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Source Effects on Surface Waves From Nevada Test Site Explosions

H. J. Patton

E. S. Vergino

November 1981

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SOURCE EFFECTS ON SURFACE WAVES FROM NEVADA TEST SITE EXPLOSIONS

ABSTRACT

Surface waves recorded on the Lawrence Livermore National Laboratory (LLNL) digital network have been used to study five underground nuclear explosions detonated in Yucca Valley at the Nevada Test Site. The purpose of this study is to characterize the reduced displacement potential (RDP) at low frequencies and to test secondary source models of underground explosions. The observations consist of Rayleigh- and Love-wave amplitude and phase spectra in the frequency range 0.03 to 0.16 Hz. We have found that Rayleigh-wave spectral amplitudes are modeled well by a RDP with little or no overshoot for explosions detonated in alluvium and tuff. On the basis of comparisons between observed and predicted source phase, the spall closure source proposed by Vieceilli does not appear to be a significant source of Rayleigh waves that reach the far field. We tested two other secondary source models, the strike-slip, tectonic strain release model proposed by Toksöz and Kehrner and the dip-slip thrust model of Massé. The surface-wave observations do not provide sufficient information to discriminate between these models at the low F-values (0.2 to 0.8) obtained for these explosions. In the case of the strike-slip model, the principal stress axes inferred from the fault slip angle and strike angle are in good agreement with the regional tectonic stress field for all but one explosion, Nessel. The results of the Nessel explosion suggest a mechanism other than tectonic strain release.

INTRODUCTION

The explosion source has been the object of intensive study in seismology for over two decades. The goals of the study are to improve the ability to discriminate between earthquakes and explosions and to estimate yield. In large part, improvements depend upon advances in the knowledge of the source physics and upon development of models of the seismic source. A good deal of the uncertainty in our present capabilities is because there is no widely accepted source model. For example, investigators are still raising questions

about the source time function of explosions and the role of secondary sources (see Müller,¹ Springer,² and Masse³).

We have been studying surface waves from underground explosions detonated in Yucca Valley at the Nevada Test Site (NTS). Our purpose is to gain a better understanding of the generation of low-frequency seismic waves from explosions. This paper is a progress report of research in the past two years. We present the data in the section entitled Waveform Data. The results of filtering the data that characterize the frequency content and arrival times of low-frequency waves is given in the section entitled Filtering of Waveform Data. We carry out spectral analysis of the seismograms and calculations of surface-wave source spectra in the sections entitled Spectral Analysis and Surface-Wave Source Spectra, respectively. Our efforts to deduce the shape of the reduced displacement potential (RDP) at low frequencies and to model three secondary sources (spall slapdown, tectonic strain release and thrust faulting) are described in the sections entitled Modeling the Explosion Source and Secondary Sources of Seismic Waves. Conclusions to date are given in the last section.

WAVEFORM DATA

We considered for study the seismograms from 11 underground nuclear explosions detonated at NTS. Table 1 contains pertinent geologic and seismic data about these explosions. The surface waves from only 5 of the 11 explosions could be analyzed because of the high microseismic noise level in the winter and spring months, as is shown in the section on Spectral Analysis. We indicate in Table 1 the explosions that were precluded from study using long-period surface waves. Of the five studied in this report, two explosions (Hearts and Pyramid) were below the water table and the rest were above. All the explosions occurred in Yucca Valley (see Fig. 1).

The waveforms were digitally recorded on the four Lawrence Livermore National Laboratory (LLNL) seismic stations surrounding NTS. As may be seen in Fig. 2, these stations are between 200 and 400 km from NTS and are approximately 90° apart in azimuth. The three-component seismograph system at each station is flat to velocity between 30 s and 10 Hz (see Denny⁴).

The broadband waveforms for the Nessel explosion are shown in Figs. 3 to 6, where the time frame is set so that 0.0 s is the origin time of the explosion. Positive deflection on the vertical component record indicates

Table 1. Epicentral and pertinent geologic data for explosions in this study.

Date	Name of explosion	Latitude (°N)	Longitude (°W)	Medium ^a	Depth of burial (m)	DPz (m)	D _{H20} (m)	^b m _b
08/03/79	Burzet	37.08	116.07	AL	450	849	510	4.5
03/08/79	Offshore	37.02	116.01	TU	396	660	467	4.8
08/29/79	Nessel	37.12	116.07	AL	464	975	541	4.7
09/06/79	Hearts	37.09	116.05	TU	640	1071	507	5.8
09/08/79	Pera ^c	37.15	116.04	TU	200	503	553	3.7 ^d
11/29/79	Backgammon ^c	36.99	116.02	AL	229	1120	471	3.8
12/14/79	Azul ^c	37.14	116.06	AL	205	755	561	3.6 ^d
02/28/80	Tarko ^c	37.13	116.09	AL	369	670	564	4.4
03/08/80	Norbo ^c	37.18	116.08	TU	271	402	553	3.9
04/03/80	Liptaur ^c	37.15	116.08	AL	417	834	581	4.7
04/16/80	Pyramid	37.10	116.03	TU	579	783	540	5.3

^a AL denotes alluvium; TU denotes tuff.

^b Body-wave magnitudes from the Earthquake Data Reports (EDR) of the U.S. Geological Survey.

^c Denotes events for which signal to noise ratio at frequencies below 0.1 Hz precluded analysis of surface waves.

^d M_L .

Figure 1. Map of Yucca Valley showing locations of explosions studied in this paper. Fault traces are taken from U.S.G.S. geologic map.⁵

Figure 2. Locations of Lawrence Livermore National Laboratory broadband seismograph stations used in this study.

Figure 3. Broadband velocity seismograms of the Nessel explosion recorded at Mina. The vertical, radial, and transverse components of motion are so identified. Several arrivals of seismic phases are marked on the vertical component record.

Figure 4. Broadband velocity seismograms of the Nessel explosion recorded at Kanab. The vertical, radial, and transverse components of motion are so identified. Several arrivals of seismic phases are marked on the vertical component record.

Figure 5. Broadband velocity seismograms of the Nessel explosion recorded at Landers. The vertical, radial, and transverse components of motion are so identified. Several arrivals of seismic phases are marked on the vertical component record.

Figure 6. Broadband velocity seismograms of the Nessel explosion recorded at Elko. The vertical, radial, and transverse components of motion are so identified. Several arrivals of seismic phases are marked on the vertical component record.

upward ground motion; on the radial component, positive indicates ground motion away from NTS; and on the transverse component, positive indicates counterclockwise motion.

We mark the arrival time of P_n and the arrival times of the principal wave packets of P_g and L_g on these figures. The arrivals of high frequency energy in P_n , P_g , and L_g are very clear on these broadband records. In this study, particular attention has been paid to the surface-wave arrivals. This includes both vertical and transverse L_g waves, Rayleigh waves, and Love waves. Although L_g waves travel faster than Rayleigh and Love waves, their time separations are small for the epicentral distances in this study.

FILTERING OF WAVEFORM DATA

In order to characterize the surface waves in terms of frequency content and arrival times of significant energy, the waveforms have been filtered. We will demonstrate that L_g waves and surface waves can be separated on the basis of frequency content, although they are not separated in time. The importance of frequency separation will be evident when spectra are interpreted later in this study.

LOW-PASS FILTERING

The procedure for low-pass filtering is described in detail in Appendix A. The filters are computed in the frequency domain and applied to the Fourier spectrum of the signal in a selected time window (see Table 2). We selected filters with corner frequencies at 0.2, 0.33, and 0.5 Hz for vertical component waveforms and at 0.125, 0.2, 0.33, and 0.5 Hz for transverse component waveforms. The filters have zero phase.

Examples of the low-pass filtering of signals recorded at Landers are given in Fig. 7. The L_g wave travels at about 3.4 km/s and most of its energy is in the frequencies higher than 0.33 Hz. The Airy phase of the fundamental-mode Rayleigh wave travels at about 2.8 km/s and is the predominant arrival for periods longer than 5 s (Fig. 7a). This is also true of the Love waves which travel at about 3.1 km/s (Fig. 7b). There appears to be considerable scattered energy for wave periods between 2 and 5 s, which could be due to

Table 2. Time windows for low-pass filtering.

Stations	Vertical component (s)	Transverse component (s)
Mina	60 to 130	55 to 130
Kanab	80 to 160	60 to 150
Landers	80 to 160	65 to 155
Elko	110 to 190	95 to 185

multipathing of the fundamental-mode Rayleigh waves and scattering of higher modes. The most important feature is that for periods longer than 5 s the seismic energy is carried principally by the fundamental-mode Rayleigh and Love waves. This is confirmed from the group velocity dispersion which will be presented in the next section. For periods less than 5 s there is appreciable energy arriving in addition to that carried by the fundamental-mode surface waves.

NARROW-BAND FILTERING

We have narrow-band-filtered the data to study the arrival times of surface-wave energy as a function of frequency. The results will be used to measure group velocity dispersion and to determine the frequencies where multipathing and seismic wave scattering become important.

The procedure for narrow-band filtering is described in detail in Appendix A. Again the filters are computed in the frequency domain and applied to the Fourier spectra of waveforms for the time windows in Table 3. The narrow-band filters were computed using a Gaussian function as described by Dziewonski et al.⁶ The center frequencies were selected at 0.33, 0.25, 0.22, 0.20, 0.18, 0.167, 0.125, 0.10, 0.083, and 0.0625 Hz. The filters have zero phase.

Filtered traces for the vertical and transverse components at the Landers station are shown in Figs. 8 and 9, respectively. From the plots in these figures and others like them, it has been found that for center periods longer than about 5 s the seismic energy arrives in distinct wave groups. At shorter

Figure 7. Low-pass digital filtering of the broadband record shown in the top frame of (a) and (b). Figure (a) is the vertical component of motion at Landers for the Offshore explosion with the filter corner placed at 0.5, 0.333, and 0.2 Hz. Figure (b) is the transverse component of motion with the filter corner placed at 0.5, 0.333, 0.2, and 0.125 Hz.

Table 3. Time windows for narrow-band filtering and spectral analysis.

Stations	Vertical component (s)	Transverse component (s)
Mina	60 to 210	45 to 195
Kanab	70 to 220	50 to 200
Landers	70 to 220	50 to 200
Elko	110 to 260	85 to 235

periods there are multiple arrivals with significant amplitude. These other short-period arrivals are probably higher-mode and multipathing surface waves. Of all stations, Landers shows the least contamination by multiple arrivals.

The velocity of wave groups were determined by first measuring the arrival time of the center of the wave group. This time is adjusted for the group delay time through the seismometer system (see Rodgers et al.⁷). Then the adjusted times are divided into the epicentral distance to obtain the group velocity of Rayleigh/Love waves for a frequency which is the center frequency of the narrow-band filter. We note that the correction for group delay through the seismometer system was small for the frequencies of interest in this study. The largest delay is about 3 s at the lowest frequency, 0.06 Hz.

The Rayleigh-wave dispersion curves for each station path are shown in Fig. 10(a). The Love-wave dispersion curves are shown in Fig. 10(b). The results from just the Hearts explosion are plotted. There was quite good agreement between the results from explosions Hearts and Nessel. The Love- and Rayleigh-wave group velocities at periods longer than 8 s are significantly lower on the path to Mina. Lower Rayleigh-wave phase velocities are also observed on this path (see Patton⁸). We believe these velocities are caused by lower velocities and/or thicker crust in the Basin and Range structure northwest of NTS.

Theoretical group velocity curves for the earth structure proposed by Priestley and Brune⁹ for the Basin and Range Province of the western U.S.

Figure 8. Narrow-band filtering of the broadband record shown in the top frame. Beneath top frame are filtered records with the center frequency set at 0.33, 0.25, 0.22, 0.20, 0.18, 0.167, 0.125, 0.10, 0.083, and 0.0625 Hz. Landers' vertical component recording of the Hearts explosion is shown in the top frame.

Figure 9. Narrow-band filtering of the broadband record shown in the top frame. Beneath top frame are filtered records with the center frequency set at 0.33, 0.25, 0.22, 0.20, 0.18, 0.167, 0.125, 0.10, 0.083, and 0.0625 Hz. Landers' transverse component recording of the Hearts explosion is shown in the top frame.

Figure 10. (a) Rayleigh-wave group velocity dispersion curves for paths between the Nevada Test Site and each of the Lawrence Livermore National Laboratory seismograph stations. (b) Love-wave group velocity dispersion curves for paths between the Nevada Test Site and each of the Lawrence Livermore National Laboratory seismograph stations.

are shown with the observations in Fig. 10. The general agreement of our observations with the theoretical curves supports the identification of these seismic waves as Rayleigh and Love waves for the period range 4 to 20 s.

SPECTRAL ANALYSIS

The results of the previous section indicate that the seismic energy at frequencies below 0.2 Hz is contained in the fundamental-mode Rayleigh/Love waves generated by the explosions. This is important because the low-frequency spectra of broadband waveforms can be interpreted as due to the motion of a single type of seismic wave, either Rayleigh or Love waves. Analysis of frequencies higher than 0.2 Hz will require multi-mode separation techniques, filtering of secondary arrivals, and/or more selective windowing of seismic energy before it is possible to make interpretations.

With the high frequency limit so determined, we turn to the low frequency limit of our analysis. This is determined by two factors: (1) the low frequency corner of the seismograph response and (2) the level of background noise relative to signal strength. The free period of the seismometer determines the corner frequency. The free period is 30 s for all components and all stations. The second factor was considered by analyzing the spectra of noise samples as discussed below.

SIGNAL AND NOISE SPECTRA

The procedure for the spectral analysis of signals and noise samples is described in detail in Appendix A. Time windows for the signals are given in Table 3. Noise windows, the same length as the signal windows, were selected before the onset of P-waves. A few examples of amplitude spectra of signal and noise are given in Fig. 11. Arrows indicate the lowest frequency with signal significantly above the noise. All signal spectra were compared with the noise spectra to estimate the lowest frequency with satisfactory signal to noise ratio. It should be noted that the background noise in the winter and spring months (December through April) was an order of magnitude above the noise level during the summer months. The microseismic noise was large enough that the

Figure 11. Displacement amplitude spectra of signal and noise time series. The arrow indicates the lowest frequency with satisfactory signal to noise ratio for (a) the vertical component of motion recorded at Mina for the Nessel explosion and (b) the transverse component of motion recorded at Kanab for the Pyramid explosion.

surface waves for several events indicated in Table 1 could not be studied. The magnitude threshold for surface-wave studies is as high as m_b 4.6 during these high noise time periods.

SURFACE-WAVE SOURCE SPECTRA

In this section, we calculate source spectra using both the signal amplitude and phase spectra computed in the previous section. The amplitude and phase source spectra will be modeled for source parameters in subsequent sections.

SOURCE AMPLITUDE SPECTRA

A Hanning operator was applied to smooth the amplitude spectra computed in the previous section. The smoothed amplitude spectra were normalized to a propagation distance of 500 km by multiplying by the factor $\sqrt{r/500}$, where r is the epicentral distance. No correction was made for attenuation of surface-wave amplitudes because we expect that the effect of attenuation is small for the short epicentral distances and long wavelengths in this study. For example, the surface-wave attenuation factor is $e^{-\eta r}$ where $\eta = \pi/QUT$, Q is quality factor, U is group velocity, and T is period. Our greatest epicentral distance is about 400 km. Assuming a very low Q of 50, the attenuation factor is about 0.4 for a 10 s period wave traveling 3 km/s. This value of the attenuation factor represents an extreme because of the low Q value and maximum distance. A more reasonable Q value of 200 gives an attenuation factor of about 0.8. On the basis of these calculations, we argue that attenuation of surface wave amplitudes is not more than a factor of 2 for periods (6 to 25 s) and distances (200 to 400 km) in this study.

SOURCE PHASE SPECTRA

The surface-wave source phase, ϕ^S , which is measured in cycles, was computed by the following equation:

$$\phi^S = \phi^O + ft - \frac{fr}{c} \quad (1)$$

where:

ϕ^0 = the Fourier phase obtained in the previous section,

f = the frequency in Hz,

t = the time delay in seconds between the zero time of the explosion and the start time of the Fourier transform window,

r = the epicentral distance in kilometers, and

c = the phase velocity in km/s.

The term fr/c is the phase delay due to propagation, which is subtracted from the phase delay equalized to the zero time of the explosion, $\phi^0 + ft$, to obtain the source phase. This calculation gives values of the far-field source phase relative to zero time of the explosion. The phase velocities of Love and Rayleigh waves were taken from the studies of Priestley and Bruce⁹ and Patton,⁸ respectively.

RESULTS

The Rayleigh-wave source amplitude and phase spectra for five explosions are shown in Figs. 12 and 13, respectively.

The spectra for explosions Pyramid, Nessel, and Burzet show more variability than do the spectra for explosions Hearts and Offshore. For example, the phase spectra at Elko show significant phase shifts in the case of explosions Pyramid, Nessel, and Burzet. The amplitude spectra at Elko for the Pyramid explosion seems to be enriched in high frequencies relative to the other stations. Kanab's amplitude spectrum at frequencies above 0.1 Hz has a peculiar dip, unlike the spectra at the other stations. This feature does not appear to change much from explosion to explosion.

An isotropic explosive source does not generate Love waves. However, Love waves were observed for all explosions. The Love-wave amplitude spectra are shown in Fig. 14. Many of the Love-wave amplitude spectra appear to be enriched in the higher frequencies. This is especially true for frequencies higher than 0.10. The enhancement of the higher frequencies is most apparent for the Nessel and Pyramid explosions (Figs. 14c and b, respectively).

The Love-wave phase spectra are shown in Fig. 15. The error in the Love-wave phase measurements is greater than that in the Rayleigh-wave measurements because the Love-wave phase velocities are not known as accurately as the Rayleigh-wave phase velocities. Greater uncertainties in the Love-wave phase velocity account for some of the wild variations in the Love-wave phase.

Figure 12. Rayleigh-wave amplitude spectra for explosions (a) Hearts, (b) Pyramid, (c) Nessel, (d) Offshore, and (e) Burzet. All spectra are equalized to a distance of 500 km.

Figure 13. Rayleigh-wave source phase spectra for explosions (a) Hearts, (b) Pyramid, (c) Nessel, (d) Offshore, and (e) Burzet. Error bar represents the error in source phase at low and high frequencies for a 1% error in phase velocity on a path length equal to that of the farthest station, Elko.

Figure 14. Love-wave amplitude spectra for explosions (a) Hearts, (b) Pyramid, (c) Nessel, (d) Offshore, and (e) Burzet. All spectra are equalized to a distance of 500 km.

Figure 15. Love-wave source phase spectra for explosions (a) Hearts, (b) Pyramid, (c) Nessel, (d) Offshore, and (e) Burzet. Error bar represents the error in source phase at low and high frequencies for a 2% error in phase velocity of a path length equal to that of the farthest station, Elko.

Love-wave phase spectra for the Hearts, Offshore, and Burzet explosions (Figs. 15a, d, and e, respectively) are all similar. The Love-wave phase spectra for Nessel (Fig. 15c) appear to be shifted by a half cycle (i.e., π) relative to the phase for the other events at each station except Mina. The phase spectra for Pyramid (Fig. 15b) are difficult to interpret.

MODELING THE EXPLOSION SOURCE

The purpose of this section is to investigate the characteristics of the reduced displacement potential that affect the generation of low-frequency seismic waves. We will then attempt to model the Rayleigh-wave source spectra to deduce the "low-frequency" RDP for the five explosions in this study.

The seismic source due to the detonation of underground nuclear explosion will be regarded as a point source because of the long wavelength of our observations. For a spherically symmetric explosive source, Love¹⁰ obtained a point source representation consisting of three mutually perpendicular, outward directed, dipole forces of equal strength. The seismic moment function, $p(\tau)$, associated with one of these dipole forces (the product of the force strength times the arm length of the dipole force) is related to medium parameters at the source and the reduced displacement potential, $\psi(\tau)$ (see Miller,¹¹ and Tsai and Aki¹²) as follows:

$$p(\tau) = 4\pi\rho\alpha^2\psi(\tau) \quad , \quad (2)$$

where ρ is the density, α is compressional velocity, and τ is the reduced travel time at a radius, r , from the center of the explosion. The radial displacement at this radius is written in terms of the RDP as

$$D(r, \tau) = - \frac{\partial}{\partial r} \left[\frac{\psi(\tau)}{r} \right] \quad , \quad (3)$$

in the case of an infinite homogeneous elastic medium. The seismic moment of the explosion source, M_0 , is the static level that the function $p(\tau)$ reaches as $\tau \rightarrow \infty$. Miller¹ used the two equations above to relate the moment to the

displacement, D_1 , at the elastic sphere around the explosion and to the surface area, S_1 , of the sphere

$$M_e = (\lambda + 2\mu) S_1 D_1, \quad (4)$$

where λ and μ are elastic medium constants at the radius of the sphere.

The spectrum of Rayleigh waves in a vertically heterogeneous medium at a distance, r , from the explosion source may be written using the excitation formalism of Saito¹³ and the moment tensor representation

$$u(r, \omega) = \frac{Y_1(0)}{4CUI_1} \sqrt{\frac{2}{\pi k r}} e^{-i(\frac{\omega r}{C} - \frac{3\pi}{4})}$$

$$\left[(M_{xx} + M_{yy}) \frac{kY_3(h)}{2} - M_{zz} \frac{Y_2(h) + \lambda(h)kY_3(h)}{\lambda(h) + 2\mu(h)} \right] \quad (5)$$

where M_{xx} , M_{yy} , and M_{zz} represent the spectrum of the moment functions of each of the dipole forces. The Lamé parameters, μ and λ , are a function of depth only, where h is the shot depth. The Y_i are eigen functions of Rayleigh waves in a vertically heterogeneous medium, which satisfy the wave equations derived by Saito¹³ and Takeuchi and Saito.¹⁴ For the spherically symmetric source described above, the spectrum of the moments may be written as

$$M_{xx}(\omega) = M_{yy}(\omega) = M_{zz}(\omega) = P(\omega) = 4\pi\rho\alpha^2\Psi(\omega) \quad (6)$$

where $P(\omega)$ and $\Psi(\omega)$ are the spectra of the functions, $p(\tau)$ and $\psi(\tau)$, respectively. It is clear from this mathematical description that the spectrum of the RDP is an essential source parameter controlling the surface wave spectrum. The spectral characteristics of the RDP can be recovered from the surface-wave spectrum, provided that the medium is accounted for by the medium responses expressed in terms of the Y_i in Eq. (5) and the propagation from source to receiver.

REDUCED DISPLACEMENT POTENTIAL

Three commonly suggested functional forms of the RDP are: (1) a step function (permanent displacement), (2) an impulse function (a delta function with no permanent displacement), and (3) a function with overshoot (i.e., an RDP with finite rise time, overshoot, and a permanent static displacement which is less than the peak value of the overshoot). A mathematical representation of the function with overshoot (see Von Seggren and Blandford¹⁵) is

$$\frac{\psi(t)}{\psi(\infty)} = \left\{ 1 - e^{-Kt} \left[1 + Kt - B(Kt)^2 \right] \right\} H(t) \quad (7)$$

where K controls the rise time and width of the overshoot, B controls the amount of overshoot, and $H(t)$ is the Heaviside function. A step function is obtained by making K very large and $B = 0$; i.e., $K = 1000$, $B = 0$. The impulse function cannot be represented by this formula because the behavior of the function at large t is a constant of value 1. The amplitude scale factor, $\psi(\infty)$, is defined at large times and determines the permanent static displacement on the elastic sphere around the explosion point. The permanent static displacement is directly proportional to the explosion moment, as shown in Eq. (4).

PARAMETER STUDY

In order to examine the effects of the RDP on the surface-wave source spectrum, a parameter study was carried out involving the mathematical functions described above. The frequency dependence of $P(\omega)$ was determined by the spectrum of the RDP time function. The amplitude scale factor was set to give a seismic moment of 10^{25} dyn-cm in every case. For the impulse, the scale factor corresponds to the peak strength of the dipole force system. The medium model adopted to calculate Y_L is the Gutenberg continental earth model (for medium parameters see Tsai and Aki¹⁶).

The results of the parameter study are shown in Fig. 1b. The Rayleigh-wave amplitude and phase spectra in the frequency range, 0.03 to 0.167 Hz are shown for the different RDP functions. The extremes are represented by the impulse and step functions. The Von Seggren-Blandford time functions show

Figure 16. The effect of K and B (the risetime and overshoot parameters in Von Seggren and Blandford's mathematical representation of the RDP¹⁵) on Rayleigh-wave spectra. The parameter, B , is held constant in (a) amplitude spectra and (b) phase spectra. The parameter, K , is held constant in (c) amplitude spectra and (d) phase spectra.

some characteristics of the impulse and step functions depending on the frequency and the parameter values. Specifically, when the risetime is held constant and overshoot is varied, the shape of the amplitude spectrum for the case $K = 5$ and $B = 10$ is very close to the shape of the spectrum for an impulse. The phase spectrum for this case is delayed about 0.15 cycles more than an impulse. If we went to high enough B , both the amplitude and the phase spectra would be very close to that of the impulse over this limited frequency range. When overshoot is held constant and risetime is varied, the effect on the Rayleigh-wave spectrum is less than the effect due to overshoot. The risetime is expected to scale with the cube-root of the yield of the explosion (see Carpenter et al.¹⁷). For the explosions in this study, K should certainly be greater than two. On the basis of results in Fig. 16, we can safely dismiss risetime as a critical parameter in modeling the long period surface-wave spectra.

MODELING RESULTS

The results of the parameter study indicate that some of the variability of the observed Rayleigh-wave spectra could be caused by differences in the RDP from shot to shot. There is experimental evidence for dependence of the RDP on the shot medium (see Werten and Herbst¹⁸). Furthermore, for a given explosion there may be directional dependence of the RDP. For example, horizontal traveling P-waves appear to have a different RDP than downward traveling P-waves (see Blandford¹⁹). There could be an azimuthal dependence of the RDP due perhaps to an anisotropy of the medium's physical properties. In this section, all of the variability seen in the observed Rayleigh-wave spectra is assumed to arise from the RDP alone. In order to match the observed spectra, it will be necessary to invoke azimuthal dependence. Since other source effects may be responsible for introducing asymmetries into the seismic wave radiation and since, furthermore the RDP concept is derived from a spherically symmetric model, it may be appropriate to call the function obtained from the modeling an "apparent" RDP.

The trial and error fit is made to just the observed amplitude spectrum. Only the overshoot parameter, B , was varied, with the risetime, $1/K$, fixed at a value of 0.2. The seismic moment, M_0 , was determined by scaling the

theoretical spectrum to each observed spectrum individually. Examples of the comparisons between theoretical and observed spectra are shown in Fig. 17 and the results are summarized in Table 4.

There are several noteworthy results in Table 4. First, there appear to be small differences in the values of the parameter B between events. The differences between stations are more noticeable than the differences between explosions. We note that Elko and Landers consistently "see" a source with more overshoot than do Mina or Kanab. This is most apparent in the amplitude (and phase) spectra of Rayleigh waves recorded at Elko for events Nessel and Pyramid.

EFFECT OF CRUSTAL STRUCTURE

Hudson and Douglas²⁰ investigated the effect of shallow crustal structure on the excitation of Rayleigh waves by explosion sources and showed that the Rayleigh-wave excitation by explosions in an alluvium crust is greater than the excitation by explosions in a granitic crust, particularly at frequencies above 0.1 Hz (see Fig. 1 of Ref. 20). At low frequencies, the effect of shallow crustal structure on Rayleigh-wave excitation is small. Nevertheless, it is possible that the frequency dependence of the Rayleigh-wave amplitudes attributed to RDP is an artifact of the earth model assumed in

Table 4. Apparent reduced displacement potential.

Stations	Explosions		
	Hearts	Nessel	Pyramid
Mina	B = 2.0 $M_e = 2.9 \times 10^{23}$	B = 2 to 5 $M_e = 8 \times 10^{21}$	B = 2.0 $M_e = 7.5 \times 10^{22}$
Kanab	B = 2.0 $M_e = 2.5 \times 10^{23}$	B = 2 to 5 $M_e = 7.4 \times 10^{21}$	B = 2.0 $M_e = 7.8 \times 10^{22}$
Landers	B = 5 to 10 $M_e = 9 \times 10^{22}$	B = 5.0 $M_e = 9 \times 10^{21}$	B = 5.0 $M_e = 4.7 \times 10^{22}$
Elko	B = 5.0 $M_e = 1.9 \times 10^{23}$	B = 10.0 or impulse $M_e = 7.4 \times 10^{21}$	B = 10.0 or impulse $M_e = 4.9 \times 10^{22}$

Figure 17. Comparison of observed Rayleigh wave amplitude spectra with theoretical spectra obtained by adjusting the parameters B and M_e (see text) for each station individually. The explosion is Nessel.

the calculation of the theoretical spectra. In order to check this, we examined an alternative earth model.

The parameters of a model appropriate for the Basin and Range Province of western U.S. are given in Table 5. The upper mantle velocities and densities are taken from the study of Priestley and Brune.⁹ The crustal P-wave velocities are based on the results of Prodehl²¹ for a refraction line from NTS to Elko. The crustal S-wave velocities were chosen to agree with the Rayleigh-wave phase velocity dispersion between NTS and Elko (see Patton⁸). The Rayleigh-wave spectra for explosions in this velocity model are compared to the spectra in the Gutenberg model in Fig. 18.

The comparison in Fig. 18 indicates that the amplitude excitation by explosions in the new velocity model is significantly greater than the excitation in the Gutenberg model at high frequencies. Indeed, the amplitude spectrum for a source with overshoot ($B = 5$) in the Gutenberg model is very similar to the spectrum for a step-function source in the Basin and Range velocity model. The Rayleigh-wave phase spectrum for an explosion source is not affected by the crustal structure in the frequency range of interest.

Table 5. Basin and Range velocity structure.

Layer thickness (km)	P-wave velocity (km/s)	S-wave velocity (km/s)	Density (g/cc)
1.25	3.20	1.88	2.20
20.75	6.00	3.46	2.78
10.00	6.80	3.87	2.96
29.00	7.80	4.50	3.30
40.00	7.80	4.12	3.30
16.00	7.81	4.10	3.40
20.00	7.85	4.05	3.40
20.00	7.87	4.05	3.42
20.00	7.92	4.06	3.44

DISCUSSION

The velocity model in Table 5 is probably a good approximation of the best plane-layered model to represent the medium between NTS and the Livermore stations (with the possible exception of Mina). Therefore, on the basis of the results in Table 4 and the comparisons in Fig. 18, we conclude that little or no overshoot is required to model the shape of observed Rayleigh-wave amplitude spectra below 0.16 Hz for any explosion, including Burzet and Offshore. What overshoot is present in the RDP appears to be greater for azimuths north and south of NTS (Elko and Landers) than for azimuths east and west (Mina and Kanab).

It was argued in the section on Surface-Wave Source Spectra that the effect of attenuation on the spectra was small enough to ignore because of the short path lengths. Nevertheless, attenuation might be great enough to cancel the effects of overshoot at the highest frequencies where our modeling is particularly sensitive. We considered this possibility but found two lines of evidence against it. One is the fact that the observed amplitude spectra for the closer stations (Mina and Kanab) were modeled by an RDP with less overshoot than the spectra observed at Landers or Elko which have greater epicentral distances. The second evidence is the Rayleigh wave source phase in Fig. 13. Although the error at high frequency on each data point is too large to discriminate between overshoot or no overshoot, on average the observed phase spectra seem to be consistent with small ($B \sim 2$) overshoot. The phase spectra at Elko for explosions Pyramid, Nessel, and Burzet are notable exceptions.

The fact that the Rayleigh-wave radiation is asymmetric and shows variability from explosion to explosion is not completely surprising, since Love waves, an indicator of secondary sources or source asymmetry, were also recorded. However, the amplitudes of the long-period Love waves are quite small compared to the Rayleigh waves. It is questionable whether the Love-wave source generates Rayleigh waves large enough to perturb the explosion's isotropic radiation in the fashion and to the degree that we observe. We will address this question and the modeling of the Love waves in the next section.

Figure 18. Comparison of Rayleigh-wave spectra calculated for the Basin and Range velocity model in Table 5 and for the Gutenberg velocity model. Notice that the shape of the spectrum calculated for the Basin and Range model using a step function resembles the shape of the spectrum with overshoot ($B = 5$) of the Gutenberg model.

SECONDARY SOURCES OF SEISMIC WAVES

In addition to the explosion source, there are secondary sources of seismic waves caused by the interaction of the shock wave with the surrounding medium. Secondary sources are known to contribute significantly to the seismic wave field of an underground explosion, as evidenced by the commonly observed shear waves (SH) and Love waves on the seismograms of these events. Indeed, a significant proportion of the seismic wave field at low frequencies can be excited by the secondary source(s). In this section we explore secondary sources that could be dominating the generation of low-frequency seismic waves. These sources are: spall slapdown, shown by Vi Farrell²² to be an efficient Rayleigh-wave source; thrust faulting model of Massé,³ and tectonic strain release by earthquake triggering (see Brune and Pomeroy,²³ Aki,²⁴ Aki et al.,²⁵ and Aki and Tsai²⁶).

SPALL CLOSURE

Vi Farrell²² describes spallation as the parting of horizontal layers of rocks in the earth at a depth where the tensile stress of the shock wave reflected off the free surface exceeds the tensile strength of the medium. The spalled layers experience ballistic flight and eventually free-fall back to the earth's surface. The impact of the spalled layers on the surface of the earth is termed spall closure and has been shown to be an efficient means of exciting Rayleigh waves (see Vi Farrell²²). In this section we explore briefly the possibility that the long-period Rayleigh waves were generated by this secondary source.

In the formulation of a mathematical source representation, the spallation event (i.e., the parting of layers in tension) is usually dismissed as being a small or inefficient source of seismic waves compared to the spall closure event. The body-force representation of spall closure is a downward-directed force distribution, normal to the surface. For long wavelengths this

distribution is reduced to a single point force with impulse, I , equal to (Viecelli²²)

$$I = \frac{\pi}{3} \rho d_o r_o^2 (2gh_o)^{1/2} \quad (8)$$

where

r_o = the radius of a spalled plate of material with density ρ ,

d_o = the thickness of the plate,

h_o = the maximum height it attains, and

g = acceleration of gravity.

In a homogeneous half space, an impulsive downward point force generates Rayleigh waves with the same shape amplitude spectrum as an explosive source with step function time dependence (see Aki et al.²⁷). The difference is that the downward force generates Rayleigh waves which are delayed by $\pi/2$ radians at all frequencies relative to the explosion's Rayleigh waves. These characteristics of Rayleigh waves in a homogeneous half space also hold true in a layered earth structure at least in the frequency range of interest in this study.

Since spallation and spall closure are commonly observed on near-field strong motion accelerographs both for past explosions (see Eisler et al.²⁸) and for the recent explosions, including some of the shots in this study (Warsaw²⁹), the question arises whether spall closure generates significant amounts of long-period seismic energy that reach the far-field. Comparisons between observed Rayleigh-wave spectra for the Nessel explosion and theoretical spectra based on the model of spall closure described above are shown in Fig. 19. The impulse obtained from the fit of the theoretical to the observed amplitude spectra is 1.3×10^{16} dyn-s which is in good agreement with the value obtained from the yield-impulse relationship reported by Viecelli.²² (For Hearts and Pyramid, the observed impulse was about a factor of 3 greater than the predicted value.) However, the theoretical source phase for the model of spall closure does not match the observations. The observed phase values are significantly less than the predicted values. Consequently, the source phase observations indicate that spall closure as proposed by Viecelli²² is not the source of long period Rayleigh waves in the far-field.

Figure 19. Comparison of observed Rayleigh-wave amplitude and phase spectra for Nessel explosion with the calculated spectra for spall closure model.

It may be that the explosion and spall closure sources combine to generate the long-period waves as proposed by Bache et al.³⁰ and Peppin.³¹ However, a significant contribution by spall closure is not supported by our phase observations. A multiple source model with significant spall component also predicts source-phase delays greater than 0.375 cycles, which is not observed in any of the spectra. Furthermore, the asymmetries in Rayleigh-wave radiation patterns and the Love-waves cannot be modeled by the addition of spall closure since it radiates isotropically. We concur with the conclusions reached by Bache et al.³⁰ that spall closure probably does not contribute greatly to the generation of long-period waves recorded in the far-field, at least for the Yucca Valley explosions in this study.

THRUST FAULTING

Massé³ has recently proposed a new source model which has four "stages" corresponding to various sources of seismic radiation for underground nuclear explosions. The first stage is the explosion itself. The other stages are all secondary sources, the third stage being spall closure which was discussed in the previous section. The second stage is induced thrust faulting along preexisting joints and fracture planes close to the source. Rather than a tectonic release, Massé envisions a passive sliding on planes of weakness with the passage of the shock wave from the explosion. Support for this type of faulting at NTS comes from observational studies of seismic waves reviewed by Massé and from field observations of vertical movement on faults in the source region after underground explosions (see McKeown and Dickey³²). In the Massé source model, thrust faulting is the only source that generates SH waves and Love waves.

The thrust faulting believed to be induced is shown in detail in Fig. 20, reproduced from Massé.³ The pattern of faulting is not spherically symmetric about ground-zero, as may be seen in this figure. Rather, the strikes of the faults tend to follow the "geologic fabric" of the source medium. According to Massé, the dip angle of the faults are commonly found to be close to 45°.

The problem is to formulate a mathematical source representation for the geometry of thrust faults shown in Fig. 20. This representation can be quite easily formulated for a slip dislocation on planar faults. We know from

Figure 20. Top view shows surface fracture pattern produced above an explosion detonated in Yucca Valley. Side view shows theorized thrust faults produced by the explosion's compressional stress wave. This figure is reproduced from a paper by Massé.³

elastodynamics that a displacement discontinuity for a point source is equivalent to a point double-couple force system having no net angular moment. The orientation of the double-couple in the case of thrust faults is such that one couple acts along the dip of the fault and the second acts at right angles to the fault, canceling the angular moment of the first couple. If we consider 45° dipping faults, the orientation of the double-couple is identical for any of the thrust faults in Fig. 20 whether they dip to the north or to the south. Hence, for long wavelength seismic waves, all of the thrust faults can be replaced by a single double-couple behaving as a step function in time. The seismic moment of this couple will constitute the sum of the moments of all the thrust faults that slipped with the passage of the shock wave.

We explored the possibility that thrust faulting is a secondary source of long-period seismic waves through the following method. First, the strike of the thrust faults and the total seismic moment were determined by phase and amplitude spectra of the Love waves, respectively. Since fault strike and moment are the only free parameters in the secondary source defined above, the Love-wave data alone will constrain the secondary source representation for each explosion. Second, we superimposed the thrust source on the explosion (see Patton³³) and adjusted the ratio of the strength of the thrust source to the strength of the explosion in order to minimize the difference between observed and calculated Rayleigh-wave spectra. The ratio of source strengths is the F parameter used in the study by Toksöz and Kehrner.³⁴ Müller¹ obtained the relationship between F and the seismic moments both of the explosion, M_e , and of the earthquake, M_q ,

$$F = \frac{\alpha^2}{2\beta^2} \frac{M_q}{M_e} \quad (9)$$

where α and β are P- and S-wave velocities in the source region, respectively. Once the ratio F is determined, the seismic moment of the explosion may be calculated using Eq. (9).

The parameters obtained from the data fit are given in Table 9. These parameters are the seismic moment and fault strike of the secondary source (in this case a thrust fault), the ratio of source strengths, F, and the seismic

Table 5. Parameters of secondary source models obtained from data fit.

Explosion	Source model ^a	M_q^b (dyn-cm)	Fault strike ^b (°)	F	M_e^b (dyn-cm)	RMS ^c
Hearts	SS	3.1×10^{22}	340	0.3	$1.5 \cdot 10^{23}$	0.11
	DS	6.2×10^{22}	295	0.5	$1.9 \cdot 10^{23}$	0.13
Pyramid	SS	6.6×10^{21}	340	0.2	$4.9 \cdot 10^{22}$	0.17
	DS	1.3×10^{22}	295	0.3	$6.5 \cdot 10^{22}$	0.18
Offshore	SS	4.1×10^{21}	340	0.7	$8.8 \cdot 10^{21}$	0.10
	DS	8.1×10^{21}	295	0.8	$1.5 \cdot 10^{22}$	0.15
Nessel	SS	9.3×10^{20}	300	0.2	$7.0 \cdot 10^{21}$	0.12
	DS	1.9×10^{21}	255	0.3	$9.5 \cdot 10^{21}$	0.11
Burzet	SS	2.2×10^{21}	340	0.6	$5.5 \cdot 10^{21}$	0.15
	DS	4.4×10^{21}	295	0.8	$8.2 \cdot 10^{21}$	0.19

^a SS = strike-slip model (see Toksöz and Kehr³⁴).

DS = dip-slip thrust model (see Mass³³).

^b From Love waves, fault strike measured from north, positive clockwise.

^c Root mean squared of differences between observed and calculated Rayleigh-wave logarithm amplitude spectra for all stations.

moment of the explosion. Also given in this table is the RMS error between observed and calculated amplitude spectra. This error reflects the quality of fit to the Rayleigh-wave amplitude data for all stations.

Before discussing the results in Table 6, we consider another model, the strike-slip model of Toksöz and Kehr.

TECTONIC STRAIN RELEASE

There are two possible mechanisms for the release of tectonic stress (or strain) by an underground explosion. One mechanism is the formation of a region of crushed rocks around the shot point with essentially zero shear strength. The surrounding medium, which is under preexisting deviatoric stress, relaxes with the formation of a zero-stress cavity. This is the stress relaxation model (see Press and Archambeau³⁵ and Archambeau and Sammis³⁵). The other mechanism calls for the shock wave to interact with

structural inhomogeneities; e.g., a nearby fault. The transient stress wave is great enough to overcome frictional stress on the fault and triggers an earthquake. This is the earthquake-trigger model (see Brune and Pomeroy,²³ and Aki²⁴). We shall adopt the earthquake-trigger model in this study and attempt to interpret our observations using the strike-slip fault model proposed by Toksöz and Kehr³⁴ for NTS.

In the model of Toksöz and Kehr³⁴, underground explosions release tectonic stress by strike-slip faulting on prominent geologic faults and explosion-produced faults aligned with the geologic fabric in the source region. Figure 21, which is reproduced from Toksöz and Kehr³⁴, shows the fault-strike orientations obtained from the analysis of surface waves for explosions in Yucca Valley. There is generally good agreement between these orientations and the north-south geologic fabric of the Yucca Valley. A right-lateral motion on the faults was assumed by Toksöz and Kehr³⁴ in order to be consistent with the regional tectonic stress field, which shows generally northwest-southeast extension; e.g., Zoback and Zoback.³⁷

Because slip on faults is an efficient source of shear waves, the effect of stress release by underground explosions on surface waves can be quite significant, as shown by the calculations in Figs. 22 and 23. These calculations pertain to an earthquake, modeled by a point double-couple source with step-function time dependence, superimposed on an explosion which also has step-function time dependence. The orientation of the double-couple is appropriate for a right lateral strike-slip fault with fault strike 22° west of north. Figures 22 and 23 show the dependence of Rayleigh-wave spectra on F , the ratio of source strengths defined earlier, and on the depth of the double-couple. The Rayleigh-wave spectra are complicated because of the interaction of waves from two sources with different source phases. The effect of the interaction is greater in one azimuth, Elko, than it is in the other, Mina. At Elko, it is apparent that the effect is smaller for the 5-km-deep source than it is for the 1-km-deep source. In the case of 1-km-deep source, the spectra are dominated by the tectonic component for F values of 1.5 and above. For the 5-km-deep source, the spectra show the effect of the tectonic component at just the lowest frequencies (~ 0.04 Hz) for F values of 2. Since Toksöz and Kehr³⁴ assumed a surface source, their F values represent a minimum strength of the tectonic component to produce the effects on the surface waves which they observed.

Figure 21. Map of Yucca Valley showing the fault plane orientations of explosion studied by Toksöz and Kehrler.³⁴ This figure is reproduced from their paper.

Figure 22. Rayleigh-wave spectra calculated for a multiple-source model proposed by Toksöz and Kehr³⁴ (strike-slip tectonic release superimposed on an explosion). Shown are the (a) amplitude spectra and (b) phase spectra as a function of F value for the case when the tectonic stress release occurs at a depth of 1 km and the (c) amplitude spectra and (d) phase spectra as a function of F value for the case when the tectonic stress release occurs at a depth of 5 km. The calculations are for a receiver azimuth corresponding to Mina's.

Figure 23. Rayleigh-wave spectra calculated for a multiple-source model proposed by Toksöz and Kehr³⁴ (strike-slip tectonic release superimposed on an explosion). Shown are the (a) amplitude spectra and (b) phase spectra as a function of F value for the case when the tectonic stress release occurs at a depth of 1 km and the (c) amplitude spectra and (d) phase spectra as a function of F value for the case when the tectonic stress release occurs at a depth of 5 km. The calculations are for a receiver azimuth corresponding to Elko's.

In applying the Toksöz and Kehrér model to our surface wave data, we followed the same trial and error method that was used to estimate fault strike direction and F value for the thrust model. Furthermore, we are able to establish the direction of slip movement on the fault from the Love-wave source-phase data. Indeed, the Love-wave source phase spectra do yield slip directions consistent with the tectonic stress field for three out of the five explosions, i.e., Hearts, Offshore, and Burzet. The source parameters obtained from the data fit are given in Table 6. Examples comparing theoretical spectra to the observed Rayleigh- and Love-wave spectra are shown in Figs. 24 through 32.

DISCUSSION OF MODELING RESULTS

The trial-and-error search for an F-value gave a clear minimum in the RMS residuals for both source models, strike-slip and dip-slip thrust, in the limited range $0 \leq F \leq 1.0$. There were indications that minima existed for F-values greater than 1.0. However, these minima may be discarded because source models with large F-values predict, in some or all azimuths (see Fig. 22 and works of Harkrider,³⁸ Massé,³ and Patton³³) Rayleigh-wave phase reversals which are not supported by the observations in Fig. 13.

Before discussing the RMS residuals of the Rayleigh-wave fit, we should mention that the Love-wave amplitude and phase observations may be fit equally well by either the strike-slip or the dip-slip thrust model. The only adjustments needed to equalize the fits are to rotate the fault by 45° and double the seismic moment for the dip-slip event, as many are seen in the third and fourth columns in Table 6.

The surprising result in Table 6 is that the Rayleigh-wave observations can also be fit equally well, or nearly so, for either model when the F-value is less than 1.0. This may be seen by comparing the RMS values of the strike-slip and dip-slip models in Table 6 for each event. Offshore explosion shows the largest contrast (0.10 vs 0.16). Yet, in light of the closeness of the calculated spectra shown in Fig. 27 and the uncertainties in the observed spectra, this contrast is not sufficient to discriminate. Aki and Tsai²⁶ demonstrated that discrimination between dip-slip normal faulting and strike-slip models was not possible from observations of long-period Rayleigh- and Love-wave amplitudes. Here, we have a similar situation despite observations of both spectral amplitude and phase at higher frequencies.

Figure 24. Observed Rayleigh-wave amplitude spectra for the Hearts' explosion and theoretical spectra computed for the strike-slip model in Table 6 from (a) Mina, (b) Kanab, (c) Landers, and (d) Elko.

Figure 25. Observed Love-wave amplitude spectra for the Hearts' explosion and theoretical spectra computed for the strike-slip model in Table 6 from (a) Mina, (b) Kanab, (c) Landers, and (d) Elko.

Figure 26. Observed (a) Rayleigh- and (b) Love-wave source phase spectra for the Hearts' explosion and theoretical spectra computed for the strike-slip model in Table 6.

Figure 27. Observed Rayleigh-wave amplitude spectra for the Offshore explosion and theoretical spectra computed for the strike-slip model in Table 6 from (a) Kanab, (b) Landers, and (c) Elko. In addition to the strike-slip model, we show theoretical spectra for the dip-slip model in Table 6.

Figure 28. Observed Love-wave amplitude spectra for the Offshore explosion and theoretical spectra computed for the strike-slip model in Table 6 from (a) Kanab, (b) Landers, and (c) Elko.

Figure 29. Observed (a) Rayleigh- and (b) Love-wave source phase spectra for the Offshore explosion and theoretical spectra computed for the strike-slip model in Table 6.

Figure 30. Observed Rayleigh-wave amplitude spectra for the Nessel explosion and theoretical spectra computed for the strike-slip model in Table 6 from (a) Mina, (b) Kanab, (c) Landers, and (d) Elko.

Figure 31. Observed Love-wave amplitude spectra for the Nessel explosion and theoretical spectra computed for the strike-slip model in Table 6 from (a) Mina, (b) Kanab, (c) Landers, and (d) Elko.

Figure 32. Observed (a) Rayleigh- and (b) Love-wave source phase spectra for the Nessel explosion and theoretical spectra computed for the strike-slip model in Table 6.

For explosions Hearts, Offshore, and Burzet (possibly Pyramid, although the observations are much poorer) it is tempting to favor the strike-slip model over dip-slip thrust because of the results of fitting the Love waves. The estimate of fault azimuth, $N20^{\circ}W$, is consistent with the geologic mapping of the Yucca Fault and nearby splinter faults (see Fig. 1). The sense of motion on the fault in the model is right-lateral, which implies a $N65^{\circ}W$ direction of the least-compressive stress axis. This direction is in good agreement with the tensional axis of the Massachusetts Mountain Earthquake determined from P-wave waves (see Fischer et al.³⁹) and surface waves (see Patton⁸).

Although the surface-wave observations alone are insufficient to discriminate between strike-slip and dip-slip, they do indicate that the secondary source of the Nessel explosion is different from those of the other explosions. This is supported by the 40° rotation in the fault strike required to fit the Love-wave source phase (see Fig. 32). A strike-slip event for this explosion does not seem to fit well into the picture of an explosion releasing tectonic strain like the other explosions do.

If the secondary source of the Nessel explosion is dip-slip thrust, the cause is not likely to be tectonic strain release. The least-compressive stress axis is oriented vertically and the maximum compressive stress, inferred from the fault strike, is $N15^{\circ}W$. We should note that the strength of Nessel's secondary source is the weakest of all explosions; a seismic moment of 1.9×10^{21} dyn-cm corresponds to an earthquake with M_L of 3.6 according to the moment-magnitude relationship of Wyss and Brune.⁴⁰

If many faults slipped, as Massé theorizes in the thrust model, the moment of Nessel's secondary source may be regarded as the sum of moments on all the faults that slipped during the explosion. For simplicity, we assume that there are just two thrust faults extending from the detonation point to the free surface. The moment on each fault is 1.0×10^{21} dyn-cm and the fault length is about 0.65 km ($\sqrt{2} \times$ Nessel's depth of burial). The average slip, u , on a fault can be calculated by Aki's⁴¹ formula

$$u = M / \mu A$$

where μ is the rigidity and A is the fault area. The rigidity of alluvium is about 3×10^{10} dyn/cm². Taking the width of each thrust fault to be

1 km, we calculate an average displacement of 5 cm. If many more faults are involved, there is not likely to be a clear expression of vertical thrust faulting on the surface near the shot point.

In Fig. 33, we plot body-wave magnitude vs the logarithm of seismic moment for the explosions in this study and for other explosions fired in Yucca Tuff summarized in the study of Aki et al.²⁷ The scatter of the data on this plot also does not allow the discrimination between dip-slip and strike-slip models. Regardless of which explosion moment we do use, it is evident that the slope of the data on this plot is greater than unity in the range $4.5 < m_b < 6.0$. In fact, the slope of the data is close to 1.3. This result appears to be consistent with the empirical $m_b:M_s$ relationship for NTS explosions reported by Marshall et al.⁴² (the relationship is $M_s = 1.43 m_b - 3.8$) provided that M_s is proportional to $\text{Log } M_e$ for $M_s < 4.5$.

The proportionality between M_s and $\text{Log } M_e$ for explosions with $M_s < 4.5$ is predicted from the source spectrum scaling models of both Aki et al.²⁷ and Peppin.³¹ The results in the section on Modeling the Explosion Source which concern the low-frequency RDP would imply that the explosion source spectrum is flat or nearly so below 0.2 Hz. This is also predicted from Peppin's model and from the model of Aki et al.²⁷ for overshoot ratios less than 2:1. Furthermore, the observations in Fig. 33 suggests that the far-field source spectrum for explosions in tuff with $m_b > 5$ has a corner (with or without overshoot) at frequencies below 1 Hz. The model of Aki et al. is consistent with these observations. Regarding corner frequencies, Peppin's model appears to be applicable only to near-regional observations which were the basis for this model, since the source spectrum (see Fig. 10 of Ref. 31) does not have a corner frequency less than 1 Hz even for megaton explosions ($m_b > 6$).

Before concluding our discussion, we should make several comments about the match of theoretical Love-wave spectra to the observed in Figs. 25, 26, 28, 29, 31, and 32. Both the amplitude and the phase spectra are modeled satisfactorily at low frequencies between 0.06 and 0.1 Hz. However, the theoretical spectra do not account for the high spectral amplitudes observed at frequencies above 0.1 Hz.

The shape of the theoretical amplitude spectra is affected by the medium model, source parameters (depth and orientation of the double-couple), and the time function of the source. The average velocity model in Table 5 is probably a good estimate of the best plane-layered model representing the medium between

Figure 33. A plot of m_b (given in Table 1) vs logarithm of seismic moment of explosions studied in this paper and in the paper by Aki et al.²⁷ A line with unity slope is shown on this plot for reference.

NTS and the LLNL stations. Further refinements of the plane-layered model are not likely to enhance the excitation of high frequencies substantially. Source parameters, such as focal depth, affect the Love wave excitation; however, the amplitudes at high frequencies are reduced rather than enhanced as the focus moves deeper (see Figs. 2 and 3 of Tsai and Aki¹⁶) For shallow sources, the orientation of the double-couple does not change the shape of the amplitude spectrum greatly.

More high frequencies could be introduced into the source model through the source time function of the secondary source. This is completely analogous to the effect of the RDP on the Rayleigh-wave spectra of the explosion. An impulse time function would increase the slope of the excitation spectrum by ω over that of a step function. However, the improvement that would result in the fit to the Love-wave amplitude spectra would be offset by a loss of fit to the Love-wave phase spectra.

We speculate that there may be more than one source of Love-waves in the frequency range 0.06 to 0.16 Hz. The observations at low frequencies (<0.1 Hz) are modeled well by the double-couple source with step function time dependence, the source representation proven to be appropriate for earthquake strain release. However, this source model does not account for the enhanced amplitudes at high frequencies. The implication is that another source dominates at high frequencies (>0.1 Hz). Furthermore, we speculate that this source must be very inefficient at generating low frequency seismic waves.

CONCLUSIONS

In this paper we have reported on surface-wave studies of five underground nuclear explosions detonated in Yucca Valley. We draw the following conclusions:

1. The amplitudes of explosion-generated Rayleigh waves in the frequency range 0.03 to 0.16 Hz are modeled well by an RDP with little or no overshoot. This result holds for explosions in alluvium and tuff, above and below the water table.

2. For explosions in this study, spall closure as proposed by Viacellular²² does not appear to be a significant source of Rayleigh waves that reach the far-field.
3. There are secondary sources of seismic waves for all explosions as indicated by the presence of Love waves and non-isotropic Rayleigh-wave amplitude and phase spectra.
4. The observations of Love- and Rayleigh-wave amplitudes and source phases alone are not sufficient to discriminate between the strike-slip model and dip-slip thrust model at the low F-values (0.2 to 0.8) obtained for these explosions. In the case of the strike-slip model, the principal axes inferred from the fault slip and strike are in good agreement with the regional tectonic stress field for all but one explosion, Nessel. The results from the Nessel explosion suggest a mechanism other than tectonic strain release. Unfortunately, there is little hope to confirm that Nessel's source is different from the other explosions from field observations of surface faulting.

FUTURE WORK

This paper has reported on progress in our research carried out over the past year or so. There is a need to continue work on all aspects of this research. We take the opportunity here to mention a few areas of future work.

Augmented Datasets

We plan to augment the present dataset with three-component digital data from Sandia Laboratory's seismic station network surrounding NTS. This will allow a closer examination of the azimuthal variation in seismic wave generation which, in turn, will result in better constraints on the deviatoric part (non-explosive part) of the source description.

RDP at Higher Frequencies

We plan to continue work on the RDP by studying the L_g phase. This relatively "broad-band" phase will provide information at higher frequencies

than the fundamental-mode surface waves do and, yet, should overlap sufficiently to tie into our low-frequency description of the RDP.

Love-wave Generation

We plan to pursue the finding of enriched Love-wave spectral amplitudes at high frequencies by including additional observations of explosions and earthquakes in the western U.S. If the enriched amplitudes are caused by a source effect, we may see differences between Love waves from earthquakes and explosions.

Improved Inversion Techniques

We plan to improve on the inversion techniques for source parameters by implementing automated inversion schemes and methods to model larger datasets simultaneously.

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APPENDIX A.
PROCEDURES FOR ANALYSIS TECHNIQUES

The purpose of this appendix is to present the detailed procedures for each of the following analysis techniques: (1) low-pass filtering, (2) narrow-band filtering, and (3) Fourier spectral analysis. Explicit mathematic formulas referenced in these procedures are given at the end of the appendix.

PROCEDURE FOR THE LOW-PASS FILTERING

STEP 1. Time windows were selected to include vertical Lg and Rayleigh waves and transverse Lg and Love waves. Table 2 gives the time windows for each component and station.

STEP 2. The waveform data were windowed with a boxcar function with the number of points equal to the closest power of two.

STEP 3. The windowed data were fast Fourier transformed. Amplitude and phase spectra were computed (see Definition of Amplitude and Phase Delay Spectra).

STEP 4. Low-pass filter (see Cosine Squared Taper for Low-Pass Filtering) was applied to the amplitude spectrum.

STEP 5. The filtered waveform was obtained by performing an inverse FFT.

PROCEDURE FOR NARROW-BAND FILTERING

STEP 1. Time windows were selected to include all arrivals having velocities slower than about 3.9 km/s.

STEP 2. The waveform data were windowed with a 20% cosine taper function (see Cosine Window for Shaping $f(t)$ before Transforming) and zero filled to a power of two points.

STEP 3. The windowed data were fast Fourier transformed. Amplitude and phase spectra were computed.

STEP 4. The narrow-band filter (see Narrow-Band Filter) was applied to the amplitude spectrum.

STEP 5. The filtered waveform was obtained by computing the inverse FFT.

PROCEDURE FOR SPECTRAL ANALYSIS OF SIGNALS AND NOISE SAMPLES

STEP 1. Time windows were selected to include the surface wave arrivals. These windows are given in Table 3. Noise windows, the same length as the signal windows, were selected. The windows were taken before the onset of P waves in the time period -125 to 25 s relative to the detonation time ($t = 0.0$).

STEP 2. The waveform data were windowed with a 10% cosine taper function (see Cosine Window for Shaping $f(t)$ before Transforming) and zero filled to the closest power of two points.

STEP 3. The windowed data were fast Fourier transformed. Amplitude and phase spectra were computed (see Definition of Amplitude and Phase Delay Spectra).

STEP 4. The transfer function of the LLNL seismological system was removed to obtain amplitude and phase spectra of ground displacement. We used the analytic form of the transfer function (see Nakanishi⁴³).

DEFINITION OF AMPLITUDE AND PHASE DELAY SPECTRA

Let $f(t)$ be a seismogram record of interest in the time frame $t_1 \leq t \leq t_2$. We compute the Fourier transform, $F(\omega)$, of the record as follows:

$$F(\omega_k) = A(\omega_k) e^{-i\phi(\omega)_k} = \int_{t_1}^{t_2} f(t) e^{-i\omega_k t} dt ,$$

where ω_k is a particular frequency. If $\text{Re}(F_k)$ refers to the real part of F at the frequency ω_k and $\text{Im}(F_k)$ refers to the imaginary part, then

$$A(\omega_k) = \sqrt{\text{Re}(F_k)^2 + \text{Im}(F_k)^2}$$

and

$$\phi(\omega_k) = \text{TAN}^{-1} \left[\frac{-\text{Im}(F_k)}{\text{Re}(F_k)} \right],$$

where $A(\omega_k)$ is the amplitude spectrum and $\phi(\omega_k)$ is the phase delay spectrum.

COSINE-SQUARED TAPER FOR LOW-PASS FILTERING

Let $\Delta\omega$ be a constant frequency increment and ω_c be a corner frequency. Let N (an odd integer) be the number of frequency points in the taper. The frequency limits of the taper are

$$\omega_L = \omega_c - \Delta\omega \cdot \frac{N-1}{2}$$

and

$$\omega_H = \omega_c + \Delta\omega \cdot \frac{N-1}{2}.$$

Then, the functional form of the taper operator, $T(\omega)$, is as follows:

$$T(\omega) = \begin{cases} 1 & \omega < \omega_L \\ \cos^2 \frac{\pi(\omega - \omega_L)}{2(\omega_H - \omega_L)} & \omega_L \leq \omega \leq \omega_H \\ 0 & \omega > \omega_H \end{cases}$$

COSINE WINDOW FOR SHAPING $f(t)$ BEFORE TRANSFORMING

Let Δt be a constant time increment and N be the total number of points in the interval $t_1 \leq t \leq t_2$. If P refers to the percent of the interval with cosine taper, then $N \cdot P/100$ is the number of points affected by the taper. Let M be the total number of points affected by the taper. Of this number, half are affected at the beginning and half are affected at the end. We define new times, t_3 and t_4 , as

$$t_3 = t_1 + \Delta t \cdot \frac{M}{2}$$

and

$$t_4 = t_2 - \Delta t \cdot \frac{M}{2}.$$

Then, the functional form of the window operator, $W(t)$, is as follows:

$$W(t) = \begin{cases} \frac{1}{2} \left[1 - \cos \frac{\pi(t - t_1)}{(t_3 - t_1)} \right] & t_1 \leq t \leq t_3 \\ 1 & t_3 \leq t \leq t_4 \\ \frac{1}{2} \left[1 + \cos \frac{\pi(t - t_4)}{(t_2 - t_4)} \right] & t_4 \leq t \leq t_2. \end{cases}$$

NARROW-BAND FILTER

The design of a narrow-band filter used in this study is the same as Dzierwonski et al.⁶ Let ω_c be the center frequency. The functional form of the narrow-band filter is as follows:

$$H(\omega) = \begin{cases} 0 & \omega < (1 - \text{BAND}) \cdot \omega_c \\ e^{-a(\omega - \omega_c)^2 / \omega_c} & (1 - \text{BAND}) \cdot \omega_c \leq \omega \leq (1 + \text{BAND}) \cdot \omega_c \\ 0 & \omega > (1 + \text{BAND}) \cdot \omega_c, \end{cases}$$

where BAND is the bandwidth of the filter and α is a parameter controlling the amplitude at the cut-off frequencies. Specifically, we introduce a parameter, β , such that

$$\beta = -\ln [H(\omega_L)] = -\ln [H(\omega_H)] \quad ,$$

where

$$\omega_L = (1 - \text{BAND}) \cdot \omega_c$$

$$\omega_H = (1 + \text{BAND}) \cdot \omega_c$$

and

$$\alpha = \beta / \text{BAND}^2 \quad .$$

Satisfactory results are obtained when BAND equals 0.5 and β equals 3.15.

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