“$V_{S\,30}$ - A Basis for Characterization of Seismic Site Response for Site-specific, Regional, and Global Mapping of Seismic Hazard

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Harbin Institute of Technology
Harbin, China

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Outline

- **Definition $V_{S\,30}$**
- **$V_{S\,30}$ as a Basis for Characterization of Site-Specific Site Response**
  - **Theoretical Dependence of Amplification on $V_{S\,30}$**
  - **Empirical Dependence of Amplification on $V_{S\,30}$**
  - **$V_{S\,30}$ correlations with $V_{S\,Z}$ at other depths**

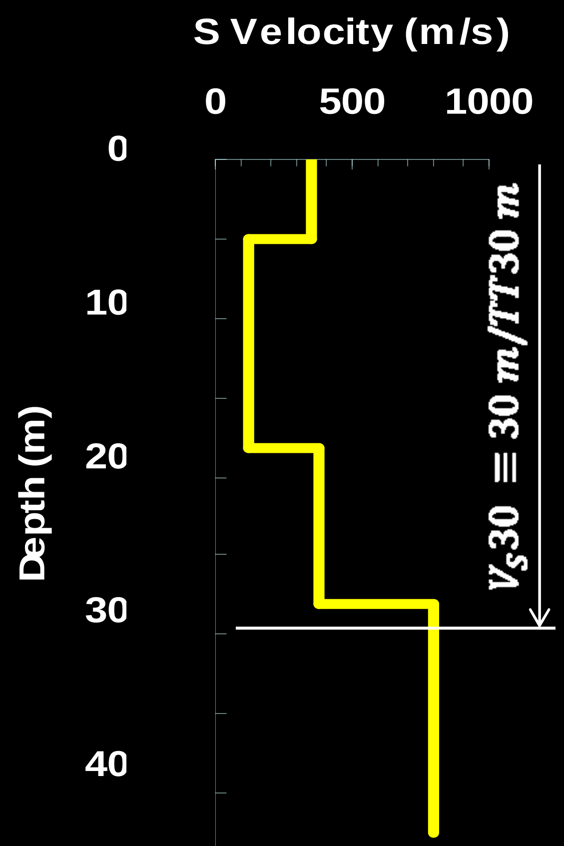
- **$V_{S\,30}$ as a Basis for Mapping Site Response**

  Correlations of $V_{S\,30}$ with:
  - **Physical Properties -- Site Class definitions**
  - **Geologic Age**
  - **Topographic Slope**

- **Applications of $V_{S\,30}$**
  - **Site-Specific Response Characterization – Site Classes, Site Coefficients, Building Codes**
  - **Regional Site Response Mapping – GMPEs, ShakeMaps, PSHA, GEM**

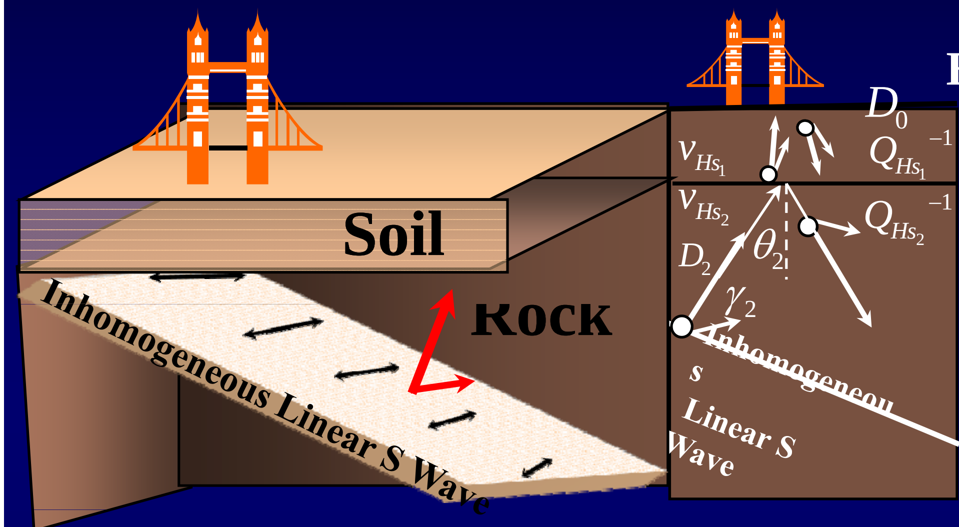
$V_{S\,30}$ Definition

$$V_S30 \equiv 30\,m/Travel\ time\ to\ 30\,m$$



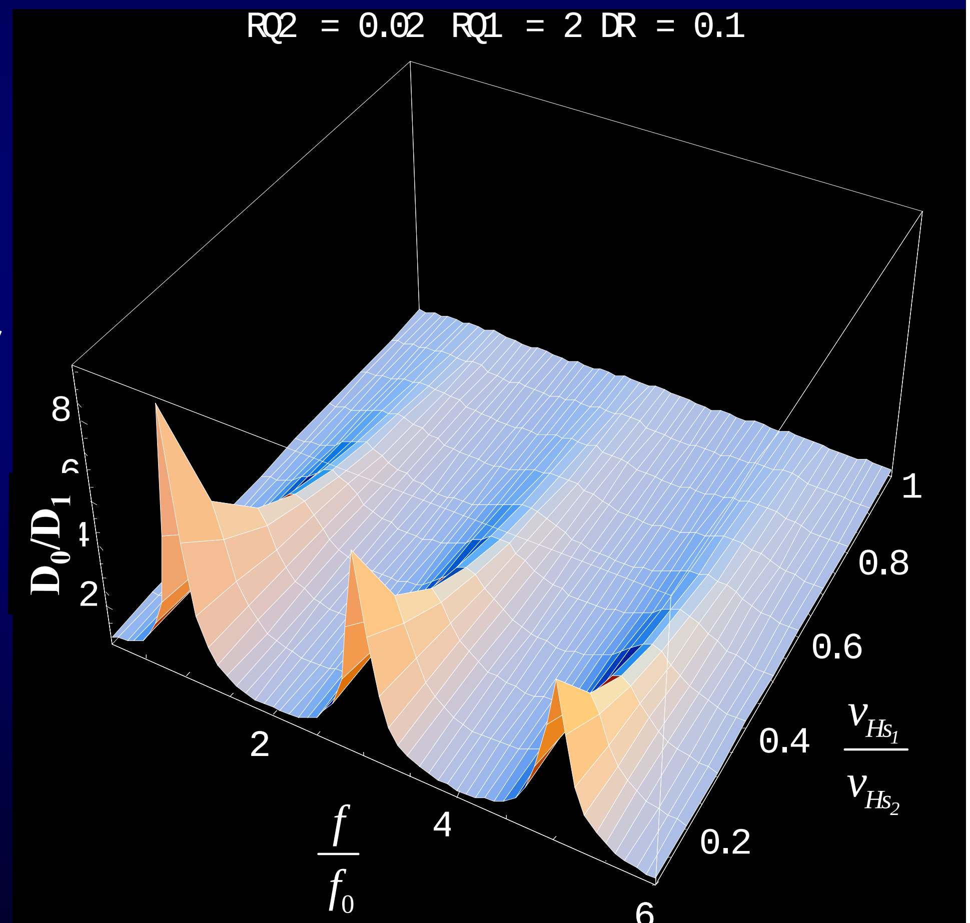
(from Borcherdt, 1994)

Theoretical Response of a Viscoelastic Soil Layer versus Vs Ratio and Normalized Fre_uenc_



Amplitude Response versus Frequency

Homogeneous Linear S Wave, Vertical Incidenc



Solution:

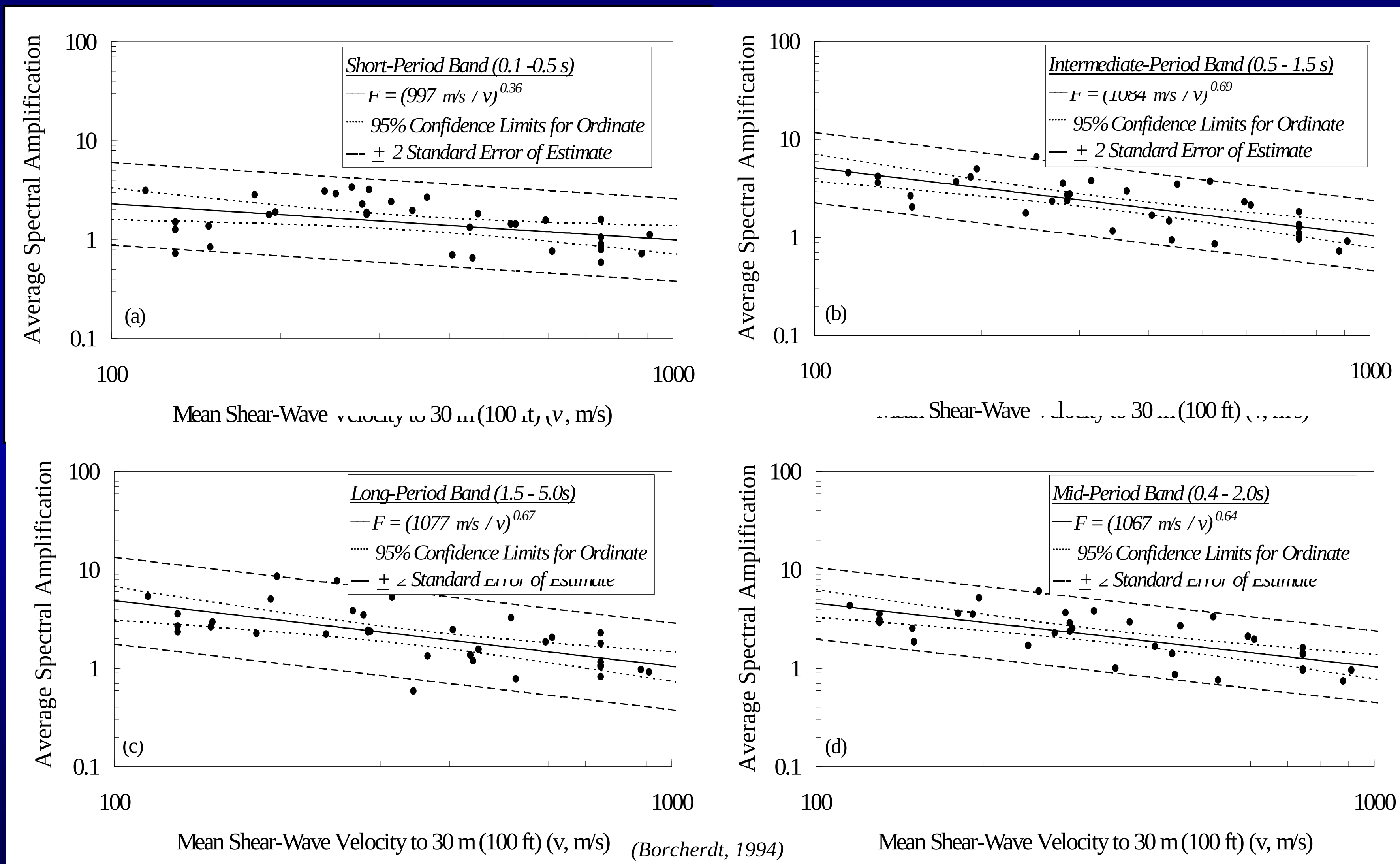
$$\frac{D_0}{D_1} = F[(inc.\ wave\ field\ par.),(material\ par.)]$$

$$\frac{D_0}{D_1} = F[(\theta_2, , _2, \frac{f}{f_0}),(\frac{v_{Hs_1}}{v_{Hs_2}}, Q_{Hs_1}^{-1}, Q_{Hs_2}^{-1}, \frac{\rho_1}{\rho_2})]$$

where f_0=fundamental frequency.

Empirical Spectral Amplification Values versus $V_{S\,30}$

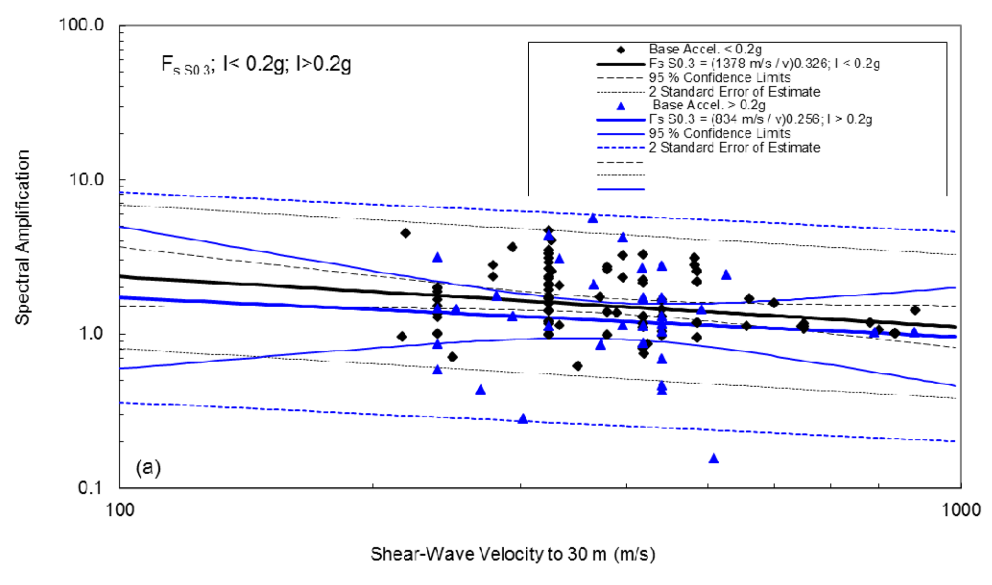
Loma Prieta Earthquake; $I_a < 0.1g$

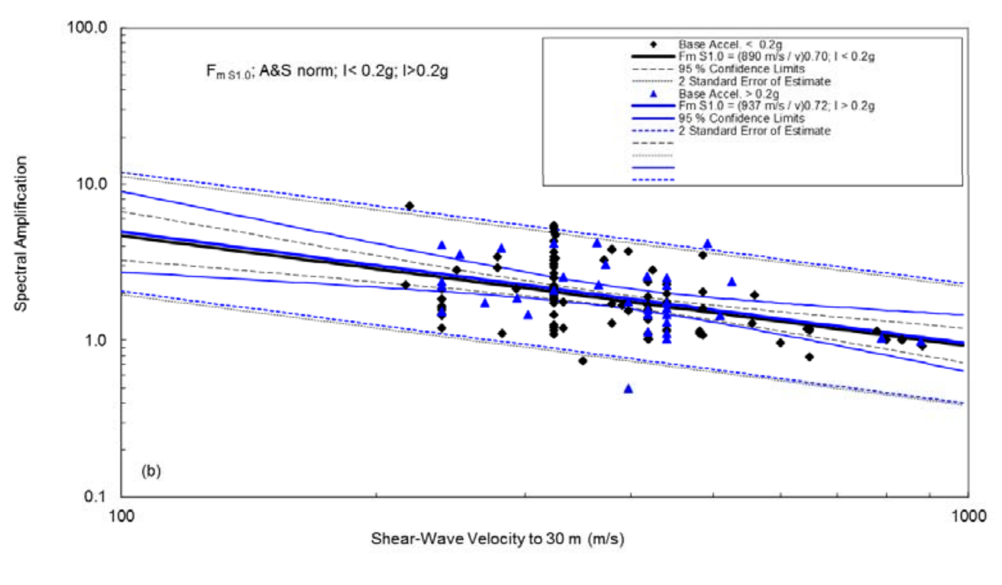


(Borcherdt, 1994)

Empirical Spectral Amplification Values versus $V_{S\ 30}$

Northridge Earthquake; I_a < 0.2g, I_a > 0.2g





Empirical Dependence of Amplification on $V_{S\,30}$

(Site Coefficients for Seismic Design)

Short- and Mid-Period Amplification Factors are:

$$F_a = (V_{ref} / V_{S\,30})^{m_a}$$

and

$$F_v = (V_{ref} / V_{S\,30})^{m_v}$$

where,

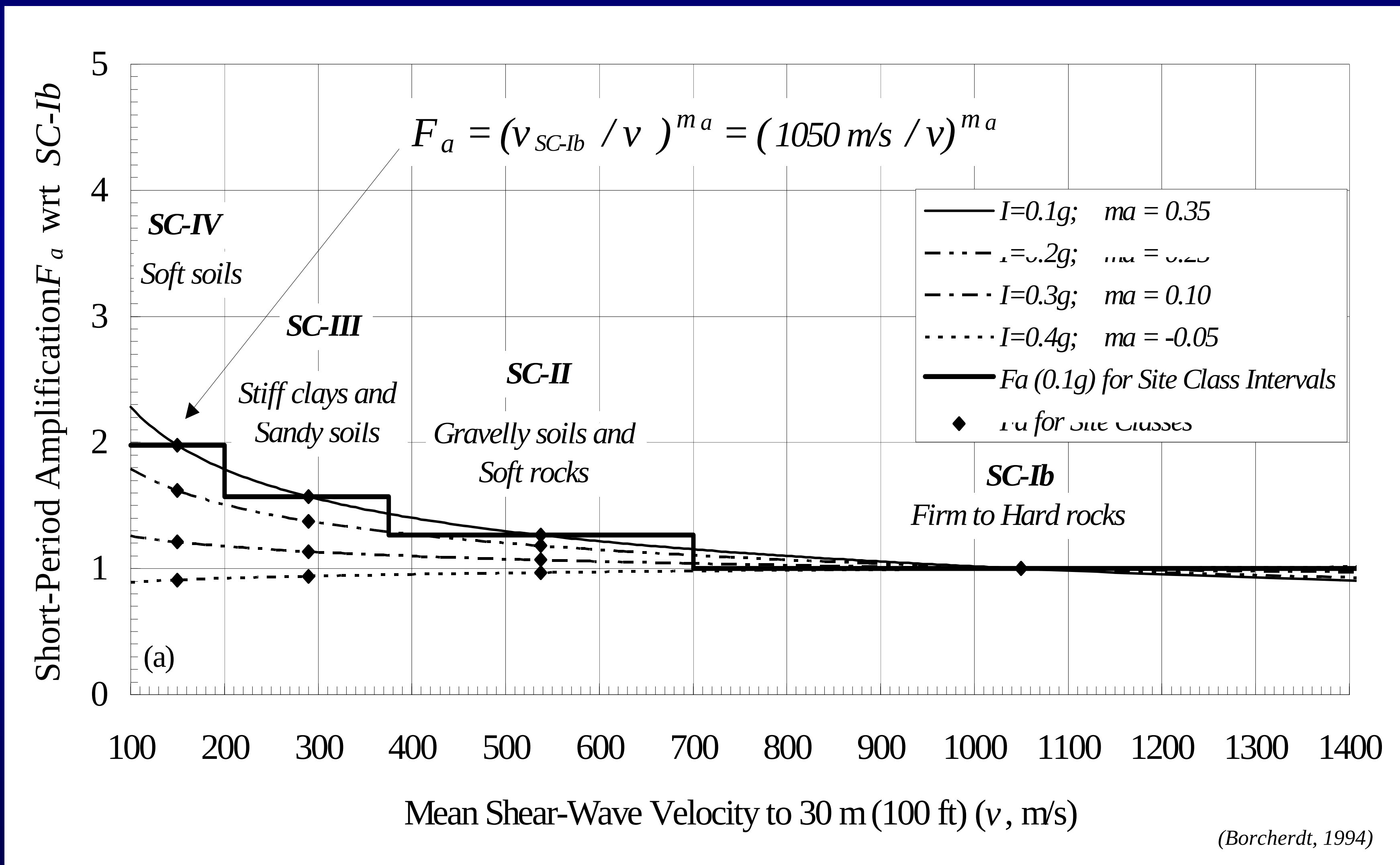
1) $V_{S\,30}$ is inferred or measured mean shear-wave velocity to 30 m at site,

2) V_{ref} is $V_{S\,30}$ for reference ground condition,

3) m_a and m_v depend on input ground motion level.

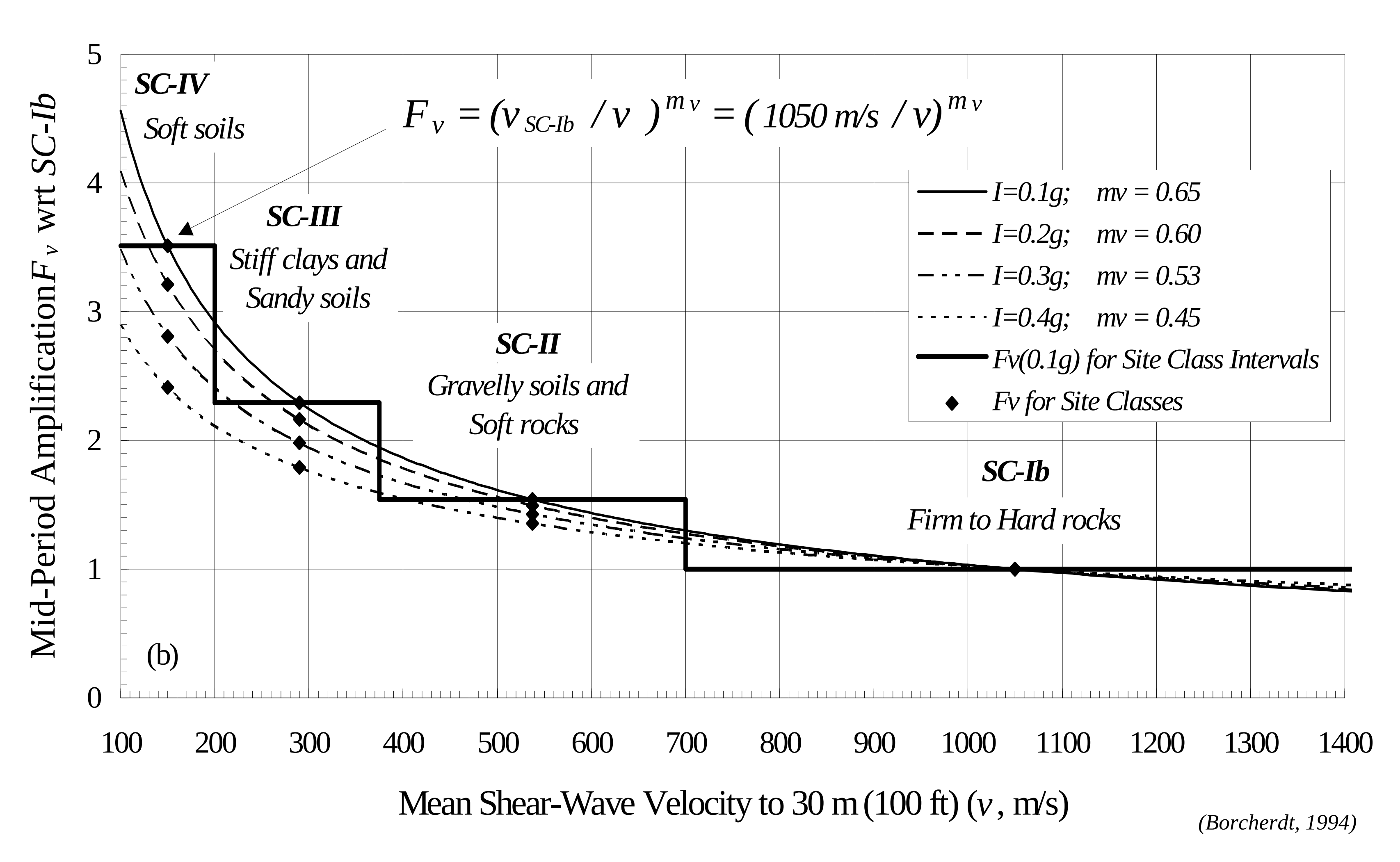
F_a versus Input Amplitude & $V_{S\,30}$

I_a = 0.1, 0.2, 0.3, 0.4 g *(linear scales)*



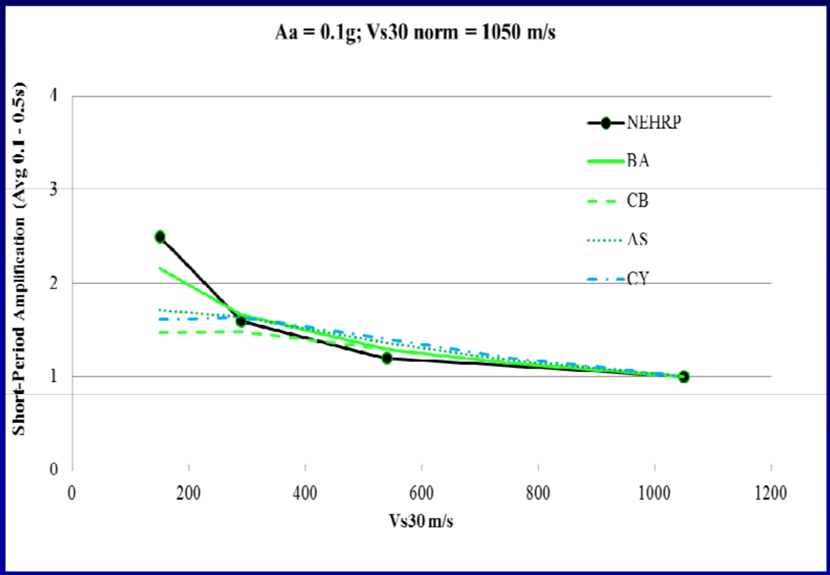
F_v versus Input Amplitude & $V_{S\,30}$

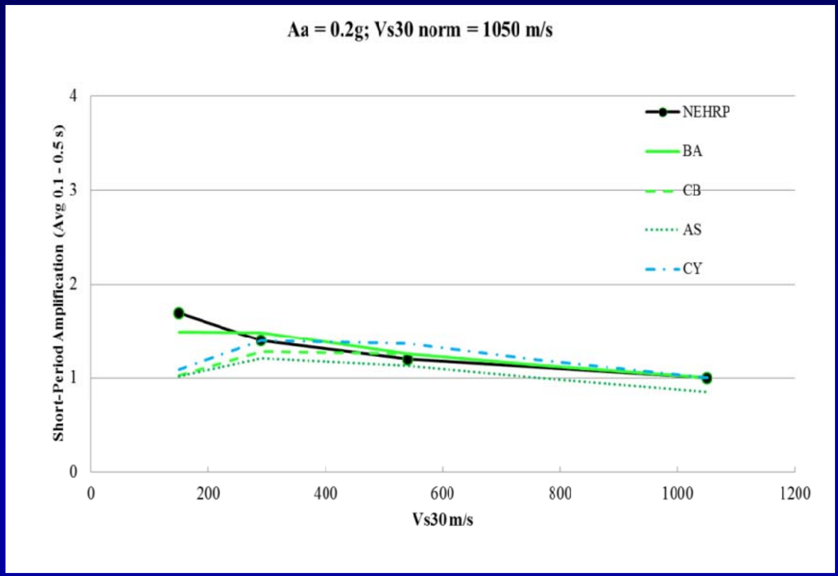
I_v = 0.1, 0.2, 0.3, 0.4 g *(linear scales)*

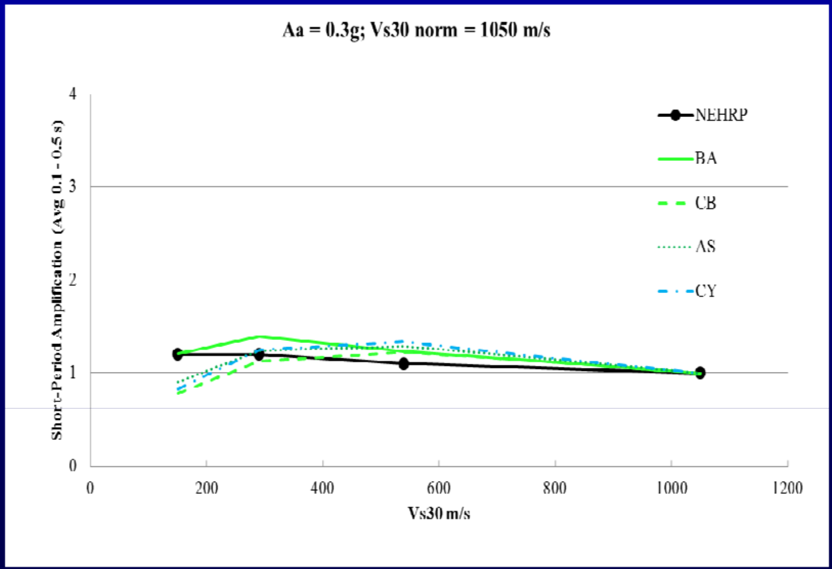


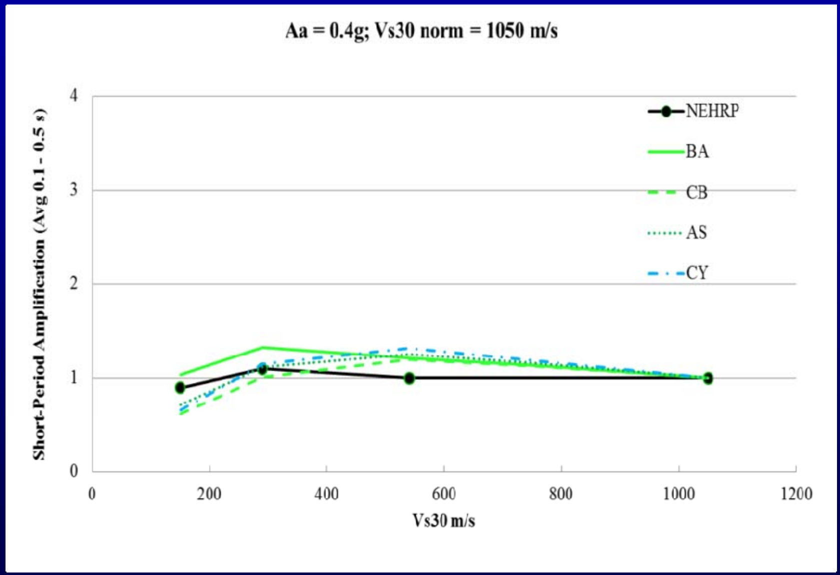
NEHRP & NGA Short-Period Amplification *versus* $V_{S\ 30}$

Aa=0.1g; Avg. 0.1-0.5s; Vs30 norm 1050 m/s



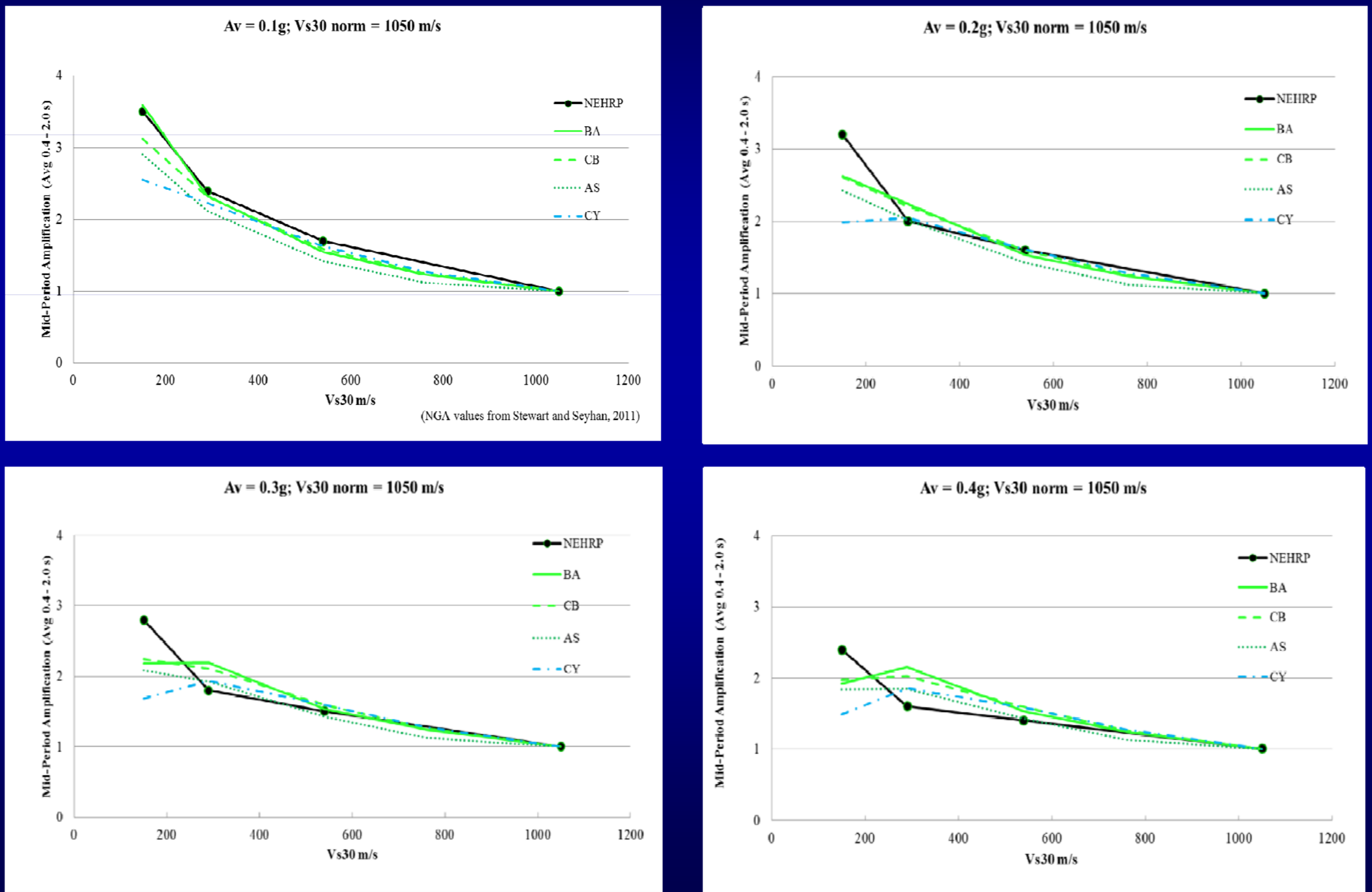






NEHRP & NGA Mid-Period Amplification *versus* $V_{S\ 30}$

Av = 0.1g; Avg. 0.4-2.0 s; Vs30 norm 1050 m/s



$V_{S\,30}$ Correlation with $V_{S\,Z}$ at other Depths

$V_{S\,30}$ as a function of $V_{S\,Z}$ at another depth:

$$Log[V_{S\,30}] = c_0 + c_1\ Log[V_{S\,Z}] = G(V_{S\,Z})$$

(Cadet, et al., 2009; Boore, et al., 2011)

Hence, amplification as a function of $V_{S\,30}$:

$$F_a = (V_{S\,30\,ref} / V_{S\,30})^{m_a} = F_a(V_{S\,30\,ref}, V_{S\,30})$$

Implies amplification as a function of $V_{S\,Z}$ at other depths:

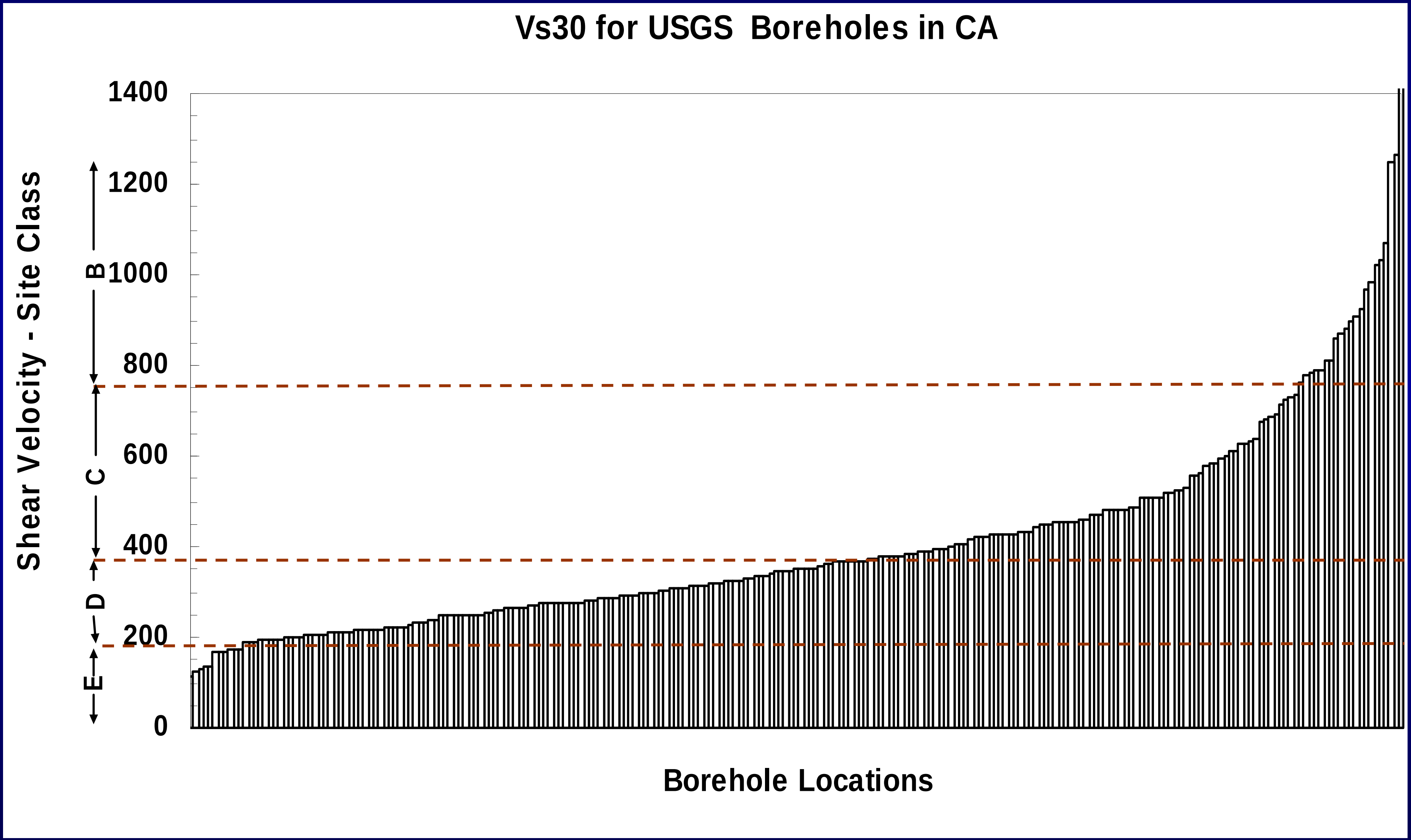
$$F_a = H_a(V_{S\,Z\,ref}, V_{S\,Z})$$

$V_{S\,30}$ as a Basis for Mapping Site Response

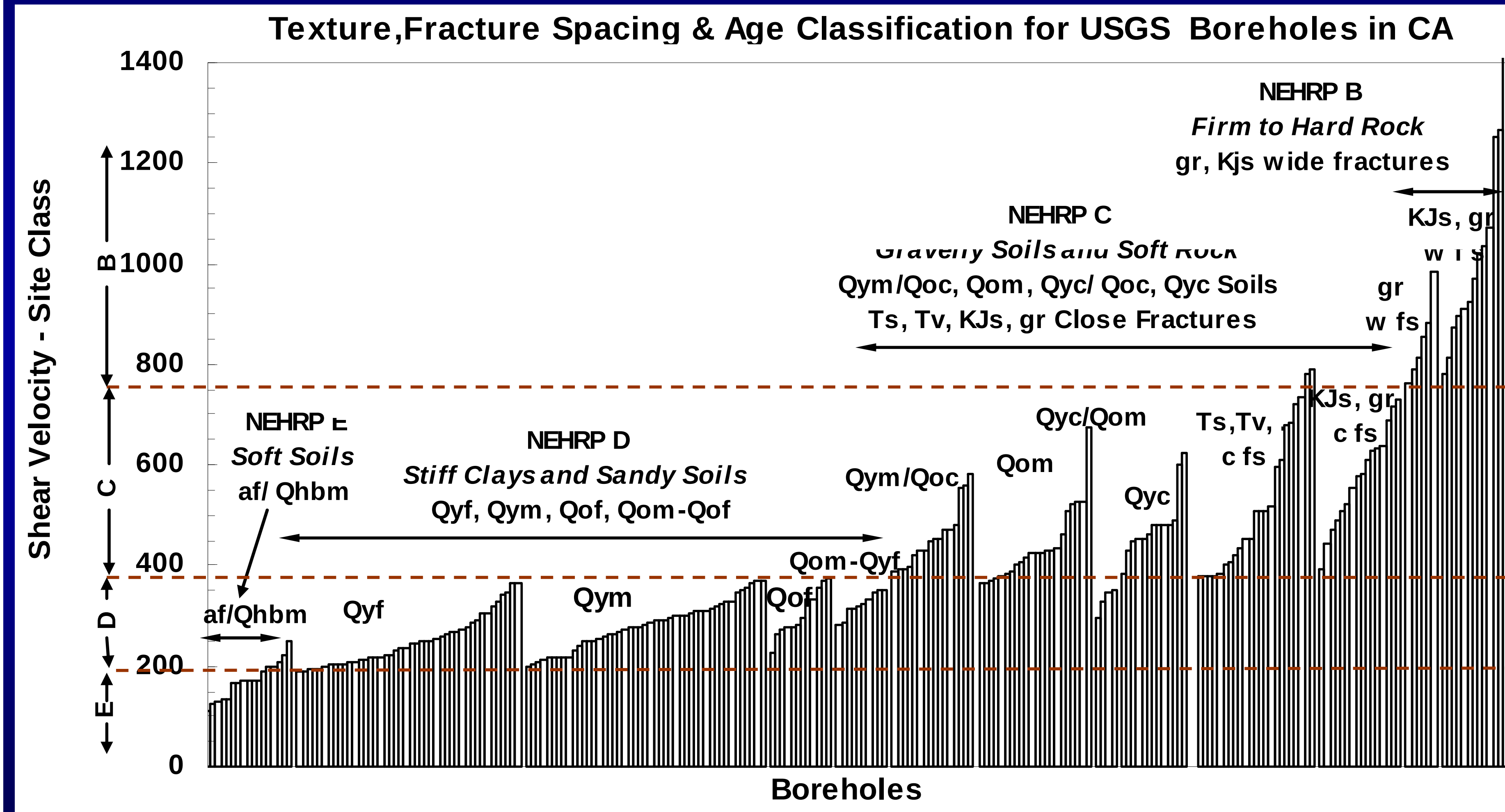
Correlations of $V_{S\,30}$ with:

- Physical Properties -- Site Class definitions
- Geologic Age
- Topographic Slope

$V_{S\,30}$ for USGS Boreholes in CA

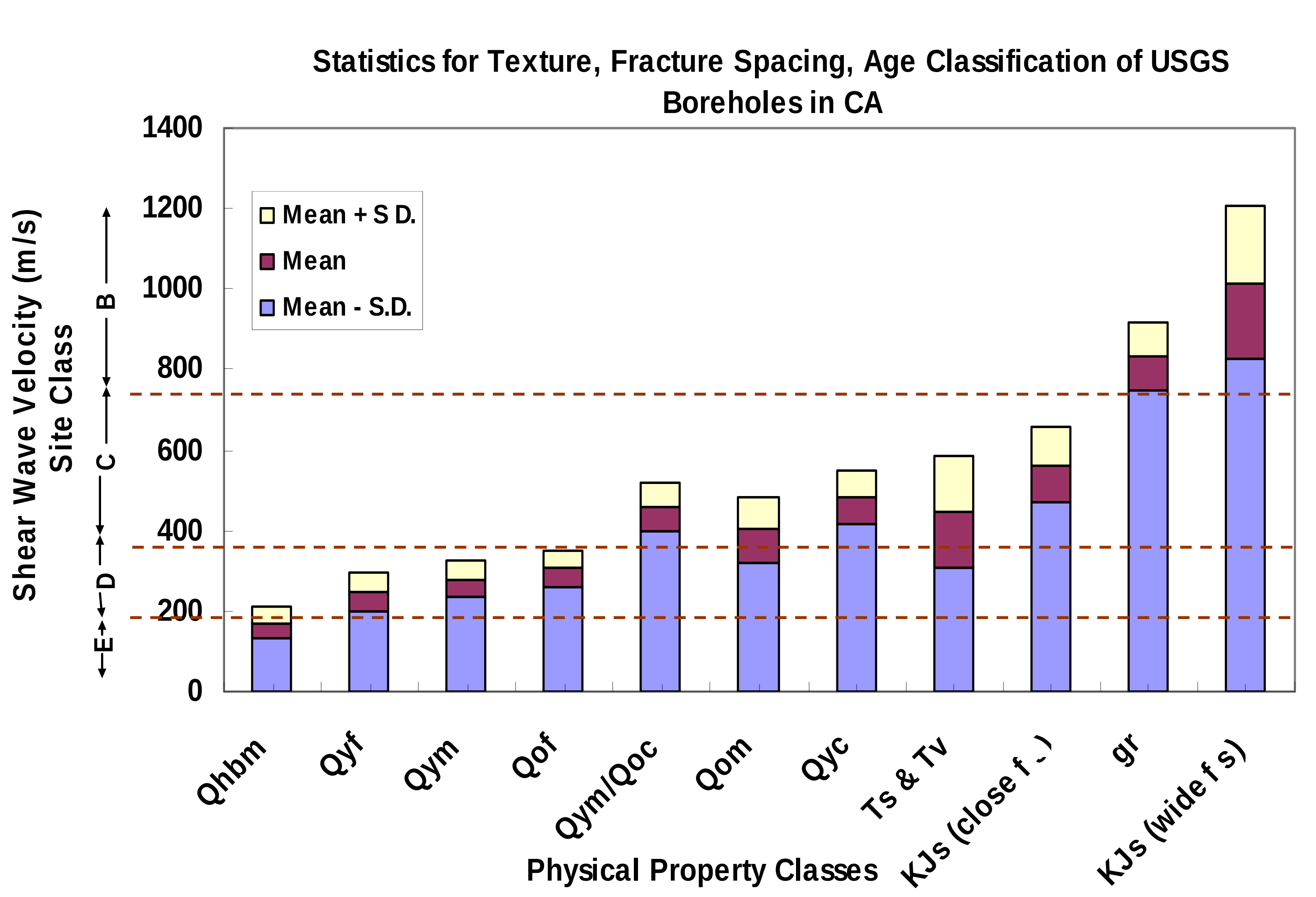


$V_{S\ 30}$ versus Physical Property Classification for USGS Boreholes in CA Suggests Seismically Distinct Units

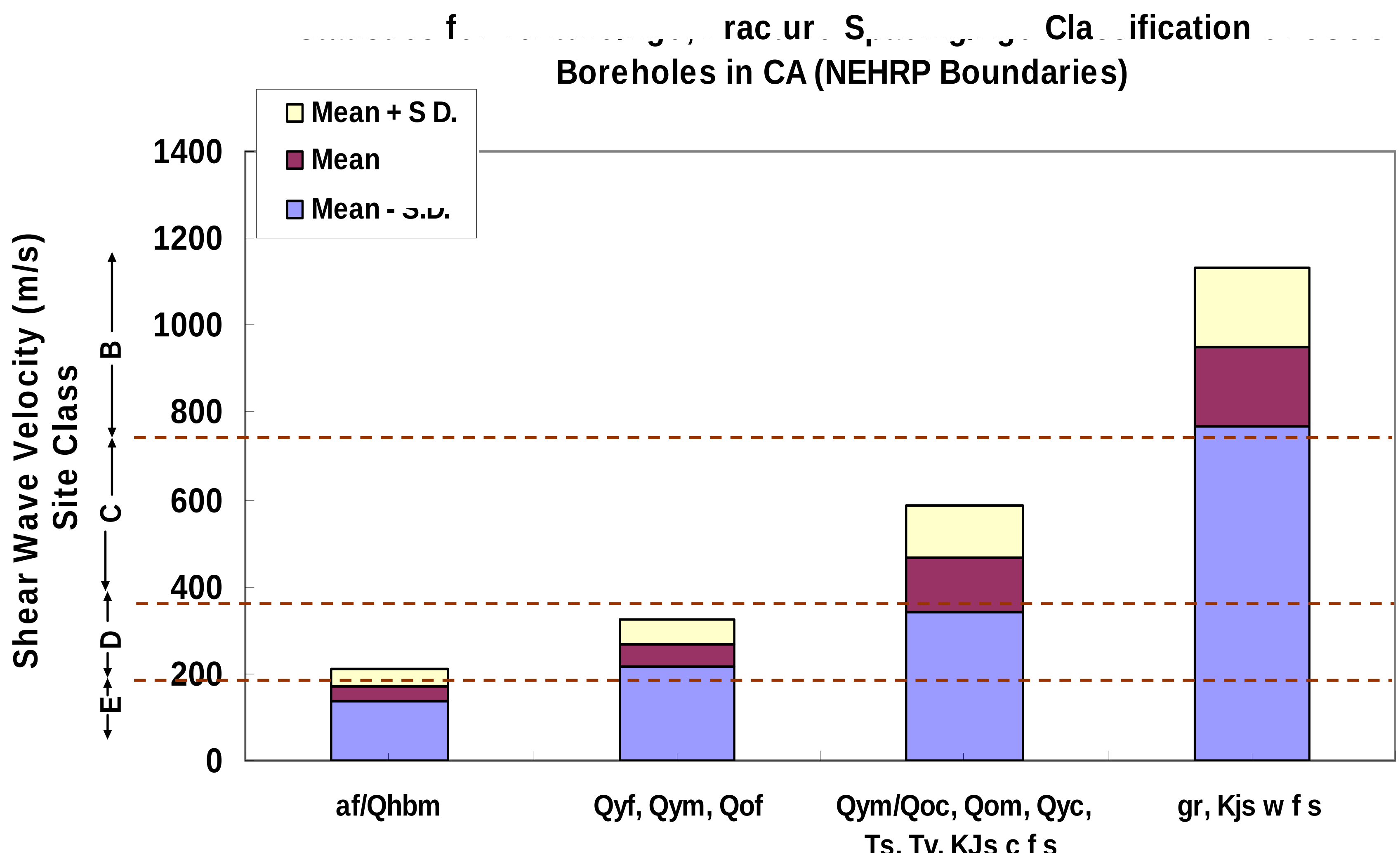


$V_{S\,30}$ Statistics for Physical Property Classification

(Texture, Fracture Spacing, & Age -- USGS Boreholes in CA)

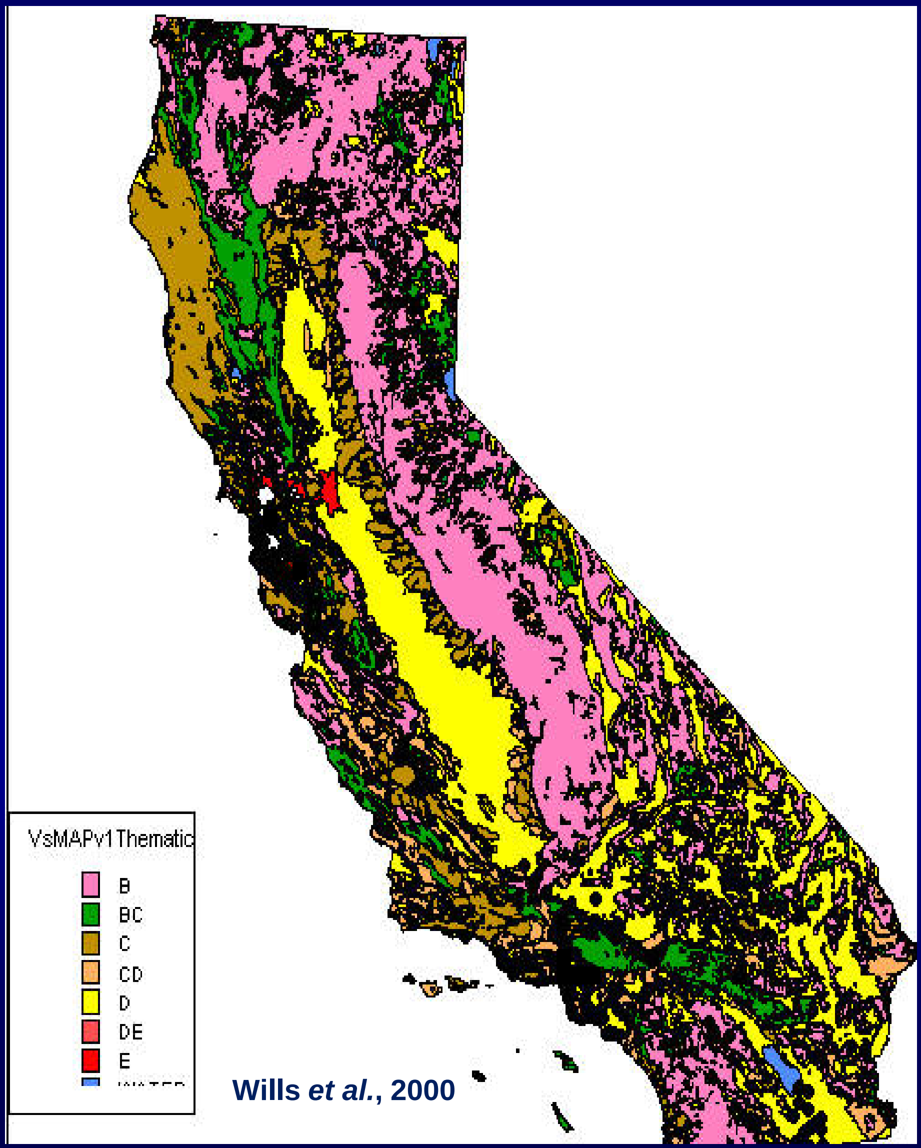


Vs30 Statistics for Physical Property NEHRP Site Classes
(Texture, Fracture Spacing, & Age -- USGS Boreholes in CA)

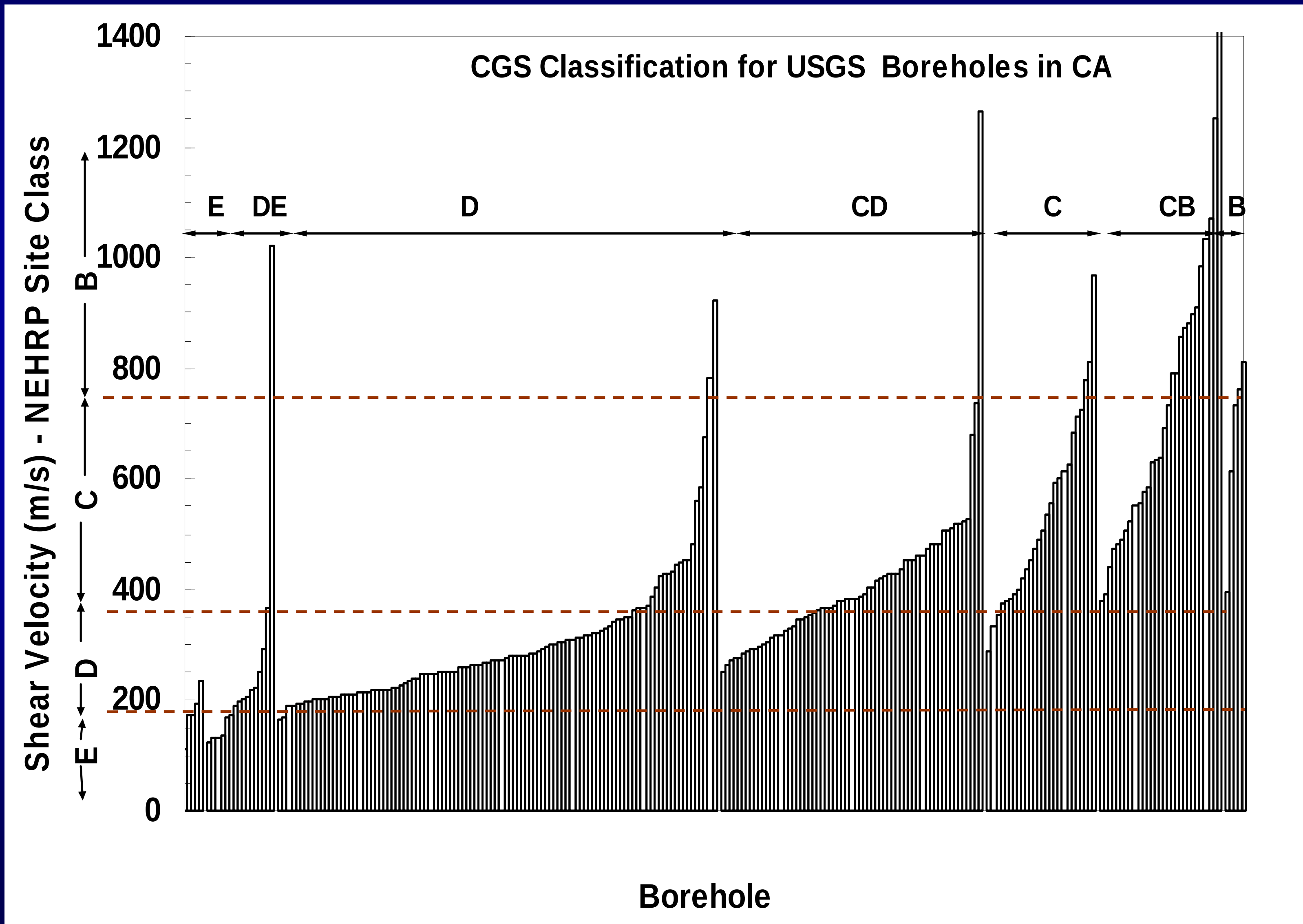


(from Borcherdt, 1994)

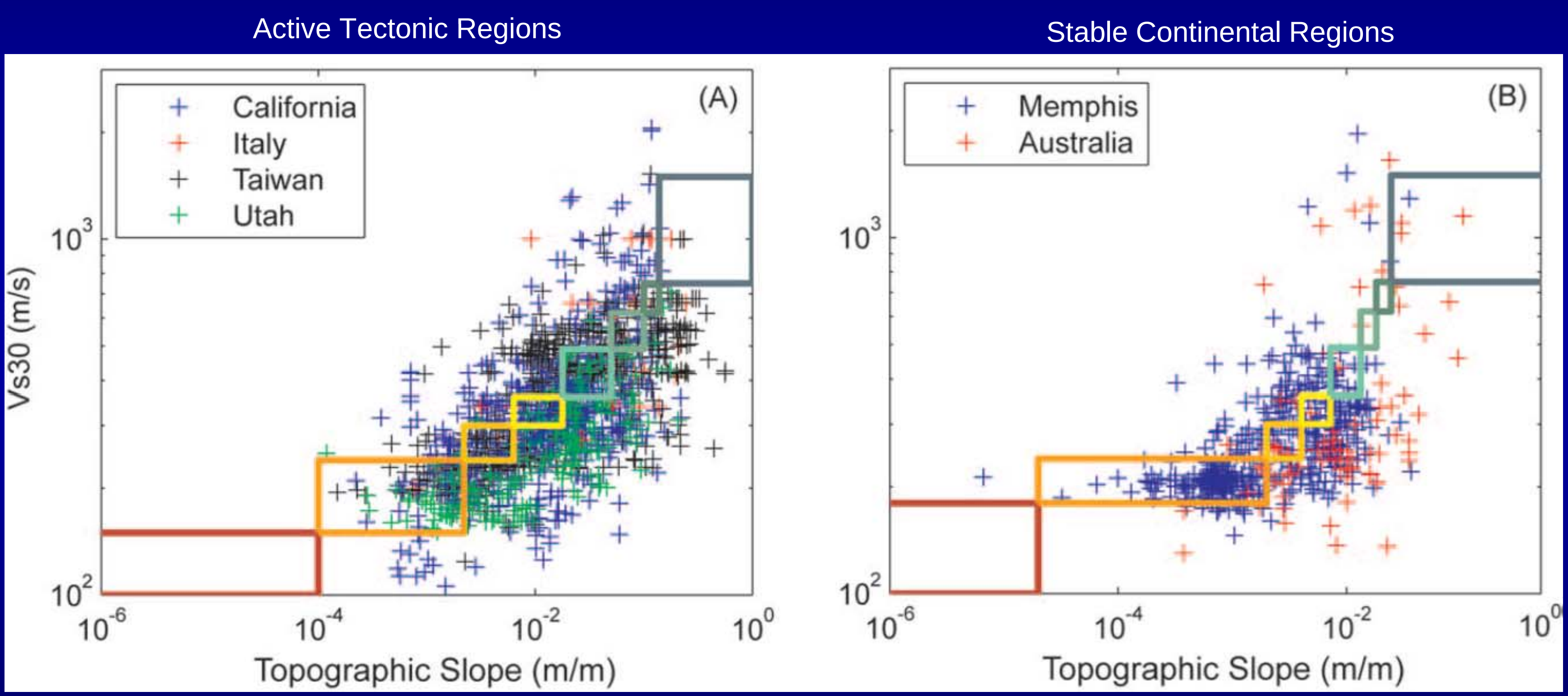
Geologic Site Condition Map
($V_{S\,30}$ correlations with Geologic Age)



CGS Geologic Classification versus $V_{S\,30}$



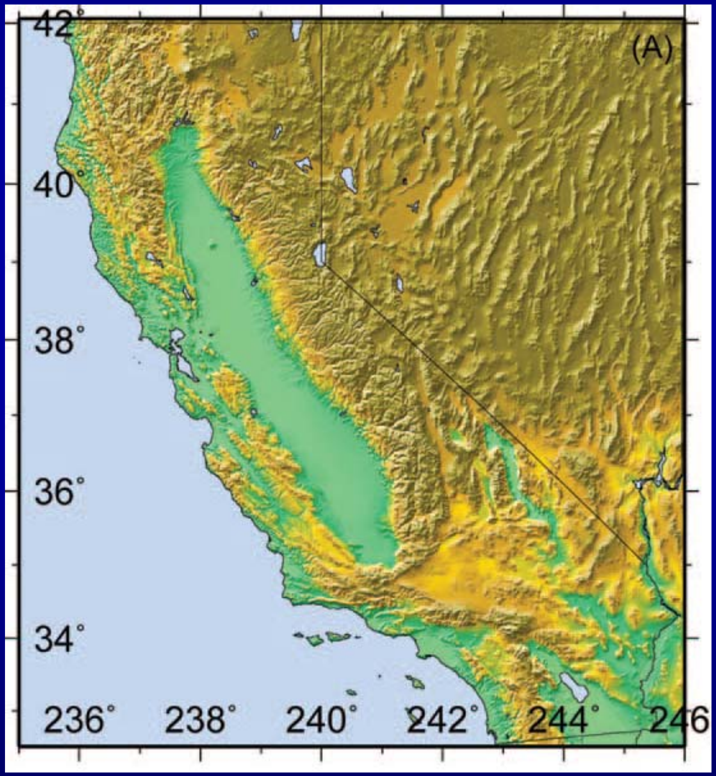
$V_{S\,30}$ Correlations with Topographic Slope



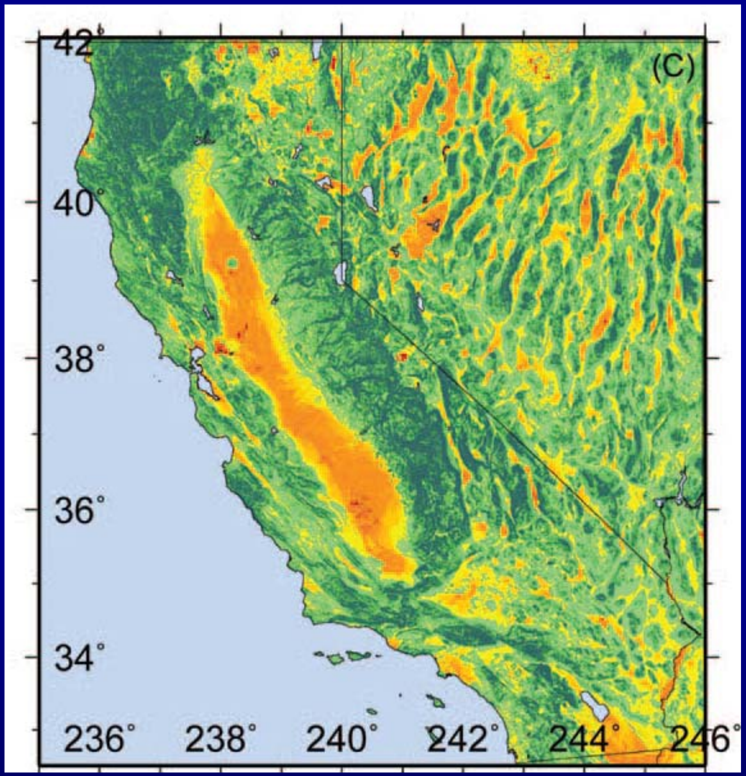
(from Wald and Allen, 2007)

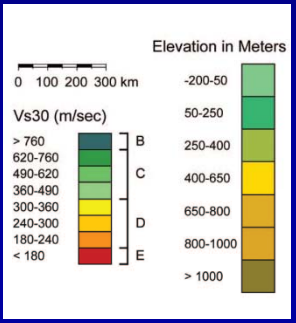
$V_{S\,30}$ Map
(Derived from Topographic Slope)

Topographic Relief (elevation)



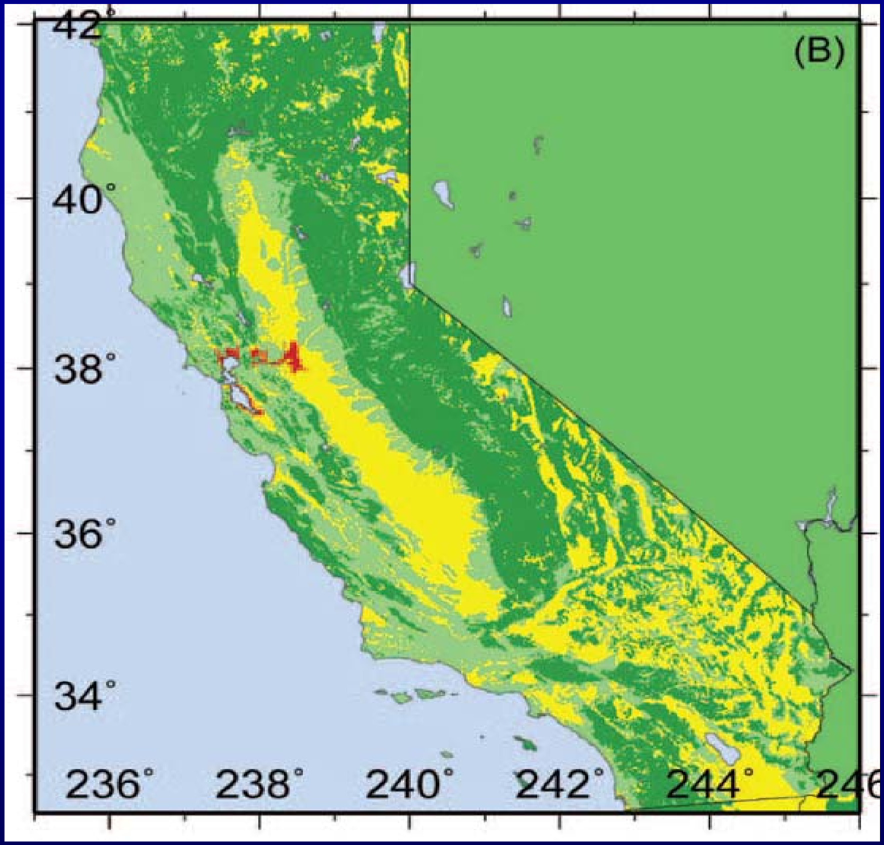
Vs30 (topographic slope)



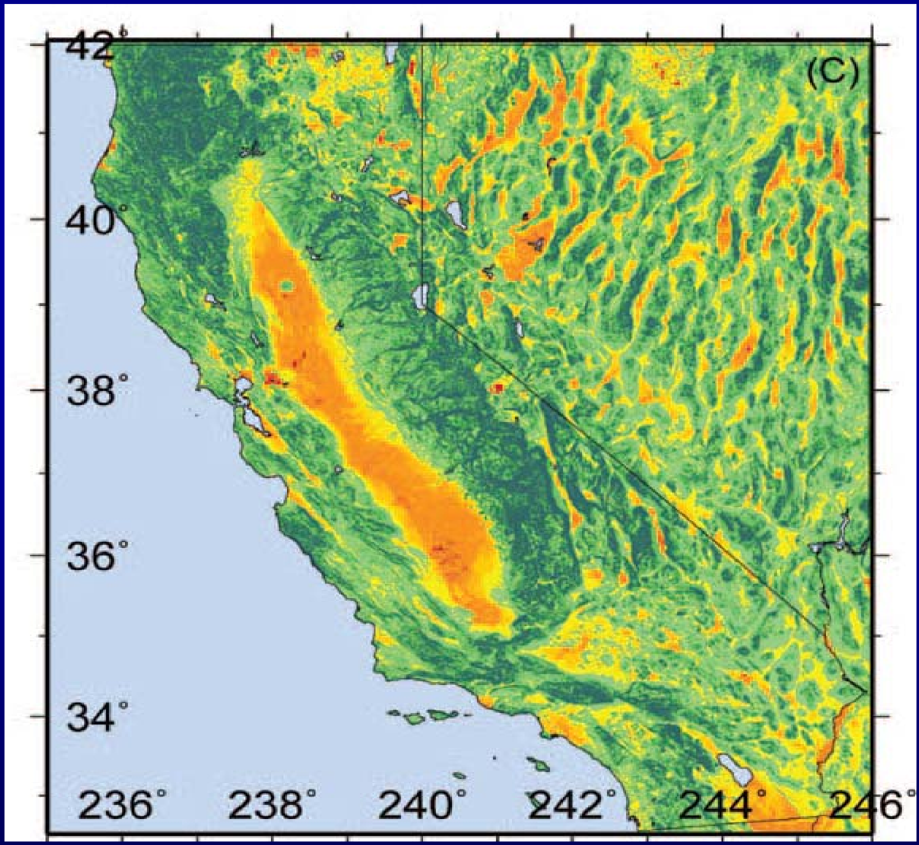


$V_{S\,30}$ Maps
(Derived from Geologic Age and Topographic Slope)

Vs30 (geologic age)



Vs30 (topographic slope)



(Wald and Allen, 2007)

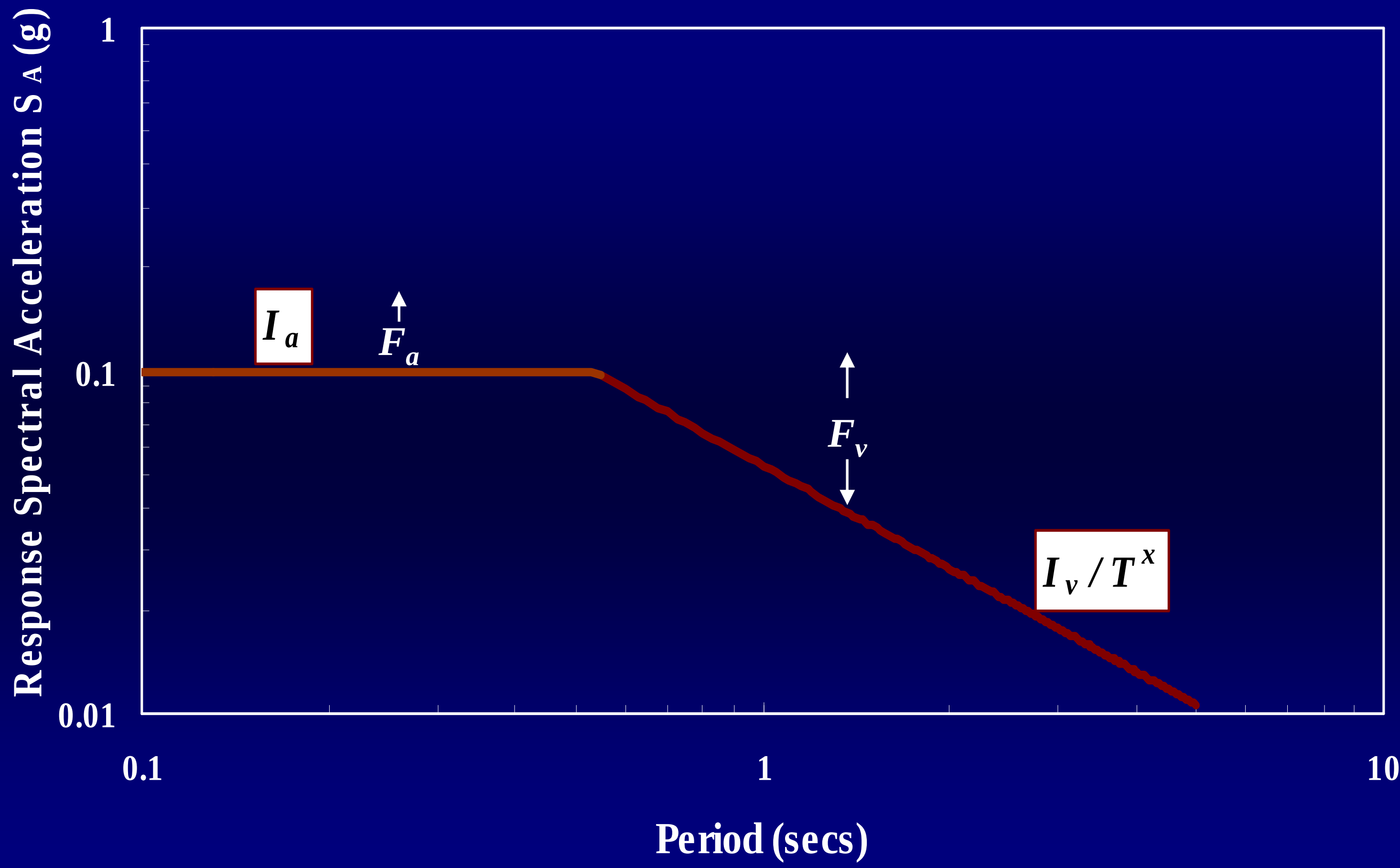
Applications of $V_{S\,30}$

- **Site-Specific Response Characterization**
  - **Site Classes & Site Coefficients for Site-specific Design Spectra, Building Codes**
  - **Ground Motion Prediction Equations (GMPE) developed as continuous function of Vs30**

- **Regional Site Response Mapping**
  - **ShakeMaps**
  - **PSHA Maps**
  - **Global Earthquake Model (GEM)**

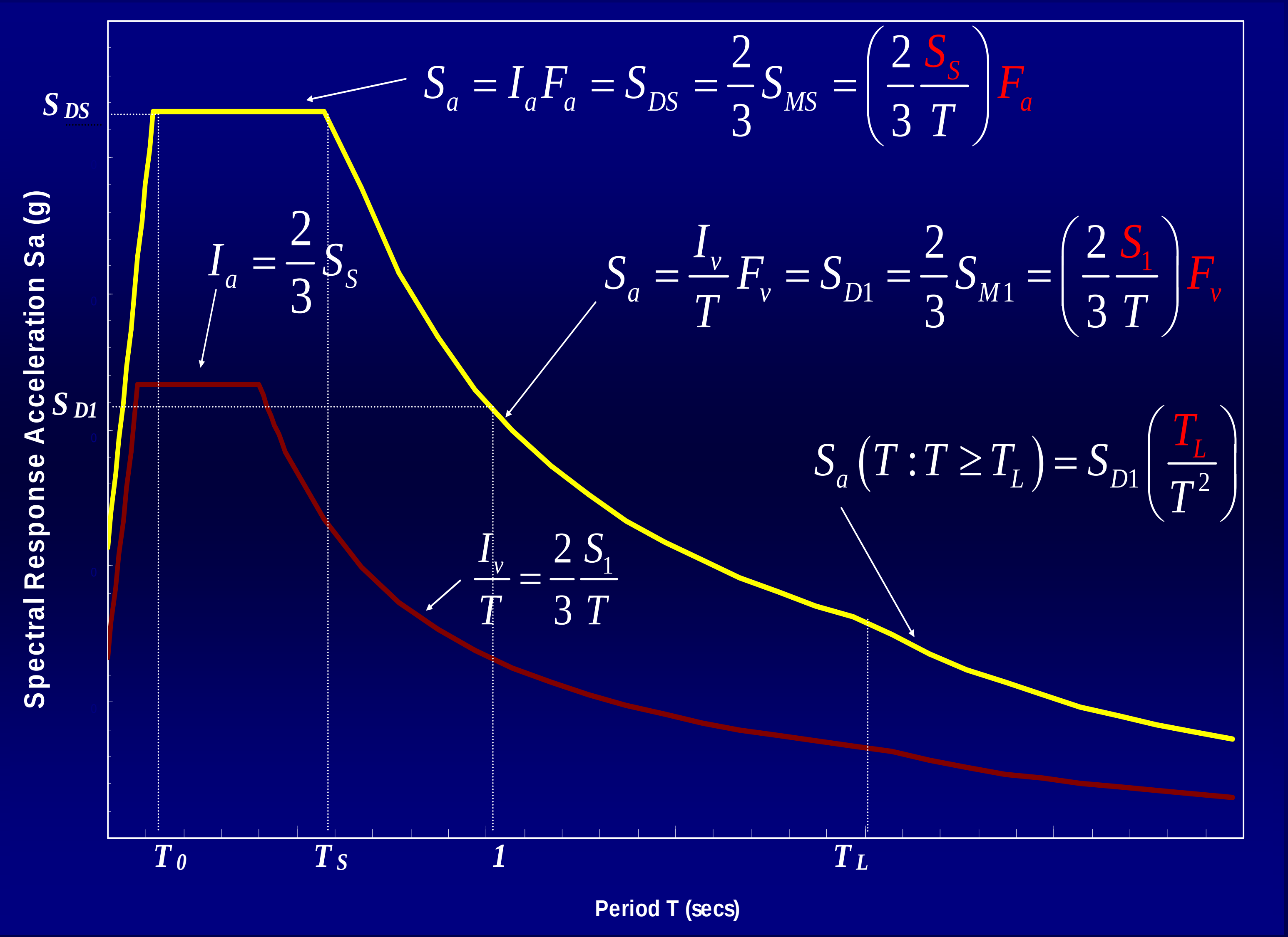
Definition of Site-Dependent Response Spectra (log-log scale)

(NEHRP, UBC, IBC, ASCE 7 Provisions)



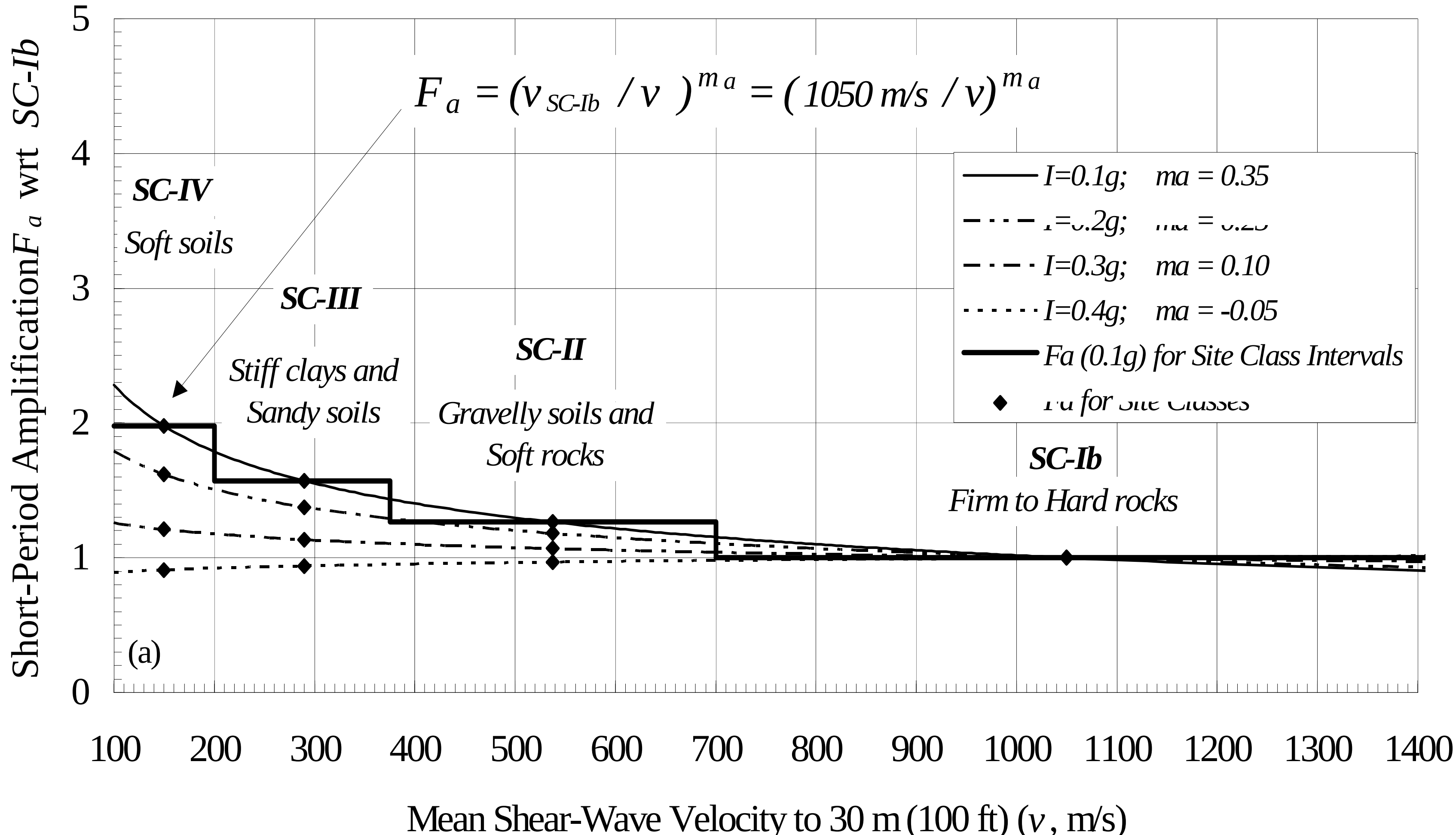
Site-Dependent Response Spectra (linear-linear scale)

(NEHRP, UBC, IBC, ASCE 7 Provisions)



F_a versus Input Amplitude & $V_{S\,30}$

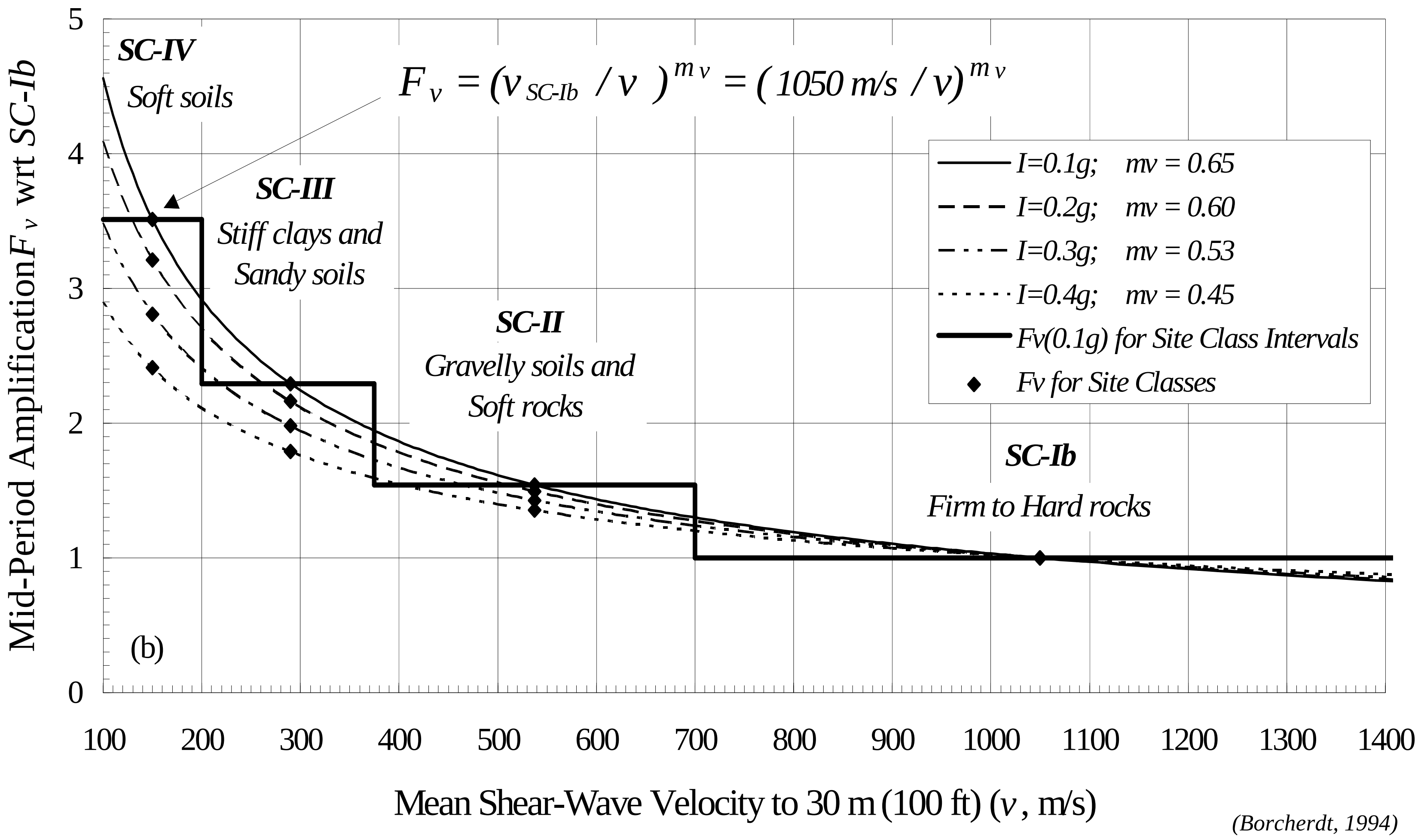
I_a = 0.1, 0.2, 0.3, 0.4 g *(linear scales)*



(Borcherdt, 1994)

F_v versus Input Amplitude & $V_{S\ 30}$

I_v = 0.1, 0.2, 0.3, 0.4 g *(linear scales)*



Short-Period Site Coefficient F_a

(NEHRP, UBC, IBC, AASHTO, ASCE 7 Provisions)

Site Class	$A_a \leq 0.1$ $S_s < 0.25$	$A_a = 0.20$ $S_s = 0.50$	$A_a = 0.30$ $S_s = 0.75$	$A_a = 0.40$ $S_s = 1.00$	$A_a \geq 0.50$ $S_s \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	*
F	*	*	*	*	*

* Site-specific geotechnical investigation and dynamic site response analysis shall be performed.

Mid-Perio_ Site Coefficient F_v

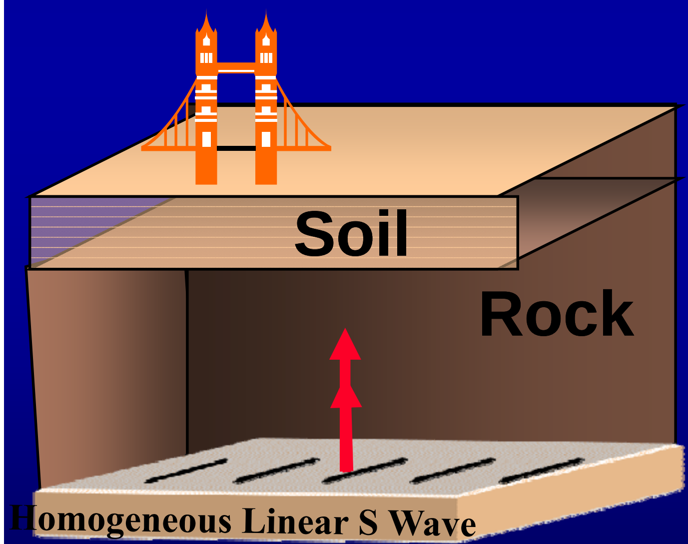
(NEHRP, UBC, IBC, AASHTO Provisions)

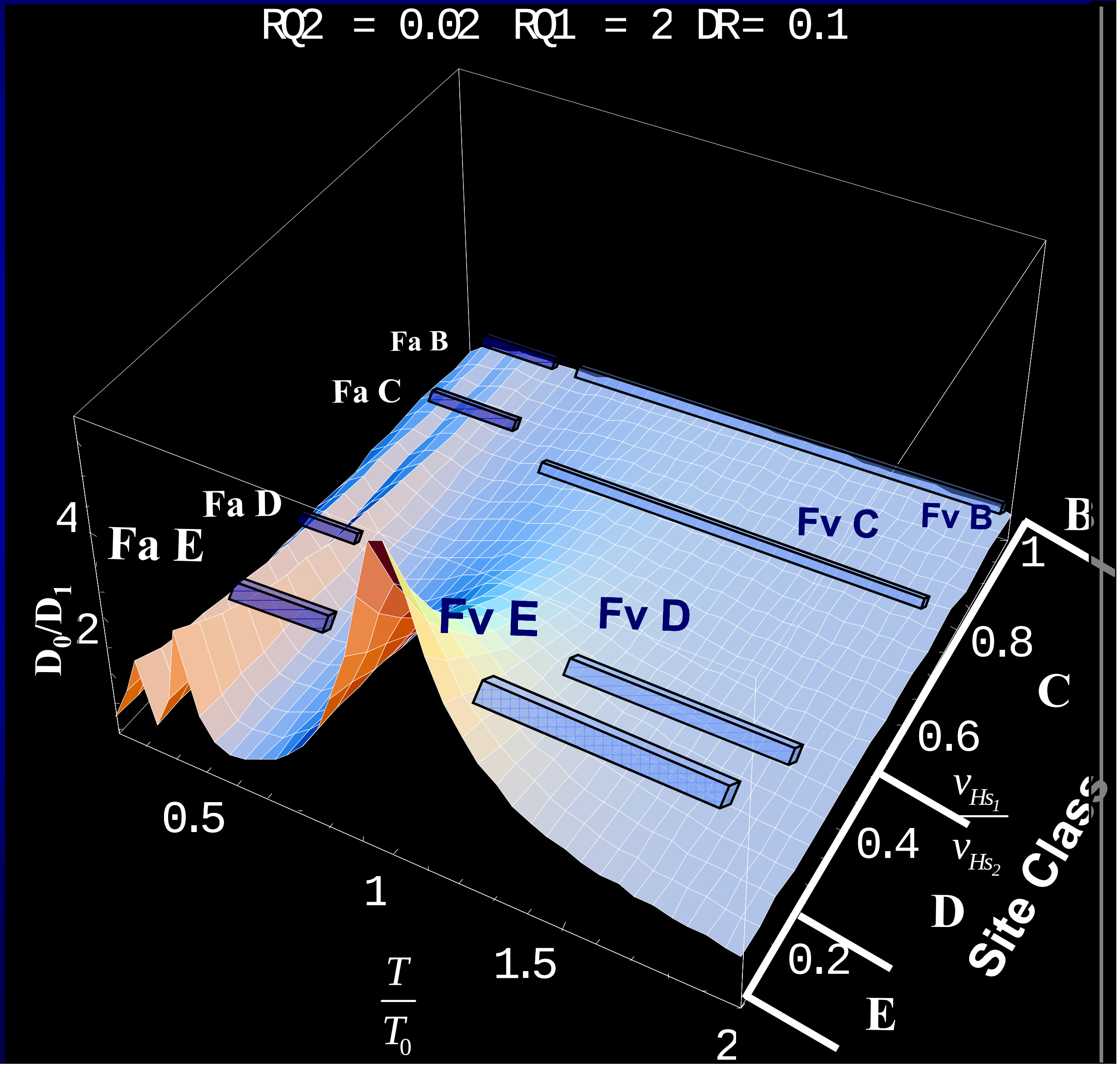
Site Class	$A_v \leq 0.1$ $S_l < 0.1$	$A_v = 0.20$ $S_l = 0.20$	$A_v = 0.30$ $S_l = 0.30$	$A_v = 0.40$ $S_l = 0.40$	$A_v \geq 0.50$ $S_l \geq 0.50$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	*
F	*	*	*	*	*

*** Site-specific geotechnical investigation and dynamic site response analysis shall be performed.**

Response versus Period, Shear Velocity, and Code Site Class

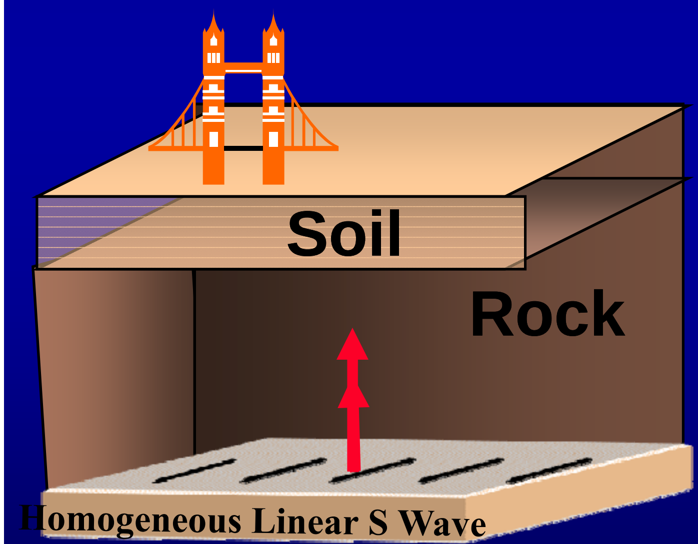
Anelastic Soil Layer
Damping Ratio 5%
Vertical Incidence

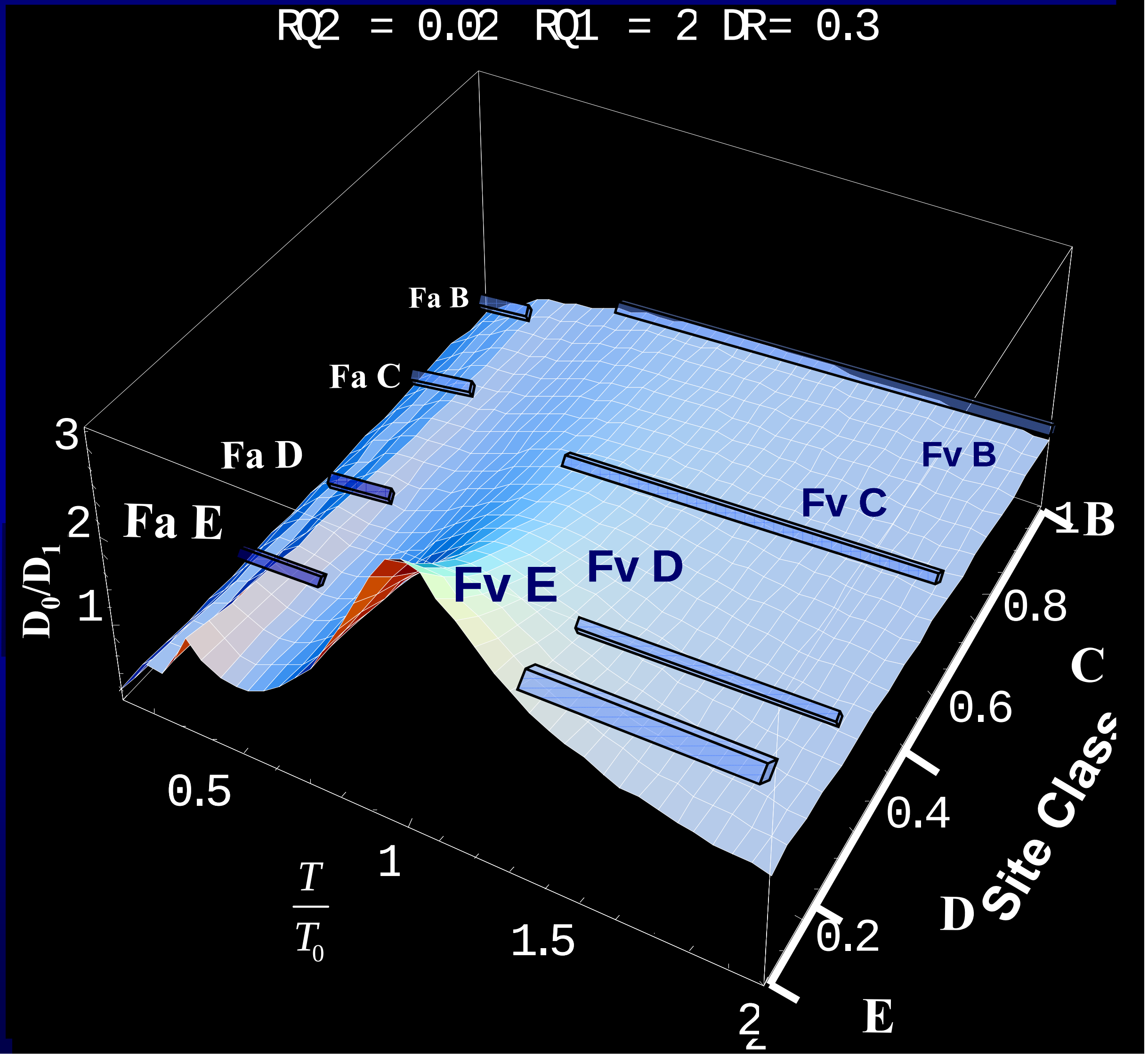




Code Site Coefficients and Theoretical Response 15 % Damping or I_a~ υ.4 g

Anelastic Soil Layer
Damping Ratio 15 %
Ia ~0.4 g
Vertical Incidence





NGA Ground Motion Prediction Equations

GMPE = $f\,(V_{S\,30})$

GMPE

$$\ln Y = f_{mag} + f_{dis} + f_{style\,of\ faulting} + f_{site} + f_{sed} + \varepsilon$$

Where, site condition term = $f_{site}\left(V_{S30}\right)$

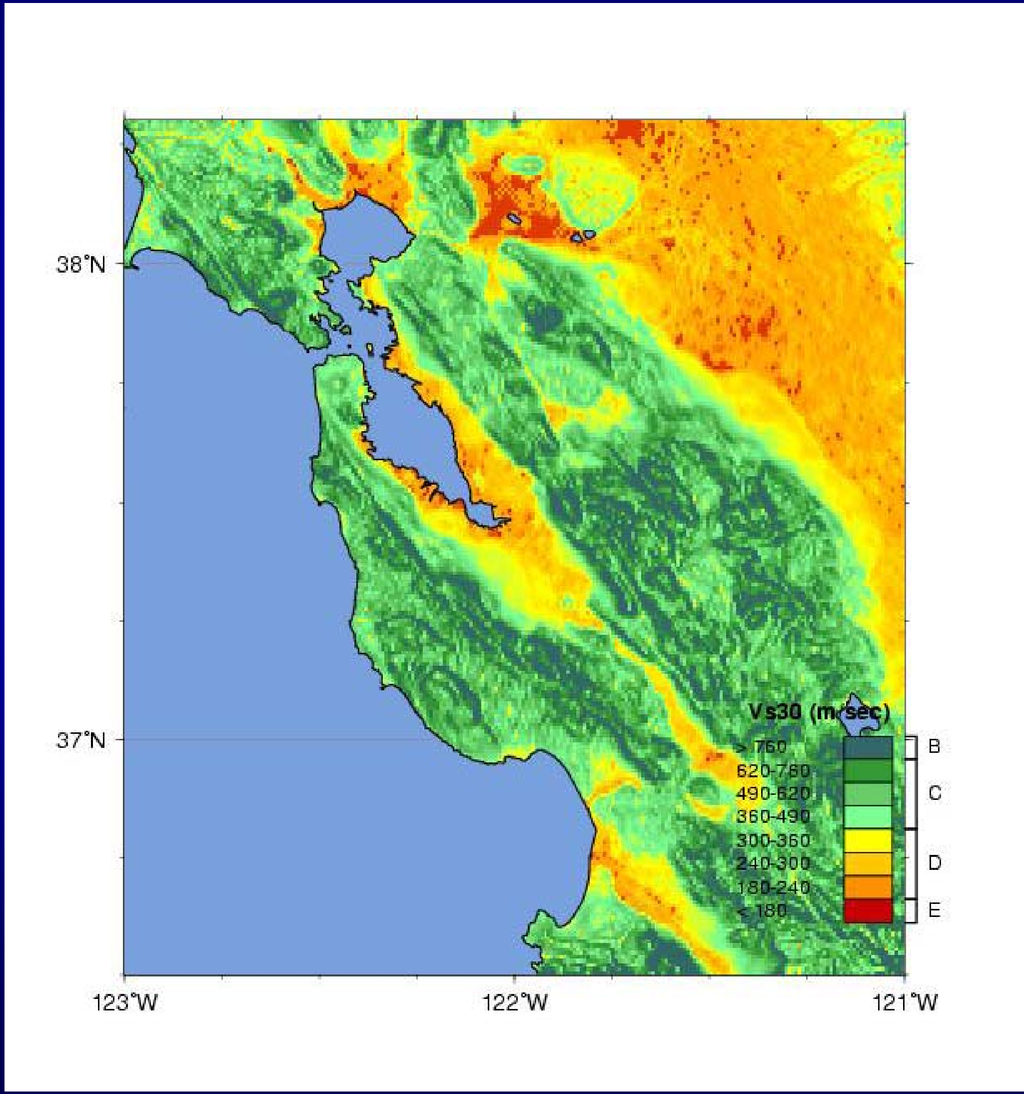
$$f_{site} = \begin{cases} c_{10}\ln\left(\dfrac{V_{S30}}{k_1}\right) + k_2\left\{\ln\left[A_{1100} + c\left(\dfrac{V_{S30}}{k_1}\right)^n\right] = \ln\left[A_{1100} + c\right]\right\} & ;\ V_{S30} < k_1 \\ \left(c_{10} + k_2 n\right)\ln\left(\dfrac{V_{S30}}{k_1}\right) & ;\ k_1 \le V_{S30} < 1100 \\ \left(c_{10} + k_2 n\right)\ln\left(\dfrac{1100}{k_1}\right) & ;\ V_{S30} \ge 1100 \end{cases}$$

(from Campbell and Bozorgnia, 2004)

$V_{S\ 30}$ for Regional Site Response Mapping

ShakeMaps

$V_{S\,30}$ Map (Topographic Slope)
(San Francisco Bay Region)

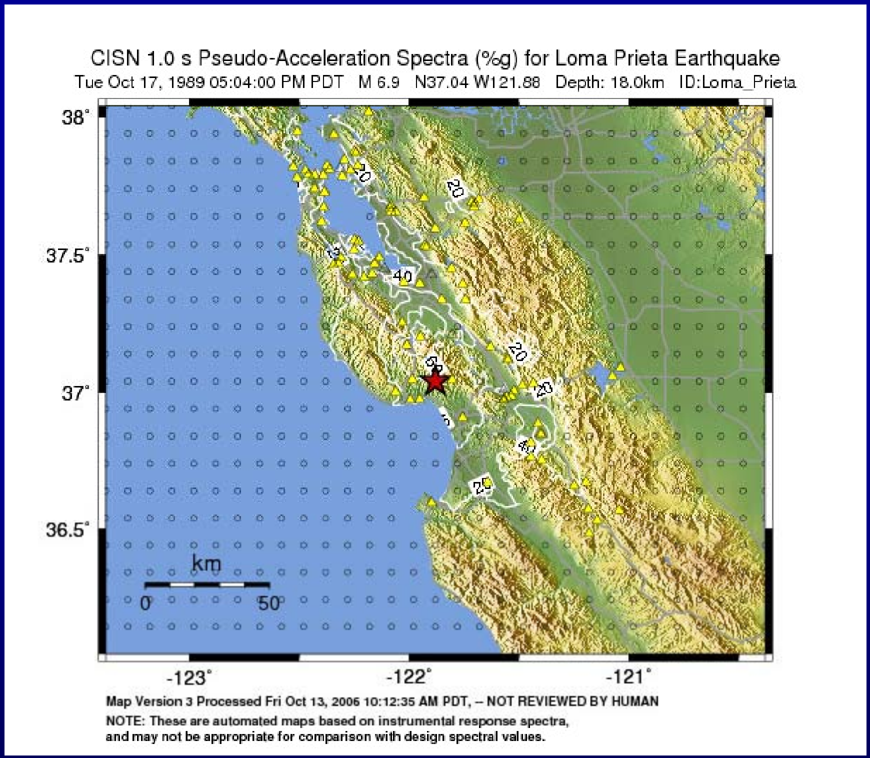


http://earthquake.usgs.gov/hazards/apps/vs30/

Spectral Acceleration ShakeMaps
Loma Prieta Earthquake
(San Francisco Bay Region)

Spectral Acceleration 0.3 Sec

Spectral Acceleration 1.0 Sec



http://earthquake.usgs.gov/hazards/apps/

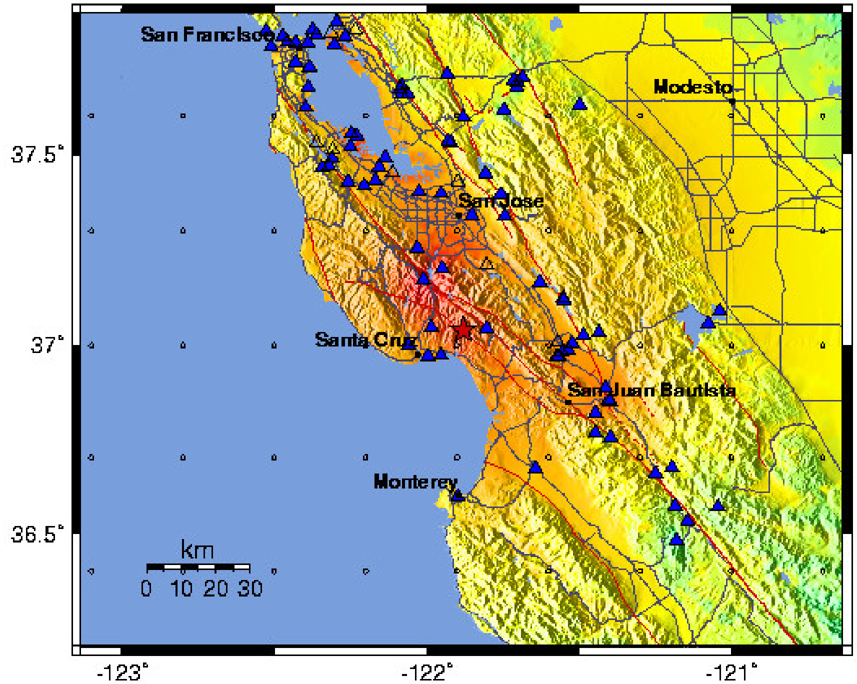
Instrumental Intensity ShakeMap

Loma Prieta Earthquake

(San Francisco Bay Region)

CISN Rapid Instrumental Intensity Map for LomaPrieta Earthquake

Tue Oct 17, 1989 05:04:00 PM PDT M 6.9 N37.04 W121.88 Depth: 18.0km ID:LomaPrieta

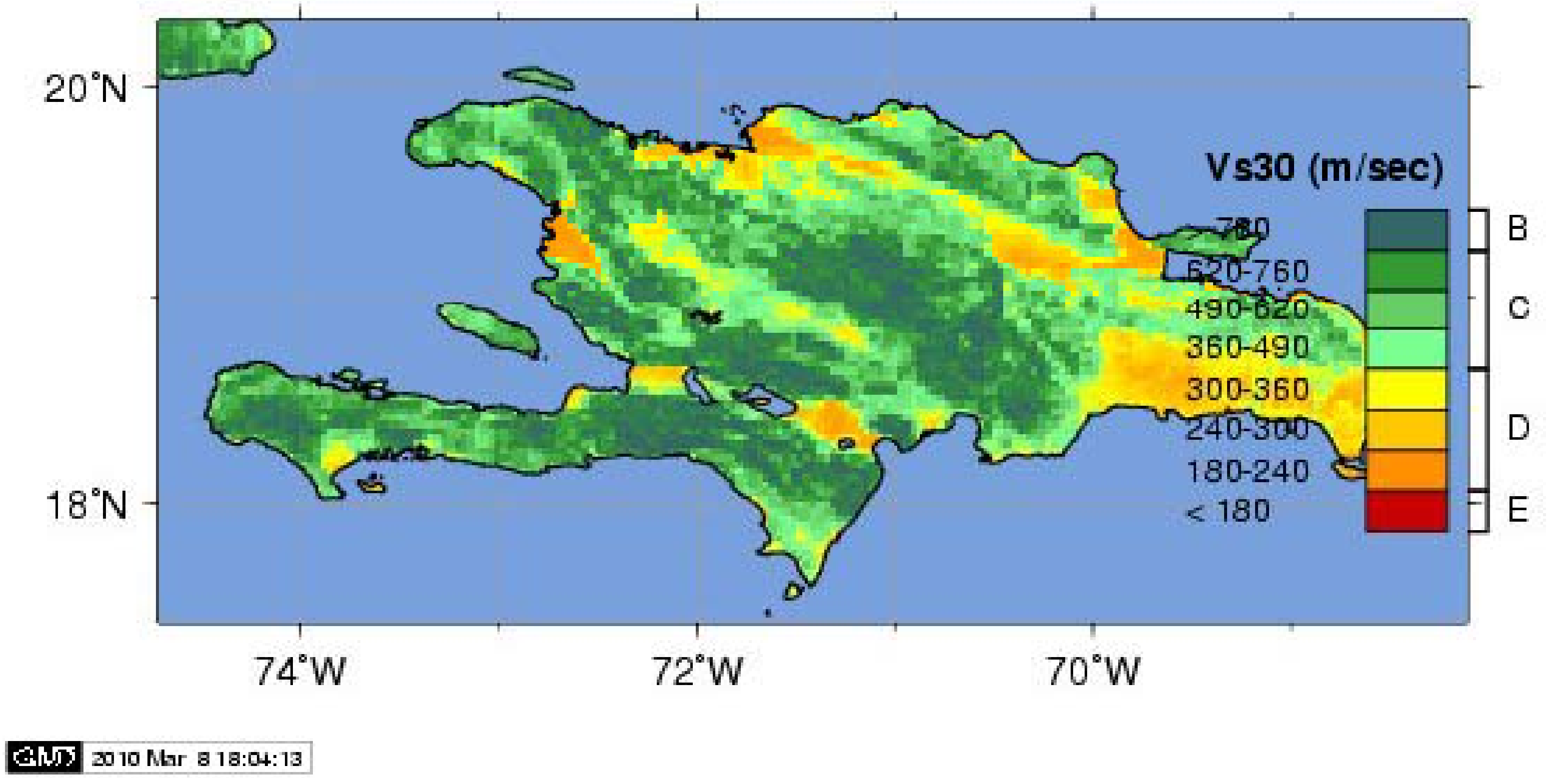


PROCESSED: Wed Jun 18, 2003 11:12:02 AM PDT,

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

http://earthquake.usgs.gov/hazards/apps/

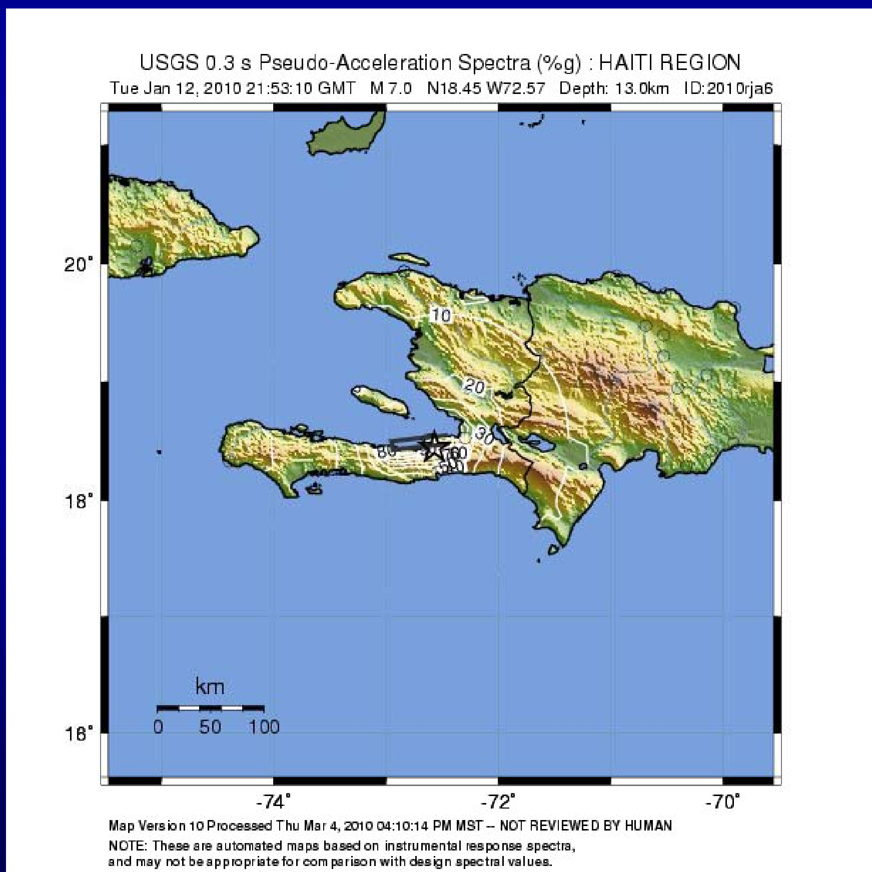
$V_{S\,30}$ Map (Topographic Slope)
(Haiti Region)



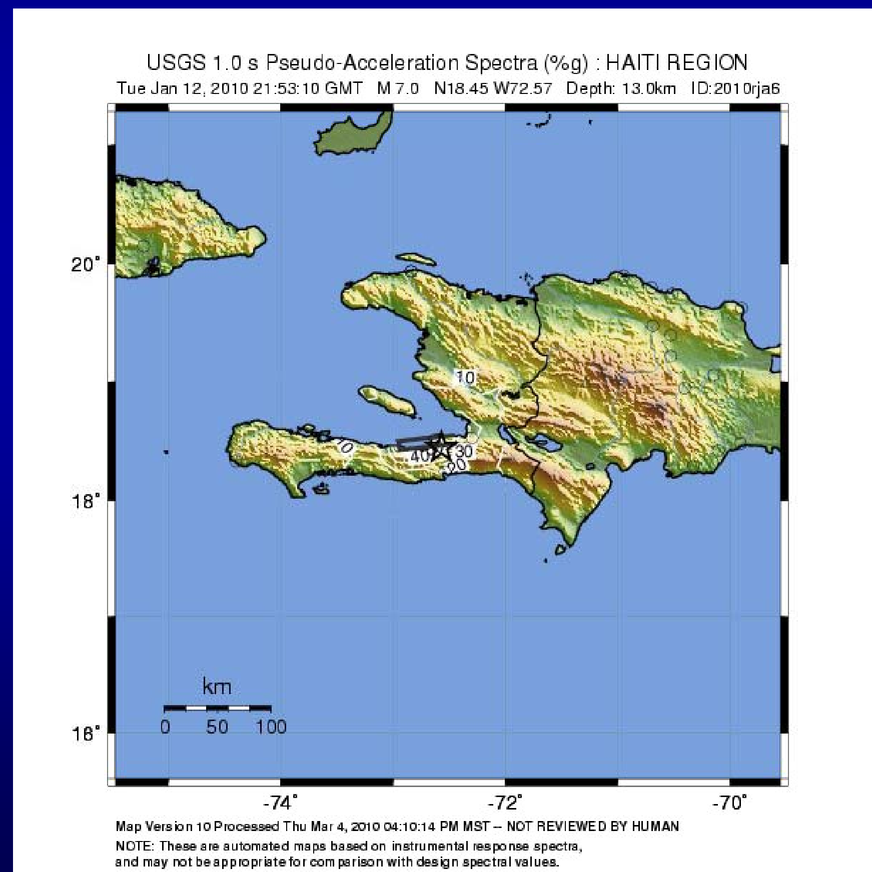
http://earthquake.usgs.gov/hazards/apps/vs30/

Spectral Acceleration ShakeMaps
Tohoku Japan Earthquake M 9.0)
(Honshu Japan Region)

Spectral Acceleration 0.3 Sec

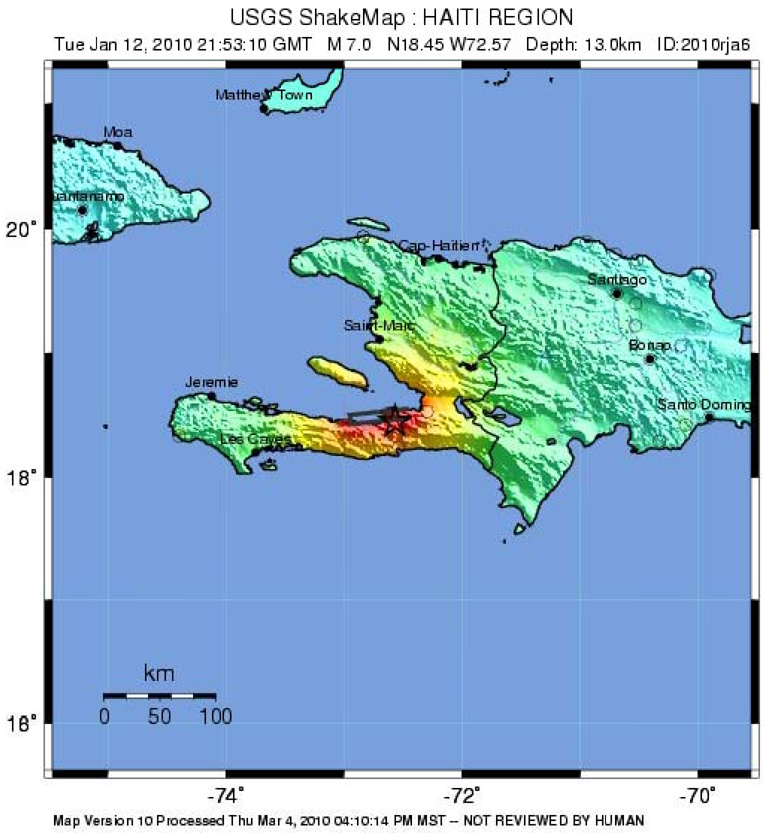


Spectral Acceleration 1.0 Sec



http://earthquake.usgs.gov/hazards/apps/

Instrumental Intensity ShakeMap
Haiti Earthquake M 7.0)



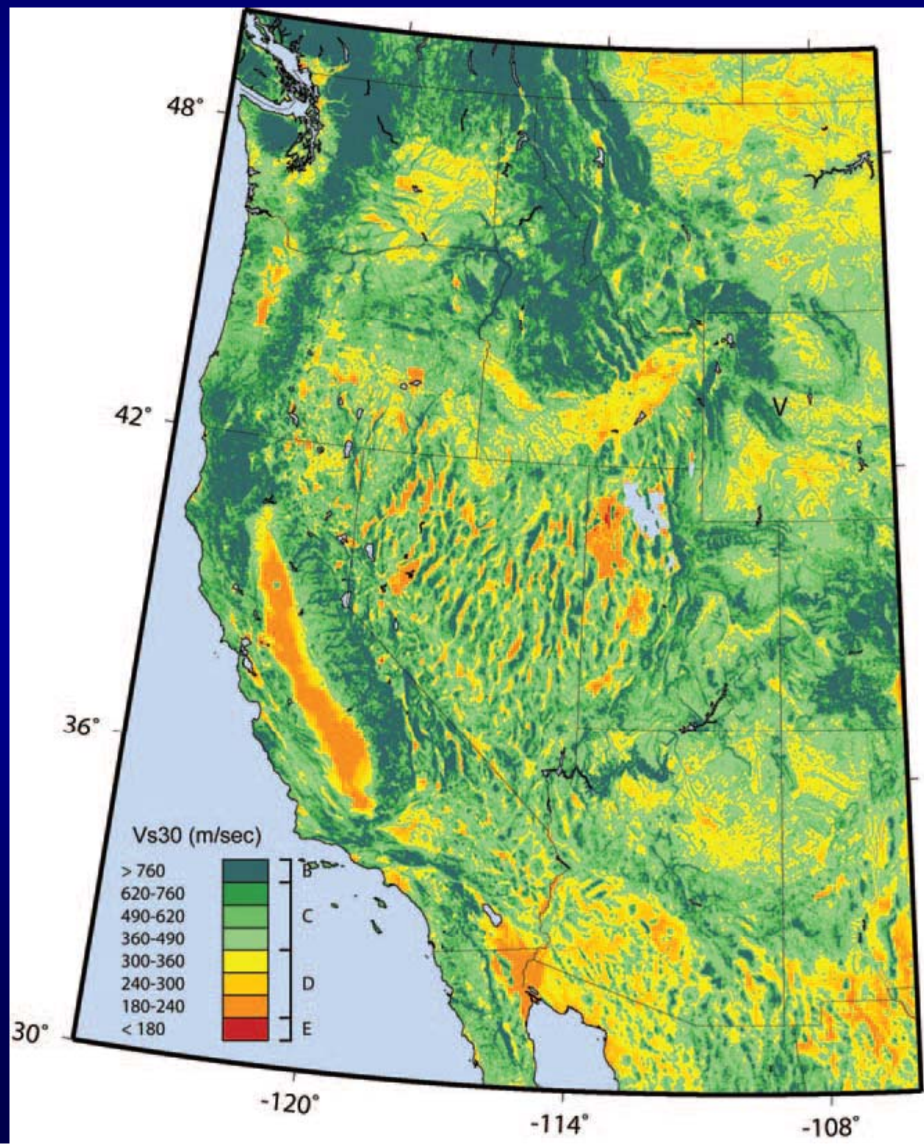
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

http://earthquake.usgs.gov/hazards/apps/

$V_{S\,30}$ for Seismic Hazard and Risk Mapping

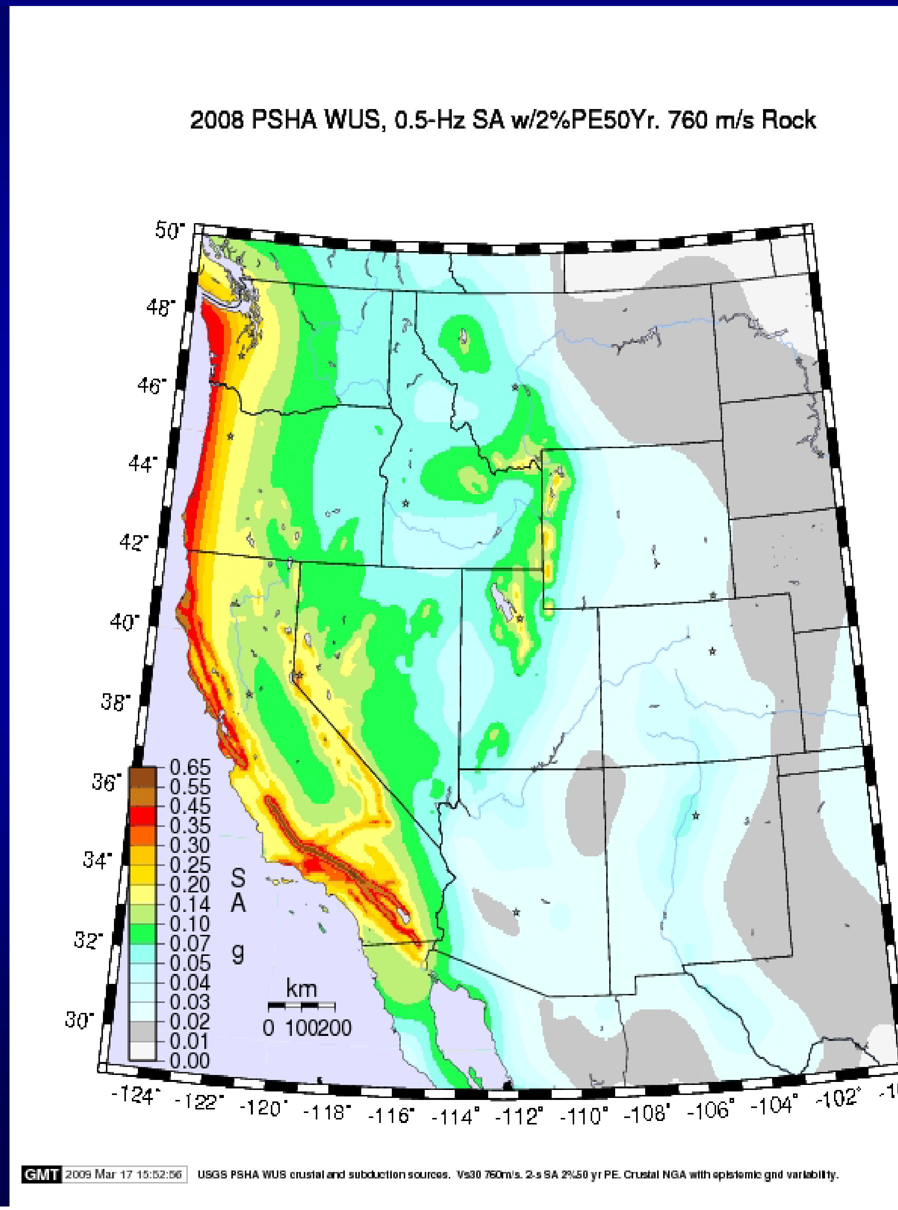
- **PSHA Maps**
- **GEM Global Seismic Hazard Mapping Project**

$V_{S\,30}$ Map (Topographic Slope) (Western US)

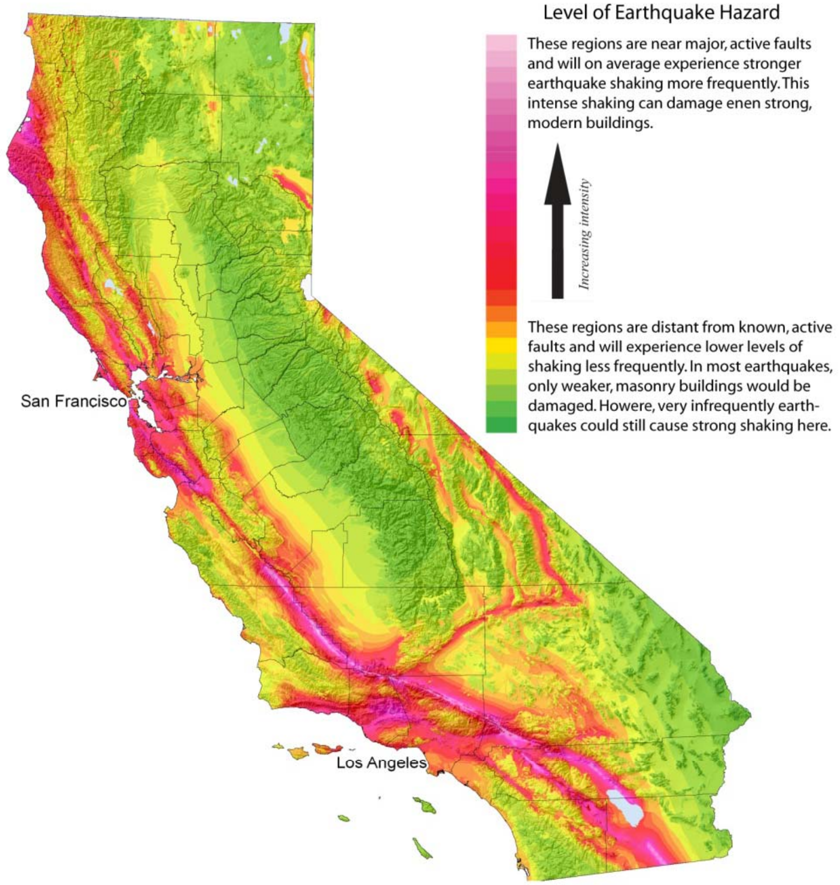


PSHA Map for Rock

(NGA GMPE 2008 SA @2 s, 2% PE 50 yr, $V_{S\,30}$ = *760 m/s)*



PSHA Map Including Site Conditions ($V_{S\,30}$)
(SA @1 s, 2% PE 50 yr)



(Kalkan and Grazier, 2010)

Global GMPE for GEM

(Site condition characterization based on $V_{S\,30}$)

Global GMPEs for

Global Earthquake Model (GEM)

PEER

GEM

GLOBAL EARTHQUAKE MODEL

Bozorgnia and others, 2011

Conclusions

- **Theoretical models and empirical measurements show $V_{S\ 30}$ shows a strong correlation with amplification, Fa and Fv, at specific sites.**
- **Correlations of $V_{S\ Z}$ with $V_{S\ 30}$ imply $V_{S\ Z}$ at other depths can be used to predict $V_{S\ 30}$ and amplification, Fa and Fv.**
- **Correlations of $V_{S\ 30}$ with Physical Properties, Geologic Age, and Topographic Slope imply $V_{S\ 30}$ can be mapped on regional and global scales.**
- **Hence, $V_{S\ 30}$ serves as a useful basis for characterization of site response for specific sites and for regional mapping purposes for the appropriate applications.**
- **Important applications of $V_{S\ 30}$ include:**
  - **Unambiguous definitions of site classes and site coefficients for routine design in building codes**
  - **Characterization of site response for GMPEs for use in Site Specific, Regional, and Global Mapping of Seismic Hazard for appropriate interpretations: ShakeMaps, PSHA Maps, GEM Model**

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