Final Technical Report

Empirical Assessment of Site Amplification and Development of NEHRP Factors for CEUS: Collaborative Research with Pacific Engineering and Tufts University

USGS Award Numbers: G12AP20003 and G12AP20004
12/1/2011 to 8/3/2013

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Date: November 4, 2013

ABSTRACT

In order to estimate the average shear-wave velocity to 30 m, $\overline{V_S}(30\text{m})$, at recording stations in Central and Eastern North America (CENA), we develop a map based on mapped surface geology and topographic slope. The available velocity profile database for CENA does not sufficiently sample firm and hard rock sites, so we augment the velocity database with assigned $\overline{V_S}(30\text{m})$ values at strong motion stations that are documented to be located on firm and hard rock sites. First, we develop an updated slope-based $\overline{V_S}(30\text{m})$ model for CENA that incorporates the firm and hard rock sites. We then separate the data into general geologic categories to identify differences in the $\overline{V_S}(30\text{m})$-slope relationship. The differences in the $\overline{V_S}(30\text{m})$-slope trend between the different geologic categories are modest, but the variability and thus the uncertainty varies significantly between geologic units. For example, the uncertainty is much larger within glaciated sediments than within non-glaciated sediments because there are many flatlying yet stiff soil or rock sites in the glaciated areas.

1.0 INTRODUCTION

As a single parameter quantifier of site amplification, measurement of the average shear-wave velocity to a depth of 30m, $\overline{V_S}(30\text{m})$, has become a generally accepted description of site conditions (Borcherdt, 1994a, 1994b; Martin and Dobry, 1994; Rinne, 1994; Dobry et al., 1999). $\overline{V_S}(30\text{m})$ has been incorporated into U.S. building codes (NEHRP, 1994, 1997; UBC, 1997; BSSC, 2000, 2004) and recently incorporated into Ground Motion Prediction Equations (GMPEs) (Boore et al., 1997; Atkinson and Boore, 2006; Power et al., 2008).

Empirical observations have consistently revealed a strong dependence of ground motions on site conditions. Del Barrio, in the 1855 Proceedings of the University of Chile states[*]"...a movement.... must be modified while passing through media of different constitutions. Therefore, the earthquake effects will arrive to the surface with higher or lesser violence according to the state of aggregation of the terrain which conducted the movement. This seems to be, in fact, what we have observed in the Colchagua Province (of Chile) as well as in many other cases" (Del Barrio, 1855). In 1862, Mallet (1862) noted the effect of geology upon earthquake damage. Milne (1908) observed that in soft "damp" ground it was easy to produce vibrations of large amplitudes and long duration, while in rock it was difficult to produce vibrations of sufficient amplitude to be recorded. Wood (1908) and Reid (1910), using apparent intensity of shaking and the distribution of damage in the San Francisco Bay area during the 1906 earthquake, gave evidence that the severity of shaking can be substantially affected by the local geology and soil conditions. Gutenberg (1927, 1957) developed amplification factors representing different site geologies by examining recordings of microseisms and earthquakes from instruments located on various types of ground.

Quantification of site effects on earthquake recordings range from simple rock verses soil characterizations (Abrahamson and Shedlock, 1997) to surfical geology (Hayashi et al., 1971; Mohraz, 1976; Seed et al., 1976; Borcherdt, 1970; Borcherdt and

[*]Translated from the old Spanish by Professor Ricardo Dobry.

Glassmoyer, 1992; Bonilla et al., 1997; Harmsen, 1997) and currently to $\overline{V_S}(30\text{m})$ (Borcherdt 1994a; 1994b; Power et al., 2008; Atkinson and Boore 2006).

Although not without controversy (e.g., Castellaro et al., 2008), $\overline{V_S}(30\text{m})$ captures stable differences in mean site amplification across frequency, albeit with considerable aleatory variability. While not a replacement for a site-specific analysis of amplification, an average velocity over only the top 20m to 30m is sufficient to statistically characterize a profile to depths that affect wavefields to periods of several seconds (Power et al., 2008) because profiles exhibit a correlation in shear-wave velocity with depth (EPRI, 1993; Silva et al., 1996, (Appendix C by G. Toro); Boore et al., 2011). As such $\overline{V_S}(30\text{m})$ has supplanted binary site descriptors such as rock verses soil and discrete geology related descriptors such as Geomatrix categories, providing a continuous and quantitative transition of site amplification with a clearly defined site condition. The addition of a soil depth parameter, such as the depth to a significant impedance contrast (e.g., basement rock) would enhance predictive power. For example, a 30m deep soil site will have less amplification at low-frequency ($f \leq 1$ Hz) than a 100m deep soil site, both with the same $\overline{V_S}$ (30m) (Silva et al., 1999; Abrahamson and Silva 2008). While perhaps somewhat incomplete, $\overline{V_S}(30\text{m})$ alone reflects a significant improvement over previous non-quantitative site descriptors and has been generally adopted as a primary tool for mapping generic site amplification.

To provide a basis for mapping of $\overline{V_S}(30\text{m})$, there are three general correlation techniques which have been implemented: (i) surficial geology (Wills and Silva, 1998; Wills and Clahan, 2004, 2006); (ii) generic site categories or classifications such as Geomatrix, Campbell, or Spudich (Chiou et al., 2008) which are loosely based on geology, anticipated depth to rock, or local setting such as wide or narrow valley; and (iii) remote sensing techniques (physiographic characteristics) such as topographic slope (Wald and Allen, 2007) and terrain (Yong et al., 2009, 2010, 2011). Thompson et al. (2010) and Wald et al. (2011) showed that an additional geostatistical step could be applied along with the above mapping methods locally refine the maps to be consistent with measurements.

All three correlation approaches reflect surrogates for profile stiffness and each have basic strengths and shortcomings that are reflected in their related epistemic uncertainties in $\overline{V_S}(30\text{m})$ estimates (Chiou et al., 2008). While intermethod measurement error or differences in $\overline{V_S}(30\text{m})$ estimates are typically small, around a few percent (COV; Moss, 2008), intermethod differences or measurement type epistemic uncertainty tends to be much greater with a COV around 10% to 20% (Moss, 2008). When spatial variability is included, as in correlations with surficial geology or generic site categories such as Geomatrix, the variability (epistemic uncertainty in median $\overline{V_S}(30\text{m})$ estimates) in terms of $\sigma_{\ln}$ increases to about 0.3 to 0.4 (Wald and Allen, 2007). There is some evidence of increasing variability with increasing profile stiffness (Chiou et al., 2008; Moss, 2008).

To provide context for the spatial variability associated with category assignments, it is informative to look at the assignment of variability (epistemic uncertainty) for sites with measured $\overline{V_S}(30\text{m})$ adopted for the PEER NGA GMPE development (Chiou et al., 2008). The assumption would naturally be zero and any number greater than zero implies uncertainty. However practical access issues as well as the lateral extent of surface techniques necessitated a working definition of "at a site".

Based on Borcherdt's (2002) experience with drill rig access in the USGS multi year drilling effort, PEER adopted a working definition such that any measurement within 300m of a recording instrument was defined to be "at the site". Based on analyses of clusters of measurements and professional judgment, the σ_{ln} reflecting spatial variability over distances up to 300m ranged from 0.05 for the softest sites (NEHRP Category E) to 0.30 for stiff sites (NEHRP Category A) (Chiou et al., 2008). These variabilities are similar to those of the intermethod COV 10% to 20% for firm soil sites, due to limited multimethod measurements at stiff sites, and reflect, to a significant extent, spatial variability due to the practical limitation of measurement proximity as well as the extended apertures of surface methods.

For physiographic methods such as topographic slope (Wald and Allen, 2007) and terrain (Yong et al., 2008), the variability over all $\overline{V_S}(30\text{m})$ is about 0.35 (σ_{ln}) for California, where the density of measurement is greatest. This epistemic uncertainty, about 0.35, is commensurate with that of correlations of surficial geology and generic site categories (e.g., Geomatrix) suggesting the world-wide utility of physiographic methods (Wald and Allen, 2007; Yong et al., 2008). It should be pointed out all correlation techniques, including physiographic, fundamentally rely on sufficient sampling of the correlate with measured $\overline{V_S}(30\text{m})$ where regional differences may exist (e.g., Western North America (WNA) verses CENA; Wald and Allen, 2007). Such a dependence reflects a fundamental shortcoming of correlation methods as it necessities an assessment regarding what may constitute a "regional difference" in correlation between $\overline{V_S}(30\text{m})$ and the underlying parameter that is mapped. As a result, applications of correlations to regions lacking sufficient measurements to confirm or assess existing models must be accompanied by a significant increase in epistemic uncertainty and may be subject to significant bias as well.

To summarize, variabilities in $\overline{V_S}(30\text{m})$ estimates are about 0.2 (σ_{ln}) for measurements within about 300m and range up to about 0.3 to 0.4 when using correlations of surficial geology, generic site categories, or topographic slope and terrain. These estimates of epistemic uncertainty provide a context for assessing the accuracy of the $\overline{V_S}(30\text{m})$ mapping for CENA.

2.0 PROFILE DATABASE

The profiles database of Pacific Engineering provides the fundamental $\overline{V_S}(30\text{m})$ data for the development of the CENA maps. The database consists of measured velocities determined by both borehole (suspension, crosshole, downhole, seismic cone) and surface (ReMi, SASW, MASW, reflection, refraction) techniques and includes compressional-wave velocities if available. Each profile was vetted by examining the accompanying acquisition information or metadata. Suspension profiles were smoothed by eye (reduced resolution) to provide velocity estimates more representative of the area surrounding the borehole. Seismic cone interpretations typically reflect interval velocities that may result in rapidly varying velocities with depth. Because the interval velocity interpretation relies on differences in travel times, small errors can accumulate, resulting in spurious velocity estimates. For cases where waveforms and arrival times were available, the seismic cone data have been reinterpreted with the traditional downhole approach with velocities and layer thicknesses based on sections of constant slope in travel time plots (e.g., Boore and Thompson, 2007). For seismic cone profiles

where travel times were not available, rapidly varying layer velocities were smoothed by eye, as with the suspension log profiles. The intent of the smoothing (reduction in resolution) of rapidly varying velocities with depth (due to very high frequencies for suspension log data (≈ 500 + Hz)) and seismic cone profiles (interval interpretations) was to provide velocity estimates representative of wide apertures around the boreholes. Since shear-wave velocities estimated with surface methods reflect laterally averaged values (along one azimuth only depending on the technique and survey implementation), the smoothing of rapidly varying (vertical) local velocities was intended to produce a similar resolution across techniques and provide a more rational basis for averaging profiles, one of many applications of the profile database (Wills and Silva, 1998; Wills and Clahan, 2004, 2006; Chiou et al., 2008).

For $\overline{V_S}(30\text{m})$, the profile database computes the time average to 30m for profiles which extend to at least 30m. For cases where measurements do not extend to 30m, the deepest layer velocity is continued to 30m (constant extrapolation). Profiles which extend to at least 20m provide a very reliable $\overline{V_S}(30\text{m})$ estimate with a bias of about 2% (underprediction, Yu and Silva, 2011) and standard deviation of about 0.04 to 0.07 ($\sigma_{\ln}$, Yu and Silva, 2011; Boore, 2004) and were used for the CENA map development. Profiles with depths less than 20m were not used because a regional calibration to CENA profiles was not available to avoid biased extrapolations based on a gradient extrapolation (Boore et al., 2011; Yu and Silva, 2011).

2.1 CENA Profiles

Currently the profile database contains over 3000 measured profiles with 632 in CENA (Figure 1). For CENA, the data are:

1. Public domain contributions: Eggert et al. (1994), Streat et al (1995), Beresnev and Atkinson (1997), Schneider and Mayne (1999), Street and Woolery (2001), Woorlery and Wang (2002), Odum et al. (2003), Williams et al (2003), Anderson et al. (2003), Gomberg et al (2003), Williams et al. (2003), Wang et al. (2003), Bauer (2004), Kociu et al. (2004), Street et al. (2004), Woolery and Wang (2005), Bauer (2005, 2006), Hoffman et al. (2006), Rosemblad (2006), Jaume (2006), Anderson et al. (2007), Banab and Motazedian (2007), Rosenblad et al. (2007), Geovision (2008), McIntyre (2008), Read et al.(2008), Pehrne and Melaney (2009), Odum et al.(2008), Rosenblad and Li (2009), Odum et al.(2010),Liu and Adams (2010), Odum et al.(2011),
2. A large number of profiles from the southeastern US; Georgia and the Carolinas and about 30 profiles available for New York City from a recent project with Weidlinger Associates, Inc. and URS,
3. The Eastern Canadian recording site profiles from Beresnev and Atkinson (1997),
4. Recording site velocity information compiled by Chris Cramer during processing of the NGA-East CEUS and Canada recordings as received from the data providers and transmitted to PEER,
5. Profiles from DOE sites Savannah River, South Carolina; Paducah, Kentucky; Oak Ridge National Laboratory, Tennessee; and Portsmouth, Ohio, all from internal seismic hazard projects,
6. Available site information for the ECTN sites compiled in a report to PEER by Lin and Adams (2010),

7. There are about 23 COL (Combined Operating License) nuclear power plant applications under review by the NRC. All of the sites have extensive velocity measurements available at the NRC web site. Profiles reflecting original (unimproved) site conditions have been included,
8. USGS measurements in CEUS available in open file reports: e.g. Jack Odumn and Robert Williams (USGS, Golden Colorado), Robert Bauer et al. (2007),
9. Profiles available from individuals: e.g. Ron Andrus (Clemson University), Ron Street and Edward Woolery (University of Kentucky), Glen Rix (Georgia Tech), Steven Jaume (College of Charleston), and Martin Chapman (Virginia Tech),
10. The profile database also contains a large number of profiles from privately funded seismic hazard projects of Pacific Engineering located in Oklahoma, Mississippi, Missouri, Texas, Georgia, Carolinas, Virginia, Tennessee, New York, and New Jersey.
11. Profiles collected as part of the ARRA funded profiling effort (Yong et al., 2013).
12. Profiles collected for EPRI GMM review project. (EPRI, 2004, 2006).

Due to the private nature of many profiles, the database is considered proprietary.

2.1.1 Inferred CENA Profiles at Recording Sites

A significant limitation of available $\overline{V_S}(30\text{m})$ measurements is reflected in the sample size of NEHRP Category A (> 1,500m/s) as well as Category B sites which exceed 1,000m/s. The profile database currently contains only 17 profiles with $\overline{V_S}(30\text{m})$ exceeding 1,000m/s and only 6 profiles exceeding 1,500m/s.

The sampling of very stiff profiles ($\overline{V_S}(30\text{m}) \geq 1{,}000$m/s) in CENA is comparable to that of WNA with both regions having about 1-2% of the measured profiles with $\overline{V_S}(30\text{m})$ at or above 1,000m/s. In contrast to WNA, this sampling for CENA is surprising as CENA recordings, perhaps dominated with eastern Canada stations, generally reflect a much larger percentage of rock sites, particularly hard rock (Atkinson and Assatourians, 2010; Atkinson and Boore, 2006). The dichotomy of a small absolute number of $\overline{V_S}(30\text{m})$ measurements at or exceeding 1,000m/s in the CENA and a large number of hard rock recording sites in the CENA presents two potential issues:

1. Insufficient sample size upon which to develop correlations,
2. Apparent inconsistency between recording site classifications as hard rock and $\overline{V_S}(30\text{m})$ assignments (related to 1 above and discussed in Section 3).

The consequence of very few high $\overline{V_S}(30\text{m})$ measurements would likely result in a bias in developing correlations with proxy methods as well as a possible undersample of the extent of high $\overline{V_S}(30\text{m})$ areas. The high $\overline{V_S}(30\text{m})$ sampling issue impacts the application of the topographic slope method of Wald and Allen (2007) to CENA as their highest $\overline{V_S}(30\text{m})$ bin is greater than 760m/s (NEHRP BC boundary). The available velocity data do not permit a distinction between NEHRP B and A sites, with NEHRP A and B/C being the current reference site condition for CENA GMPEs (EPRI, 2004; Atkinson and Boore; 2006, 2010).

For recording site classifications, because the CENA has a considerable region of shallow (≤ 30 m) soils overlying firm (sedimentary) and hard (crystalline) rock (Section 3.1), an ambiguity exists regarding the appropriate $\overline{V_S}(30\text{m})$ to associate with recording sites which may have instruments buried either within or very close to rock. In such

cases measurements adjacent to the instruments properly reflect soil and underlying rock but with a $\overline{V_S}(30\text{m})$ value that is inappropriate for recordings and not reflective of the actual amplification.

To address both the sample size and shallow soil/instrument issues in a very approximate manner, we decided to augment the measurement database with the hard rock category shear-wave velocity assignments of Gail Atkinson (Atkinson and Assatourians, 2010) for recording sites. Based on the site geology Atkinson assumed an average shear-wave velocity of 2 km/s, generally taken as a $\overline{V_S}(30\text{m})$. Many of the sites actually reflect shallow soil but with the instruments founded at or very close (few meters) to rock. The inclusion of these assumed site velocities added 131 hard rock samples for correlations that more accurately reflect amplification at hard rock recording sites even though the surficial geology may actually be shallow soil. Such shallow soil sites exist in wide regions of the CENA across many states.

To more accurately represent actual $\overline{V_S}(30\text{m})$ at the recording sites to estimate surface amplification, the $\overline{V_S}(30\text{m})$ of 2 km/s was lowered to 1.5 km/s as a rough approximation. For example only 1m of 200m/s over 2 km/s material reduces the $\overline{V_S}(30\text{m})$ to about 1,500m/s. While there are no data to support that this condition exists on average, it simply serves as an example that it takes very little low velocity shallow material to significantly reduce a high rock $\overline{V_S}(30\text{m})$. In the CENA, shallow soils may be tills or loess with shallow shear-wave velocities well above 200m/s, but several meters thick. To better quantify actual recording site $\overline{V_S}(30\text{m})$ values that reflect amplification, it is strongly recommended the PEER NGA-East project take the following steps:

1. Compile a list of CENA rock and shallow soil sites, screen which are confirmed with instruments located at or very near rock, and request the providers have their technicians (who routinely visit the sites) assess sensor proximity to rock,
2. After the characterization in step 1, fund and encourage more measurements at CENA rock and shallow soil sites at locations where surface measurements reasonably reflect recording site amplification.

3.0 ISSUES IN Vs(30m) MAP DEVELOPMENT FOR CENA

A natural approach to augment the sparse $\overline{V_S}(30\text{m})$ measurements in the CENA would involve applying proxy correlations developed in the more data rich WNA to the CENA. However, there are a number of issues which complicate the development of $\overline{V_S}(30\text{m})$ maps for CENA and prevent an unbiased implementation of WNA proxy correlations to CENA. These issues do not reflect fundamental difference in the dynamic material properties of soils and rocks between WNA and CENA due to lithology or age, but are a consequence of the relative differences in distributions of similar soil and rock types and ages. The relative areal extents of soil and rock types varies substantially between WNA and CENA, necessitating region-specific correlations of $\overline{V_S}(30\text{m})$ proxies in general and in particular for recording stations located at very shallow soil sites. The following discussion illustrates the issues.

3.1 Shallow Soils

The existence of very shallow (1m to 10m) soils overlying firm rock (e.g., shale) or hard rock (e. g., granite) is not common in WNA (Wills and Silva, 1998; Silva et al., 1999; Wills and Clahan, 2004, 2006) and presents a significant issue for assigning

$\overline{V_S}(30\text{m})$ estimates to CENA recording sites because there are significant regions in the CENA where shallow soils overly firm and hard rock but recording instruments may actually be founded directly on rock. As Figure 2 illustrates for the glaciated region in the CEUS, with the exception of the Michigan, Illinois, and Williston basins, much of the bedrock is overlain by soils with an estimated thickness of less than 15m. In these areas, recording instruments may be at or within 3m to 6m of rock, especially those located in basements of buildings.

For such cases, $\overline{V_S}(30\text{m})$ estimates, measured or inferred from correlations, will reflect a combination of soil and rock while the recorded ground motions will have the response of firm or hard rock site conditions. Shallow soil sites overlying firm or hard rock may especially be an issue in general for physiographic proxies such as terrain (Yong et al., 2008) and topographic slope (Wald and Allen, 2007). The particular attributes of physiographic proxies may reflect significantly deeper soils, not distinguishing between regions of shallow soils and deep soils and depend on which conditions dominate the database of measurements used for calibration. This issue affects any proxy method implemented in the CENA and may result in increased epistemic uncertainty in moderate $\overline{V_S}(30\text{m})$ estimates (e.g., NEHRP category B sites) that include shallow soils over firm or hard rock. For WNA, $\overline{V_S}(30\text{m})$ in the moderate range (≈ 500 m/s to 1,000 m/s) typically reflects soft rock with a moderate gradient reaching 3 km/s at depths beyond about 2 km (Boore and Joyner, 1997; Silva, 1997; Silva et al., 1999). With surface velocities around 300 m/s, recording site placement typically reflects little embedment and $\overline{V_S}(30\text{m})$ estimates provide a reliable measure of deeper velocities. As a result a moderate $\overline{V_S}(30\text{m})$ value may reflect significantly different amplification for WNA and CENA sites. This is further complicated by the location of instruments at shallow soil sites in the CENA with amplification actually reflecting much higher $\overline{V_S}(30\text{m})$ values than indicated by the profile.

Examples of shallow soil sites with instruments founded in rock are ECTN sites OTT, WBO, CKO, and GRQ with shear-wave velocity profiles measured by Beresnev and Atkinson (1997). The $\overline{V_S}(30\text{m})$ values for the four sites are: 760 m/s, 1,734 m/s, 1,203 m/s, 1,889 m/s respectively. The corresponding $\overline{V_S}(30\text{m})$ for the rock material beneath the shallow soils are 1,670 m/s, 3,110 m/s, 2,190 m/s, and 2,850 m/s respectively. The average ratio of the "actual" measured $\overline{V_S}(30\text{m})$ (soil plus rock) to "effective" $\overline{V_S}(30\text{m})$ (at the instrument) is about 1.8, clearly indicating an unacceptably large bias.

3.2 Distribution of Hard Verses Firm Rock Properties

Related to the ambiguity of $\overline{V_S}(30\text{m})$ within CENA estimates at shallow soil sites but with instruments at or very close to underlying rock is the distribution of sedimentary rocks beneath soils in the CENA. North of Cairo Illinois, the northern extent of the Mississippi Embayment and in Missouri, Ohio, Indiana, and Michigan, the soils are typically shallow (except for deeper parts of the Michigan and Illinois basins, Figure 2) and are directly underlain by sedimentary rocks such as sandstones, siltstones, and shales (Soller, 2004; Figure 3). The areal extent of the underlying sedimentary rock includes the Gulf Coastal region (EPRI; 1993, 2004) and north into Oklahoma.

Typical shear-wave velocities for these gas and coal bearing sedimentary rocks range from about 1.5 km/s to 2.5 km/s, significantly below the 2.83 km/s assumed for

hard reference rock conditions in the CENA (EPRI, 2004). As Figure 3 illustrates for the CEUS glaciated regions, much of the region has sedimentary rock directly underlying the soils (Soller, 2004). In many areas the sedimentary rocks may extend thousands of feet before Precambrian hard rock basement is encountered.

For the areas of shallow soils underlain by sedimentary rock, realistic $\overline{V_S}(30\text{m})$ estimates for instruments located at or very near rock should reflect lower velocities than corresponding shallow soil sites underlain by crystalline rock. The latter sites include the Piedmont and Blue Ridge with saprolite overlying hard crystalline basement rocks as well as the north eastern US and eastern Canada where thin veneers of till overly hard rock.

3.3 Distribution of Soil Properties Between WNA and CENA

An additional factor in potential differences between WNA and CENA soils relevant to proxy correlations is the relative dominance of till and loess. These Quaternary sediments are much more widespread in CENA. For example till and glacial outwash is present in western Washington around Seattle but is widespread in the glaciated region of CENA (Figure 4). Loess soils are common along the eastern bank of the Mississippi River near Memphis Tennessee and form the bluffs of the Uplands region there. Loess exists in the WNA, for example in areas of eastern Washington, but is typically much thinner than in the uplands in CENA.

Both till and loess reflect higher velocities than more widespread soils in WNA yet may have similar proxy attributes (Wald and Allen, 2007; Yong et al., 2011) and extrapolations for measurements that do not extend to 30m (Boore et al., 2011; Yu and Silva, 2011) may be subject to significant bias. The potential regional bias in $\overline{V_S}(30\text{m})$ and proxy correlations between WNA and CENA likely extends outside North America and worldwide implementation should be accompanied by region-specific assessments with local $\overline{V_S}(30\text{m})$ measurements.

4.0 Vs(30m) MAP DEVELOPMENT

Silva et al. (2011) developed a $\overline{V_S}(30\text{m})$ map for the CEUS and assessed a number of alternative proxies, including surface geology (Fullerton et al., 2003), terrain (Yong et al., 2011), and topographic slope (Wald and Allen, 2007). Based on the velocity data available at the time, and the need for a model that extends into Canada (the Fullerton map only covers CEUS), Silva et al. (2011) based their map on the Wald and Allen (2007) topographic slope model, but modified it to account for hard rock sites because the Wald and Allen (2007) model gives a maximum $\overline{V_S}(30\text{m})$ of 760 m/s which is too low for the CEUS where hard rock conditions are pervasive. Silva et al. (2011) developed two models: one for “actual” conditions and one for “effective” conditions, as discussed in 3.1. The “actual” model is given by

$$\ln \overline{V_S}(30\text{m}) = \begin{cases} 180 & \text{for } m \le 10^{-4} \\ 6.440 + 0.1353 \ln(m) & \text{for } 10^{-4} < m \le 2\times10^{-3} \\ 6.709 + 0.1787 \ln(m) & \text{for } 2\times10^{-3} < m \le 10^{-2} \\ 8.822 + 0.6374 \ln(m) & \text{for } 10^{-2} < m \le 2\times10^{-2} \\ 8.051 + 0.4406 \ln(m) & \text{for } 2\times10^{-2} < m \le 4\times10^{-2} \\ 9.033 + 0.7420 \ln(m) & \text{for } 4\times10^{-2} < m \le 0.1 \\ 1500 & \text{for } m > 0.1 \end{cases} \quad (1)$$

and the "effective" model is given by

$$\ln \overline{V_S}(30\text{m}) = \begin{cases} 180 & \text{for } m \le 10^{-4} \\ 6.440 + 0.1353 \ln(m) & \text{for } 10^{-4} < m \le 2\times10^{-3} \\ 6.709 + 0.1787 \ln(m) & \text{for } 2\times10^{-3} < m \le 10^{-2} \\ 8.822 + 0.6374 \ln(m) & \text{for } 10^{-2} < m \le 2\times10^{-2} \\ 8.051 + 0.4406 \ln(m) & \text{for } 2\times10^{-2} < m \le 4\times10^{-2} \\ 10.032+1.0560 \ln(m) & \text{for } 4\times10^{-2} < m \le 0.1 \\ 2000 & \text{for } m > 0.1 \end{cases} \quad (2)$$

where m is the slope gradient. Following Wald and Allen (2007), the gradient (i.e., maximum slope) was computed from 30 arc-sec SRTM data (Farr and Kobrick, 2000) using the GMT command "grdgradient" (Wessel and Smith, 1991). This command uses the central difference technique to approximate the derivative of the elevation surface in two orthogonal directions. The gradient, m, is then computed as the vector sum of the two components. In the time since the completion of Silva et al. (2011), the database has been expanded and thus we refine the previously developed model in this report and investigate an alternative geology classification system that was not considered previously.

4.1 Surficial Geology

For our purposes, the Soller et al. (2009) map provides a number of advantages to the Fullerton et al. (2003) map that was considered by Silva et al. (2011). First, there are a number of stations within the CEUS that were not covered by the Fullerton et al. (2003) map, and this problem was addressed by the Soller et al. (2009) map because it covers the entire US. Second, the total number of units in the Soller et al. (2009) has been simplified relative to the Fullerton et al. (2003) map, which makes interpretation easier. For Canada, we employed the Fulton (1996) map.

The first challenge in developing the geology proxy is to unify the two different geologic maps for Canada and the US. To accomplish this, we group the units in each map into four simple categories: 1) sediments, 2) glaciated sediments, 3) residual soils, and 4) rock. The correspondence between the mapped units and these simple categories is given in Table 1. These categories are mapped in Figure 5, which shows that the classification is relatively consistent across the US-Canada border. The Soller et al. (2009) map includes a classification of soil thickness, shown in Figure 6. Unfortunately, there is no similar description for soil thickness in the Fulton (1996) map.

Table 2 gives the mean, standard deviation (s), and the number of samples (n). The mean and s are computed from the natural logarithm of $\overline{V_S}(30\text{m})$; the mean is

exponentiated while *s* is reported in natural log units. This table illustrates the large amount of variability within the glacial sediments and residual soils, while the variability is comparatively small in the non-glacial sediments. There are only 6 values in the rock group, all of which are assumed rock stations (i.e., $\overline{V_S}(30\text{m})$=2.0 km/s).

Table 3 gives the same summary statistics but breaking down each unit by thickness. The trend of the means for the non-glacial sediments is promising, ranging from 220 m/s up to 350 m/s as the thickness decreases. It is interesting to note that the largest variability is for thin sediments, which has a standard deviation more than twice that of thick or patchy sediments. The trouble with this breakdown is that there are a number of rows with only a handful of measurements, and so the estimated statistics, particularly the standard deviations, are not reliable. Further, analogous classifications are not available in the Fulton (1996) map for Canaada and so this classification system may not be as useful as using topographic slope to discern a trend within the geologic groupings, which we investigate in the next section.

4.2 Hybrid Slope-Geology Model

It is likely that the relationship between topographic slope and $\overline{V_S}(30\text{m})$ will be different depending on the geologic environment. To investigate this, we plot $\overline{V_S}(30\text{m})$ as a function of slope for each of the geologic groups in Figure 7. For each panel, we provide the $\overline{V_S}(30\text{m})$-slope curve from Silva et al. (2011) for reference. The mean and +/- 1 standard deviations of the $\overline{V_S}(30\text{m})$ measurements are also displayed for various slope bins. The black lines represent the geology-specific $\overline{V_S}(30\text{m})$-slope relationship; these were determined by comparing the empirical trends to the Silva et al. (2011) curve and adjusting the slope break points to bring the curve closer to the mean of the empirical data. We kept the $\overline{V_S}(30\text{m})$ values that define the curve the same because they correspond to site class boundaries. As in Table 2, Figure 7 shows the larger variability in the glacial sediments and residual soils. However, it is clear that knowing that the sediments are non-glacial allows one to use a more precise $\overline{V_S}(30\text{m})$-slope relationship.

Within the glacial sediments, there are two clear groups of data with different $\overline{V_S}(30\text{m})$values but a wide range of slopes: one at about 220 m/s and another at 2000 m/s (assumed rock sites). The slower group likely represents thick glacial fluvial and similar sediments. The faster group may include 1) very thin soil where the instrument may be placed on outcrop, or 2) very dense and highly compacted soils such as till that can exhibit $\overline{V_S}(30\text{m})$ that approach those that are typical of firm rock. The $\overline{V_S}(30\text{m})$-slope relationship given in Figure 7 for glacial sediments fits the curve to the mean value, but given the bimodal distribution of the velocities, an alternative interpretation could be a discontinuous curve given in Figure 8. The fundamental problem, however, is that both $\overline{V_S}(30\text{m})$ groups extend over a broad range of slopes, indicating that within glaciated sediments, there are extensive areas of firm to hard rock at low slopes and also soils that follow the more typical $\overline{V_S}(30\text{m})$-slope relationship for non-glaciated regions. Because of this, we have to accept larger uncertainty in estimating $\overline{V_S}(30\text{m})$ within glaciated sediments. Figure 9 gives the $\overline{V_S}(30\text{m})$ map that is produced by the relationships is Figure 7.

The bias and standard deviations (both in natural log units) for the Silva et al. (2011) and updated slope-geology model are compared in Table 4. The bias and standard deviations are broken down into bins of geologic classification and sub-bins of slope.

Using all the available data, the table shows that adding the geologic classifications decreases the bias and standard deviation. The overall standard deviation is about 18% lower when we include the four general geologic classifications in the model.

To evaluate the model, we provide the slope-$\overline{V_S}(30\mathrm{m})$ pairs in Table 5. For estimating the standard deviation of the model, we recommend using the value reported in Table 4 for the appropriate geology/slope bin if the number of samples is 30 or more. If the number of samples is less than 30, then we recommend using the standard deviation reported in the nearest bin within the same geologic group that has more than 30 samples. For example, if evaluating the $\overline{V_S}(30\mathrm{m})$ in glacial sediments where the slope is less than 1e-3 (n = 3 in Table 4), the appropriate standard deviation should be 0.903 (from the bin for glacial sediments with slope between 1e-3 and 1e-2).

ACKNOWLEDGEMENTS

The authors are grateful for support provided by FM Global, PEER, and the Professional Development Program of Pacific Engineering. This work has also benefitted from discussions with David Wald, Harold Magistrale, Albert Kottke, and David Lidke. We thank Albert Kottke for recommending the Fulton (1996) map for Canada, and David Lidke for recommending the Soller et al. (2009) map for the US. We also thank Gail Atkinson for sharing her station classifications which we used to augment the Pacific Engineering $\overline{V_S}(30\mathrm{m})$ database.

Reference:

Abrahamson, N.A., and W.J. Silva (2008). "Summary of the Abrahamson and Silva NGA ground-motion relations, *Earthquake Spectra."* **24**, 67-97.

Abrahamson, N.A and K.M. Shedlock (1997). "Overview." *Seis. Research Lett.,* 68(1), 9-23.

Anderson, N., T. Thitimakorn, A. Ismail, and D. Hoffman (2007). "A comparison of four geophysical methods for determining the shear wave velocity of soils." *Envir. & Engineering Geoscience,* 13(1), 11-23.

Anderson, N., G. Chen, S. Kociu, R. Luna, T. Thitimakorn, A. Malovichko, D. Malovichko, and D. Shylakov (2003). "Vertical shear-wave velocity profiles generated from spectral analysis of surface waves: field examples." Prepared for Missouri Department of Transportation Final Report, RDT 03-006.

Atkinson, G. and D. M. Boore (2011). "Modifications to existing ground-motion prediction equations in light of new data." *Bull. Seism. Soc. Am.101, 1121-1135.*Atkinson, G. and K. Assatourians (2010). "Attenuation and source characteristics of the June 23, 2010 M 5.0 Val Des Bois, Quebec earthquake." *Seismol. Res. Lett.* 81, 849-860.

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

Banab, K.K. and D. Motazadian (2007). "Shear wave velocity profile determination based on the multi-channel analysis of surface waves method for NEHRP site classification in the city of Ottawa." 9th Canadiam conference on earthquake engineering, Ottawa, Ontario, Canada.

Bauer, R. A, W.J. Su, R. C. Counts, M.D. Karaffa (2007). "Shear wave velocity, geology and geotechnical data of earth materials in the Central U.S. urban hazard mapping areas." USGS Final Technical Report, External Grant Award Number 06-HQ-GR-0192.

Bauer, R. A., J. Hill, E. Kvale, J. Palmer, Z. Wang, W-J, Su, K. Kukielka (2005). "Shear wave velocity, geology and geotechnical data of earth materials in the Central U.S. urban hazard mapping areas." *USGS* external award number 05-HQ-GR-0056.

Bauer, R. A. (2004). "Central U.S. shear wave velocity database with accompanying geological/geotechnical information of nonlithified geologic materials." *USGS* external award number 04-HQ-GR-0074.

Beresnev, I. A., and G. M. Atkinson (1997). “Shear-wave velocity survey of seismographic sites in eastern Canada: calibration of empirical regression method of estimating site response.” *Seism. Res. Lett.* 68, 981–987.

Bonilla, L.F., J.H. Steidl, G.T., Lindley, A.G Tumarkin and R.J. Archuleta (1997). "Site amplification in the San Fernando Valley, California: Variability of Site-effect estimation using the S-wave, coda, and H/V methods.” *Bull. Seism. Soc. Am.*, 87(3), 710-730.

Boore, D.M., E.M. Thompson, and H. Cadet (2011). “Regional correlations of V_{S30} and velocities averaged over depths less than and greater than 30m.” *Bull. Seism. Soc. Am.,* in-press.

Boore, D.M., E.M. Thompson (2007). “On using surface-source downhole-receiver logging to determine seismic slownesses.” *Soil Dynamics and Earthquake Engineering,* 27, 971-985.

Boore, D. M., and W. B. Joyner (1997). “Site amplification for generic rock sites.” *Bull. Seism. Soc. Am.* 87, 327–341.

Boore, D. M., W. B. Joyner, and T. E. Fumal (1997). “Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: a summary of recent work.” *Seismol. Res. Lett.*, 68, 128–153.

Borcherdt, R. D. (2002). “Empirical evidence for acceleration-dependent amplification factors.” *Bull. Seism. Soc. Am*., 92(2), 761-782.

Borcherdt, R. D. (1994a). "Simplified site classes and empirical amplification factors for site-dependent code provisions.” Proc. Of the *NCEER/SEAOC/BSSC* Workshop on Site Response During Earthquakes and Seismic Code Provisions, University of Southern Calif., Los Angeles, 1992, *edited* by G.R. Martin.

Borcherdt, R. D. (1994b). "Estimates of site-dependent response spectra for design (methodology and justification). *Earthquake Spectra,* 10(4), 617-653.

Borcherdt, R. D. and Glassmoyer, G. (1992). "On the Characteristics of Local Geology and Their Influence on Ground Motions Generated by the Loma Prieta Earthquake in the San Francisco Bay region, California." *Bull. Seism. Soc. Am.,* 82(2), 603-641.

Borcherdt, R.D. (1970). "Effects of local geology on ground motion near San Francisco Bay." *Bull. Seism. Soc. Am.*, 60(1), 29-61.

Building Seismic Safety Council (2000). “National Earthquake Hazards Reduction Program (NEHRP) Part 1: Recommended Provisions for seismic regulations for new buildings and other structures.” *2000 Edition (FEMA 368).* Prepared by the

Building Seismic Safety Council for the Federal Emergency Management Agency, Washington D.C.

Building Seismic Safety Council (BSSC) (2004). "NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures." 2003 Edition (*FEMA* 450), National Institute of Building Sciences, Washington, D.C.

Castellaro, S., F. Mulargia, and P.L. Rossi (2008). "Vs30: Proxy for seismic amplification?" *Seism. Res. Lett.*, 79(4), 540-543.

Chiou, B., R. Darragh, N. Gregor, and W. Silva (2008). "NGA project strong-motion database." *Earthquake Spectra*, **24**: 23-44.Dobry, R., R. Ramos, and M.S. Power (1999). "Site factors and site categories in seismic codes." *MCEER*-99-0010.

Ebel, J.E. and W-Y Kim (2006). "Shake Maps For Earthquakes In The Northeastern United. States: Collaborative Research with Columbia University and Boston College" *USGS award number* 06HQGR0019 and *award number* 06HQGR0022.

Eggert, D.L., A.C. Samuelson, D. Bray, S.W. Chang, W.R. Eckhoff, K. Kayabali, E.J. McClees, T.R. West, M.C. Woodfield, B. Zheng (1994). "Final report to the city of evansville: shear-wave and earthquake hazard mapping of Evansville, Indiana." *Indiana Geological Survey*, Open File Report 94-19.

Electric Power Research Institute (EPRI) (2004). "CEUS Ground motion project" Palo Alto, Calif: Electric Power Research Institute, Final Report, EPRI Technical Report 1009684.

Electric Power Research Institute (EPRI) (2004, 2006) "Ground-motion model (GMM) review project: Shear wave velocity measurements at seismic recording stations." Palo Alto, Calif.: Electric Power Res. Inst., 3002000719.

Electric Power Research Institute (EPRI) (1993). "Guidelines for determining design basis ground motions." Palo Alto, Calif: Electric Power Research Institute, vol. 1-5, EPRI TR-102293.

vol. 1: Methodology and guidelines for estimating earthquake ground motion in eastern North America.
vol. 2: Appendices for ground motion estimation.
vol. 3: Appendices for field investigations.
vol. 4: Appendices for laboratory investigations.
vol. 5: Quantification of seismic source effects.

Farr, T.G., and M. Kobrick (2000). "Shuttle radar topography mission produces a wealth of data." *EOS* 81, 583-585.

Fullerton, D.S., C.A. Bush and J.N. Pennell (2003). "Map of surficial deposits and materials in the eastern and central United States (East of 102° West Longitude), *U.S. Geological Investigations Series* I-2789.

Fulton, R. J. (1996). Surficial Materials of Canada, Geological Survey of Canada, Natural Resources Canada. Ottawa. Map 1880A, Scale 1:5,000,000.

Geovision Geophysical Services (2008). "*P-S suspension logging borehole G-B-1.*" I-73 Project, Little Pee Dee River, Near Mullins, South Carolina, Report 8451-01.

Gomberg, J., B. Waldron, E. Schweig, H. Hwang, A. Webbers, R. VanArsdale, K. Tucker, R.Williams, R. Street, P. Mayne, W. Stephenson, J. Odum, C. Cramer, R. Updike, S. Hutson, and M. Bradley (2003). "Lithology and shear-wave velocity in Memphis, Tennessee." *Bull. Seism. Soc. Am.* 93(3), 986–997.

Gutenberg, B. (1957). "Effects of ground on earthquake motion." *Bull. Seism. Soc. Am*., 47(1), 221-250.

Gutenberg, B. (1927). "*Grundlagen der Erdlebenkunde*." Berlin.

Harmsen, S.C. (1997). "Determination of site amplification in the Los Angeles urban area from inversion of strong-motion records." *Bull. Seism. Soc. Am*., 87(4), 866-887.

Hayashi, S., H. Tsuchida, and E. Kurata (1971). "Average response spectra for various subsoil conditions." *Third Joint Meeting, US-Japan Panel on Wind and Seismic Effects,* UJNR, Tokyo.

Hoffman, D., N. Anderson and J.D. Rogers (2006). "St. Louis metro area shear wave velocity testing." *USGS* award number 06HQGR0036.

Jaume, S.C. (2006). "Shear-wave velocity profiles via seismic cone penetration test and refraction microtremor techniques at ANSS strong motion sites in Charleston, South Carolina." *Seis. Res. Lett.*, 77(6), 771-779.

Kociu, S., R. Luna, N. Anderson, W. Zheng, and D. Hoffman (2004). "Nonlinear soil response to strong ground motion: determination based on SASW velocity profiles." MoDNR, Geological Survey & Resource Assessment.

Lin, L. and J. Adams (2010). "Compilation of shear wave velocities for eastern Canada for use in the NGA-East project." Report prepared for the NGA-East project.

Mallet, R. (1862). "*Great Neopolitan earthquake of 1857, London*." 2 vols.

Martin II, J.R. and G.W. Clough (1994). "Seismic parameters from liquefaction evidence." J. of Geotech. Engineering, 120(8), 1345-1361.

McIntyre, J.L. (2008). *"An evaluation of earthquake ground-motion site effects at two sites underlain by deep soils in Western Kentucky."* The Graduate School University of Kentucky.

Milne, J. (1908). "*Seismology*", Kegan, Paul, Trench, Trubner + Co, Ltd.,, London. 2nd edition.Mohraz, B. (1976). "A study of earthquake response spectra for different geological conditions." *Bull. Seism. Soc. Am.*, 66(3) 915-935.

Moss, R.E.S. (2011). "Reduced sigma of ground-motion prediction equations through uncertainty propagation." *Bull. Seism. Soc. Am.,* 101(1), 250-257.

Moss, R.E.S. (2008). "Quantifying measurement uncertainty of thirty-meter shear-wave velocity." *Bull. Seism. Soc. Am.,* 98(3), 1399-1411.

NEHRP97 (1998) "*NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures." FEMA* 302 303, 1997 Edition.

NEHRP (1994) *"Recommended Seismic Provisions for Seismic Regulations for New Buildings and Other Structures." FEMA* 1999 Edition.

Odum, J.K., R.A. Williams, W.J. Stephenson, and D. M. Worley (2010). "Shallow seismic velocity and V_s30, at 5 ANSS sites in Southern Illinois and Evansville, Indiana." SRL Draft.

Odum, J.K., W.J. Stephenson, R.A. Williams (2010). "Predicted and observed spectral response from collocated shallow, active- and passive-source Vs data at five ANSS sites, Illinois and Indiana, USA." *Seis. Res. Lett.*, 81(6), 955-964.

Odum, J.K., R.A. Williams, W.J. Stephenson, and D.M. Worley (2003). "Near-surface S-wave and P-wave seismic velocities of primary geological formations on the Piedmont and Atlantic Coastal Plain of South Carolina, USA." *USGS* Open-File Report 03-043.

Odum, J.K., W.J. Stephenson, R.A. Williams, and D.M. Worley (2008). "Analysis of shallow VS and site response at five ANSS stations located within 50 km of the **M** 5.4 Mt. Carmel Earthquake, Illinois and Indiana U.S.A." *Seis. Res. Lett.,* 80(2), 303-305.

Pehme, P and M. Melaney (2009). *"Borehole Geophysical Logging in DGR-1 and DGR-2."* DGR Site Characterization Document, Intera Engineering Project 06-219, Document ID: TR-07-08.

Power, M., B. Chiou, N. Abrahamson, Y. Bozorgnia, T. Shantz, C. Roblee (2008). "An overview of the NGA project." *Earthquake Spectra,* 24(1), 3-21.

Read, K. H. El. Naggar, and D. Eaton (2008). “Site-response spectra for POLARIS station sites in Southern Ontario and Quebec.” *Seis. Res. Lett.*, 79(6), 776-784.

Reid, H.F. (1910). "The California earthquake of April 18, 1907." *The Mechanics of the Earthquake*, Carnegie Inst. of Washington, Publ. 87, 21.

Rinne, E.E. (1994). “Development of new site coefficients for building codes.” *Proc. Fifth U.S. Nat. Conf. On Earthquake Engineering*, Chicago, 3, 69-78.

Romero, S. M., and G. J. Rix (2001). “Ground Motion Amplification in Mississippi Embayment deposits.” *Seism. Res. Lett.,* **72,** 283.

Rosenblad, B.L., J. Li (2009). “Performance of active and passive methods for measuring low-frequency surface wave dispersion curves.” *Journal of Geotechnical and Geoenvironmental Engineering,* in press.

Rosenblad, B.L., J. Li, F-Y Menq, and K. H. Stokoe (2007). “Deep shear wave velocity profiles from surface wave measurements in the Mississippi embayment.” *Earthquake Spectra,* 23(4), 791-808.

Rosenblad, B.L. (2006). “Deep shear wave velocity profiles of Mississppi embayment sediments determined from surface wave measurements.” *USGS* award No. 06HQGR0131.

Schneider, J. A., P.W. Mayne (1999). “Soil liquefaction response in Mid-America evaluated by seismic Piezocone tests.” *Mid-America Earthquake Center*, Report MAE-GT-3A.

Seed, H.B., C. Ugas and J. Lysmer (1976). "Site-dependent spectra for earthquake resistant design." *Bull. Seism. Soc. Am.*, 66(1), 221-243.

Silva, W.J. (1997). "Characteristics of vertical strong ground motions for applications to engineering design." *Proc. of the FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities,* I.M. Friedland, M.S Power and R. L. Mayes eds., Technical Report NCEER-97-0010.

Silva, W.J., N. Abrahamson, G. Toro and C. Costantino (1996)."Description and validation of the stochastic ground motion model." Report Submitted to Brookhaven National Laboratory, Associated Universities, Inc. Upton, New York 11973, Contract No. 770573.

Silva, W. J.,S. Li, B. Darragh, and N. Gregor (1999). "Surface geology based strong motion amplification factors for the San Francisco Bay and Los Angeles Areas."A PEARL report to PG&E/CEC/Caltrans, Award No. SA2120-59652.

Silva, W.J., E. Thompson, H. Magistrale, and C. Wills (2011). Development of a Vs(30m) Map for Central and Eastern North America (Cena): Median Estimates And Uncertainties, Final Report to FM Global.

Soller, D.R. (2004). "Thickness and character of quaternary sediments in the glaciated United States east of the Rocky Mountains." Quaternary Glaciations-Extent and Chronology, Part II, *Editors* J. Ehlers and P.L. Gibbard, 363-372, Published by Elsevier B.V.

Soller, D.R., Reheis, M.C., Garrity, C.P., and Van Sistine, D.R. (2009). Map database for surficial materials in the conterminous United States: U.S. Geological Survey Data Series 425, scale 1:5,000,000 [http://pubs.usgs.gov/ds/425/].

Street, R. and E. Woolery, J-M. Chiu (2004). "Shear-wave velocities of the post-paleozoic sediments across the upper Mississippi embayment." *Seis. Res. Lett.*, 75(3), 390-405.

Street, R. and E. Woolery (2001). "Surface-to-bedrock, shear-wave and geotechnical investigation of the Mississipi embayment between the 35th and 36th parallels: collaborative research with The University of Kentucky and University of Memphis." *USGS award number* 01HQGR0118.

Street, R., Woolery, E. and Wang, Z. (1995). "A short note on shear-wave velocities and other site conditions at selected strong-motion stations in the New Madrid seismic zone." Seis. Resea. Letters, 66(1), 56-63.

Thompson, E. M., L. G. Baise, R. E. Kayen, Y. Tanaka, H. Tanaka (2010). "A geostatistical approach to mapping site response spectral amplifications." *Engineering Geology*, 114(3-4), 330-342.

Toro, G.R. and W.J. Silva (2001). "Scenario earthquakes for Saint Louis, MO, and Memphis, TN, and seismic hazard maps for the Central United States Region including the effect of site conditions." *U.S. Geological Survey* Award Number 1434-HQ-97-GR-02981, Final report.

Uniform Building Code (1997) "*Uniform Building Code*." Published by nternational Conference of Building Officials, Whittier, California.

Wald, D.J. and T. I. Allen (2007). "Topographic slope as a proxy for seismic site conditions and amplification." *Bull. Seism. Soc. Am.,* 97(5), 1379-1395.

Wald, D.J., L. McWhirter, E.M. Thompson, A.S. Hering (2011). "A new strategy for developing Vs30 maps." 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion. August 23-26, University of California Santa Barbara.

Wang, Z., E. A. Woolery, J. A. Schaefer (2003). “A short note on ground-motion recordings from the 18 June 2002, Darmstadt, Indiana earthquake.” *Seismological Res. Lett.*, 74(2), 148-152.

Wessel, P., and W. H. F. Smith (1991). “Generic mapping tools.” *EOS Trans. AGU* 72, 441.

Williams, R.A., W.J. Stephenson, J.K. Odum, and D.M. Worley (2003). “Seismic velocities from high-resolution surface-seismic imaging at six ANSS sites near Memphis, Tennessee.” *USGS* Open-File Report 03-218.

Williams, R.A., S. Wood, W.J. Stephenson, J.K. Odum, R. Street, and D.M. Worley (2003). “Surface seismic refraction/reflection measurement determinations of potential site resonances and the areal uniformity of NEHRP site class D in Memphis, Tennessee.” *Earthquake Spectra,* 19(1), 159-189.

Wills, C. J. and K. B. Clahan (2006). “Developing a map of geologically defined site-condition categories for California.” Bull. Seism. Soc. Am., 96(4A), 1483-1501.

Wills, C. J. and K. B. Clahan (2004). “NGA: Site condition metadata from geology.” PEER project 1L05.

Wills, C.J. and W.J. Silva (1998). "Shear wave velocity characteristics of geologic units in California." Earthquake Spectra, 14(3), 533 556.

Withers, M.M. (2007). “Mid-America ShakeMap: a Large Regional Implementation.” USGS Award No.: 06HQGR0048, Final Technical Report.

Wood, H.O. (1908). "Distribution of apparent intensity in San Francisco, in the California earthquake of April 18, 1906." Report of the State Earthquake Investigation Commission, Wash., D.C.: Carnegie Institute, 1, 220 245.

Woolery, E.W. and Z. Wang (2002). “A compreshensive geotechnical investigation and installation of a borehole accelerometer array in the New Madrid seismic zone.” USGS award number 02HQGR0101.

Woolery, E.W. and Z. Wang (2005). “Seismic velocity measurements at expanded seismic network sites.” UK/KRCEE Doc #:P8.3 2005.

Yong, A., S. E. Hough, J. Iwahashi, and A. Braverman (2011). “A terrain-based site characterization map of California with implications for the contiguous United States.” *Bull. Seism. Soc. Am.,* in-press.

Yong, A., S.E. Hough, A. Braverman, and J. Iwahashi (2010). “A terrain-based Vs30 estimation map of the contiguous United States.” *Seism. Res. Letters,* 81(2), 294.

Yong, A., S. E. Hough, M. J. Abrams, H. M. Cox, C. J. Wills, and G. W. Simila (2008). "Site characterization using integrated imaging analysis methods on satellite data of the Islamabad, Pakistan, Region." *Bull. Seism. Soc. Am.,* 98(6), 2679-2693.

Yong, A., Martin, A., Stokoe, K., and Diehl, J., 2013, ARRA-funded VS30 measurements using multi-technique approach at strong-motion stations in California and central-eastern United States: U.S. Geological Survey Open-File Report 2013–1102, 60 p.

Yu, T. and W.J. Silva (2011). "Development of $\overline{V_S}(30\text{m})$ estimates for sites which recorded the May 12, 2008 **M** 7.9 Wenchuan earthquake, 2011." Report to PEER in preparation.

Table 1. Surface geology groupings for the US and Canada.

Group	US – Soller et. al. (2009)	Canada – Fulton (1996)
Sediments	Alluvial sediments, thin Alluvial sediments, thick Eolian sediments, mostly dune sand, thin Eolian sediments, mostly dune sand, thick Calcareous biological sediments Coastal zone sediments, mostly fine-grained Coastal zone sediments, mostly medium-grained Eolian sediments, mostly loess, thin Eolian sediments, mostly loess, thick Eolian sediments on southern High Plains Organic-rich muck and peat, thin Organic-rich muck and peat, thick Residual materials developed in alluvial sediments Playa sediments Lacustrine sediments	Alluvial Deposits: stratified silt, sand, clay, and gravel; floodplain, delta, and fan deposits; in places overlies and includes glaciofluvial deposits. (A) Marine Mud: Fluid silty clay and clayey silt: deposited as quiet water sediments. (mM) Lacustrine Sand: Sand and locally gravel; deposited as sheet sands, lags, and beaches. (sL) Marine Sand: Sand and locally gravel; deposited as sheet sands, lags, and beaches. (sM) Organic deposits: peat, muck and minor inorganic sediments; large bog, fen, and swamp areas where organic fill masks underlying surficial materials; generally >2 m thick. (O) Eolian Deposits: sand and minor silt: dunes, blowouts, and undulating plains: In most places overlies deltaic sediments, coarse lacustrine sediments, or glaciofluvial deposits. (E) Lacustrine Mud:Fluid silty clay and clayey silt: deposited as quiet water sediments. (mL)
Glaciated Sediments	Proglacial sediments, mostly fine grained, thin Proglacial sediments, mostly fine grained, discontinuous Proglacial sediments, mostly coarse-grained, thick Proglacial sediments, mostly fine grained, thick Proglacial sediments, mostly coarse-grained, discontinuous Proglacial sediments, mostly coarse-grained, thin Glaciofluvial ice-contact sediments, mostly sand and gravel, discontinuous Glaciofluvial ice-contact sediments, mostly sand and gravel, thin Glaciofluvial ice-contact sediments, mostly sand and gravel, thick Glacial till sediments, mostly silty, discontinuous Glacial till sediments, mostly silty, thin Glacial till sediments, mostly clayey, discontinuous	Glaciofluvial Plain, sand and gravel; deposited as outwash sheets, valley trains, and terrace deposits (Gp) Glaciofluvial Complex, sand and gravel and locally diamicton; undifferentiated ice contact stratified drift, and outwash; locally includes till and rock (Gx) Fine grained (Glacio)Marine, dominantly silt and clay, locally containing stones; deposited as quiet water sediments (fM) Coarse grained (Glacio)Marine, sand and gravel; deposited as sheet sands, deltas, and extensive flights of beaches (cM) Lag (Glacio)Marine, sand, gravel, and pockets of finer sediment; thin to discontinuous sediment veneer and residual lag developed during marine submergence; includes areas of washed till and rock (Mv) Fine grained (Glacio)Lacustrine, silt, and clay, locally containing stones;

	Glacial till sediments, mostly clayey, thin Glacial till sediments, mostly clayey, thick Glacial till sediments, mostly silty, thick Glacial till sediments, mostly sandy, discontinuous Glacial till sediments, mostly sandy, thin	deposited as quiet water sediment (fL) Coarse grained (Glacio)Lacustrine, sand, silt, and gravel; deposited as deltas, sheet sands, and lag deposits (cL) Till Blanket, thick and continuous till (Tb) Till Veneer, thin and discontinuous till; may include extensive areas of rock outcrop (Tv)
Residual Soils	Residual materials developed in igneous and metamorphic rocks Residual materials developed in sedimentary rocks, discontinuous Residual materials developed in fine-grained sedimentary rocks Residual materials developed in bedrock, discontinuous Residual materials developed in bedrock, thin Colluvial sediments, discontinuous Colluvial sediments, thin Colluvial and alluvial sediments Colluvial sediments and loess Colluvial sediments and residual material Residual materials developed in sedimentary rocks, thin Residual materials developed in carbonate rocks, discontinuous Residual materials developed in carbonate rocks, thin Residual materials developed in bedrock, with alluvial sediments, discontinuous Residual materials developed in bedrock, with alluvial sediments, thin	Colluvial Rubble, rubble and silt; derived from carbonate and consolidated fine clastic sedimentary rock substrate (rC) Colluvial Fines, silt, clay, and fine sand; derived from substrate weakly consolidated shale and siltstone substrate (fC) Colluvial Sand, Sand and gravel; derived from poorly lithified sandstone and conglomerate substrate (sC) Colluvial Blocks, Blocks, and rubble with sand and silt; derived from crystalline bedrock, medium grade metamorphic substrate, and cemented sandstone (bC)
Rock	Basaltic and andesitic volcanic rocks Rhyolitic volcanic rocks	Alpine Complexes, rock, colluvium, and till; rock and Quaternary deposits complex in an area, characterized by alpine and glacial landforms (Ra) Undivided, rock with minor Quaternary deposits (R) Quaternary Volcanics, consolidated lava, breccia and tephra; dominantly basaltic and andesitic in composition; includes flows, volcanic piles, and cinder cone (V)

Table 2. $\overline{V_S}(30\mathrm{m})$ summary statistics by geologic groupings.

Group	Mean	*s*	*n*
Sediments	309	0.337	462
Glacial Sediments	899	0.954	179
Residual Soils	515	0.854	73
Rock	2000	--	6

Table 3. Summary statistics by geologic group and thickness.

Group	Thickness	Mean	*s*	*n*
Sediments	Thick	220	0.133	13
	Thin	260	0.342	196
	Patchy	350	0.154	249
Glacial Sediments	Thick	239	0.408	7
	Thin	533	0.878	86
	Patchy	800	1.05	3
Residual Soils	Thin	305	0.308	3
	Patchy	527	0.864	70

Table 4. Comparison of bias and variability (natural log units).

	Slope		Silva et al. (2011)		Slope-geology		
	Min	Max	Bias	s	Bias	s	n
Sediments	--	1e-3	-0.034	0.156	-0.034	0.156	50
	1e-3	1e-2	-0.014	0.251	-0.014	0.251	346
	1e-2	0.1	-0.130	0.464	-0.037	0.432	66
	0.1	--	--	--	--	--	0
Glacial sediments	--	1e-3	0.034	0.028	-0.150	0.011	3
	1e-3	1e-2	0.486	0.911	0.002	0.903	77
	1e-2	0.1	0.850	0.691	0.148	0.669	91
	0.1	--	0.136	0.429	-0.046	0.429	8
Residual soils	--	1e-3	--	--	--	--	0
	1e-3	1e-2	0.061	0.740	-0.124	0.682	37
	1e-2	0.1	0.288	0.818	0.069	0.794	36
	0.1	--	--	--	--	--	0
Sediments	--	--	-0.032	0.286	-0.019	0.276	462
Glacial sediments	--	--	0.648	0.808	0.072	0.767	179
Residual Soils	--	--	0.173	0.782	-0.029	0.741	73
Rock	--	--	1.352	0.385	0	0	6
All	--	1e-3	-0.030	0.153	-0.040	0.154	53
	1e-3	1e-2	0.083	0.523	-0.020	0.468	462
	1e-2	0.1	0.425	0.783	0.068	0.622	197
	0.1	--	0.136	0.429	-0.046	0.429	8
All	--	--	0.169	0.609	0.003	0.501	720

Table 5. Points for evaluating the slope-geology model.

			Slope m/m					
	$\overline{V_S}(30\text{m})$ m/s		Sediments		Glacial Sediments		Residual Soils	
NEHRP	Min	Max	Min	Max	Min	Max	Min	Max
E	--	180	--	1e-4	--	1e-4	--	1e-4
D	180	270	1e-4	2e-3	1e-4	6e-4	1e-4	2e-3
	270	360	2e-3	1e-2	6e-4	2e-3	2e-3	6e-3
C	360	560	1e-2	4e-2	2e-3	6e-3	6e-3	1e-2
	560	760	4e-2	5e-2	6e-3	1e-2	1e-2	3e-2
B	760	1500	5e-2	7e-2	1e-2	4e-2	3e-2	0.2
A	1500	--	7e-2	--	4e-2	--	0.2	--

* For rock, use 2000 m/s for all slopes.

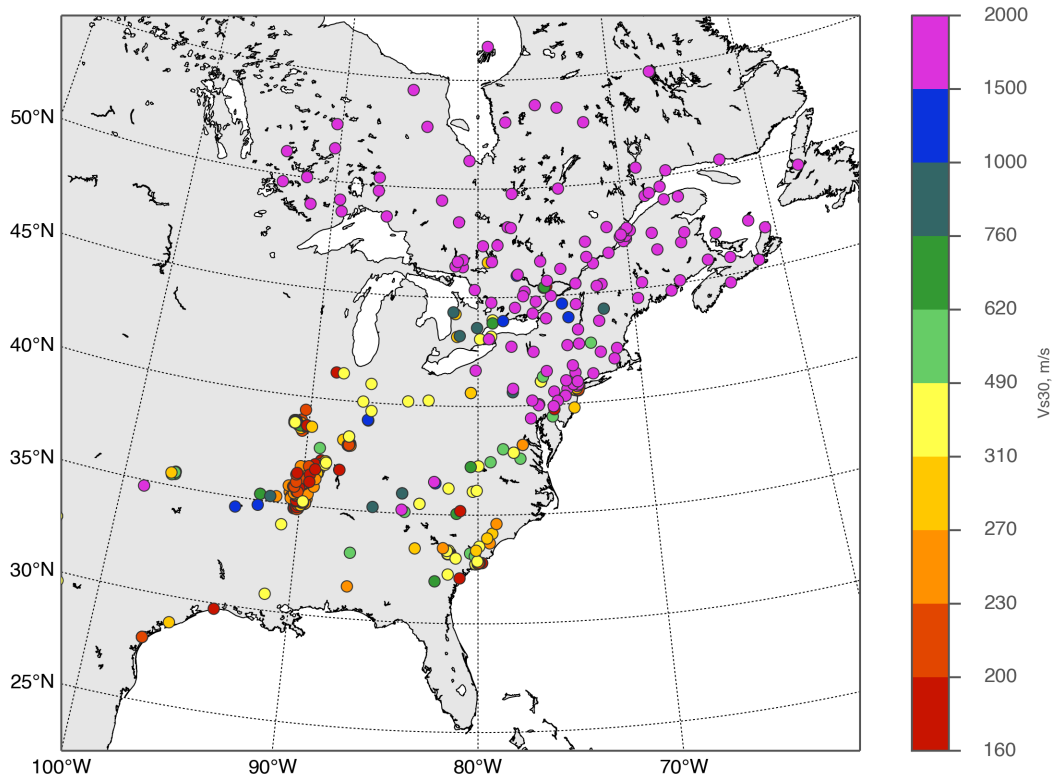

Figure 1. Distribution of the $\overline{V_S}(30\text{m})$ database used in developing the CENA $\overline{V_S}(30\text{m})$ map. CENA is considered to extend from 105° longitude eastward and includes Canada. Recording sites (triangles) are shown and the dense suite of stations in the Midwest are portable arrays and not simultaneously occupied. Note many of the NEHRP A sites reflect assumed $\overline{V_S}(30\text{m})$ values (Section 2.1.1).

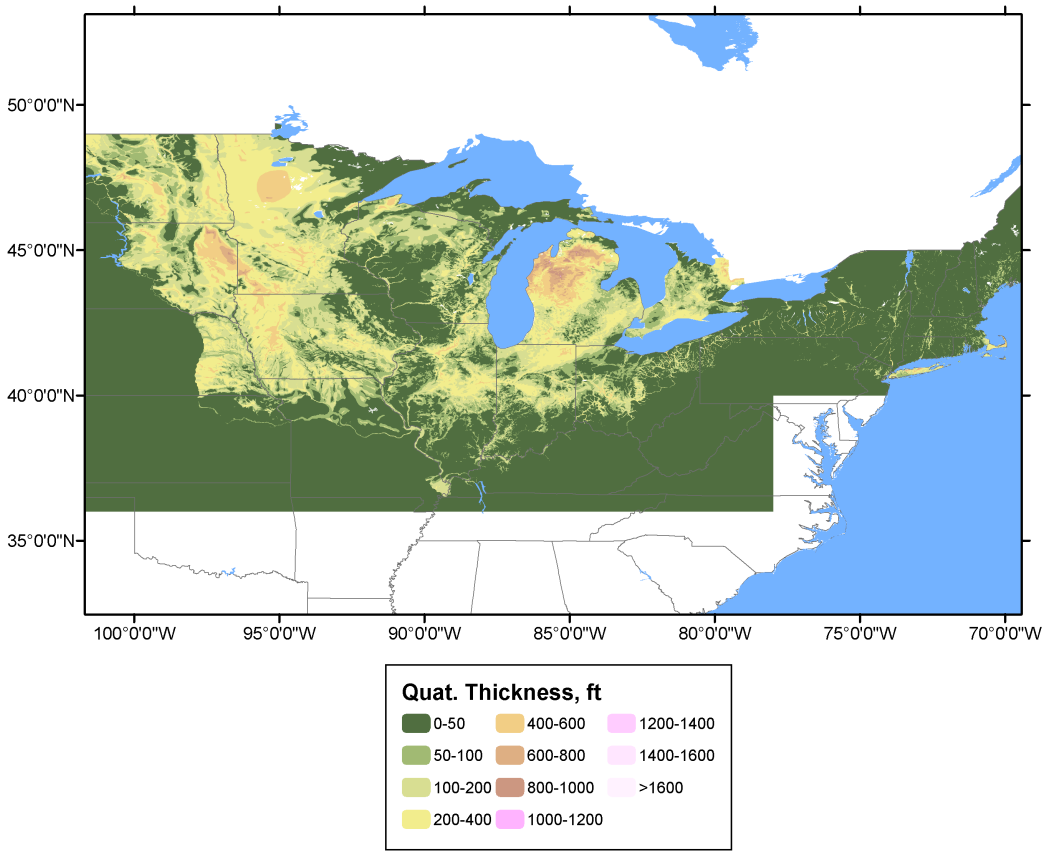

Figure 2. Map of Quaternary sediment thickness for the glaciated regions in the CEUS (based on Soller, 2004).

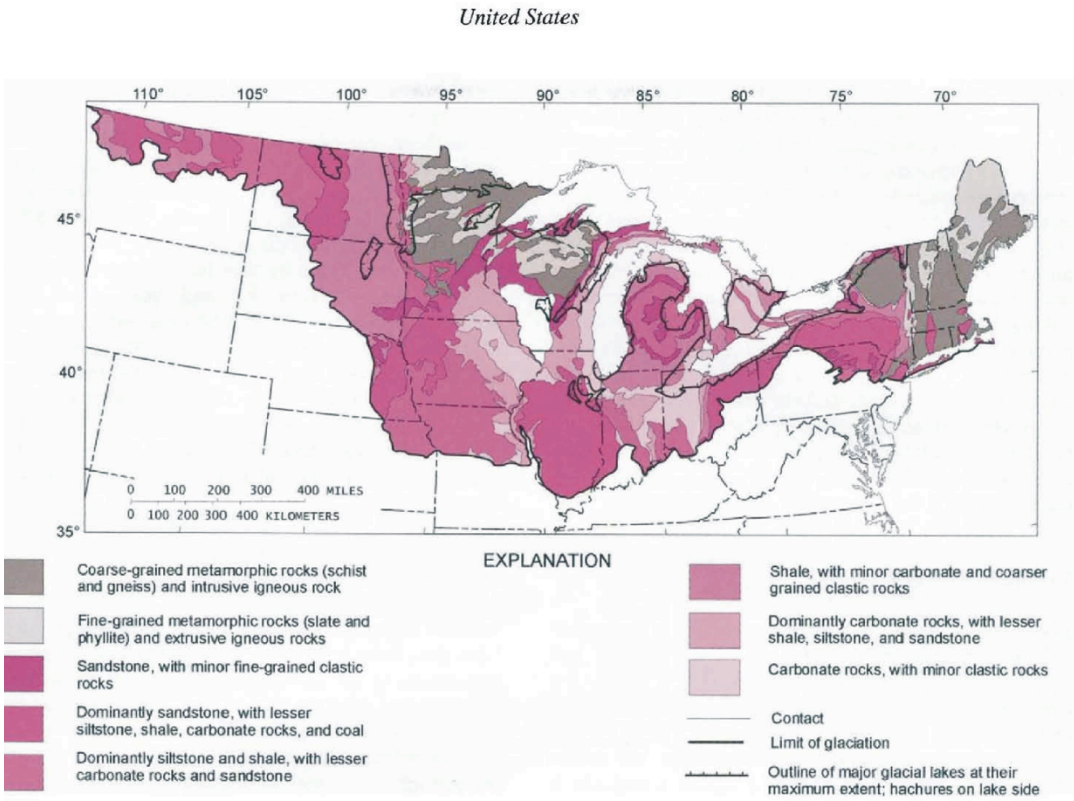

Figure 3. Map of bedrock lithology beneath the Quaternary sediments in the glaciated region of the CEUS (from Soller, 2004).

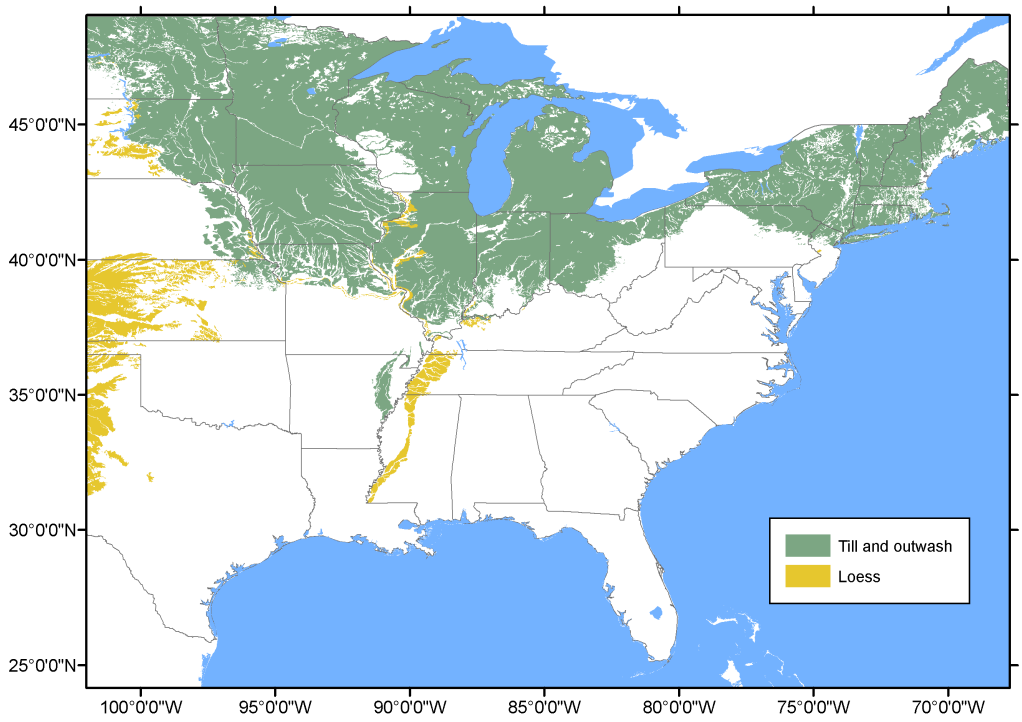

Figure 4. Spatial distribution of glacial Till and outwash as well as Loess in the CEUS based on the Fullerton et al. (2003) map of surficial deposits.

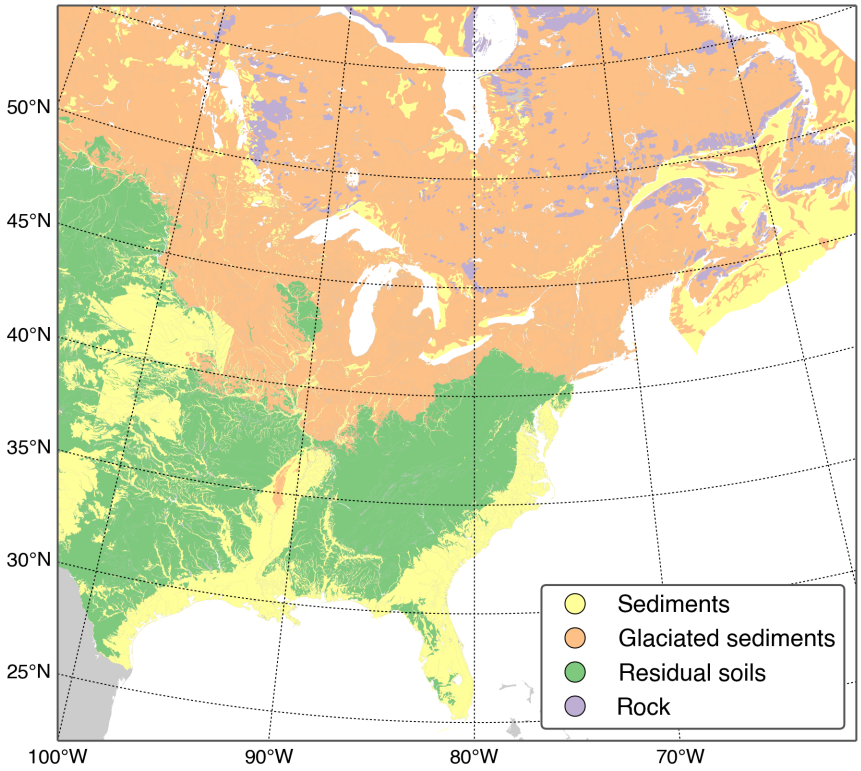

Figure 5. Map of the simplified geologic groupings in Table 1.

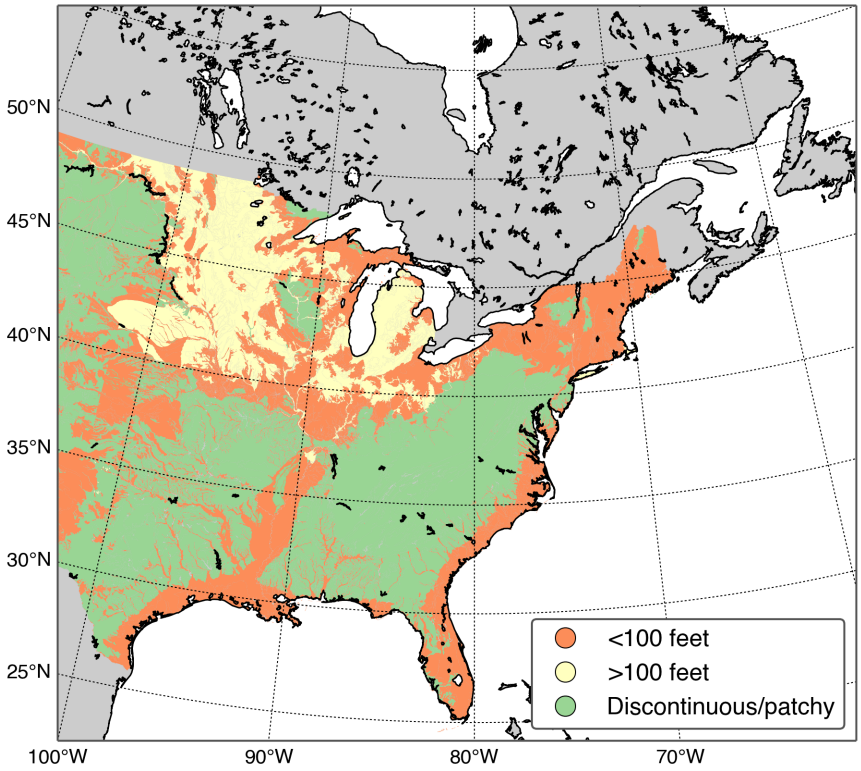

Figure 6. Map of soil thickness provided by Soller et al. (2009).

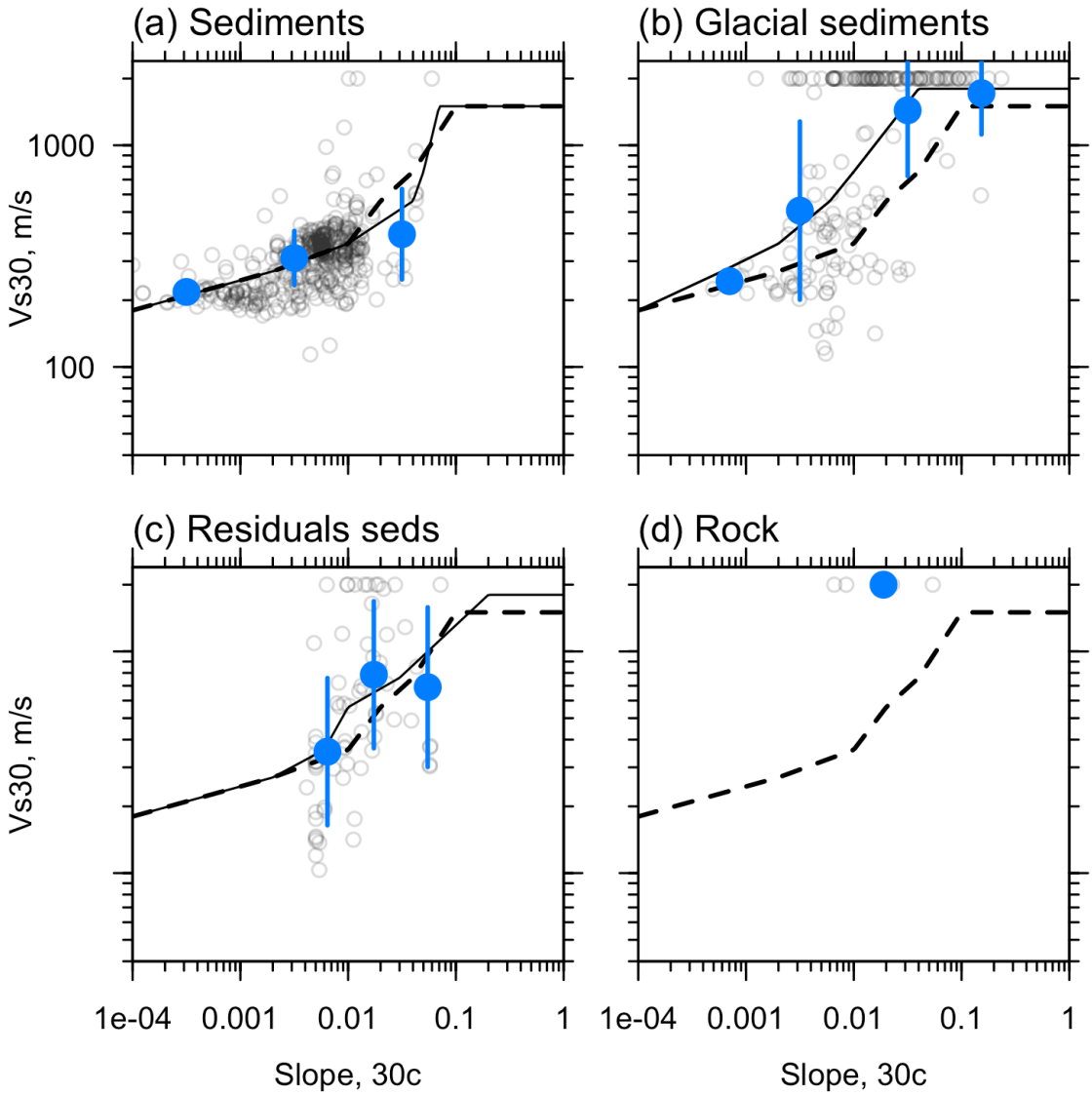

Figure 7. Slope versus $\overline{V_S}(30\text{m})$ for (a) sediments, (b) glacial sediments, (c), residual soils, and (d) rock. The dashed line is the Silva et al. (2011) $\overline{V_S}(30\text{m})$-slope relationship and the dots/bars represent the median and +/-1 standard deviation of $\overline{V_S}(30\text{m})$ for various slope bins. The solid line represents the updated model.

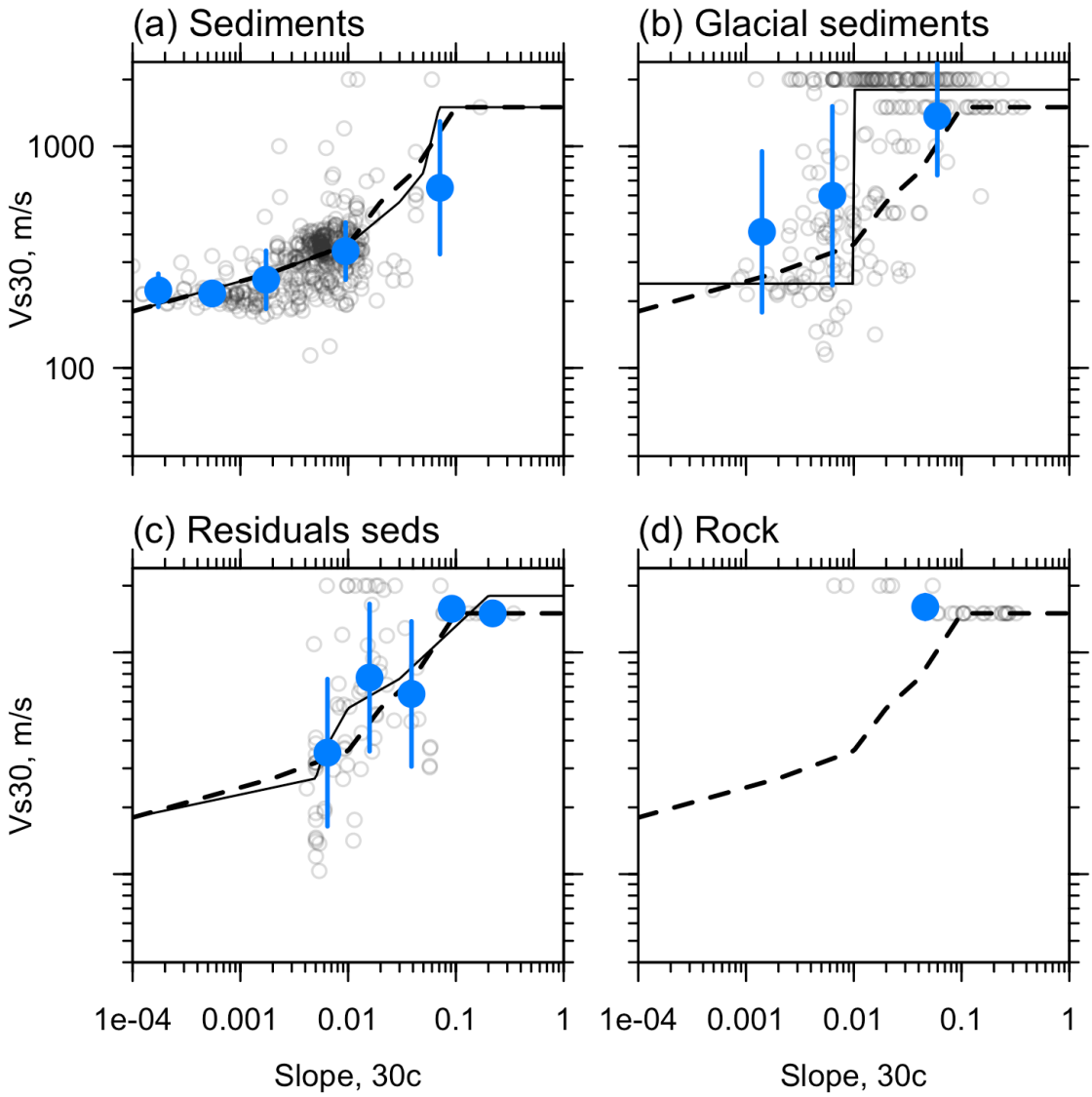

Figure 8. Same as Figure 7 except for the interpretation of the $\overline{V_S}(30\text{m})$-slope relationship for glacial sediments in (b).

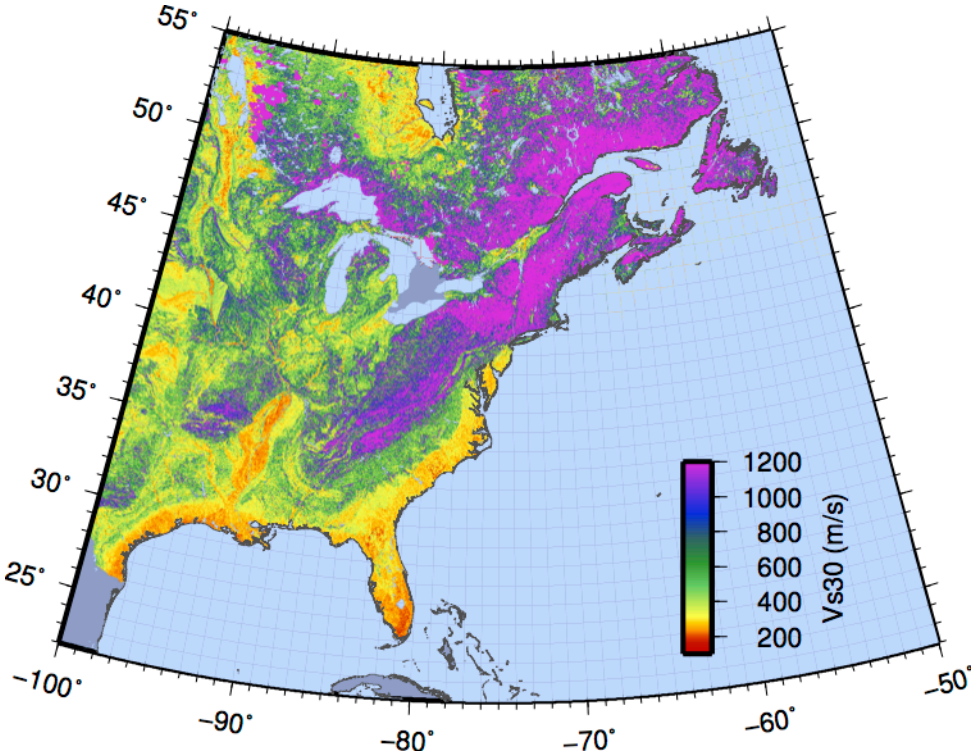

Figure 9. Map of $\overline{V_S}(30\mathrm{m})$ based on the hybrid model illustrated in Figure 7 where the slope-$\overline{V_S}(30\mathrm{m})$ relationship is different for the four simplified geologic groups as described in Table 1.