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

J.R. Murphy, et al.

Science Applications International Corporation
1710 SAIC Drive
McLean, VA 22102

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AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

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14. ABSTRACT

Over the past two years we have been analyzing P wave seismic source coupling characteristics of underground nuclear explosions in dry, porous media. The technical objectives of this research have been to develop a "Mueller/Murphy" frequency dependent analytic seismic source model for explosions in such media and to apply the model to quantitative assessments of seismic detection, identification and yield estimation capabilities relevant in nuclear test monitoring. Broadband seismic data recorded at the Lawrence Livermore National Laboratory (LLNL) regional network stations from 63 nuclear explosions conducted above the water table at the Yucca Flat testing area of the Nevada Test Site (NTS) were analyzed and compared to observations and models for explosions in good coupling media below the water table. The results of these analyses indicate that the P wave seismic source functions for underground nuclear explosions in dry, porous media can be well-approximated by simply dividing the P wave source functions for the same explosions in saturated tuff, predicted by the validated Mueller/Murphy source model, by a frequency independent gas-filled porosity (Gp) reduction factor (RF) given by $RF = 1.75 * 10^{0.024Gp}$.

15. SUBJECT TERMS

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1. Summary

Over the past two years we have been analyzing the P wave seismic source coupling characteristics of underground nuclear explosions in dry, porous media. The technical objectives of this research investigation have been to develop a “Mueller/Murphy” [1] frequency dependent analytic seismic source model for explosions in such media and to apply the model to quantitative assessments of seismic detection, identification and yield estimation capabilities relevant in nuclear test monitoring.

The data used in these analyses consisted of broadband seismic data recorded at the Lawrence Livermore National Laboratory (LLNL) regional network stations from nuclear explosions conducted above and below the water table at the Yucca Flat testing area of the Nevada Test Site (NTS). These data have included a sample of 63 explosions conducted in dry, porous media above the water table at Yucca Flat that sample a range of gas-filled porosities (Gp) extending from near zero to almost 30%, have a mean yield of about 10 kt and a mean scaled depth of burial of about 150 $m/kt^{1/3}$.

The statistical source scaling analyses of these data revealed that the dependence of the observed P wave spectral amplitudes on Gp is essentially independent of frequency over the range 0.5 to 10 Hz, with the logarithm of the spectral amplitudes at a fixed yield decreasing with increasing Gp as -0.024Gp. That is, the effect of Gp on the P wave seismic source spectrum can be expressed as a frequency independent factor, which greatly simplifies the source scaling analysis. It has been further determined that the theoretical Mueller/Murphy seismic source scaling with yield and source depth of burial determined for explosions in water saturated tuffs, such as those found below the water table at Yucca Flat, is also applicable to low yield explosions in dry, porous media. That is, these results indicate that the P wave seismic source functions for underground nuclear explosions in dry, porous media can be well approximated by simply dividing the P wave source functions for the same explosions in saturated tuff predicted by the well-calibrated Mueller/Murphy source model by the derived frequency independent Gp reduction factor. It follows that, given an estimate of Gp for the dry, porous source emplacement medium of an explosion of monitoring interest, a P wave seismic yield estimate for that explosion can be readily determined from the established relations for explosions in “good coupling” media by accounting for the expected frequency independent effect of Gp on the radiated P wave amplitude.

This documented reduction in seismic coupling efficiency has significant implications with respect to seismic detection and yield estimation capability. Thus, for example, the m_b value at a given yield expected for an explosion in a medium characterized by a Gp value of 30% is nearly a full magnitude unit lower than that expected for the same explosion in a good coupling medium. Consequently, since this reduction in seismic amplitude has been found to be approximately independent of frequency, the yield detection thresholds for a given monitoring network would be expected to be nearly a factor of 10 higher for explosions in such media than those typically quoted for explosions in good coupling media.

2. Introduction

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. The objective of the research investigation summarized in this report has been to derive a reliable seismic source model that can be used to quantitatively address seismic detection, identification and yield estimation capability with respect to small underground nuclear tests that might be conducted in low-coupling, dry porous media such as the tuff and alluvium found above the water table at the Nevada Test Site (NTS).

2.1. Seismic Source Coupling for Underground Nuclear Explosions

Fortunately, from the perspective of nuclear test monitoring, the low frequency seismic waves traditionally used for monitoring purposes have been found to be remarkably insensitive to the detailed characteristics of the source emplacement medium. Thus, for example, as is illustrated in Figure 1, a single m_b/yield relation has been found to be applicable to all underground nuclear explosions conducted in various hard rock media at the former Soviet Semipalatinsk test site, as well as to underground explosions conducted in salt at the former Soviet Azgir test site.

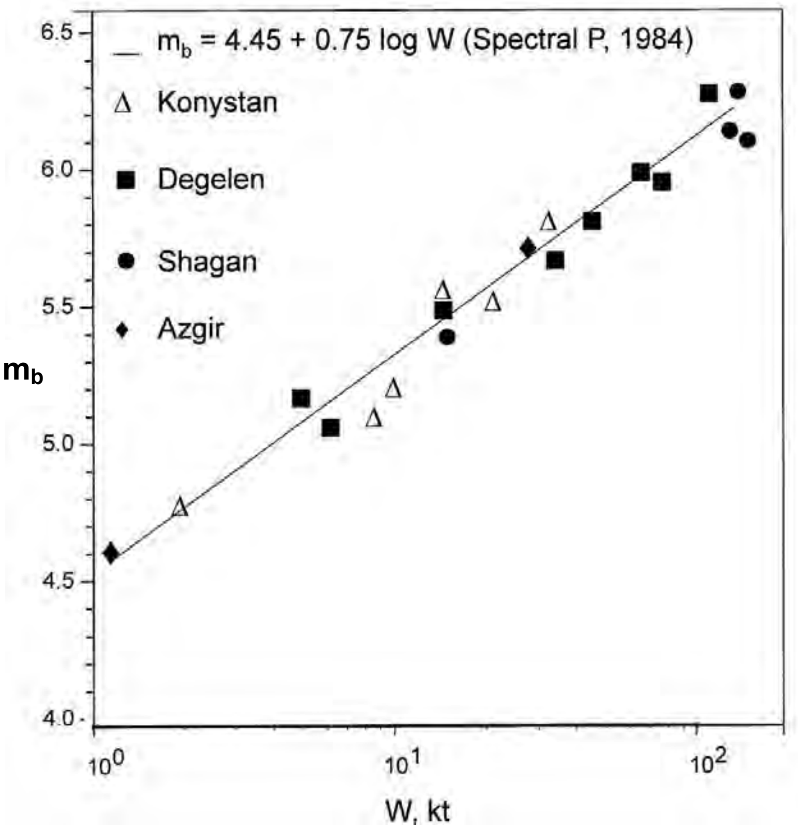


Figure 1. Comparison of m_b/Yield Observations for Explosions in Hard Rock at the Former Soviet Semipalatinsk Test Site (Shagan, Degelen and Konystan Testing Areas) and in Salt at the Former Soviet Azgir Test Site [2]

In Figure 1, the solid line corresponds to the nominal m_b/yield relation for explosions at the Semipalatinsk test site. Note that although the measured laboratory physical properties of salt and granite are dramatically different, the observed low frequency seismic coupling for explosions of the same yields in these two media is found to be essentially identical. Moreover, as is shown in Figure 2, this same m_b/yield relation is very consistent with the observations from the more than 120 Soviet Peaceful Nuclear Explosion (PNE) tests that were conducted in a wide variety of geologic emplacement media at locations all across the territories of the former Soviet Union. Similar comments apply to the observations shown in Figure 3 for explosions conducted in granite at the French Sahara and NTS test sites, where it can be seen that a common m_b/yield relation applies to both the U.S. and French explosions in granite, as well as to explosions conducted in water-saturated volcanic rocks found below the water table at NTS. Thus, the observational data strongly indicate that the seismic source coupling efficiency is very similar for all explosions in "good coupling" media (i.e. hard rock or water saturated media).

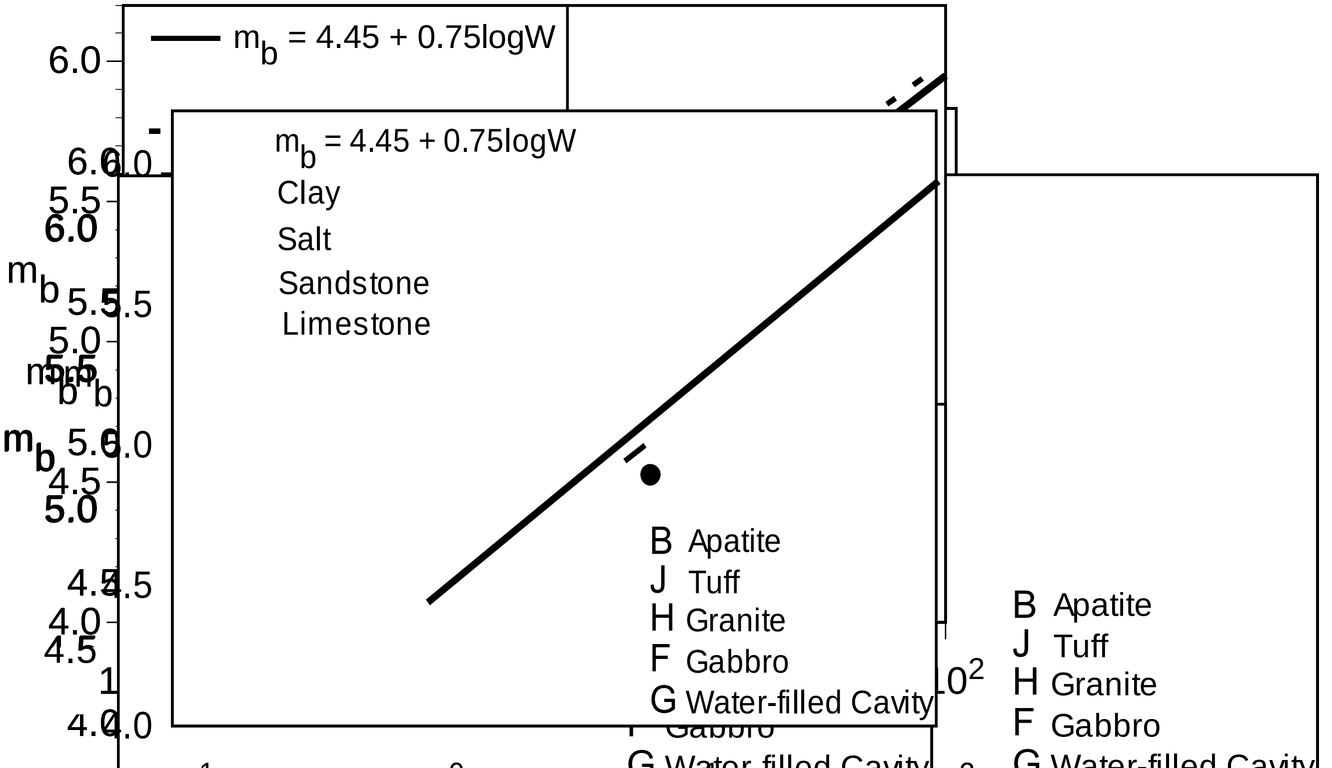


Figure 2. Comparison of m_b/Yield Data for Shallow Soviet PNE Explosions in Various Media [5]

Comparison of m_b/yield data for shallow Soviet PNE explosions in various media. The solid line corresponds to the nominal m_b/yield relation for explosions at the Soviet Semipalatinsk test site.

Figure 4 Comparison of m_b/yield data for shallow Soviet PNE explosions in various media (Sultanov et al., 1993). The solid line corresponds to the nominal m_b/yield relation for explosions at the Soviet Semipalatinsk test site.

In Figure 2, the solid line corresponds to the nominal m_b/yield relation for explosions at the Soviet Semipalatinsk Test Site.

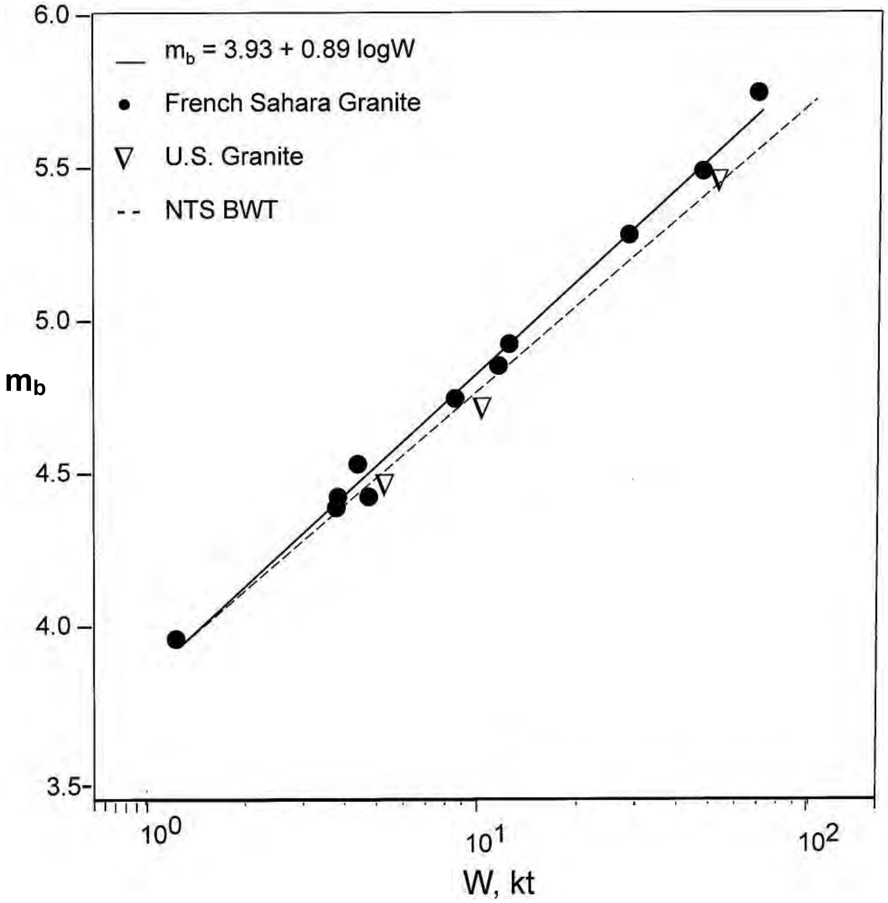
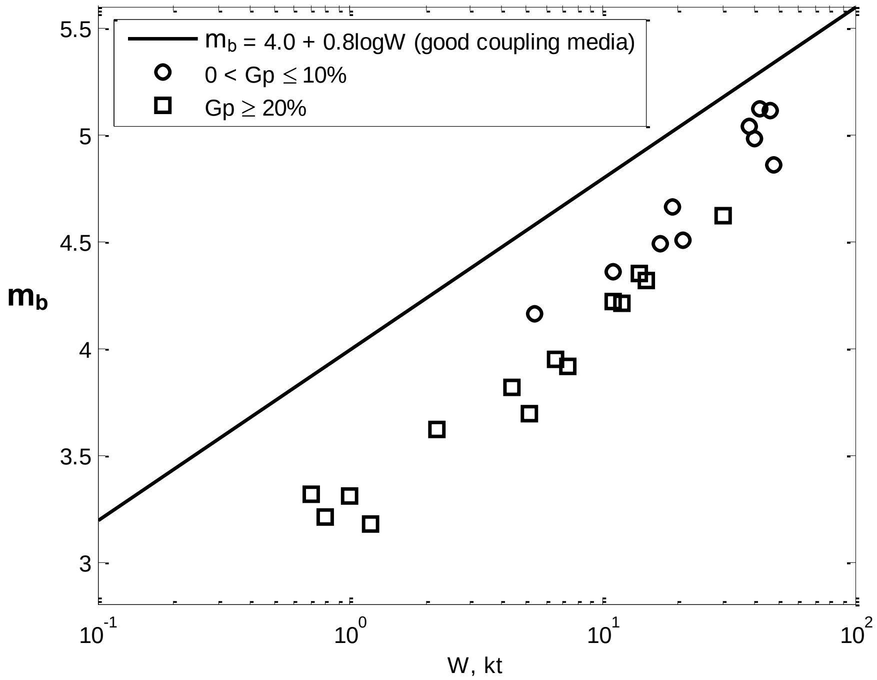


Figure 3. Comparison of m_b/Yield Data for French and U.S. Explosions in Granite with the Nominal m_b/Yield Relation for Explosions Conducted Below the Water Table (BWT) at NTS [1]

The only media which consistently give different m_b/yield results for fully tamped explosions than those for good coupling media are for explosions in saturated clay or water, which at a fixed yield are higher on average by about 0.5 units m_b (and therefore provide no special monitoring challenge), and for explosions in dry, porous media which are lower on average by about 0.5 units m_b. This reduced coupling for the latter is illustrated in Figure 4, where m_b/yield data for selected explosions conducted in dry, porous tuff and alluvium above the water table at NTS are compared with the nominal NTS m_b/yield relation for explosions in good coupling media. It can be seen that these observed data fall below this good coupling m_b/yield relation by nearly a full order of magnitude in some cases, and that the offset appears to increase with increasing air-filled porosity, Gp (percent by volume, measured at shot depth). While this observed reduction in seismic coupling is not as pronounced as that for the cavity decoupling evasion scenario, which is expected to be as much as two orders of magnitude lower than that for good coupling media, it is large enough to significantly affect nuclear test monitoring strategy. Thus, there is a need for a quantitative seismic source model for explosions in such media.



Comparison of observed m_b/yield data for explosions conducted in dry, porous tuffs and alluvium above the water table at NTS with the nominal NTS m_b/yield relation for explosions conducted in good coupling media. Gp denotes the measured air-filled porosity (percent by volume) at the detonation point.

Figure 4. Comparison of Observed m_b/yield Data for Explosions Conducted in Dry, Porous Tuff and Alluvium Above the Water Table at NTS with the Nominal NTS m_b/Yield Relation for Explosions Conducted in Good Coupling Media. (personal communication, Bill Walter, LLNL, 2009)

In Figure 4, Gp denotes the measured air-filled porosity (percent by volume) at the detonation point. Theoretical investigations of the seismic source characteristics of underground nuclear explosions have been ongoing since the initiation of underground testing in 1957. The most ambitious of these have attempted to proceed according to "first principles"; that is, by beginning at the point and instant of detonation and calculating outward in space and time using nonlinear finite difference codes based on fundamental physical laws. However, because of the complex nature of the response of real earth materials over the enormous range of pressures encountered in tamped underground nuclear explosions, it has yet to be demonstrated that such theoretical simulation models are fully capable of accurately reproducing all of the observed variations in seismic coupling. For this reason, an alternate approach has been pursued in parallel to the formal one in which measured ground motion data from explosions have been used to infer simple analytic approximations to the nuclear seismic source function as well as scaling laws to describe the dependence of the source characteristics on variables such as explosion yield, depth of burial and emplacement medium. One such approximate source model which has been extensively tested and verified against a wide variety of observed seismic data is that proposed by Mueller and Murphy some 40 years ago [1 & 4]. This research resulted in the formulation of seismic source models for underground nuclear explosions in granite, saturated tuff/rhyolite, salt and sandstone/shale media which have proved to be remarkably consistent with seismic observations from underground nuclear explosions conducted in conjunction with the U.S., Former Soviet Union, French and Chinese nuclear testing programs. [2 & 5] However, because it was generally believed at the time of the original Mueller/Murphy model formulation that only low yield nuclear explosions could be conducted in dry porous media at potential testing locations within the Soviet Union, explosions in such media were considered to be of secondary importance with respect to nuclear test monitoring and, consequently, no attempt was made at that time to derive and validate a corresponding approximate “Mueller/Murphy” seismic source model for underground nuclear explosions in low-coupling, dry, porous media. More recently, U.S. nuclear monitoring requirements have expanded to focus more on global monitoring of possible smaller, clandestine nuclear tests. Such low yield tests could well be conducted in low-coupling media in many countries of potential monitoring interest and, therefore, there is a need for an appropriate seismic source model for explosions in such media which can be used to quantitatively assess nuclear monitoring capability.

In the context of the simple spherically symmetric approximation to the nuclear seismic source function, the reduction in seismic coupling efficiency for explosions in dry, porous media can be qualitatively understood with reference to the sketch shown in Figure 5.

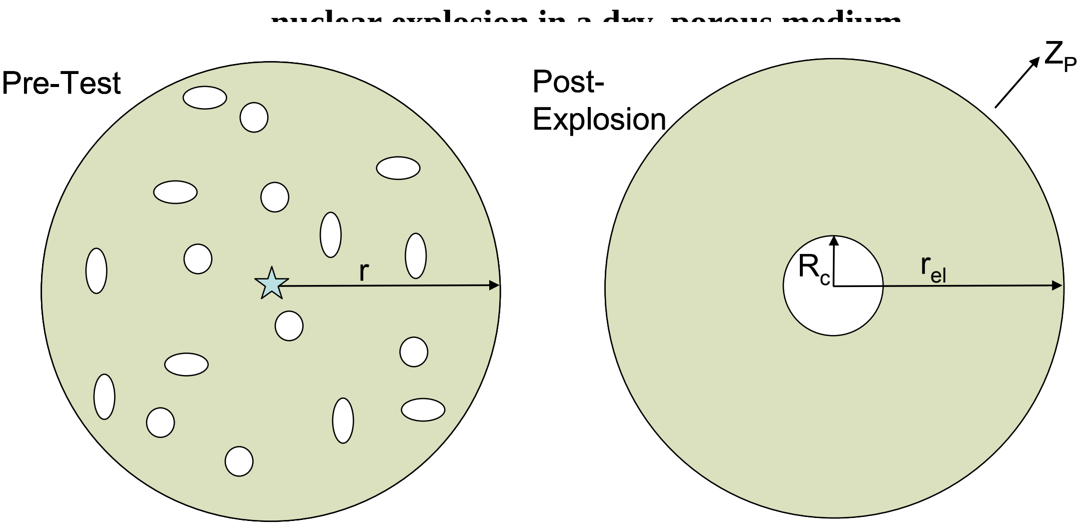


Figure 5. Phenomenology Associated with an Underground Nuclear Explosion in a Dry, Porous Medium

In the low frequency limit, the seismic source function for underground explosions, S(ω), can be expressed as:

$$\lim_{\omega\to 0} S(\omega) \sim r_{el}^2 * Z_P(r_{el})$$

where r_{el} is the elastic radius and Z_P is the permanent displacement at r_{el} induced by the explosion. By conservation of mass

$$Z_P(r_{el}) = d * \frac{R_c^3}{3r_{el}^2}$$

where R_c is the radius of the cavity produced by the explosion and d is the so-called “compaction factor” (Mueller and Murphy, 1971). In approximately incompressible media, like hardrock, d ≈ 1. However, in media with air-filled porosity, d can be significantly less than 1 due to the crush-up of the open pore spaces produced by the outgoing strong shock wave induced by the explosion. This leads to a reduction in the low frequency seismic coupling efficiency.

Now, it can be shown [6] that, in the low frequency limit, the seismic source function for underground explosions, S(ω), can be expressed as

$$\lim_{\omega\to 0} S(\omega) \approx r_{el}^2 Z_P(r_{el}) \qquad (1)$$

where r_{el} is the elastic radius at which the medium response to the outgoing shock wave induced by the explosion transitions to linear elastic response, and $Z_P(r_{el})$ is the permanent displacement at r_{el} induced by the explosion. By conservation of mass

$$Z_P(r_{el}) = d \frac{R_c^3}{3\, r_{el}^2} \qquad (2)$$

where R_c is the final radius of the cavity produced by the explosion and d is the so-called “compaction factor.” [1] In approximately incompressible media such as granite, d ≈ 1. However, in media with air-filled porosity, d can be significantly less than 1 due to the crush-up of the open pore spaces produced by the strong outgoing shock wave induced by the explosion. This leads to a reduction in the low frequency seismic coupling efficiency.

2.2. Background

Over the years, a number of studies have been conducted that have addressed various elements of the effects of source medium air-filled porosity on seismic coupling. The most pertinent of these for the purposes of the present study are those that focused on data recorded from NTS explosions at the four Lawrence Livermore National Laboratory (LLNL) broadband, near-regional stations, MNV, KNB, LAC, and ELK, whose locations are shown on a map of the region in Figure 6.

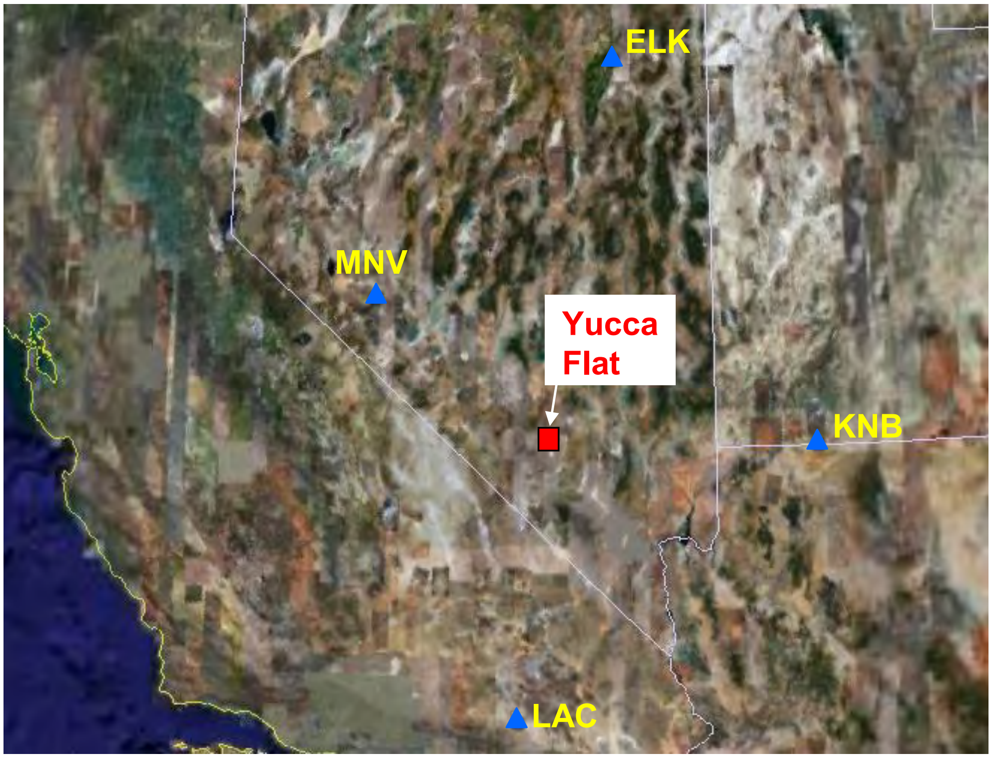


Figure 6. Map of the Western United States Showing the Yucca Flat Testing Area of NTS and the Locations of the Four LLNL Broadband Stations at ELK (Elko, Nevada), KNB (Kanab, Utah), LAC (Landers, California), and MNV (Mina, Nevada)

Map of the Western United States showing the Yucca Flat testing area of NTS and the locations of the four LLNL broadband stations at ELK (Elko, Nevada), KNB (Kanab, Utah), LAC (Landers, California), and MNV (Mina, Nevada).

One such study which directly addressed the effect of source medium gas-filled porosity on P wave coupling was a regional explosion yield estimation analysis described in a paper by Vergino and Mensing [7]. In that paper, the authors described their analysis of a collection of seismic data recorded at the LLNL network stations from a large sample of NTS explosions in the 1-300 kt yield range, which sampled emplacement environments both above and below the water table at the various testing areas within the site. For the purposes of their analysis they proceeded by first filtering the broadband data through a synthetic WWSSN response and then estimating $m_b(Pn)$ by applying standard time domain magnitude estimation procedures to the resulting narrowband data. They then evaluated the dependence of this $m_b(Pn)$ magnitude measure on explosion yield (W) and percent gas-filled porosity at the working point of the explosion (Gp) assuming a simple linear functional relationship of the form

$$m_b(Pn) \quad = \quad a_R + b\log W + c\,G_p \tag{3}$$

where a_R denotes the network-averaged m_b intercepts for the various testing areas (i.e. North and South Yucca Flat, Pahute Mesa, Rainier Mesa), b is the slope of the magnitude/yield relation, which is assumed to be the same for all testing areas, and c is the porosity scaling coefficient, assumed to be linear. Detailed statistical analyses were conducted to estimate the coefficients a_R, b and c, and it was found that the best-fitting value of c for their assembled data set was about -0.027. Thus, over the sampled range of air-filled porosity, which extended from 0 to about 30%, this simplified scaling law predicts about a 0.8 magnitude unit decrease in m_b(Pn) at a fixed yield, consistent with the observed m_b/yield data shown in Figure 4 above. While this study was very carefully conducted and clearly delineated the low coupling characteristics of explosions in dry, porous media, it had some obvious limitations with respect to the goals of the present study. In particular, it focused exclusively on narrowband, time domain data, and assumed a highly-simplified, frequency-independent variation of seismic coupling with degree of gas-filled source medium porosity. Consequently, the results of this study do not provide an adequate basis for defining a frequency dependent seismic source model for underground explosions in such low coupling source media.

A related study which did consider frequency dependence was the spectral yield estimation analysis conducted by Taylor and Dowla. [8] They proceeded by calculating and analyzing Pn, Pg and Lg spectra derived from LLNL network recordings of 311 explosions conducted above and below the water table at NTS. In agreement with the previous results of Vergino and Mensing [7], they also found that the percentage of air-filled porosity in the explosion emplacement medium had a very large effect on the low frequency seismic coupling efficiency. However, they also found that the degree of air-filled porosity affected the overall spectral composition of the signals, leading to reduced high frequency content for explosions in dry porous media relative to that of explosions of comparable yield detonated in saturated media below the water table. Given their large samples of observed data from explosions of various yield detonated in a wide range of source emplacement environments, they decided to approach yield estimation through “template matching”, in which the observed spectra for a given explosion were quantitatively compared with the sample of spectra from explosions of known yield in the database. The yield estimate for the new event was then obtained by calculating the mean of the yields of the top 7 “best-matched” explosions. They found that this template matching procedure adequately separated the explosions in low versus good coupling media, and provided yield estimates that were very similar to those obtained by Vergino and Mensing [7] using their m_b(Pn) approach. While this analysis of Taylor and Dowla [8] did successfully demonstrate systematic spectral differences associated with the degree of air-filled porosity of the emplacement medium, their template matching approach is obviously limited to very well calibrated test sites for which large samples of observed regional phase spectra are available from explosions of known yield and source medium properties. Moreover, since the results represented a weighted average of Pn, Pg, and Lg spectra and no attempt was made to formulate an explicit P wave seismic source model, these study results are not directly applicable to global monitoring of nuclear tests in such source media.

In a more recent study, Jones and Taylor [9] examined the effects of source media on observed Lg spectra from NTS explosions. Once again, these authors used data recorded at the LLNL network stations to estimate Lg spectra for 160 NTS explosions conducted both above and below the water table, and computed network-averaged Lg spectra for each explosion by combining the spectral estimates from the four network stations. The stated objective of the study was to determine which near-source factors control the observed Lg spectral shape. The analysis approach was based on determining a “master spectrum” which was defined as the average of the observed Lg spectra for 6 explosions in the yield range from 70 to 140 kt which were detonated below the water table at Yucca Flat. A grid search technique was then employed to determine the low frequency amplitude ratios and corner frequency shifts which would best reconcile the Lg spectrum for any selected explosion with the “master spectrum”. The observed amplitude ratios were subsequently normalized for source size effects by multiplying by the cube of the ratio of the observed cavity radius for each explosion to the average cavity radius corresponding to the “master spectrum”, to roughly compensate for effects due to differences in the yields of the explosions. The remaining residuals with respect to the “master spectrum” were then used to define a seismic coupling factor, C, and it was demonstrated once again that the low frequency seismic coupling efficiency decreases by about on full order of magnitude as the percentage of air-filled porosity of the emplacement medium increases from 0 to 25%. However, the authors eventually concluded that the coupling factor C correlates better with variations in observed scaled cavity radius than with the variations in air-filled porosity, and they attributed this to the fact that observations of cavity radius tend to be more accurate than corresponding measurements of air-filled porosity of the medium at the working point. Another factor which probably contributes to this improved correlation is that it is likely that the scaled cavity radius depends on the medium properties to some extent; and, consequently, this parameter is not truly independent of the source coupling, which complicates the interpretation of the results to some extent. In any case, the results of this study again demonstrated the reduced coupling characteristics of explosions in dry, porous media and extended previous results to examine seismic source scaling as a function of various explosion source parameters. However, as with the other studies referenced above, that of Jones and Taylor [9] has some significant limitations with respect to the goals of the present study. For example, their scaling analyses were formulated in terms of measured cavity radii, which is clearly not a parameter that is directly accessible for monitoring clandestine underground nuclear explosions. More fundamentally, this study focused exclusively on analyses of the characteristics of observed Lg spectra, and it is now well-established that the seismic source of Lg from explosions is not the same as that for direct P (e.g. [10 & 11]). Consequently, these results are not directly applicable to P wave coupling, which still constitutes the primary measure of seismic detectability in nuclear monitoring studies.

In summary, there have been a number of previous studies which have dealt with various aspects of seismic source coupling in the dry, porous tuff and alluvium media found above the water table at NTS. The results of these different studies have been generally consistent in that they indicated reductions in 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. Clearly, such reductions in coupling efficiency have significant implications with respect to the seismic monitoring of small, clandestine nuclear explosions. However, at the present time, there is no simple seismic source model for explosions in such media comparable to the Mueller/Murphy source model for explosions in good coupling media such as hardrock or water-saturated sediments. Such a model is needed to support nuclear monitoring applications related to the frequency dependent seismic detection, identification and yield estimation of small underground nuclear tests in low coupling media.

2.3. Report Overview

This report describes the results of a research investigation conducted with the objective of defining a frequency dependent seismic source scaling model for underground nuclear explosions conducted in low-coupling, dry porous media. The report consists of five sections, including these introductory remarks and the preceding Summary. Section 3 describes the technical approach, including the characteristics of the seismic data sample selected for analysis, the data processing procedures employed and the statistical modeling approach employed to define the frequency dependent seismic source scaling. This is followed in Section 4 by a summary of the seismic source scaling results and a discussion of the significance of these results with respect to seismic monitoring of underground nuclear tests conducted in such dry porous media. The report concludes with Section 5 in which the principal conclusions resulting from this research investigation are summarized.

3. Technical Approach

3.1. Description of the Selected Data Sample

The seismic source scaling analysis has focused on broadband digital data from NTS explosions at the four near-regional stations of the LLNL seismic network, the locations of which were shown previously on the map of Figure 6. Seismic data recorded at these stations were provided to us by LLNL (personal communication, Bill Walter, 2009), approximately 100 of which were underground nuclear tests conducted above the water table in dry porous media. Because the available data sample from LLNL station MNV (Mina, Nevada; $\Delta \approx 240$ km) is the most complete, it was used for the statistical scaling analyses, and selected data from the other three LLNL stations were used to test the robustness of the seismic source scaling inferred from the MNV data.

Table 1 lists the 63 NTS explosions in the MNV data sample that were conducted above the water table in dry, porous media at the Yucca Flat testing area, together with the associated source media, explosion depths of burial (h) and measured gas-filled porosities of the emplacement media at shot depth (Gp). The distribution of the measured Gp values for these 63 explosions is summarized in Figure 7. It can be seen that these measured Gp values range from near zero to almost 30%, with a mean value of about 15%. This distribution is broad enough to provide a good basis for quantitatively defining the dependence of seismic source coupling on the percentage of gas-filled porosity of the source emplacement medium.

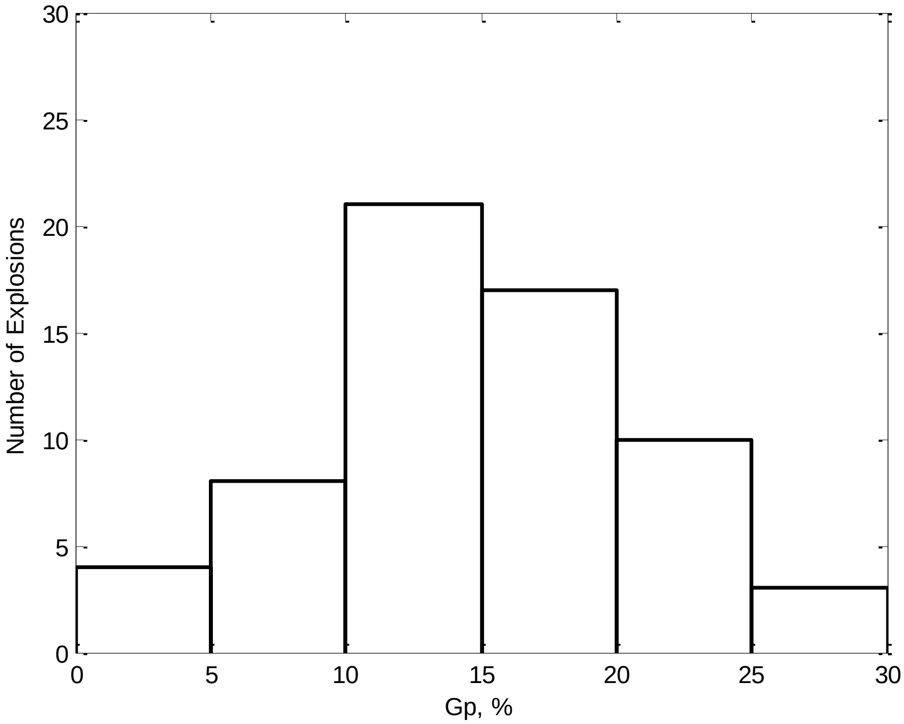


Figure 7. Distribution of Observed Gas-Filled Porosity (Gp) Values for the Selected Sample of 63 Yucca Flat Explosions Recorded at Station MNV

Table 1. Selected Explosions Conducted in Dry Porous Media Above the Water Table at Yucca Flat [12]

Event Name	Date	Medium(1)	h, m(2)	Gp, %(3)
Nessel	8/29/1979	A	464	10.5
Pera	9/08/1979	T	200	19.0
Backgammon	11/29/1979	A	229	18.0
Azul	12/14/1979	A	205	17.2
Tarko	2/28/1980	A	369	11.6
Norbo	3/08/1980	T	271	18.5
Canfield	5/02/1980	T	351	20.0
Flora	5/22/1980	A	335	13.0
Huron King	6/24/1980	A	320	13.0
Duchess	10/24/1980	T	427	11.0
Dauphin	11/14/1980	T	320	17.0
Clairette	2/05/1981	A	354	14.0
Aligote	5/29/1981	T	320	8.0
Niza	7/10/1981	T	341	15.2
Pineau	7/16/1981	T	207	29.0
Islay	8/27/1981	T	294	23.0
Trebbiano	9/04/1981	T	305	22.0
Cernada	9/24/1981	A	351	20.0
Paliza	10/01/1981	T	472	6.0
Tilci	11/11/1981	A	445	10.1
Akavi	12/03/1981	T	494	14.0
Caboc	12/16/1981	T	335	16.0

Tenaja	4/17/1982	T	357	12.0
Kryddost	5/06/1982	T	335	16.7
Kesti	6/16/1982	T	289	15.7
Queso	8/11/1982	A	216	23.4
Cerro	9/02/1982	A	229	22.0
Frisco	9/23/1982	T	451	17.1
Seyval	11/12/1982	A	366	18.0
Manteca	12/10/1982	A	413	11.8
Coalora	2/11/1983	T	274	25.0
Cheedam	2/17/1983	T	343	19.7
Crowdie	5/05/1983	A	390	5.9
Laban	8/03/1983	A	326	10.9
Sabado	8/11/1983	T	320	16.0
Gorbea	1/31/1984	T	388	10.0
Agrini	3/31/1984	A	320	10.0
Correo	8/02/1984	T	334	13.0
Dolcetto	8/30/1984	T	365	12.0
Breton	9/13/1984	T	483	9.9
Vaughn	3/15/1985	T	426	11.0
Ville	6/12/1985	T	293	22.3
Maribo	6/26/1985	T	381	22.5
Ponil	9/27/1985	T	365	10.0
Roquefort	10/16/1985	T	415	23.6
Panamint	5/21/1986	T	480	15.1
Tajo	6/05/1986	T	518	5.0
Cornucopia	7/24/1986	A	381	11.4
Tornero	2/11/1987	T	298	15.0
Brie	6/18/1987	T	203	14.0
Abilene	4/07/1988	T	245	17.0
Rhyolite	6/22/1988	A	207	11.3
Bullfrog	8/30/1988	T	489	3.6
Texarkana	2/10/1989	T	503	5.0
Kawich Red	2/24/1989	T	370	13.0
Ingot	3/09/1989	T	500	8.0
Palisade	5/15/1989	T	335	15.9
Tulia	5/26/1989	T	398	20.0
Metropolis	3/10/1990	T	469	11.7
Austin	6/21/1990	T	350	25.0
Coso Bronze	3/08/1991	T	330	11.7
Lubbock	10/18/1991	T	457	4.5
Galena Yellow	6/23/1992	T	290	11.8
Event Name	**Date**	**Medium(1)**	**h, m(2)**	**Gp, %(3)**

(1) A, alluvium; T, tuff
(2) Explosion depth of burial in meters
(3) Air-filled porosity, % by volume

The corresponding distribution of this MNV sample with reported explosion yield is shown in Figure 8. The individual values range from about 0.5 to 40 kt, with a mean value of around

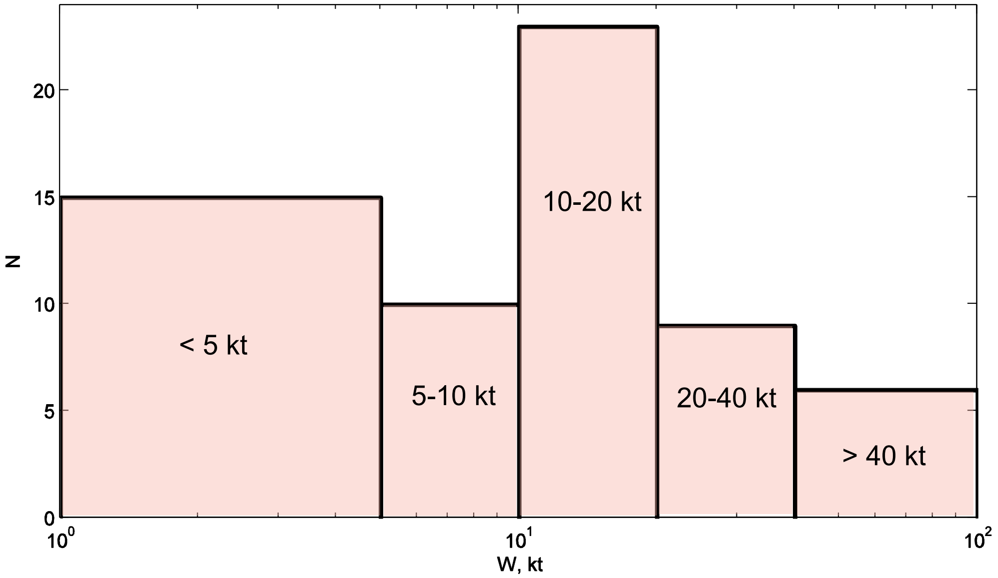


Figure 8. Distribution of Yield Values for the Selected Sample of Yucca Flat Explosions Conducted Above the Water Table and Recorded at Station MNV

Distribution of yield values for the selected sample of Yucca Flat explosions conducted above the water table and recorded at station MNV. The mean yield for this sample of explosions is approximately 10 kt.

Combining these yield estimates with the associated source depth of burial values from Table 1 leads to the distribution of the explosion sample with scaled depth of burial (m/kt$^{1/3}$) shown in Figure 9. It can be seen that these scaled depth values are fairly tightly clustered around a mean scaled depth of about 150 m/kt$^{1/3}$. As will be discussed in the following section, this narrow distribution of scaled depths has some important implications with respect to the statistical estimation of the seismic source scaling parameters.

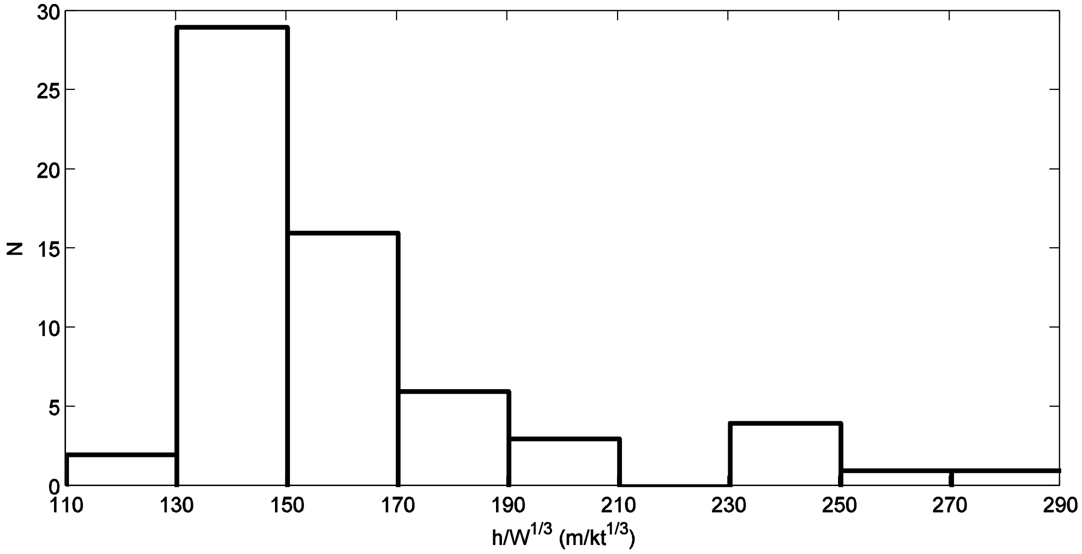


Figure 9. Distribution of Scaled Depth Values for the Selected Sample of Yucca Flat Explosions Conducted Above the Water Table and Recorded at Station MNV

A systematic review of the available LLNL network seismic data indicated that it is generally of excellent quality. This fact is illustrated in Figure 10 which shows a record section of vertical component seismic data recorded at station MNV from selected Yucca Flat explosions. In this figure the top ten traces correspond to recordings of low yield explosions conducted in dry, porous media above the water table at Yucca Flat, while the bottom three traces represent recordings of much larger explosions conducted in saturated tuffs below the water table at Yucca Flat. It can be seen from this figure that the broadband signal-to-noise ratios for the initial P waves are generally quite high, even for the smaller explosions in low coupling media.

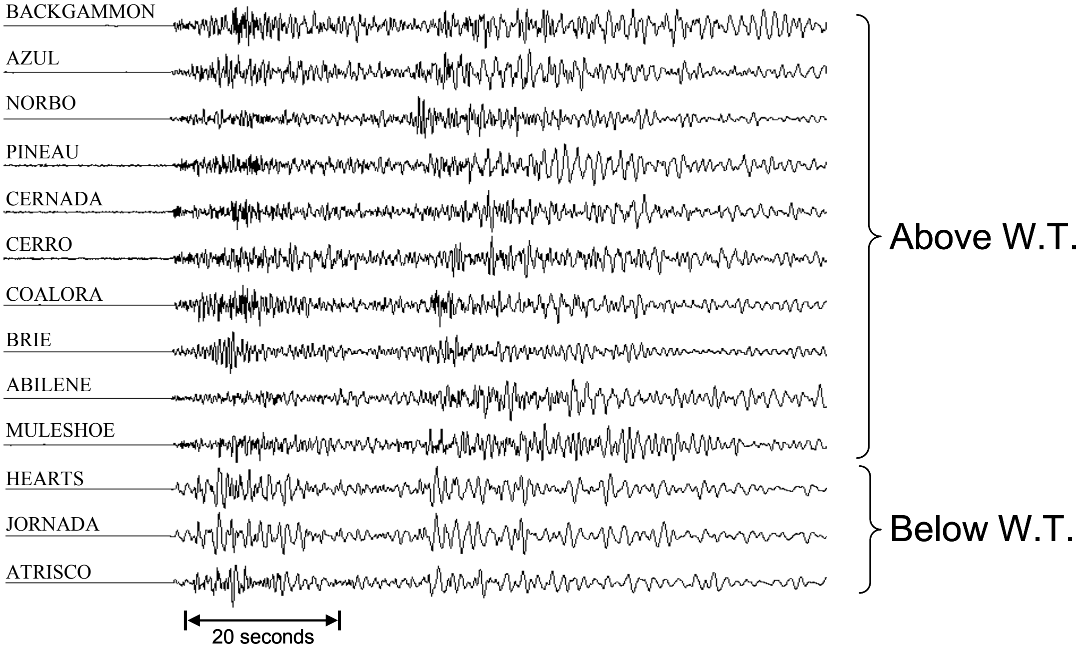


Figure 10. Data Recorded from Selected Yucca Flat Explosions at LLNL Station MNV

Data recorded from selected Yucca Flat explosions at LLNL station MNV.

In Figure 10, the top ten traces correspond to low yield explosions conducted above the water table (Above W.T.) at Yucca Flat; while the bottom three traces correspond to higher yield explosions conducted below the water table (Below W.T.) at Yucca Flat.

3.2. Signal Processing and Source Scaling Analysis Methodology

P wave spectra corresponding to the seismic data recorded from the 63 Yucca Flat explosions of Table 1 at station MNV have been estimated over the frequency band 0.5 to 10 Hz using the initial 10 seconds of the recorded P waves, together with spectra for the associated 10 seconds of pre-signal noise. These spectra have then been smoothed to an effective resolution of about 0.25 Hz to provide the P wave spectral amplitude data used in the scaling analysis. Since these data were recorded at a fixed station from explosions in the same Yucca Flat testing area of NTS, it has been assumed that the frequency dependent propagation path effects are essentially the same for all events and, consequently, that the scaling of these observed P wave spectral data should reflect the scaling of the associated P wave seismic source functions.

With regard to the statistical scaling model, because these selected explosions were conducted over such a narrow range in scaled depth, as was documented in Figure 9 above, source depth is approximately proportional to the cube root of the yield, and any depth dependence of the seismic source is absorbed into the yield dependence for this sample of explosions and cannot be independently estimated through statistical analyses. Therefore, the observed P wave spectra from these explosions, P(ω), have been represented by the simple functional form

$$P(\omega) \quad = \quad k(\omega)\, W^{a_1(\omega)}\, 10^{a_2(\omega) G_P} \qquad (4)$$

where W is the explosion yield, Gp the percent gas-filled porosity of the emplacement medium at shot depth and k, a_1, a_2 are frequency-dependent scaling coefficients to be estimated from the observed spectral data via least squares analysis using the linearized from of equation (4):

$$\log P(\omega) \quad = \quad \log k(\omega) \quad + \quad a_1(\omega) \log W \quad + \quad a_2(\omega) G_P \qquad (5)$$

Note that the assumed functional dependence of the P wave spectral amplitudes on Gp in equation (5) is simply a generalized, frequency dependent version of that employed previously by Vergino and Mensing [7] (cf. equation (3) above) in their analysis of narrowband m_b(Pn) data. Although alternate functional dependencies could certainly be considered, it has been found that this simple relation provides a good description of the observed variations in P wave spectral amplitude level as a function of Gp, as will be documented in the following section.

Our basic approach to defining a seismic source scaling model for explosions in dry, porous media is to use the results of the statistical analysis procedure described above to define the average MNV spectral amplitude level as a function of Gp at the average yield and scaled depth of burial of the selected explosion sample. These average spectra are then compared with an average spectrum for the same yield and scaled depth of burial determined from MNV recordings of selected explosions conducted below the water table in saturated media at Yucca Flat. Since these below the water table reference explosions will generally not have been conducted at either the average yield or scaled depth of burial of the corresponding average explosion in dry, porous media, it is necessary to first scale the observed spectra of the reference explosions to account for differences in yield and depth of burial. This is accomplished using the previously well-documented and validated Mueller/Murphy [1] seismic source scaling model for explosions in water saturated volcanic rocks. The resulting average observed P wave spectral ratio then provides a quantitative basis for modifying the known Mueller/Murphy seismic source for explosions conducted below the water table in saturated tuff to obtain a seismic source model applicable to explosions in dry, porous media. The results of applying this analysis approach are summarized in the following section of this report.

4. Results and Discussion

Frequency dependent seismic source scaling relations for underground nuclear explosions in dry, porous media have been derived by fitting equation (5) above to the P wave spectral amplitudes derived from the observed station MNV recordings of the 63 Yucca Flat explosions of Table 1 using the least squares criterion. While the signal to noise ratios of these P wave spectral data were found to be generally good over the entire frequency band extending from 0.5 to 10 Hz for the selected sample of explosions, P wave spectral amplitude estimates associated with signal to noise ratios of less than 2.0 were eliminated from the statistical analysis to avoid noise contamination of the results. A somewhat unexpected result of this statistical analysis has been the finding that the dependence of P wave spectral amplitude on Gp is essentially independent of frequency over the entire analysis band extending from 0.5 to 10 Hz. This fact is confirmed in Figure 11 which shows a comparison of the prediction σ values (i.e. the standard deviations of the logarithms of the ratios of predicted to observed spectral amplitudes) as a function of frequency obtained using the statistically derived frequency dependent Gp scaling coefficients and a frequency independent Gp scaling in which the coefficient on Gp was held fixed at the average of the derived frequency dependent values.

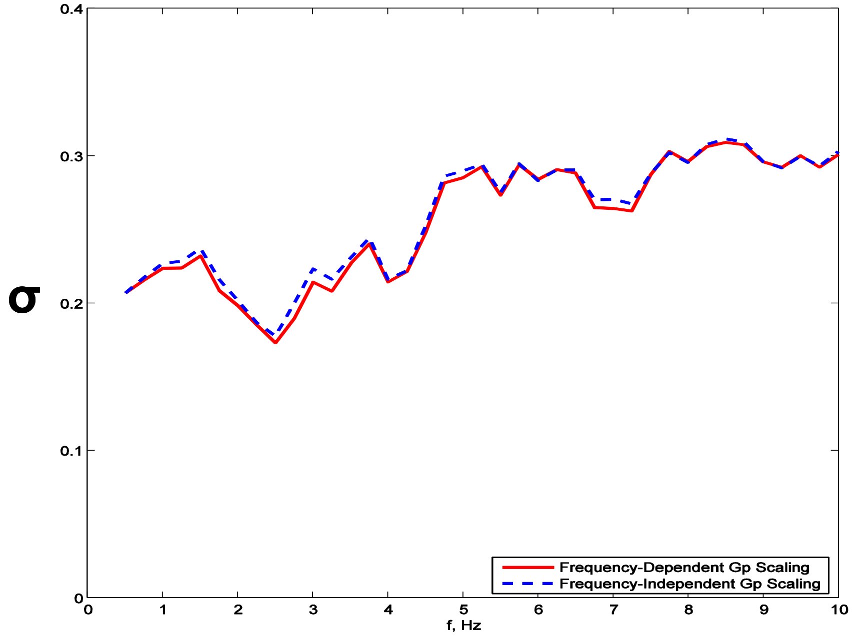


Figure 11. Comparison of Prediction Standard Deviations (σ) as a Function of Frequency (f) for Scaling Analyses Conducted with Frequency Dependent (Solid Line) and Frequency Independent (Dashed Line) Gp Scaling

Comparison of prediction standard deviations (σ) as a function of frequency (f) for scaling analyses conducted with frequency dependent (solid) and frequency independent (dashed) Gp scaling. These results indicate that the scaling with Gp is essentially independent of frequency.

It can be seen that the results obtained using these two models are essentially identical, confirming that the Gp scaling is independent of frequency within the statistical uncertainties of the least squares solution. The average value of the Gp scaling coefficient (i.e. a_2 in equation (5)) in this case is -0.024, which agrees quite well with the coefficient value of -0.027 obtained previously by Vergino and Mensing [7] in their analysis of the m_b(Pn) magnitude measure scaling dependence on Gp. This result greatly simplifies the seismic source modeling analysis for explosions in dry, porous media in that it implies that for any fixed explosion yield and source depth of burial, the P wave spectral amplitudes expected for different values of Gp are offset from one another by frequency independent constant values, decreasing by about a factor of 5 as Gp varies from near zero to 30%.

It has been found that this statistically derived scaling model provides quite good predictive capability over the range of source parameters encompassed by the selected sample of explosions. For example, Figures 12 and 13 show comparisons of predicted and observed MNV P wave spectra for explosions of essentially the same yields and significantly different Gp values. Similarly, Figure 14 shows comparisons of predicted and observed MNV P wave spectra for explosions with comparable Gp values (~20%) and m_b(Pn) values (and associated yields) varying over nearly a full order of magnitude. These comparisons confirm that the statistically derived scaling with both yield and Gp are in good agreement with the measured MNV P wave spectral data and consequently, they provide a robust method for estimating the expected MNV P wave spectra corresponding to Yucca Flat explosions in dry, porous media characterized by a range of Gp values at the sample average yield and scaled depth of burial of 10 kt and 150 m/kt$^{1/3}$, respectively.

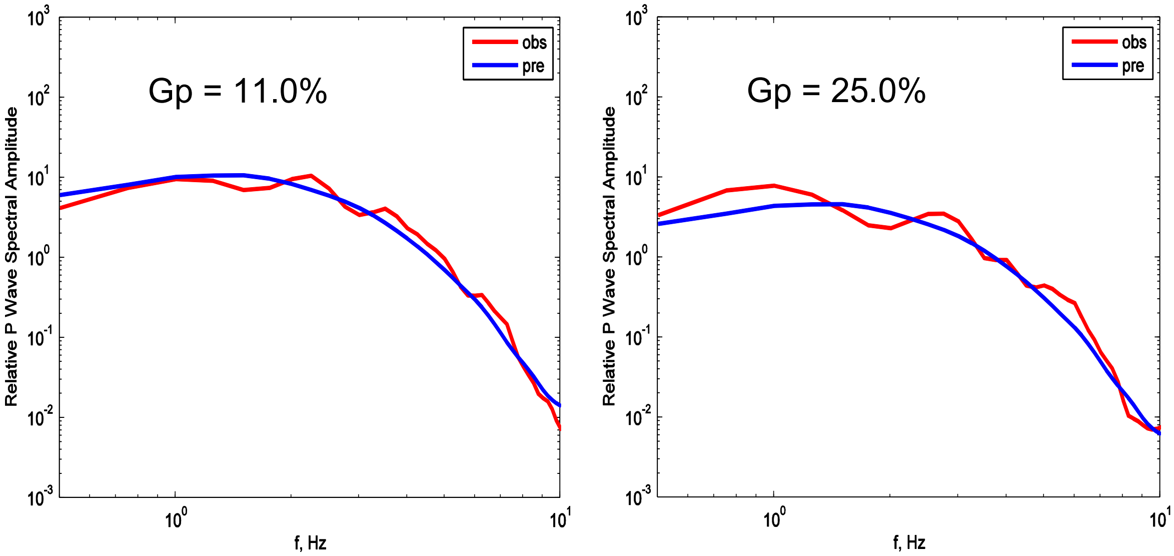


Figure 12. Comparison of Predicted and Observed MNV P Wave Spectra for Explosions of Comparable Yield Conducted in Media with Significantly Different Gas-Filled Porosity (Gp) Values

Comparison of predicted and observed MNV P wave spectra for explosions of comparable yield conducted in media with significantly different gas-filled porosity (Gp) values.

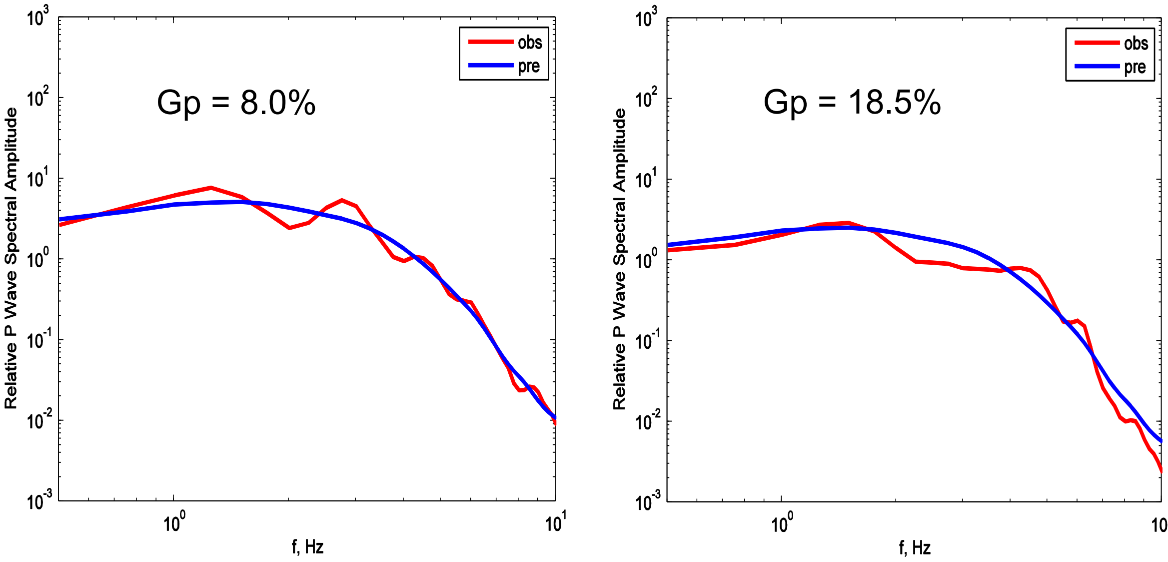
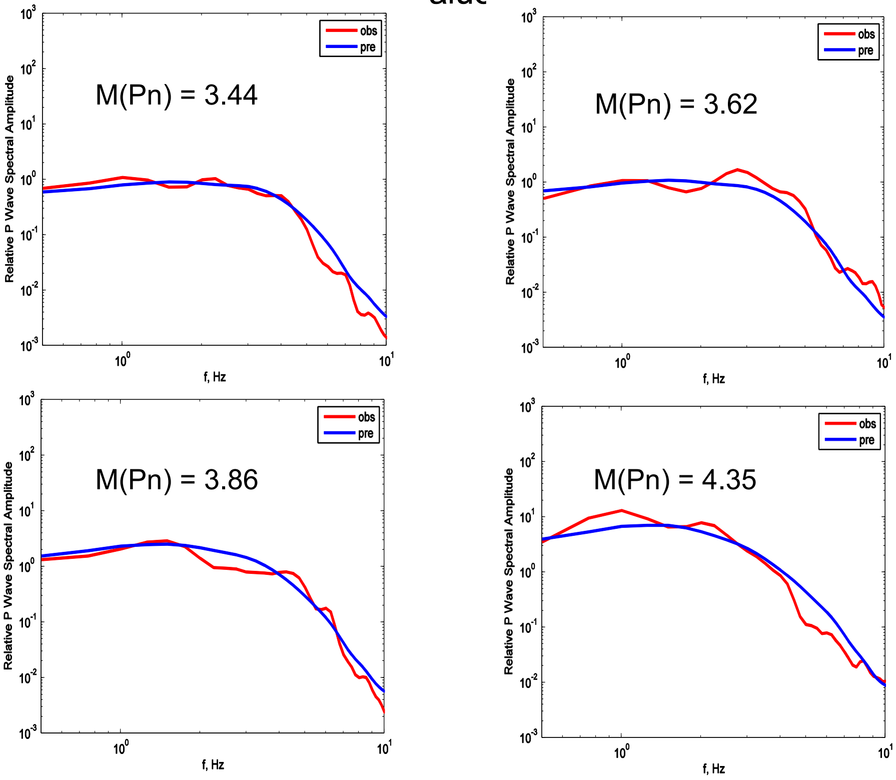


Figure 13. Comparison of Predicted and Observed MNV P Wave Spectra for Explosions of Comparable Yield Conducted in Media with Significantly Different Gas-Filled Porosity (Gp) Values

Comparison of predicted and observed MNV P wave spectra for explosions of comparable yield conducted in media with significantly different gas-fill osity (Gp) value

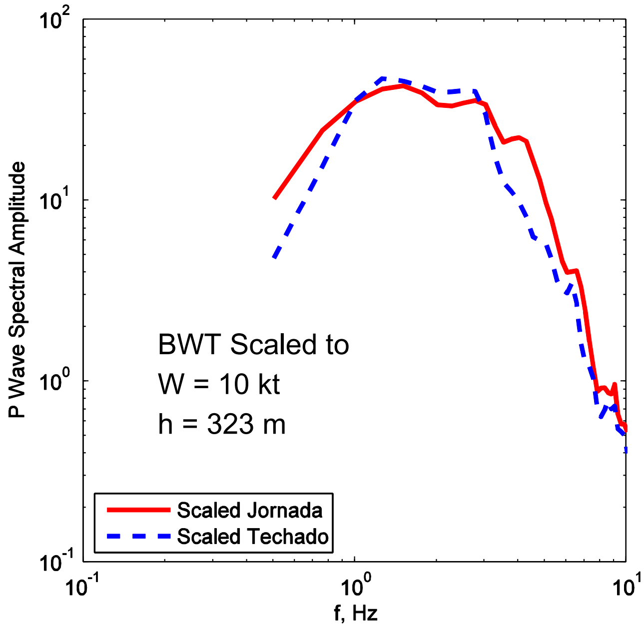


Comparison of predicted and observed MNV P wave spectra for explosions of different yields conducted in media with comparable (Gp ≈ 20%) gas-filled porosity values.

Figure 14. Comparison of Predicted and Observed MNV P Wave Spectra for Explosions of Different Yield Conducted in Media with Comparable (Gp ≈ 20%) Gas-Filled Porosity Values

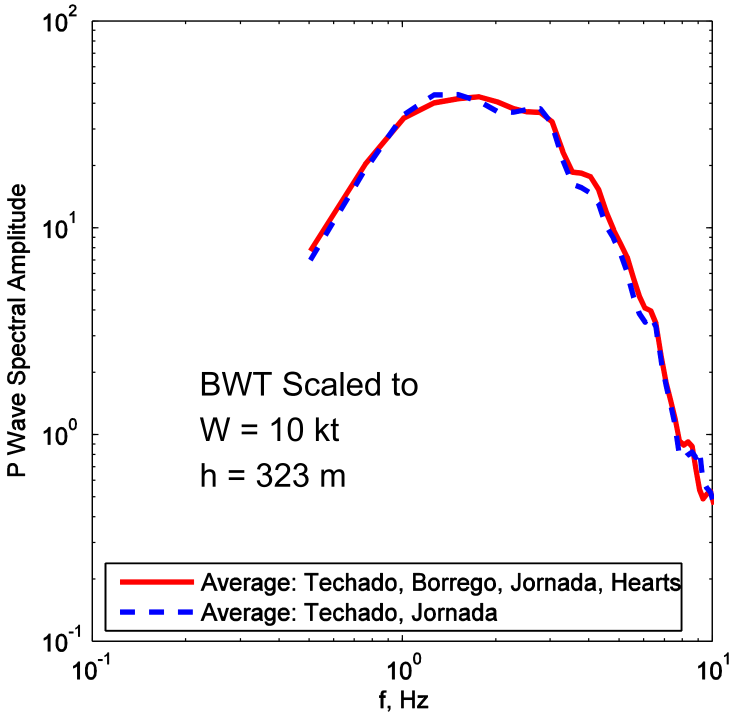
In order to provide a basis for the quantitative definition of a general seismic source model for explosions in dry, porous media, MNV P wave spectra derived from selected explosions conducted below the water table in saturated tuff at Yucca Flat have been scaled to the average dry, porous sample yield and depth of burial values of 10 kt and 323 m (i.e. $h/w^{1/3} = 150 m/kt^{1/3}$) using the well-documented and validated Mueller/Murphy [1] seismic source scaling model for underground nuclear explosions in saturated tuff media. A sample of four below the water table explosions was selected for this analysis, two of which (Hearts, Jornada) had yields significantly larger than the reference yield of 10 kt, and two of which (Techado, Borrego) had yields significantly smaller than the reference yield of 10 kt. Since these explosions were detonated below the water table at Yucca Flat, the two smaller explosions were significantly overburied with respect to the reference scaled depth of burial of $150 m/kt^{1/3}$ and, consequently, theoretical scaling for depth effects plays an important role.

The extent to which the theoretical Mueller/Murphy source scaling reconciles the observed MNV P wave spectra for such below the water table explosions with different yields and scaled depths of burial is illustrated in Figure 15 for the explosions Jornada and Techado. It can be seen that these yield and depth scaled spectra for explosions differing in yield by about two orders of magnitude are very comparable. Figure 16 shows a comparison of the average of the scaled MNV P wave spectra from Figure 15 with the average of the MNV scaled P wave spectra obtained using the data recorded from all four of the selected below the water table explosions (i.e. Techado, Borrego, Jornada and Hearts). It can be seen that all these estimates are very comparable, indicating that the selected sample provides a very robust estimate of the average MNV P wave spectrum expected for a 10kt explosion at a depth of 323m in a saturated tuff medium below the water table at Yucca Flat.



Comparison of station MNV scaled P wave spectra for explosions in saturated tuff below the water table (BWT) at Yucca Flat with yields significantly larger (Jornada) and smaller (Techado) than the mean yield of approximately 10 kt of the sample of explosions in dry, porous media. It can be seen that the application of the Mueller/Murphy scaling relations brings these two spectra into very good agreement.

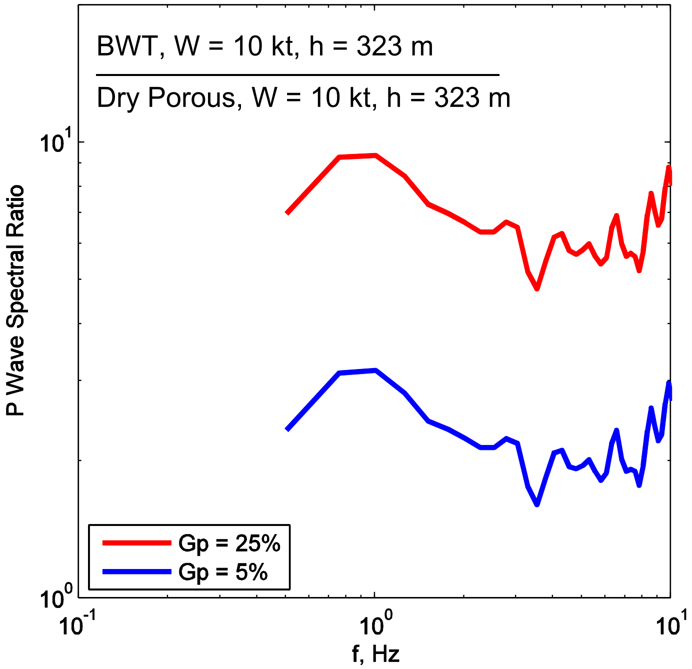
Figure 15. Comparison of Station MNV Scaled P Wave Spectra for Explosions in Saturated Tuff Below the Water Table (BWT) at Yucca Flat with Yields Significantly Larger (Jornada) and Smaller (Techado) Than the Mean Yield of Approximately 10 kt of the Sample of Explosions in Dry, Porous Media



Comparison of the average station MNV scaled P wave spectrum at 10 kt for Techado and Borrego with that corresponding to a larger sample of below the water table (BWT) explosions. It can be seen that these data provide a very consistent estimate of the MNV P wave spectrum expected for a 10 kt explosion at a depth of 323 m in saturated tuff at Yucca Flat.

Figure 16. Comparison of the Average Station MNV Scaled P Wave Spectrum at 10 kt for Techado and Borrego with That Corresponding to a Larger Sample of Below the Water Table (BWT) Explosions

Taking the ratio of the average observed saturated tuff scaled MNV P wave spectrum from Figure 16 to the corresponding predicted MNV P wave spectra for explosions with a yield of 10 kt and depth of 323 m in dry, porous media obtained using the statistically derived scaling model, gives the P wave source spectral ratio estimates for Gp values of 5% and 25% shown in Figure 17. Note that these source spectral ratios are approximately independent of frequency over the analyzed band from 0.5 to 10 Hz. This implies that the P wave seismic source functions for explosions in dry, porous media have a comparable corner frequency and high frequency rolloff rate to that of the corresponding Mueller/Murphy saturated tuff P wave source function, at least at the sample average yield and depth values of 10kt and 323m. This inference is confirmed in Figure 18 which shows a comparison of the results of dividing the theoretical Mueller/Murphy P wave source function for the reference explosion in saturated tuff by the source spectral ratio estimate corresponding to Gp = 25% in Figure 17, with that obtained by simply dividing that same source function by a frequency independent constant value of 6.5. It can be seen that these two estimates of the P wave source function for a 10kt explosion at a depth of 323m in dry, porous media are very comparable, showing the same corner frequency and ω^{-2} rolloff above the corner frequency as the corresponding saturated tuff source function. That is, the P wave source function for an explosion with a yield of 10kt and a depth of 323m in a dry, porous medium can be well approximated from the corresponding theoretical Mueller/Murphy P wave seismic source function for the same explosion in saturated tuff by simply dividing by a frequency independent constant.



Spectral ratios of the estimated station MNV P wave spectrum for a 10 kt explosion at a depth of 323 m in saturated tuff to the corresponding MNV predicted spectra for 10 kt explosions in dry, porous media characterized by Gp values of 5% and 25%. Note that the ratio does not approach 1 as Gp → 0, but approaches a frequency independent average value of about 1.75. This ind

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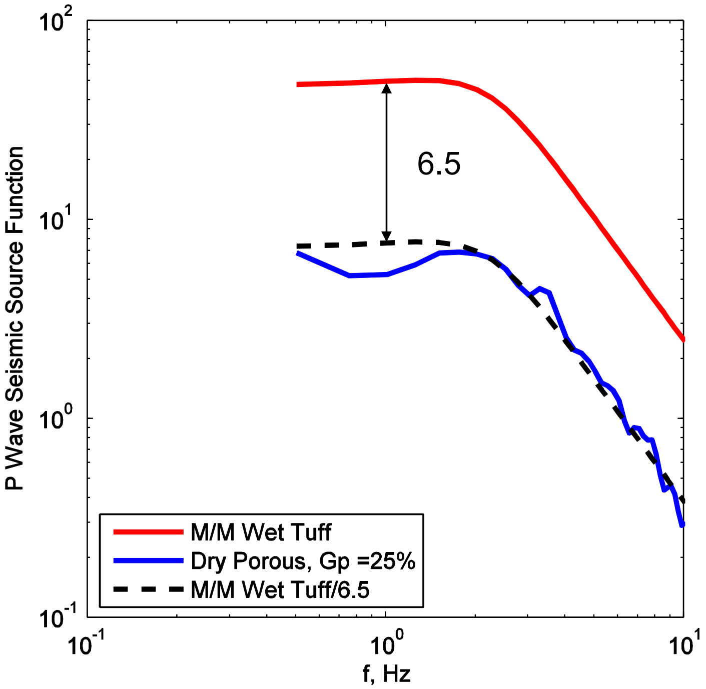
Figure 17. Spectral Ratios of the Estimated Station MNV P Wave Spectrum for a 10 kt Explosion at a Depth of 323 m in Saturated Tuff to the Corresponding MNV Predicted Spectra for 10 kt Explosions in Dry, Porous Media Characterized by Gp Values of 5% and 25%



Comparison of the P wave source function estimate for a 10 kt explosion at a depth of 323 m in a dry, porous medium characterized by a Gp value of 25% with the corresponding Mueller/Murphy source function for the same explosion in saturated tuff. It can be seen that these two source function estimates can be reconciled by an essentially frequency independent relative coupling factor of about 6.5.

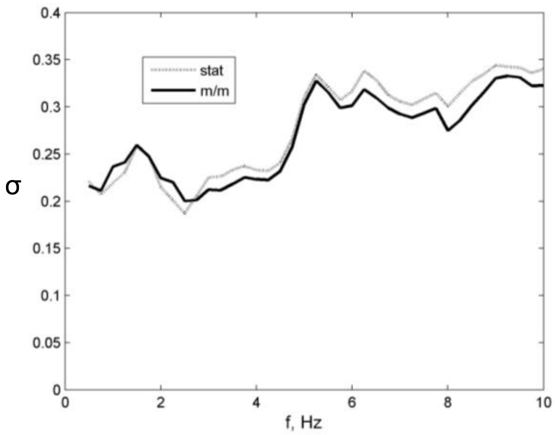
Figure 18. Comparison of the P Wave Source Function Estimate for a 10 kt Explosion at a Depth of 323 m in a Dry, Porous Medium Characterized by a Gp Value of 25% with the Corresponding Mueller/Murphy Source Function for the Same Explosion in Saturated Tuff

With reference to Figure 17, it can be seen that this reduction factor (RF) that maps the Mueller/Murphy saturated tuff source into the corresponding dry, porous media source for the reference explosion is given approximately by the relation

$$RF \quad = \quad 1.75 * 10^{0.024G_p} \qquad (6)$$

Note that this factor does not go to 1 in the limit as Gp approaches zero. This means that explosions in dry, porous media couple less well than explosions below the water table even in the limit of very small Gp values. That is, the absence of water results in a decrease in seismic source coupling efficiency, even in the absence of any appreciable air-filled porosity.

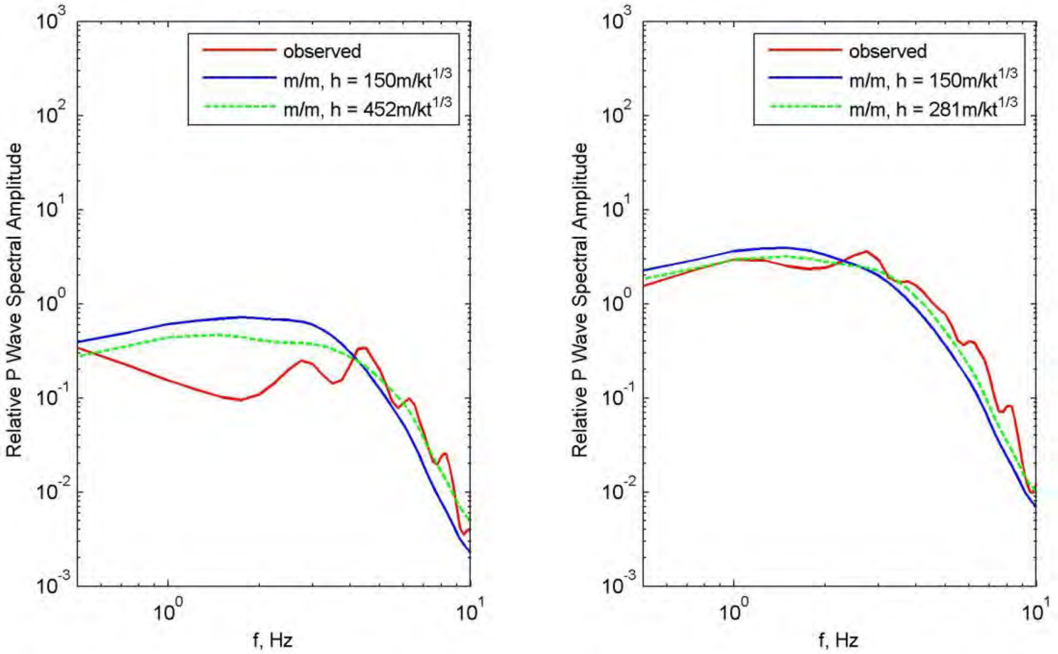
Given the observed strong correlation between the inferred seismic source for an explosion with a yield of 10kt and a depth of 323m in dry, porous media with the corresponding theoretical Mueller/Murphy seismic source predicted for the same explosion in saturated tuff, it is reasonable to ask whether the Mueller/Murphy seismic source scaling with yield and source depth of burial determined for explosions in saturated tuff might not also be generally applicable to explosions in dry, porous media, particularly for the lower yield explosions of principal interest in nuclear test monitoring. This hypothesis has been tested by comparing the prediction σ values as a function of frequency obtained by scaling the nominal W = 10kt, h = 323m MNV P wave spectrum for explosions in dry, porous media using both the statistical yield scaling model and the Mueller/Murphy yield and depth scaling model derived for explosions in saturated tuff, for all explosions in the selected analysis sample with yields less than or equal to 20kt (i.e. 48 of the 63 selected explosions). In both cases, the effects of variations in Gp were accounted for using the previously validated frequency independent Gp scaling relation. The prediction σ results as a function of frequency obtained using these two source scaling models are shown in Figure 19, where it can be seen that they are very similar over the entire frequency range from 0.5 to 10 Hz. This indicates that the theoretical Mueller/Murphy source scaling for explosions in saturated tuff is indeed applicable to low yield explosions in dry, porous media.



Comparison of prediction standard deviations (σ) as a function of frequency obtained using the statistical yield scaling model (stat) and the Mueller/Murphy (m/m) yield and depth scaling model for explosions in saturated tuff, evaluated over all explosions in the selected dry, porous sample with yields less than or equal to 20 kt.

Figure 19. Comparison of Prediction Standard Deviations (σ) as a Function of Frequency Obtained Using the Statistical Yield Scaling Model (Stat) and the Mueller/Murphy (m/m) Yield and Depth Scaling Model for Explosions in Saturated Tuff, Evaluated Over All Explosions in the Selected Dry, Porous Sample with Yields Less Than or Equal to 20 kt

In fact, it can be seen from Figure 19 that the prediction σ values obtained using the Mueller/Murphy source scaling are actually uniformly slightly lower than the corresponding σ values obtained using the statistically derived source scaling model for all frequencies above about 2.5 Hz. This initially puzzling observation can be explained by the fact that the Mueller/Murphy model has an additional degree of freedom in that it explicitly accounts for variations in actual scaled depths between explosions relative to the sample average scaled depth of 150m/kt$^{1/3}$. That is, although the scaled depths of most of the selected explosions in the dry, porous media sample cluster fairly tightly around the mean value of 150m/kt$^{1/3}$ (cf. Figure 9), there are a few outlier events and these are modeled more accurately, particularly at high frequencies, by accounting for the effects of variations in scaled depth using the Mueller/Murphy saturated tuff source scaling model. This fact is illustrated in Figure 20 which shows comparisons of Mueller/Murphy predicted and observed MNV P wave spectra for the two outlier explosions characterized by scaled depths most different from the average value of 150m/kt$^{1/3}$ (i.e. $h/W^{1/3}$ = 452m/kt$^{1/3}$, left, and $h/W^{1/3}$ = 281m/kt$^{1/3}$, right). In these figures, the Mueller/Murphy predictions corresponding to both the nominal scaled depth of 150m/kt$^{1/3}$ and the actual scaled depths are shown and it can be seen that in both cases the predictions are improved by incorporating the Mueller/Murphy predicted source depth scaling, particularly at high frequencies.



Comparisons of Mueller/Murphy (m/m) predicted and observed MNV P wave spectra for the two explosions characterized by scaled depths most different from the average value of 150m/kt$^{1/3}$ (i.e. $h/W^{1/3}$ = 452m/kt$^{1/3}$, left and $h/W^{1/3}$ = 281m/kt$^{1/3}$, right). Mueller/Murphy predictions corresponding to both the nominal scaled depth of 150m/kt$^{1/3}$ and the actual scaled depth are shown to illustrate the predicted depth effect.

Figure 20. Comparisons of Mueller/Murphy (M/M) Predicted and Observed MNV P Wave Spectra for the Two Explosions Characterized by Scaled Depths Most Different from the Average Value of 150 m/kt$^{1/3}$ (i.e. $h/W^{1/3}$ = 452 m/kt$^{1/3}$, left, and $h/W^{1/3}$ = 281 m/kt$^{1/3}$, right)

Mueller/Murphy predictions corresponding to both the nominal scaled depth of 150 m/kt$^{1/3}$ and the actual scaled depth are shown in Figure 20 to illustrate the predicted depth effect. The analysis results presented above indicate that the P wave seismic source functions for underground nuclear explosions in dry, porous media can be well approximated by dividing the P wave source functions for the same explosions in saturated tuff predicted by the well-calibrated

Mueller/Murphy P wave source model by the frequency independent reduction factor given by equation (6). The uncertainty in such source predictions is quantified by the frequency dependent σ values derived for the Mueller/Murphy model prediction results shown in Figure 19 above. A remaining question concerns whether there are components of this prediction uncertainty that might be correlated with the explosion source conditions that could be reduced given more accurate measurements of the physical properties of the source emplacement media.

One such factor that is evident from detailed comparisons of predicted and observed station MNV P wave spectra is uncertainty in the measured values of the gas-filled porosity, Gp. Since the expected effects of variations in gas-filled porosity are independent of frequency (cf. equation (6)), such uncertainty can potentially be identified by looking for systematic, frequency independent offsets between predicted and observed spectra. Two of the most prominent examples of this effect from the selected sample are shown in Figures 21 and 22 where the predictions corresponding to both the reported Gp value (left) and a Gp value adjusted to eliminate the average offset between predicted and observed (right) are shown. It can be seen that, in these cases, adjustments to Gp on the order of ±10% bring the predicted and observed station MNV P wave spectra into much closer agreement over the entire analyzed frequency band. These are extreme examples for this selected set of explosions and, in fact, the predictions associated with the reported values of Gp provide very good fits to the observed data in most cases.

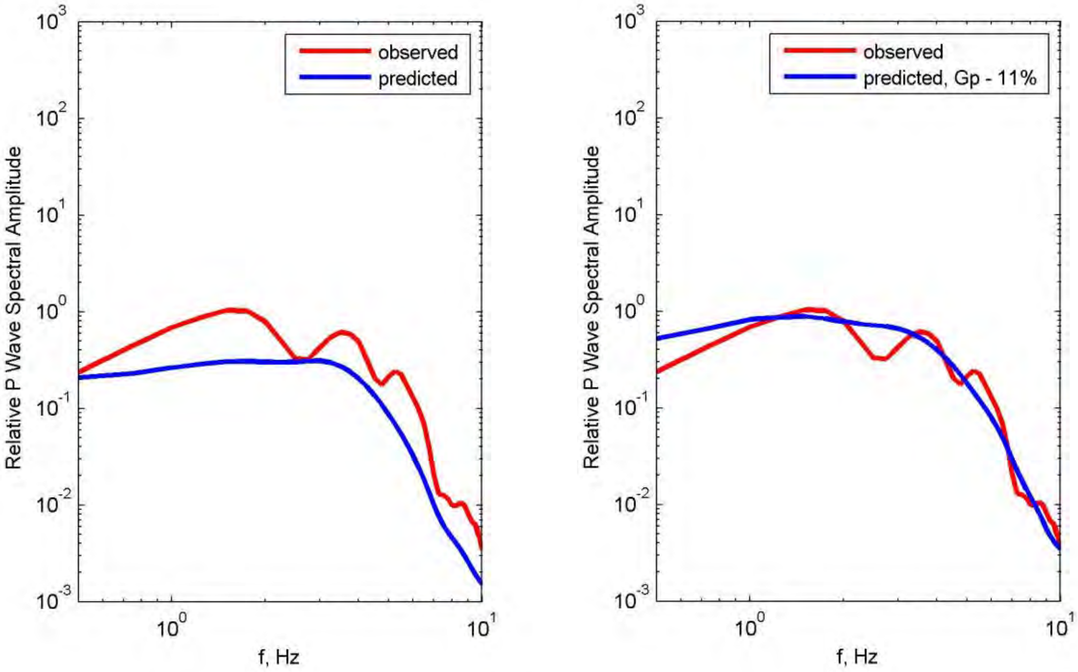


Figure 21. Comparisons of the Observed MNV P Wave Spectra for a Selected Explosion with the Predictions Corresponding to the Reported Gp Value (left) and a Revised Gp Value That Eliminates the Average Frequency Dependent Offset Between Predicted and Observed (Right)

Comparisons of the observed MNV P wave spectra for a selected explosion with the predictions corresponding to the reported Gp value (left) and a revised Gp value that eliminates the average frequency dependent offset between predicted and observed (right). In this case, the average offset corresponds to an effective decrease in Gp of about 11%.

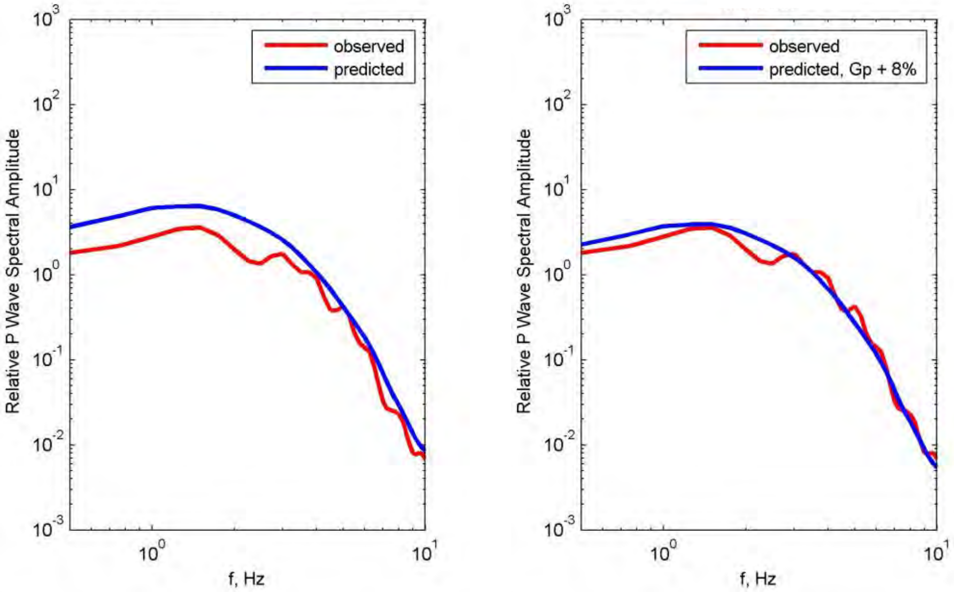


Figure 22. Comparisons of the Observed MNV P Wave Spectra for a Selected Explosion with the Predictions Corresponding to the Reported Gp Value (Left) and a Revised Gp Value That Eliminates the Average Frequency Dependent Offset Between Predicted and Observed (Right)

Comparisons of the observed MNV P wave spectra for a selected explosion with the predictions corresponding to the reported Gp value (left) and a revised Gp value that eliminates the average frequency dependent offset between predicted and observed (right). In this case, the average offset corresponds to an effective increase in Gp of about 8%.

In Figure 21, the average offset corresponds to an effective decrease in Gp of about 11%; in Figure 22, the average offset corresponds to an effective increase in Gp of about 8%. In an attempt to approximately quantify the uncertainty in the reported Gp values for these explosions, the ratio of predicted to observed spectra, logarithmically averaged over the entire 0.5 to 10 Hz band, was computed for each event and a revised prediction was made for the modified Gp value that eliminated this average offset. The change in Gp values for that subset of the explosions for which these offsets appeared to be essentially independent of frequency were then tabulated and statistically analyzed. The resulting average change in Gp was found to be +1.0% with an associated standard deviation of 5.5%. That is, these results suggest that the average uncertainty in the reported Gp values for this sample of explosions is on the order of ±5%, which is not surprising given the difficulty of estimating precise values of Gp from in-situ core samples. This translates into about 25% of the variance of predicted versus observed spectra, which is significant. However, it is difficult to see how this uncertainty could be reduced in actual monitoring situations where it is unlikely that access to in-situ source medium physical property data would be available. Therefore, such uncertainty will generally have to be accepted and incorporated into the overall prediction uncertainty budget for monitoring purposes such as yield estimation.

A second potential source factor related anomaly evident from detailed comparisons of predicted and observed station MNV P wave spectra is that the source corner frequencies for some explosions in dry alluvium appear to be overestimated by the Mueller/Murphy source model for explosions in saturated tuff. This misfit is illustrated in Figures 23 and 24 for two of the selected explosions in alluvium. In these figures, the left panel shows the comparison with the original prediction, while the right panel shows the comparison with a modified prediction resulting from reducing the source corner frequency by 40%. It can be seen that the modified predictions provide much better fits to the observed high frequency data observed from these two explosions.

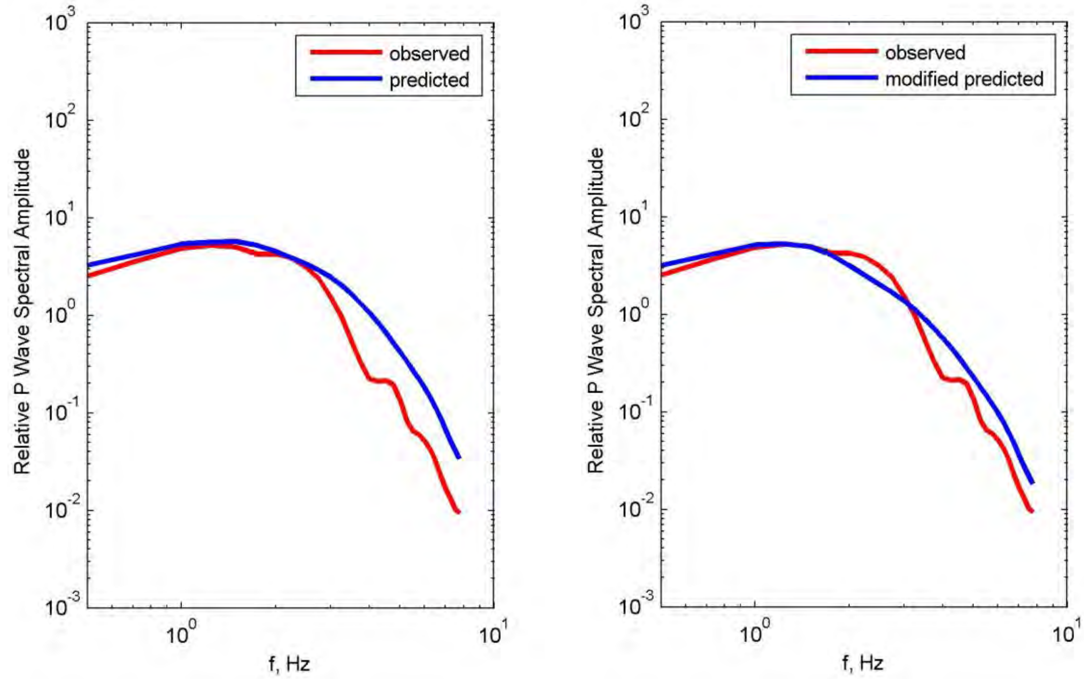


Figure 23. Comparisons of the Observed MNV P Wave Spectra for a Selected Explosion in Alluvium with the Nominal Prediction (Left) and a Modified Prediction Incorporating a 40% Reduction in the Source Corner Frequency (Right)

Comparisons of the observed MNV P wave spectra for a selected explosion in alluvium with the nominal prediction (left) and a modified prediction incorporating a 40% reduction in the source corner frequency (right).

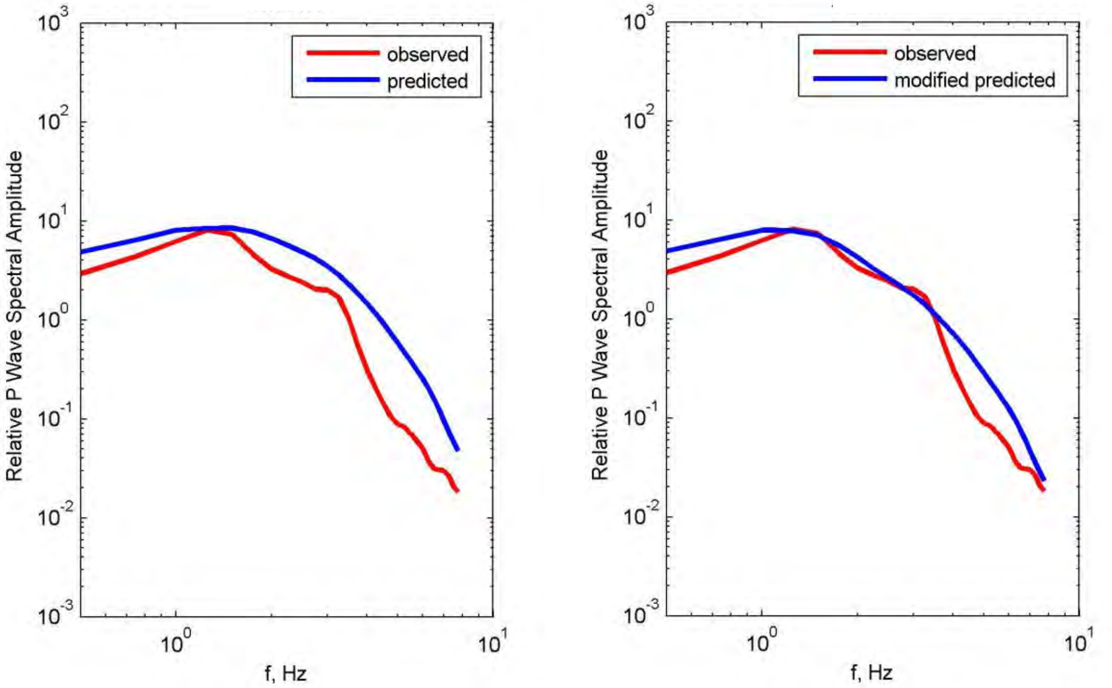
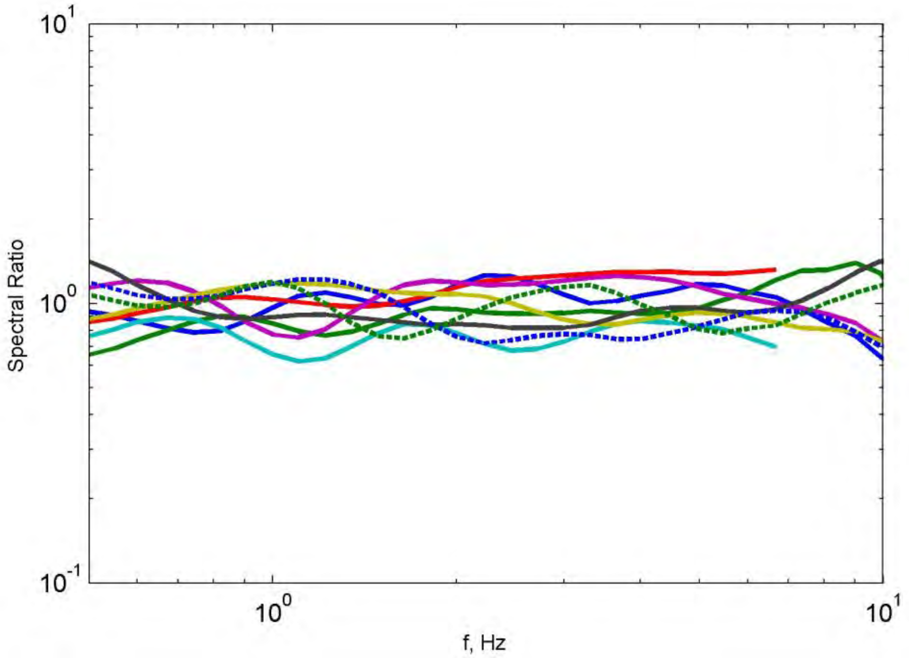


Figure 24. Comparisons of the Observed MNV P Wave Spectra for a Selected Explosion in Alluvium with the Nominal Prediction (Left) and a Modified Prediction Incorporating a 40% Reduction in the Source Corner Frequency (Right)

Comparisons of the observed MNV P wave spectra for a selected explosion in alluvium with the nominal prediction (left) and a modified prediction incorporating a 40% reduction in the source corner frequency (right).

In one sense, this is perhaps not surprising in that the source medium compressional wave velocities reported by Springer et al [12] for explosions in dry alluvium are typically somewhat lower on average than those for explosions in dry tuff. However, in the present case, there doesn't seem to be any consistent correlation of reduced source corner frequencies with reported source medium velocities. That is, the observed corner frequencies for the majority of explosions in alluvium in the selected sample are well fit by the basic model, even in cases in which the reported source medium velocities are lower than the average for explosions in alluvium. Moreover, there is no consistency among the explosions that are found to be better fit by the lower corner frequencies in that reported source medium velocities for these explosions are found to be both lower than and higher than the average for explosions in alluvium. Thus, as with the Gp variable, it is difficult to see how the uncertainty resulting from such misfits could be reduced in actual monitoring situations where it is unlikely that the source medium velocity estimates would be more accurate than the measured NTS values. It again follows that such uncertainties will have to be accepted and incorporated into the overall prediction uncertainty budget for monitoring applications.

A remaining question concerns the robustness of the source scaling results based on analyses of data recorded at the single MNV station. As was noted previously, this single station approach was taken because the available data sample from MNV is the most complete and the only one suitable for this quantitative assessment of the seismic source scaling for explosions conducted in dry, porous media above the water table at Yucca Flat. However, such data are not sufficient for addressing questions such as whether any event to event variations in the azimuthally dependent radiation from the sources might be leading to bias in the scaling results. In a preliminary attempt to address such issues, a subset of seven explosions have been identified for which high quality data are available from all four LLNL network stations (MNV, KNB, LAC, ELK) and network-averaged P wave spectra have been computed for each of these explosions and compared with the corresponding single station MNV P wave spectra. Although this sample of explosions is small, it does cover the full range of yield and Gp values encompassed by the original MNV sample. Network-averaged P wave spectra for the selected explosions were estimated by simply logarithmically averaging the spectral amplitudes observed at the four stations. A MNV station correction factor was then defined by averaging the ratios of the MNV P wave spectra to the corresponding network-averaged P wave spectra over the seven explosions. Figure 25 shows the frequency dependent ratios of the station-corrected MNV P wave spectra to the corresponding network-averaged spectra for each of the selected explosions. It can be seen that the single station MNV and network-averaged P wave spectra correlate very well, showing variations of less than a factor of 1.5 over the entire analyzed frequency range from 0.5 to 10 Hz. More specifically, it has been found that these small variations between explosions show no consistent correlation with yield or Gp that could bias the scaling results obtained using the station MNV spectra alone. Based on these initial results, it is concluded that the P wave scaling results obtained using the station MNV data do indeed accurately reflect the seismic source scaling characteristics of underground nuclear explosions conducted in dry, porous media.



Spectral ratios of station-corrected MNV P wave spectra to corresponding LLNL network-averaged P wave spectra for the sample of seven selected explosions for which high quality seismic data are available from all four network stations.

Figure 25. Spectral Ratios of Station-Corrected MNV P Wave Spectra to Corresponding LLNL Network-Averaged P Wave Spectra for the Sample of Seven Selected Explosions for Which High Quality Seismic Data Are Available from All Four Network Stations

5. Conclusions

While experience has indicated that underground nuclear explosions conducted 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 explosions in a given tectonic environment, explosions in dry, porous media, such as the tuff and alluvium found above the water table at NTS, 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. Consequently, a reliable seismic source model for such explosions is needed for any comprehensive assessment of nuclear test monitoring capability. Over the past two years, we have been analyzing seismic data recorded at the LLNL network station MNV from explosions conducted above and below the water table at the Yucca Flat testing area at NTS. P wave spectra over the frequency band from 0.5 to 10 Hz have been estimated for a sample of 63 explosions conducted in dry, porous media above the water table. The measured gas-filled porosities (Gp) at the working points of these explosions range from near zero to almost 30%, while the associated yield values extend over approximately two orders of magnitude around a mean yield of about 10 kt. Statistical scaling analyses of the dependence of these observed P wave spectral amplitudes on explosion yield and Gp support the following conclusions regarding the seismic source characteristics of explosions in dry, porous media:

(1) The dependence of the P wave seismic source coupling on Gp is essentially independent of frequency over the entire range from 0.5 to 10 Hz, with the logarithms of the spectral amplitude levels at a fixed yield decreasing with increasing Gp as -0.024Gp.

(2) The seismic source function estimated for a reference 10 kt explosion in a dry, porous medium on the basis of the statistical analysis results is found to have a comparable source corner frequency to that expected for the same explosion in saturated tuff, with both showing a high frequency roll-off proportional to ω^{-2}.

(3) Comparisons of the frequency dependent prediction uncertainty values for low yield explosions in dry, porous media obtained using the statistical yield scaling model and the Mueller/Murphy yield and depth scaling model, derived for explosions in saturated tuff, indicate that they are very comparable over the entire frequency range from 0.5 to 10 Hz.

(4) The results of these analyses indicate that the P wave seismic source functions for underground nuclear explosions in dry, porous media can be well-approximated by simply dividing the P wave source functions for the same explosions in saturated tuff, predicted by the validated Mueller/Murphy source model, by a frequency independent Gp reduction factor (RF) given by

$$RF = 1.75 * 10^{0.024G_p}$$

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