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SPECTRAL RATIOS FOR EXPLOSIONS IN SALT

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Comparison of the P-wave spectra at common stations from the events GNOME, SALMON, and three nuclear tests in salt in the USSR shows that amplitudes are greatly enhanced by shallow burial. The scaling theory of Mueller and Murphy partially accounts for the enhancement, but there remain major differences between theory and observation, particularly at frequencies above 1 Hz. If material properties of salt at the different sites are different then that, and not the depth, may have caused the difference. Effects of pP, consistent with a reflection coefficient of approximately 0.5, can be seen in the spectral ratios.

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ABSTRACT

Comparison of the P-wave spectra at common stations from the events GNOME, SALMON, and three nuclear tests in salt in the USSR shows that amplitudes are greatly enhanced by shallow burial. The scaling theory of Mueller and Murphy partially accounts for the enhancement, but there remain major differences between theory and observation, particularly at frequencies above 1 Hz if effects of pP, consistent with a reflection coefficient of approximately 0.5, can be seen in the spectral ratios.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The scaling of seismic signals that nuclear detonations emit has generated a great deal of interest among workers. This interest exists because of the possible use of cavities, created in salt by nuclear detonations or by solution mining to decouple nuclear tests, in the event of a threshold or comprehensive test-ban treaty. See, for example, Springer, et al. (1968), Murphy (1969), Dahlman and Israelson (1977), Blandford (1977).

The United States has carried out two nuclear explosions in salt: one, GNOME, in New Mexico, and the other, SALMON, in Louisiana; see Table I. Other seismic events may be tentatively identified with underground nuclear detonations in salt discussed by the USSR as part of their program for peaceful uses of nuclear explosions (see Nordyke (1973), or Dahlman and Israelson (1977). A few such events are given in Table I, selected because they took place during the operational period of the LRSM network. In Figure 1 the events and LRSM stations used are plotted on an azimuthal-equidistant map centered at RKON and in Table II are given the stations' parameters and the distances to the events for which data were recorded.

The essential issue is whether or not a satisfactory scaling theory exists that enables prediction, from the spectrum of a calibration explosion, of the spectrum of an explosion at a different yield and depth than that of the calibration explosion.

Springer, D., M. Denny, J. Healy, and W. Mickey, 1968. The Sterling experiment: decoupling of seismic waves by a shot-generated cavity, J. Geophys. Res., V. 73, P. 5995-6011.

Murphy, J.R., 1969. Discussion of paper by D. Springer, M. Denny, J. Healy, and W. Mickey, The Sterling experiment: decoupling of seismic waves by shot-generated cavity, J. Geophys. Res., v.74, p. 6714-6718.

Dahlman, O., and H. Israelson, 1977. Monitoring underground nuclear explosions, Elsevier, New York.

Blandford, R.R., 1977. Discrimination between earthquakes and underground explosions, Ann. Rev. Earth Planet. Sci., v.5, p. 111-122.

Nordyke, M.C., 1973. A review of Soviet data on the peaceful uses of nuclear explosions, UCRL-51414, Lawrence Livermore Lab., California.

TABLE I

List of events

GNOME	Dec. 10, 1961	19:00:00	32.264N,	103.866W,	360.6 m
	3.1 kt,	Soldado Salt,	2.13 - 2.46 gm/cm^3,	4.08 km/sec	
	Werth and Herbst (1963)		pP delay .36 sec (Springer, 1974)		
SALMON	Oct. 22, 1964	16:00:00	31:08:31.6N,	89:34:11.8W,	828 m
	5.3 kt,	Salt,			
	Springer and Kinneman (1971, 1975)		pP delay 0.58 sec (Springer, 1974)		
North of Caspian (A)	April 22, 1966	02:58:04	47.86N,	47.72E,	161.4 m
	1.1 kt,	Salt,	pP delay 2 x .161/4.08 = 0.08 sec		
	Nordyke (1973)				
BUKARA	May 21, 1968	03:59:12	38.916N,	65.159E,	2.45 km
	47 kt (Dahlman and Israelson, 1977)				
		Salt,	pP delay 1.63 sec (Marshall, 1972)		
	Nordyke (1973)				
North of Caspian (B)	July 1, 1968	04:02:02	47.922N,	47.950E,	590 m
	25 kt	Salt,	pP delay .34 sec (Marshall, 1972)		
	Nordyke (1973)				

Seismic events North of Caspian are associated with appropriate yield, depth and material data on the basis that events A and B are in a region of salt domes and are "nearby" each other as quoted from USSR sources by Nordyke. The Bukara event is associated by virtue of being "late in Spring of 1968".

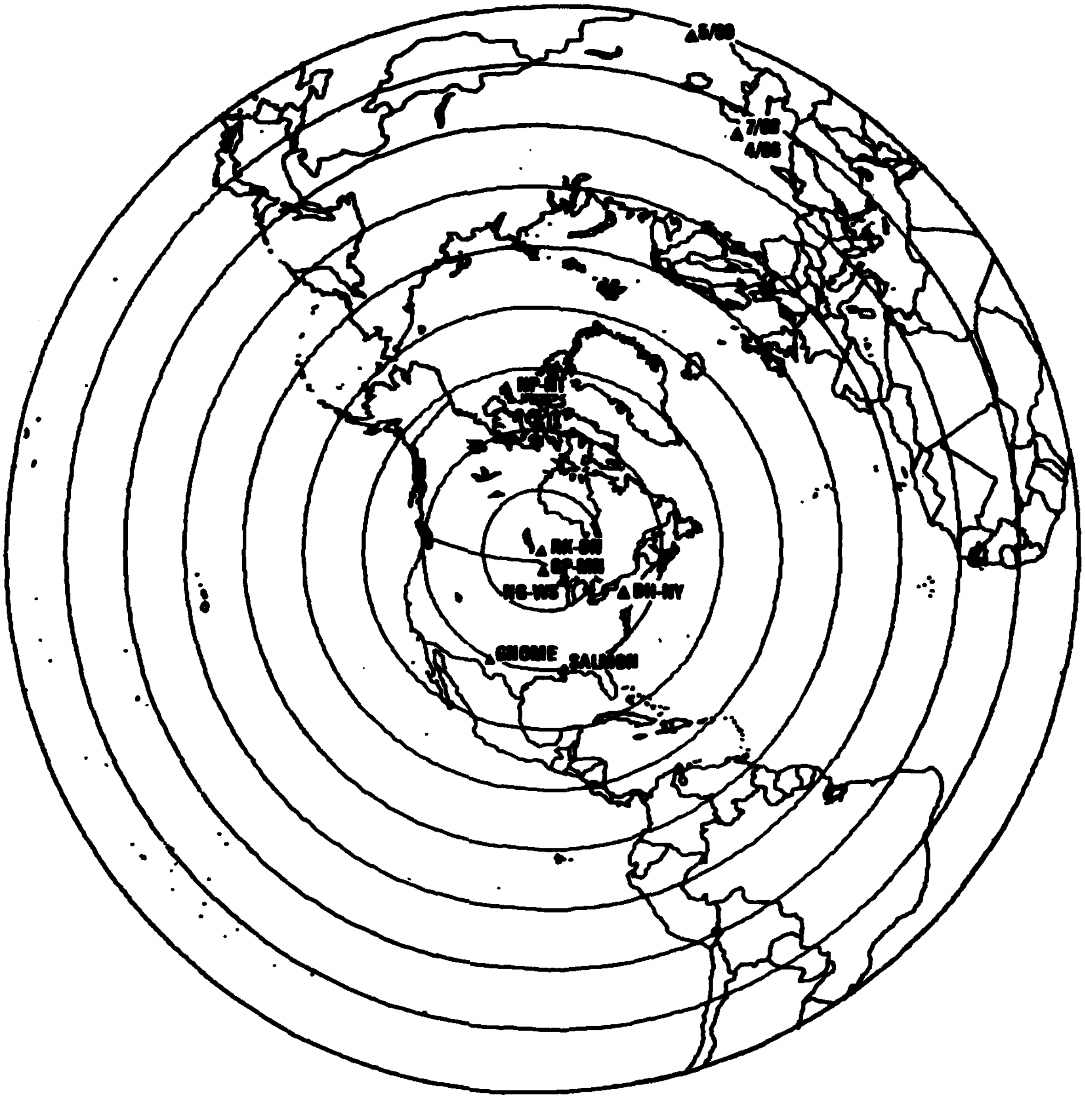

Figure 1. Locations of stations and events.

TABLE II

Station locations, distance to events

RKON	Red Lake, Ontario	50:50:20N,	93:40:20W
Salmon	19.93^{o}	21 May 1968	88.74^{o}
22 April 1966	76.24^{o}	1 July 1968	76.25^{o}
NPNT	Mould Bay, Northwest Territories	76:15:08N,	119:22:18W
Salmon	47.36^{o}	21 May 1968	65.09^{o}
22 April 1966	55.89^{o}	1 July 1968	55.86^{o}
DHNY	Delhi, New York	42:14:39N,	74:53:18W
Gnome	25.04^{o}		
Salmon	16.14^{o}		
NGWS	Niagra, Wisconsin	45:45:27N,	88:08:57W
Gnome	18.16^{o}		
GPMN	Grand Rapids, Minnesota	47:39:52N,	93:29:22W
Salmon	16.78^{o}		

Haskell (1967), drawing on the experimental data presented by Werth and Herbst (1963), presented a cube-root scaling law which predicted ω^{-4} scaling of the displacement amplitude spectrum at high frequencies. Von Seggern and Blandford (1972) (HVB) noted that this spectrum leads to disagreement with observations for the series of tests at LONGSHOT, MILROW and CANNIKIN, all in Amchitka. Von Seggern and Blandford modified Haskell's theory, yielding an ω^{-2} asymptotic slope at high frequencies and establishing that the spectral ratios of the three Amchitka events at RKON were in agreement with the modified theory. Blandford (1976) showed that the predicted first motion amplitude ratios using the modified Haskell source spectrum were in good agreement with the observed values reported by von Seggern and Blandford. Von Seggern and Blandford also pointed out that by using observed source parameters of velocity, density, and depth, the theory of Mueller and Murphy (1971) (MM) gave a spectral ratio at 1 Hz which was in good agreement with the observed first motion ratios.

Thus, based on analyses performed to date, either the HVB or the MM theory gives a fairly good accounting of the Amchitka short-period scaling relations. Further detailed work might make choosing between the theories for these events possible.

For explosions in tuff at NTS, Blandford (1976) has shown good agreement between the observed and calculated spectral ratios and first motion observation (the "a" phase) at MNNV and KNUT for the events BUTEO, REX, SCOTCH, and BENHAM.

Haskell, N. A., 1967. Analytic approximation for the elastic radiation from a contained underground explosion, J. Geophys. Res., v. 72, p. 2583-2587.

Werth, G. C. and R. F. Herbst, 1963. Comparison of amplitudes of seismic waves from nuclear explosions in four mediums, J. Geophys. Res., v. 68, p. 1463-1475.

von Seggern, D. H. and R. Blandford, 1972. Source time functions and spectra for underground nuclear explosions, Geophys. J. R. A. S., v. 31, p. 83-97.

Mueller, R. A., and J. R. Murphy, 1971. Seismic characteristics of underground nuclear detonations: Part I, Seismic scaling law of underground detonations, Bull. Seism. Soc. Am., v. 61, p. 1675-1692.

Blandford, R. R., 1976. Experimental determination of scaling laws for contained and cratering explosions, SDAC-TR-76-3, Teledyne Geotech, Alexandria, Virginia.

Theoretically calculated ratios were based on the von Seggern-Blandford parameterization of the Werth-Herbst data for tuff. Murphy, in a private communication, claims an equally good fit to the data using the Mueller-Murphy theory. This author considers that Murphy's fits do not seem as good, and the question should still be regarded as a debatable one. Certainly at low frequencies, the HVB theory predicts the widely observed M_s:log yield slope of 1.0 at both Amchitka and NTS whereas Murphy (1977) appeals to spall to explain the deviation from the MM-predicted slope of 0.76.

While the Werth and Herbst tuff potential is satisfactory for regional distances, Blandford (1976) was forced to use a granite potential to fit teleseismic observations of NTS events. He suggested that this action reflected a difference in coupling as a function of take-off angle. On the other hand, Murphy (1977) was able to use his tuff potential for short-period observations at both regional and teleseismic distances. However, concluding from this apparent greater generality that the MM theory is superior is not possible because important differences in detail between the two papers exist, in terms of both theoretical calculations and observed data.

Murphy suggested that long-period P observations for LONGSHOT, MILROW, and CANNIKIN presented by Basham and Horner (1973) supported his 0.76 long-period log(amplitude):log(yield) slope. However, calculations by Blandford and Shumway (1977) showed that the slope of less than 1.0, observed by these authors, can be explained with the HVB model together with a surface pP reflection coefficient of -1.0 at low frequencies. Thus, on balance, the HVB scaling seems to work better than MM.

Questions of variation in material as a function of depth complicates these discussions. Such questions should not develop with explosions in salt and, therefore, comparisons of the different theories with respect to the data from explosions in salt provokes considerable interest.

Murphy, J. R., 1977. Seismic source functions and magnitude determinations for underground nuclear detonations, Bull. Seism. Soc. Am., v. 67, p. 135-158.

Basham, P. W., and R. B. Horner, 1973. Seismic magnitudes of underground nuclear explosions, Bull. Seism.Soc. Am., v. 63, p. 105-131.

In the rest of this report the two theories are first summarized, and then spectral ratio predictions are compared to the data.

THEORY

The Haskell-von Seggern-Blandford theory gives

$$\frac{cr}{\psi(\infty)}\left| U(\omega) \right| = \left[A'(\omega/k)^2 + 1\right]^{\frac{1}{2}} \Big/ \left[(\omega/k)^2 + 1\right]^{3/2}, \qquad (1)$$

where U is the displacement spectral amplitude at radial frequency ω, c is the medium velocity, r is the radial distance, $\psi(\infty)$ is the asymptotic reduced displacement potential, $A'=2B+1$ where B is the overshoot parameter, and $k=k_o (Y/5)^{1/3}$, where k_o is the time constant for a 5 kiloton explosion, and Y is the yield in kilotons. Fitting the corresponding formula for the reduced displacement potential to the data for the GNOME test from Werth and Herbst (1963) gives B=1.3, k_o=20.

The Mueller-Murphy theory gives for the far-field displacement spectrum

$$U(\omega) = \left(\frac{p(\omega) r_{el}}{4\mu}\right)\left(\frac{i\omega}{cr}\right)\frac{c^2}{(\omega_o^2 + i\ \omega_o\omega - \beta\omega^2)} \qquad (2a)$$

where $p(\omega)$ is the Fourier transform of the pressure at the elastic radius, r_{el}, is the modulus of rigidity and $\omega_o = c/r_{el}$.

The expression for p(t) is

$$p(t) = \left[P_o e^{-at} + P_{oc}\right] H(t)$$

with Fourier transform

$$p(\omega) = (P_{os} - P_{oc})/(a + i\omega) + P_{oc}/i\omega \qquad (2b)$$

where $P_{os} = P_o + P_{oc}$.

From the Mueller-Murphy (1971) paper the following relations for variations in yield and depth can be deduced (the zero superscripts denote calibration values).

$$\text{a)}\quad p_{os} = \left(\frac{h}{h_o}\right) p^o_{os} \qquad \text{c)}\quad p_{oc} = \left(\frac{Y}{Y^o}\right)^{.87}\left(\frac{h^o}{h}\right)^{.33}\left(\frac{r^o_{el}}{r_{el}}\right)^3 p^o_{oc}$$

$$\text{b)}\quad r_{el} = \left(\frac{Y}{Y^o}\right)^{1/3}\left(\frac{h^o}{h}\right)^{1/n} r^o_{el} \qquad \text{d)}\quad \alpha = (r^o_{el}/r_{el})\alpha^o \qquad (3)$$

Choosing SALMON = 5.3 kt, as a calibration event, the following parameters may be taken from Mueller (1969)

$$\begin{array}{ll} h = 828\text{m} & r^o_{el} = 299\text{m} \\ \rho = 2.2\ \text{gm/cm}^3 & p^o_{os} = 370\ \text{bars} \\ \lambda = \mu = 1.6\text{x}10^5\ \text{bars} & p^o_{oc} = 70\ \text{bars} \\ n = 1.87 & \alpha^o = 50\ \text{sec}^{-1} \end{array} \qquad (4)$$

To apply the Mueller and Murphy theory to calculate spectral ratios, the calibration parameters (see in (4)) are obtained, and then the scaled parameters, applying (3) in order a,b,c,d, are deduced. These ratios are then inserted in (2a,b) to obtain the final spectrum for other yields and depths.

Both the HVB and MM theories have their weaknesses when predicting source potentials in a new medium. The von Seggern-Blandford theory proceeds from a measured reduced displacement potential, but a different potential must be measured for each material; no capability to scale to different medium parameters exists. Blandford (1976), in reviewing work by Chabai (1965), demonstrated that cube-root scaling will fail for "shallow enough" events.

Mueller, R. A., 1969. Seismic energy efficiency of underground nuclear detonations, Bull. Seism Soc. Am., v. 59, p. 2311-2324.

Chabai, A. J., 1965. On scaling dimensions of craters produced by buried explosions, J. Geophys. Res., v. 70, p. 5075-5098.

The MM theory contains several parameters, n, r_{el}, P_{os}, P_{oc}, that are estimated by spectral analysis of individual events either with the theory acting as a mediator or by statistical analysis of many events in which, unaccounted-for parameters, such as water content and porosity, might have been operating.

Thus, neither theory may be relied upon a priori in application to shallow events; the test must be on agreement with data other than that used to parameterize the theory. Note that $n = 1.87$ is different from $n = 2.4$ used by Mueller and Murphy (1971) for all media, including salt. Calculations using $n = 2.4$ are not significantly different from those using 1.87.

Some of the parameters (equation 4) have been estimated for other events by Mueller and Murphy (1971) using the formulas below. These formulas, when applied to salt are specifically appropriate for SALMON and yield the parameters in equation (4). r_{el} and k are obtained by spectral analysis of near-field and far-field data as shown by Mueller (1969). n is determined by a plot of $r_{el}/Y^{1/3}$ versus ρh (see Mueller and Murphy (1971).

Also,

$\alpha = k\omega_o = k(c/r_{el})$ where k = (1.5, tuff), (2.0, rhyolite), (2.4, shale), (4.5 salt; 3.20 Mueller (1969),

$P_{os} = \sim 1.5\ \rho gh$ (2.06 ρgh salt, Mueller, 1969)

$P_{oc} = \frac{4\mu}{3}(r_c/r_{el})^3$ where $r_c = 16.3\ Y^{.29}(E^{0.62}\ \rho^{-0.24}\ \mu^{-0.67})h^{-0.11}$

where $(E^{0.62}\ \rho^{-0.24}\ \mu^{-0.67})$ = (1.513, granite), (1.721, salt), (1.758, rhyolite), (1.927, tuff), (1.761, alluvium).

DATA ANALYSIS

In Figure 2 are sample signals from events listed in Table I. Since the distances from NPNT to the events of interest lie between 47° and 65°, a distance range in which multiple arrivals should cause few problems, these particular waveforms are included. In Figures 3b,c,d, the spectral ratios at RKON are quite similar to those at NPNT, when allowance is given for the change in overall amplitude due to distance as determined by Veith and Clawson (1972).

The only common station in the LRSM network for the events GNOME and SALMON is DHNY. These traces are included primarily to show the peculiar nature of the SALMON signal. This signal is at a distance of 16.14 degrees, which is the transition between P_n and P as first arrival.

Spectra for these signals are calculated by taking a 12.8 second signal window (256 points at 20 samples per second) starting 4 seconds in front of the signal. A 2 second taper is applied at the beginning and at the end of the noise window which is of equal length and ends 4 seconds in front of the signal. The same 2 second taper is also at the beginning and the end of the signal window. Both time series are Fourier transformed and the power spectrum is smoothed by 5. If the ratio of the smoothed amplitude spectra of the signal to that of the noise is greater than 3, then the ratio is plotted as in Figures 3a,b,c,d. Also in these figures are the theoretical ratios determined by the Haskell-von Seggern-Blandford (HVB) theory, and the Mueller-Murphy (MM) theory. The theoretical ratios have been modified by the effects of pP on both spectra, assuming a reflection coefficient of 0.5 for all events and pP delay times as given in Table I.

In Figure 3 the observed spectral ratios have been corrected by means of the P factors of Veith and Clawson (1972) to reflect what they would have been had the stations been at equal distances from the events. These authors showed that their distance amplitude corrections are more nearly correct at regional distances than Gutenberg's.

Veith, K. F., and Clawson, G. E., 1972. Magnitude from short-period P-wave data: Bull. Seism. Soc. Am., v. 62, p. 435-452.

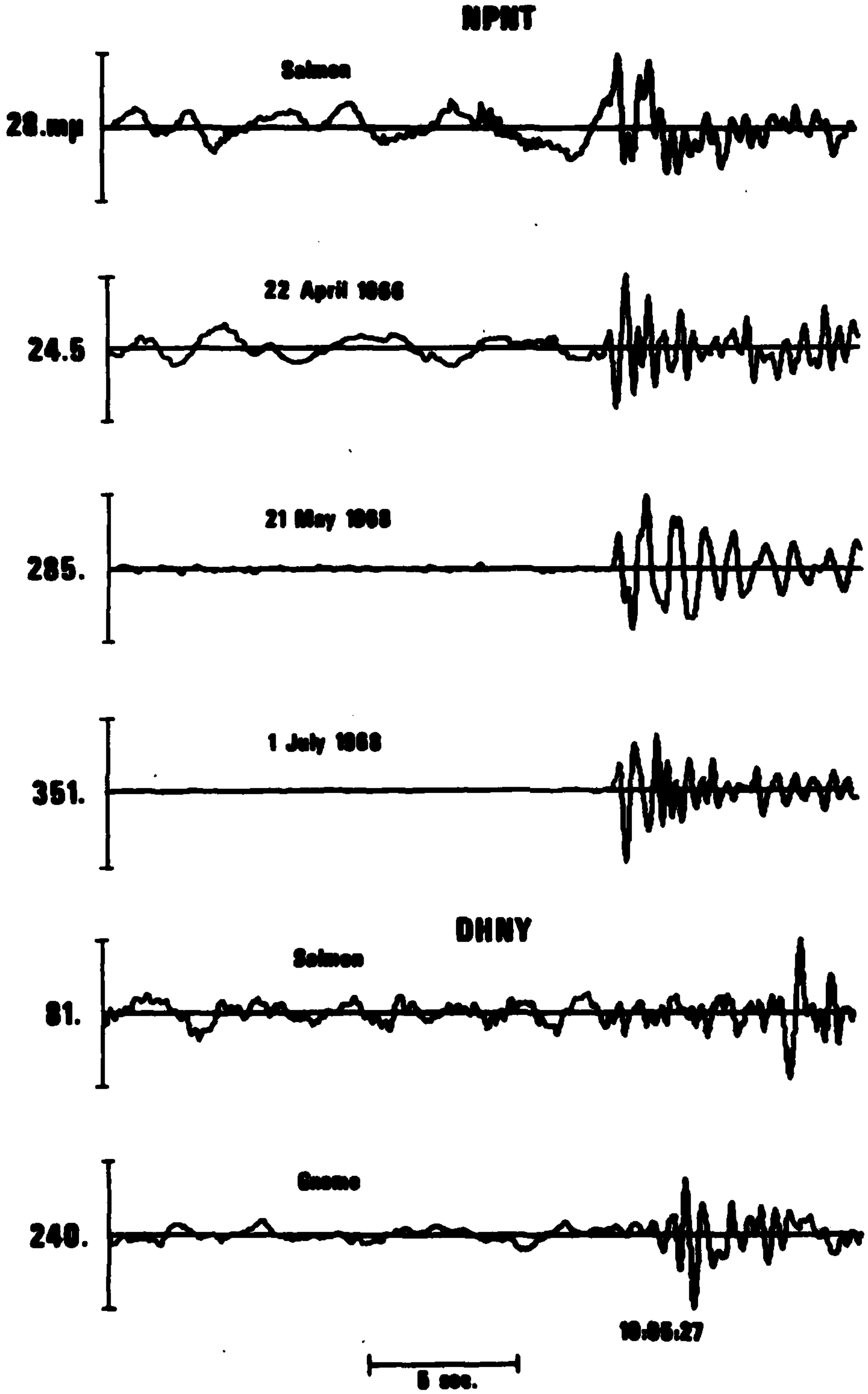

Figure 2. Selected waveforms.

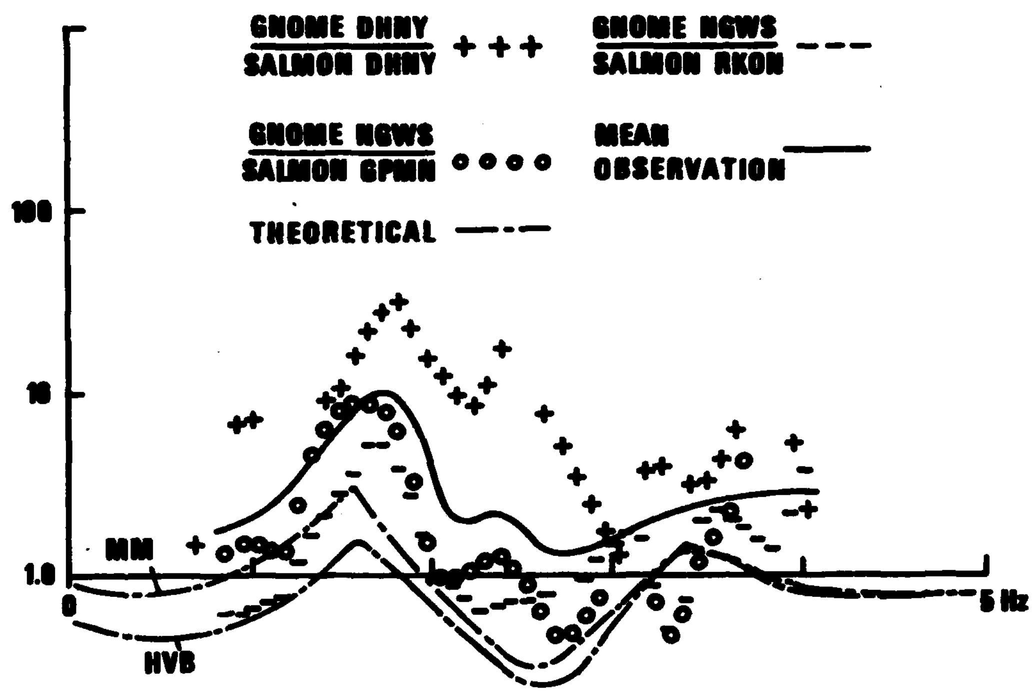

Figure 3a. Spectral ratios, theoretical and observed GNOME/SALMON. SALMON.

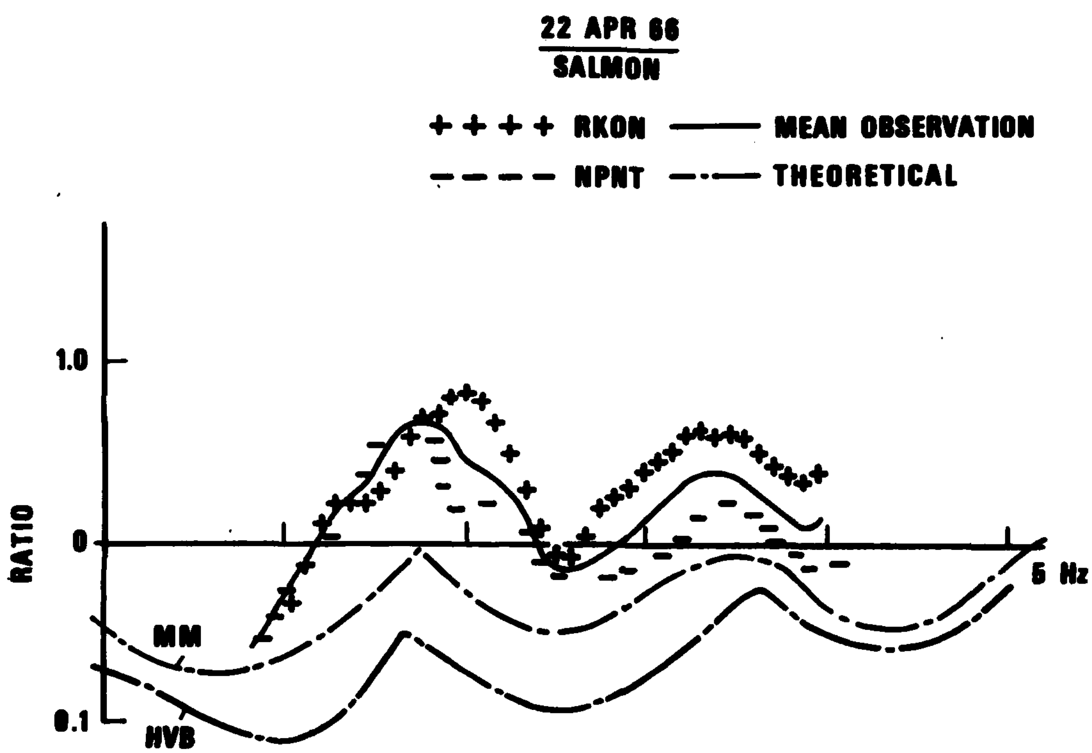

Figure 3b. 22 April 1966/SALMON.

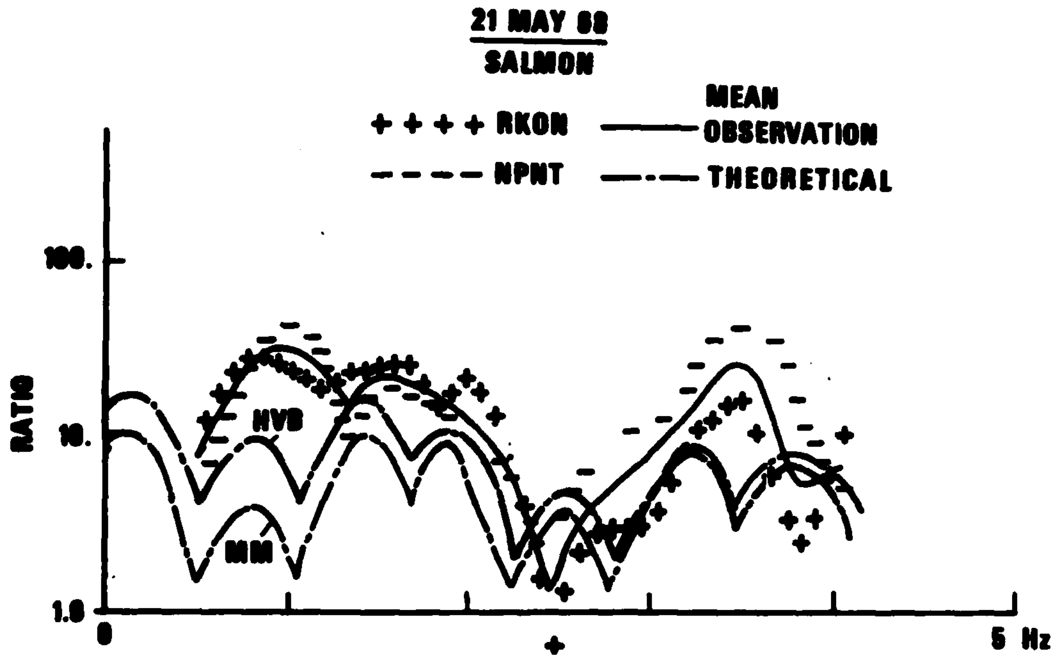

Figure 3c. 21 May 1968/SALMON.

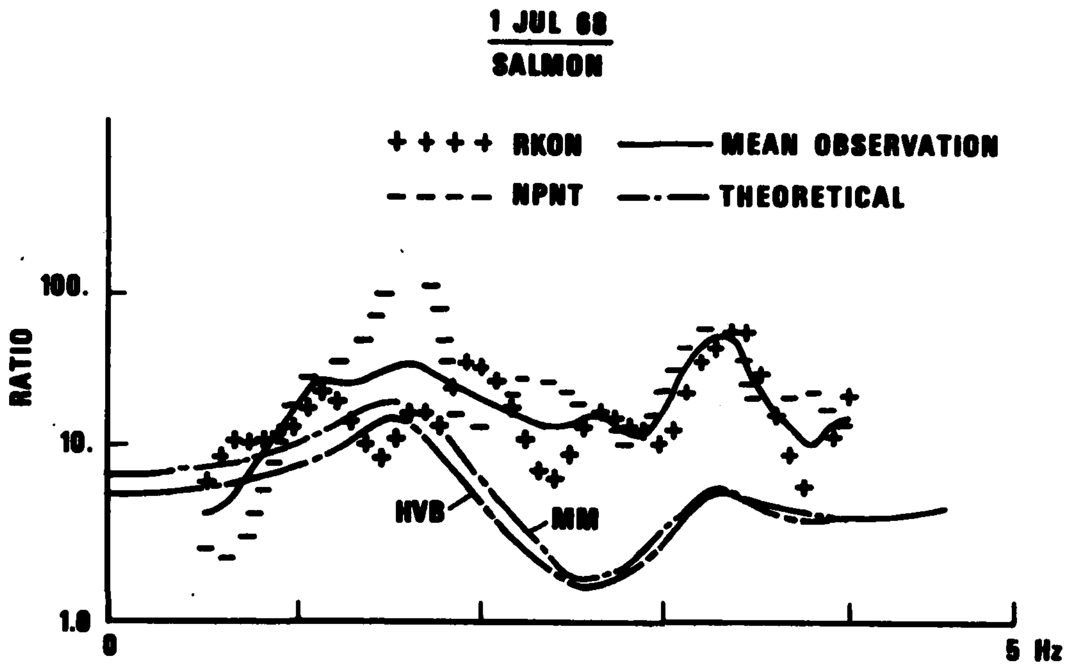

Figure 3d. 1 July 1968/SALMON.

In Figure 3a for GNOME/SALMON the overall shape of the spectral ratio is in agreement with the theory for all stations, and the effects of pP are quite prominent; the DHNY spectral ratio is a factor of 10 or more higher than theoretically predicted. If this spectrum, and the average spectrum where it is included, is discarded, then at around 1 Hz the Mueller-Murphy theory is in good agreement with the absolute value and trend of the spectral ratio, but the HVB theory gives a ratio 0.3 magnitude units low. While above 1.3 Hz, the MM theory continues to be closer to observation than does the HVB theory, both are 0.3 to 0.5 magnitude units below observed values in the frequency range 1.5-3.0 Hz. Above 3 Hz the theories are very close and are consistent with the data. Still, if much weight is given to the DHNY ratio, then both theories predict far too small a ratio.

The absolute level of the DHNY spectrum is suspect for two reasons. The distance to GNOME is 25.05°. At this distance Nuttli (1972) showed a sharp increase in ampltiude (~ 0.4 m_b) associated with the 650 km discontinuity. This amplitude maximum is not seen in the distance correction factors of Veith and Clawson (1972). Also, at 16.14°, the distance to SALMON, $m_{8.5}$ appropriate to this path according to Evernden (1967) predicts 0.3 m_b units greater amplitude than Veith and Clawson's curve. Although these two effects would roughly cancel each other, they illustrate the *a priori* variability of this particular ratio.

However, results from Figure 3b suggest that the SALMON/GNOME DHNY ratio is not the aberration it appears to be. Here, RKON and NPNT agree that above 1 Hz the MM theory is low by perhaps a factor of 5, while the HVB theory is low by a factor of 10. Note, however, that near 1 Hz the MM theory is only 0.3. magnitude units smaller than observed. Again effects of pP are visible in the data.

Nuttli, O. W., 1972. The amplitudes of teleseismic P waves, *Bull. Seism. Soc. Am.*, v. 62, p. 343-356.

Evernden, J. F., 1967. Magnitude determination at regional and near-regional distances in the United States, *Bull. Seism. Soc. Am.*, v. 57, p. 591-639.

In Figure 3c, for the overburied event, both theories are in agreement with data above 1.5 Hz. However, at around 1 Hz the MM theory appears to "overcompensate" for the great depth of the 21 May 1968 event and predict too small an amplitude. The MM prediction is, perhaps, a factor of 10 low compared to observation. On the other hand, the HVB theory is also perhaps a factor of 5 low.

In Figure 3d both theories are in good agreement with observation around 1 Hz, and both give values much too low above 2 Hz.

Figure 4 shows the displacement spectra for SALMON, from Springer, et al. (1968) and for GNOME from Werth and Herbst (1963). From 2-4 Hz the spectra are nearly the same at 1 Hz. GNOME is perhaps 0.1 magnitude units lower. The resulting predicted spectral ratio is very close to that given in Figure 3a for MM up to 2 Hz. Above 2.5 Hz the spectral ratio from Figure 4 increases from 0.2 to 0.4 magnitude units above the MM line; resulting in even more similarity with teleseismic ratios.

Thus, if the DHNY observations are neglected, the close-in measurements appear to correctly predict the teleseismic observations and demonstrate that neither scaling law does a satisfactory job.

As an aid to proper use of these relative spectra it may be of use to present some new results on the teleseismic magnitude of SALMON.. Evernden (1967) using regional stations and teleseismic stations out to 4000 km determined an m_b of 4.27. Jordan et al. (1966) presented m_b values at teleseismic distances together with the magnifications of those stations at which no signal could be detected. Jordan et al. used Gutenberg's distance-amplitude relationship to compute m_b and suggested that an improved distance-amplitude relationship should be developed. In this paper Veith and Clawson's (1972) curve is used. Using Jordan's 11 observations for $\Delta > 30^{\circ}$ yields an average m_b of 4.77.

Jordan, J.N., W.V. Mickey, W. Helterbran, and D.M. Clark, 1966. Travel times and amplitudes from the SALMON explosion, J. Geophys. Res., 71, p. 3469-3482.

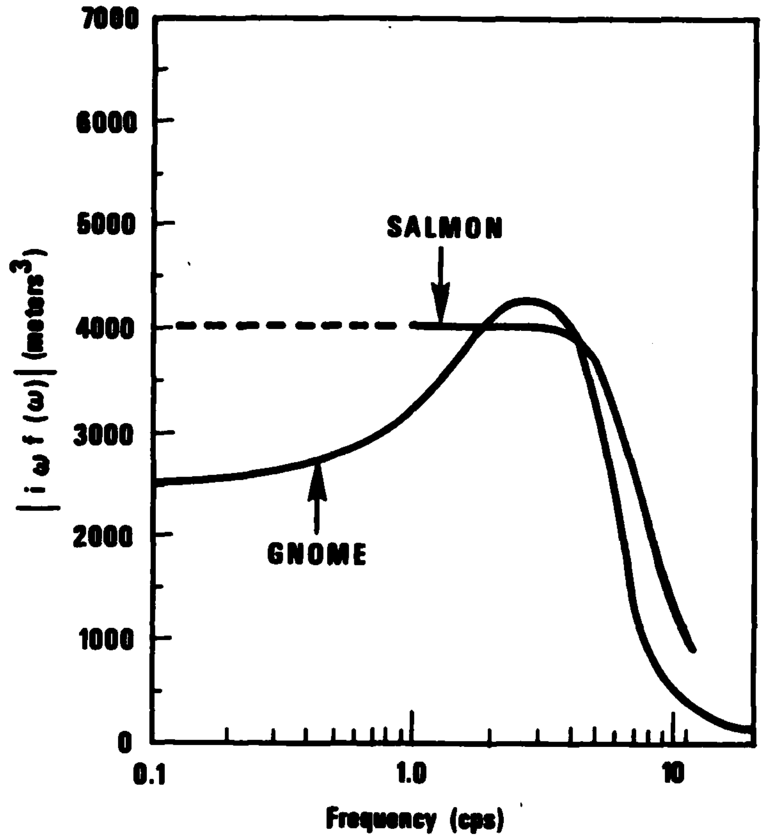

Figure 4. Comparison of GNOME source spectrum to SALMON source spectrum. From Werth and Herbst (1963) and Springer, et al. (1968).

Recently Ringdal (1976) has developed a method of making maximum likelihood estimates of magnitude using the knowledge that at stations where the signal was looked for but not observed, its amplitude was less than the noise level at that station. At each non-observing station one may compute a magnitude greater than the magnitude which would be computed had the signal been detected. Jordan et al. indicated 28 non-observing stations between 30° and 90°. If it is assumed that in their careful analysis a 2 millimeter/1 Hz signal would have been detected at a X20 view, then upper limits to 28 unobserved magnitudes may be computed. They range from 4.28 to 5.58. Using these magnitude limits in Ringdal's estimation procedure yields a maximum likelihood estimate for SALMON of 4.45.

Ringdal, F., 1976. Maximum likelihood estimation of seismic event magnitude from network data, Bull. Seism. Soc. Am., 66, p. 789-802.

SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH

In the broadest sense no existing theory seems to give a satisfactory explanation for the observations. Near 1 Hz the MM theory gives an accurate result for shallow and intermediate depth events, but does worse than the HVB theory for a deep event. Apparently in salt an important depth effect exists, but neither theory satisfactorily accounts for it.

Except for the SALMON/GNOME ratio at DHNY the data seem to be internally consistent; the author would predict much the same results if further spectral data were made available. Considerably more data is available on film, and much could be learned from predicting detailed waveforms and then comparing them to the observations on the film, especially in terms of spectral content, as visible in the time domain, and with respect to absolute amplitude. The MM theory might well show up considerably better in such a comparison since the higher frequency data is often not evident in the time domain. Nonetheless, a satisfactory answer to the question of what occurs at high frequencies is important because detection is optimum well above 1 Hz at regional distances.

Clearly, the effects of pP are visible in the data and for an accurate comparison with observation these effects of pP must be taken into account.

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