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Current research on empirical trends and models of earthquake source scaling

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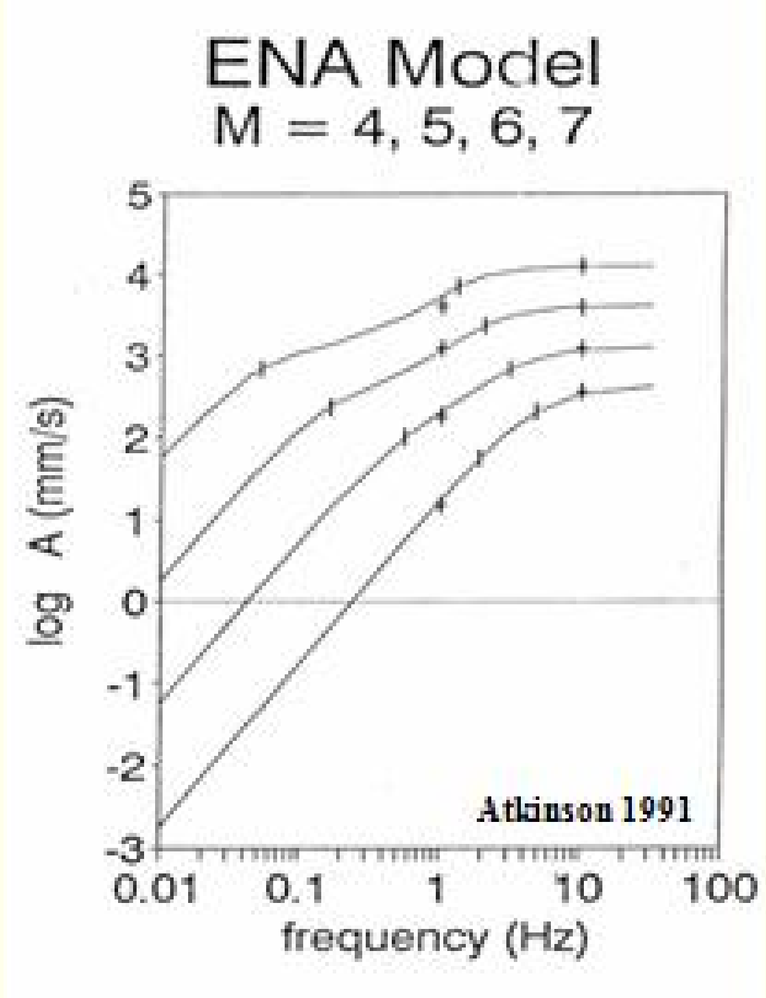
PART 1

Splitting $\boldsymbol{f_{max}}$: separating site-controlled and source-controlled contributions
into the upper cutoff of acceleration spectrum
of a local earthquake

(*A.A Gusev, E.M.Guseva 2015)*.

Empirical scaling laws for FSA, with f_{c2} feature



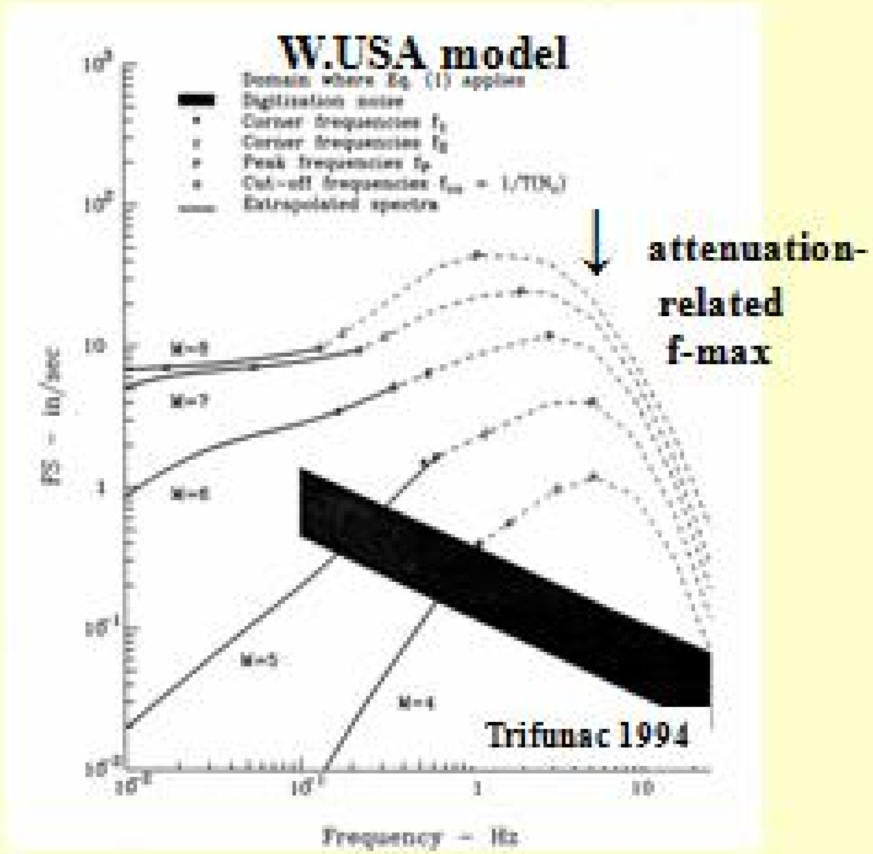
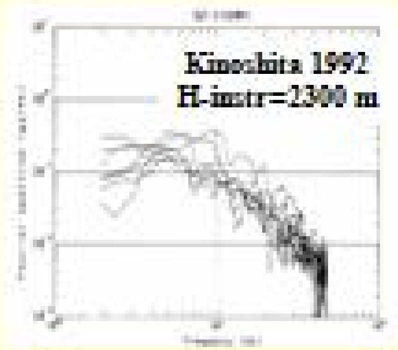


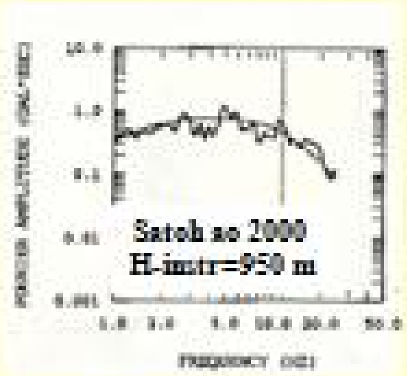
Illustration of features of observed acceleration spectra

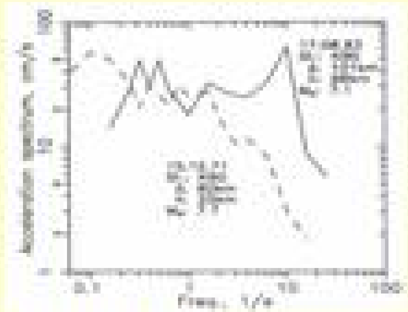
Source-related *f*-max: examples

Low to moderate magnitudes
Instruments in deep boreholes, eliminated attenuation-related f_{max}
Found, typically: source-related f_{max} between 10 and 25 Hz,

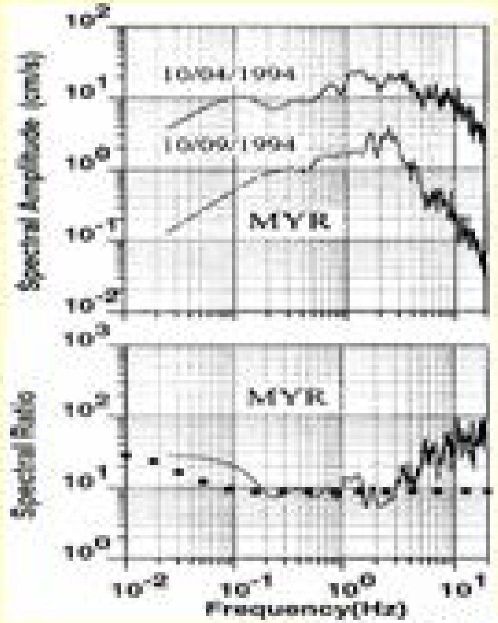
Magnitudes 7-8
Pairs of earthquakes recorded at the same station
One of the two events have unusually low source-related $f_{max} \approx 3$ Hz
Attenuation-related f_{max} is present as usual
Can be eliminated by analyzing spectral ratio







Gusev a.o. 1997



Sasatani 2001

Schematic of spectral scaling

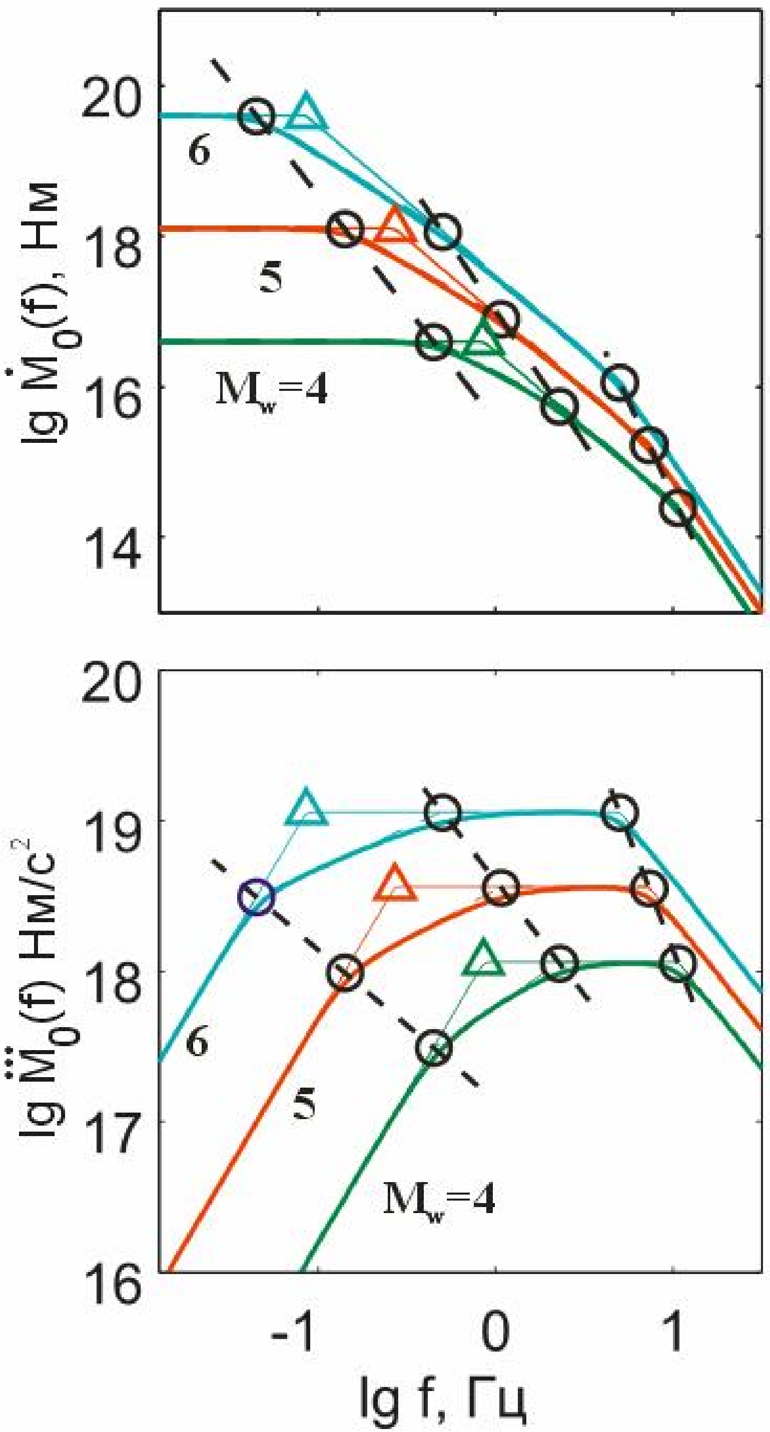
with trends of fc1, fc2 and fc3

Note fc0 (Δ): standard parameter

when data are analysed

based on Brune 1970 spectral

nodel.



"Source-controlled f_{max}", or 3rd corner frequency, f_{c3} : does it exist? how it scales?

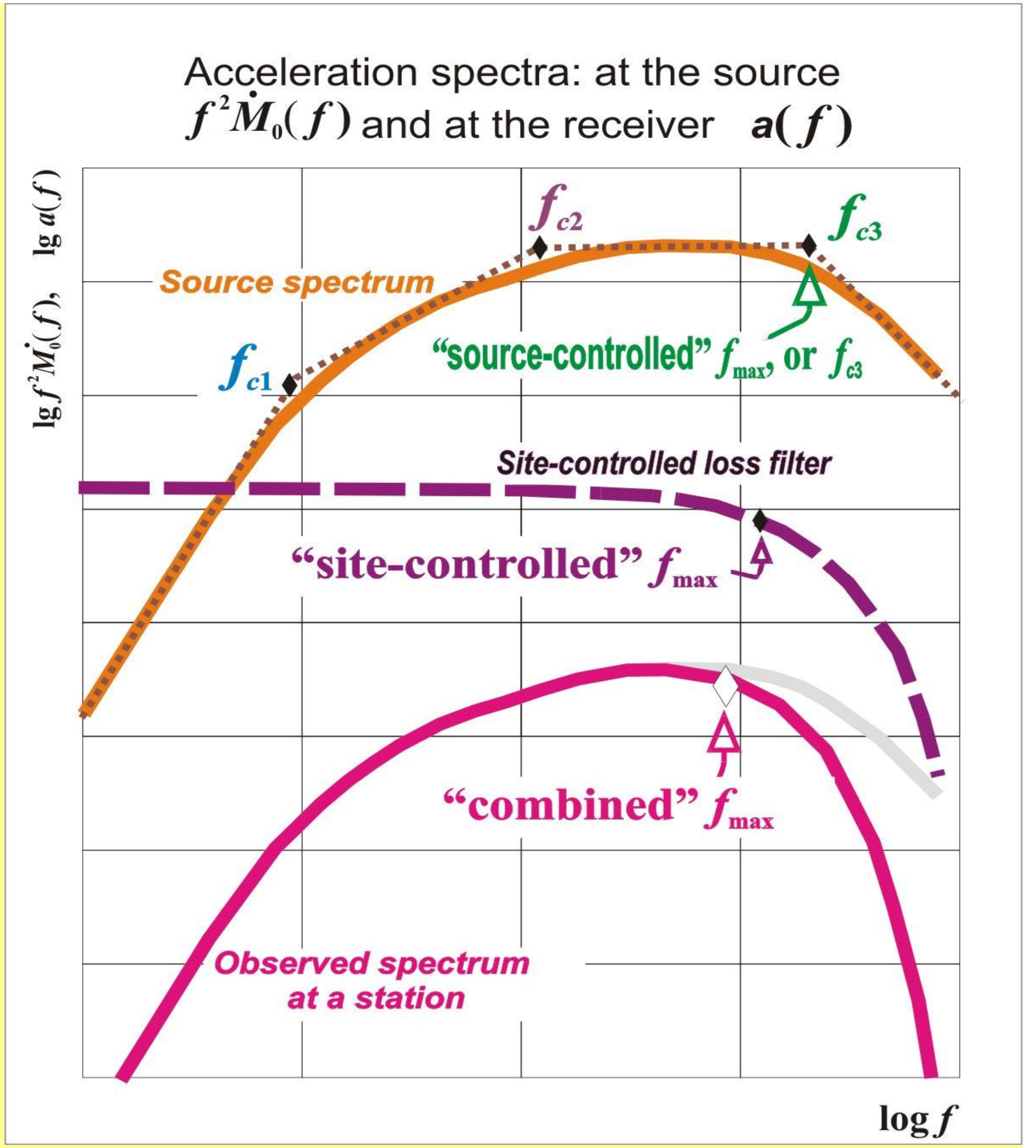
HISTORY

Hanks (1982) emphasized the "$\boldsymbol{f_{max}}$" phenomenon: $a(f)$ shows **HF cutoff**.

Papageorgiou and Aki(1983) and *Gusev* (1983) ascribed it to **source**; *Aki* (1988) noticed f_{max} vs M_0 trend with **unusual scaling** that might support this idea

Hough and Anderson (1984) have shown convincingly that **site-related loss** controls f_{max}

Still, accumulated evidence suggests that f_{max} is a complex feature; it incorporates **both site**-controlled and **source**-controlled components



Outline of the study

1. Compile a preliminary attenuation model ($Q(f)$, κ_0)
2. (a) Use it to correct observed spectra for propagation loss
   (b) From corrected spectra, extract f_{c3} and also f_{c2}
3. Using the observed spectra within the limited [f_{c2} ,f_{c3}] frequency range, adjust the attenuation model
4. Repeat steps 2 an 3 until convergence
5. Discuss the obtained f_{c3} data set

Data set used

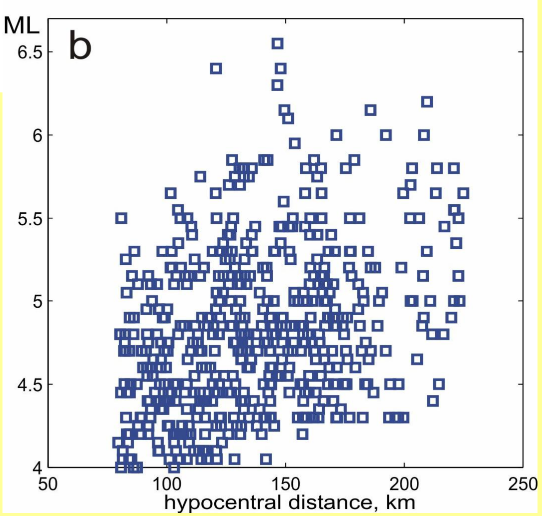
Records of ***S-wave*** group
by low-gain digital accelerograph
(HN channel, ***80 sps***)
of IRIS BB station PET

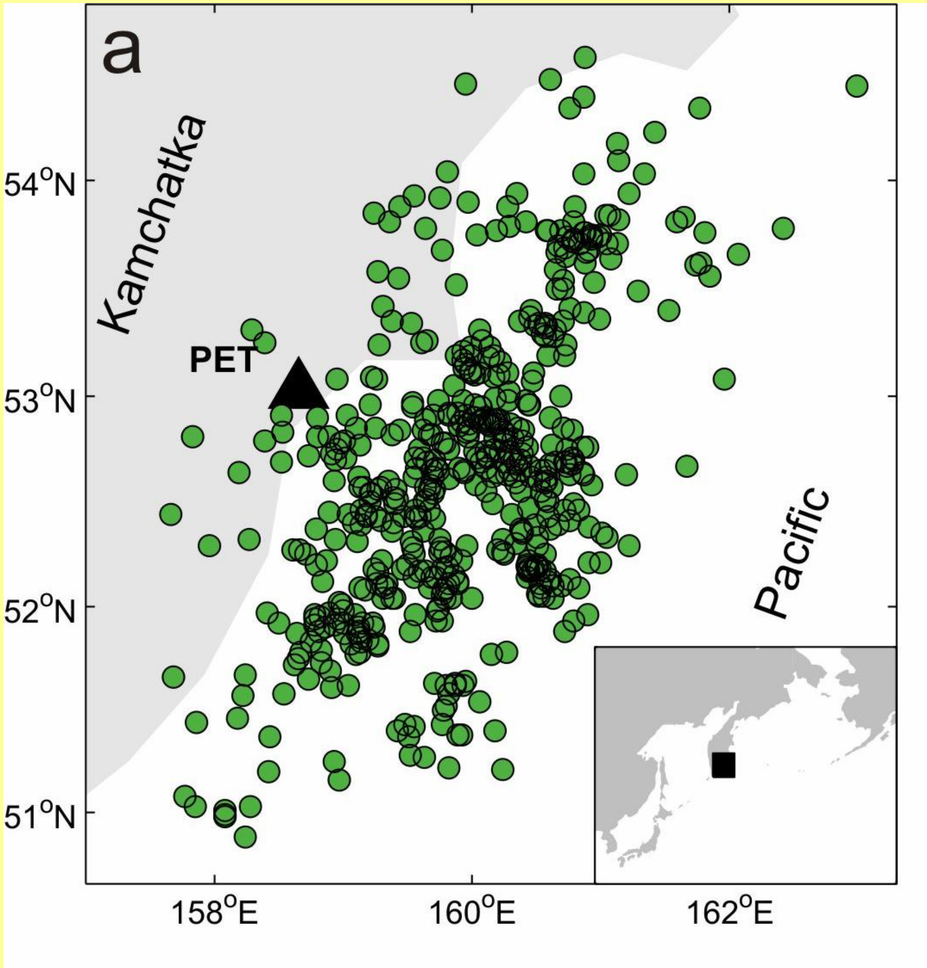
439 records of 1993-2005
+ additional ***130***

Hypo distance ***80-220 km***

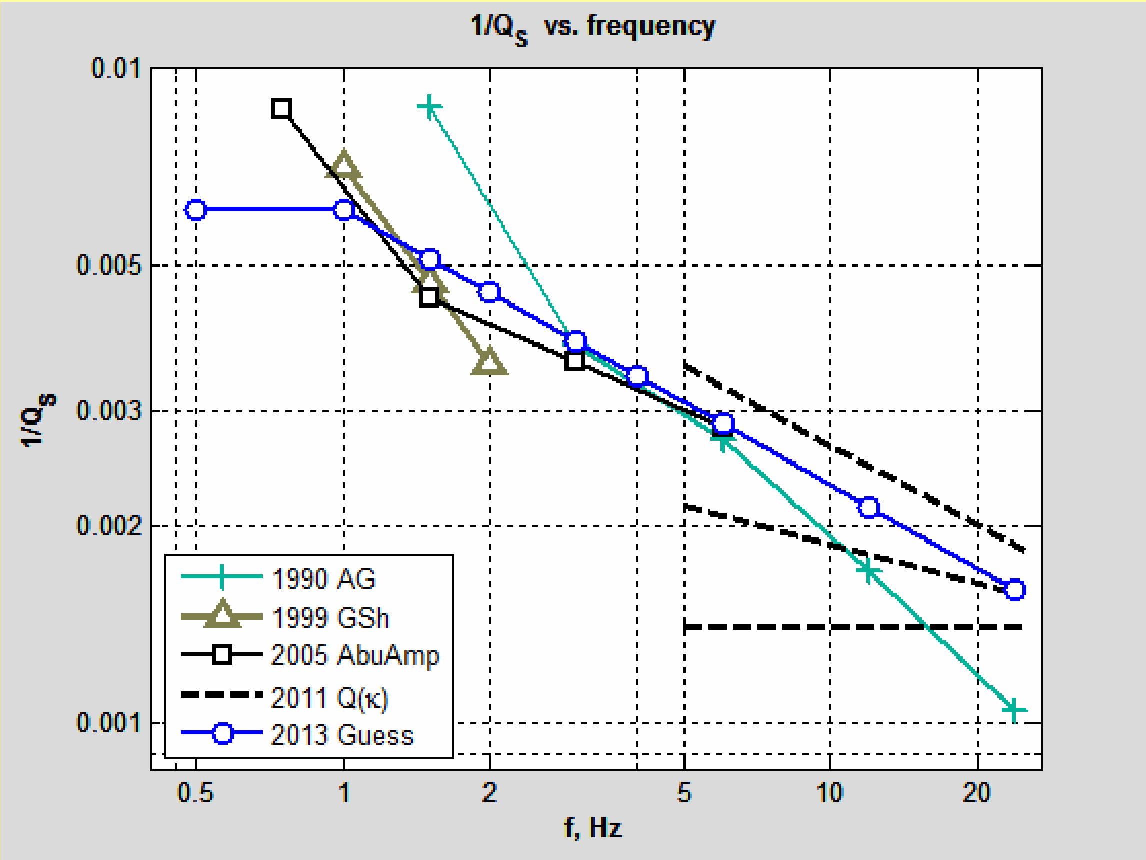
Depth range ***0-200 km***,
mostly 0-50 km

M_L = ***4 - 6.5***





Compilation of the initial loss model on the basis of earlier results



accepted $\mathbf{Q_S(f)}$ model:

Main sources used in compilation:

in the 1-6 Hz band from (Abubakirov 2005) who used coda-normalized spectral levels of band-filtered data

in the 5-25 Hz band based on (Gusev Guseva 2011) who analyzed kappa values;

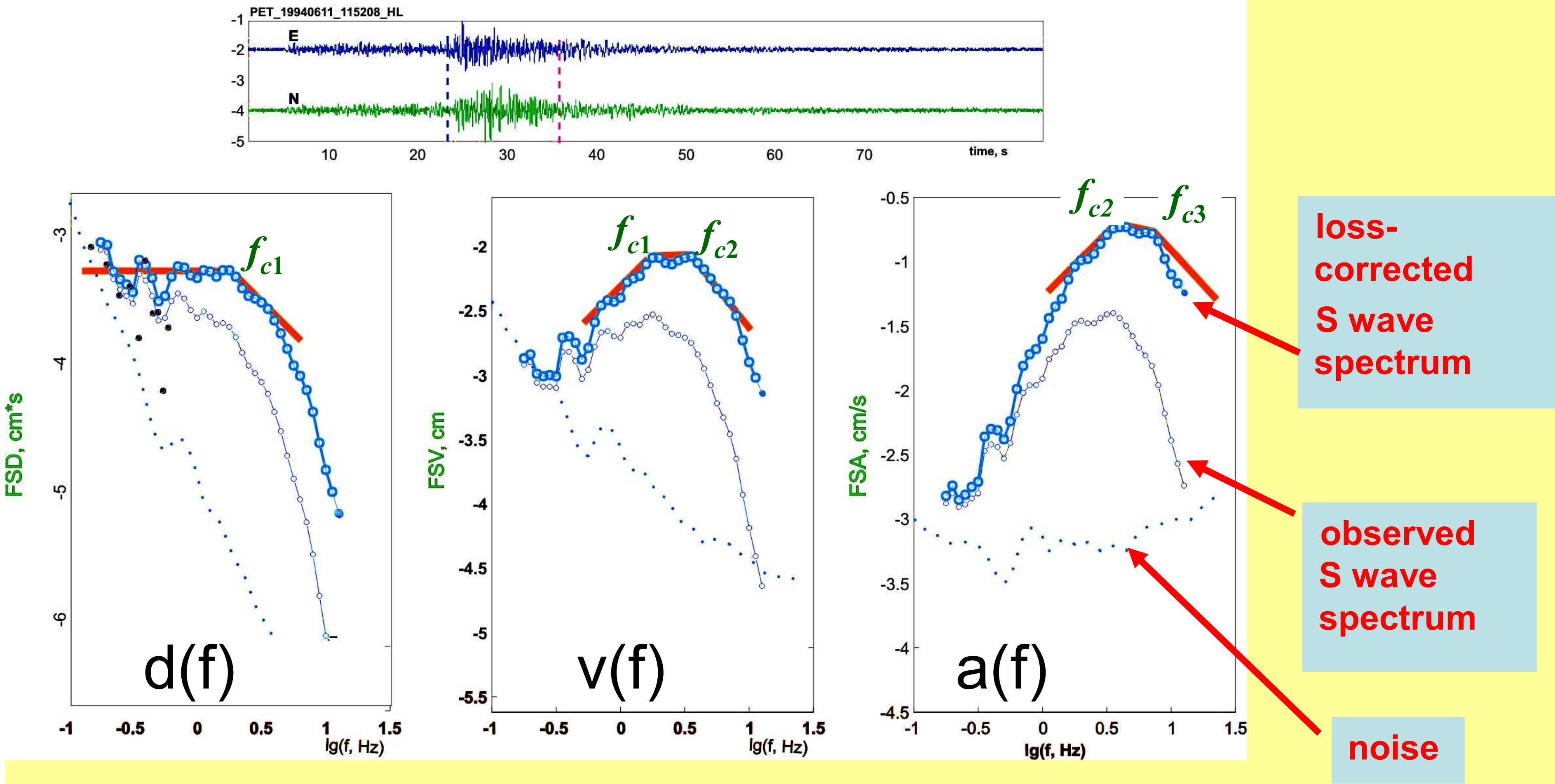
accepted trend at r=100 km:

$\boldsymbol{Q_S(f)=165\, f^{0.42}}$

also $\boldsymbol{\kappa_0=0.016}$ **s**

and slow decay of $\boldsymbol{Q_S^{-1}}$ vs. $\boldsymbol{r}$

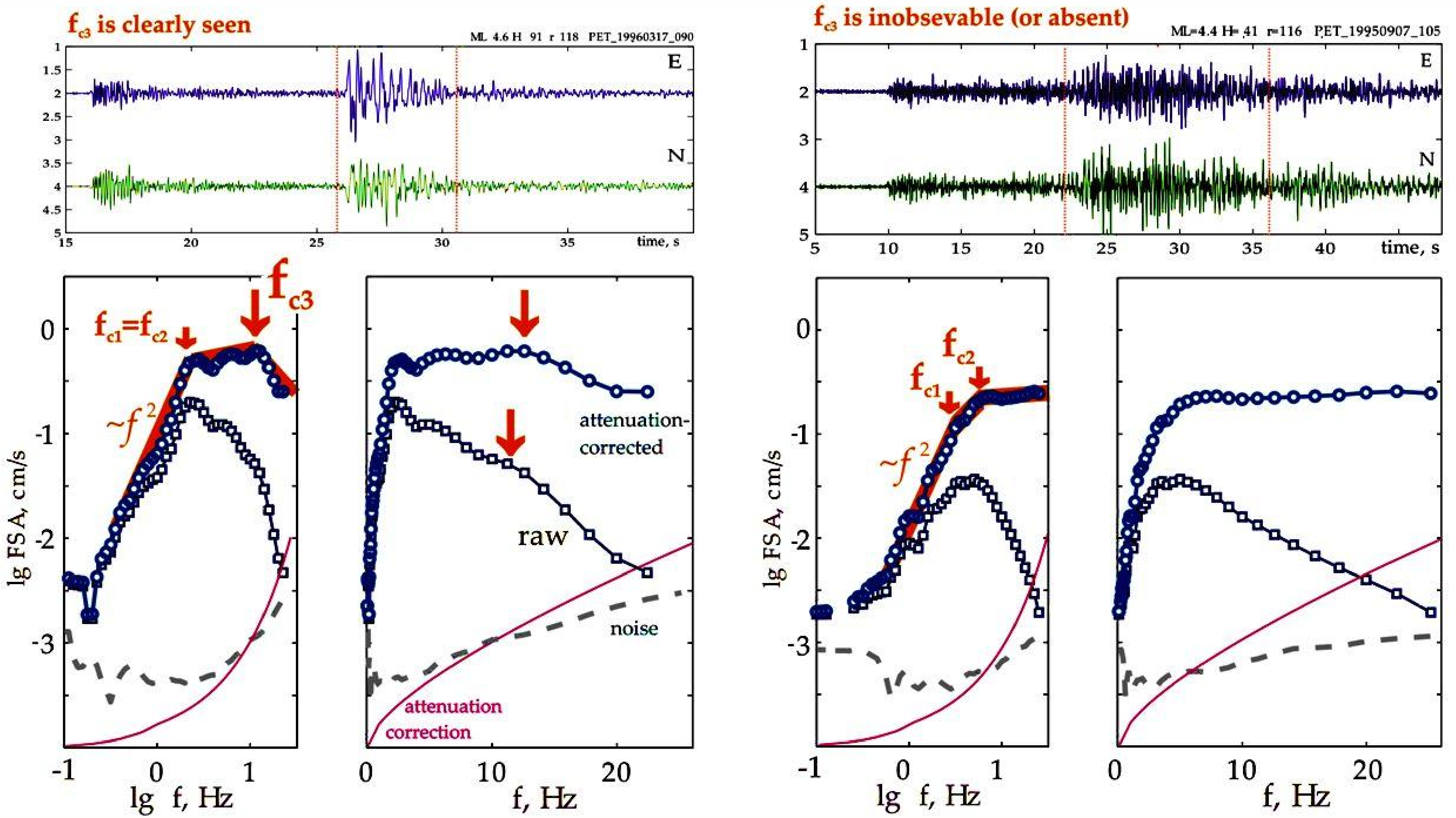
Example of processing in a case when each of f_{c1}, f_{c2} and f_{c3} is observable



spectral smoothing window used: 0.15 log units (1/2 octave)

when picking f_{ci}, slope of selected "plateaus" in v(f) and a(f) plots was kept in the range ±0.5

More example cases: f_{c3} may be observable or unobservable/absent



Here is why f_{c3} is difficult to notice when working in the log-linear scale

ITERATIVELY: find adjusted *S*-wave attenuation model using non-linear inversion.

Assumed attenuation model for loss factor in *S*-wave Fourier spectrum:

$-\log_e \{A(f) / A_0(f)\} = \pi f \kappa_0 + \pi f (r/c) Q^{-1}(f, r)$

where: r - hypocentral distance

κ_0 – constant loss factor for a site; $\kappa_0 \approx \ln 2/\pi f_{\text{max-loss}}$

c - wave velocity; and $Q(f,r)$ – path quality factor:

$$Q^{-1}(f, r) = Q_0^{-1} (f/f_0)^{-\gamma} (1+q(r-r_0)/r_0)$$

where f_0 =1 Hz, r_0 =100 km, c=3.8km/c;

and **unknowns in inversion** are: κ_o, Q_o, γ, q

$Q_S(\,f\,|r{=}100\text{km})$:

Guess 2013:

$Q_S(f)=165\,f^{\,0.42}$ + $\kappa_0=0.016$ s

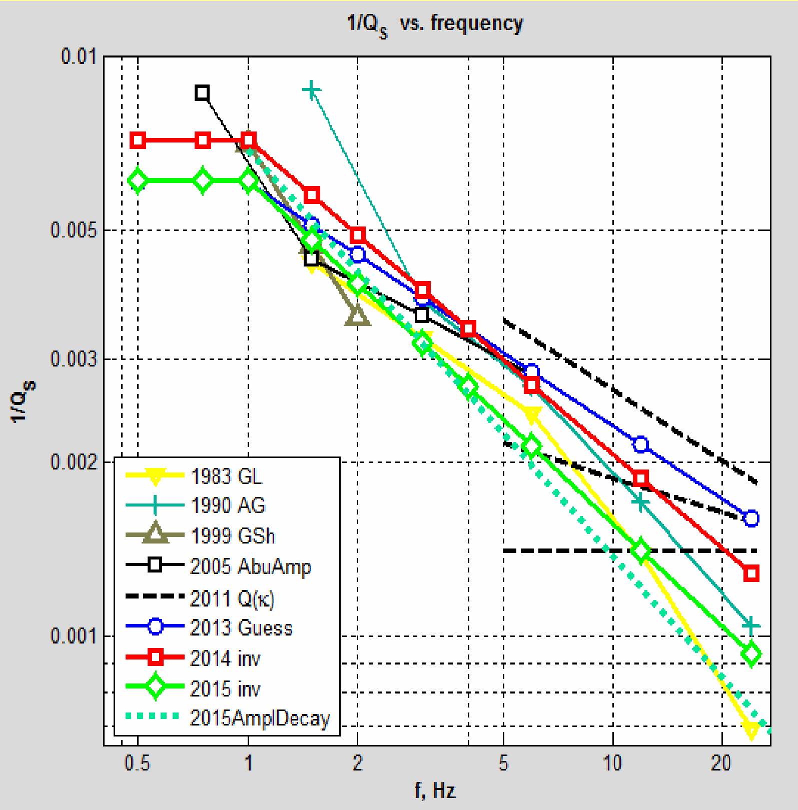
Inverted 2014 (1st iteration):

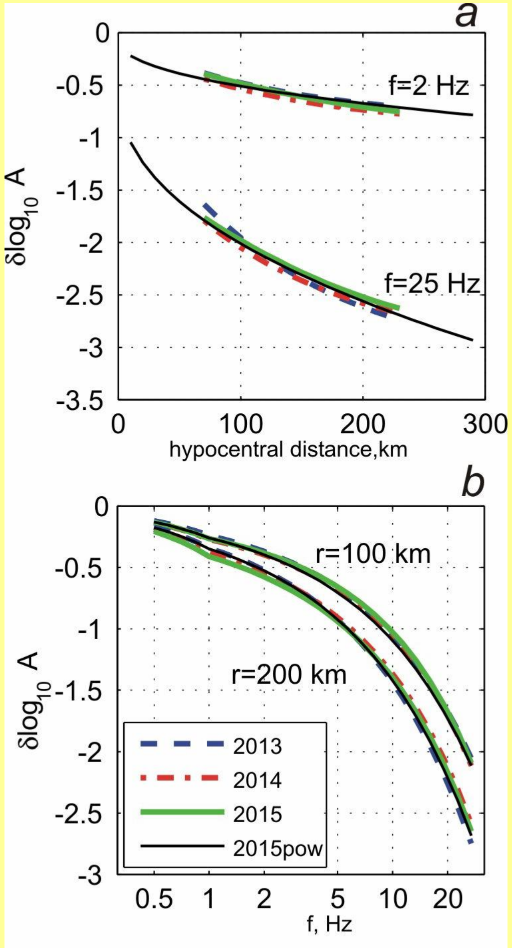
$Q_S(f)=(140\pm33)\,f^{\,0.54\pm0.08}$ + $\kappa_0=0.027\pm0.07$ s

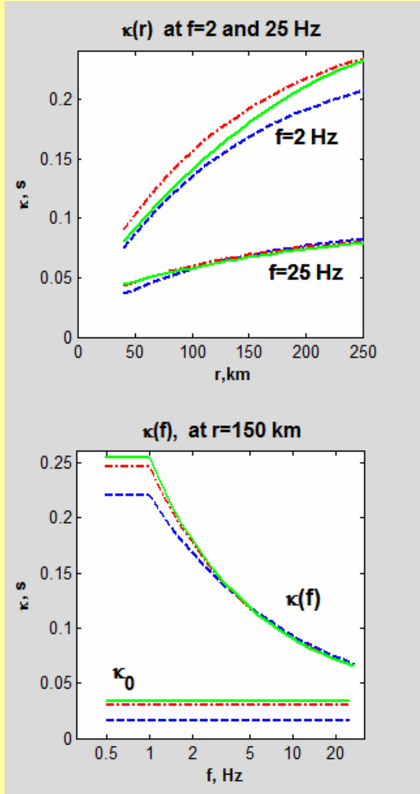
Inverted 2015 (2nd iteration):

$Q_S(f)=164\,f^{\,0.59}$ + $\kappa_0=0.034$

Comparing initial and inverted loss models



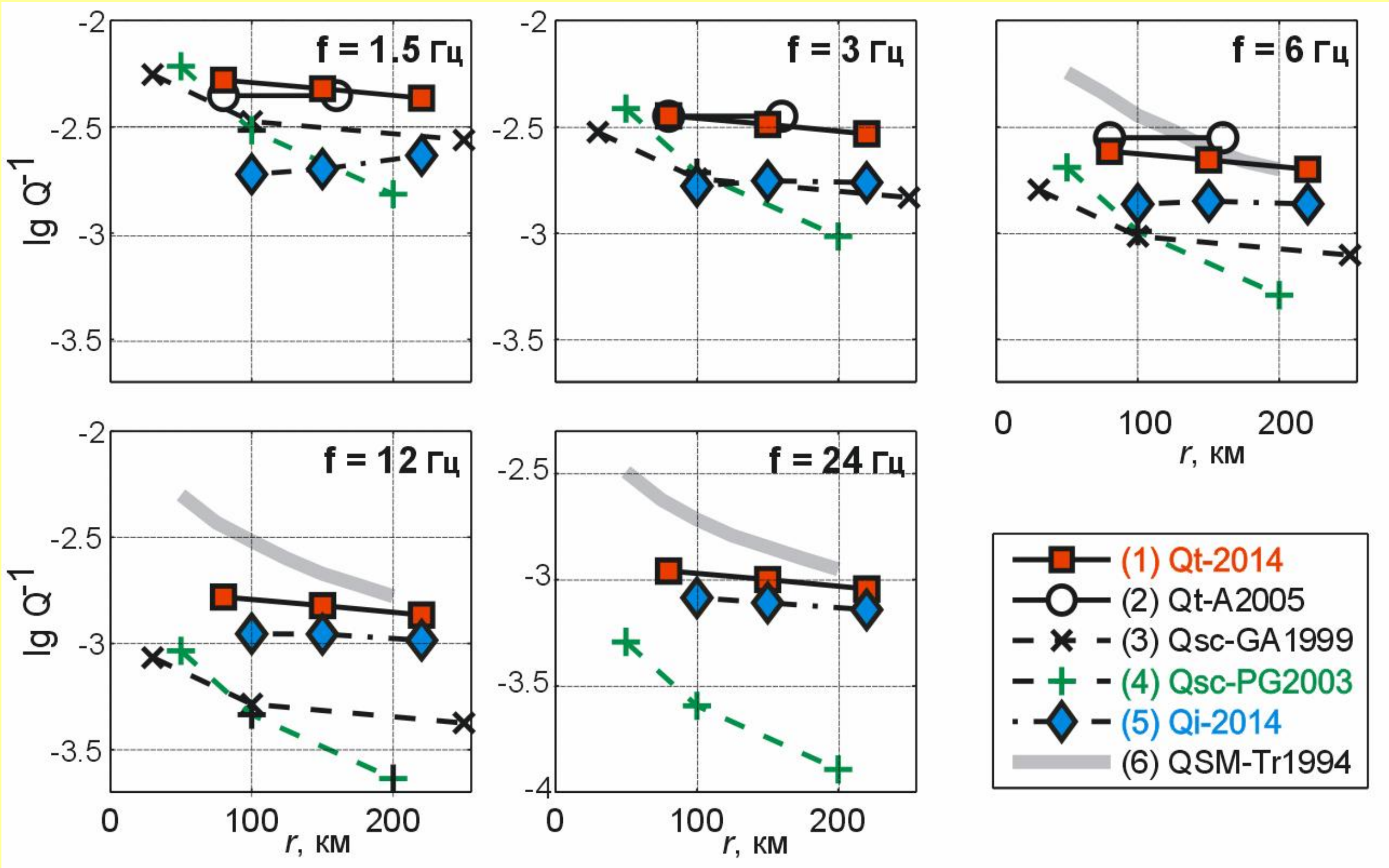




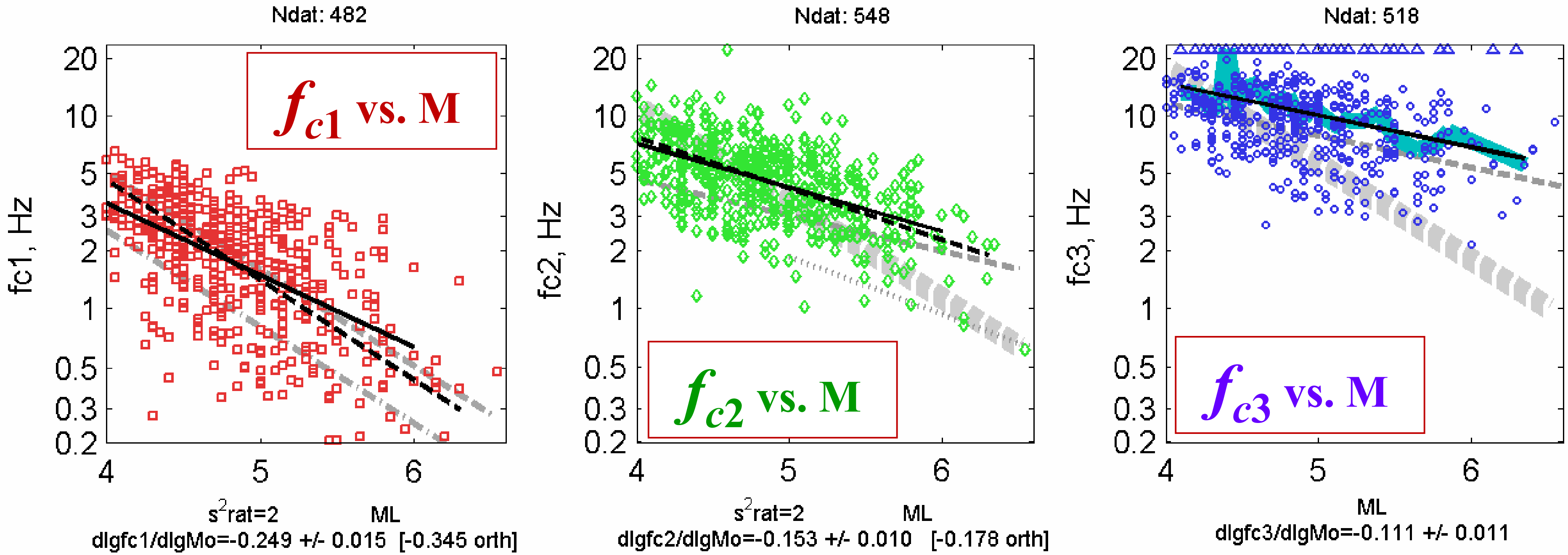
Loss variants **2014** and **2015** match

CONVERGENCE!

Attenuation: Qtotal, Qscattering and Qintrinsic



*fc*1,2,3 trends side by side: see how scaling varies



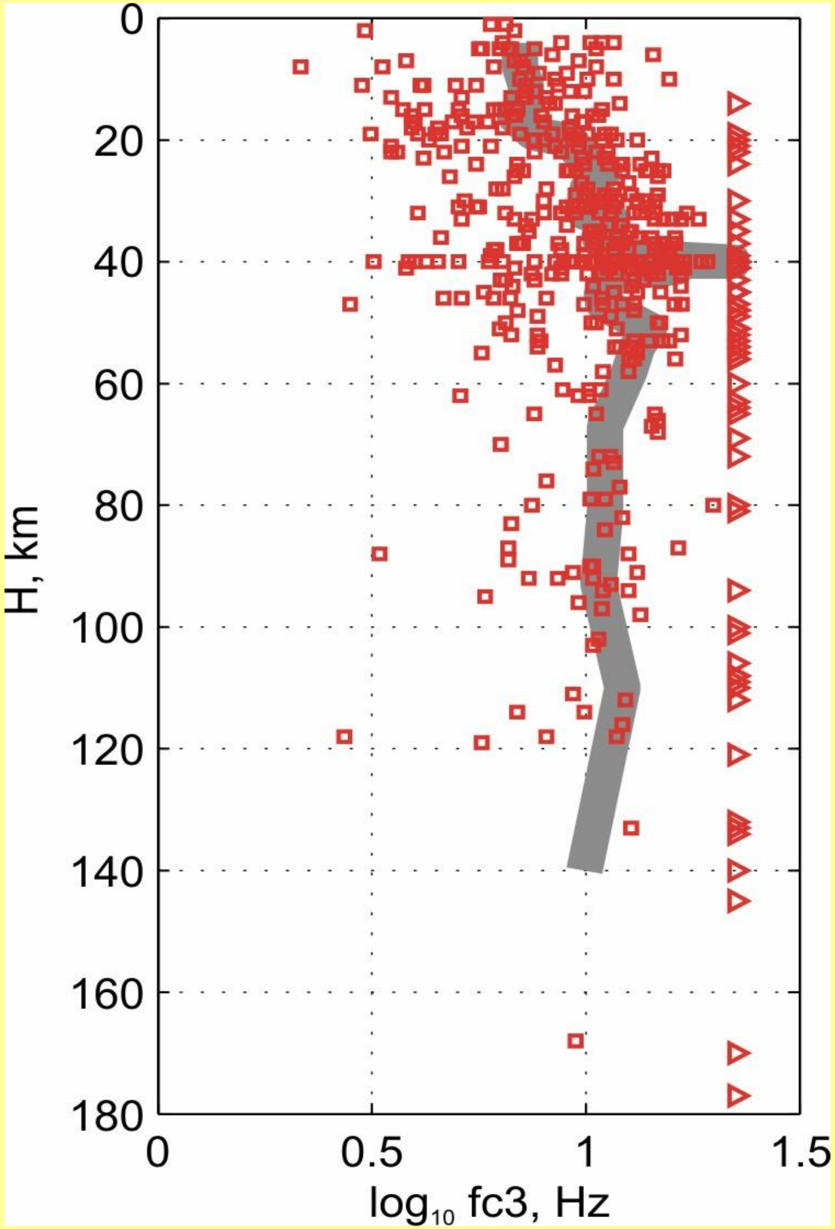
(1) Each of the 3 trends is different

(2) Assumption of *similarity*:

≈holds for f_{c1};

breaks for f_{c2} and f_{c3}

grey trends:
(1) Taiwan, globe
(2) ENA WUSA
(3) Aki 1988



$f_{c3}(H)$

f_{c3} grows with depth up to 50 km

PART 2

Possible physics that underlies the existence of f_{c3} and the trend of f_{c3} vs. M_0

Formation of f_{c3} can be attributed to the summary effect of the following factors (probably complementary action):

(1) lower (or high-wavelength) limit of the size of fault surface heterogeneity [Gusev 1990]

(2) finite fault zone thickness (gauge layer etc.)[Papageorgiou&Aki 1983]

(3) finite cohesive zone width [Campillo 1983]

The trend $f_{c3} \propto f_{c1}^{0.2\text{-}0.3}$ or $f_{c3} \propto M_0^{\approx -0.1}$ suggests that f_{c3} slowly decreases with source size

An underlying *cause* of such a trend may be *variations of maturity of fault* surface :

the greater *distance* fault walls have slipped, the larger is their *wear*, and:

(1) the lower is the upper cutoff of heterogeneity spectrum [by abrasion]

(2) the wider/thicker is weak fault zone [by wear product accumulation]

[Gusev 1990; Matsu'ura 1990,1992].

Characteristic time hypothesis

- Introduce charateristic time of a fault surface: $T_{is} = T_{c3} = 1/f_{c3}$: it takes T_{is} for rupture to run distance $L_{is} \approx v_r * T_{is}$ where v_r – rupture velocity like 2.5-3.5 km/s. We assume $T_{is} \approx T_{c3} = 1/\, f_{c3}$.
- Also assume $T_{c1} = 1/\, f_{c1}$ near to rupture duration, and
- $T_{c2} = 1/\, f_{c2}$ near to local rise time of slip

Dimensionless description of a fault

- let $\tau_1 = T_{c1}/\ T_{c3} = f_{c3}/f_{c1}$, be normalized rupture duration,
- and $\tau_2 = T_{c2}/\ T_{c3} = f_{c3}/f_{c2}$ be normalized rise time
- then key dependence is $\tau_2 = \tau_2\ (\tau_1)$.
- also one can set normalized rupture velocty as unity, then normalized rupture size is $\lambda_1 = \tau_1$;

Dependence of f_{c1}, f_{c2} and f_{c3} on M_0.

for f_{ci}, define

$$\alpha_i = -d \lg f_{ci} / d \lg M_0$$

Orthogonal regression gives, for *fc*1:

α_1=0.315±0.019,

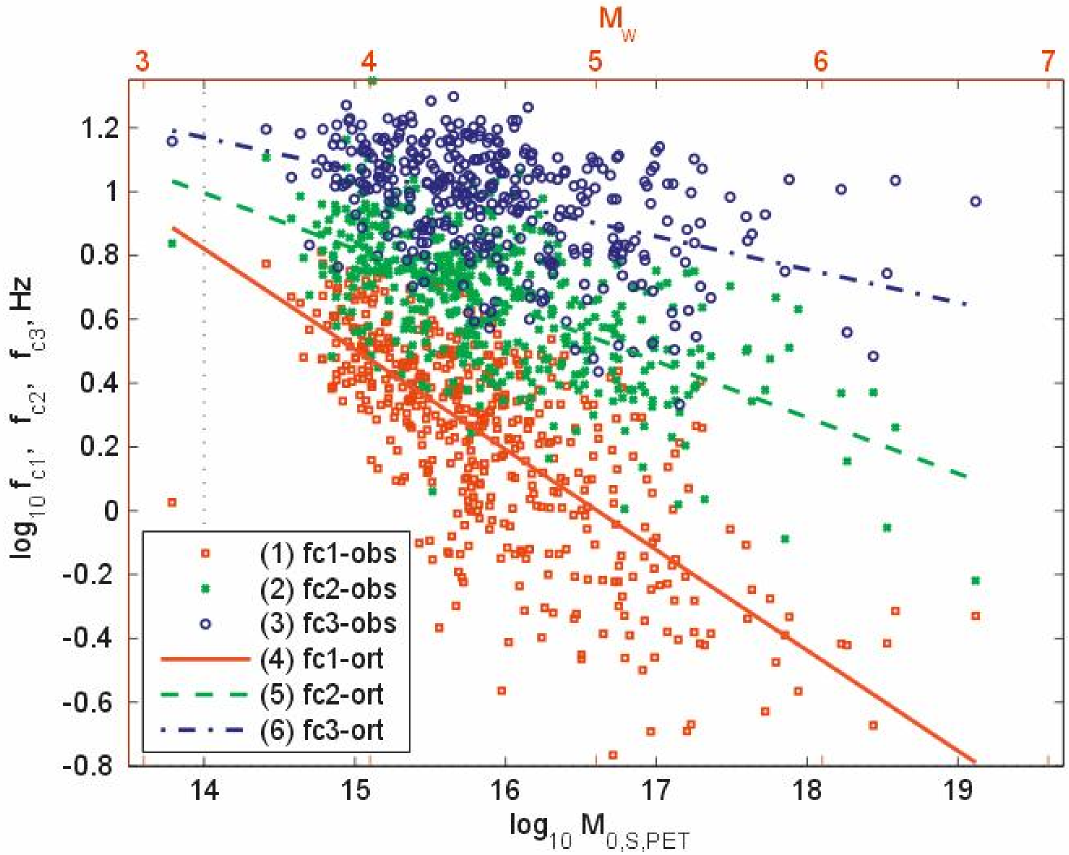
(near to similarity that predicts α_1=1/3);

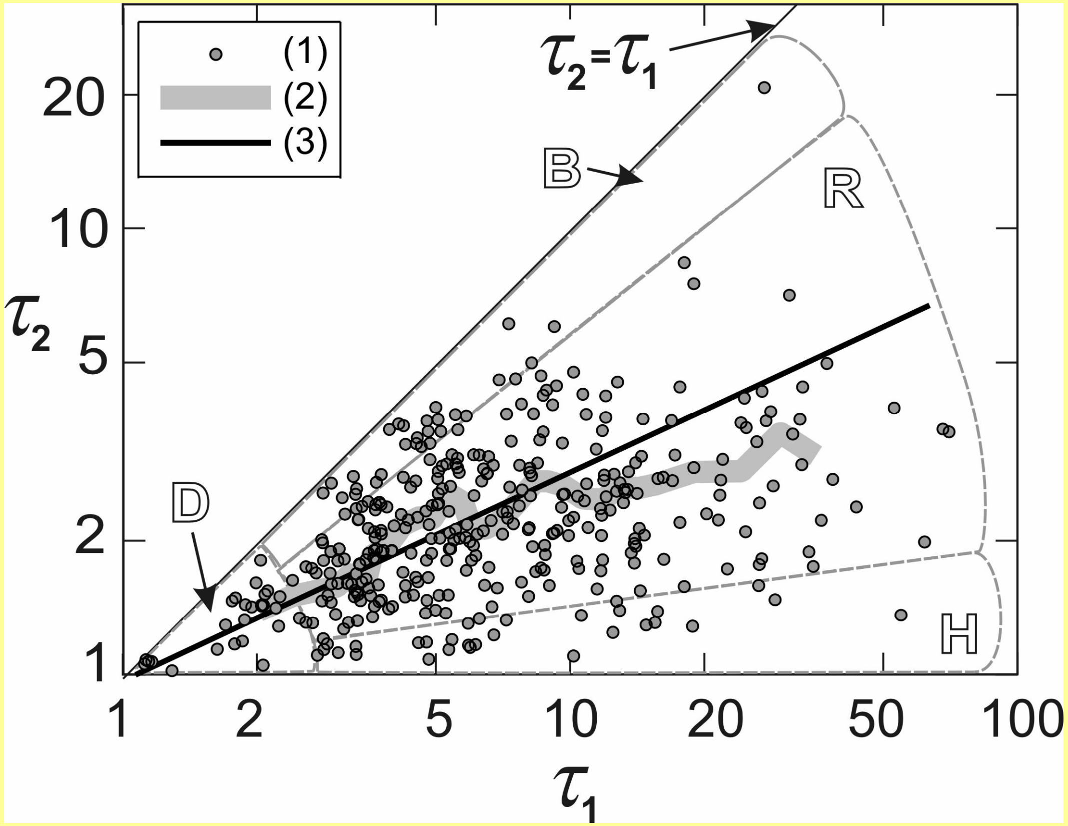
Also:

α_2=0.176±0.017 and

α_3=0.103±0.025.

Both show significant break of similarity.





Individual values *of* τ_1 and τ_2 for 430+ Kamchatka data

- Zone B: Brune1970 style, $L \approx W$
- Zone H: Haskell 1964 style, $L >> l$
- Zone D: Kostrov 1964-Dahlen 1974 style (ω^{-3} spectrum)
- Zone R: regular behavior:

There are analogies in many fields that study stochastic modes of

- interface motion
- growth of solid: atoms, suspended particles etc
- growth of lichen, cancer, etc
- fire fronts
- deflagration (burning front in gas)
- imbibtion (wetting, blotting)
- ferromagnetic domain wall motion
- crack edge propagation

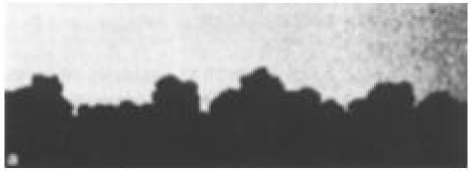
in all these phenomena, rough, often fractal (self-similar) lines are formed

Rough interfaces in disordered media

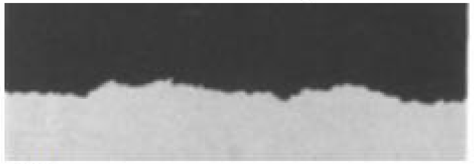
Burned paper

Ink in paper

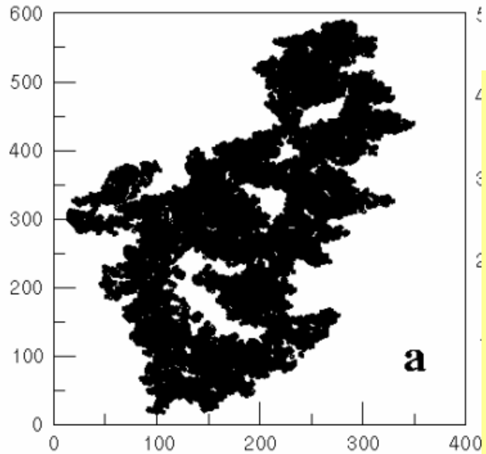
Lichen



Bacterium colony



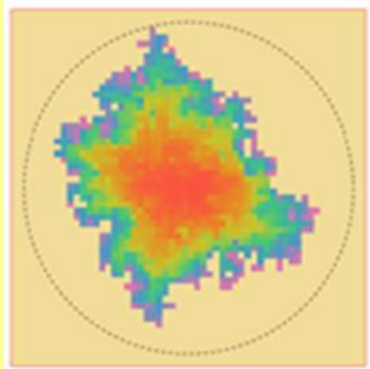
Torn paper



Forest fire,
from satellite image

REAL

- Bonami 2008
- Buldyrev et al 1993
- Caldarelli 2001
- Gouyet 2005
- Halpin-Healy 1995
- Schmittbuhl et al 2003



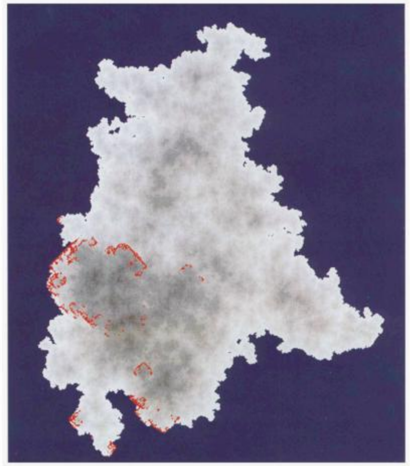


Fig. 4. Horizontal projection of the cluster of model B ($p = 0.8009 = p_c$) which was started at the center of the screen 2[illegible] time steps ago. The current diameter of the cluster is about 2^{10}. The blue area shows the flat interface that is left dry since the beginning of the process. Darkest shades of gray correspond to the largest heights of the interface. Red dots forming "fractal dust" indicate cells that become wet at the current time step.

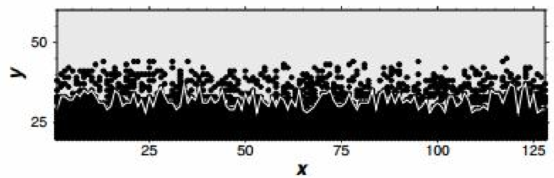
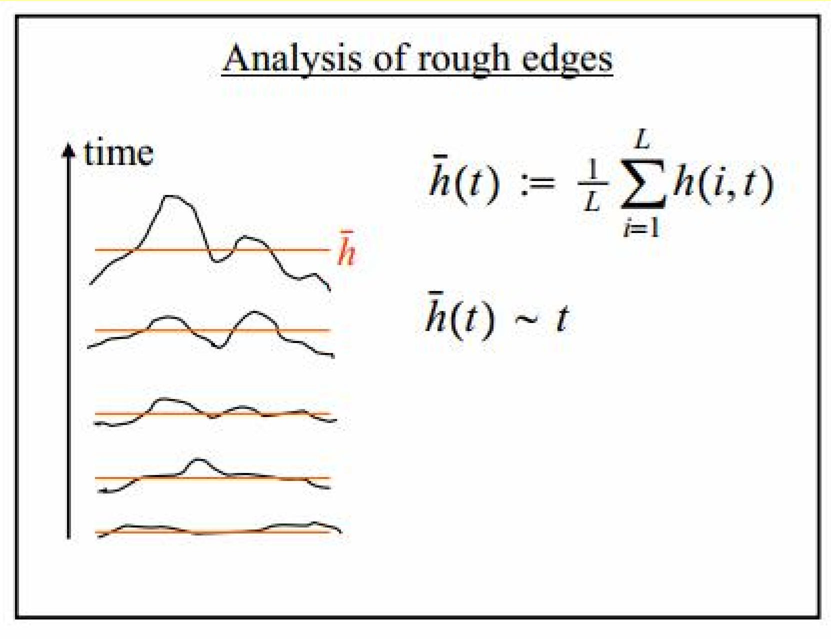
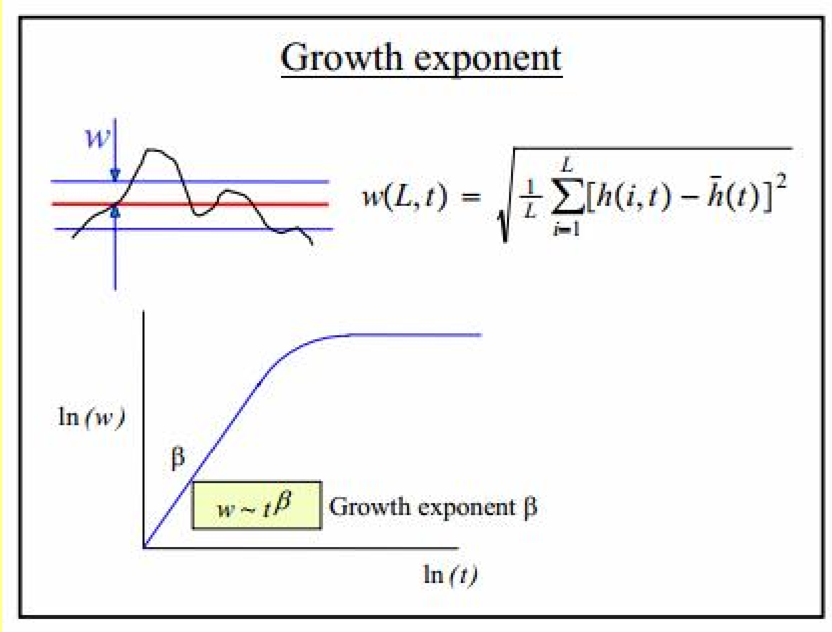


FIG. 1. The crack front for a 128 × 128 system. The fracture is propagating from bottom to top. The broken springs are black dots. The crack front is drawn as a white line.

SIMULATED





growth exponent β

defined by **:**

rms width $\propto$ time$^{\beta}$

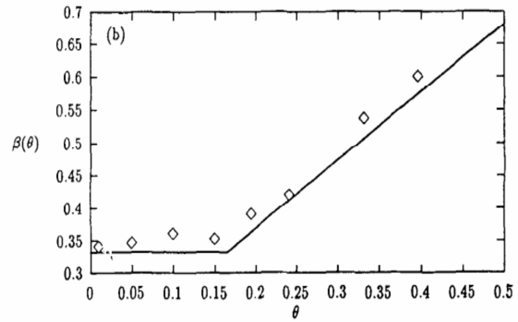
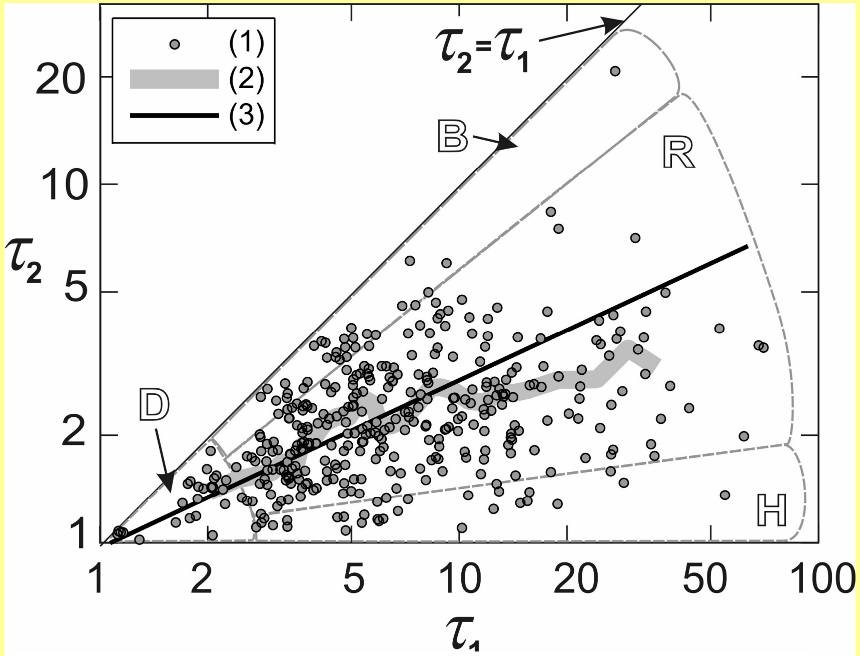


Fig. 4.18. Ballistic deposition subject to temporally correlated noise [LSW92], simulation results for (a) saturation width exponent $\chi = \alpha$, and (b) early-time index β.



Slope of orthogonal regression line:
β = 0.47±0.043.

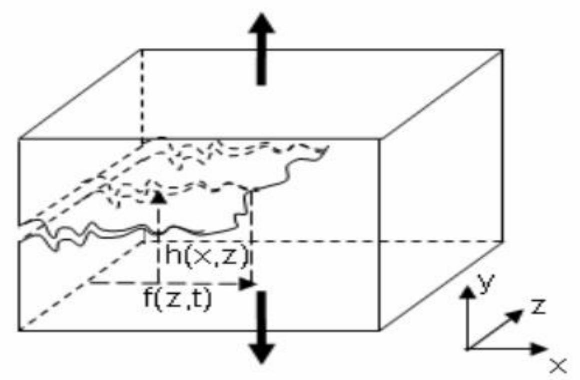


Figure 14. Sketch and notation of a crack front propagating in a 3D material.

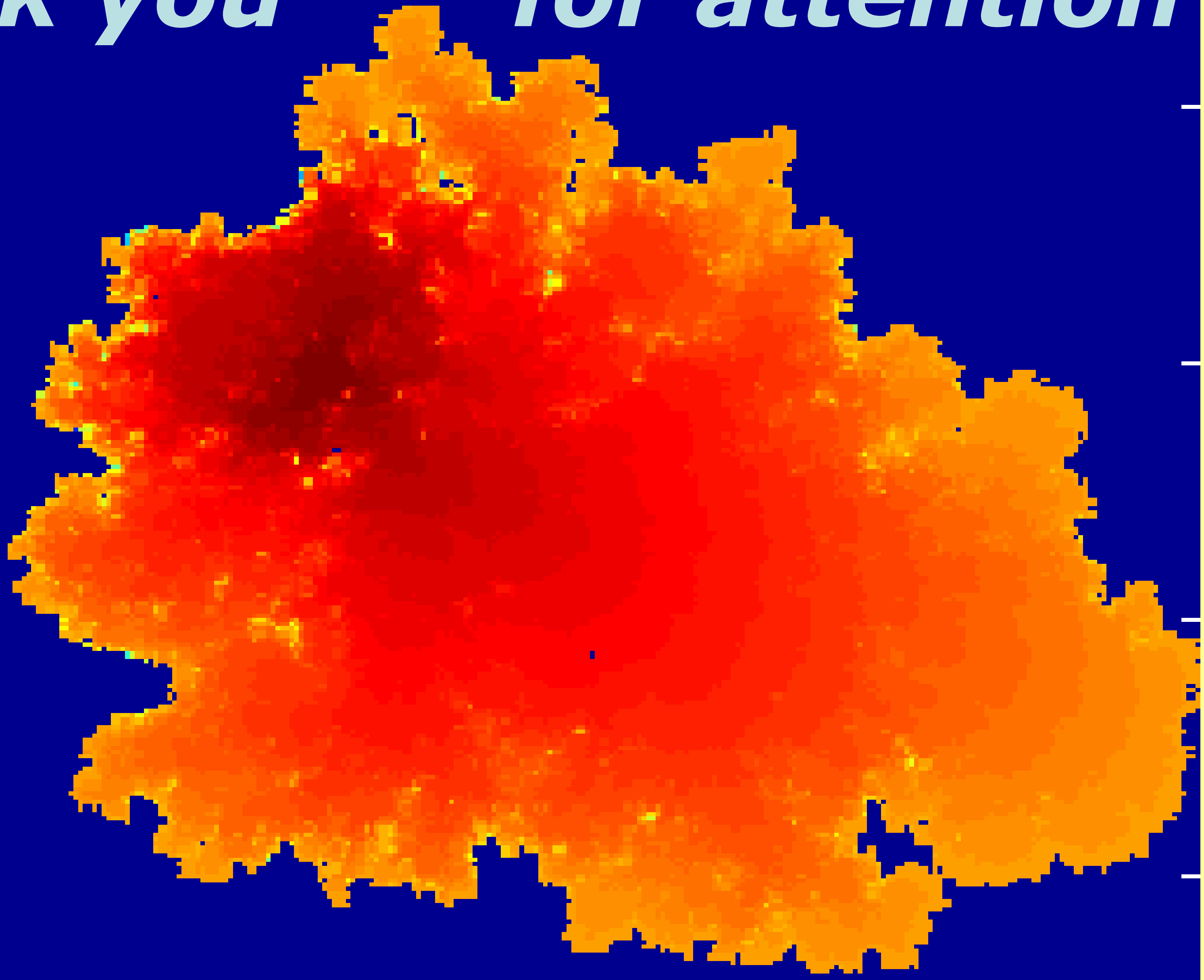
Slope β of rms width vs time trend

$$\beta = -d\lg\tau_2 / d\lg\tau_1$$

	β
τ2(τ1) earthquake data	
Kamchatka, **individual data**	0.47
Kamchatka, *trends*	*0.34*
W.USA etc Aki 1988, *trends*	*0.57*
Middle Asia, Rautian data, *trends*	*0.42*
Theoretical models	
Eden growth	1/3
Directed percolation depinning	0.65
Observed trends	
Crack in PMMA	0.55
paper burning	0.47
superconductor transformation front	0.65
imbibition	0.60

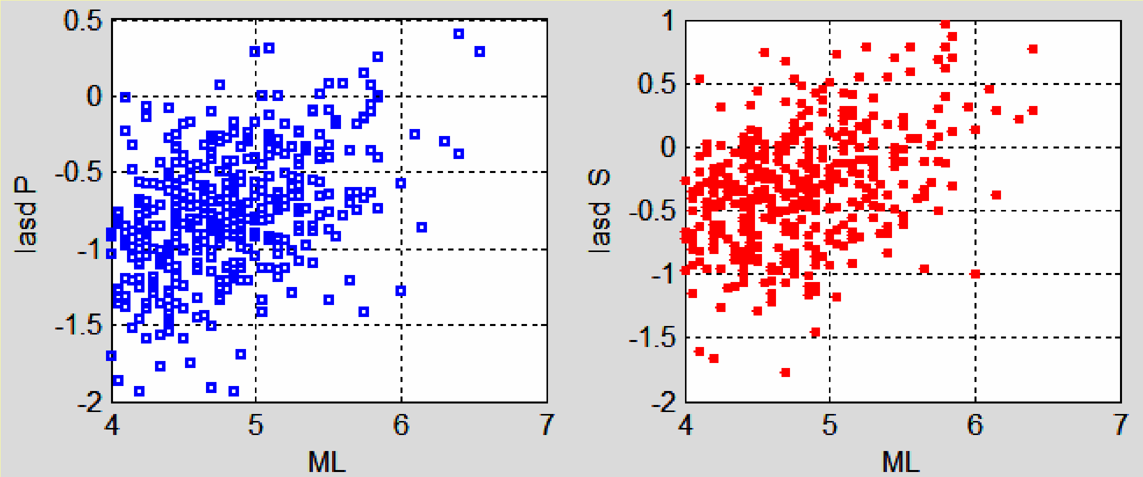
point of growth!

thank you for attention

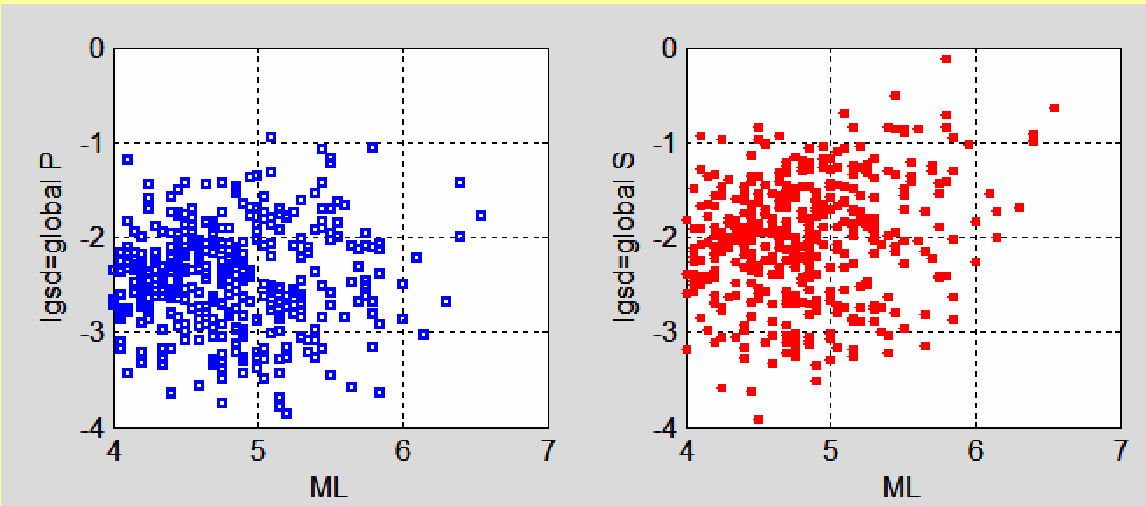


thank you for attention

Apparent stress σ_a vs M: no similarity



Stress drop $\Delta\sigma$ vs. M: approximate similarity

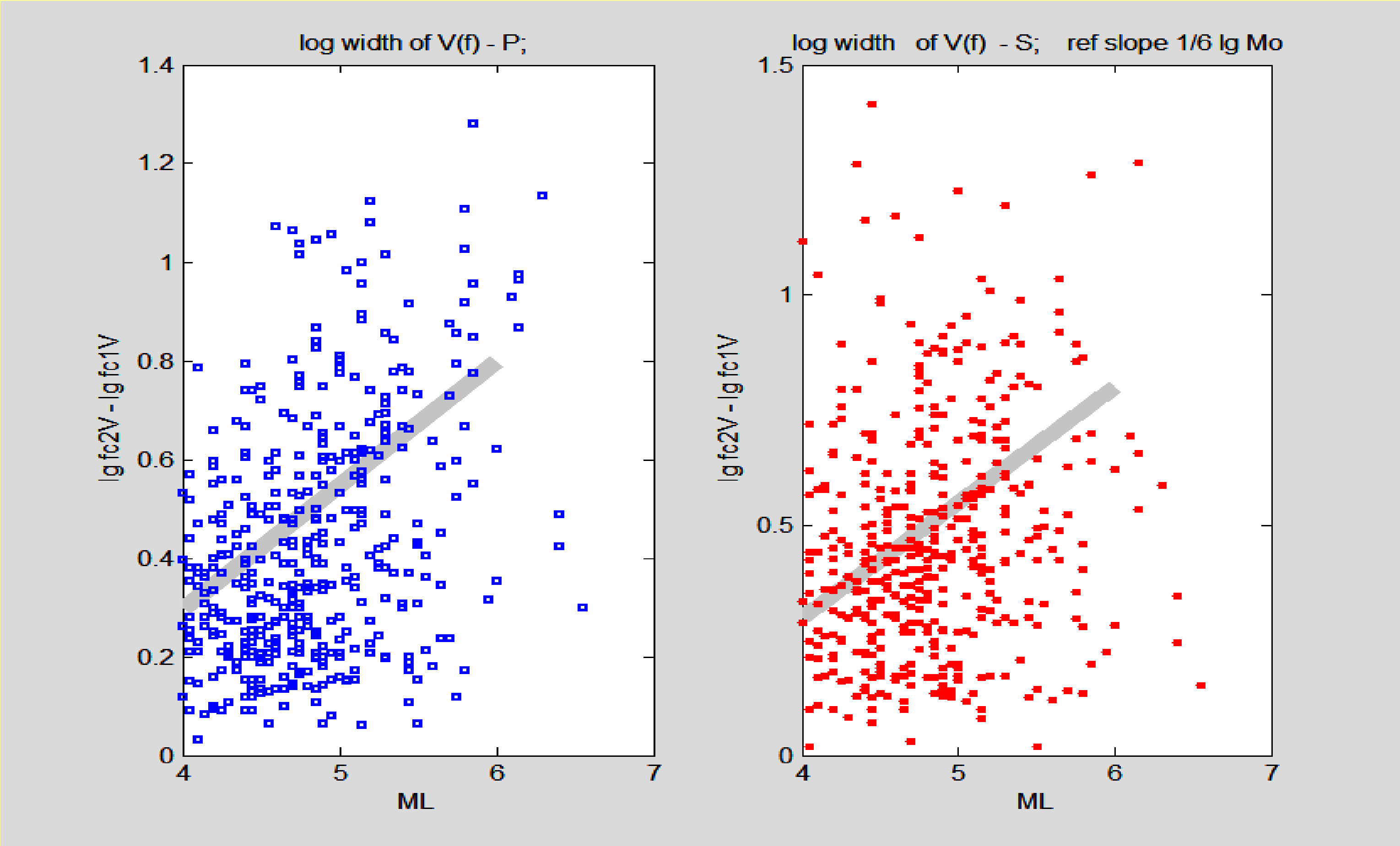


Two ways of checking the similarity assumption make different results

$$\sigma_a = \frac{E_s}{M_0} \propto \frac{v_{\max}^2(f)(f_{c2} - f_{c1})}{d(f)|_{f=0}}$$

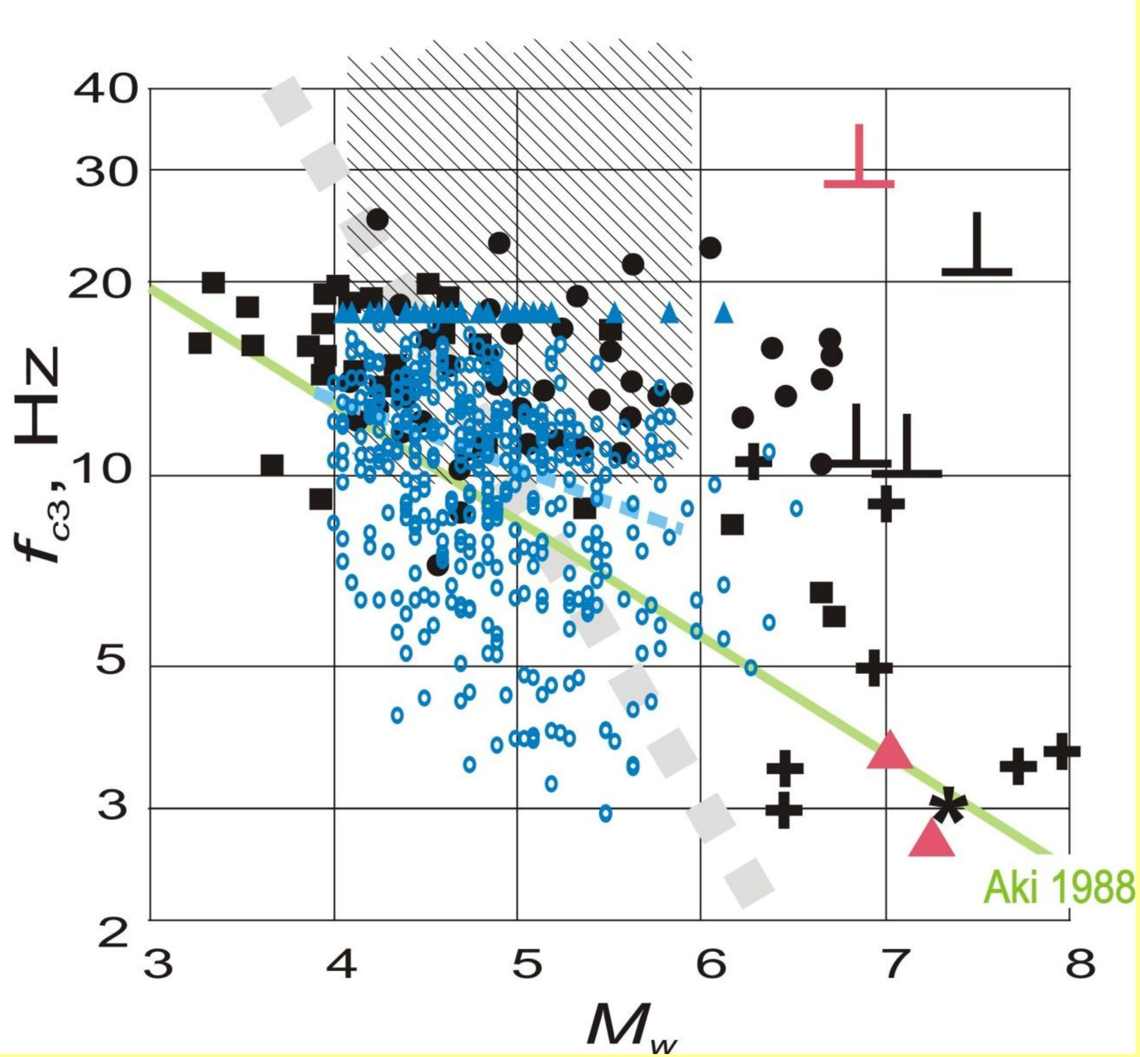
$$\Delta\sigma \approx \frac{M_0}{R^3} \propto \cdot f_{c1}^3 \cdot d(f)|_{f=0}$$

$LV = \log f_{c2} - \log f_{c1}$: log-width of velocity spectrum V(f) vs. M
(similarity would result in M-independent LV)



Variation of LV with M causes M-dependence of σ_a at a fixed $\Delta\sigma$

Trend of f_{c3} vs. M_w : new data compared to compilation-2010



black: compilation [Gusev 2013]

o ▲ 2015 Kamchatka data

Aki 1988

▲⊥ Faccioli 1986

High f_{c3} :

NO ANOMALY

An important part of the general picture