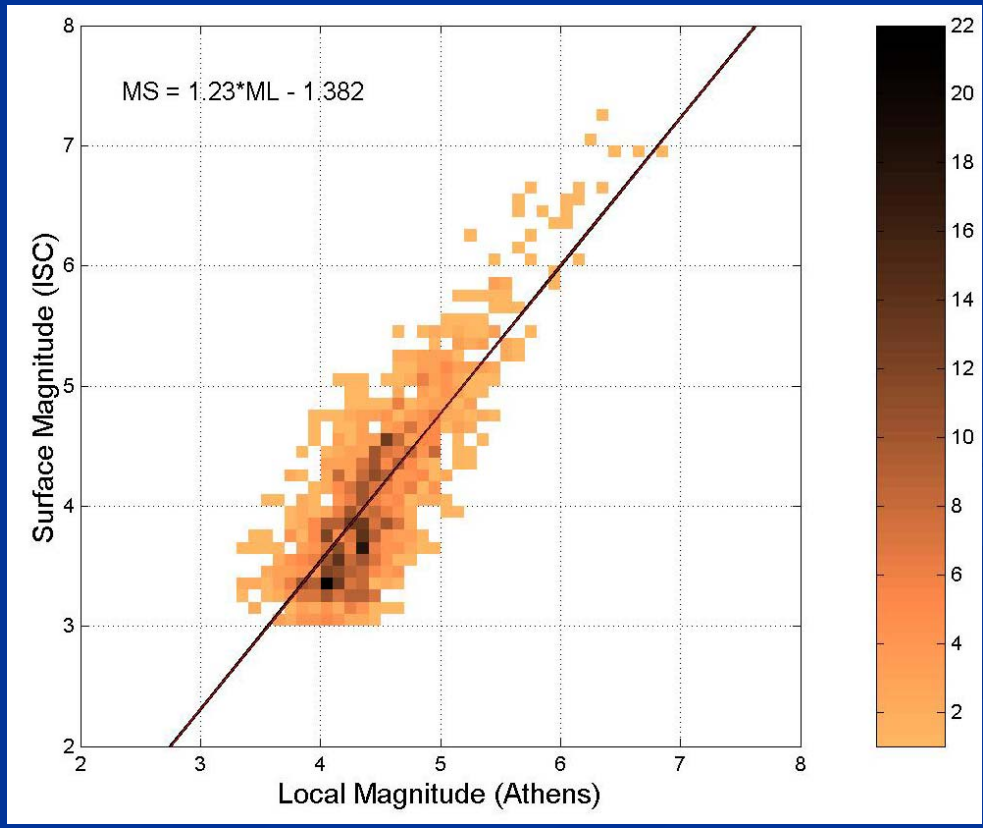
Rate change corrected, using method of Zuniga & Wyss, (1995)

DATA REDUCTION II

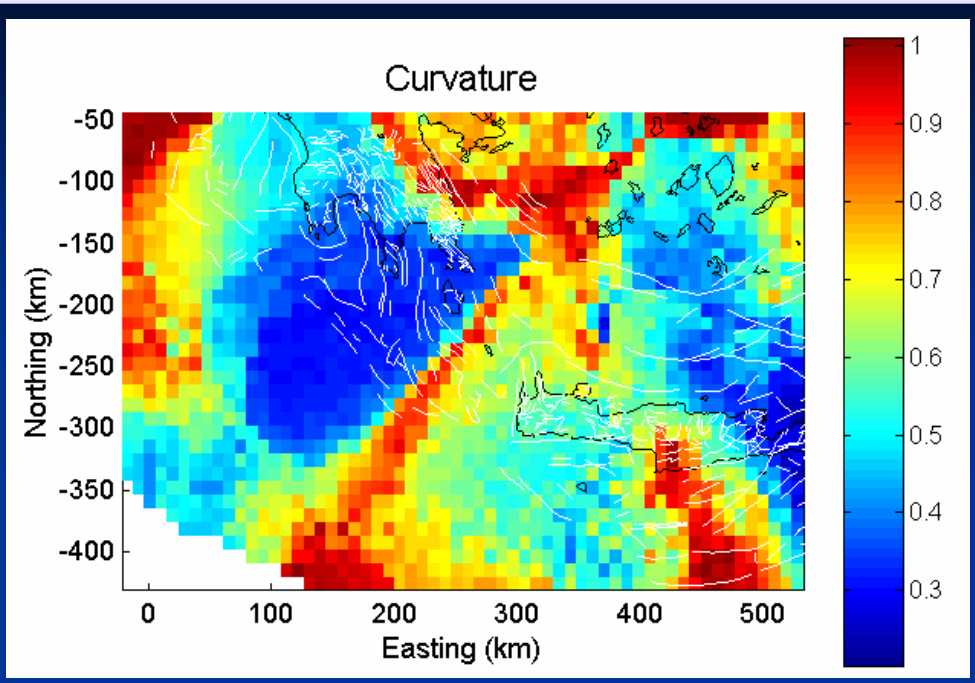
- NOA reports M_L but existing empirical relations converting magnitude to Moment, Energy and Benioff Strain require M_S.

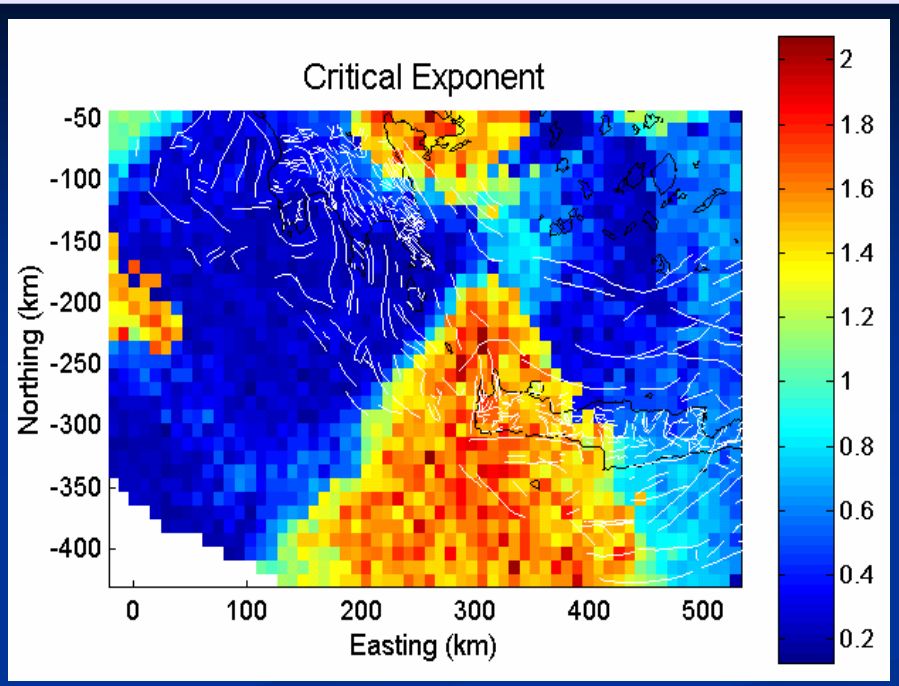
★ **Using the common events contained in the respective catalogues, NOA M_L is converted to ISC M_S :**

$$M_{S\,(ISC)} = 1.68 M_{L(NOA)} - 3.35$$



APRIL 2002: CURVATURE AND CRITICAL EXPONENT





- Curvature shows areas of stronger or weaker power-law behaviour,

but

- Power-law behaviour observed both when seismicity is accelerating ($n<1$) or decelerating ($n>1$)

The distribution of the critical exponent shows a well structured butterfly pattern with nearly sharp boundaries between exponents greater or smaller than unity !!!

POSSIBLE INTERPRETATION

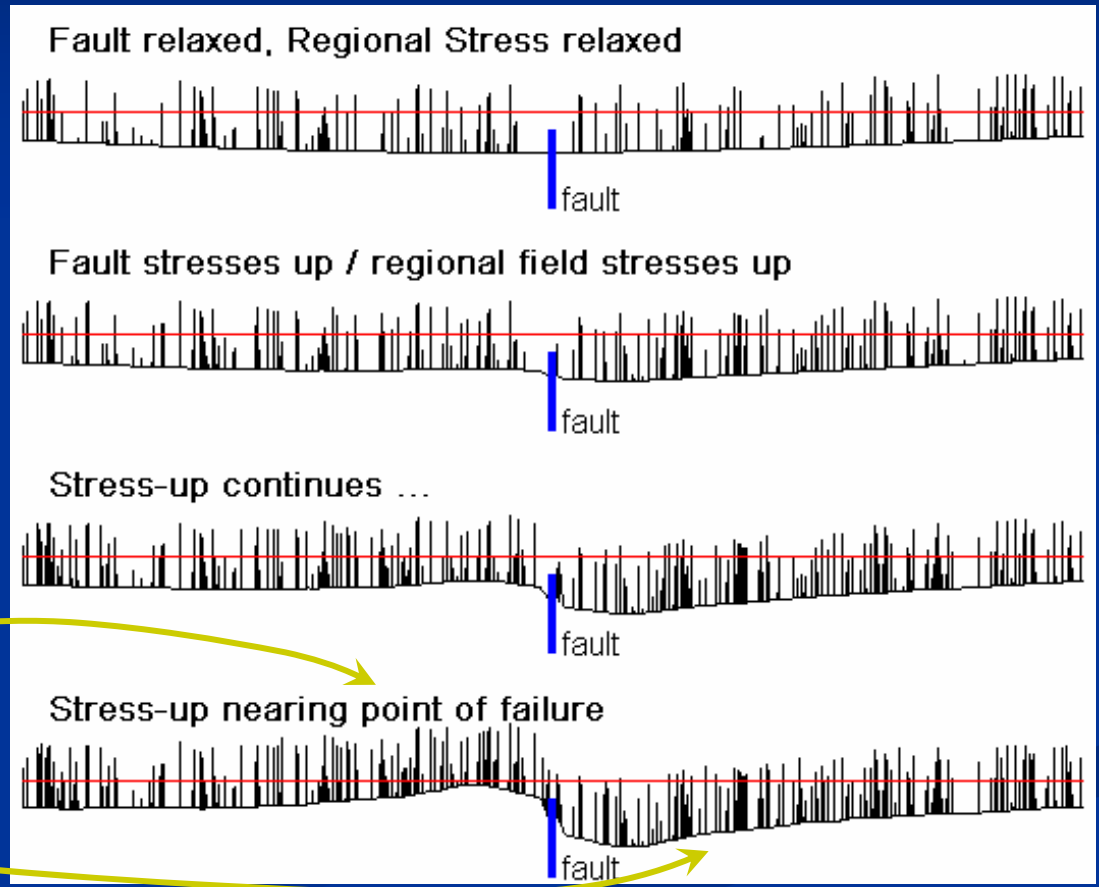
Borrowing and expanding an idea from Bowman King (2001) and King and Bowman (2001), the observed characteristics of distributed accelerating / decelerating seismicity can possibly be understood in terms of a model combining simple elastic rebound and stress transfer.

Failure threshold

Self-organization of the regional fault system / Regional damage mechanics at work here

Acceleration observed here

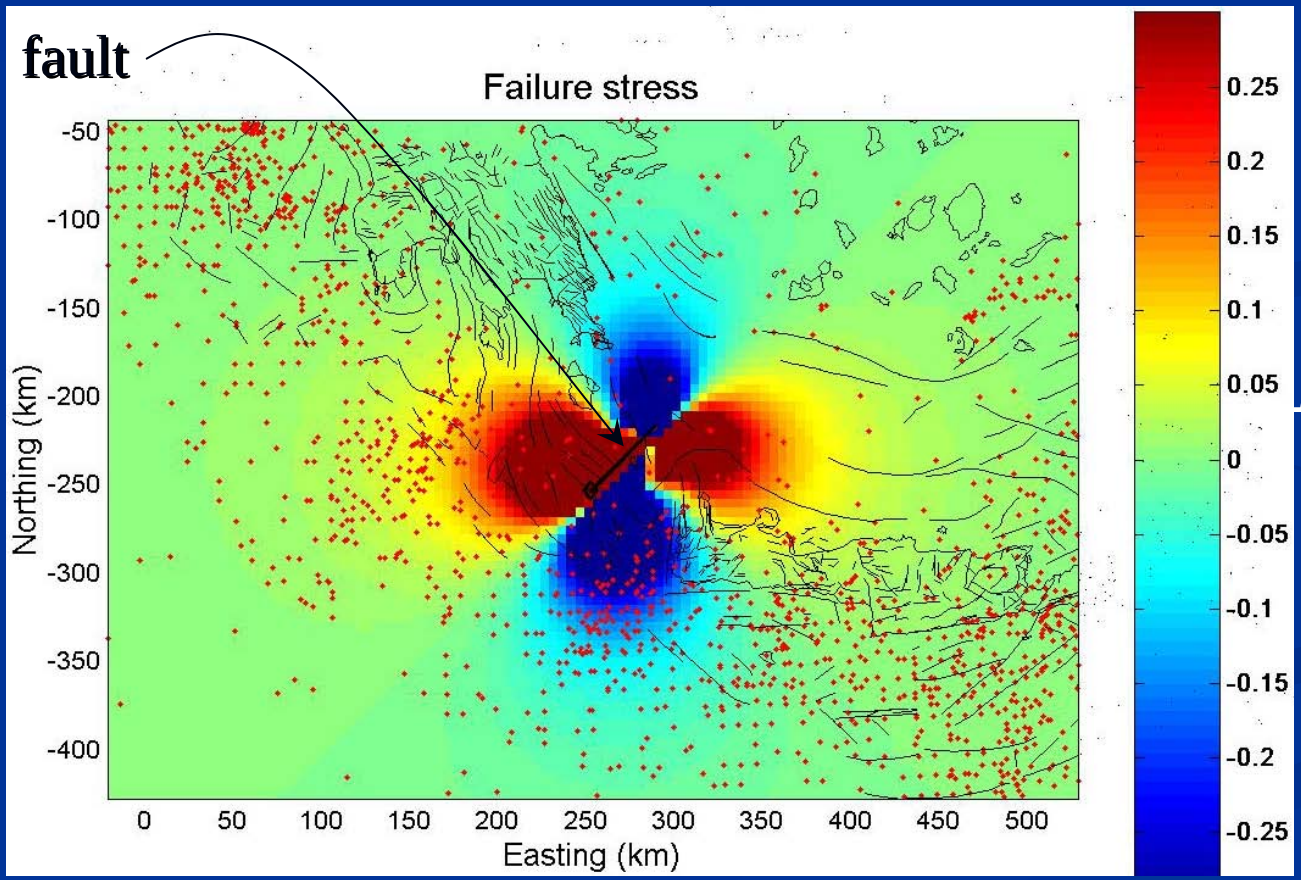
Deceleration observed here

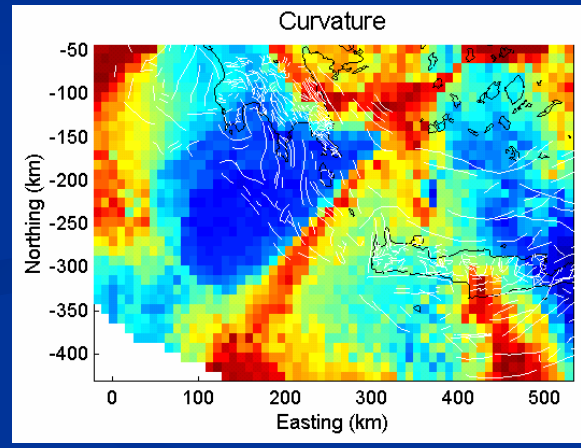


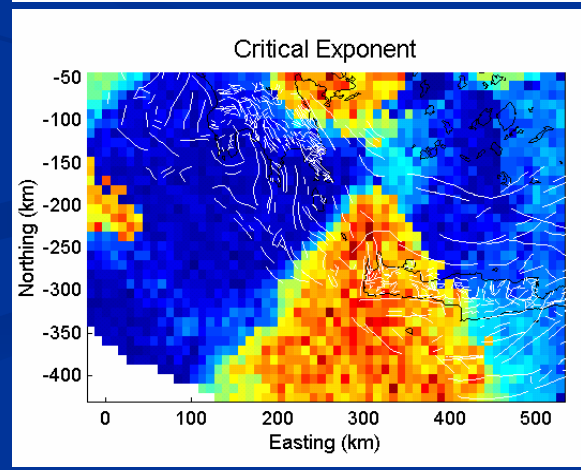
☞ **Regions of acceleration / deceleration are defined by the stress field required to rupture a fault with a specified orientation and rake.**

APRIL 2002: STRESS MODEL FOR THE POWER-LAW BEVAVIOUR I

- Define a **fault** with $\varphi=45^{o}$, $\delta=80^{o}$, $\lambda=150^{o}$, **capable of producing a M=7 earthquake** in a medium with Young's modulus $\approx 7\times10^{7}$ Pa.
- Compute failure stress at the depth of 10km.
- Failure stress is herein defined as $(\sigma_1 + \sigma_3)/2$

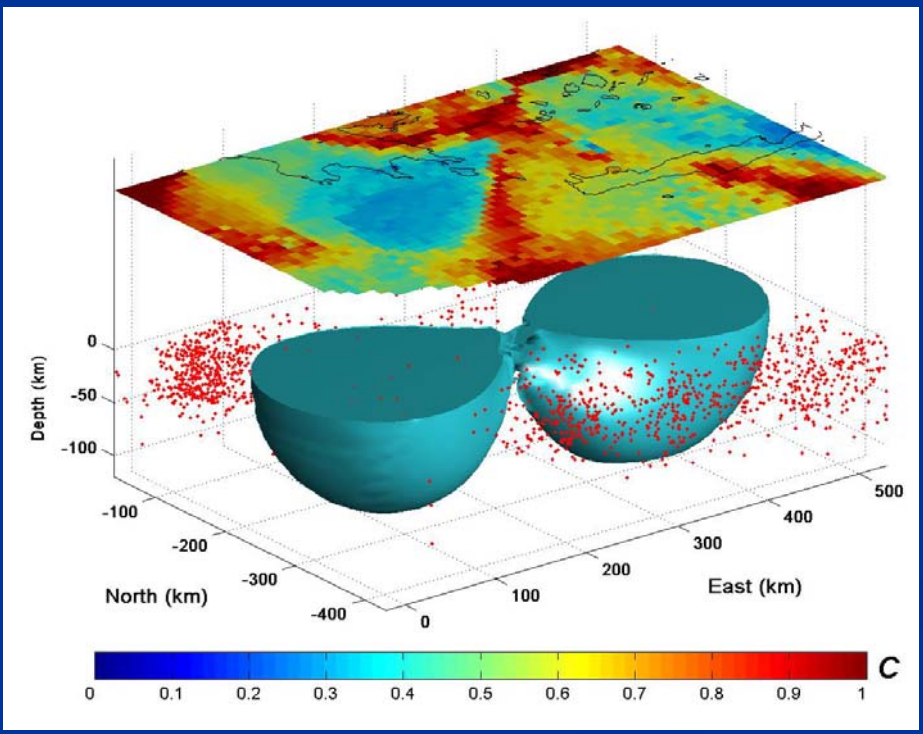


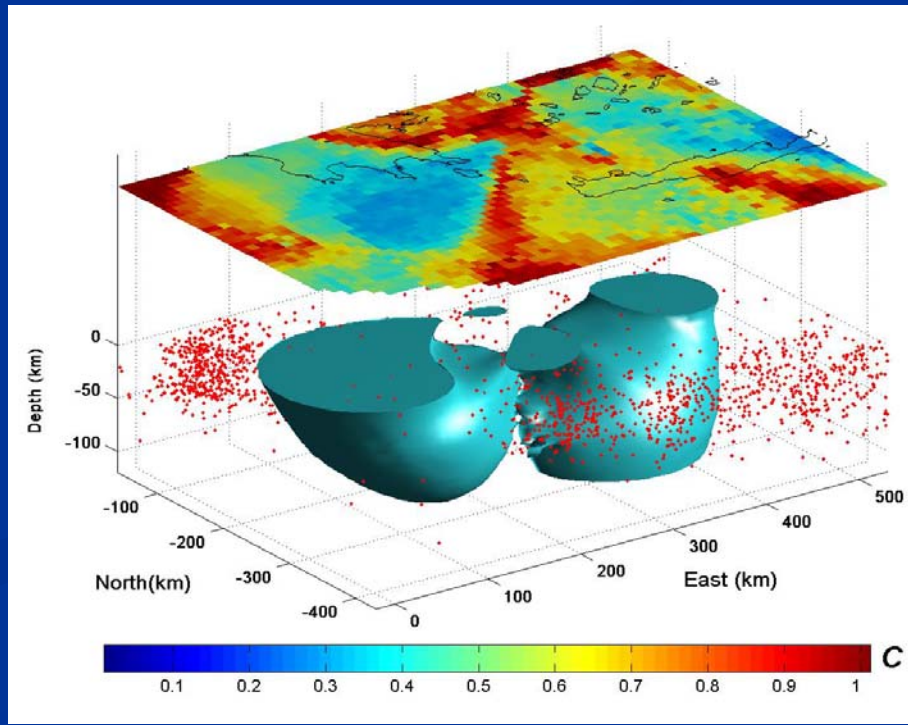




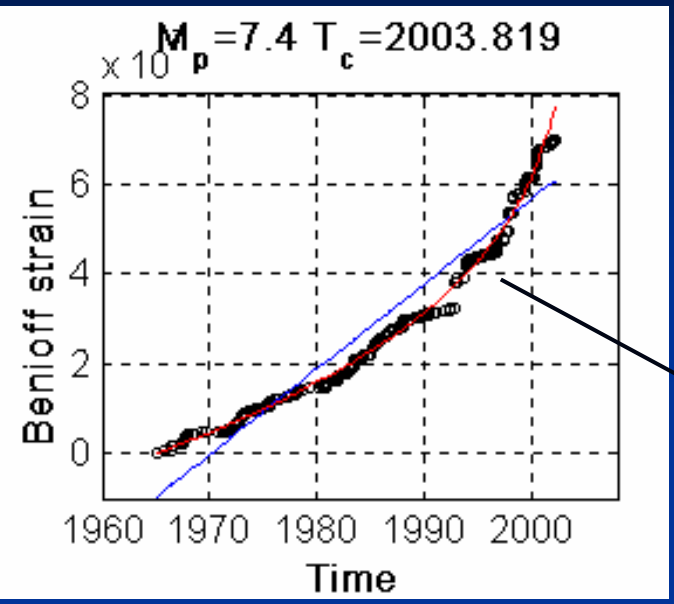
APRIL 2002: STRESS MODEL FOR THE POWER-LAW BEVAVIOUR II

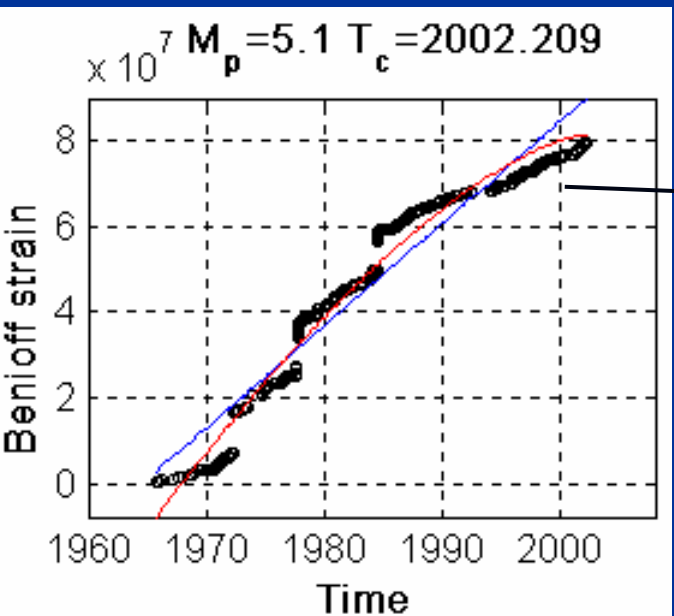
- Two fault models: One at upper crustal depths and one at intermediate depths: known seismicity trends in the area are also of intermediate depth.
- The observed distribution of curvature correlates better with the stress bright spots of the intermediate depth fault (location and pear shape of the western accelerating lobe, quiescent channel, location and shape of the eastern accelerating lobe).





APRIL 2002: STRESS MODEL FOR THE POWER-LAW BEVAVIOUR III



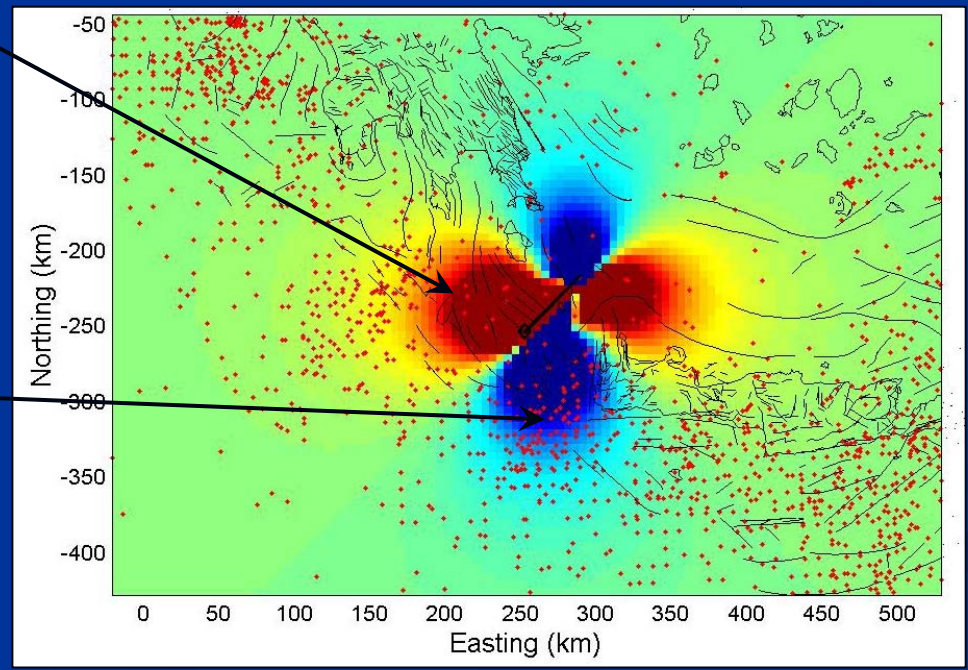


Time dependence of acceleration and predicted parameters:

How big : M = 7.2 – 7.4

When : T_c = 2003.2 - 2004

Where : Near Antikythira island, SW Hellenic Arc, between Crete and the Peloponnese



APRIL 2002: DISCUSSION

Q Do we have an earthquake prediction ?

A In the absence of a concrete case-history, it is very difficult, if not impossible to assess.

If so,

Q Are the predicted parameters, especially the magnitude, fairly reasonable ?

A **Yes**, for the area, **but** power-law acceleration is a renormalization process, so that when a new element is added, (i.e. a large pre-schock), the sequence is renormalized and the predicted model parameters may change significantly (recall the observed time-history of acceleration).

 If, however, it is correct that pre-shock magnitudes get progressively larger with approaching to failure, recent seismicity patterns indicate that the critical point may be relatively nigh

! It is not at all necessary that a large earthquake will occur at the end of the process. The stored energy may be dissipated with low rate aseismic event(s) or with a series of smaller earthquakes.

☹ It is always possible that we are wrong !

JANUARY 2006: AN EARTHQUAKE

Recently, a large earthquake ***did*** occur in the area, with the following parameters:

Time: 2006-01-08 at 11:34:53.1

Magnitude: M_w = 6.7 (NOA M_L = 6.9)

Location: 36.31 °N; 23.25 °E

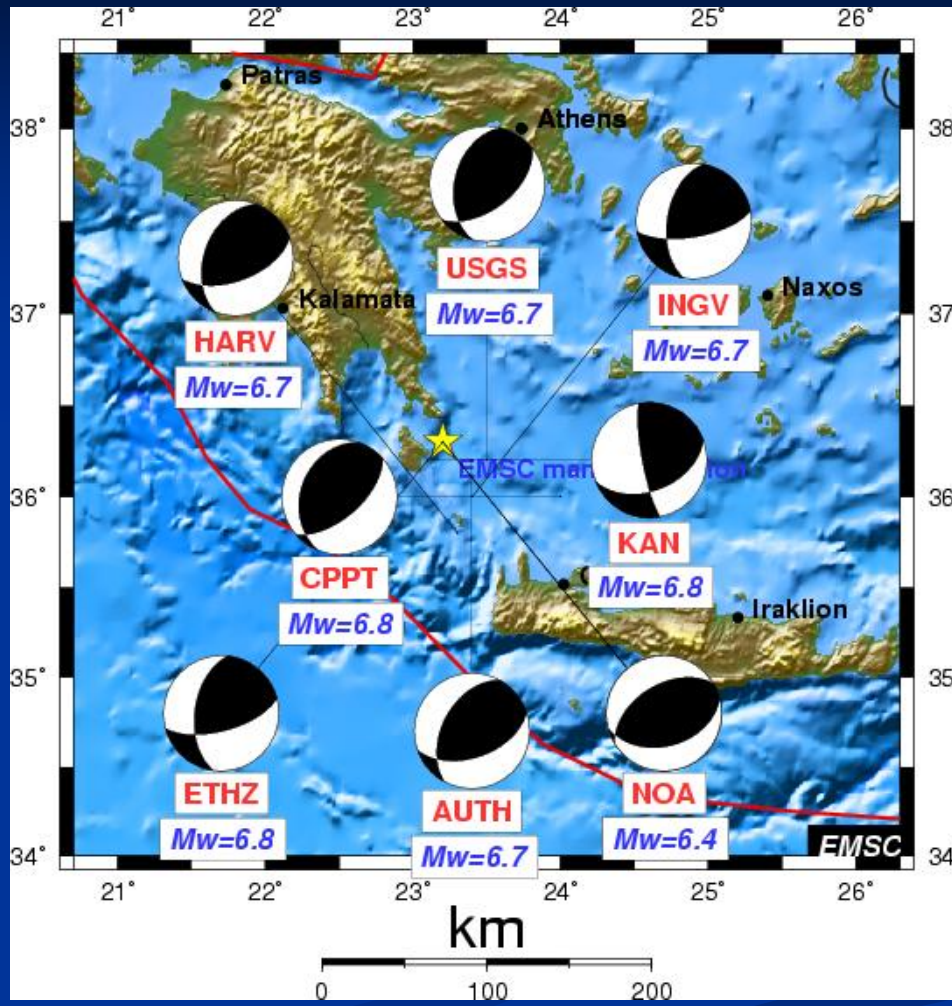
Depth: 60 km

Fault: N-NE to NE *oblique slip thrust*

⟨φ⟩ = 198°; ⟨δ⟩ = 50°; ⟨λ⟩ = 52°

or

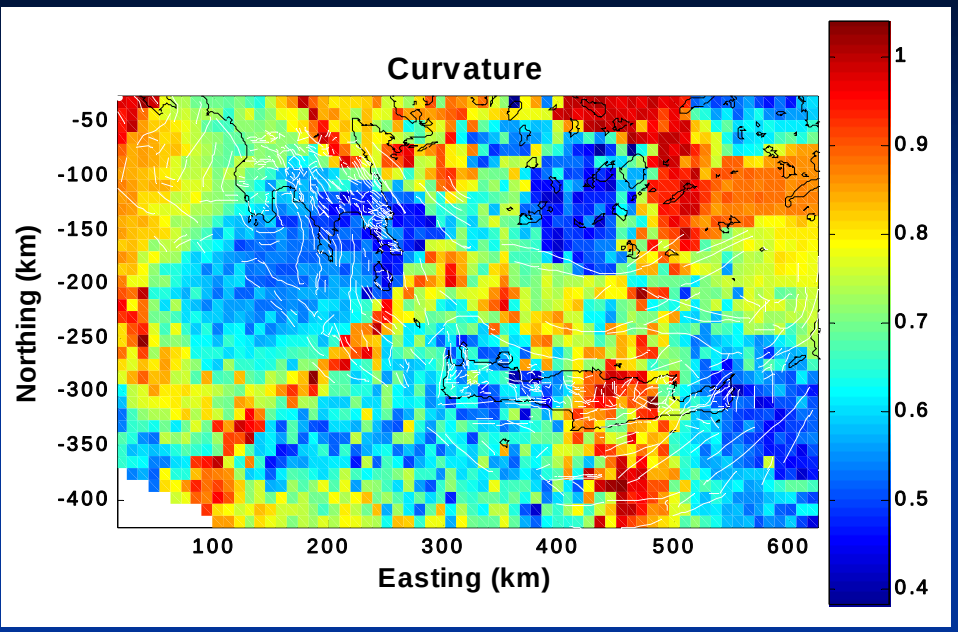
⟨φ⟩ = 68°; ⟨δ⟩ = 56°; ⟨λ⟩ = 125°

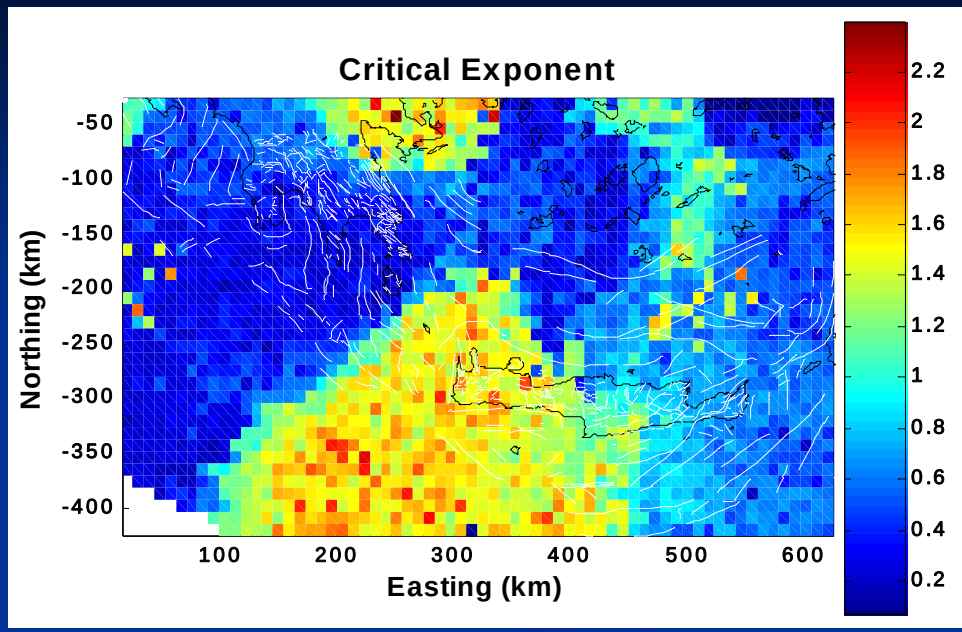


Was this *the* earthquake?

Figure courtesy of the European-Mediterranean Seismological Centre @ URL http://www.emsc-csem.org

JANUARY 2006: CURVATURE AND CRITICAL EXPONENT

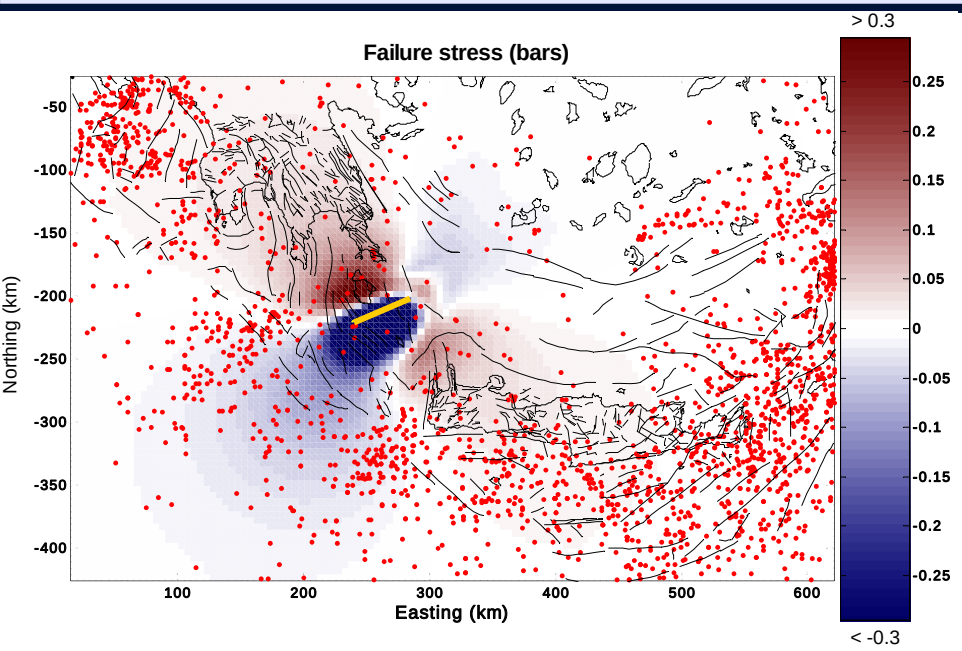


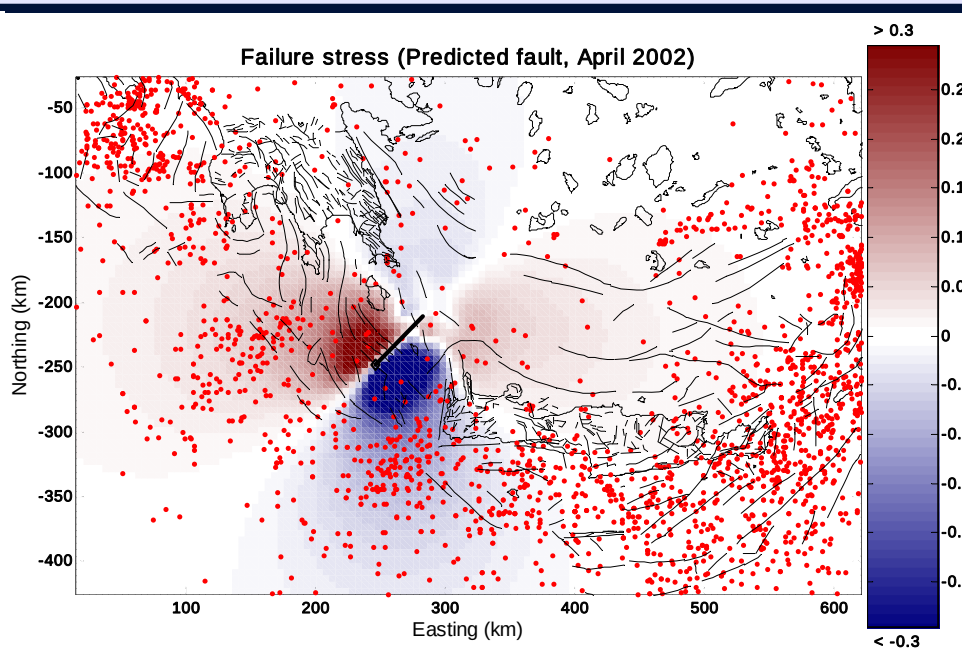


- Distribution of *curvature* same as in 2002, with areas of stronger or weaker power-law behaviour.
- Lower curvatures (better power-law) at, and to the NW of Kythira.

The distribution of the *critical exponent* is the same as in 2002, exhibiting a *butterfly pattern* with nearly sharp boundaries between exponents greater or smaller than unity !!!

JANUARY 2006: STRESS MODEL OF THE ACTUAL FAULT

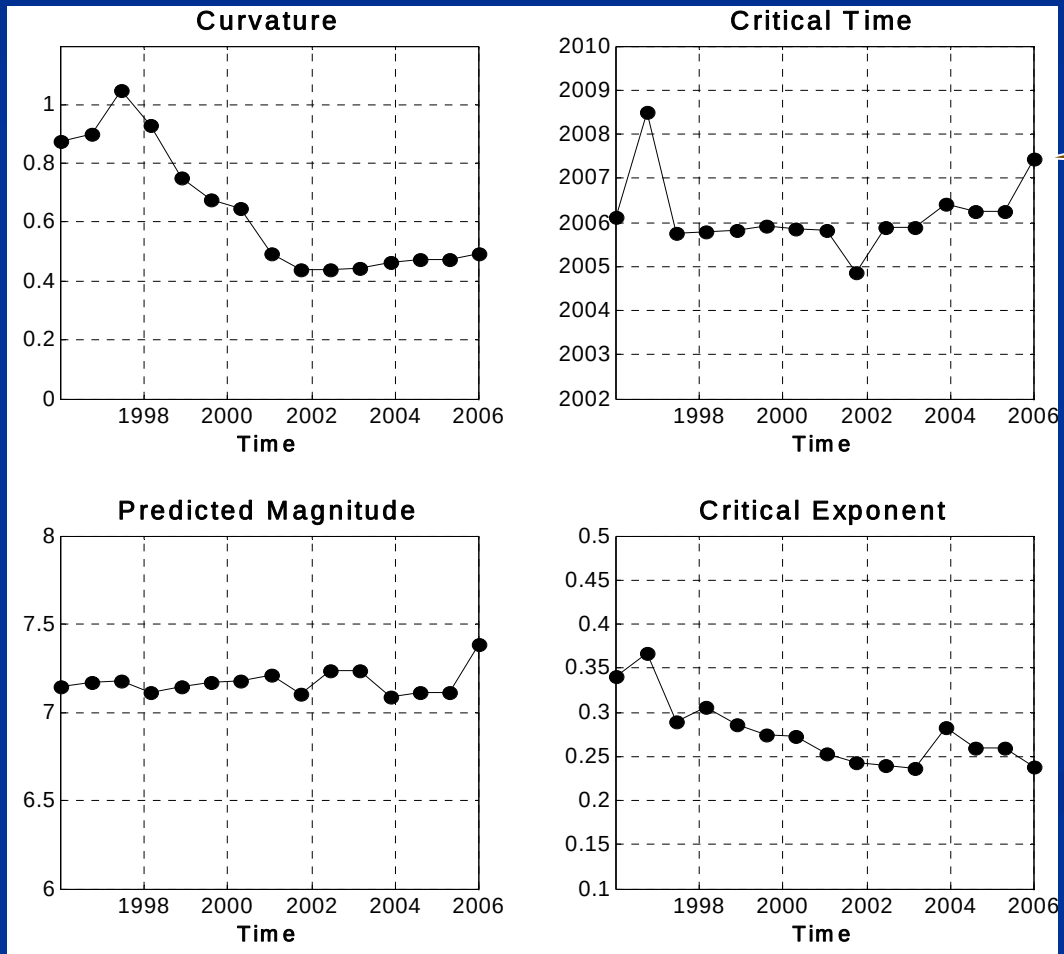




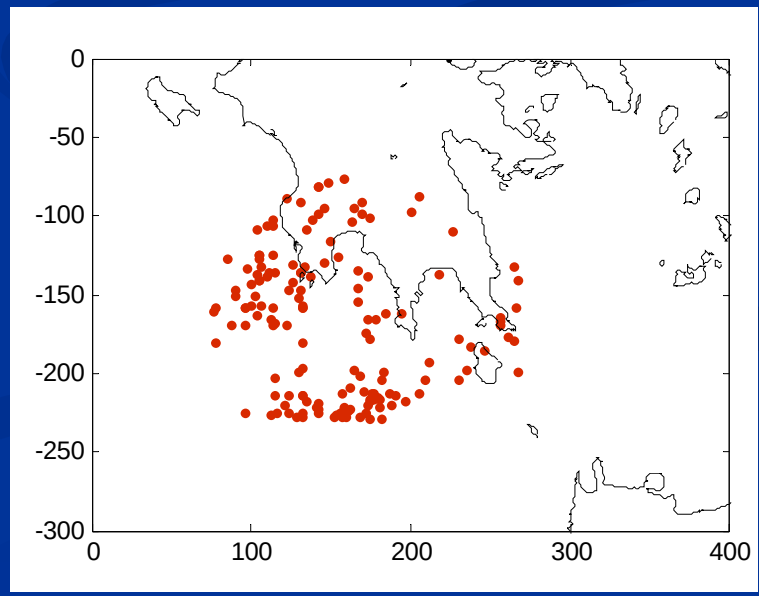
- **Left:** The 8 January 2006 fault with **φ = 68°; δ = 56°; λ = 125°** and epicentre at (36.11ºN, 23.36ºE).
- **Right:** The **"predicted"** fault with **φ =45º, δ =80º, λ =150º**, located by trial and error within 30 km of the actual fault.
- **Both:** Magnitude M_s = 6.9; Depth to: 45 km; Young's modulus ≈ 18 ×10^7 Pa.
- **Figures show failure stress at the depth of 20 km.**
- **Patterns of positive / negative stress transfer somewhat different but with little effect on the outcome because they have overall similar characteristics.** Such simple models could anyhow be only gross approximations of reality.

JANUARY 2006: TIME DEPENDENCE OF ACCELERATION

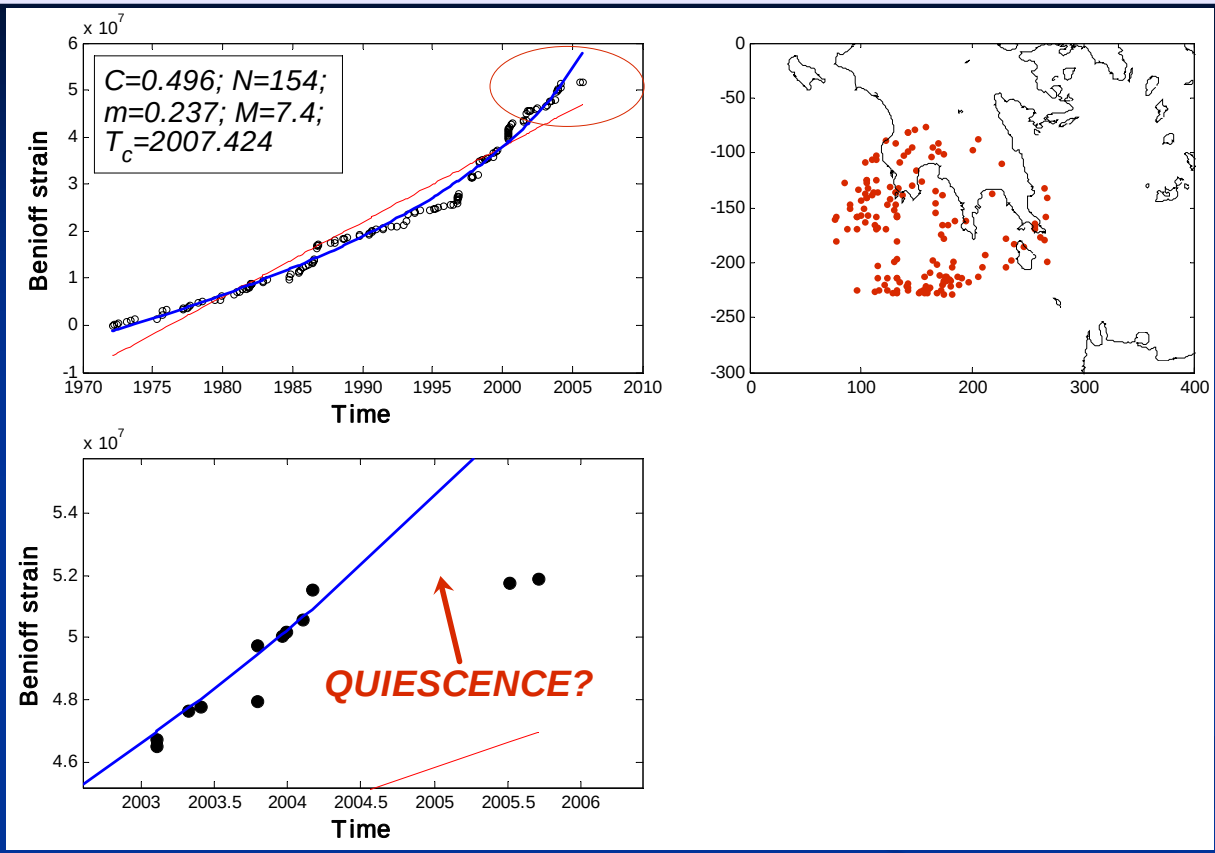
- Time-to-failure analysis applied in exactly the same way as in April 2002.
- We show representative results from a sample of earthquakes in the positive stress transfer domain (drafted out of several different populations with similar results).



- Stable, almost accurate determination of parameters,
- **but note the shift in the predicted *critical time* after 2004 and the jerk at the end of 2006**



JANUARY 2006: THE END OF THE CYCLE – QUIESCENCE?



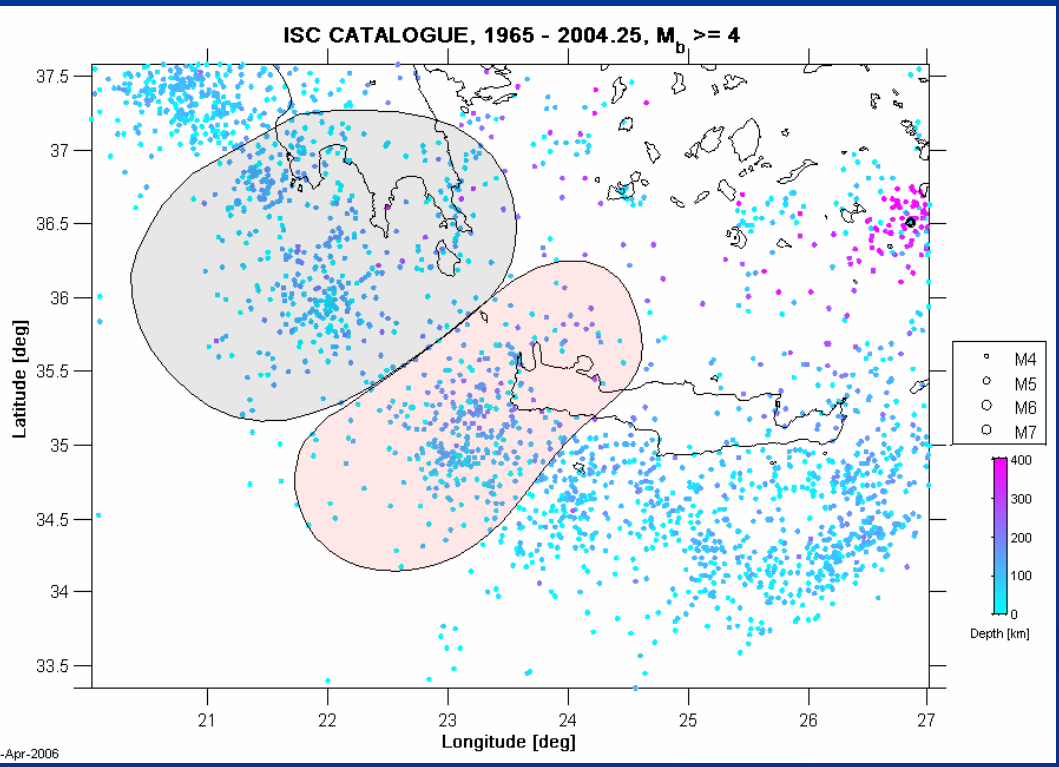
There are **no earthquakes in the positive stress transfer area** between early 2004 and late 2005, with 2 events appearing after 2005.5, clearly ***not*** fitting into the accelerating pattern and producing the anomalies observed in previous slide!

- It is possible that the critical state was attained as early as 2004
- The earthquake broke out 1.5 years later meaning that additional (unknown) factors delayed the global transition (failure).
- In the meanwhile, the area went quiescent!

AN INDEPENDENT TEST : THE FRACTAL DIMENSION I

If the stress-transfer model leading to the above analysis is representative of seismogenetic processes, then:

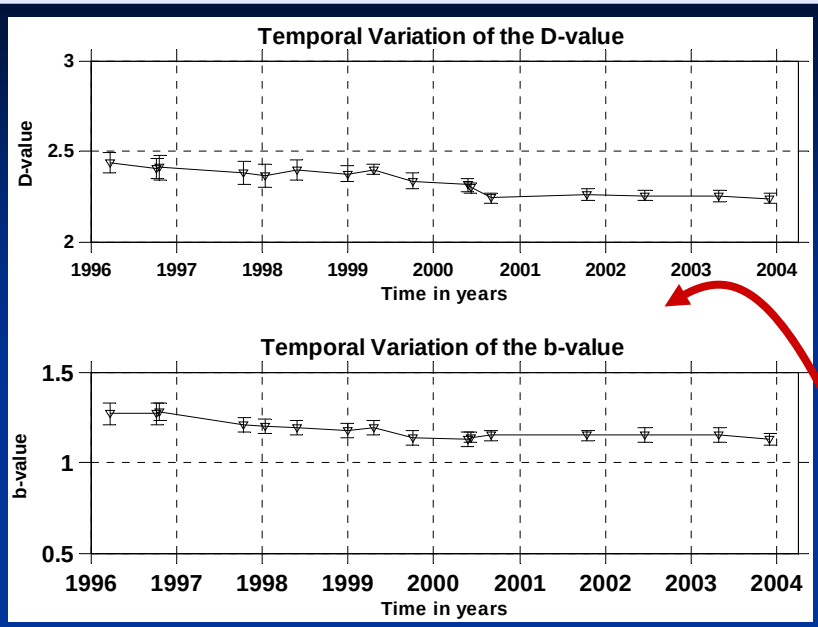
- The acceleration of seismic release rates would necessitate ***increasingly stronger clustering***, therefore, a persistently ***decreasing fractal dimension.***
- Conversely, deceleration of seismic release rates (relaxation) would imply a ***stable fractal dimension,*** *(or even an* ***increasing*** *fractal dimension).*

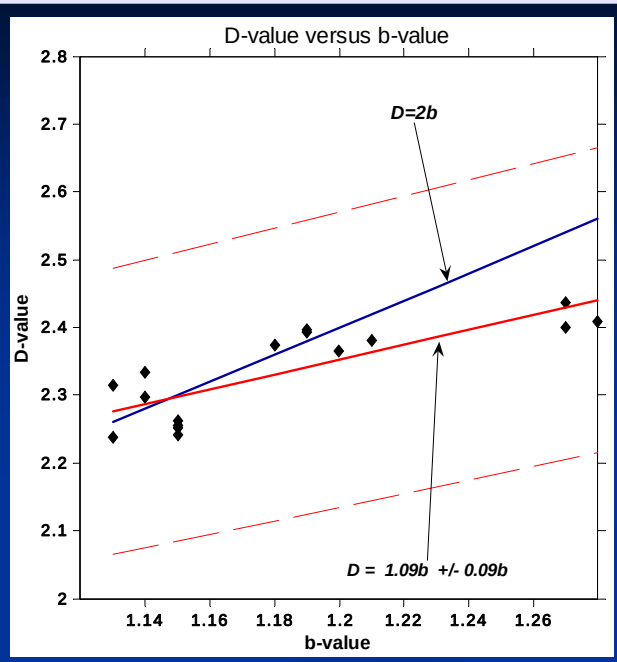


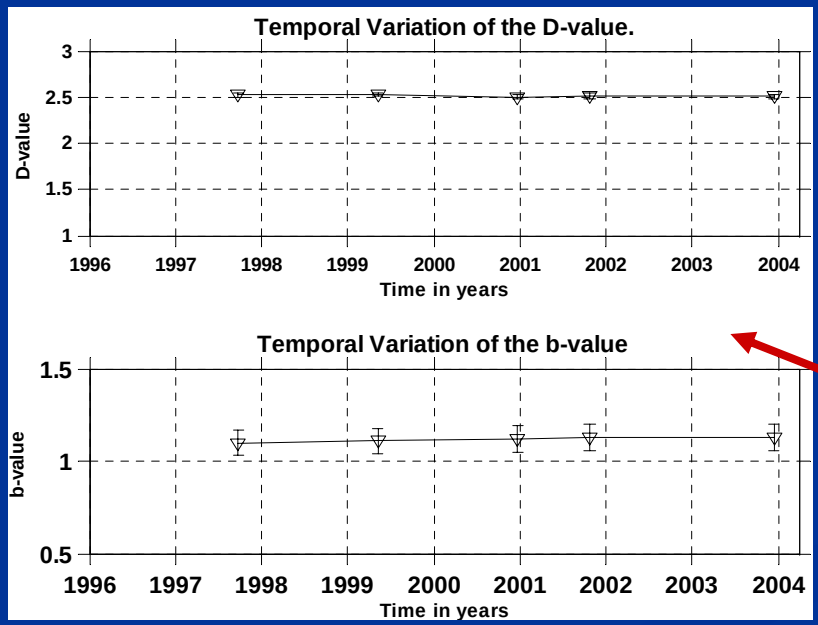
To investigate we use the ISC catalogue

- Better for this objective as it has better epicentral and hypocentral determinations.
- NOA depth estimates are *notoriously inaccurate.*
- Data available only up to 2004.24, just as needed!
- Compute D^3 using the *Correlation Integral.*

AN INDEPENDENT TEST: THE FRACTAL DIMENSION II







- ✓ Statistically significant and corresponding ***decrease*** of D^3 and ***b -values observed*** in the *area of* ***positive*** *stress transfer* (acceleration).
- ✓ The relationship between D^3 and b is ***linear***
- ✓ **No change in D^3 and *b-values* observed in** *area of negative stress transfer* **(deceleration).**

DISCUSSION

Q **Was this *the* earthquake?**

A **Two independent lines of compelling evidence suggest that *it probably WAS!***

A **More importantly, *the evidence lend support to a physical model of earthquake preparation that is both tenable and testable!***

Q **Were the predicted parameters, especially the magnitude and time, fairly reasonable ?**

A **The *epicentral area* was *accurately* estimated.**

A **The predicted *faulting mechanism was fairly guessed.***

A **The *predicted magnitude* was *overestimated by 0.4 - 0.5* at 2002. *Re-evaluation* on the basis of the actual fault *improved estimation to within 0.2 - 0.3* of the observed magnitude.**

A **The *predicted time* was *wrong by 2 years* at 2002 – subsequently it improved (e.g. *Tzanis and Vallianatos, 2004*). *Re-evaluation* on the basis of the actual fault, *improved the prediction* to within 0.3 years of the actual time of occurrence.**

- **The *error* in the 2002 estimation could possibly be due to contamination of earthquake population used for estimation by *unrelated events* – The acceleration process is non-linear and therefore very sensitive!**

Q **Are we absolutely sure?**

A **NO! In the absence of a concrete case-history, it is very difficult, if not impossible to answer affirmatively. *We must be very cautious!***

☞ **The acceleration-by-stress-transfer model may soon be put to the test!**