Development of Geologic Site Classes for Seismic Site Amplification for Central And Eastern North America

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SUMMARY:
The time-averaged shear wave velocity in the upper 30 m of a site (V_{s30}) is the most common site parameter used in ground motion prediction equations for the evaluation of seismic site response. It is often the case that V_{s30} is not available at sites with earthquake recordings; for example in the NGA-East site database only 45 of 1149 sites have measured values of V_{s30}. Accordingly, estimates of V_{s30} are often made on the basis of available proxies that are widely available such as ground slope, geomorphic terrain categories, and surface geology. We compile a database of 1930 measured and inferred V_{s30} values in Central and Eastern North America (CENA) to test slope and geomorphology-based proxy methods. The results indicate that these existing proxy methods are biased for sites with V_{s30} greater than 400 m/s. Based on a careful review of geological conditions in the CENA, we propose nineteen geologic classes based on setting (i.e., glaciated or non-glaciated), age, and depositional environmental that can form the basis for geology-based proxy estimates of V_{s30} as well as for simplified stratigraphic columns.

Keywords: V_{s30}, geology, NGA East, site classification

1. INTRODUCTION

The Next Generation Attenuation Relationships for Central and Eastern North America (NGA-East) project is a multidisciplinary program to develop a new set of comprehensive and broadly accepted ground motion prediction equations (GMPEs) for the Central and Eastern North America (PEER, 2012). To help facilitate GMPE development, a database of ground motions recorded in the study region was developed that includes recordings at 1149 stations across the Central and Eastern North America (CENA), shown in Figure 1. The recordings from these stations will be used to calibrate the proposed models for weak motions from earthquakes with M_w<6 which are currently the vast majority of CENA motions. Because simulations for source and path effects are performed for hard rock conditions, ground motion recordings must be corrected to the reference rock condition by removing site effects prior to use in model calibration.

Site effects refer to changes in ground motion characteristics (e.g., amplitude, frequency content, duration, etc.) due to soil and geological conditions. A number of site descriptors have been used in empirical site amplification factors including: NEHRP site class (BSSC, 1997), time-average shear-wave velocity to 30 m depth (V_{s30}), and geotechnical site categories (Geomatrix "third letter"; Chiou et al., 2008). Because V_{s30} is the most commonly used site parameter in modern GMPEs (e.g., Stewart et al., 2012), it is adopted as the site parameter for the CENA. Unfortunately, geophysical conditions at CENA recording stations are poorly characterized, with profiles from which V_{s30} can be computed being available at only 45 of the 1149 stations. Stewart et al. (2012) describe proxy-based methods for V_{s30} estimation, which are typically based on topographic slope (Wald and Allen, 2007), geomorphology-based terrain categories (Yong et al., 2012), geotechnical categories (Chiou et al., 2008), or surface geology (Wills and Clahan, 2006). All of these methods are strongly influenced (in some cases entirely controlled) by V_{s30} data from California. Only the slope-based method has recommendations for conditions in the CENA. Prior experience has shown that when applying proxy-

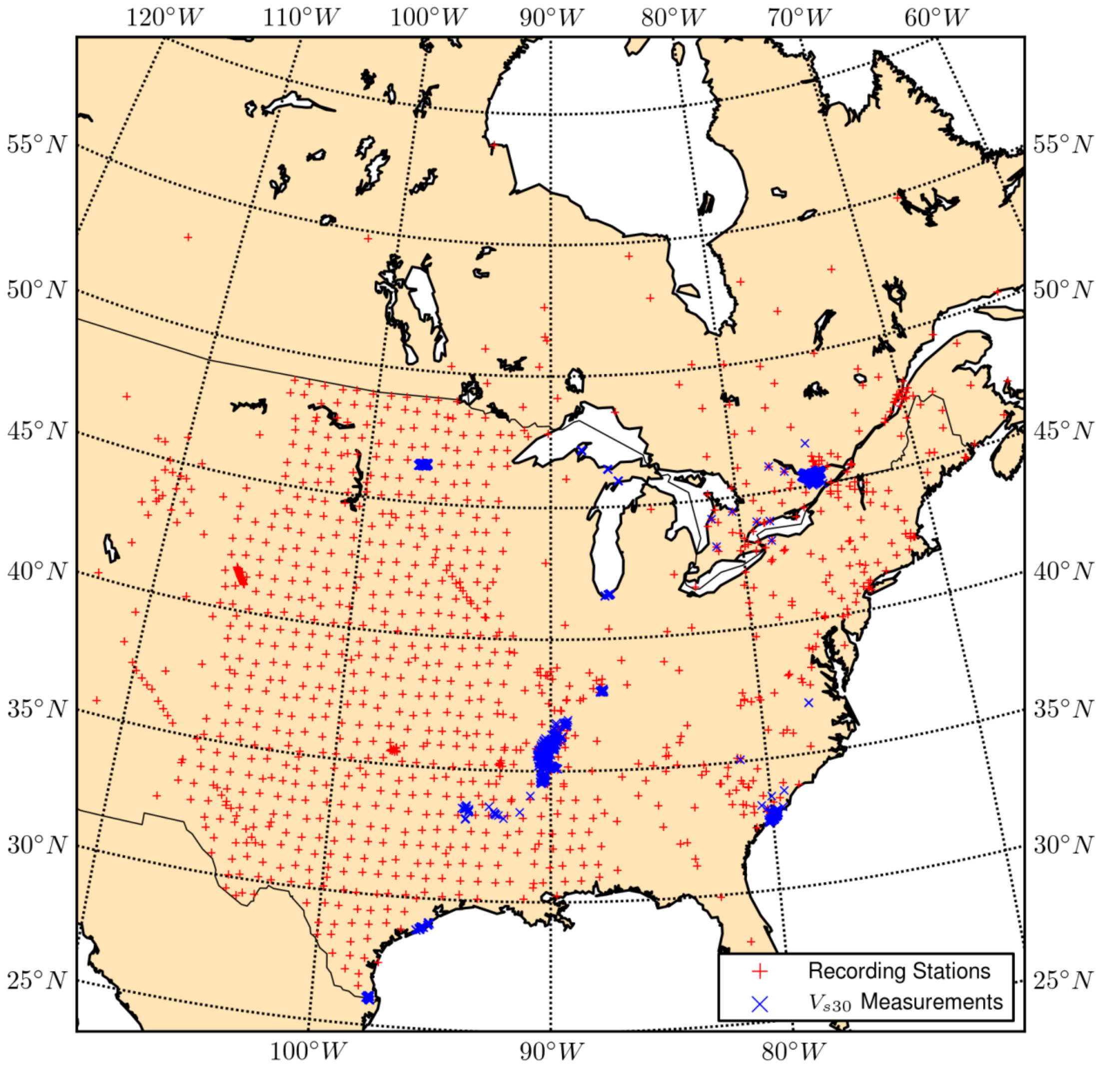

Figure 1. Locations of ground motion recording stations and V_{s30} measurements.

based methods developed for one region to another, good results can be obtained for soil conditions (typically alluvium), but difficulties can be encountered for rock site conditions (Scasserra et al., 2009).

We compile a database of 1930 V_s profiles in the CENA (mostly not at ground motion stations) to test proxy-based V_{s30} estimation procedures and to support the development of new proxy methods based at least in part on surface geology. We propose a set of geologic classes based on setting (i.e., glaciated or non-glaciated), age, and depositional environmental. For each geologic class, preliminary estimates of V_{s30} are developed along with simplified stratigraphic columns. The soil columns will be used in subsequent work to evaluate relatively generic site factors that account for geologic conditions in CENA, which in some cases are expected to include important effects of sediment depth in addition to V_{s30} as controlling parameters on site amplification.

2. SLOPE AND GEOMORPHOLOGY PROXY METHODS FOR ESTIMATING V_{S30}

The Wald and Allen (2007) methodology correlates V_{s30} to topographic slope from 30 arcsec digital elevation model (DEM) data that is available world-wide. Wald and Allen (2007) provide estimates of V_{s30} within discrete slope bins for active and stable continental regions. The velocity database used by Wald and Allen (2007) for stable continental regions was based on 432 V_s measurements from

Tennessee, Missouri, Kentucky, and Arkansas.

The Yong et al. (2012) method is based on an automated terrain classification procedure by Iwahashi and Pike (2007) that considers slope along with geomorphological factors including convexity and texture to classify a site into one of 16 different terrain classes. This technique utilizes the same globally available DEMs employed by Wald and Allen (2007). The V_{s30} estimates are based on 201 measurements from California along with 644 values inferred from the geology proxy of Wills and Clahan (2006). Yong et al. (2012) compared their model and the Wald and Allen (2007) CENA model to 325 V_{s30} measurements from southeast Canada, South Carolina, Illinois, Missouri, and Arkansas. The comparison showed that the Yong et al. (2012) model had a smaller standard deviation (147 m/s) than the Wald and Allen (2007) model for stable continental regions (213 m/s). The V_{s30} predicted by Wald and Allen (2007) ranges from 180 to 760 m/s, whereas that predicted by Yong et al. (2012) ranges from 200 to 550 m/s.

3. PROFILE DATABASE

We assembled a database of 1930 V_{s30} values from measurements in CENA by Gomberg et al. (2003), Motazedian et al. (2011), Rosenbald et al. (2010), Holzer et al. (2010), Beresnev and Atkinson (1997), Mohanan et al. (2006) and Murphy (2003). Because the database of measured values is thinly populated for rock site conditions, measured values are supplemented with 97 V_{s30} values of 2000 m/s inferred by Siddiqqi and Atkinson (2002) for ground motion recording stations located on “hard rock” in Eastern Canada. Despite the large size of the database there are two significant limitations. First, as shown in Figure 1, the data are clustered and miss many areas with ground motion instruments. Second, as shown in Figure 2, the data preferentially sample Quaternary alluvium (V_{s30} < 350 m/s) and nearly all of the measurements above 450 m/s are from Ottawa, Canada (Motazedian et al., 2011). Along with V_{s30}, each site in the profile database has a latitude and longitude, enabling look-up of proxy-based metrics such as ground slope and terrain category.

Using the measurement location, the Wald and Allen (2007) estimate of the V_{s30} for stable continental regions was determined from the raster images provided by the USGS (2011). Comparison of these estimated V_{s30} values with the values in the profile database demonstrate the weak connection between V_{s30} and topographic slope in CENA region, as shown in Figure 3. The median value within each of the slope bins varies from 180 to 250 m/s and does not follow the trend of increasing V_{s30} with increasing topographic slope presumed by Wald and Allen (2007). Each of the locations was also assigned a terrain class courtesy of A. Yong (2012, *pers. communication*) and are compared with the

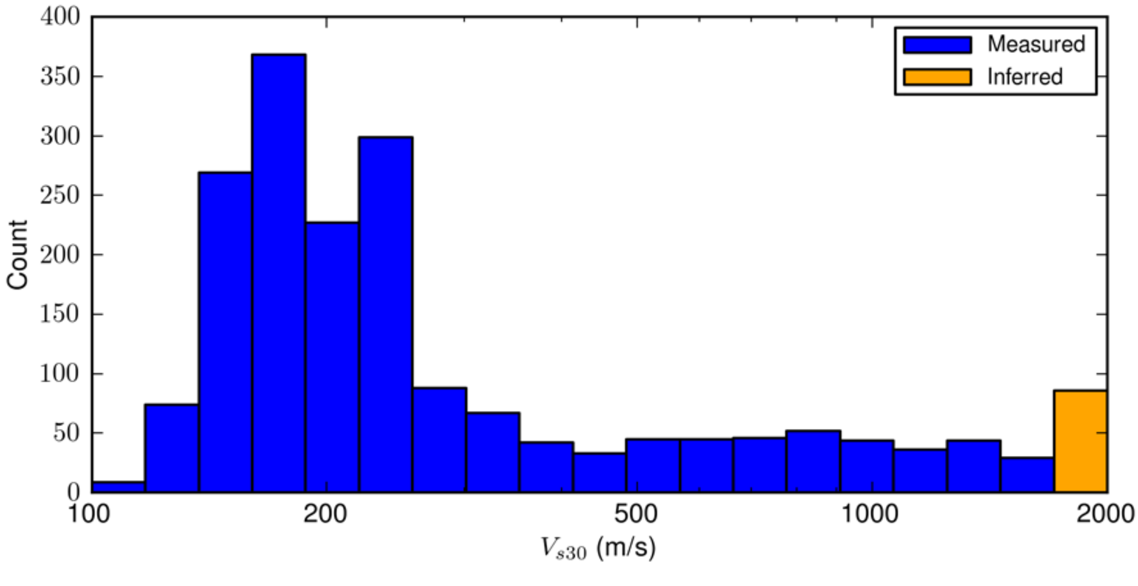

Figure 2. Histogram of collected measured and inferred V_{s30} values. Inferred values from Siddiqqi and Atkinson (2002).

values in the profile database in Figure 4. The estimated V_{s30} values are significantly different from the measured and inferred values and indicate that this methodology is not appropriate for all of CENA. Residuals (R) were calculated between measured and proxy-based V_{s30} in natural log units, as shown in Figure 5. The residuals for the Wald and Allen (2007) method (Figure 5a) show standard deviations ranging from 0.42 to 0.92 ($\sigma_{ln\,V}$). The uncertainty is lowest for the 2nd and 3rd flattest slope bins and highest (0.88 to 0.92) for the three steepest slope bins. The total uncertainty of the Wald and Allen (2007) method across all categories is σ_{lnV}=0.92. The residuals for the Yong et al. (2012) method have both positive and negative values, although most median residuals are positive. The total uncertainty of the Yong et al. (2012) method across all categories is σ_{lnV}=0.73.

A subset of the data in the profile database from Motazedian et al. (2011) includes sediment thickness in addition to V_{s30}. As shown in Figure 6, in proximity to Ottawa, Canada, the thickness of the sediment varies from 1 to 160 m. Figure 6 shows that sediment thickness strongly correlates to V_{s30}. For example, as the sediment thickness changes from 20 to 4 m, V_{s30} increases from 300 to 2000 m/s.

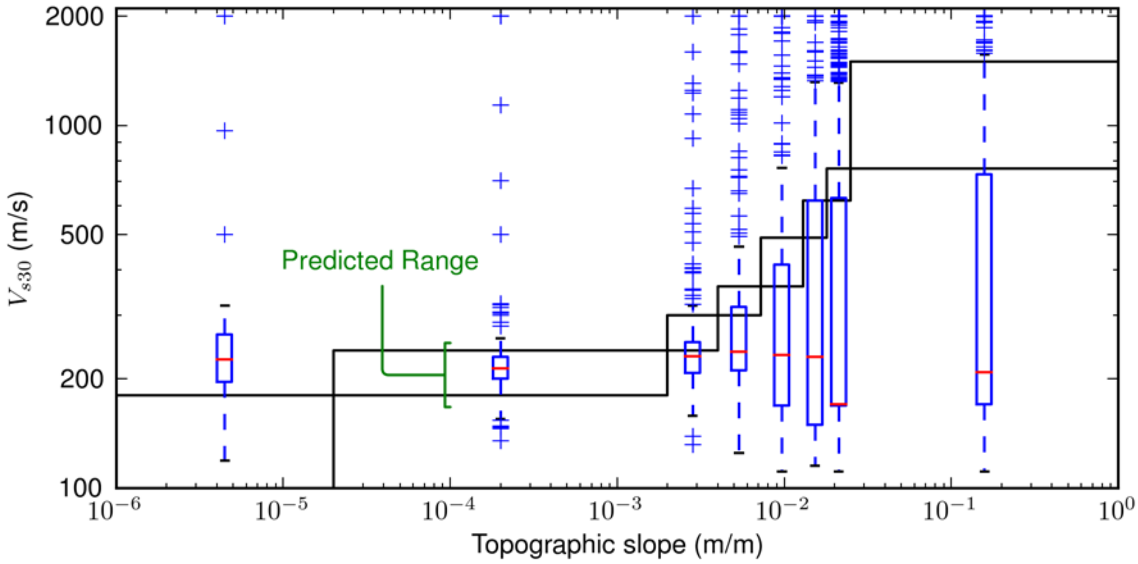

Figure 3. Box plots of the measured and interpreted V_{s30} values grouped by topographic slope and compared to the V_{s30} range from the Wald and Allen (2007) stable continental model. The box plot depicts the median (red bar), 25% and 75% percentiles (blue bar), minimum and maximum values (black bar), and potential outliers (blue plus symbol).

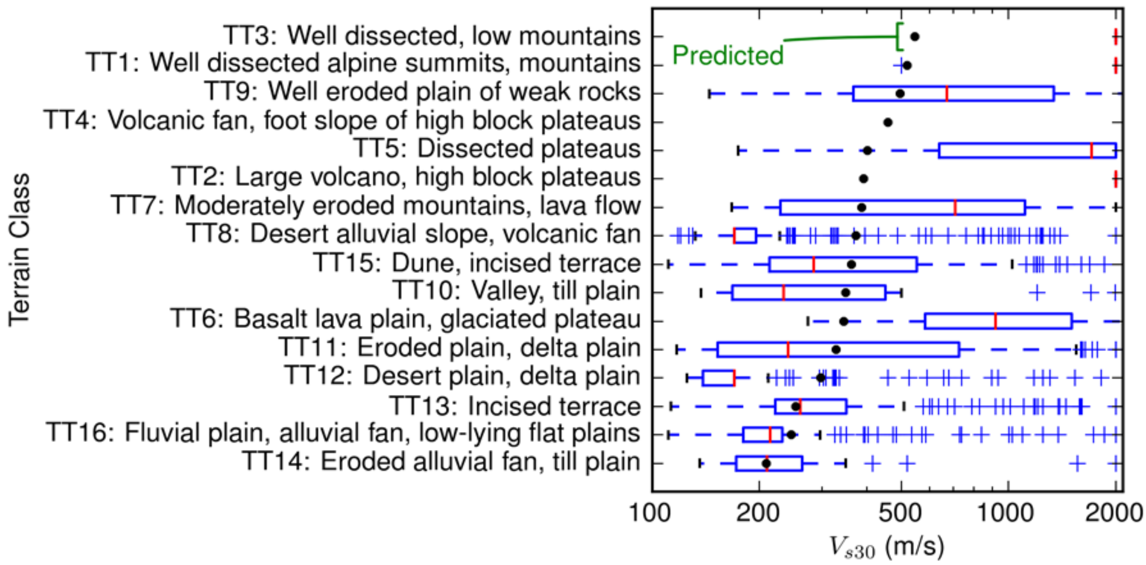

Figure 4. Boxplots of the measured and interpreted V_{s30} values grouped by terrain type compared to the mean values (dots) from the Yong et al. (2012) model. Explanation of box plot format given with Figure 3.

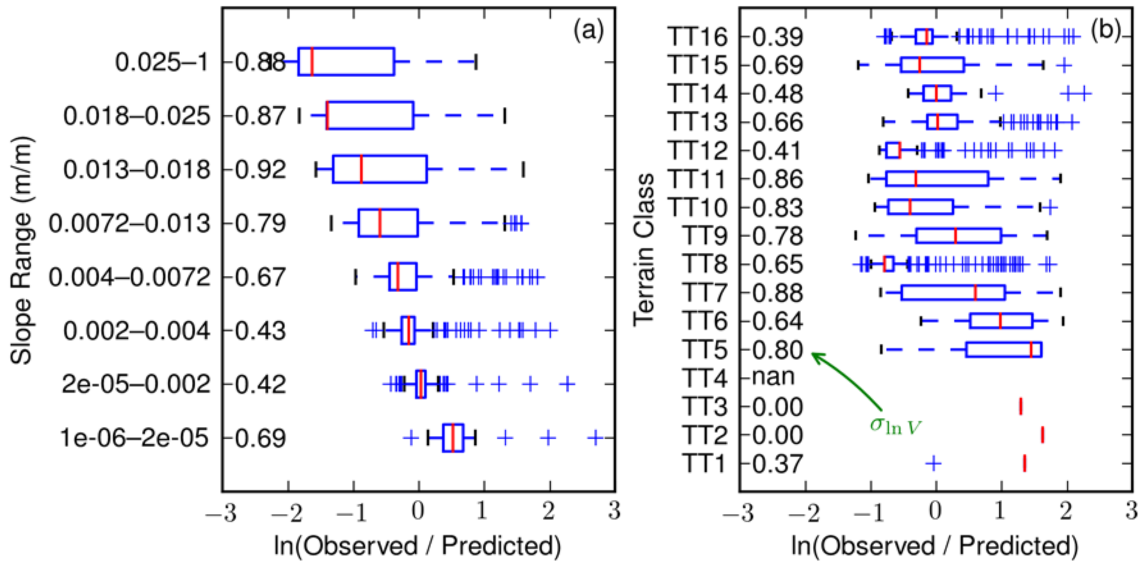

Figure 5. Boxplots of the residuals along with standard deviations (σ_{ln}) for the slope- (a) and terrain- (b) based proxy methods. The total uncertainty (σ_{ln}) of the slope- and terrain-based proxy methods is 0.92 and 0.72, respectively. Explanation of box plot format given with Figure 3.

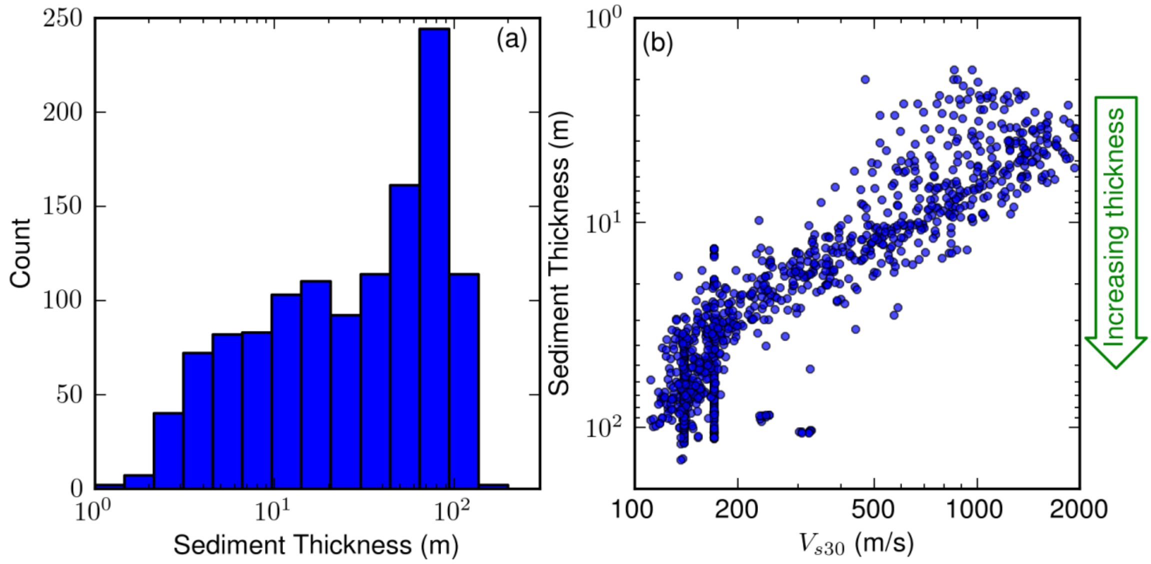

Figure 6. Sediment thickness near Ottawa, Canada, from Motazedian et al. (2011). (a) Distribution of sediment thickness and (b) the influence of sediment thickness on V_{s30}.

The effect of sediment thickness on site response and V_{s30} would be expected to depend on the impedance contrast at the soil-rock contact. For glaciated regions, this contact can be abrupt, whereas in non-glaciated regions weathering of the bedrock may lead to more gradual transitions. These effects are not captured by the slope and terrain proxies, but can be included through consideration of geologic conditions. This provides partial motivation for development of new geology-based proxies for V_{s30} estimation, as described in the following section.

4. DEVELOPMENT OF GEOLOGIC CLASSES FOR PROXY-BASED VS30 ESTIMATION

Surface geology has been shown to be an effective proxy for V_{s30} based on prior work in California and Italy. For such correlations to be effective, variations of velocities within the broad geological categories typically shown in geological maps (e.g., Quaternary alluvium, Qa) need to be captured. This can be accomplished by either using relatively detailed categories (e.g., separating thin and deep Qa), region-specific categories (e.g., for alluvium in the Imperial Valley and Los Angeles basin), or geologic information coupled with geomorphological data (e.g., slope or other terrain descriptors). For California, correlations based on 19 relatively detailed geological categories (including region-specific categories) are provided by Wills and Clahan (2006), which were used in the NGA project database (Chiou et al., 2008). Medians and standard deviations of V_{s30} are provided for each category. As described by Stewart et al. (2012), current recommendations are to use the Wills and Clahan values for rock sites (i.e., geologic age that is Tertiary or older), and to use relations based on ground slope for Quaternary sediments (Wills and Gutierrez, 2008). We expect proxies based on California data would be ineffective for CENA, especially for rock conditions, due to significantly different geological and tectonic histories and the presence of glaciations in many areas of CENA.

Withers (2007) and Ebel and Kim (2006) developed assigned shear-wave velocities to the approximately 200 Fullerton et al. (2003) units using NEHRP classes to relate the lithology (e.g. particle size and texture) to an velocity range, as well as an assumed thickness and bedrock velocity. However, this method is not used as measurements are not explicitly considered in during the classification process.

Following a careful review of major sources of surface geology mapping (Fullerton et al., 2003, for US; Fulton, 1986, for Canada), we developed 19 geologic categories for sites with soil materials exposed at the ground surface to delineate typical site conditions in the CENA, as shown in Table 1. All site conditions in Table 1 consist of surficial soils to match the mapping protocols used by Fullerton et al. (2003) and Fulton (1986). Additional rock categories will be applicable on more detailed geological maps for relatively local regions, but are not considered at this stage. Some of the soil categories shown in Figure 1 will often have rock very near the surface, such as the residual soil categories.

As shown in Figure 7, the CENA region is comprised of three major geologic divisions: glaciated, non-galciated, and residual soils (Table 1). In the northern part of the region, glaciation has been a

Table 1. Geologic classes defined for the Central and Eastern Northern America.

Major Unit (Age)	Sub-unit	Abbrev.	Thick. (m)	Soil Class	Mean V_{s30} (m/s)	σ_{lnV} (m/s)
Old Glacial Sediments (Older than Wisconsin)	Glaciomarine and Lacustrine	OGm	9	ONm	--	--
	Outwash and alluvium	OGo	7	ONa	--	--
	Tills	OGt	16	ONa	--	--
Young Glacial Sediments (Wisconsin and younger)	Glaciomarine and Lacustrine	YGm	8	YNm	520	0.53
	Outwash and alluvium	YGo	11	YNa	470	0.67
	Tills	YGt	16	YNa	300	0.45
	Discontinuous Till	YGd	5	YNa	1050	0.39
Old Non-Glacial Sediments (Mid-Pleistocene and older)	Alluvium	ONa			--	--
	Colluvium	ONc			--	--
	Loess	ONl			250	0.11
	Lacustrine, Marine and Marsh	ONm			290	0.22
Young Non-Glacial Sediments (Holocene and late Pleistocene)	Alluvium	YNa			220	0.14
	Colluvium	YNc			--	--
	Loess	YNl			--	--
	Lacustrine, Marine and Marsh	YNm			230	0.12
	Beach, dune, and sheet sands	YNs			210	0.18
Residual Sediments	Residual from metamorphic and igneous rock	RRm			--	--
	Residual from sedimentary rock	RRs			--	--
	Residual from soils	RSs			--	--

major factor with the last glaciation occurring during the Wisconsin Age (110,000 to 10,000 years ago). The glaciated type is subdivided into young (Wisconsin and younger) and old (older than Wisconsin) groups. The southern portion of the region is non-glaciated, with major categories consisting of residual soils (e.g., along the Appalachian Mountains) and transported sediments (alluvium, colluvium, loess, lacustrine, marine, etc.) that are segregated by mode of deposition and age. A major consideration in the subdivisions of glaciated and non-glaciated classes is the delineation of depositional conditions typically associated with fine-grained versus coarse-grained soils. Fine grained materials will be typically encountered in lacustrine, marine, and marsh conditions; whereas relatively silty and/or sandy materials will typically be encountered in alluvium, beach, dune, and loess deposits.

Using the map in Figure 5, we associated one of the 19 surface geology categories from Table 1 with each site in the profile database, as shown in Figure 8. The lack of spatial cover by the measurements

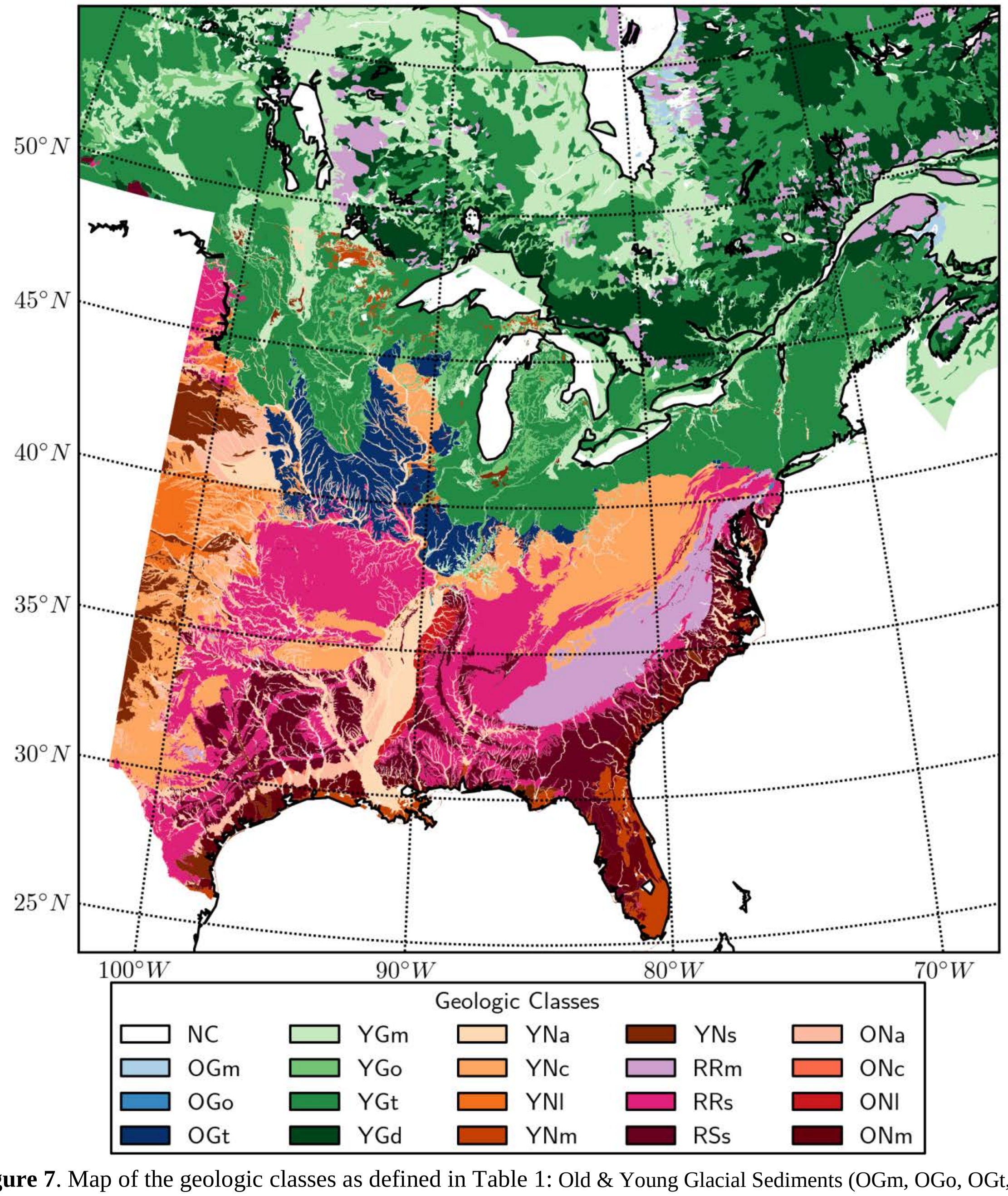

Figure 7. Map of the geologic classes as defined in Table 1: Old & Young Glacial Sediments (OGm, OGo, OGt, YGm, YGo, YGt, YGd); Old & Young Non-Glacial Sediments (ONa, ONc, ONl, ONm, YNa, YNc, YNl, YNm, YNs); and Residual Sediments (RRm, RRs, RSs).

results in some geologic classes with many measurements (e.g., 902 in YGt) and others with none. For residual and non-glaciated geologic classes with less than 10 measurements, we do not report category V_{s30} values at this time. For non-glaciated geologic classes with more than 10 observations, the mean V_{s30} is computed from the measured values. For the geologic classes from glaciated regions, the estimated mean V_{s30} is computed using a combination of the measurements and a simple model with sediment and rock layers. The sediment thickness is taken as the average thickness reported by Fullerton et al. (2003), except for YGd for which we used an estimated mean thickness of 5 m. The remaining depth of the profile was assumed to be rock with a shear-wave velocity of 3000 m/s. The velocity of the soil was approximated using analogous soil type from the non-glaciated region listed in Table 1. This methodology was used in an attempt to increase the amount of information that we have regarding the site conditions because of the highly-clustered nature of data in the glaciated region. The proposed mean V_{s30} values are shown in Figure 9a and listed in Table 1. No V_{s30} is proposed for the old non-glaciated colluvium (ONc) geologic classes, because the material was not sampled by measurements.

The residuals between the predicted and measured V_{s30} are shown in Figure 9b. The standard deviation (σ_{lnV}) of the residuals is 0.46, which is an improvement over the values 0.88 and 0.73 for the slope and

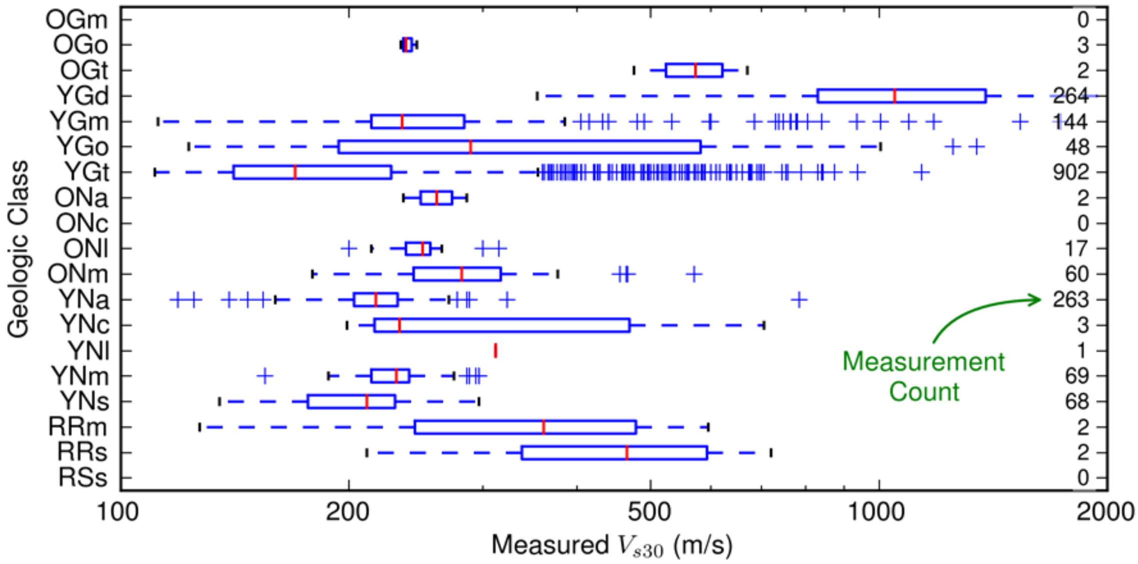

Figure 8. V_{s30} values grouped by geologic class (see Table 1). Explanation of box plot format given with Figure 3.

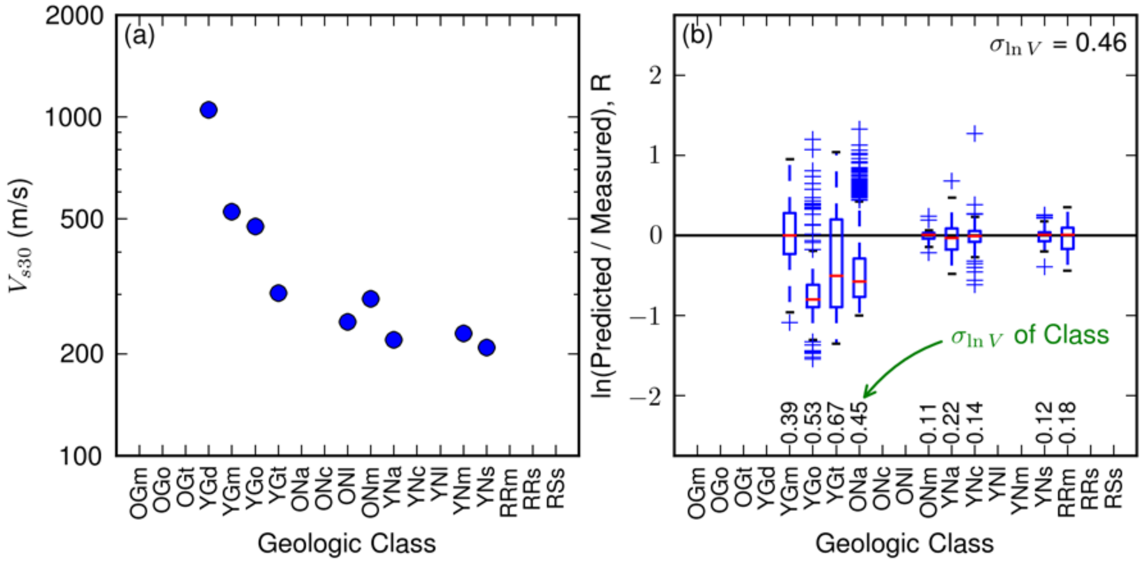

Figure 9. (a) Proposed values of V_{s30} based on geology and measurements and (b) residuals computed from the measured and predicted V_{s30} values. Explanation of box plot format given with Figure 3.

terrain proxy methods, respectively (Figure 5). However, a σ_{lnV} of 0.46 is somewhat larger than the typical value of 0.35 for V_{s30} models in active tectonic regions (e.g., CA), because of increased availability of data used in the development these models. The σ_{lnV} of the individual classes varies from 0.02 to 0.77 and depends on the number of observations. For geologic classes with more than 100 measurements, σ_{lnV} ranges from 0.17 (YGd with 264 measurements) to 0.77 (YGt with 902 measurements). The mean biases for the glaciated soils, which depend on both measurements and simplified stratigraphic columns, range from 0 for YGm to 0.8 for YGo. The wide range in σ_{lnV} for glaciated soils is due to the importance of sediment depth on V_{s30}.

5. LIMITATIONS

The geologic classes developed in this study use the most complete V_{s30} database for the CENA region currently available. However, the data are highly-clustered with many measurements from the same geologic class occurring in proximity to each other. For this reason, the actual uncertainty associated with applying the V_{s30} in Table 1 to sites having the same geologic description may be higher than what is indicated in Figure 9b. The sediment thickness is a controlling factor for the estimation of V_{s30} within glaciated regions.

For the estimation of V_{s30} at ground motion recording stations, the practice of embedding the instruments at depths ranging from 2 to 6 m needs to be accounted for. This embedment of the instruments has a particularly significant effect on V_{s30} estimates for glaciated sites where sediment thickness effects are important, as discussed in Beresnev and Atkinson (1997).

6. CONCLUSIONS

A database of 1930 V_{s30} values measured at sites in Central and Eastern North America (CENA) was developed. The database was used to evaluate the effectiveness of slope- and terrain-based proxy estimates of V_{s30}. The evaluation demonstrated that both methods had considerable uncertainty and tended to underestimate the V_{s30} at sites with relatively high V_{s30}. To support the development of geology-based proxy for V_{s30} estimation, 19 geologic classes were selected for the CENA region that distinguish zones of similar geologic setting, age, and depositional environment. For residual and non-glaciated soils with less than 10 measurements, the mean V_{s30} values were computed using a combination of mean V_{s30} from measurements and proxy-methods with weight factors based on the reciprocal of the standard error. For non-glaciated soils with more than 10 measurements, the mean V_{s30} was estimated solely from measurements. For the glaciated soils, the mean V_{s30} was estimated using a combination of measurements and a simple site model. The inclusion of the simple site model was applied to improve the estimate by including data from the non-glaciated regions. The total standard deviation (σ_{lnV}) is 0.46, which is smaller than that of the Wald and Allen (2007) and Yong et al. (2012) models.

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