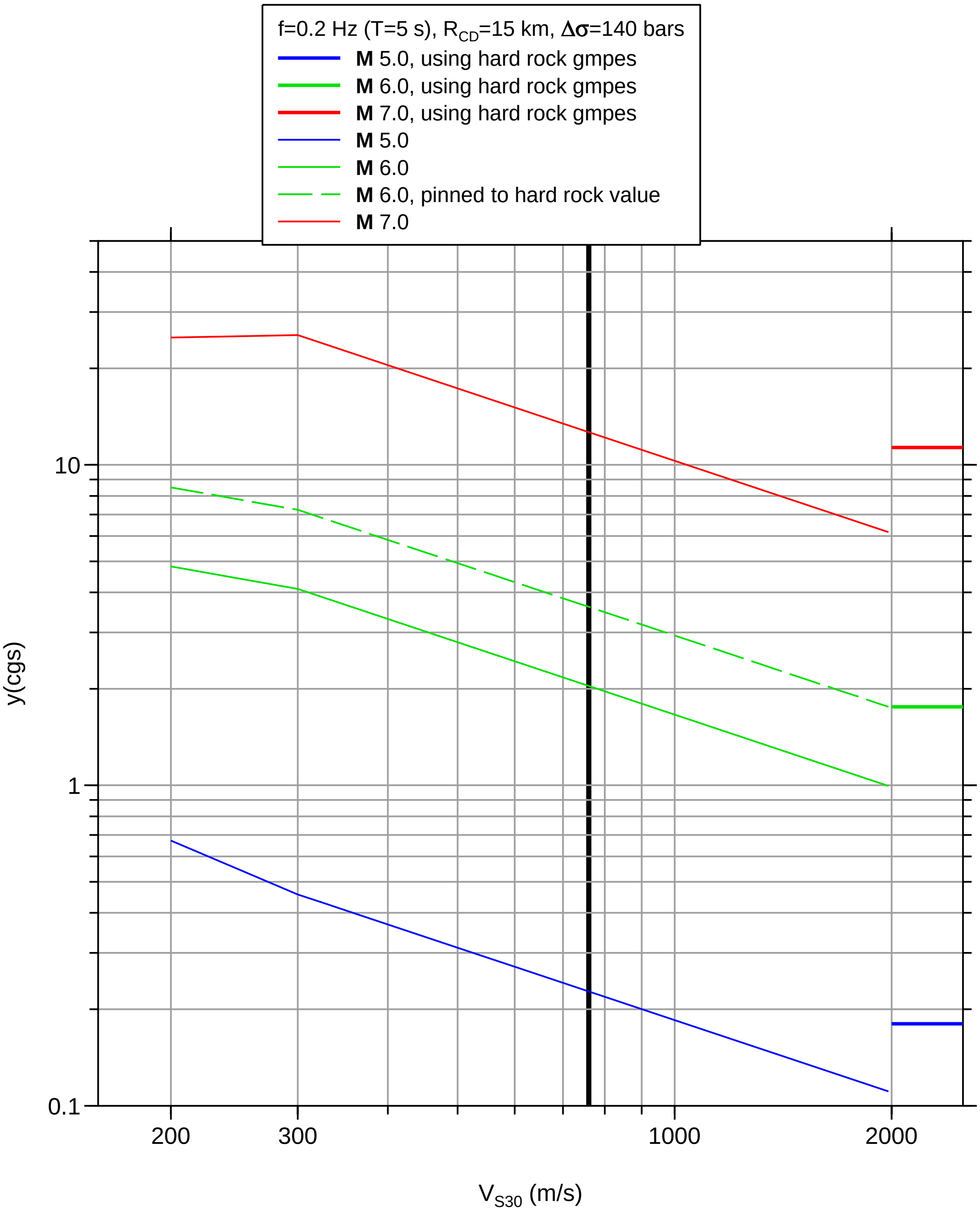
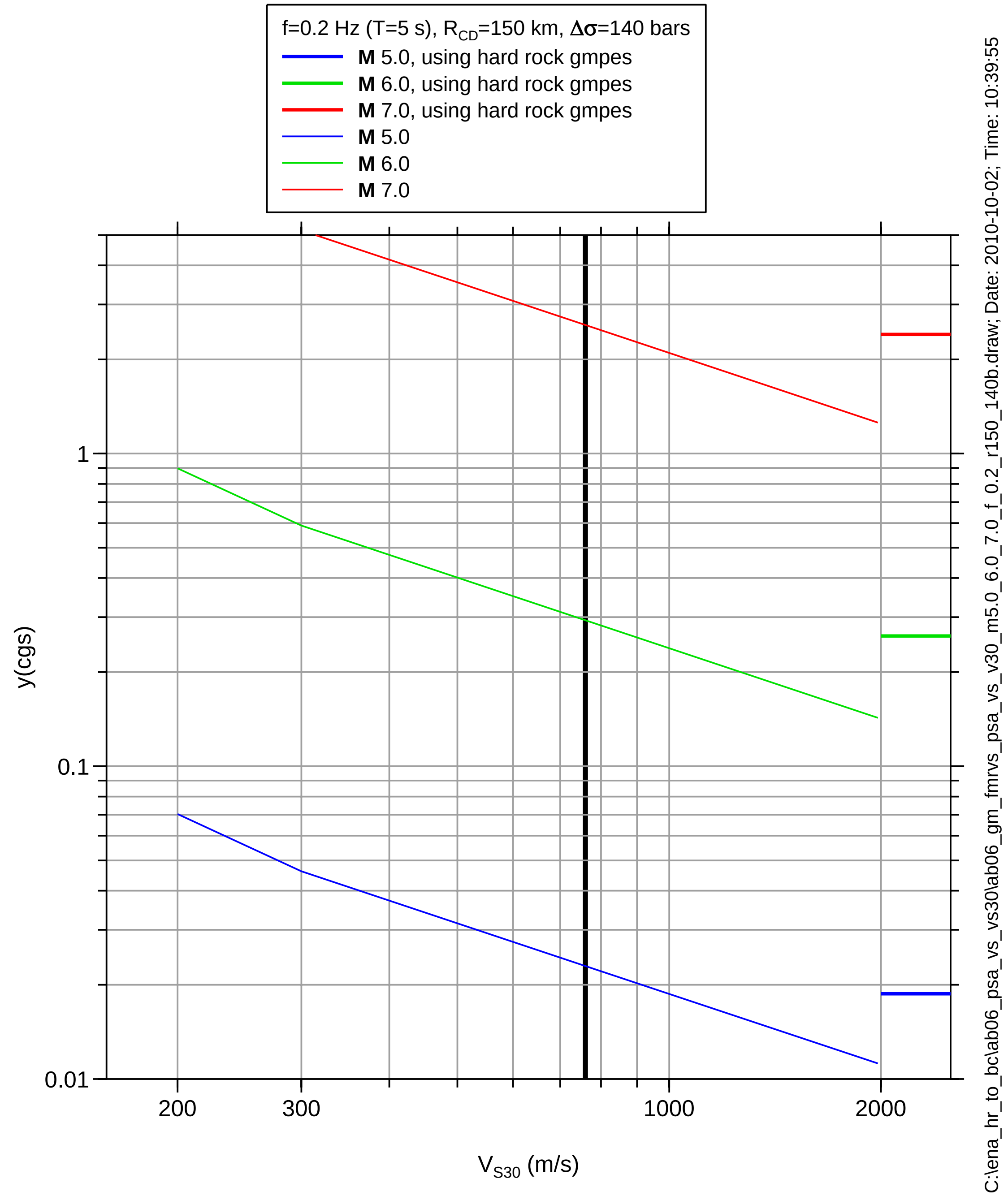
Comparing Atkinson and Boore (2006) (AB06) motions for hard rock GMPEs and BC gmpes, with site amplifications as a function of V_{S30}.

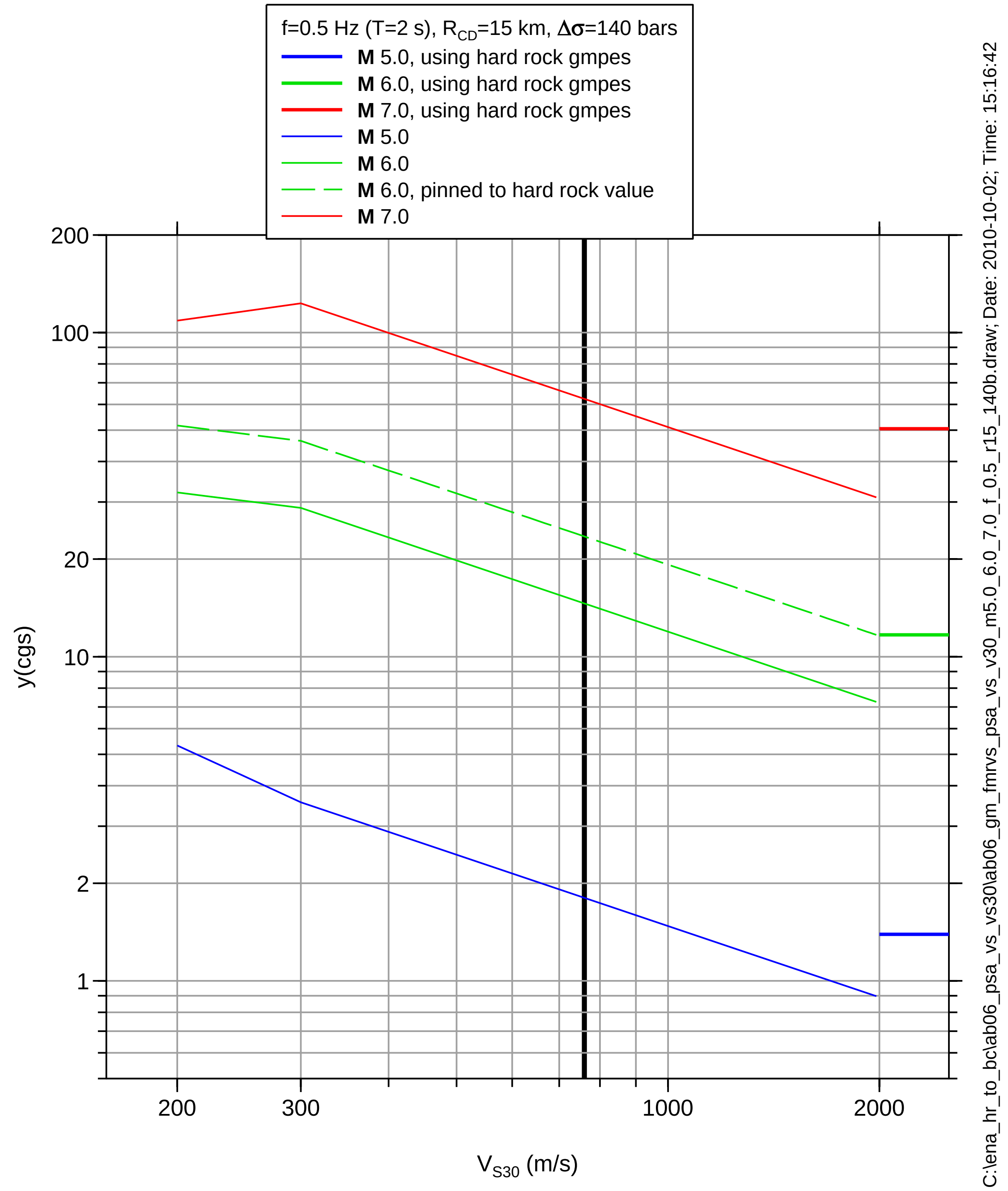
AB06 has two sets of coefficients, one for hard rock and one for BC conditions ($V_{S30} = 760 \text{ m/s}$). The site amplifications for the BC simulations are given in Table 4 of AB06. These were derived using the velocity profile in Frankel et al. (1996), using square-root-impedance calculations (but note that the average kappa used in deriving the BC motions was 0.02 s, whereas that used by Frankel et al. was 0.01 s). (For the convenience of the reader, the relevant portions of the AB06 paper discussing the development of the BC motions and also the equations for soil response are included at the end of this document.) In addition, soil amplification factors from Boore and Atkinson (2008) (BA08) are provided to allow the prediction of ground motions for sites with V_{S30} not equal to 760 m/s (the BA08 amplifications are based on Choi and Stewart, 200x). But these coefficients were not to be used for $V_{S30} > 1300 \text{ m/s}$. These notes show the consequence of ignoring that stipulation. The figures are for PSA at f=0.2, 0.5, 1.0, 5.0, 10.0 Hz (T=5, 2, 1, 0.2, and 0.1 s) and for PGA (f=99 in the figures, although this is not the oscillator frequency at which PSA~PGA in ENA; see http://www.daveboore.com/daves_notes/daves_notes_at_what_period_does_psa_equal_pga.pdf). Each figure shows *PSA* vs V_{S30}, for **M** 5, 6, and 7 and $\Delta\sigma = 140 \text{ bars}$. Separate figures are given for $R_{CD} = 15 \text{ km}$ and 150 km. The results should be self explanatory. A heavy vertical black line is plotted at the BC boundary velocity of 760 m/s. Did we constrain the two to give the same amplification for f=5 Hz and $V_{S30} = 2000 \text{ m/s}$? No.

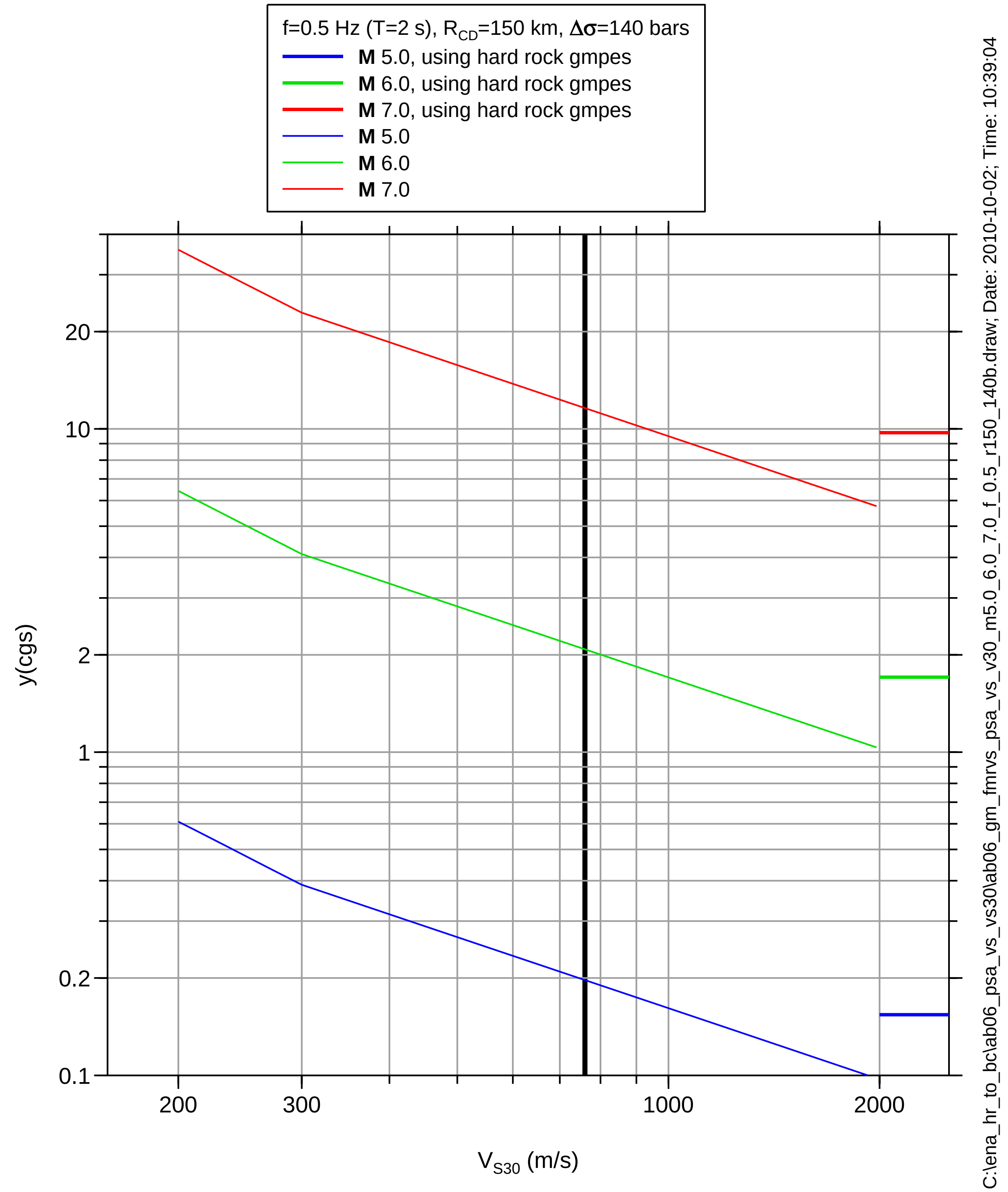
To show the effect of using the AB06 soil amplifications to go from hard rock to softer material, for R= 15 and **M** 6 I plot with dashed green lines the result of pinning the ground motions from the AB06 soil coefficients to the AB06 hard rock values.



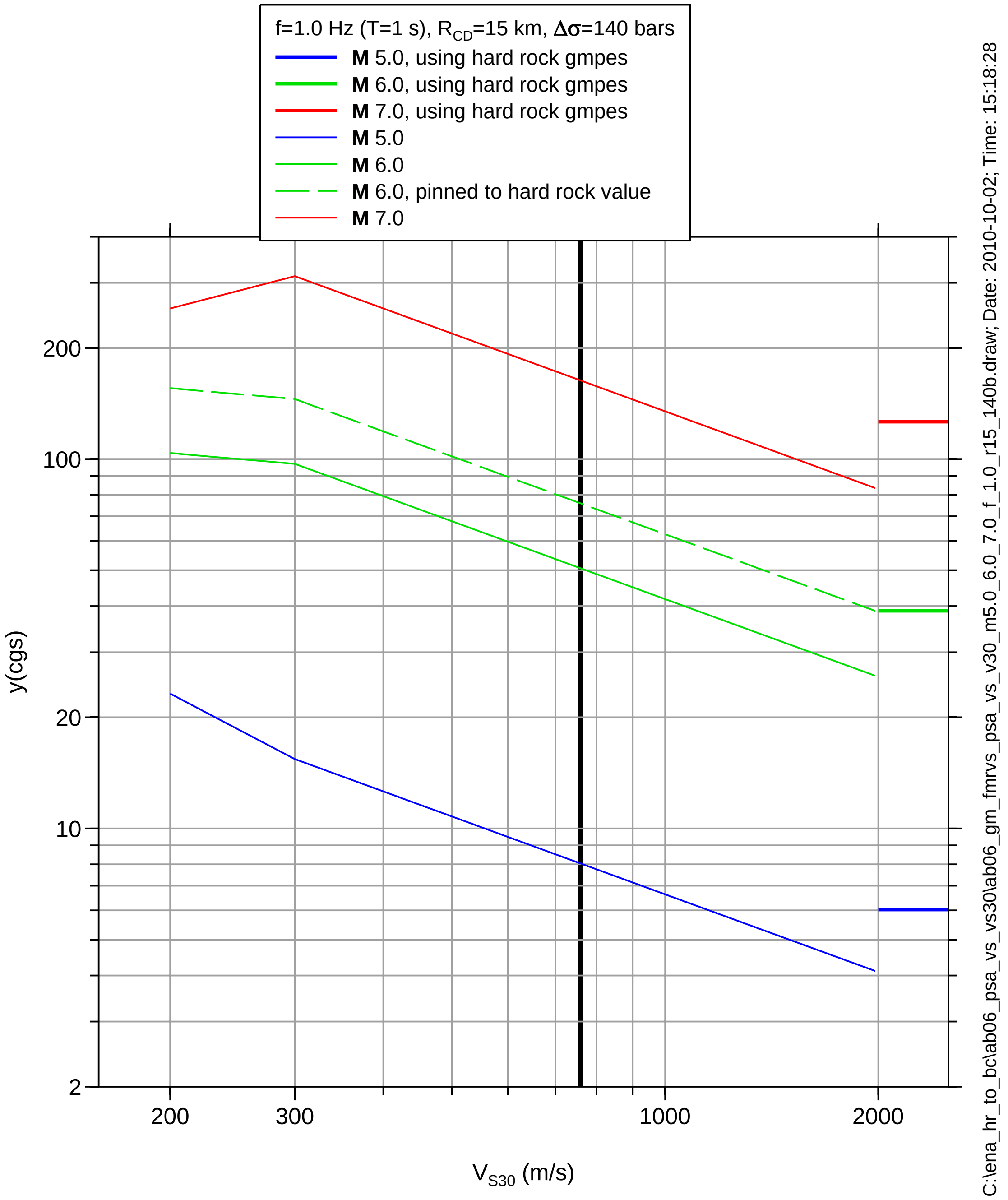
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_0.2_r15_140b.draw; Date: 2010-10-02; Time: 15:15:50

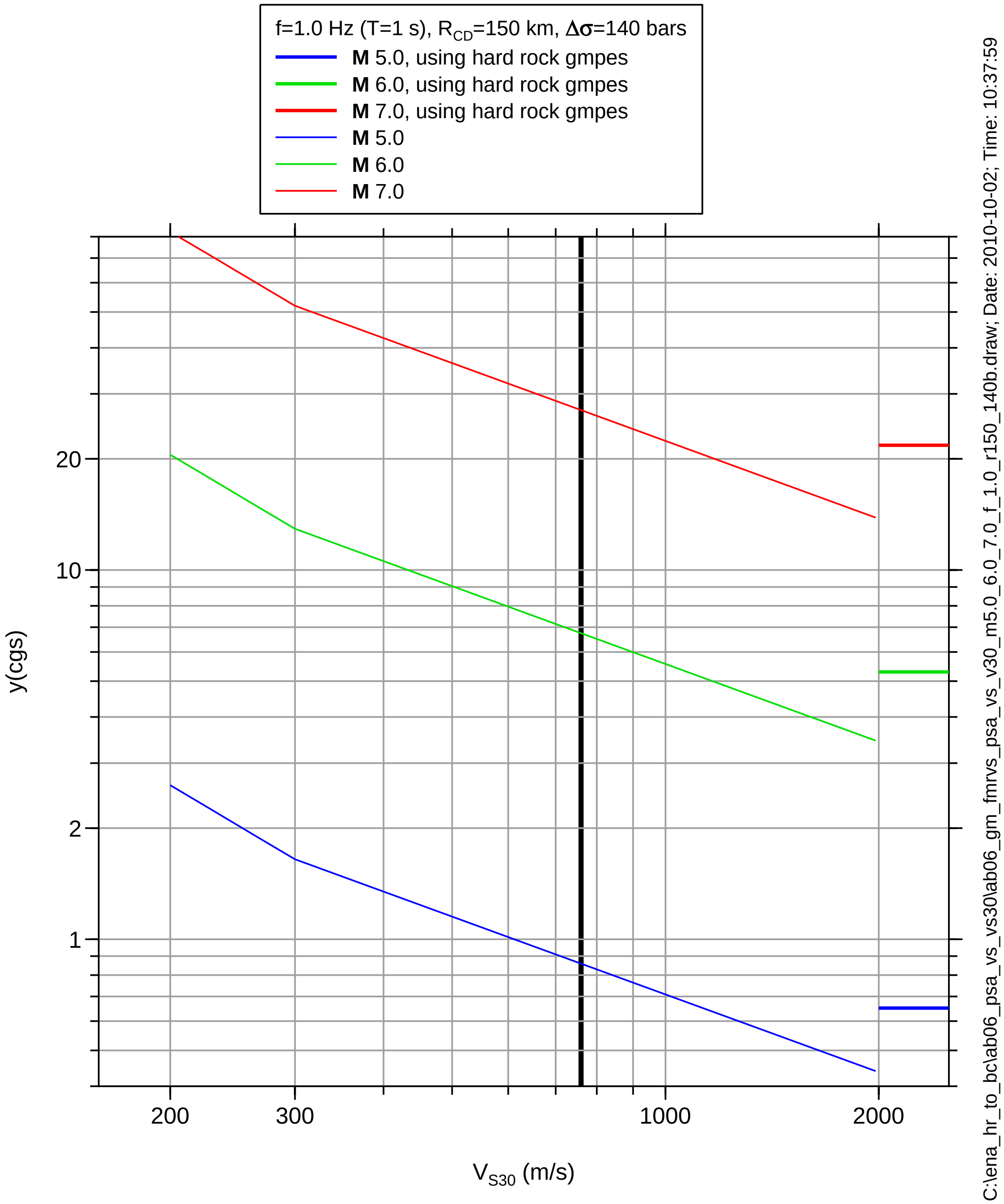

f=0.2 Hz (T=5 s), R_{CD}=150 km, Δσ=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 7.0
y(cgs)
1
0.1
0.01
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_0.2_r150_140b.draw; Date: 2010-10-02; Time: 10:39:55

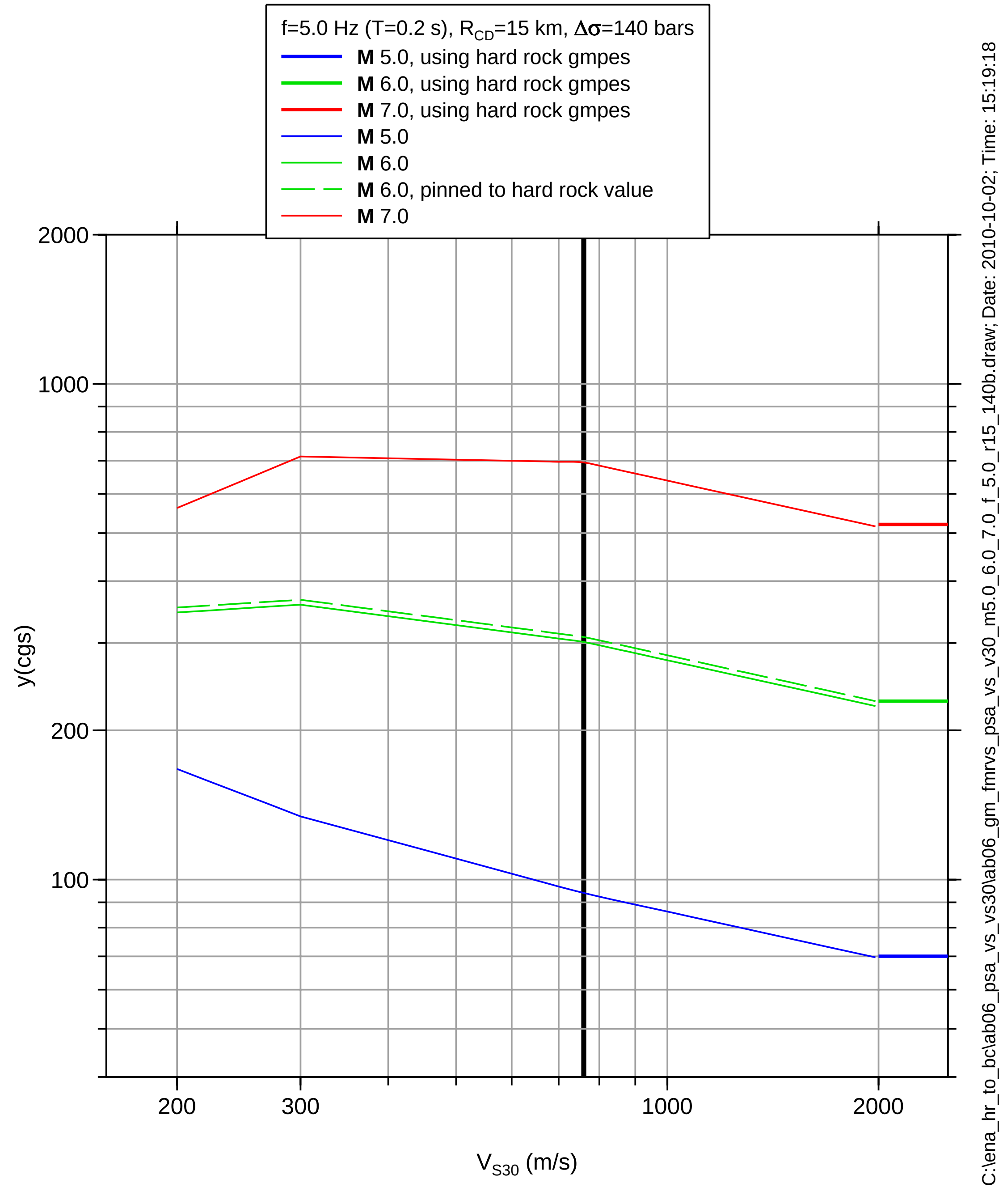

f=0.5 Hz (T=2 s), R_{CD}=15 km, $\Delta\sigma$=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 6.0, pinned to hard rock value
M 7.0
200
100
20
10
2
1
y(cgs)
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_0.5_r15_140b.draw; Date: 2010-10-02; Time: 15:16:42



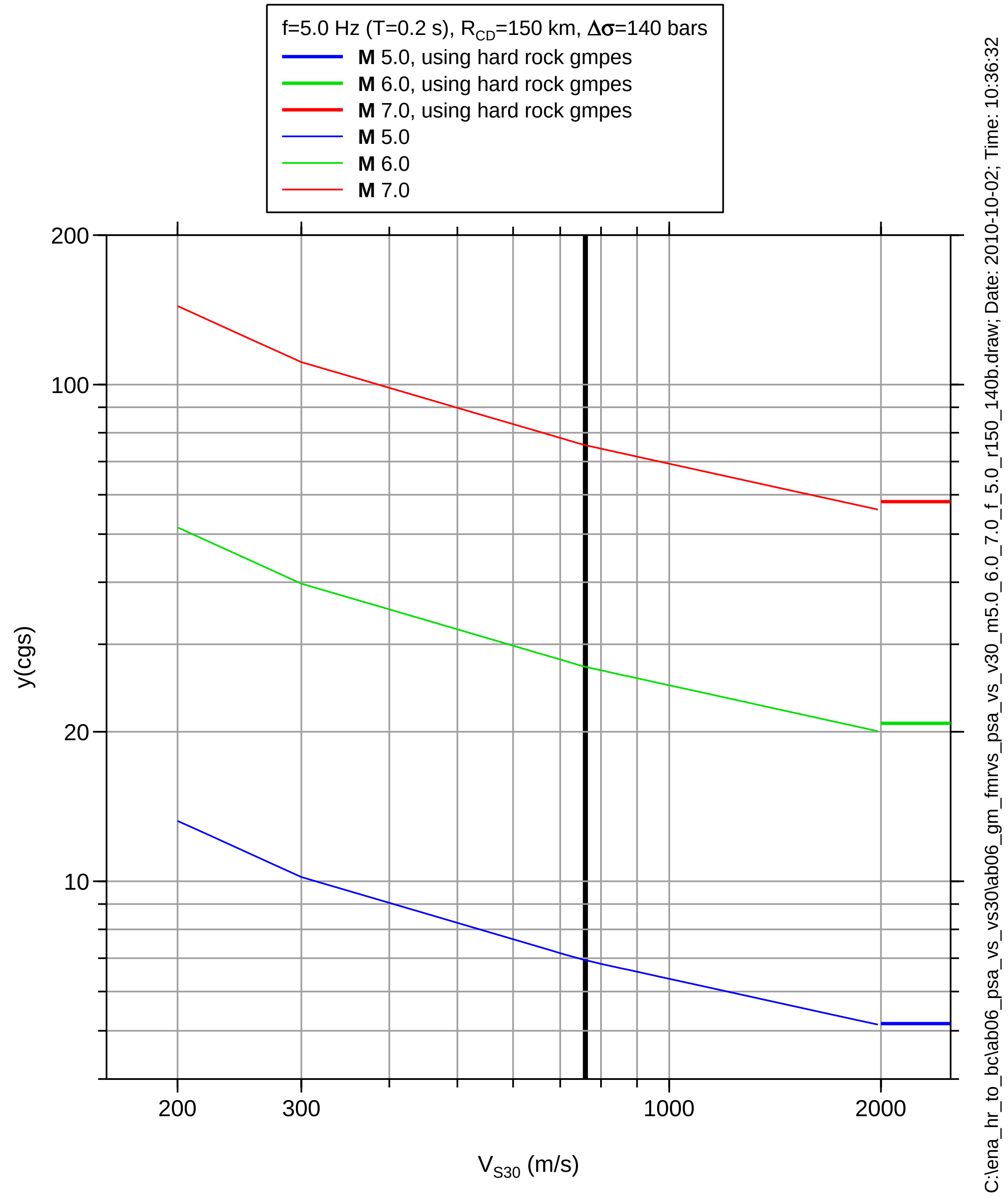
f=0.5 Hz (T=2 s), R_{CD}=150 km, Δσ=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 7.0
y(cgs)
20
10
2
1
0.2
0.1
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_0.5_r150_140b.draw; Date: 2010-10-02; Time: 10:39:04

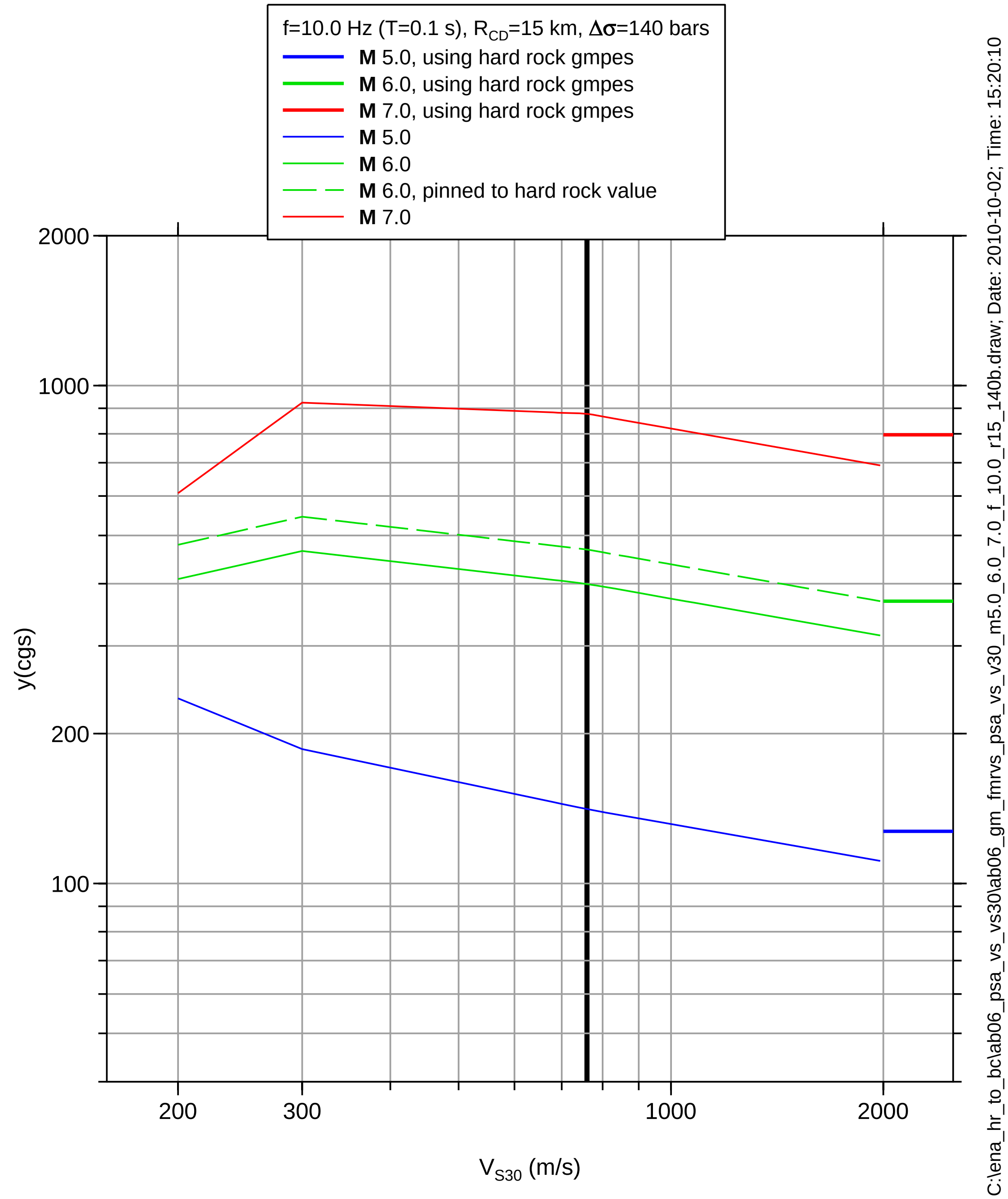

f=1.0 Hz (T=1 s), R_{CD}=15 km, $\Delta\sigma$=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 6.0, pinned to hard rock value
M 7.0
y(cgs)
200
100
20
10
2
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_1.0_r15_140b.draw; Date: 2010-10-02; Time: 15:18:28

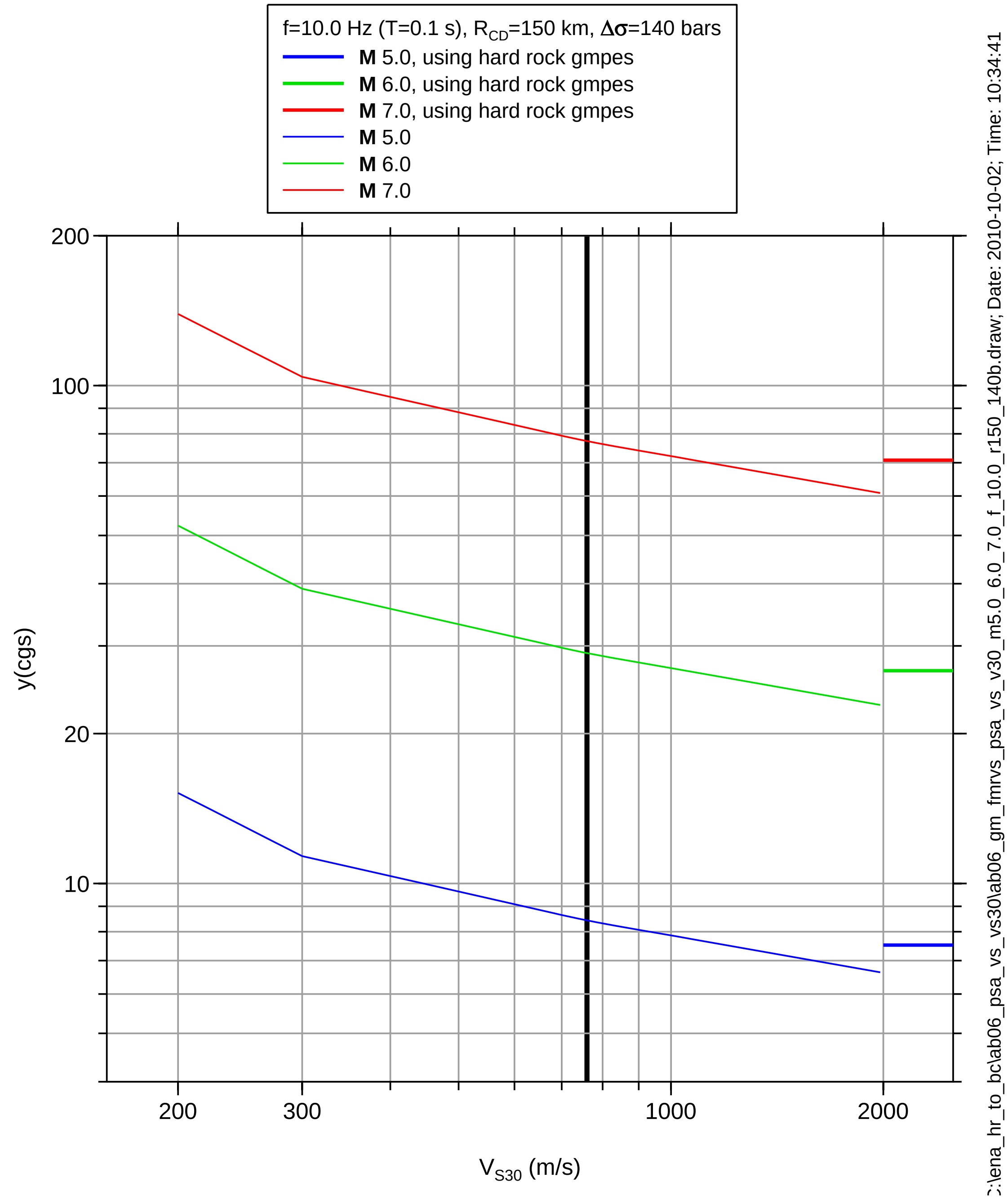

f=1.0 Hz (T=1 s), R_{CD}=150 km, $\Delta\sigma$=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 7.0
y(cgs)
20
10
2
1
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_1.0_r150_140b.draw; Date: 2010-10-02; Time: 10:37:59

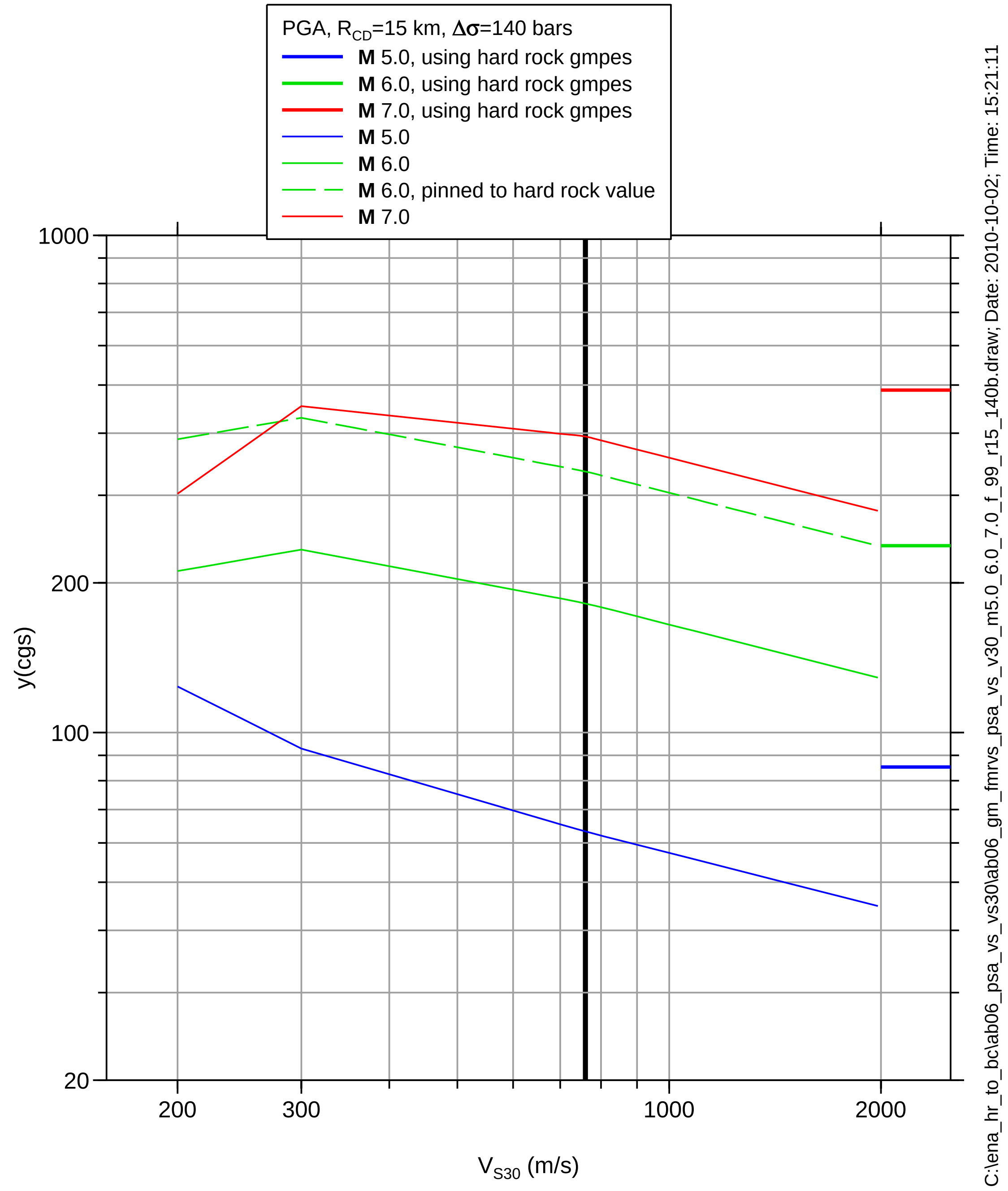


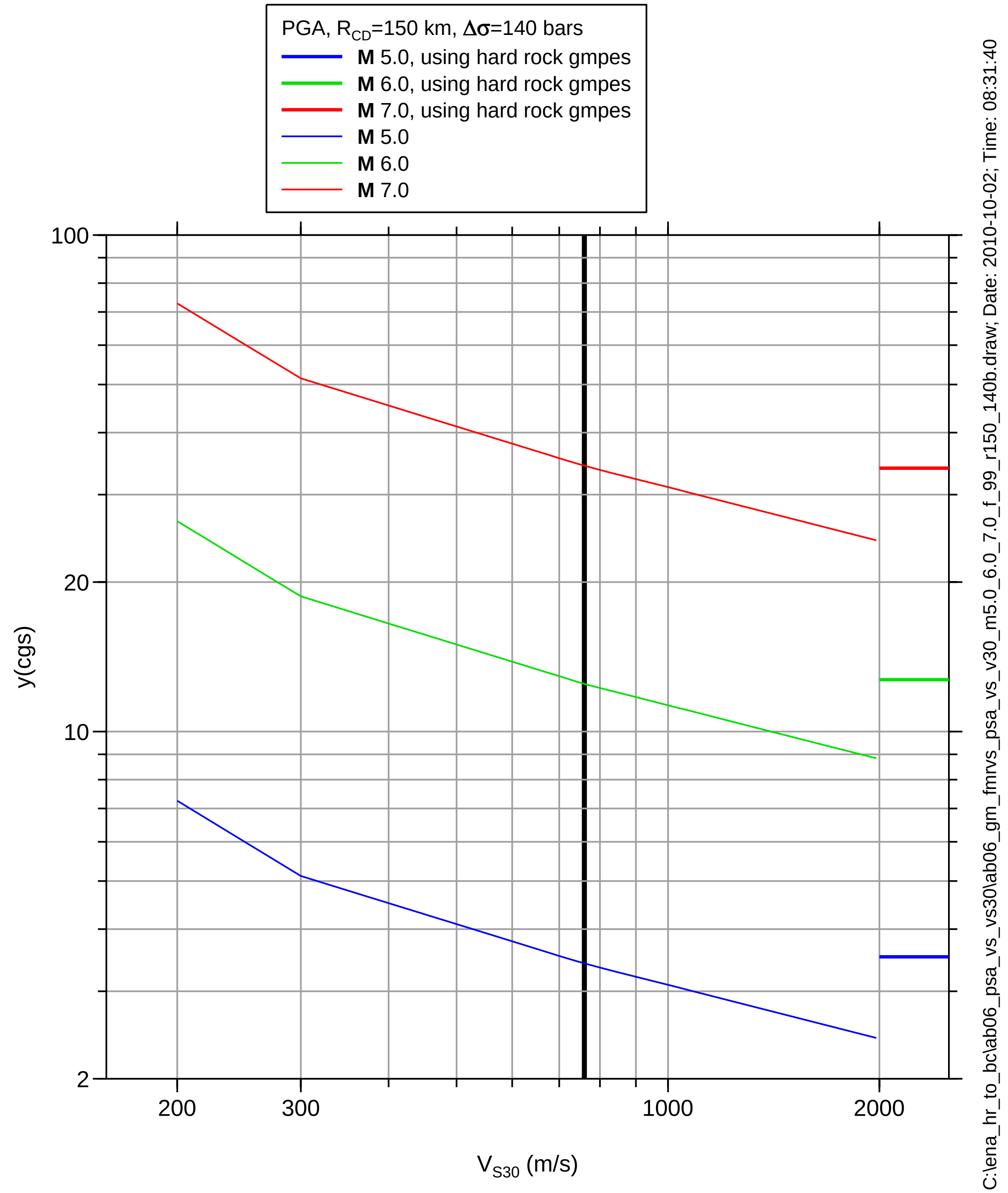
f=5.0 Hz (T=0.2 s), R_{CD}=15 km, $\Delta\sigma$=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 6.0, pinned to hard rock value
M 7.0
2000
1000
200
100
y(cgs)
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_5.0_r15_140b.draw; Date: 2010-10-02; Time: 15:19:18


f=5.0 Hz (T=0.2 s), R_{CD}=150 km, $\Delta\sigma$=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 7.0
200
100
20
10
y(cgs)
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_5.0_r150_140b.draw; Date: 2010-10-02; Time: 10:36:32


f=10.0 Hz (T=0.1 s), R_CD=15 km, Δσ=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 6.0, pinned to hard rock value
M 7.0
2000
1000
200
100
y(cgs)
200
300
1000
2000
VS30 (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_10.0_r15_140b.draw; Date: 2010-10-02; Time: 15:20:10


f=10.0 Hz (T=0.1 s), R_{CD}=150 km, $\Delta\sigma$=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 7.0
200
100
20
10
y(cgs)
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_10.0_r150_140b.draw; Date: 2010-10-02; Time: 10:34:41


PGA, R_{CD}=15 km, $\Delta\sigma$=140 bars
M 5.0, using hard rock gmpes
M 6.0, using hard rock gmpes
M 7.0, using hard rock gmpes
M 5.0
M 6.0
M 6.0, pinned to hard rock value
M 7.0
1000
200
100
20
y(cgs)
200
300
1000
2000
V_{S30} (m/s)
C:\ena_hr_to_bc\ab06_psa_vs_vs30\ab06_gm_fmrvs_psa_vs_v30_m5.0_6.0_7.0_f_99_r15_140b.draw; Date: 2010-10-02; Time: 15:21:11



Some observations:

1. The amplifications have little dependence on **M** and R, as expected (except for higher frequencies, small V_{S30}, large **M** and small R, where nonlinear effects are important).

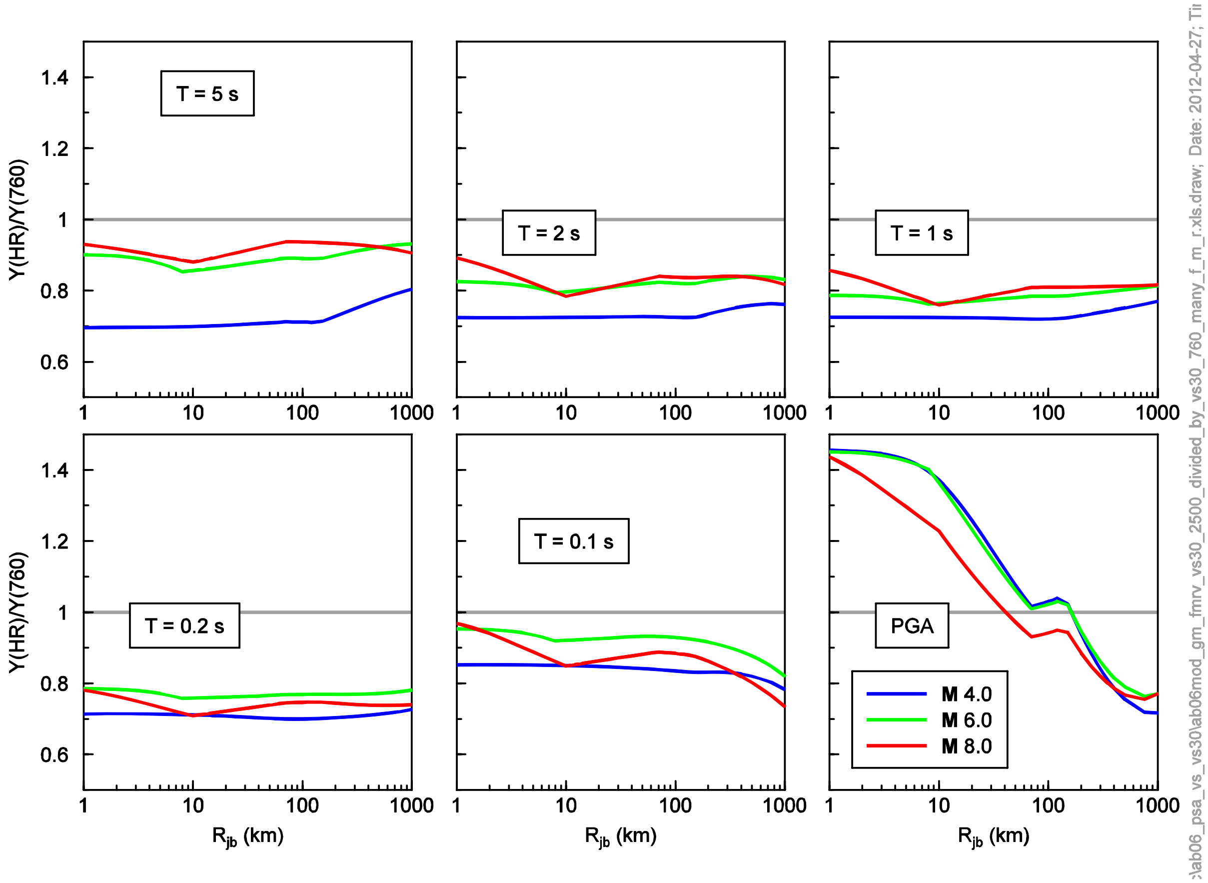
2. If I had used soil amps to go from HR to softer material, in all but the f=5 Hz cases the motions would be overpredicted (by a factor of 1.9 for PGA).

Discussion:

The results above suggest a procedure for modifying stable continental region GMPEs (SCR GMPEs) developed for Vs30 that are lower than 2000 m/s to very hard rock site conditions (e.g., Somerville et al., 2009) use Vs30=865 m/s):

1. Use the soil amps in GMPEs such as the NGA-W GMPEs to modify the PSA values from the Vs30 used in the derivation of the SCR GMPEs to Vs30=760 m/s.

2. Use ratios of AB06 (modified as in AB11) PSA for very hard rock to BC to modify the modified SCR GMPE PSA values. Here is a figure of the AB06 ratios for many M, R, and periods (the values greater than unity for PGA are due to the very low value of kappa used for hard rock---0.005 s vs 0.02 s for BC.



I'll provide a table of ratios upon request.

Note that the suggested procedure is dependent on the velocity profile and kappa used by AB06 in deriving their BC amplifications. In particular, for short period PSA and PGA the kappa used in the AB06 BC simulations would give very different results than if a different value of kappa was used (e.g., Frankel et al. (1996) used kappa=0.01 s). I have not shown that here, but it is in a draft note that Ken Campbell and I are preparing. Also see Van Houtte et al. (2011).

References

Atkinson, G.M. and D.M. Boore (2006). Earthquake ground-motion prediction equations for eastern North America, *Bull. Seismol. Soc. Am.* **96**, 2181—2205.

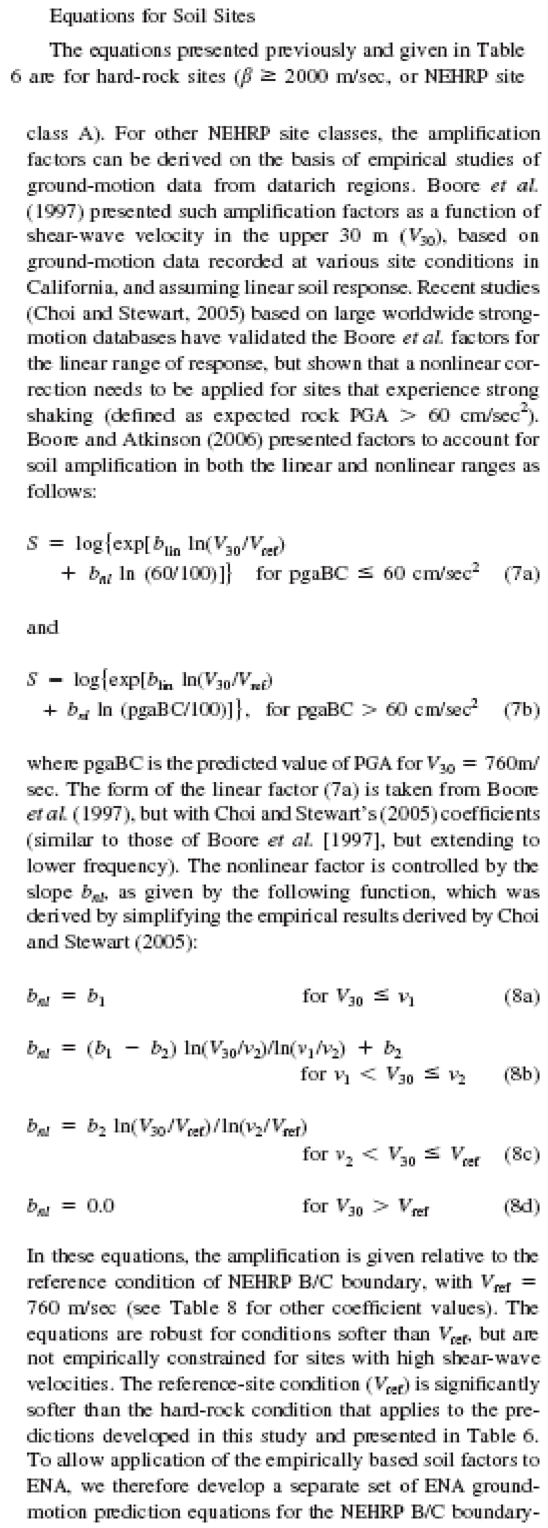
Boore, D. M. and G. M. Atkinson (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, *Earthquake Spectra* **24**, 99--138.

Choi, Y. and J. P. Stewart (2005). Nonlinear site amplification as function of 30 m shear wave velocity, *Earthquake Spectra* **21**, 1–30.

Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E. Leyendecker, N. Dickman, S. Hanson and M. Hopper (1996). National seismic hazard maps: Documentation June 1996, *U. S. Geological Survey Open-File Report* **96-532**, 69 pp.

Van Houtte, C., S. Drouet, and F. Cotton (2011). Analysis of the origins of κ (kappa) to compute hard rock to rock adjustment factors for GMPEs, *Bull. Seismol. Soc. Am.* **101,** 2926--2941.

Excerpt from AB06 regarding the soil amplifications:



Equations for Soil Sites

The equations presented previously and given in Table 6 are for hard-rock sites ($\beta \geq 2000$ m/sec, or NEHRP site class A). For other NEHRP site classes, the amplification factors can be derived on the basis of empirical studies of ground-motion data from datarich regions. Boore *et al.* (1997) presented such amplification factors as a function of shear-wave velocity in the upper 30 m (V_{30}), based on ground-motion data recorded at various site conditions in California, and assuming linear soil response. Recent studies (Choi and Stewart, 2005) based on large worldwide strong-motion databases have validated the Boore *et al.* factors for the linear range of response, but shown that a nonlinear correction needs to be applied for sites that experience strong shaking (defined as expected rock PGA > 60 cm/sec^2). Boore and Atkinson (2006) presented factors to account for soil amplification in both the linear and nonlinear ranges as follows:

$$S = \log\{\exp[b_{\text{lin}} \ln(V_{30}/V_{\text{ref}}) + b_{nl} \ln(60/100)]\} \quad \text{for pgaBC} \leq 60 \text{ cm/sec}^2 \qquad (7a)$$

and

$$S = \log\{\exp[b_{\text{lin}} \ln(V_{30}/V_{\text{ref}}) + b_{nl} \ln(\text{pgaBC}/100)]\}, \quad \text{for pgaBC} > 60 \text{ cm/sec}^2 \qquad (7b)$$

where pgaBC is the predicted value of PGA for $V_{30} = 760$m/sec. The form of the linear factor (7a) is taken from Boore *et al.* (1997), but with Choi and Stewart's (2005) coefficients (similar to those of Boore *et al.* [1997], but extending to lower frequency). The nonlinear factor is controlled by the slope b_{nl}, as given by the following function, which was derived by simplifying the empirical results derived by Choi and Stewart (2005):

$$b_{nl} = b_1 \qquad \text{for } V_{30} \leq v_1 \qquad (8a)$$

$$b_{nl} = (b_1 - b_2)\ln(V_{30}/v_2)/\ln(v_1/v_2) + b_2 \qquad \text{for } v_1 < V_{30} \leq v_2 \qquad (8b)$$

$$b_{nl} = b_2 \ln(V_{30}/V_{\text{ref}})/\ln(v_2/V_{\text{ref}}) \qquad \text{for } v_2 < V_{30} \leq V_{\text{ref}} \qquad (8c)$$

$$b_{nl} = 0.0 \qquad \text{for } V_{30} > V_{\text{ref}} \qquad (8d)$$

In these equations, the amplification is given relative to the reference condition of NEHRP B/C boundary, with $V_{\text{ref}} = 760$ m/sec (see Table 8 for other coefficient values). The equations are robust for conditions softer than V_{ref}, but are not empirically constrained for sites with high shear-wave velocities. The reference-site condition (V_{ref}) is significantly softer than the hard-rock condition that applies to the predictions developed in this study and presented in Table 6. To allow application of the empirically based soil factors to ENA, we therefore develop a separate set of ENA ground-motion prediction equations for the NEHRP B/C boundary-site condition. This involves redoing the simulations, but replacing the crustal amplification model that is applicable to hard rock ($V_{30} \geq 2000$ m/sec) with one that is applicable to a near-surface velocity of 760 m/sec in ENA; we used the model given in Table A6 of Frankel *et al.* (1996), but with a source velocity of 3.7 km/sec rather than 3.6 km/sec. The amplification model was derived using the square-root-impedance method of Boore and Joyner (1997; see also Boore, 2003), in which amplification is computed based on the seismic-impedance gradient; for each frequency, the depth corresponding to a quarter wavelength is calculated, and the amplification is estimated based on the square root of the seismic-impedance ratio between the source region and the quarter-wavelength depth. Table 4 presents the resulting amplification factors.

The amplification factors of Table 4 are multiplied by the $\exp(-\pi f \kappa_0)$ operator in the simulations. For hard-rock sites, κ_0 was assumed to be uniformly distributed between 0.002 and 0.008 (see Table 1). For NEHRP B/C boundary-site conditions, we assume κ_0 is uniformly distributed between 0.01 and 0.03.

The simulations for NEHRP B/C boundary conditions were regressed to equation (5) to determine the coefficients for the prediction equations as given in Table 9. The prediction equations of Table 9 can be used with the soil response factors of Boore and Atkinson (2006), as given in equation (7a),(7b) with the coefficients as listed in Table 8, to calculate expected ENA ground motions for any specified V_{30}. This makes the implicit assumption that relative amplification effects of different soil conditions in ENA are the same as those for active tectonic regions. Note that the stress-amplification factors of equation (6) can be applied to the B/C boundary predictions to consider alternative values of the stress parameter.

Table 4
Site Amplification Factors Used in the Simulations for NEHRP B/C Boundary ($V_{30} = 760$ m/sec)

Frequency (Hz)	Amplification Factor
0.0001	1.000
0.1014	1.073
0.2402	1.145
0.4468	1.237
0.7865	1.394
1.3840	1.672
1.9260	1.884
2.8530	2.079
4.0260	2.202
6.3410	2.313
12.540	2.411
21.230	2.452
33.390	2.474
82.000	2.497

Amplification is based on square-root-impedance calculations and the velocity model in Table A6 of Frankel *et al.* (1996).