Implications of the **M**9 Tohoku earthquake for Cascadia interface GMPEs

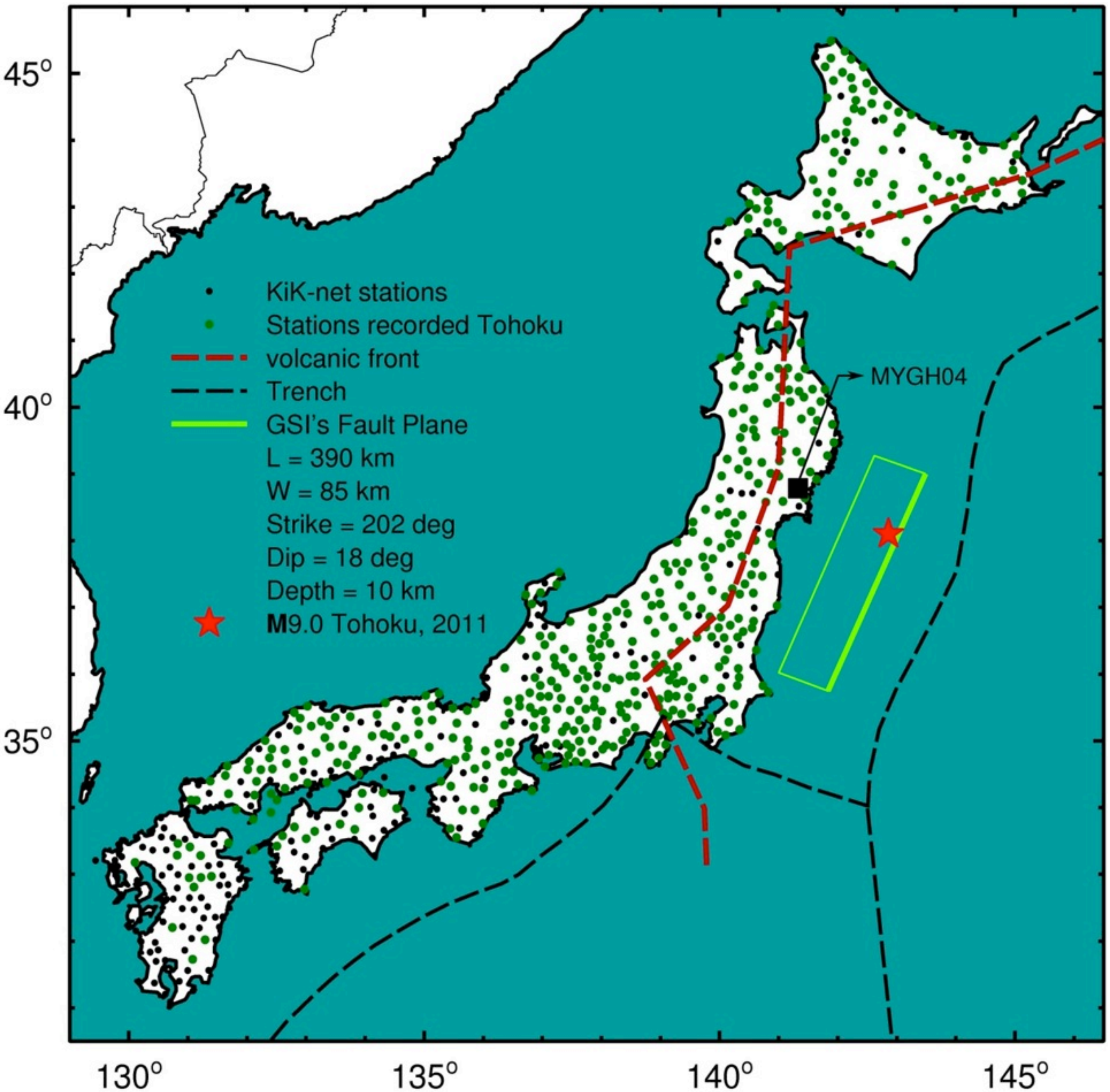
Gail Atkinson and Hadi Ghofrani
Western University

Overview

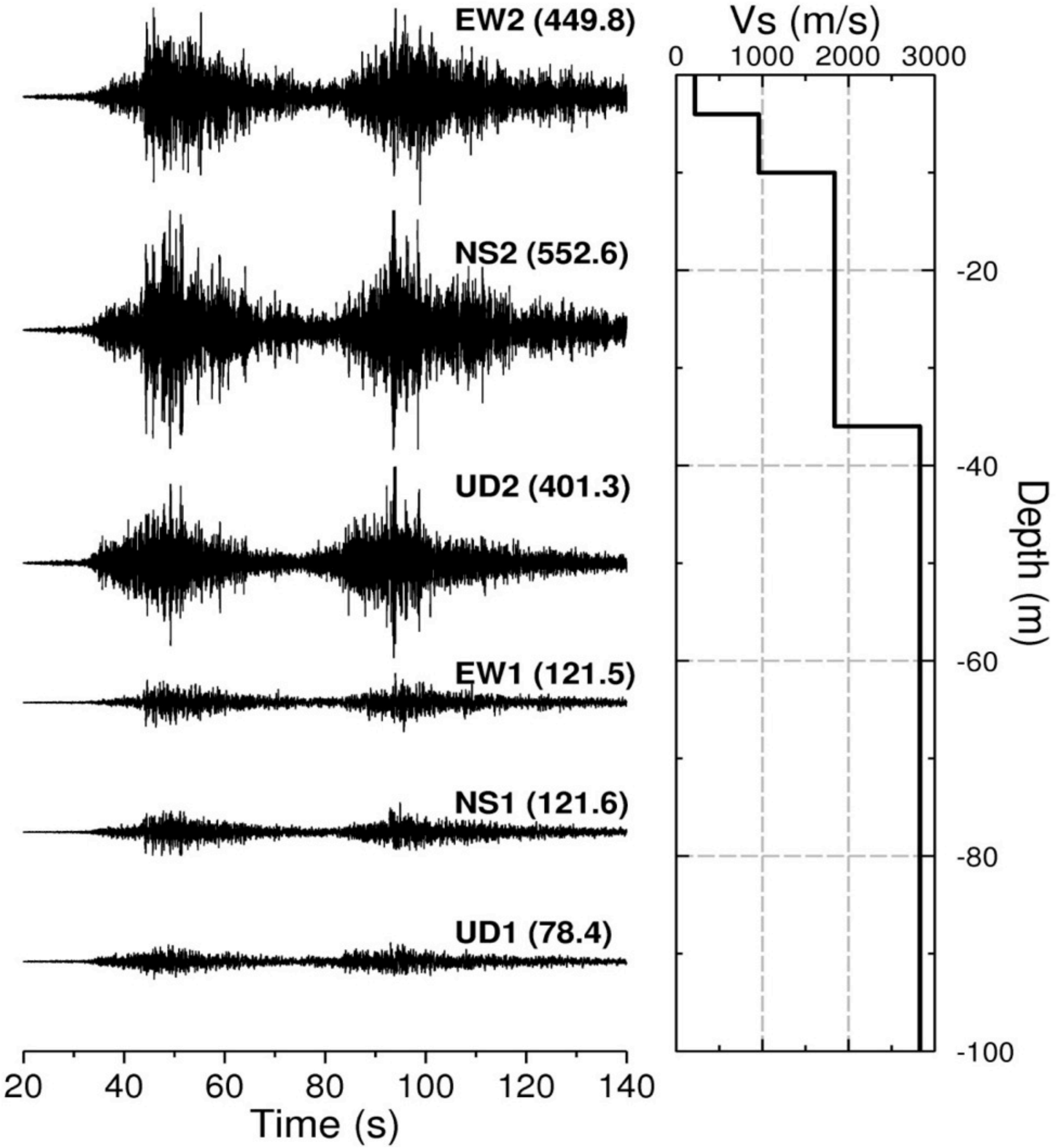
- Tohoku M9 mainshock generated strong motions, especially at high frequencies, to large distances (PGA~30%g on NEHRP C sites ~100km)
- High-frequency motions driven by large site response of shallow Japanese deposits
- Non-linearity was not pervasive, though observed clearly at some sites
- Need to understand site response in order to transfer lessons from Tohoku to Cascadia (where site response issues are different)

Analysis of Tohoku motions

- Hundreds of excellent records at distances from ~40 to hundreds of km (KNET-green)
- Excellent network of borehole and co-located surface stations (KiK-net-black) that facilitate site response studies



Borehole records show site response:

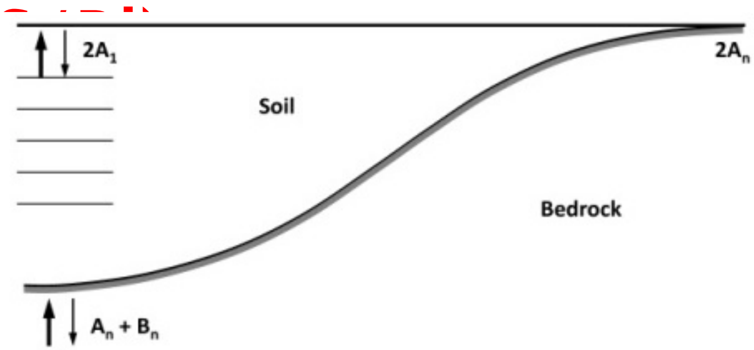


Comparison of observed surface and borehole ground motions for MYGH04 station of the KiK-net.

NEHRP C.
Rcd=91km.

The values at the end of each trace list the peak ground acceleration in cm/s^2.

Compute site response at each station from ratio of surface/borehole records, corrected for “depth effect” (to determine



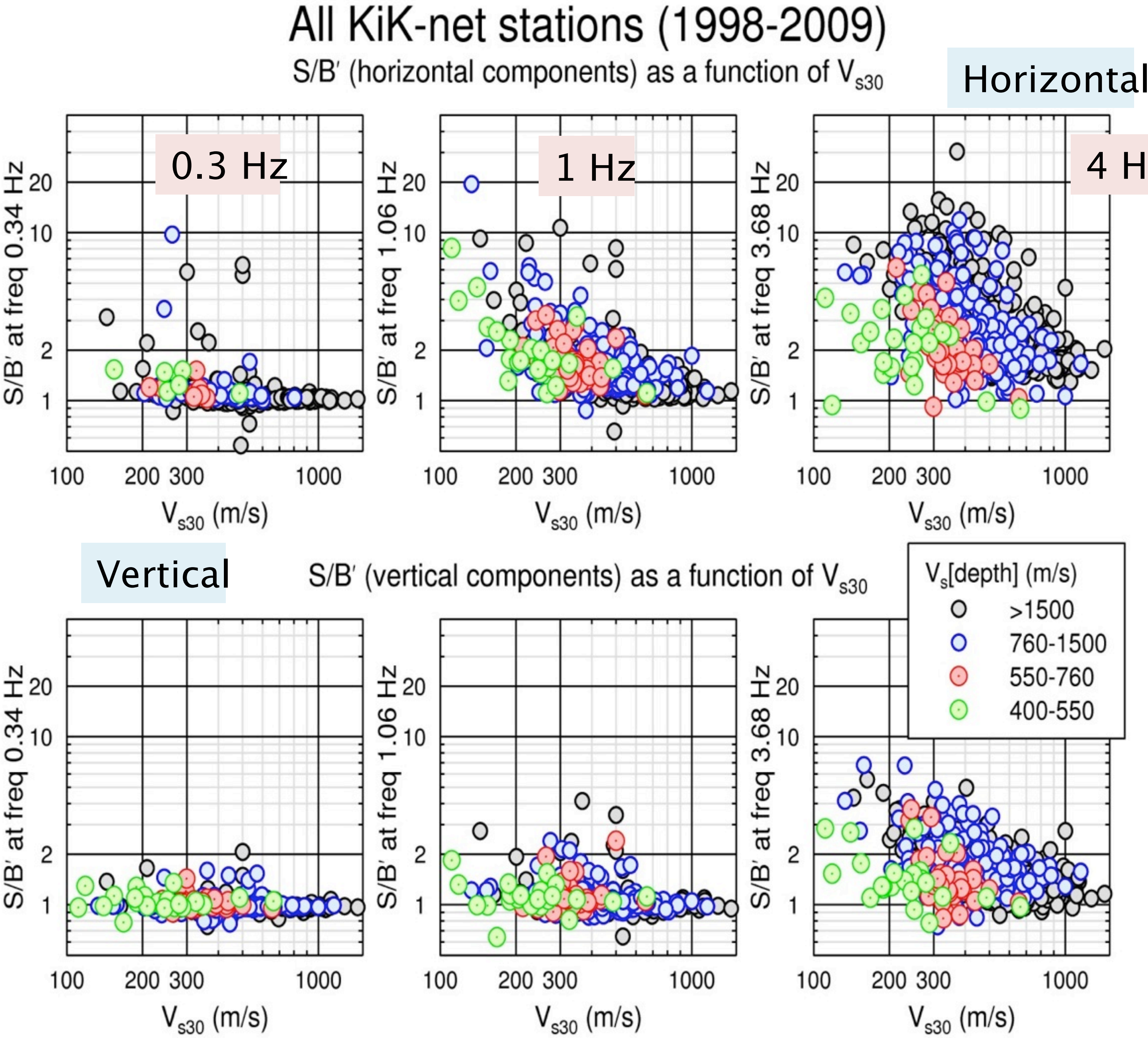
- Destructive interference of downgoing reflected waves with incident waves at borehole level complicates S/B ratio
- Use cross-spectrum techniques for correction based on coherency of waveforms at surface and downhole
- Multiply S/B by coherence (C^2) to get corrected S/B’
- Modest correction in most cases

$$C^2 = \frac{|S_{12}(f)|^2}{S_{11}(f)S_{22}(f)}$$

$S_{11}(f)$ and $S_{22}(f)$ are power spectral densities at surface and downhole, respectively, $S_{12}(f)$ is the cross-power-spectral density function (Steidl et al., 1996).

Analyze site response in detail for stations of KiK-net, having borehole data

- Analyze the Tohoku events
- Also analyze all other events of **M**>5.5 1998-2009, to provide multiple records at each station
- Most records will be in the linear amplification range
- There are from 4 to 150 records for each of stations, recording 258 events, for a total of 30,453 records



Horizontal

0.3 Hz

1 Hz

4 Hz

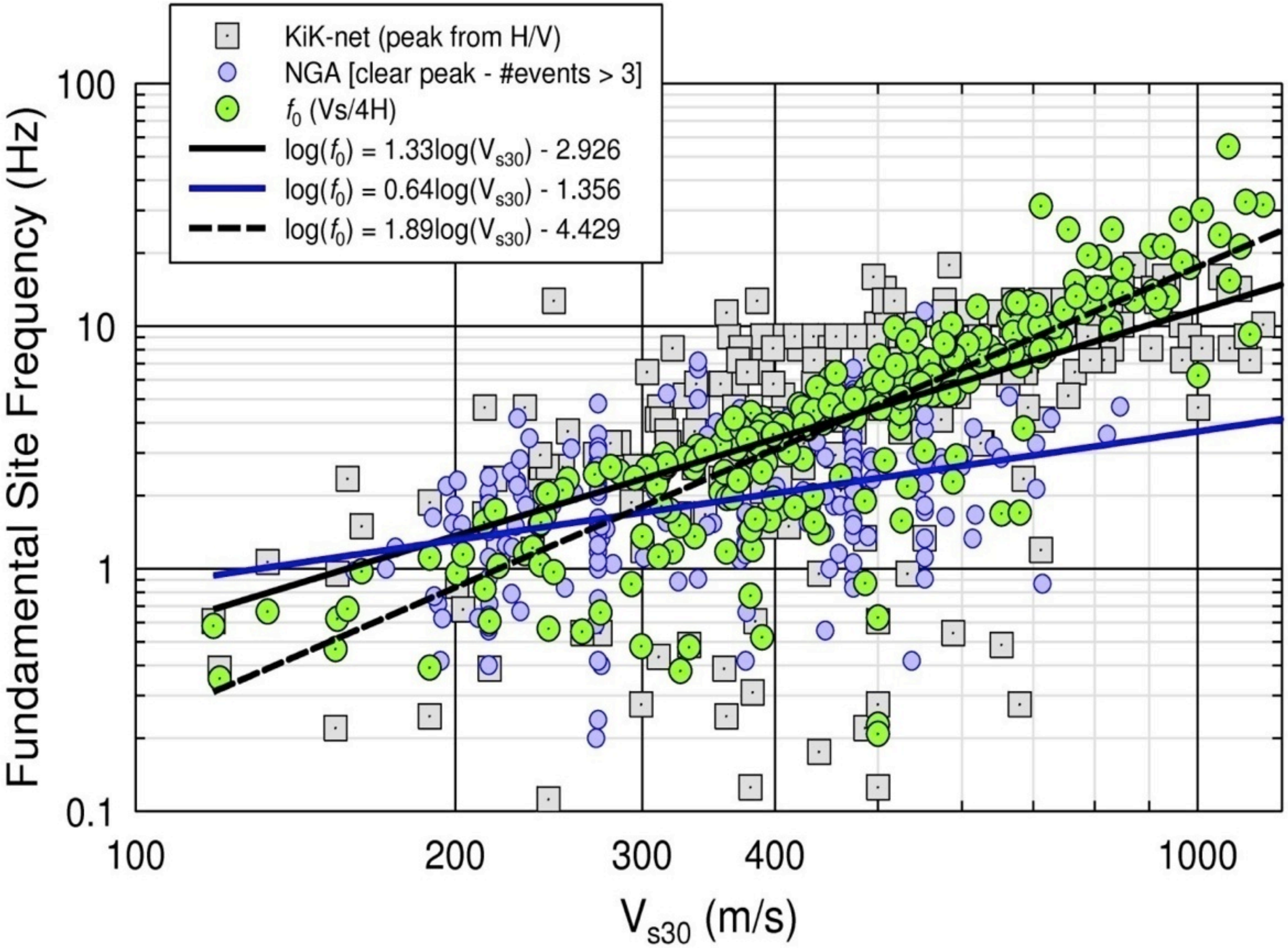
Vertical

Amplification for all events :

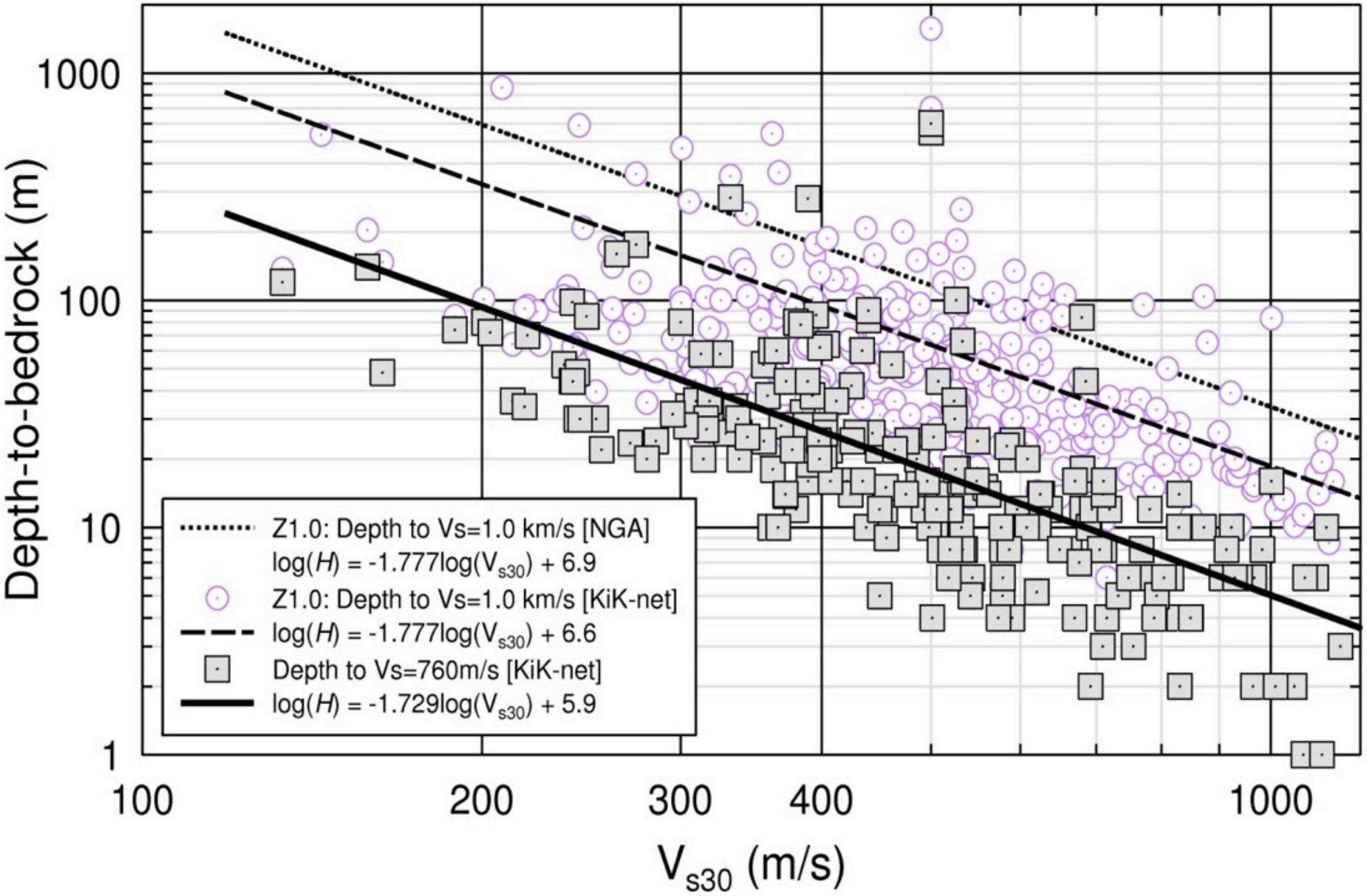
Surface / borehole (after correction for depth effect)

Note significant amplifications at high frequency, even for Vs30~500

Comparison of fundamental site frequency (sites with clear peak) from H/V and (Vs/4H) in Japan – they agree (in range that is well constrained).
NGA data for other regions (using H/V) are overlain in blue – show lower site frequency for same Vs30

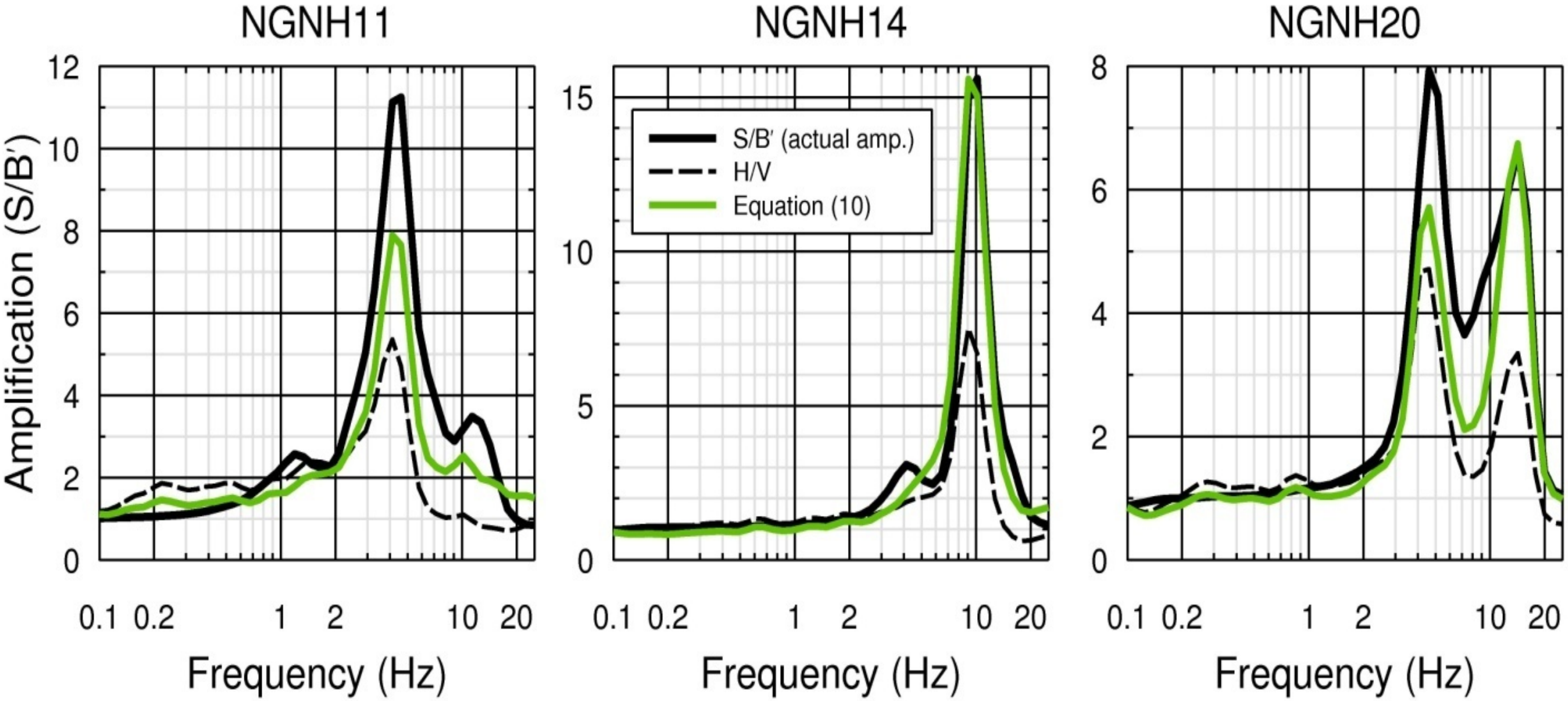


Depth to bedrock vs Vs30. Japan data (gray) shows depth to Vref=760m/s – we can adjust this line to equivalent for Vref=1km/s (dashed).
This allows comparison with NGA data (purple) depth to Vref=1km/s.
Note higher depth to bedrock for NGA data compared to Japan.



Amplification functions derived from KiK-net data (all events) for some typical stations – from S/B’, from H/V, and from an equation we propose that uses peak H/V frequency (fo) to make a “corrected H/V” amplification estimate (green).

Equation will be useful for regions without borehole data.

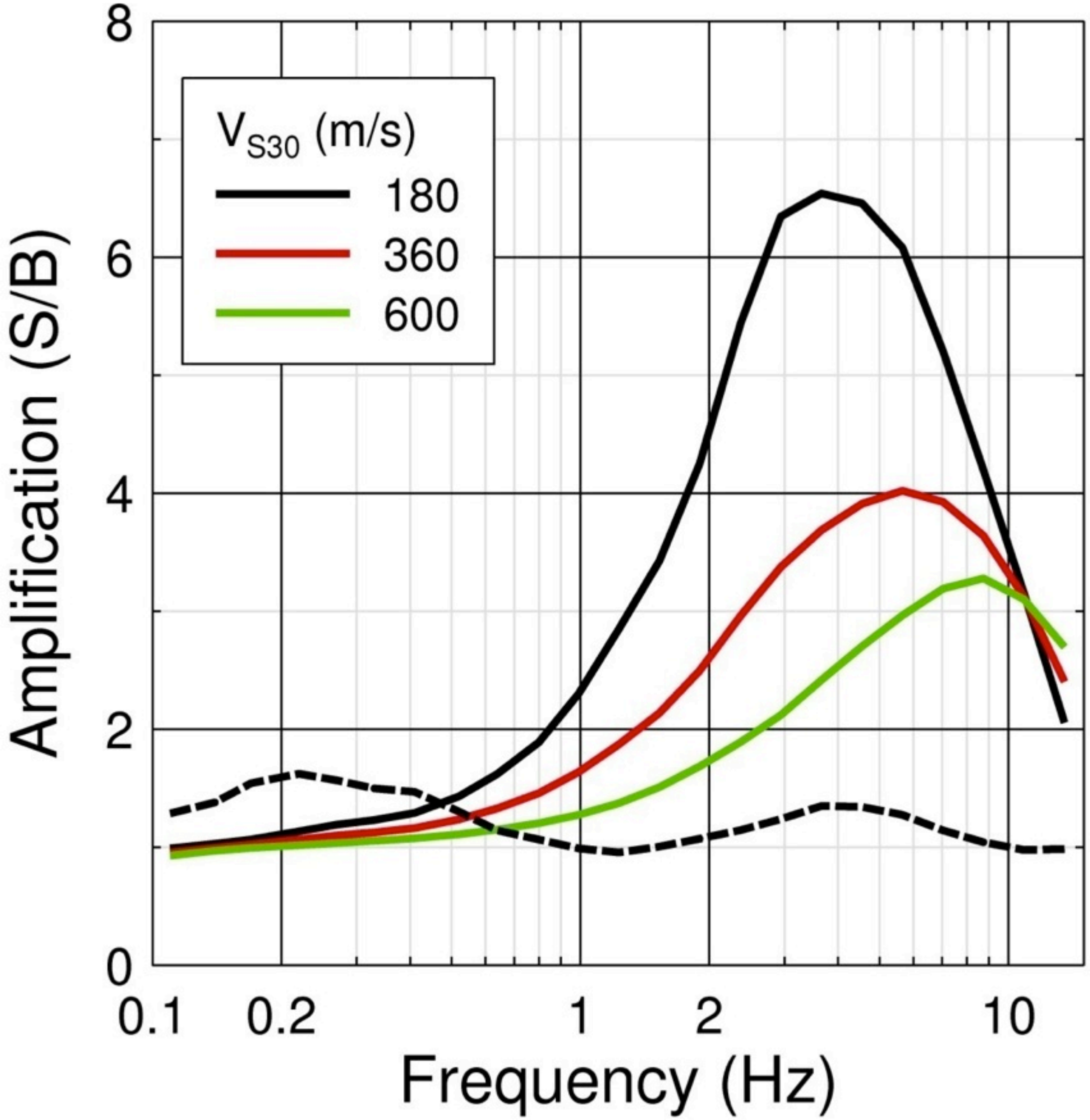


Amplification (S/B’) for different NEHRP site classes in Japan, from regression of KiK-net data (all events), where Vs30 is the explanatory site variable.

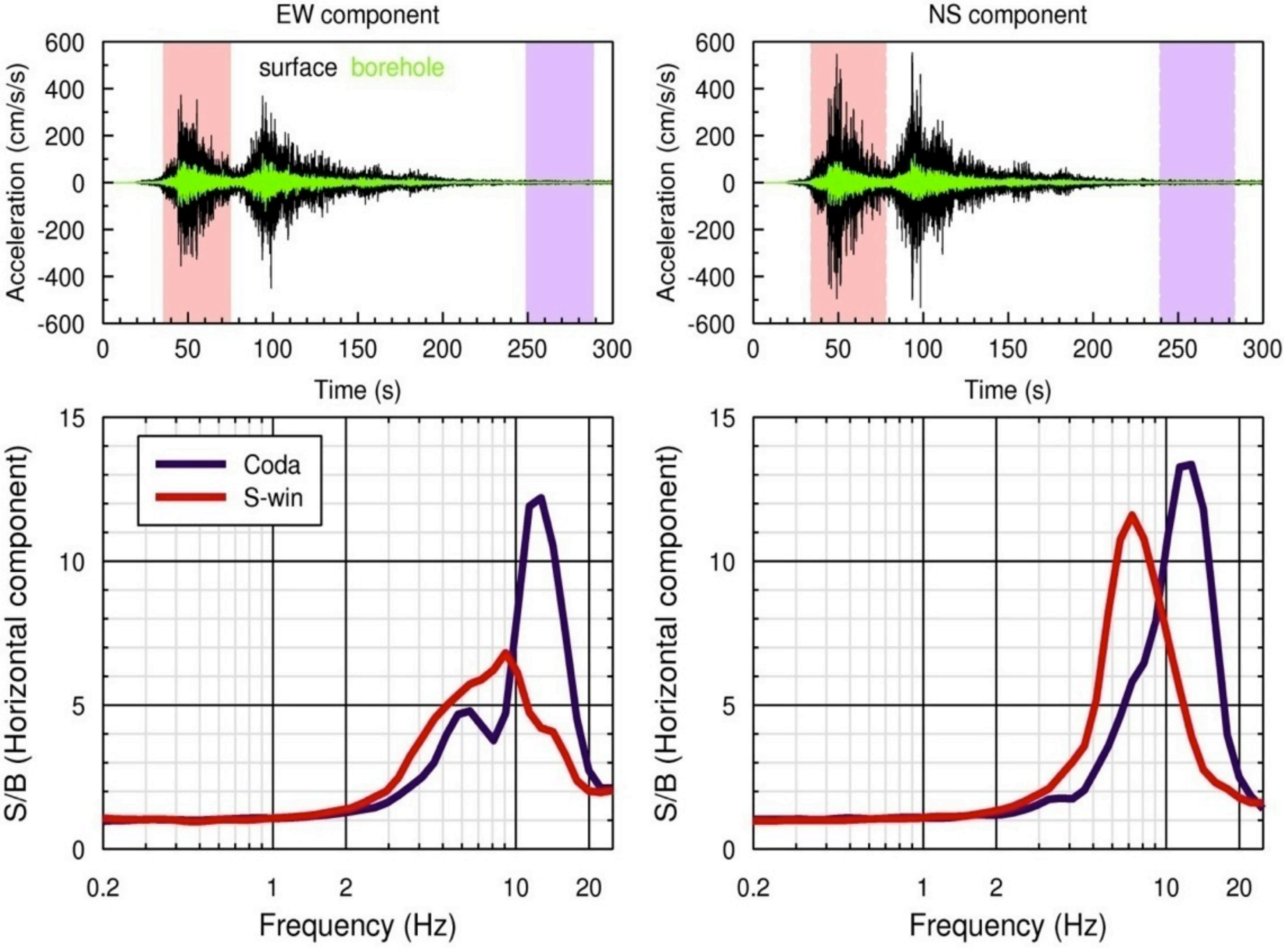
The estimated amplification for a reference velocity of 760 m/s is shown in black (dashed line).

Note high values at f>2Hz.

Also fit kappa=0.044

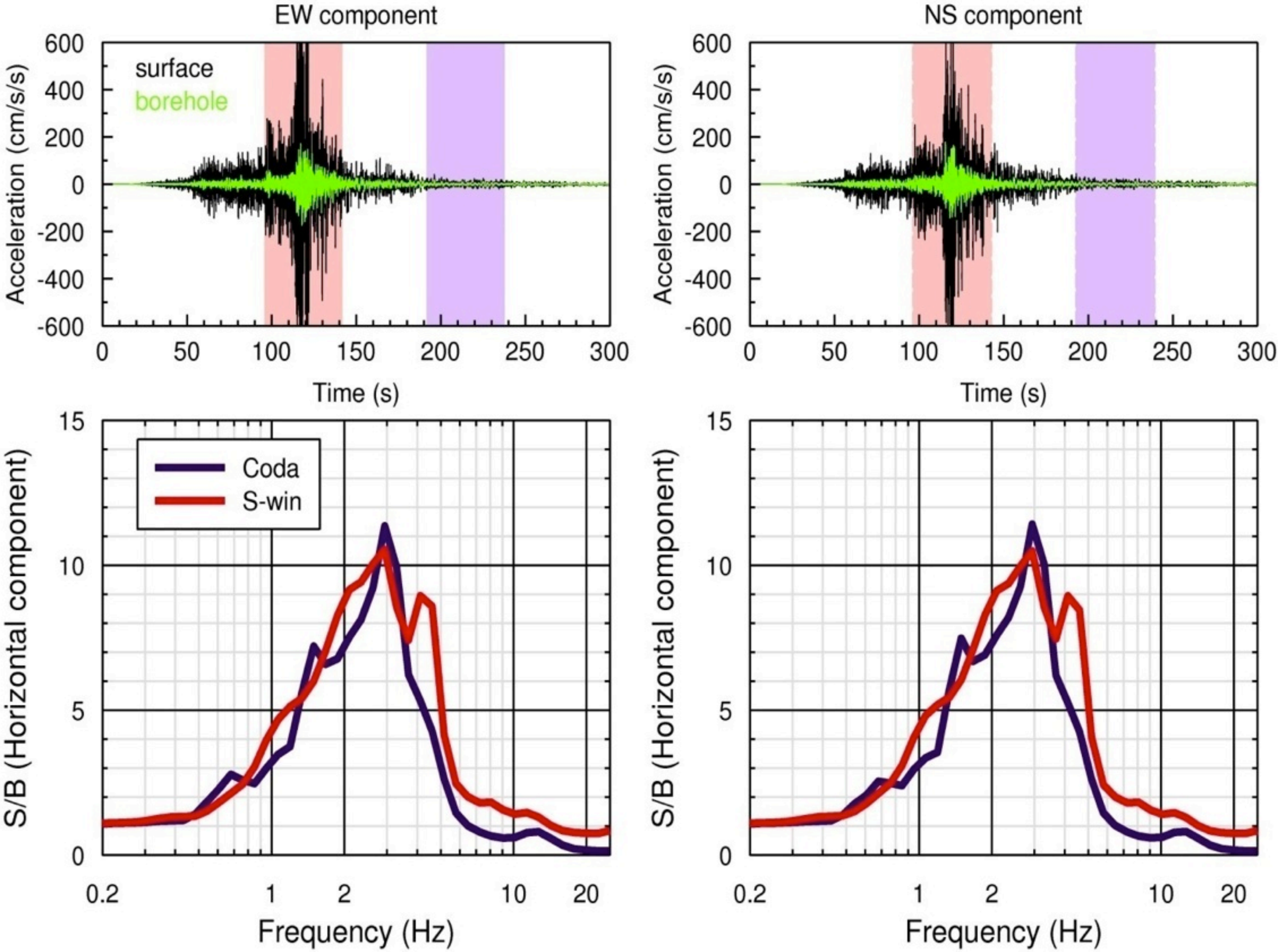


Nonlinearity – use in-record estimate from strong shaking versus coda

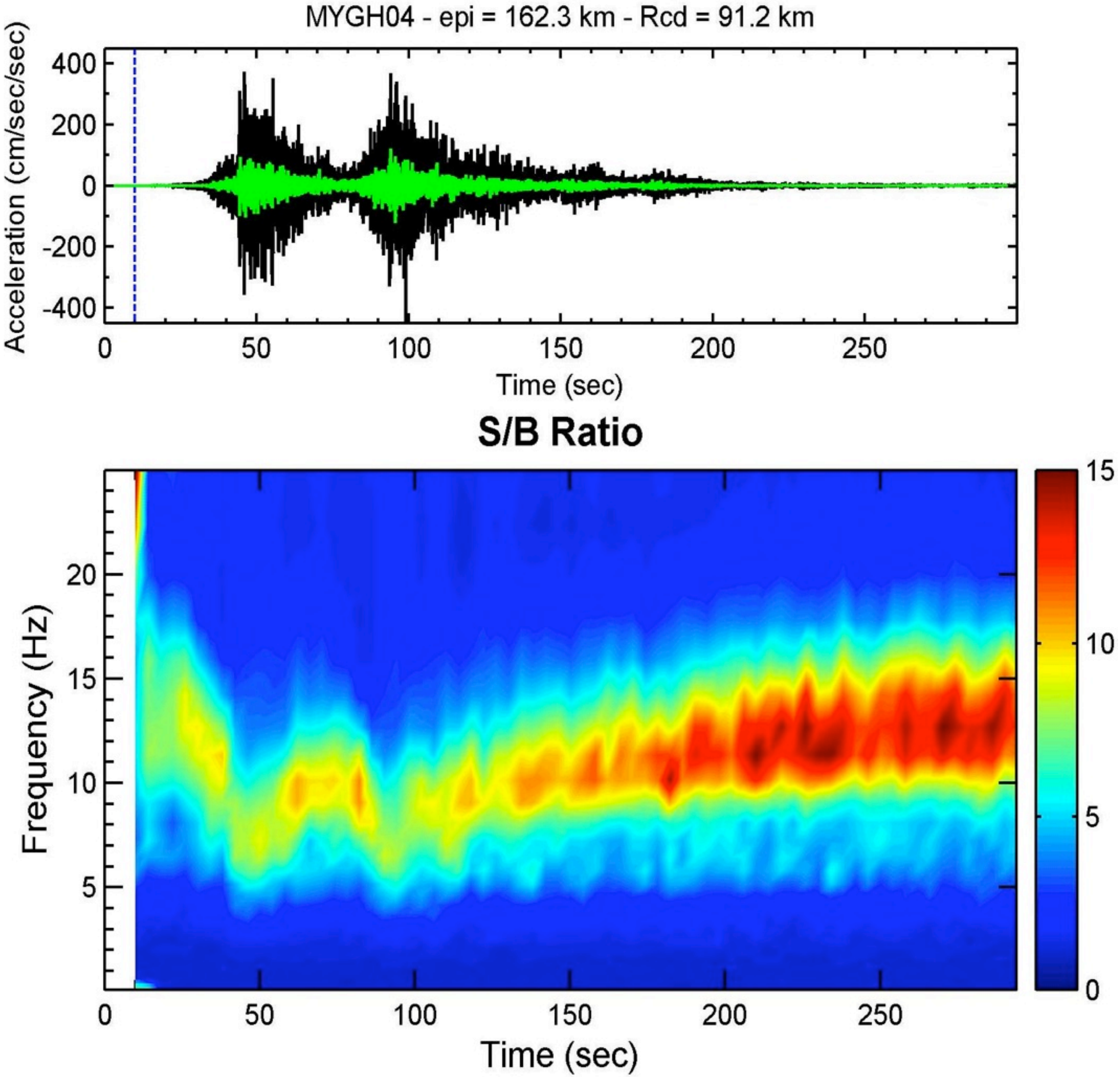


Amplification (S/B’) at MYGH04 for the S-window (red) and coda-window (blue). Tohoku mainshock. Clear Nonlinearity. PGA~0.5g

An example of S-window vs. coda amplification where no non-linearity is evident.

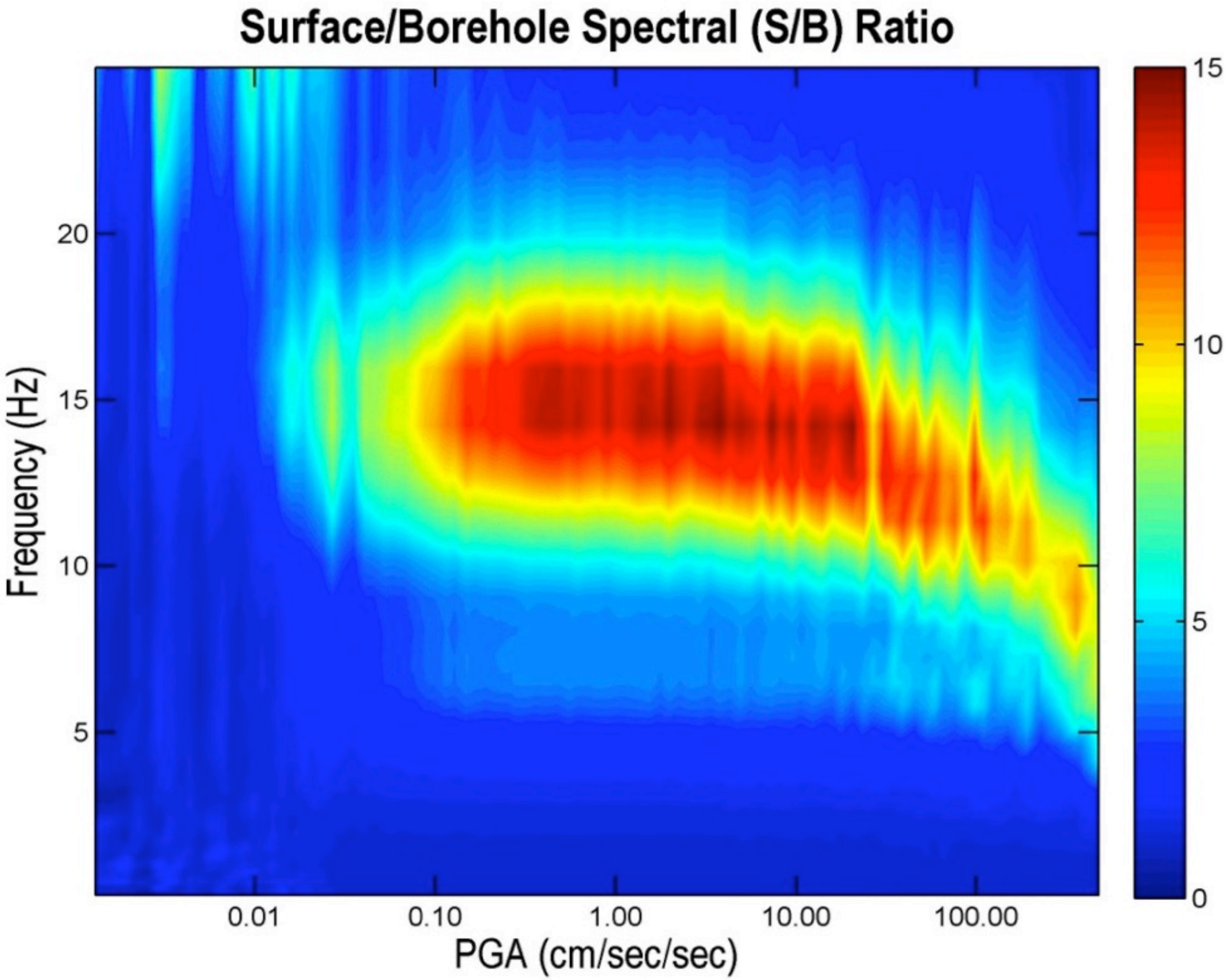


Amplification (S/B') at TCGH16 for the S-window (red) and coda-window (blue).
PGA~0.5g
Vs30=213m/s



Systematic search for development of non-linear behavior as motion progresses, using moving-window FFT. Hot colors show larger amplifications. Clear nonlinearity here.

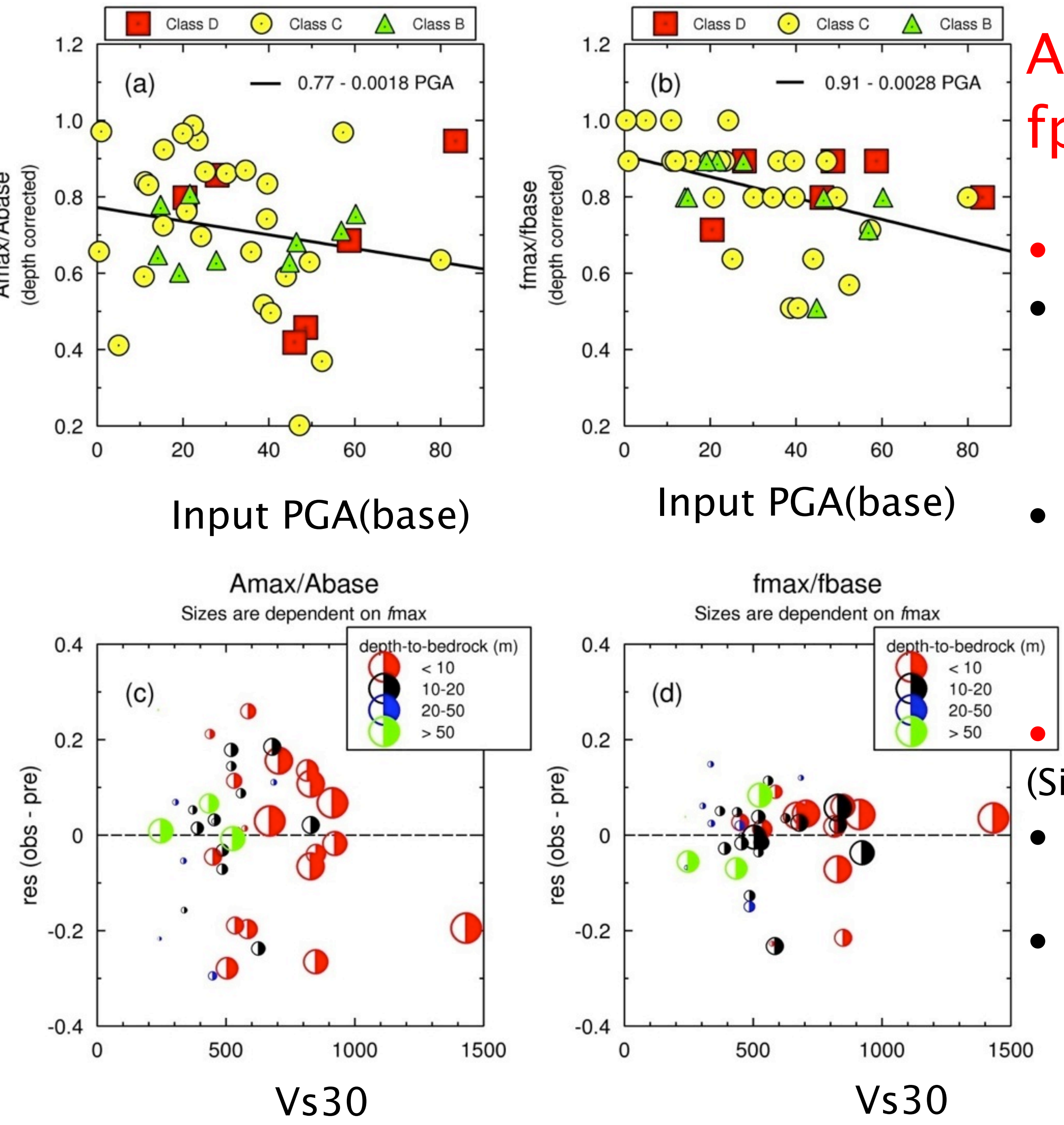
Can also look at nonlinearity vs. PGA (instead of time). This is same station (MYG04). Threshold for nonlinearity ~ 25 cm/s^2



Generalizing non-linearity evaluation

- Use the amplification for Tohoku mainshock (A_{ms}) relative to that averaged over all events(A_{lin}) to assess nonlinearity of site amplification
- Also examine the frequency of the peak amplification (fp_{MS}) for Tohoku in comparison to that for other events (fp_{lin})

A_{MS}/A_{lin} (left) fp_{MS}/fp_{lin} (right)

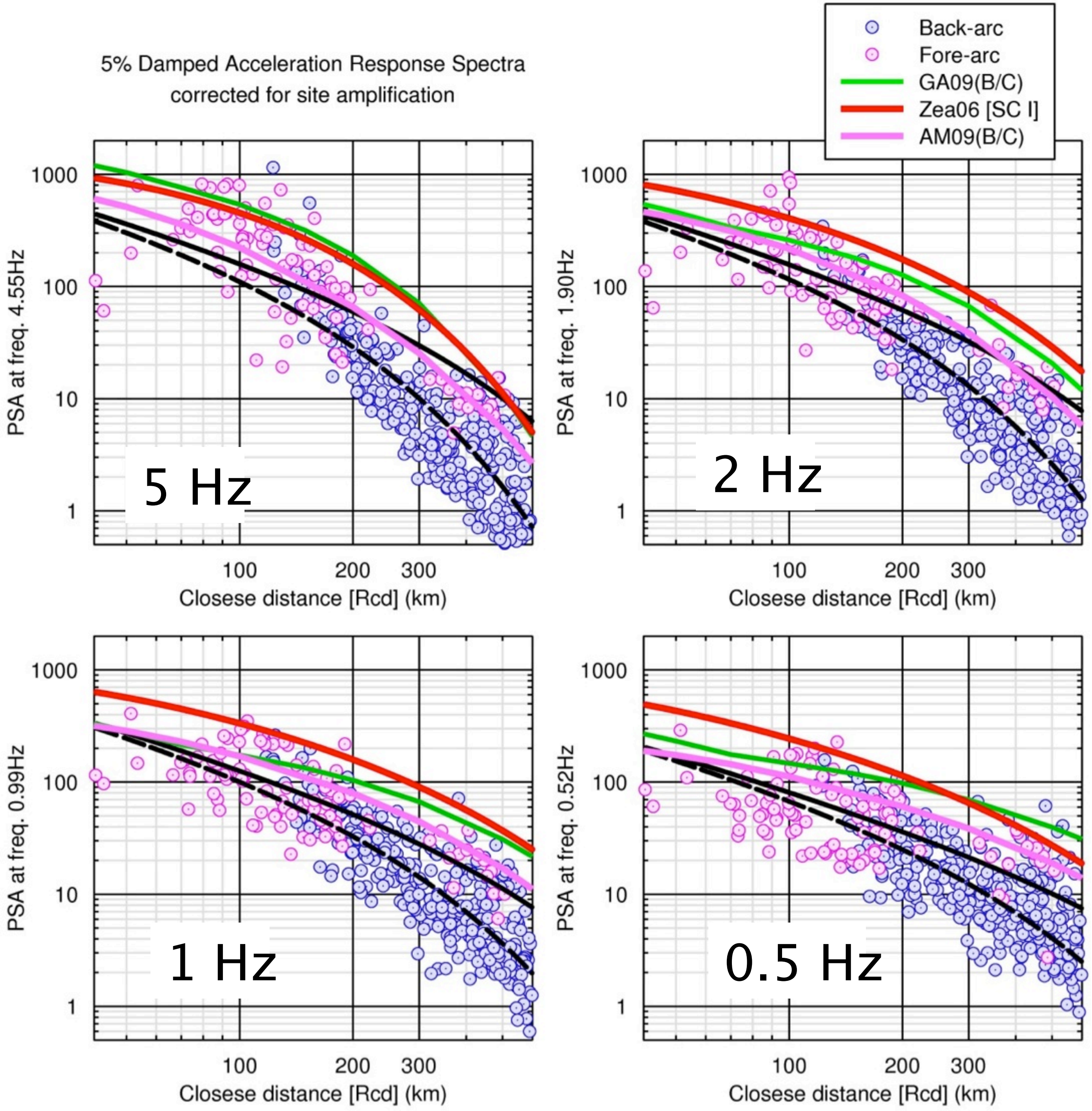


- Versus PGA (top)
- There is a slight trend for amplification (-.0018 +/- .0014)
- There is a significant trend for peak freq. (-0.0028 +/- .0009)

- Versus Vs30 (bottom)

(Size of symbol reflects fp)

- No apparent trends in Vs30
- Vs30 not good measure of soil stiffness in Japan due to shallow layers



Implications of Tohoku MS motions (all stns) for GMPEs

After removing site-amp functions from data, to correct them to B/C (pink=fore-arc, blue=back-arc)

Compare to GMPEs (Zhao, red; AtkinsonMacias; pink GodaAtkinson (green)

Conclusions

- Tohoku motions very strong at high frequencies, but this was due in large part to strong site effects
- Nonlinearity was not pervasive
- Motions for B/C boundary in reasonable accord with Cascadia GMPEs like Atkinson and Macias, 2009 (after site effects removed)
- BUT site amplifications are MUCH larger to go from B/C to other conditions than we consider in standard code factors