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Investigation of Geographic Rules for Improving Site-Conditions Mapping

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Introduction

This project attempts to contribute to improving characterization of the near-surface conditions of sites throughout California by developing geographic rules that may be used with geologic maps of California, and potentially extended to other areas. Explaining the variations in seismic shaking because of site conditions has been an ongoing research topic for over 20 years. Tinsley and Fumal (1985) assigned individual shear-wave velocities to each geologic unit in their test area, taking into account age, grain size and depth. In 1994, the Northridge earthquake resulted in unexpected variations in damage and ground motions in and around the Los Angeles area. Immediately, a number of studies were launched to study ground motions in southern California. Park and Elrick (1998) extracted the shear-wave velocity average to 30 meters (m) depth, Vs30. Their results show that Vs30 varies with grain size and age, and accordingly grouped the geologic units in southern California into eight different categories. Similarly, Wills and Silva (1998) assembled a database of shear-wave velocity measurements and correlated those with the materials described in borehole logs.

Wills and others (2000) published a site-conditions map for all of California based on the U.S. Geological Survey's National Earthquake Hazards Research Program (NEHRP) Vs30 categories, correlation of geologic units with Vs30 from Wills and Silva (1998) and generalization of the statewide 1:250,000 scale geologic maps. The "preliminary site conditions map" of Wills and others (2000) was found to correlate with seismic amplification (Field, 2000) and represented a credible first approximation for consideration of site conditions in seismic hazard estimates. Wills and others (2000) noted two main problems with this map: the lack of precision inherent in using the 1:250,000 scale geologic maps and the range of Vs30 in young alluvium due to variations in thickness, grain size and possibly regional differences in deposition and weathering.

More recent work by Wills and Clahan (2006) attempted to outline areas corresponding to geologic units with distinct Vs30. This effort provided an estimate of Vs30 for use in the Pacific Earthquake Engineering Research Center's Next Generation Attenuation (NGA) Equation project by applying the shear-wave velocity characteristics of geologic units, similar to the units described by Wills and Silva (1998), to all sites in the NGA database. This effort resulted in a set of 17 generalized geologic units that are classified by their shear-wave velocity, and a map of California showing those units. One key change in this map from previous maps is that we subdivided areas of young alluvium so that they are more homogenous in Vs30. Generally, our subcategories of young alluvium were defined geographically, rather than by using detailed geologic information. The geographic rules were kept as simple as possible: alluvium is expected to be thin in narrow valleys and small basins, coarse-grained near the base of steep mountains, and thick in the center of major basins. Using these rules, applied "by eye," the map prepared by Wills and Clahan (2006) separates geologic units within the young alluvium that appear to have different shear-wave velocity (Table 1). Deep basins with an abundance of shear-wave velocity information, the Imperial Valley and the Los Angeles basin, also can be shown to have significant regional differences in Vs30. Estimates of the mean and standard deviation of Vs30 from this map were provided to the NGA equation developers. All of the five attenuation equation developer

Table 1. Geologic units and shear-wave velocity characteristics developed by Wills and Clahan (2006). For each geologic unit, the number of profiles located in that map unit, the mean and standard deviation of Vs30 for those profiles, and the mean and standard deviation of the natural log (ln) of Vs30 are reported.

Geologic Unit	Geologic Description	Number of profiles	Mean Vs30	Std. Dev.	Vs30 from Mean of ln	Std. Dev. of ln
Qi	Intertidal Mud, including mud around the San Francisco Bay	20	160	39	155	0.243
af/qi	Artificial fill over intertidal mud around San Francisco Bay.	44	217	94	202	0.357
Qal, fine	Quaternary (Holocene) alluvium in areas where it is known to be fine.	13	236	55	229	0.238
Qal, deep	Quaternary (Holocene) alluvium in areas where it is more than 30m thick.	161	280	74	271	0.250
Qal, deep, Imperial V	Quaternary (Holocene) alluvium in the Imperial Valley	53	209	31	207	0.135
Qal, deep, LA Basin	Quaternary (Holocene) alluvium in the Los Angeles basin.	64	281	85	270	0.275
Qal, thin	Quaternary (Holocene) alluvium in narrow valleys, small basins, and adjacent to the edges of basins.	65	349	89	338	0.244
Qal, thin, west LA	Quaternary (Holocene) alluvium in part of west Los Angeles.	41	297	45	294	0.150
Qal, coarse	Quaternary (Holocene) alluvium near fronts of high, steep mountain ranges and in major channels.	18	354	82	345	0.223
Qoa	Quaternary (Pleistocene) alluvium	132	387	142	370	0.273
Qs	Quaternary (Pleistocene) sand deposits.	15	302	46	297	0.171
QT	Quaternary to Tertiary (Pleistocene - Pliocene) alluvial deposits.	18	455	150	438	0.266
Tsh	Tertiary (mostly Miocene and Pliocene) shale and siltstone units.	55	390	112	376	0.272
Tss	Tertiary (mostly Miocene, Oligocene, and Eocene) sandstone units.	24	515	215	477	0.386
Tv	Tertiary volcanic units.	3	609	155	597	0.240
Kss	Cretaceous sandstone of the Great Valley Sequence in the central Coast Ranges.	6	566	199	539	0.332
serpentine	Serpentine.	6	653	137	641	0.204
KJf	Franciscan complex rock.	32	782	359	712	0.432
xtaline	Crystalline rocks, including Cretaceous granitic rocks, and metamorphic rocks.	28	748	430	660	0.489

teams used estimates of Vs30, measured at the strong-motion instrument site or from this map, as their primary term for site conditions. The developer teams found that the Vs30 values from the new map were more effective in reducing the residuals in the ground motion than broader Vs categories based on NEHRP categories.

Like previous steps toward improved site-conditions mapping, preparation of the map by Wills and others (2006) has raised a series of questions:

- Is there a clear distinction based on the size of basin or width of valley that could do as well or better than the current visual classification of areas where thin alluvium affects Vs30?
- Can the higher velocities in "coarse alluvium" be related to geographic position at the base of high mountains or could they be due to soil formation in desert environments? Is it possible to separate these two effects?
- Can other geographic rules (e.g. distance from bedrock, slope, or surface roughness) do as well or better at differentiating Vs30 in alluvium?
- Are there systematic variations in Vs among "crystalline rocks"? Can those be correlated with slope, surface roughness, or other geographic criteria?
- How much can we improve estimation of Vs30 by using higher resolution geologic maps?

Developing Maps of Shear-Wave Velocity Based on Geologic Maps

Geologic maps use age, environment of deposition, and grain size to define units. Although the physical properties that control shear-wave velocity, such as grain size, density, and fracture spacing, do tend to vary between geologic units, they are not the defining criteria for most geologic units. As a result, there are numerous geologic units with essentially the same shear-wave velocity characteristics and there is considerable variability within most geologic units. For some classes of units, Tertiary shale for example, Vs30 values vary over a relatively small range, and the predicted variation in seismic amplification is small enough that the average Vs30 is a useful predictor of amplification on that type of materials. The challenge in preparing a map of shear-wave velocity based on geologic maps is to group those units that have similar velocity.

To prepare the statewide map of shear-wave velocity units, Wills and others (2000) and Wills and Clahan (2006) generalized from small-scale geologic maps that cover the State, grouping units with similar physical properties. One way to create more accurate and precise maps of shear-wave velocity is to use more detailed geologic maps. Larger-scale geologic maps ensure more precision in the location of contacts between geologic units and more accuracy in the description of geologic units, and in their assignment to shear-wave velocity classes. To test the potential improvements from using detailed geologic maps, we compiled geologic maps covering the Los Angeles basin and surrounding mountains and valleys. The geologic maps from Morton and Miller (2006), Saucedo and others (2003), and work in progress on the Los Angeles 1:100,000-scale quadrangle (California Geological Survey, in progress) were prepared from mapping conducted at 1:24,000 scale or larger and represent the most detailed available mapping for the area. The geologic units on those maps were classified according to the shear-wave velocity units of Wills and Clahan (2006). Two significant changes result from using these more detailed geologic maps, as illustrated in Figure 1. The first is that areas of young alluvium are more extensive on the more detailed maps. The second is that many of the Tertiary bedrock units that had been grouped with Tertiary shale in the generalized statewide map are shown on the more detailed maps as Tertiary sandstone.

Young alluvium is more commonly shown on detailed maps than on regional maps, particularly in the narrow valleys of mountainous areas. This occurs because narrow areas of alluvium in mountainous areas are simplified and removed from small-scale maps. In the Los Angeles area, the detailed maps show more young alluvium in mountain valleys and particularly in the hills east of downtown Los Angeles. Within the Los Angeles region as shown on Figure 2, the area of young alluvium on the more detailed maps is 4 percent larger than the area shown on the generalized maps. This increase represents 110 square kilometers, most of which had been mapped as bedrock. Most of the additional areas are thin alluvium in narrow valleys or at the base of mountains and therefore they have velocities higher than alluvium in the deep basins, but lower than most bedrock.

Tertiary sedimentary rocks were divided into sandstone and shale for the preliminary shear-wave velocity map of California (Wills and others, 2000), which was based on units shown on the 1:250,000 scale Geologic Atlas of California (published between 1958 and 1972) and a few more recent maps. The units on the Geologic Atlas are defined by time, rather than lithology, however. Wills and others (2000) grouped all Paleocene, Eocene, and Oligocene rocks as sandstone, and Miocene and Pliocene rocks as shale, because as a statewide generalization, more of the early Tertiary rocks are sandstone whereas more of the late Tertiary rocks are shale. In detail, however, there are many areas where this generalization is not correct. In the Los Angeles area, this generalization resulted in sandstones of the Topanga, Puente and Fernando Formations, among others, being grouped with

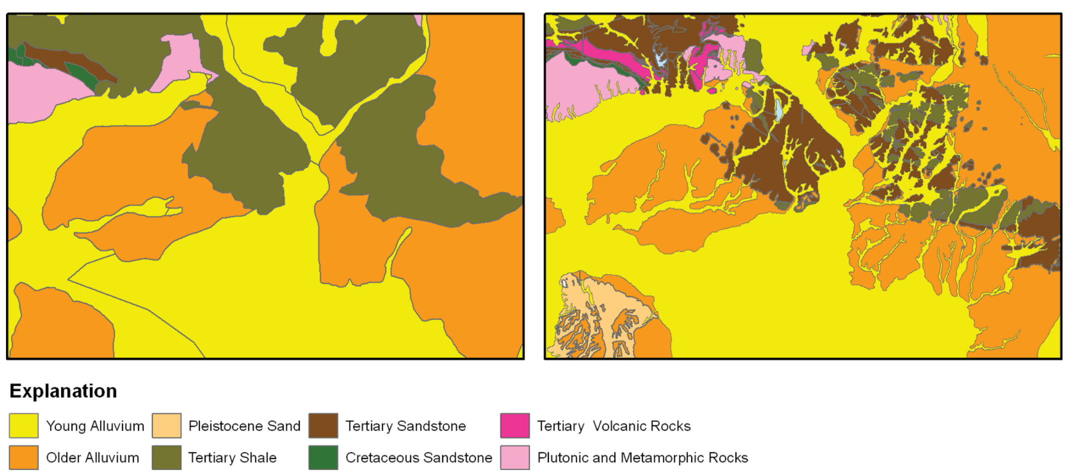

Figure 1. Examples of the difference in using more detailed geologic maps in preparation of shear-wave velocity maps. These two maps show the Los Angeles and Hollywood 7.5-minute quadrangles, some of the most densely populated parts of the Los Angeles region. The area shown is about 15 miles across. The left map is from the statewide map prepared by Wills and Clahan (2006), based on small-scale geologic maps. The right map is based on 1:24,000 mapping prepared for the CGS Seismic Hazard Mapping Program by Mattison and Loyd (1998a, b). [A more legible color version of this figure is available at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT08_GutierrezFig1.pdf*]

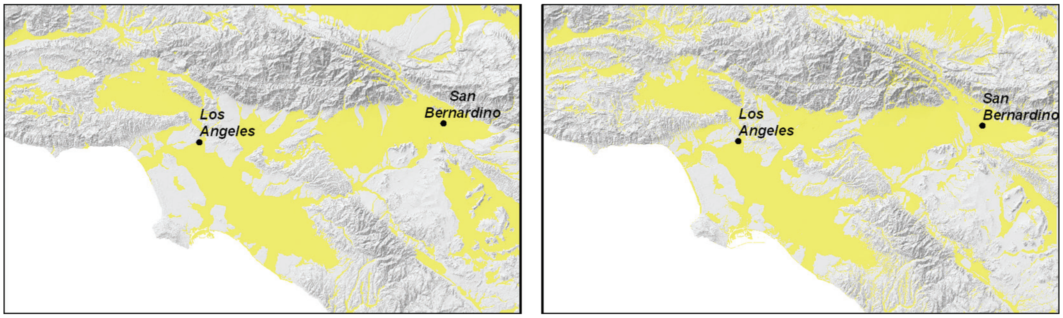

Figure 2. Examples of the difference in extent of young alluvium, shown in yellow, depicted on generalized and more detailed geologic maps. These two maps show the Los Angeles and surrounding areas that were included in this study. The left map is derived from the statewide map prepared by Wills and Clahan (2006), based on small-scale geologic maps. The right map is based on more detailed 1:24,000 mapping. Within the Los Angeles region, the area of young alluvium on the more detailed maps is 4 percent larger than the area shown on the generalized maps. [A more legible color version of this figure is available at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT08_GutierrezFig2.pdf*]

shale. With the more detailed maps, and designations based on lithologic descriptions of the individual units, the area mapped as shale is only 40 percent of the previous map, while the area mapped as sandstone increased by a factor of more than three.

Based on the above comparison in the Los Angeles area, detailed geologic maps result in more accurate maps of shear-wave velocity both because of the inherent increase in the precision of the mapping and also because of the ability to test and revise simplifying assumptions that are required when working with more generalized maps.

Developing Maps of Shear-Wave Velocity in Alluvial Basins

Differentiating shear-wave velocity units is most important for recently deposited materials, because these materials tend to have the lowest velocities and therefore the greatest potential for seismic amplification. Recent deposits in basins and plains are also where people tend to settle and urban centers grow. Variations in amplification across an urban area, because of variations in shear wave velocity between different geologic materials, can have a significant effect on the area's distribution of earthquake damage and losses.

In some cases, there is a simple correspondence between geologic unit characteristics and velocity. For example, estuarine or marsh deposits tend to be rapidly deposited silt and clay, of low density. Because estuarine deposits are recognized as having different properties from the surrounding deposits, they are usually mapped as geologic units. They also have a narrow range of shear-wave velocity so these "bay mud" and "intertidal mud" deposits have long been recognized as areas of enhanced seismic shaking. Other geologic units, alluvial fan deposits in particular, can have a wide range of density and grain size. Recent alluvial deposits range in Vs30 from about 200 to about 400 meters per second (m/s), which overlaps the range of "bay mud" at the low end and the range of "soft rock" at the high end. This range in Vs30 results in a range of amplification that is also about a factor of two (graphs in Wald and Mori, 2000). This range in velocity is related to the density and grain size of the deposit, as well as soil forming processes that, with time, can increase velocity by filling pore spaces with clay or calcium carbonate or decrease velocity by the weathering of large clasts.

Although the factors that lead to the large range of shear-wave velocity in recently deposited alluvium are well recognized, a poor correlation between geologic (or "soils") map units has repeatedly been noted. Thelen and others (2006) showed that 50 measurements of Vs30 in coarse alluvium of the northern San Gabriel Valley had an average velocity above the range predicted for the NEHRP-based CD Site Class (mean Vs30 of 360 m/s), and large variance. In Las Vegas and Reno, NV, Scott and others (2004, 2006) found poor Vs30 predictability from mapped alluvial units. Park and Elrick (1998), and Steidl (2000) attempted to correlate geologic maps of southern California with seismic amplification, without much success. Steidl did not even find significant differences in amplification between younger and older alluvium, probably because of the way those units were defined and mapped on the maps that he used in his study.

There may be many reasons for poor correlation between mapped geologic units and Vs30 in Quaternary deposits, but some basic reasons can be inferred from the nature of geologic maps of Quaternary deposits and the methods by which they are made. Geologic maps use divisions of geologic time as the first level discriminator between units. This is useful because "older alluvium" or "Pleistocene alluvium" commonly includes all alluvial deposits where soil-forming processes, compaction, and cementation have significantly raised the shear-wave velocity. Older alluvium also has a narrow enough range of Vs30 that it is mapped as a single site-condition category on the map of Wills and Clahan (2006). Geologic maps commonly use environment of deposition as a second level discriminator between geologic units. This can be useful when environment of deposition leads to a narrow range of grain size and density, as in estuarine deposits discussed above. Recent alluvial fan and basin deposits are commonly mapped as "Younger alluvium" or "Holocene alluvium." These deposits underlie areas of active or recently active deposition of sediment, with slight or no modification due to cementation or weathering. Because these deposits underlie large areas within urban regions, several methods have been developed to further subdivide these units. Third-level discriminators of geologic units within young alluvial fans are most commonly based on age, commonly with additional descriptors based on grain size. These subdivisions within recent alluvial fan deposits depend on interpretations of the relative age of geomorphic surfaces and on descriptions of the near-surface materials from boreholes or test pits.

The subdivisions within Holocene (recent) alluvial fan deposits have proven most problematic for correlating between geologic maps and shear-wave velocity. It seems clear that geologic maps show detailed units defined by typical grain size within areas of young alluvium. Since grain size is the principal physical difference between alluvial deposits that have different shear-wave velocity, these units should correlate with Vs30. The most common result of studies to examine this correlation is that areas mapped as coarse alluvium have no significant difference from those mapped as fine alluvium (Park and Elrick, 1998; Steidl, 2000; Scott and others, 2004, 2006). This disappointing result has led some to doubt the value of geologic maps for estimating Vs30. This result is not surprising, however, when one considers how these maps are made and the patterns of deposition of materials on alluvial fans. Geologic maps that show variations in grain size in recent alluvium are almost always based on information from the upper few meters of the deposits. On alluvial fans, the locations of channels, where coarser materials are deposited moves across the fan over time. In cross section, deposits tend to be a mass of the average grain size of the fan with lenses of coarser grained materials representing the channel deposits. Any point on the fan may be underlain by material representing sheet flooding over the body of the fan as well as channel deposits. The proportions of those materials do not change depending on whether a coarser channel deposit happens to be at the surface. As a result, grain size designations based on the materials at the surface are commonly not representative of the average of the materials within the upper 30 m.

An additional problem in correlating Vs30 with the material at the surface, and represented on geologic maps, is that Holocene alluvium is rarely 30 m thick. Where the young alluvium is thinner, Vs30 can be strongly influenced by the underlying material. This can be a significant issue where alluvium at the surface is underlain by material with much higher velocity, such as crystalline bedrock. Fortunately, locations where "thin alluvium" is found can be anticipated. Wills and Clahan (2006) designated areas at the edges of large basins and in narrow valleys as "thin alluvium" based only on distance from the basin edge. Boundaries drawn by Wills and Clahan (2006) a few kilometers from the edges of most alluvial basins in California did separate measured profiles in "deep alluvium" with a mean Vs30 of about 280 m/s from those in "thin alluvium" with a mean Vs30 of about 350 m/s.

Young alluvium is typically deposited in a subsiding basin. Since such basins have formed over much longer time scales than the Holocene, younger alluvium at the surface is typically underlain by older alluvium with somewhat similar properties. In this typical case, where young alluvium overlies older alluvium, the thickness of the young alluvium appears to be less significant than the thickness of the older alluvium. In the west Los Angeles area, 41 shear-wave velocity profiles have been measured in an area where geologic logs clearly document less than 30 m of young alluvium underlain by older alluvium. The mean Vs30 for this area is not significantly different from the mean Vs30 for deep alluvium in the Los Angeles basin, or from deep alluvium in other basins in California (Wills and Clahan, 2006).

Any system to predict the Vs30 in young alluvial deposits needs to consider several concepts outlined above:

1. Differences in Vs in young alluvial deposits correlate with grain size. Compaction, soil formation and cementation have lesser effects.

2. Grain size of the surface material does not reliably indicate the average grain size in the upper 30 m.

3. Grain size generally decreases downstream from the apex of an alluvial fan.

4. Slope of alluvial fans also decreases downstream from the apex, so there should be a positive correlation between slope and average grain size.

5. The thickness of the young alluvial deposits has a significant effect on Vs30 where harder material is within 30 m of the surface. The effect does not appear to be significant where the young alluvium is underlain by older alluvium.

Wills and Clahan (2006) made use of these concepts in developing their geologically based Vs30 map of California. In this study we hope to refine the rules they used in making their map, examine the relative importance of different factors, and apply the rules that best distinguish Vs30 categories to detailed geologic maps.

Since grain size at the surface of an alluvial fan deposit has only slight predictive power for the average grain size in the upper 30 m, and does not distinguish areas where the alluvium is less than 30 m thick, an alternate method is needed to distinguish Vs30 units in young alluvium. Two methods have been attempted: either construct a detailed three-dimensional model showing the variation in thickness of deposits and their different velocities, or identify some useful proxy for the average grain size within an alluvial fan deposit. Tinsley and Fumal (1985) and Holzer and others (2005) have demonstrated that three-dimensional models showing the thickness of layers with differing velocity can be used to predict Vs30, or other parameters, across parts of the Los Angeles and San Francisco-Oakland urban areas. Constructing a three-dimensional velocity model of the upper 30 m is very time- and data-intensive, however, so if site-conditions maps of large areas are needed, a useful proxy for average grain size must be found.

For this study we tested two potentially useful proxies for Vs30 in young alluvium. Both take advantage of the decrease in the average grain size in alluvial fan deposits with distance from the apex of the fan. Since the apex of the fan, the point where the stream begins to deposit material, commonly coincides with a mountain front, grain size typically decreases with distance from the mountain front. Similarly, the stream's gradient, and its ability to transport material, decreases away from the mountain front. The result is relatively steep, coarse-grained deposits near the mountain front grading into less steep, finer grained alluvial deposits farther away. The distal alluvial fan deposits may grade into basin, marsh, lake, or fluvial deposits that have even lower gradients. A system for dividing young alluvial deposits by average grain size could take advantage of the decrease in grain size with distance from the source, or the decrease with stream gradient (slope of the surface of the fan).

For the map of Wills and Clahan (2006), young alluvium is divided into eight different categories: Qal, fine; Qal, deep; Qal, deep, Imperial V; Qal, deep, LA basin; Qal, thin; Qal, thin, west LA; and Qal, coarse. These categories take advantage of the general velocity gradient away from mountain fronts, and the available subsurface data that show where the alluvium in the subsurface is generally fine, or show that alluvium in one basin (the Imperial Valley) has lower velocity than in other basins in the State. In order to test more general rules for subdividing the younger alluvium, we have combined all these mapped categories into one and then split that map unit based on geographic rules that may be useful proxies for grain size and Vs30. The overall goal is to find methods that result in well-defined, reproducible polygons that have smaller ranges of Vs30 than the interpretive polygons of Wills and Clahan (2006). For this analysis we are using the same database of Vs30 measurements as used in that earlier work.

Variability of Vs30 in Young Alluvium, with Lateral Distance from Rock

In reviewing the measured shear-wave velocity in young alluvium, Wills and Silva (1998) noted that near the edges of alluvial basins Vs30 tended to be higher and much more variable, largely because certain 30-m profiles included young alluvium over higher velocity material. This led Wills and Clahan (2006) to establish a unit they called "thin alluvium" designated simply by assuming that the alluvium in narrow valleys, small basins and close to the edges of larger basins may be less than 30 m thick. The geographic limits of this were drawn "by eye." The Vs30 in "thin alluvium" designated in this way does appear to be higher and more variable in Vs30 than in "deep alluvium" (Table 1). Unfortunately, because the geographic extent of these areas was approximately drawn based on individual judgment, application to other areas is difficult. In order to apply the same rules in a more systematic way, we have tested the variability of Vs30 in young alluvium with distance from "rock."

To test variability of Vs30 in young alluvium with distance from rock, we used the digital map of Wills and Clahan (2006) and drew polygons enclosing areas within 1, 2, 5, and 10 km from rock. We included Tertiary sandstone and shale, Franciscan and other Cretaceous rocks, and all metamorphic, volcanic, and plutonic rocks in the "rock" category. Older alluvium and Pliocene-Pleistocene alluvial units were not included as "rock". A distance category corresponding to one of these "distance from rock" polygons was then applied to each site where shear-wave velocity has been measured. Sorting the Vs30 measurements by distance category yields the values shown in Table 2 and Figure 3.

Table 2. Vs30 values in young alluvium sorted by distance from rock.

	0-1 km	1-2 km	2-5 km	5-10 km	>10 km
Mean	328.7	314.0	298.0	262.0	212.8
Standard Deviation	96.5	67.3	63.2	59.8	31.6
Mean+SD	425.2	381.3	361.2	321.9	244.5
Mean-SD	232.3	246.7	234.7	202.2	181.2
Minimum	190.0	212.0	172.4	150.6	162.9
Maximum	629.0	452.9	457	478.1	318.4
Count	107	51	59	68	64

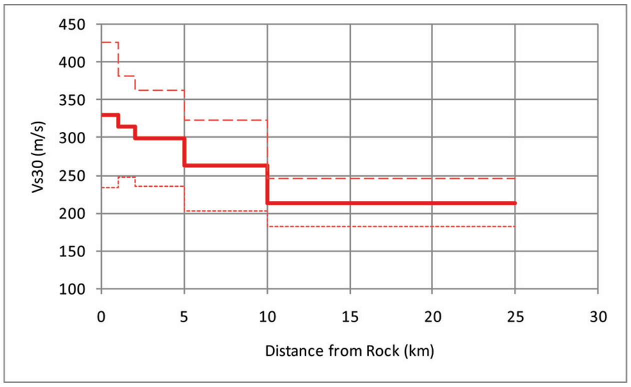

Figure 3. Variation of Vs30 with distance from rock. The solid red line represents the mean Vs30, the dashed red line represents the mean Vs30 plus the standard deviation, and the dotted red line represents the mean Vs30 minus the standard deviation.

As expected, mean Vs decreases with distance from rock. The variability in Vs30 also appears to decrease significantly with distance. The decrease in variability is most apparent between sites from 0-1 km and those from 1-2 km, suggesting that sites more than 1 km from the edge of an alluvial basin are much less likely to encounter higher velocity material within 30 m of the surface. Variability of Vs30 in young alluvium also appears to decrease at distances of over 10 km from rock. This may be because the alluvial deposits at distances greater than 10 km from rock tend to be basin and floodplain deposits composed of silty sand and clay.

Variability of Vs30 in Young Alluvium, with Slope

Another option for subdividing young alluvial deposits is to sort them by the slope of the ground surface. Slope reflects the stream gradient, and therefore the stream's ability to transport material. Thelen and others (2006) noted that for a series of Vs profiles along the San Gabriel River across the Los Angeles basin, Vs30 was proportional to stream power. On a much larger scale, Wald and Allen (2007) proposed that surface slope in all materials could be a useful proxy for Vs30. Although Wald and Allen showed a correlation between slope and Vs30, and this appears to be a useful first approximation, the correlation probably reflects a number of separate causes. In depositional areas, the correlation between slope and Vs30 probably reflects stream power, as proposed by Thelen and others In erosional areas, in contrast, slope may reflect the surface material's resistance to erosion. Although both of these factors may lead to a correlation between higher velocity and steeper slopes, we have examined the correlation of Vs30 with slope in young alluvium (in depositional settings), not the correlation of Vs30 with slope in bedrock (in erosional settings).

Creation of Slope Maps from Digital Elevation Models

Digital Elevation Model Selection

Digital Elevation Models (DEMs) are digital representations of the Earth's surface and are available from various sources, at various resolutions and extents. For this study we chose to compare elevation data from the USGS National Elevation Dataset (NED) (available at *http://ned.usgs.gov/*) and NASA's Shuttle Radar Topography Mission (SRTM) (available at *http://www2.jpl.nasa.gov/srtm/*). These datasets are available in resolutions ranging from 10 to 90 m (1/3 arc-second to 3 arc-second) and both cover the entire State of California.

In order to determine which dataset was better suited for the purpose of producing a statewide slope map, we generated preliminary shaded relief and slope maps using Environmental Systems Research Institute's (ESRI) ArcInfo – ArcGIS, version 9.2, and the ArcGIS Spatial Analyst extension. A cursory review of the maps revealed that the 90-m datasets produced a better generalized surface than the higher resolution data which contained many unwanted artifacts. Further comparisons between the 90-m USGS and 3 arc-second SRTM data revealed that the SRTM data still contained many artifacts, possibly related to vegetation and/or manmade structures, producing an overall rougher surface (Figure 4). Therefore, the 90-m USGS dataset was chosen for our slope analysis. The selected USGS dataset was derived from the USGS 1 arc-second (30-m cell size), 1:24,000-scale seamless DEM. The statewide DEM was projected from decimal degrees to Albers conic, and resampled to a 90-m cell size.

DEM Preparation

In many areas, the digital elevation data produced by the USGS are derived from the interpolation of contour lines. As a result, "step-like" or "rice paddy" artifacts are visible on derivative shaded relief and slope maps. To reduce the effect of these artifacts and obtain a better estimate of slope, the 90-m DEM grid was generalized by calculating the mean elevation value over a specified neighborhood of pixels and applying the calculated value to the central pixel. We generated three generalized slope grids using a 3x3, 5x5, and 9x9 pixel square and compared the results (Figure 5). All generalization processes were effective in diminishing artifacts from the original dataset, but the 9x9 pixel square generalization produced the best definition of large-scale geomorphic features such as alluvial fans and depositional basins.

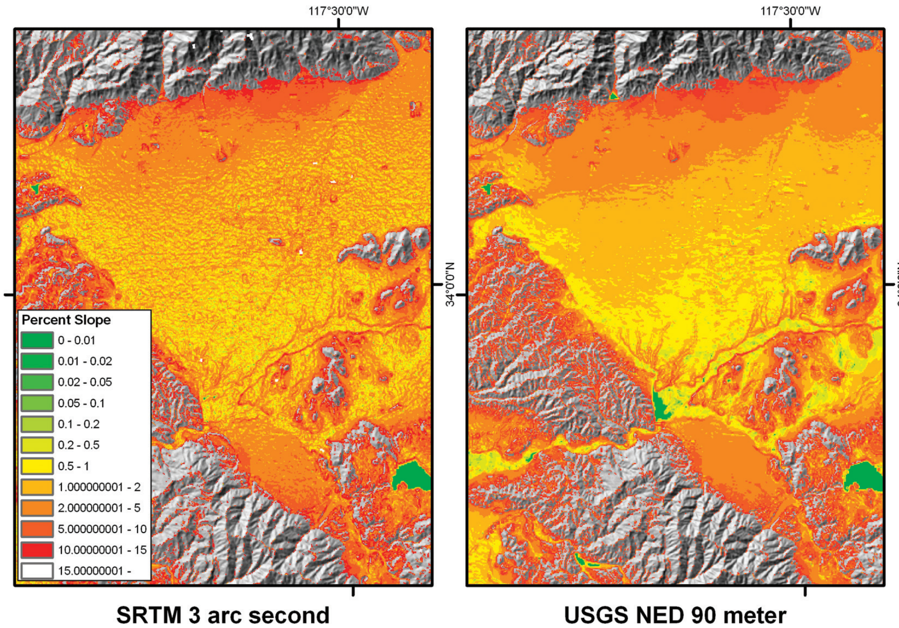

Figure 4. Example of preliminary slope maps generated from the SRTM 3 arc-second and USGS NED 90-m datasets. Note the rough surface depicted in the slope map derived from the SRTM data compared to the slope map derived from the USGS NED data. [A more legible color version of this figure is available at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT08_GutierrezFig4.pdf*]

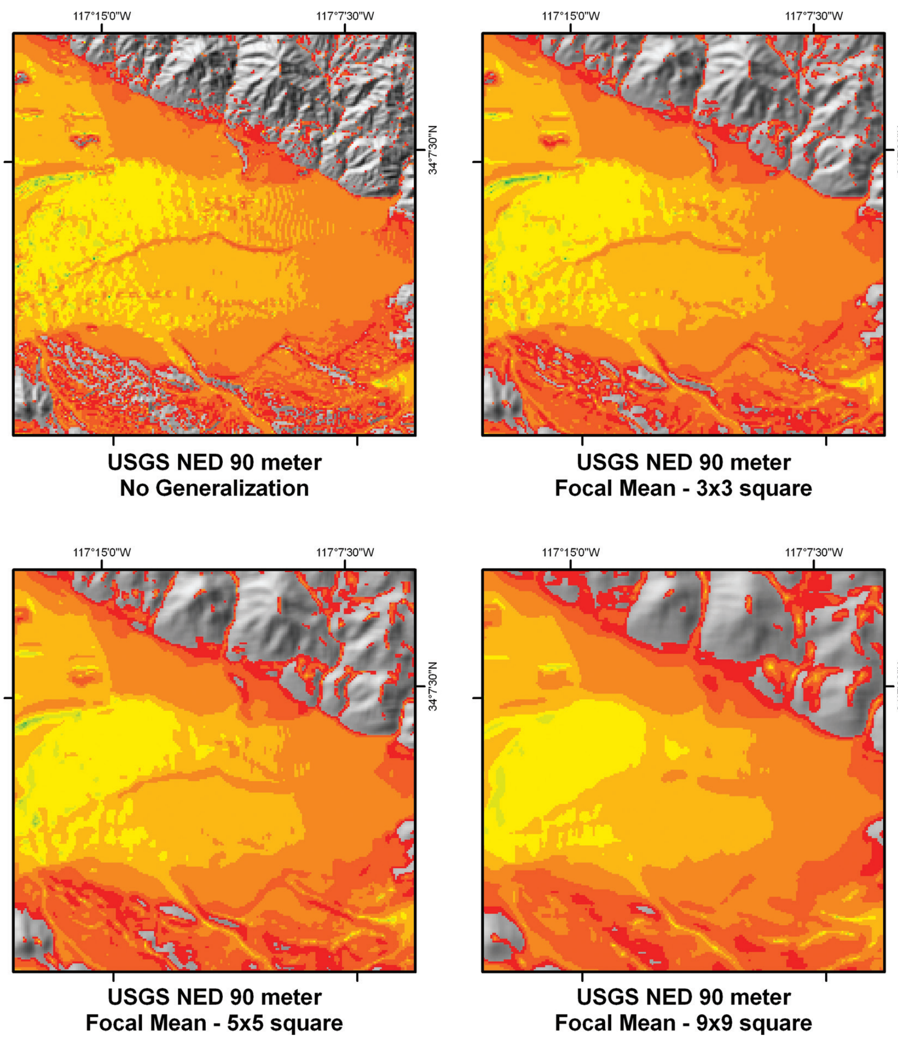

Figure 5. Example of artifacts visible in preliminary slope maps derived from the original unmodified dataset and datasets resulting from the generalization process over a 3x3, 5x5, and 9x9 pixel square. [A more legible color version of this figure is available at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT08_GutierrezFig5.pdf*]

Slope Map Generation

As described above, the USGS NED 90-m DEM was prepared using a generalization process in order to remove artifacts inherent to the data. Spatial Analyst was then used to process the generalized DEM and create a grid depicting the percent slope for each pixel. The slope grid was originally reclassified into 12 classes as shown in Table 3 and graphically shown in Figure 6. Upon examining the data, we found there were only a few or no profiles in each of the four flattest slope categories, and so all measurements less than 0.1 percent slope were grouped into one category. The reclassified slope grid was then used to create a polygon shapefile from contiguous pixels of the same slope class using the "Convert Raster to Features" function in Spatial Analyst.

Table 3. Slope categories originally correlated with Vs30.

Percent Slope	Number of profiles	Mean Vs30	Sd of Vs30
0 - 0.01	*		
0.01 - 0.02	*		
0.02 - 0.05	*		
0.05 - 0.1	21	224	34
0.1 - 0.2	43	227	47
0.2 - 0.5	61	248	54
0.5 - 1	75	303	74
1 - 2	49	320	91
2 - 5	58	356	86
5 - 10	14	353	87
10 - 15			
15 -			
* insufficient data, grouped with category below			

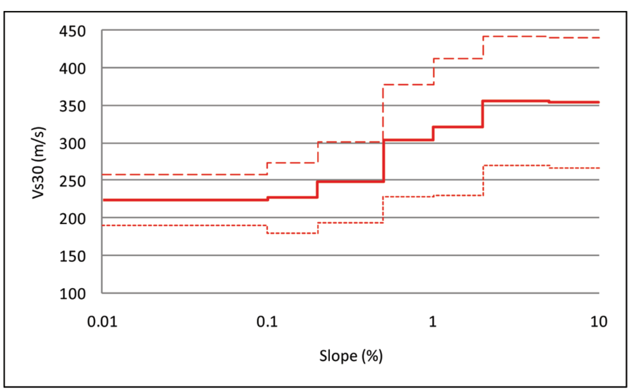

Figure 6. Variation of Vs30 with slope, all categories shown. The solid red line represents the mean Vs30, the dashed red line represents the mean Vs30 plus the standard deviation, and the dotted red line represents the mean Vs30 minus the standard deviation.

Based on our initial analysis, it appeared that the number of slope categories could be further reduced, and the resulting maps simplified. In depicting the boundaries of slope categories on geologic maps, we found that in several cases there appeared to be a coincidence between the 0.5 percent slope boundary from the slope map with the boundary between the lower ends of alluvial fans and adjoining basin or floodplain deposits. Vs30 between 0.5 percent and 1.0 percent appeared similar to Vs30 between 1.0 percent and 2.0 percent, and Vs30 between 2.0 percent and 5.0 percent appeared similar to Vs30 between 5.0 percent and 10.0 percent. We therefore tested whether three simplified categories could subdivide the Vs30 in young alluvium. The results of that test are shown in Table 4 and Figure 7. Comparing the mean and standard deviation of Vs30 with the categories defined by Wills and Clahan (2006) (Table 1) shows that these simplified slope categories result in fewer ranges of Vs30 in young alluvium, and ranges that have comparable standard deviations. This result for the California data, and the potential that the same slope categories can be used in other areas, suggests that these simplified slope categories can be used to develop the next generation map of shallow shear-wave velocity.

Table 4. Simplified slope categories used to develop shallow shear wave velocity.

Slope	Number of profiles	Mean Vs30	Sd of Vs30
$\leq$0.5	169	231	55
0.5-2	124	306	78
>2	73	353	87

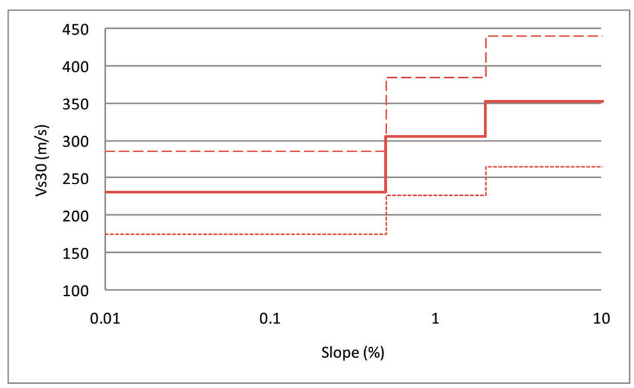

Figure 7. Variation of Vs30 for three simplified slope categories. The solid red line represents the mean Vs30, the dashed red line represents the mean Vs30 plus the standard deviation, and the dotted red line represents the mean Vs30 minus the standard deviation.

Discussion

We have developed two rules that can be applied with available GIS data to develop maps of shear-wave velocity. Subdividing areas underlain by young alluvium either by distance from bedrock or by slope results in polygons with ranges of Vs30 values that are at least as well-defined as the ranges for polygons from the map of Wills and Clahan (2006) using a method that is more objective and reproducible. Either of these rules will allow completion of revised shear-wave velocity maps of California, or potentially of other areas, that define areas with specific ranges of Vs30 as well or better than the previous map and method.

The remaining questions are which of these two rules produces the better delineation of shear-wave velocity classes, and which produces the best correlation with seismic amplification? A study of the correlation of either of these maps with seismic amplification is beyond the scope of this study, but correlations with other geological features suggest that subdivision based on slope is likely to provide better correlation with amplification. One distinct difference between the slope-based and the distance-based maps of the Los Angeles area (Figures 8 and 9) is that the distance-based rule results in concentric gradation of predicted Vs30 in the larger alluvial basins, whereas the slope-based rule results in asymmetric gradation of predicted Vs30. The asymmetric slopes of the San Fernando, San Gabriel, and upper Santa Ana River basins are the result of large alluvial fans that have their sources in the San Gabriel and San Bernardino Mountains north of the Los Angeles Basin, and much smaller uplifts and resultant alluvial fans along the south sides of those basins. The topography and mapped geology delineate steep, coarse-grained alluvial fans along the northern edges of these basins which grade to less-steep and finer grained deposits to the south. In each of these basins, the finest-grained materials, and many of the low Vs30 measurements, are along the southern edges of these basins, where a distance from bedrock rule would predict relatively high Vs30. Although the statewide dataset does not clearly distinguish the slope-based rule for subdividing young alluvium as better than the distance-based rule, slope appears to more clearly correlate with grain size and possibly with Vs30 in these asymmetric basins. Additionally, as noted above, the boundary on the slope maps between slopes steeper and less steep than 0.5 percent coincides with a boundary on some geologic maps between sandy and gravelly alluvial fan deposits and floodplain and basin deposits that are commonly finer grained. This coincidence suggests that a slope-based boundary may have better correlation with grain size than the distance-based boundaries.

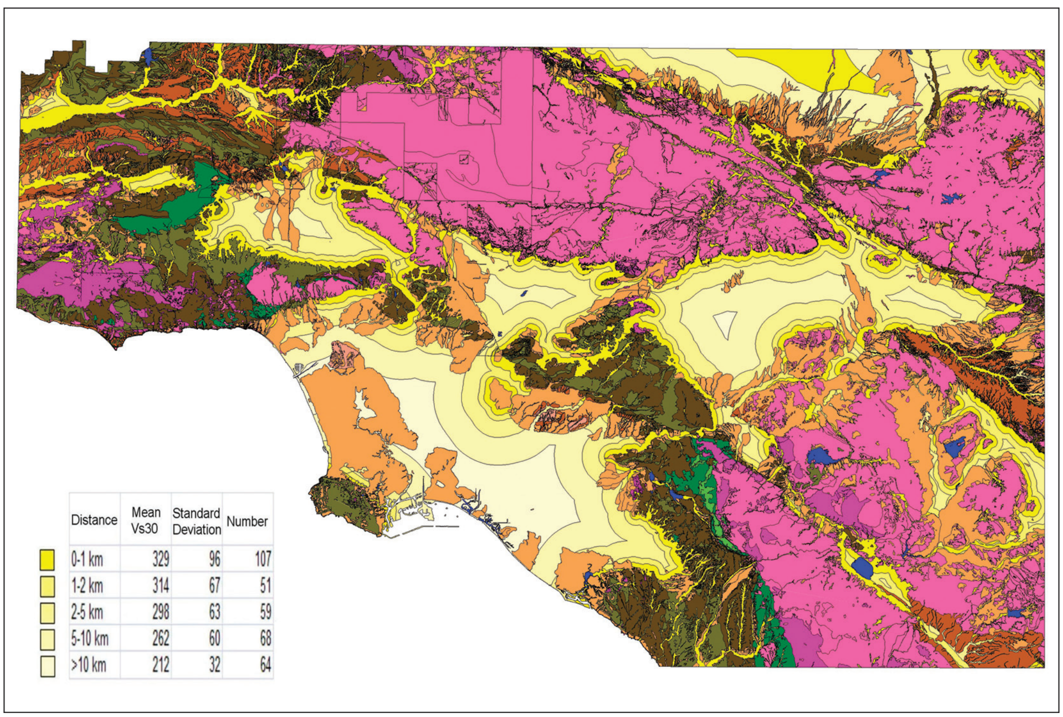

Figure 8. Preliminary map of shear-wave velocity in the Los Angeles region using detailed (1:24,000) geologic maps, the lateral distance from bedrock as a method to classify younger alluvium, and the classification of Wills and Clahan (2006) for other units. Young alluvium shown in shades of yellow, other units as defined on Figure 1. Using distance from bedrock and larger scale geologic maps results in better definition of velocity categories and more precision in location of boundaries than that of the previous statewide map. [A more legible color version of this figure is available at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT08_GutierrezFig8.pdf*]

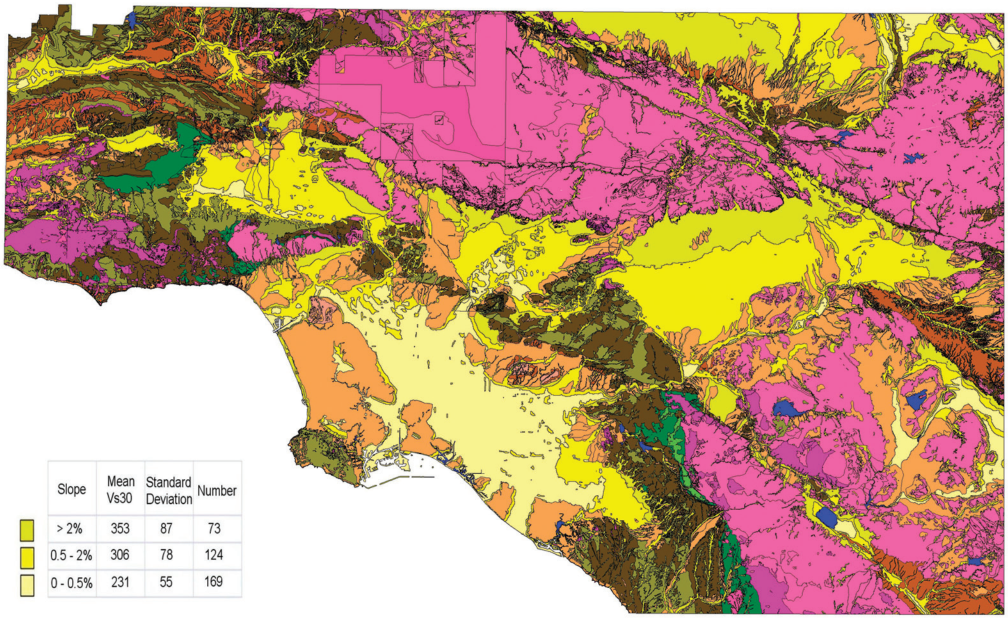

Figure 9. Preliminary map of shear-wave velocity in the Los Angeles region using detailed (1:24,000) geologic maps, land slope as a method to classify younger alluvium, and the classification of Wills and Clahan (2006) for other units. Young alluvium shown in shades of yellow, other units as defined on Figure 1. Using slope and larger scale geologic maps results in better definition of velocity categories and more precision in location of boundaries than that of the previous statewide map. [A more legible color version of this figure is available at *http://ngmdb.usgs.gov/Info/dmt/docs/DMT08_GutierrezFig9.pdf*]

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