AN ANALYSIS OF THE SEISMIC SOURCE CHARACTERISTICS OF EXPLOSIONS IN LOW-COUPLING DRY POROUS MEDIA

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ABSTRACT

The dependence of seismic source coupling of underground nuclear explosions on the characteristics of the explosion source medium is an important consideration in any assessment of nuclear test monitoring capability. In particular, while experience has indicated that normal depth explosions in almost all hardrock and water saturated emplacement media (i.e., "good-coupling" media) are roughly consistent with a single m_b/yield relation for any fixed tectonic source region, explosions in dry, porous media such as the dry tuffs and alluvium found above the water table at the Nevada Test Site (NTS), are typically observed to have m_b values at a given yield that are lower than those in hardrock by about 0.50 ± 0.25 magnitude units. With the exception of the complex cavity decoupling evasion scenario, which is not always feasible, explosions in such low-coupling media define the lower bound on the detection capability required to successfully monitor small, clandestine underground nuclear tests. However, at the present time, no fully reliable seismic source model is available to support quantitative analyses of broadband data recorded from such explosions. The technical objectives of this program are to develop a "Mueller/Murphy" frequency dependent seismic source model for underground nuclear explosions in dry, porous media and to then apply this model to a quantitative assessment of seismic yield estimation capability for such explosions as functions of explosion yield and depth of burial, as well as detailed physical properties of the source medium such as compressional wave velocity and percent by volume of air-filled porosity. This is being accomplished by conducting quantitative source scaling analyses of broadband regional seismic data recorded from explosions in such media at NTS to define their frequency dependent source coupling characteristics relative to the already well-documented seismic source coupling of corresponding explosions in "good-coupling" media at that same test site. The ultimate objective of the project is to improve U. S. operational nuclear test monitoring capability by providing a reliable seismic source model which can be used to quantitatively address seismic detection, identification and yield estimation capability with respect to small underground nuclear tests which might be conducted in such low-coupling media.

OBJECTIVES

The technical objectives of this research program are to develop an analytic approximation for a frequency dependent seismic source model for underground nuclear explosions in dry, porous media analogous to the Mueller/Murphy model for explosions in hardrock and water-saturated media, and to then apply this model to a quantitative assessment of seismic monitoring capability relative to explosions in such media. This is being accomplished by conducting source scaling analyses of broadband seismic data recorded from explosions in such media at NTS to define their frequency dependent source coupling characteristics relative to the already well-documented seismic source coupling of corresponding explosions in "good-coupling" media at that same test site. The ultimate objective is to improve U.S. operational nuclear test monitoring capability by providing a reliable seismic source model that can be used to quantitatively address seismic detection, identification and yield estimation capability as functions of yield, depth of burial and the physical characteristics of the source medium for small underground nuclear tests which might be conducted in such low-coupling media.

RESEARCH ACCOMPLISHED

This project is just beginning, so the following discussion focuses primarily on background and plans as opposed to accomplishments to date. It has long been recognized that normal depth explosions in almost all hardrock and water-saturated emplacement media (i.e., "good-coupling" media) are roughly consistent with a single mb/yield relation for any fixed tectonic source region. In fact, the only media which are known to give consistently different results for fully tamped explosions are saturated clay or water and dry, porous media, such as the dry tuff and alluvium found above the water table at NTS. These observations are summarized in Figure 1, where it can be seen that the average mb value for explosions of fixed low yield in saturated clay or water is expected to be higher by about 0.50 ± 0.25 magnitude units, while the value for explosions in dry, porous media is expected to be lower by about 0.50 ± 0.25 magnitude units relative to that for explosions of the same yield in good-coupling media. It follows that, with the exception of cavity decoupled explosions, which are not always technically feasible, small explosions in dry, porous media pose the greatest challenge to effective seismic monitoring.

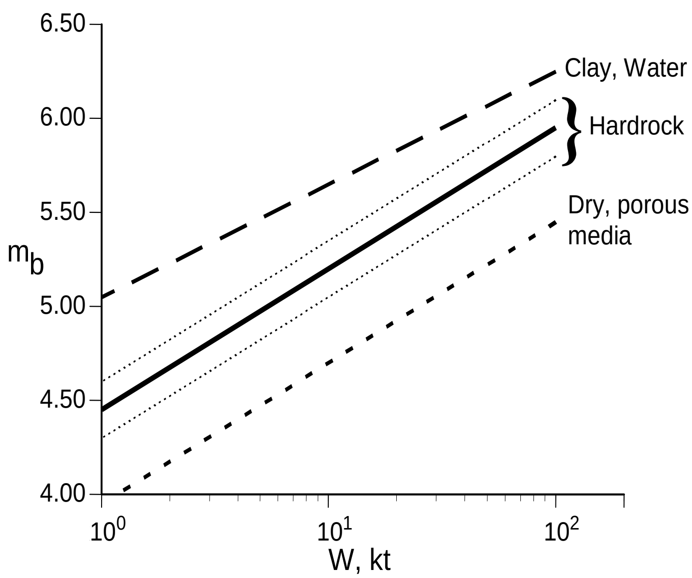

Figure 1. Comparison of mb/yield relations for fully tamped underground nuclear explosions in a fixed tectonic source environment, illustrating the effects of source medium on seismic coupling. It can be seen that the average mb value for explosions of fixed low yield in dry, porous media is expected to be lower by about 0.50 ± 0.25 magnitude units relative to that for explosions of the same yield in hardrock media.

There have been several previous studies of the effects of source medium gas porosity on seismic source coupling of explosions. Vergino and Mensing (1990) examined the effects of gas porosity on mb by filtering the broadband Lawrence Livermore National Laboratory (LLNL) network regional data observed from a large sample of NTS explosions through a synthetic WWSSN response and then estimating mb(Pn) values by applying the standard time-domain estimation procedures to the resulting narrowband data. They postulated a simple linear dependence of mb on the measured gas-filled porosity at the working point of the explosion, and estimated that the average mb value at a fixed yield decreases by about 0.8 magnitude units over the sampled range of air-filled porosity, which extended from about 0 to 30% in this study. Taylor and Dowla (1991) looked at Pn, Pg and Lg spectra from NTS explosions in dry, porous media and also found evidence of reduced low-frequency coupling, as well as possible reduced high-frequency content relative to comparable explosions in saturated media. Their analysis focused on yield estimation through "template matching" - i.e., by comparing observed spectra from new NTS explosions with those observed from previous explosions of known yield. Jones and Taylor (1996) looked at the effects of dry porosity on observed Lg spectra from NTS explosions. Once again, they found reduced seismic coupling and they formulated a source scaling model in terms of observed cavity radius, a variable that is not generally known for explosions of potential monitoring interest. Thus, the results of these different previous studies have been generally consistent in that they all indicated reductions of low frequency seismic coupling efficiency of as much as one full order of magnitude in such media relative to the coupling efficiency of explosions of the same yield conducted in water saturated media below the water table at NTS. However, at the present time, there is no simple P wave seismic source model for explosions in dry, porous media comparable to the Mueller/Murphy (1971) source model for explosions in hardrock or water-saturated sediments. Such a model is needed to support nuclear test monitoring applications related to the frequency dependent seismic detection, identification and yield estimation of small underground nuclear tests in low-coupling media.

As in the previous studies referenced above, the primary source of data for this study are the broadband data recorded from NTS explosions at the four near-regional stations of the LLNL seismic network. We currently have digital data recorded at those stations from some 150 NTS explosions, approximately 100 of which were underground nuclear tests conducted above the water table in dry, porous media. These data are generally of excellent quality, as is illustrated in Figure 2, which shows a record section of data recorded from selected Yucca Flat explosions at LLNL station MNV. In this figure, the top ten traces correspond to recordings of low yield (W < 20 kt) explosions in dry, porous media above the water table (above W.T.) at Yucca, while the bottom three traces represent recordings of larger (~140 kt) explosions conducted in saturated tuffs below the water table (below W.T.) at Yucca. It can be seen that the broadband signal to noise ratios are generally quite high, even for the smaller explosions in low coupling media.

In addition to yields and depths of burial, a number of physical properties of the source emplacement media have been tabulated for these NTS explosions and published in a recent, comprehensive seismic source summary by Springer et al (2002). These include average working point P-wave velocities and densities, as well as measurements of gas-filled porosity and water content. Each of these properties is known to affect the seismic source characteristics of the explosions to some extent, so it is important that their variability be incorporated into any systematic analysis of seismic source coupling.

The distribution of measured gas-filled porosity (percent by volume) values at the working points of the 94 NTS explosions in the station MNV dataset which were detonated in dry, porous media above the water table is shown in Figure 3, where it can be seen that the values range from near zero to almost 30%. Here, the distribution of measured values is observed to be nearly uniform in the range of 0 to 20%, and then decreases somewhat between 20% and 30%. However, even at these higher porosity values, there are still 14 explosions in this database with gas-filled porosity values greater than 20%, so it appears that the available data should be adequate to define the quantitative dependence of frequency dependent seismic source coupling on the percentage of gas-filled porosity of the test medium.

In order to illustrate our proposed analysis procedures, we selected a sample of data recorded at LLNL station MNV from low-yield explosions conducted in highly porous, dry media above the water table at Yucca Flat. Since nuclear tests at NTS were generally conducted at scaled depths of greater than about $125 m/kt^{1/3}$ to ensure containment of the radioactive byproducts of the explosions, we confined our attention to tests conducted at depths of less than 270 m to ensure that the yields were less than 10 kt without needing to reference specific classified yield values. From this

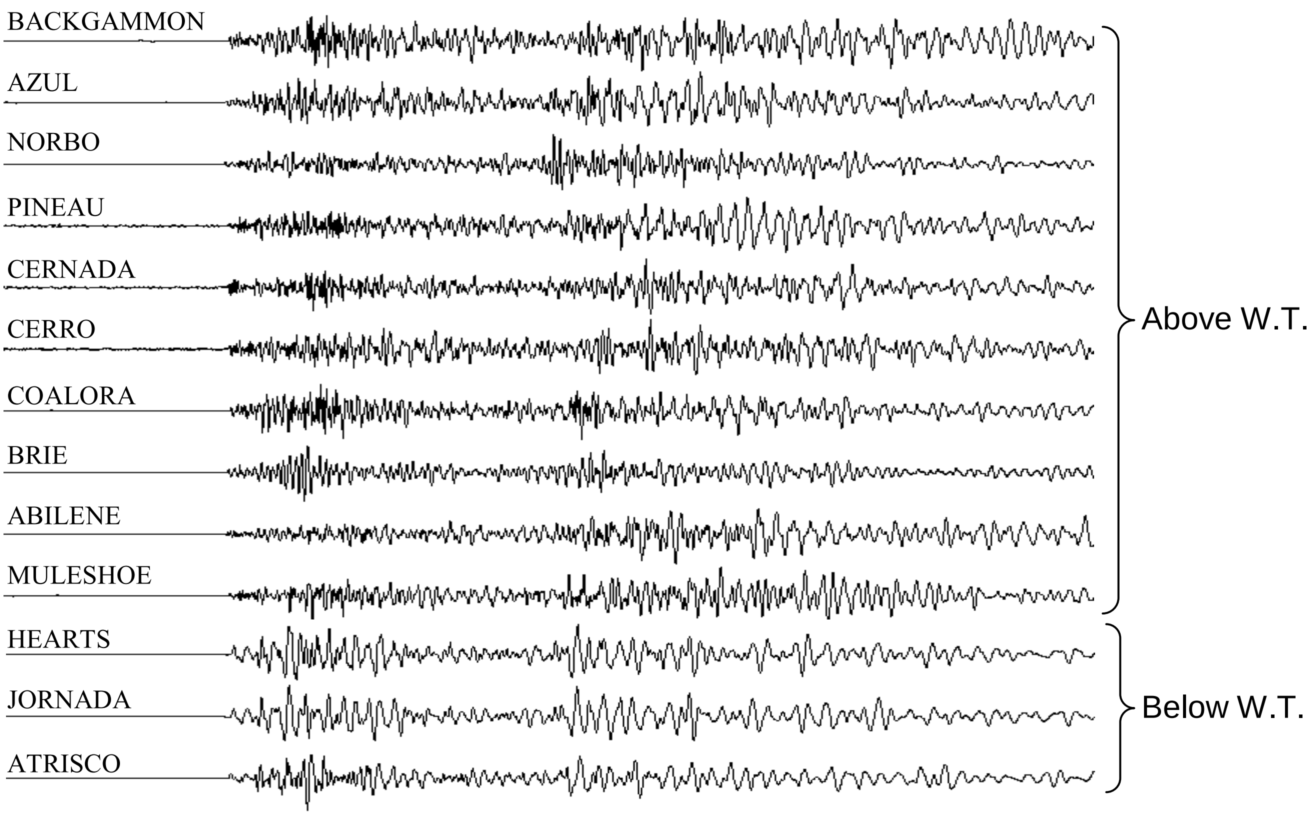

Figure 2. Data recorded from selected Yucca Flat explosions at LLNL station MNV. The top ten traces correspond to recordings of low yield (W < 20 kt) explosions in dry porous media above the water table (above W.T.) at Yucca, while the bottom three traces are recordings of larger explosions conducted in saturated tuff below the water table (below W.T.) at Yucca.

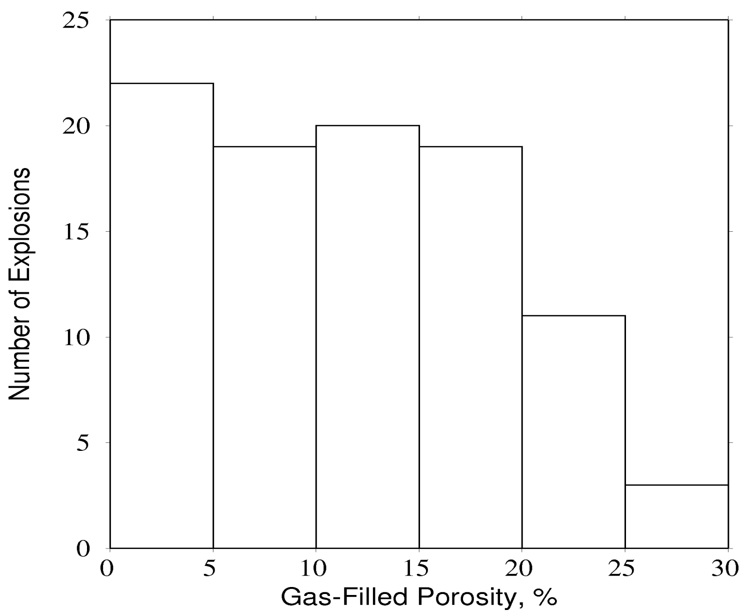

Figure 3. Distribution of reported emplacement medium gas-filled porosity percentages for the selected sample of explosions detonated above the water table at NTS.

subset of the available MNV data, we selected those explosions conducted in dry media having gas-filled porosity values in the highest 20–30% range. This yielded a sample of 9 Yucca Flat explosions for which the data recorded at station MNV were processed and analyzed. As a first step in this analysis, the spectral compositions of the initial P-wave arrivals were estimated for each of these explosions. Smoothed P-wave spectra computed from the first 10 seconds of the signal following P onset are compared for the 9 selected explosions in Figure 4.

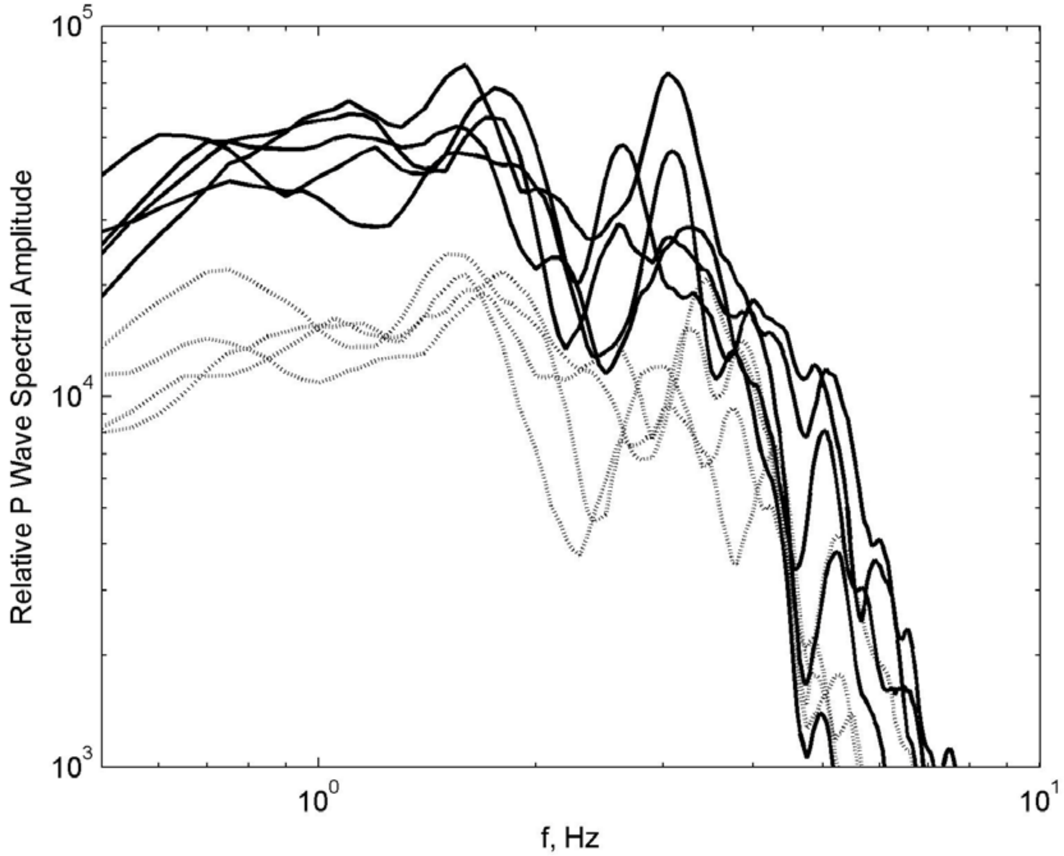

Figure 4. Comparison of P-wave spectra at station MNV for a selected sample of 9 low-yield (W < 10 kt) explosions conducted in high gas-filled porosity (20-30%) media above the water table at Yucca Flat. Two subgroups of explosions having different apparent average yields are differentiated by solid versus dashed lines.

It can be seen that these spectra all have fairly similar shapes and that they appear to separate into two subgroups having average low-frequency amplitude levels which differ by about a factor of three. Consequently, these two subgroups of individual spectra were averaged separately to obtain the two P-wave spectral estimates shown in Figure 5. It can be seen from this figure that the differences in both low frequency amplitude level and corner frequency between these two average spectra are consistent with what would be expected from a significant difference in average yield between these two subgroups of explosions.

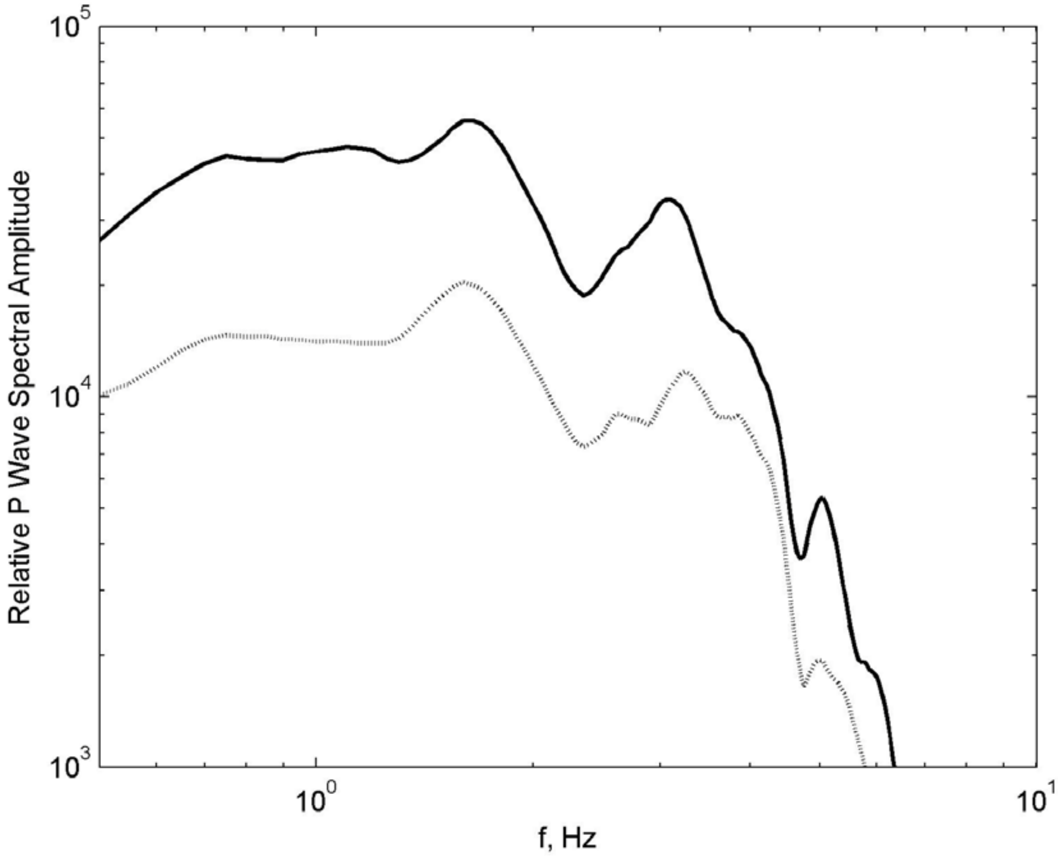

Figure 5. Average station MNV P-wave spectra corresponding to the two subgroups of explosions in dry, porous media shown in the previous figure. These average spectra are taken to be characteristic of P-wave seismic source coupling for two groups of low-yield (W < 10 kt) explosions in such media having average yields which differ by about a factor of 3.

In order to assess the effects of the high gas-filled porosity of the source media in which these explosions were detonated on the frequency dependent source coupling efficiency, it is necessary to make comparisons with corresponding P-wave spectra from explosions of the same yields and depths of burial in good-coupling, saturated media below the water table at Yucca. Unfortunately, there are no low-yield explosions that were conducted in this depth range at Yucca which were detonated in saturated media below the water table, so some scaling is required to make a valid comparison. Three explosions that were conducted in saturated tuff below the water table at Yucca Flat for which yields and depths of burial have been published in the open literature (Springer et al, 2002) are HEARTS, JORNADA and ATRISCO. Each of these had announced yields very close to 140 kt and depths of burial of about 640 m. The P-wave spectra computed from the station MNV recordings of these three explosions were logarithmically averaged to obtain the station MNV P-wave spectral estimate representative of a 140 kt explosion at a depth of 640 m in saturated tuff below the water table shown as a solid line in Figure 6. The Mueller/Murphy source model has been used to scale this average observed spectrum to obtain estimates of the saturated tuff spectra corresponding to the yields and depths of burial of the two average P-wave spectra for explosions in dry, porous media, as shown in Figure 5. We plan to eventually use actual yield values, but for present, unclassified purposes, the observed depths of burial constrain the yields to be less than 10 kt, while the observed Pn signal to noise ratios are characteristic of yields greater than about 1 kt. Therefore, given the differences in the low-frequency amplitude levels for the average spectra of Figure 5, we assigned nominal yields of 2.5 kt and 7.5 kt to the smaller and larger subgroup averages, respectively, in order to illustrate the methodology. The results of scaling the

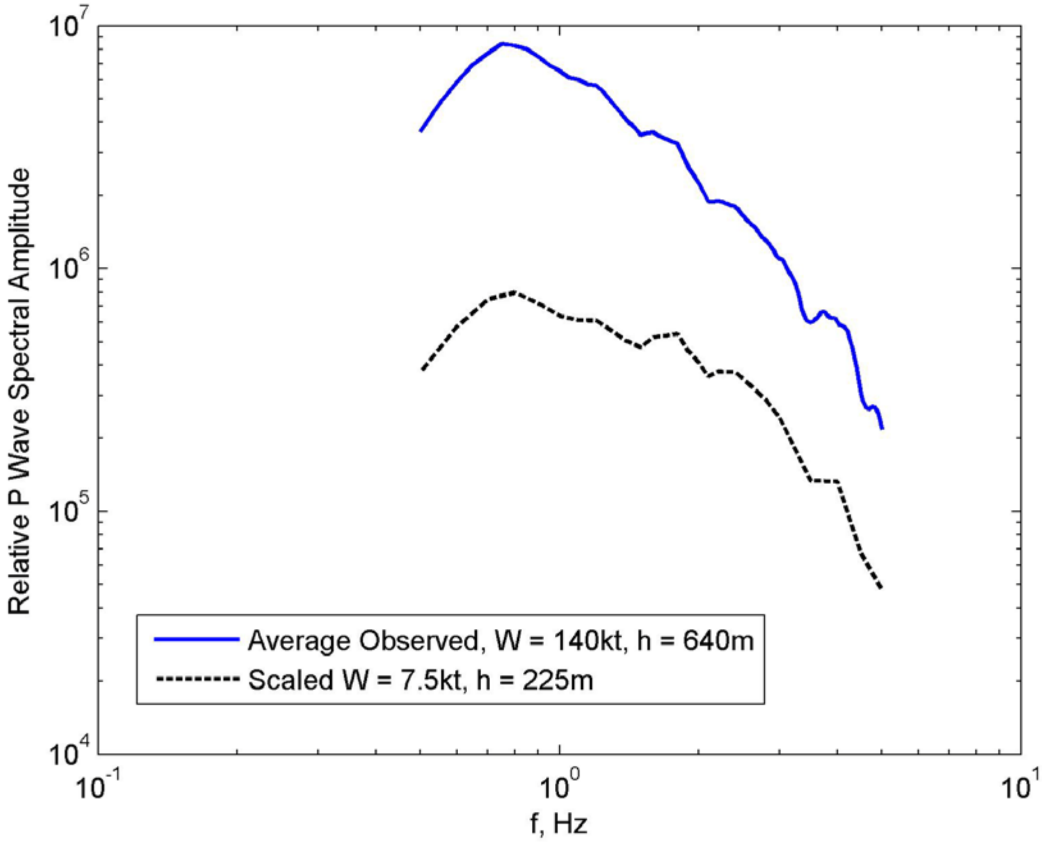

Figure 6. Comparison of the average observed station MNV P wave spectrum corresponding to a 140 kt explosion at a depth of 640 m in saturated tuff at Yucca Flat (solid) with the corresponding P-wave spectrum obtained by scaling to W = 7.5 kt, h = 225 m in that same source medium using the Mueller/Murphy seismic source scaling model (dashed).

average observed spectrum corresponding to W = 140 kt , h = 640 m in saturated tuff to W = 7.5 kt, h = 225 m using the Mueller/Murphy source scaling model are shown as a dashed line in Figure 6, where the frequency dependent nature of the combined yield and depth scaling is clearly evident. This scaled spectrum, together with a corresponding one for a W = 2.5 kt, h = 225 m explosion in the saturated tuff medium were divided by the average spectra for the two subgroups of explosions in dry, porous media to quantify the frequency dependent effects of gas-filled porosity on seismic source scaling efficiency. The resulting spectral ratios are shown in Figure 7, where it can be seen that the two ratios are very consistent and roughly independent of frequency over the range extending from 0.5 to 10 Hz, although there is some very weak suggestion of a possible increase in the spectral ratios with increasing frequency above the respective source corner frequencies which might correlate with an increase in the high-frequency rolloff rate for explosions in dry, porous media as was inferred by Taylor and Dowla (1991). This issue will need to be carefully evaluated in our analysis of the complete data set. In any case, the consistency of the two relative coupling estimates shown in Figure 7 seems to confirm the inferred factor of three difference in the average yields of the two subgroups of selected explosions in dry, porous media, and suggests a reduction in the low-frequency coupling by an average factor of 10–20 due to the effects of gas-filled porosity, at least for these explosions in media with estimated gas-filled porosities in the range of 20–30%.

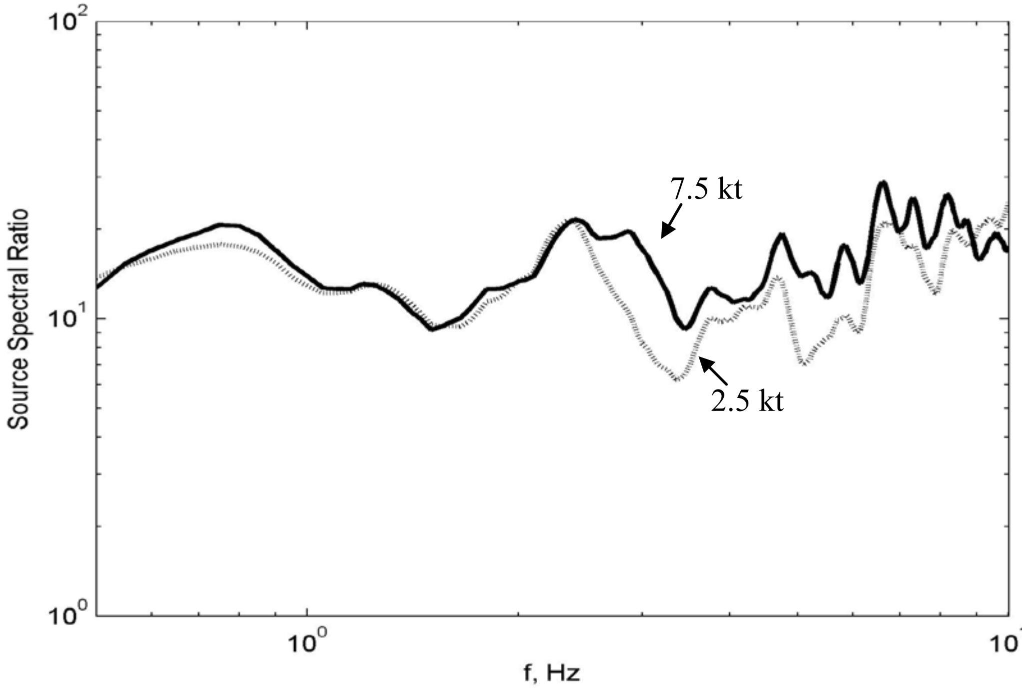

Figure 7. P-wave source spectral ratios for Yucca Flat explosions in saturated tuff relative to explosions of the same yields and depths of burial in dry, porous tuff and alluvium. It can be seen that the two ratios are essentially identical, consistent with the Mueller/Murphy source scaling for the inferred factor of 3 difference in the average yields of the two subgroups of selected explosions in dry, porous media.

The implications of these P-wave spectral ratios with respect to the seismic source function for explosions in high gas-filled porosity media are indicated in Figure 8, which shows a comparison of the Mueller/Murphy seismic source predicted for a 7.5 kt explosion at a depth of 225 m in saturated tuff with the corresponding approximation to the seismic source for that same explosion in dry tuff/alluvium media obtained by dividing the saturated tuff source by a frequency independent factor of 15, consistent with the average spectral ratio results from Figure 7. Also shown on this figure is the Mueller/Murphy source corresponding to the explosion at that depth in saturated tuff that would be expected to produce the same low frequency amplitude level as that of the inferred dry tuff/alluvium seismic source. Note that the yield of this matching saturated tuff explosion (i.e., 0.35 kt) is significantly smaller than the 7.5 kt yield of the corresponding inferred dry tuff/alluvium source and, consequently, its source corner frequency is significantly higher. This has important implications with regard to seismic yield estimation for clandestine underground nuclear tests in unknown source media. That is, for a given observed low frequency amplitude level, the high -requency spectral amplitude levels could be used to determine whether the explosion was conducted in a low- or high-coupling source medium, resulting in a more confident seismic estimate of the yield of the explosion. This diagnostic difference would be even further enhanced if, in fact, the seismic source for explosions in dry, porous media is characterized by an increase in the high-frequency rolloff rate relative to that for explosions in saturated tuff/rhyolite emplacement media.

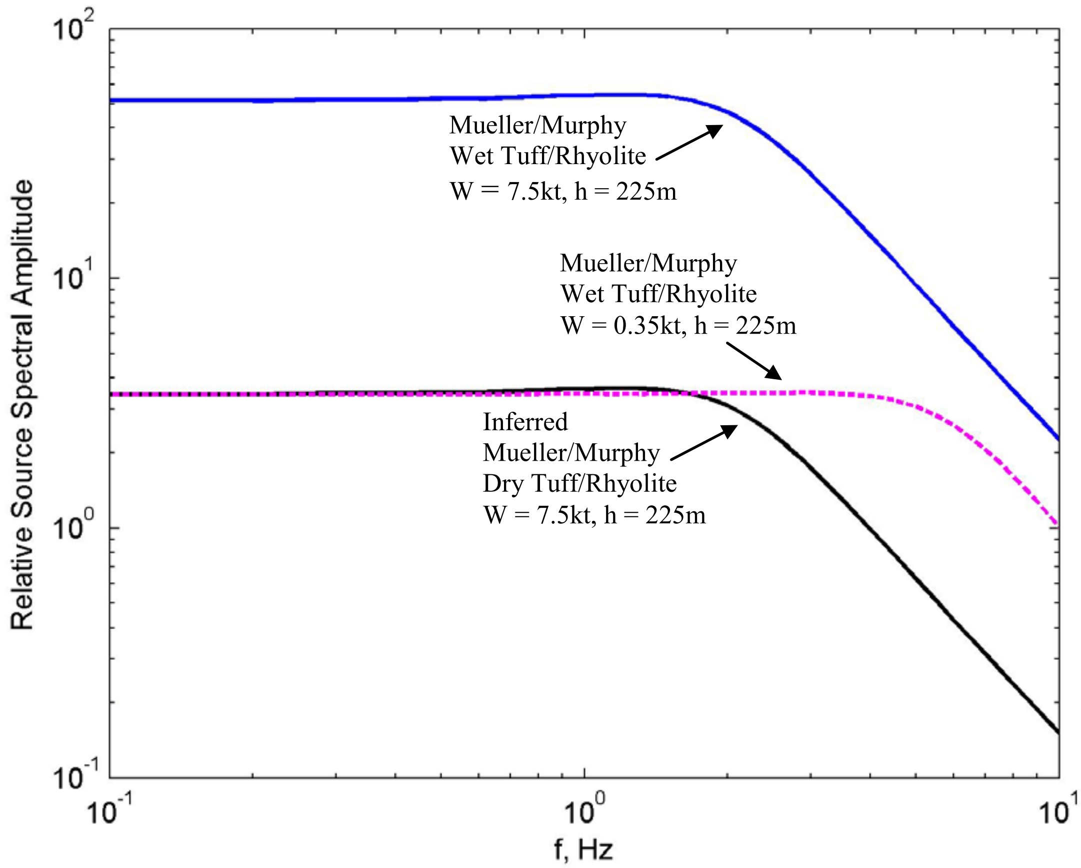

Figure 8. Comparison of the inferred seismic source for a 7.5 kt explosion at a depth of 225 m in dry tuff/alluvium source media with the corresponding Mueller/Murphy seismic sources predicted for 7.5 kt and 0.35 kt explosions at that same depth in a saturated tuff emplacement medium. It can be seen that interpreting the observed spectrum from an explosion in dry tuff as if it were conducted in saturated tuff could lead to a seismic yield estimate which is low by more than a factor of 20 in this case.

CONCLUSIONS AND RECOMMENDATIONS

The dependence of seismic source coupling of underground nuclear explosions on the characteristics of the explosion source medium is an important consideration in any assessment of nuclear test monitoring capability. While experience has indicated that explosions in almost all hardrock and water-saturated emplacement media are roughly consistent with a single mb/yield relation in any fixed tectonic source region, explosions in dry, porous media are observed to have low-frequency seismic source coupling at a given yield that is as much as an order of magnitude lower than that in hardrock. The objectives of this research study are to develop a "Mueller/Murphy" frequency-dependent seismic source model for underground nuclear explosions in such media and to then quantitatively assess the implications of this model with respect to seismic monitoring capability. While this project is just beginning and it is too early for any definitive conclusions, preliminary analysis of selected broadband near-regional data recorded from NTS explosions in dry, porous media have confirmed the previously reported large reduction in low-frequency seismic coupling efficiency relative to that expected from explosions in good coupling media. Moreover, these preliminary results suggest that, while the source corner frequencies for explosions in such media may be diagnostically lower than those expected from explosions of the same yields and depths of burial in good coupling media, the spectral roll-off rates above the corner frequency appear to be roughly comparable in both media. More careful analyses of larger datasets will of course be required to further test the validity of these tentative conclusions.

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