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Lithostratigraphy and Shear-Wave Velocity in the Crystallized Topopah Spring Tuff, Yucca Mountain, Nevada

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Abstract – Evaluation of the seismic response of the proposed spent nuclear fuel and high-level radioactive waste repository at Yucca Mountain, Nevada, is in part based on the seismic properties of the host rock, the 12.8-million-year-old Topopah Spring Tuff. Because of the processes that formed the tuff, the densely welded and crystallized part has three lithophysal and three nonlithophysal zones, and each zone has characteristic variations in lithostratigraphic features and structures of the rocks. Lithostratigraphic features include lithophysal cavities, rims on lithophysae and some fractures, spots (which are similar to rims but without an associated cavity or aperture), amounts of porosity resulting from welding, crystallization, and vapor-phase corrosion and mineralization, and fractures. Seismic properties, including shear-wave velocity (V_s), have been measured on 38 pieces of core, and there is a good "first order" correlation with the lithostratigraphic zones; for example, samples from nonlithophysal zones have larger V_s values compared to samples from lithophysal zones. Some samples have V_s values that are beyond the typical range for the lithostratigraphic zone; however, these samples typically have one or more fractures, "large" lithophysal cavities, or "missing pieces" relative to the sample size. Shear-wave velocity data measured in the tunnels have similar relations to lithophysal and nonlithophysal rocks; however, tunnel-based values are typically smaller than those measured in core resulting from increased lithophysae and fracturing effects. Variations in seismic properties such as V_s data from small-scale samples (typical and "flawed" core) to larger scale traverses in the tunnels provide a basis for merging our understanding of the distributions of lithostratigraphic features (and zones) with a method to scale seismic properties.

I. INTRODUCTION

Part of the assessment of the seismic response of the proposed spent nuclear fuel and high-level radioactive waste repository at Yucca Mountain, Nevada, depends on understanding the seismic properties of the host rocks -- the crystallized part of the Topopah Spring Tuff of Miocene age. A variety of rock and seismic properties data has been collected from the tuff in the past 25 years [OCRWM, 2003]; however, in the last 4 years a concerted effort has been made to correlate shear-wave velocity (V_s) properties with specific lithostratigraphic units in the tuff. Samples were collected from numerous surface-based and tunnel-based boreholes. The seismic measurement techniques used are simple compared to other techniques; however, the measured values are of high technical quality and can be evaluated with a variety of analytical methods. This paper describes: (1) variations in features in six lithostratigraphic units of the densely welded and crystallized part of the Topopah Spring Tuff, (2) the seismic measurement techniques used in the laboratory and the tunnels at Yucca Mountain, and (3) correlation of the V_s properties of core with specific lithostratigraphic units.

II. LITHOSTRATIGRAPHIC SETTING, FEATURES, AND ROCK PROPERTIES

The Topopah Spring Tuff is a large-volume, pyroclastic-flow deposit (or ignimbrite) that was erupted and deposited about 12.8 million years ago [Sawyer and others, 1994]. The Topopah Spring Tuff has been described as a compound cooling unit [Christiansen, 1979] resulting from more than one eruption and deposition event. At Yucca Mountain, however, the tuff appears to be a single cooling unit, and the variations in depositional features are consistent with the aggradational accumulation from a pyroclastic flow [Buesch and Spengler, 1998]. The importance of a single depositional and cooling event is that the processes of deposition, welding (including the redistribution of vapor in the deposit), crystallization, and cooling result in a simpler and more predictable distribution of lithostratigraphic features and units than would be formed with a compound cooling unit. The tuffis divided into lithostratigraphic units (members, zones, and subzones) on the basis of the distribution of lithostratigraphic features such as the amount of crystal fragments (previously referred to as phenocrysts), the amount of welding, the amount of lithophysae, and whether the material is glass (vitric) or crystallized [Buesch and others, 1996; Buesch and Spengler, 1998] (Fig. 1). The lithostratigraphic units form a stratiform geometry where the vertical section of units can be traced laterally through the mountain, although some units pinch out laterally. Because many lithostratigraphic features (and therefore units) are the cumulative result of deposition, welding, and cooling processes, the lithostratigraphic framework represents the three-dimensional distribution of rock properties, such as density and porosity (and the types of porosity). It is in this context of lithostratigraphic units and distributed rock properties that core samples from the various units have been analyzed for shear-wave velocity characteristics.

In the densely welded and crystallized rocks of the Topopah Spring Tuff, the lithostratigraphic features and the associated depositional, welding, and cooling processes are:

1. Depositional features include crystal fragments, glass shards, and pumice and lithic clasts. Crystal fragments are from crystals that had grown in the magma chamber prior to eruption, glass shards and pumice clasts are from fragmentation of the magma during eruption, and lithic fragments are incorporated from the walls of the magma chamber, conduit, or vent area, or picked up along the ground surface. For properties such as porosity, the amount of crystal fragments and lithic clasts does not substantially affect the properties (unless the fragment or clast amounts are large compared to sample size).
2. During welding, glass shards and pumice clasts deformed, resulting in an overall decrease in porosity to form a dense, glassy rock (vitrophyre) typically with less than 10 percent porosity [Buesch, 2000]. Distribution of welding-influenced porosity varies based on whether vapor, which was initially interstitial to the depositional grains, was redistributed away from some areas and accumulated elsewhere. Where the vapor accumulated at super-lithostatic pressure, cavities formed and inflated to form lithophysae.
3. During crystallization of the glass matrix, the minerals formed typically are 65 to 75 percent feldspar with 25 to 35 percent silica polymorphs (quartz, cristobalite, and tridymite) [Chipera and others, 1995], and most features associated with crystallization form a spatially systematic distribution that resulted from varying amounts of interaction with the vapor. Rims of fine-grained material, described in Figure 2, formed in locations with the greatest exposure to the vapor (around lithophysal cavities and along fractures). Spots are similar to rims, except there is no cavity. Thin borders of very fine-grained material formed around many rims (Fig. 2). The matrix-groundmass near the borders typically differs in color and is slightly coarser grained than the matrix-groundmass farther from the lithophysae or fracture (Fig. 2). Porosity of these crystallization features varies substantially; porosity of the matrix-groundmass is about 10 percent, and rim and spot materials are about 30 percent with a range from 20 to 40 percent [Otto and Buesch, 2003] (Fig. 2).

4. In some rocks, the vapor corroded parts of the glass prior to crystallization and created an enhanced porosity.
5. During the cooling of the rocks, two processes operated independently. As temperature decreased throughout the cooling process, the volume decreased as the glass crystallized, and both the glass and crystallized material contracted volumetrically, forming fractures. During the cooling sequence when elements in the vapor become supersaturated, minerals (especially tridymite) precipitated from the vapor, and in some rocks this vapor-phase mineralization resulted in a porosity decrease.

These processes of welding (including redistribution of vapor), crystallization, vapor-phase corrosion, and mineralization, and fracturing determine the lithostratigraphic features, micro- to macro-scale structure, and properties of specific rocks and lithostratigraphic units as a whole. The various scales at which these processes were active determine the dimensions of the resulting features (lithophysae, rims, spots, porosity resulting from vapor-phase corrosion or mineralization, and fractures). Typical ranges in sizes are: lithophysal cavities, 1 mm to 1.8 m in diameter; rims, <1 mm to 89 cm wide; spots, 1 to 32 cm in diameter; vapor-phase corroded cavities, <1 mm to 10 cm in diameter; fracture apertures, 5 μm to 52 cm wide; and fracture lengths, <2 mm to 51 m (David C. Buesch, U.S. Geological Survey, unpublished data; and U.S. Department of Energy, unpublished Yucca Mountain Project data). With these ranges in sizes and abundance of the various features relative to sample size (whether measured in cm^3, m^3, dkm^3, or km^3), variations in property values can be better understood, and possibly scaling relations could be established from small-scale samples measured in the laboratory to large-scale field measurements [Buesch, 2000]. Porosity has been used as an example of rock properties because it is easily measured and variations in porosity can be correlated to different types of features and lithostratigraphic units; in addition, porosity correlates well with many hydrogeologic and mechanical properties [Flint, 1998; Price, 1988].

III. MEASUREMENT OF SHEAR WAVE PROPERTIES

The unconfined, free-free, resonant column (FFRC) test [Stokoe and others, 1994] was used to measure V_s properties in core samples. This is a simple test because a pressurizing chamber is not required (the V_s of core generally is insensitive to confining pressure over pressures appropriate to the project [DOE, unpublished Yucca Mountain Project data), end platens are not needed on the ends of the core, and the nodal point (the point in the specimen that does not move) automatically occurs at the mid-length of the specimen for first-mode testing, so one end platen does not have to be "fixed". In the FFRC test, samples are suspended from a frame such that they are "free" to move when a low-level compressional or torsional (shear) impulse is applied at one end of the sample (Fig. 3). Small accelerometers are placed on the other end of the sample to measure compressional or torsional (shear) motion. This test takes less than 1 hour per sample (excluding trimming the ends of the core) and cores of nearly any size can be tested. Characteristics measured on samples include compression-wave (V_c) and shear-wave velocities (V_s), material damping in compression (D_c) and shear (D_s), and Quality factor in compression (Q_c) and shear (Q_s), calculated using the relation of $Q = 1/(2D)$. Although both compression and shear data were collected, only shear data, primarily shear-wave velocity data, will be discussed in this paper.

Samples for FFRC tests vary in core diameters and lengths, but typically core samples are 45 to 96 mm in diameter and 157 to 268 mm long. Before testing, the mass and cylindrical volume are measured for each sample, and Total Unit Weight (γ_t) is calculated. Samples are inspected for overall "homogeneity" of textures; for example, whether or not all features such as lithophysae or spots are relatively small compared to the sample size. Samples also are inspected for features (which can be referred to as "inhomogeneities" or "flaws") that might influence V_s and other measurements, such as fairly continuous fractures, relatively large lithophysae, or missing pieces of the core. Inherent in the sampling of core for testing is that selected pieces represent some of the best quality material, even though there might be some "flaws", because the part of the rock including many fractures or lithophysae, or large textural and structural variability such as abundant rims or spots, typically results in rubble or segments of non-recovered core.

For measurements of shear wave properties, including V_s at scales larger than what can be measured in the laboratory, 7-m-long profiles (or transects) have been established in the tunnels at Yucca Mountain. Profiles are along the tunnel walls and consist of a series of nails that were driven into shallowly drilled holes. Small accelerometers were attached to the nails using magnets such that various transect lengths could be sampled, and the applied energy source was from different-sized hammers. Rayleigh wave velocities for a wide range of frequencies were measured. With this information, forward modeling of the Rayleigh wave velocities versus frequency characteristics was used to determine the V_s versus depth profile behind the tunnel wall.

IV. RELATIONS OF SEISMIC PROPERTIES TO LITHOSTRATIGRAPHIC ZONES

Laboratory testing of core from the Topopah Spring Tuff using the unconfined, FFRC test for shear-wave velocity (V_s) measurements has continued since 2002. Thus far, 38 samples of core from 6 of the crystallized lithophysal and nonlithophysal zones have been tested. Because samples were collected from a variety of boreholes, they are not placed in the context of a linear lithostratigraphic section, they are grouped only by lithostratigraphic zones. There is a good "first order" correlation of the total unit weight (γ_t), shear-wave velocity (V_s), damping in shear (D_s), and Quality factor in shear (Q_s) values of a sample and the lithophysal or nonlithophysal characteristics of the unit from which the sample was collected (Figs. 4, 5, and 6).

1. Nonlithophysal rocks in the crystal-poor middle nonlithophysal zone (Tptpmn) and lower nonlithophysal zone (Tptpln) have very similar γ_t, V_s, D_s, and Q_s values, although the rocks in the Tptpln typically have slightly larger γ_t, V_s, and Q_s, and smaller D_s (Figs. 4 and 5). These relations are consistent with the larger density and smaller porosity measured in similar rocks from the Tptpln compared to the Tptpmn [Flint, 1998], and greater amounts of quartz compared to cristobalite that typically occur in rocks from the Tptpln compared to those in Tptpmn [Chipera and others 1995].
2. Compared to nonlithophysal rocks in the Tptpmn and Tptpln, rocks in the crystal-rich nonlithophysal zone (Tptrn) have smaller γ_t, V_s, slightly smaller Q_s, and larger D_s (Figs. 4 and 5). In fact, there is considerable overlap in the γ_t and V_s values from Tptrn with many of those from the upper and lower lithophysal zones (Tptpul and Tptpll, respectively). These relations are consistent with the slightly greater porosity in the Tptrn compared to Tptpmn and Tptpln [Flint, 1998], which results from the increased amounts of vapor-phase corrosion in the matrix-groundmass and of pumice clasts in the Tptrn, and similar porosity to rocks in the Tptpul and Tptpll [Flint, 1998].
3. Compared to rocks in the Tptpll, samples from the Tptpul have greater range in γ_t, V_s, D_s, and Q_s, and rocks in the Tptpll typically have slightly larger γ_t, V_s, and Q_s, and smaller D_s (Figs. 4 and 5). As with the Tptpmn and Tptpln, the relations of γ_t, V_s, D_s, and Q_s are consistent with the lithostratigraphic position of the Tptpul and Tptpll relative to depth in the deposit and the measured density, porosity, and amounts of quartz versus cristobalite in similar rocks from these lithostratigraphic zones [Flint, 1998; Chipera and others, 1995].
4. Samples from the crystal-rich lithophysal zone (Tptrl) are within the ranges of γ_t, D_s, and Q_s in the Tptpul and Tptpll; however, V_s is slightly smaller (Figs. 4 and 5). These relations in the Tptrl compared to the Tptpul and Tptpll are

consistent with slightly increased amounts of vapor-phase corrosion in the matrix-groundmass and of pumice clasts in the Tptrl.

Variations in shear-wave velocities in samples within a specific lithostratigraphic zone, especially values that are outside the typical range for the zone, can be accounted for by the presence of specific lithostratigraphic features. Features that have the greatest effect on properties include (1) the amount, sizes, and spacing (distribution) of lithophysal cavities, (2) small pore structures in features such as rims, spots, and the matrix-groundmass, and (3) fractures. Of the four samples that are affected (flawed) by these features (filled blue symbols in Figs. 4 and 5), the Tptrl sample has missing pieces and large lithophysae, the two Tptpll samples have fractures, missing pieces, and large lithophysae, and the Tptpln sample has numerous small fractures.

The good correlation of V_s values for core in the Topopah Spring Tuff to the lithostratigraphic units and characteristics of the rocks in specific samples supports the use, as a first approximation, of extrapolating seismic characteristics to other parts of the mountain, especially when viewed from the perspective of geologically determined and distributed lithostratigraphic properties. It is important to note, however, that the seismic testing of core samples in the laboratory does not capture the impact on V_s of large-scale features such as fractures and larger lithophysae that exist in the field. This difference is shown by comparing laboratory-determined V_s values with V_s values measured in the tunnel transects from the Tptpul, Tptpmn, and Tptpll (Fig. 6). Overall, differences in mean values between zones exist in the field, but to a lesser extent than determined in the laboratory. The standard deviations in the tunnel data from Tptpll and Tptpmn are much greater than for core, primarily because core from these zones typically has fewer variations in the amounts and sizes of features such as lithophysal cavities, rims, and spots (i.e., less variable properties). In contrast, the standard deviation in the tunnel data from Tptpul is much greater than for core, primarily because core from this zone typically has many variations in the amounts and sizes of features such as lithophysal cavities, rims, and spots (i.e., more variable properties). As with the core, detailed analyses of the tunnel data in the context of variations in sizes, amounts, and possibly orientation of lithostratigraphic features (including fractures) relative to geometric relations of the transects and probably the wave paths hold great potential for understanding the ability to scale the impact of various features from core to larger scale conditions.

V. CONCLUSIONS

Because rocks of the Topopah Spring Tuff formed by the processes of deposition, welding (including the redistribution of vapor), crystallization, vapor-phase corrosion and mineralization, fracturing, and cooling; the features, structures, and associated rock properties occur in an overall stratiform geometry. There is a good correlation in the seismic properties such as shear-wave velocities measured on small-scale core samples and larger scale tunnel transects, and these values are consistent with the variations within and between the associated lithostratigraphic units. These core data are but one part of the data needed for building an understanding of the distribution of seismic properties that can be used in evaluating and modeling the potential future response to seismic events at Yucca Mountain.

VI. ACKNOWLEDGMENTS

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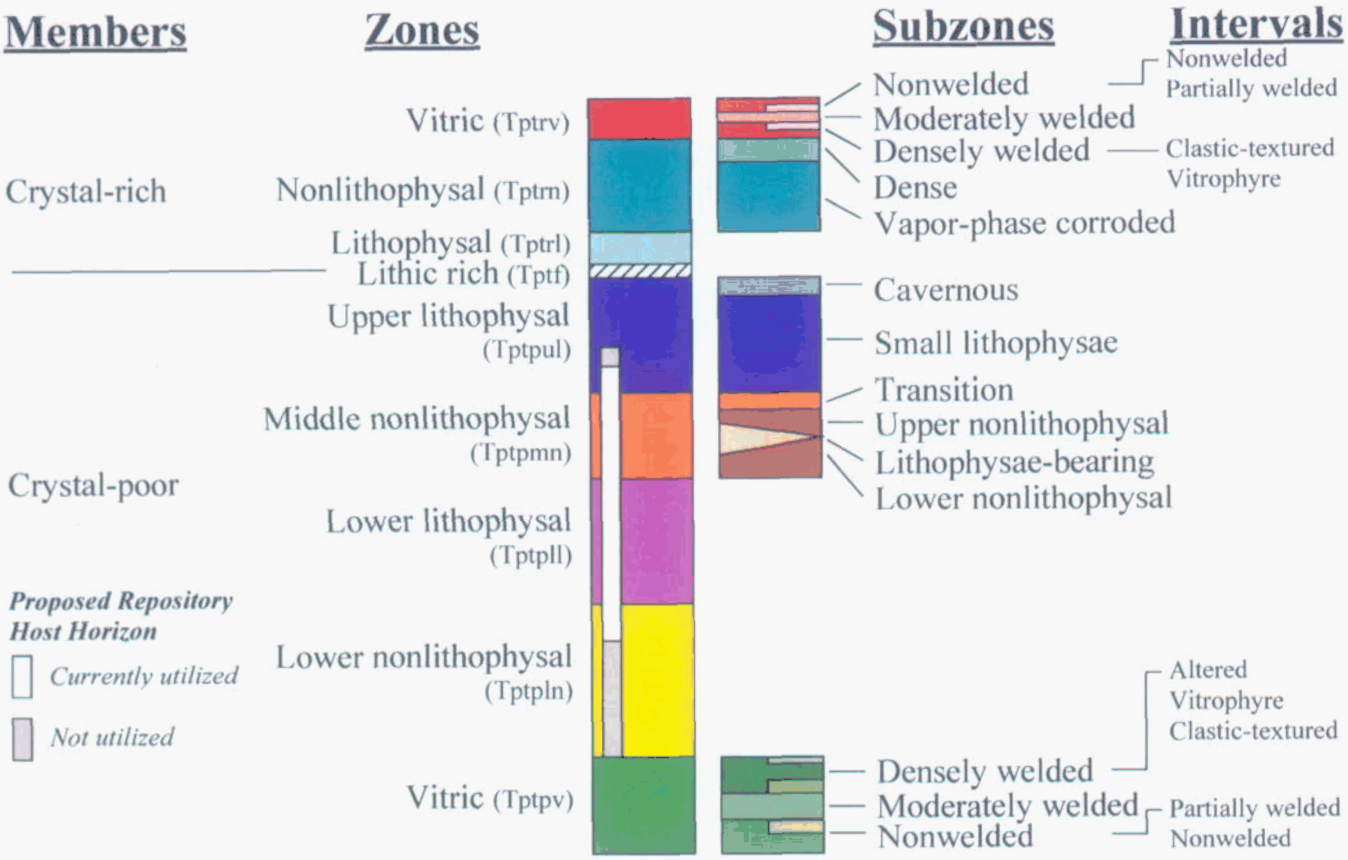


Figure 1. Members, Zones, Subzones, and Intervals of the Topopah Spring Tuff at Yucca Mountain, Nevada.

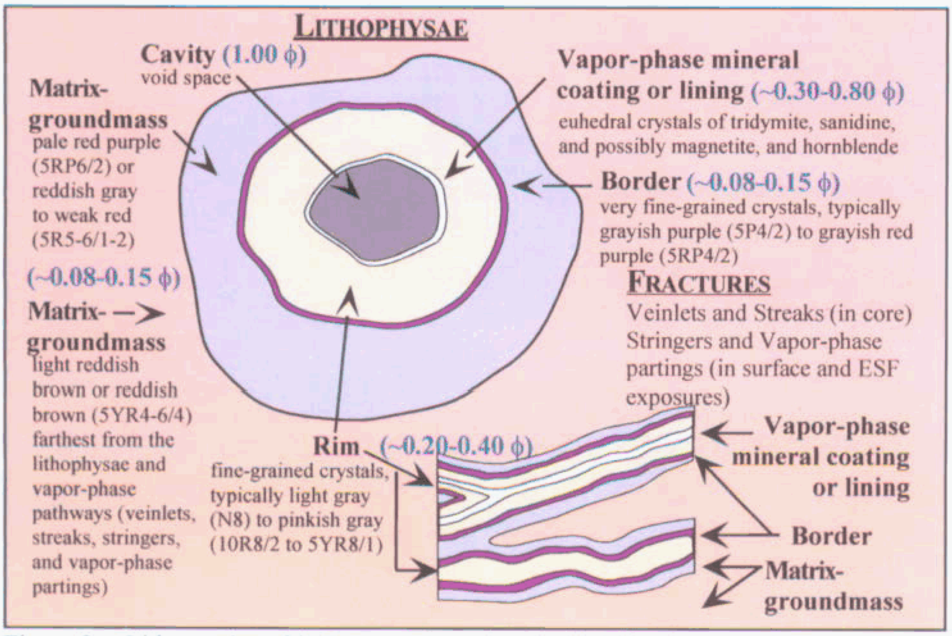
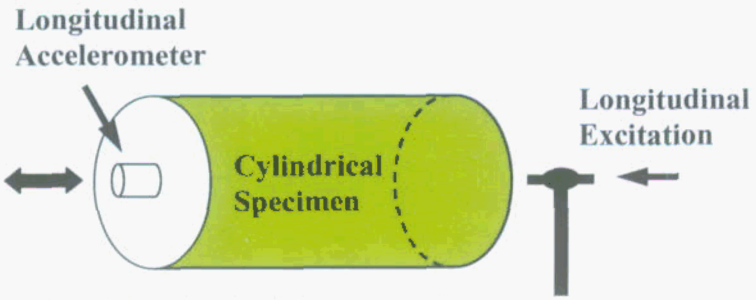
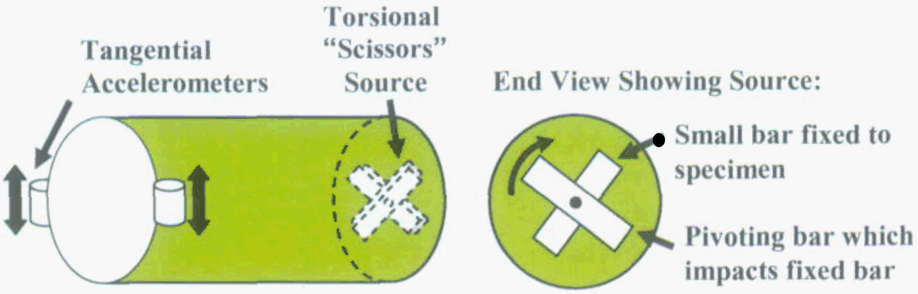


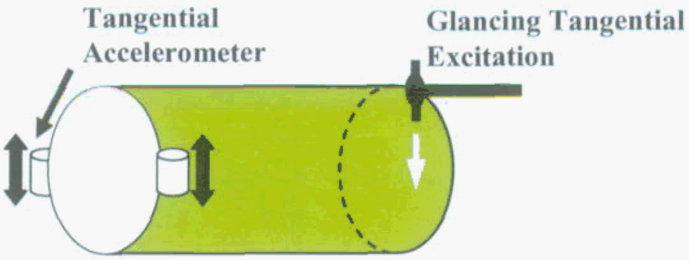
Figure 2. Lithostratigraphic Features Associated with Lithophysae and Fractures in the Crystallized Topopah Spring Tuff at Yucca Mountain, Nevada. (ESF, Exploratory Studies Facility).



a. Compressional (Longitudinal) Resonance Tests



b. Torsional Resonance Tests with a "Scissors" Source



c. Torsional Resonance Tests with a Tangential Impact

Figure 3. General Test Configurations for Unconfined, Free-Free Resonance Measurements: (a) Compressional (Longitudinal) Resonance Tests, and (b) and (c) Torsional Resonance Tests (after Stokoe and others, 1994).

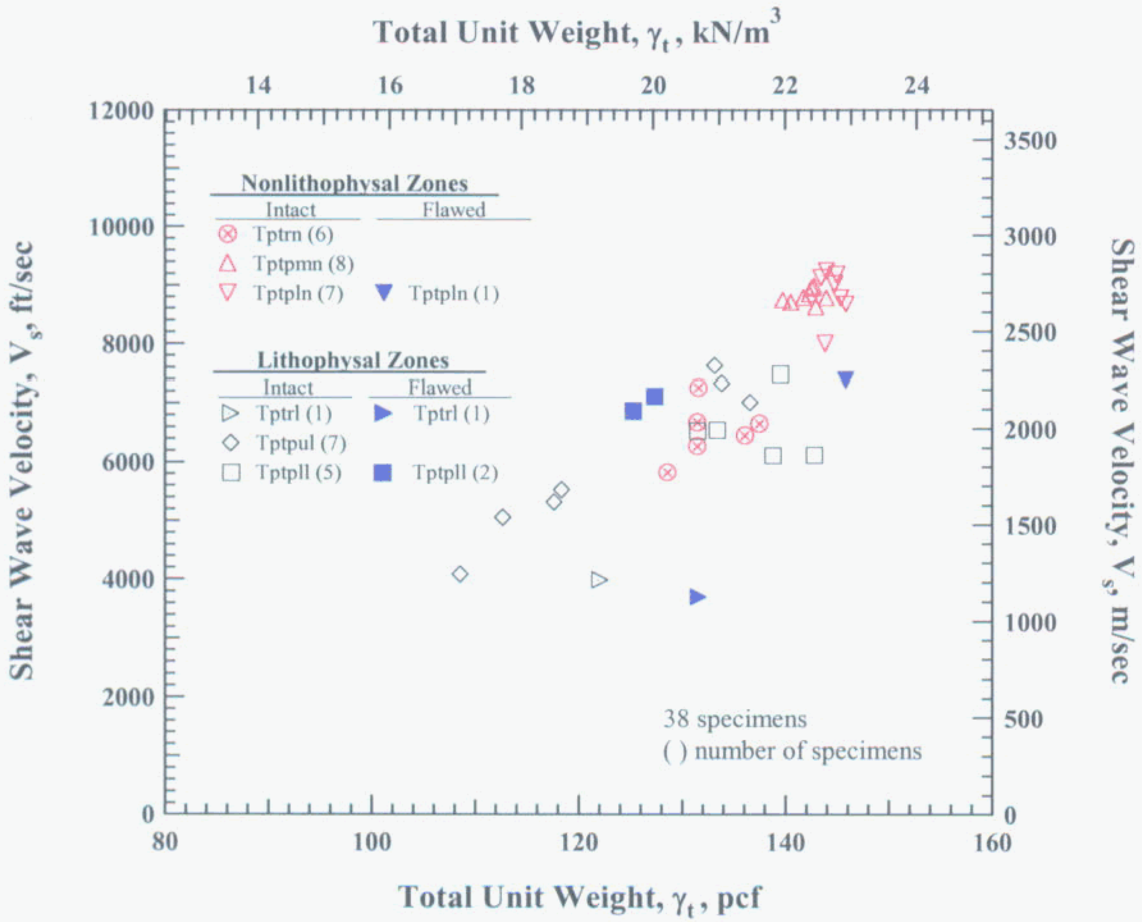


Figure 4. Shear Wave Velocity with Total Unit Weight from Unconfined, Free-Free Resonant Column (FFRC) Tests for Specimens from Nonlithophysal and Lithophysal Zones of the Topopah Spring Tuff, Yucca Mountain, Nevada.

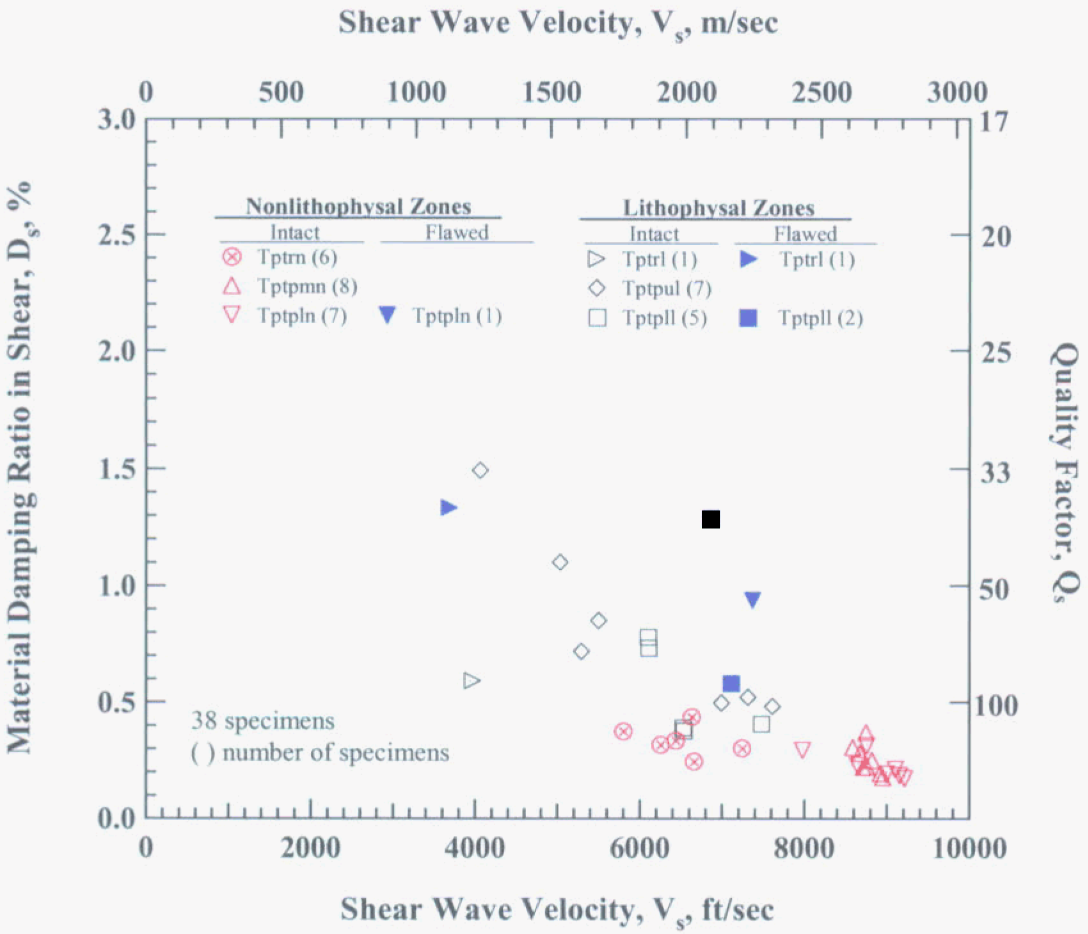


Figure 5. Material Damping Ratio with Shear Wave Velocity from Unconfined, Free-Free Resonant Column (FFRC) Tests for Specimens from Nonlithophysal and Lithophysal Zones of the Topopah Spring Tuff, Yucca Mountain, Nevada.

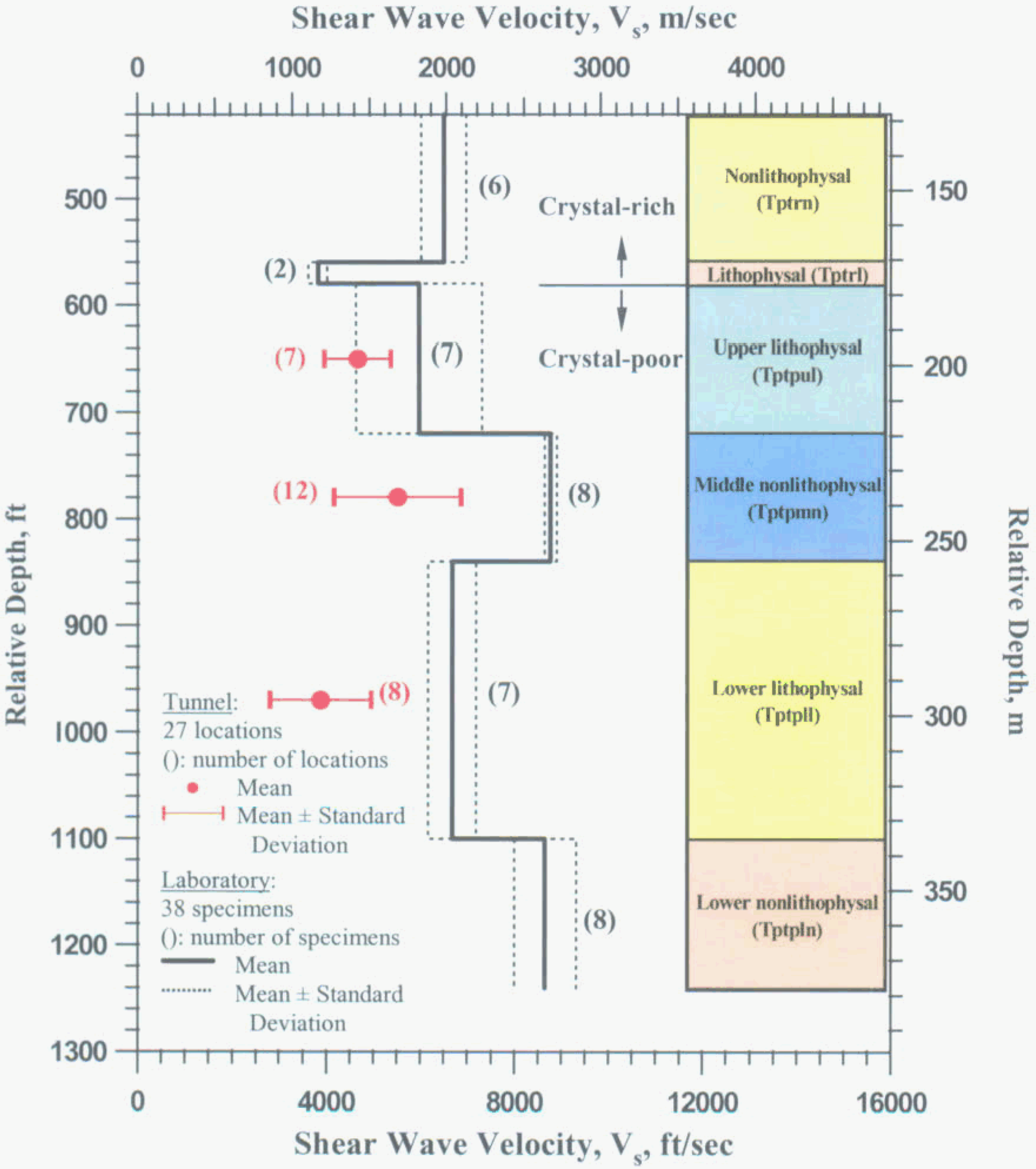


Figure 6. Comparison of V_s Values in Core Samples and Tunnel Locations From Respective Lithostratigraphic Units in the Topopah Spring Tuff, Yucca Mountain, Nevada. Depths are of Relative Position and Thickness of the Lithostratigraphic Units.