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TESTING GEOLOGIC BOUNDARIES FOR VS MAPPING IN LAS VEGAS, NEVADA

Helena MURVOSH [1], Barbara LUKE[2], and Wanda TAYLOR[3]

ABSTRACT

As part of an interdisciplinary effort to study earthquake hazards and related risks in the Las Vegas Valley, Nevada (USA), a three-dimensional map of shear-wave velocity (V_S) of the Valley to a target depth of 500 m is being developed. An extensive catalogue of the Valley's lithology from well logs and exposures will be used to aid in interpolation of the V_S data. Geographic partitioning of the Valley is being tested for the map development. Potential partitions are alluvial fan boundaries and boundaries separating predominant soil types. To test these boundaries, V_S data from three alluvial fans and a predominantly clay area were compared. This preliminary study suggests a geographic boundary separating the east areas of the Valley from the west. Additional studies incorporating a larger dataset are required to confirm outcomes of this study and to determine whether further subdivision is warranted.

Keywords: velocity, lithology, shear-wave, interpolation, Las Vegas, clay

INTRODUCTION

Internationally popular vacation destination Las Vegas, Nevada, is one of the fastest growing cities in the United States and is located in one of two U.S. states ranked third in strong seismic activity (Anderson and Miyata, 2006). To better understand the consequences of earthquakes and to educate local residents on ways to protect themselves from harm in the event of an earthquake, a team of seismologists, geologists, and engineers is working toward a comprehensive understanding of the earthquake hazards for the Las Vegas Valley and related risks to human safety and structural performance.

As part of this effort, the team is developing a three-dimensional (3-D) shallow (target depth 500 m) shear-wave velocity (V_S) map of the Valley, which will be used for site response analyses, ultimately to develop earthquake hazard maps for the Valley. To that end, surveys are to be conducted across the Valley to expand an existing dataset of shallow V_S profiles. The existing V_S dataset consists of approximately 80 sites. This includes body- and surface-wave measurements performed by both researchers and private consultants (Liu, 2006).

Body-wave measurements include downhole and crosshole methods. These methods allow direct determination of V_S. Because they are intrusive, borehole-based measurements provide accurate local detail. Surface wave measurements include the active-source spectral-analysis-of-surface-wave (SASW) and multichannel-analysis-of-surface-wave (MASW) methods and the passive-source refraction

[1] Civil Engineer, Stanley Consultants, Las Vegas, NV, Email: murvoshhelena@stanleygroup.com.
[2] Associate Professor, Department of Civil & Environmental Engineering, University of Nevada, Las Vegas, Las Vegas, NV, Email: barbara.luke@unlv.edu.
[3] Professor and Chair, Department of Geoscience, University of Nevada, Las Vegas, Las Vegas, NV, Email: wanda.taylor@unlv.edu.

microtremor (ReMi) method. With these methods, the Rayleigh wave phase velocity is measured as a function of frequency, then V_S profiles are derived through inversion. Surface wave methods sample a broader volume of a site than do the borehole methods. In contrast to the localized borehole-based measurements, the V_S from a deep surface wave measurement is representative of a considerable volume of earth. Surface wave methods are cost-effective and efficient. The passive-source method is the most efficient, because no source equipment is required. It is beneficial for obtaining deep data and for quickly obtaining a single, representative velocity value. However, active-source methods are preferred for shallow measurements. Results from active- and passive-source surface-wave measurements can be combined to obtain V_S profiles to great depths that are rich in detail at shallow depths (e.g., Martin et al., 2006; Liu et al., 2005). At a few key sites, both borehole-based and surface wave measurements are conducted, for purposes of validation.

Supplementary to the detailed, project-specific dataset, the public record is being mined to acquire V_S profiles and 30-meter depth-averaged V_S ($V_{S(30)}$) values. By 2003, all of the local public-works agencies had adopted the International Building Code (IBC). Since that time, surveys performed by geotechnical consulting firms or their consultants to determine $V_{S(30)}$ in accordance with the IBC have become increasingly common (Murvosh et al., 2006). At present, 67 such surveys have been retrieved and compiled. Lithologic logs from shallow (6- to 12-m) boreholes drilled at these sites are also available.

The V_S survey locations archived to date are shown on Figure 1. The existing dataset and the additional surveys retrieved from the public record are archived on a website (http://www.ce.unlv.edu/egl/lv_archives/) for public access.

The combined datasets total nearly 140 V_S profiles, approximately one for every 11 square km of the 1600-km^2 Valley. Despite this, V_S data coverage for many areas is sparse. Thus, determination of V_S by interpolation might be subject to considerable error for some parts of the Valley. Therefore, an extensive catalogue of the Valley's lithology, developed from well logs over 30 m deep, exposures and basin structure, and local faults gleaned from geological and geophysical observations will be consulted as a basis for interpolating velocity. The term "lithology" in this paper is used broadly to encompass both the lithified and non-lithified components of the basin sediments.

This paper explores whether the Valley should be partitioned geographically to perform the V_S-lithology correlation. For the purpose of this research, geographic partitioning is defined as assigning geographic boundaries across which V_S will not be interpolated. Furthermore a lithology can be assigned a unique velocity value or profile on either side of the boundary. For example, gravel located on one side of a boundary may have a different V_S than gravel located on the other side. To study this question, we assumed that geographic partitioning should be applied. We then defined four study areas within four geologically distinct areas in the Valley: an area within which clay predominates in the upper 30 meters, and three areas located in different alluvial fans, each with a different source material. Finally, we compared average V_S profiles and $V_{S(30)}$ values from the four areas. For this preliminary study, the comparisons were performed for small samples. If distinct differences in V_S between the areas were found, this would indicate the potential usefulness of geographic partitioning, and in the next step of the study, the entire V_S dataset would be incorporated. The importance of considering depth when assigning velocity values to lithology is also discussed in this paper.

BACKGROUND STUDIES FOR V_S - LITHOLOGY CORRELATION

Use of a much larger lithology dataset to interpolate a smaller V_S dataset over a broad area is gaining popularity for developing V_S maps. For any city in the U.S., the amount of data available regarding soil type, lithology and geologic structure is greater by far than the amount of V_S data available. For example, lithologic logs recorded during well drilling are often archived by public agencies, geotechnical reports filed with public agencies contain borehole logs, soil maps are available from the U.S. Department of Agriculture Natural Resources Conservation Service, and geologic maps are available from state and national geologic offices. Previous studies for other sites have shown correlations between lithology and V_S, as discussed below.

In their development of earthquake-scenario and probabilistic ground-shaking maps for Salt Lake City, Utah, Wong et al. (2002) defined five distinct site-response units according to a study that grouped surficial geologic units on the basis of predominant grain size. They then developed average shallow V_S profiles for each unit from V_S measurements. For verification purposes, profiles for two of the units were compared to similar sediment types found in Northern California.

Gomberg et al. (2003) developed a 3-D lithologic model for the upper 30 m in Memphis, Tennessee, from a database of more than 1200 well and borehole logs by identifying the depths to the interfaces between the five uppermost major lithologic units. The major units occur in layers. The depth to each unit was estimated from the lithologic model at the locations of 76 V_S profiles. A velocity value was then assigned to each lithologic unit based on the corresponding depth at each survey location, resulting in 76 V_S estimates for each unit. The results were examined to determine whether the V_S values for each unit fell within a narrow range, an indication that lithology could be used to approximate velocity. Although the authors found considerable overlap in the range of velocities estimated for each unit, they determined that each range was narrow enough to permit assignment of a velocity value to each unit. Their velocity-lithology correlations did not explicitly address depth. However, because the lithologic units are layered, depth inherently becomes a part of the correlation.

Scott et al. (2006) studied the relationship between measured $V_{S(30)}$ values and mapped geologic formations, soil types, and a shallow stratigraphic model for the Las Vegas Valley. The V_S data for 49 locations along a 13-km transect plus 30 other locations scattered across the Valley were compared to a stratigraphic model compiled from over 1100 well logs, geologic maps, and a Paleozoic bedrock map of the Las Vegas Valley compiled by Langenheim et al. (2001). The geologic model of the Valley-fill sediments comprised six summary geologic units: pre-Cenozoic, Oligocene to Miocene, carbonate, gravel, sand, and clay. Histograms illustrated distributions of velocities for all of the units except the sand unit, where no V_S measurements were made. The effects of depth on V_S were not considered in compiling the histograms. The velocity-lithology correlations were then used to develop a shallow V_S model and the model was compared to the measured V_S values. The authors determined that this method could not be used directly to accurately extrapolate $V_{S(30)}$ across the Valley and suggested employing geographic partitioning techniques instead.

Geographic partitioning is supported by site response analyses performed by Liu (2006; Luke et al., 2006) for the Las Vegas Valley. Using the same dataset as Scott et al., Liu defined two seismic response zones according to the predominant lithology in the upper 30 m: 1) clay and 2) coarse-grained and mixed-grain size materials. This research is summarized by Luke et al. (2007).

VALLEY GEOLOGY

The Las Vegas Valley is located in the Basin and Range geomorphic province (Figure 1). The Sheep and Las Vegas Ranges are located to the north. To the east are Frenchman and Sunrise mountains. The River Mountains and McCullough Range are located to the south and the Spring Mountains to the west. These ranges are composed of Proterozoic metamorphic rocks, Paleozoic marine sedimentary rocks, Mesozoic marine and terrestrial sedimentary rocks, and Cenozoic volcanic and terrestrial sedimentary rocks. The maximum depth to Paleozoic bedrock is near 5 km and occurs ~5 km west of Frenchman Mountain (Langenheim et al., 2001).

Wyman et al. (1993) provided an extensive description of the Valley's geology, especially with regard to the shallow soils that are tested in a V_S survey. They described the Valley as northwest-trending, generally following the geometry of the right-lateral strike-slip Las Vegas Valley Shear Zone. The Valley is underlain by coalescing alluvial fans. The major source of alluvial deposits is the Spring

Mountains. These deposits become increasingly finer from west to east, with increasing distance from the source and with decreasing elevation. From the lowest elevations just west of Frenchman and Sunrise mountains, elevations increase eastward across a small alluvial fan sourced from those mountains. The Pittman Fan at the southeast end of the Valley is sourced from the River Mountains and the McCullough Range. Fan locations shown on Figure 1 are from Plume (1989). Although the ages of the fan source rocks differ, this difference would not contribute to differences in V_S values between fans because the age of the fans themselves is approximately the same.

Cemented soils and medium-dense to denser sands and gravels typically occur in alluvial fans surrounding the Valley, but also occur in the predominantly clay areas. The most extremely cemented deposits, known locally as caliche, are located in the western and central portions of the Valley (Wyman et al., 1993). Caliche is heavily carbonate-cemented fines, sand or gravel. It has a high V_S, with reported laboratory values of 2350 m/s (Stone and Luke, 2001) and field values measured as high as 2000 m/s (Tecle et al., 2003). It appears in lenses that can have thickness up to 2 m or more. It can occur as an inclusion at any depth within the shallow sediments and in any lithology.

By studying the well logs across the Valley, Taylor et al. (2004) verified that clay deposits dominate in the deep, central and south part of the Valley, and the coarse- and mixed-grain size deposits dominate in the shallower, west, part of the Valley.

TESTING BOUNDARIES FOR V_S -LITHOLOGY CORRELATIONS

Based on the Valley's geology and research by Liu (2006) establishing two seismic response zones, we assumed that a geographic boundary between the fine- and coarse-grained materials exists. Because of the different source materials for the alluvial fans in the Valley, we also tested the hypothesis that the coarse-grained material could be subdivided by fan. Four study areas were established from four geologically distinct areas: three alluvial fans (Red Rock, Flamingo, and Pittman), each with different source material (clastic, carbonate and igneous rocks, respectively), and the clay-rich area. The source and predominant materials for the four areas and key generic mechanical properties are listed in Table 1. Not surprisingly, the bulk modulus and density of clay are substantially lower than those of the source materials of the fans. The mechanical properties of the fan sources also differ among themselves. This suggests a potential for differences between V_S of the fans.

Locations of the V_S surveys selected for study are shown in Figure 1. Study sites near boreholes were favored so that the V_S profiles could be compared to well logs in the future. The selection of sites to investigate the clay area was based on the proximity of the sites to each other (1.4 km maximum) and to a lithologic control location (less than 1 km). Seventeen Flamingo Fan locations were chosen based on their proximity to boreholes (less than 1 km). Three of these V_S datasets (identified in Figure 1) had only single-valued $V_{S(30)}$ data. No deep ($\geq$ 30-m) boreholes are located in the Red Rock Fan, so borehole location did not factor into site selection. Only one V_S dataset was available for the Pittman Fan. The closest recorded well location is 1.4 km away; however, the site of the V_S test is known by the authors to contain 0 to 3 m of fill over 8 to 13 m of silty sand.

An average V_S profile was calculated for each of the four areas (Figure 2). The number of V_S surveys averaged for each area is shown in Table 1. The data scatter and overlap of the V_S values among areas are also shown in Figure 2. The $V_{S(30)}$ values are plotted according to area in Figure 3.

DISCUSSION

The clay area and the Pittman Fan have substantially lower average V_S values (Figure 2) for all depths, as well as lower $V_{S(30)}$ values (Figure 3), than the Red Rock and Flamingo Fans. The difference in values is consistently 1000 m/s and is a strong indication that a geographic boundary can be used to separate the eastern areas of the Valley from the western areas. Partitioning based on the predominance of clay in the upper 30 m concurs with the findings of Liu (2006). The V_S profile for the Pittman Fan is from a single survey; additional surveys in the Pittman Fan are necessary to determine whether the profile is representative of the Fan overall. These additional surveys are also needed to determine whether the V_S values for the clay and Pittman Fan areas differ enough to warrant subdividing these areas.

Below 5 m depth, the average V_S of the Flamingo Fan is 50 to 300 m/s greater than that of the Red Rock Fan. The $V_{S(30)}$ values for the Red Rock Fan are scattered, with two locations having values more than 200 m/s higher than the other locations in this area. The shallow borehole logs for those locations showed caliche layers as shallow as 0.2 m and as thick as 6 m. Without these two sites, the $V_{S(30)}$ data for the Red Rock Fan are more tightly clustered at lower values than those for the Flamingo Fan. Further study is needed to determine whether the difference is great enough to warrant subdividing these areas.

The differences in V_S between the study areas may be due to differing lithology of the source materials. The bulk moduli for the fan source materials and clay are plotted in Figure 4. Overall, the moduli of the source material/predominant lithology of the west areas (Red Rock and Flamingo Fans) are higher than those of the east areas (Pittman Fan and clay area). This pattern correlates with the pattern found for the V_S values of the sediments, higher in the west areas than the east. In addition, the ranking of the west areas according to modulus of the source material/predominant lithology corresponds to the ranking according to V_S of the sediment, with the Flamingo Fan having the highest V_S and source material of highest modulus, followed by the Red Rock Fan.

The Valley's lithology varies both vertically and laterally. In general, V_S increases with depth due to the effects of confining pressure. However, a high-velocity caliche layer can occur above a lower-velocity layer like clay (e.g., Tecle et al. 2003). The consequences of high-velocity caliche inclusions that are irrespective of host material were not considered in this initial investigation, but must be addressed to produce a reliable 3-D V_S map. Methods to account for the caliche in the partitioning scheme are being researched. Correlation distances are also being researched to determine reasonable distances over which V_S data may be extrapolated. The results of these studies will factor into site-selection for additional V_S measurements.

CONCLUSIONS

Identification of appropriate geologic boundaries to more precisely use lithology to interpolate V_S is essential to developing a useful 3-D shallow (to 500 m) V_S map of the Las Vegas Valley. Four areas were targeted to test potential geologic boundaries based on their different source or predominant materials: clay, and Red Rock, Pittman, and Flamingo Alluvial Fans. Selected V_S data were averaged by area and compared. The V_S values from the clay area and the Pittman Fan are substantially lower than those from the Red Rock and Flamingo Fans. The V_S values from the Red Rock Fan are lower than those from the Flamingo Fan. These differences in V_S can be explained by differences in mechanical properties between the clay area and the fans, and possibly also by differences in the source materials for the different fans. This study indicates that it might be appropriate to partition the Valley according to fan locations as well as predominant lithologies. This conclusion is tentative, however, because the datasets were small, especially for the Pittman Fan. Studies incorporating a larger dataset and including new V_S surveys are planned to verify that a geographic boundary may be used to separate the east and west areas of the Valley in developing the 3-D V_S map and to determine whether further subdivision of these areas is warranted. Correlations of V_S to lithology for the Valley must also consider effects of depth. Because caliche deposits occur at various depths and with varying thickness, increases in V_S due to source material and confining pressure must be considered separately from those resulting from cementation.

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Table 1 –Generic material properties of study areas' source materials/predominant lithology

Area	Source material description	Source material/ predominant lithology	Shear modulus (GPa)	Bulk modulus (GPa)	Density (g/cm^3)	No. of V_S profiles
Red Rock Alluvial Fan	Clastic rock – Sandstone, shale, conglomerate, gypsum beds, and limestone [1]	Sandstone [3]	---	21.37	2.2	12
		Shale [3]	---	58.19	2.81	
Flamingo Alluvial Fan	Carbonate rocks – Mostly limestone and dolomite but includes conglomerate, quartzite, sandstone and shale [1]	Limestone [3]	---	51.0	2.3	14
		Dolomite [2]	45-51.6	76.4-94.9	2.87-2.88	
Pittman Alluvial Fan	Igneous rocks – Volcanic flows, flow breccias, and shallow intrusives of dacite, andesite, and basalt [1]	Basalt [3]	---	33.9	2.2	1
Clay	N/A	Clay [2]	1.4-9	1.5-25	1.58-2.6	4

[1] Plume, 1989.
[2] Generic material properties from Mavko et al., 1998.
[3] Generic material properties from Rahn, 1996.

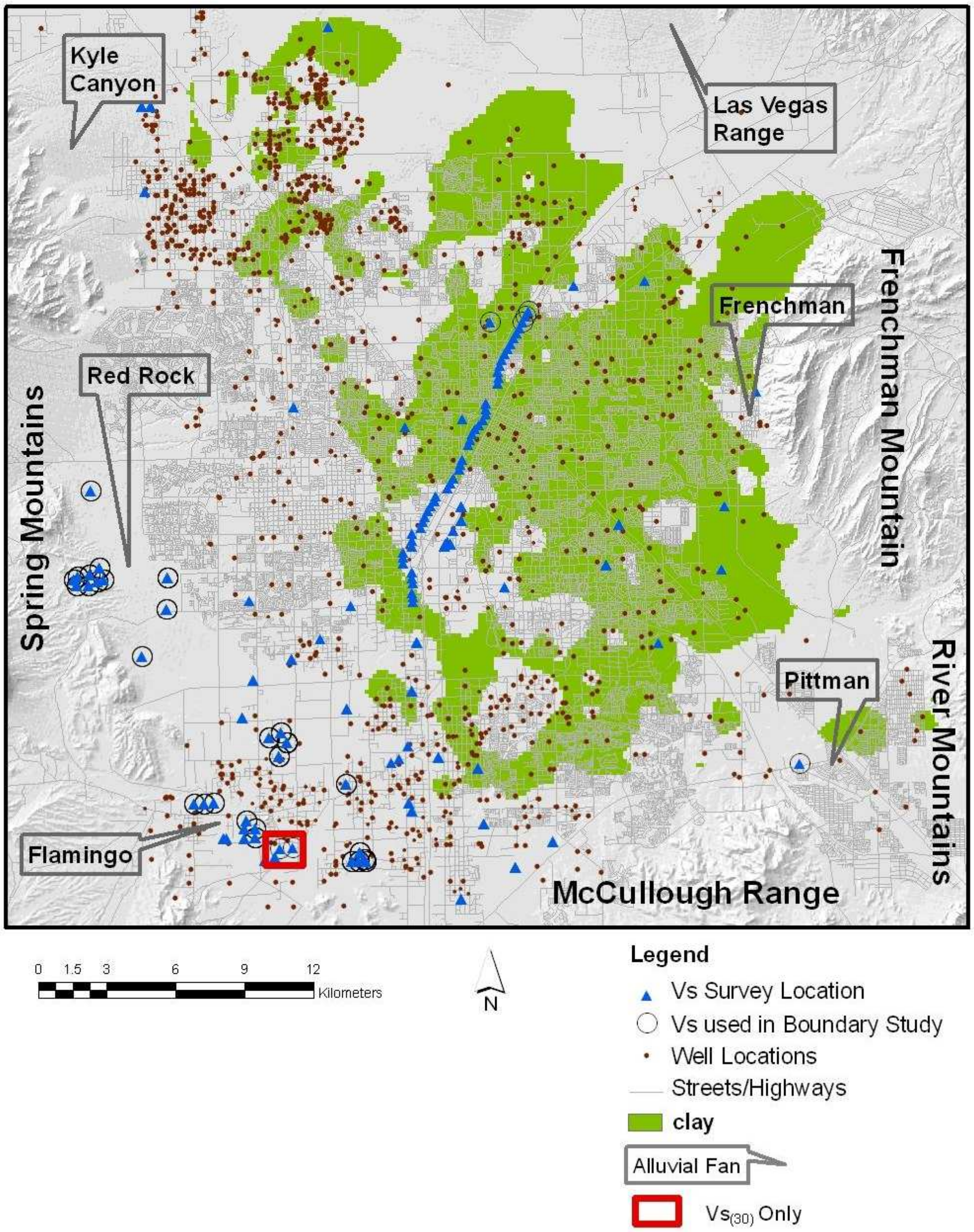

Figure 1. The Las Vegas Valley: Bounding mountain ranges, alluvial fans, lithologic well logs and V_S datasets. Areas where clay predominates in the upper 30 m are shaded.

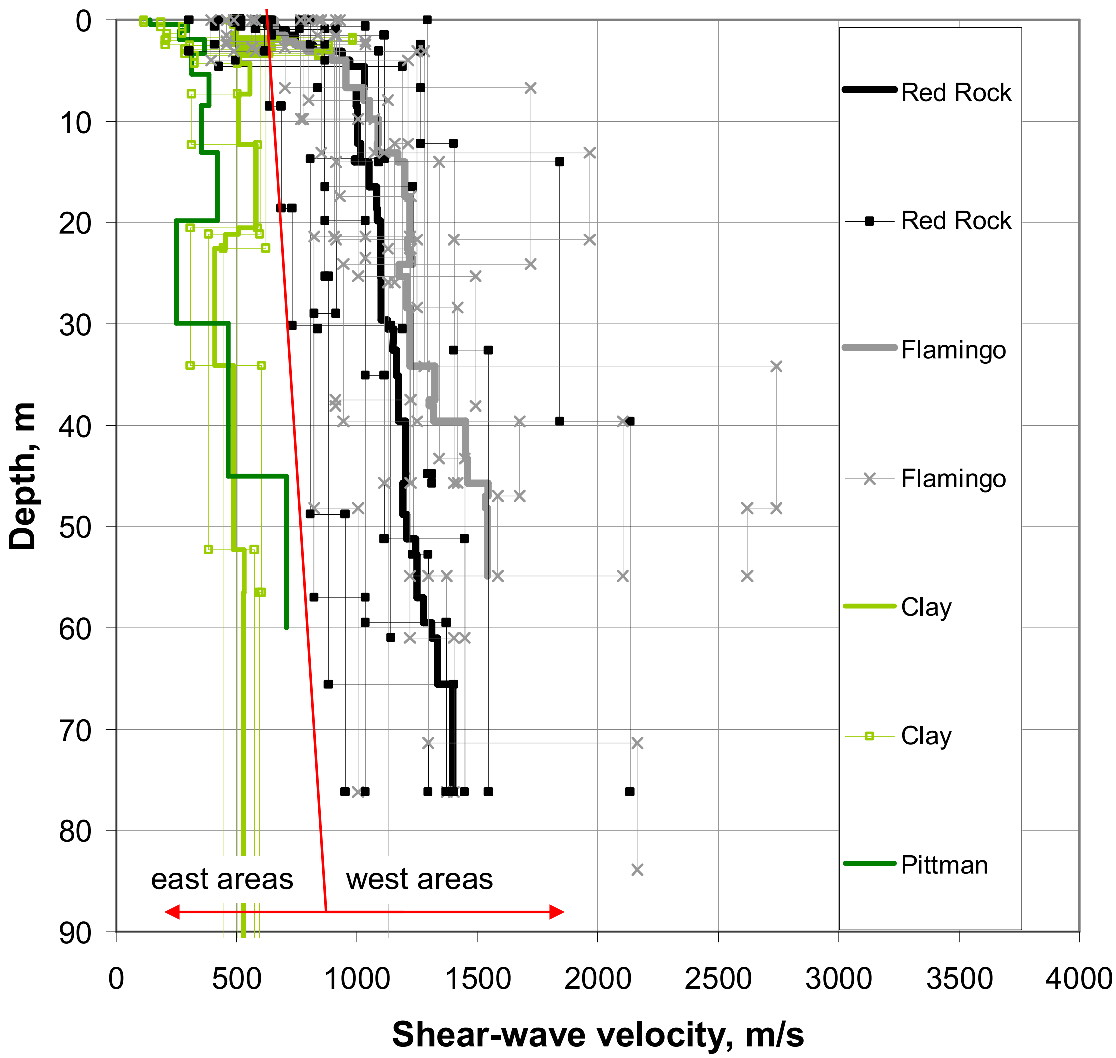

Figure 2. V_S **versus depth: original** V_S **data (shown with symbols) and average** V_S **profiles (no symbols) for the four areas studied.**

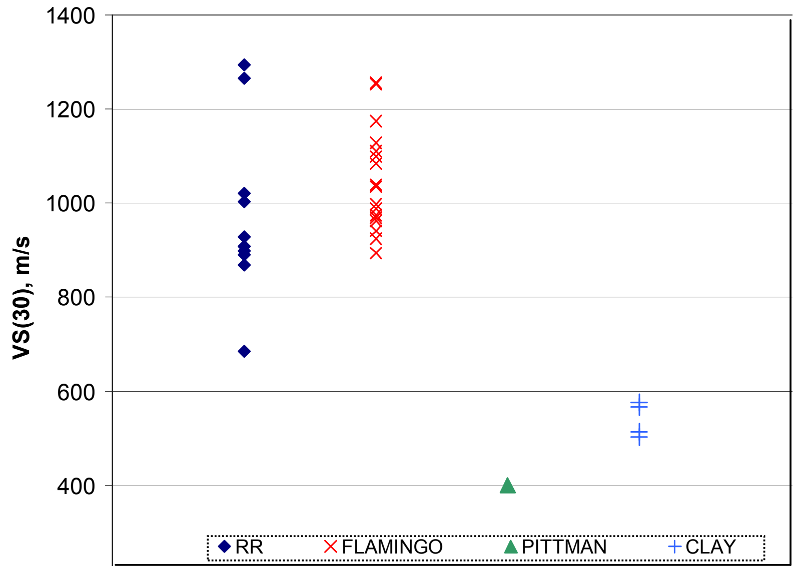

Figure 3. $V_{S(30)}$ **values for the four areas studied.**

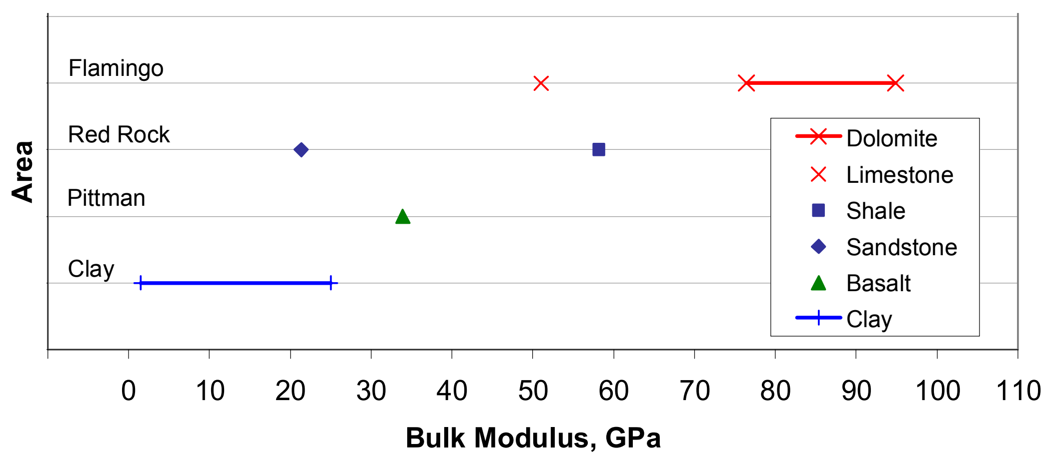

Figure 4. Bulk modulus of the source materials/predominant lithology.

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