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Estimating the relative yields of Novaya Zemlya tests by waveform intercorrelation

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Summary. The relative size of 15 underground nuclear explosions at the Novaya Zemlya test site is determined by applying a relative waveform analysis called intercorrelation to 566 teleseismic short-period *P*-waves. The waveforms are corrected for the effects of *pP* interference and yield scaling of the explosion source functions so that signals from different events recorded at the same station can be analytically compared. For events within a single test site, this procedure accounts for common path and receiver effects. Relative explosion source strengths in the 0.5–2.0 Hz frequency band determined by intercorrelation are consistent with the results of conventional m_b analysis. Absolute yield estimates from both intercorrelation and m_b analyses have much greater uncertainty due to unknown baselines. The yield estimates for the 15 events range from 36 to 3886 kt, assuming that $t_\alpha^* = 0.5$ s and that yield scaling relations for the Amchitka test site are appropriate for Novaya Zemlya. The *pP* delay times obtained from intercorrelation of Novaya Zemlya events are similar to the delay times for Amchitka events with equivalent yields, consistent with both being hardrock sites. The analytical waveform comparisons also provide criteria for identifying anomalous events. The Novaya Zemlya test site has two subsites separated by about 300 km. One of the 11 events in the Northern subsite and one of the four events in the Southern sub-site have anomalous waveforms. A waveform modelling study indicates that the anomalous Southern event was a double explosion. Northern and Southern Novaya Zemlya have different waveform and amplitude patterns, apparently caused by different focusing and defocusing of seismic energy by laterally varying structure near the sources.

Key words: nuclear explosion, intercorrelation, Novaya Zemlya yield

Introduction

Increasing the accuracy of yield estimates obtained from seismic observations of underground nuclear explosions requires new techniques that extract more information from the signals than conventional m_b measurements. One procedure that has been proposed, which utilizes the complete waveform information, is intercorrelation (Mellman & Kaufman 1981; Lay, Burdick & Helmberger 1984a; Lay 1985). This relative waveform analysis compares seismic signals, usually short-period P-waves, from two events recorded at the same station. For two events that occur close together, the signals have common propagation and receiver effects; therefore, any primary differences in the waveforms can be attributed to differences in the explosion source functions and pP interference. By convolving each signal with an estimate of the effective source function for the other event, the resultant waveforms can be matched to one another. Applying the procedure to many stations simultaneously and optimizing the overall waveform agreement provides estimates of the pP–P lag times, $|pP|/|P|$ amplitude ratios, and relative source strength for the two events. Additional complexity in the differential source functions arising from crustal reverberations near the source, slapdown phases, or tectonic release can be included if necessary.

The previous studies using intercorrelation have analysed data from U.S. tests in Amchitka (Lay *et al.* 1984a) and NTS (Lay 1985). These events have known source depths, reliable nearfield source models, and announced yields; providing absolute scaling relations. Comparable information is not currently available for Soviet tests, so intercorrelation, like m_b analysis, can only provide relative yield estimates. Acknowledging this uncertainty, we have applied intercorrelation to Novaya Zemlya events to obtain accurate relative size estimates. Standard m_b analysis is also performed to estimate the relative size of the tests. The amplitude measurements are compared with the intercorrelation results and are also used to some extent in the intercorrelation analysis. The relative size estimates based on m_b values are very close to those obtained by the intercorrelation analysis. Absolute yields can be computed reliably if and when calibration becomes available. For the purposes of this paper, absolute yields are estimated by assuming an average t^* and ψ_∞-yield scaling relation.

The pP–P delay times obtained from the intercorrelation analysis of Novaya Zemlya events are similar to the delay times for Amchitka (a hardrock site) events of equivalent yield. Furthermore, Novaya Zemlya events have substantially smaller pP delay times than events at Pahute Mesa (softrock site). These results are consistent with the expectation that Novaya Zemlya is a hardrock site. The three largest Southern Novaya Zemlya events and three Northern Novaya Zemlya events have smaller pP delay times than the average Northern Novaya Zemlya population. This is apparently caused either by underburial or by burial in material with a higher overburden velocity.

The Northern and Southern subsites have systematically different waveform and amplitude patterns. These appear to result from focusing and defocusing by laterally varying velocity structure near the sources. The possible effects of tectonic release are also considered, but are shown to be much smaller than the observed variations.

Amplitude analysis

Short-period P-wave recordings from 90 WWSSN and CSN stations in the distance range $25° < \Delta < 95°$ were collected for 15 Novaya Zemlya explosions. Fig. 1 is a map of the two subsites at Novaya Zemlya and the stations used in this study. The two sites are separated by about 300 km. Table 1 gives the epicentral information and an initial set of yield estimates for the 11 Northern Novaya Zemlya (NNZ) and four Southern Novaya Zemlya (SNZ) events

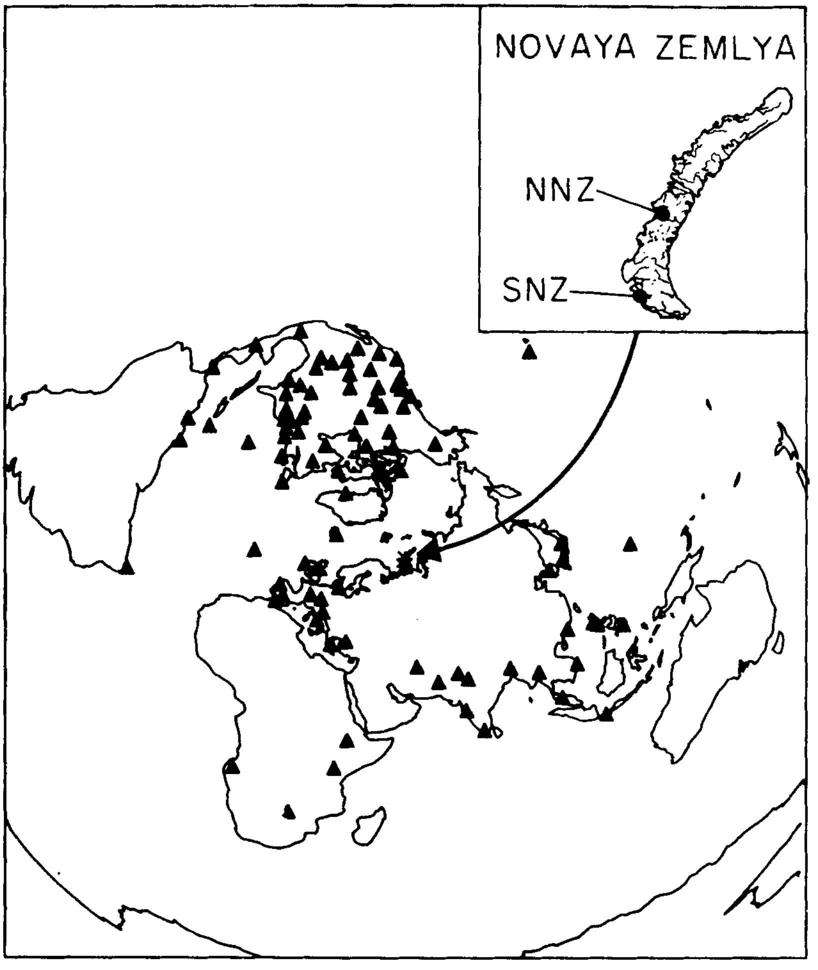

Figure 1. Map of the Novaya Zemlya test sites. Locations of the Northern (NNZ) and Southern (SNZ) testing areas are shown. An azimuthal equidistance projection centred on Novaya Zemlya shows the distribution of stations used in the study.

studied. The yield estimates are from Dahlman & Israelson (1977) and are based on relative amplitudes and an absolute baseline from PNEs of announced yield in the Soviet Union.

Burger *et al.* (1985) provide all the observed waveforms, amplitudes, and magnitudes for each of the events. We will investigate four types of measurements in this section: amplitudes and magnitudes based on A^{ab} (first peak to first trough amplitude) and A^{bc} (first trough to second peak amplitude). Magnitudes are calculated by

$$m_b = \log (A/T) + P(\Delta), \tag{1}$$

where $P(\Delta)$ is the distance correction defined by Veith & Clawson (1972).

A previous study of Novaya Zemlya event amplitudes using a small set of North American WWSSN stations indicated a systematic difference in average amplitude patterns between NNZ and SNZ (Butler & Ruff 1980). The ratio of these patterns has about a factor-of-3 azimuthal variation in relative amplitude across North America. This result prompted us to treat the two subsites separately in our analysis.

Table 1. Explosion data set.*

Date	O.T.	Lat (°N)	Lon (°E)	Est. Yield (kt)
		Northern Novaya Zemlya		
Oct. 27, 1966	05:57:58	73.44	54.75	770
Oct. 21, 1967	04:59:58	73.37	54.51	210
Nov. 7, 1968	10:02:05	73.40	54.86	310
Oct. 14, 1969	07:00:06	73.40	54.81	340
Oct. 14, 1970	05:59:57	73.31	55.15	2100
Sep. 27, 1971	05:59:55	73.39	55.10	770
Aug. 28, 1972	05:59:57	73.34	55.08	690
Sep. 12, 1973	06:59:54	73.30	55.16	2700
Aug. 29, 1974	09:59:58	73.37	55.09	870
Aug. 23, 1975	08:59:58	73.37	54.64	550
Oct. 21, 1975	11:59:57	73.35	55.08	700
		Southern Novaya Zemlya		
Sep. 27, 1973	06:59:58	70.76	53.87	210
Oct. 27, 1973	06:59:57	70.78	54.18	3200
Nov. 2, 1974	04:59:57	70.82	54.18	1600
Oct. 18, 1975	08:59:56	70.84	53.69	1400

* Locations, origin times, and estimated yields from Dahlman & Israelson (1977).

Fig. 2 shows the azimuthal pattern of ab amplitudes for NNZ and SNZ. The mean and standard error of the amplitudes at each station are plotted, after correcting for event size following the least-squares procedure described by Butler & Ruff (1980). As usually proves true for distinct test sites, the event-size-corrected amplitude scatter at each station is less than a factor of two about the mean, but the variation in the station means spans nearly 2 orders of magnitude.

The *ab* amplitude patterns shown in Fig. 2 display large variations with azimuth, but it is difficult to detect any long-wavelength trends in the data. The amplitude pattern from Pahute Mesa has a sin 2θ variation with azimuth (Lay, Wallace & Helmberger 1984b). No obvious trends of this nature are present for Novaya Zemlya. However, it is clear that NNZ and SNZ have different amplitude patterns. This intersite difference is isolated by taking the ratio of the observed station averages, as shown at the bottom of Fig. 2. The relative pattern shows a stable trend across North America (azimuths 300°–360°). The ratios range over a factor of 10, justifying the separate treatment of the two subsites.

Average amplitude and magnitudes for each event are computed using the average station corrections for each measurement type as weighting factors. This reduces the bias due to nonuniform station coverage between events (Lay 1985). The mean and standard deviations for each measurement are listed in Table 2. The standard deviations are given assuming that the station corrections have no uncertainty. However, this is not the case; thus we also present the complete standard deviations and standard errors of the mean for m_b^{ab} taking into account the uncertainty of the station corrections. For comparison, amplitude data for U.S. tests with announced yields are included in Table 2. The announced yield for GREELEY and the estimated yield for the 8/29/74 NNZ event (Table 1) are the same; however, the latter event has an average amplitude three times larger and a magnitude 0.3 greater than for GREELEY. It is clear that a substantial t^* difference must exist if the estimated yields of Dahlman & Israelson (1977) are approximately correct.

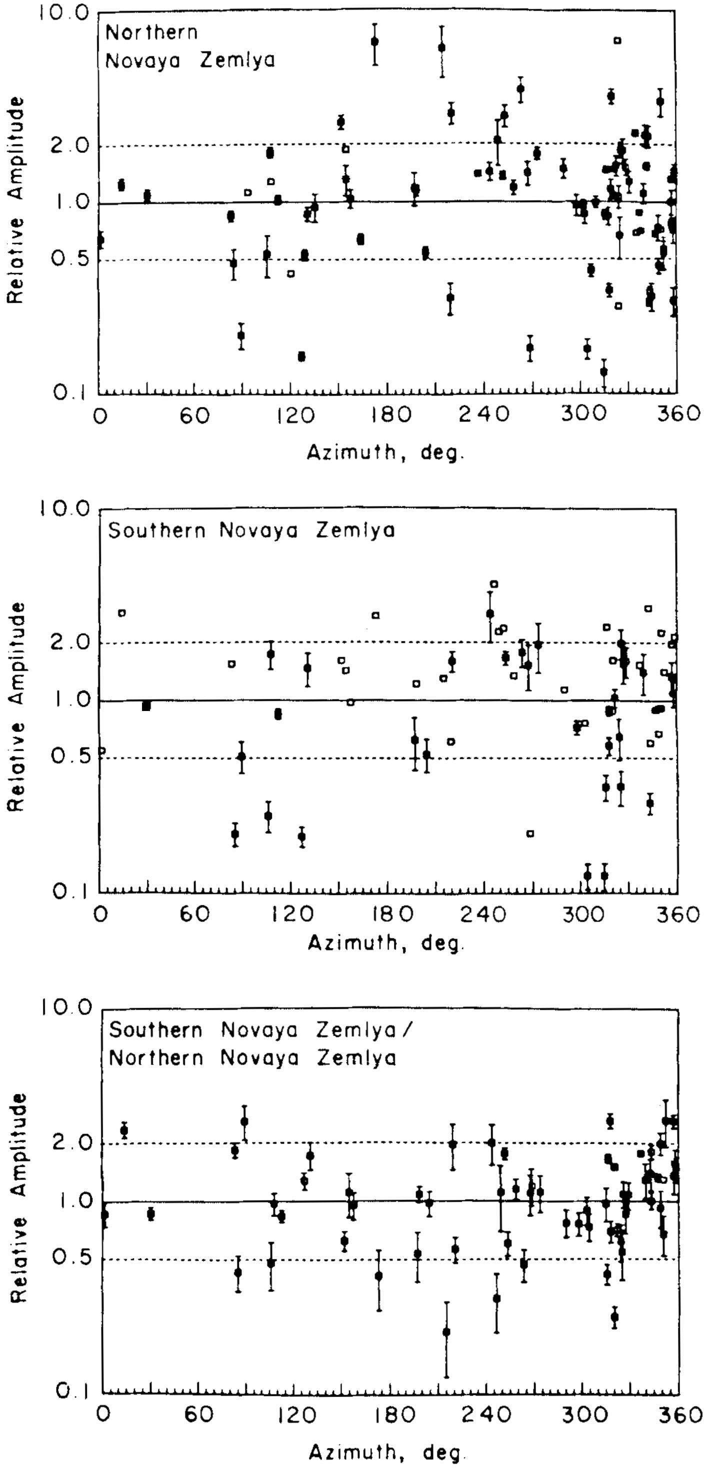

Figure 2. Azimuthal plot of the mean station amplitudes for the NNZ test site (top), SNZ (middle), and the ratio of SNZ–NNZ (bottom). Error bars are the standard errors of the mean. The open squares represent average station amplitudes for stations where only one event is observed.

Table 2. Amplitudes and magnitudes for Novaya Zemlya events.*

Event	A^{ab}	A^{bc}	m_b^{ab}	m_b^{bc}	m_b^{ab} SD**	m_b^{ab} SEM**
10/27/66	1319± 285 (51)	1748± 452 (45)	6.38±0.10 (44)	6.50±0.11 (44)	0.14	0.04
10/21/67	292± 60 (57)	407± 76 (49)	5.65±0.09 (49)	5.79±0.08 (49)	0.13	0.04
11/07/68	458± 168 (62)	650± 115 (58)	5.83±0.08 (58)	5.99±0.08 (58)	0.13	0.05
10/14/69	607± 166 (54)	830± 176 (48)	5.97±0.09 (48)	6.12±0.08 (48)	0.14	0.05
10/14/70	3191± 831 (34)	4717±1357 (27)	6.72±0.12 (27)	6.88±0.12 (27)	0.16	0.05
9/27/71	1860± 331 (32)	2502± 439 (26)	6.53±0.08 (26)	6.63±0.09 (26)	0.13	0.04
8/28/72	1033± 248 (46)	1420± 375 (42)	6.25±0.10 (41)	6.37±0.09 (41)	0.15	0.05
9/12/73	3762±1209 (21)	5340±1913 (17)	6.84±0.15 (18)	6.98±0.17 (17)	0.20	0.06
8/29/74	1385± 221 (36)	1975± 350 (33)	6.39±0.07 (33)	6.53±0.08 (33)	0.14	0.05
8/23/75	1369± 247 (46)	1852± 488 (39)	6.37±0.08 (38)	6.50±0.11 (39)	0.14	0.05
10/21/75	1280± 415 (31)	1878± 693 (28)	6.35±0.17 (29)	6.50±0.18 (28)	0.21	0.06
9/27/73	199± 33 (22)	319± 50 (22)	5.52±0.08 (22)	5.73±0.07 (22)	0.12	0.06
10/27/73	5506± 583 (12)	7983±1493 (12)	6.98±0.07 (12)	7.14±0.10 (12)	0.13	0.07
11/02/74	2954± 531 (22)	4460± 694 (22)	6.73±0.09 (22)	6.90±0.09 (22)	0.14	0.06
10/18/75	1781± 399 (26)	2808± 564 (25)	6.48±0.09 (26)	6.68±0.09 (25)	0.14	0.07

* The numbers following the ± are standard deviations not including the uncertainty of the station corrections. The numbers in the () are the number of observations used for each measure.

** The complete standard deviations (SD) and standard errors (SEM) for m_b^{ab} including the uncertainty of the station corrections.

Amplitudes and Magnitudes for some U.S. events

Event	Announced Yield (kt)	A^{ab}	A^{bc}	m_b^{ab}	m_b^{bc}
LONGSHOT	80	189			5.8++
MILROW	1000	947			6.4++
CANNIKIN	5000	2414			6.6++
SCOTCH	155	104	156	5.39	5.57
HALFBEAK	365	251	386	5.81	6.00
GREELEY	870	422	592	6.09	6.24
BENHAM	1150	505	746	6.16	6.33
BOXCAR	1300	472	668	6.12	6.27

++ ISC m_b corresponds to m_b^{bc}

Intercorrelation analysis

The amplitude data show a large amount of scatter, presumably due to differing path and receiver effects. Because of this scatter, yield estimates based on amplitude or m_b rely on obtaining numerous data from all azimuths so that an accurate average can be obtained. The complete waveform approach is free of these uncertainties because it (inherently) accounts for receiver and path complexities. Furthermore, intercorrelation can account for differences in the sources, such as varying corner frequency, overshoot, or burial depth, which may affect the amplitudes. Fig. 3 shows short-period *P*-waves from five NNZ events. The waveforms change substantially from station to station for a given event due to differing propagation effects. Also, the *P*-waves at a given station evolve with explosion size due to changes in source time function and burial depth. It is thus desirable to account for the effects of variable source functions and *pP* arrivals in the analysis of these signals.

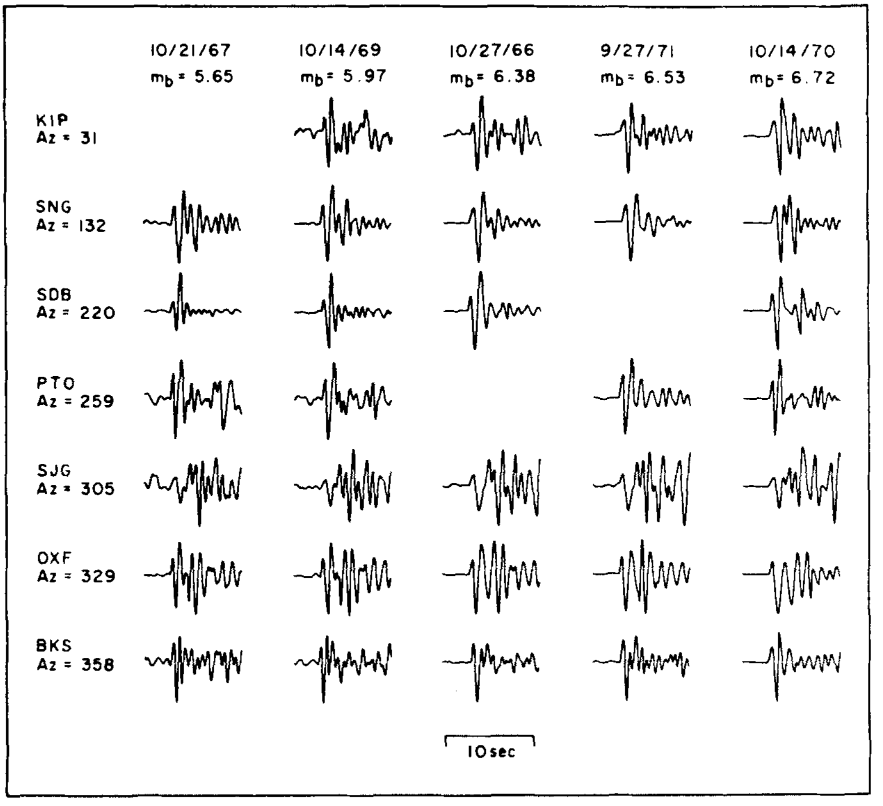

Figure 3. Comparison of short-period P-waves from several NNZ events recorded at WWSSN stations.

Preliminary forward modelling calculations for the 10/21/67 event showed that pP lag times of less than 0.7 s were required to match the simple P-waves at numerous stations (Burger *et al.* 1985). Such short lag times may bias amplitude or m_b measurements due to pP interference with direct P. The comparison of intercorrelation and amplitude relative size

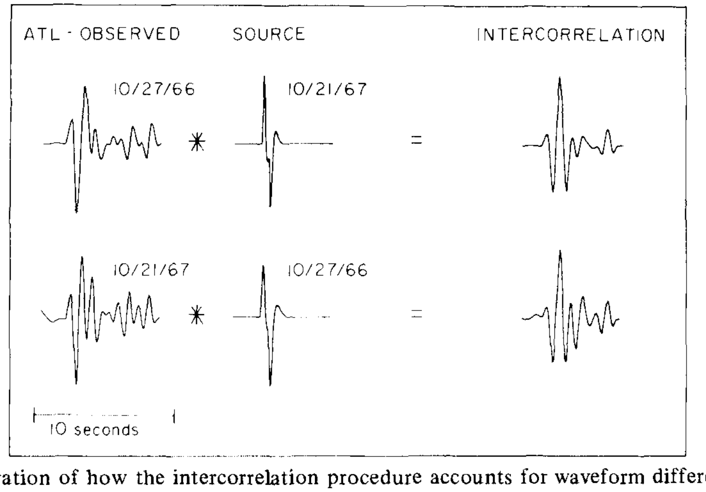

Figure 4. Illustration of how the intercorrelation procedure accounts for waveform differences produced by the source. The observed P-wave is convolved with the effective source function of the other event. The effective source function includes the pP arrival and the explosion time function.

estimates will address the question of whether variations of the effective source functions, including the *pP* arrival, influence the amplitude results.

The intercorrelation procedure is illustrated in Fig. 4 (following Lay *et al.* 1984a and Lay 1985). Each seismogram from one event is convolved with the source function and a spike train representing direct *P* and *pP* for another event. The seismograms from the other event are convolved with the source function and $P + pP$ spike train of the first event. The two intercorrelation waveforms at each station are then analytically compared to each other, and source models that produce the best waveform match are found. The intercorrelation procedure is applied to many stations simultaneously.

To incorporate differences in explosion source functions, it is necessary to adopt a parameterized description of the explosion source. Such parameterizations are abundant in the literature (Mueller & Murphy 1971; von Seggern & Blandford 1972; Helmberger & Hadley 1981). We follow Lay *et al.* (1984a) and Lay (1985) in adopting the modified Haskell source model given by

$$\psi(t) = \psi_\infty [\![1 - \exp(-Kt)[1 + Kt + (Kt)^2/2 - B(Kt)^3]]\!], \qquad (2)$$

where ψ_∞ is the DC source strength, K is a rise–time parameter, and B controls the time function overshoot. The parameters ψ_∞ and B trade-off inversely in narrow-band data, so we are unable to resolve these parameters uniquely. However, for a given value of B (we choose $B = 1$), there is a unique value of ψ_∞.

Allowing for source function corner frequency scaling with yield requires that we estimate values of K. In the previous studies of U.S. tests, direct measurements of K were available from near-field modelling for several events. However, similar information is not presently available for Soviet tests. We estimated values of K for each Novaya Zemlya event based on empirical relations between K, A^{ab} and yield from the previous NTS modelling, with modifications for average t^* ($t^* = 0.5$ s was assumed for Novaya Zemlya). Burger *et al.* (1985) give the detailes of this calculation, and Table 3 presents the results. While the absolute values of K are uncertain, the relative values have appropriate yield scaling of the source functions.

The intercorrelation waveforms for each station pair are analytically compared using two norms. The waveform norm is given by

$$N_W = \frac{1}{n} \sum_{i}^{n} (1 - CCC_i), \qquad (3)$$

Table 3. Estimated K-values.

Event	K (1/sec)
10/27/66	8.4
10/21/67	12.1
11/07/68	10.9
10/14/69	10.2
10/14/70	6.8
9/27/71	7.8
8/28/72	9.0
9/12/73	6.6
8/29/74	8.3
8/23/75	8.4
10/21/75	8.5
9/27/73	13.3
10/27/73	6.0
11/02/74	6.9
10/18/75	7.8

where n is the number of stations for a given pair of events and CCC_i is the normalized cross-correlation coefficient for the ith station. N_W is most sensitive to differences in the zero crossings between two signals and is often used in waveform inversion studies. The optimal *pP* parameters are chosen on the basis of minimizing N_W. Absolute amplitude information is retained in the amplitude norm, given by

$$N_a = \frac{1}{n}\sum_{i}^{n} \int_t [I_i(t) - J_i(t)]^2 dt, \tag{4}$$

where $I_i(t)$ and $J_i(t)$ are the intercorrelated waveforms. For the optimal *pP* parameters, the

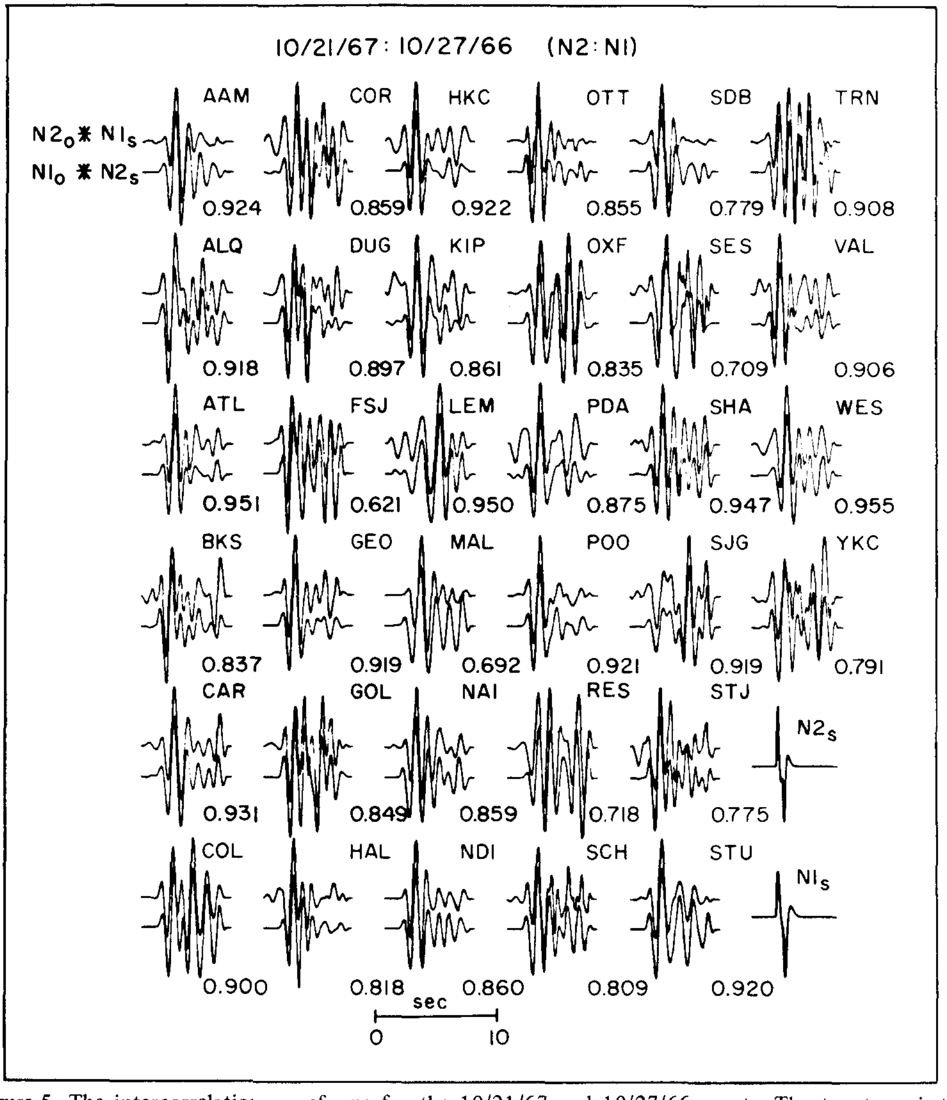

Figure 5. The intercorrelation waveforms for the 10/21/67 and 10/27/66 events. The top trace is the 10/21/67 observed signal convolved with the effective source function of 10/27/66. The bottom trace is the 10/27/66 observation convolved with the 10/21/67 effective source function. The numbers shown are normalized cross-correlation coefficients for each pair. The effective source functions for each event are given at the lower right.

amplitude norm is minimized to determine the relative source strength, or ψ_∞ ratio between the events.

The parameters in the effective source model are the values of *pP* delay (*pP*–*P*) and *pP* reflection coefficient ($|pP|/|P|$). The intercorrelations were performed for variable *pP* models for both events until the optimal *pP* parameters were found. A seven second time window was used. For each event, *pP*–*P* was allowed to vary between 0.3–1.0 s and $|pP|/|P|$ was allowed to range between 0.3 and 1.2. This procedure differs from the previous applications of intercorrelation, which used reference events with fixed *pP* parameters. The intercorrelation procedure was applied to all possible combinations of eleven NNZ events to determine their relative sizes and *pP* parameters. This was also done for the four SNZ events separately. In order to relate the relative size of events in the two subsites, two NNZ events (10/21/67 and 9/27/71) were intercorrelated with the SNZ events.

It was found that an absolute minimum N_W existed for each event-pair intercorrelation, thereby determining the optimal source models. The intercorrelation waveforms and source models for 10/21/67:10/27/66 are shown in Fig. 5. For this event-pair; $N_W = 0.1415$, $pP–P = 0.55$ and $|pP|/|P| = 0.85$ for 10/21/67; and $pP–P = 0.6$ and $|pP|/|P| = 1.1$ for

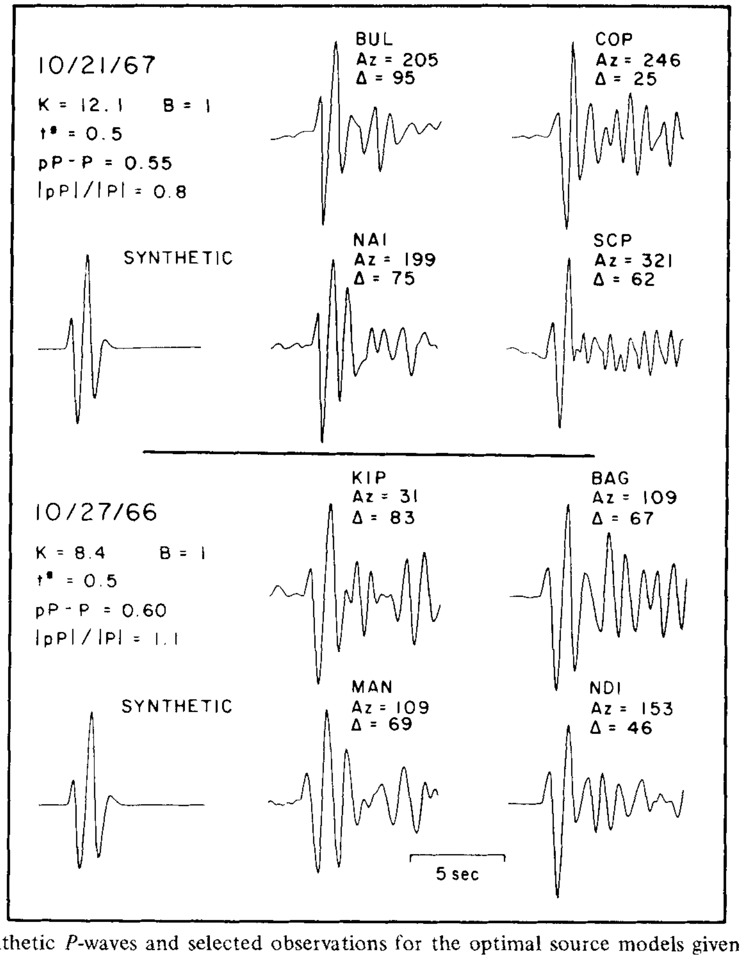

Figure 6. Synthetic *P*-waves and selected observations for the optimal source models given in Fig. 5 for the 10/21/67 and 10/27/66 events.

10/27/66. In this example, we have 34 estimates of $\psi_{\infty 66}/\psi_{\infty 67}$, with an average value of 5.10.

To check the intercorrelation results, synthetic *P*-waves were computed for the source models in Fig. 5. Fig. 6 shows synthetic seismograms and selected observations for the 10/21/67 and 10/27/66 events. Using the optimal source models and $t^* = 0.5$ s, we can estimate absolute values for ψ_∞ by matching the average *ab* amplitudes observed for each event. For the 10/21/67 event, $\psi_\infty = 1.7 \times 10^{10}\,\mathrm{cm}^3$, and for the 10/27/66 event, $\psi_\infty = 8.7 \times 10^{10}\,\mathrm{cm}^3$. These ψ_∞ values differ by a factor of 5.12, consistent with the relative size obtained by intercorrelation (5.10). The absolute values of ψ_∞ are dependent on the choice of t^*. For the 10/21/67 event, a $t^* = 0.65$ gives $\psi_\infty = 2.7 \times 10^{10}\,\mathrm{cm}^3$, whereas a $t^* = 0.35$ gives $\psi_\infty = 0.94 \times 10^{10}\,\mathrm{cm}^3$. Thus, absolute scaling cannot be achieved without a reliable t^* estimate or without an absolute ψ_∞ determined from near-field modelling. Because of this tradeoff, we are primarily concerned with estimating the relative size of the Novaya Zemlya tests. To match the m_b^{ab} value of the 10/21/67 event requires ψ_∞ 1.1×10^{10} cm^3, a factor of 1.5 smaller than from matching A^{ab}. This is due to the different averaging algorithms used in determining the average amplitudes (normal) and magnitudes (log-normal). We will present absolute yield estimates based on the ψ_∞ values from matching the amplitude data.

Burger *et al.* (1985) give detailed results for each intercorrelation of the Novaya Zemlya events, including individual event-pair *pP* parameters, relative size, and waveform norms. This paper will summarize those results. The average values of *pP–P* and $|pP|/|P|$ for each event are given in Table 4. For each intercorrelation pair, we found that the optimal *pP–P* delay times were better resolved (on the basis of an absolute waveform norm) than the optimal $|pP|/|P|$ ratios. The intercorrelation technique is more sensitive to relative *pP* differences than to absolute *pP* parameters. Lay *et al.* (1984a) found that introducing a third arrival, representing spall, for Amchitka event intercorrelations changed the optimal *pP–P* delays by less than 0.1 s. Furthermore, the relative source strength estimates were changed

Table 4. Intercorrelation results.

Event	pP-P (sec)•	|pP| / |P|•	$\psi_\infty/\psi_{\infty REF}$**
10/27/66	0.74	1.04	5.26±1.91 (0.43)
10/21/67	0.56	0.80	1.0 ±0.42 (0.11)
11/07/68	0.58	1.04	1.53±0.54 (0.12)
10/14/69	0.64	1.00	2.22±0.74 (0.16)
10/14/70	0.65	0.95	11.29±4.34 (1.01)
9/27/71	0.73	1.06	7.47±2.55 (0.66)
8/28/72	0.66	1.06	4.10±1.44 (0.36)
9/12/73	0.71	1.15	16.24±7.80 (2.20)
8/29/74	0.71	1.12	5.44±2.00 (0.48)
8/23/75	0.62	1.08	5.28±1.90 (0.45)
10/21/75	0.69	1.05	4.96±2.33 (0.56)
9/27/73	0.55	0.97	0.68±0.22 (0.06)
10/27/73	0.70	1.18	20.49±7.87 (2.71)
11/02/74	0.58	1.10	10.85±4.00 (1.10)
10/18/75	0.55	0.95	8.53±3.40 (1.00)

• The pP parameters for NNZ events are from NNZ:NNZ intercorrelations. The pP parameters for SNZ events are from SNZ:SNZ intercorrelations.

** The source strength relative to the 10/21/67 NNZ event. The numbers following the ± are the complete standard deviations and the numbers in ( ) are the complete standard errors.

by only a few percent. Thus, these *pP* estimates are considered to be 'effective' *pP* parameters, appropriate to the degree to which the simple source parameterization is valid. However, the *pP* estimates for Amchitka events are in close agreement with independent results. The *pP* behaviour of the Novaya Zemlya events will be further discussed later in this paper.

One of the benefits of applying intercorrelation to all possible event-pairs is that it removes any bias caused by anomalous or incorrect master event information. This process is also statistically more appealing. Lay (1985) demonstrated that different master events give different estimates, thus the use of all events on an equal basis provides an improved statistical average of relative size. In order to combine the relative size estimates from different events, a least-squares procedure was used. Multiplicative factors were found for each of the 15 Novaya Zemlya events that simultaneously minimized the scatter in the relative ψ_∞ estimates for the events. The multiplicative factors are then removed in order to put all the relative size estimates on a common baseline. The relative source strengths were computed with the 10/21/67 NNZ event as the reference. Thus all source strengths are relative to the 10/21/67 ψ_∞, and are given as $\psi_\infty/\psi_{\infty\mathrm{REF}}$. The mean relative source strengths, standard deviations and standard errors are given in Table 4. The standard deviations and standard errors include both the scatter in the mean relative event size estimates from combining different master events as well as the station-to-station scatter in each intercorrelation event-pair relative size estimate. The latter uncertainty (20–40 per cent standard deviation) is typically larger than the former. The total variance is the sum of the variance of the mean estimates and the average variance of each individual intercorrelation relative size estimate including that event.

The source strengths of the southern events are given relative to the reference northern event. The true relative size between northern and southern events will be the same as the estimated relative sizes if the two subsites have identical source velocity and t^* properties. If this were not the case, we could modify the SNZ sizes by a simple correction factor, which may or may not be frequency dependent, appropriate for a NNZ–SNZ t^* bias or velocity difference. This will not be considered in this analysis, but any estimation of absolute yields must include the possibility of such baseline differences.

Comparison of intercorrelation and amplitude results

The relative source strength can be estimated from the amplitude and magnitude measurements through simple ratioing of amplitudes. Table 5 gives the source strength estimates relative to the 10/21/67 event from A^{ab}, A^{bc}, m_b^{ab}, and m_b^{bc} measurements compared to the intercorrelation estimates.

Linear regressions of the amplitude and magnitude data were performed on the intercorrelation relative size estimates. Fig. 7 shows the results for the magnitude comparisons. The resulting linear regression curves are given by

$$\log(A^{ab}) = (2.455 \pm 0.0175) + (0.9458 \pm 0.0218)\log(\psi_\infty/\psi_{\infty\mathrm{REF}}), \quad (5)$$

$$\log(A^{bc}) = (2.613 \pm 0.0209) + (0.9429 \pm 0.0261)\log(\psi_\infty/\psi_{\infty\mathrm{REF}}), \quad (6)$$

$$m_b^{ab} = (5.654 \pm 0.0173) + (0.9922 \pm 0.0216)\log(\psi_\infty/\psi_{\infty\mathrm{REF}}), \quad (7)$$

$$m_b^{bc} = (5.810 \pm 0.0214) + (0.9826 \pm 0.0267)\log(\psi_\infty/\psi_{\infty\mathrm{REF}}). \quad (8)$$

The standard deviations for both slope and intercept are small and the coefficients of regression are 0.9966, 0.9951, 0.9969, and 0.9952, respectively. This indicates that the log amplitude and magnitude measurements follow well-defined linear trends with the inter-

Table 5. Relative size estimates from intercorrelation, amplitude, and magnitude measurements.

Event	Intercorrelation	A^{ab}	A^{bc}	m_b^{ab}	m_b^{bc}
10/21/67	1.0	1.0	1.0	1.0	1.0
11/07/68	1.53	1.55	1.59	1.48	1.58
10/14/69	2.22	2.08	2.04	2.09	2.15
8/28/72	4.10	3.54	3.49	3.98	3.89
10/21/75	4.96	4.38	4.62	4.90	5.13
10/27/66	5.26	4.52	4.30	5.25	5.13
8/23/75	5.28	4.69	4.55	5.25	5.13
8/29/74	5.44	4.74	4.85	5.37	5.50
9/27/71	7.47	6.37	6.15	7.58	7.24
10/14/70	11.29	10.93	11.59	11.75	12.19
9/12/73	16.24	12.80	13.12	15.10	14.09
9/27/73	0.681	0.682	0.784	0.741	0.873
10/18/75	8.53	6.10	6.90	6.71	7.74
11/02/74	10.85	10.12	10.96	11.86	13.12
10/27/73	20.49	18.86	19.50	21.53	22.75

correlation relative size estimates. The slopes of less than unity indicate that the amplitude and magnitude data on average slightly underestimate relative size with respect to intercorrelation.

The following general conclusions may be drawn from the comparison of relative sizes and the regression analysis. First, *ab* measurements agree with the intercorrelation results more closely than do the *bc* measurements. This is attributed to the greater effect of *pP* on the *bc* cycle. Second, the m_b measurements tend to agree with the intercorrelation estimates slightly better than the amplitude data. This may be the result of the period correction made in the magnitude analysis, which may help account for differences in K between events. Thus, m_b^{ab} is considered to be the best of the four amplitude measurements. However, none of the amplitude measurements differ significantly from the intercorrelation results,

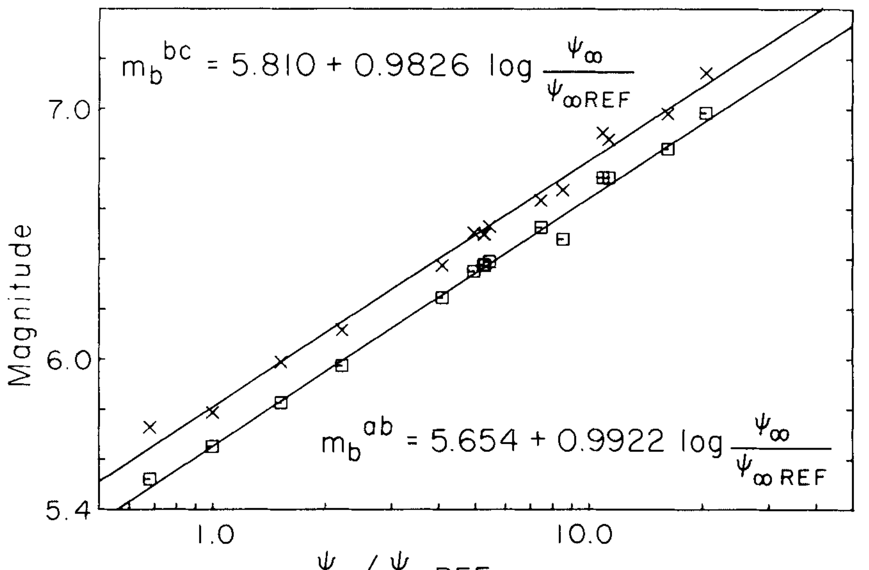

Figure 7. Linear regression of magnitude on relative size. Magnitudes are given in Table 2 and relative size estimates are given in Table 4.

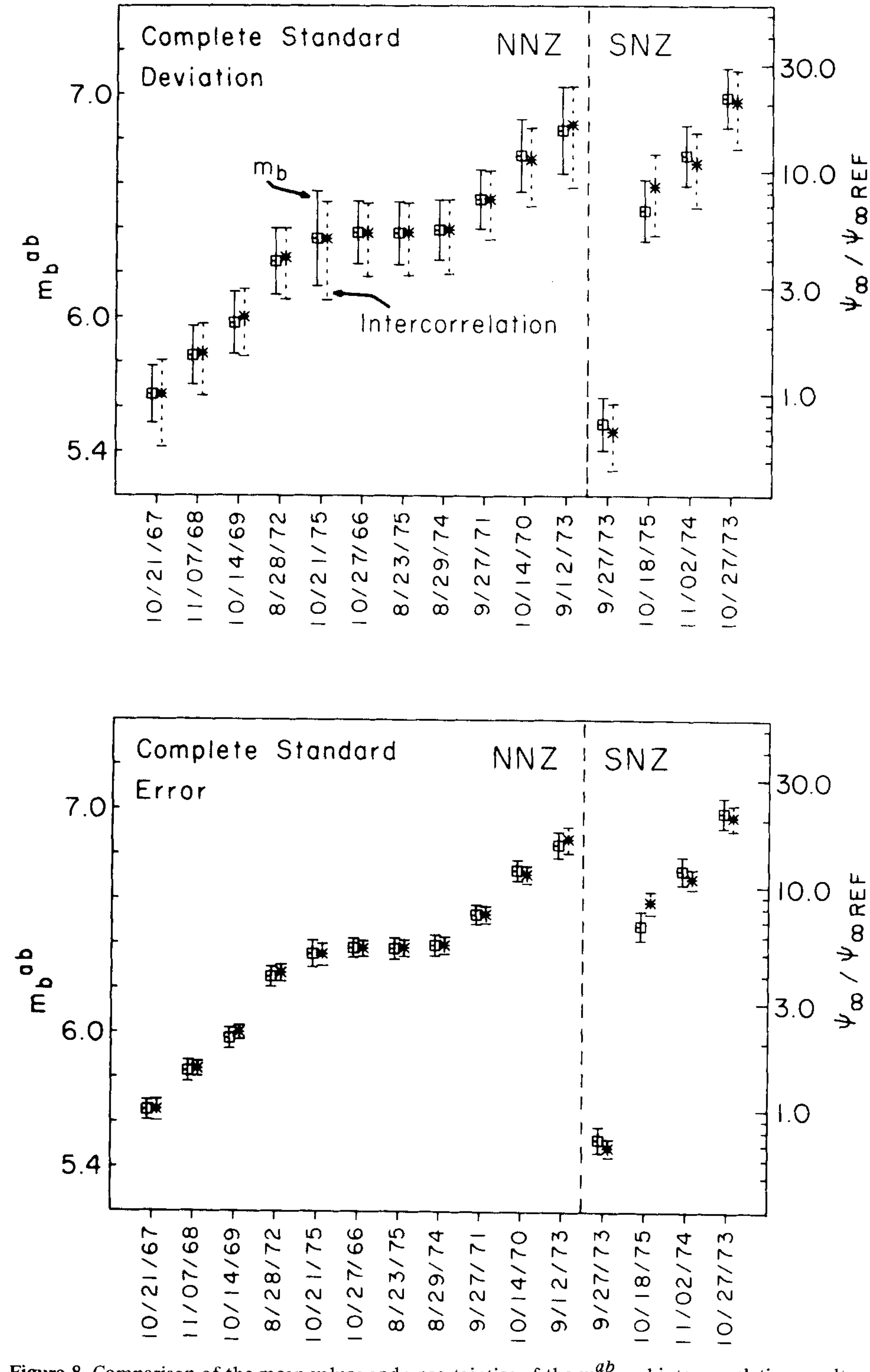

Figure 8. Comparison of the mean values and uncertainties of the m_b^{ab} and intercorrelation results.

indicating that variable source functions and *pP* interference do not degrade the amplitude or magnitude results for the Novaya Zemlya explosions.

Fig. 8 shows the comparison of the m_b^{ab} and intercorrelation mean values and uncertainties. The uncertainties of the intercorrelation results are given in Table 4 and the uncertainties of the m_b^{ab} results are the complete standard deviations and standard errors given in the last two columns of Table 2. The mean values and uncertainties are shown to be similar for both types of analyses. The standard deviations of the intercorrelation results are slightly larger than those of m_b^{ab}, but the standard errors of m_b^{ab} are slightly larger than those of intercorrelation. The largest contributor of uncertainty in the intercorrelation values is the station-to-station scatter in an individual intercorrelation event-pair. This type of scatter is attributed to differences in near-source structure or in later phases such as caused by spall or tectonic release. These could be identified by larger intercorrelation wave-form mismatches and could thus form the criterion for excluding anomalous data from the averaging, thereby improving the mean estimates and reducing the uncertainty in the inter-correlation results.

Seismic yield estimates

While relative source strengths can be reliably determined, there is much greater uncertainty in estimating the absolute yields. Two basic parameters must be known for each test site. These are the baseline of the ψ_∞-yield relation and the yield-scaling slope. For the Amchitka test site, Lay *et al.* (1984a) found that for $B = 1$,

$$\log \psi_\infty = 8.95 + 0.728 \log Y. \tag{9}$$

This relation differs in both baseline and slope from that obtained from Pahute Mesa by Lay (1985), which has $\log \psi_\infty \alpha\, 0.86 \log Y$. The latter relation is closer to the theoretical long-period scaling of $\log \psi_\infty \alpha\, 0.89 \log Y$ (Bache 1982). Lay, Helmberger & Harkrider (1984c) showed that in order to match the long-period observations from Amchitka, Equation (9) must be modified to allow for decreasing B with increasing yield. The question arises

Table 6. Estimated yields (kt) from intercorrelation.

Event	Equation (9)*	Equation (10)**
10/27/66	600	395
10/21/67	61	61
11/07/68	110	98
10/14/69	183	150
10/14/70	1714	932
9/27/71	973	586
8/28/72	426	298
9/12/73	2824	1402
8/29/74	629	410
8/23/75	604	397
10/21/75	554	370
9/27/73	36	40
10/27/73	3886	1820
11/02/74	1624	891
10/18/75	1166	680

* Amchitka ψ_∞-yield scaling.

** Theoretical ψ_∞-yield scaling.

whether B varies with yield at Novaya Zemlya as well. This can only be answered by a future study of broad-band signals.

Since we kept $B = 1$, we estimate yield using (9), as well as using the theoretical scaling,

$$\log \psi_\infty = C + 0.89 \log Y. \tag{10}$$

To obtain absolute ψ_∞ values, we use the results of the previous forward modelling with $t^* = 0.5$, which gave $\psi_\infty = 1.7 \times 10^{10}\ \text{cm}^3$ for the 10/21/67 event. The constant in Equation (10) is set at 8.64 so that we obtain the same yield for the 10/21/67 event as obtained from (9). The resulting yield estimates for the Novaya Zemlya events are given in Table 6. The difference in the slopes of the yield scaling relations results in a factor of two difference in the yield estimates for the largest events. If we assume $t^* = 0.65$, all of the yields would be larger by a factor of 1.9, whereas a t^* of 0.35 would decrease the yield estimates by a factor of 0.44. The absolute levels are also uncertain due to the assumption that the coupling is the same for both Amchitka and Novaya Zemlya. Clearly, calibration events are the only feasible means of reducing these baseline and scaling problems.

pP behaviour

It is important to study *pP* behaviour due to its effects on estimating yield from m_b measurements. Fig. 9 gives the *pP–P* delay times as a function of estimated yield (from Equation 9) for the Novaya Zemlya events. As expected, *pP–P*, an indicator of burial depth, increases with yield. There are two general populations of events shown in Fig. 9. The three largest SNZ events (darkened) and the 10/14/70, 9/12/73, and 8/23/75 NNZ events (circled) are one population. The remaining eight NNZ events and smallest SNZ event comprise the other population. The latter population of NNZ events exhibits a clear linear relation

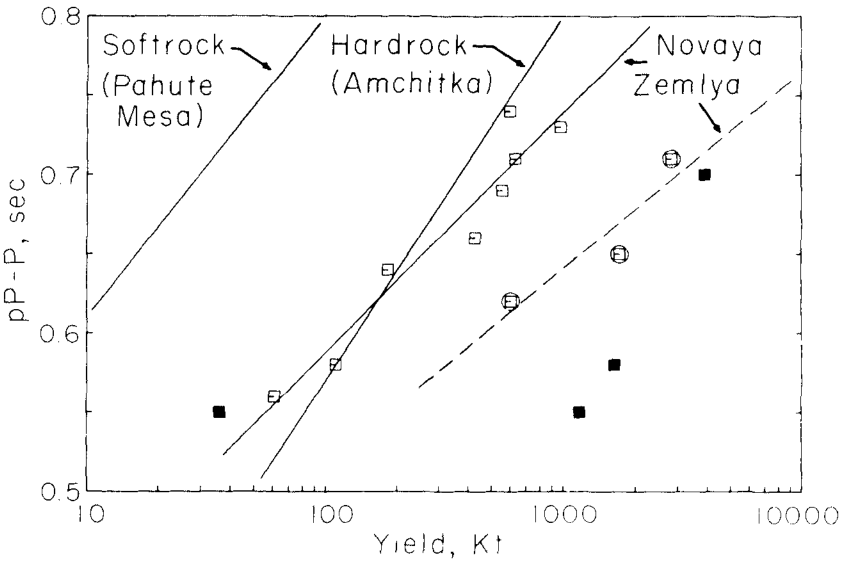

Figure 9. *pP–P* delay times as estimated from the intercorrelation analysis as a function of yield. The SNZ events are darkened. The Novaya Zemlya events not belonging to the normal population of NNZ events are circled. Linear relations for *pP–P* versus log yield are shown for Novaya Zemlya, Amchitka, and Pahute Mesa events.

between $pP\text{–}P$ and log yield as shown by the solid line. This relation is given by

$$pP\text{–}P\,(\text{sec}) = 0.28 + 0.15 \log Y(\text{kt}) \qquad (11)$$

The largest SNZ events and the three outlying NNZ events have smaller *pP* delay times than the normal NNZ population. The linear regression of the NNZ events with earlier *pP* arrivals is given by the dashed line in Fig. 9. The smaller *pP* delay times indicate that those events were either underburied or detonated in faster material.

The three largest SNZ events have even smaller *pP* times than the circled NNZ events. It is surprising that the smallest SNZ event (9/27/73) has nearly the same *pP* delay as SNZ events more than 30 times its yield. This would indicate that the 9/27/73 event was either overburied or it was detonated in very different material than other SNZ events.

It is interesting to compare the Novaya Zemlya $pP\text{–}P$ delay times with events from a hardrock test site (Amchitka) and a softrock test site (Pahute Mesa). Lay *et al.* (1984a) obtained *pP* delay times for Amchitka events. Using those times for MILROW (0.8 s, $Y = 1000\,\text{kt}$) and LONGSHOT (0.55 s, $Y = 80\,\text{kt}$), we obtain the expected $pP\text{–}P$ – log yield relation for a hardrock site shown in Fig. 9. The normal population of NNZ events have *pP* delay times similar to the Amchitka relation, confirming that Novaya Zemlya is a hardrock site. Furthermore, these *pP* delay times are much smaller than those for Pahute Mesa. The regression of *pP* delay times (from Lay 1985) for Pahute Mesa events is also given in Fig. 9.

Fig. 10 gives the $|pP|/|P|$ estimates as a function of yield. The $|pP|/|P|$ relative amplitude generally increases with size. We have allowed the *pP* reflection coefficient to be greater than 1 because of the uncertain nature of *pP* in explosion signals. Anelastic processes such as spall are thought to account for $|R_{pp}|$ observation being greater than 1, as well as longer than expected $pP\text{–}P$ times (Burdick, Wallace & Lay 1984). Three events in particular appear to have anomalously low *pP* reflection coefficients: 10/21/67, 10/14/70 from NNZ and 10/18/75 from SNZ. The *pP* reflection coefficients for the Amchitka events are also shown on Fig. 10. The Novaya Zemlya $|pP|/|P|$ amplitudes are larger than the Amchitka amplitude ratios, suggesting that different anelastic processes are operating at the two test sites.

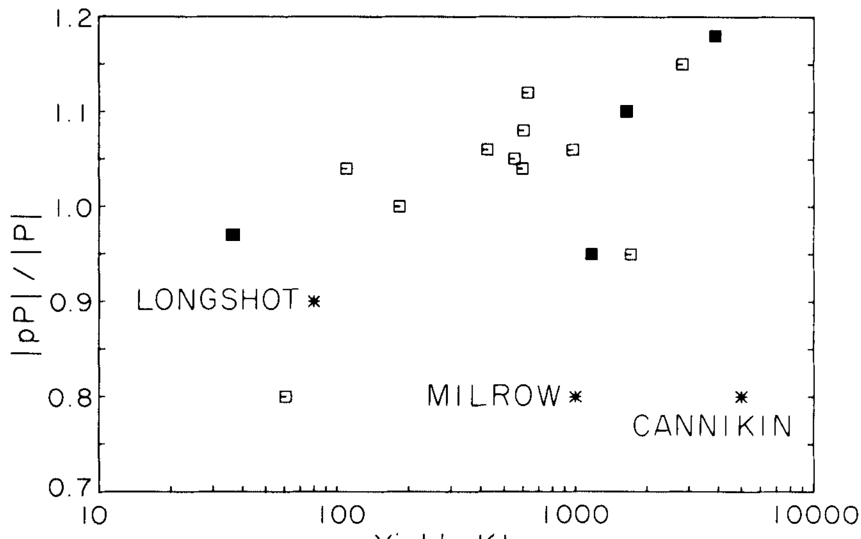

Figure 10. *pP* reflection coefficients as estimated from the intercorrelation analysis as a function of yield. The SNZ events are darkened. The *pP* reflection coefficients for the Amchitka tests are shown as stars.

Anomalous events

A complete waveform analysis lends itself to the identification of anomalous events (Lay 1985), as demonstrated for NTS. Anomalous events are generally thought to be the result of either anomalous *pP* or spall arrivals, or tectonic release. Events that are characteristically different in some aspect not accounted for by the source parameterization will have large waveform norms. This section identifies anomalous events at Novaya Zemlya and confirms that NNZ and SNZ events are substantially different from one another.

Lay *et al.* (1984a) and Lay (1985) show that N_W normally increases as the relative size between intercorrelated events increases. Fig. 11 shows N_W for Novaya Zemlya intercorrelations with the 10/21/67 NNZ event plotted as a function of source strength, demonstrating that N_W increases with relative size for NNZ events. Thus, to avoid misleading N_W results, we compared the waveform norms between events of the same size. Six events are particularly suited for this analysis; 10/27/66, 9/27/71, 8/28/72, 8/29/74, 8/23/75, and 10/21/75 in NNZ. Of these six events, the 10/21/75 event gives systematically large waveform mismatches. However, when the 10/21/75 event is intercorrelated with much larger NNZ events, the waveform norms are small, indicating that the 10/21/75 event behaves more like a larger explosion. There is no evidence of an anomalous *pP* arrival for the 10/21/75 event since its *pP* parameters are not different from other events with similar yield. Furthermore, the tectonic release from the 10/21/75 event is not particularly different from other events (Burger *et al.* 1986). Nevertheless, the systematically different waveforms for the 10/21/75 event indicate that it is an anomalous event. The cause for this is not known.

The intercorrelation results strongly suggest that the 10/18/75 SNZ explosion is a particularly anomalous event. Even when intercorrelated with other SNZ events, large waveform norms are found for this event. The azimuthal amplitude pattern of the 10/18/75 event is not dramatically different from other SNZ events. However, its relative size determined from amplitude measurements does differ somewhat from the intercorrelation estimates –

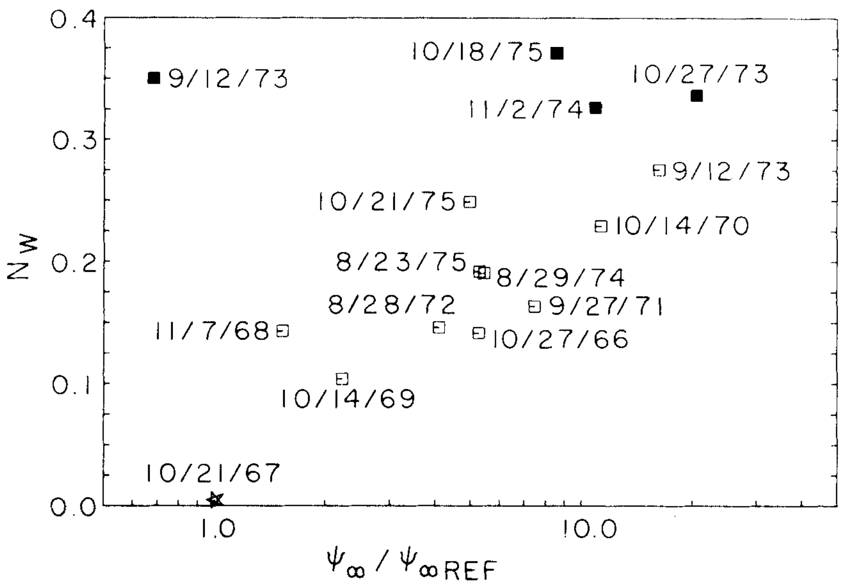

Figure 11. The waveform norms for the 10/21/67 NNZ event intercorrelated with all the Novaya Zemlya events as a function of size. The SNZ events are darkened. The star denotes the 10/21/67 relative size.

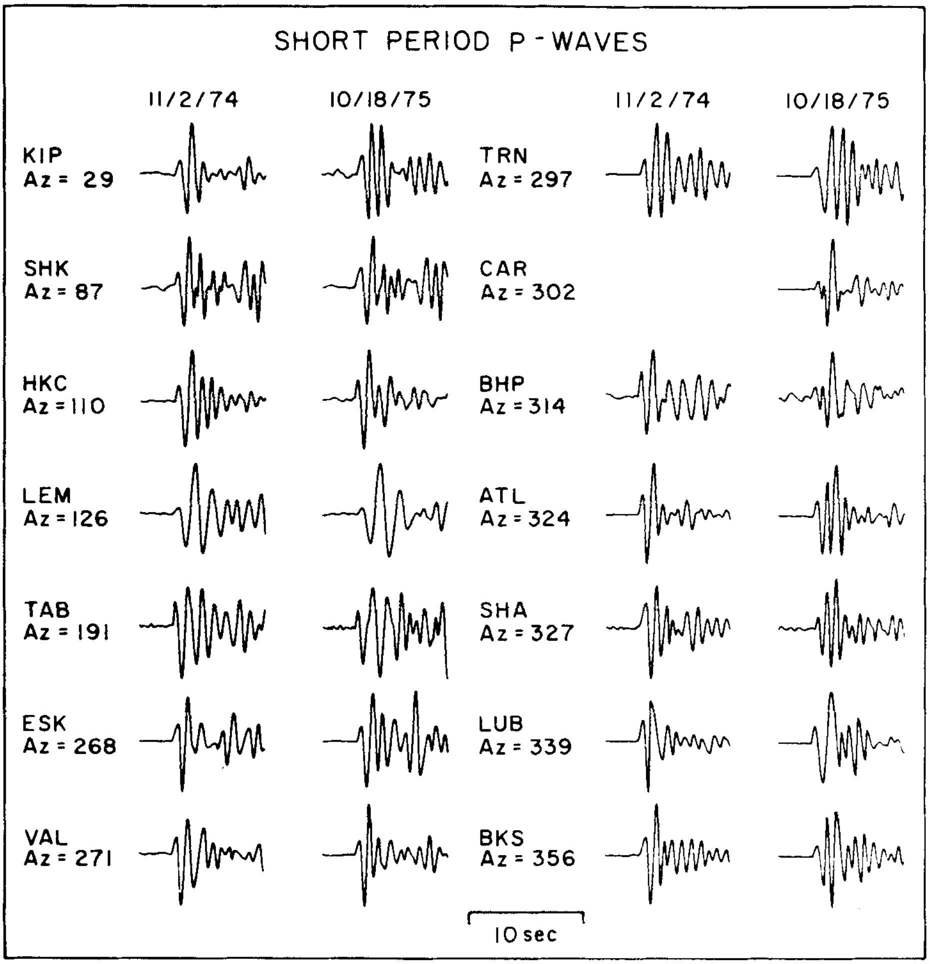

Figure 12. Comparison of short-period *P*-waves from the 11/2/74 and 10/18/75 SNZ events. Note the differences in waveforms at common stations.

more so than for other events. Short-period and long-period *P*-waveforms seem to indicate an interference phenomenon occurring for this event. Fig. 12 shows short-period *P*-waves from the 11/2/74 and 10/18/75 events at several stations. The 11/2/74 event is similar in size to the 10/18/75 event, thus one would not expect large differences in the waveforms. At many stations, such as SHK, HKC, LEM, and TRN, the waveforms are similar. But at several stations, particularly KIP, BHP, and ATL, the waveforms are distinctly different. At those stations with dissimilar waveforms, there seem to be additional cycles in the waveform (i.e. KIP, ATL, etc.) or very different waveforms (i.e. CAR and BHP). Explosions of similar size (and presumably burial depth and frequency content) should not exhibit such differences.

Fig. 13 shows long-period *P*-waves at several stations. Once again, many stations have similar waveforms, but several stations clearly exhibit a split first upswing in the *P*-waves of the 10/18/75 event that is not present for the 11/2/74 event. This is most evident in the observations at stations COL, KBL, NAI and IST. Furthermore, the split *P*-waves are only

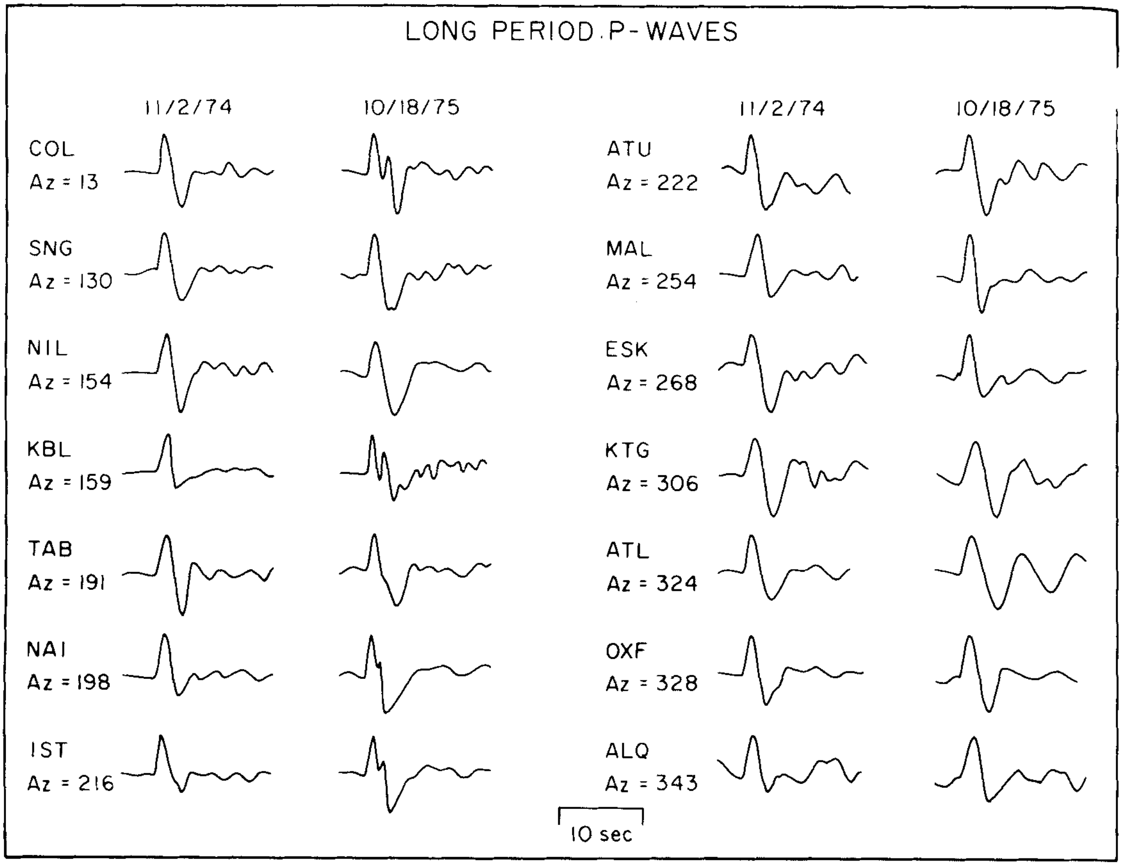

Figure 13. Comparison of long-period *P*-waves from the 11/2/74 and 10/18/75 SNZ events. Note the split first upswing in the 10/18/75 observations at COL, KBL, TAB, NAI, and IST.

observed at azimuths around 15° (COL) and around 195° (NAI, etc.), 180° apart from each other.

A near-source velocity discontinuity might result in such an interference phenomenon, but it is not likely that it would be observed in only narrow ranges of azimuth. It is possible that an azimuthally varying source such as tectonic release or asymmetric spall could account for the anomalous nature of the 10/18/75 event. However, Burger *et al.* (1986) found that the 10/18/75 event does not appear to have an unusually large component of tectonic release. Asymmetric spall or anomalous source coupling should still be considered, but their effects are difficult to predict given our present knowledge of these processes.

One reasonable explanation is that two explosions set off simultaneously, but separated in space, could cause an azimuthally varying interference phenomena. At some azimuths, the travel times from the two events would be nearly identical, resulting in a simple, constructive interference of pulses. But at certain azimuths (180° apart), the travel times would be sufficiently different such that a split pulse in the long-period *P*-waves could be observed.

Fig. 14 shows synthetic *P*-waves for the 10/18/75 event assuming a double explosion model. The stations are those for which observed waveforms are shown in Figs. 12 and 13. The synthetics are computed for two identical explosions separated by 21 km (along a line running 15° east of north) detonated simultaneously. Also shown are synthetics for a single

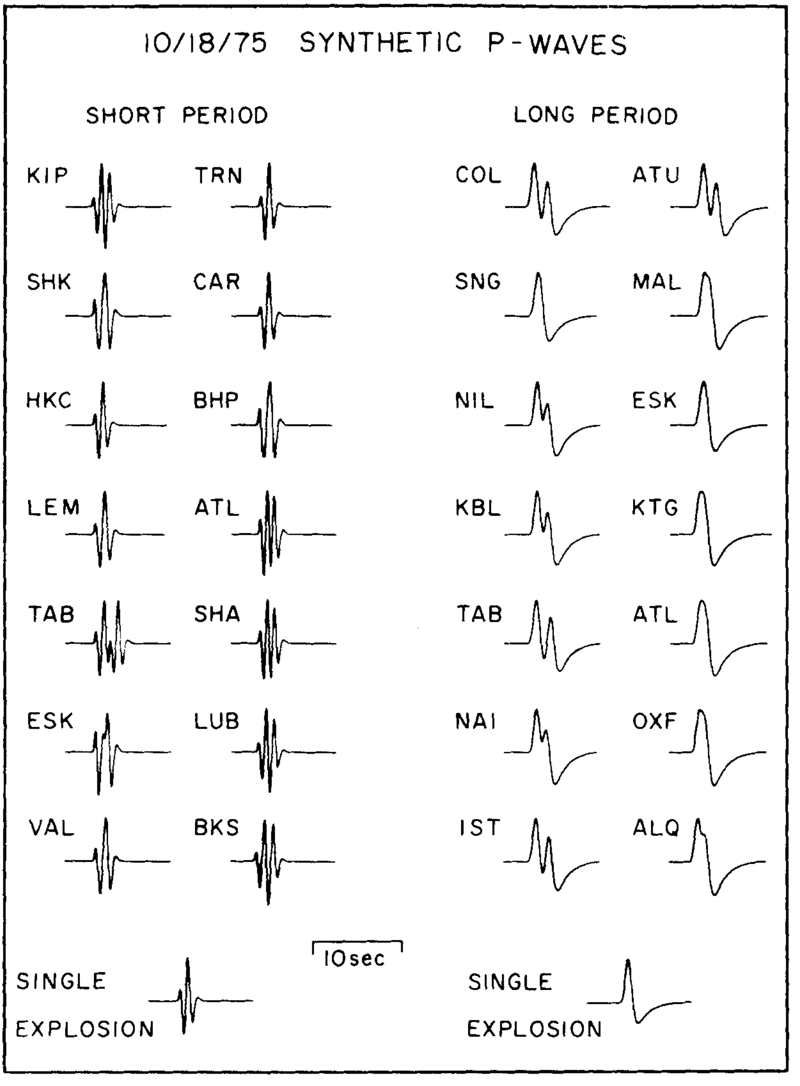

Figure 14. Synthetic short-period and long-period *P*-waves for the 10/18/75 SNZ event. The synthetics are computed for two explosions detonated simultaneously separated by 21 km. Short-period $t^* = 0.5$ s and long-period $t^* = 0.9$ s are assumed. Also shown are synthetic *P*-waves for a single explosion. *pP* delay is 0.55 s, *pP* relative amplitude is 0.9, and *K* is 7.8 (1/s).

explosion. A short-period t^* of 0.5 s and a long-period t^* of 0.9 s are used. There is general agreement of both short-period and long-period synthetics with the observations in terms of the complexity of the waveforms. Variations in t^* will either accentuate or obscure the complexity of the signals, particularly for the split long-period *P*-waves.

It is possible that more complicated models involving more than two explosions may better explain the observations. For now we will satisfy ourselves with the simple two-explosion model. Traveltime residuals predicted by the two explosion model are on the order of 0.6 s. The short-period analog recordings are unable to resolve such short time residuals. More accurate digital recordings could possibly solve this problem.

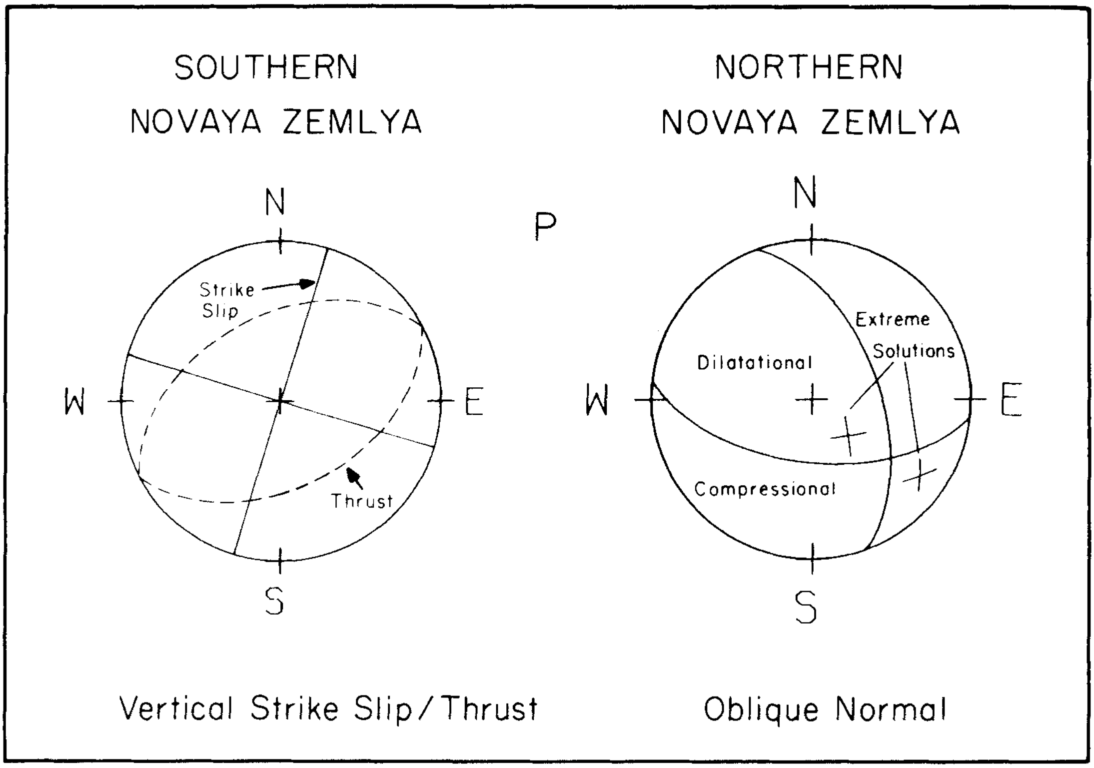

Figure 15. The *P*-wave radiation patterns for SNZ and NNZ tectonic release mechanisms. SNZ tectonic release is either vertical strike slip or 45° thrust and NNZ tectonic release is oblique normal. The extreme orientations for the NNZ double couple are also shown. (Modified from Burger *et al.* 1986.)

The amplitude and magnitude analyses discussed earlier demonstrate that NNZ and SNZ have different azimuthal amplitude patterns, suggesting that the two sites are characteristically different. The results of intercorrelation are consistent with this conclusion. Fig. 11 also shows the waveform norms for the SNZ events (darkened) as a function of size relative to the 10/21/67 event. The SNZ events have larger waveform norms than events of similar size from the north. Most dramatic is the 9/27/73 event which is a factor of 1.6 smaller than 10/21/67 but has an extremely large N_W (0.3498). Intercorrelations with the 9/27/71 NNZ event again result in larger N_W for the SNZ events than for events of similar yield from NNZ. The large waveform mismatches when SNZ events are intercorrelated with NNZ events indicates that the two subsites have different waveform patterns. It might be expected that the large spatial separation of the two subsites could contribute to the large mismatches due to slightly different source–receiver propagation paths from the two sites. On the other hand, the NTS event FAULTLESS (located 150 km from Pahute Mesa) did not have overly large waveform norms when intercorrelated with events at Pahute Mesa (Lay *et al.* 1985). Furthermore, the *pP* delay times of the SNZ events (Fig. 9) are generally smaller than NNZ events of the same yield. This confirms that the two subsites should be treated separately.

Discussion

So far, we have not allowed for varying *B* or additional arrivals from tectonic release of spall. The quality of the waveform fits confirms that parameterizing the effective source with only

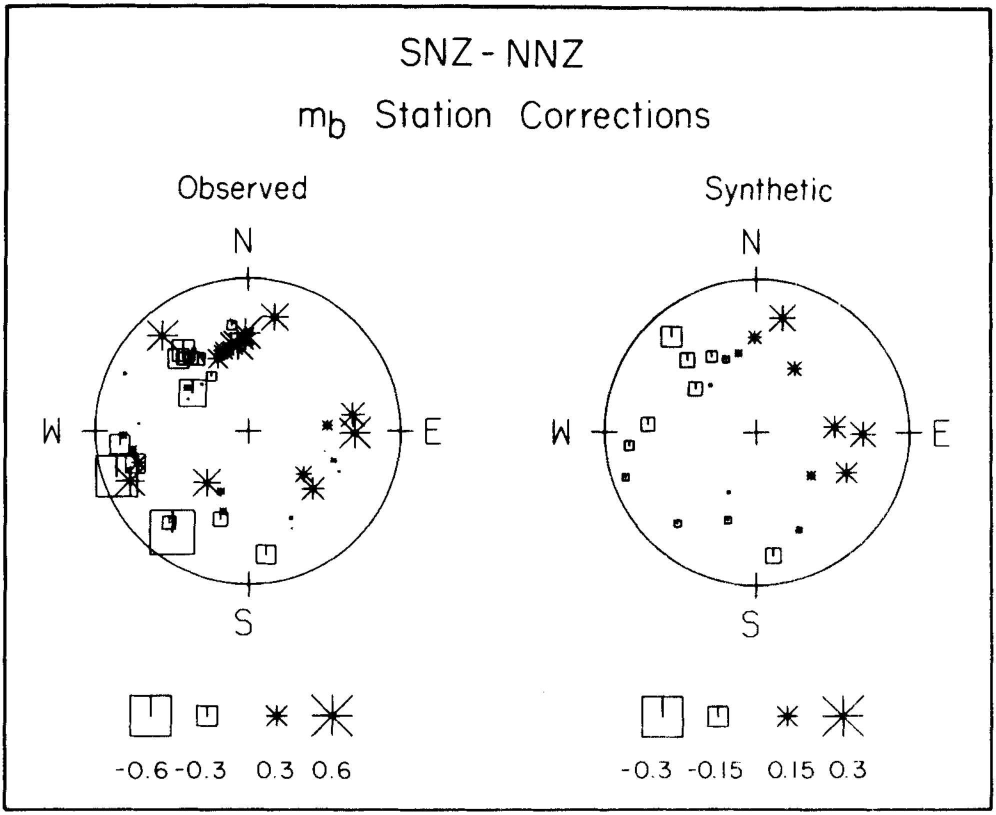

Figure 16. Comparison of observed (left) and synthetic (right) SNZ - NNZ magnitude station residuals.

direct P and pP arrivals is adequate. The effects of varying B would only result in different ψ_∞-yield relations. However, this could be accounted for given reliable calibration yields. For example, when B is allowed to vary for Amchitka tests, the ψ_∞-yield relation is different; but both relations accurately predict seismic yield using intercorrelation ψ_∞

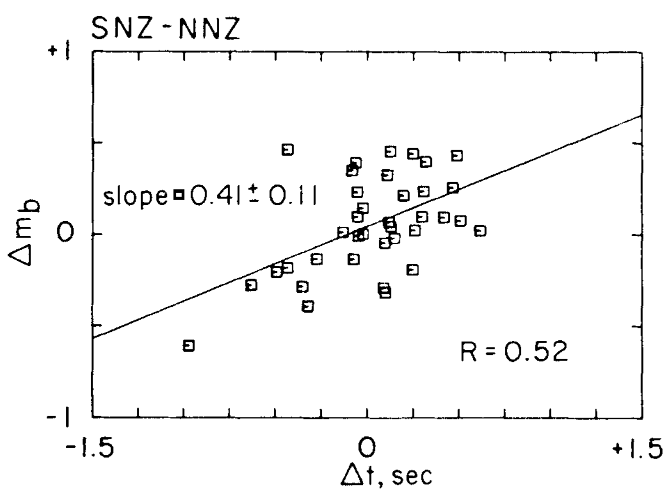

Figure 17. Correlation of the SNZ–NNZ travel time residual with the SNZ–NNZ magnitude residual. The linear regression slope and regression coefficient are shown.

estimates. Further research is necessary to determine if and how B scales with yield (or depth). If calibration yields reveal that yield scales with log ψ_∞ with a slope different than 0.89, this might suggest that B varies at Novaya Zemlya. A different K-scaling relation than we used would also result in a slightly different ψ_∞-yield relation. Once again, calibration yields would resolve this problem.

The pP delay times obtained from intercorrelation are consistent with delay times for other hardrock sites for events of similar yield. However, these delay times are still slower than elastic predictions. Assuming depth-yield scaling for Amchitka is appropriate for the normal population of Northern Novaya Zemlya events, a 1000 kt event with an average overburden velocity of 3.5 km s^{-1} would have an elastic pP delay of 0.69 s, 0.04 s smaller than the estimate given by Equation 11. It is surprising that six Novaya Zemlya events have even smaller pP delay times than the normal population of NNZ events and elastic predictions. This is caused either by being underburied or by being detonated in harder-faster rock. If the cause is harder-faster rock, there may be differences in coupling.

Northern and Southern Novaya Zemlya have different azimuthal amplitude and waveform variations. Two hypotheses have been suggested for azimuthal amplitude patterns at Pahute Mesa: tectonic release (Lay *et al.* 1984b) and focusing effects (Lynnes & Lay 1984). Because the azimuthal patterns are different between the two nearby test sites, either different tectonic release mechanisms or different near-source focusing and defocusing of seismic energy are required to cause the different azimuthal patterns. We will briefly consider both possibilities.

Burger *et al.* (1986) have studied long-period body waves to determine the tectonic release characteristics at Novaya Zemlya. Fig. 15 shows the focal mechanisms of events from NNZ and SNZ. The orientation of the double couple at NNZ is oblique normal and the orientation at SNZ is either vertical strike slip or 45° thrust. Burger *et al.* (1986) demonstrate that the 45° thrust mechanism would require a long-duration time function (over 2 s) for the double couple source. This would result in the tectonic release having little effect on the short-period P-waves. The vertical strike-slip orientation also produces only a slight effect on the short-period P-waves; thus SNZ is expected to have little contamination from tectonic release for either mechanism. Therefore, we choose the vertical strike-slip orientation and argue that it makes no difference which mechanism we choose. Following the assumptions of Lay *et al.* (1984b) and the previous calculations of Burger *et al.* (1985), we computed the synthetic SNZ–NNZ m_b azimuthal pattern for the average moments and orientations given by Burger *et al.* (1986). Those calculations are summarized in Fig. 16. The azimuthal trends are well matched, but the amplitude of the synthetic variations is at least a factor of two too small. Furthermore, these calculations were performed with assumptions that maximized the effect of tectonic release on short-period P-waves. Such assumptions include the source–time history and location of the double couple.

Short-period P-wave ISC travel time residuals were analyzed to determine if focusing and defocusing is a reasonable explanation of the different azimuthal amplitude patterns. The SNZ–NNZ travel time residuals are correlated with the SNZ–NNZ m_b variations in Fig. 17. The slope of the least-squares linear relation shows that fast times correlate with low amplitudes, indicating that focusing and defocusing is present. The regression coefficient for this relation is 0.52, thus there is a positive correlation which exceeds the 99 per cent significance level. Differencing the SNZ and NNZ patterns removes any receiver and path effects, thus near-source structure variations are isolated. Without having a realistic laterally varying structure for Novaya Zemlya, we cannot predict the expected m_b variations associated with the observed travel time variations. However, the correlation shown in Fig. 17 demonstrates that focusing and defocusing is present to some degree.

Conclusions

The intercorrelation technique is a powerful tool for studying explosions at foreign test sites, providing information on the relative size and *pP* behaviour of these events. The effects of variable source function and of *pP* are incorporated into the intercorrelation analysis. The relative sizes obtained by intercorrelation do not differ greatly from those obtained from amplitude and m_b measurements, indicating that variable effective source functions do not bias the amplitude measurements for this set of Novaya Zemlya explosions. Magnitude data tend to agree better with the intercorrelation results than the amplitude data, presumably due to the period correction in the m_b analysis which helps account for source function differences. Similarly, the *ab* measurements agree bettei with intercorrelation than *bc* measurements because *pP* has less of an effect on the *ab* cycle. Yield estimates are presented but we acknowledge that calibration shots are required to obtain accurate absolute yield estimates.

There are two populations of events obeying different *pP*–*P* delay–log yield relations. The *pP* delay times for the larger population of Northern Novaya Zemlya events are similar to Amchitka events of equivalent yields. The other population of events exhibit smaller *pP* delay times, the result of being underburied or being detonated in harder-faster rock. The 10/21/75 NNZ and 10/18/75 SNZ events show clear waveform differences from other events within the test sites. Examination and analysis of *P*-waveforms demonstrates that the 10/18/75 event was actually two explosions set off simultaneously 21 km from each other. Southern Novaya Zemlya and Northern Novaya Zemlya are shown to have different azimuthal amplitude and waveform variations. They are apparently caused by the focusing and defocusing of seismic energy near the source.

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