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Problems Associated with Pg/LG Ratios from NTS Explosions Affecting Seismic Discrimination

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ABSTRACT

In this report, a number of problems regarding the performance of the P_g/L_g discriminant for NTS explosions are addressed. Although many of these problems are reasonably well understood on a conceptual level through the use of simple equivalent elastic-source modeling, details concerning the physical cause for the observed variations are poorly known. The high-frequency P_g/L_g discriminant has been studied between frequencies of 0.5 and 10 Hz using 294 NTS explosions and 114 western U.S. earthquakes recorded at four broad band seismic stations operated by Lawrence Livermore National Laboratory (Taylor, 1995). The discriminant is shown to be very effective and multivariate discrimination analysis using both maximum-likelihood Gaussian classifiers and a backpropagation neural network show that approximately 95% of the events can be correctly identified. Despite the effectiveness of the P_g/L_g discriminant, however, a number of questions remain regarding its physical basis and transportability to other geophysical regions. Problems that remain to be resolved regarding explosion ratios include: 1) the improved separation between earthquakes and explosions as frequency is increased; 2) complications in the ratio as a function of frequency; 3) the apparent material/depth dependence of the explosion ratio; and 4) outliers. Outliers of concern are explosions having a low P_g/L_g ratio and appearing similar to many earthquakes. It is also noted that large magnitude NTS explosions ($m_b > 6$) are characterized by the largest P_g/L_g ratios and are similar to signals expected for pure explosions. This observation has implications for the remarkable performance of the high-frequency P_g/L_g ratio from the East Kazakh Test Site of the Former Soviet Union and the Lop Nor Test Site in China, where the preponderance of data analyzed to date is from large explosions.

INTRODUCTION

Recent renewed interest in monitoring a Comprehensive Test Ban Treaty (CTBT) has brought about a resurgence in the study of regional discriminants. The physical basis of many of the discriminants is known reasonably well, but as evidenced by studies in different geophysical regions, we still do not understand enough to predict discrimination performance in regions having no seismic data. We have recently completed a study of the high-frequency P_g/L_g discriminant applied to NTS explosions and western U.S. earthquakes (Taylor, 1995). The paper of Taylor (1995) mainly addressed the discrimination performance of the high-frequency P_g/L_g discriminant using multivariate discrimination techniques. In this paper, we conduct a follow-on study where we discuss outstanding problems observed in the high-frequency P_g/L_g discriminant at NTS that need to be resolved if we are to obtain a physical basis of the discriminant and its transportability to other geophysical regions. NTS is an ideal location for attempting to understand the physical basis of discriminants because we have so much experience and knowledge about its geologic and geophysical properties. Presumably, it will be necessary to study the discriminants using complex modeling techniques constrained by the geologic information and close-in ground motion data. Recent work by Walter *et al.*, (1995) using Nevada Test Site (NTS) explosions and earthquakes located on the NTS has shed much light on the physical basis of the P_g/L_g discriminant, but as outlined below, questions still remain.

In this report, we will first briefly review the discrimination study of Taylor (1995), and then discuss interesting trends in the data and outliers that are not completely understood. Although many of these problems are reasonably well understood on a conceptual level through the use of simple equivalent elastic-source modeling, details concerning the physical cause for the observed variations are poorly known. It is hoped that this paper will serve as a guide for future modeling efforts to improve our physical understanding of seismic discriminants.

P_g/L_g RATIO OBSERVATIONS FROM NTS

Figure 1 shows the distance-corrected P_g/L_g discriminant for NTS explosions and western U.S. earthquakes in the 1-2 and 6-8 Hz frequency bands plotted as a function of magnitude. The separation between earthquakes and explosions is seen to improve at higher frequencies, although there are fewer measurements at 6-8 Hz because of poor signal-to-noise ratios caused by propagation effects. The improved separation of earthquakes and explosions is further illustrated in Figure 2, showing the amplitude ratio for the six different frequency bands and one standard deviation error bars. The important element in Figure 2 is the rapid increase in the P_g/L_g ratio with frequency for the explosions. This suggests that either the P_g amplitude is increasing with frequency and/or the L_g amplitude is decreasing with frequency. Spectral observations indicate that the rapid decrease in L_g amplitude with frequency is mainly responsible for the increase in the ratio with frequency (Gupta *et al.*, 1992; Jones and Taylor, 1995). Details of the increase of the explosion P_g/L_g ratio with frequency are further illustrated in Figure 3 where significant peaks and troughs are observed. From analysis of L_g spectral ratios between normal-depth and nearby overburied NTS explosions, Patton and Taylor (1995) suggested that the spectral nulls are caused by the depth signature of a secondary source (compensated linear vector dipole, CLVD) on R_g that scatters into L_g. This scattering of R_g into L_g also boosts the low-frequency L_g and explains the increase in the P_g/L_g ratio with frequency observed in Figures 2 and 3. The actual physical cause of this CLVD is unknown. Possible candidates for secondary sources having a CLVD mechanism are some type of shear source such as passive block motion (Patton, 1991) or cavity rebound (Jones *et al.*, 1993).

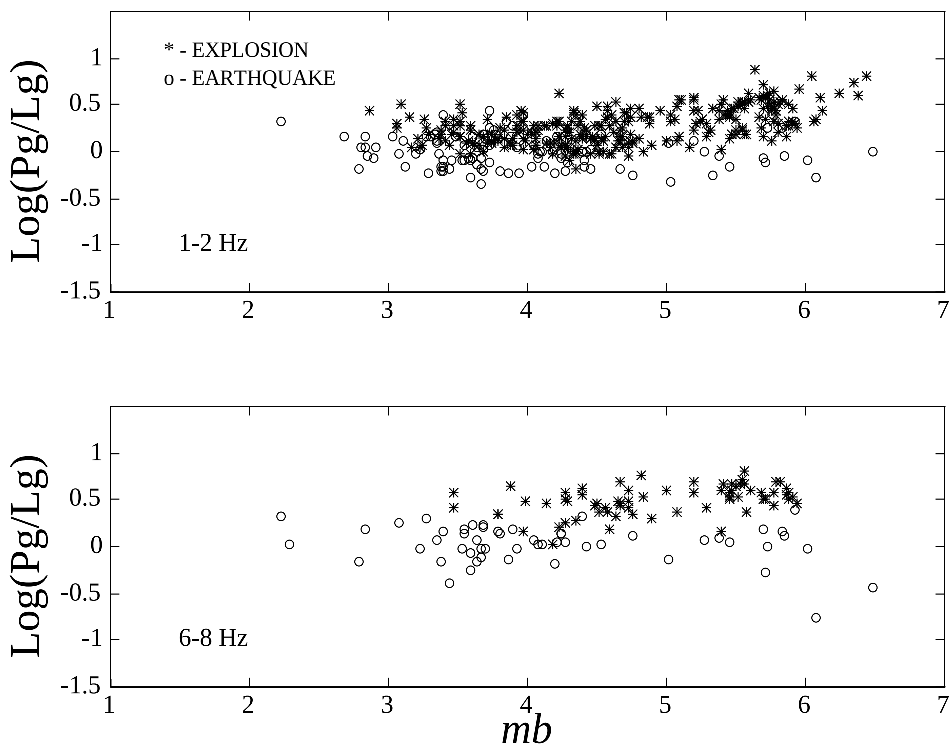

Figure 1. Logarithm of P_g /L_g ratios for 1-2 and 6-8 Hz frequency bands plotted as a function of magnitude.

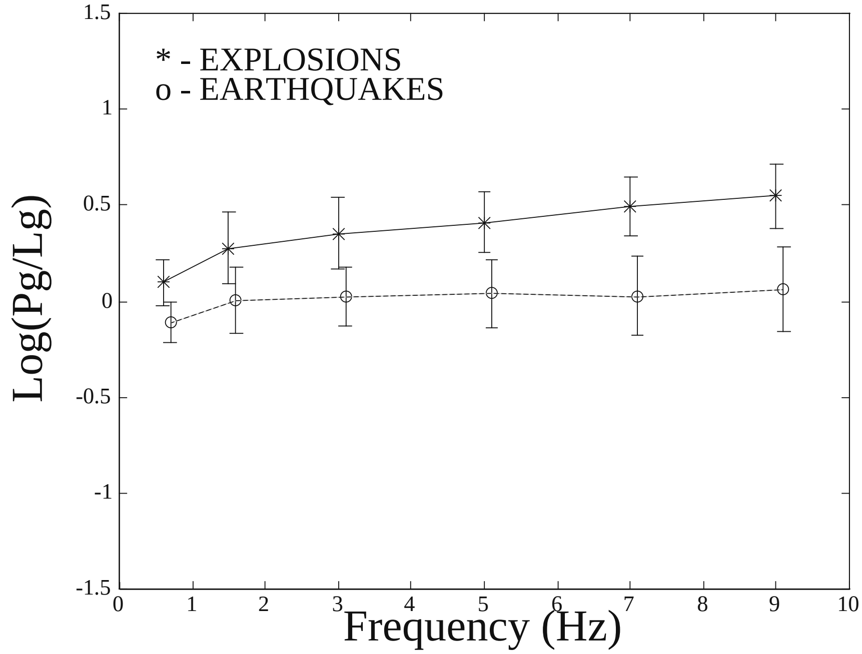

Figure 2. Mean of the logarithm of P_g/L_g ratios (distance corrected) and 1 standard deviation for six different frequency bands for earthquakes and explosions.

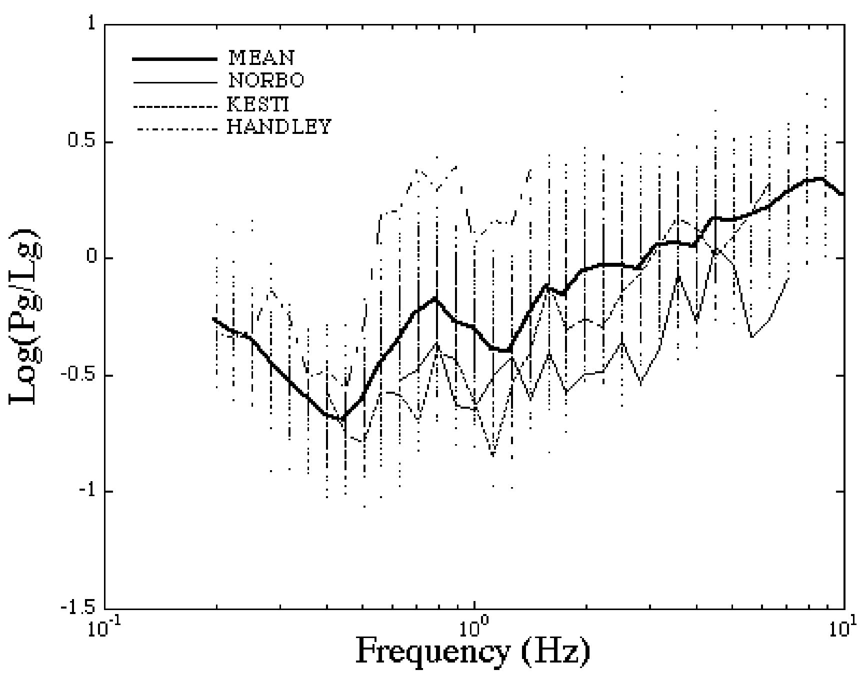

Figure 3. Logarithm of P_g/L_g ratio as a function of frequency for NTS explosions having spectral measurements at all four LLNL stations (no distance correction). Also shown is the mean ratio and ratios for three selected explosions.

In order to flag outliers for special event studies, we computed the residual from the mean ratio for each of the explosions included in Figure 3 having measurements for at least 17 different frequencies (out of a possible 41 between 0.1 and 10 Hz) at all four stations. The logarithm of the P_g/L_g residual is shown versus the logarithm of the P_g/L_g amplitude ratio in the 1-2 and 6-8 Hz bands in Figure 4. A good correlation is observed between the residual and the amplitude ratio in both bands and in the subsequent discussion, we will discuss the residual. We flagged four explosions having the most negative residual and these are listed as the first four entries in Table 1. The explosion that was characterized by the lowest P_g/L_g amplitude ratio was NORBO and was consistently misclassified as an earthquake in the multivariate study of Taylor (1995). In this sense, NORBO and possibly other explosions are outliers. However, examination of Figure 3 suggests that NORBO is really at the margin of a distribution, and not necessarily an outlier in a statistical sense. Additional explosions were also flagged when those with fewer station measurements were included.

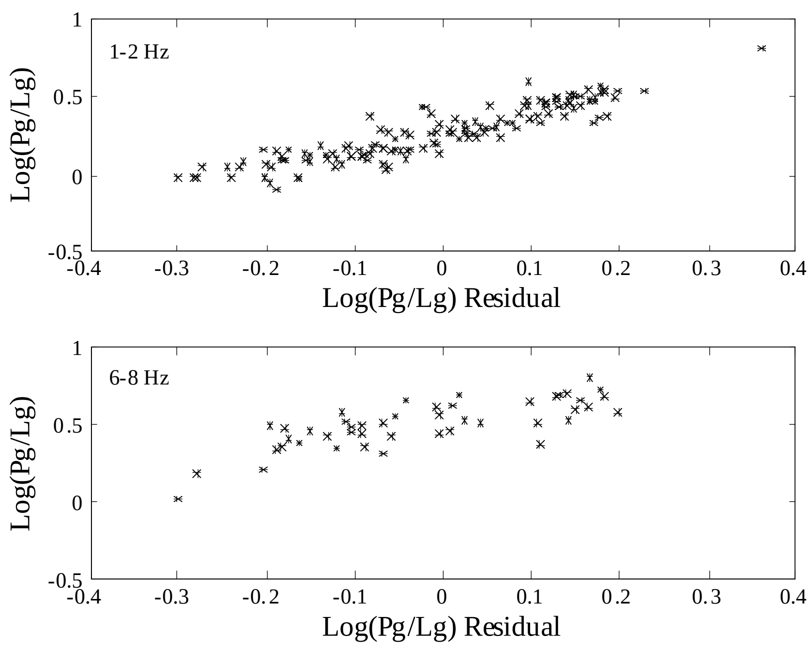

Figure 4. Logarithm of P_g /L_g residual versus the logarithm of P_g /L_g amplitude ratio in the 1-2 (top) and 6-8 Hz (bottom) bands.

Interestingly, one of the explosions listed in Table 1 is PERA as having a low P_g/L_g ratio. PERA was used as a "normal" explosion in a comparative study of QUESO that had an abnormally low L_g spectral ratio (Taylor *et al.,* 1991). In this study, the roles of the two explosions appear to be reversed. PERA has a low P_g/L_g ratio whereas that of QUESO is almost 0.2 magnitude units higher and more typical of other NTS explosions.

Also listed in Table 1 and shown in Figure 3 is an explosion with a very high P_g/L_g ratio (HANDLEY). In general, the largest NTS explosions are the most explosion like (i.e. have the largest P_g/L_g amplitude ratios). Because the very large NTS explosions were recorded on an earlier analog electronic system, the system noise was very large at high frequencies (above about 3 Hz) so high-frequency measurements are unavailable. This tendency for the largest NTS explosions to look the most explosion like has implications for discrimination studies in more remote regions, where regional data are only available for large explosions. For example, preliminary analysis of the high-frequency P_g/L_g discriminant from the Lop Nor Test Site in China and from the East Kazakh Test Site of the Former Soviet Union show remarkable discrimination performance (e.g. Hartse *et al.,* 1995). Most of the events analyzed are of large magnitude and it might be expected that discrimination performance will degrade at lower magnitudes (assuming it is possible to extrapolate from NTS to other test sites). As will be further discussed below, however, it appears that near-source material effects can affect the P_g/L_g discriminant and it may not be possible to extrapolate NTS experience to other test sites, particularly for the small explosions detonated in weak rocks with high gas-filled porosity.

It is not clear why the larger NTS explosions are more explosion like. The observation could be related to near-source material effects or, as discussed by Barker *et al.,* (1990) and Patton and Taylor (1995), finiteness effects of secondary sources from large explosions may cause a more rapid decay of the high-frequency L_g spectrum relative to a point-source explosion.

Seismograms for NORBO (large negative P_g/L_g residual - earthquake like), KESTI (near-zero residual - "normal"), and HANDLEY (large positive residual - explosion like) at ELK (Δ ~ 400 km) are shown in Figure 5. The seismograms have all been high pass filtered at 1 Hz and the relatively small P_g/L_g amplitude ratio for NORBO is evident as well at the large ratio for HANDLEY.

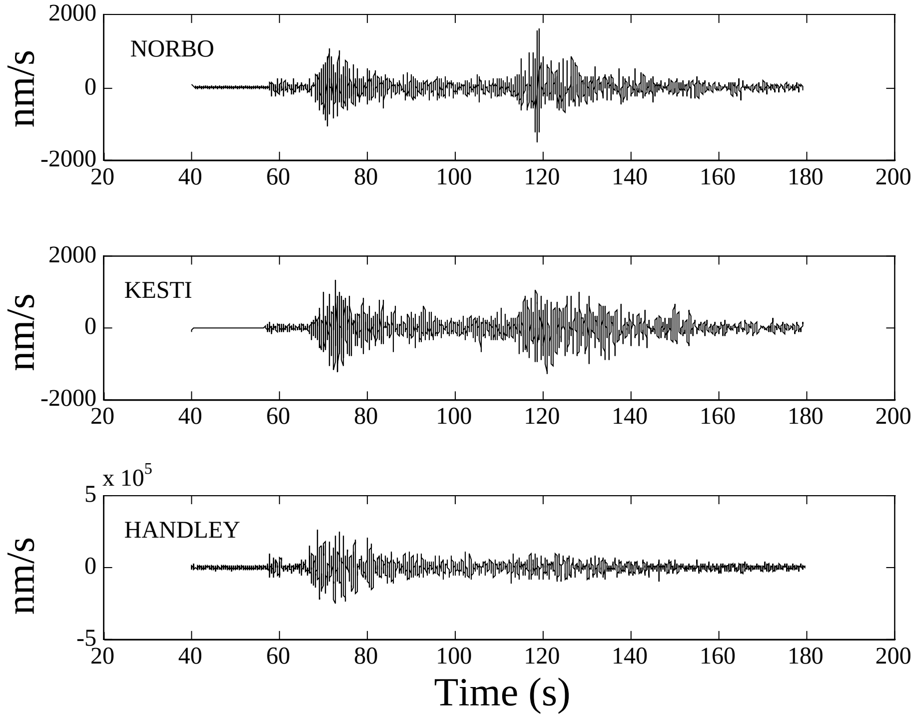

Figure 5. Seismograms at LLNL station ELK (Δ ~ 400 km) for NORBO (large negative P_g / L_g residual - earthquake like), KESTI (near-zero residual - "normal"), and HANDLEY (large positive residual - explosion like).

The relationship of the P_g/L_g residual relative to various working-point parameters is shown in Figure 6. It should be noted that Figure 6 does not change significantly if the P_g/L_g ratio at either 1-2 Hz or 6-8 Hz are substituted for the residual. In each figure, the explosions are separated on the basis of being detonated in high-strength, low gas-filled porosity (GFP) media (circles), or low-strength, high GFP media (asterisks) using the criteria of Walter *et al.*, (1995). Using a plot similar to that in the lower right portion of Figure 6, it was found by Walter *et al.*, (1995) that the equation $\log(\rho\alpha^2) = 0.093\text{GFP} + 9.4$ could be used to separate explosions into one of two populations for plotting purposes.

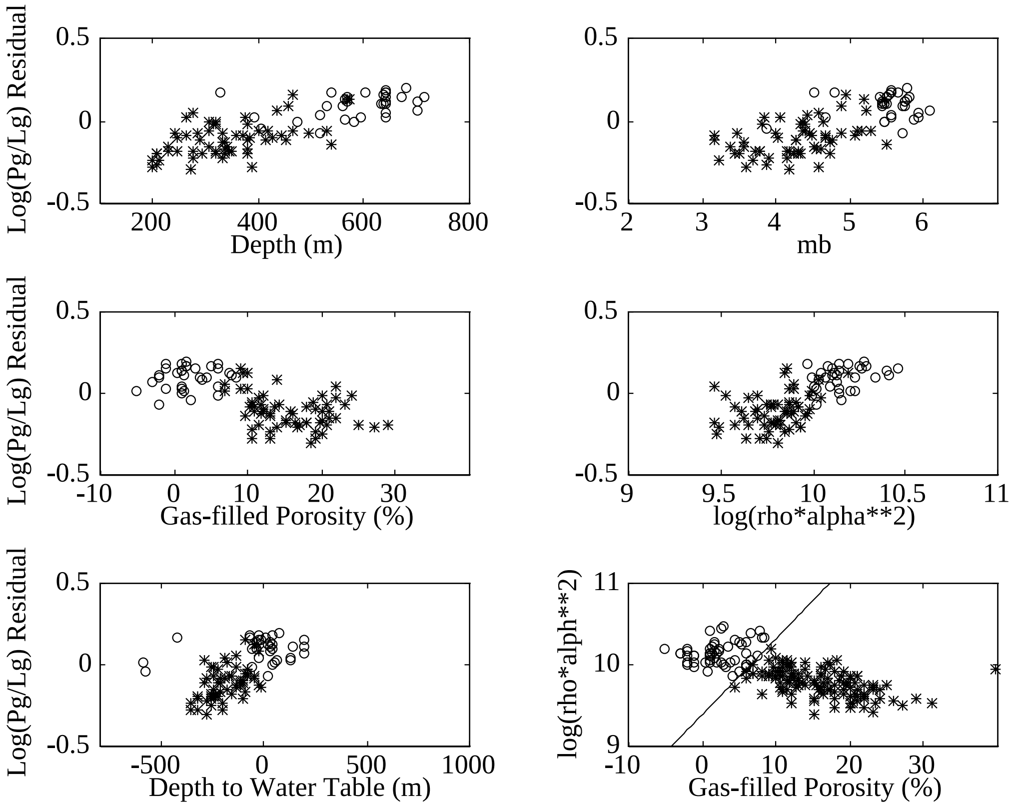

Figure 6. Relationship of the P_g/L_g residual relative to working point depth (m; upper left), magnitude (upper right), gas-filled porosity (%; middle left), $\log(\rho\alpha^2)$ (Kg/(ms^2; middle right), depth to water table (m; where negative is above the water table, lower left), and $\log(\rho\alpha^2)$ versus gas-filled porosity (lower right). Asterisks indicate low strength, high GFP emplacement conditions and circles high strength, low GFP (see text for details). Line in lower right is used to separate high strength, low GFP emplacement from low strength, high GFP and is given by $\log(\rho\alpha^2) = 0.093\text{GFP} + 9.4$ (Walter *et al.*, 1995).

The P_g/L_g residual appears to be highly correlated with a number of parameters such as depth, magnitude (yield), gas-filled porosity, and $\rho\alpha^2$. It should be noted that no significant difference is observed in Figure 6 if the working-point compressional velocity, α, is substituted for $\rho\alpha^2$. Unfortunately, because of containment practices at NTS, all of these parameters are highly correlated and it is difficult to uniquely identify the dominant causative effect. However, arguments have been made that material properties (e.g. working point velocity, GFP, or material strength (as indicated by $\rho\alpha^2$)) are the controlling factors rather than depth or magnitude (Gupta *et al.*, 1992; Walter *et al.*, 1995).

For example, in the upper left portion of Figure 6, an F test was used to test whether the slope of a regression of the residual on depth was zero. The regression of the residual on depth for all data showed a significant dependence on depth at the 95% confidence level. However, regressing the residual versus either of the two sub populations in Figure 6 indicated either no dependence on depth (for the high strength, low GFP media) or a very weak dependence (for the low strength, high GFP) at the 95% level of confidence. This corroborates earlier work of Gupta *et al.*, (1992) and Walter *et al.*, (1995) that near-source material properties are affecting the P_g/L_g amplitude ratio.

Additionally, the P_g/L_g ratio for the normal depth explosion BASEBALL (m_b = 5.9, depth = 564 m) and overburied explosion BORREGO (m_b = 4.0, depth = 563 m) versus frequency are very similar suggesting that explosion size is not a factor. Gupta *et al.*, (1992) argue against a GFP effect of coupling on the P_g/L_g ratio by citing earlier yield estimation studies (e.g. Patton, 1988) suggesting a similar dependence of P and L_g amplitudes on GFP. As mentioned above, however, because of the strong correlation of various working point parameters at NTS with depth and magnitude, it is very difficult to isolate the dominant effect on the P_g/L_g ratio.

Much of the discussion of factors affecting the P_g/L_g ratio have focused on L_g since effects on L_g appear to be controlling the discriminant. However, differences are observed between the performance and character of the P_n/L_g discriminant relative to the P_g/L_g discriminant. For example, the material dependence observed on the P_g/L_g discriminant in Figure 6, does not appear to be evident on the P_n/L_g discriminant (Walter *et al.*, 1995). This implies that the excitation of P_g is also an important consideration in understanding the discriminant. As discussed by Walter *et al.*, (1995), the attenuation-corrected P_n spectrum appears to reflect the actual source spectrum and that additional source, or near-source effects complicate the P_g and L_g signals.

Possibly the simplest explanation for the material effect on the P_g/L_g ratio is to attribute it to source region elastic properties on P_g excitation. The P-wave displacement spectrum from a point-source explosion (using ray theory) is given by (Aki and Richards, 1980)

$$u(\omega) = \frac{\dot{M}_0(\omega)}{4\pi\rho_s^{1/2}\rho_r^{1/2}\alpha_s^{5/2}\alpha_r^{1/2}R} \tag{1}$$

where R is the geometric spreading factor, $\dot{M}_0(\omega)$ is the moment-rate spectrum (proportional to the reduced velocity potential), ρ is the density, α is the compressional wave velocity, and subscripts s and r denote source and receiver locations, respectively. If we assume that two explosions are detonated in close proximity to one another and are of similar size (so that common distance and source terms in equation 1 cancel) in different media (denoted by subscripts l and h), an approximation for the ratio of the P-wave excitation from (1) is given by (e.g. Stevens and Day, 1985)

$$\log\frac{u_l(\omega)}{u_h(\omega)} = \frac{1}{2}\log\frac{\rho_h\alpha_h^3}{\rho_l\alpha_l^3} \qquad (2)$$

Using the criteria of Walter *et al.*, (1995) to separate explosions into high-strength, low GFP media (h) and low-strength, high GFP media (l), we obtain for the P_g/L_g residual in Figure 6 the mean values of $\overline{\rho}_l = 1767 \pm 146$, $\overline{\rho}_h = 1989 \pm 160$ kg/m^3 and $\overline{\alpha}_l = 1879 \pm 304$, $\overline{\alpha}_h = 2627 \pm 496$ km/s from the containment database (e.g. Howard, 1979). Inserting these values into equation (2) gives a predicted ratio of 0.24 (factor of 1.74) which is very similar to the observed value of 0.20 (factor of 1.60; Figure 6 upper left). Thus, the improved separation of earthquakes and explosions at large magnitudes observed in Figure 1, may simply be caused by differences in P_g excitation with elastic parameters (which typically correlate with depth and yield) for the explosions at NTS. One argument against this hypothesis, however, is the fact that the P_n/L_g ratio does not show as strong of a material dependence as observed for the P_g/L_g ratio (Walter *et al.*, 1995).

DISCUSSION AND CONCLUSIONS

Based on discrimination studies from NTS, a number of problems regarding the physical basis of the P_g/L_g discriminant remain. Focusing on the NTS explosions, these include;

1) The increase of the P_g/L_g ratio with frequency (leading to improved separation of earthquakes and explosions at high frequencies; Figure 2);
2) The complicated nature of the P_g/L_g ratio with frequency (Figure 3);
3) Near-source material effects on the P_g/L_g ratio (including velocity structure; Figure 6);
4) The cause of outliers (Figure 3).

The first two items are thought to be reasonably well understood on a conceptual level, but the modeling to support it has mainly involved descriptions of simple elastic point sources in elastic media. The details of the R_g to L_g scattering are not clear (e.g. the relative importance of velocity heterogeneity versus topographic effects, cf. Jih, 1995). The complexities in the P_g/L_g ratio with frequency (Item 2) observed in Figure 3 are thought to be due to the imprint of the depth signature of a CLVD secondary source on R_g (that scatters into L_g). However, the physical mechanism of this secondary source is unknown.

Item 3 is not as large of an effect as items 1 and 2 (e.g. about a factor of 2 increase in the ratio for explosions detonated in high-strength, low GFP media, Figure 6) but is still not well understood. As indicated by Figure 6, near-source material effects appear to be affecting the discriminant. This effect could be due to the nonlinear dynamic response of the near-source media to the explosion shock wave or, as discussed above, could simply be due to elastic and/or geometric effects related to the working-point velocity, free surface, and overall crustal velocity structure. For example, it is well-known that the amplitude of the L_g wave from a point-source explosion is strongly dependent on the ratio of the working-point compressional velocity and the shear velocity of the upper mantle (e.g. Xie and Lay, 1994).

Knowledge of the physical basis of discriminants is important to CTBT monitoring. A physical understanding of discriminants allows for the prediction of discrimination performance in different geologic settings where seismic data are unavailable. The analysis of discrimination outliers aids in obtaining an improved understanding of discriminants and also provides information about how they may break down or be spoofed. In this report, we have identified some observations in the P_g/L_g discriminant and flagged some outliers from NTS that are not totally understood. Because of the abundant geologic and geophysical information from NTS, detailed analysis of these features and outliers may be amenable to detailed near-source modeling and propagation to regional seismic distances (e.g. Taylor and App, 1994). It is hoped that these modeling studies will lead to an improved understanding of discriminants and their performance in different geologic regions.

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TABLE 1
GEOPHYSICAL PARAMETERS FOR SPECIFIC NTS EXPLOSIONS

Event	Date	Hole	Residual*	m_b+	Depth (m)	Rock	V_p (m/s)	ρ (Mg/m^3)	GFP (%)
NORBO	3/8/80	U8C	-0.30	4.2	271	Tuff	1962	1.69	8.5
PERA	9/8/79	U10BD	-0.28	3.4	200	Tuff	1627	1.65	19.0
GORBEA	1/31/84	U2CQ	-0.28	4.6	388	Tuff	1713	1.76	10.4
CARNELIAN	7/28/77	U4AF	-0.27	3.9	208	Alluvium	1752	1.80	12.8
KESTI	6/16/82	U9CN	-0.11	4.2	289	Tuff	1670	1.74	15.7
HANDLEY	3/27/70	U20M	0.36	6.4	1209	Tuff	3160	2.20	0.0

* - Residual is P_g/L_g residual from mean (see text for details)
\+ - m_b is actually from L_g magnitude scale (Taylor, 1995)

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