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**IMPLICATIONS OF EXPLOSION GENERATED SPALL MODELS:
REGIONAL SEISMIC SIGNALS**

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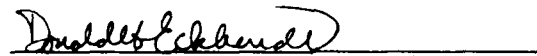


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13. ABSTRACT (Maximum 200 words) <p>The contribution of the spall source to the short period regional explosion seismogram is studied using new parametric models for the spallation seismic source derived from (2-D) axisymmetric nonlinear finite difference simulations for underground nuclear explosions. It is concluded that in high-velocity crustal structures spall may be a significant source of short period Lg and may significantly affect the Pg excitation.</p> <p>Regional phase excitation from a vertical point force and a horizontal tension crack are examined. A new general derivation for the equivalence between the two representations at low frequencies (horizontal wavelength \gg spall depth) is given. Numerical calculations show that the vertical point force at the free surface above the spall is a good approximation in the short period bandwidth but degrades at high frequencies (horizontal wavelength $<$ half the spall depth).</p> <p>A smoothing operator is presented to account for the distributed finite nature of the spall. This operator represents a distributed spall disk with zero motion at the tip, and has an upward concave spall surface. It is proportional to $\omega^{-5/2}$ at high frequencies. Since the spall source is proportional to ω^2 for low frequencies, the far-field signal should be significant only for a narrow band of frequencies (0.5-2.0 Hz).</p> <p>The parameterized model of Barker and Day (1990) is used to compare regional waveforms from spall and explosion sources in a high-velocity crustal model. The short-period Lg signal is completely dominated by the spall source. The spall source for a 680 m deep, 125 KT explosion corresponds to a 6.2 $m_b(Lg)$ in the Stevens (1986) model for Eastern Kazakhstan. Simulations suggest that if spall is a significant source of Lg excitation then $m_b(Lg)$ should be sensitive to scaled depth of burial.</p>				
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I. SUMMARY

The contribution of the spall source to the short period regional explosion seismogram is studied using new parametric models for the spallation seismic source derived from two-dimensional (2-D) axisymmetric nonlinear finite difference simulations for contained underground nuclear explosions. It is concluded that for high-velocity crustal structures spall may be a significant source of short period Lg and may significantly affect the Pg excitation.

Two seismic source representations for spall are compared. Regional phase excitation from a vertical point force and a horizontal tension crack are examined. A new general derivation for the equivalence between the two representations at low frequencies (horizontal wavelength \gg spall depth) is given. Numerical calculations show that the vertical point force at the free surface above the spall is a good approximation in the short period bandwidth but degrades at high frequencies (horizontal wavelength $<$ half the spall depth).

A smoothing operator is presented to account for the distributed finite nature of the spall. This operator has the desirable characteristics that it represents a distributed spall disk with zero motion at the tip, has an upward concave spall surface. It falls-off proportional to $\omega^{-5/2}$ at high frequencies. Since the spall source is proportional to ω^2 for low frequencies, the far-field signal should be significant only for a narrow band of frequencies compared to the broadband explosion signal. This narrow band can be expected to coincide with the traditional short period seismic band (0.5-2 Hz) for explosions in the 1

to 150 Kt yield range at normal depths of burial.

The parameterized model of Barker and Day (1990) is then used to examine the significance of spall signature in regional waveforms compared to the explosion contribution to the seismogram. Green's functions are computed for a high-velocity near-surface layer crustal model. It is found that for reasonable amounts of spall, the short period Lg signal is completely dominated by the spall source. The Barker and Day spall source for a 125 Kt explosion buried at 680 meter depth corresponds to a 6.2 $m_b(Lg)$ in the Stevens (1986) crustal model for Eastern Kazakhstan. The Pg signal may be dominated by the spall source for a narrower bandwidth. Simulations suggest that if spall is a *significant source of Lg excitation* then $m_b(Lg)$ should be sensitive to scaled depth of burial.

II. INTRODUCTION

It was shown by Day, *et al.* (1983) that a proper seismic source representation for spall must conserve momentum and therefore the spall signal has no "zero" frequency source strength. Day, *et al.* then showed that for low frequency surface waves an equivalent force model for spall could be represented by a vertical point force. They demonstrated that in the low-frequency limit, the vertical opening of a horizontal tension crack is equivalent to a vertical force on the surface with a suitable time history. In recent years this spall model has been increasingly used to represent the seismic spall signal at higher frequencies than it was initially applied. Stump (1984) has shown that for the purposes of source inversion, suitable combinations of vertical point forces and explosion sources can not be distinguished from an explosion plus a tension crack. In subsequent work, Stump (1985) has used the Day, *et al.* model combined with an *ad-hoc* smoothing operator to model small contained chemical explosions. Recently, Patton (1988) has used the Day, *et al.* model as modified by Stump to model regional Rayleigh and Lg waves by moment tensor inversion for the NTS explosion HARZER. Patton concluded that the spall signal was a significant contributor to the Lg signal below 1 Hz. Johnson (1988) using near-source data performed moment tensor inversions for HARZER and another NTS explosion, CHANCELLOR, and found similar results to Patton. In both cases, it was found that a source secondary to the explosion could be represented as either a vertical point force, F_z , or an additional contributor to the vertical couple, M_{zz} . Recently, Taylor (1989) used the modified Day, *et al.*

model to argue that spall is a significant contributor to regional Pg and that depth of burial (and hence relative size of spall) influences the proposed Murphy and Bennett (1983) high/low frequency spectral ratio discriminant.

In this paper, we present a more general derivation of the vertical point force at the surface as an approximation for the buried tension crack representation. We show that the approximation is valid in a more general context than originally shown by Day, *et al.* (1983) and examine the limitations of the approximation. Green's functions for point source loads and buried tension cracks are examined in the time and frequency domain for a simple crustal structure. We see that the vertical point force approximation may suffice for many applications. However, the radiation pattern and frequency dependence of the tension crack differs from the point force at high frequencies and the tension crack representation may be a more accurate representation.

Following the discussion regarding the seismic source representation of spall, we discuss possible smoothing operators to be used to represent the finite extent of spall. A take off angle dependent smoothing operator is chosen that has reasonable high frequency behavior, zero displacement at the tension crack tip, and has a concave upward spall surface.

Finally, we examine spall modeling results of Barker and Day (1990) based on axisymmetric spall models that fit teleseismic P waves radiated by 2-D axisymmetric nonlinear finite difference explosion simulations. Regional seismograms are computed based on their spall model and the relative excitation of Pg and Lg are compared from the explosion and spall sources.

III. AN EQUIVALENT FORCE REPRESENTATION FOR SPALL

Day, *et al.* (1983) suggested that spall may be represented as a horizontally oriented tension crack that opens and closes in the vertical direction (see Figure 1). Given this simplification, we can write that the far field displacement due to the motion on a surface is given by (Aki and Richards, 1980)

$$u_i(\omega, r) = \int_{\Sigma} n_j(\eta) \delta u_k(\omega, \eta) C_{jkpq}(\eta) \frac{\partial G_{ip}(\eta)}{\partial \eta_q} d^2\eta \quad (1)$$

where Σ is the spall surface with unit normal, $n_j(\eta)$, and $\delta u_k(\eta)$ is the motion across the surface, $C_{jkpq}(\eta)$ is the elastic modulus tensor, and $G_{ip}(\eta)$ is the Green's tensor for the medium. For the opening of a horizontal tension crack $n(\eta)$ and $\delta u(\eta)$ are parallel in the vertical direction, $j=z$, and we can write, $T_{izz}(\eta) = C_{zzpq}(\eta) \frac{\partial G_{ip}(\eta)}{\partial \eta_q}$, which by reciprocity is the vertical stress component at the source location, η , due to a point force in the i 'th direction at the receiver location, r . Equation (1) becomes,

$$u_i(\omega, r) = \int_{\Sigma} \delta u_z(\omega, x, y) T_{izz}(x, y) dx dy. \quad (2)$$

We expand T_{izz} in a Taylor expansion about the free surface, $z=0$,

$$T_{izz} = T_{izz} \Big|_{z=0} + z \frac{\partial T_{izz}}{\partial z} \Big|_{z=0} + \dots \quad (3)$$

By virtue of the free surface, the first term is zero, and Equation (2) becomes

$$u_i(\omega, r) = h_s \int_{\Sigma} \delta u_z(\omega, x, y) T_{izz}(x, y) \Big|_{z=0} dx dy \quad (4)$$

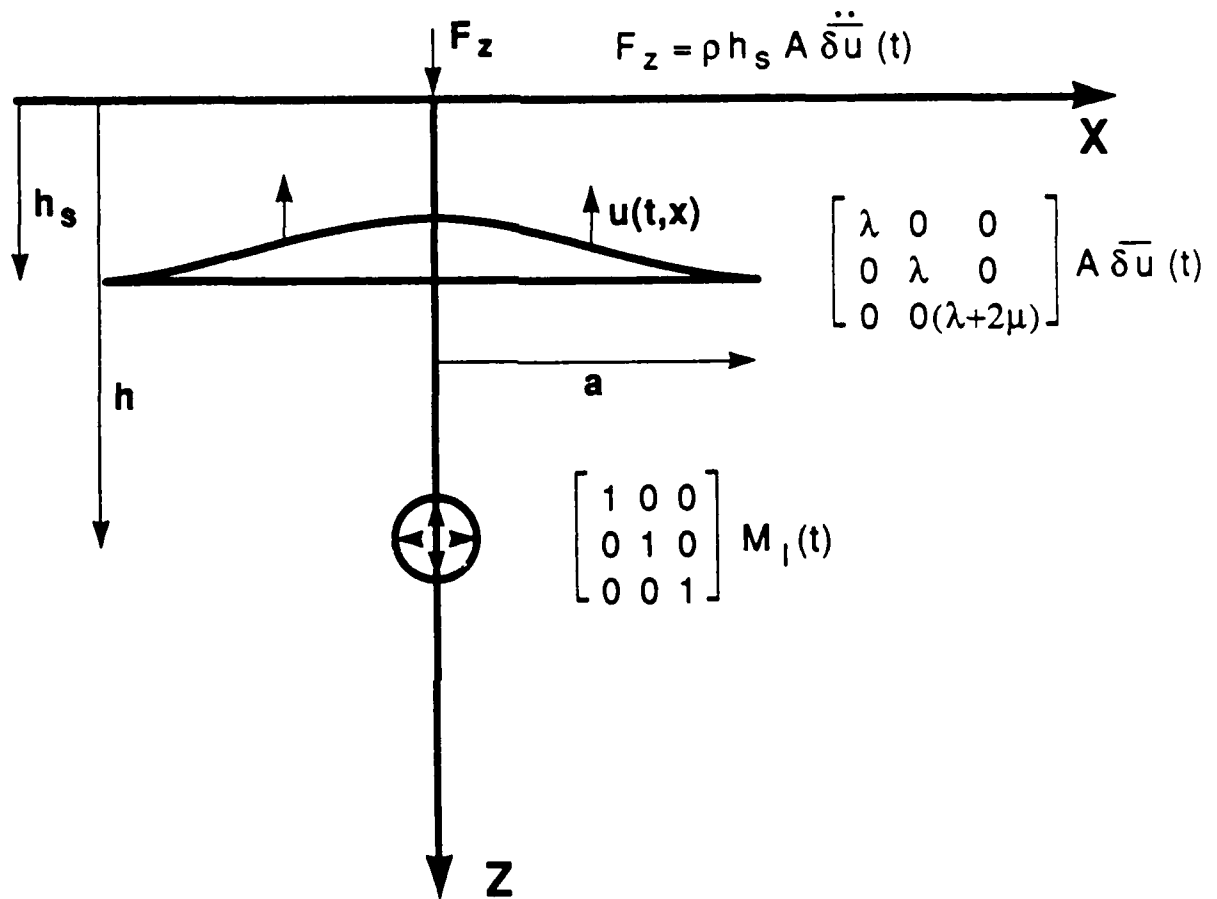


Figure 1. The axisymmetric spall above the explosion is modeled as a circular horizontal tension crack that opens and closes in the vertical direction. The spall is parameterized by the source depth h_s , the crack radius a , and the displacement time function $u(t,x)$. The radiation from a horizontal tension crack is equivalent at low frequencies to the radiation from a vertical point force, F_z , at the surface proportional to the second time derivative of δu . The moment tensor source representation for the tension crack is proportional to δu . A is the area of the crack, ρ is the density, and λ and μ are the Lamé parameters for the medium.

where h_s is the spall depth. Since T_{ijk} is the stress field due to G_{ij} , we may write the z'th component of the equation of motion,

$$\frac{\partial T_{izz}}{\partial z} + \frac{\partial T_{iyz}}{\partial y} + \frac{\partial T_{ixz}}{\partial x} = -\omega^2 \rho G_{iz}. \quad (5)$$

If we apply Equation (5) to the free surface, $z=0$, then the partial derivatives with respect to x and y are zero since $T_{iyz} = T_{ixz} = 0$ for $z=0$, and we have that,

$$\left. \frac{\partial T_{izz}}{\partial z} \right|_{z=0} = -\omega^2 \rho G_{iz}(z=0). \quad (6)$$

Substitute Equation (6) into Equation (4),

$$u_i(\omega, r) = -\rho h_s \omega^2 \int_{\Sigma} \delta u_z(\omega, x, y) G_{iz}(x, y, z=0) dx dy \quad (7)$$

$$u_i(\omega, r) = -\rho h_s A \omega^2 \overline{\delta u_z} G_{iz} = -m_s \omega^2 \overline{\delta u_z} G_{iz} = i \omega l_s G_{iz}. \quad (8)$$

Thus, $-\rho h_s \omega^2 \delta u_z(\omega, x, y)$ is interpreted as the vertical force per unit area at the free surface, $z=0$. Note that the equivalent force is applied to the free surface above the spall surface, and that the force has the time history of the spall acceleration. In contrast, the tension crack source has the time history of the spall displacement. The spall momentum, l_s , is given by the spall mass, $m_s = \rho h_s A$, times the mean velocity, $i \omega \overline{\delta u_z}$ and therefore the equivalent spall force, $F_s = i \omega l_s$. In this manner we can relate estimates of spall mass, and momentum to an equivalent point force. Alternatively, we could use Equation (2) to describe the source as a buried tension crack,

$$u_i(\omega, r) = \overline{\delta u_z} A T_{izz} = \overline{\delta u_z} A [\lambda G_{ix,x} + \lambda G_{iy,y} + (\lambda + 2\mu) G_{iz,z}] \quad (9)$$

There are several approximations inherent in the derivation of Equation (7). Since a Taylor expansion was used from the free surface, it is likely that the representation will break down for seismic wavelengths on the order of the spall depth. Related to this limitation is the fact that the radiation pattern for a point force at the free surface is not exactly the same as that for a tension crack at depth.

We address these two limitations by comparing the regional Green's functions for a surface point force and the buried horizontal tension crack. Equations (8) and (9) imply that $\rho h_s \omega^2 G_{iz}(z=0) \approx T_{izz}(z=h_s)$. Figure 2 shows the Green's functions for buried tension cracks compared to the Green's function for a vertical point force at the free surface. The Green's functions were computed for the vertical displacement at a distance of 300 km using the Eastern Kazakhstan crustal model from McLaughlin, *et al.* (1988) (see Table 1). A wavenumber integration code was used to compute the full response of the medium from 0 to 5 Hz. The tension crack ($T_{zzz}(t)$) and vertical point force ($\rho h_s \ddot{G}_{zz}(t)$) Green's functions are all plotted to the same scale. We see that the relative amplitudes of the Pg, Lg, and Rg are similar when we compare the point force and tension crack representations for depths less than 500 m. However, the individual wavepackets in the Pg can be seen to vary with depth for the tension crack sources.

VERTICAL FORCE VERSUS TENSION CRACKS (0 TO 5 HZ)

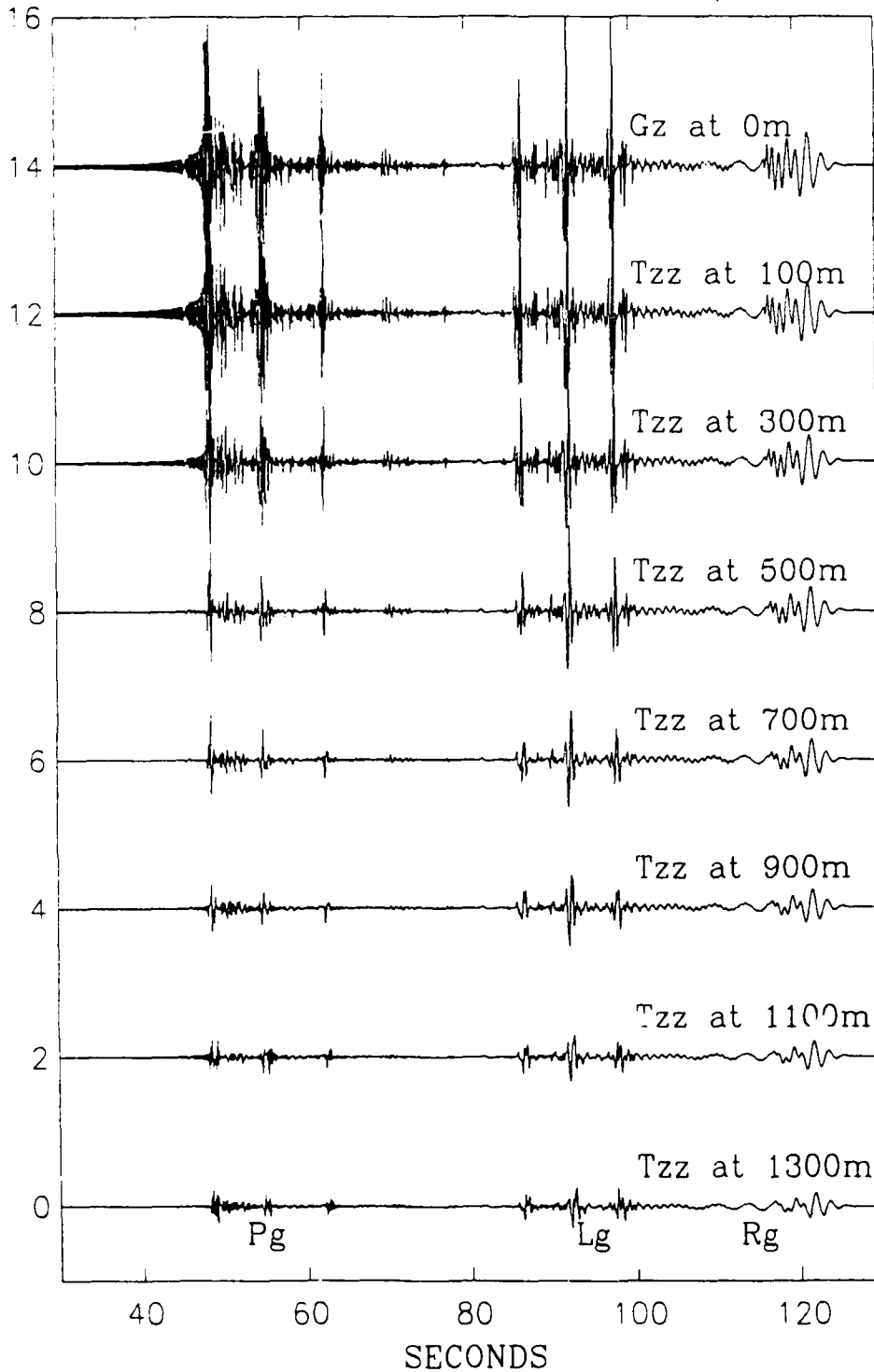


Figure 2. The broadband (0 to 5 Hz) vertical displacement at a distance of 300 km due to a vertical point force at the surface is compared to that motion due to tension cracks at depth. Pg, Lg and Rg wavepackets are indicated. Similarity of waveforms degrades for depth > 300 m in this bandwidth (0-5 Hz).

h(km)	α (km/s)	β (km/s)	ρ (gm/cc)	Q_{μ}	depth(km)
2.000	5.020	2.790	2.700	100.0	0.000
1.000	5.400	3.000	2.700	150.0	2.000
2.488	5.900	3.300	2.700	200.0	3.000
10.976	6.100	3.400	2.700	600.0	5.488
5.488	6.308	3.541	2.702	525.9	16.464
5.488	6.597	3.703	2.807	500.0	21.952
5.488	6.736	3.781	2.858	450.0	27.440
5.564	6.782	3.807	2.875	400.0	32.928
6.504	6.795	3.814	2.879	350.0	38.492
8.006	8.147	4.573	3.372	179.5	44.996
9.359	8.138	4.568	3.369	167.5	53.002
10.940	8.106	4.550	3.358	159.4	62.361
12.780	8.065	4.527	3.343	153.8	73.301
14.950	8.047	4.517	3.336	150.3	86.081
17.470	8.070	4.530	3.345	148.7	101.031
20.420	8.117	4.556	3.361	148.1	118.501
23.880	8.154	4.577	3.375	147.9	138.921
27.910	8.161	4.581	3.378	147.4	162.801
32.630	8.145	4.572	3.372	146.8	190.711
38.140	8.120	4.558	3.363	146.2	223.341
∞	8.101	4.547	3.356	145.8	261.481

Figure 3 shows an enlargement of the Pg waveforms in Figure 2. A visual comparison shows that correct phasing occurs between the point force and the tension crack sources for low frequencies while differences are most pronounced at high frequencies and greater depths due to interference effects between pP and P components of the Pg wavetrain.

To illustrate this further, Figure 4 compares the point source and buried tension crack sources in the frequency domain for windows taken around the Pg, Lg, and Rg phases. We see that the shallowest tension crack (100 m) is well represented by a point force up to 5 Hz for the Pg, Lg, and Rg. Modulation of the 700 m tension crack source is clearly present in the Lg ratio due to sS+S interference. It appears that the vertical point force representation is a good approximation to the buried tension crack at least up to spall depths of 1/2 the wavelength. For spall depths of 500 meters this corresponds to about 5.0 Hz for P waves in this model and about 2.8 Hz for S waves. For this velocity structure the differences at several slownesses (Pg, Lg, and Rg) between the tension crack and vertical point force representation are probably not significant below 5 Hz for spall depths shallower than 300 m.

VERTICAL FORCE VERSUS TENSION CRACKS (0 TO 5 HZ)

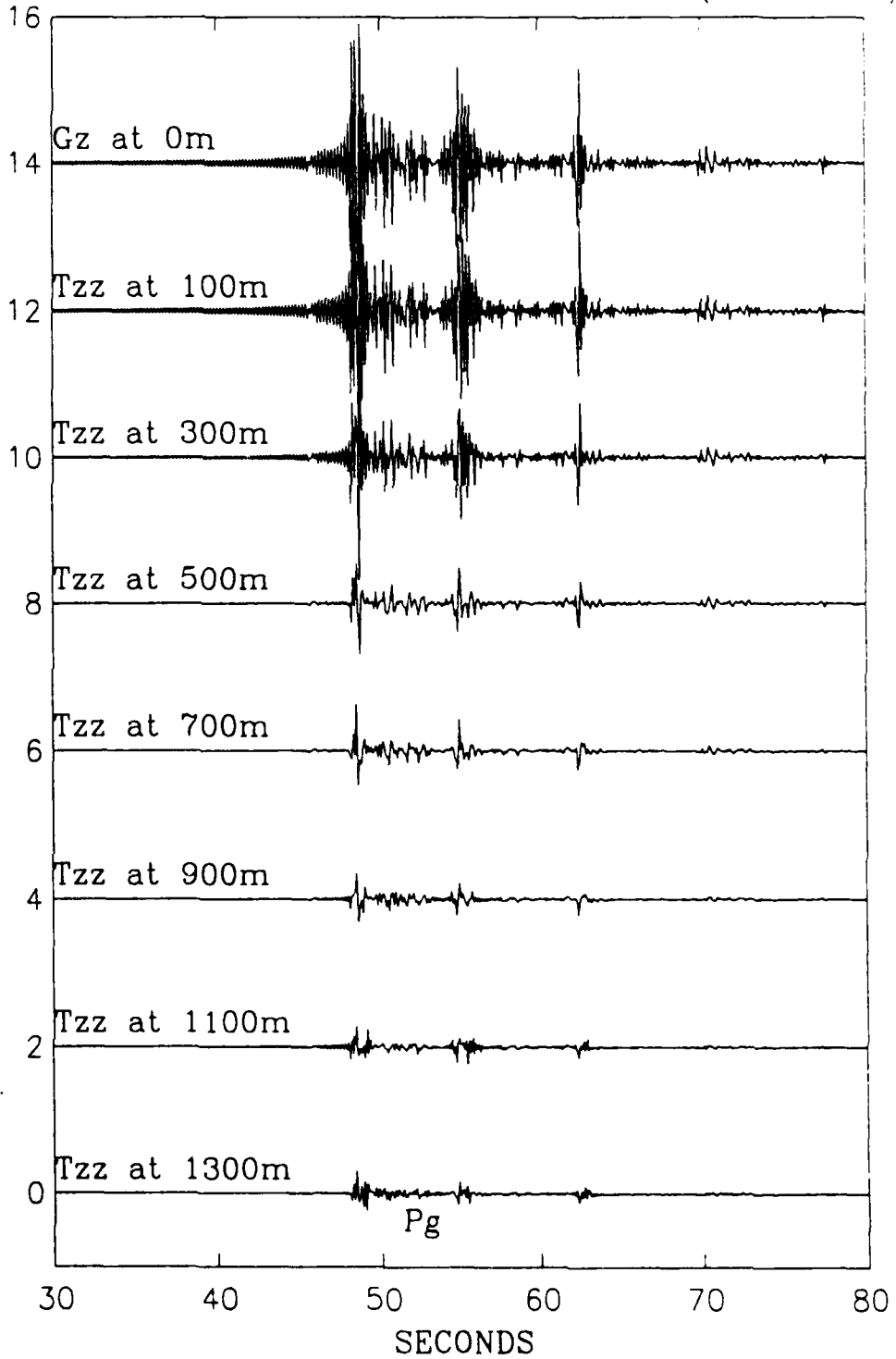


Figure 3. An enlargement of the Pg waveforms of Figure 2. Note that the similarity of the waveforms degrades for depth > 300 m.

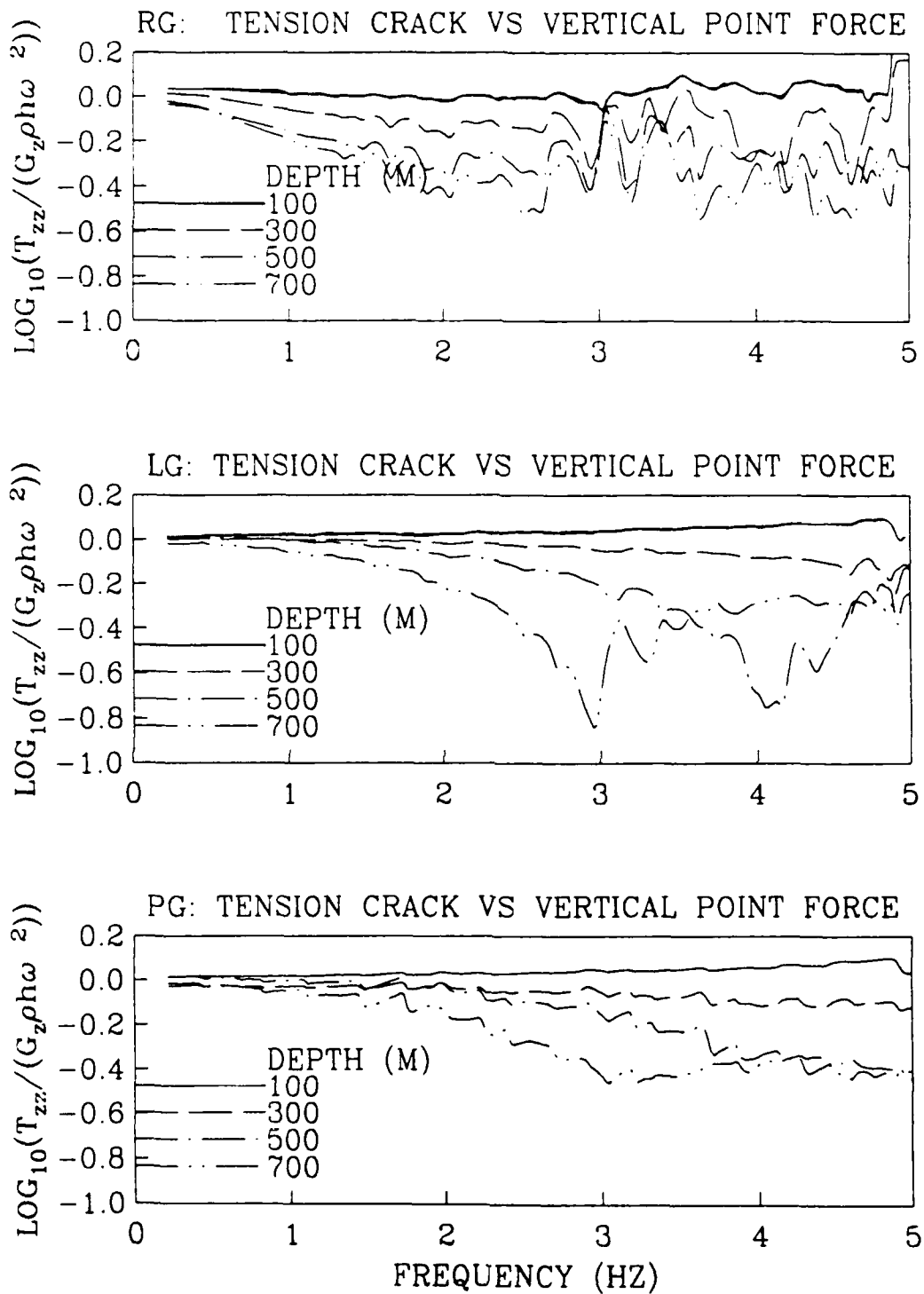


Figure 4. Spectral ratios of the tension crack seismograms over the vertical point force seismogram of Figure 2. Windows were taken around the Pg, Lg and Rg phases. Tension crack seismograms for source depths of 100, 300, 500 and 700 m are shown. In general, the approximation of the tension crack by the vertical point force degrades with depth of the tension crack.

IV. THE FINITE EXTENT OF SPALL

At high frequencies, the distributed nature of spall is not adequately represented by a single point force on the surface or even by the moment tensor representation of a tension crack. We wish to derive some simple expressions for the high frequency asymptotic behavior of the spall signal in the far field. Suppose that the spall displacement is specified over a disk of radius, a , then for a wavepacket with horizontal wavenumber, $k = \omega \frac{\sin(\phi)}{c}$, where ϕ is the incidence angle, the far field displacement at range, r , will be approximated by

$$\begin{aligned} u_i(\omega, r, k) &\approx U_i(\omega, r, k) \int_{\Sigma} S(\omega, x, y) e^{-ikx} dx dy & (10) \\ &= U_i(\omega, r, k) \int_0^{2\pi} \int_0^a S(\omega, s, \theta) e^{-ikscos(\theta)} s ds d\theta \end{aligned}$$

$U_i(\omega, r, k) S(\omega, s, \theta)$ describes the contribution to the seismogram with horizontal wavenumber k from a location on the spall disk. If we assume that $U_i(\omega, r, k) S(\omega, s, \theta)$ is independent of θ then we have a zero'th order Hankel transform of the form,

$$u_i(\omega, r, k) \approx U_i(\omega, r, k) 2\pi \int_0^a S(\omega, s) J_0(ks) s ds. \quad (12)$$

If we assume that $U_i(\omega, r, k) S(\omega, s, \theta)$ is uniform over the disk then we have

$$u_i(\omega, r, k) \approx U_i(\omega, r, k) \frac{2\pi a^2}{(ka)} J_1(ka) = U_i(\omega, r, k) E(k), \quad (13)$$

where $J_1(\cdot)$ is the 1'st order Bessel function. For large ka , $E(k)$ is approximated by $\sqrt{2/\pi} a^{3/2} (ka)^{-3/2} \cos(ka - 3\frac{\pi}{4})$. Therefore, this smoothing function imposes an

$\omega^{-3/2}$ asymptotic roll-off at high frequencies.

A convenient form for the spall distribution is $S(\omega, s) = (a^2 - s^2)/a^2$, since it has zero displacement at the crack tip and the spall separation is concave upward. Under this assumption the smoothing function has spectral form,

$$E(k) = \frac{4\pi a^2}{(ka)^2} J_2(ka), \quad (14)$$

which is proportional to the 2'nd order Bessel function and for large ka rolls-off like $\omega^{-5/2}$. This simple model is preferred because it has the physically reasonable property of zero displacement at the crack tip, and the spall surface is concave upward as suggested by Eisler and Chilton (1964). Because this continuous spall distribution function is zero at the crack tip the smoothing operator falls off faster than ω^{-2} at high frequencies. Given the sparsity of information regarding the radial dependence of spall, this simple model will suffice to compare the relative importance of the seismic spall source with that of the explosion source. It should be noted that any simple continuous distribution function with zero at the crack tip will fall-off faster than ω^{-2} at high frequencies and therefore the far-field signal at high frequencies should be dominated by the explosion source.

V. SPALL SIGNAL SYNTHETICS

Barker and Day (1990) have used teleseismic P waves predicted by 2-D axisymmetric nonlinear finite difference simulations of explosions to derive parametric models for the equivalent spall source. They found that the differences between the nonlinear simulations and linear point explosion sources could be modeled by a simple parametric spall model. Their model is a circular horizontal tension crack of radius, a , depth, h_s , and has a uniform initial velocity distribution between v_1 and v_2 . The reader is referred to Barker and Day for a detailed motivation of the model. The function $\delta U(t)$ appropriate for use in Equations (8) or (9) is given by

$$\delta U(t) = t(v_2 + v_1)/2 - gt^2/2, \quad 0 \leq t \leq \frac{2v_1}{g} = t_1 \quad (15)$$

$$\delta U(t) = \frac{t(v_2 - gt/2)^2}{2(v_2 - v_1)}, \quad \frac{2v_1}{g} = t_1 < t \leq \frac{2v_2}{g} = t_2$$

The 2-D nonlinear axisymmetric finite difference simulations are described in McLaughlin, *et al.* (1988) and are intended to simulate 125 Kt explosions at 200, 300, 680, and 980 meter depths in a Shagan River Test Site structure. We concentrate on the 680 and the 980 meter depth of burials which correspond to roughly normal scaled depth of burial ($122 \text{ m/Kt}^{1/3}$) and 60% overburied ($196 \text{ m/Kt}^{1/3}$) respectively. The spall parameters determined by Barker and Day are listed below in Table 2. Figure 5 shows the equivalent spall sources for the 680 m depth simulation as determined by Barker and Day (1990) for teleseismic P, and regional Pn, Pg, and Lg. The smoothing operator

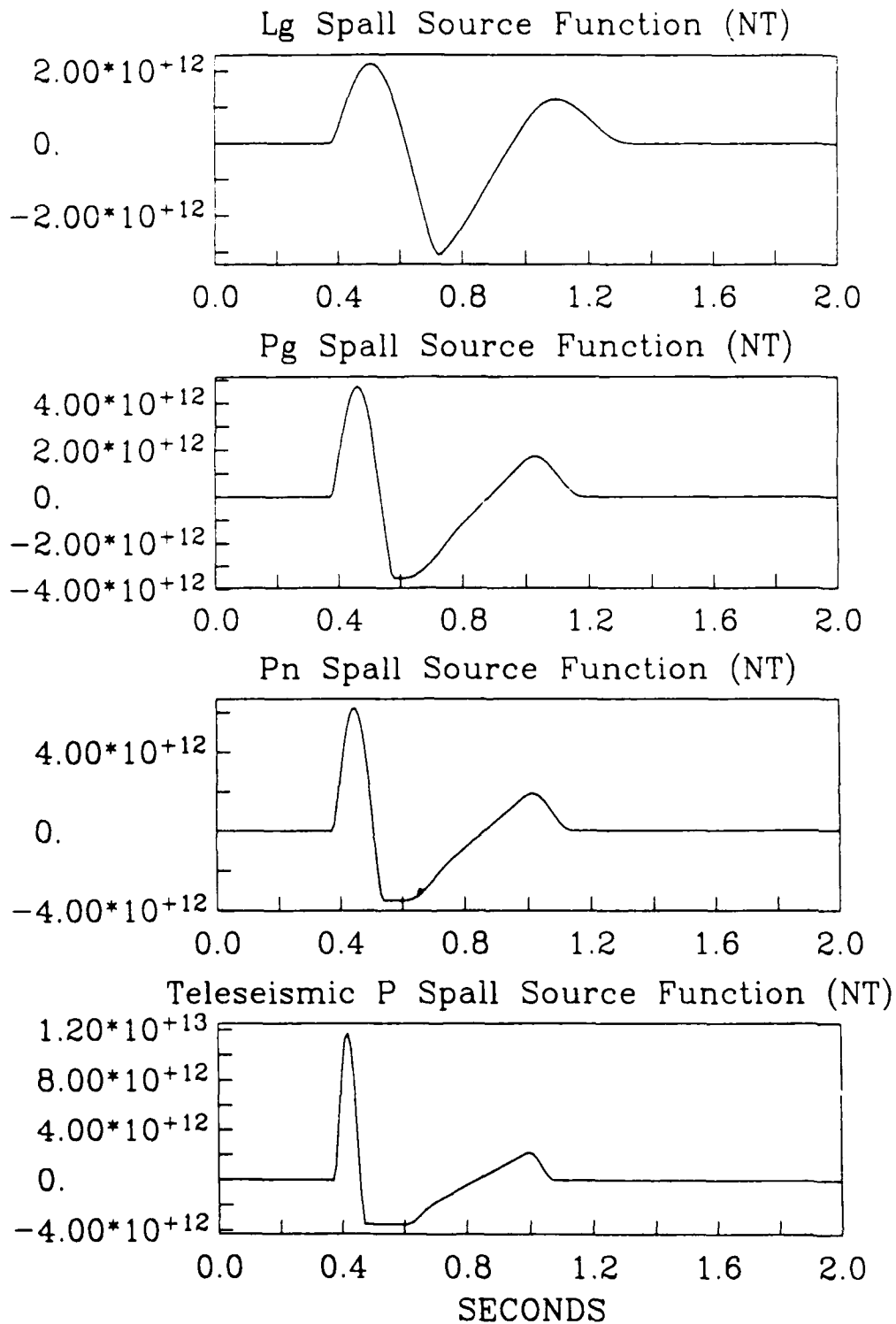


Figure 5. The equivalent spall source (for source depth of 680 m from Table 2) for four different apparent phase velocities corresponding to teleseismic P, Pn, Pg, and Lg. The smoothing operator $E(t)$ simulates the distributed nature of the source. Slower phases are more sensitive to the size of the spall disk.

of Equation (14) was used to model the finite extent of the spall surface while the spall source time function was specified by Equation (15). Apparent velocities of 14, 8.2, 6.5, and 3.7 km/s were chosen to represent the teleseismic P, Pn, Pg, and Lg respectively. Note that the spall is characterized by a high frequency opening pulse followed by a low frequency unloading and a small spall closure pulse. Because this spall model opens simultaneously over the entire spall disk but distributes the closure, the spall closure pulse is small compared to the opening pulse.

The Lg and Pg spall sources are smoother and lower frequency than the Pn and teleseismic P spall sources. The lower the apparent velocity of the seismic phase, the more important the extended size of the source. Spectra are shown in Figure 6. We see that the model predicts a sharply peaked source spectrum for the regional phases and in particular the Lg falls-off very rapidly for frequencies above 2 Hz.

	200	300	680	980
source depth (m)	200	300	680	980
v_1 (m/s)	1.1	1.1	1.1	1.1
v_2 (m/s)	14.	12.	3.	1.3
a (m)	600	625	650	650
h_s (m)	100	150	200	200
I_s (10^{12} Nt-s)	2.31	3.26	1.47	0.86

EFFECTIVE SPALL SOURCE FUNCTION SPECTRA

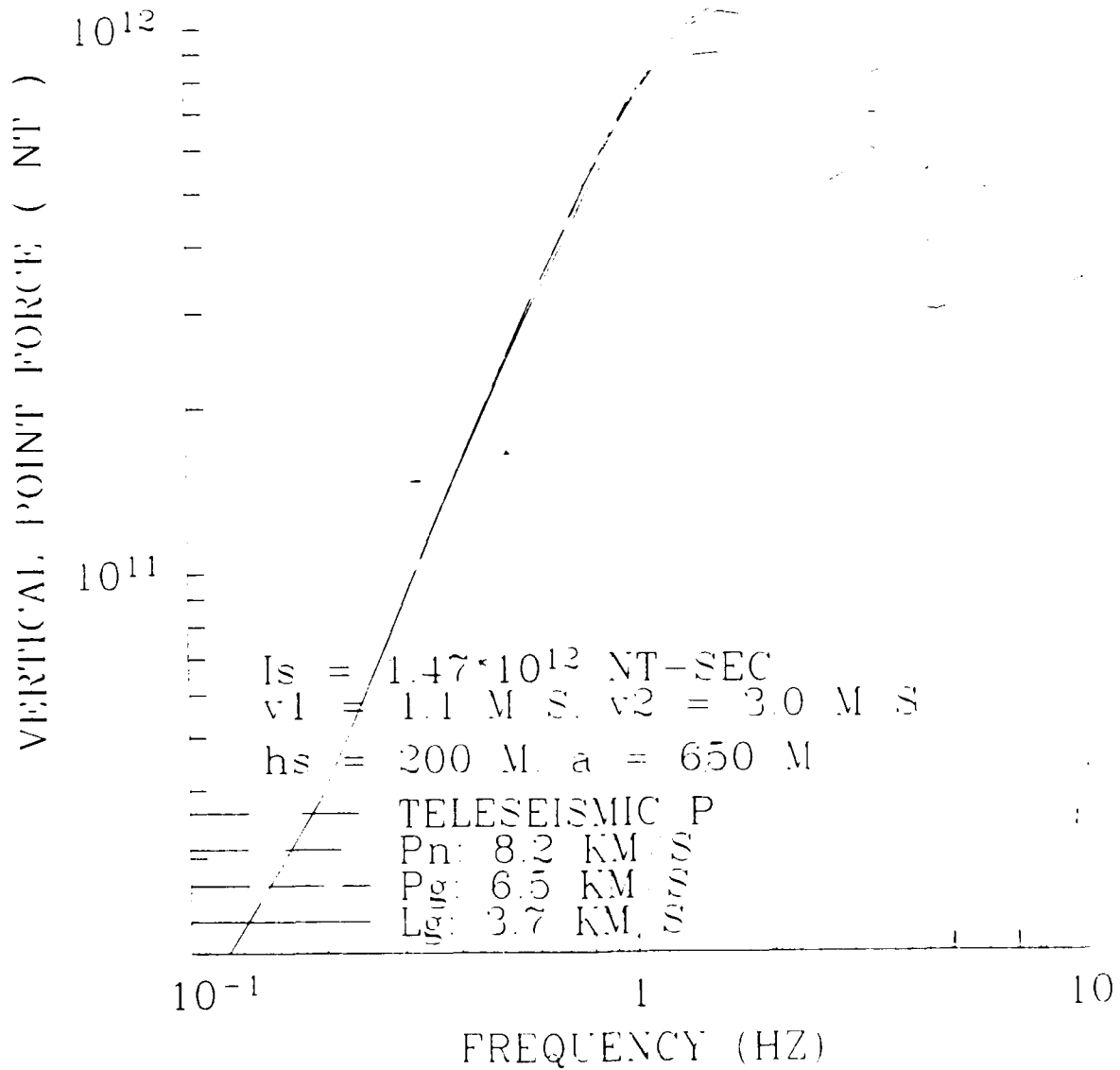


Figure 6. Spectra of the time series of Figure 5. Note that the Lg equivalent spall source falls-off more rapidly than the Pg or Pn spall source.

Figure 7 shows the tension crack Green's function for a distance of 300 km convolved with the appropriate Pg and Lg spall source functions compared with the explosion Green's function and the appropriate explosion RDP. Note that the Lg explosion signal is insignificant compared to the Lg spall signal. Based on Nuttli's (1986) formulas, $m_b(Lg) = 6.2$ for the synthetic spall+explosion Lg signal using $Q = 350$, and $f = 1$ Hz. In contrast, the explosion synthetic $m_b(Lg)$ is 4.9. Given Nuttli's NTS $m_b(Lg)$:yield formulas the total Lg excitation is about twice as large as would be predicted for a 125 Kt NTS explosion.

It should be emphasized that the explosion source is located in a high-velocity ($\alpha > 4500$ m/s) layer. The phase velocities of Lg are less than the P-wave velocity of the source medium and the explosion is an inefficient source for Lg in such a model. The explosion is a more efficient source of Lg for a low-velocity medium such as NTS (see Barker, *et al.* 1990).

In comparison to the Lg, the raw displacements of the Pg spall and explosion signals are of the same order of magnitude. Spectra of the Pg and Lg signal windows are compared in Figure 8. The spall contribution dominates the Lg signal up to 3 Hz. At 1 Hz the spall contribution to Lg is 20 times larger than the explosion contribution. At 1 Hz, the Pg spall contribution is about twice as strong as the explosion part. The explosion source dominates the Pg signal above 1.5 Hz.

If we compare the Barker and Day spall model with other published spall sources, we find that it is intermediate in strength. Viacelli (1973) found for

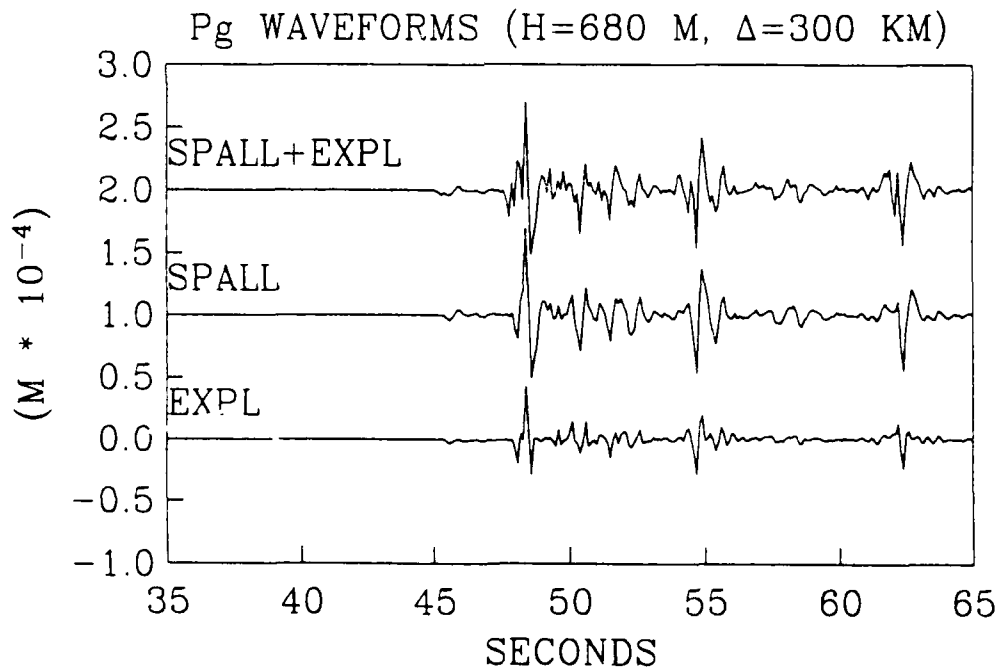
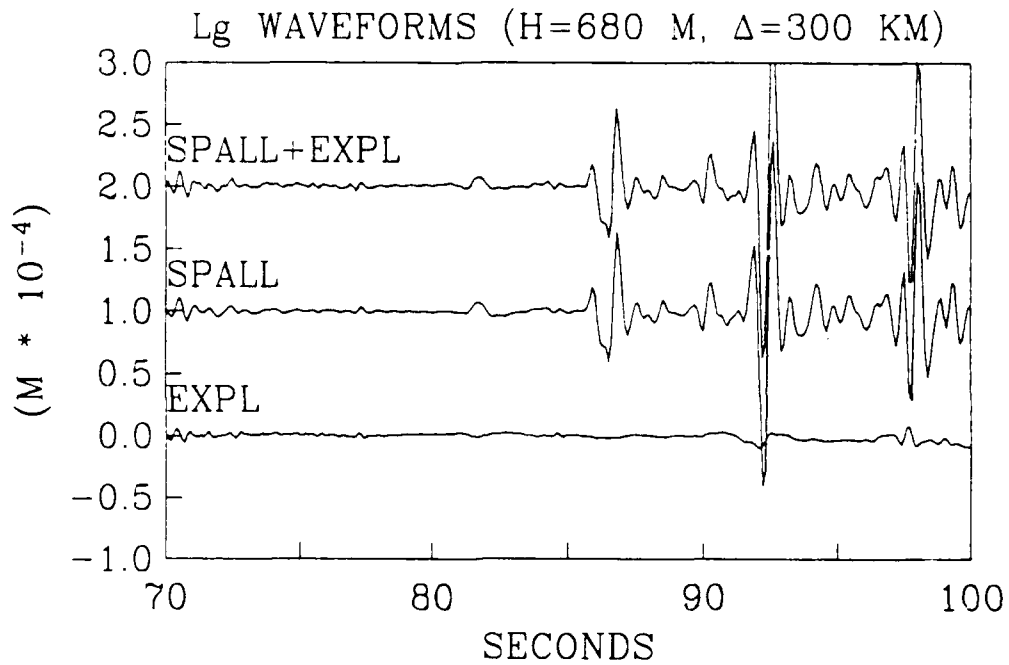


Figure 7. Synthetic Lg and Pg waveforms at a distance of 300 km for the 680 meter depth of burial 125 KT simulation. Note that the Lg spall signal dominates the Lg explosion signal while the Pg spall signal is slightly larger than the explosion Pg signal.

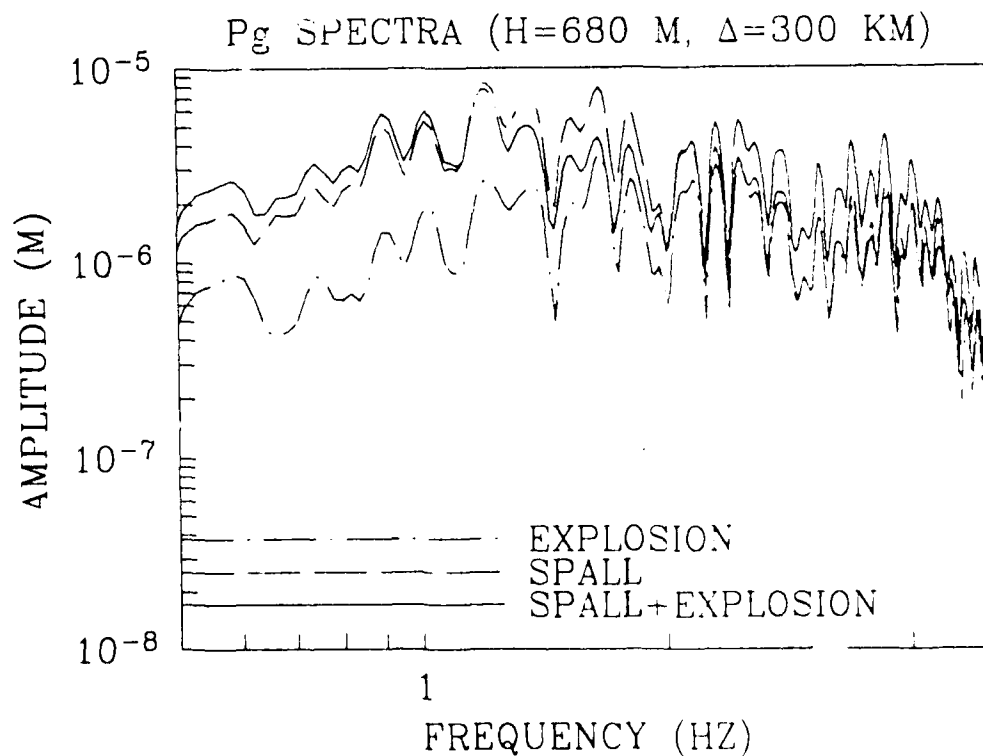
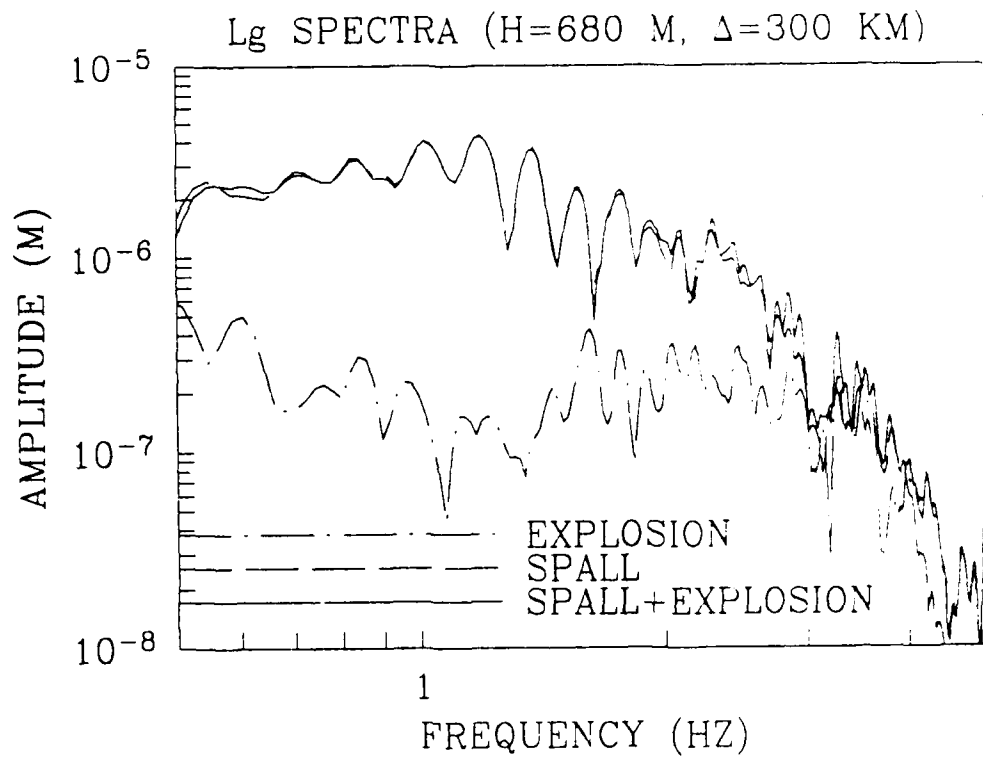


Figure 8. Spectra of the time series in Figure 7. Note that the Lg spall signal is 20 times larger than the Lg explosion signal at 1 Hz and the Pg spall signal is about two times larger than the explosion Pg signal at 1 Hz.

explosions at normal scaled depth of burial that spall momentum scaled linearly with yield as $4.6 \cdot 10^9$ Nt-s/Kt. The Barker and Day spall model for the 680 meter depth of burial corresponds to about 2.5 times the spall predicted by Viecelli's scaling relationship. This is about the same factor found between Viecelli's scaling relationship and the 2-D nonlinear finite difference PILED RIVER simulations described in Day, *et al.* (1983). Sobel's (1978) scaling relationships predict spall momenta several times larger than the Barker and Day model. It appears that the 2-D Shagan River nonlinear simulations predict spall momenta roughly intermediate between the Viecelli (1971) and Sobel (1978) scaling relationships.

Patton (1988) estimated spall momentum for the Pahute Mesa, NTS, explosion HARZER, to lie between 1 and $2 \cdot 10^{12}$ Nt-s with an explosion moment between 7 and $5.7 \cdot 10^{15}$ Nt-m. The simulation shown in Figures 7 and 8 had an explosion moment of about $1.4 \cdot 10^{16}$ Nt-m. The spall momentum for the simulation is therefore a factor of about two lower than Patton's estimate for HARZER based on simple linear moment scaling.

Figures 9 and 10 show the Lg and Pg waveforms and their spectra for the 980 meter depth of burial simulation using the spall parameters listed in Table 2. Note that in comparison to the 680 meter depth of burial calculation, the 980 meter deep explosion contribution to Pg is larger than the spall contribution. The spall produces only 5 to 7 times more Lg at 1 Hz than the explosion, and the bandwidth is narrower for which spall is a greater source of Lg than the explosion. The total Lg amplitude at 1 Hz for the 980 meter depth of burial is

one-fourth the Lg amplitude for the 680 meter simulation.

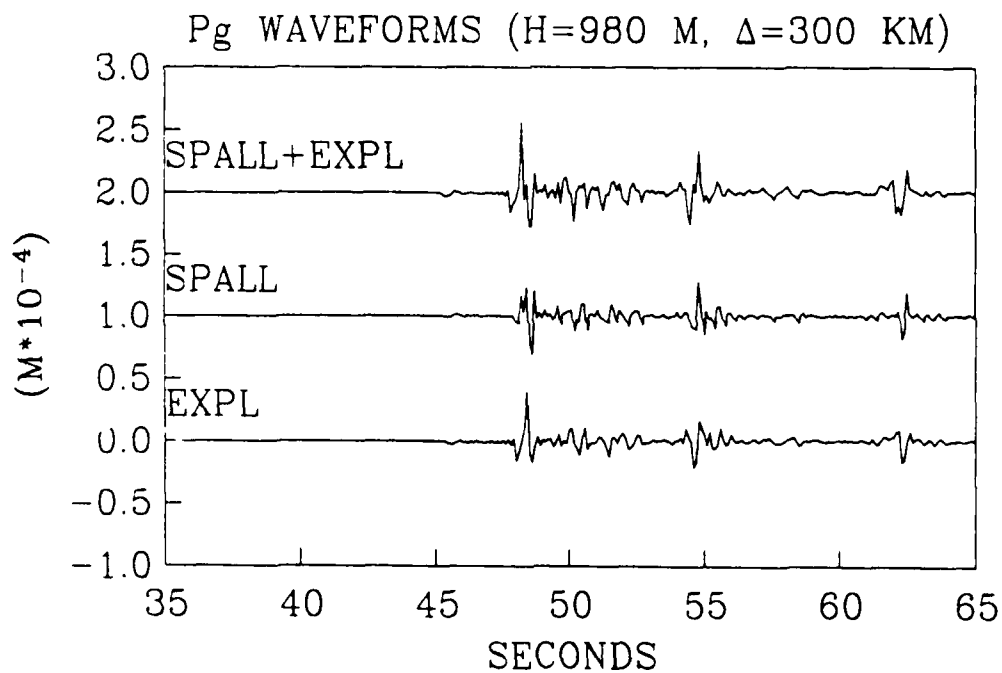
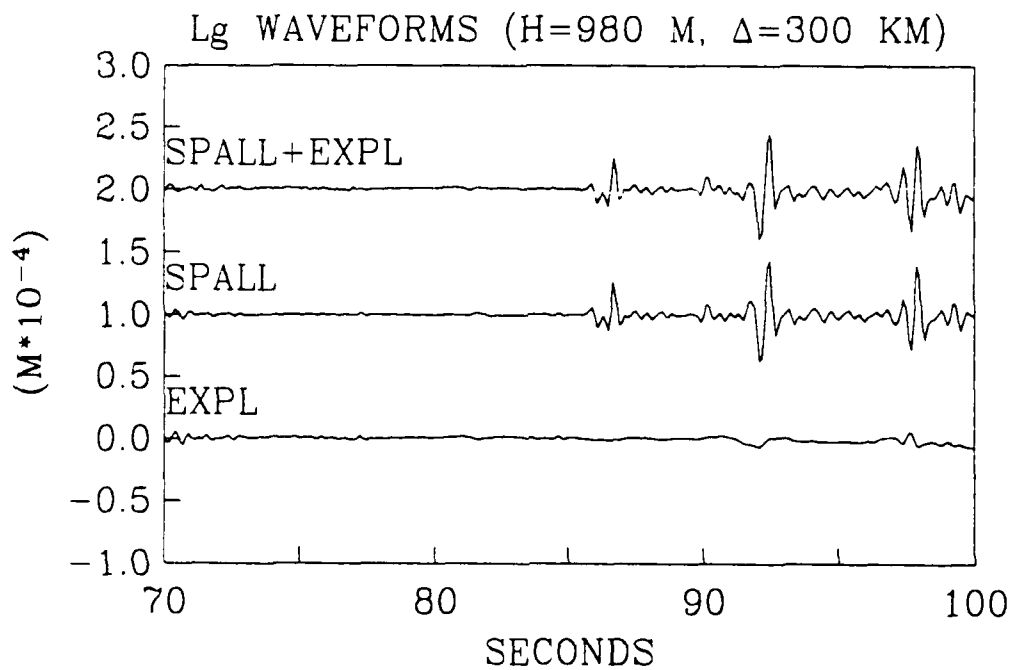


Figure 9. Synthetic Lg and Pg waveforms at a distance of 300 km for the 980 meter depth of burial 125 KT simulation. The Lg spall signal dominates the Lg explosion signal while explosion Pg signal is slightly larger than the spall Pg signal.

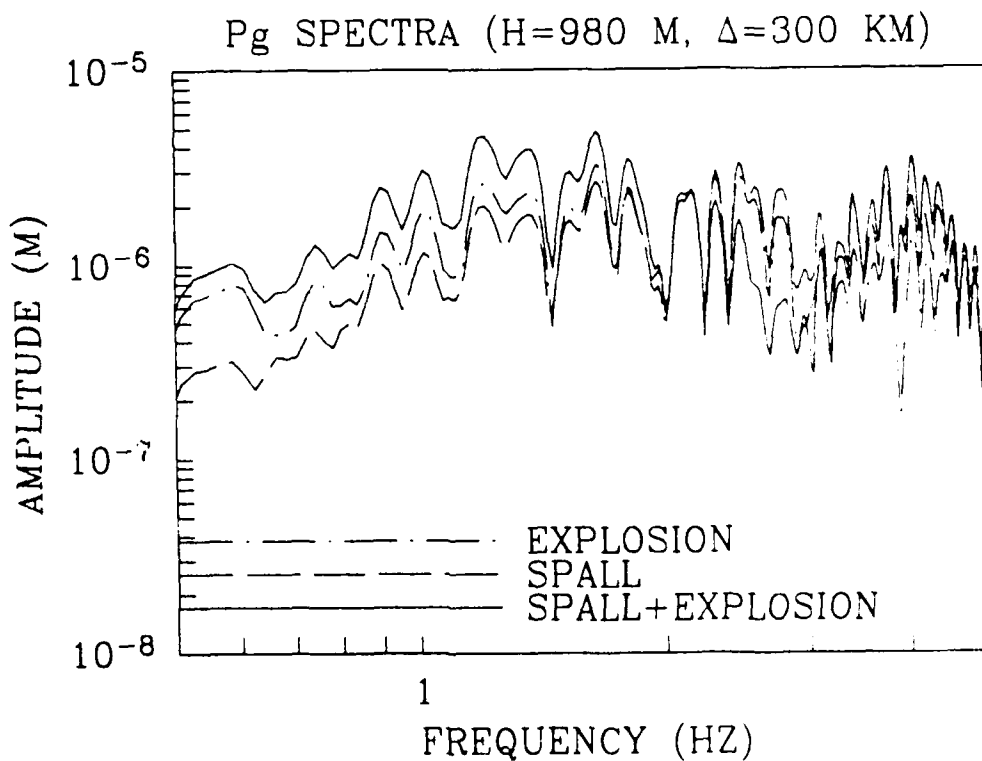
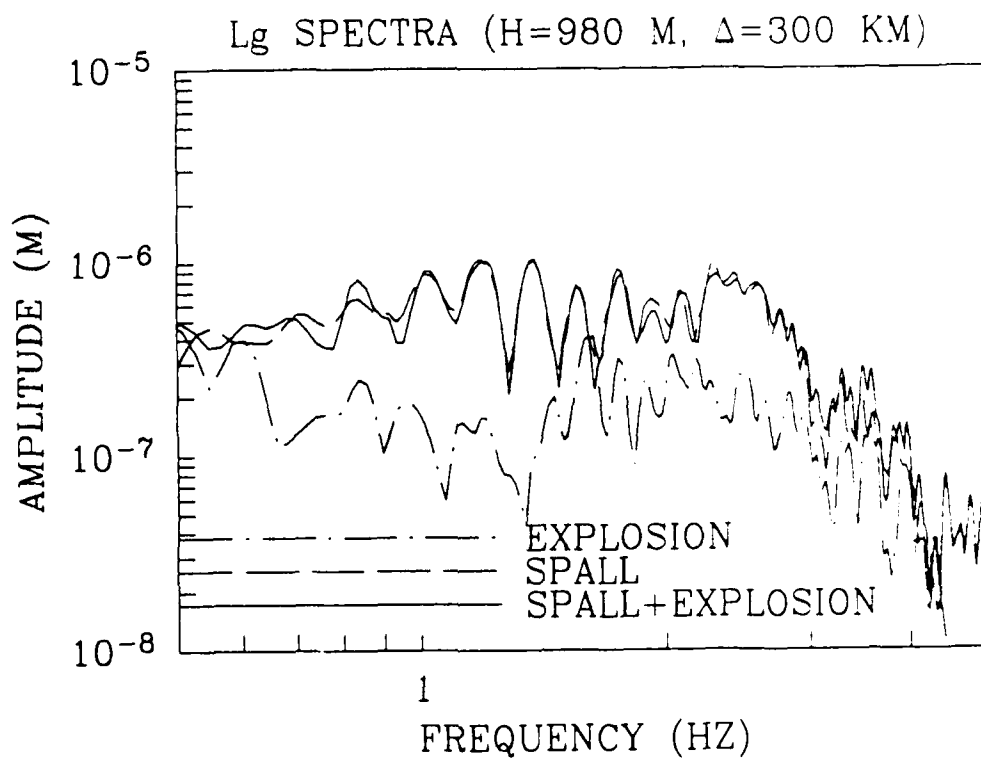


Figure 10. Spectra of the time series in Figure 9. Note that the Lg spall signal is about 5 to 7 times larger than the Lg explosion signal, while the explosion Pg signal is larger than the spall signal at nearly all frequencies.

DISCUSSION AND CONCLUSIONS

We have presented a more general derivation that a vertical point force at the surface may approximate the source of seismic radiation for a buried tension crack. The approximation was tested for a simple velocity structure, and it was found valid for frequencies up to 5 Hz, and spall depths shallower than 500 meters. One caveat to this conclusion is that the Green's functions were computed for a fairly high velocity structure with a thick surface layer. The frequencies for which the approximation is valid may be lower for lower velocity source structures or more complicated velocity structures.

A smoothing operator that simulates the distributed nature of the spall was presented. The smoothing operator (filter) has the desirable characteristics that it has zero motion at the crack tip, and the spallation surface is concave upward, therefore the spectrum falls-off at high frequencies faster than ω^{-2} . A specific model is presented that falls-off at high frequencies proportional to $\omega^{-5/2}$. Because the spall signal is proportional to ω^2 for low frequencies, the spall signal is expected to be a narrow band signal compared to the main explosion signal.

The spall model and parameters of Barker and Day (1990) were used to synthesize regional waveforms for Pg and Lg and the spall contribution to the seismogram was compared to the point explosion contribution. The Lg and Pg signals were found to be significantly affected by the spall source for the 2-D axisymmetric nonlinear finite difference simulations.

We reach a conclusion similar to Taylor (1989) that spall is probably a significant contributor to the regional Pg signal. This is not unexpected since spall partially cancels the pP and replaces it with a lower frequency and delayed spall signal. In addition we conclude that spall is almost certainly a significant contributor to the Lg signal for high-velocity crustal structures. It is important to note that for explosions in a low-velocity ($\alpha < 4500$ m/s) near-surface layer, the explosion excitation of Lg is more efficient. The relative excitation, explosion versus spall, of Lg is not as divergent in a low-velocity source structure as in a high-velocity source structure. These conclusions require adjustment for NTS structures (see Barker, *et al.* 1990).

It should be noted that the spall model used in this paper contains approximations and lacks characteristics that should become important at higher frequencies (>5 Hz) than were examined in this paper. First of all, the spallation does not occur across a simple surface. The spall is distributed over a volume and therefore the spall parameters (v_1, v_2, h_s, a) represent integrals over a non-linear volume. Caution should be used in making too detailed physical interpretations of these model parameters. Second, the entire spall surface does not open simultaneously. This will further smooth the initial spallation signal. Third, the spall is not axisymmetric and it may radiate SH waves as well as have non axisymmetric radiation patterns for P and SV waves.

It is clear from our simulations that the spall source will depend on scaled depth of burial. Overburied explosions will tend to spall less mass for a shorter time and hence have a smaller amplitude and higher frequency spall signature.

We should expect that spall scaling will also depend on material properties and structure above the emplacement as well as the properties of the rock near the working point. Since the effects of gravitational forces on containment do not scale linearly with yield, we also expect that spallation may be more important for smaller explosions. For example, Stump (1985) found for chemical explosions in alluvium, that the spall mass was 2 to 3 times larger than that predicted by Sobel's scaling relationship. This may have been due to either weaker material properties or lack of linear scaling of gravitational effects with yield.

The $m_b(Lg)$ predicted for the normal buried simulation (Figure 7) is roughly 0.6 to 0.7 magnitude units larger than the $m_b(Lg)$ predicted for the 60% over buried simulation (Figure 8). If spall is the dominant source for Lg excitation then we should expect $m_b(Lg)$ to depend upon scaled depth of burial. However, given the robust nature of $m_b(Lg):yield$, it is likely that other mechanisms are responsible for at least some of the Lg excitation.

The presence of transverse Lg from explosions implies that non axisymmetric nonlinear mechanisms or scattering are also responsible for Lg excitation. Although non axisymmetric spall may excite transverse Lg (Lg-SH), it has been argued by Gupta and Blandford (1983) that the Lg-SH signal grows relative to the vertical and radial components of Lg (Lg-SV) out to a couple of hundred km. This may imply that scattering is operating along the path but does not in itself explain the initial excitation of Lg-SV. Conversion of compressional energy may be converted at interfaces with significant velocity contrasts besides the free surface. Or, scattering by near source lateral heterogeneity may

contribute to the excitation of Lg and Lg-coda.

A number of overburied explosions have excited Lg as efficiently as normally buried explosions. These explosions have been located in diverse geologic environments at scaled depths of burial greater than normal containment depth ($\approx 120 \text{ m/Kt}^{1/3}$) and include SCOTCH ($180 \text{ m/Kt}^{1/3}$ in tuff), REX ($250 \text{ m/Kt}^{1/3}$ in tuff), SALMON ($475 \text{ m/Kt}^{1/3}$ in salt), GNOME ($250 \text{ m/Kt}^{1/3}$ in salt), RULISON ($750 \text{ m/Kt}^{1/3}$ in shale), GASBUGGY ($420 \text{ m/Kt}^{1/3}$ in shale), and RIO BLANCO ($>420 \text{ m/Kt}^{1/3}$ in sandstone) (yields and depths from Springer and Kinnaman, 1971 and 1975). Nuttli (1986) has estimated the yields of six of these events to within 50% based on $m_b(Lg)$, and Blandford, *et al.* (1981) have shown that the relative Lg excitation from GNOME and SALMON is consistent with their yield ratio. The Lg excitation by these seven events argues that there are other mechanisms that contribute to Lg since spall was reduced for these explosions. A number of these events were located in geologically complicated environments and scattering may have been important (SALMON, GNOME) for some of the events. Events at NTS (SCOTCH and REX) were detonated in low-velocity materials ($\alpha < 4500 \text{ m/s}$) and the relative Lg contribution of spall and explosion is more nearly equal in an NTS structure. RIO BLANCO consisted of three 30 Kt explosions separated by 120 m and therefore the nonlinear zone may have deviated from spherical symmetry which would have introduced a CLVD component to the source and excited Lg. Furthermore, moderate spall was documented for RIO BLANCO by Toman *et al.* (1973). Murphy and Archambeau (1986) argue that RULISON was contaminated by

tectonic release in the short-period frequency band and the Lg excitation may reflect this deviatoric source. Murphy and Archambeau also found it necessary to incorporate spall into the modeling of teleseismic P waves for GASBUGGY and RULISON even though these events were overburied. In addition, GASBUGGY and RULISON were detonated in layered material with P-wave velocities less than or equal to 4500 m/s so the explosion source could excite Lg directly. Consequently, there appear to be no clear cut cases where an overburied explosion, uncontaminated by non-spherical effects, was detonated in high-velocity layered rock for which we have $m_b(Lg)$ measurements.

Based on nonlinear finite difference simulations for explosions in brittle high-velocity rock we conclude that spall should be a significant source of Lg. Other mechanisms such as near-source scattering may also be viable mechanisms for Lg excitation. A theoretical basis for yield estimation or discrimination based on Lg will require a better understanding of these mechanisms.

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