Provisional Empirical Ground-Motion Model (EGMM)

D. M. Boore
G. M. Atkinson

July, 2006

SHORT VERSION

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$$\ln Y = F_M(\mathrm{M}) + F_D(r_{jb}, \mathrm{M}) + F_S(V_{30}, r_{jb}, \mathrm{M}) + \varepsilon\sigma$$

Magnitude Dependence (Primary):

For $M \leq M_h$:

$$F_M(\mathrm{M}) = e_1 U + e_2 S + e_3 N + e_4 R + e_5(\mathrm{M} - M_h) + e_6(\mathrm{M} - M_h)^2$$

For $M > M_h$:

$$F_M(\mathrm{M}) = e_1 U + e_2 S + e_3 N + e_4 R + e_7(\mathrm{M} - M_h) + e_8(\mathrm{M} - M_h)^2$$

Mechanism	U	S	N	R
unspecified	1	0	0	0
strikeslip	0	1	0	0
normal	0	0	1	0
reverse	0	0	0	1

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Distance dependence:

$$F_D(r_{jb}, \mathrm{M}) = [c_1 + c_2(\mathrm{M} - M_{ref})]\ln(r / r_{ref}) + [c_3 + c_4(\mathrm{M} - M_{ref})](r - r_{ref})$$

where

$$r = \sqrt{r_{jb}^{\ 2} + h^2}$$

$$F_S = F_{LIN} + F_{NL}$$

$$F_{LIN} = b_{lin} \ln(V_{30} / V_{ref})$$

$pga4nl \le a_1$

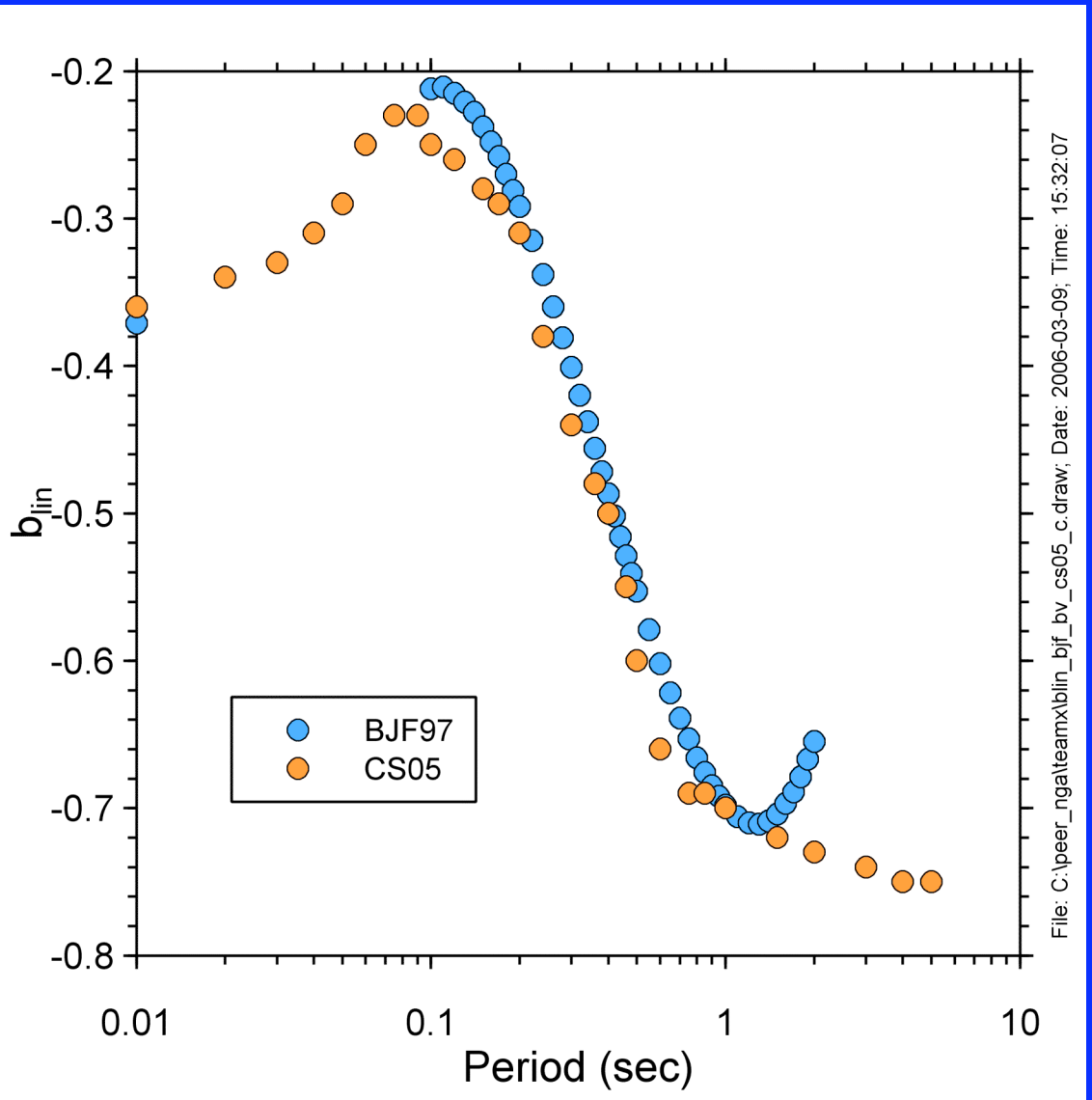
$$F_{NL} = b_{nl} \ln(pga\_low / 0.1)$$

$a_1 < pga4nl \le a_2$

$$F_{NL} = b_{nl} \ln(pga\_low / 0.1) + c[\ln(pga4nl / a_1)]^2 + d[\ln(pga4nl / a_1)]^3$$

$a_2 < pga4nl$

$$F_{NL} = b_{nl} \ln(pga4nl / 0.1)$$



Several developers finding upward trend in blin for longer periods (expected) (maybe we should have used BJF97!)

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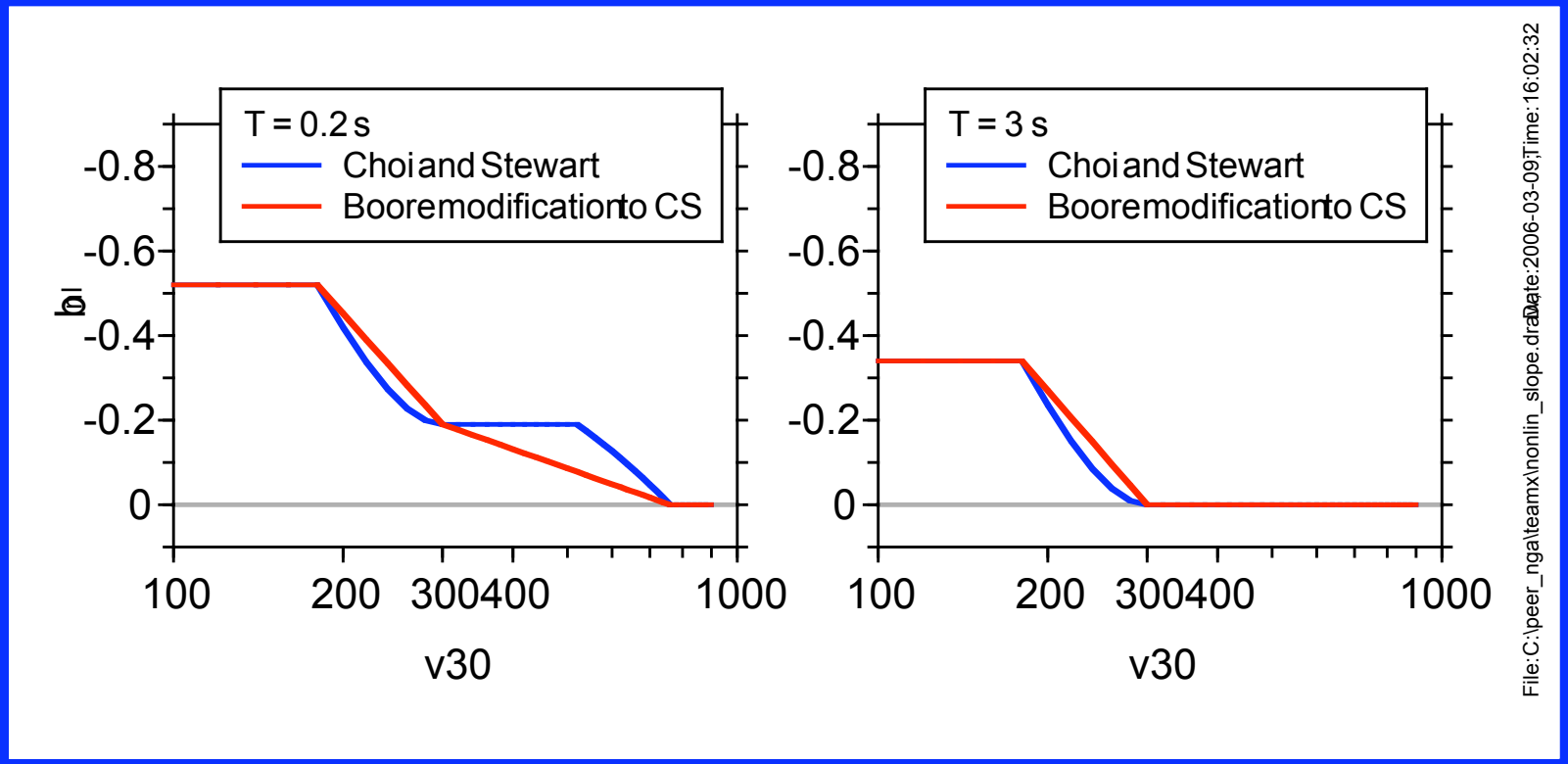
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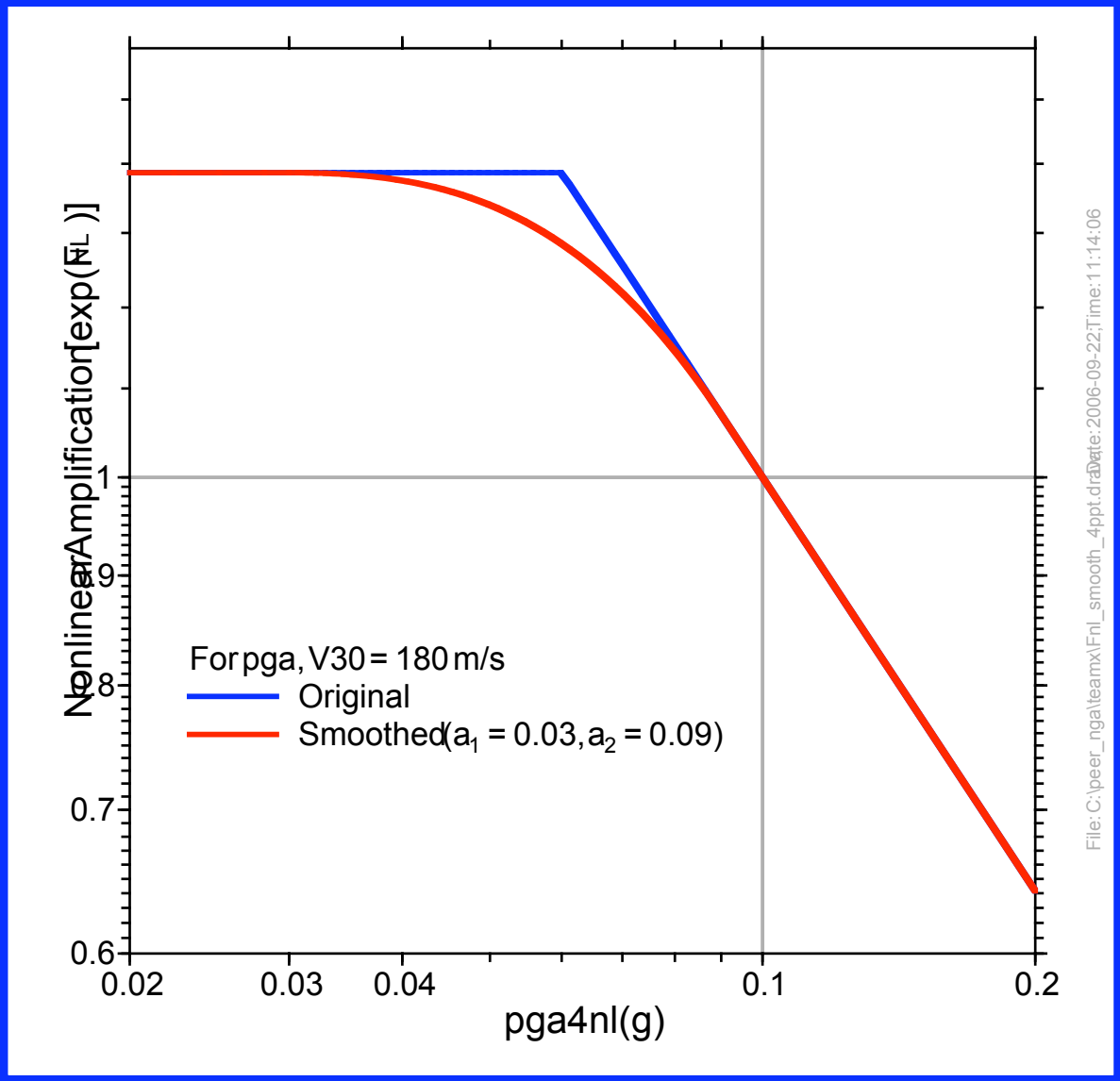
Change in July, 2006, version



Numbers of Data and Events Used in Regression

Stage 1

Period	ndata	ndata_x137
pgv	1604	1224
pga	1604	1224
0.1	1604	1224
0.2	1604	1224
1.0	1586	1206
2.0	1473	1094
3.0	1282	905

Stage 2

Period	nevents
pgv	58
pga	58
0.1	58
0.2	58
1.0	56
2.0	52
3.0	46

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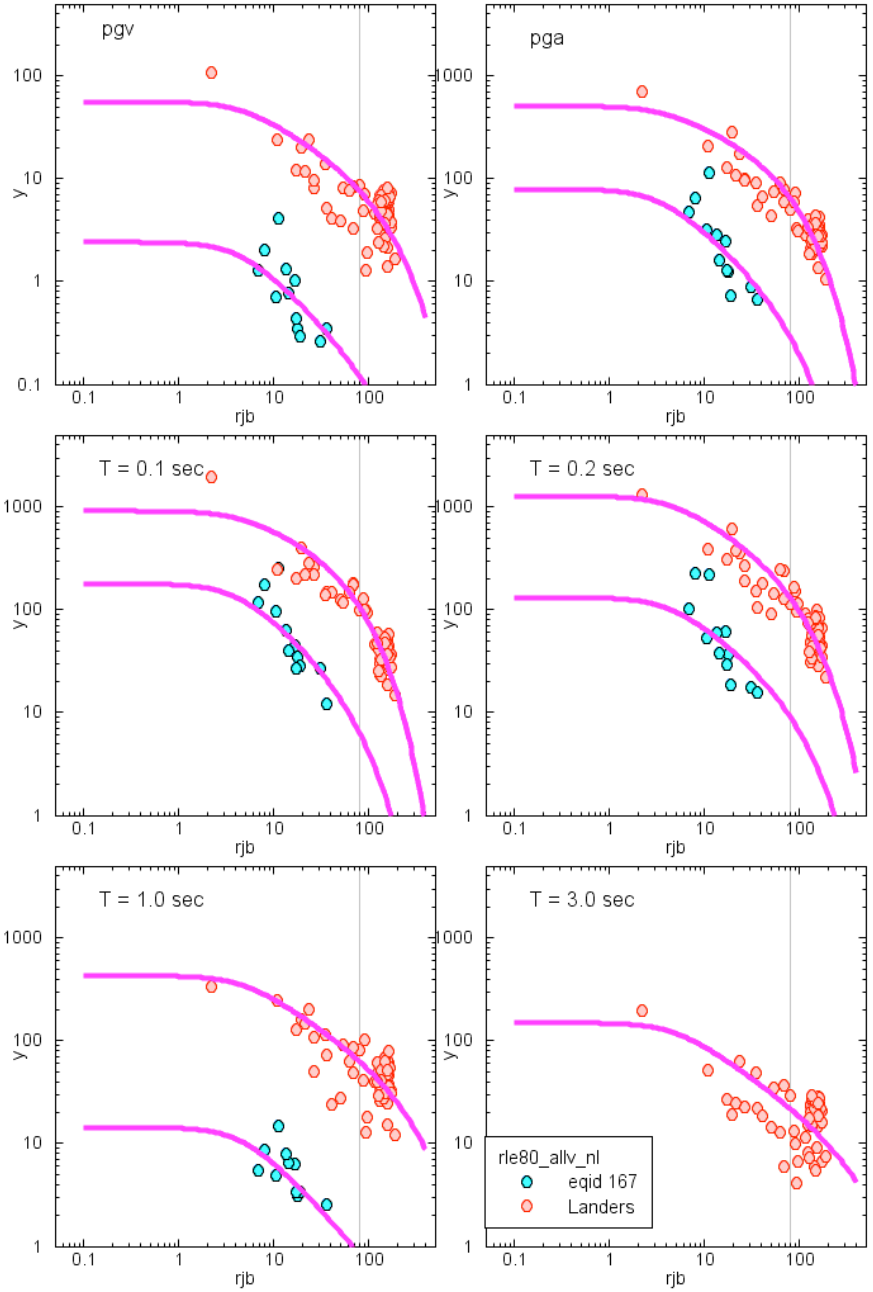
New (M-dependent distance dependence)



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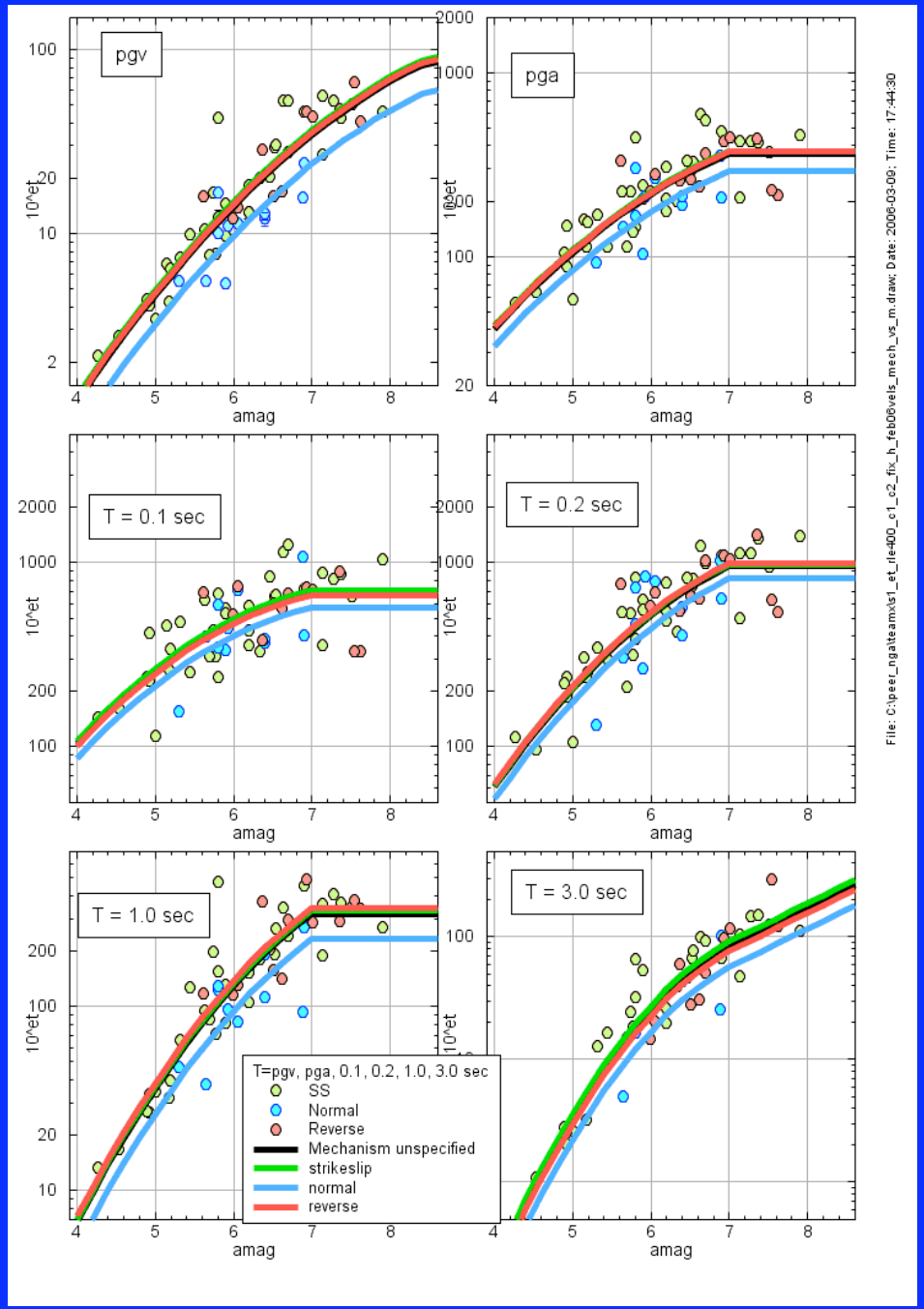

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Comparison of Aleatory Uncertainty (natural log)

per	sig1:ba05	bjf97	sig2u:ba05	bjf97	sigtu:ba05	bjf97
pgv	0.52		0.29		0.59	
pga	0.51	0.43	0.27	0.18	0.57	0.47
0.10	0.53	0.44	0.33	0.00	0.63	0.44
0.20	0.53	0.44	0.29	0.01	0.60	0.44
1.00	0.58	0.47	0.31	0.21	0.65	0.52
2.00	0.59	0.50	0.40	0.28	0.71	0.62
3.00	0.57		0.41		0.71	

Total uncertainty greater than before and very consistent with other developers

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Questions?

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Specific Exclusion Criteria for Boore-Atkinson equations

- missing metadata used in the analysis or one component of horizontal motion is missing
- aftershocks
- focus/rupture in deep crust, oceanic plate, or stable continental region
- poorly located events
- non “free-field” recordings (basements, large structures, dam crests, abutments, toes)
- Proprietary records (some from Kobe)
- S-triggered records

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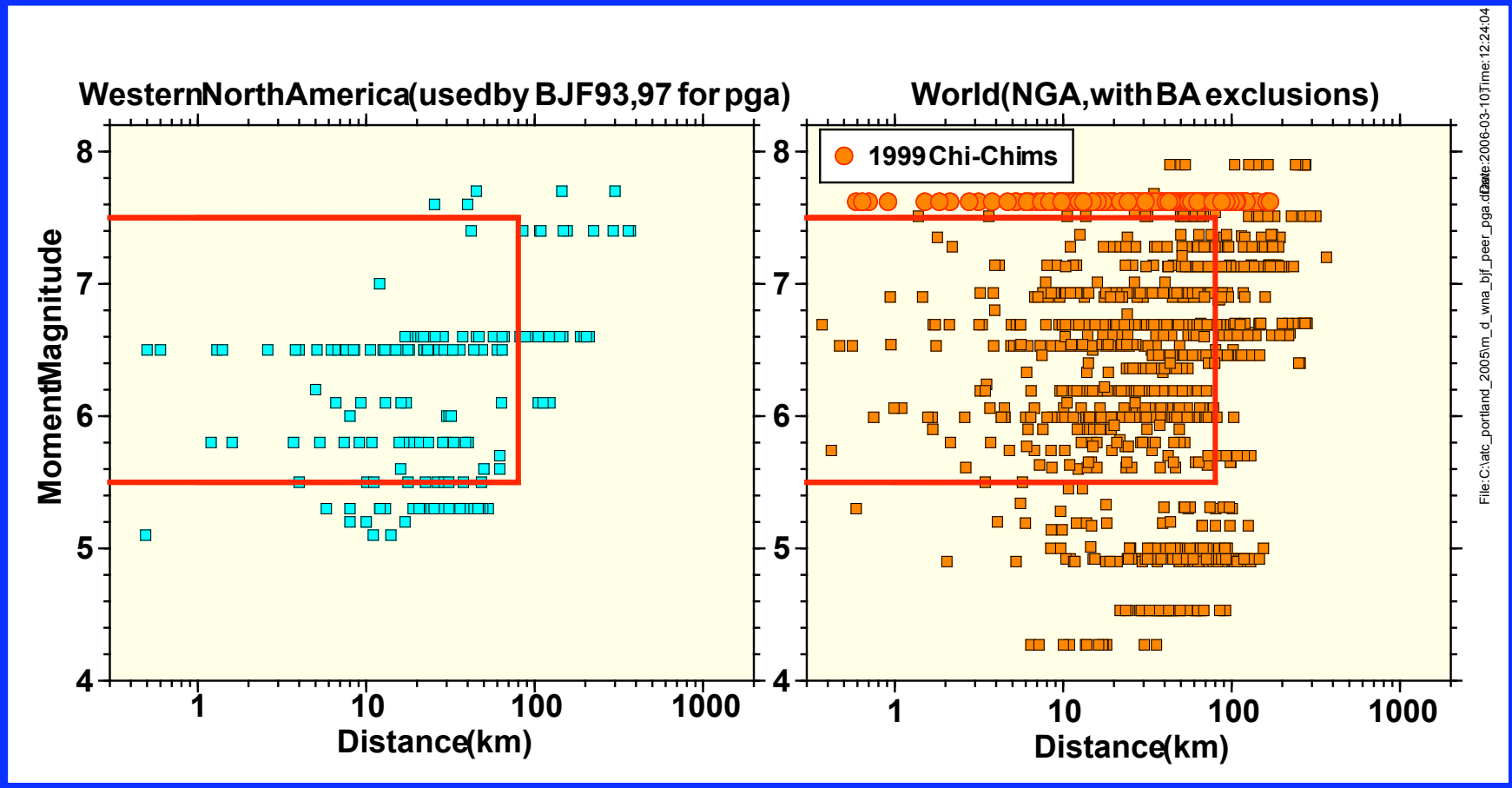
For PGA



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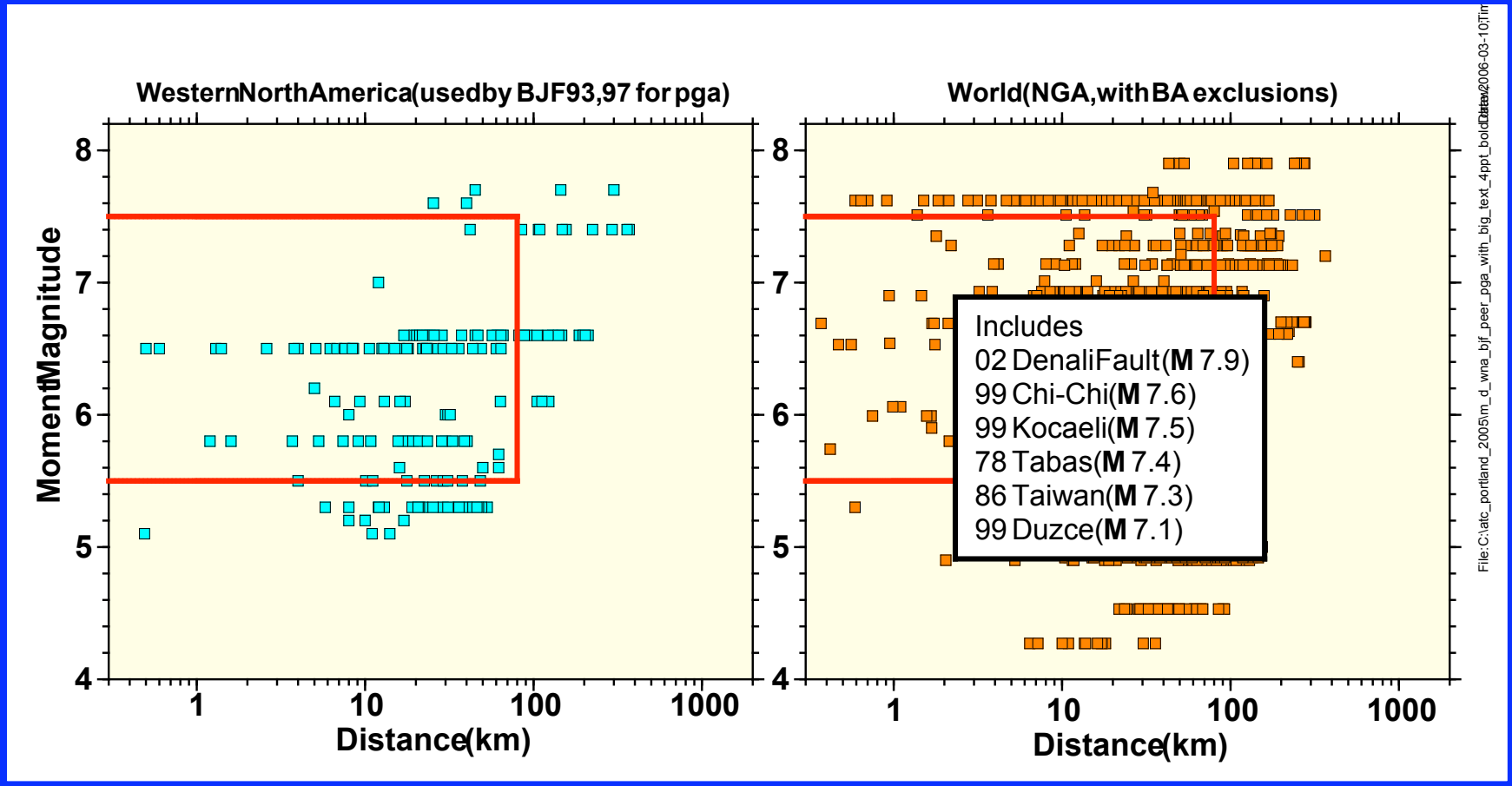

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Some earthquakes not included:

1987 Elmore Ranch, CA (add USGS data)

1992 Cape Mendocino, CA (add USGS data)

1997 Umbria-Marche, Italy, events

2002 Molise, Italy

2003 Zemmouri, Algeria (**M** 6.8)

2003 San Simeon, CA (**M** 6.4)

2003 Bam, Iran (**M** 6.5)

2004 Parkfield, CA (**M** 6.0)

2004 Chuetsu, Japan (**M** 6.6 + AS)

2005 Zarand, Iran (**M** 6.3)

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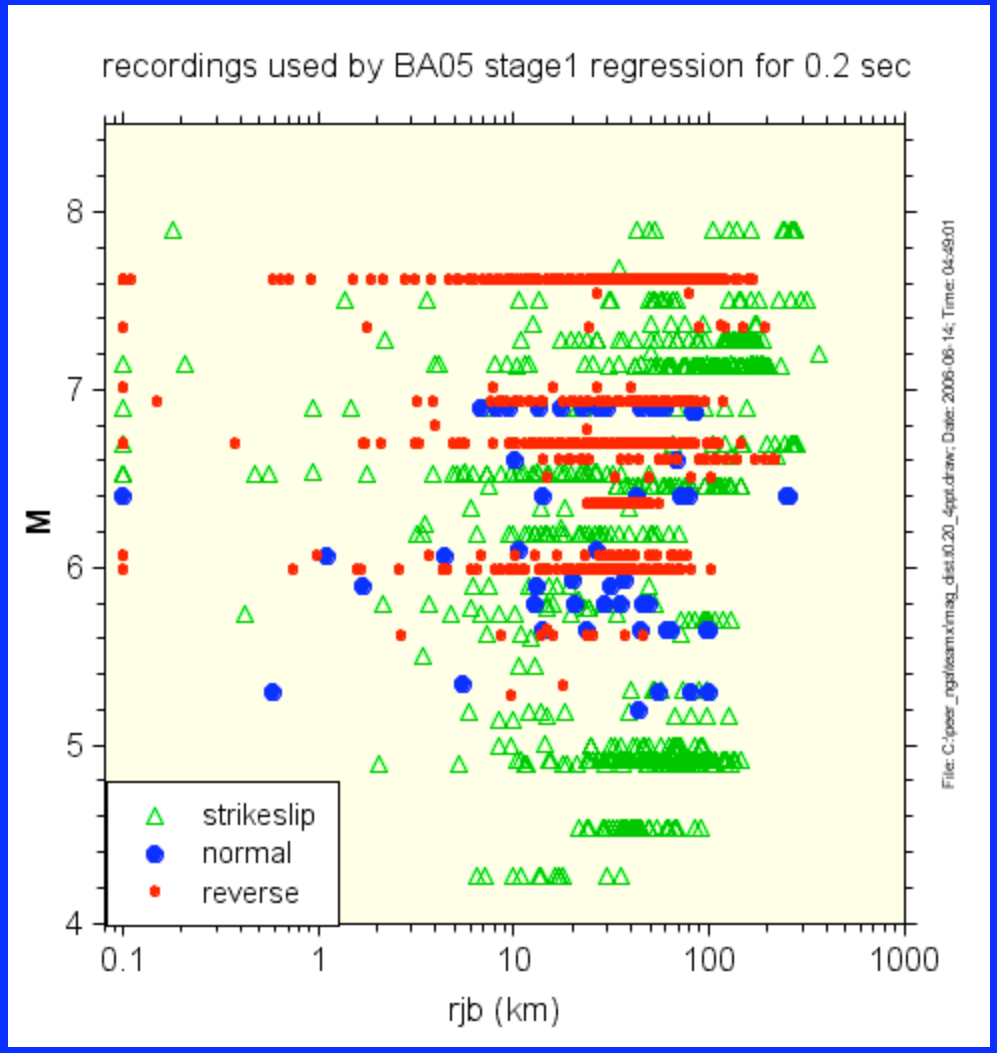
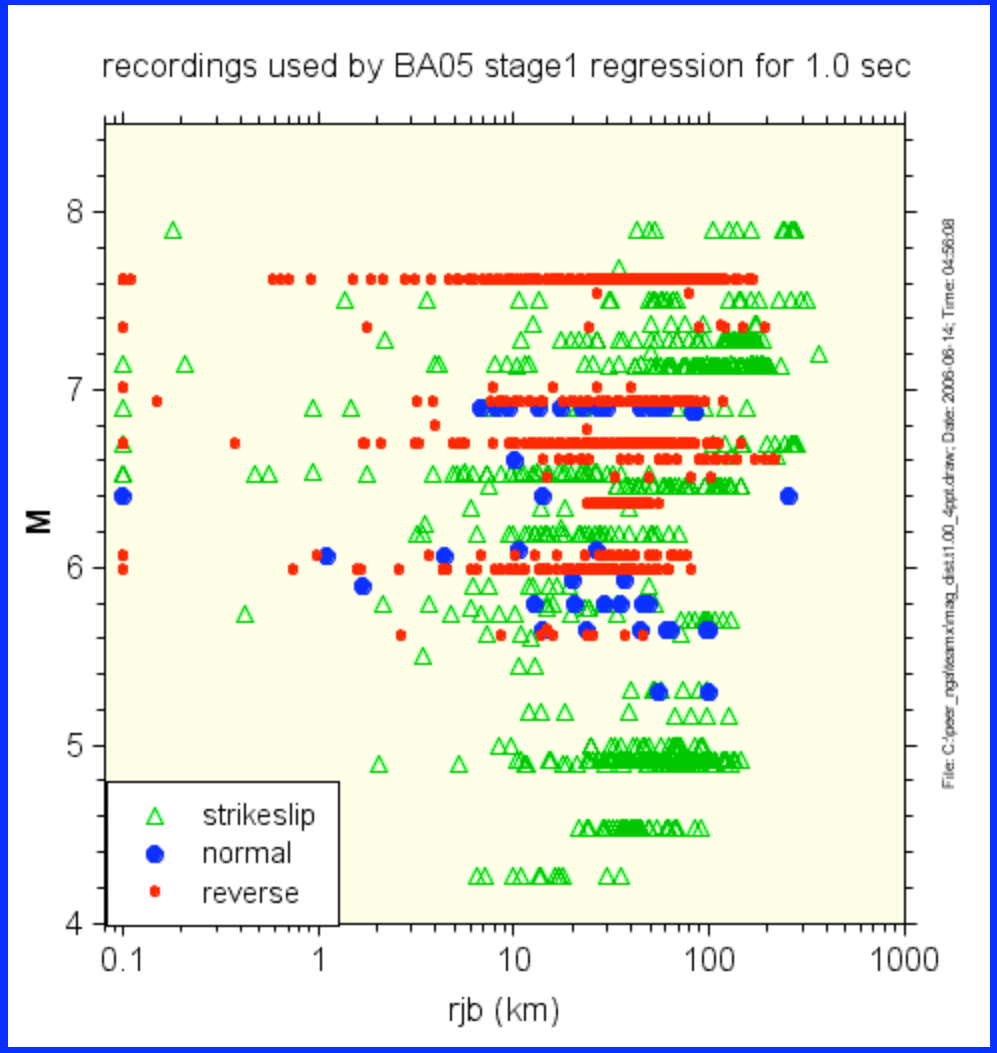

recordings used by BA05 stage1 regression for 0.2 sec
M
8
7
6
5
4
0.1
1
10
100
1000
rjb (km)
strikeslip
normal
reverse



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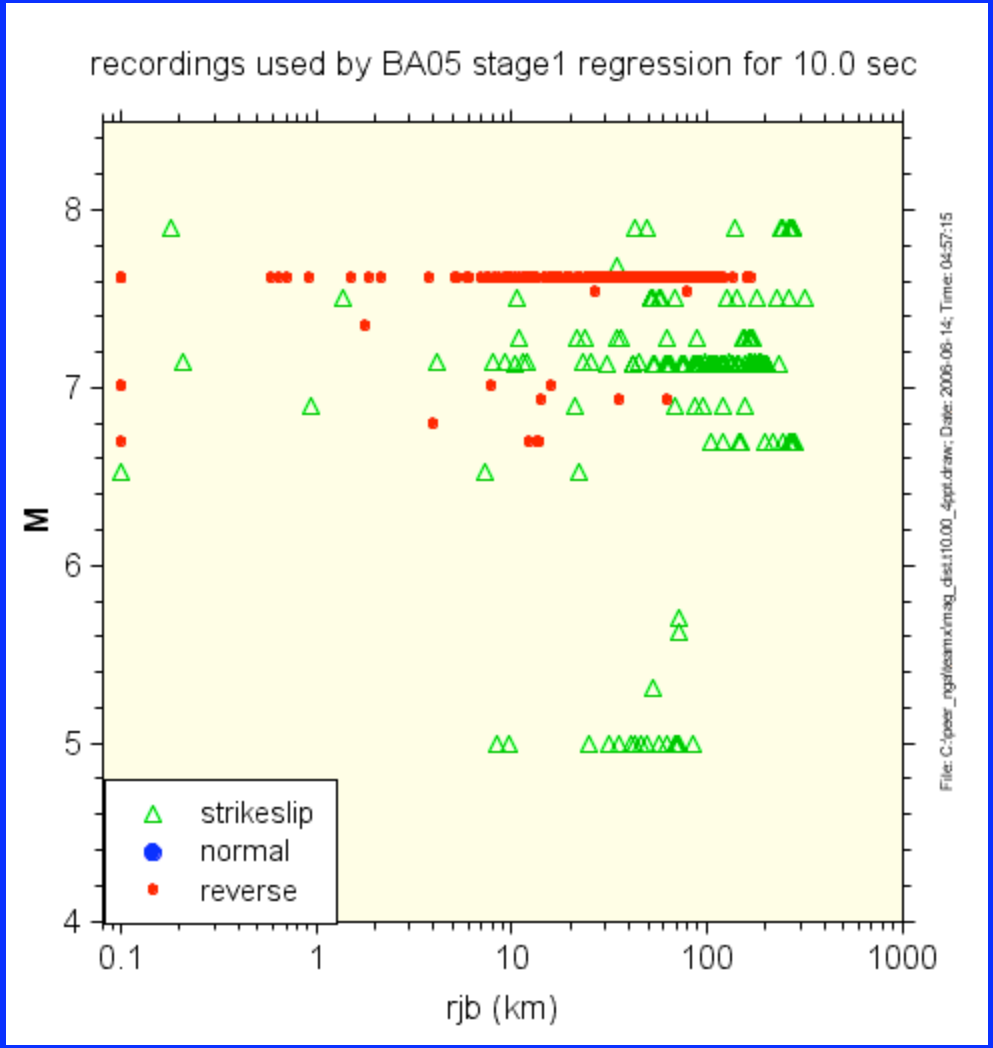

Not used yet, but available for use.

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Network ("broadband") data largely ignored as a source of ground-motion data, but can be very useful to determine path characteristics

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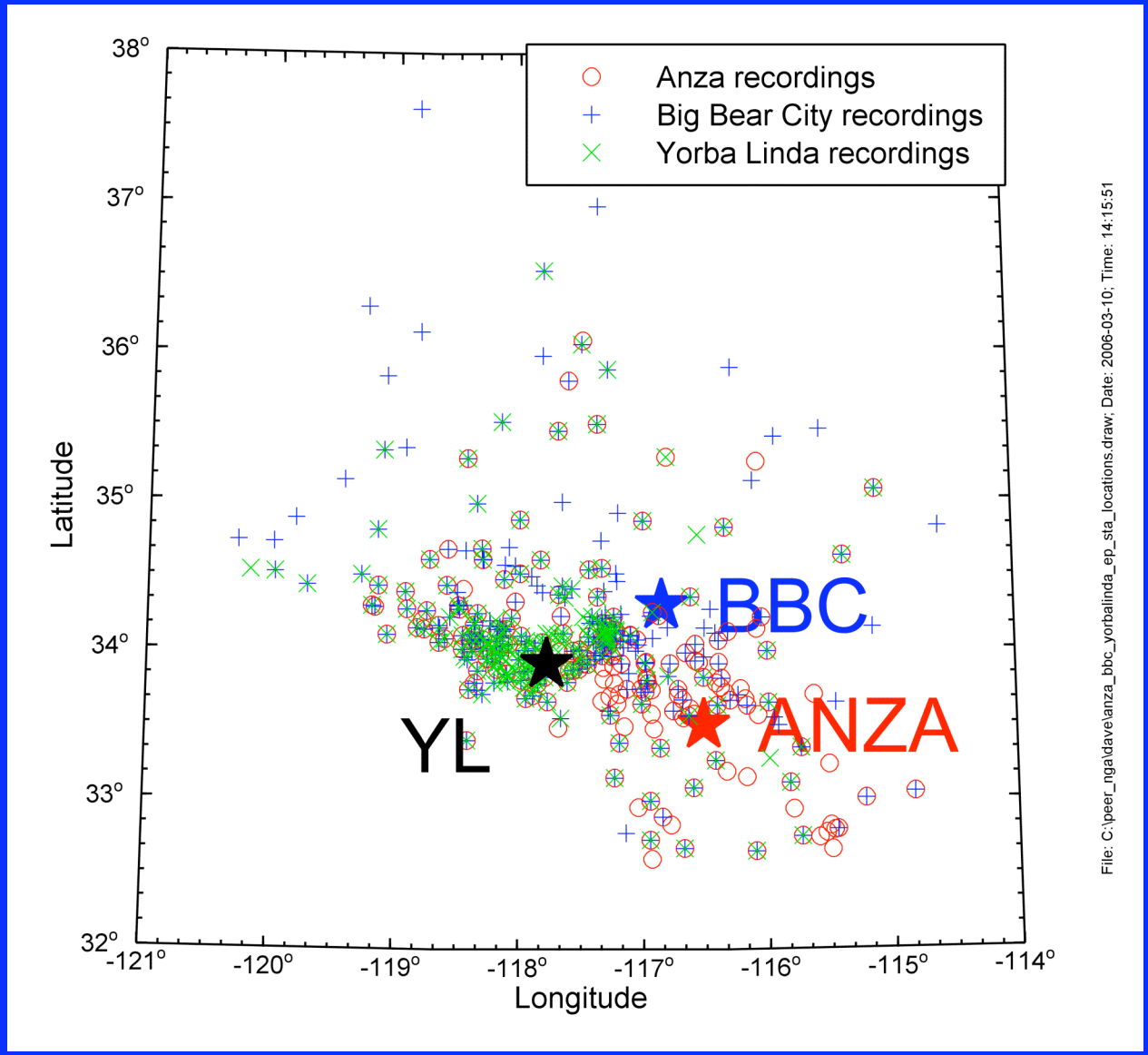

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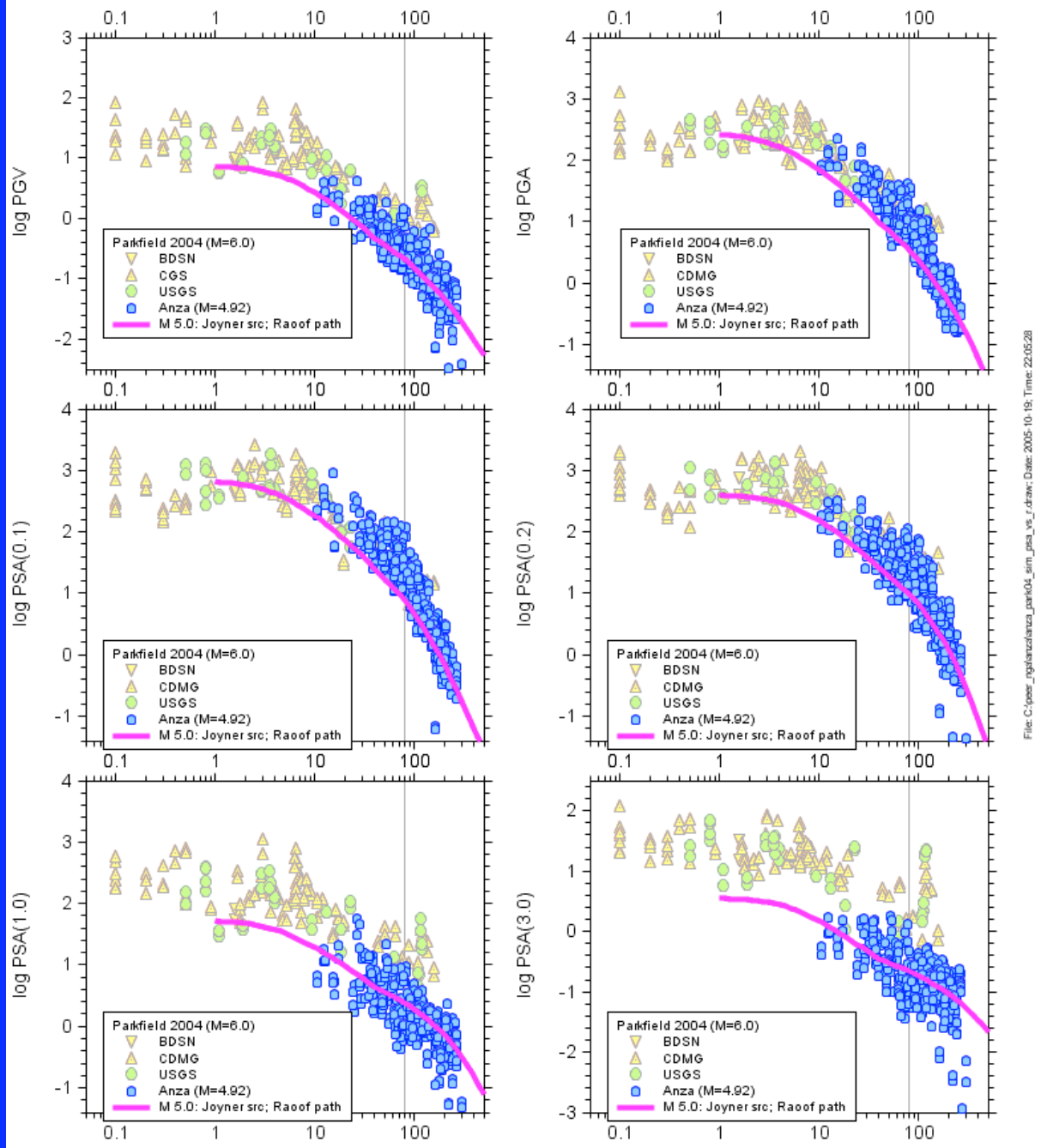

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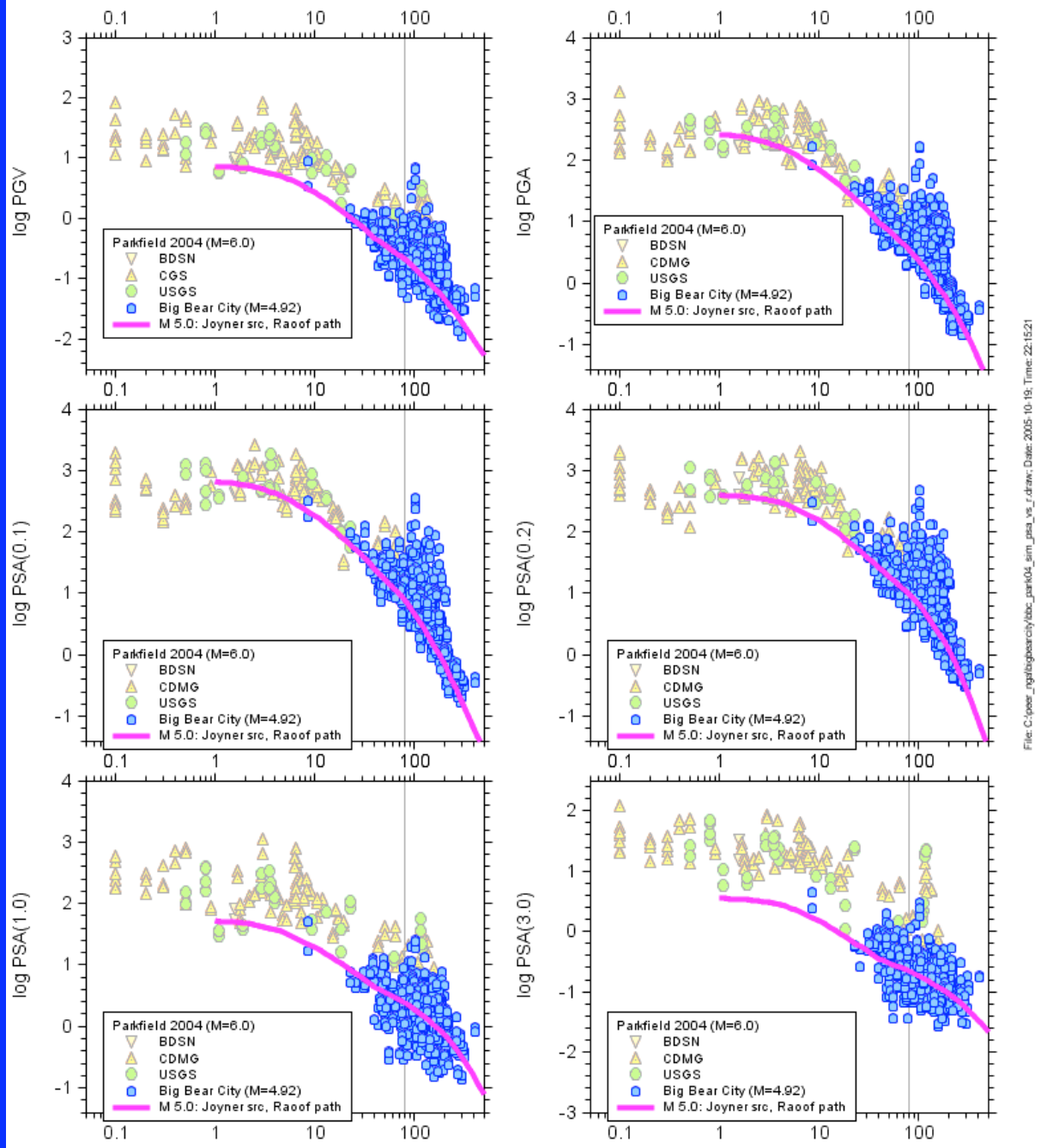

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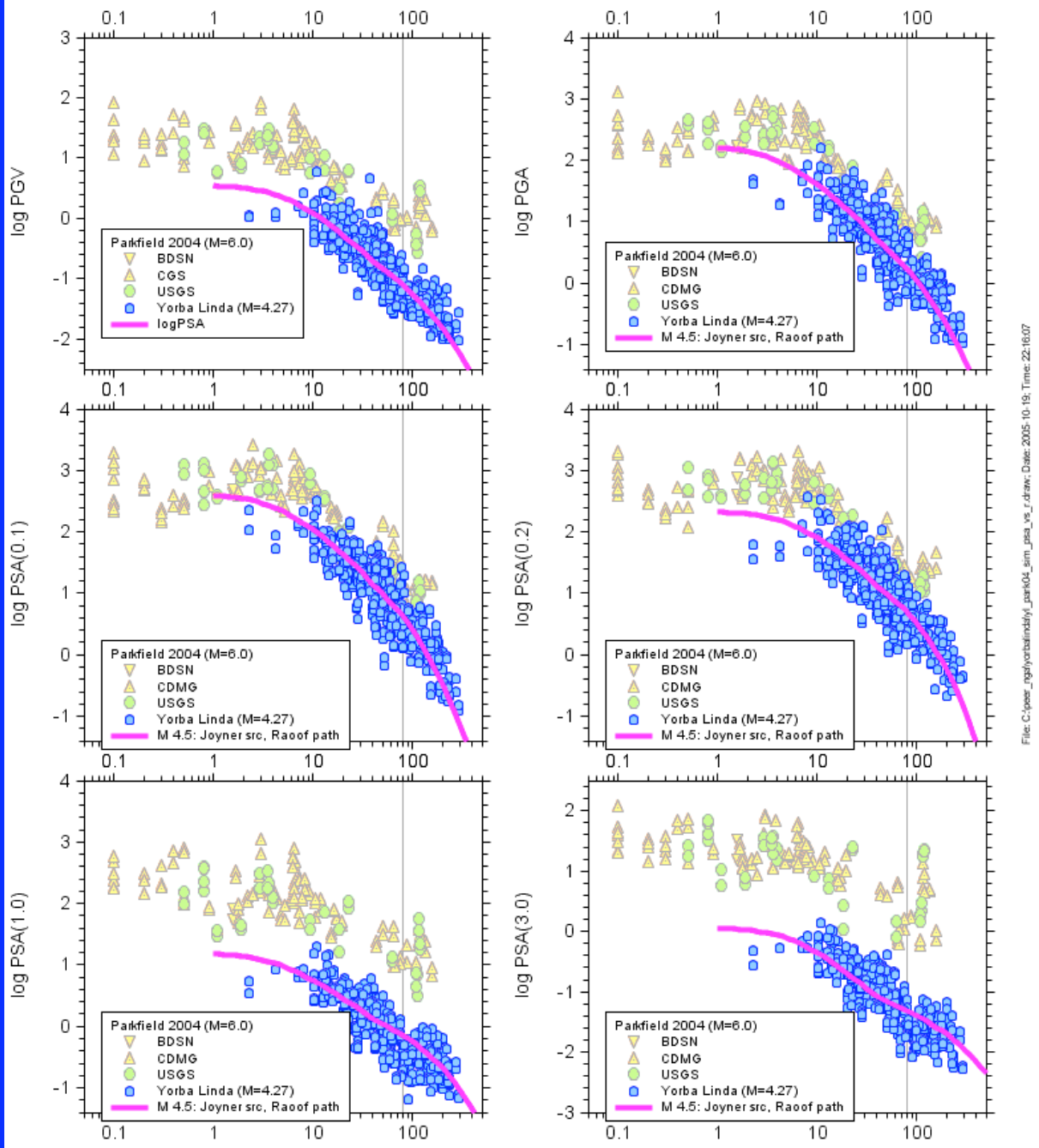

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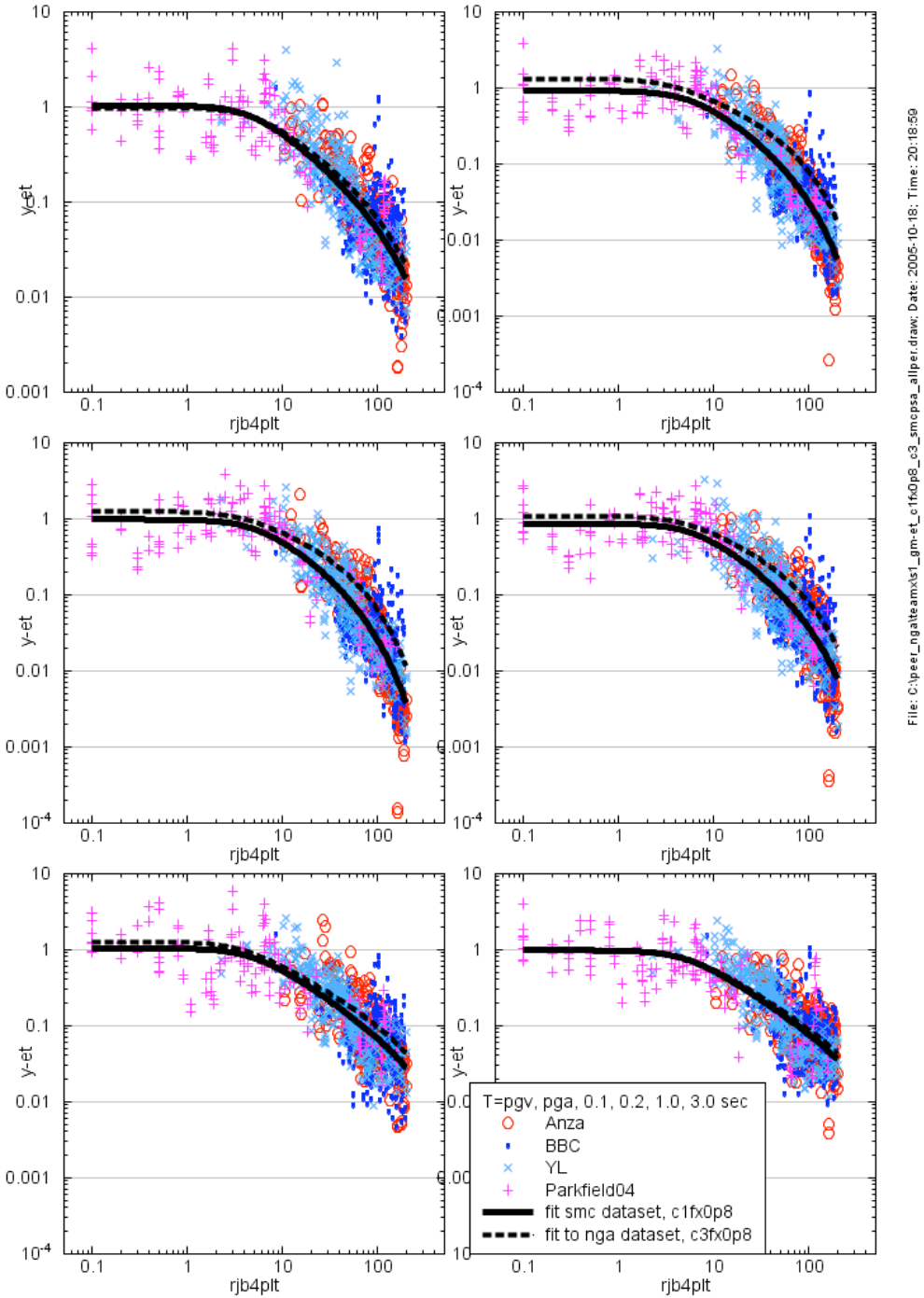
Use data to constrain anelastic attenuation coefficient



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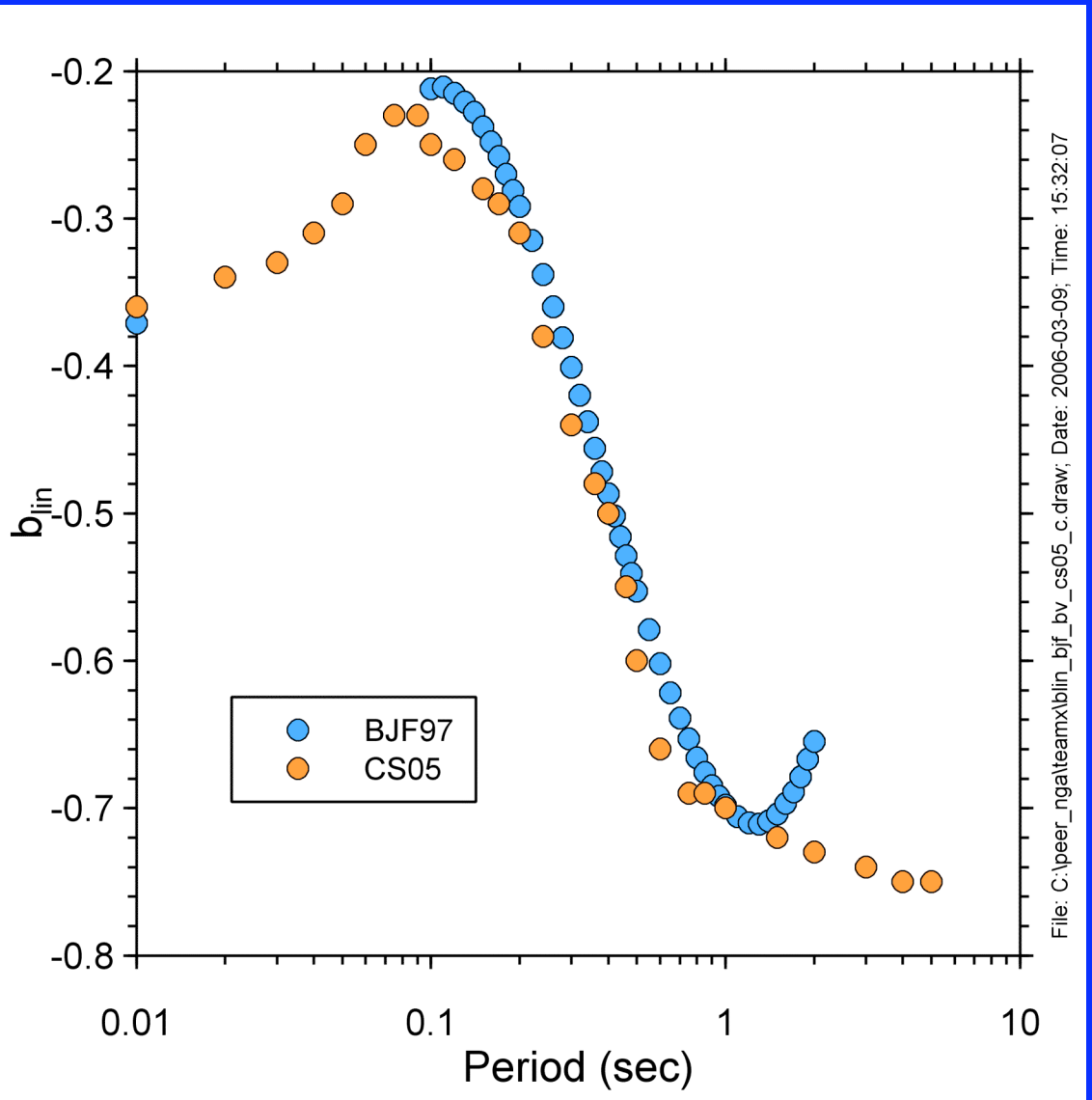

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$$V_{30} \leq v_1$$

$$b_{nl} = b_1$$

$$v_1 < V_{30} \leq v_2$$

$$b_{nl} = (b_1 - b_2)\ln(V_{30} / v_2) / \ln(v_1 / v_2) + b_2$$

$$v_2 < V_{30} \leq v_{ref}$$

$$b_{nl} = b_2 \ln(V_{30} / v_{ref}) / \ln(v_2 / v_{ref})$$

$$v_{ref} < V_{30}$$

$$b_{nl} = 0.0$$

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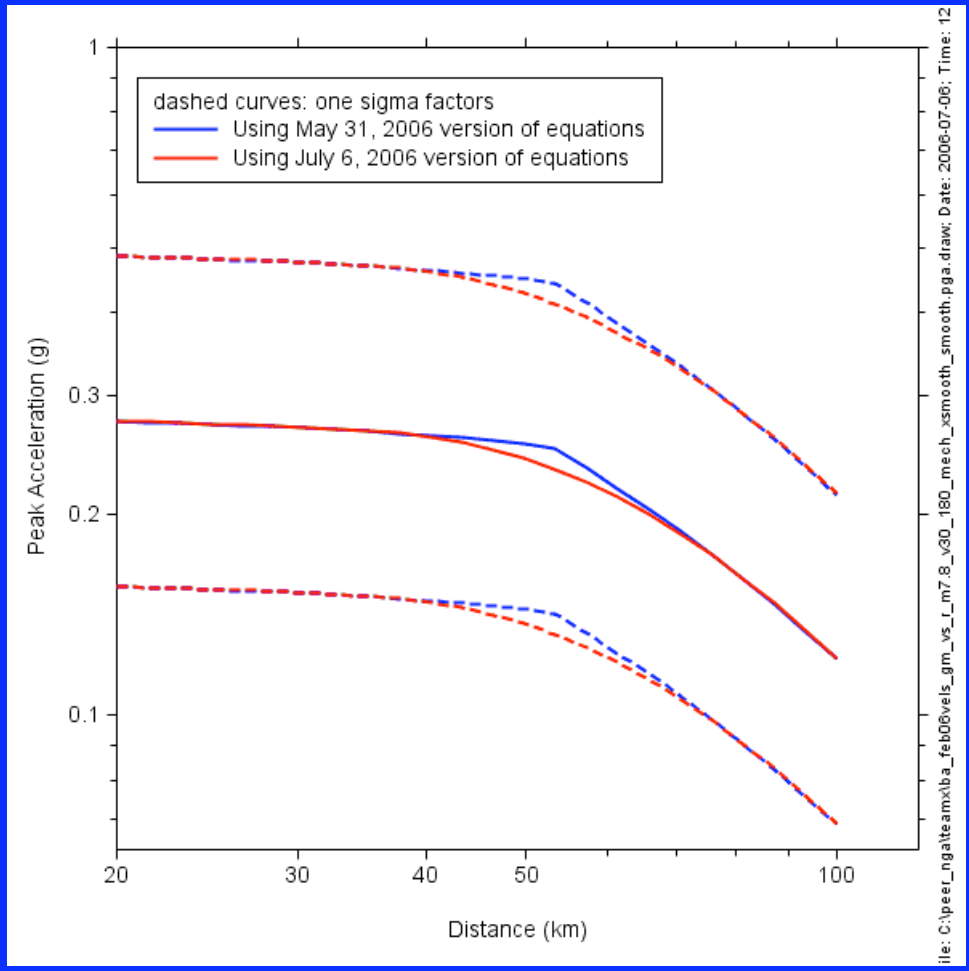
July, 2006 change: smooth transition from linear to nonlinear amps



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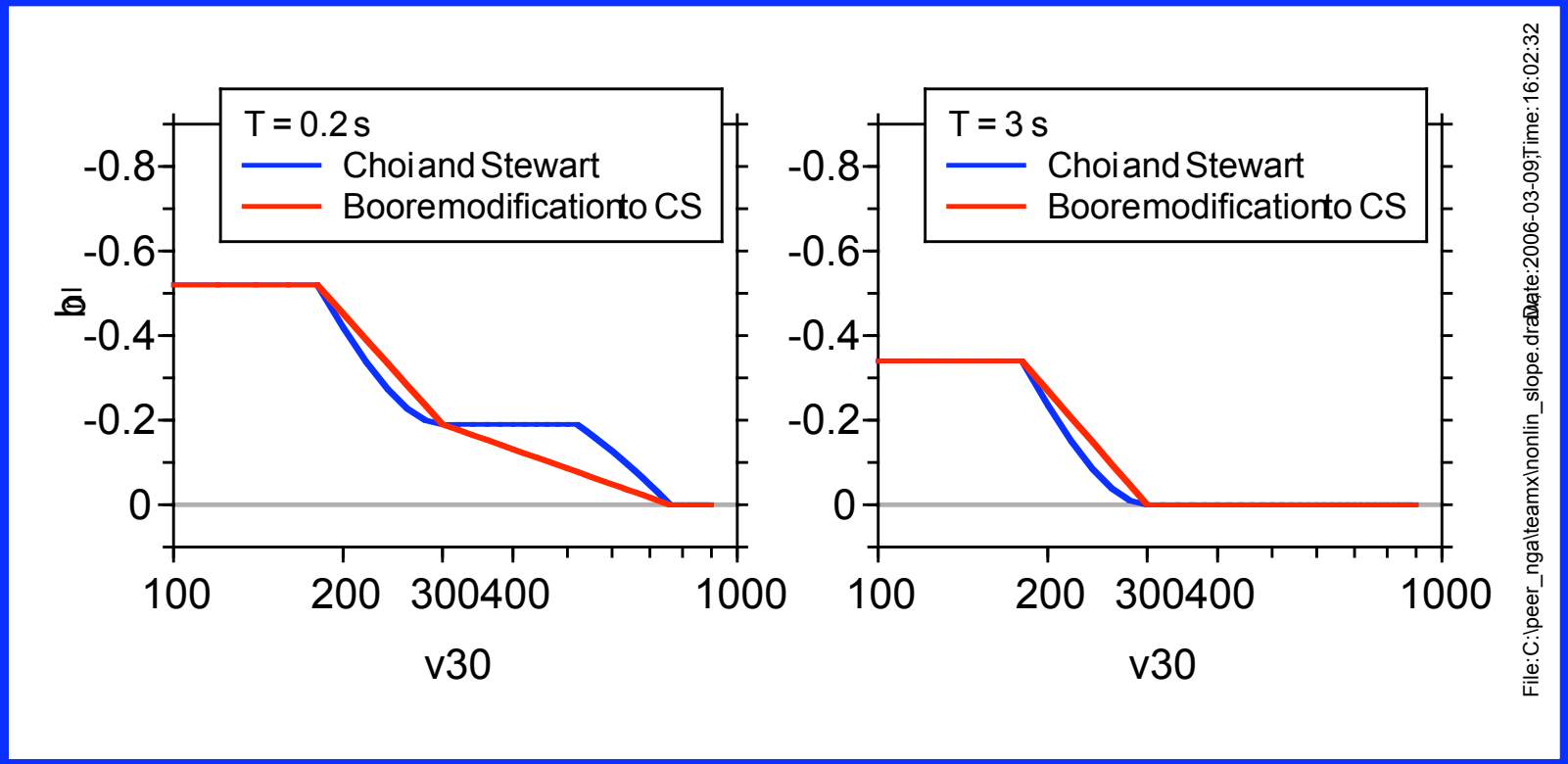
T = 0.2 s
Choi and Stewart
Boore modification to CS
-0.8
-0.6
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0
100
200
300
400
1000
v30
T = 3 s
Choi and Stewart
Boore modification to CS
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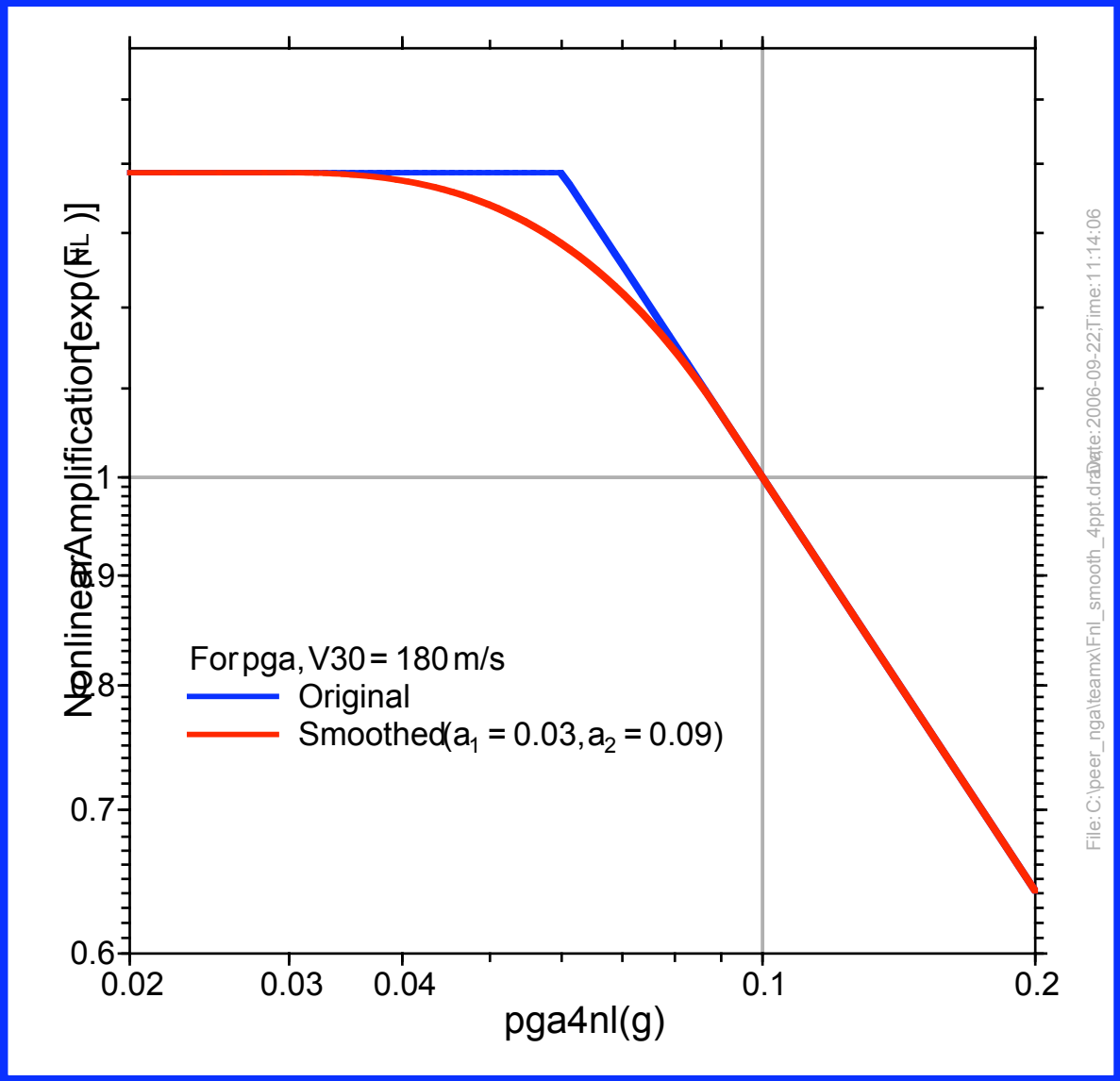
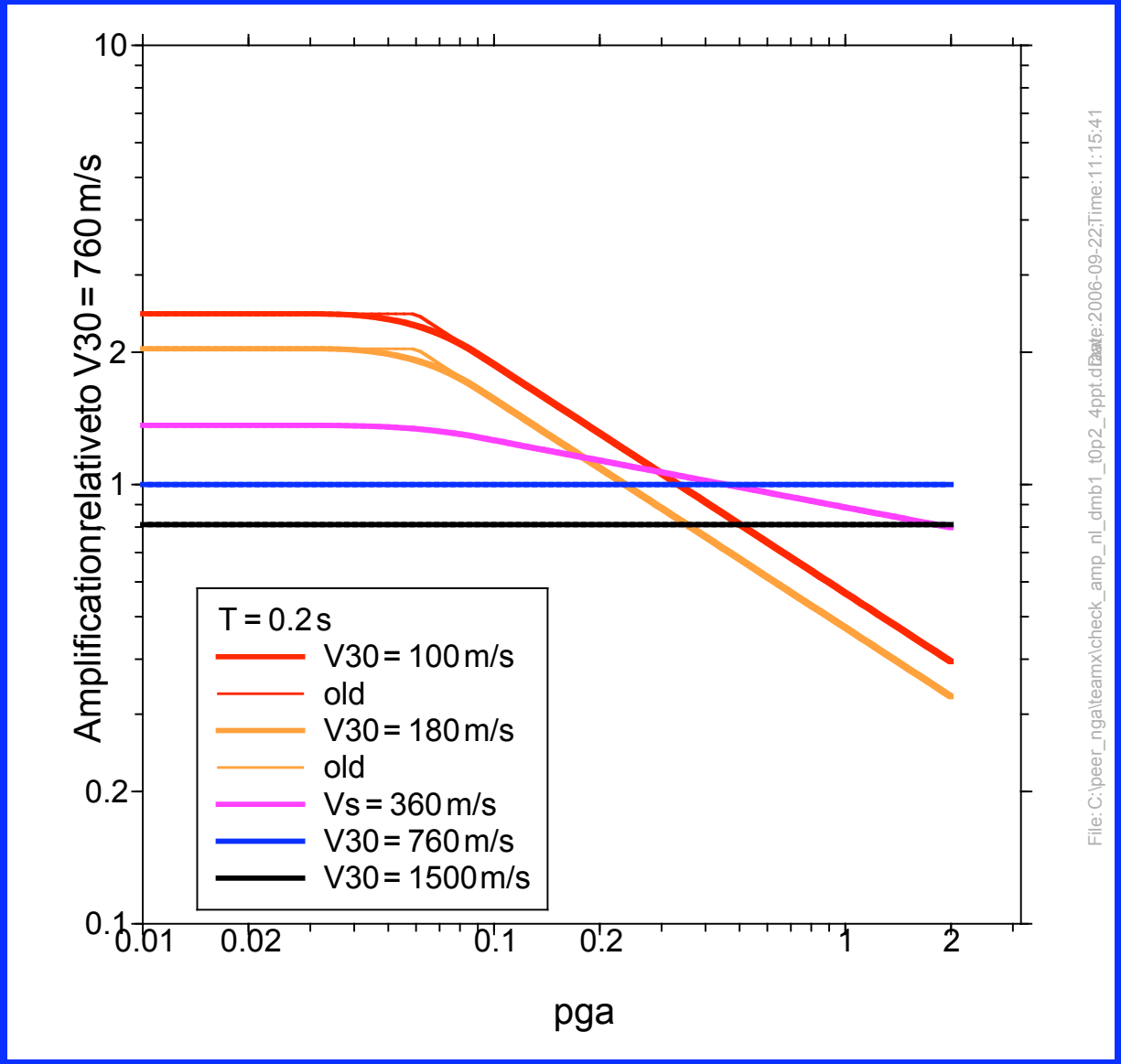
-0.6
-0.4
-0.2
0
100
200
300
400
1000
v30
File:C:\peer_ngalteamx\nonlin_slope.drw Date:2006-03-09 Time:16:02:32

Change in July, 2006, version





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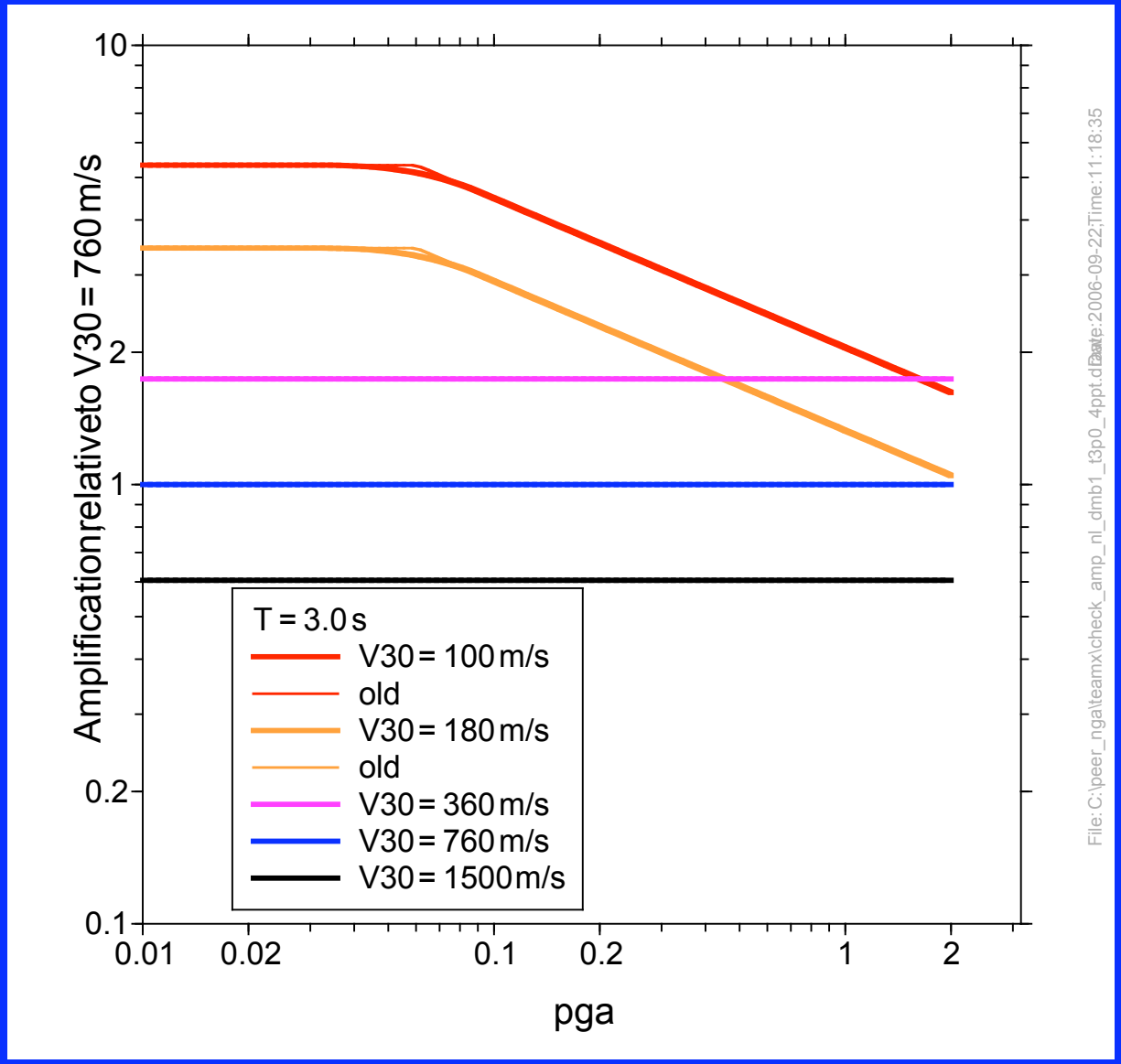

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The analysis used the two-stage regression discussed by Joyner and Boore (1993, 1994). All regressions were done period-by-period; there was no smoothing of coefficients.

The NGA data were first adjusted for linear and nonlinear site amplification to a v30 values of 760 m/s, using FS above.

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The First Regression Stage: Distance dependence:

$$F_D(r_{jb}, \mathrm{M}) = [c_1 + c_2(\mathrm{M} - M_{ref})]\ln(r / r_{ref}) + [c_3 + c_4(\mathrm{M} - M_{ref})](r - r_{ref})$$

where

$$r = \sqrt{r_{jb}^{\ 2} + h^2}$$

C_3 from analysis of augmented dataset
C_4 = 0 to avoid increasing FD with distance in some cases

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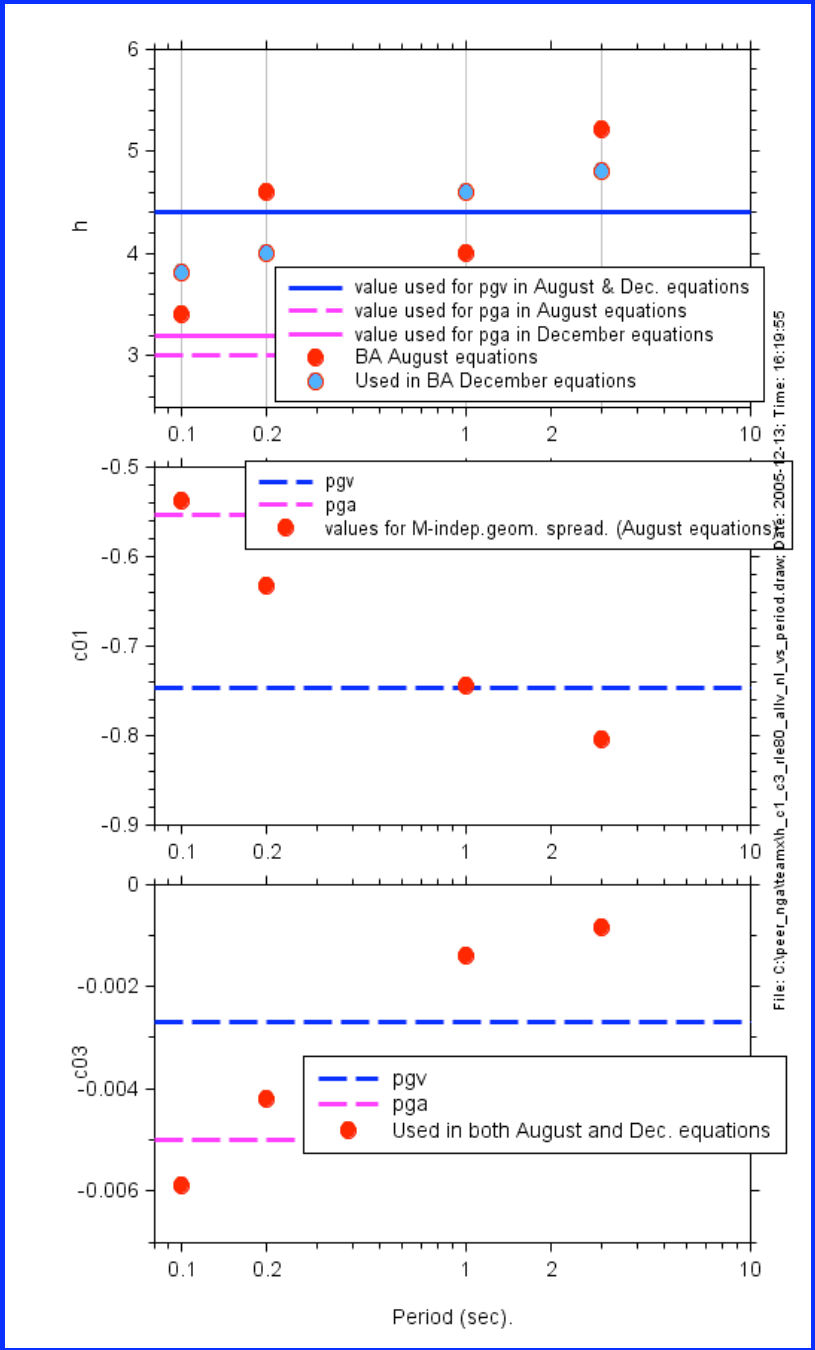
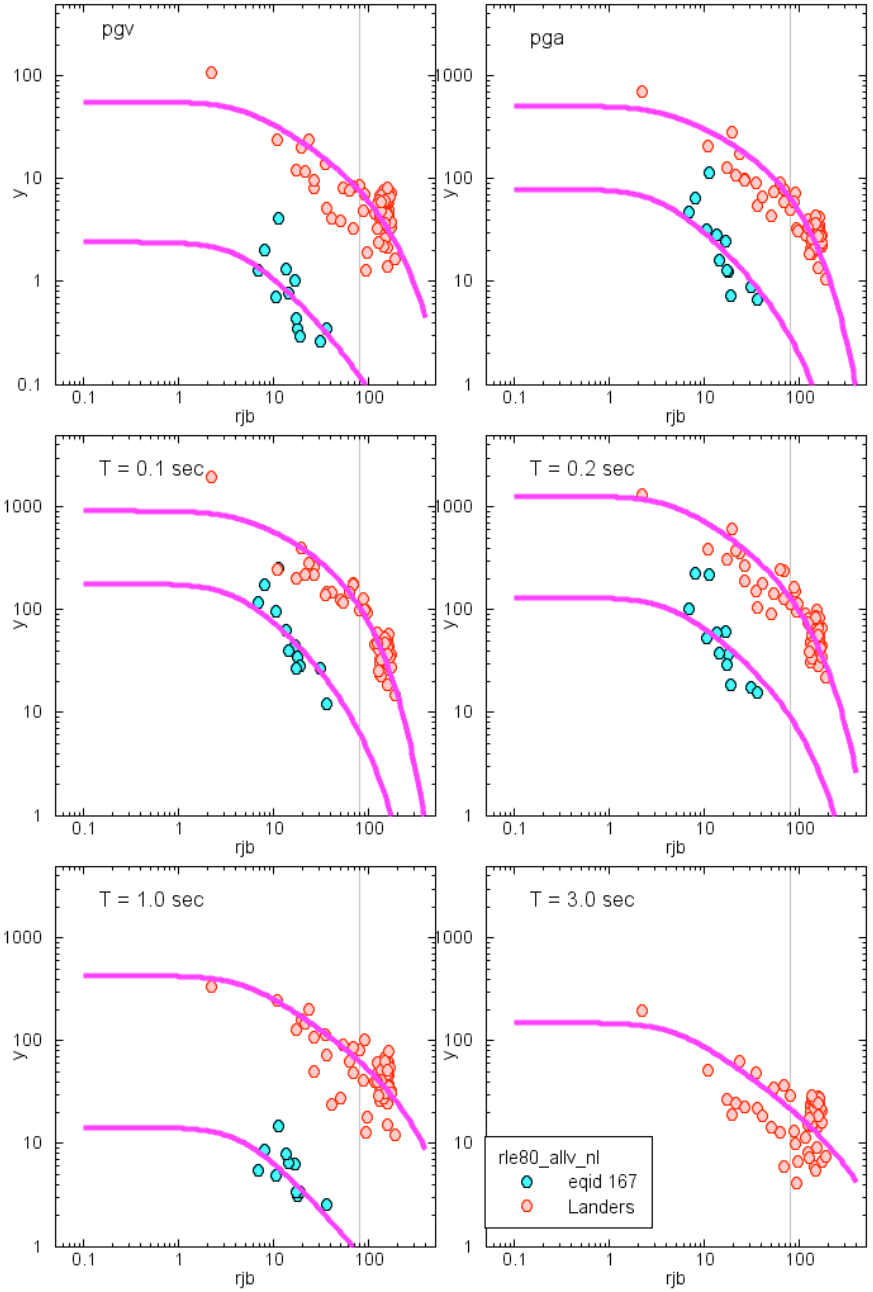
The final set of provisional equations were determined by fixing the pseudodepth h at slightly smoothed versions of those given in an earlier study (August 2005), with only c1 and c2 as free regression coefficients for the stage1 regression (in addition to event terms, which are basically the average ground motions for a single event projected to a distance of rref).

NOTE: Gspread < -1!



New (M-dependent distance dependence)



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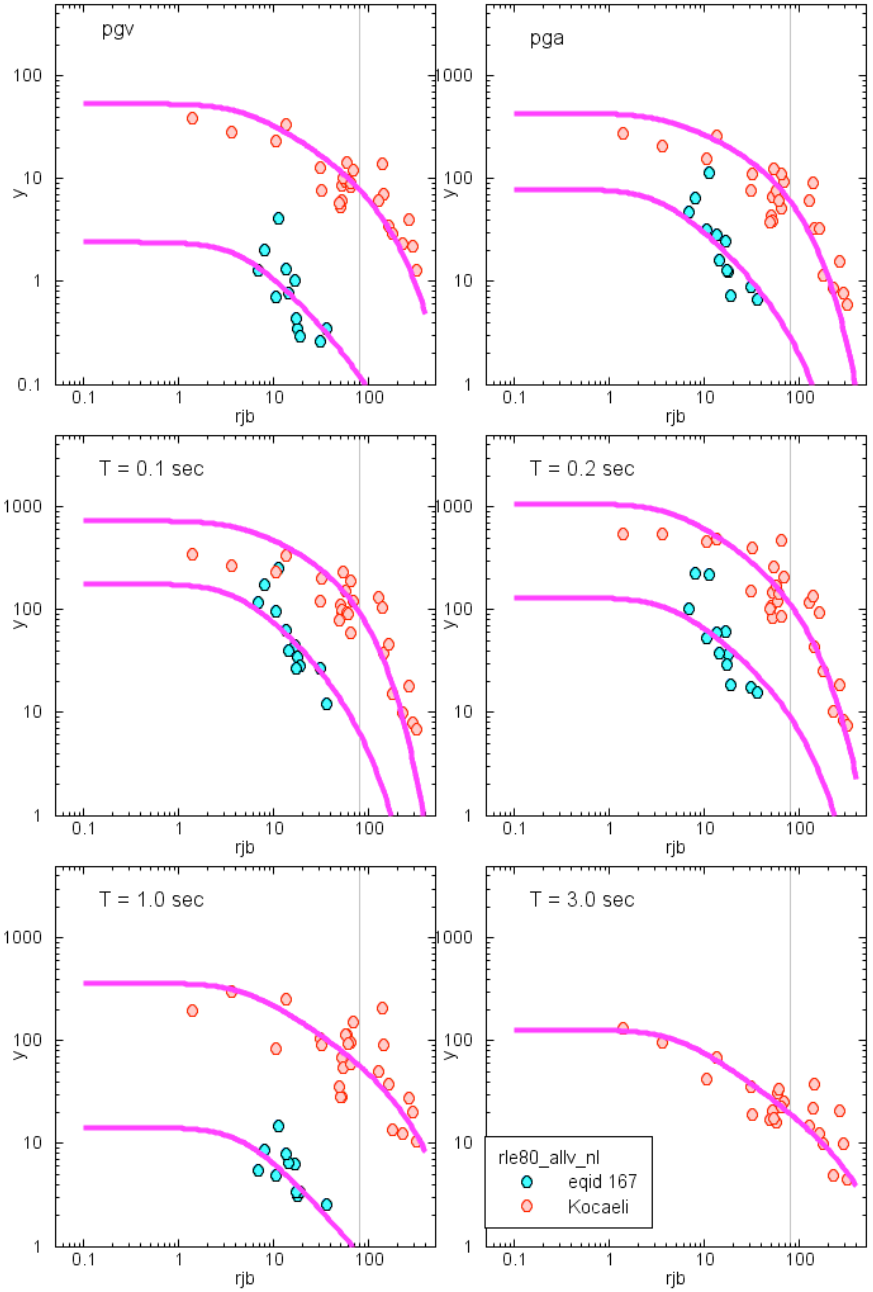
New (M-dependent distance dependence)



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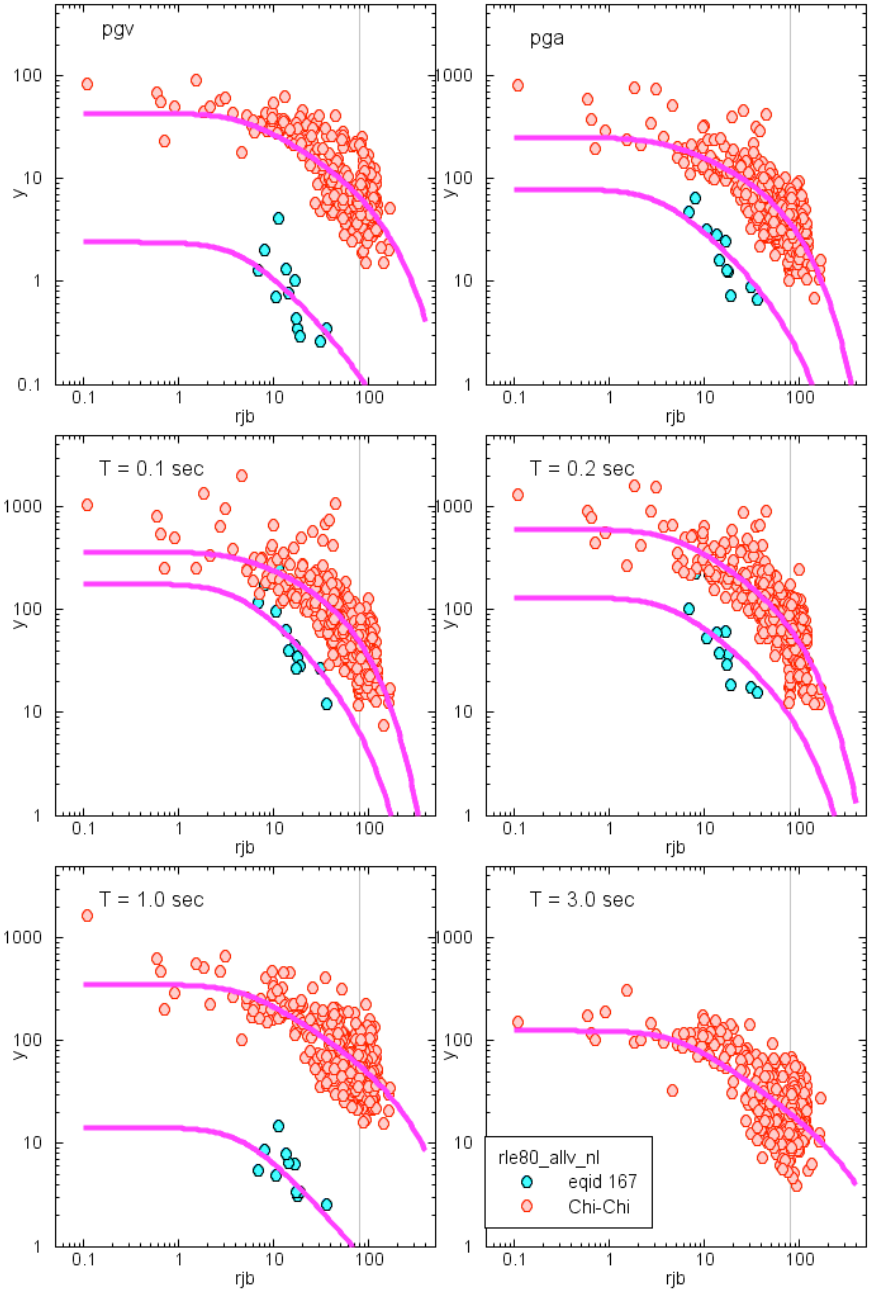

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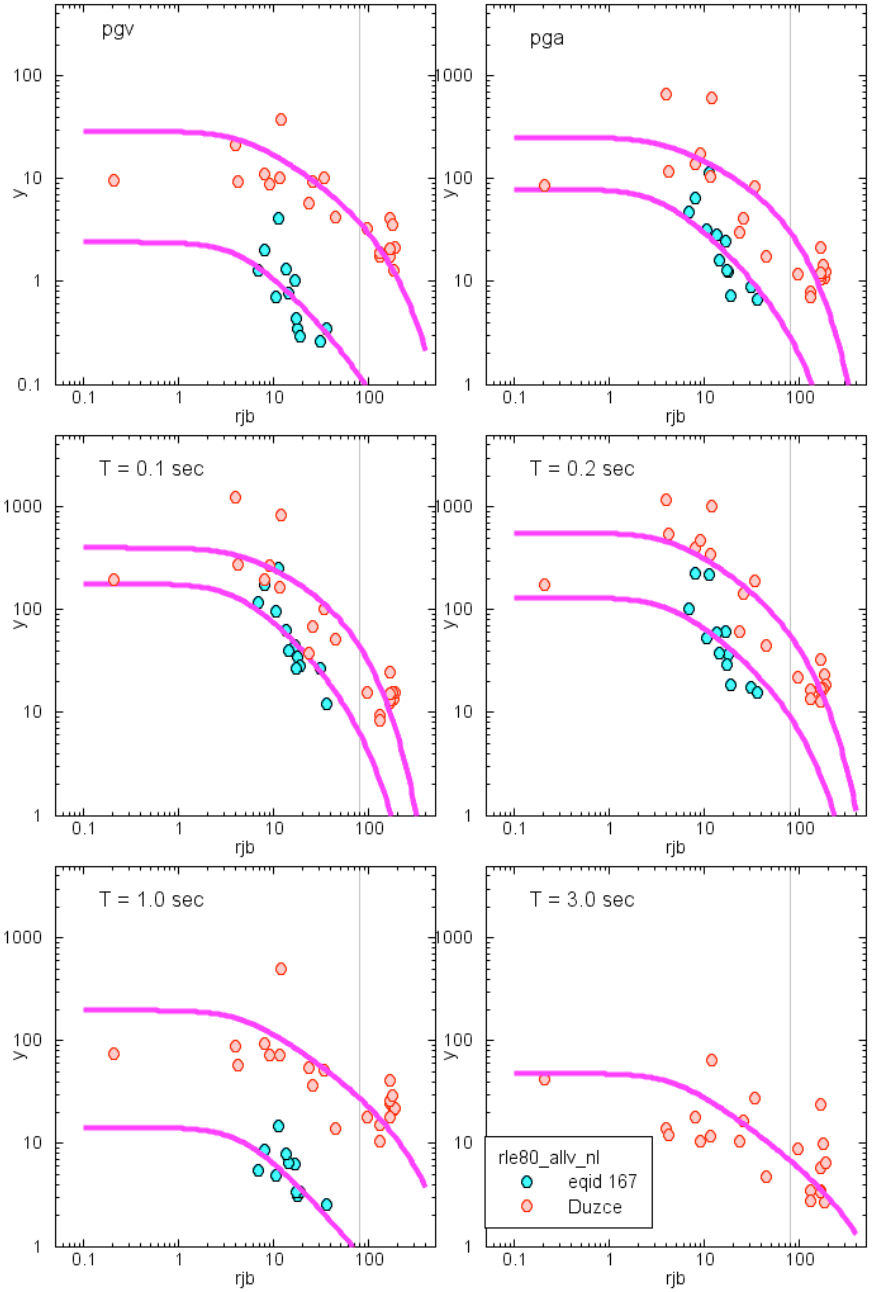

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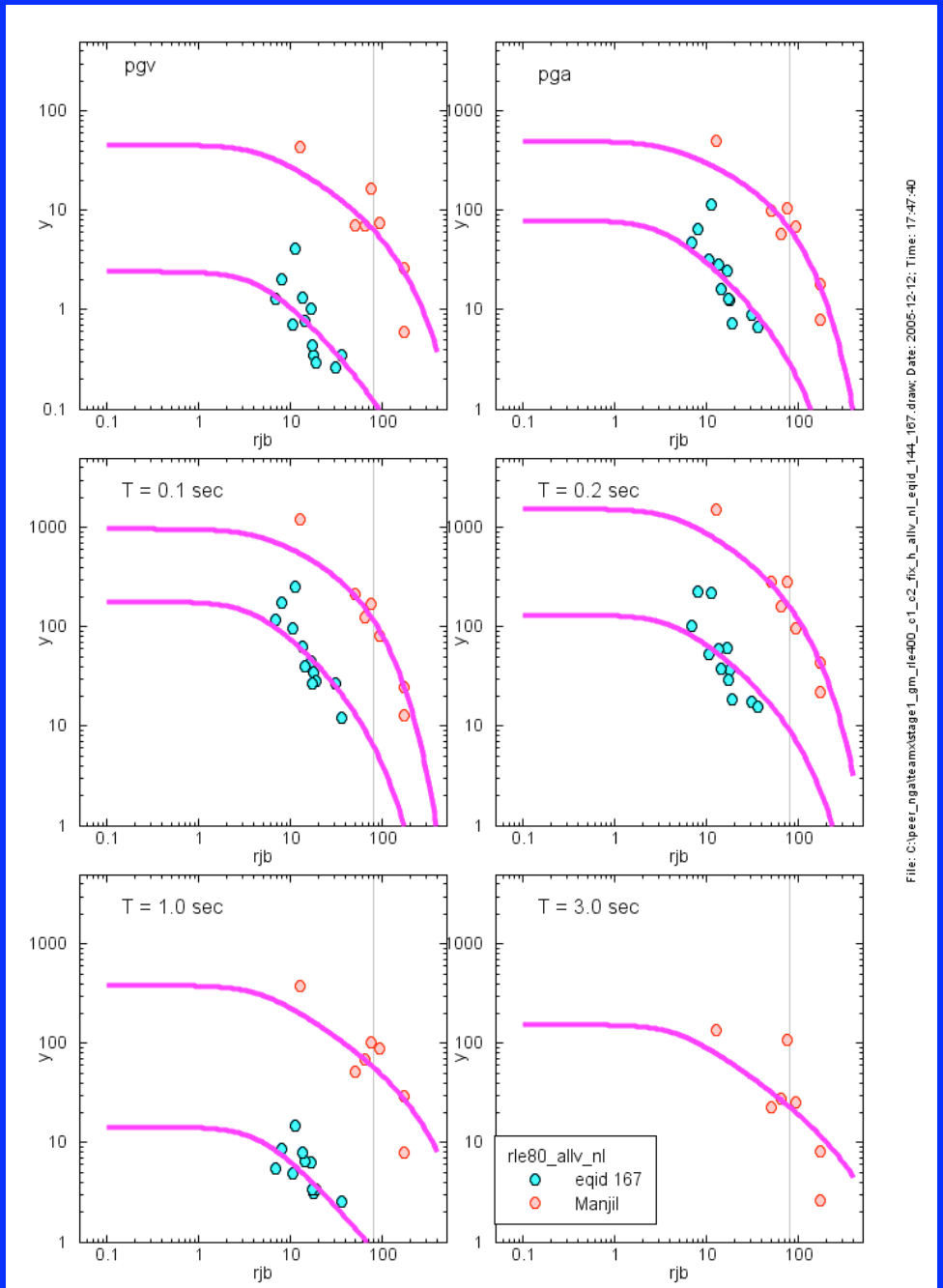

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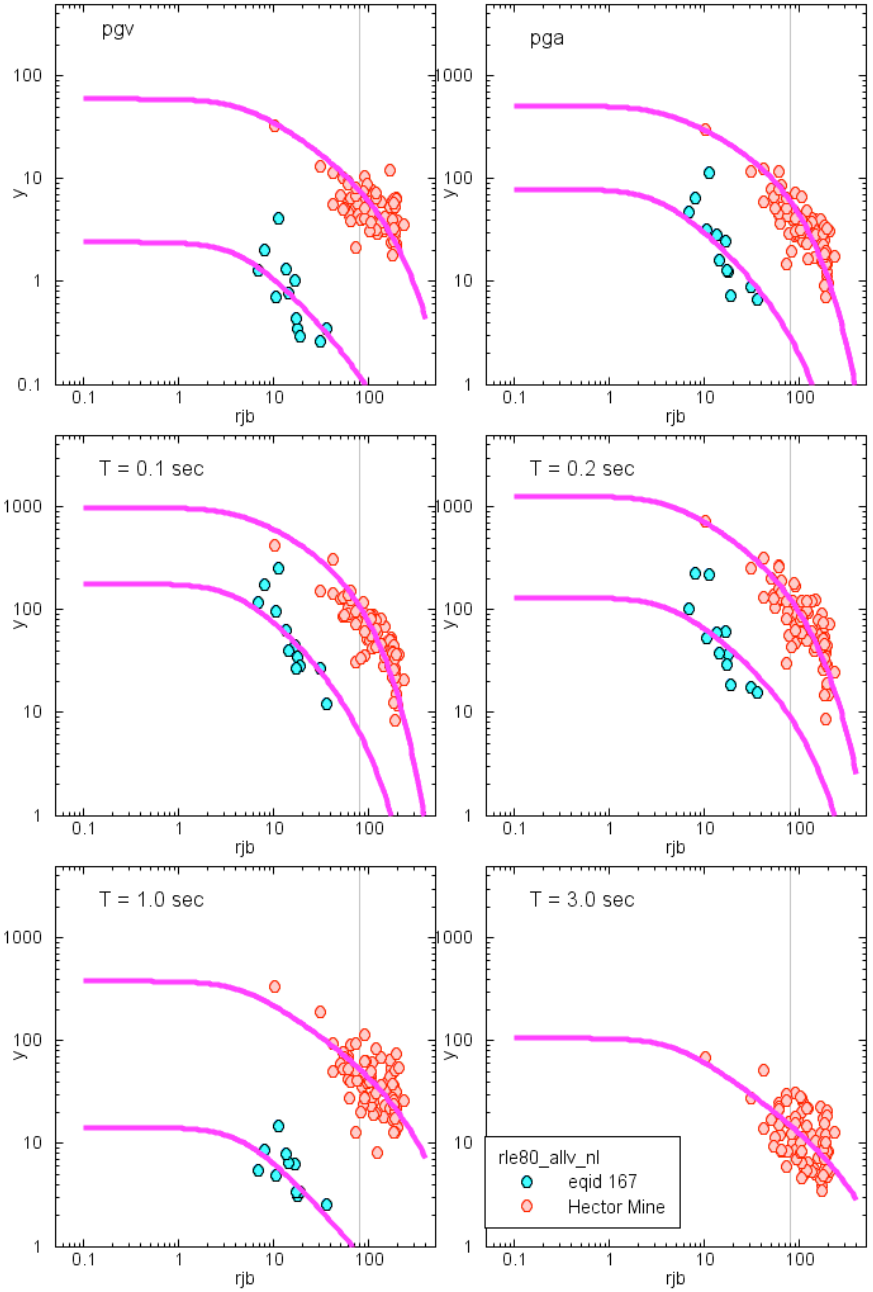

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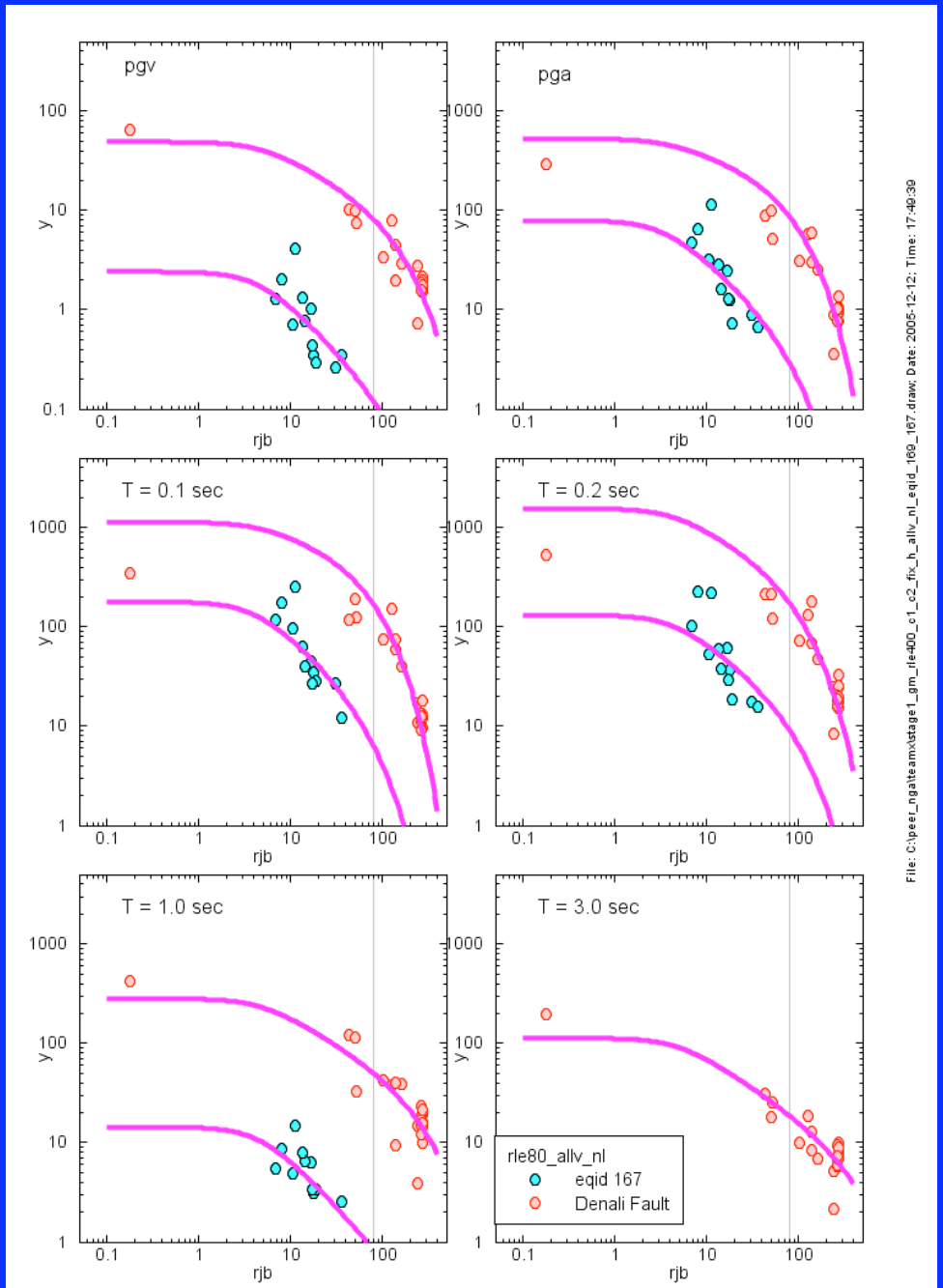
New (M-dependent distance dependence)



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The event terms from the first regression were used in a weighted stage2 regression. As discussed in Joyner and Boore (1993), the stage2 regression was iterative in order to solve for σ_2. Only events with more than one observation were used in the regression. The following algorithm was used for the magnitude dependence:

Do a single quadratic fit. If the **M** for which the quadratic starts to decrease (**M**max) is greater than 8.5, use this regression for the magnitude dependence.

If **M**max is less than 8.5, then do a two-segment regression, hinged at **M**h, with a quadratic for **M** ≤ **M**h and a linear function for **M**h < M. If the slope of the linear function is positive, use this regression for the magnitude dependence. If the slope of the linear segment is negative, redo the regression constraining the slope of the line above **M**h to be 0.0.

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Magnitude Function

Motions Reduced to Reference Distance
(5 km)

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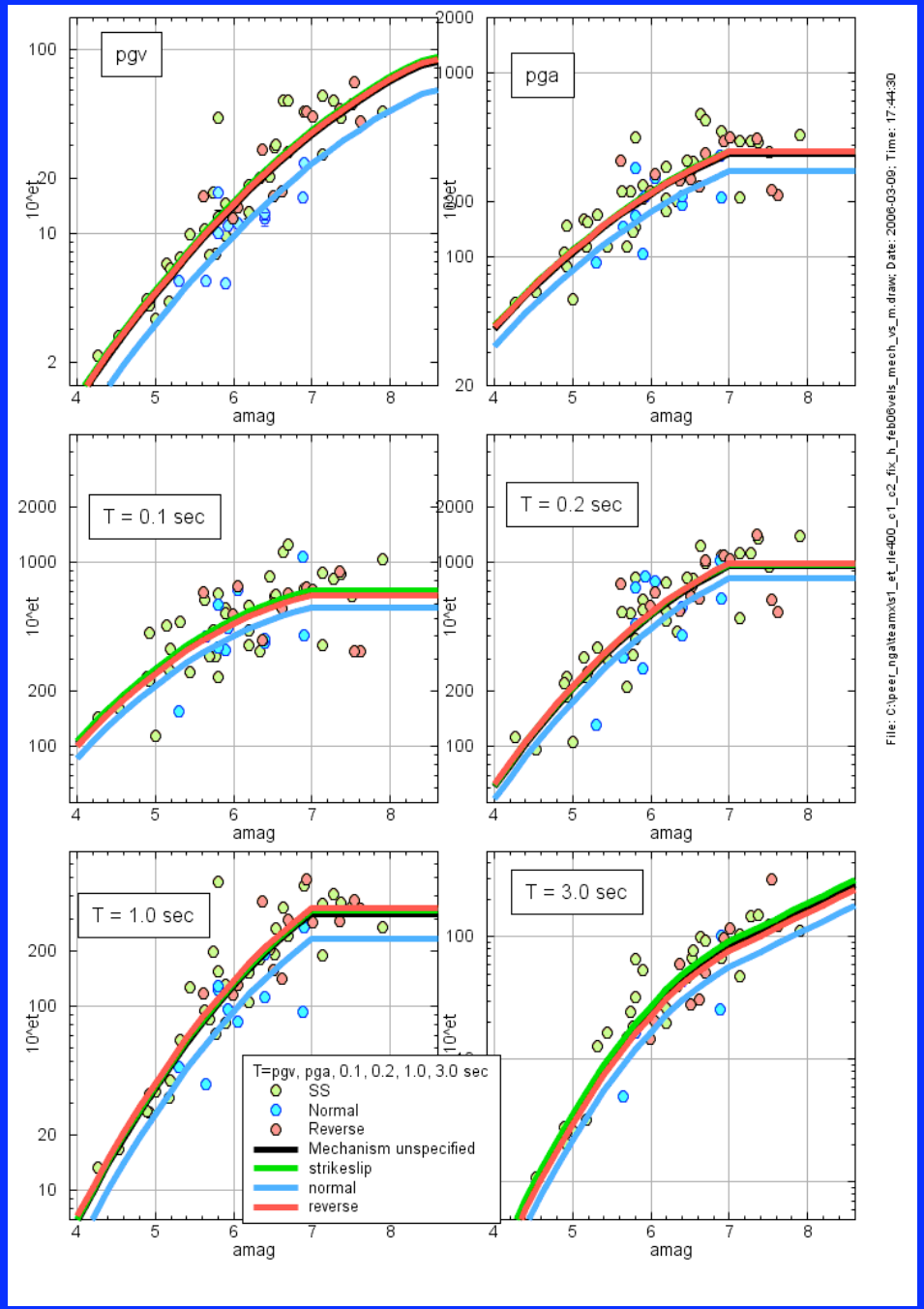

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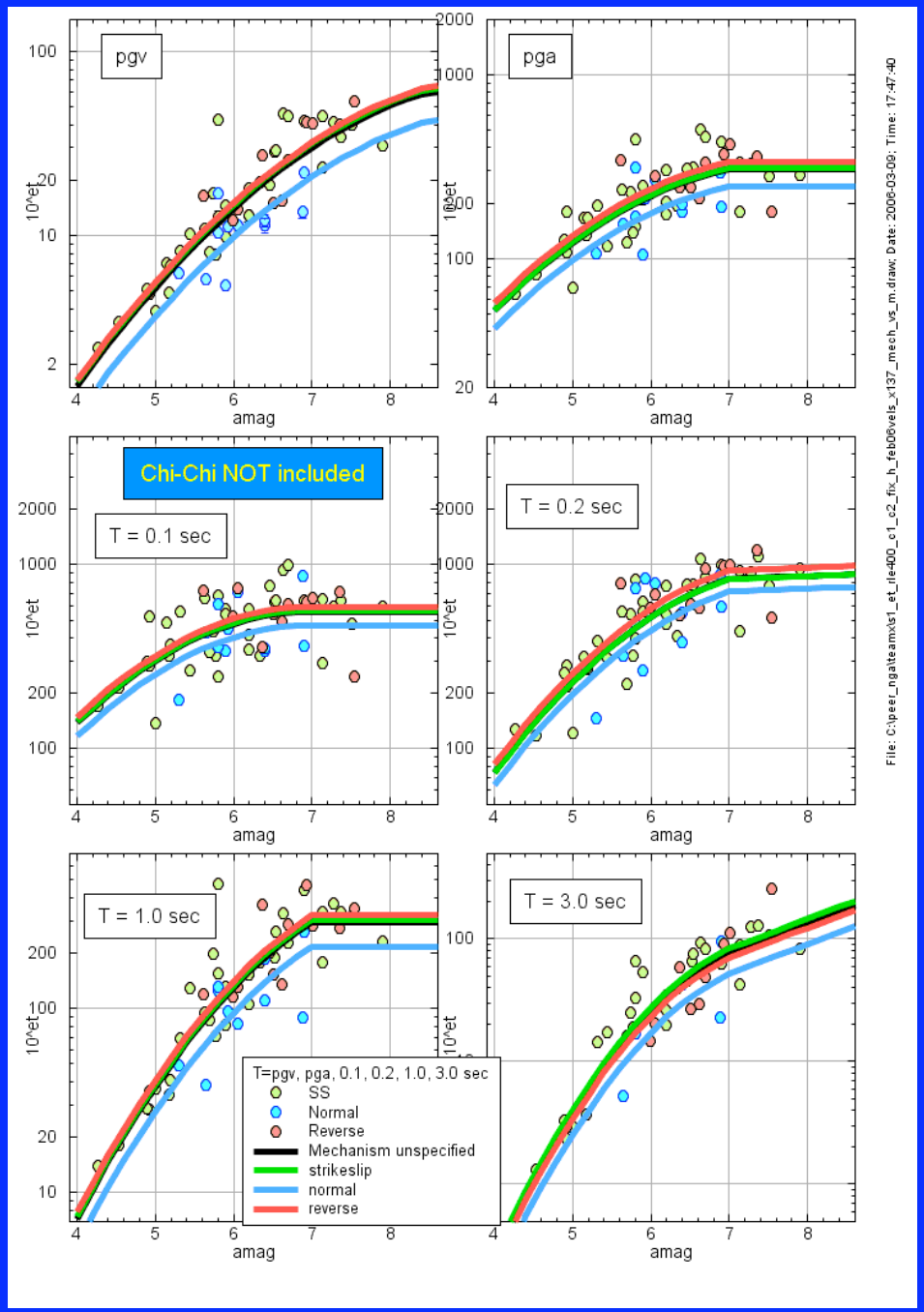
Excluding Chi-Chi from both stage1 and stage2 regressions



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Combined stage1, stage2 motions

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Numbers of Data and Events Used in Regression

Stage 1

Period	ndata	ndata_x137
pgv	1604	1224
pga	1604	1224
0.1	1604	1224
0.2	1604	1224
1.0	1586	1206
2.0	1473	1094
3.0	1282	905

Stage 2

Period	nevents
pgv	58
pga	58
0.1	58
0.2	58
1.0	56
2.0	52
3.0	46

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Comparison of Aleatory Uncertainty (natural log)

per	sig1:ba05	bjf97	sig2u:ba05	bjf97	sigtu:ba05	bjf97
pgv	0.52		0.29		0.59	
pga	0.51	0.43	0.27	0.18	0.57	0.47
0.10	0.53	0.44	0.33	0.00	0.63	0.44
0.20	0.53	0.44	0.29	0.01	0.60	0.44
1.00	0.58	0.47	0.31	0.21	0.65	0.52
2.00	0.59	0.50	0.40	0.28	0.71	0.62
3.00	0.57		0.41		0.71	

Total uncertainty greater than before and very consistent with other developers

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Compare with BJF97

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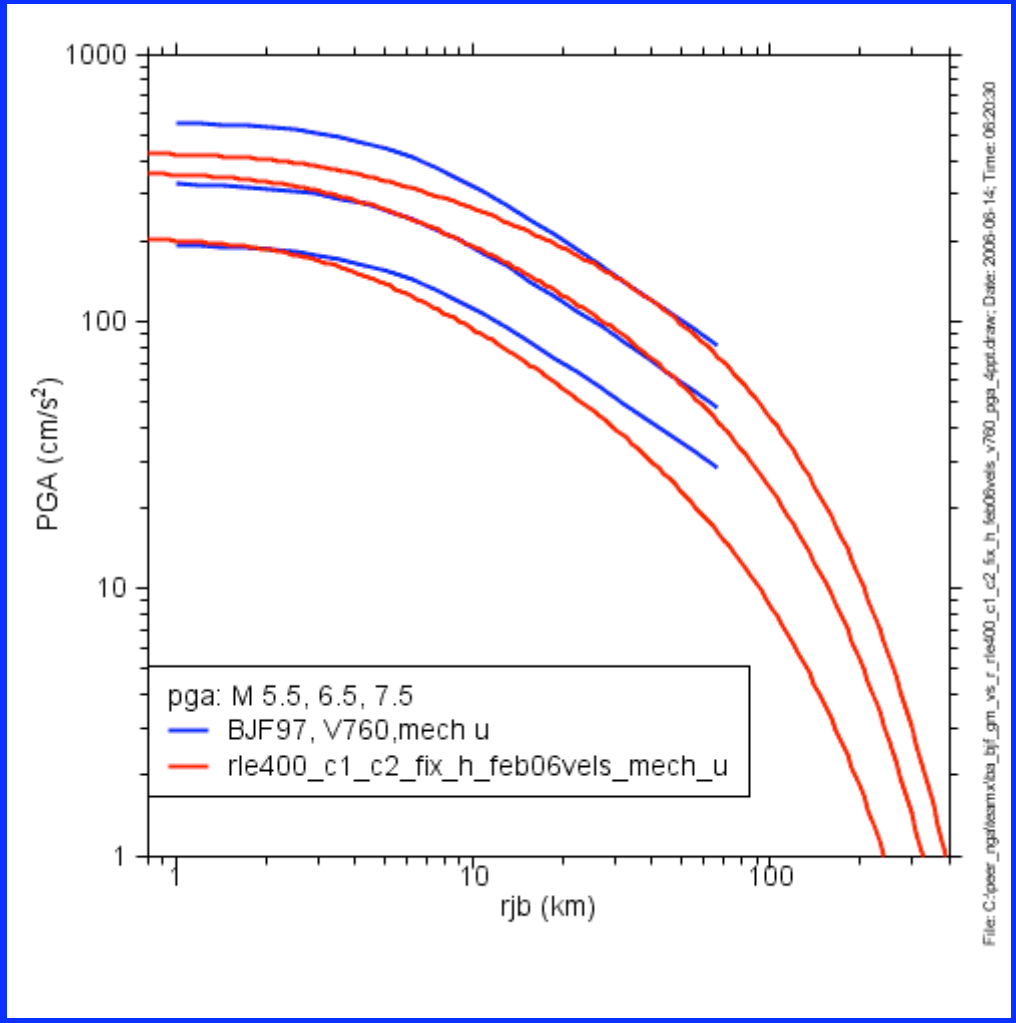

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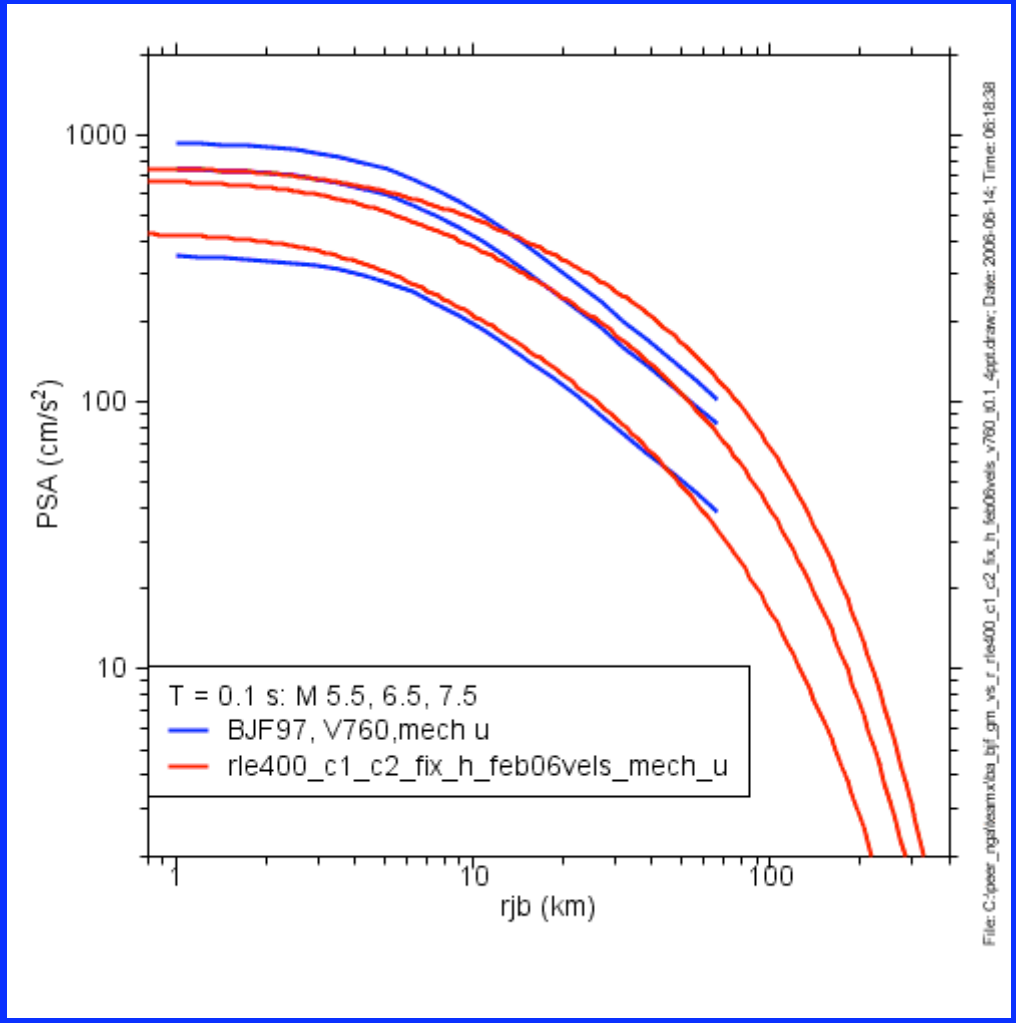

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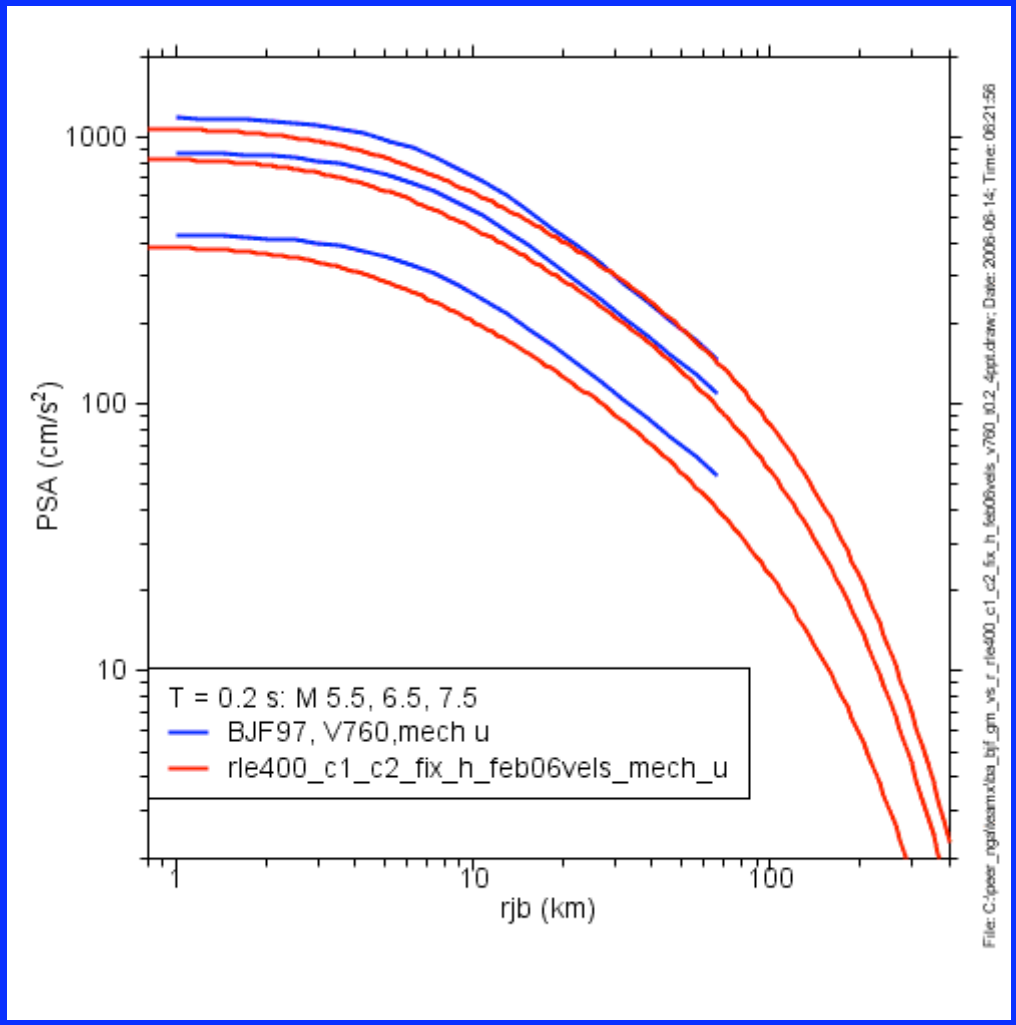

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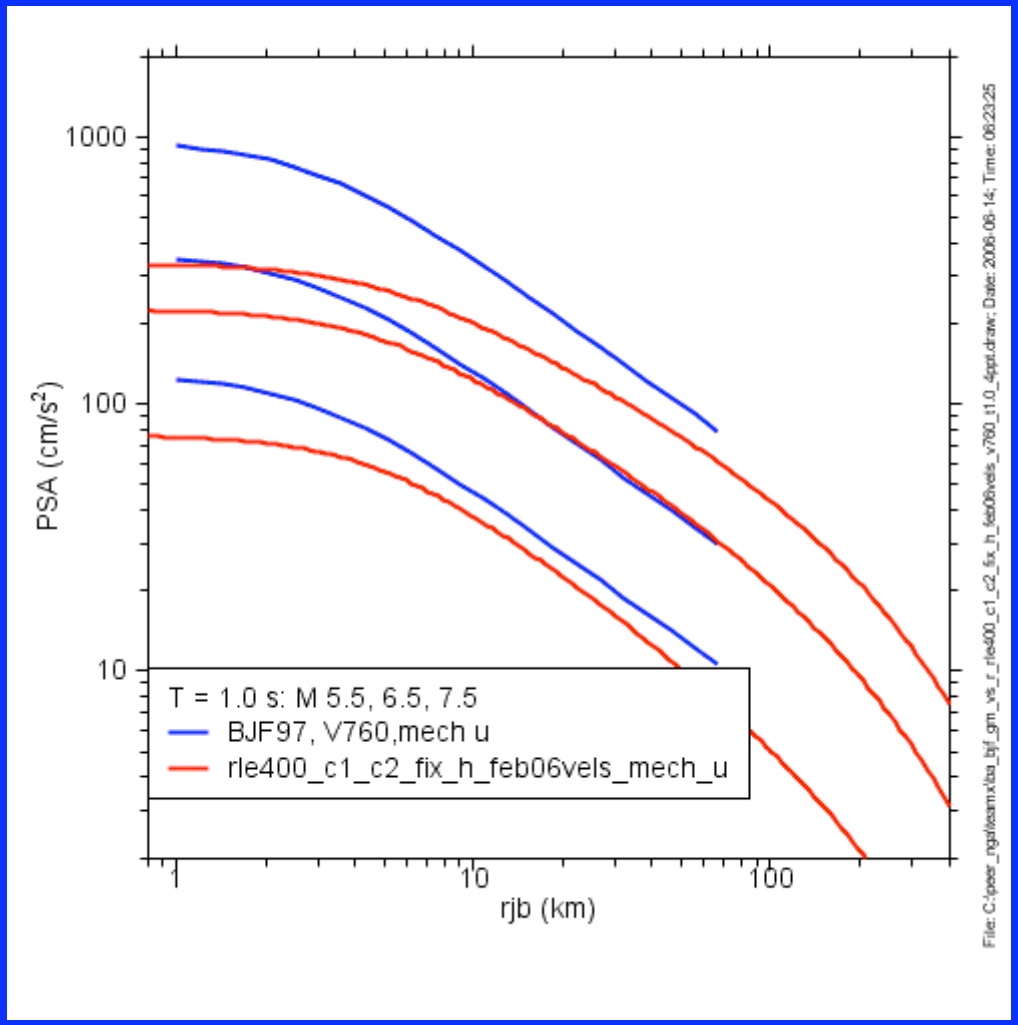
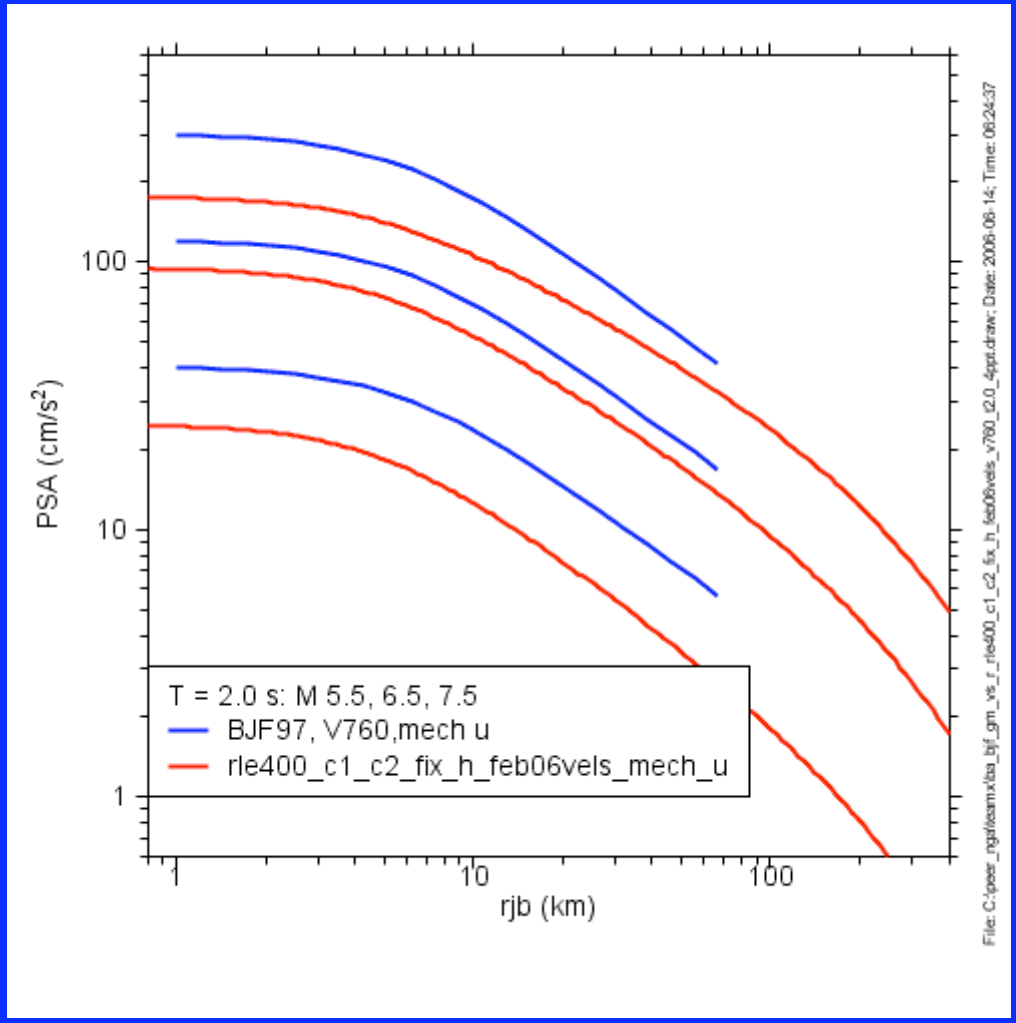

1000
100
10
PSA (cm/s²)
1
10
100
rjb (km)
T = 1.0 s: M 5.5, 6.5, 7.5
BJF97, V760,mech u
rle400_c1_c2_fix_h_feb06vels_mech_u



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Compare with CB Jan06

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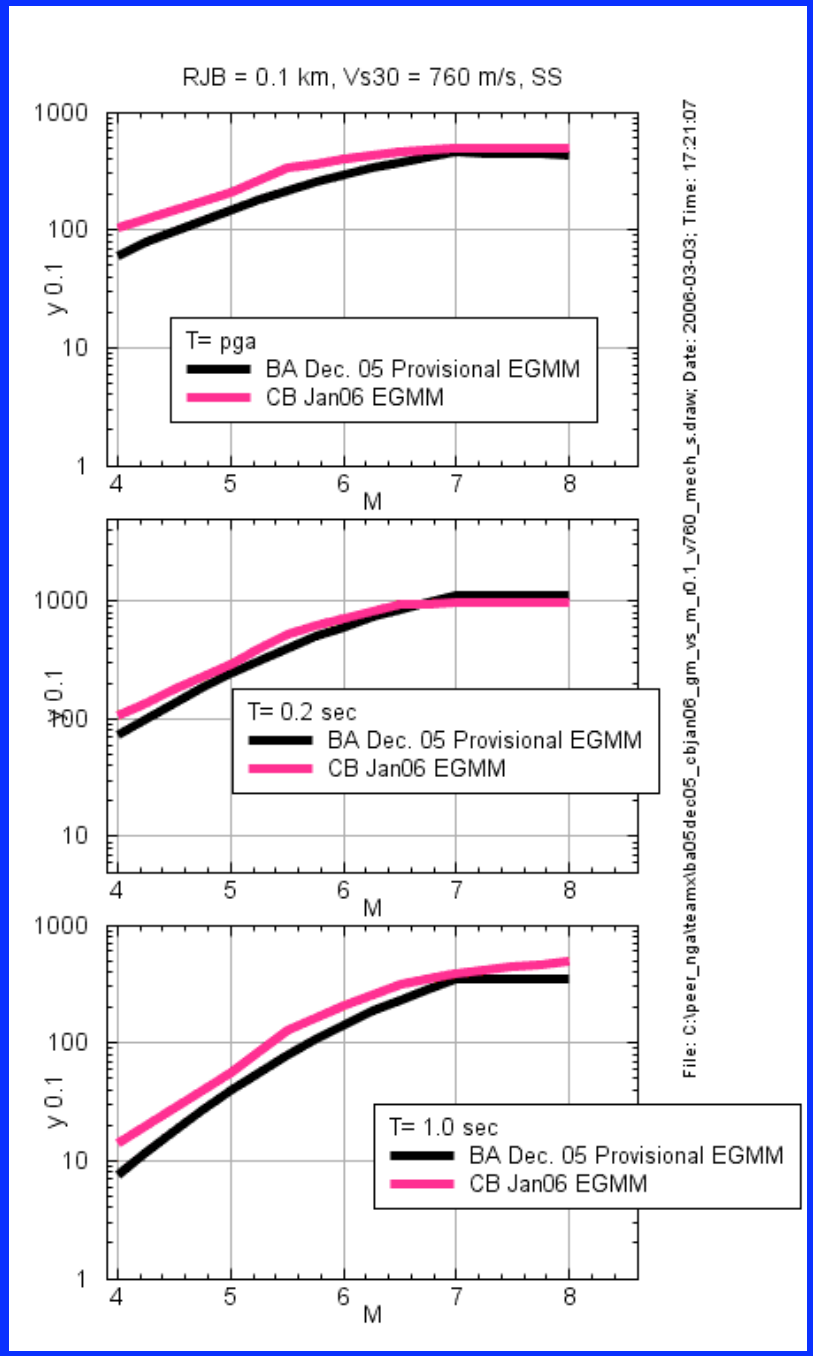

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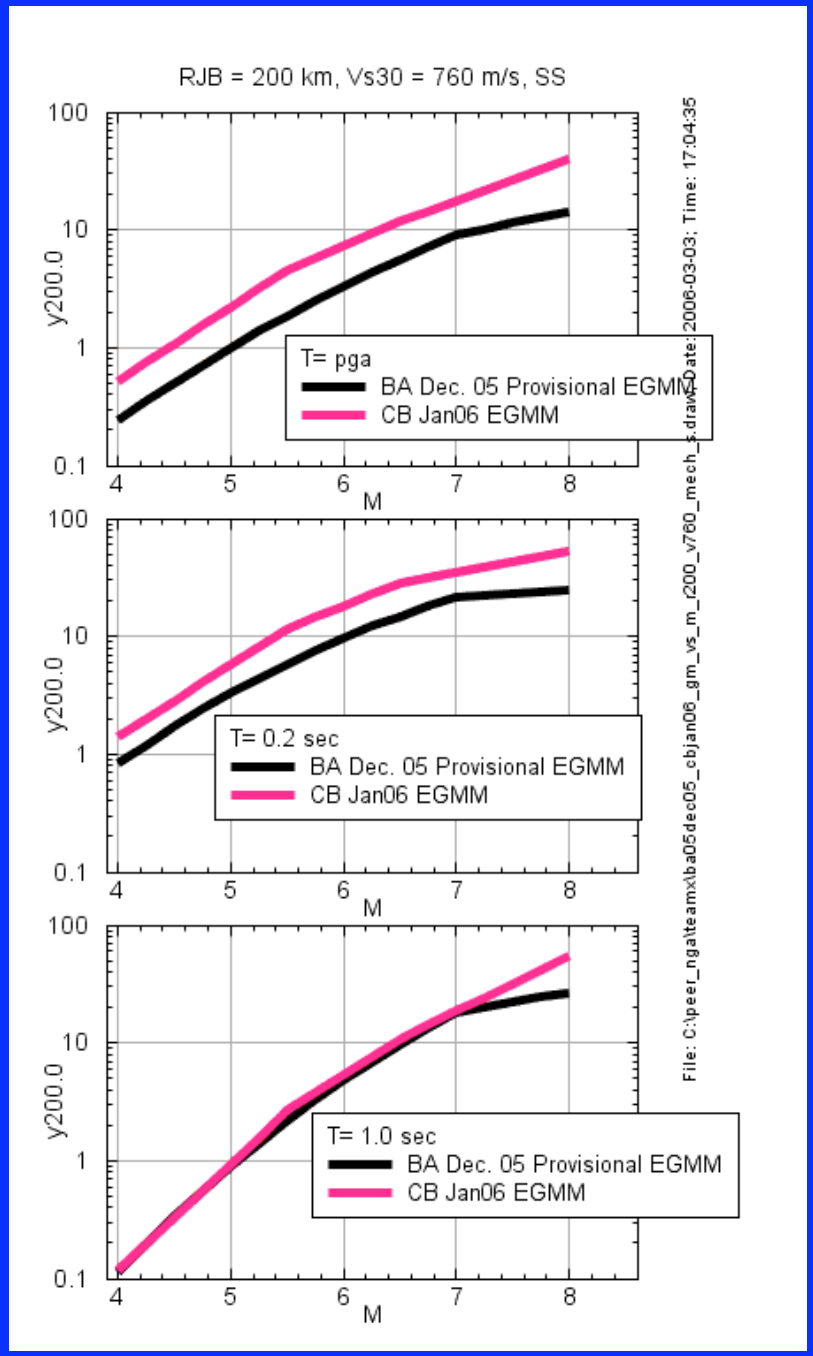

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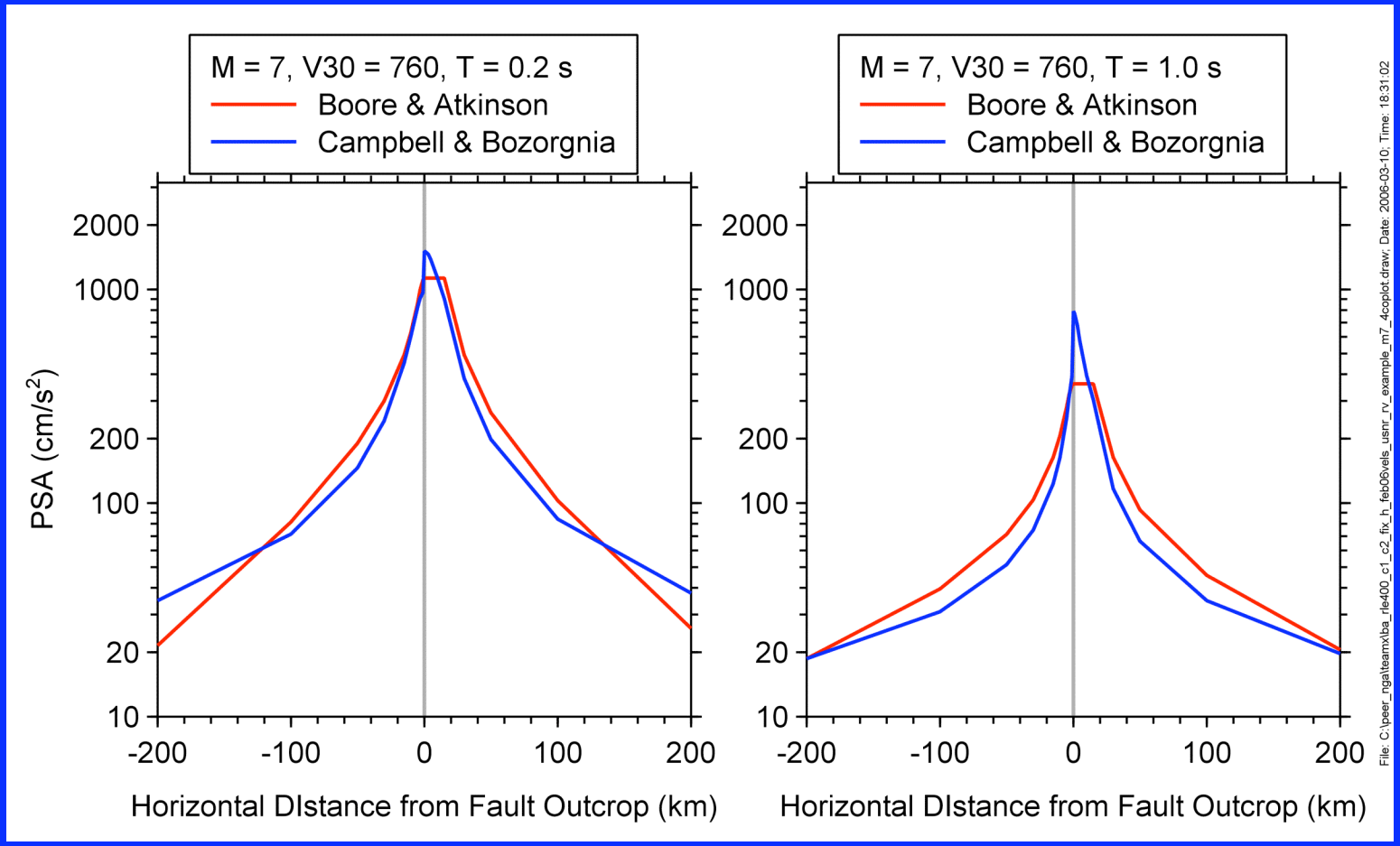

45 degree dip to right, to 15 km depth

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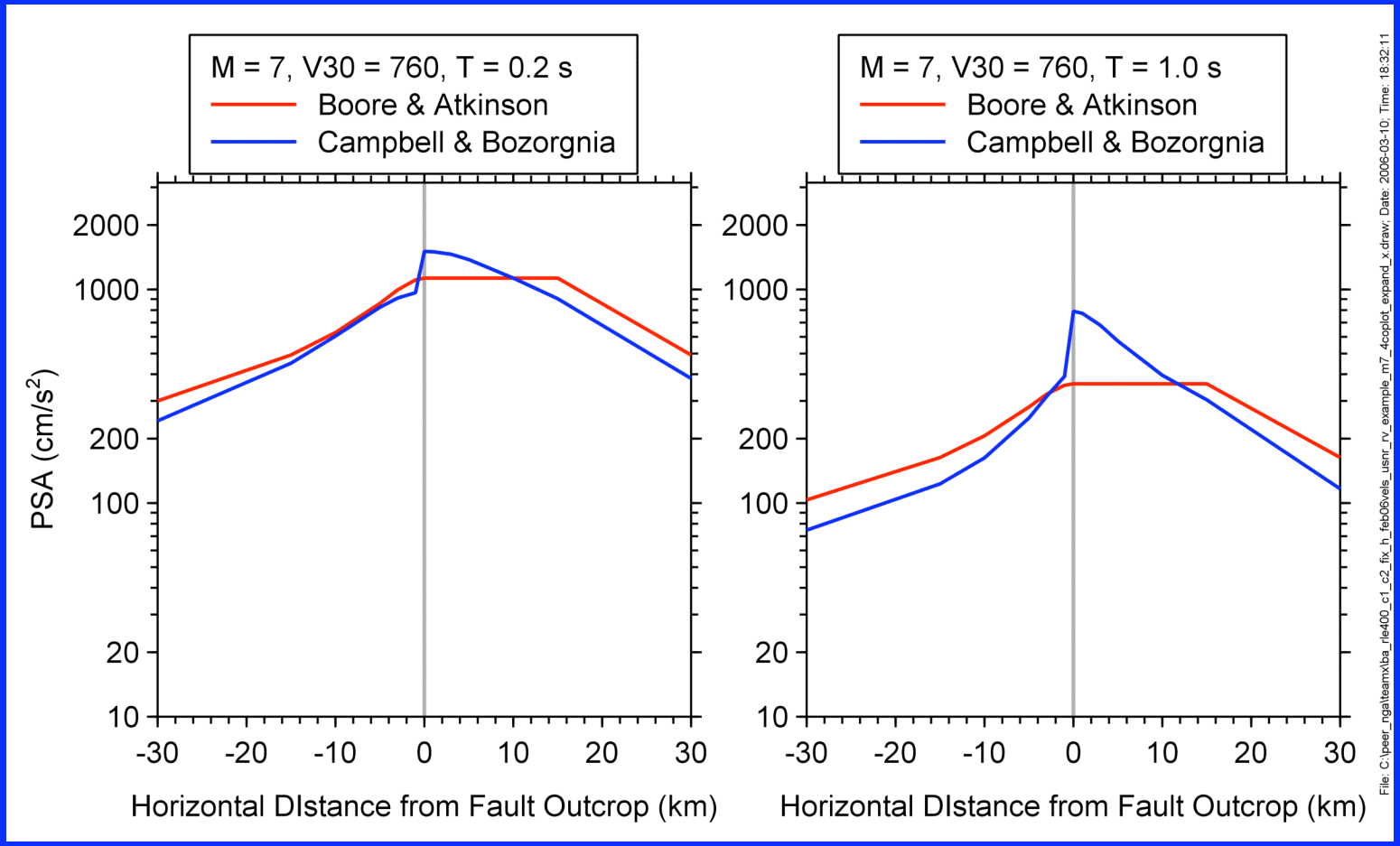

45 degree dip to right, to 15 km depth

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Observed & Theoretical M Scaling

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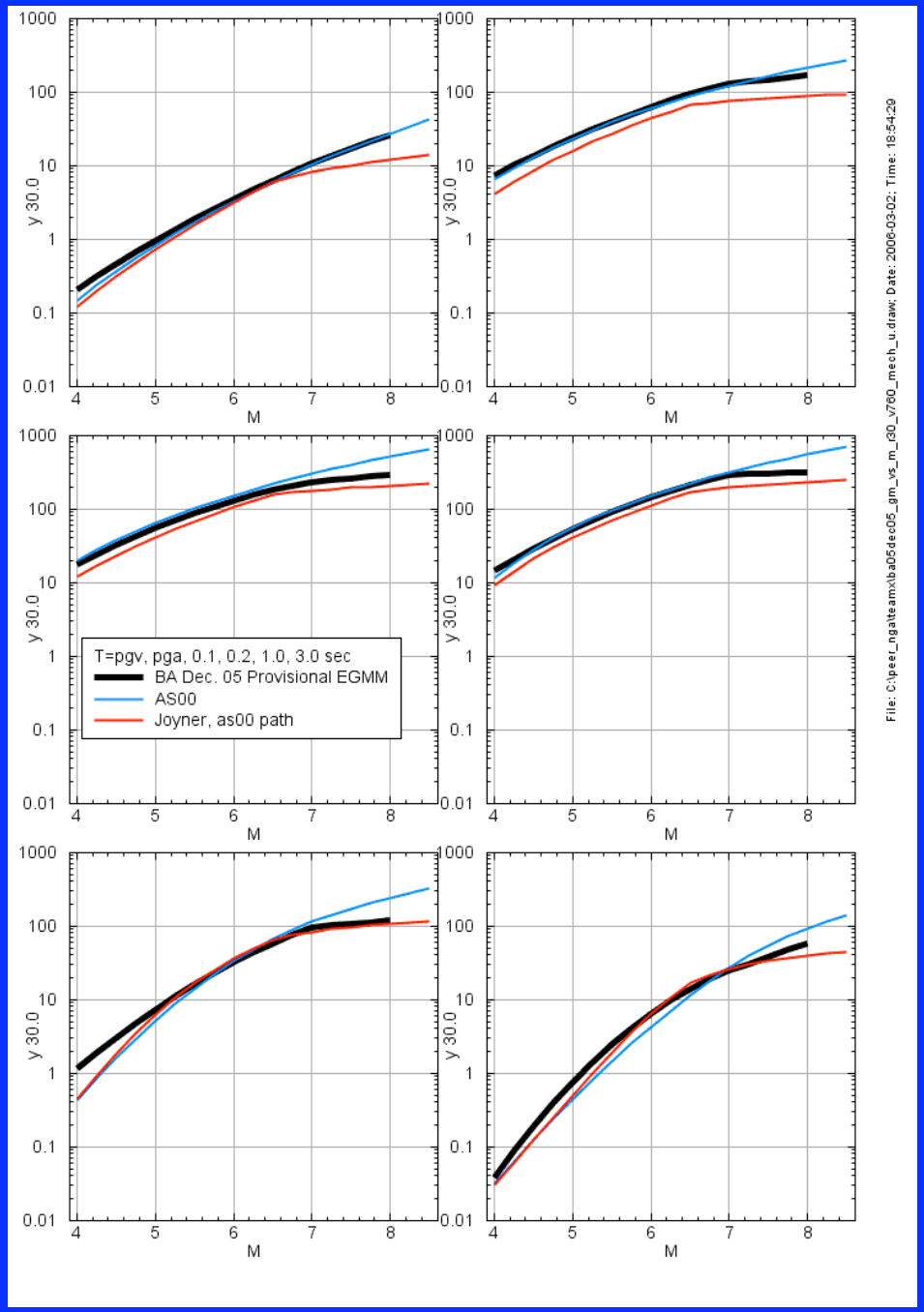

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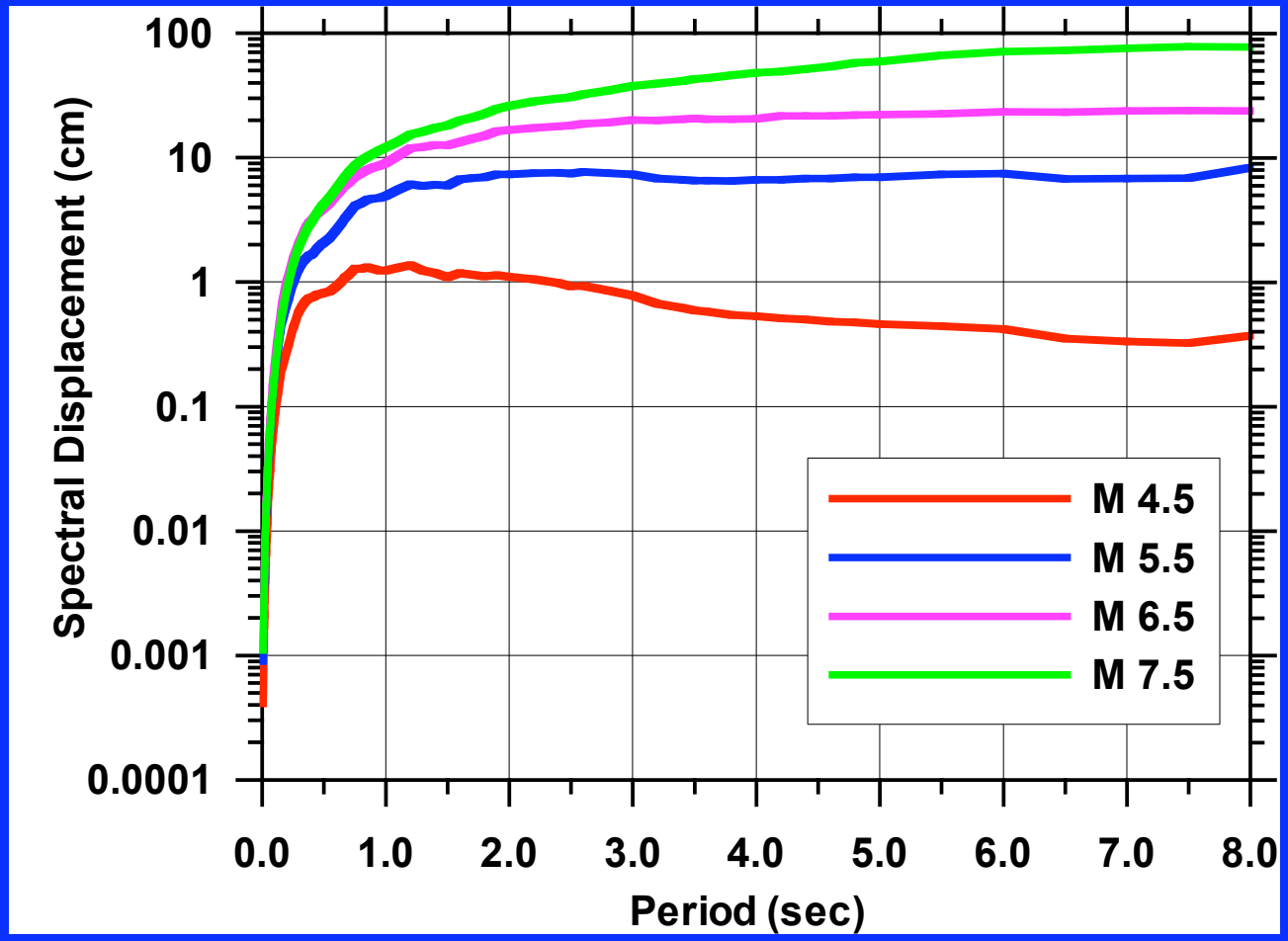
Behavior at Long Periods

Near-Source Relative Displacement Spectra



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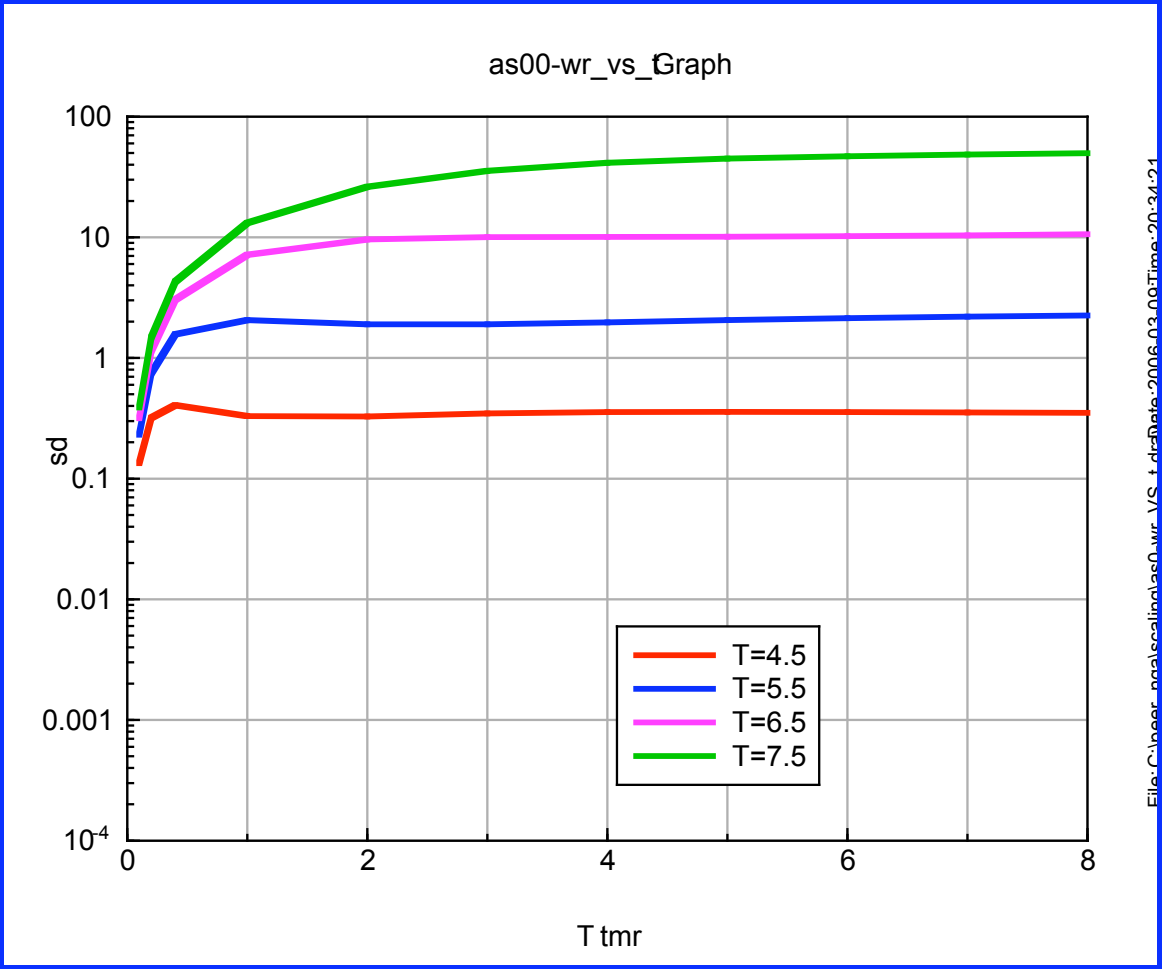
Campbell & Bozorgnia

Atkinson & Silva double corner frequency model



END

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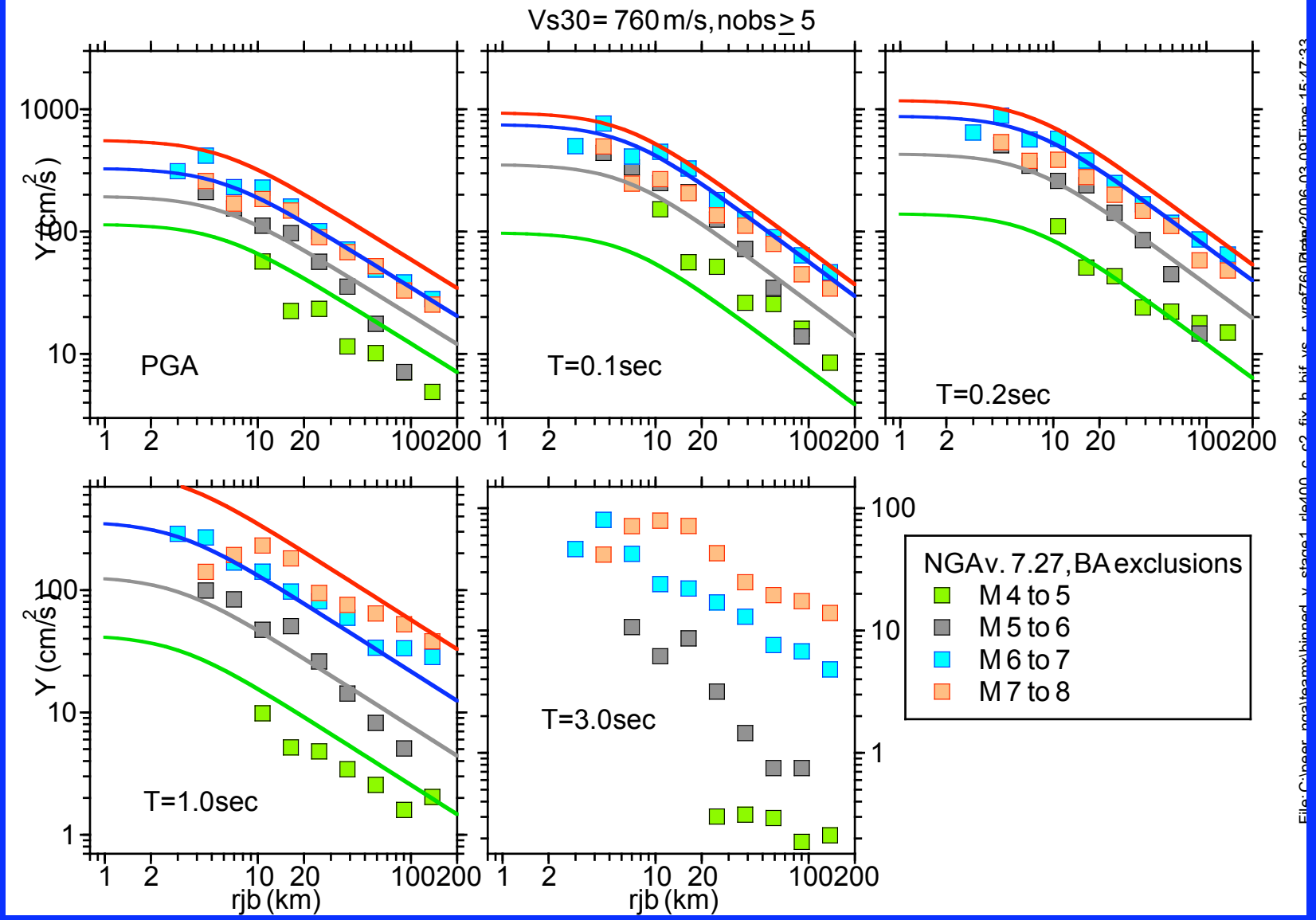

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Measure of Ground-Motion Intensity: GMRotI50

Boore, D. M., J. Watson-Lamprey, and N. A. Abrahamson (2006). Orientation-independent measures of ground motion, BSSA (in press)

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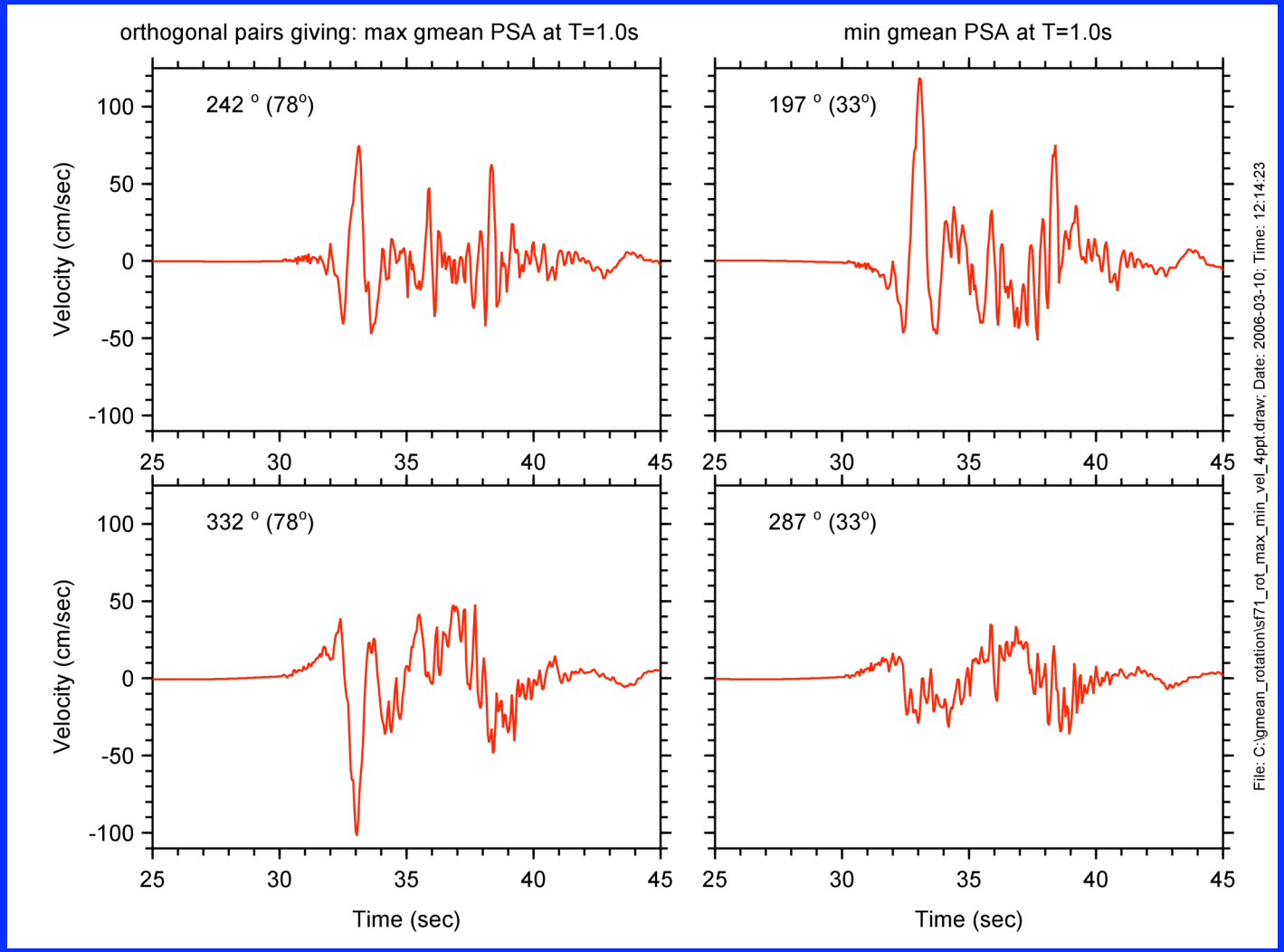
The geometric means of these two sets of records differ by a factor of 2 at T = 1 s



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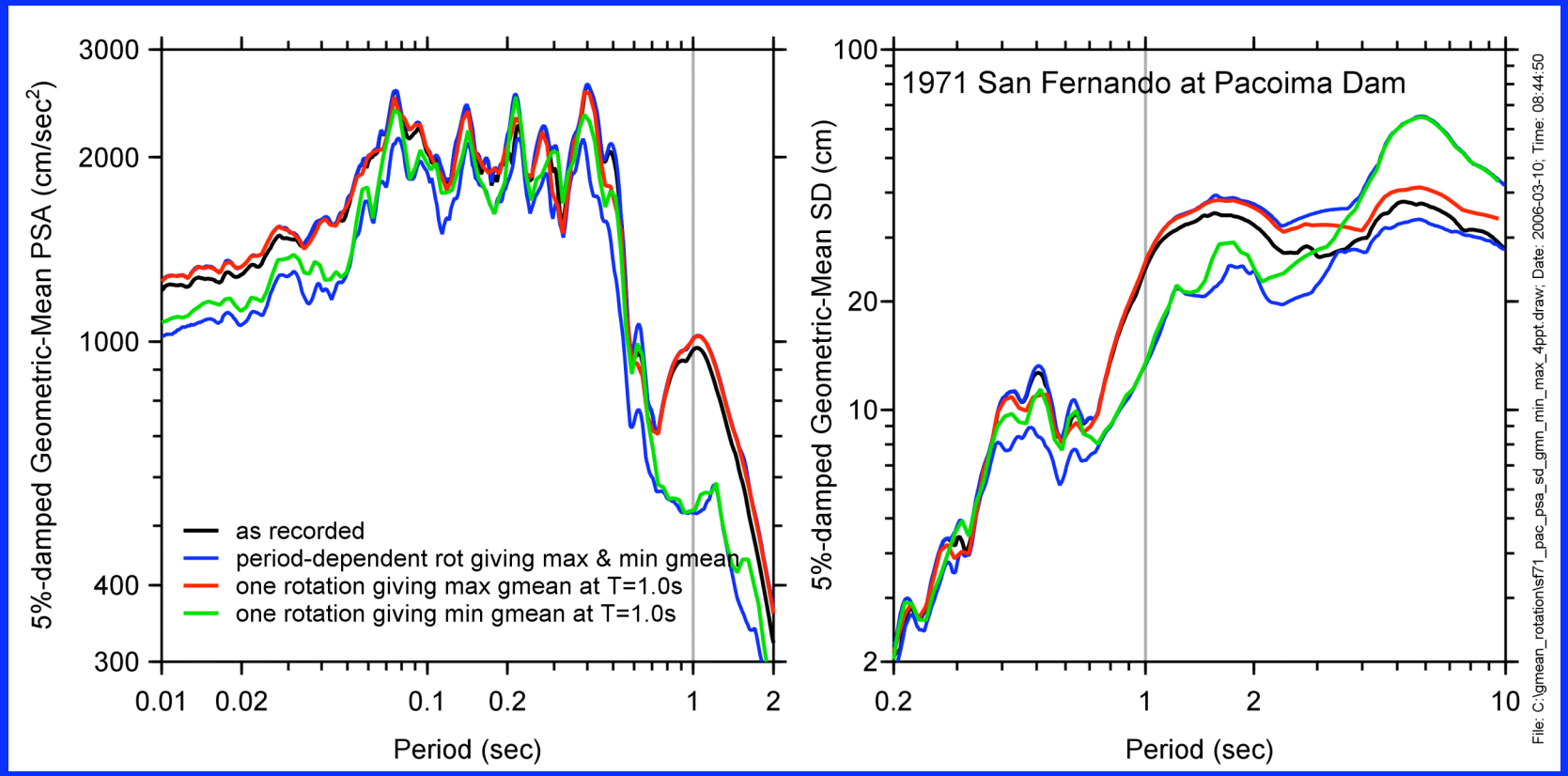

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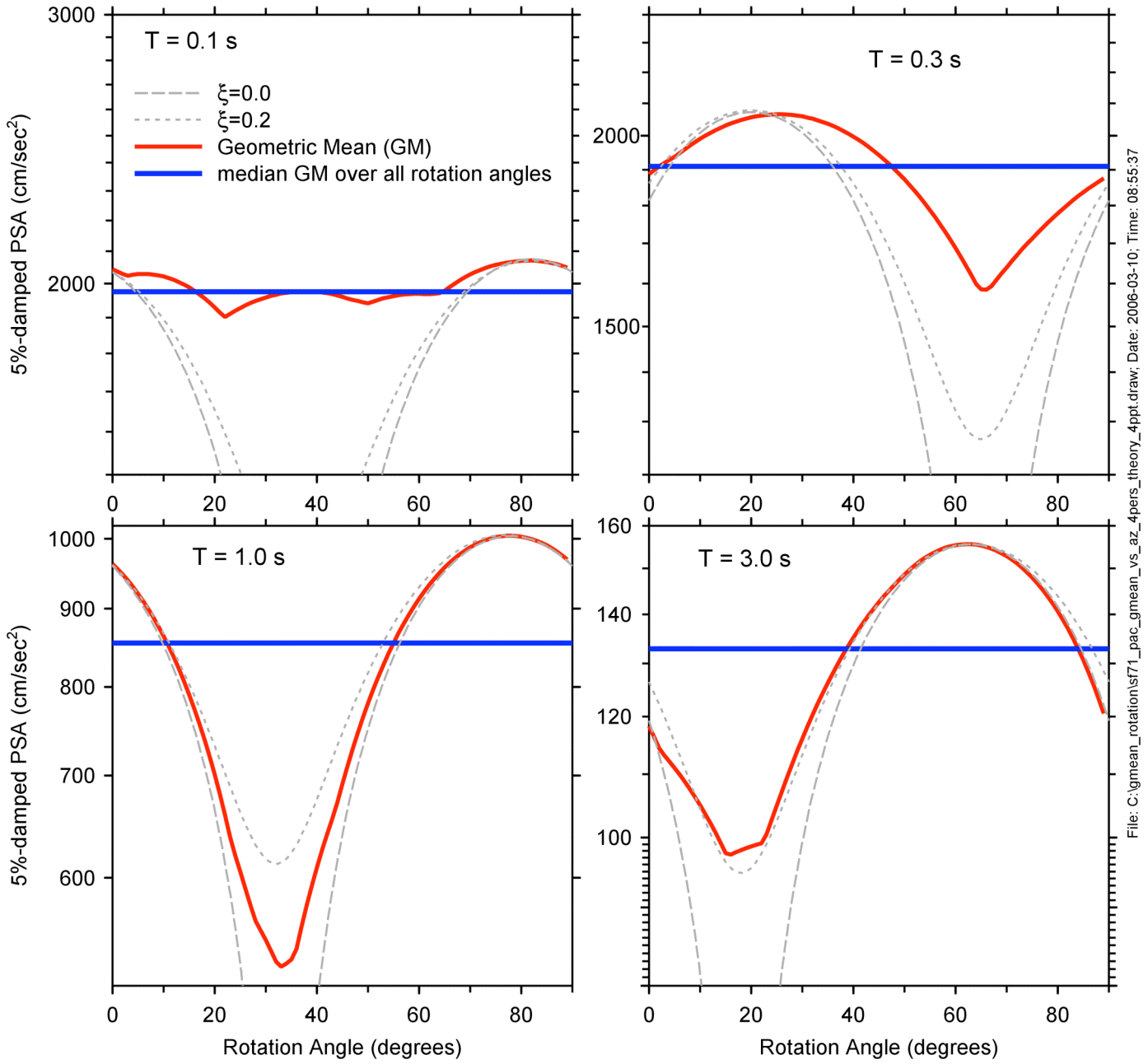
Basis of GMRotD50



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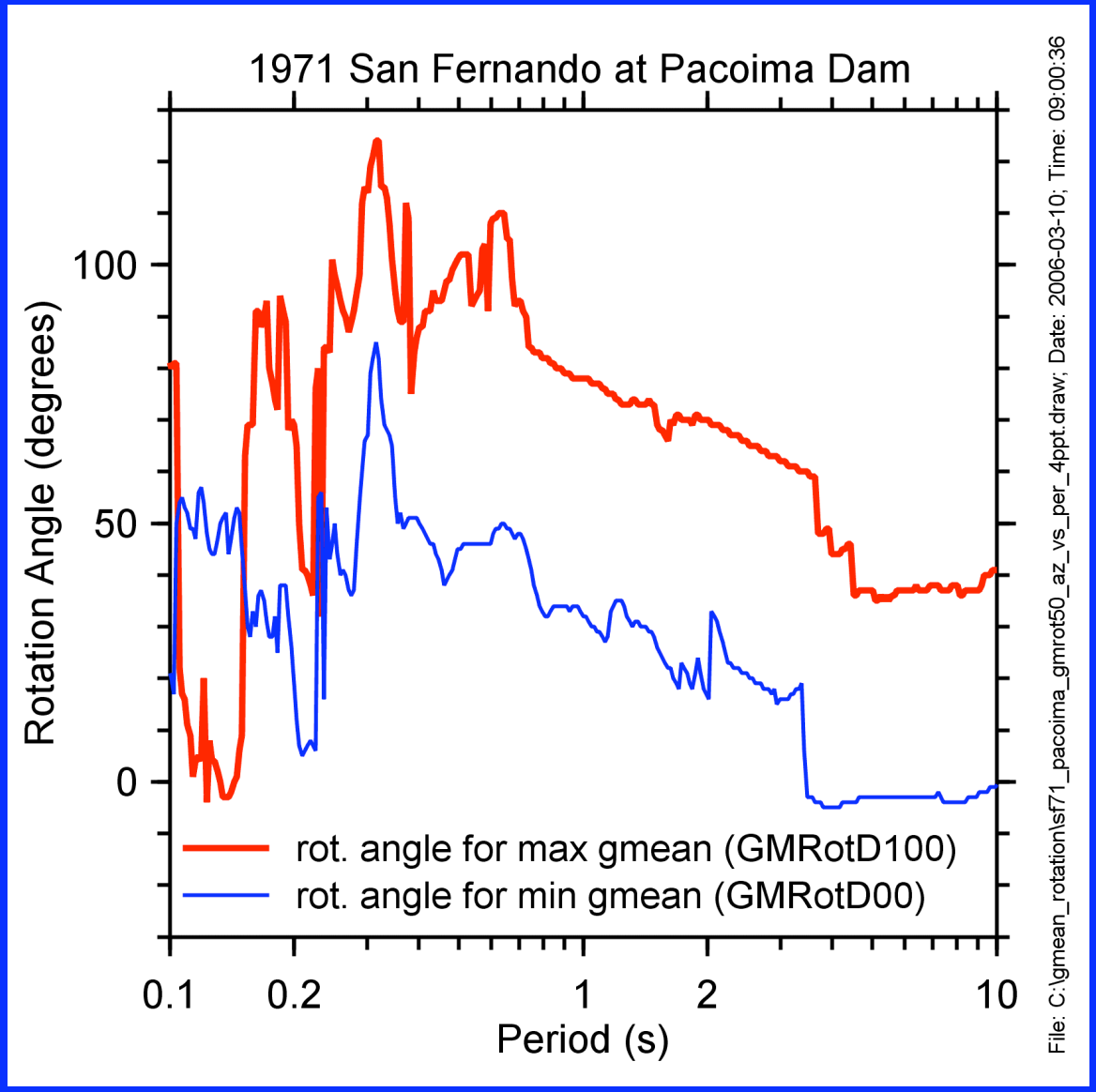
But azimuth can depend on period, so a single rotation will not give GMRot



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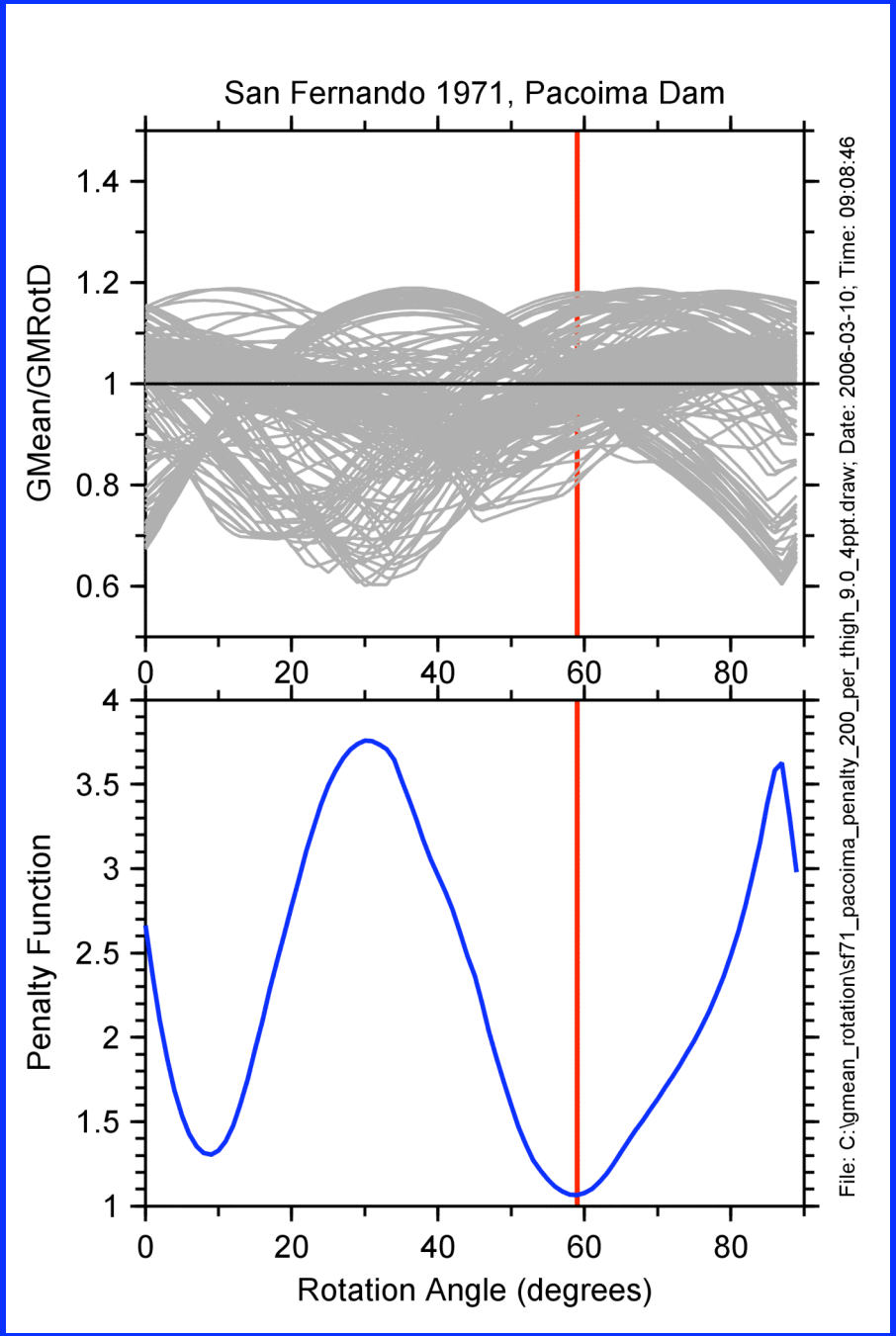
Find the one angle that gives the least dispersion in geometric mean over a range of periods. The geometric mean for this rotation angle is GMRotI50



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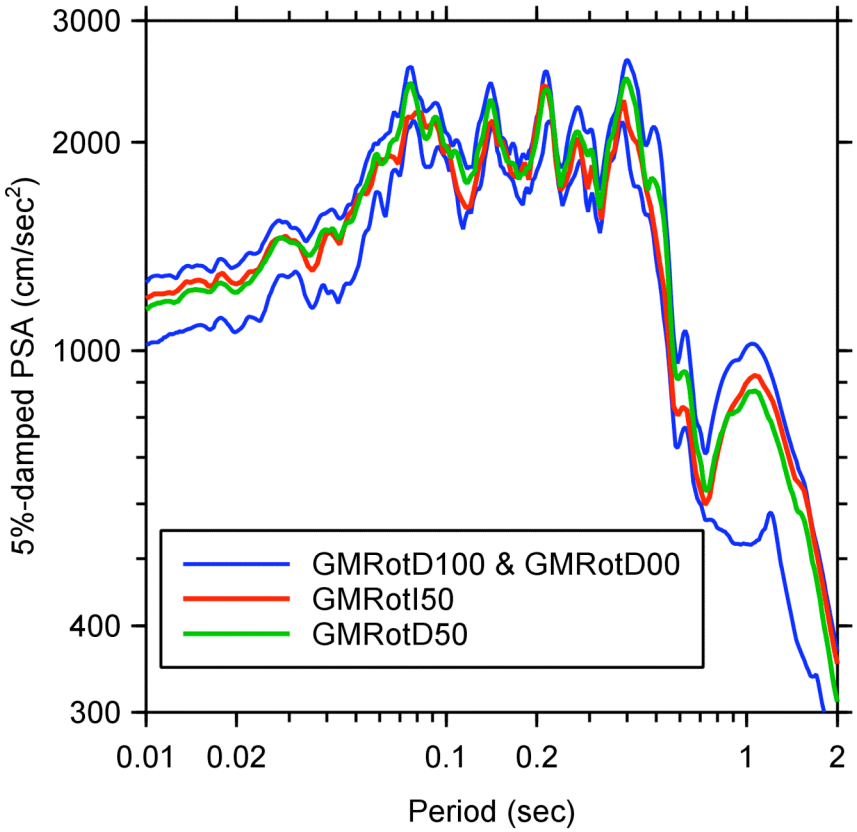
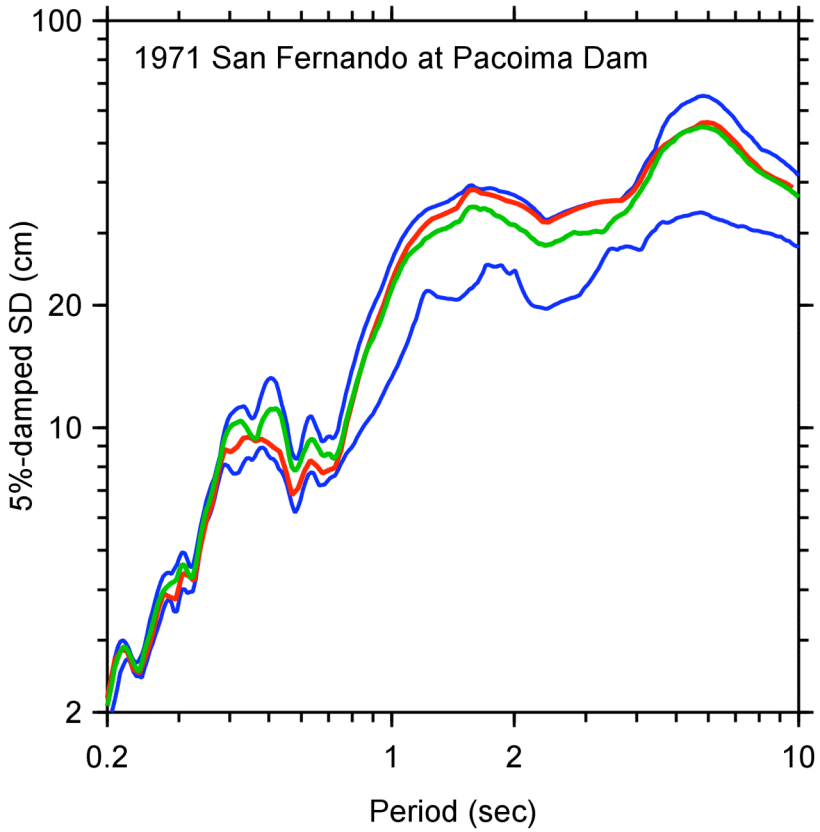
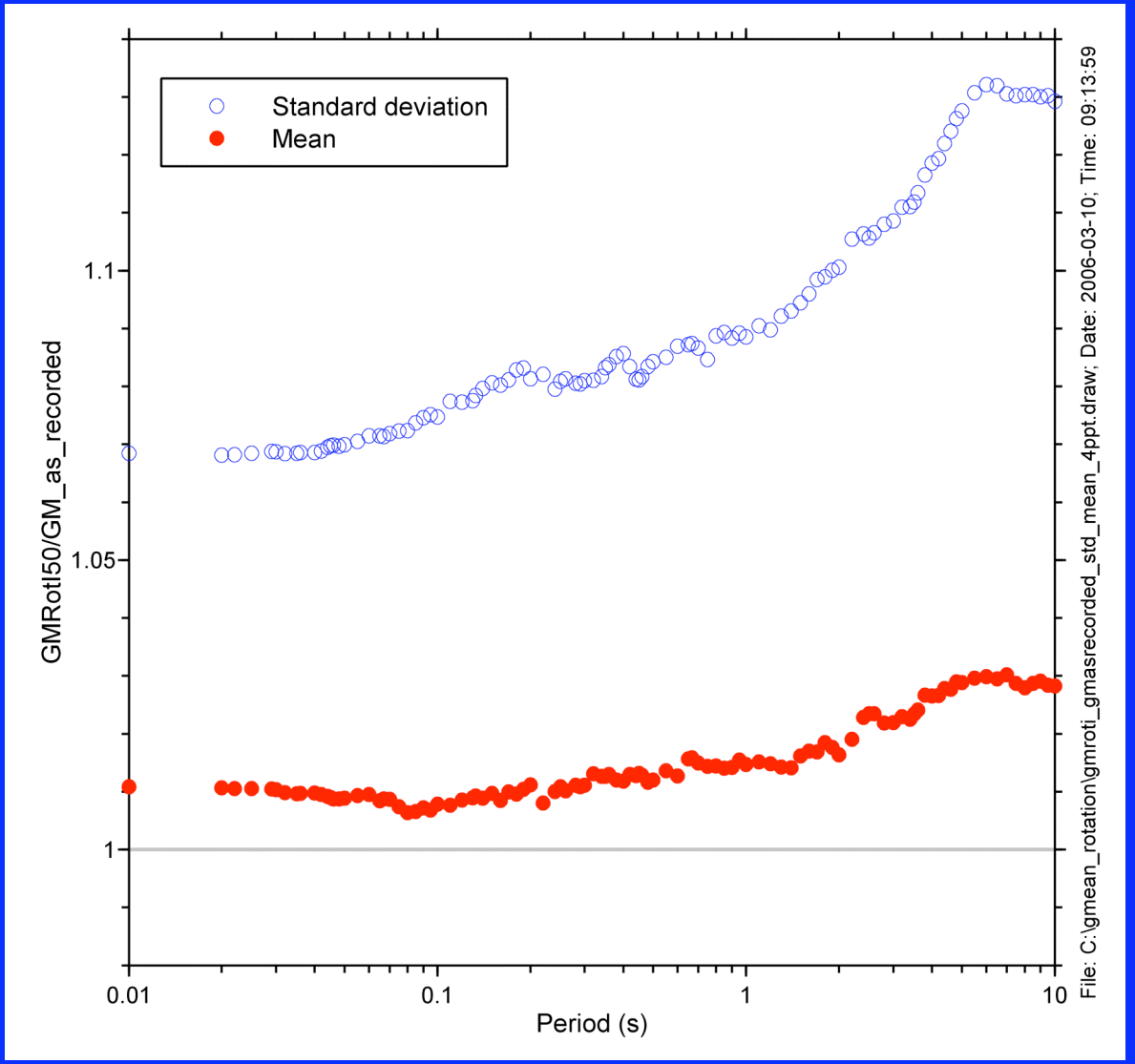

3000
2000
1000
400
300
5%-damped PSA (cm/sec²)
0.01
0.02
0.1
0.2
1
2
Period (sec)
GMRotD100 & GMRotD00
GMRotI50
GMRotD50


1971 San Fernando at Pacoima Dam
100
20
10
2
5%-damped SD (cm)
0.2
1
2
10
Period (sec)

Does not differ much from as-recorded GM, but there are some indications that overall uncertainty is reduced. Effect is probably most important at longer periods



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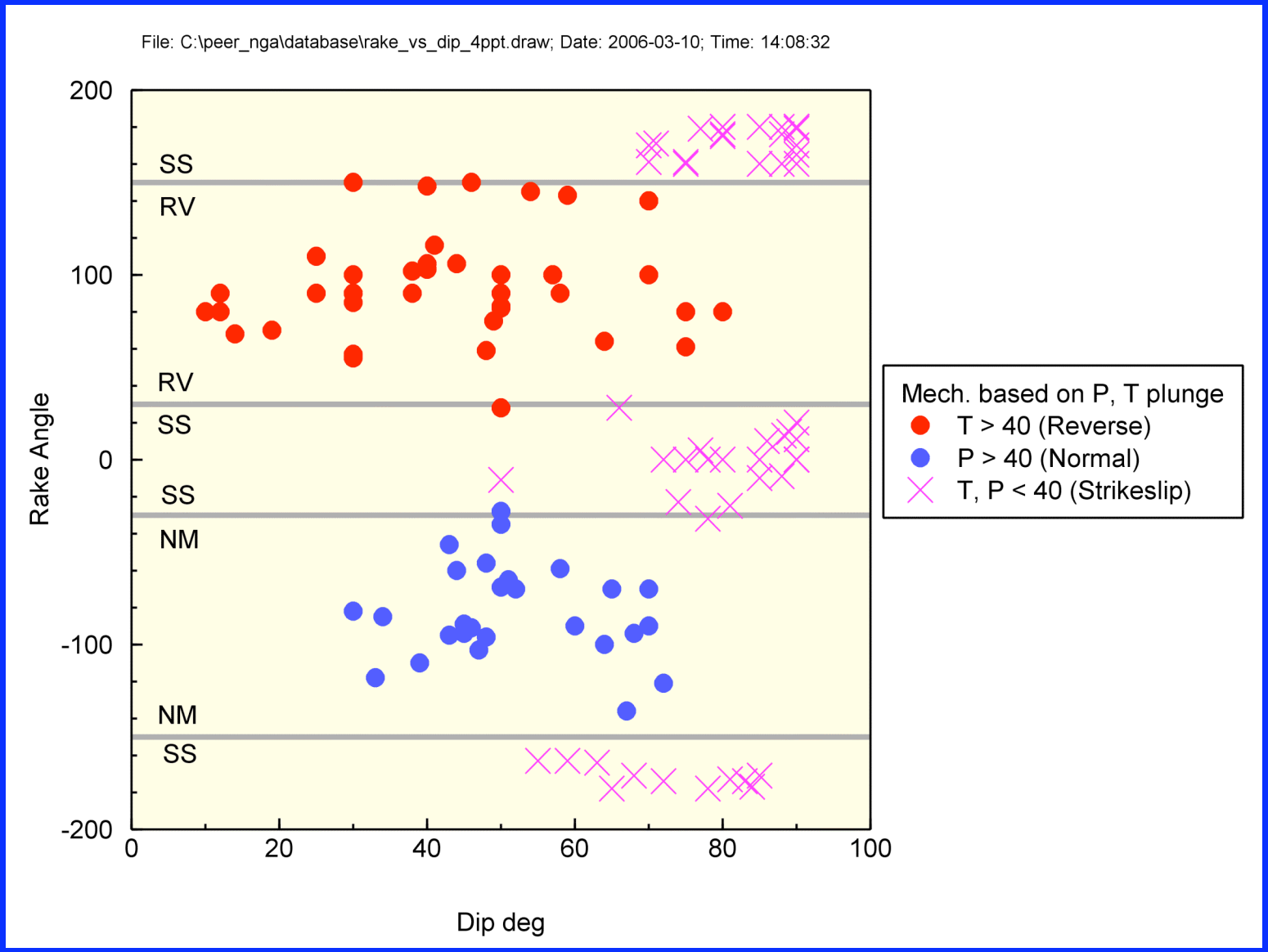

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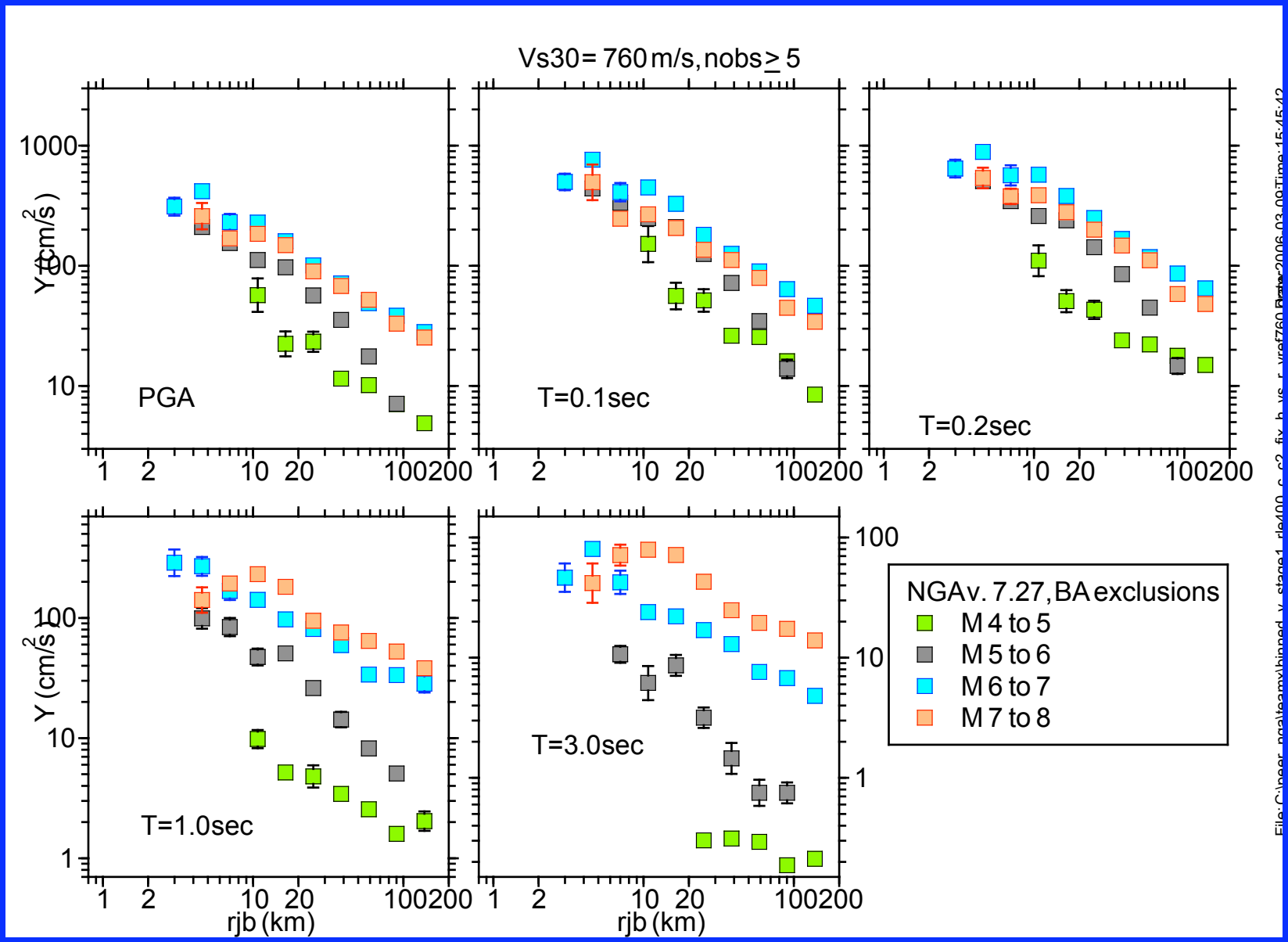

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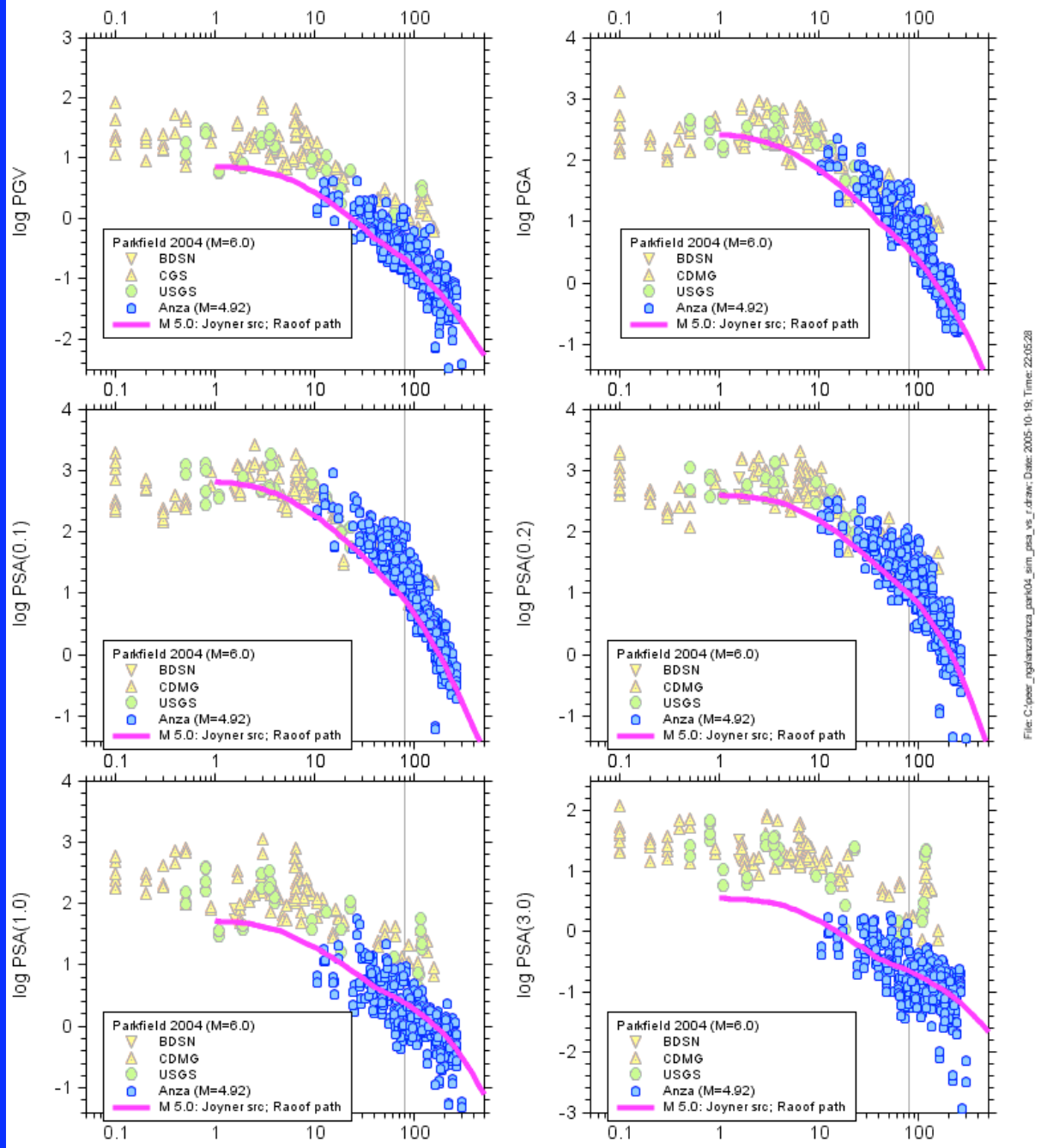

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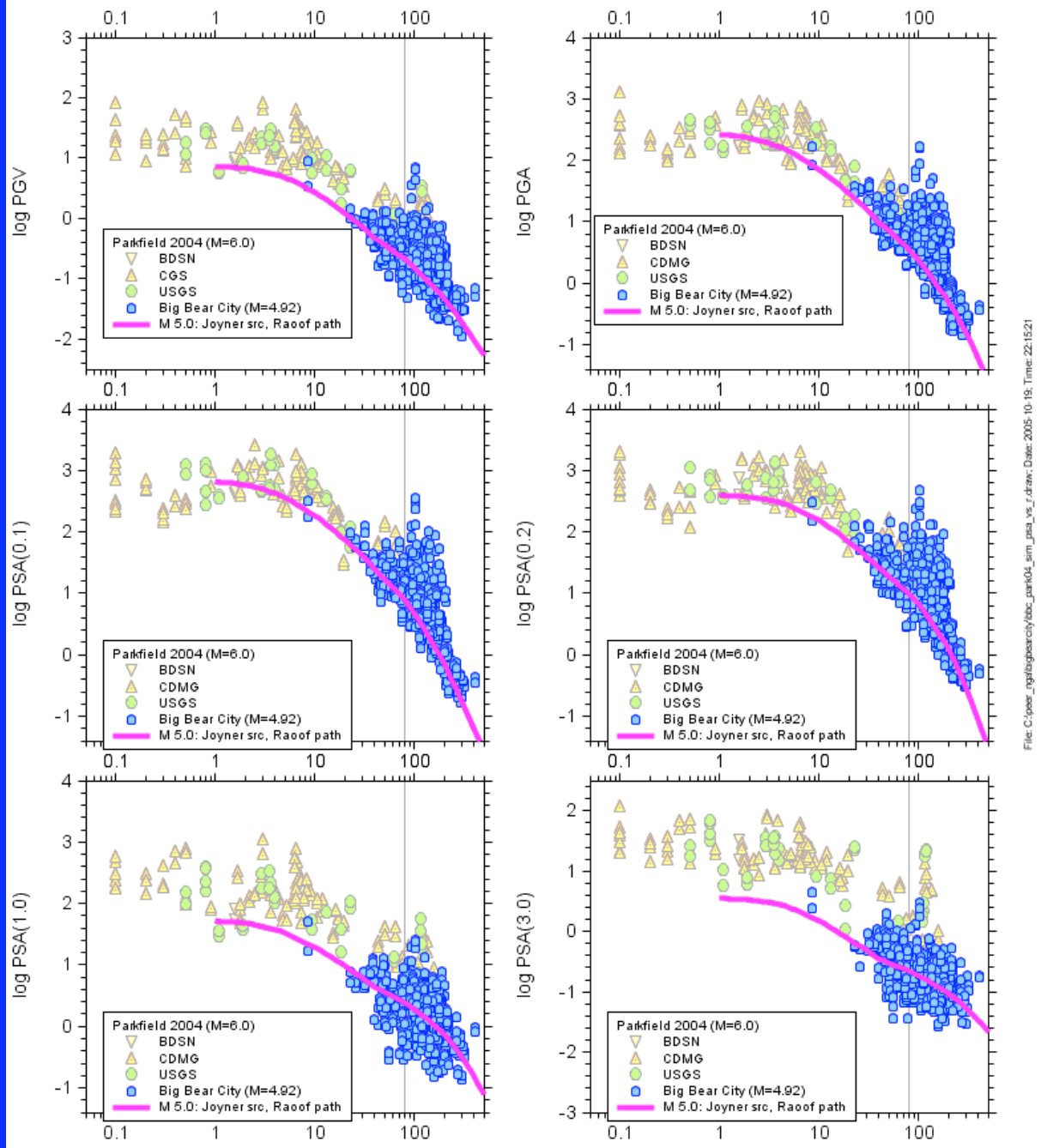

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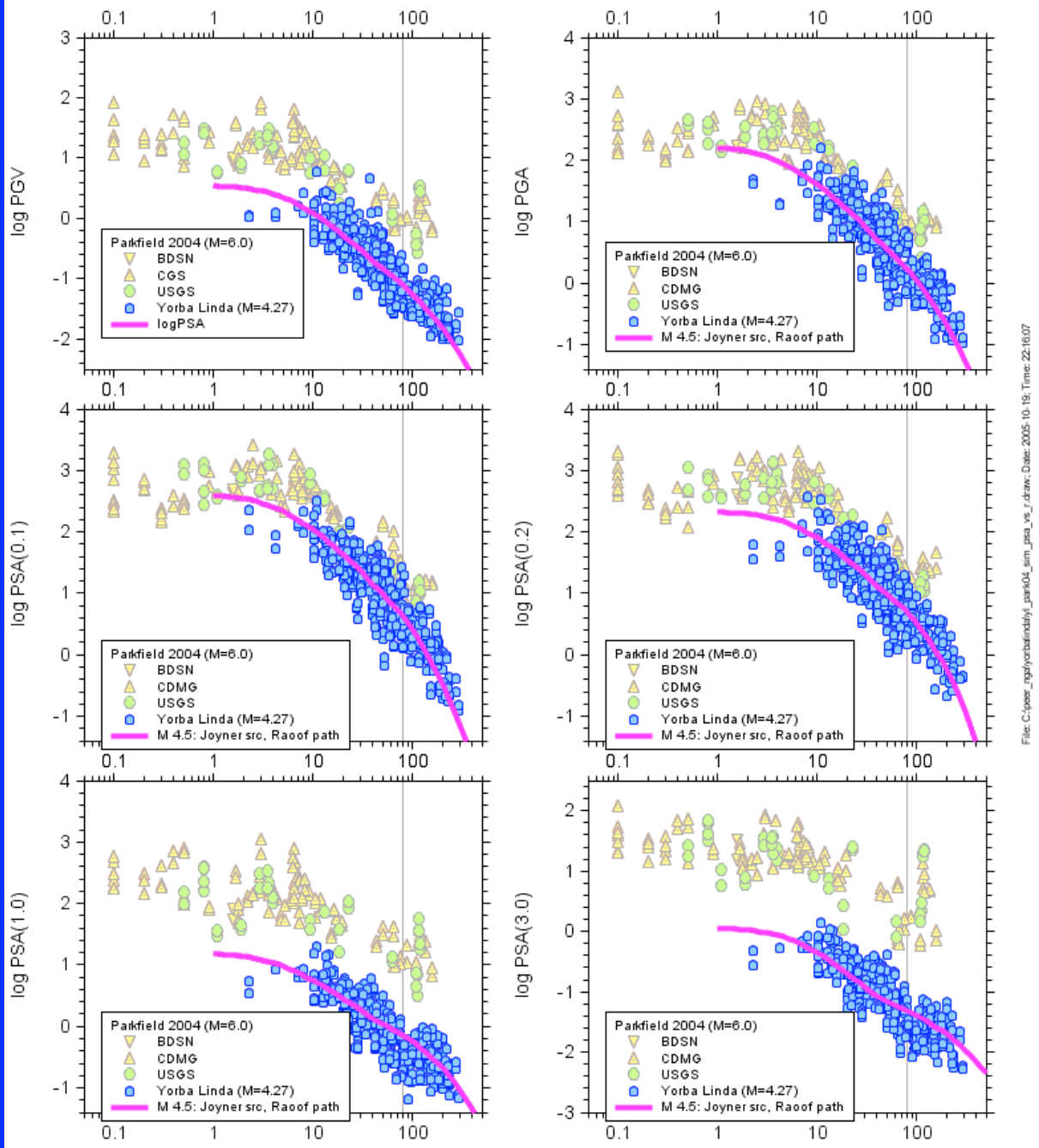

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The distance dependence is determined in the first stage. Because of the increasing sparseness of data beyond about 80 to 100 km, a good fit to the distance decay was obtained using a single effective geometrical-spreading term--- what is termed here the "c1" and "c2" coefficient ("c2" for magnitude dependence).

But because the data from several earthquakes under-represented in the database clearly show a curvature (in log-log space), We did a separate analysis of a more complete dataset for three small events (compiled by J. Boatwright and L. Seekins) and for the 2004 Parkfield earthquake. The effective anelastic coefficient c3 obtained from this analysis was then used in the regression of the NGA dataset.

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Attempt to let both c1 and c3 be free resulted in positive values of c3 for some periods, and this would lead to an increase of ground motion for great enough distances.

After experimenting with various constraints, values of c3 were fixed in regression of the NGA dataset, with only the c1 and c2 coefficients, pseudo depth h, and “event terms” (average motion at the reference distance) as free variables.

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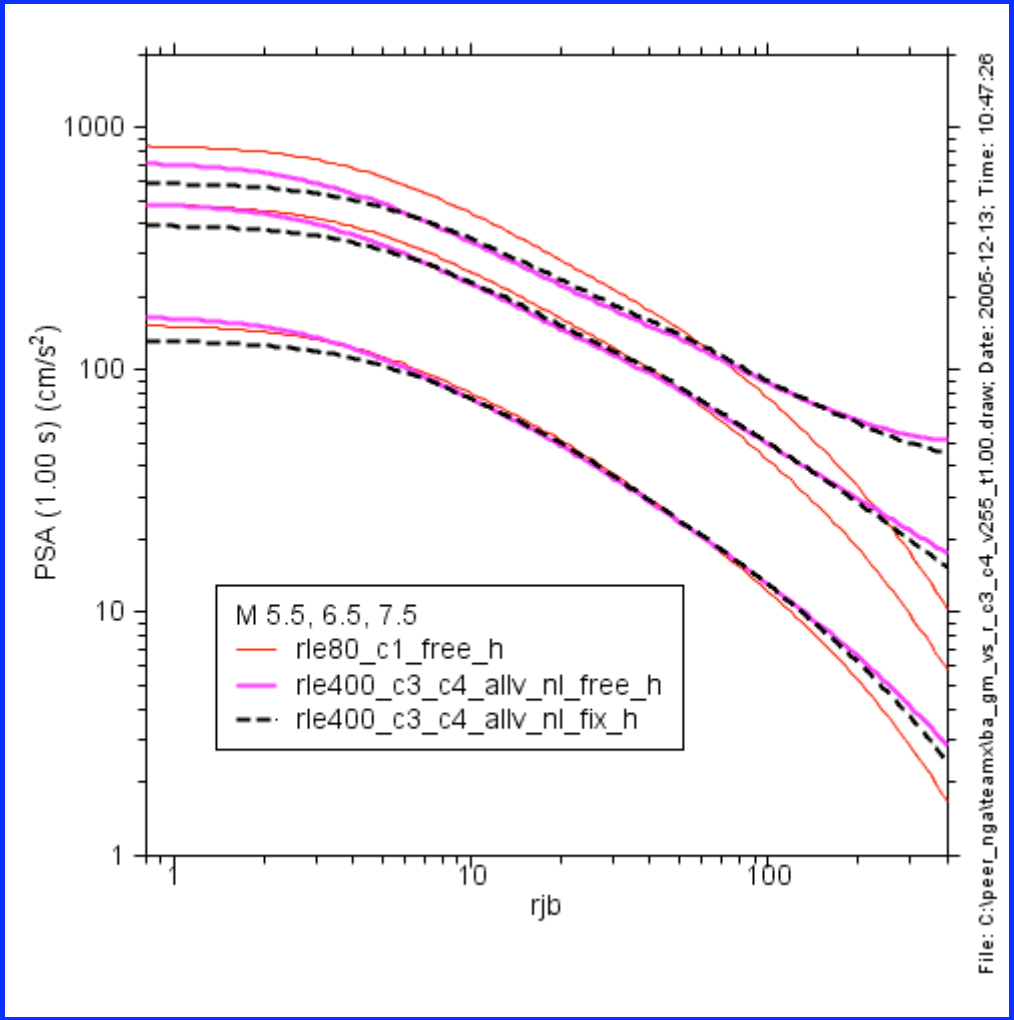
To add magnitude dependence, we used all data less than 400 km and tried letting the coefficient c4 be a regression variable. The resulting equations, however, showed a tendency for increasing motions with distance (for large distances), for longer periods.



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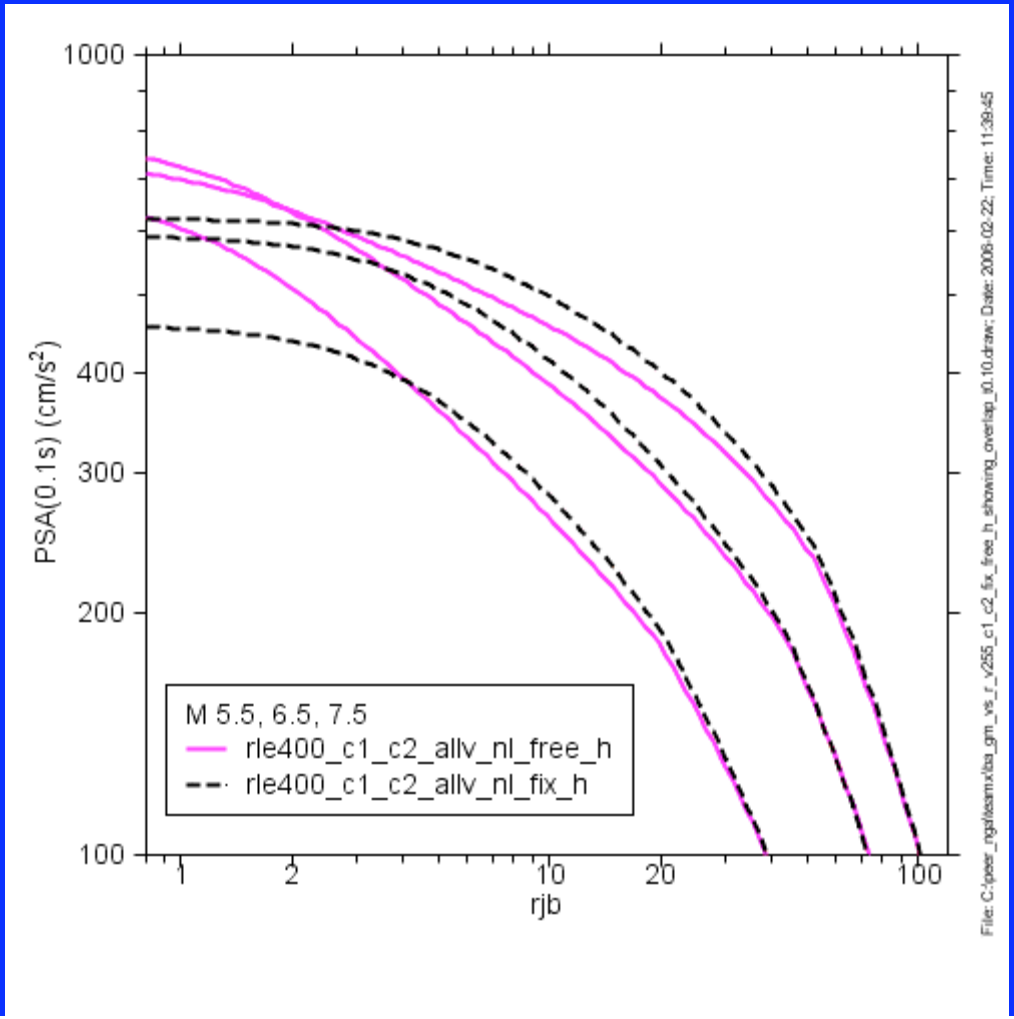
We then tried letting the coefficient c2 be free. When we also let the pseudodepth h be free, we found that the curves for large earthquakes showed some overlap at close distances (a figure is shown below). IMPORTANT: Note that this figure also shows the sensitivity of the ground motions to h for small distances.



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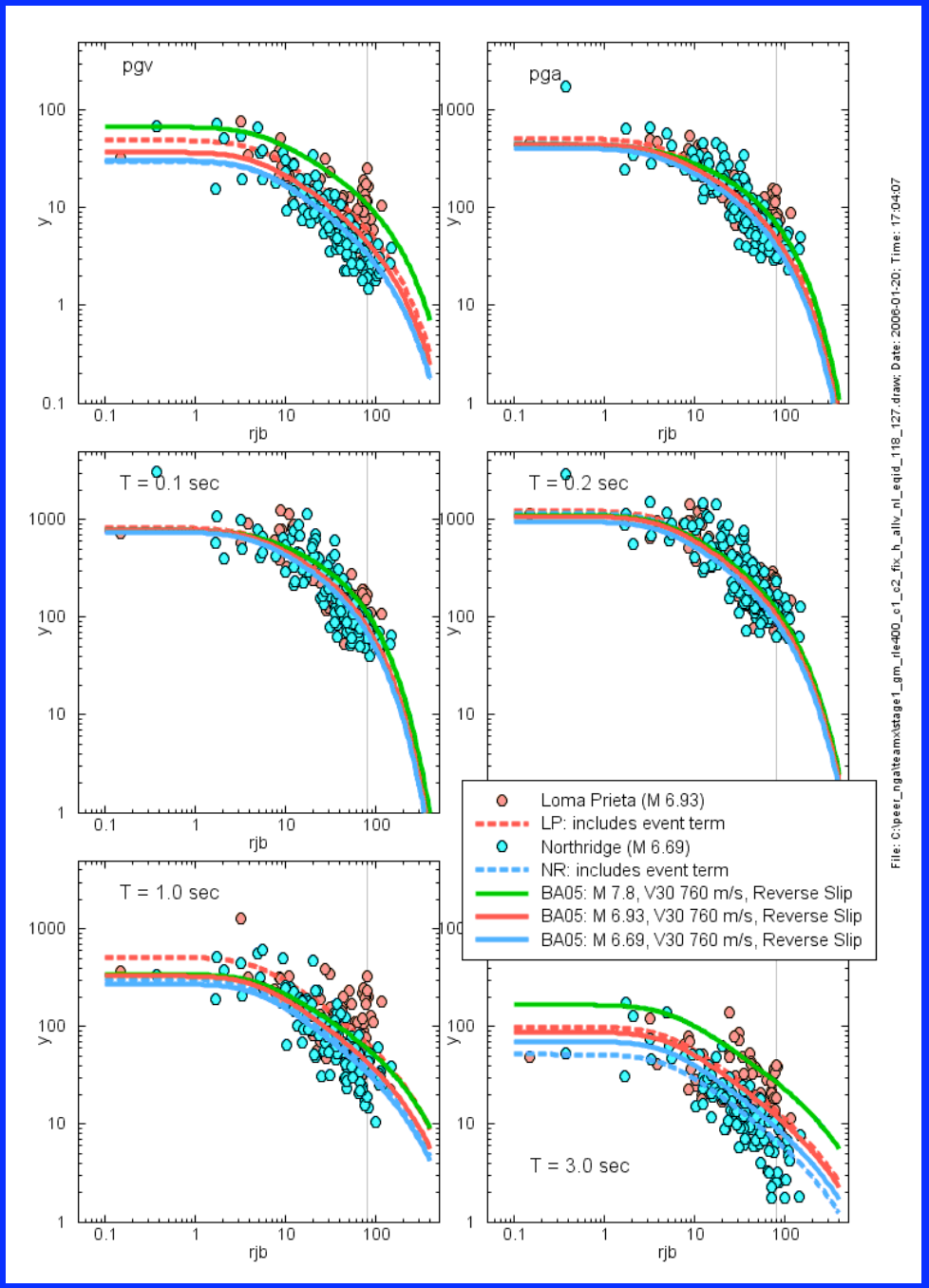

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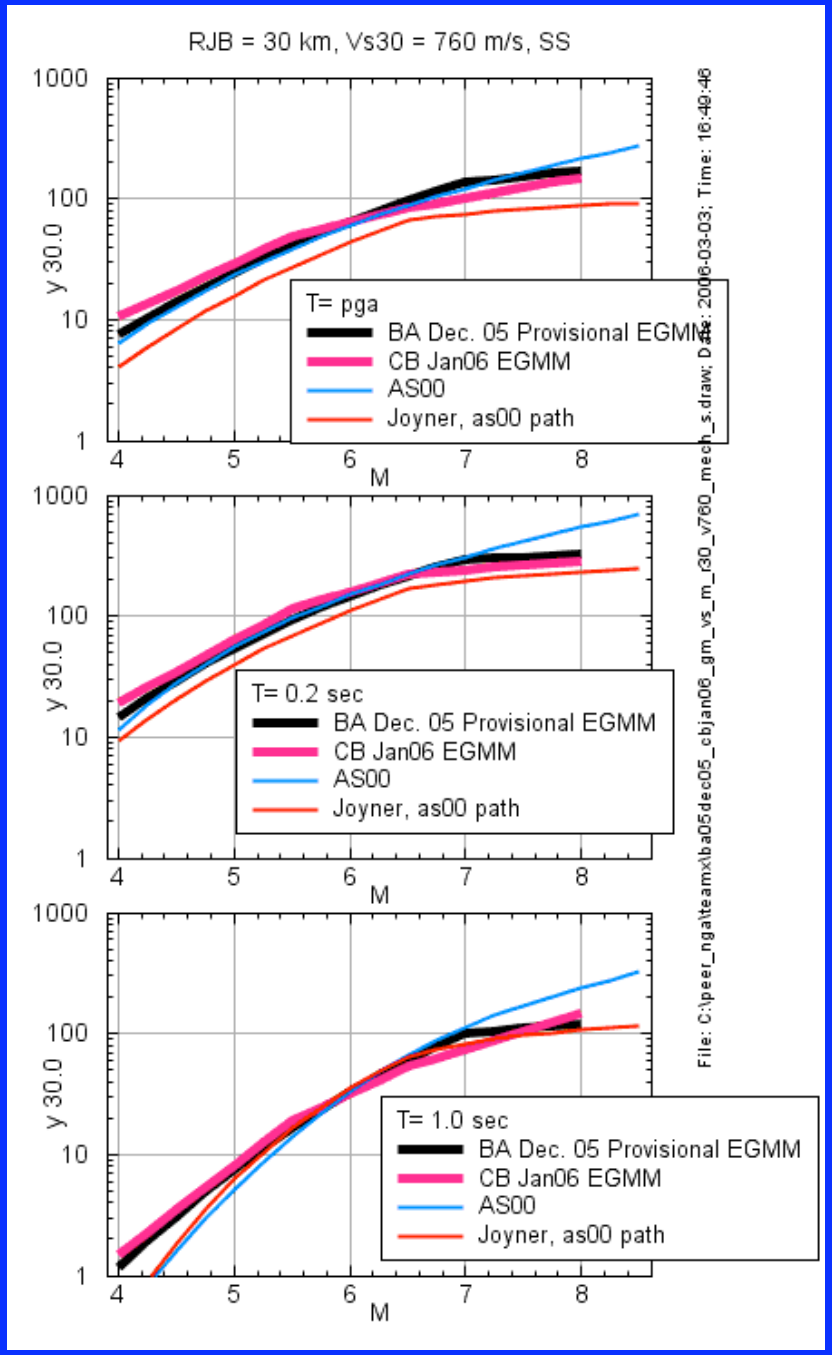

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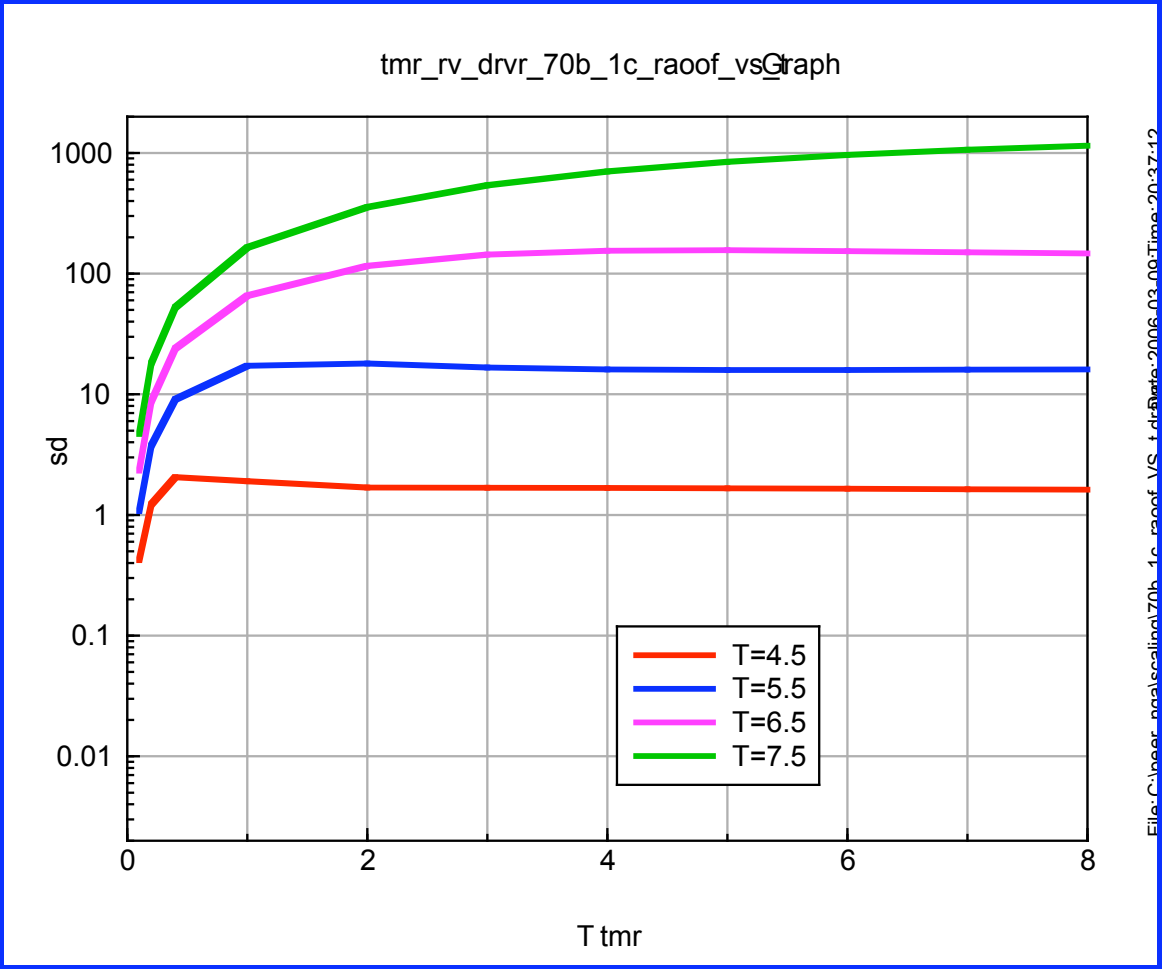
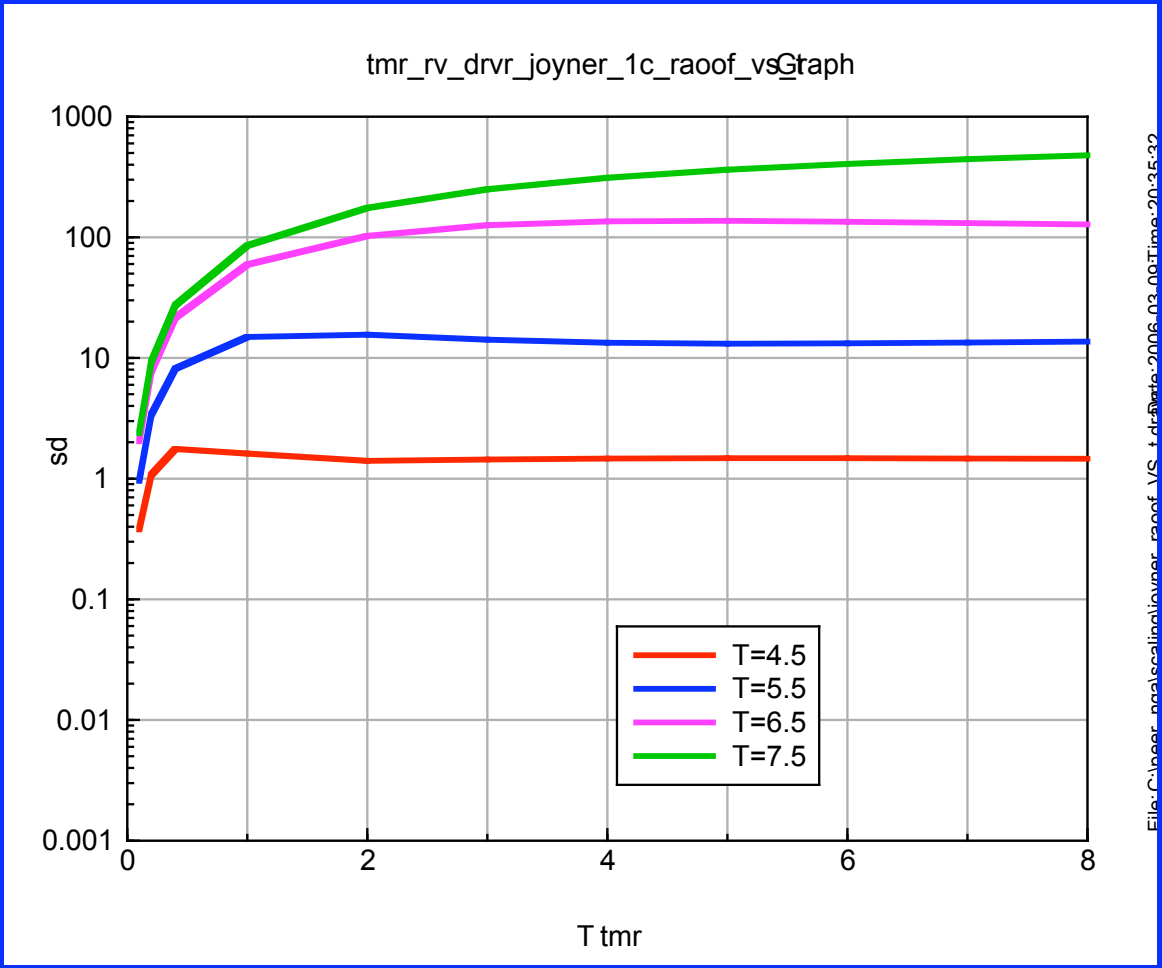
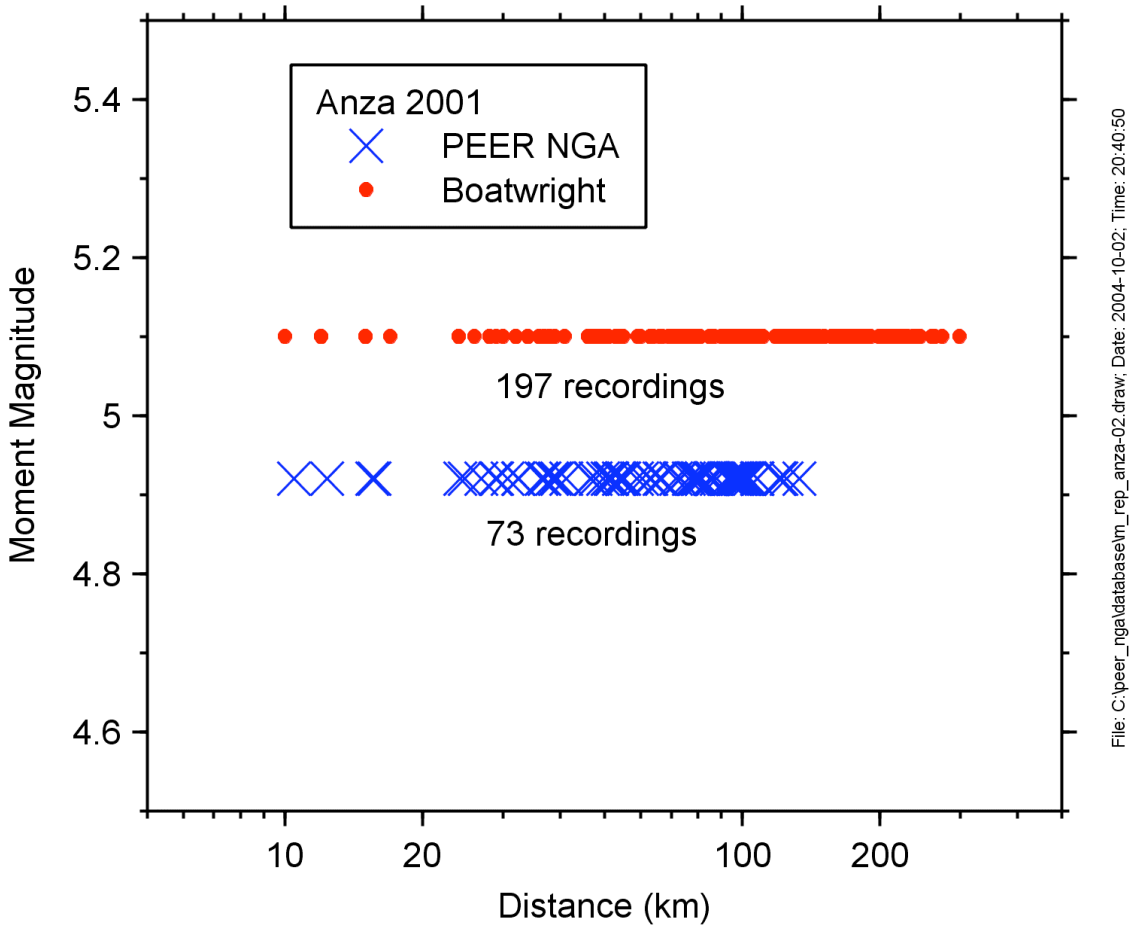
Single corner frequency, constant stress parameter scaling



(Ignore vertical axis– wrong distance used in simulations)

Joyner source model (not self similar above **M** 6.5)





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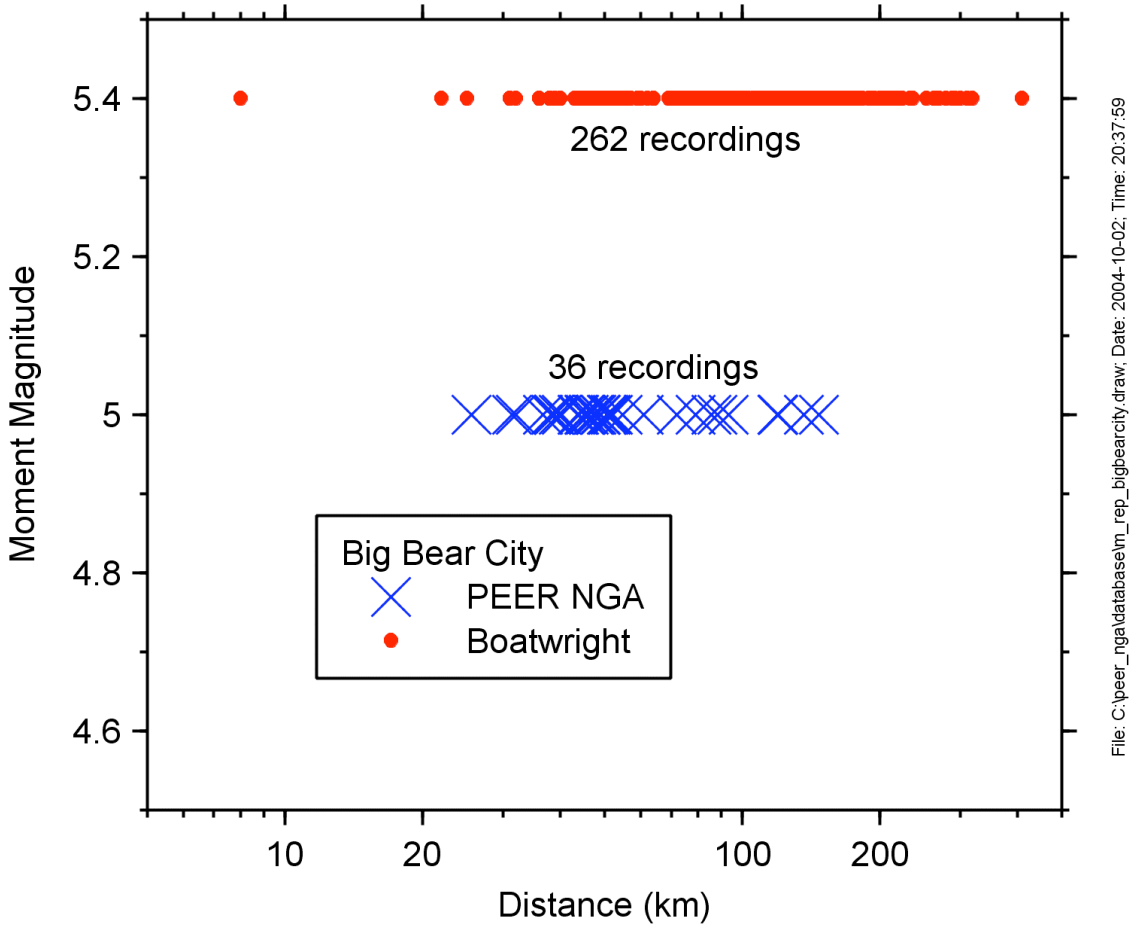

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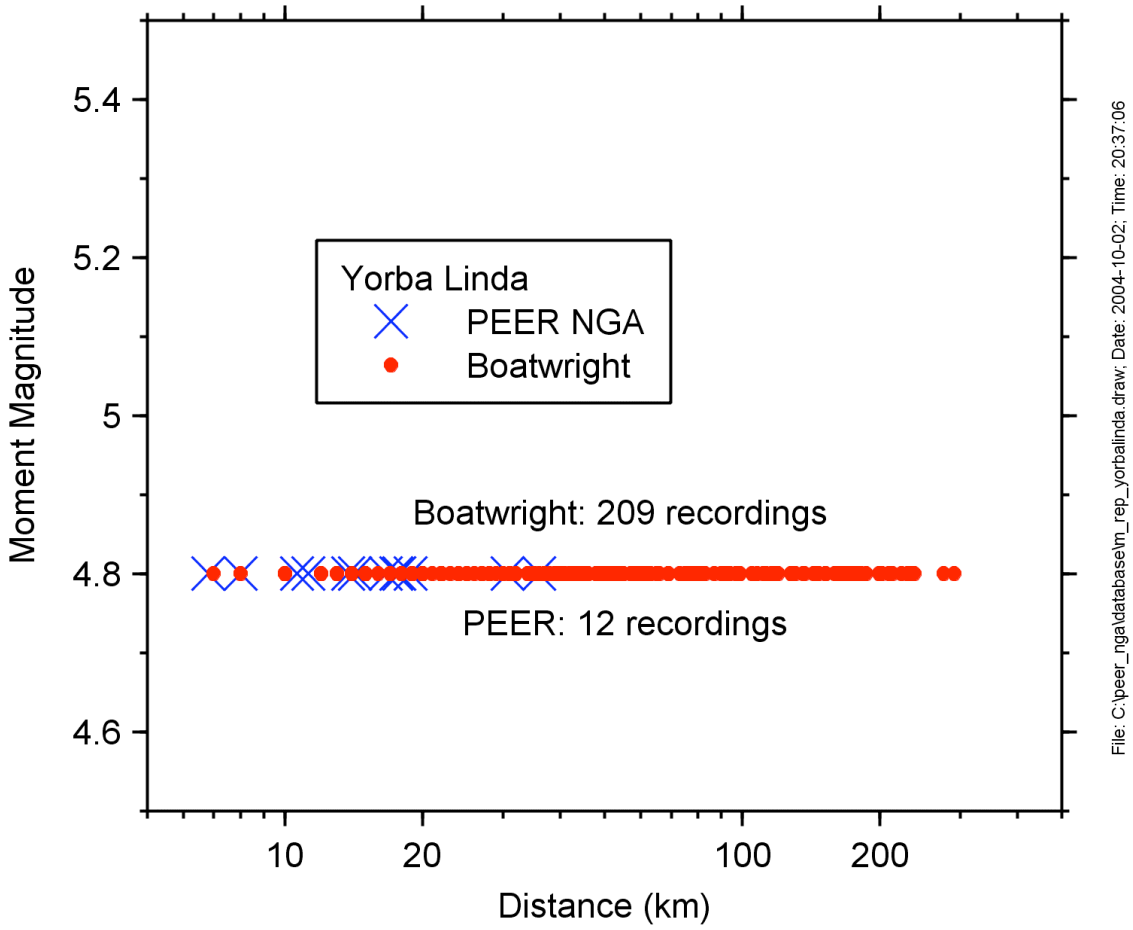

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Some characteristics of the dataset

- Distance decay
- Magnitude dependence

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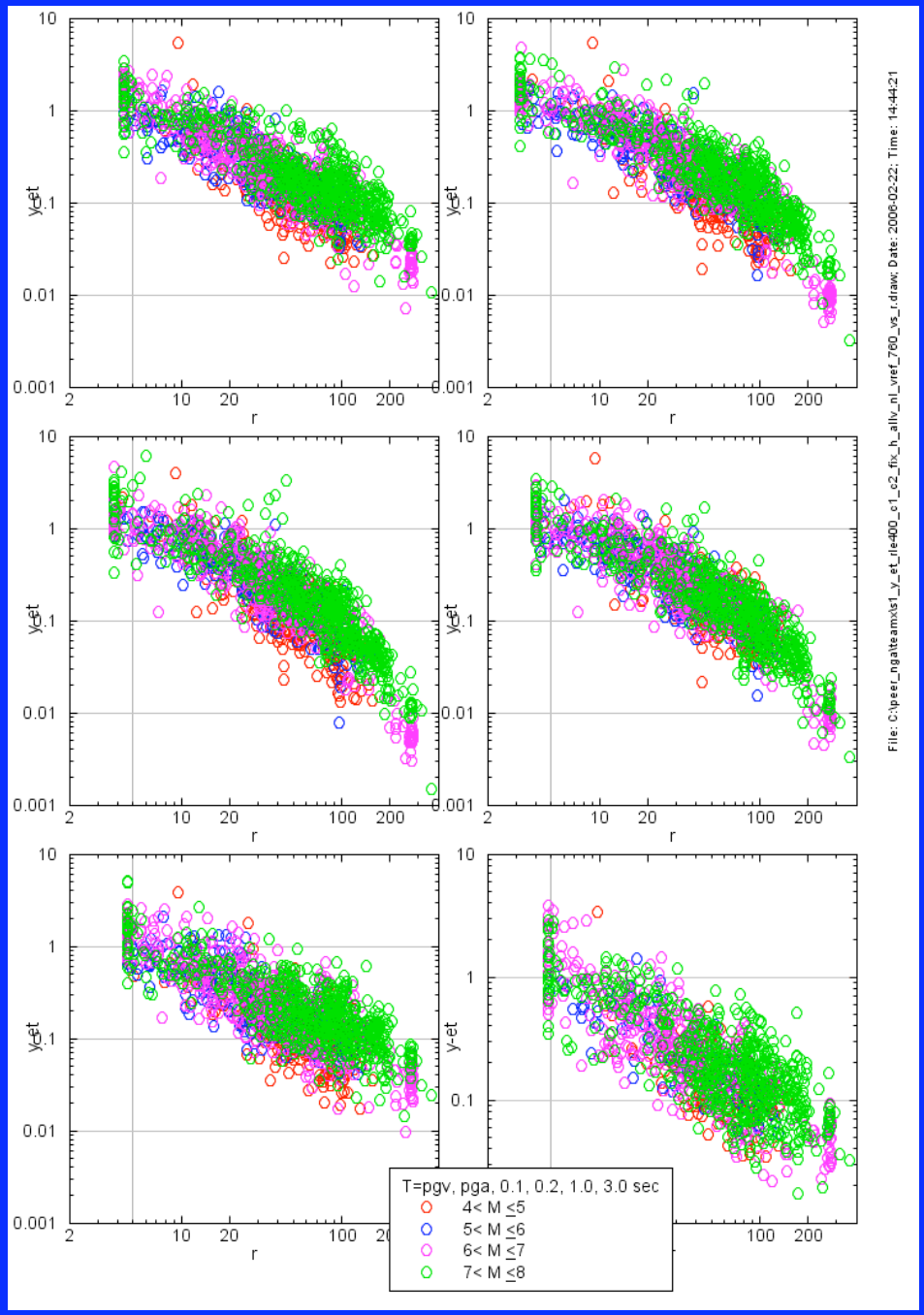
Not a strong magnitude dependence to distance decay



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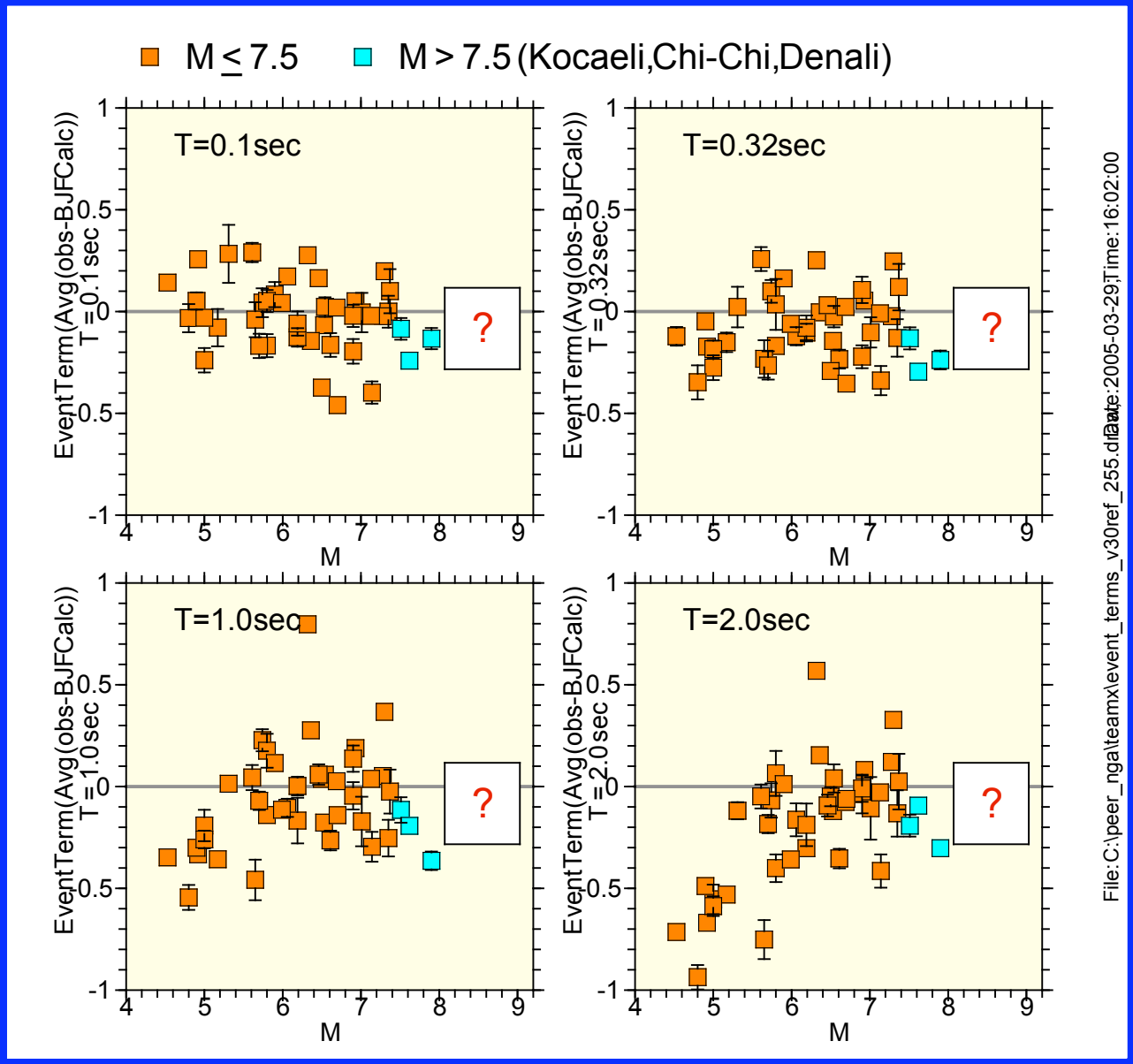
M ≤ 7.5
M > 7.5 (Kocaeli,Chi-Chi,Denali)
T=0.1sec
T=0.32sec
T=1.0sec
T=2.0sec
EventTerm(Avg(obs-BJFCalc))
T =0.1 sec
T =0.32sec
T =1.0sec
T =2.0sec
M
?
File:C:\peer_nga\teamx\event_terms_v30ref_255.dra Date:2005-03-29 Time:16:02:00

Boore-Atkinson	Campbell-Bozorgnia
M	**M**
R_{JB}	R_{JB}, R_{CD}
Vs_{30}	Vs_{30}
mechanism	mechanism
	Depth to top of rupture
	Depth to 2.5 m/s velocity

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Boore-Atkinson	Campbell-Bozorgnia
Soil nonlinearity (taken from Choi and Stewart)	Soil nonlinearity (from theory and empirical data analysis)
	Hanging-wall effects
	Basin depth effects

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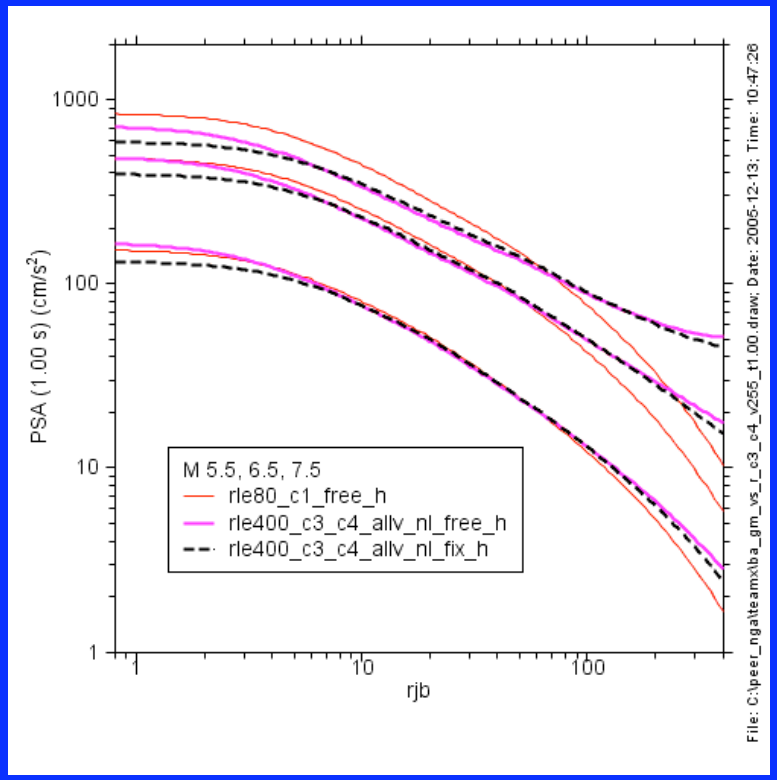

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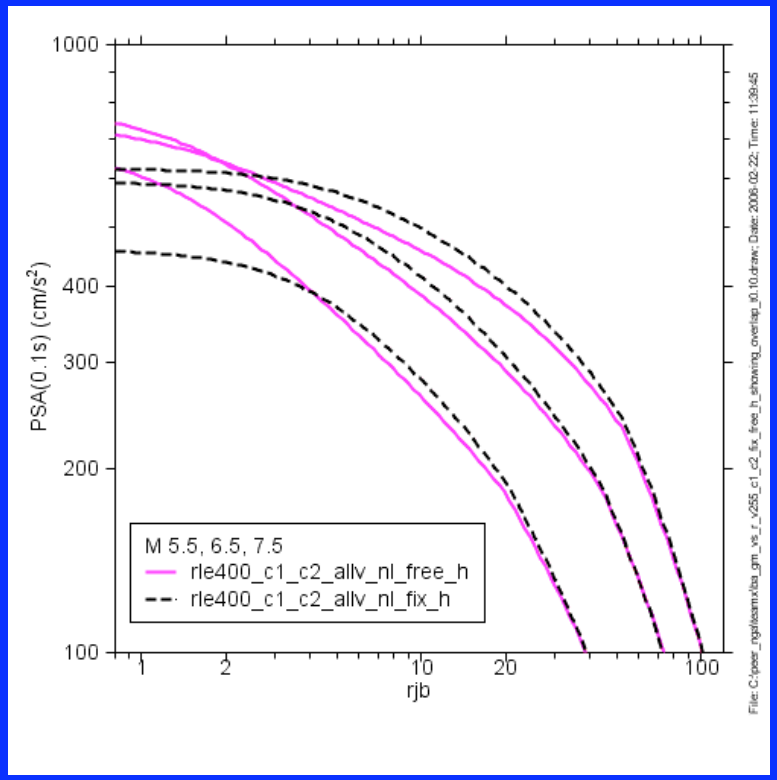

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$$\ln Y = F_M(\mathrm{M}) + F_D(r_{jb}, \mathrm{M}) + F_S(V_{30}, r_{jb}, \mathrm{M}) + \varepsilon\sigma$$

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