Campbell-Bozorgnia NGA Empirical Ground Motion Model for the Average Horizontal Component of PGA, PGV and SA at Selected Spectral Periods Ranging from 0.01–10 Seconds

Kenneth W. Campbell[1] *and Yousef Bozorgnia*[2]

[1] EQECAT Inc., Beaverton, Oregon

[2] PEER, University of California, Berkeley, California

Workshop on Implementation of the Next Generation Attenuation Relationships (NGA) in the 2007 Revision of the National Seismic Hazard Maps

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Next Generation Attenuation Project

- Partnered research program
  - **PEER Lifelines Program**
    - Pacific Earthquake Engineering Research Center (PEER)
    - California Energy Commission (CEC)
    - California Department of Transportation (Caltrans)
    - Pacific Gas and Electric Company (PG&E)
  - **U.S. Geological Survey (USGS)**
  - **Southern California Research Center (SCEC)**
- Multi-disciplinary, 3-year project bringing together
  - Seismologists
  - Geophysicists
  - Geologists
  - Geotechnical engineers
  - Structural engineers

NGA Project Details

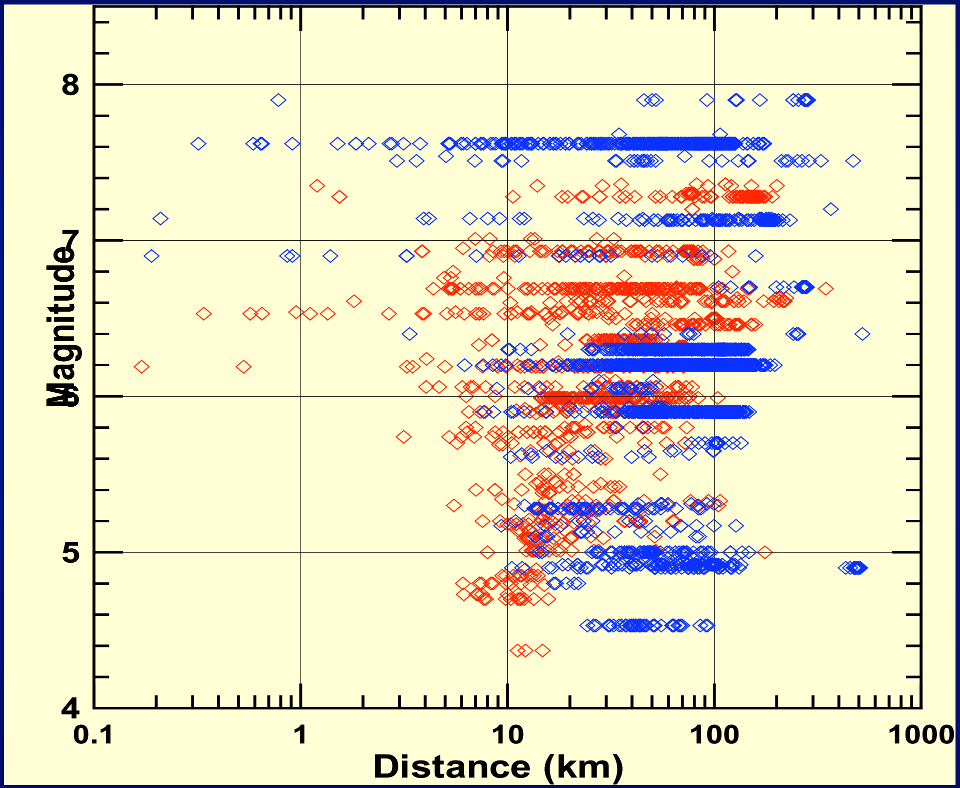
- NGA empirical ground motion model developers
  - **Abrahamson & Silva** (updating their 1997 model)
  - **Boore & Atkinson** (updating Boore et al., 1997 model)
  - **Campbell & Bozorgnia** (updating their 2003 model)
  - **Chiou & Youngs** (updating Sadigh et al., 1997 model)
  - **Idriss** (updating his 1993 & 1996 models)
- All developers started with a common database
  - Worldwide earthquakes
  - Shallow crustal earthquakes in active tectonic regions
  - Metadata (e.g., magnitude, distance, etc.)
  - Uniformly processed strong-motion recordings

NGA Project Details

- NGA developers applied their own selection criteria to the common database, with the proviso that
  - Criteria are explicitly defined and documented
  - Criteria are shared with other developers
  - Reasons for excluding data are justifiable
  - Other developers are notified if metadata is modified
- NGA supporting studies
  - 1-D ground-motion simulations of rock ground motion
  - 3-D ground-motion simulations of basin response
  - 1-D ground-motion simulations of shallow site response

NGA Project Database

- NGA strong-motion database:
  - **172** worldwide earthquakes
  - **1,400** recording stations
  - **3,500** multi-component strong-motion recordings
  - **Over 100** parameters describing source, path, and site conditions



Previous Data New Data

NGA Project Requirements

- Ground motion model
  - Provide a model for median ground motion
  - Provide a model for aleatory standard deviation
- Ground motion parameters
  - Horizontal components (Geometric Mean, FN, FP)
  - PGA, PGV, PGD (optional)
  - Spectral acceleration (minimum of 20 periods from 0 –10 s)
- Applicable magnitude range
  - Use moment magnitude
  - 5.0 – 8.5 (strike-slip faulting)
  - 5.0 – 8.0 (reverse faulting)

Developer Scope

- Applicable distance range
  - Select preferred distance measure
  - 0 – 200 km
- Style of faulting (fault mechanism)
  - Strike slip
  - Reverse
  - Normal
- Site classification
  - Select preferred site classification scheme
  - Classification scheme need not include “very soft soil”
  - Provide translation to NEHRP site categories

Some Critical Issues Addressed

- Over-saturation at short distances
  - Data generally required it regardless of functional form
  - Issue for short periods, short distances, large magnitudes
  - Developers were divided on whether to allow it
  - Some concern about stability in future events
  - *We allow saturation but not over-saturation*
- Rupture aspect ratio (L/W)
  - We initially proposed it to model breakdown in self-similarity
  - We abandoned its use because of data inconsistencies
  - Its effect trades-off with magnitude scaling in the regression
  - *We will reconsider its use once inconsistencies are resolved*

Some Critical Issues Addressed

- Depth to coseismic rupture
  - Higher ground motions from buried & blind reverse faults are empirically supported and included in our model
  - Also supported by laboratory and numerical ground-motion simulations when weak upper layers are included
  - Not empirically supported for many strike-slip faults
  - *We include buried effects for reverse faults, implying similar ground motions for large surface-rupturing reverse and strike-slip events*
- Extrapolation to 10-second period
  - Small-to-moderate events are not reliable to long periods
  - Large events provide empirical constraints to 10 seconds
  - There is no developer consensus on how to extrapolate
  - *We extrapolate to small magnitudes using seismological constraints and assuming constant displacement beyond a corner period*

Some Critical Issues Addressed

- Functional form of aleatory standard deviation
  - Should it be a function of magnitude or amplitude?
  - Results support independence on **M**, dependence on PGA
  - Large near-fault scatter in 2004 Parkfield EQ is consistent with predicted uncertainty
  - *We include decreasing aleatory uncertainty with lower V_{S30} and higher rock PGA*
- Treatment of epistemic uncertainty
  - Should it be a function of magnitude and distance?
  - Developers agree the use of multiple models is insufficient
  - Developers agree it should be increased in parameter ranges where data are limited and models are extrapolated
  - *We will develop an epistemic uncertainty model using bootstrap and jackknife statistical methods*

Some Critical Issues Addressed

- Normal-faulting earthquakes
  - Should normal-faulting events have lower ground motions and hanging-wall effects
  - Spudich et al. (1999) found strike-slip and normal-faulting ground motions were lower for extensional regions as compared to strike-slip events in both extensional and non-extensional regions
  - Ambraseys et al. (2005) found normal-faulting events to have lower ground motions than strike-slip events at short periods
  - Differences between extensional and non-extensional regimes are not empirically supported after including the effects of normal faulting
  - Empirical results support statistically insignificant reduction at short periods and increase on hanging wall; laboratory and numerical modeling support hanging wall effects but are inconsistent regarding lower ground motions
  - *We include hanging-wall effects and slight reduction at short periods*

Some Critical Issues Addressed

- Use of large worldwide earthquakes
  - Does the use of large worldwide earthquakes bias the predictions in California and the WUS?
  - Data are not sufficient to resolve this issue statistically
  - Studies have shown that ground motions from moderate sized events in similar tectonic regimes are similar in U.S., Japan, Europe and Taiwan, inferring the same might be true for large events
  - Many studies outside of the U.S. use near-source data from events in the U.S.
  - Topic is controversial, but some seismologists suggest there is no theoretical basis for assuming ground motions are not similar in similar tectonic regimes worldwide
  - *As in our previous models (1981–2003), we include large worldwide events to constrain magnitude scaling at* $\mathbf{M} > 7.0$*, mitigated by disallowing over-saturation when predicted by the regression*

General Data Selection Criteria

- Earthquakes
  - Located in shallow continental lithosphere
  - Located in tectonically active regions
  - Generally reliable earthquake metadata
- Recordings
  - Negligible embedment effects
  - Negligible soil-structure interaction effects
  - Generally reliable path and site metadata

CB-NGA Specific Exclusion Criteria

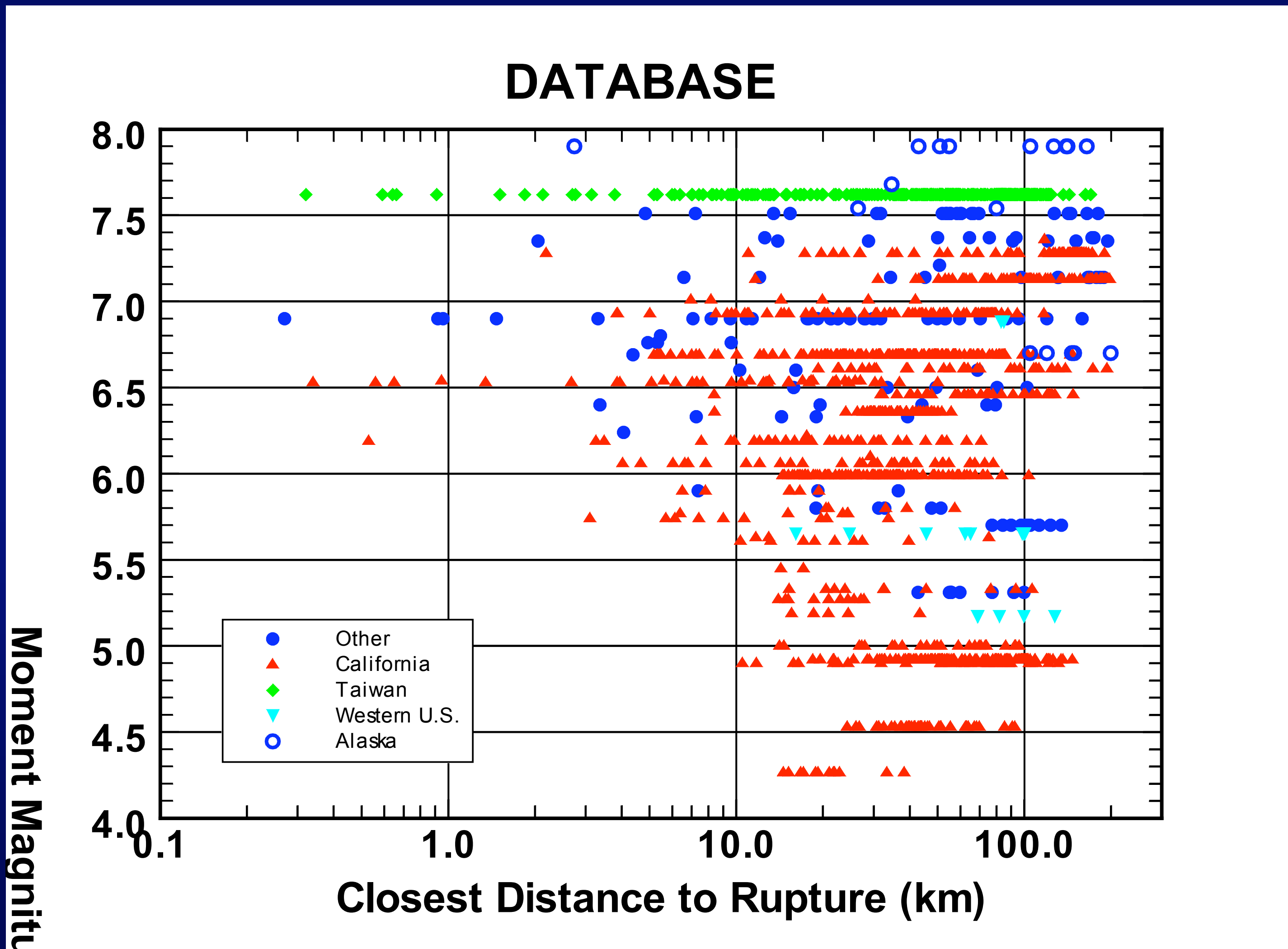
- Only one horizontal and/or vertical component
- No measured or estimated value of V_{S30}
- No rake angle, focal mechanism, or P-T plunge
- Focus/rupture in deep crust, oceanic plate, or SCR
- *Aftershocks (but not "triggered" events)*
- *Poorly recorded events (depending on magnitude)*
  - N < 5 for $\mathbf{M} < 5.0$
  - N < 3 for $5.0 \le \mathbf{M} < 6.0$
  - N < 2 for $6.0 \le \mathbf{M} < 7.0$ and all $R_{RUP} > 60$ km

CB-NGA Specific Exclusion Criteria

- Non-free-field recordings
  - Building basement or superstructure
  - Embedded or downhole
  - Toe, base, or crest of dam (but not abutments)
- Demonstrated strong topographic effects
  - Tarzana Cedar Hill Nursery
  - Pacoima Dam upper-left abutment
- Recordings considered unreliable
  - LDGO recordings from 1999 Duzce, Turkey earthquake
  - Quality “D” recordings from 1999 Chi-Chi earthquake

Distribution of Selected Recordings

64 Earthquakes, 1561 Recordings



Campbell-Bozorgnia Findings

- GM scaling with magnitude
  - Scaling decreases at large **M**, small R_{RUP}, and short periods
  - Short periods saturate at small R_{RUP} for **M** > 6.5
- GM scaling with distance
  - Rate of attenuation decreases with increasing **M**
  - All periods saturate for small R_{RUP}
- GM scaling with fault parameters
  - Higher GM for buried and blind reverse faults
  - GM same for strike slip and surface-rupturing reverse faults
  - Higher GM on hanging-wall of reverse-faults (PGA $\approx 1g$)
  - All these effects become negligible at long periods

Campbell-Bozorgnia Findings

- GM scaling with shallow soil conditions
  - GM decreases with decreasing V_{S30} (linear part)
  - GM decreases with increasing rock PGA (nonlinear part)
  - Nonlinear scaling constrained by 1-D site response simulations
- GM scaling with sediment depth
  - GM increases for depths > 3 km (basin effects)
  - GM decreases for depths < 1 km (shallow sediment effects)
  - Basin effects constrained by 3-D ground motion simulations
- Aleatory standard deviation
  - Based on better recorded events
  - Only weakly dependent on magnitude and period
  - Larger at larger magnitudes compared to C-B (2003)
  - Smaller at smaller magnitudes compared to C-B (2003)

Campbell-Bozorgnia Findings

- Epistemic uncertainty
  - Underestimated by use of multiple ground motion models
  - Need to specify a minimum value of standard deviation
  - Need to develop a separate model of standard deviation

Analysis Methodology

- Functional form development
  - Exploratory data analysis (analysis of residuals)
  - Past experience (personal and literature review)
  - Developer interaction meetings
  - Theoretical studies (site response, basin effects)
- Regression analysis (exploratory phase)
  - Two-step regression analysis (Boore et al., 1997)
  - Weighted nonlinear least squares
  - Intra-event terms fit in first step
  - Inter-event terms fit in second step

Analysis Methodology

- Regression analysis (final phase)
  - Random effects regression (Abrahamson & Youngs, 1992)
  - Maximum likelihood method with random effects
  - Iteratively smoothed regression coefficients
    - Start with least correlated coefficients
    - Smooth observed coefficient trend with period
  - Constrain coefficients as necessary
    - Compensate for over-saturation
    - Control behavior at long periods

f_1(M)

Generalized Functional Form

[redacted]

$\ln Y$	=	natural log of ground motion
f_{mag}	=	earthquake magnitude term
f_{dis}	=	source-site distance term
f_{flt}	=	style-of-faulting term
f_{hng}	=	hanging-wall term
f_{site}	=	shallow site conditions term
f_{dep}	=	sediment depth term
ε	=	random error term: *Normal* $(0, \sigma_T)$

$f_1(\mathrm{M})$

Earthquake Magnitude Term

[illegible]

M = moment magnitude

c_0–c_{12} = regression coefficients

$f_1(\mathrm{M})$

Source-Site Distance Term

[illegible]

M = moment magnitude

R_{RUP} = closest distance to fault rupture (km)

$f_1(M)$

Style-of-Faulting Term

[illegible]

[illegible]

F_{RV} = reverse-faulting indicator variable

F_{NM} = normal-faulting indicator variable

Z_{TOR} = depth to top of coseismic rupture (km)

$f_1(\mathrm{M})$

Hanging-Wall Term

[illegible]

M = moment magnitude

R_{RUP} = closest distance to fault rupture (km)

R_{JB} = closest surface distance to fault rupture (km)

F_{RV} = reverse faulting indicator variable

Z_{TOR} = depth to top of coseismic rupture (km)

δ = dip of rupture plane (degrees)

$f_1(\mathrm{M})$

Shallow Site Conditions Term

[illegible]

V_{S30} = average 30-m shear-wave velocity (m/s)

A_{1100} = PGA for V_{S30} = 1100 m/s (rock PGA, g)

k_1, k_2 = theoretical period-dependent coefficients

c, n = theoretical period-independent coefficients (theoretically constrained nonlinear soil model from Walling & Abrahamson, 2006)

$f_1(\mathrm{M})$

Sediment Depth Term

[illegible]

$Z_{2.5}$ = depth to 2.5 km/s S-wave velocity (km)

k_3 = theoretical period-dependent coefficient (theoretically constrained 3-D basin model from Day et al., 2005)

$f_1(\mathrm{M})$

Random Error Term

[illegible]

σ_T	=	total aleatory standard deviation (S.D.)
$\tau,\ \sigma$	=	inter-event and intra-event S.D. of geom. mean
$t,\ s$	=	inter-event and intra-event S.E. of regression
α	=	rate of change of f_{site} w.r.t. $\ln A_{1100}$ (rock PGA)
χ	=	S.D. of the random (arbitrary) horizontal comp.
r	=	0 for geometric mean; 1 for random component

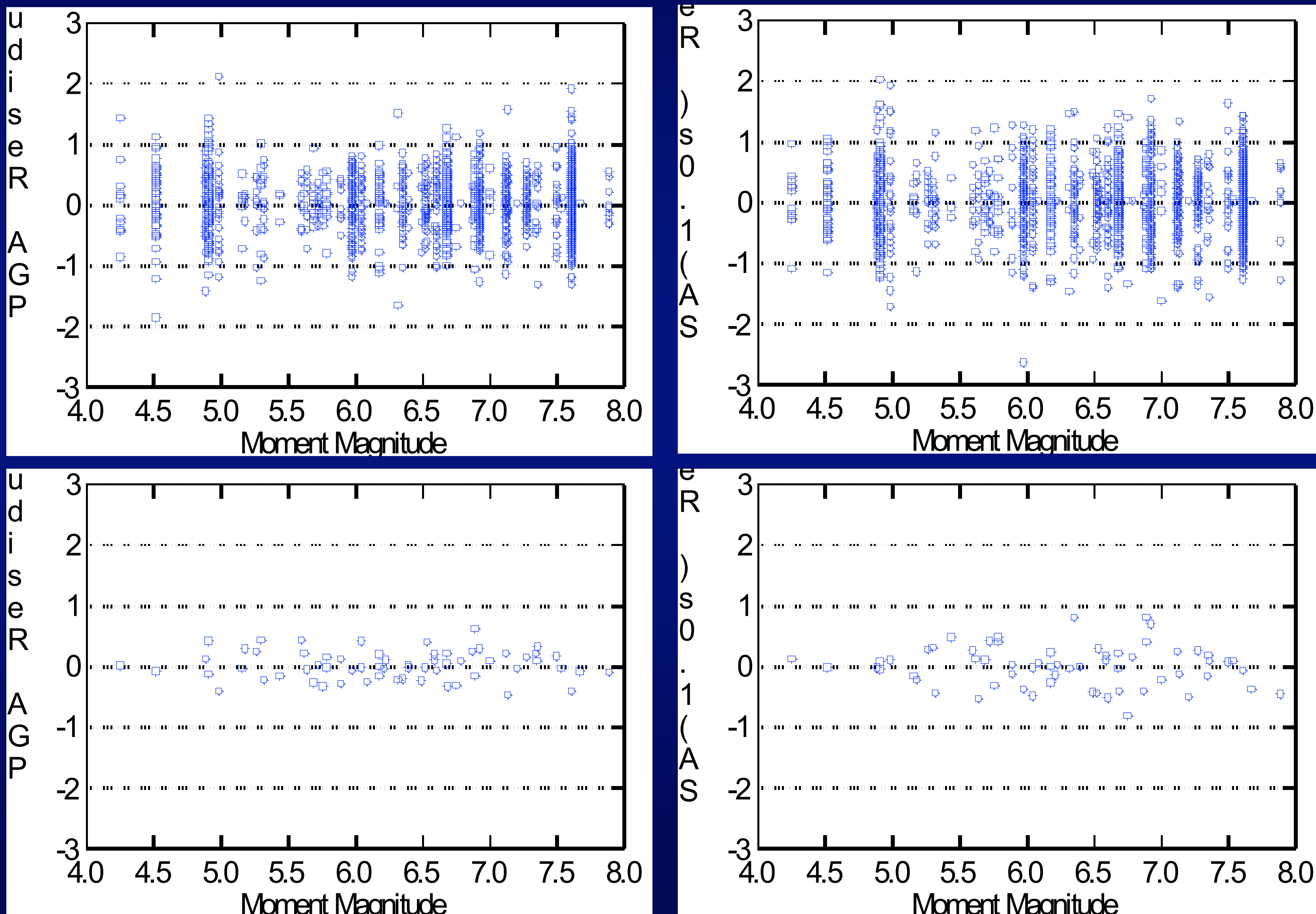
General Limits of Applicability

- Tectonic environment
  - Shallow continental lithosphere
  - Active tectonic regions
- Magnitude
  - **M** = 4.0 – 8.5 (strike-slip faulting)
  - **M** = 4.0 – 8.0 (reverse faulting)
  - **M** = 4.0 – 7.5 (normal faulting)
- Distance
  - R_{RUP} = 0 – 200 km
- Shallow site conditions
  - V_{S30} = 180 – 1500 m/s (NEHRP B – D)

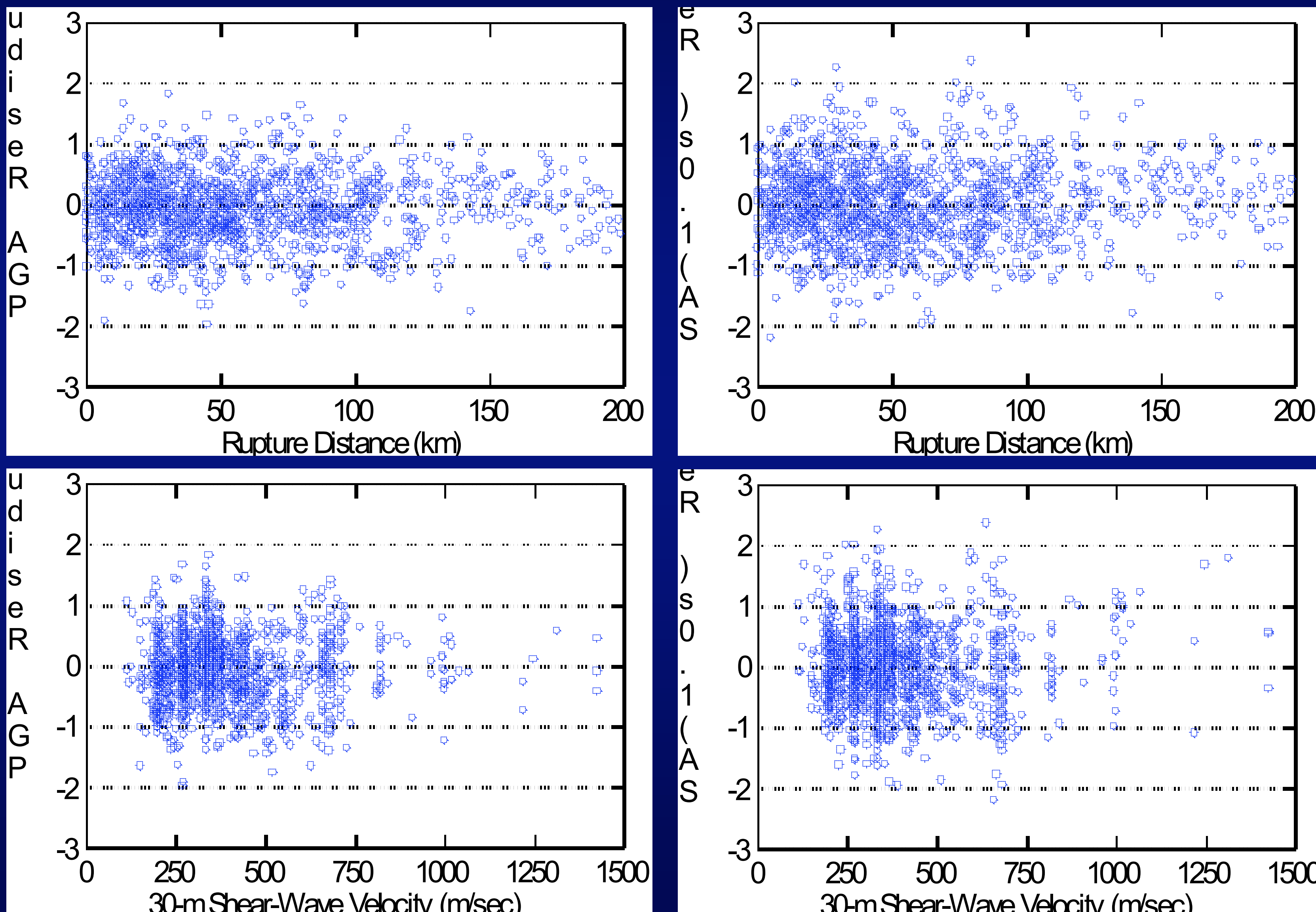
General Limits of Applicability

- Sediment Depth
  - $Z_{2.5}$ = 0 – 6 km
- Depth to top of rupture
  - Z_{TOR} = 0 – 20 km
- Dip of rupture plane
  - δ = 15 – 90°

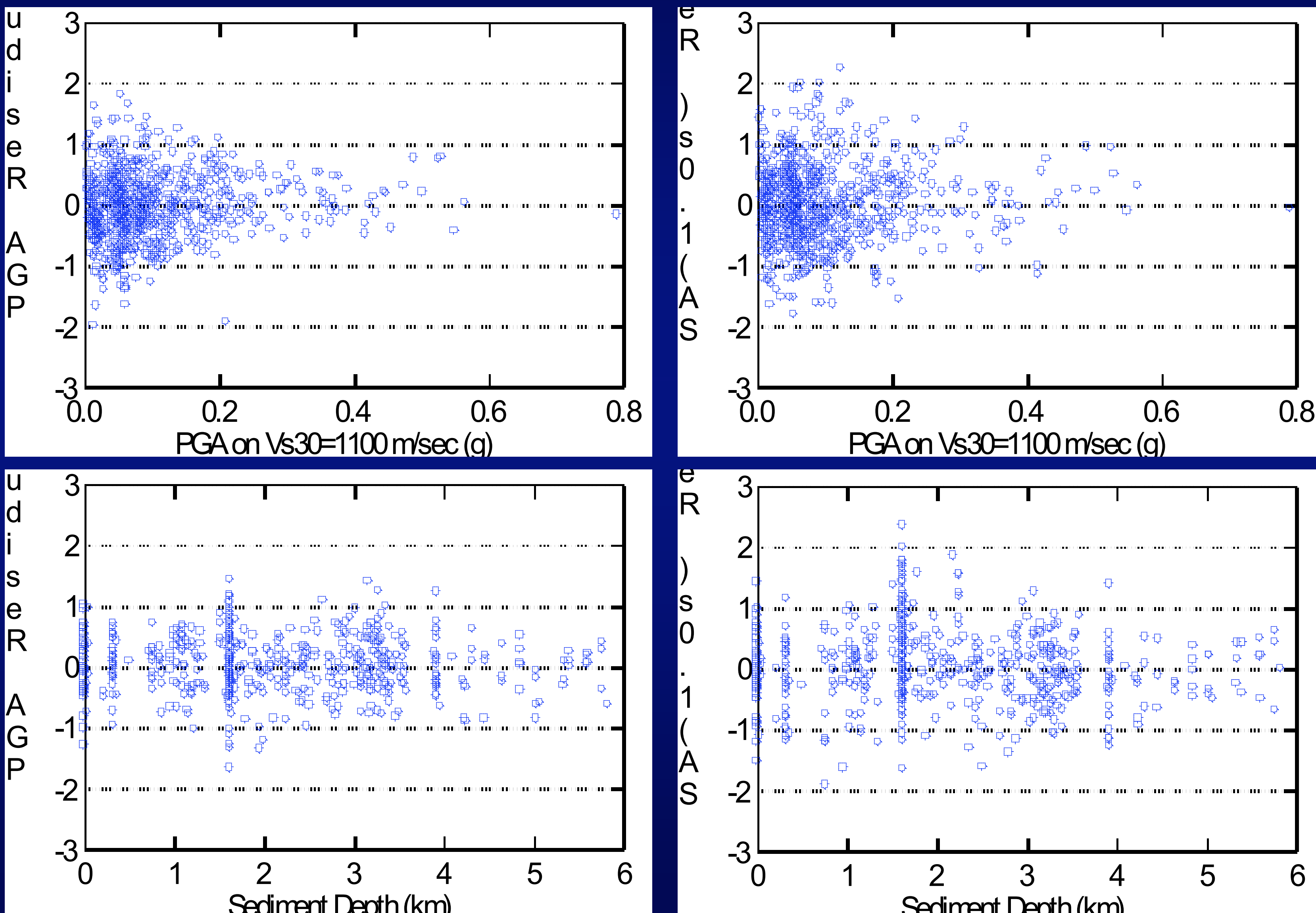
Residuals (Intra/Inter) vs. Magnitude



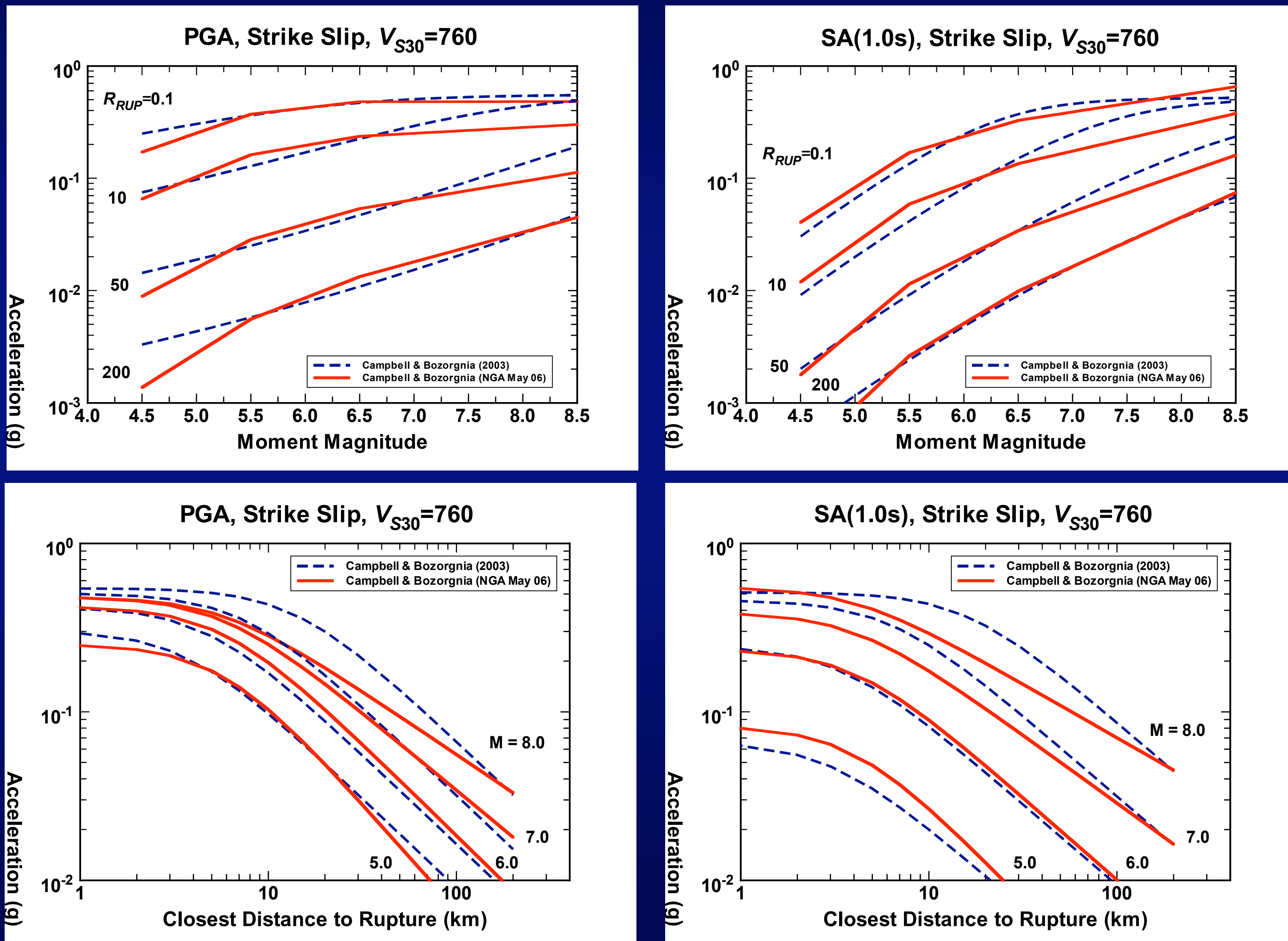
Total Residuals vs. Distance and V_{S30}



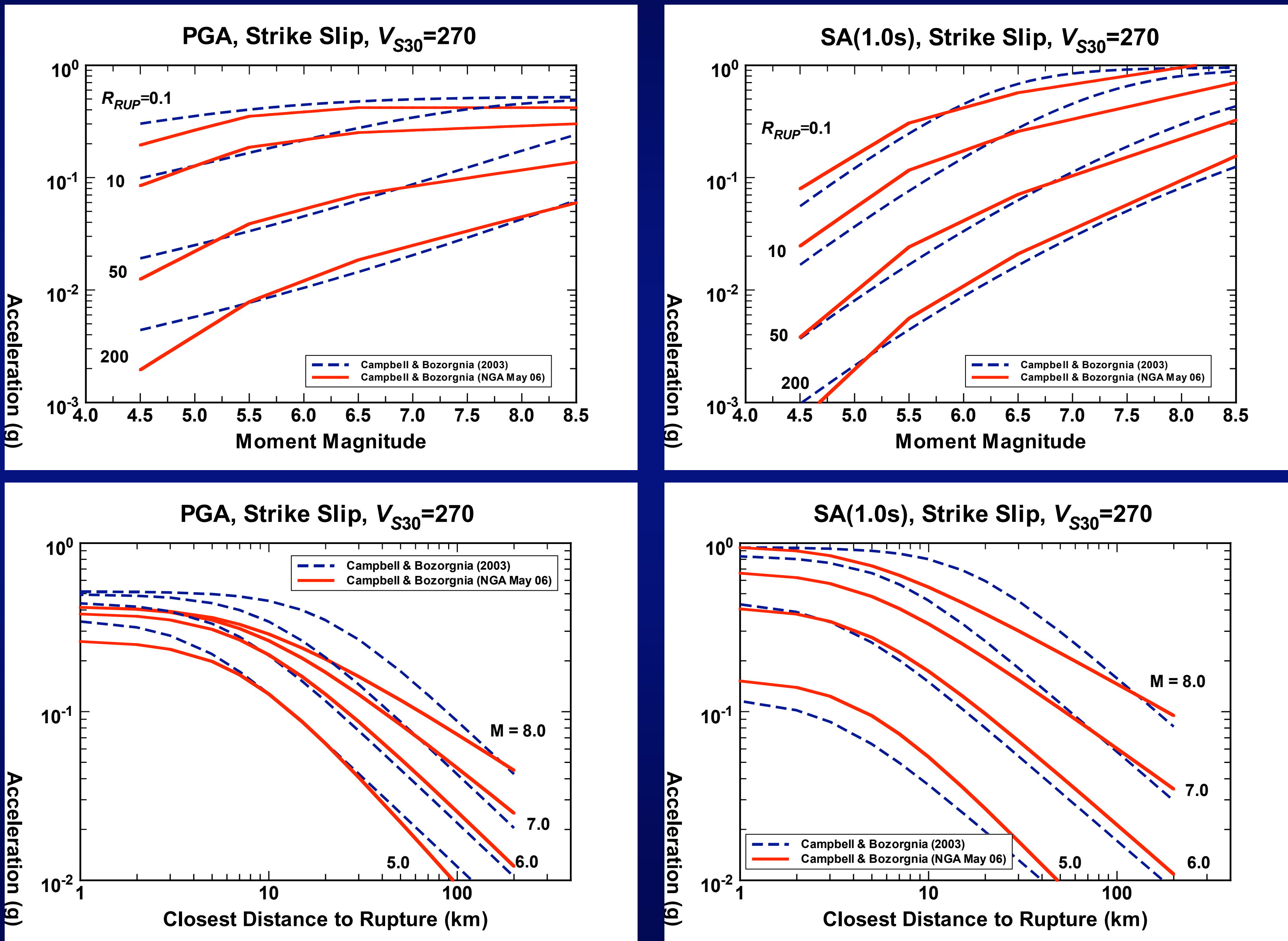
Total Residuals vs. Rock PGA and $Z_{2.5}$



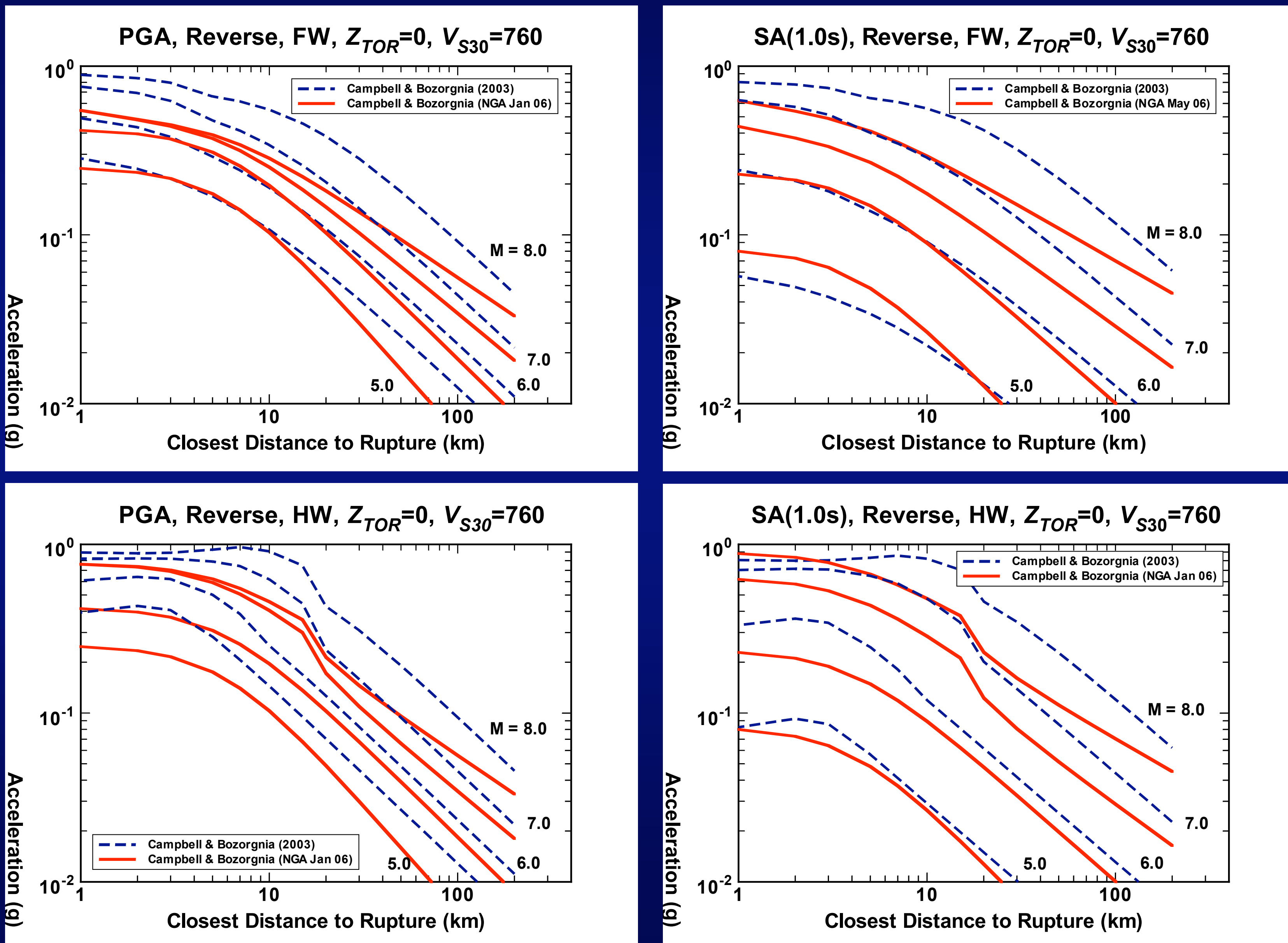
Strike Slip/Surface Reverse – NEHRP BC



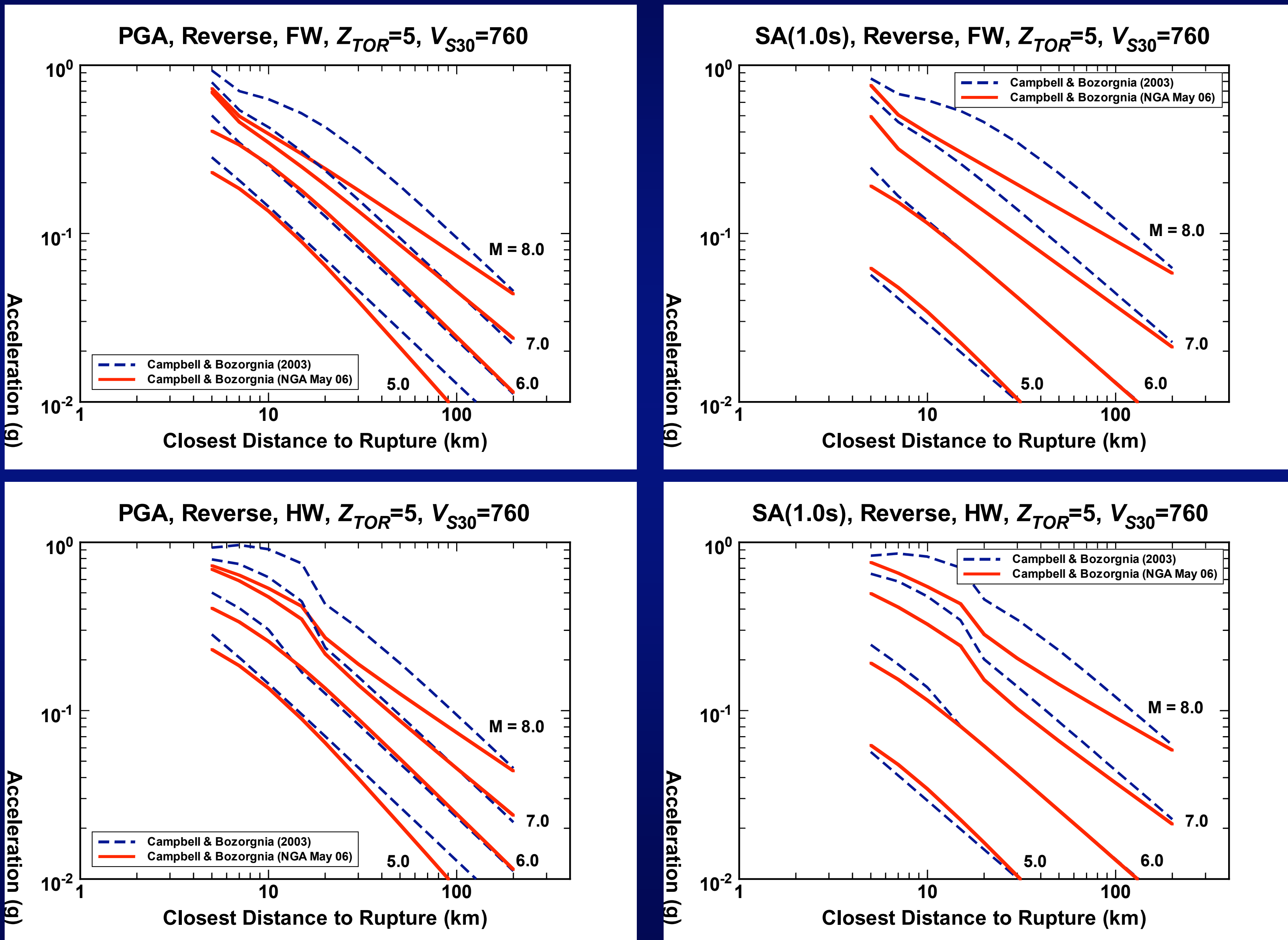
Strike Slip/Surface Reverse – NEHRP D



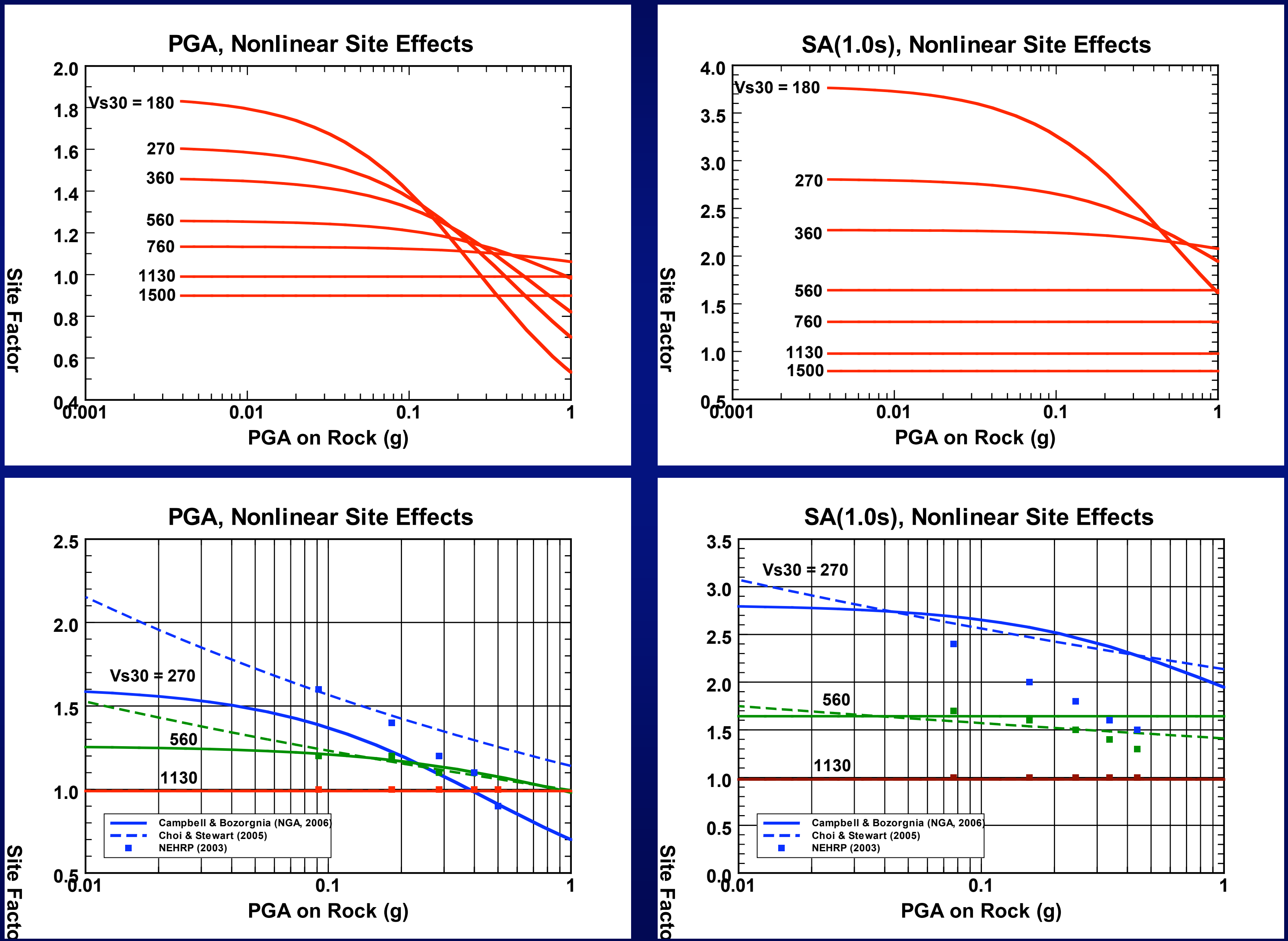
Surface Reverse – FW vs. HW



Buried Reverse – FW vs. HW

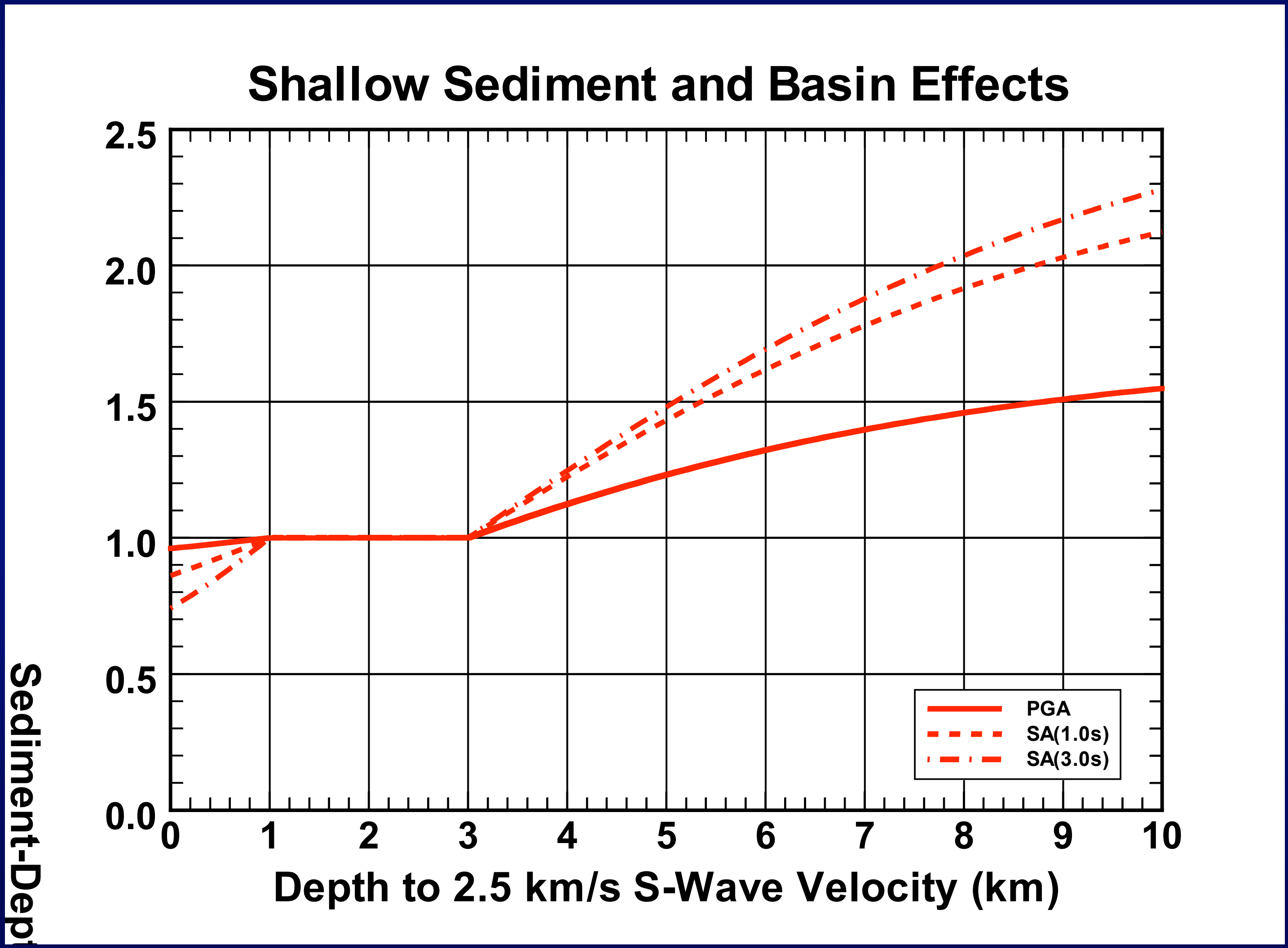


Site Effects – Shallow Site Conditions

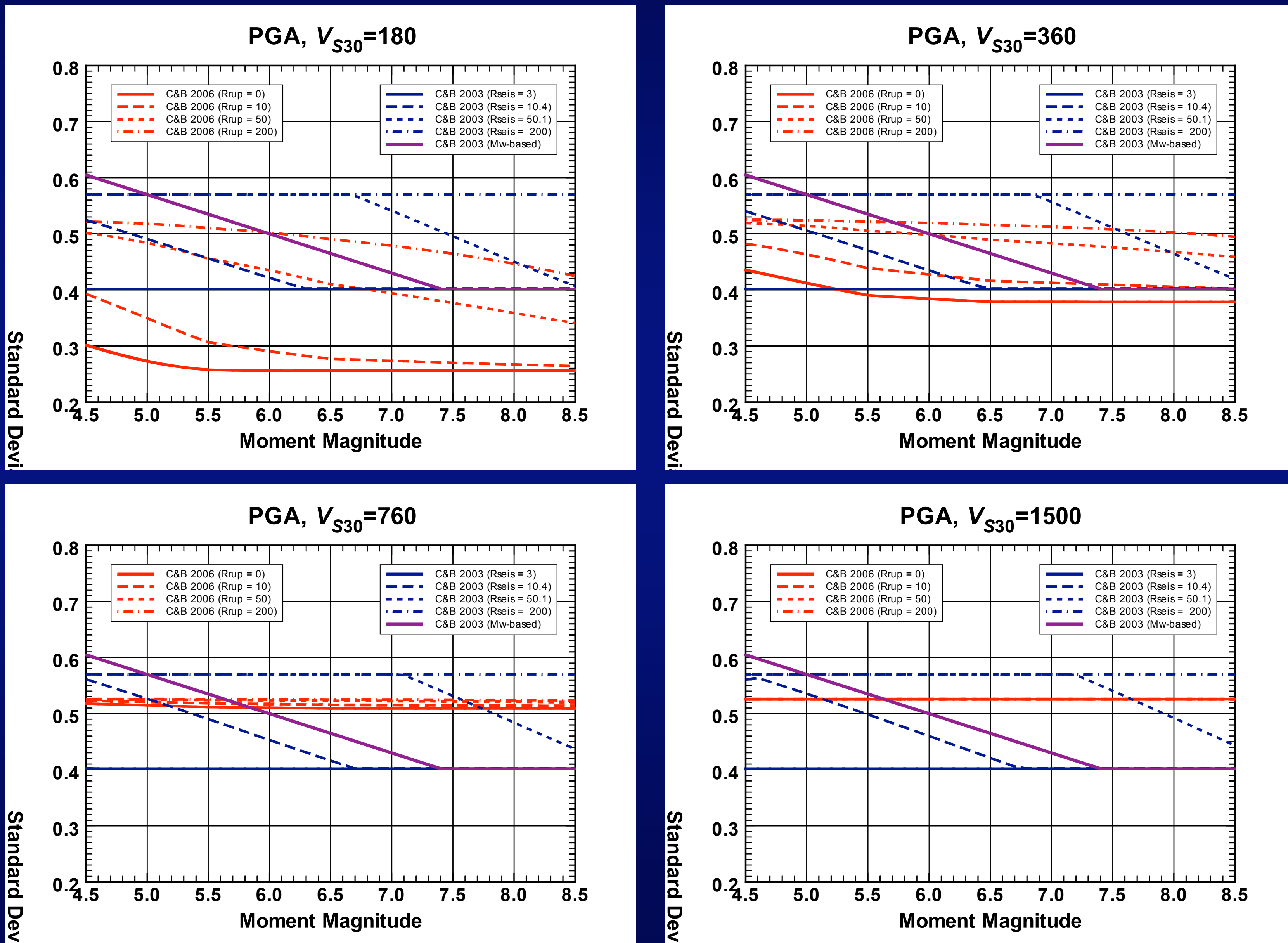


$f_1(M)$

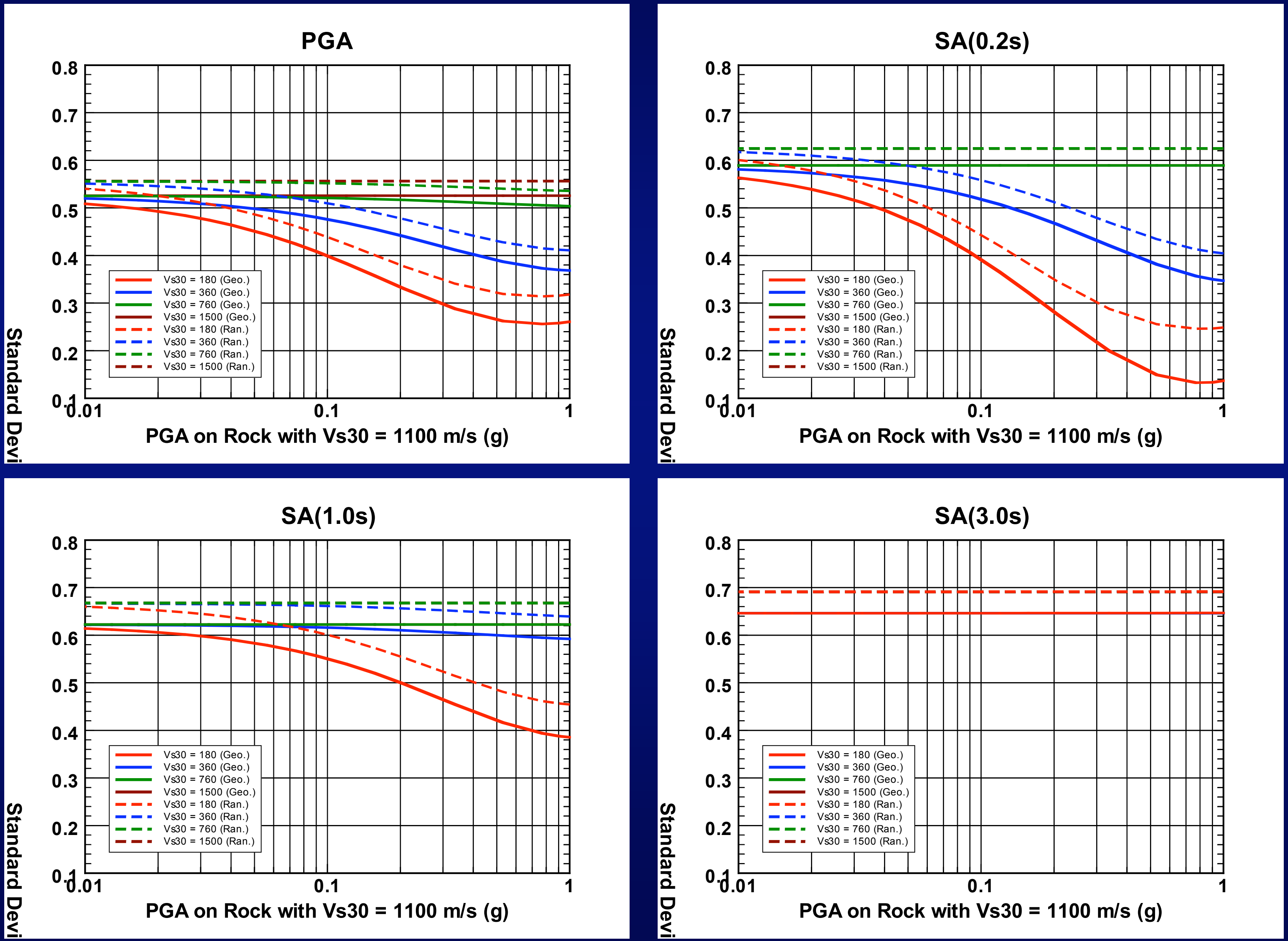
Site Effects – Sediment Depth



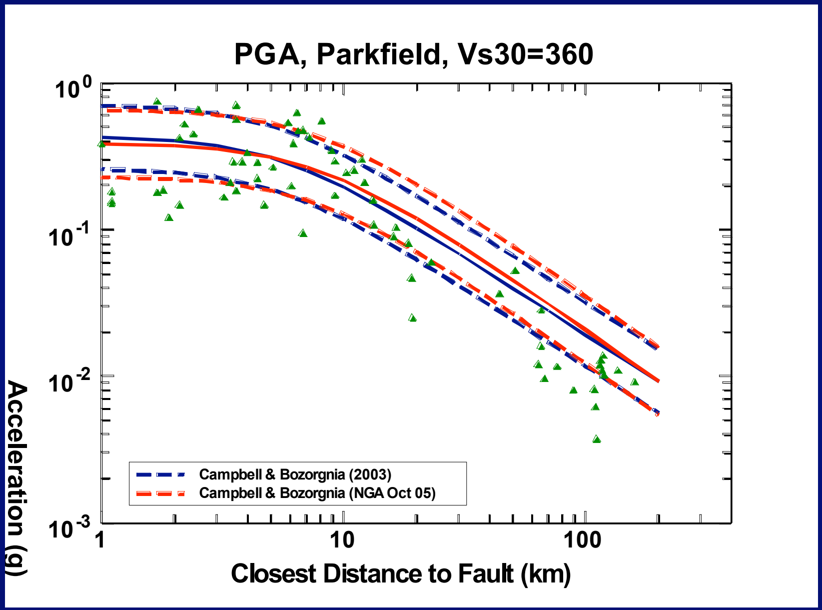
Standard Deviation vs. Magnitude

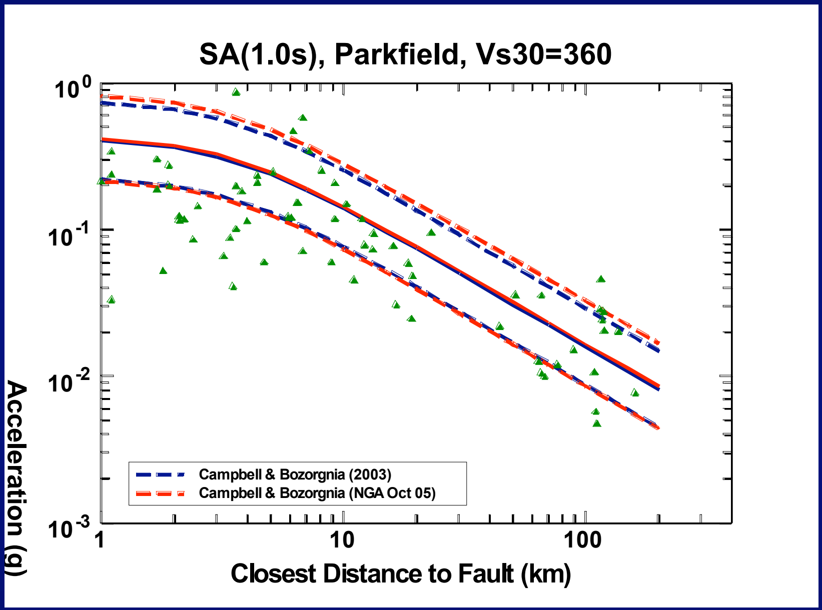


Standard Deviation vs. Rock PGA



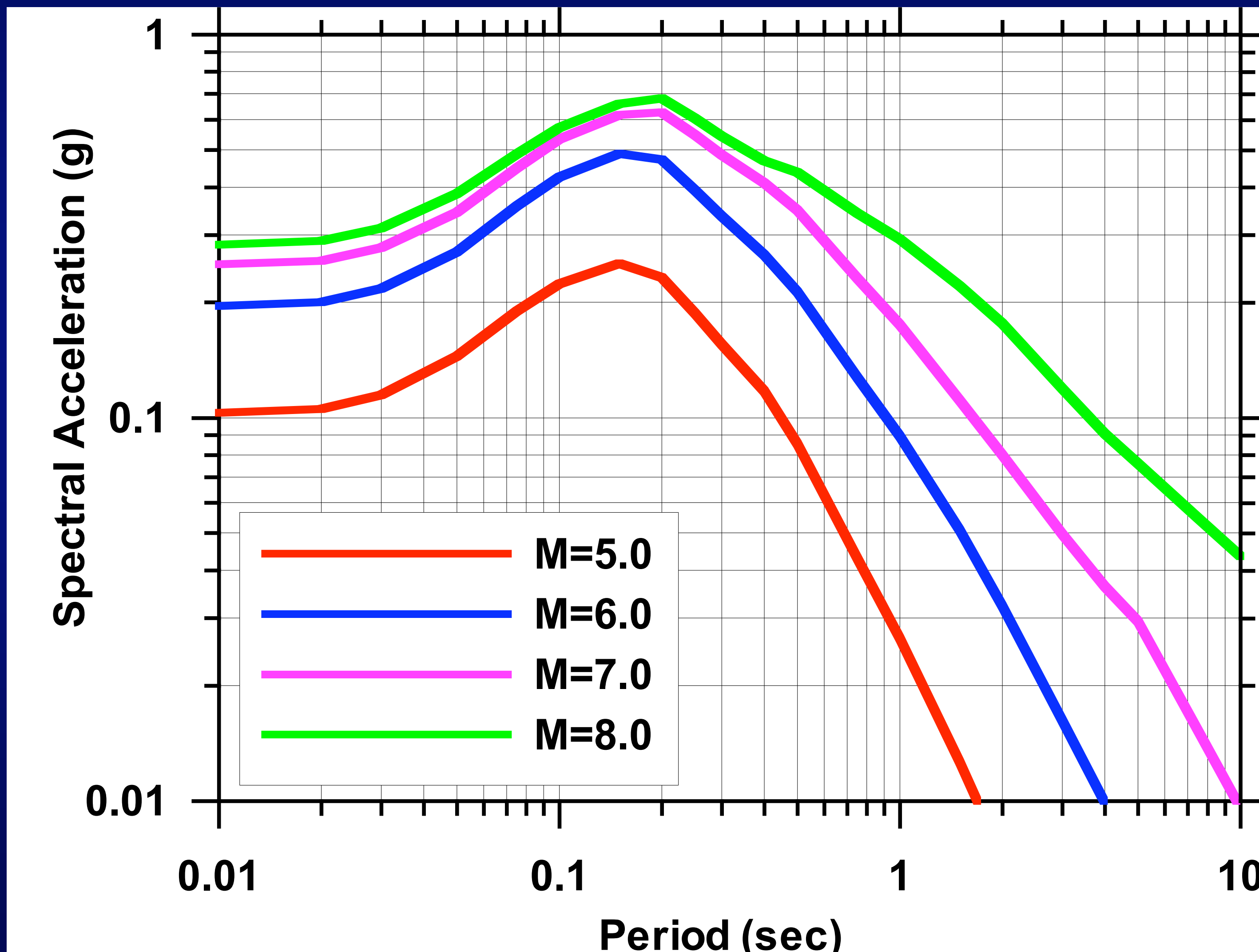
2004 Parkfield Earthquake (**M** = 6.0)





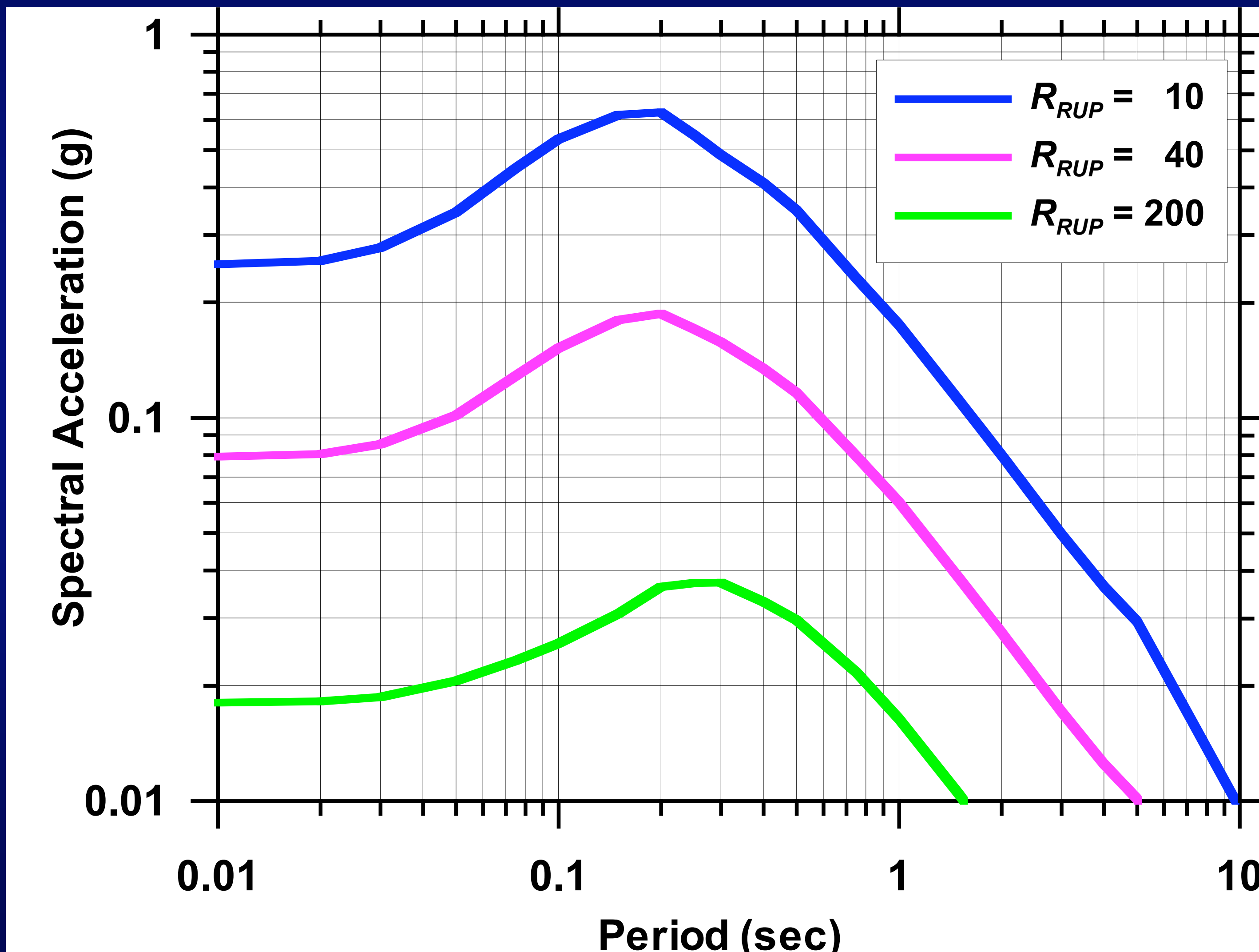
Predicted Acceleration Spectra

Strike Slip, R_{RUP} = 10 km, V_{S30} = 760 m/s



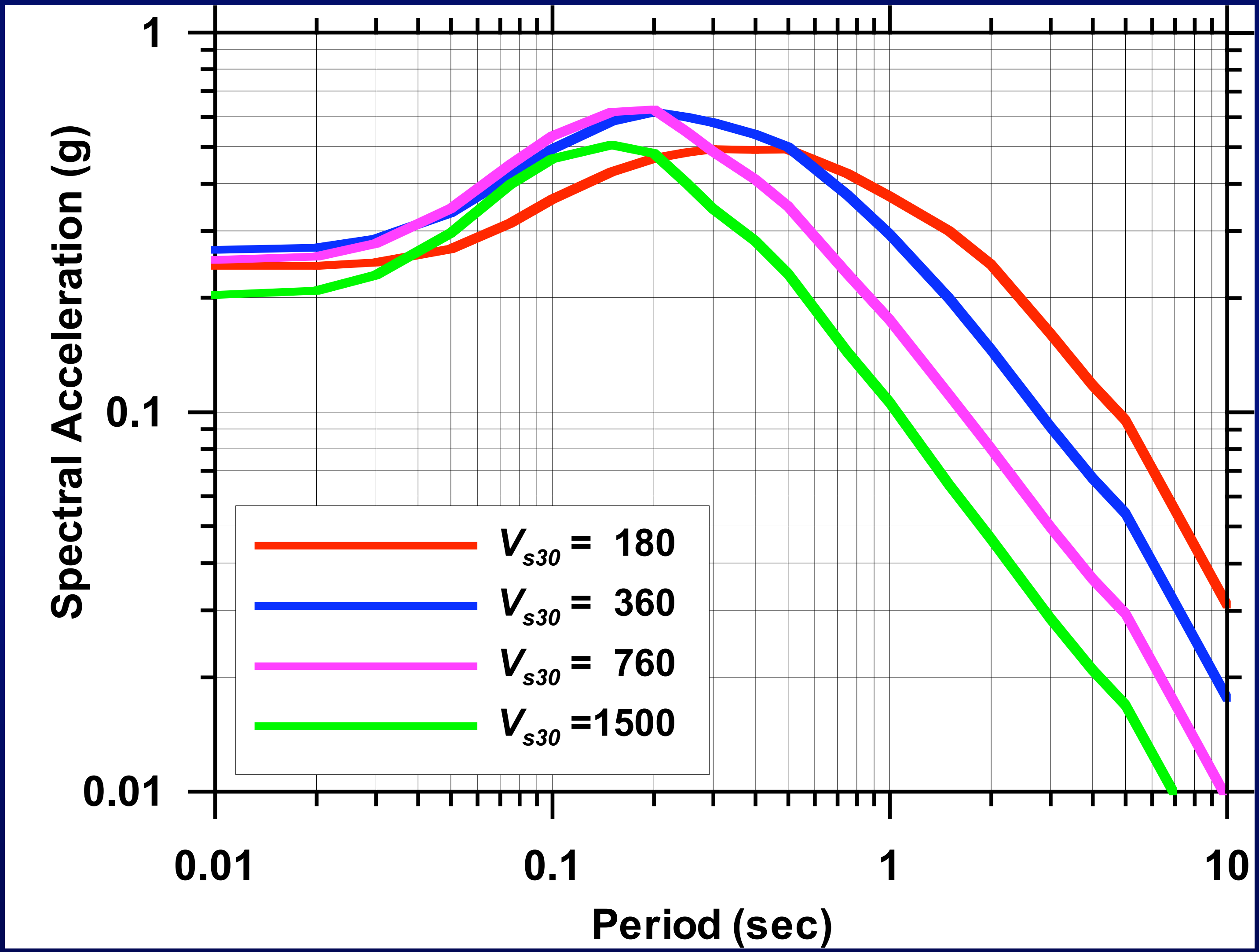
Predicted Acceleration Spectra

Strike Slip, **M** = 7.0, V_{S30} = 760 m/s



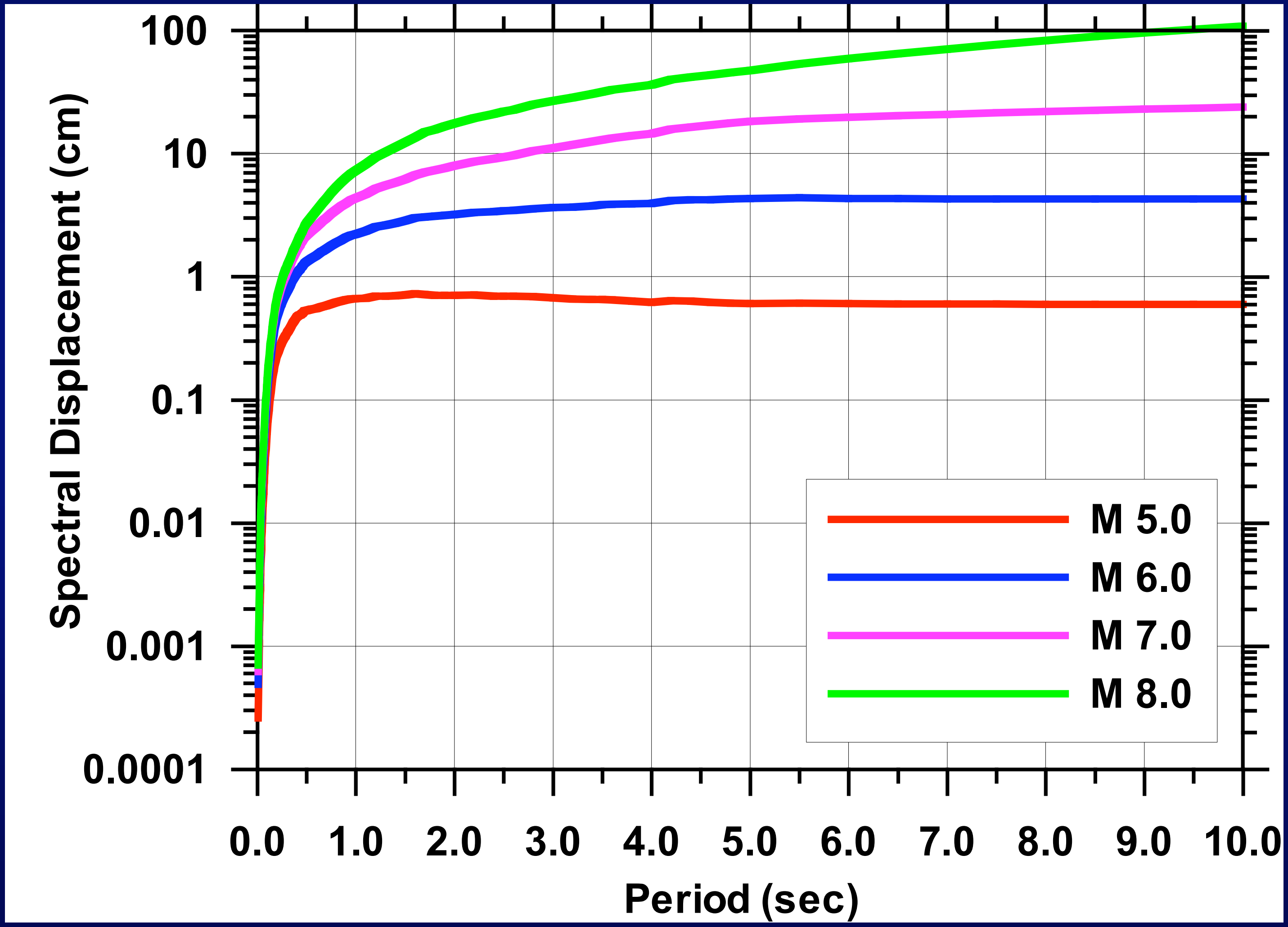
Predicted Acceleration Spectra

Strike Slip, **M** = 7.0, R_{RUP} = 10 km



Predicted Spectral Displacement

Strike Slip, $R_{RUP} = 10$ km, $V_{S30} = 760$ m/s

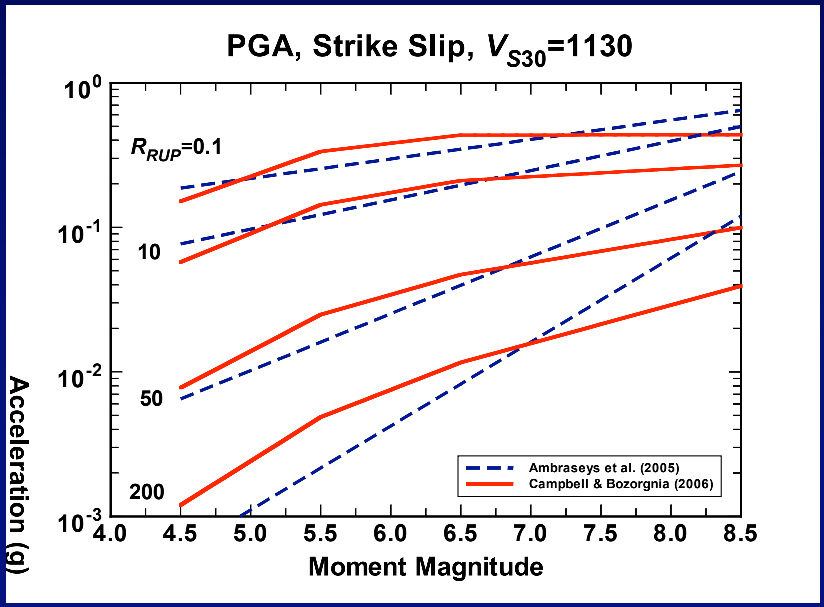


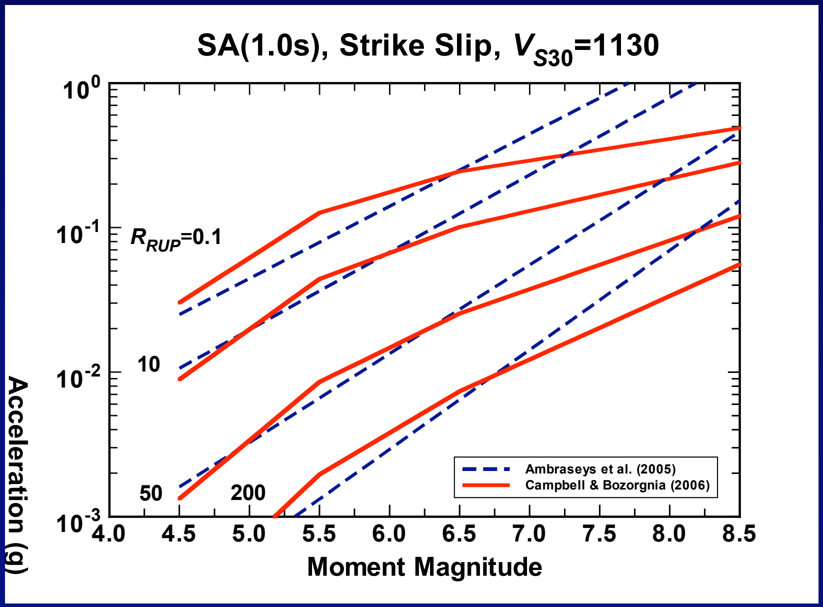
Work in Progress

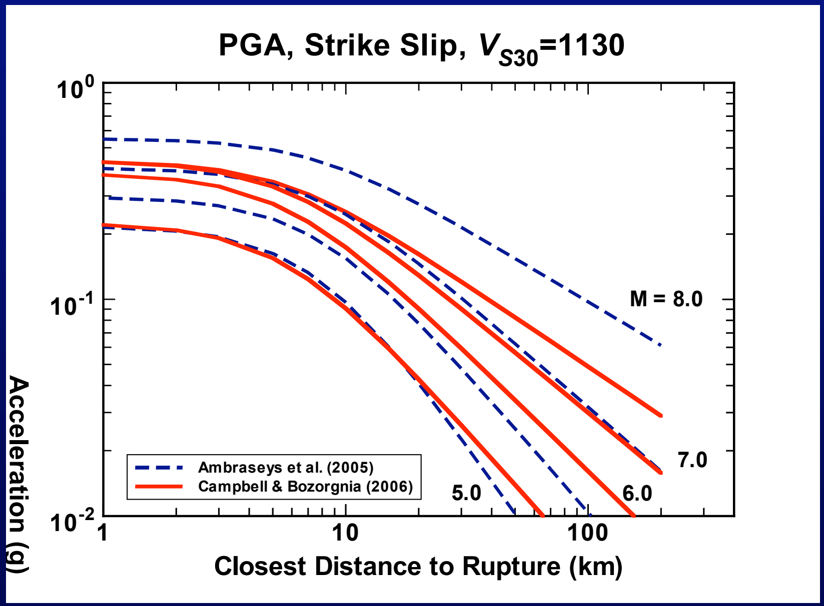
- Finish smoothing regression coefficients
  - Smooth predicted response spectra
  - Extrapolate to 10-second period
- Develop relationship for other components
  - Fault-normal (FN)
  - Fault-parallel (FP)
  - Vertical
- Add source directivity term
  - Geometric method (e.g., Abrahamson and Somerville)
  - Isochrone method (e.g., Spudich)
- Extend to other regions and tectonic environments
  - Subduction zones

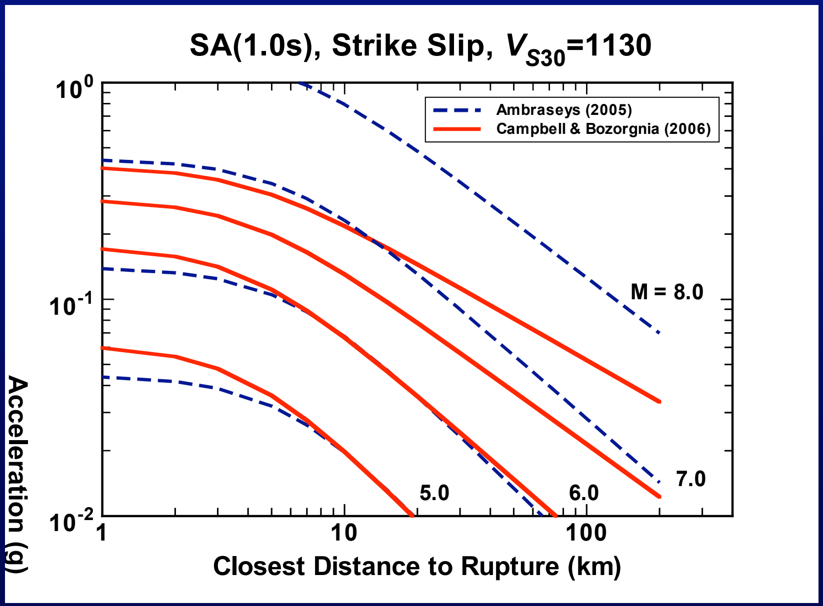
Comparison with Ambraseys et al. (2005) Empirical Ground Motion Model for Europe and Middle East

Strike Slip – NEHRP B (Rock)

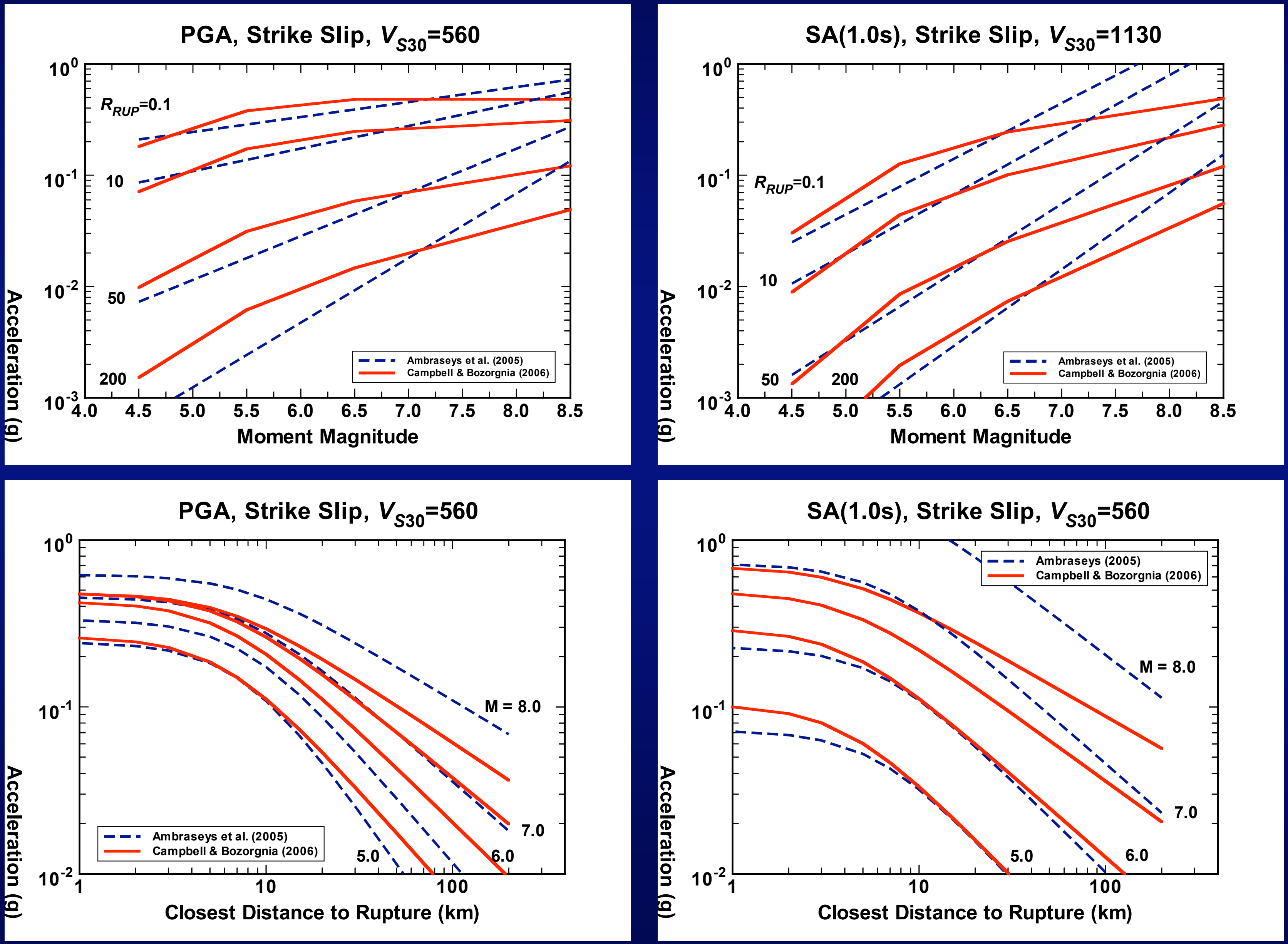




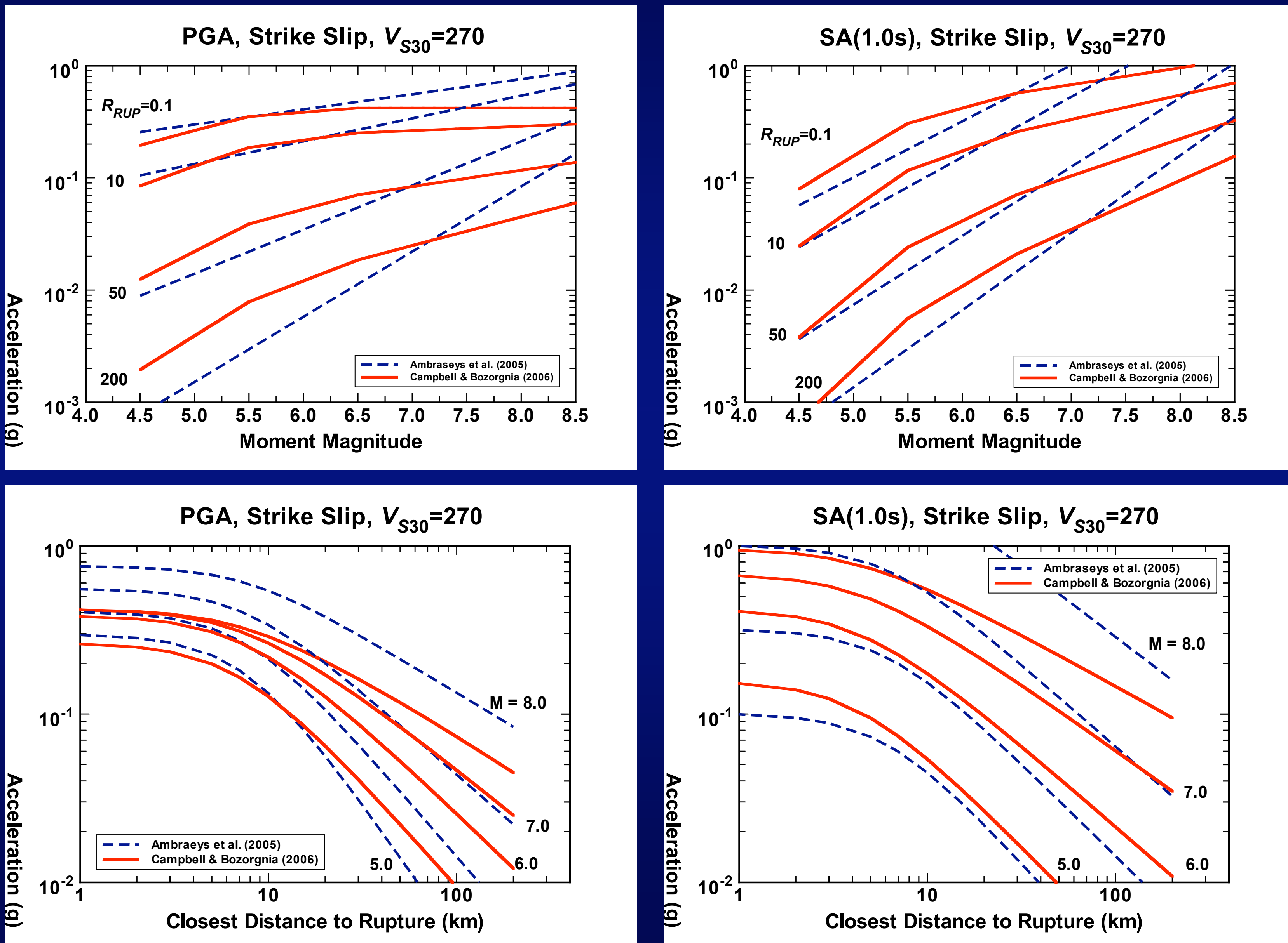




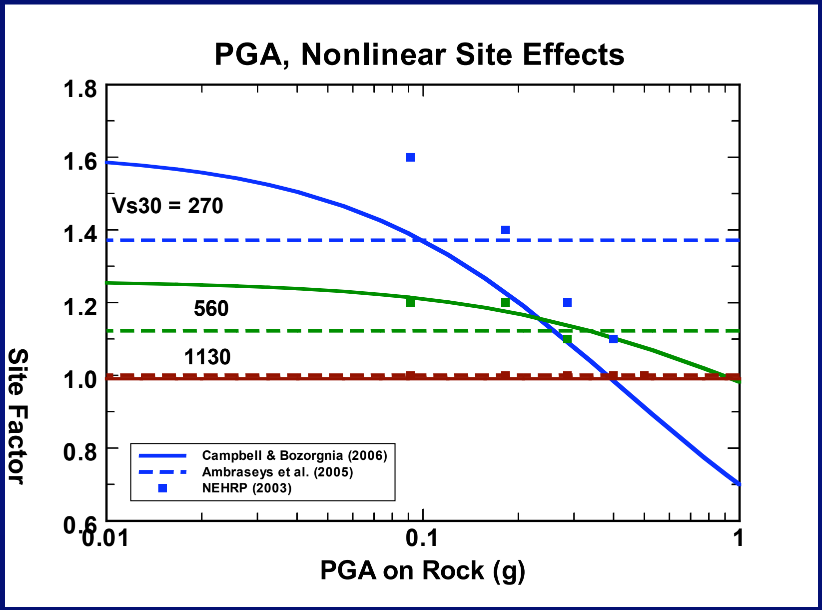
Strike Slip – NEHRP C (Stiff Soil)

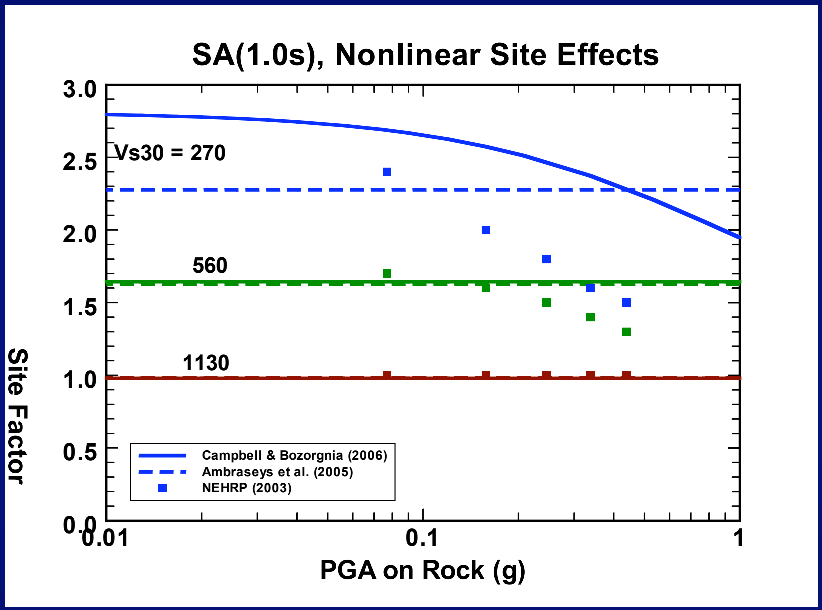


Strike Slip – NEHRP D (Soft Soil)

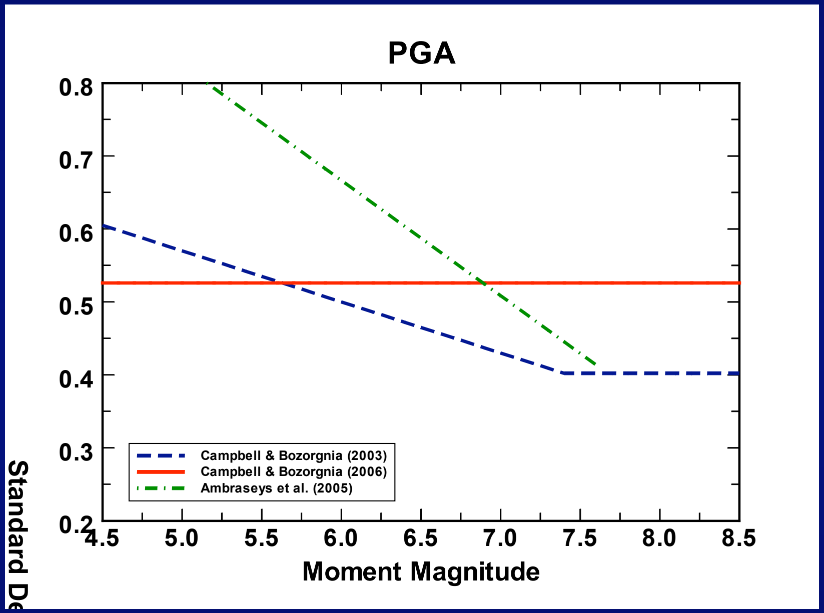


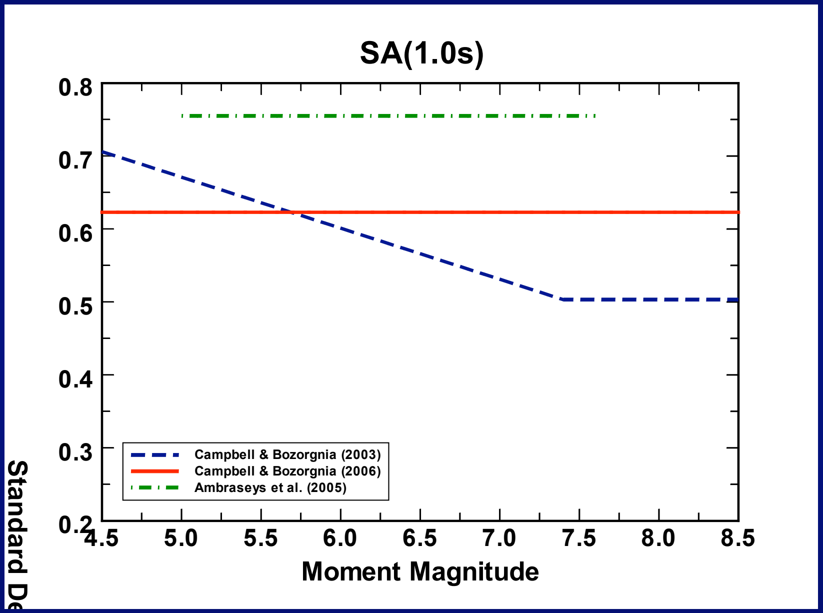
Site Effects – Shallow Site Conditions





Standard Deviation vs. Magnitude





Conclusions – Strike Slip

- Comparison with Ambraseys et al. (2005) is best for:
  - NEHRP B site conditions (Rock, V_{S30} = 1130 m/s)
  - **M** = 5.0 – 6.5
  - R_{RUP} = 10 – 100 km
- Comparison with Ambraseys et al. (2005) deteriorates for softer site conditions
  - NGA model supports nonlinear soil behavior
  - Ambraseys model assumes linear soil behavior
- Comparison with Ambraseys et al. (2005) deteriorates for large magnitudes and close distances
  - NGA model supports nonlinear magnitude scaling
  - Ambraseys model assumes linear magnitude scaling

Conclusions – Strike Slip

- Ambraseys et al. (2005) has larger standard deviations
  - NGA model applied stricter data selection criteria based on a database that was rich in metadata
  - Ambraseys model used all relevant data based on a database with limited metadata
- Preliminary conclusions
  - Need to compare NGA model directly with Ambraseys data
  - Campbell-Bozorgnia model appears to be appropriate for use for shallow crustal earthquakes in active tectonic regions of Europe
  - By analogy other NGA models are also likely to be appropriate in this region

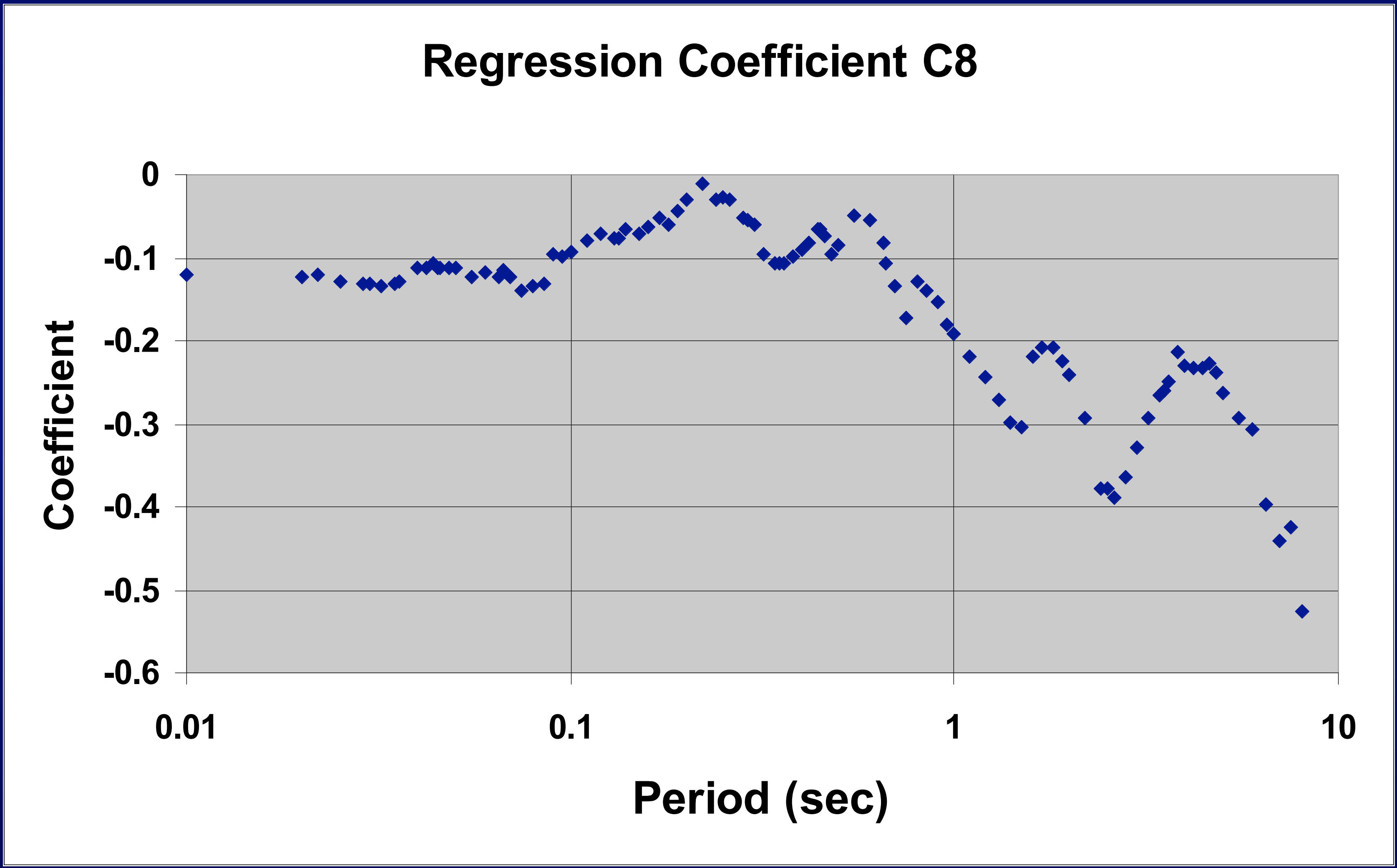
Normal Fault Issues

Normal and Normal-Oblique Events

Date	Earthquake	**M**	R_{RUP} (km)	No.
1979	Norcia, Italy	5.9	19 – 36	3
1980	Mammoth Lakes, California	6.1	5 – 15	3
1980	Irpinia, Italy	6.9	8 – 60	13
1981	Corinth, Greece	6.6	10	1
1983	Bora Peak, Idaho	6.9	83 – 85	2
1984	Lazio-Abruzzo, Italy	5.8	19 – 51	5
1987	Edgecumbe, New Zealand	6.6	16 – 69	2
1990	Griva, Greece	6.1	29	1
1992	Little Skull Mtn., Nevada	5.7	16 – 100	8
1995	Kozani, Greece	6.4	20 – 79	3
1995	Dinar, Turkey	6.4	3 – 44	2

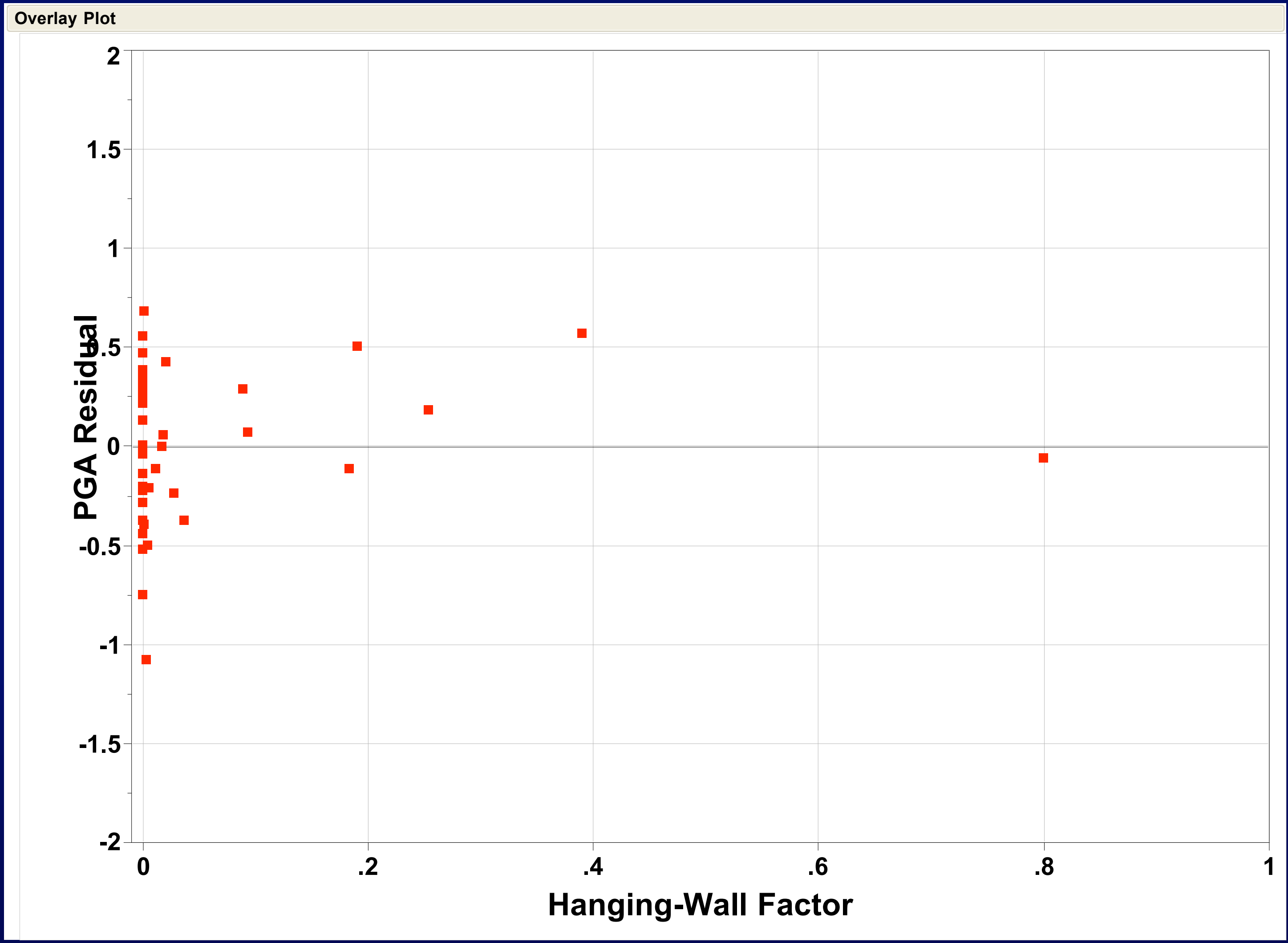
Normal-Faulting Coefficient

Unsmoothed Regression Coefficients vs. Period



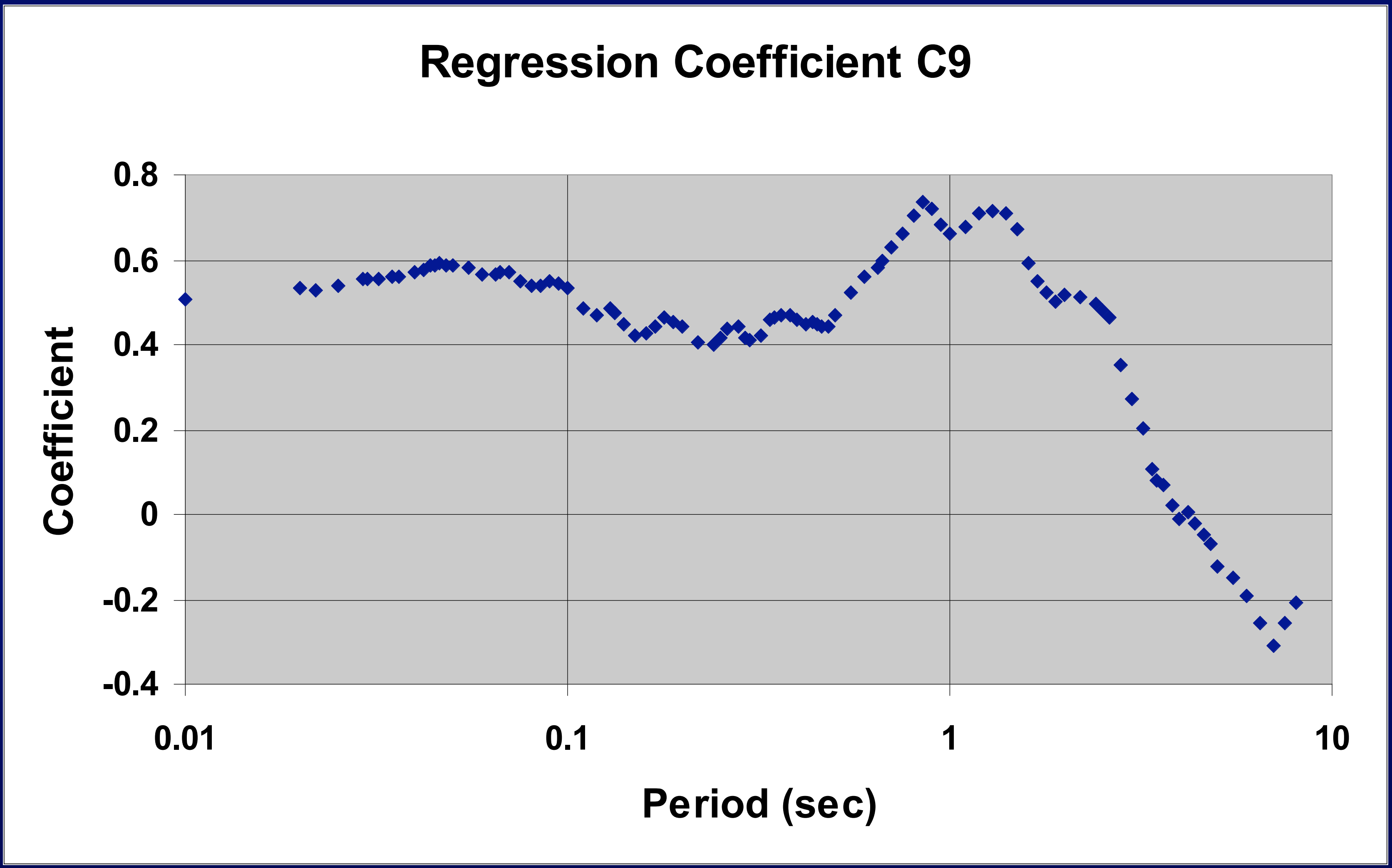
HW Factor for Normal Faulting

PGA HW Coefficient Similar to Reverse Faulting



Reverse-Faulting HW Coefficient

Unsmoothed Regression Coefficients vs. Period



Normal-Faulting Questions

- Should hanging-wall effects be included for normal-faulting events?
  - Supported by preliminary results for PGA
  - Based on only a limited number of recordings
- Should hanging-wall effects for normal-faulting be similar to reverse-faulting?
  - Supported by preliminary results for PGA
  - PGA HW term is similar to that for reverse-faulting events
  - Regression coefficient is not statistically significant

Normal-Faulting Questions

- Should normal-faulting events have lower short-period ground motion than strike-slip events?
  - Ambraseys et al. (2005) – Europe and Middle East
    - Both normal and strike slip from extensional regions
    - 8% to 24% lower than strike slip for $T < 0.13$s
    - Effect decreases to 0 between $T = 0.13$–0.32s
    - Short-period effect is statistically significant
  - Campbell and Bozorgnia (NGA)
    - No distinction between extensional and non-extensional
    - 9% to 12% lower than strike slip for $T < 0.08$s
    - Effect decreases to 0 between $T = 0.08$–0.2s
    - Effect increases to –30% from $T = 0.2$–2.0s
    - Short-period effect is marginally statistically significant

Normal-Faulting Questions

- Should normal-faulting events have lower short-period ground motion than strike-slip events?
  - Spudich et al. (1999)
    - Both normal and strike slip from extensional regions
    - Many events from California's Imperial Valley
    - 15% to 25% lower than strike slip for $T < 0.15$s
    - Effect decreases to 0 between $T = 0.15$–0.35s
    - Effect increases to –35% between $T = 1.2$–2.0s
    - Long-period effect is not significant (IV events?)
  - Spudich et al. (1999) – Compared to Boore et al. (1997) soil
    - Slightly lower than BJF97 strike slip for $T < 0.15$s
    - Effect increases to –33% from $T = 0.15$–2.0s
    - Long-period effect is statistically significant

Normal-Faulting Questions

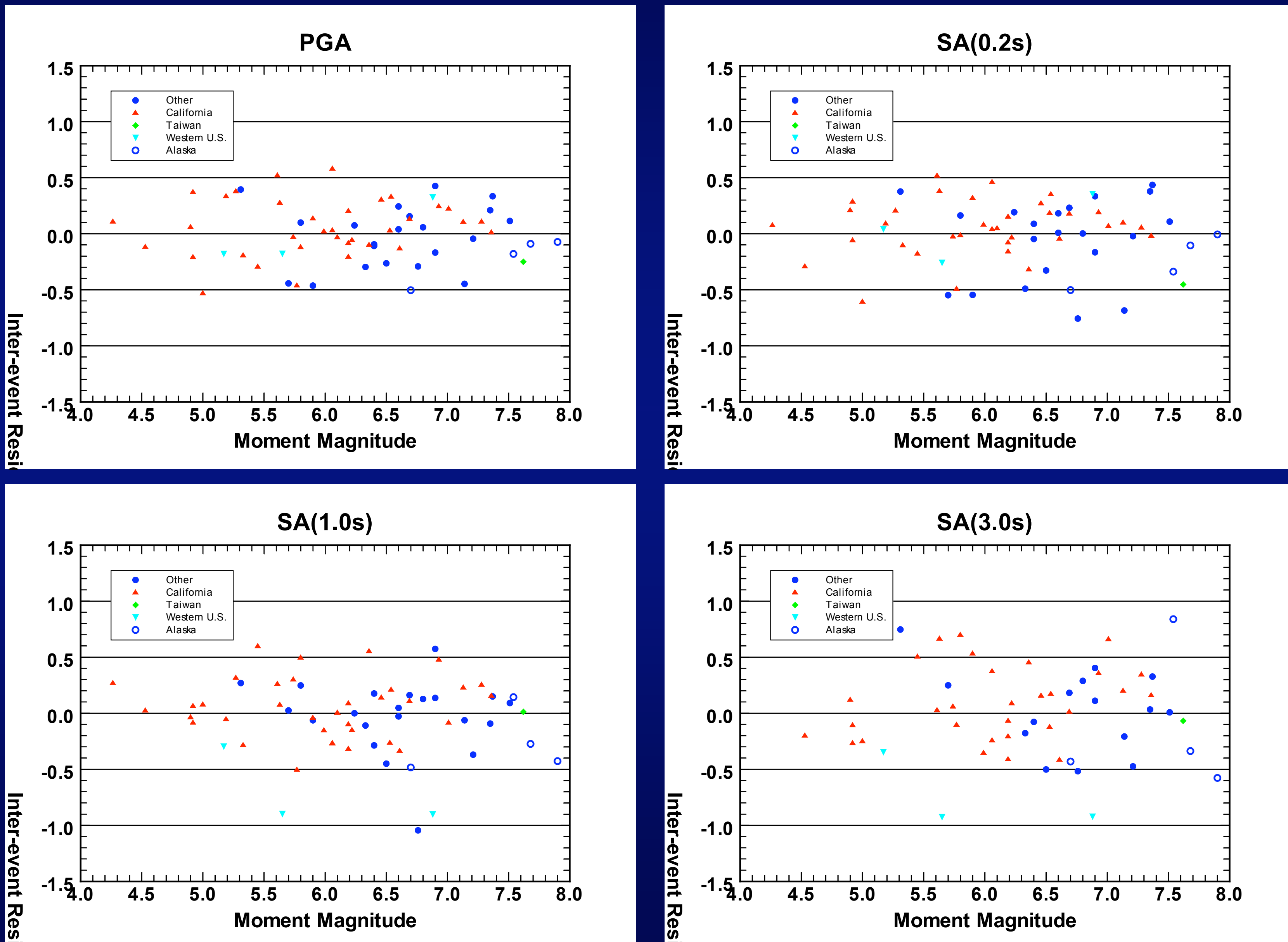
- Should normal-faulting events have lower long-period ground motion than strike-slip events?
  - Ambraseys et al. (2005) predicts similar amplitudes
    - Recordings come from same regions
    - Suggests similar static stress drops
  - Campbell and Bozorgnia (NGA) predicts different amplitudes
    - Recordings come from different regions
    - Could be systematic differences in sediment depths
  - Spudich et al. (1999) predict different amplitudes than BJF97
    - Recordings come from different regions
    - Effects are nearly identical to NGA results
    - Could be systematic differences in sediment depths

Tentative Conclusions: Normal Faulting

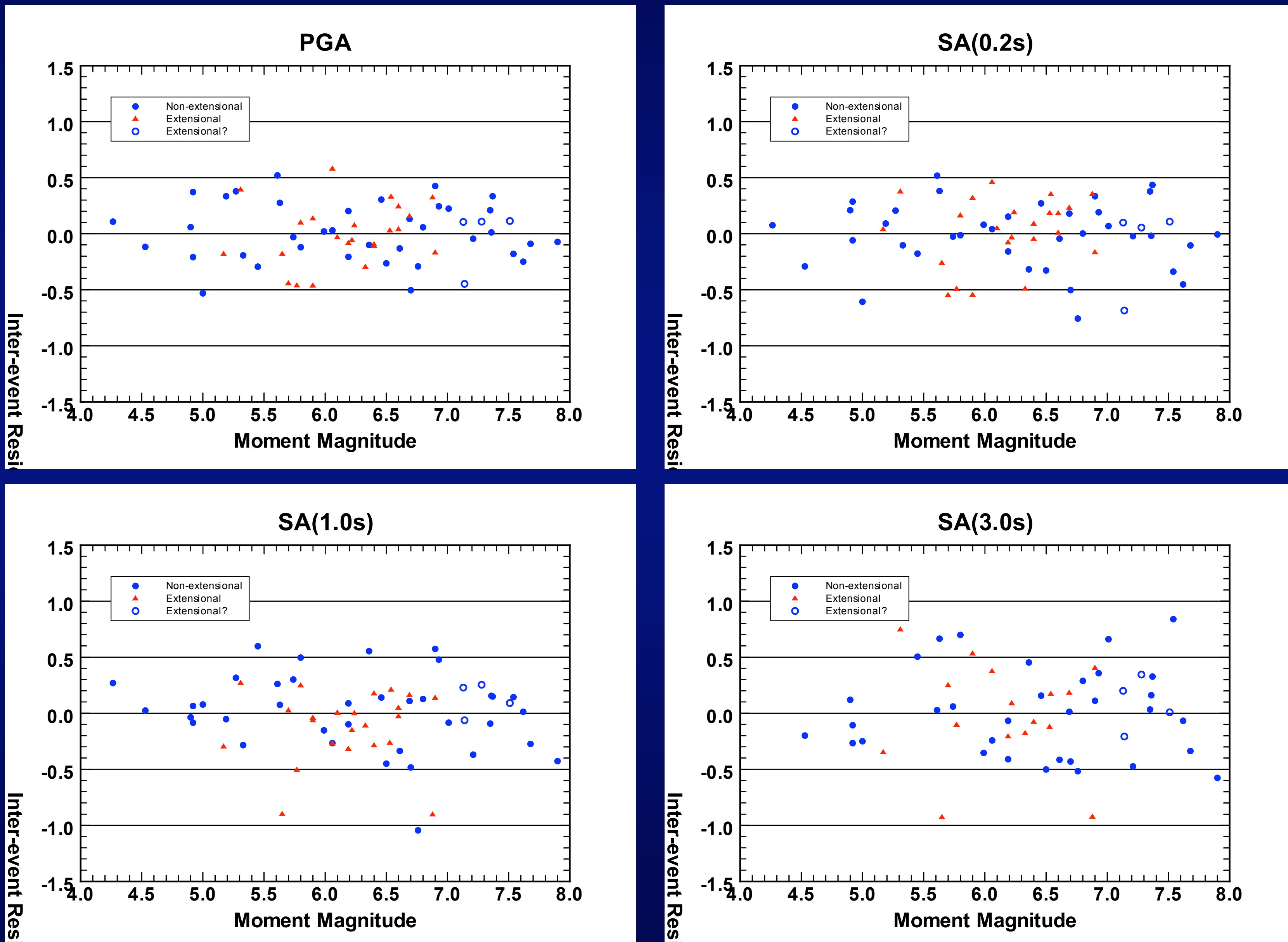
- Hanging-wall effects
  - Assumed to be the same as reverse faults
  - 63% higher than footwall for $T < 1.7$s
  - Effect phases out at $T > 3.8$s
- Normal-faulting effects
  - 11% lower than strike slip for $T < 0.09$s
  - Effect phases out at $T > 0.2$s

Regional Bias Issues

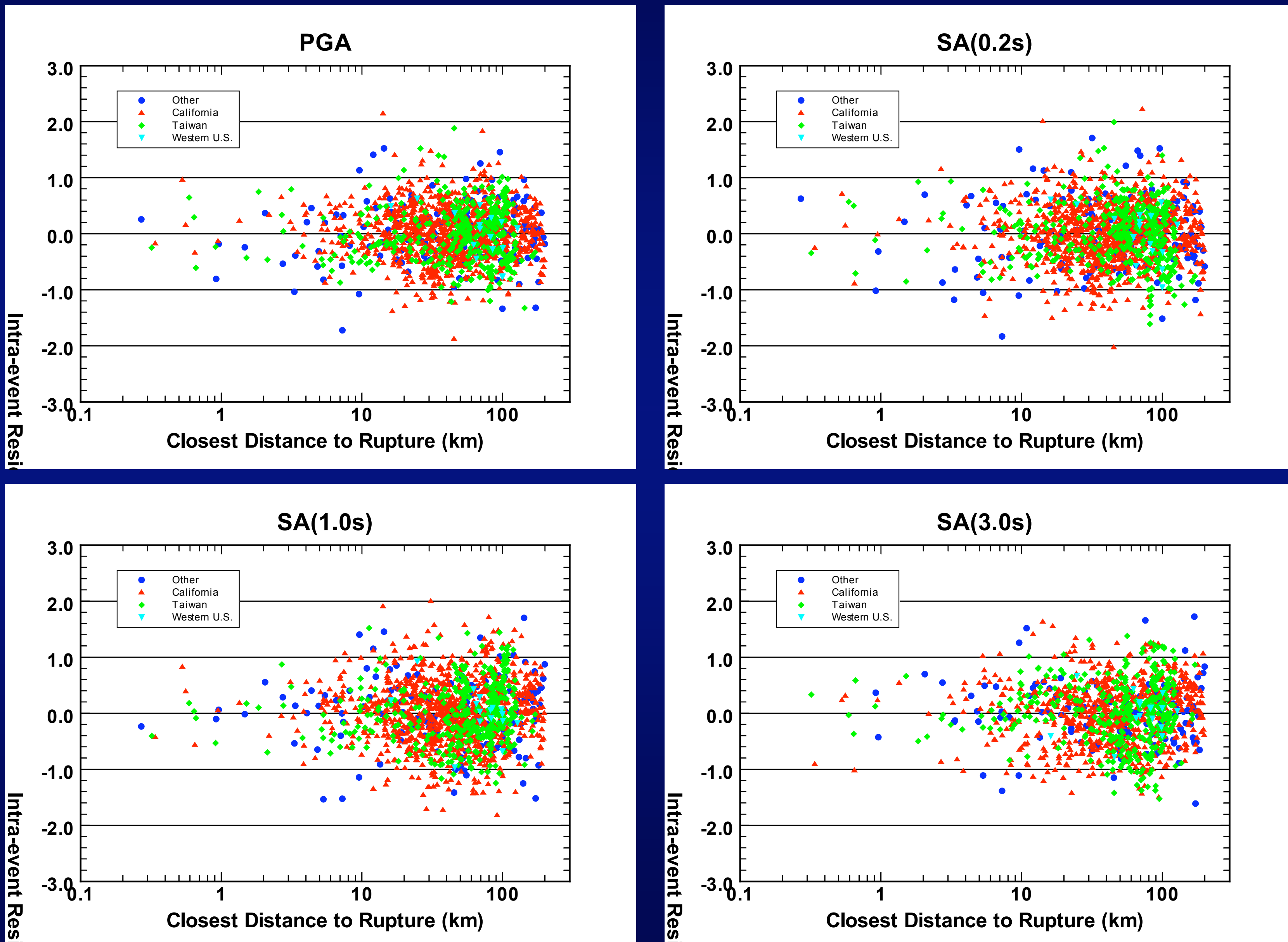
Inter-event Residuals by Region



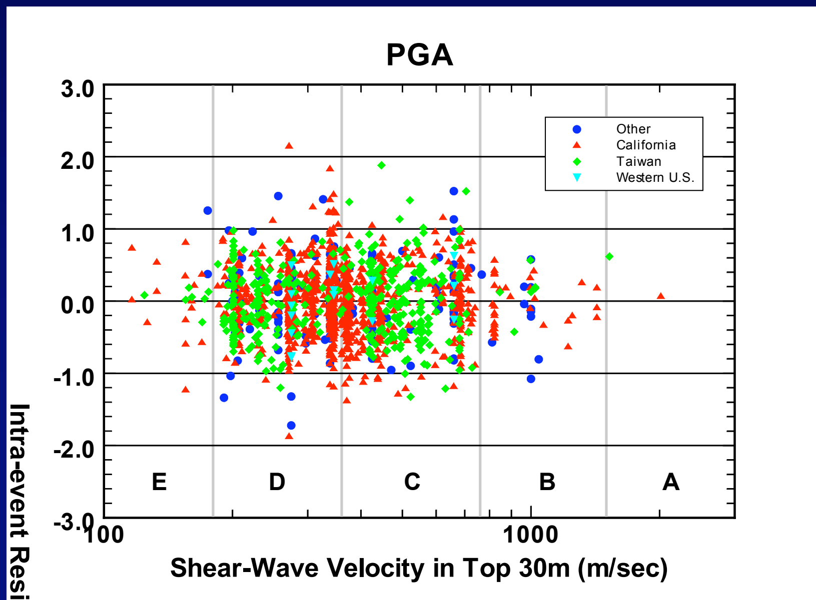
Inter-event Residuals by Stress Regime

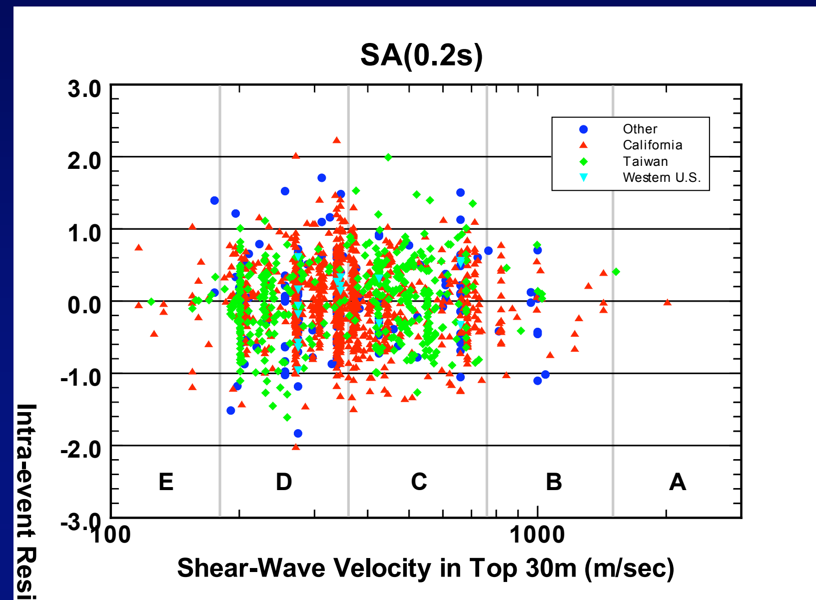


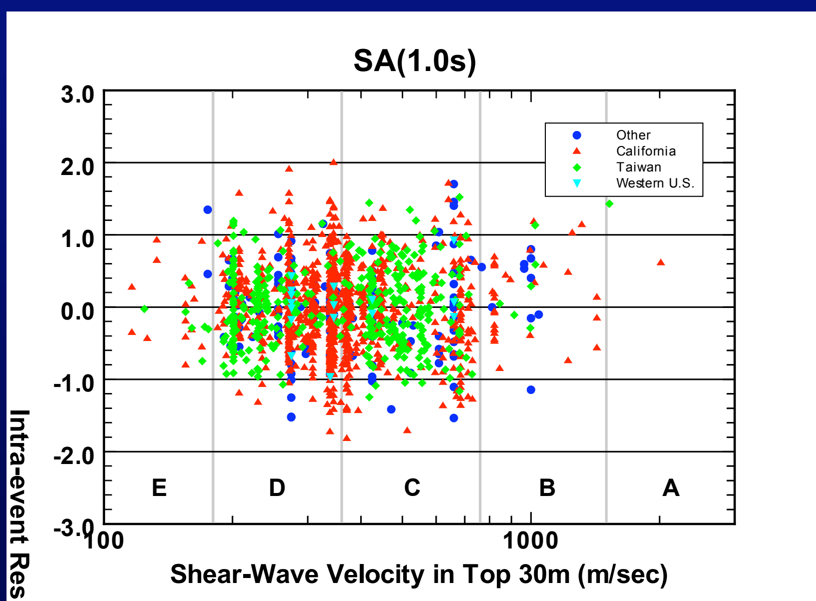
Intra-event Residuals by Region

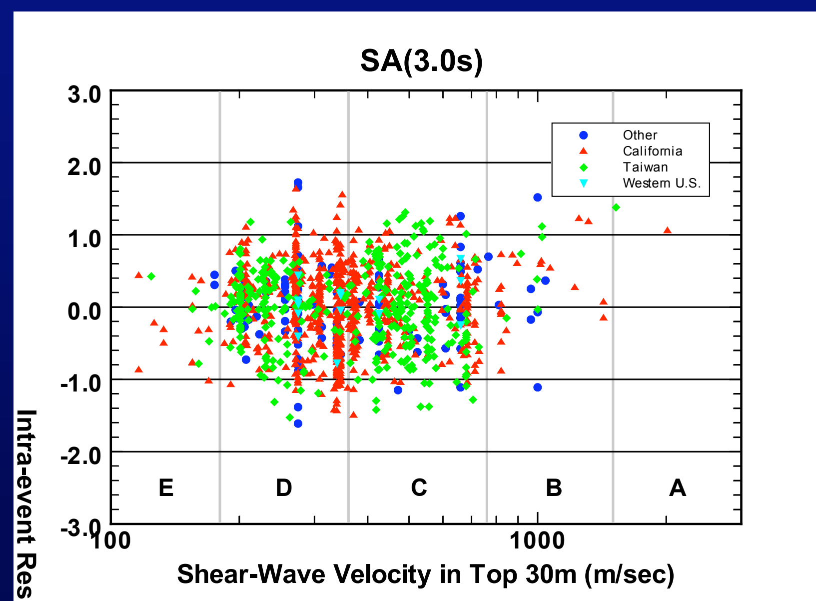


Intra-event Residuals by V_{S30}



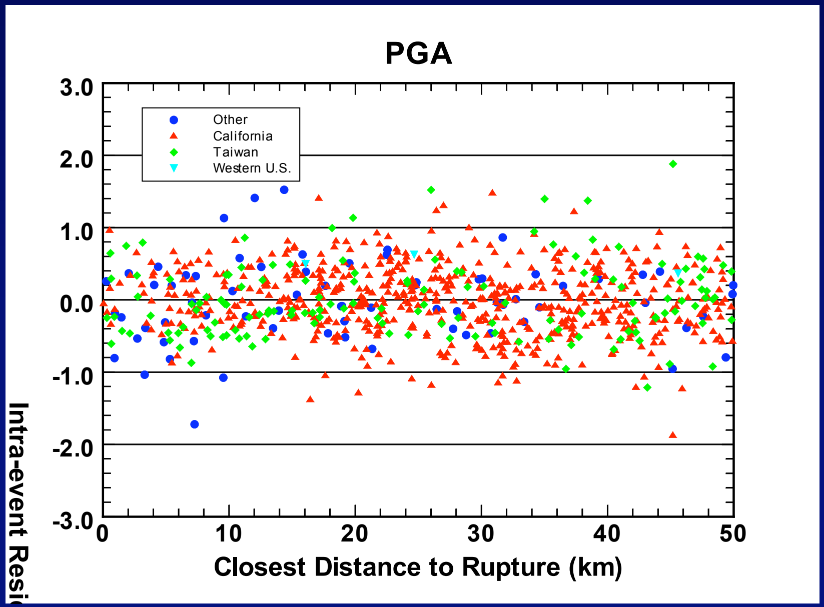


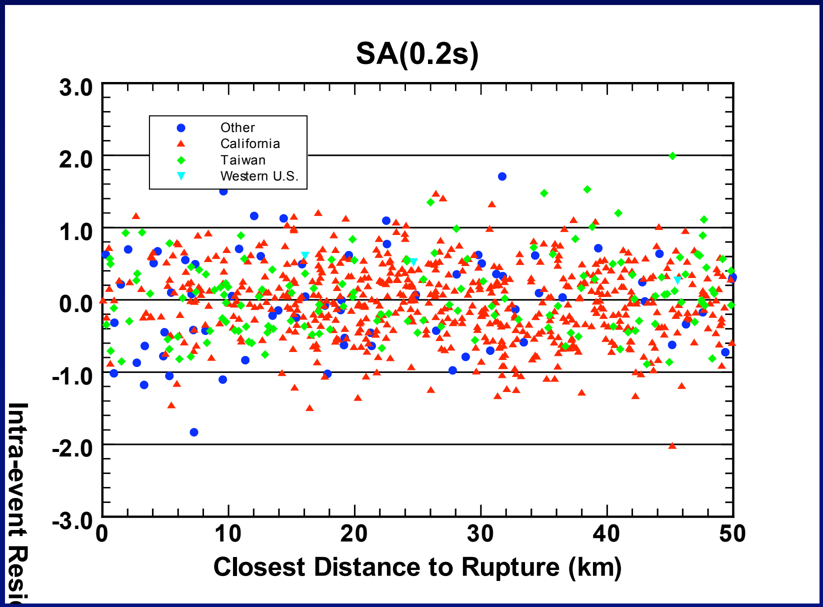


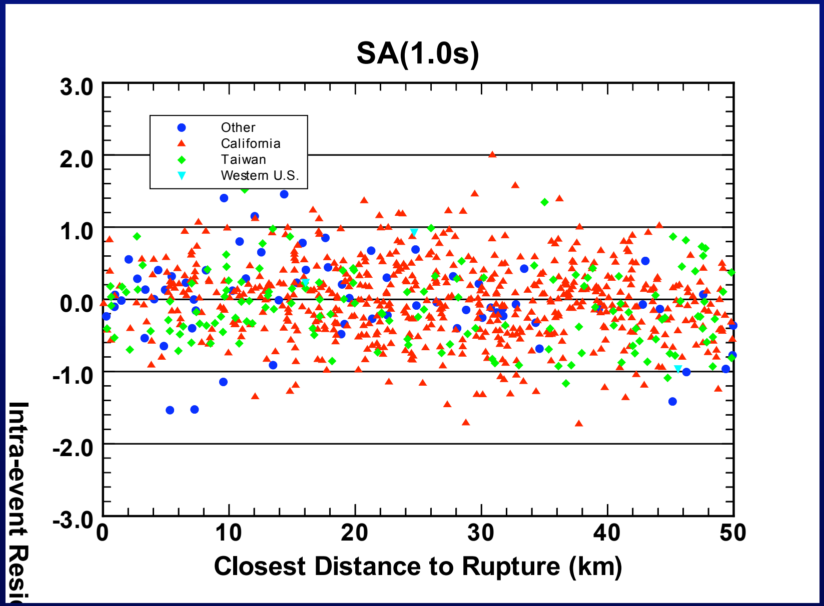


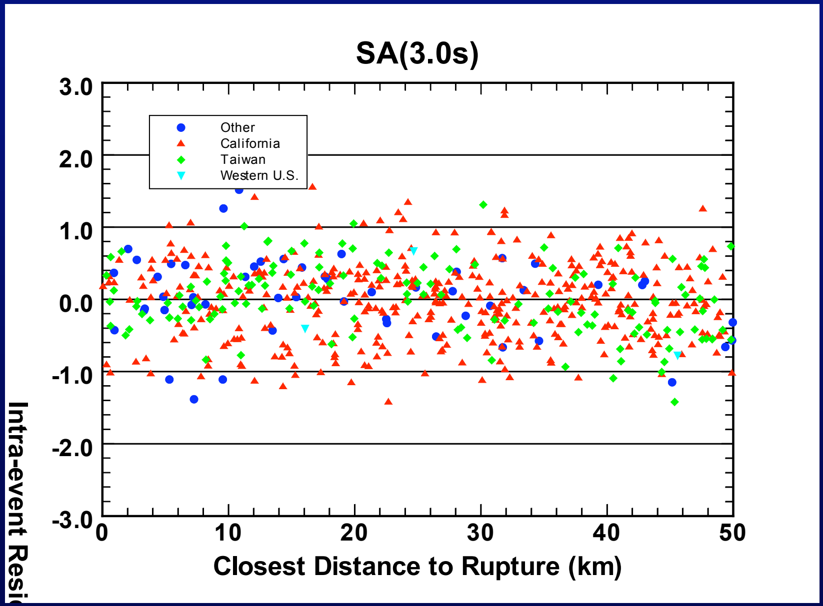
Near-Source Bias Issues

Intra-event Residuals Within 50 km



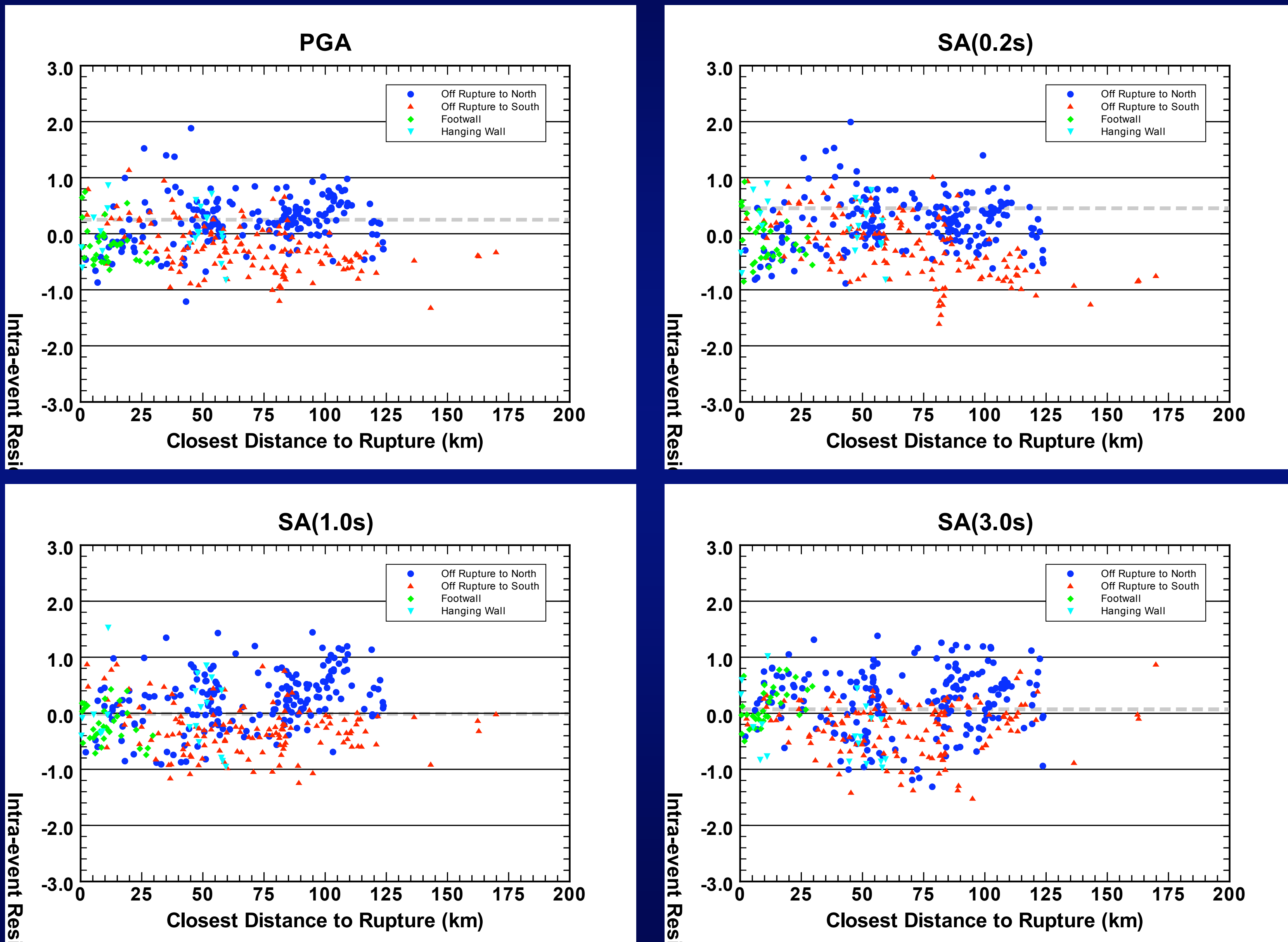




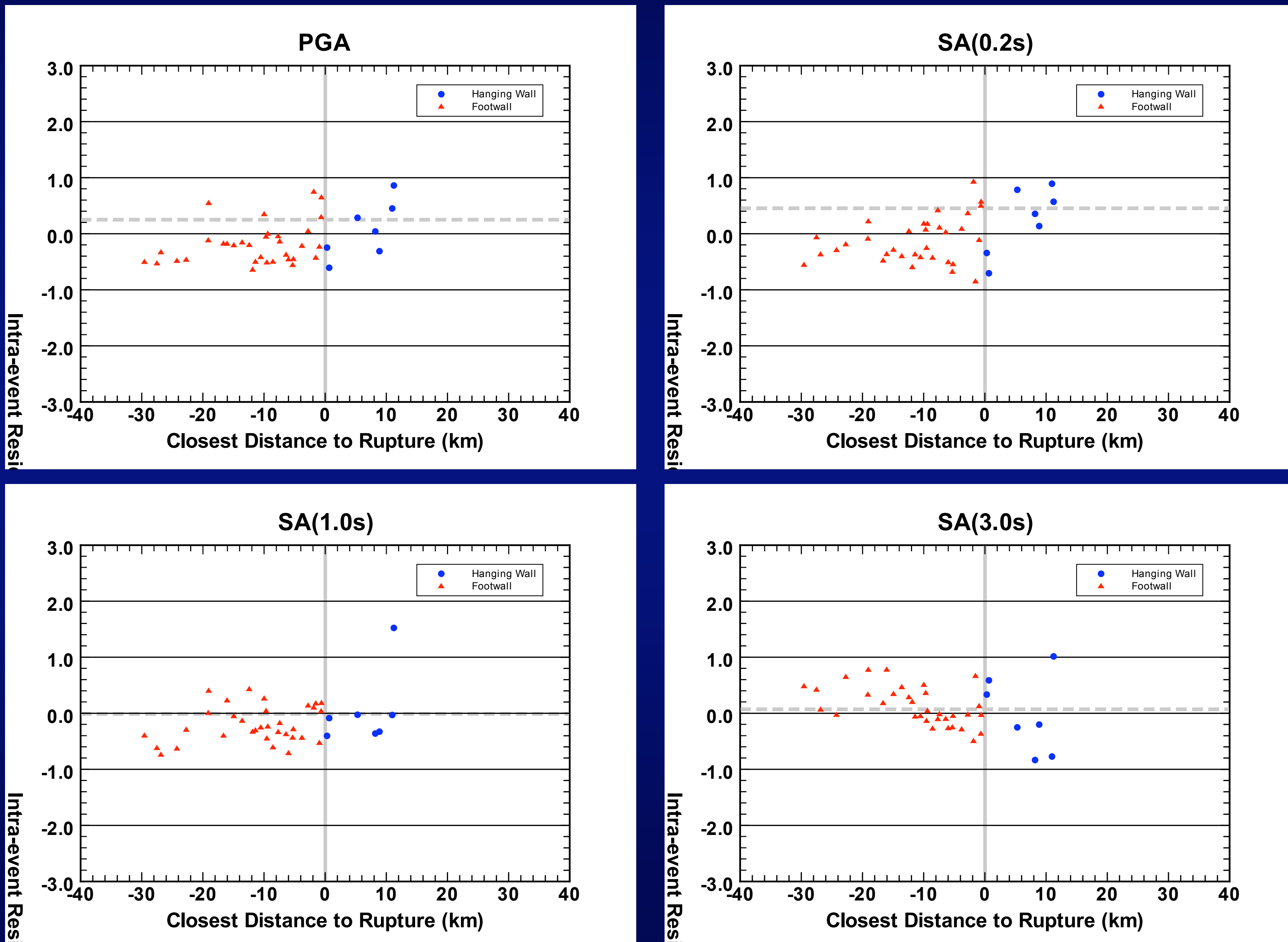


Chi-Chi Earthquake Issues

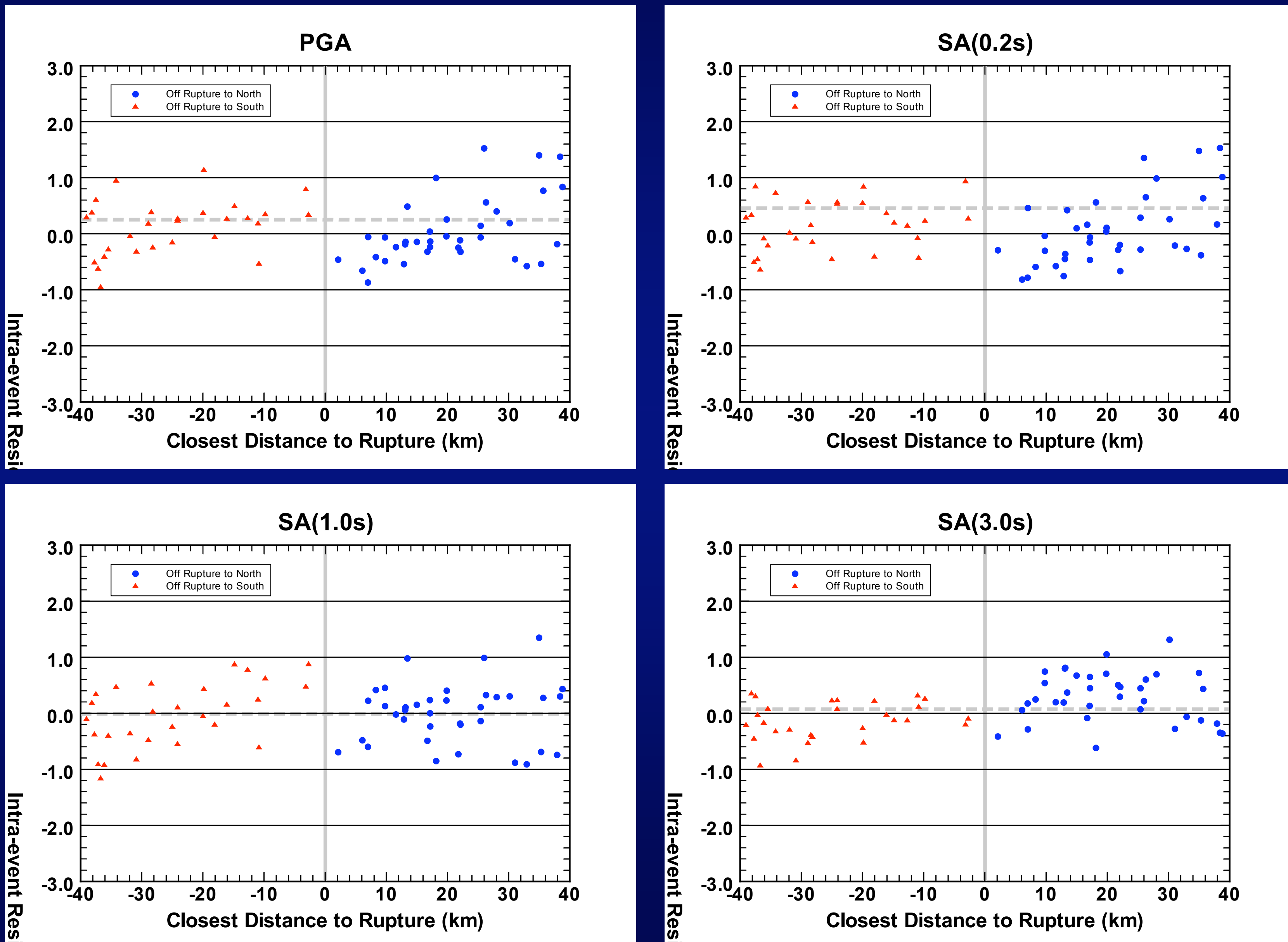
Intra-event Residuals by Distance



Intra-event Residuals by HW/FW

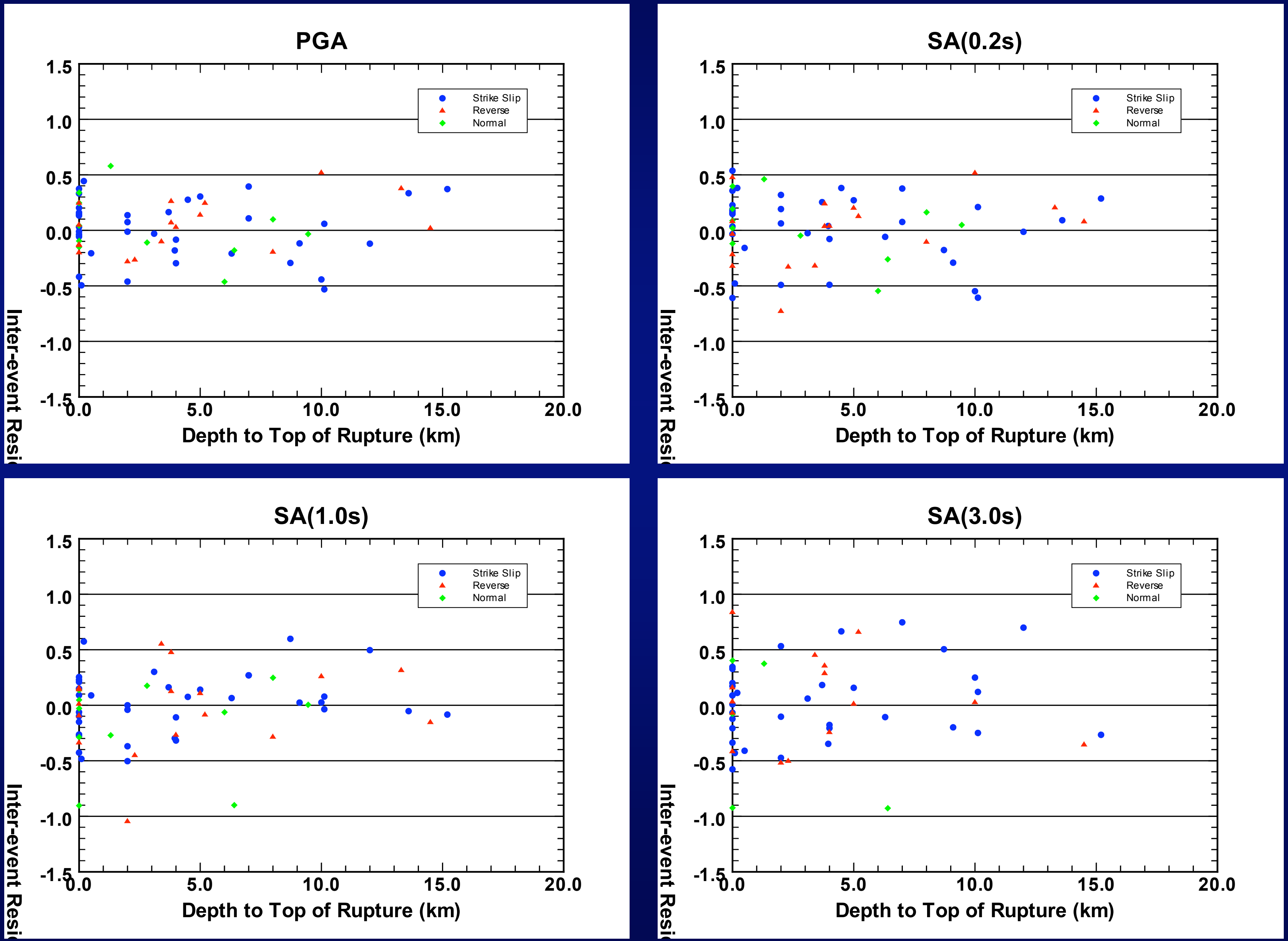


Intra-event Residuals by Direction



Buried vs. Surface Faulting Issues

Inter-event Residuals by Rupture Depth



Conclusions

- NGA project represents a significant improvement in:
  - Quantity and quality of ground-motion recordings and associated metadata
  - Number of near-source recordings from large-magnitude earthquakes
  - Number of independent variables from which to choose
  - Degree of developer and principle investigator interaction
  - Availability of supporting theoretical and numerical studies
  - Peer review through workshops, conference presentations and formal review
  - Scientific basis of the Campbell-Bozorgnia empirical ground motion model

Recommendation

We believe that our 2006 NGA empirical ground motion model is scientifically superior to our 1997 and 2003 empirical ground motion models and should be considered to supersede them

Thank You!