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# DEVELOPING A 3-D SEISMIC-ATTRIBUTE FRAMEWORK MODEL OF YUCCA FLAT, NEVADA NATIONAL SECURITY SITE

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## ABSTRACT

Using data collected during underground nuclear testing in Yucca Flat at the Nevada National Security Site, an existing 3-D hydrostratigraphic framework model (HFM) that was developed for groundwater modeling is being converted to a 3-D seismic-attribute framework model (SFM). The resulting SFM can be used to better understand seismic wave propagation from underground chemical explosive tests planned for Yucca Flat as part of the Source Physics Experiment.

The Yucca Flat HFM covers 1,250 square kilometers and depicts the distribution of subsurface geologic units, called hydrostratigraphic units, according to their ability to transmit groundwater. Many of the rock properties and geologic structures that control groundwater flow also influence seismic wave transmission, so the team reasoned that the HFM could be modified to create an SFM.

Existing geologic and geophysical data, including interval velocity measurements from down-hole seismic surveys conducted in 188 holes across Yucca Flat, were used to evaluate the HFM and develop a 3-D velocity property model. The velocity model was integrated with the HFM so that unit volumes within the HFM could be evaluated according to their seismic character.

Results to date show, as anticipated, that most of the 3-D hydrostratigraphic unit volumes in the HFM can function as seismic-stratigraphic unit volumes. Thus, with relatively minor modifications, the HFM can be converted to an SFM.

## BACKGROUND

The United States has a significant national security interest in improving its ability to detect, locate, and characterize underground nuclear explosions (UNEs), particularly low-yield UNEs, that may be conducted anywhere in the world (Snelson, 2013). One of the primary methods for monitoring for UNEs is through the analysis of seismic waves generated by the explosions, and which propagate outward through the earth from the detonation point to seismic recording sensors located around the globe (Auer, 2014). Seismic waves, whether generated by UNEs, or other man-made or natural events, propagate through different rock types at differing speeds and with different characteristics that depend largely on various rock properties and presence of other geologic features. The earth is a very heterogeneous geologic medium, and the three-dimensional (3-D) geologic structure of the earth strongly affects how seismic waves propagate both locally and regionally as they encounter different rock types, faults, and other geologic features, and interact with the variable topography of the earth's surface.

The Source Physics Experiment (SPE) is currently being conducted in Yucca Flat of the Nevada National Security Site (NNSS) (Figure 1) by the U.S. Department of Energy National Nuclear Security Administration (NNSA) to develop predictive capabilities that will enhance the United States' ability to model and characterize low-yield nuclear tests anywhere in the world (Snelson, 2013). The approach of the SPE is to conduct well characterized chemical explosions at different depths and in different geologic media to improve the understanding of how seismic waves are produced and how they propagate in different geologic settings.

Yucca Flat is an excellent site for studying seismic wave propagation from controlled explosive experiments like those conducted for the SPE. The geologic setting of Yucca Flat is diverse, but well understood, with an abundance of geologic and geophysical data from more than 50 years of subsurface characterization activities associated with the U.S. underground weapons testing program (WTP). In addition, and important for improving seismic wave propagation modeling, a 3-D geology-based computer framework model constructed for a different purpose and under another program already exists for Yucca Flat. We believe that with minimal modifications this existing framework model can function as an SFM and thus become a valuable tool for improving seismic wave propagation modeling in and around Yucca Flat.

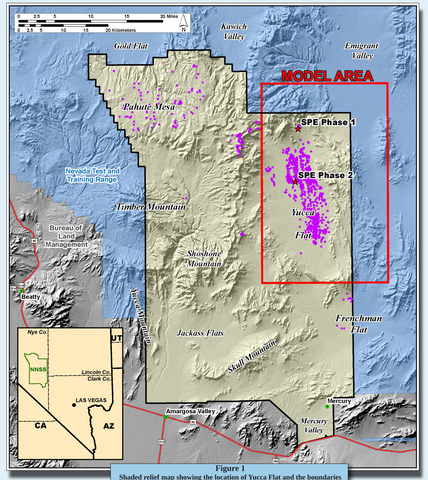



Figure 1
Shaded relief map showing the location of Yucca Flat and the boundaries of the 3-D seismic-attribute framework model. Magenta dots are UNEs.

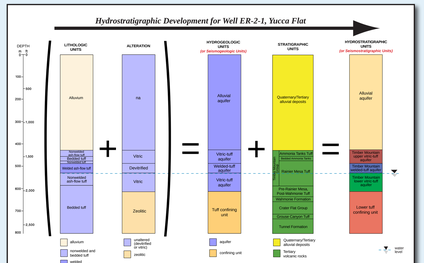
## THE YUCCA FLAT HYDROSTRATIGRAPHIC FRAMEWORK MODEL

The Underground Test Area Activity (UGTA) was initiated by the NNSA Nevada Field Office (NFO) to assess the effects of underground nuclear tests on groundwater at the NNSS (Navarro-Intera, 2013). The UGTA strategy requires the development of sophisticated groundwater flow and contaminant transport computer models to estimate the lateral and vertical movement of radionuclide contaminated groundwater over the next 1,000 years. Because groundwater flow is mainly controlled by certain physical properties of the rocks through which it flows, the development of 3-D computer framework models of the distribution of subsurface units according to their abilities to transmit groundwater was a critical first step in the development of groundwater flow and contaminant transport models. These 3-D framework models, called hydrostratigraphic framework models (HFMs), form the foundation for subsequent numerical flow and transport modeling, and have been successfully utilized by UGTA for more than 10 years.

The Yucca Flat HFM was constructed for UGTA in 2006 (BN, 2006). It covers 1,250 square kilometers in the northeastern portion of the NNSS, and includes all of Yucca Flat proper and portions of the adjacent highlands (Figure 1).

Vertically, the Yucca Flat HFM extends from the land surface to 5 kilometers below sea level. The HFM is geology-based and incorporates stratigraphic principles and rock properties to group the various rock layers beneath Yucca Flat into hydrostratigraphic units (HSUs) based on their ability to transmit ground water (Figure 2). Thus, HSUs form the main 3-D model volumes, or layers, in the HFM. The Yucca Flat HFM includes 25 HSUs as well as 178 faults that cut and offset the HSUs (Figure 3).

Many of the properties and characteristics that influence a rock's ability to transmit groundwater, such as density, porosity, and propensity to fracture, also influence the transmission of seismic waves through the rock (Figure 4). Thus, the Yucca Flat HFM is expected to be applicable for use in modeling of seismic wave propagation in and around Yucca Flat.




(Lithologic unit + Alteration) = Hydrogeologic unit + Stratigraphy = Hydrostratigraphic Unit
*SIMILARLY*
*(Lithologic unit + Alteration) = Seismogeologic unit + Stratigraphy = Seismostratigraphic Unit*

Figure 2
Illustration showing the process for establishing hydrostratigraphic units, and how it may be used in a similar way to establish seismostratigraphic units.

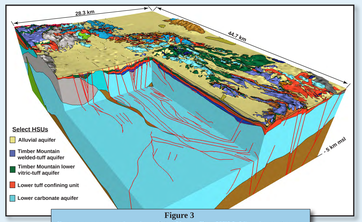



Figure 3
Cut-away perspective view of the Yucca Flat HFM. View is northeast. Colored layers are HSUs; red lines are faults.

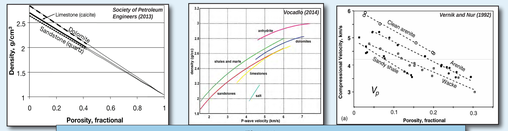



Figure 4
Three plots showing the reltionships between porosity, density, and velocity. The figure illustrates an example of the relationship between important hydrologic properties like porosity and important seismic properties like density and velocity. It suggests that a 3-D framework model, like the Yucca Flat HFM, that models rock volumes according to their hydrologic properties may also be useful in modeling seismic wave propagation.

## YUCCA FLAT SITE-CHARATERIZATION DATA FROM THE WEAPONS TESTING PROGRAM (WTP)

From 1957 to 1992, 747 UNEs were conducted in the Yucca Flat area (Navarro-Intera, 2013) (Figure 1). The individual sites for these detonations were typically the subject of intense geological and geophysical characterization. More basin-wide geological and geophysical investigations were also commonly conducted and, together with individual site characterization data, resulted in a detailed understanding of the geological and geophysical character of Yucca Flat. After 1992, environmental restoration work associated with the NNSA NFO's UGTA Activity added significantly to this institutional knowledge.

Extensive characterization studies by the WTP and environmental restoration activities in Yucca Flat have produced a diverse set of geological and geophysical data for the basin, including laboratory measurements of rock characteristics (e.g., density, water content, mineralogy), borehole geophysical logs (e.g., bulk density, acoustic impedance, seismic velocity), and field surveys (e.g., seismic reflection and refraction, gravity, resistivity, magnetotelluric, aerial and ground magnetics).

From this large, diverse assemblage of data, we chose two specific datasets to interrogate and evaluate the applicability of the Yucca Flat HFM to function as a seismic attribute model. Both datasets provide field-scale seismic velocity data for distinct subsurface intervals of rock sections beneath Yucca Flat. The first data of interest were extracted from detailed site characterization reports from 150 UNE emplacement holes in Yucca Flat (Figure 5). Of particular interest were data tables that list various physical properties of the rocks within the region of the working point (WP; i.e., depth of detonation). These data tables provided seismic compressional-wave ("p-wave") velocity for a specified interval of rock around the WP. In addition they listed other important interval-specific rock properties such as bulk density and porosity (Figure 6).

We also compiled interval velocity data from down-hole seismic surveys conducted in many of the emplacement holes drilled to site UNEs in Yucca Flat. Down-hole recording (i.e., geophone) depths were typically spaced every 50 feet in the hole, so these surveys yielded seismic velocity data at 50-foot intervals throughout the depth of the hole (Figure 7). More than 5,500 interval velocity measurements from 188 holes in Yucca Flat were compiled (Figure 5).

Both WP interval data and down-hole seismic data were originally collected and reported prior to the early 1990s. Since no WTP electronic database compilations of the data were found for this investigation, we extracted the required data from the original WTP reports and down-hole paper logs, and compiled them into a spreadsheet. Because all the velocity and other data of interest were for specific depth intervals tied to individual holes, information such as hole name, location, and surface elevation were extracted from existing UGTA databases and included with each interval velocity record. The depth of the water table was also recorded for each hole in the spreadsheet, and each velocity interval measurement was assigned a descriptor that indicated whether the entire interval was fully saturated (i.e., below the water table), unsaturated (i.e., above the water table), or partially saturated (i.e., the water table is within the interval). This information allows for evaluation of the effect of water saturation on the seismic velocity data.

A critical step in the compilation of the Yucca Flat seismic velocity dataset was to correlate each interval velocity in the database with geologic parameters of the interval (Figure 8). These parameters included stratigraphic unit, lithology (i.e., rock type), mineral alteration, and, most importantly, the HSU that the interval represented in the Yucca Flat HFM. Drill hole geologic data were extracted from various WTP-era reports, logs, and data compilations. HSU assignments were determined from Appendix C of Bechtel Nevada (2006).

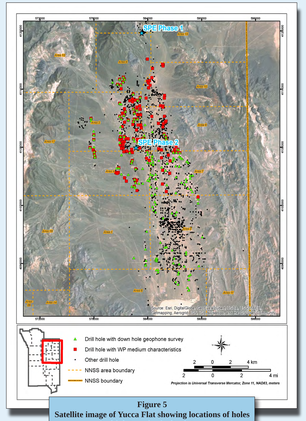



Figure 5
Satellite image of Yucca Flat showing locations of holes with interval velocity data.

Figure 6
Example of WP medium characteristics for an underground test in Yucca Flat.

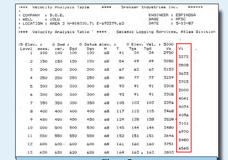


Figure 7
Example of data from a down-hole seismic survey in Yucca Flat. (Interval velocity data outlined in red.)

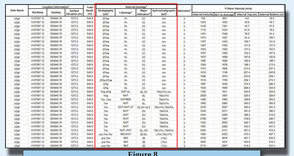


Figure 8
An example of a portion of the seismic properties database. (Geologic assignments outlined in red)

## DATA ANALYSES AND HFM EVALUATION

Linking each of the 5,526 interval velocity measurements within the seismic velocity drill hole database to geologic parameters, allows us to sort, evaluate, and statistically analyze the velocity data relative to stratigraphic unit, lithology, alteration mineralogy, and HSU. Our initial analyses show expected velocity heterogeneity within the rocks beneath Yucca Flat, and a general correlation between seismic properties and HSUs (Figure 9). Thus, most HSUs in the Yucca Flat HFM can likely function as seismostratigraphic units (SSUs). As expected, HSUs composed of denser rock types tend to have higher P-wave velocities. These higher velocity rocks typically correspond to 2 types of HSUs, dense fractured aquifer HSUs and tuff confining unit HSUs. Slower velocity rocks typically correspond to HSUs composed of highly porous, low density, and poorly fractured aquifer HSUs such as the alluvial aquifer and various vitric-tuff aquifer HSUs. Seismic velocity increases with depth in some rock types, especially alluvium, and likely represents compaction of less consolidated units by increasing overburden pressures as these units become more deeply buried (Figure 10).

Using the down-hole interval velocity data, we have constructed velocity property models within the framework of the HFM to aid in further evaluating the HFM, particularly whether lateral velocity changes occur in some HSUs (Figures 11 and 12). Initial assessments of these velocity property models indicate that they can provide an additional and efficient method to evaluate visually and analytically the 3-D distribution of velocities beneath Yucca Flat and the seismic character of HSUs.

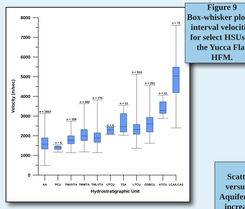



Figure 9
Box-whisker plot of interval velocities for select HSUs in the Yucca Flat HFM.

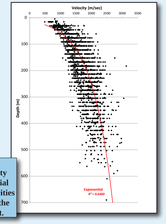



Figure 10
Scatter plot of interval velocity versus depth within the Alluvial Aquifer HSU. Plot shows velocities increasing with depth within the alluvium beneath Yucca Flat.

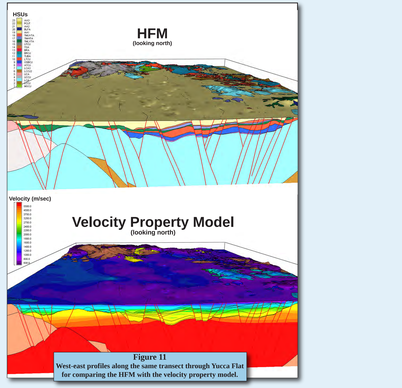



Figure 11
West-east profiles along the same transect through Yucca Flat for comparing the HFM with the velocity property model.

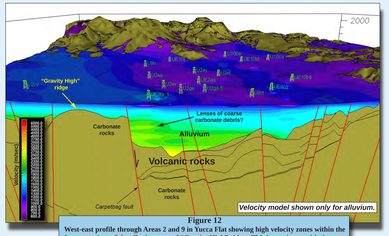



Figure 12
West-east profile through Areas 2 and 9 in Yucca Flat showing high velocity zones within the lower portions of the alluvium east of "Gravity High" ridge. This is consistent with the geologic setting that would include coarse carbonate debris eroding off the ridge and deposited in the developing Yucca Flat basin adjacent to the Carpetbag fault.

## COLLAPSE RUBBLE CHIMNEYS AND DAMAGE ZONES

Another potential complicating factor in modeling seismic wave propagation in Yucca Flat is the presence of certain features associated with individual UNEs that may contain locally altered or damaged rocks, resulting in local zones with seismic properties different than those same rocks in their undamaged state. These features include rubble chimneys that form above the WP region when the cavity created by a UNE collapses, and possible damage zones that surround the WP region. Carroll (1983) discussed the measured changes in velocity associated with damage to the rock from passage of the stress wave from a UNE. Reductions in shear wave velocities are primary indicators of this damage, but changes in P-wave velocity may also be observed very close to the collapse chimney. Carroll (1983) mainly worked in volcanic tuff, but it may be that similar changes occur in alluvium and other rock types beneath Yucca Flat.

Because sites of expended UNEs are densely clustered in many places in Yucca Flat, the demarcation of individual collapse chimneys and WP-region damage zones associated with Yucca Flat UNEs could be an important addition to any framework model used for seismic wave propagation modeling. All the specifications necessary to digitally construct in 3-D each of these individual elements for all the UNEs in Yucca Flat are unclassified (Figure 12).

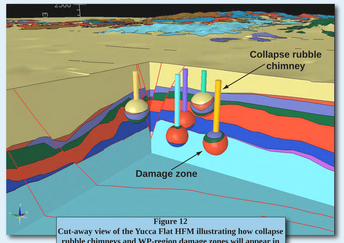



Figure 12
Cut-away view of the Yucca Flat HFM illustrating how collapse rubble chimneys and WP-region damage zones will appear in the Yucca Flat seismic-attribute model.

## CONCLUSION

Analyses of the field-scale seismic data compiled for this investigation indicate that most HSUs in the Yucca Flat HFM can function as SSUs. Therefore, with relatively minor modifications, the UGTA Yucca Flat HFM should function as a 3-D seismic-attribute framework model, and be a valuable tool for studying more precisely seismic wave propagation in Yucca Flat. Modifications to some HSUs by splitting them into more than one unit, and restricting some HSUs to include only certain portions (e.g., the interior portion) will create more appropriate SSUs, and a better seismic-attribute framework model. Developing a 3-D velocity model using the down-hole seismic data within the framework of the current HFM will allow identification of lateral velocity changes in HSUs across Yucca Flat. Modifications of HSUs that show significant lateral velocity changes into separate SSUs will also improve the framework model. Modeling collapse chimneys and damage zones associated with past UNEs in Yucca Flat as separate model elements that can be independently parameterized will improve the framework model, particularly in areas with dense clusters of UNEs.

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