Splitting *f-max* of Kamchatka spectra into site-loss-controlled and fault-controlled components: third corner frequency and ω^{-3} spectra

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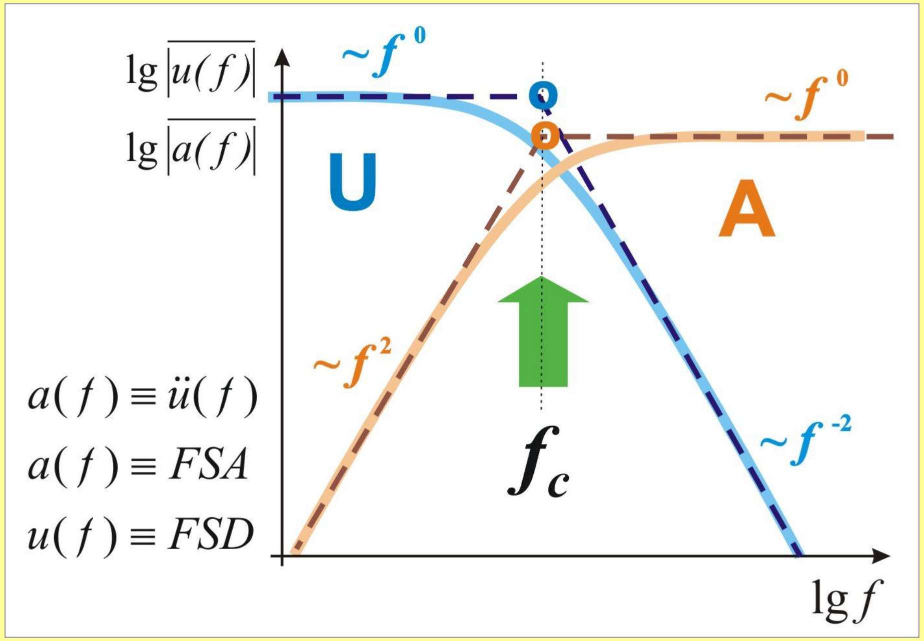
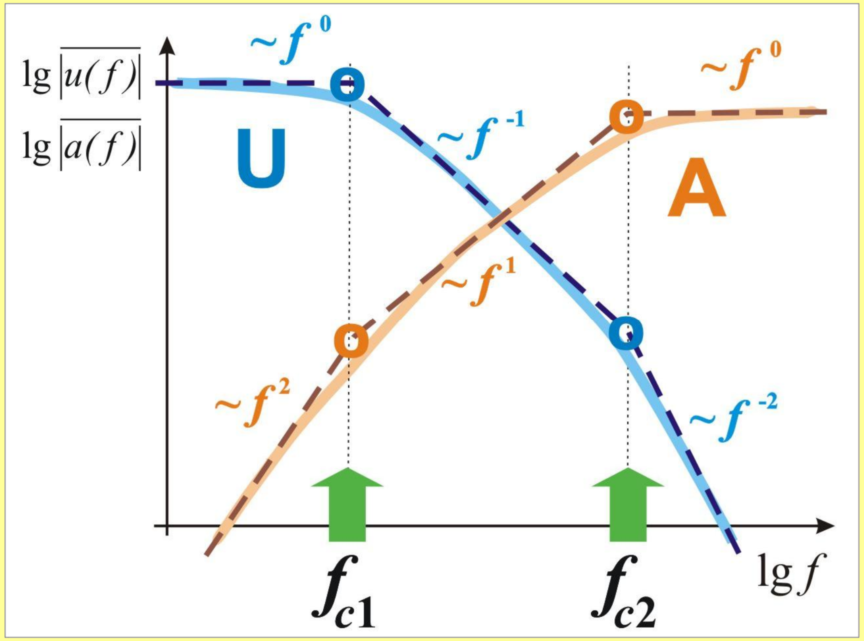
Starting point: "ω^{-2} " or "omega-square" model for the shape of far-field earthquake source spectrum after Aki 1967; its generalization by Brune 1970



Single-corner displacement *u*(*f*) spectrum after Aki(1967), also the simpler, standard variant after (Brune 1970); $\varepsilon=1$
single corner frequency f_{c1}



Two-corner *u*(*f*) spectrum, advanced, non-standard variant
after (Brune 1970) ; $\varepsilon<1$
two corner frequencies f_{c1}, f_{c2}

f_{c2} is commonly seen in observed spectra

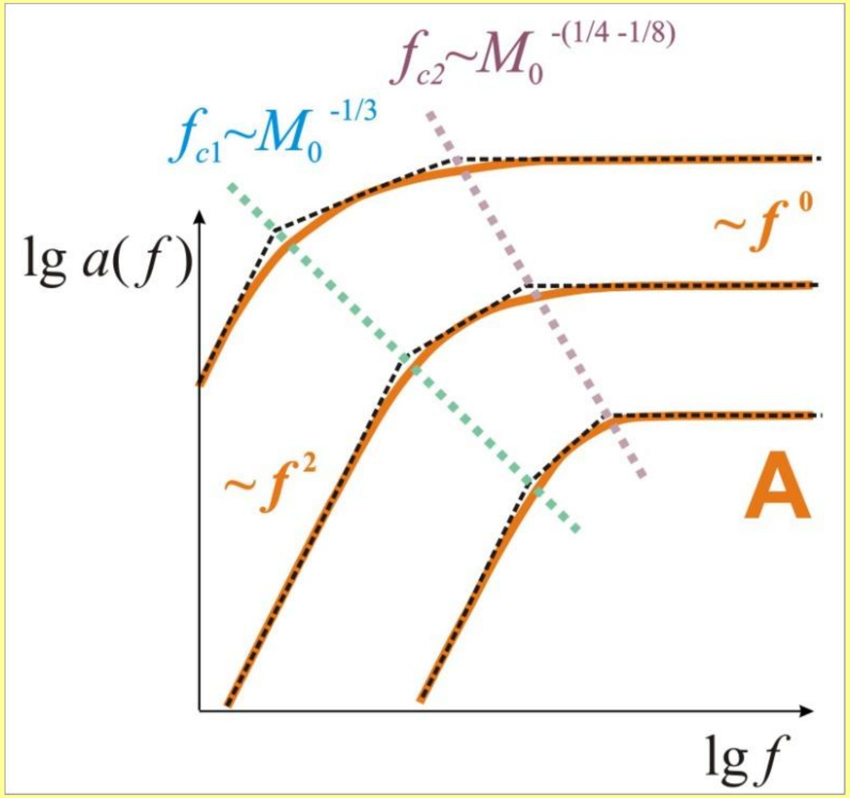
Different scaling of fc1 and fc2

$f_{c1} \propto M_0^{-1/3}$, similarity holds
(Haskell 1964, Aki 1967; and later work)

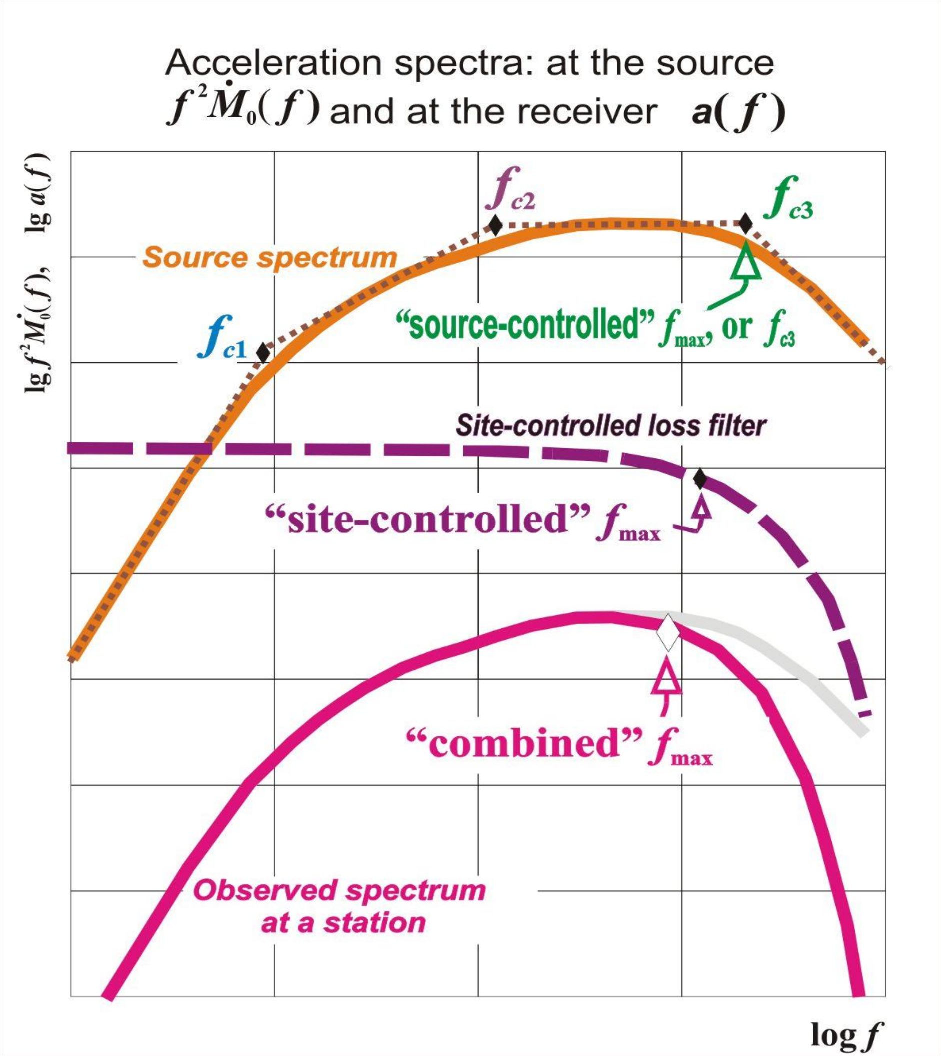
f_{c2} decays much slower than $M_0^{-1/3}$; similarity assumption violated
(Gusev 1983);

$f_{c2} \propto M_0^{-1/6}$, apprx. **(Gusev 2013)**

Problem:
how f_{c2} scales in a particular region, when processing digital data



Spectral scaling with similarity broken for f_{c2};
Shown for acceleration source spectra



Existence and scaling of f_{c3}

Hanks 1982 emphasized the "*f-max*" phenomenon (HF cutoff of *a*(*f*))

Gusev (1983) and Papageorgiou and Aki (1983) ascribed it to source

Hough and Anderson (1984) have shown convincingly that site-related loss creates *f-max*

Still, accumulated evidence suggests that *f-max* is complex and incorporate both *source*-controlled and *site*-controlled components (f_{c3} and $1/\kappa$)

Problems:

- **does f_{c3} exist for events in a particular region?**
- **if yes, how it scales?**
- **if yes, can one still use the spectral range [*fc2, fc3*] to determine *Q(f)!***

Plan of study

1. Compile a preliminary attenuation model; use it to correct observed spectra for path-related and site-related loss;

2. Estimate f_{c1}, f_{c2} and f_{c3} from individual spectra

3. Use the $[f_{c2}, f_{c3}]$ spectral band to extract second approximation of attenuation model; check and verify the acceptable accuracy of the initial model

4. Analyse $f_{c1}(Mw)$, $f_{c2}(Mw)$, $f_{c3}(Mw)$ etc

Step 1

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

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

where

r - hypocentral distance

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

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

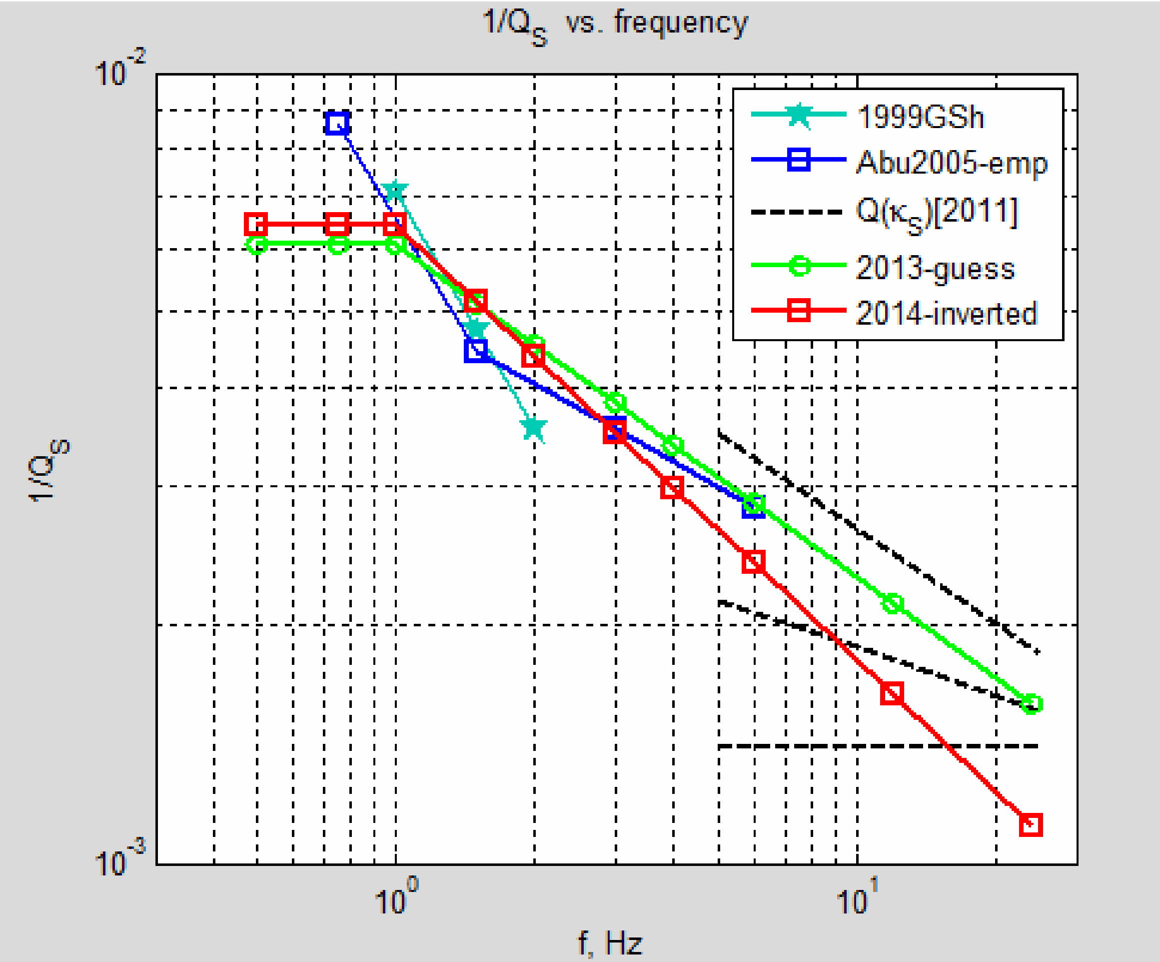
$$Q^{-1}(f, r) = Q_0^{-1} (f/f_0)^{-\gamma} (1+q(r-r_0)/r_0)$$

Model was compiled for, and data were analysed from

the vicinity of PET ("Petropavlovsk") station (Kamchatka pen.)

at r=80-220 km

Compilation of preliminary loss model



accepted **Q_S(f)** model:

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

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

accepted trend at r=100 km:

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

also κ_0=0.016s

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

Data set used

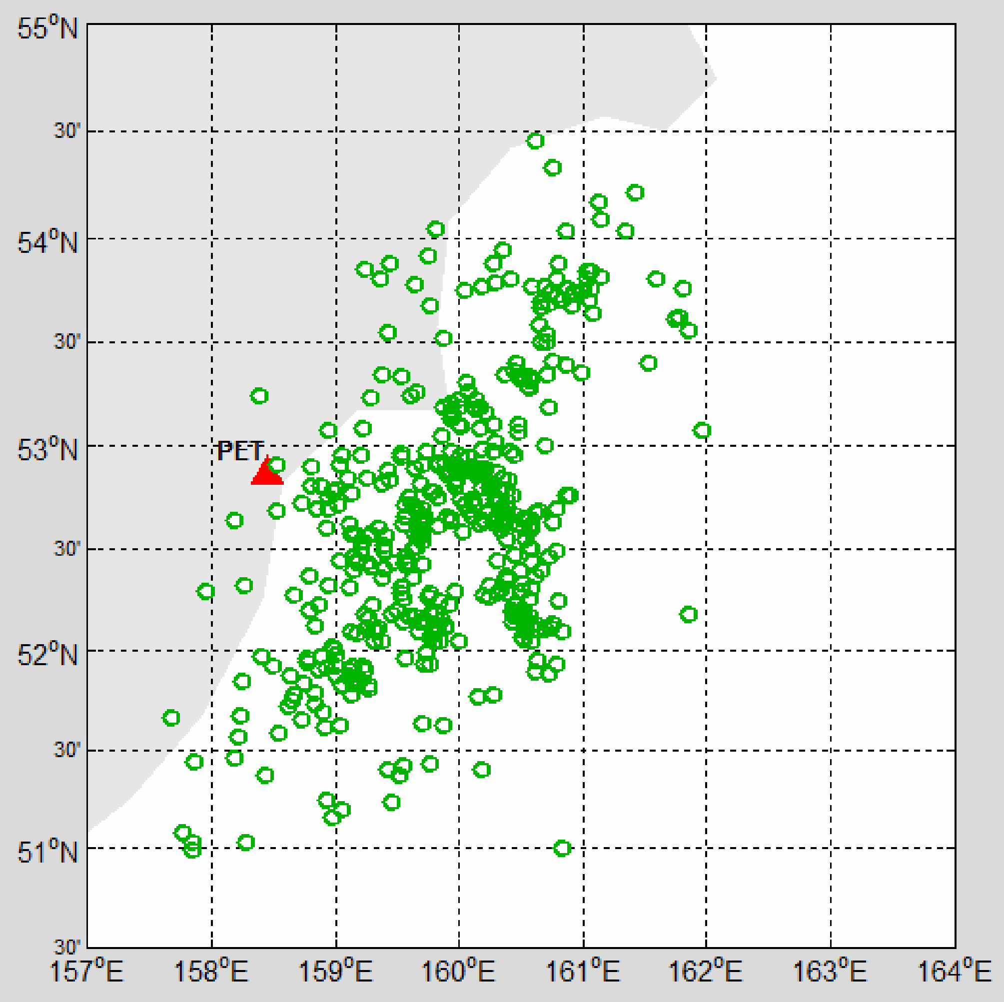
Digital records of HN channel (low-gain accelerograph) of IRIS sta. PET of 1993-2005; 80 sps

439 records;

Hypo distance 80-220 km

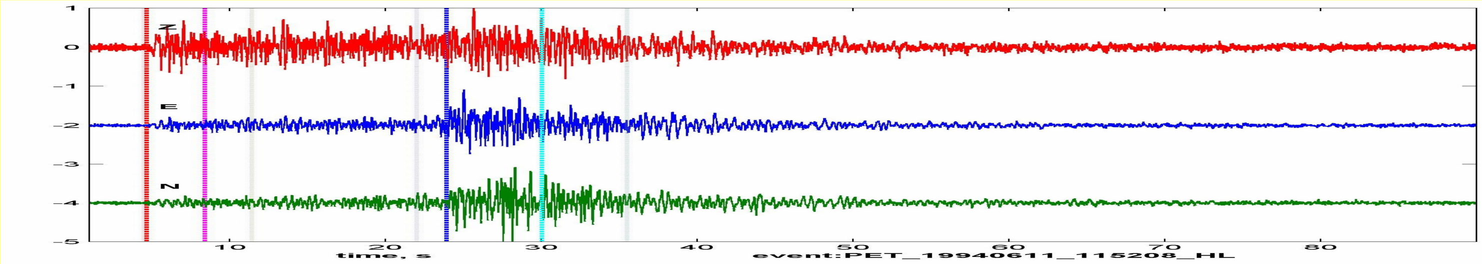
Depth range 0-200 km, mostly 0-50 km

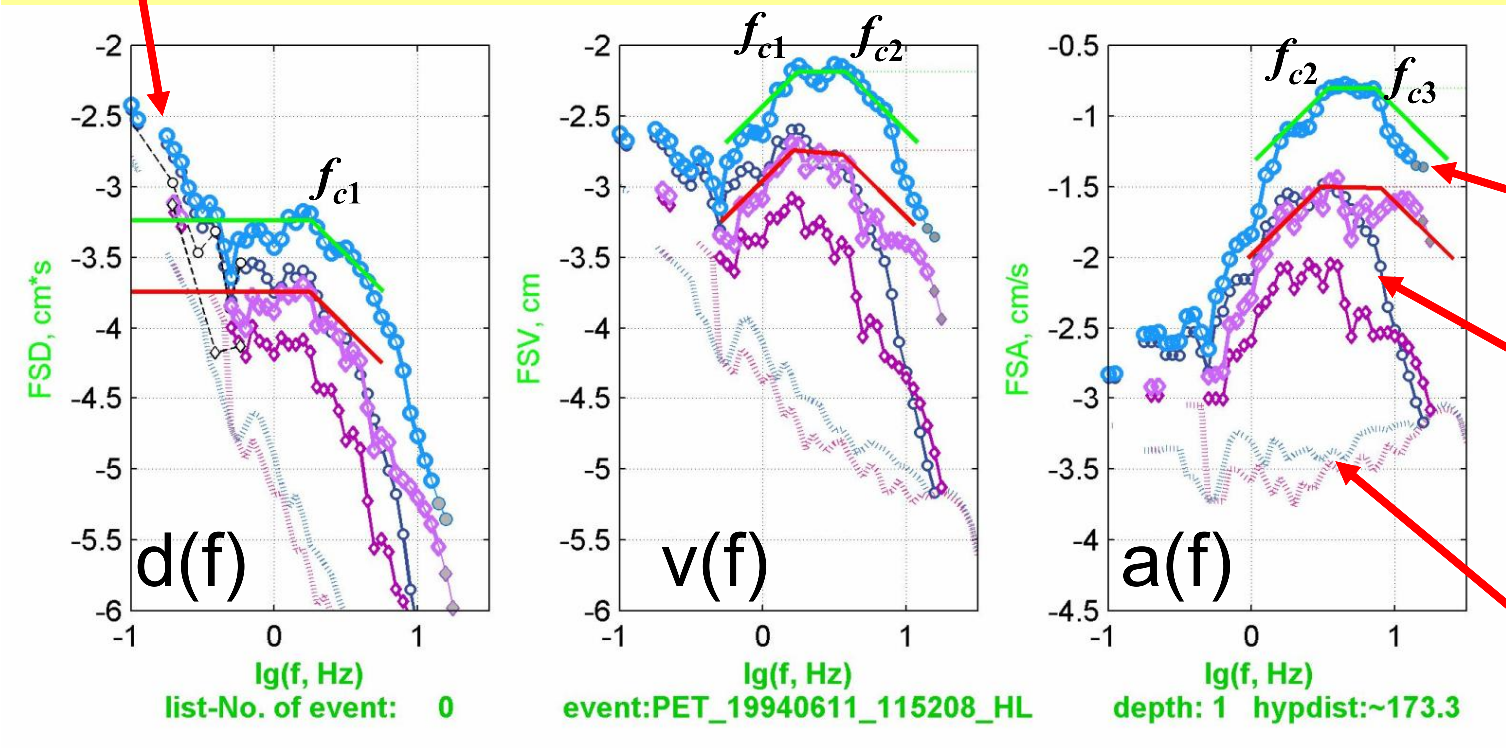
M_L=4-6.5 ($K^{\Phi 68}$=9.5-14)



Processing example

probable
higher-mode
surface wave
contribution





loss-corrected S wave spectrum

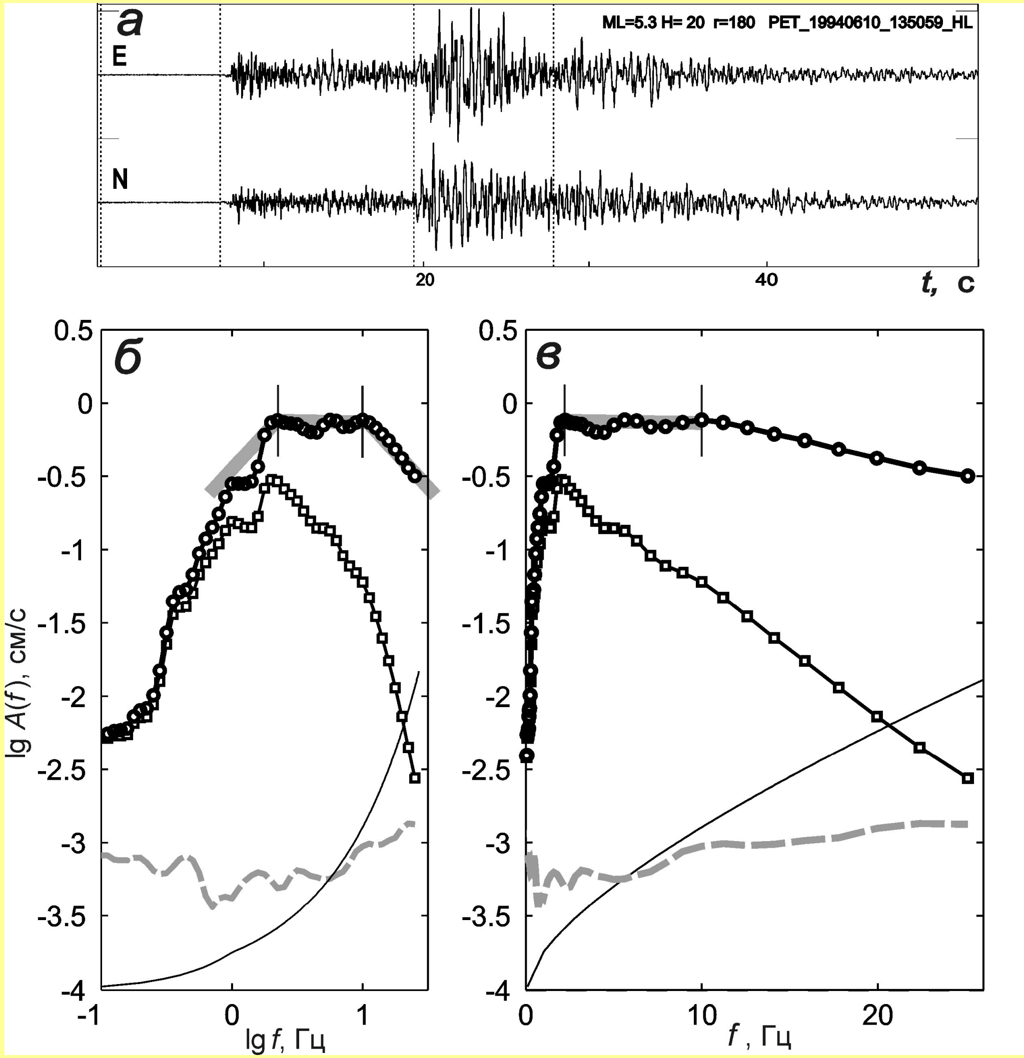
observed S wave spectrum

noise

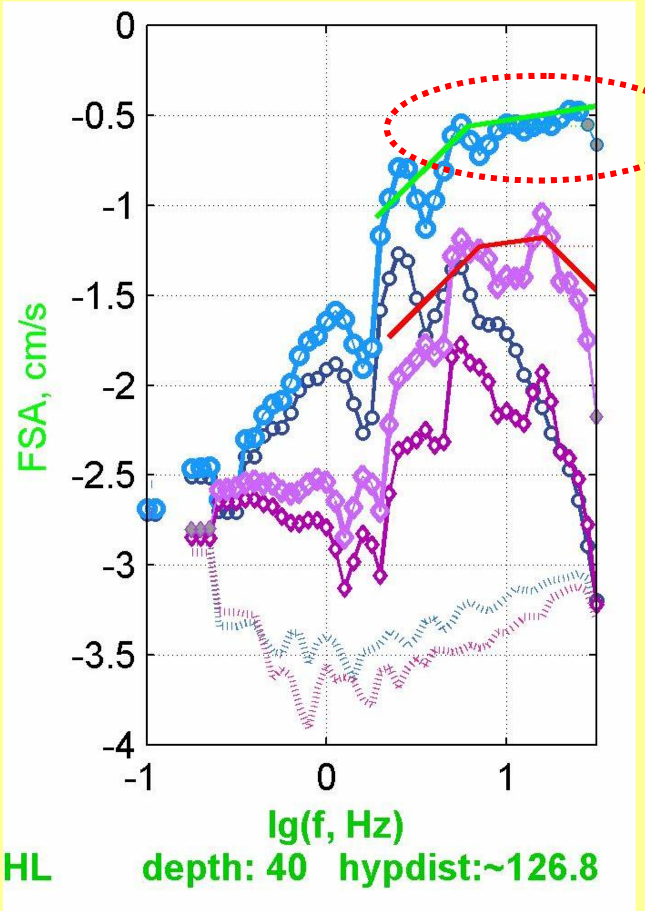
spectral smoothing window used:
0.2 log units (2/3 octave)

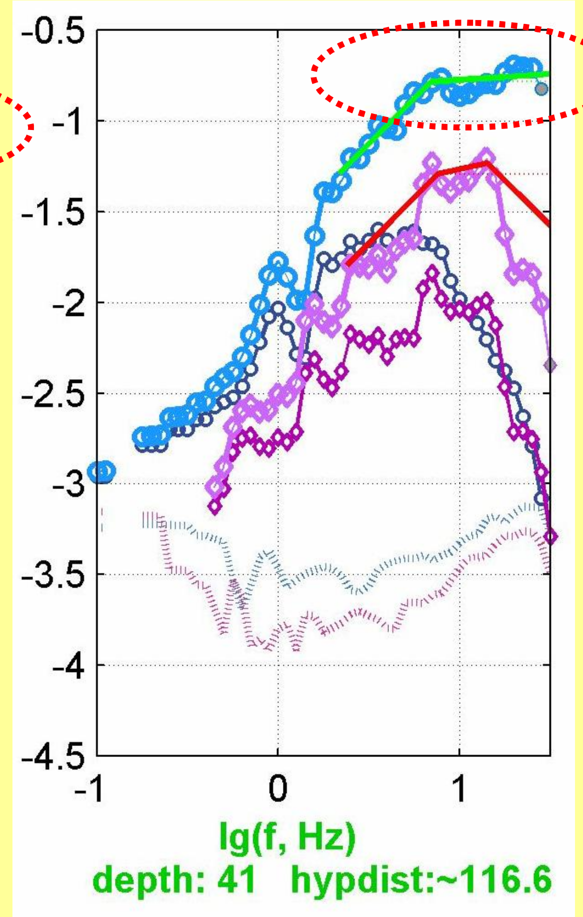
when picking f_{ci}, slope of selected “plateaus”
in v(f) and a(f) plots was kept in the range ±0.5

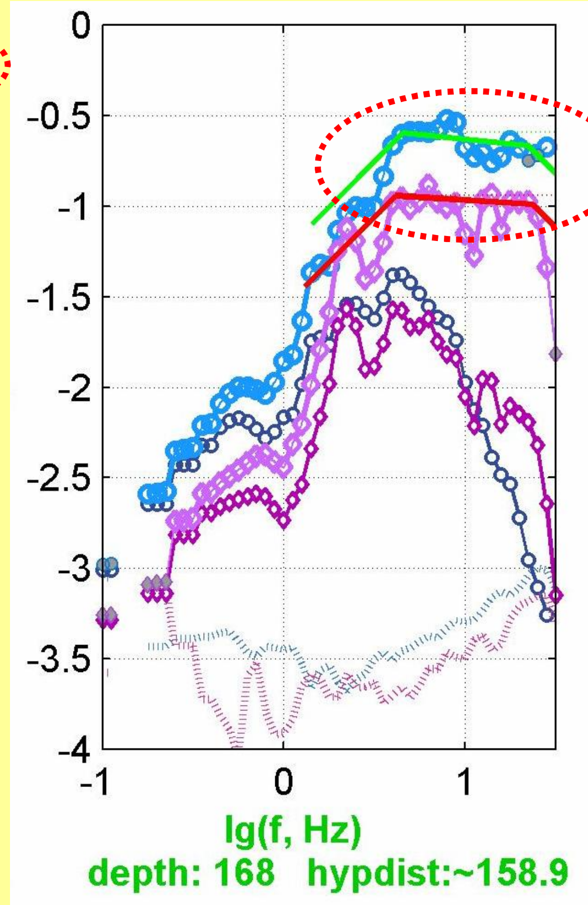
Why f_{c3} is difficult to notice during processing over log-linear scale

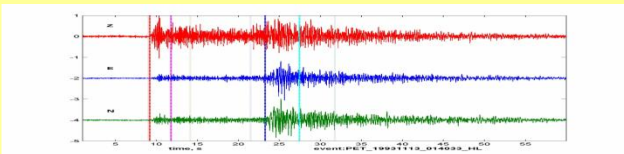


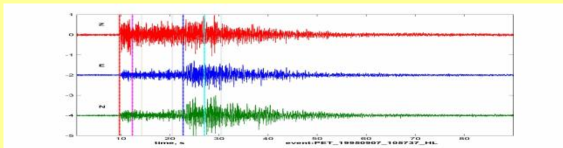
Cases when source acceleration spectrum is apprx. flat up to 25-30 Hz. Omega-square model seems applicable and loss correction seems reasonable

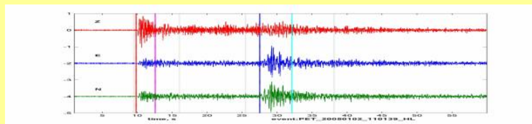




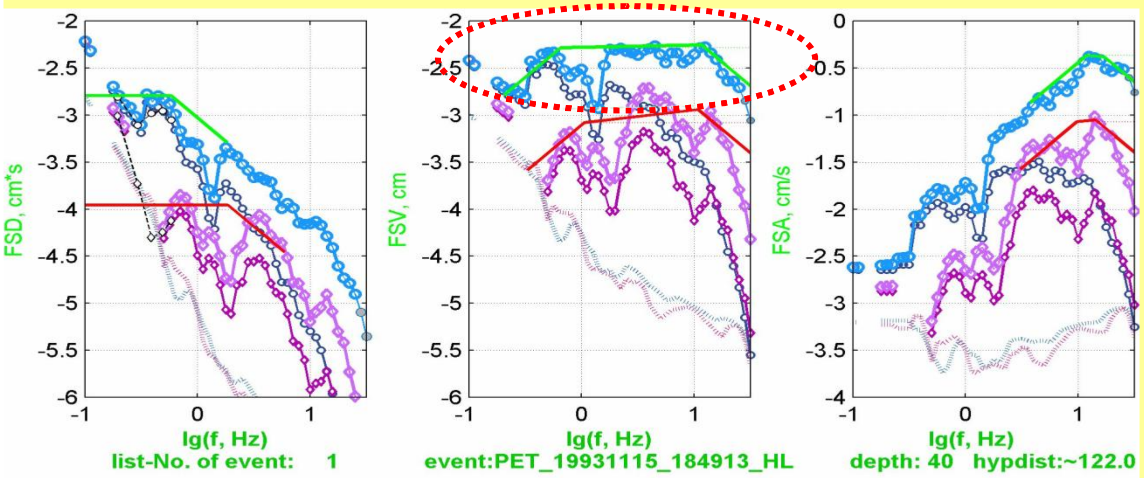


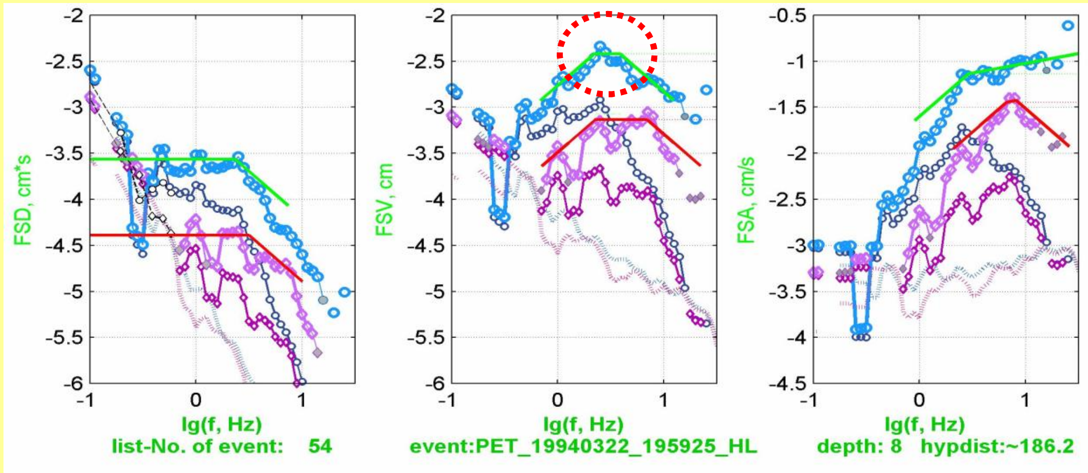




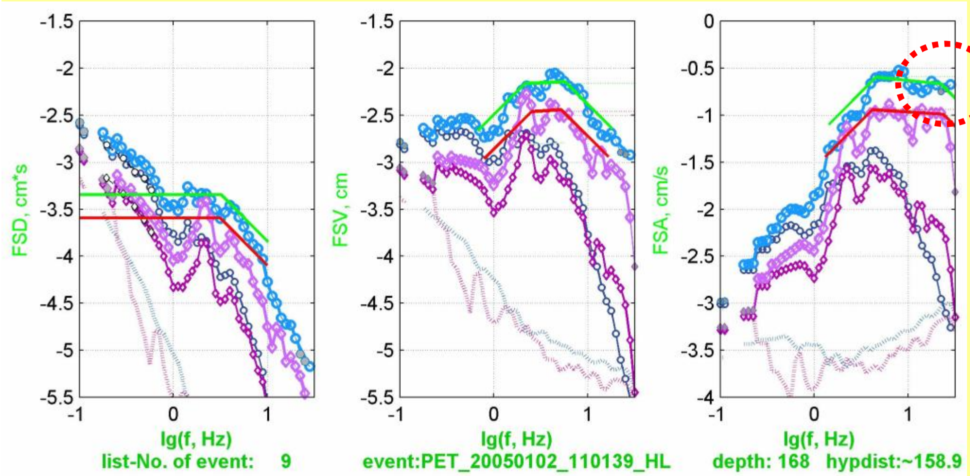


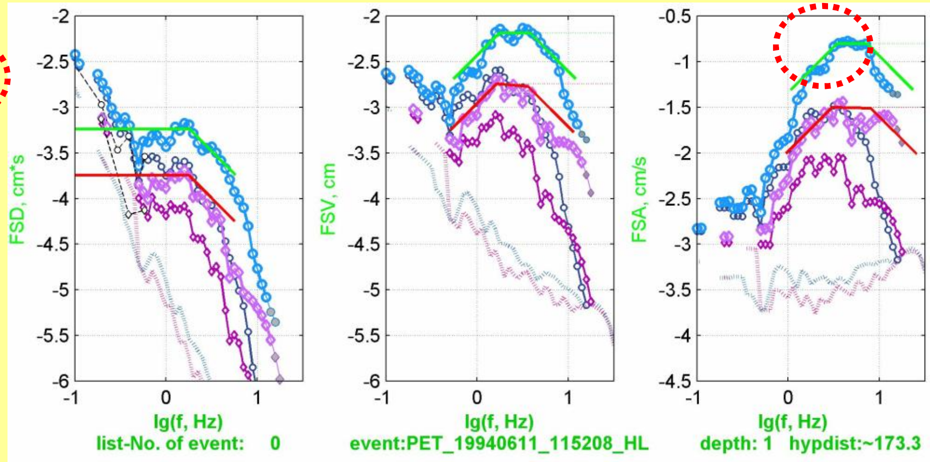
Cases of wide and narrow flat velocity spectral shape between f_{c1} and f_{c2}

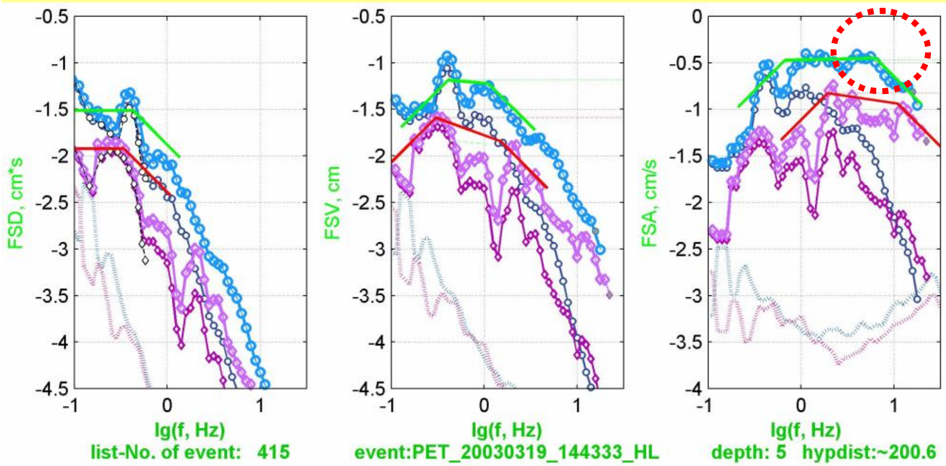


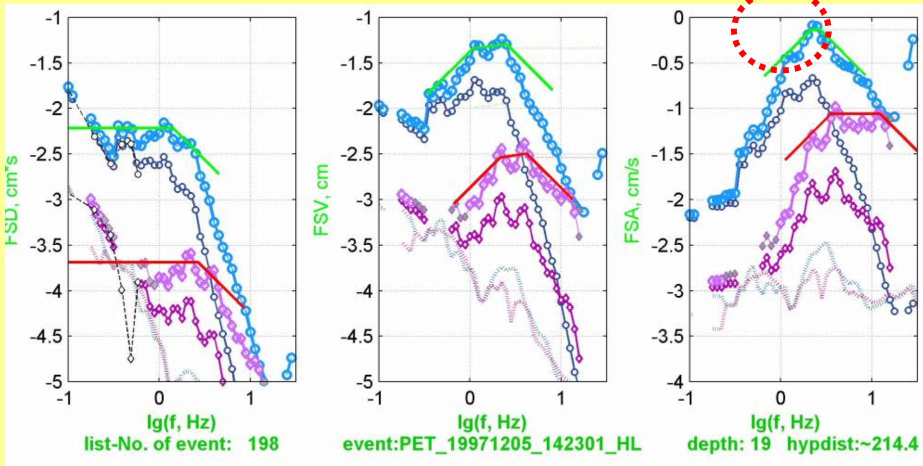


Cases when f_{c3} is absent or present over the 2-25 Hz range

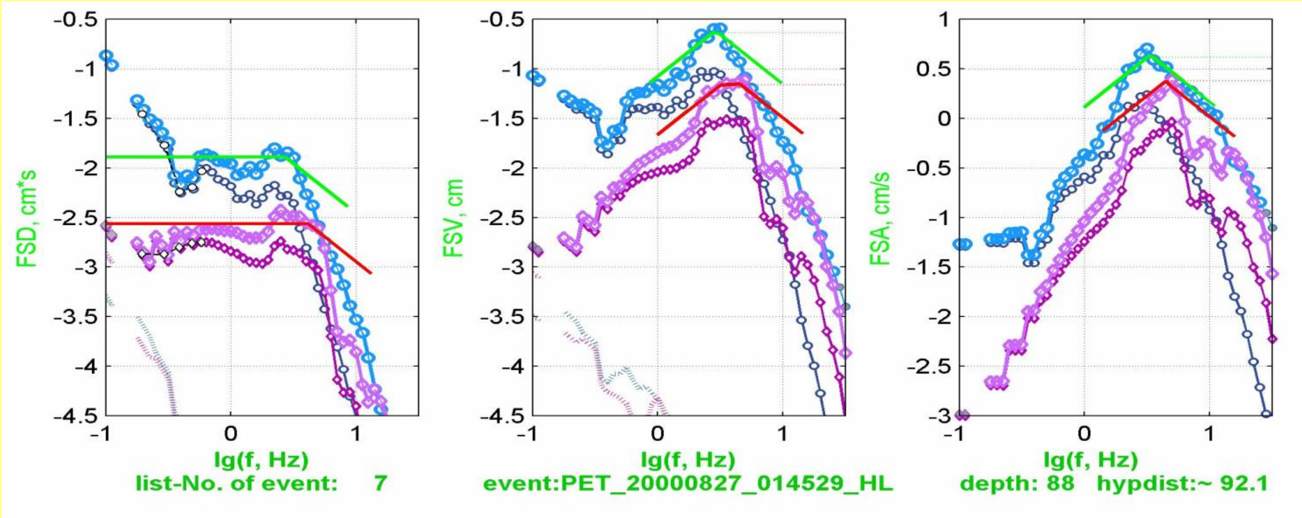


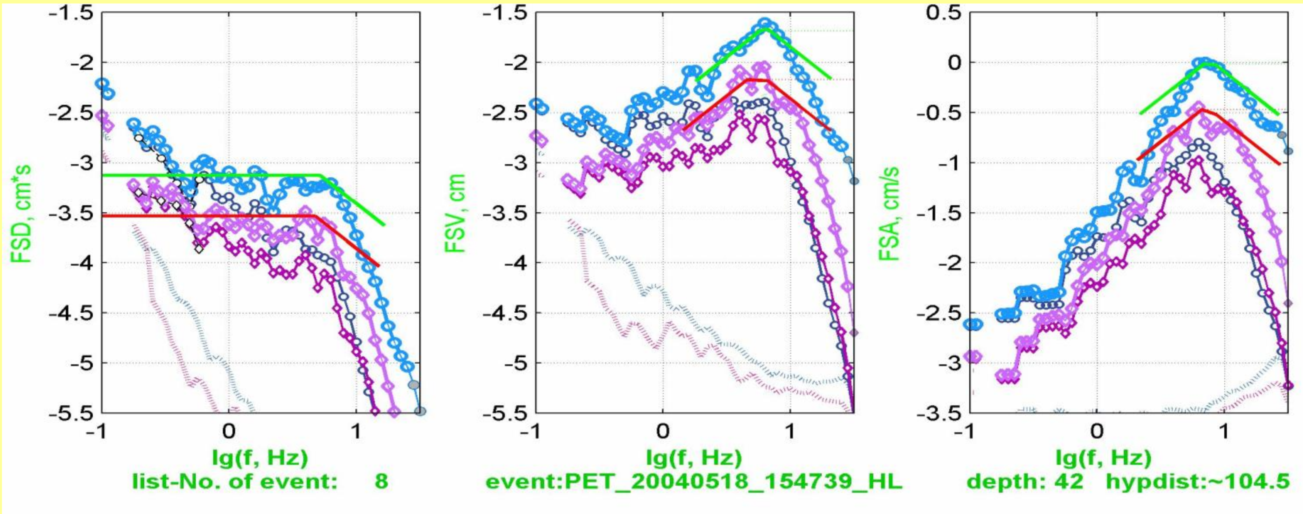






Cases of spectra of clearly the «ω^{-3}» kind (*infrequently*)





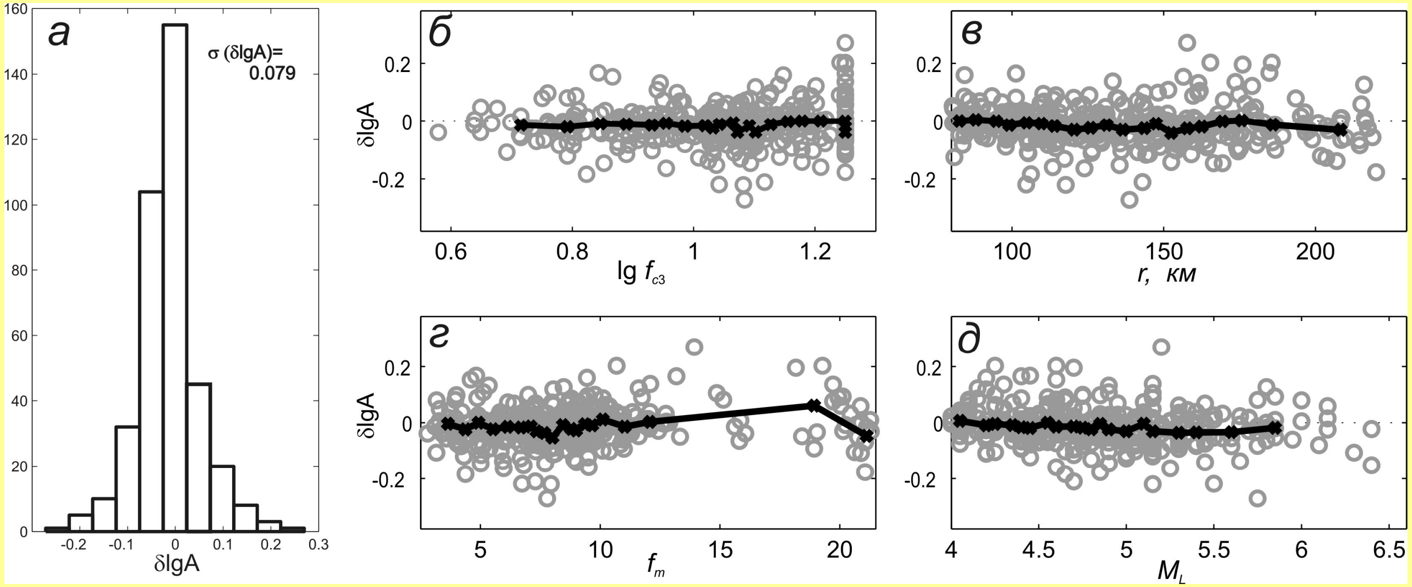
Step 3. Checking the attenuation model (for *S*-waves only) by inversion

Unknowns in inversion: κ_0, and Q_0, γ, q in:

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

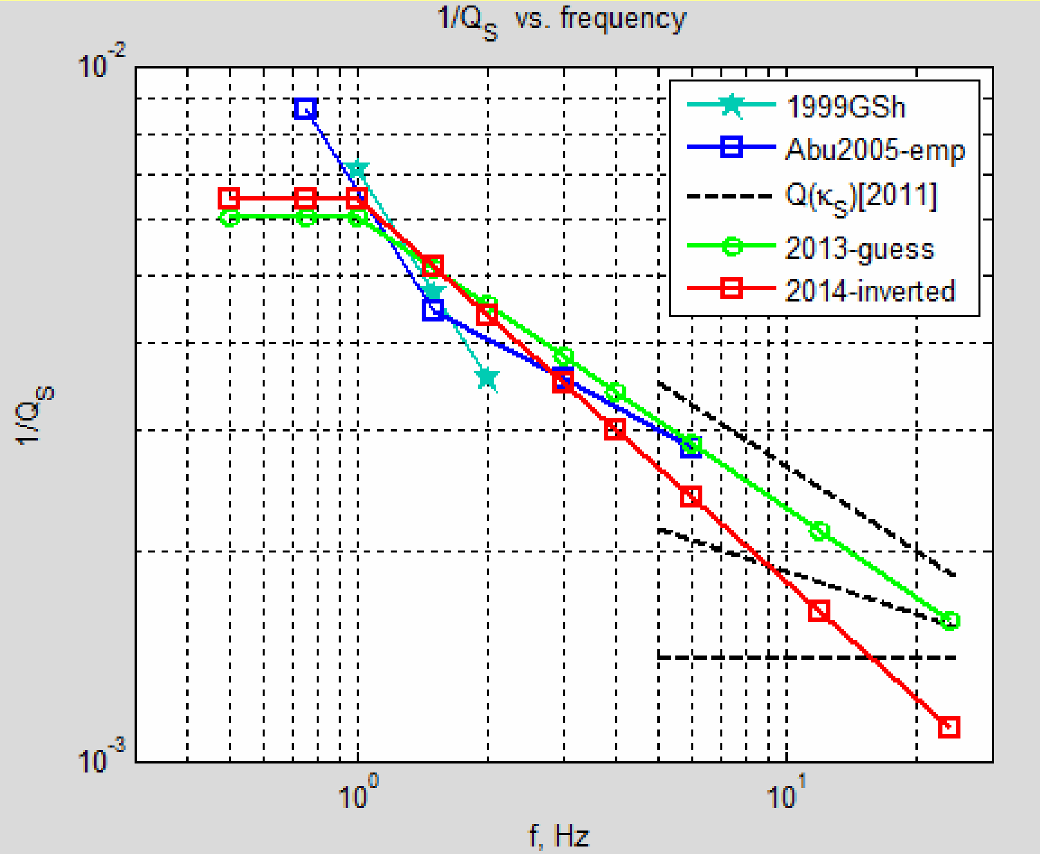
Observed/data parameter used in inversion: $\delta\log A = \log A_2 - \log A_1$

where A_2 and A_1 are spectral amplitudes at the ends of the assumedly flat source-acceleration spectrum segment



Residuals of $\delta\log A$ fitted by the attenuation model got by inversion: histogram and plots of $\delta\log A$ against f_{c3}, r, f_{mean} and M_L

Comparing preliminary and inverted loss models



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

Guess 2013:

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

combined with κ_0=0.016 s

Inverted 2014:

$Q_S(f)=156\,f^{\,0.55}$

combined with κ_0=0.030 s

preliminary estimates: Q_0 =165, γ=0.42; κ_0=0.016 s

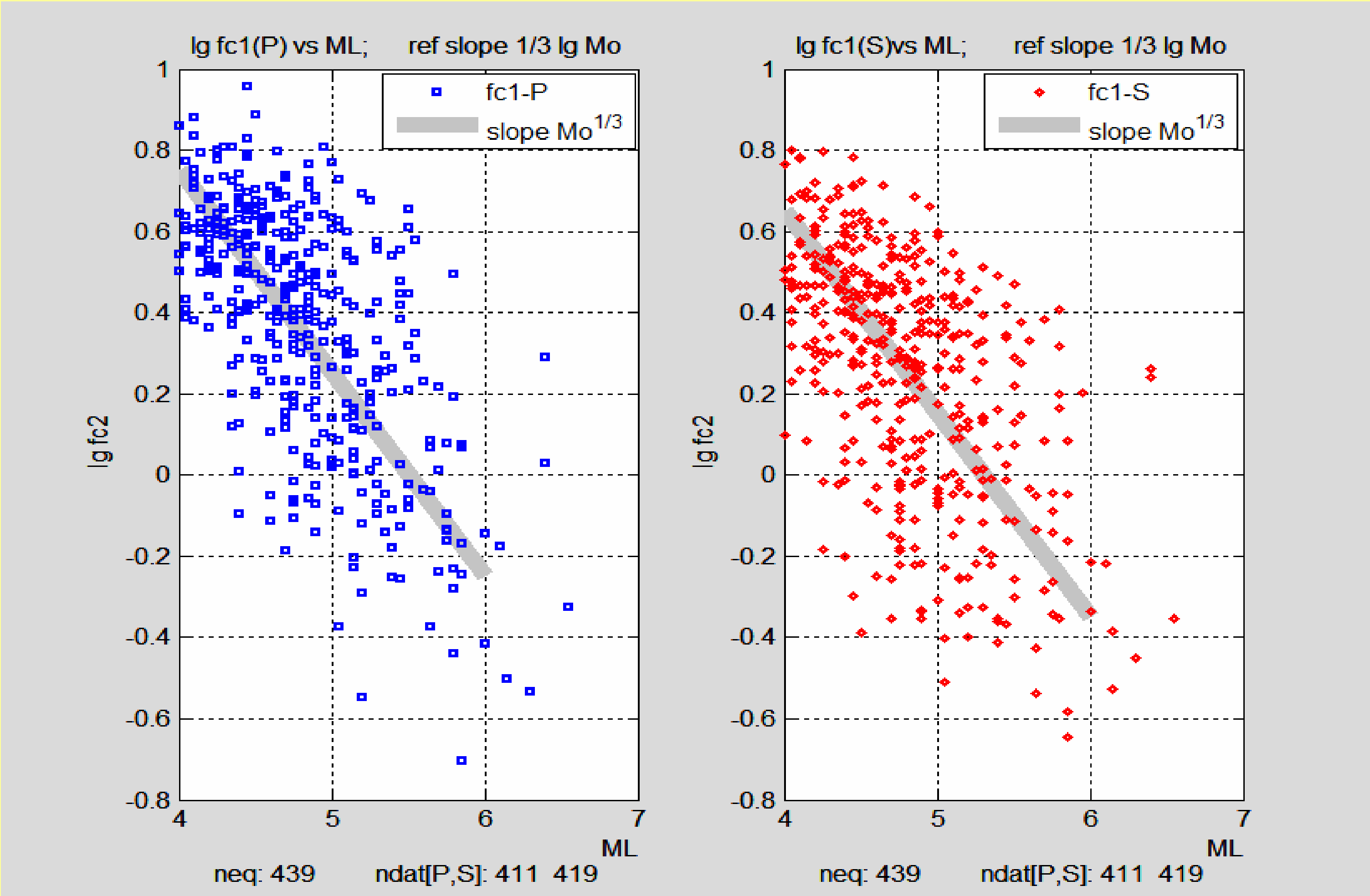
adjusted estimates: Q_0 =156±33, γ=0.55±0.08; κ_0=0.030±0.07 s

(change of predicted spectral corrections: **negligible**

Step 4. $\mathbf{f_{c1}(M)}$: $\quad dlgf_{c1}/dlgM_0 \approx -1/3$

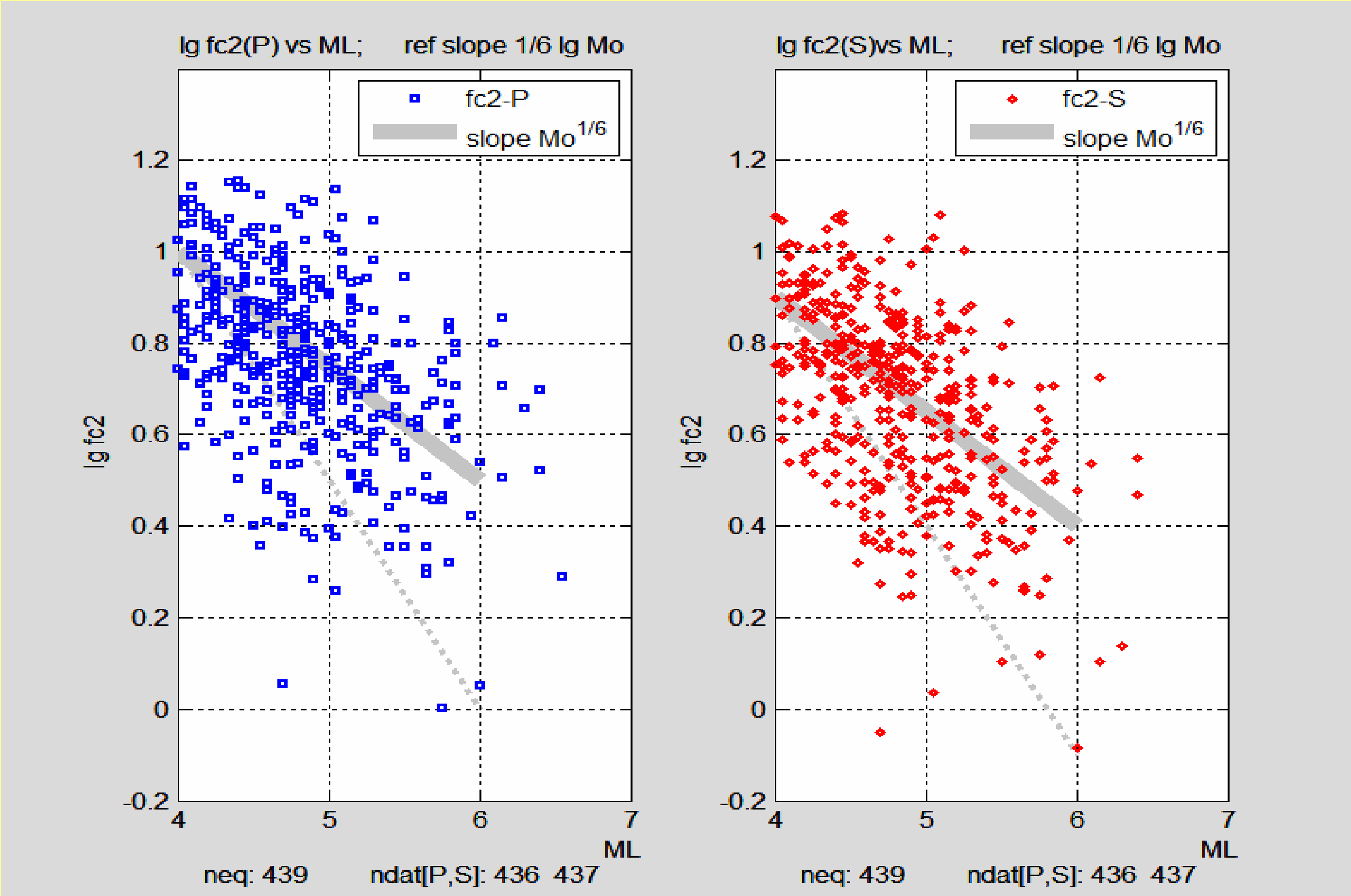
common, regular trend;

in agreement with the similarity concept



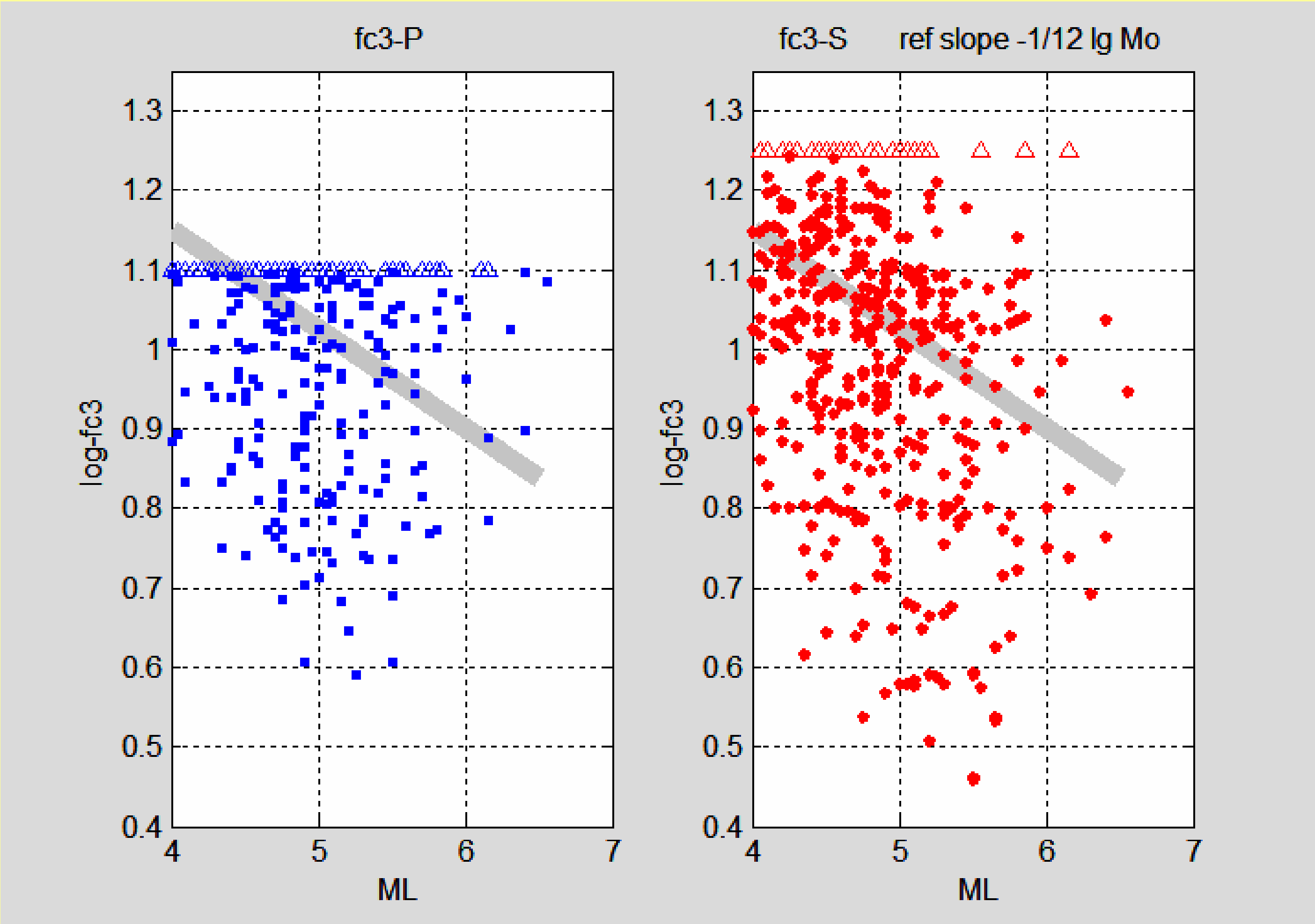
$f_{c2}(M)$: $d\lg f_{c2}/d\lg M_0 \approx 0.15\text{-}0.18\ [\pm 0.011] \ll 1/3$

similarity is definitely violated;



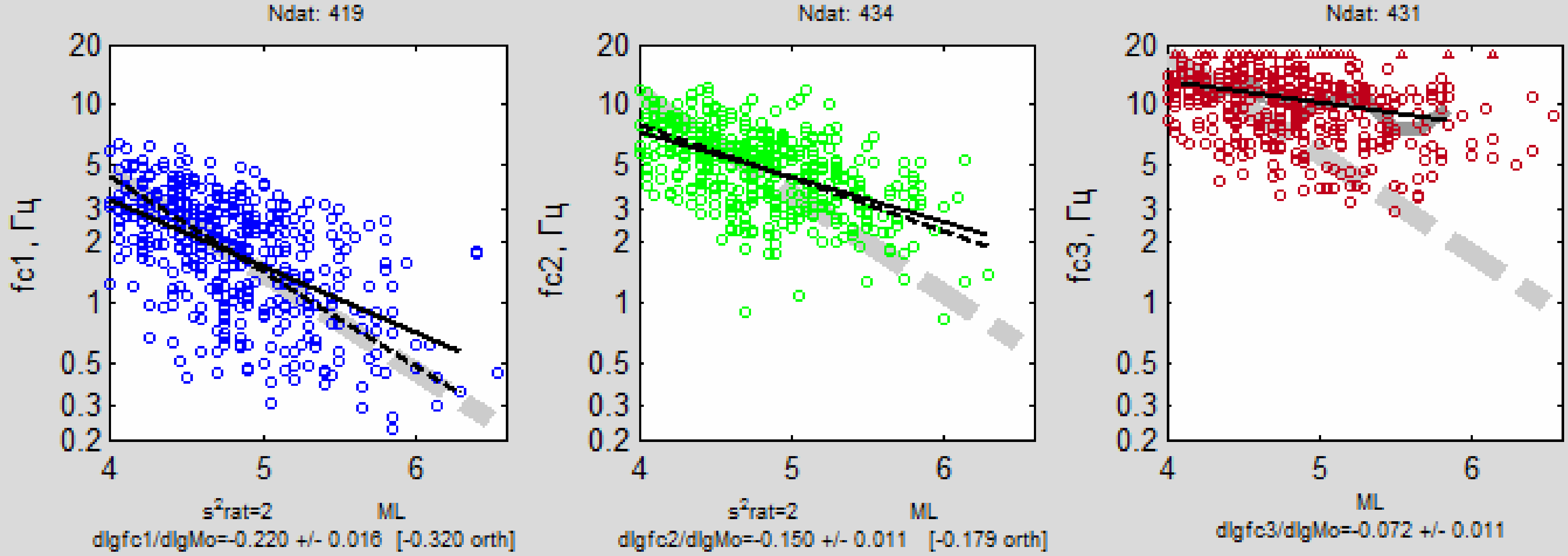
f_{c3}(M): $\mathrm{dlgf}_{c1}/\mathrm{dlgM}_0 \approx -0.08 \pm 0.013$

no similarity present

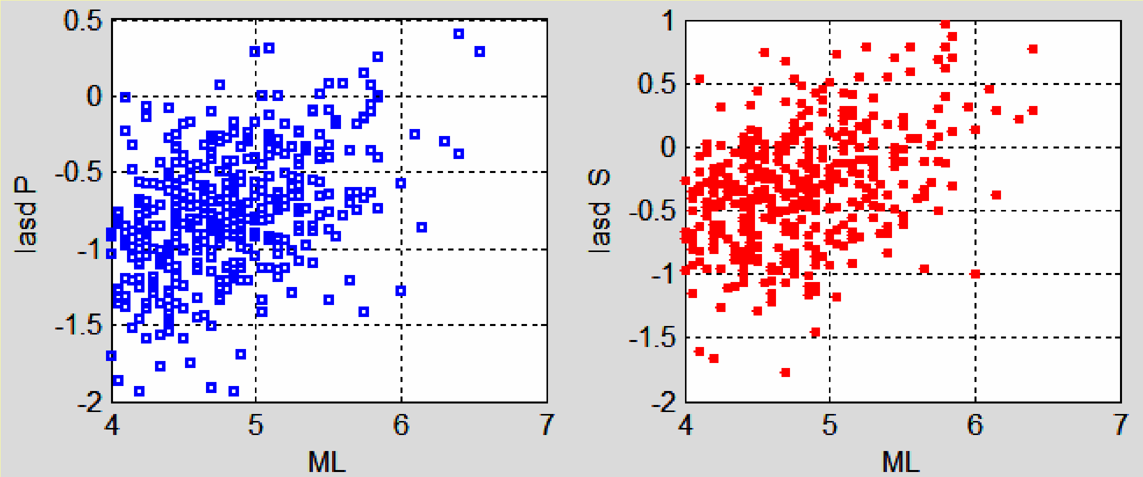


All three trends side by side (S-wave)

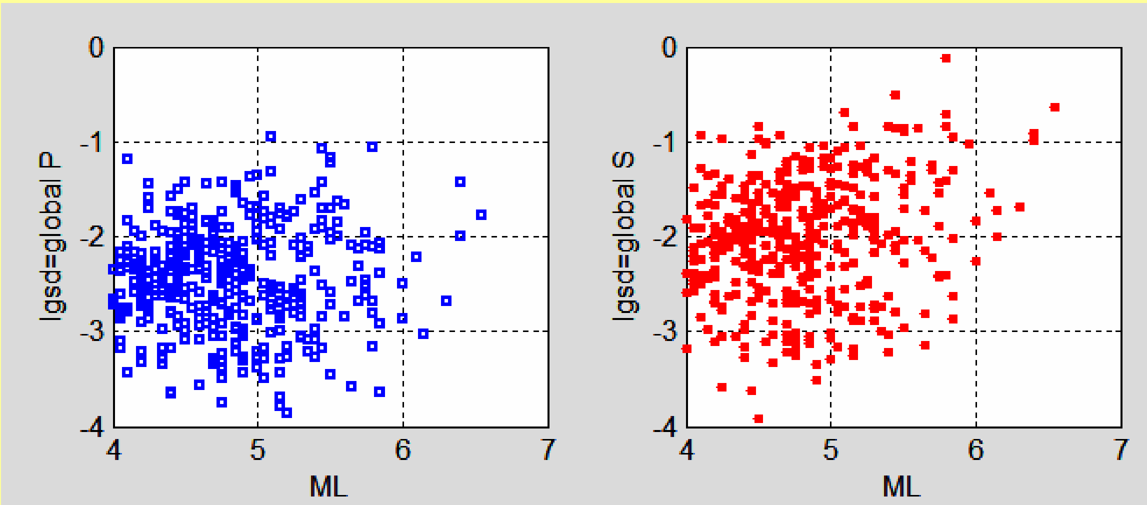
similarity assumption is invalid both for fc2 and fc3, and in different way for each



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

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

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

Possible physics that underlie trends of f_{c2}, f_{c3}

- f_{c2} is probably related to **slip pulse width**;
  the trend $f_{c2} \propto f_{c1}^{0.5\text{-}0.6}$ suggests that pulse width grows by some mechanism akin to random walk

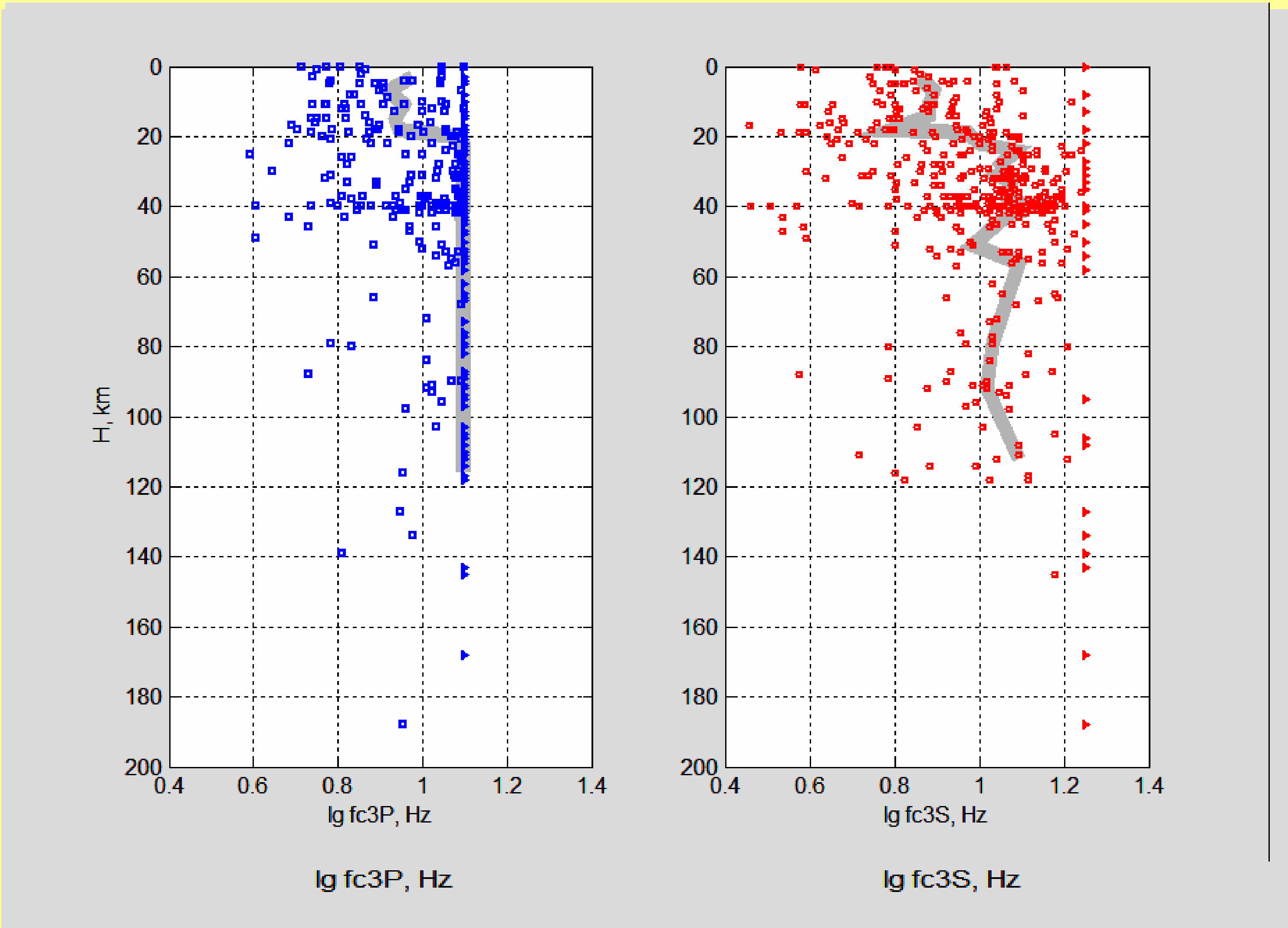
- f_{c3} is probably related to the lower limit of the size of fault surface heterogeneity, (or else to cohesion zone width, or both) (compare Aki (1983)), ;
  the trend $f_{c3} \propto f_{c1}^{0.2\text{-}0.3}$ suggests that these parameters increase with source size, however very slowly. Probably this trend reflect variations in fault surface maturity: the greater slipped distance, the larger is accumulated wear and the lower is upper cutoff of heterogeneity spectrum. (compare Gusev 1990; Matsu'ura 1990,1992).

Conclusions

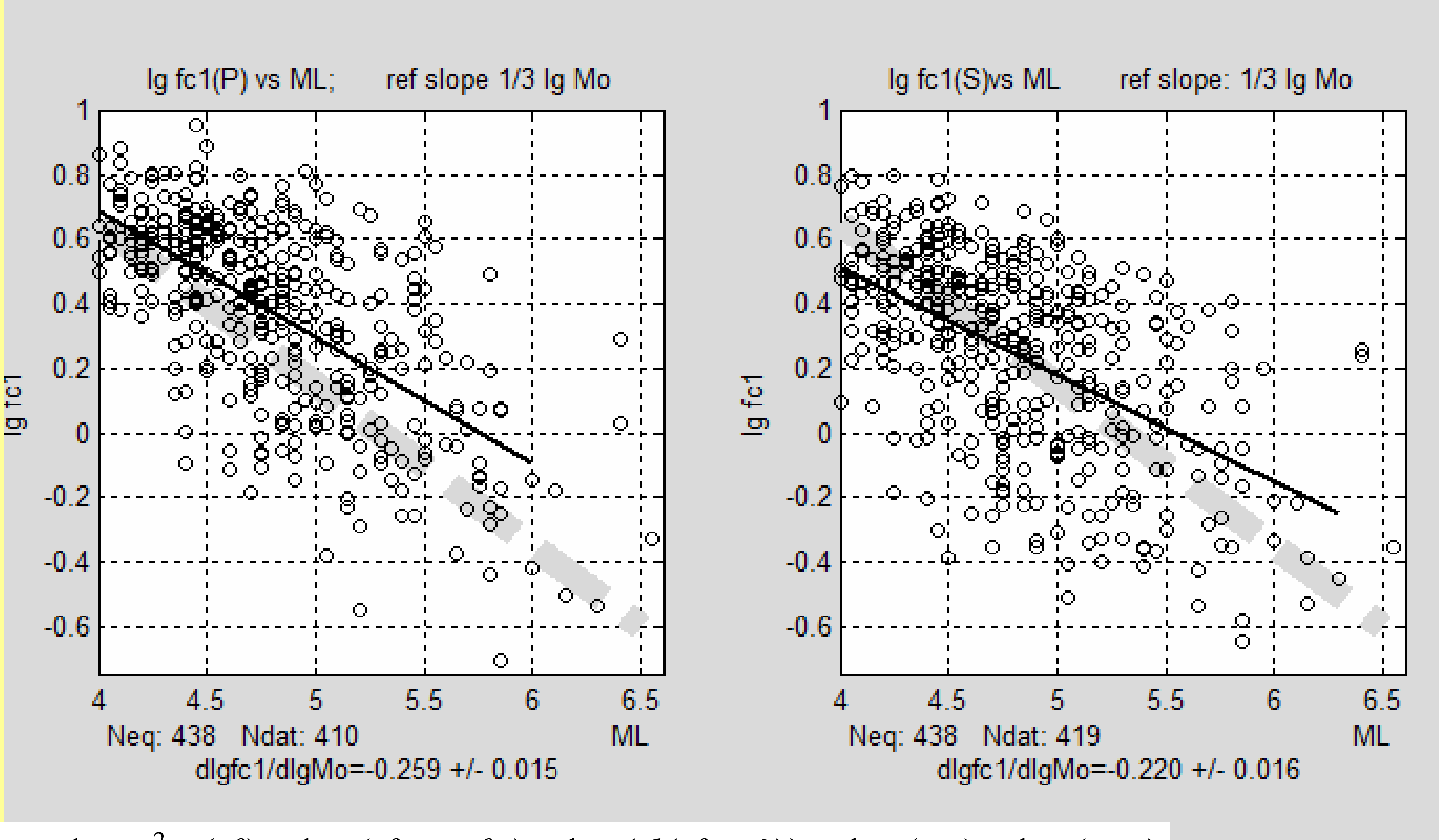
1. A procedure for processing earthquake Fourier spectra is designed that permits separate study of source-controlled and attenuation-controlled constituents of *f*-max. To enable this kind of processing, attenuation models of lithosphere around PET station for S and P waves were compiled and, for S, verified.
2. Corner frequencies f_{c1}, f_{c2}, f_{c3} of source spectra are determined, where possible, for ≈400 earthquakes of M=4-6, at hypocenter distances up to 220 km .
3. A large fraction of spectra show clear source-controlled *f*-max, or f_{c3},, with values in the range 3-20 Hz. The trend close to $f_{c3} \propto M_0^{-0.08}$ can be seen. Three-corner spectal shape is commmon, and reminds Haskell's concepts on ω^{-3} asymptotics of spectra
4. A large fraction of spectra show clear second corner frequency f_{c2} clearly above common f_{c1}. The trend of the kind $f_{c2} \propto M_0^{-0.15}$ is clearly seen.
5. Trends of both f_{c2} , and f_{c3} vs. magnitude indicate definite lack of similarity of spectra.
6. Infrequently, source spectra of the «ω^{-3}» kind are observed.

thank you for attention

$f_{c3}(H)$


H, km
0
20
40
60
80
100
120
140
160
180
200
0.4
0.6
0.8
1
1.2
1.4
lg fc3P, Hz
lg fc3S, Hz
lg fc3P, Hz
lg fc3S, Hz

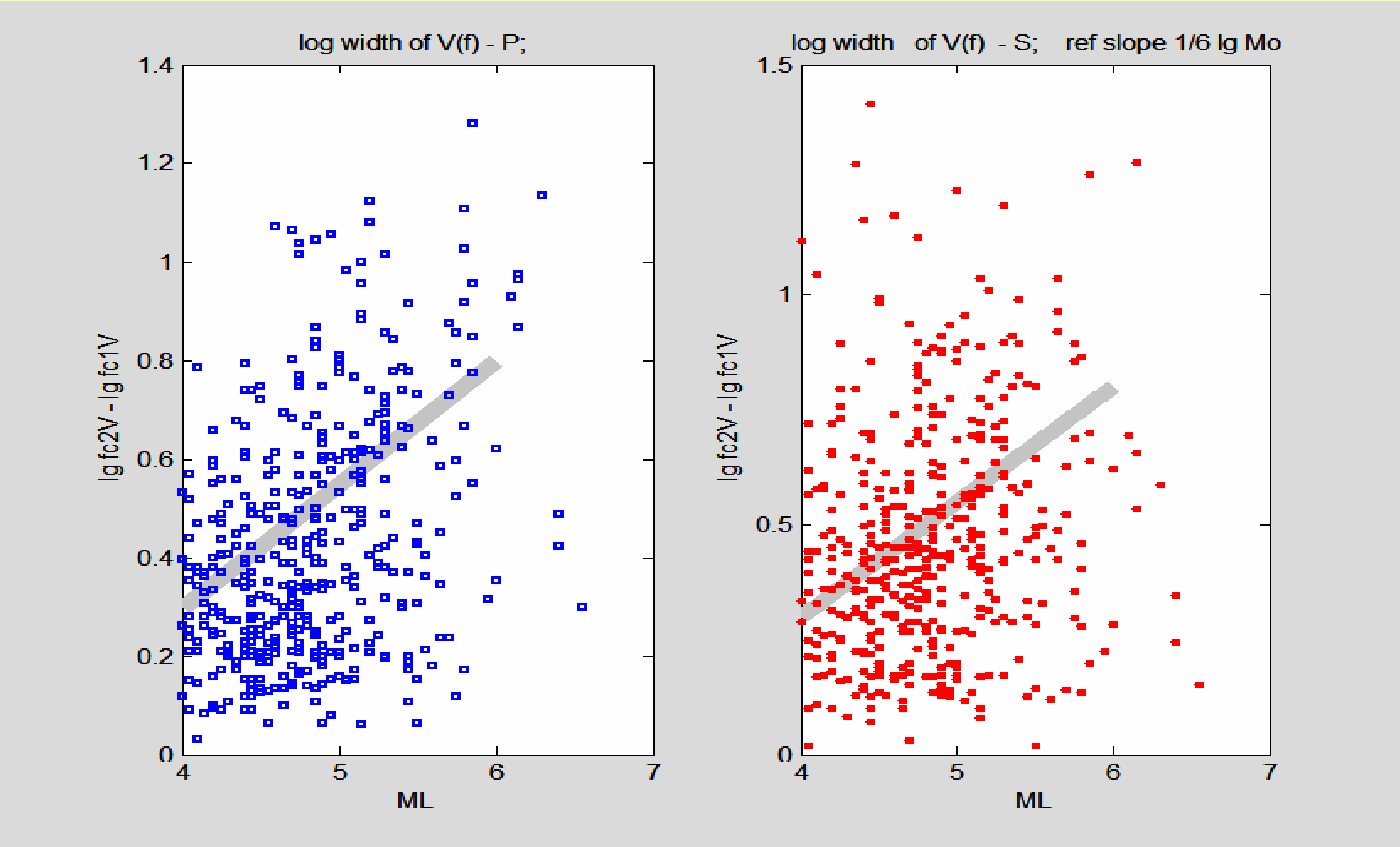
f_{c1} vs. M



$$\log \sigma_a = \log v_{\max}^2(f) + \log(f_{c2} - f_{c1}) - \log(d(f=0)) = \log(E_s) - \log(M_0)$$

$$\log \Delta\sigma = \log d(f=0) + 3\log(f_{c1}) \qquad \text{(all at } r = 1\text{ km)}$$

$LV = \log f_{c2} - \log f_{c1}$: 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 $\Delta\sigma$