ANALYSIS OF NEAR-SOURCE CONTRIBUTIONS TO EARLY P-WAVE CODA FOR UNDERGROUND EXPLOSIONS. I. WAVEFORM COMPLEXITY

By Thorne Lay and Joan L. Welc

ABSTRACT

An extensive data set of more than 1600 teleseismic short-period P waves from 46 underground nuclear explosions is analyzed to establish near-source contributions to the first 15 sec of the P signals. The near-source components are isolated by event-to-event comparisons of first-cycle magnitudes, RMS amplitudes in the first 5 and next 10 sec of the waveforms, and energy temporal centroid measurements. Events from the Nevada, Amchitka, and Novaya Zemlya test sites are analyzed separately in order to characterize overall source region variations. Event-averaged waveform complexity variations between explosions within a given site are tested for dependence on source strength, burial depth, location within the site, and tectonic release. Azimuthal patterns of the individual event complexity anomalies are used to discriminate between possible near-source influences. For events at Pahute Mesa, a strong azimuthal amplitude pattern in both the direct P waves and the P coda for all of the events is produced principally by deep mantle variations. Defocusing by a high velocity anomaly in the crust and uppermost mantle beneath the site has a stronger effect on the direct P signals than on the early P coda, resulting in a systematic, spatially varying relative pattern. Events PIPKIN and SCOTCH have the most pronounced waveform complexity anomalies, which may be related to either their position in the site or to their respective burial above the water table (PIPKIN) and deep overburial (SCOTCH). The Amchitka events show variations between direct arrival and P coda amplitudes that are similar to the Pahute Mesa data, which can be attributed to focusing and defocusing associated with the subducting Aleutian slab. Novaya Zemlya events exhibit a strong inverse relation between waveform complexity and event size, as well as having much lower early coda amplitudes relative to the direct P arrivals than the Nevada Test Site events. There is very little evidence of significant tectonic release contribution to either the direct P arrivals or early P coda for any of the test sites.

INTRODUCTION

The short-period seismic coda following direct P arrivals for both regional and teleseismic distances is generally believed to consist of randomly scattered energy resulting from ubiquitous small-scale heterogeneity near the source, along the travel path, and near the receiver (Aki, 1982). Recently, attention has focused on teleseismic P-wave coda, particularly for underground explosion signals, because the coda levels provide more stable relative size estimates than the direct P amplitudes (Ringdal, 1983; Bullitt and Cormier, 1984; Baumgardt, 1985b; Gupta et al., 1985a). This attribute, which is shared by other strongly scattered phases such as Lg (Ringdal, 1983), appears to stem from the intrinsic averaging over numerous paths for the arrivals comprising the coda, as compared with the restricted path sampling of the direct arrivals. The direct P waves are thus more susceptible to amplitude variations produced by anomalous absorption, multipath interference, and focusing or defocusing.

Additional interest in the P-wave coda from underground explosions has been sparked by several investigations (Douglas, 1984; Gupta et al., 1985b) that indicate

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that near-source information may be contained in the relatively early P-wave coda, providing a means for remotely interrogating the structure in a test site. These studies compared nearby events with similar paths in order to isolate the near-source component, and utilized the P coda arriving within 30 sec of the first arrival, an interval for which the near-source contribution to the coda is generated within a relatively small volume. This “early” coda has at least some potential for a deterministic interpretation of the near-source contribution, whereas the P coda arriving after 30 sec is clearly less sensitive to near-source processes. In some instances, it may still be possible to constrain the origin of the late coda, as in the case of the Lg to P scattering under the Urals reported by Baumgardt (1985a).

In all studies, it is difficult to confidently isolate the near-source, deep path, and near-receiver contributions to the coda. Greenfield (1971) presented some qualitative analysis attributing coda from Novaya Zemlya explosions to signal-generated noise near the source region in the form of Rayleigh-wave to P-wave conversions at topographic irregularities. However, he did not account for other possible coda contributions, such as those from signal-generated noise near the receiver (Key, 1968). Ideally, this separation of the coda contributions is performed using array analysis like that of NORSAR data by Dainty (1985), who succeeded in distinguishing near-source contributions with high apparent velocities from near-receiver contributions with low apparent velocities. However, arrays are sparsely distributed, providing little control on azimuthal variations from the various source regions.

In this study, a data intensive approach to the problem of identifying and explaining the near-source contribution to early teleseismic P-wave coda is adopted. The underlying philosophy is to statistically characterize the relative energy content of the direct P arrival and the following coda using various straightforward parametric complexity measurements, which are then compared from event to event to eliminate common receiver and deep path effects. A large, well-distributed station set is used for each source region in order to detect any slowly varying azimuthal and ray parameter trends that may be diagnostic of particular near-source phenomena, such as the radiation pattern expected for tectonic release. This approach is predicated on the idea that there is a deterministic component to the early P-wave coda, and we therefore restrict our analysis to the first 15 sec of signal following the direct arrival. This study differs from most previous analyses of waveform complexity in which small sets of anomalous waveforms were examined (e.g., Douglas et al., 1971, 1973) in that we analyze large data sets for several suites of events. Only time domain measurements are reported in this paper; the results of frequency-dependent analysis of the same data set are presented in Lay (1987a). An attempt to deterministically constrain the near-source scattering mechanisms by slant-stacking the teleseismic data set for Pahute Mesa events is described in Lay (1987b).

Data Analysis

A representative set of teleseismic short-period P waves from underground explosions at the Nevada Test Site (NTS) is shown in Figure 1. For all of the events except FAULTLESS, the waveforms differ substantially at the two World-Wide Standard Seismograph Network (WWSSN) stations, which are separated in azimuth by 51°. For a given event, these variations could be due to either source, deep path, or receiver effects. However, since the events are located quite close together (all but three being Pahute Mesa tests), a deterministic outlook would lead one to expect that the waveform differences between events at each station originate
principally near the sources. It appears that this viewpoint is generally valid for the most coherent portion of the signals (about the first 4 or 5 sec), given the success of relative waveform techniques in extracting explosion source information from the event-to-event variations of the first few cycles of the direct $P$ waves (Lay et al., 1984a; Lay, 1985; Burger et al., 1986b). However, the coda after the first few seconds is often incoherent, even between much more closely spaced stations. Thus, lacking the dense spatial sampling provided by an array, a statistical approach is necessary to extract the near-source component. While tedious visual inspection of the waveforms can identify some events with anomalous extra arrivals in the coda (as, e.g., is true at some azimuths for HALFBEAK and MUENSTER), it is difficult to quantify these features and their variability without some form of parametric measurement. The waveforms in Figure 1 do suggest that the near-source and near-receiver contributions to the signals are equally important, as is the case for the NORSAR signals from explosions analyzed by Dainty (1985).

In order to statistically characterize the waveform differences apparent in Figure 1, three types of parametric measurements have been made for each seismogram in
this study. The first is a conventional magnitude measurement using the first peak to first trough amplitude \( m_{ab} \). This is the most straightforward measure of the direct \( P \) phase from explosions that can be made reliably using analog recordings. The other two measurements were made from the digitized data after filtering with a third-order Butterworth bandpass filter from 0.2 to 2.0 Hz that removed digitizing and long-period noise. The RMS amplitudes in the first 5 sec (RMS\(^{0-5}\)), first 15 sec (RMS\(^{5-15}\)), and in the interval from 5 to 15 sec (RMS\(^{5-15}\)) after the \( P \) arrival were determined from the filtered records. The \( m_{ab} \) and RMS\(^{0-5}\) values will be referred to as measurements of the direct arrival, whereas the RMS\(^{5-15}\) values will be identified with the early \( P \) coda. The third type of waveform measurement is a normalized energy temporal centroid given by

\[
C_{tm} = \frac{\int_0^{tm} s^2(t) dt}{\int_0^{tm} s^2(t) dt}
\]

where \( s^2(t) \) is the square of the filtered signal envelope as a function of time, and the duration, \( tm \), was either 10, 12.5, or 15 sec. To reduce the noise level bias on the centroid calculations, the RMS amplitude in a noise window of duration \( tm/2 \) preceding each \( P \) arrival was removed before squaring the envelope, as illustrated in Figure 2. These centroid measurements are sensitive to the distribution of signal energy with time, with larger values indicating relatively greater coda levels (higher

**Fig. 2.** Example of three types of parametric waveform measurements made for each signal in this paper. The top trace shows the \( P \) wave train from station UME for Pahute Mesa event BOXCAR and its analytic envelope. The \( m_{ab} \) value is determined using the first peak to first trough amplitude and the first cycle period. The RMS amplitudes are calculated for the first 5, next 10, and first 15 sec of the \( P \) signal, as well as for a 7.5-sec noise window ahead of the first arrival. The lower trace shows the squared signal envelope, both with and without subtracting the RMS noise level prior to squaring. The energy temporal centroid is computed for the noise-corrected trace.
"complexity"). The RMS amplitude measurements were used to characterize complexity by computing log(RMS$^{5-15}$/RMS$^{0-5}$), for which larger values also indicate higher relative coda levels. Comparison of the two complexity measures, $C_{tm}$ and log(RMS$^{5-15}$/RMS$^{0-5}$), insures that no bias is introduced by the arbitrary time window designations used in the RMS calculations.

The three measurement procedures were applied to all available WWSSN and Canadian Seismic Network recordings of 28 NTS events, 3 Amchitka events, and 15 Novaya Zemlya events. Twenty-five of the NTS events were from Pahute Mesa, with additional events FAULTLESS (Hot Creek Valley), COMMODORE (Yucca Flat), and PILEDIVER (Climax Stock) being analyzed. Eleven of the Novaya Zemlya events were from the northern subsite, and four were from the southern subsite. Table 1 lists the events and corresponding mean $m_{av}$ values and average complexity measurements, along with the standard error of the mean and the number of observations for each estimate.

In obtaining the average $m_{av}$ values in Table 1, station-dependent path corrections were established for each test site by applying a least-squares inversion that minimizes the variance at each station for observations from a suite of events (Larry Ruff, personal communication). The zero-meaned path corrections were then used as weighting factors for each observation in computing the event averages, with the variance in the path corrections being used to estimate the variance of the individual observations (Burger et al., 1986b). The standard errors for $m_{av}$ given in Table 1 thus include the scatter in the path-corrected values as well as the uncertainty in the corrections resulting from the scatter in the individual observations. An analogous procedure was applied to the RMS amplitude measurements, in order to compare the relative event size estimates and their uncertainty. As shown below, the path corrections obtained by this procedure contain important information about both near-source and teleseismic effects on the waveforms that are common to all events in each test site.

The average centroid complexity measurements in Table 1 (for $tm = 15$ sec) were obtained by applying path corrections and synthetic event corrections to the individual measurements and then azimuthally averaging the values with a 7.5° azimuth window. The synthetic event corrections, which account for the systematic centroid shifts due to increasing $pP$ lag time and longer duration source functions for larger events, were determined by calculating the differences in centroids for synthetic $P$ waveforms computed using the complete explosion source models obtained by relative waveform analysis for events at NTS (Lay, 1985), Amchitka (Lay et al., 1984a, b), and Novaya Zemlya (Burger et al., 1986b). The path corrections, which were applied in order to eliminate deep path and near-receiver contributions to the waveform complexity, were determined by averaging the synthetic-corrected centroids for all events at a given test site for each station, and then zero-meaning the station averages. The azimuthal averaging was performed to reduce any bias in the mean due to unequal sampling of the focal sphere for those events with strong residual azimuthal patterns in the complexity measurements.

The average log(RMS$^{5-15}$/RMS$^{0-5}$) complexity measurements in Table 1 were obtained by applying path corrections derived in a similar fashion to the centroid calculations, along with a 7.5° azimuthal averaging. No synthetic event corrections were applied because of the gross nature of the RMS calculations. An attempt was made to reduce any noise level bias by subtracting the RMS noise level in a 7.5-sec duration window preceding the $P$ arrival from the RMS$^{0-5}$ and RMS$^{5-15}$ values for each signal. However, this resulted in substantially increased scatter due to the
### TABLE 1

<table>
<thead>
<tr>
<th>Event</th>
<th>$m_b$ $^{ab}$</th>
<th>$C_{15}$ (sec)</th>
<th>$\log (\text{RMS}<em>{15}/\text{RMS}</em>{0.5})$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pahute Mesa Events</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>ALMENDRO</td>
<td>5.962 ± 0.023 (45)</td>
<td>4.42 ± 0.12 (35)</td>
<td>−0.031 ± 0.017 (30)</td>
</tr>
<tr>
<td>BENHAM</td>
<td>6.160 ± 0.021 (49)</td>
<td>4.55 ± 0.08 (36)</td>
<td>0.003 ± 0.013 (28)</td>
</tr>
<tr>
<td>BOXCAR</td>
<td>6.122 ± 0.024 (47)</td>
<td>4.41 ± 0.11 (48)</td>
<td>0.006 ± 0.016 (44)</td>
</tr>
<tr>
<td>CAMEMBERT</td>
<td>6.056 ± 0.019 (45)</td>
<td>4.53 ± 0.12 (42)</td>
<td>−0.005 ± 0.017 (41)</td>
</tr>
<tr>
<td>CHESIRE</td>
<td>5.757 ± 0.024 (36)</td>
<td>4.40 ± 0.13 (37)</td>
<td>0.032 ± 0.018 (33)</td>
</tr>
<tr>
<td>COLBY</td>
<td>6.225 ± 0.022 (43)</td>
<td>4.36 ± 0.08 (37)</td>
<td>0.005 ± 0.015 (34)</td>
</tr>
<tr>
<td>ESTUARY</td>
<td>5.696 ± 0.023 (33)</td>
<td>4.38 ± 0.15 (33)</td>
<td>0.039 ± 0.020 (32)</td>
</tr>
<tr>
<td>FONTINA</td>
<td>6.188 ± 0.022 (38)</td>
<td>4.23 ± 0.17 (40)</td>
<td>−0.022 ± 0.025 (37)</td>
</tr>
<tr>
<td>GREELEY</td>
<td>6.088 ± 0.021 (61)</td>
<td>4.42 ± 0.08 (56)</td>
<td>0.002 ± 0.014 (56)</td>
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<tr>
<td>HALFBEAK</td>
<td>5.810 ± 0.021 (47)</td>
<td>4.38 ± 0.10 (39)</td>
<td>−0.027 ± 0.021 (37)</td>
</tr>
<tr>
<td>HANDLEY</td>
<td>6.336 ± 0.023 (53)</td>
<td>4.42 ± 0.09 (35)</td>
<td>−0.019 ± 0.015 (27)</td>
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<tr>
<td>INLET</td>
<td>5.705 ± 0.025 (39)</td>
<td>4.34 ± 0.11 (39)</td>
<td>−0.011 ± 0.025 (29)</td>
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<tr>
<td>JORUM</td>
<td>6.164 ± 0.020 (57)</td>
<td>4.37 ± 0.09 (46)</td>
<td>0.005 ± 0.014 (41)</td>
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<td>KASSERI</td>
<td>6.145 ± 0.025 (41)</td>
<td>4.36 ± 0.11 (36)</td>
<td>0.014 ± 0.019 (35)</td>
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<tr>
<td>MAST</td>
<td>5.806 ± 0.022 (53)</td>
<td>4.44 ± 0.11 (49)</td>
<td>−0.024 ± 0.023 (38)</td>
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<tr>
<td>MUEINSTER</td>
<td>6.109 ± 0.024 (40)</td>
<td>4.38 ± 0.10 (38)</td>
<td>−0.039 ± 0.020 (38)</td>
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<td>PIPKIN</td>
<td>5.314 ± 0.024 (42)</td>
<td>4.74 ± 0.14 (38)</td>
<td>0.054 ± 0.025 (36)</td>
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<tr>
<td>POOL</td>
<td>5.777 ± 0.025 (36)</td>
<td>4.21 ± 0.12 (34)</td>
<td>0.010 ± 0.020 (30)</td>
</tr>
<tr>
<td>PURSE</td>
<td>5.505 ± 0.023 (48)</td>
<td>4.52 ± 0.17 (47)</td>
<td>0.025 ± 0.026 (42)</td>
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<td>RICKEY</td>
<td>5.556 ± 0.027 (30)</td>
<td>4.42 ± 0.16 (31)</td>
<td>−0.019 ± 0.021 (29)</td>
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<tr>
<td>SCOTCH</td>
<td>5.390 ± 0.026 (38)</td>
<td>4.81 ± 0.12 (42)</td>
<td>0.068 ± 0.018 (38)</td>
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<tr>
<td>SLED</td>
<td>5.746 ± 0.026 (41)</td>
<td>4.33 ± 0.15 (42)</td>
<td>0.007 ± 0.018 (42)</td>
</tr>
<tr>
<td>STILTON</td>
<td>5.586 ± 0.024 (47)</td>
<td>4.33 ± 0.10 (50)</td>
<td>−0.010 ± 0.018 (48)</td>
</tr>
<tr>
<td>STINGER</td>
<td>5.345 ± 0.030 (37)</td>
<td>4.38 ± 0.16 (41)</td>
<td>−0.002 ± 0.025 (35)</td>
</tr>
<tr>
<td>TYBO</td>
<td>5.808 ± 0.021 (50)</td>
<td>4.12 ± 0.10 (48)</td>
<td>−0.048 ± 0.022 (43)</td>
</tr>
<tr>
<td><strong>Amchitka Events</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CANNIKIN</td>
<td>6.731 ± 0.024 (34)</td>
<td>4.09 ± 0.07 (31)</td>
<td>−0.033 ± 0.018 (29)</td>
</tr>
<tr>
<td>LONGSHOT</td>
<td>5.474 ± 0.030 (31)</td>
<td>4.27 ± 0.07 (42)</td>
<td>0.033 ± 0.015 (41)</td>
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<tr>
<td>MILROW</td>
<td>6.273 ± 0.021 (36)</td>
<td>4.13 ± 0.07 (42)</td>
<td>0.000 ± 0.014 (42)</td>
</tr>
<tr>
<td><strong>Northern Novaya Zemlya Events</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/27/66</td>
<td>6.379 ± 0.021 (45)</td>
<td>4.05 ± 0.07 (43)</td>
<td>0.014 ± 0.013 (41)</td>
</tr>
<tr>
<td>10/21/67</td>
<td>5.654 ± 0.018 (49)</td>
<td>4.10 ± 0.07 (57)</td>
<td>0.043 ± 0.018 (52)</td>
</tr>
<tr>
<td>11/07/68</td>
<td>5.829 ± 0.017 (58)</td>
<td>4.35 ± 0.09 (62)</td>
<td>0.044 ± 0.012 (57)</td>
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<tr>
<td>10/14/69</td>
<td>5.967 ± 0.022 (45)</td>
<td>4.12 ± 0.07 (50)</td>
<td>0.028 ± 0.012 (45)</td>
</tr>
<tr>
<td>10/14/70</td>
<td>6.728 ± 0.032 (27)</td>
<td>3.78 ± 0.13 (29)</td>
<td>−0.064 ± 0.019 (27)</td>
</tr>
<tr>
<td>09/27/71</td>
<td>6.531 ± 0.027 (25)</td>
<td>3.77 ± 0.11 (28)</td>
<td>−0.036 ± 0.020 (26)</td>
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<td>08/28/72</td>
<td>6.252 ± 0.023 (42)</td>
<td>4.02 ± 0.08 (32)</td>
<td>−0.006 ± 0.016 (29)</td>
</tr>
<tr>
<td>09/12/73</td>
<td>6.843 ± 0.046 (18)</td>
<td>3.72 ± 0.11 (15)</td>
<td>−0.093 ± 0.025 (15)</td>
</tr>
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<td>08/29/74</td>
<td>6.393 ± 0.024 (33)</td>
<td>3.96 ± 0.11 (19)</td>
<td>0.000 ± 0.015 (15)</td>
</tr>
<tr>
<td>08/23/75</td>
<td>6.377 ± 0.023 (39)</td>
<td>4.01 ± 0.08 (27)</td>
<td>−0.024 ± 0.015 (24)</td>
</tr>
<tr>
<td>10/21/75</td>
<td>6.354 ± 0.040 (29)</td>
<td>3.70 ± 0.07 (25)</td>
<td>−0.031 ± 0.012 (20)</td>
</tr>
<tr>
<td><strong>Southern Novaya Zemlya Events</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>09/27/73</td>
<td>5.518 ± 0.025 (22)</td>
<td>4.04 ± 0.03 (45)</td>
<td>0.027 ± 0.023 (37)</td>
</tr>
<tr>
<td>10/27/73</td>
<td>6.981 ± 0.039 (12)</td>
<td>3.90 ± 0.10 (5)</td>
<td>−0.074 ± 0.000 (1)</td>
</tr>
<tr>
<td>11/02/74</td>
<td>6.721 ± 0.029 (22)</td>
<td>3.95 ± 0.13 (17)</td>
<td>−0.017 ± 0.022 (12)</td>
</tr>
<tr>
<td>10/18/75</td>
<td>6.474 ± 0.027 (26)</td>
<td>4.20 ± 0.12 (20)</td>
<td>−0.002 ± 0.018 (17)</td>
</tr>
</tbody>
</table>

relatively low coda levels, so the noise corrections were omitted. The path correction procedure used in both the centroid and RMS averaging should eliminate any systematics arising from the differences in instrumentation between the WWSSN and Canadian Seismic Network stations.
RESULTS FOR NTS EVENTS

The Pahute Mesa events are of particular interest because it is known that the direct $P$ waves from all of these events have a strong azimuthal amplitude variation that has a significant near-source component (Lay et al., 1984c). Figure 3a illustrates this pattern, with the $m_{ab}^a$ path corrections for 70 seismographic stations being plotted as a function of azimuth from the source region. The scatter about each station average is very small compared to the variations between the stations. A curve with the form $A \sin[2(\theta - \theta_0)]$, where $\theta$ is the station azimuth, has been regressed to the observations in order to emphasize the slowly varying component. Using the same F-test described by Lay et al. (1984c), an $f$-ratio of 21.8 was obtained, indicating that at the 99 per cent confidence level, the $\sin(2\theta)$ component is statistically significant relative to the mean. A clear amplitude pattern, with a long wavelength range of 0.4 magnitude units (a factor of 2.5 in amplitude), is apparent, with low amplitudes being recorded by stations toward the north and north-northeast. Lay et al. (1984c) showed that while all of the Pahute Mesa events have similar azimuthal patterns, the strength of the $\sin(2\theta)$ component varies slightly with position in the Mesa. Since the amplitude patterns for NTS events located outside Pahute Mesa, such as FAULTLESS, are quite different in some cases (see Figure 5), it is likely that at least some component of this pattern originates near the Pahute Mesa source region.

Two hypotheses have been proposed to account for the near-source contribution to the Pahute Mesa amplitude pattern; either interference with strike-slip tectonic release radiation triggered by each Pahute Mesa event (Lay et al., 1984c) or defocusing by a high-velocity structure beneath the Mesa that is known to exist on the basis of travel-time structure (Lynnes and Lay, 1984). By analyzing an expanded data set of magnitude and travel-time anomalies for 57 NTS events (32 of which were located in Yucca Flat), Lynnes and Lay (1986) have shown that the

![Diagram](attachment:image.png)

**Fig. 3.** Azimuthal patterns for the station/path averages for the Pahute Mesa test site for (a) $m_{ab}^a$, (b) $\log(\text{RMS}^{0-5})$, (c) $\log(\text{RMS}^{5-15})$, and (d) $\log(\text{RMS}^{0-5}/\text{RMS}^{5-15})$. The best-fit $\sin(2\theta)$ curves obtained by regression are shown for each case.
near-source component of the $m_{0}^{ab}$ pattern common to Pahute Mesa events alone is about a factor of 1.5 in amplitude, with the lowest amplitudes being recorded at northerly azimuths. They also found that there is a 0.3-sec near-source travel-time anomaly. The defocusing hypothesis is supported by a moderate correlation found between these near-source amplitude and travel-time anomalies.

The RMS measurements made in this study provide further support for the defocusing hypothesis. The azimuthal variations of the path corrections for the log(RMS$^{5-5}$) and log(RMS$^{5-15}$) measurements are shown in Figure 3, b and c, respectively. Note the similarity between the $m_{0}^{ab}$ and log(RMS$^{0-5}$) patterns, which confirms that the first cycle magnitudes are representative of the overall P-wave amplitudes. The correlation coefficient between these two sets of station averages is 0.875 for 70 stations. The log(RMS$^{5-15}$) station averages have the same azimuthal pattern, but a slightly subdued range of variations. The f-ratios are 16.7 for the log(RMS$^{0-5}$) values and 10.4 for the log(RMS$^{5-15}$) averages for the 76 stations analyzed, indicating that the sin(2$\theta$) components are significant at the 99 per cent confidence level for both cases. If we assume that the azimuthal pattern in the log(RMS$^{5-15}$) values (the early P coda) is produced by systematic deep path or receiver variations, then taking the ratio log(RMS$^{0-5}$/RMS$^{5-15}$) of the path averages should isolate the near-source contribution common to all of the Pahute Mesa events. These ratios are plotted in Figure 3d, and a systematic azimuthal pattern is again apparent. The pattern is rotated by 30° counterclockwise from the patterns in the raw amplitude measures, and it has a reduced long-wavelength amplitude range of a factor of about 1.5. The scatter is greater than for the other measurements, but the f-ratio of 6.8 still indicates a significant sin(2$\theta$) component, with low RMS$^{0-5}$/RMS$^{5-15}$ ratios to the north and southeast. This pattern is very similar to that obtained by differencing the average $m_{0}^{ab}$ patterns for Pahute Mesa and Yucca Flat events (Lynnes and Lay 1986), indicating that a near-source component affecting all of the Pahute Mesa events has been isolated due to the variation of its effect on direct P waves compared to the early P coda.

The similarity of the azimuthal patterns in the log(RMS$^{0-5}$) and log(RMS$^{5-15}$) station averages for Pahute Mesa has some interesting implications. The measurements are correlated in Figure 4a, with the correlation coefficient being 0.846 for 76 stations. For the corresponding individual measurements, the correlation coefficient is 0.792 for 923 observations. The slope of a major axis regression between the points in Figure 4a is 0.91, reflecting the slightly smaller range of the log(RMS$^{5-15}$) values. The strong correlation between the amplitudes of the direct waves and the early coda suggests a common origin for the sin(2$\theta$) pattern they share. Lynnes and Lay (1986) found that magnitude anomalies at the same stations for Western United States earthquakes do not have a systematic pattern relative to NTS, so it is unlikely that near-receiver effects produce a significant portion of these patterns. A more likely explanation is that the common pattern in the log(RMS$^{0-5}$) and log(RMS$^{5-15}$) measurements accumulates along the deep travel paths. The direct arrivals are apparently more strongly affected by near-source focusing and defocusing (or possibly by tectonic release interference); thus, the long-wavelength pattern in the ratios (Figure 3d) is preserved.

The possibility that the common sin(2$\theta$) patterns in the log(RMS$^{5-15}$) and log(RMS$^{0-5}$) values is produced near the source region has not yet been evaluated. Generally, one would suspect that such a systematic, slowly varying pattern originates near the sources. It is certainly not reasonable to attribute it to tectonic release radiation with the strike-slip orientation that is known to predominate at
Fig. 4. Correlation plots of path average amplitude and complexity measures for the Pahute Mesa test site for (a) log(RMS_t-5) and log(RMS_5-0); (b) log(RMS_t-5) and log(RMS_5-0); and (c) C_5 and log(RMS_t-5)/RMS_5-0). The correlation coefficient (ccc) and a reference curve with a slope of 1 are shown for each case.
Pahute Mesa (Lay et al., 1984c; Wallace et al., 1985). The RMS measurement is insensitive to polarity, so any strike slip radiation would probably result in a sin(2\theta) pattern. However, given the typical instability of short-period earthquake signals near radiation nodes, even this might not be observed. The only way that tectonic release could explain the common pattern is for the interference to occur with the initial outgoing energy, with all subsequent early coda generation retaining the initial azimuthal variation. This is inconsistent with the idea that the early coda should involve substantial averaging over different paths.

The apparent similarity of the patterns in the two log(RMS) values (Figure 3, b and c) and in their ratio log(RMS^{0-5}/RMS^{5-15}) (Figure 3d) does suggest the possibility that some of the sin(2\theta) pattern in the raw amplitudes is produced by the same phenomenon that affects their relative behavior. However, Figure 4b shows that the correlation between the log(RMS^{5-15}) and log(RMS^{0-5}/RMS^{5-15}) values is actually quite low, with the correlation coefficient being only −0.138. The correlation coefficient between the log(RMS^{0-5}) and log(RMS^{0-5}/RMS^{5-15}) values is 0.411. This result indicates that the mechanism producing the overall amplitude variation is quite separate from that preferentially affecting the direct arrivals. To test whether the 5-sec cutoff in the RMS calculations affects this conclusion, Figure 4c shows a similar comparison of the log(RMS^{5-15}/RMS^{0-5}) values (note that the ratio is reversed to correspond to “complexity”) with the path averages obtained in the C15 calculations. The high correlation coefficient of 0.925 for the two complexity measures indicates that both give consistent estimates of the relative variations between the direct arrivals and the early coda.

An additional constraint on the origin of the azimuthal amplitude pattern shared by Pahute Mesa events can be obtained by comparison with events at other NTS subsites. Figure 5 shows the azimuthal patterns of \( m_b^{ab} \), log(RMS^{0-5}), log(RMS^{5-15}), and log(RMS^{0-5}/RMS^{5-15}) for the well-recorded event FAULTLESS, which was
detonated 150 km north of Pahute Mesa. The direct arrivals clearly have a very
different amplitude pattern than the Pahute Mesa events (Figure 3, a and b), with
neither of the FAULTLESS measurements having a statistically significant $\sin(2\theta)$
component. What little long wavelength component is present appears to be
completely reversed in phase from that in the Pahute Mesa patterns. The pattern
in the RMS ratio for FAULTLESS (Figure 5d) is also reversed from the correspond-
ing pattern for Pahute Mesa (Figure 3d). There is a suggestion in the ratios that
the direct arrivals to the north from FAULTLESS are enhanced relative to the
early coda, which emphasizes the differences from the Pahute Mesa patterns. If
this is the case, the $\text{RMS}^{5-15}$ values should correlate better between the two subsites
than the direct amplitude measures.

Correlations between the FAULTLESS amplitude measurements and the Pahute
Mesa path averages are shown in Figure 6. The $m_{ba}$ values have a low correlation
of 0.380 for 57 common stations, and the $\log(\text{RMS}^{0-5})$ values have an only slightly
higher correlation coefficient of 0.498. However, the correlation improves signific-
antly to 0.725 for the $\log(\text{RMS}^{5-15})$ measurements, with the major axis regression
slope for the data in Figure 6c being 0.94. This result appears to be a direct
manifestation of the greater stability of coda, even early in the wave train, relative
to the direct arrivals.

A similar comparison was made between the Pahute Mesa path averages and
measurements for the Yucca Flat event COMMODORE, which was located only 30
km east of Pahute Mesa. In this case, the correlation coefficients for $m_{ba}$, $\log(\text{RMS}^{0-5})$, and $\log(\text{RMS}^{5-15})$ were 0.695, 0.743, and 0.821, respectively. The system-
atic increase in the correlations relative to the FAULTLESS comparisons indicates that the deep mantle structure producing the $\sin(2\theta)$ pattern is located
beneath the Western United States, with paths from Pahute Mesa being most
strongly affected. Lynnes and Lay (1986) found that Pahute Mesa and Yucca Flat
events and FAULTLESS also share a strong (2.0 sec) azimuthal travel-time pattern,
with early arrivals recorded toward the northeast from NTS. This pattern does not
 correspond to known station travel-time anomalies; thus, it appears to originate in
the deep mantle, at depths greater than at least 600 km below the NTS source
region. The correlation between average path travel-time anomalies (with correc-
tions for receiver statics) and the $\log(\text{RMS}^{0-5})$ values for Pahute Mesa is 0.394 for
65 stations, with earlier arrivals tending to have lower amplitudes. Further work is
required to establish the precise location of this deep heterogeneity and whether it
actually produces defocusing.

Having established that the principal amplitude pattern shared by the Pahute
Mesa events is produced by deep mantle effects, we now examine the individual
event variations. The objective is to place additional constraints on the near-source
mechanism producing the pattern in the $\log(\text{RMS}^{0-5}/\text{RMS}^{5-15})$ path averages, as
well as to detect any anomalous event behavior. Figure 7 shows examples of
individual event measurements of this ratio for six Pahute Mesa tests. The stereo-
geographic projections are useful for recognizing both ray parameter and azimuthal
dependence of the ratios. As one would anticipate, given the pattern in the path
averages, most of the 25 Pahute Mesa events have lower amplitude ratios observed
at azimuths to the north and southeast, as is true for BOXCAR, COLBY, and
FONTINA in Figure 7. However, several of the events, such as HALFBEAK and
POOL, do not show systematically low ratios to the north. In order to extract the
long-wavelength systematics in each event's amplitude pattern, curves with the
form $A\sin[2(\theta - \theta_0)]$ were regressed to the zero-meaned $\log(\text{RMS}^{0-5}/\text{RMS}^{5-15})$ values
Fig. 6. Correlation plots of path average amplitude measurements for FAULTLESS and corresponding values for PAHUTE MESA and a reference curve with a slope of 1 are shown for each case.

(a) $\log(\text{RMS}_{-5}^{+5})$ and (c) $\log(\text{RMS}_{-1g}^{+1g})$. The correlation coefficient ($ccc$) and a reference curve with a slope of 1 are shown for each case.
for each event. While similar regressions for the $m_{ab}$ values for each event resulted in statistically significant (at the 99 per cent confidence level) sin(2$\theta$) components for all 25 events, only 7 of the events have significant sin(2$\theta$) components in the log(RMS$^{0.5}$/RMS$^{5-15}$) ratios.

Figure 8 illustrates the results of these individual event sin(2$\theta$) curve regressions. Each event passing the 99 per cent level significance test has an arrow indicating the azimuth of a northerly minimum in the sin(2$\theta$) curve fit to either the $m_{ab}$ values (Figure 8a) or the log(RMS$^{0.5}$/RMS$^{5-15}$) ratios (Figure 8b). The length of each arrow is proportional to the amplitude of the sin(2$\theta$) component, $A$, while the width is proportional to the f-ratio. The $m_{ab}$ variations are very similar to the results shown for log(ab amplitude) in Figure 9 of Lay et al. (1984c), after accounting for a 45° rotation of the arrows. The azimuths are quite uniform across the test site, with the strongest sin(2$\theta$) patterns being present for events in the central region. The log(RMS$^{0.5}$/RMS$^{5-15}$) results are quite different, with a systematic rotation of the azimuths and a systematic spatial pattern. Events in the west-central part of the site have the strongest patterns. Event ALMENDRO in the eastern region has a sin(2$\theta$) orientation close to that of the overall $m_{ab}$ pattern and appears to be distinct from the other events.

The spatial pattern in the RMS ratios further supports the interpretation that a near-source effect is responsible for the variations between direct $P$ and $P$ coda. The possibility that the near-source effect is tectonic release interference can be tested. Using tectonic release moment estimates, $M_{0,\text{tect}}$, from Wallace et al. (1985), and relative explosion source strength estimates, $\Psi \propto c$, from Lay (1985), relative F-factors were computed for each event using the definition $F = (M_{0,\text{tect}} \times 10^{-24} \text{ dyn-cm})/\Psi \propto c$. The F-factor for GREELEY (3.44) greatly exceeds that of COLBY (0.79).

![Fig. 7. Lower hemisphere equal-area stereographic projections of the individual event measurements of log(RMS$^{0.5}$/RMS$^{5-15}$) for six Pahute Mesa events. The outer perimeter of each projection corresponds to a take-off angle of 22.5°, and diamonds indicate lower than average amplitude ratios.](image)

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yet the latter event has a stronger pattern in the RMS ratio. The same is true for KASSERI ($F = 1.97$), which was located within 3 km of the GREELEY site. Other events with large $F$-factors such as BENHAM (5.26) and MUENSTER (3.40) do not have strong azimuthal patterns in their RMS ratios. Thus, it appears that tectonic release can be ruled out as an explanation for the differential patterns. The fact that PIPKIN has a very low $m_{ab}$ (Table 1) and a strong $\sin(2\theta)$ pattern indicates that explosion size is not a controlling factor either.

It seems most reasonable to attribute the pattern in Figure 8b to a structural effect, with defocusing of the direct $P$ arrival by crustal or uppermost mantle velocity heterogeneity being the most likely explanation. If this is the correct interpretation, the absence of a strong $\sin(2\theta)$ pattern in the RMS ratios for events JORUM and PURSE, which were detonated in close proximity to events with a strong pattern, must be explained. Regression of $\sin(2\theta)$ curves to the log-$\text{RMS}^{0.5-15}$ measurements for all of the events demonstrated that JORUM and BENHAM have particularly strong azimuthal patterns in the early coda, which offsets any pattern in the log-$\text{RMS}^{0.5-15}/\text{RMS}^{0.5-15}$ ratios. The pattern for PURSE is actually quite strong, but a large amount of scatter is present, perhaps due to the low signal-to-noise level, so the $\sin(2\theta)$ component did not prove statistically significant. The events on the eastern side of the Mesa show substantial variation in both orientation and amplitude of the azimuthal patterns for the RMS ratios, but it does not appear that the station coverage is adequate to systematically image the heterogeneity producing the patterns. Greater resolution of the structure should be feasible using the approach of Lynnes and Lay (in preparation), which utilizes both travel times and amplitudes.

In order to further isolate any individual event anomalies, the complexity measures in Table 1 were analyzed. For both measures, the removal of the station-averaged patterns should eliminate both the common near-source and telesismic effects on the data. By correlating $\Delta m_{ab}$ (the deviation of each $m_{ab}$ measurement from the corresponding event mean) with the $C_{15}$ values, one can test how well the telesismic effects have been removed. The correlation coefficient between these values for 943 observations of the Pahute Mesa tests is $-0.437$ before removing the path averages from the $C_{15}$ values and $-0.062$ afterward. The general correlation
between higher amplitudes and lower waveform complexity prior to removing the station corrections is a commonly observed behavior (Douglas et al., 1973). It does appear that the distant effects are adequately removed. The near-source effects are harder to account for, given the spatial variation apparent in Figure 8b. Two measures were taken to reduce any possible bias. The first was the azimuthal averaging used in computing the mean complexity factor for each event, and the second was inspection of all of the path-corrected complexity values for the presence of any azimuthal trends.

Figure 9 indicates the general characteristic of the average event properties that the complexity values measure. The stack of the area-normalized, squared signal envelopes for all stations for each event are shown for three Pahute Mesa events of increasing size and burial depth. Similar stacks for events at the other test sites are also shown. Note the double-pulse in each Pahute Mesa stack, with the pulses systematically separating with increasing magnitude. The second pulse is largely due to the \( pP \) arrival, which is anomalously delayed for the Pahute Mesa events. The coda levels after the first 5 sec of the stacks are quite smooth, reflecting the large number of traces available for each event. Rather subtle features in the coda levels are probably significant and represent event-averaged character associated with a particular event. The RMS ratio complexity measurements reflect the averaged coda level relative to the early energy, while the centroid measurements are more sensitive to the time at which small anomalous features in the coda arrive.

Of course, these stacks do not include any source or station corrections or any azimuthal weighting, so the actual values in Table 1 should be much more sensitive to the individual event complexity than measurements made from the stacked traces.

The average complexity measures in Table 1 were compared with many known event parameters, including size estimates, \( pP \) parameters obtained from relative waveform analysis, source depth, and source medium velocity. Variance-weighted regressions were performed for each parameter to assess whether any systematic trends exist. Figure 10 presents examples of the dependence of both waveform complexity measurements for Pahute Mesa events on the parameters \( m_{6 \theta \phi} \), tectonic release F-factor, and radial distance from the center of the test site.

In general, the \( \log(\text{RMS}^{0.15}/\text{RMS}^{0.5}) \) and \( C_{15} \) event averages correspond quite well, although the latter measure isolates more clearly the two anomalously complex events PIPKIN and SCOTCH. Since these events are both quite small, they produce a slight dependence on \( m_{6 \theta \phi} \) that vanishes if they are removed. The comparably small event STINGER has normal complexity, indicating that the anomalously high values are not simply the result of signal-to-noise level variation. PIPKIN and SCOTCH were also the most complex events for the \( C_{10} \) and \( C_{12.5} \) calculations. The dependence of complexity on tectonic release is quite weak for the Pahute Mesa events, although the \( C_{15} \) value for BENHAM is rather high. This low correlation is quite interesting, given the suggestion by Douglas (1984) that aftershock radiation is apparent in the coda for event GREELEY. It seems that the amplitude of any such radiation is too low to produce the enhanced coda levels expected if any aftershocks occurred in the first 15 sec after the event. A somewhat stronger correlation is found between the RMS ratios and position in the site. Increased scattering from the edges of the Mesa may explain this tendency. Such scattering should intrinsically be an azimuthally varying phenomenon, and in fact the azimuthal averaging suppresses this correlation. However, it is difficult to isolate the
effects produced by defocusing beneath the test site from this subtle spatial variation.

The anomalous events PIPKIN and SCOTCH are distinctive only in their respective burial depths. PIPKIN and RICKEY are the only two Pahute Mesa events detonated above the water table, with RICKEY being buried 0.07 km deeper. SCOTCH was deeply overburied. Event CAMEMBERT was located close to SCOTCH, and while it has a significantly lower complexity than SCOTCH, it was the third most complex event for the $C_{10}$ and $C_{12.5}$ measurements and the fourth most complex for $C_{15}$. PIPKIN was not particularly close to any other event; thus, it is possible that very local structural heterogeneity is responsible for the two events with anomalous complexity. The azimuthal variations of the individual $C_{15}$ values for SCOTCH, PIPKIN, and PURSE were inspected for any anomalous behavior. Neither SCOTCH nor PIPKIN has any diagnostic azimuthal pattern. However, event PURSE (buried 0.02 km shallower than PIPKIN) has a large cluster of high complexity values toward the northeast. PURSE was the event most strongly affected by the azimuthal averaging. The pattern of the residual complexity anomalies indicates that the path corrections undercorrected this event. In order to seek any systematic patterns in the residual complexity anomalies for the other events,
both $\sin(2\theta)$ and $\sin(4\theta)$ curves were regressed to the $C_{15}$ values for each event. FONTINA, like PURSE, appears to be undercorrected by the path averages, while HALFBEAK appears to be overcorrected, given that all three have significant $\sin(2\theta)$ components. Only COLBY and MAST had significant (at the 99 per cent level) $\sin(4\theta)$ components, and neither event has particularly strong tectonic release.

Before considering data for other test sites, it is of interest, given the strong azimuthal patterns in the direct arrivals and the early $P$ coda, to establish how well the various measurements perform at estimating relative event sizes for the NTS events. The mean relative event size estimates for the 25 Pahute Mesa events based on $m_{b}^{ab}$, $\log(\text{RMS}^{0-5})$, and $\log(\text{RMS}^{5-15})$ data sets were correlated. The correlation coefficient between the $m_{b}^{ab}$ and $\log(\text{RMS}^{0-5})$ relative size estimates was 0.983, with a major axis regression slope of 0.82 indicating slightly less variation of the RMS amplitudes. The correlation coefficient for the $m_{b}^{ab}$ and $\log(\text{RMS}^{5-15})$ estimates was 0.988, with a regression slope of 0.78. The lack of period corrections in the RMS measurements is probably the main reason that the slopes are less than one. The relative stability of each type of measurement was appraised by comparing the average standard deviation of the event means for all of the events in each of four different test sites (Table 2). Without the path corrections, the standard deviations are all increased by a factor of from 1.8 to 3.1. The three RMS values perform better than the first-cycle magnitudes for the four test sites, with the single exception of the RMS$^{5-15}$ values for Pahute Mesa. The RMS$^{0-5}$ measurements appear to be slightly more stable than the RMS$^{0-15}$ values. Magnitudes based on the first trough
to second peak amplitude ($m_6^{bc}$) are quite comparable to $m_6^{ab}$. The Pahute Mesa results indicate that as long as the path corrections are applied, the amplitude pattern effect on the relative size estimates is quite small.

**Results for Amchitka and Novaya Zemlya**

An analysis similar to that described for the NTS events was performed on the $P$ waveforms and amplitudes from the Amchitka, Northern Novaya Zemlya, and Southern Novaya Zemlya sites. The number of events available at each site is much smaller than for NTS, and only Northern Novaya Zemlya has a sufficient number (11) to examine the event-to-event behavior in detail. However, event-averaged complexity anomalies (Table 1) and average test site azimuthal patterns could be reliably determined for all three sites.

The Amchitka events exhibit an azimuthal amplitude behavior that is remarkably similar to that for the Pahute Mesa events. Figure 11 shows the azimuthal variation of the $m_6^{ab}$, log($\text{RMS}_{0-5}$), log($\text{RMS}_{5-15}$), and log($\text{RMS}_{0-5}/\text{RMS}_{5-15}$) measurements for 60 path averages. The direct amplitudes again have a stronger pattern than the early coda, although in this case no azimuthal shift of the pattern in their ratios is apparent. The $\sin(2\theta)$ component in the log($\text{RMS}_{0-5}$) values is statistically significant at the 99 per cent confidence level ($f$-ratio = 8.84), while the $\sin(2\theta)$ components in the other three cases are significant at the 95 per cent confidence level [$f = 3.55$ for $m_6^{ab}$; $f = 3.59$ for log($\text{RMS}_{5-15}$); $f = 4.94$ for log($\text{RMS}_{0-5}/\text{RMS}_{5-15}$)]. Since there are no nearby explosions with which to compare these patterns, it is difficult to establish whether the common pattern in the direct $P$ and $P$ coda measurements results from near-source or teleseismic effects. Many of the low amplitudes are recorded by stations in Europe, which tend to record low amplitudes from Pahute Mesa as well. However, the fact that the RMS ratios appear to have the same pattern as the direct $P$ waves suggests that a near-source phenomenon that preferentially affects the $P$ waves produces both the relative and the common patterns. The lowest amplitude observations are found at northern azimuths, in a direction for which the downgoing $P$ waves have trajectories similar to the subducting Aleutian plate. Defocusing by this high-velocity structure, which is known to produce a strong travel-time pattern with early arrivals to the north (e.g., Cleary, 1967; Jacob, 1972; Sleep, 1973) seems to be a plausible explanation. Douglas et al. (1973) argue that since it has proven difficult to account for all of the amplitude variations for the Amchitka events by raytracing through realistic slab models, a laterally varying low $Q$ zone may produce the low amplitude direct $P$ waves. Either

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**Table 2**

<table>
<thead>
<tr>
<th>Event Site</th>
<th>$m_6^{ab}$ (0.153 ± 0.011)</th>
<th>$m_6^{bc}$ (0.151 ± 0.010)</th>
<th>log($\text{RMS}_{0-5}$) (0.140 ± 0.016)</th>
<th>log($\text{RMS}_{5-15}$) (0.160 ± 0.022)</th>
<th>log($\text{RMS}<em>{0-5}/\text{RMS}</em>{5-15}$) (0.129 ± 0.016)</th>
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<tr>
<td>25 Pahute Mesa Events</td>
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<tr>
<td>3 Amchitka Events</td>
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<tr>
<td>11 Northern Novaya Zemlya Events</td>
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<tr>
<td>4 Southern Novaya Zemlya Events</td>
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* Error estimates are standard deviations.
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Fig. 11. Azimuthal patterns of the path averages for the Aleutian test site for (a) $m^a_b$, (b) log($\text{RMS}^{0.5}$), (c) log($\text{RMS}^{5-15}$), and (d) log($\text{RMS}^{0-5}/\text{RMS}^{5-15}$). The best-fit sin($2\theta$) curves found by regression for each case are also shown.

An explanation can be invoked to explain the observations in Figure 11, although the presence and sense of the travel-time pattern tend to favor the defocusing hypothesis. The tectonic release $F$-factors for the Amchitka events are all quite low (Lay et al., 1984b), and the events are separated by as much as 10 km, so it is unlikely that very near-source interference effects produce the amplitude pattern.

Both types of average complexity factors for the Amchitka events are plotted as functions of magnitude in Figure 12. There is a systematic decrease in complexity with increasing magnitude, which does not appear to result from noise level contamination. The slight dependence on magnitude was also manifested in correlations with other source parameters such as $pP$ lag time, source depth, and source medium velocity, so it is not clear what the controlling factor is. The baseline of the $C_{15}$ values for the Amchitka events is at the low end of the Pahute Mesa values, indicating that the average coda levels are slightly lower for the former site. This is apparent in Figure 9, where the stacked envelopes for the three Amchitka events are shown. Note that the smaller two Amchitka events do not have the double-pulse character of the Pahute Mesa events. Only CANNIKIN, which was more deeply buried than any of the Pahute Mesa events, exhibits a double pulse. This is because the Amchitka site has earlier $pP$ arrivals for the same size event due to faster overburden velocities. The scatter in the individual event patterns could not be reliably appraised given the large uncertainty in the path corrections.

The Novaya Zemlya data also exhibit an inverse relation between signal complexity and magnitude. The average complexity values for both test sites are plotted as functions of magnitude in Figure 12, with a particularly robust dependence apparent for the Northern Novaya Zemlya site. For the latter site, the correlation coefficients with magnitude are $-0.929$ for the RMS ratio measures and $-0.807$ for the $C_{15}$ values, with larger events having lower complexity. The existence of such an inverse correlation between size and complexity for Novaya Zemlya events was
Fig. 12. The magnitude dependence of the average complexity measures \( \log(\text{RMS}^{5-15}/\text{RMS}^{0-5}) \) (top row) and \( C_{15} \) (bottom row) are shown for the Amchitka, Northern Novaya Zemlya, and Southern Novaya Zemlya test sites. The correlation coefficients (ccc) and the curves for variance weighted linear regressions are shown for each case. The error bars indicate the standard error of the mean for each complexity measurement.

first noted by Davies (1970). For Northern Novaya Zemlya, the correlation coefficient between station averages for \( \log(\text{RMS}^{0-5}) \) and \( \log(\text{RMS}^{5-15}) \) is 0.886, with a major axis regression slope of 0.88, indicating that the early coda varies less. This supports the idea that preferential defocusing of the direct \( P \) waves does occur; however, it does not explain the magnitude dependence of the complexity.

The Northern Novaya Zemlya complexity values have a moderate correlation with the \( pP \) delay times but no correlation with the \( pP \) amplitudes determined by Burger et al. (1986b). The events also show no dependence on the relative tectonic release F-factors obtained by Burger et al. (1986a), with the correlation coefficient with \( \log(\text{RMS}^{5-15}/\text{RMS}^{0-5}) \) being −0.216 and that with \( C_{15} \) being −0.068. The \( C_{10} \) and \( C_{12.5} \) calculations do have clear magnitude dependence, although the correlation coefficient decreased to −0.651 for the \( C_{10} \) values. The average \( C_{15} \) values for both Novaya Zemlya sites are much lower than for Pahute Mesa, with the baseline of the observations down by 0.4 sec for \( m_b^{ab} = 5.8 \). This difference is readily apparent in Figure 9, where the relative coda levels are discernibly smaller for the Novaya Zemlya events. Also note that the early pulses are very simple, consistent with the relatively short \( pP \) delays found by Burger et al. (1986b). A reasonable explanation for this difference between test sites is that the rock types at the shotpoints in Pahute Mesa (largely Tertiary tuffs) are anomalously “soft” relative to the source rocks at the other sites, resulting in abnormally delayed \( pP \) arrivals and possibly in enhanced near-source reverberations and slapdown accompanying the steep velocity and strength gradients. An additional factor may be that Pahute Mesa overlies strong defocusing structures in a region of anomalously high attenuation, which
may result in an average diminution of the direct $P$ energy relative to the early coda in the general manner suggested by Douglas et al. (1973).

The Northern Novaya Zemlya amplitude patterns do not have any significant slowly varying azimuthal component, while the southern site has a moderate $\sin(2\theta)$ component in the $m_{ab}^{\text{ab}}$, $\log(\text{RMS}^{0.5})$ and $\log(\text{RMS}^{5.15})$ patterns, significant at the 95 per cent confidence level. The large differences in the amplitude patterns for these two sites, which are only separated by about 250 km, are discussed in detail by Burger et al. (1986b). No significant near-source $\sin(2\theta)$ or $\sin(4\theta)$ component is present in the azimuthal variation of the $\log(\text{RMS}^{0.5})/\log(\text{RMS}^{5.15})$ values for either site. As a result, the azimuthal averaging performed in the complexity calculations had much less effect than for Pahute Mesa events. The path corrections for $\log(\text{RMS}^{0.5})$ and $\log(\text{RMS}^{5.15})$ for the southern site have a poor correlation with the $m_{ab}^{\text{ab}}$ averages, and a larger range of variation than the magnitudes as well, which was not observed for the other sites. This suggests that the near-source heterogeneity is stronger at the southern site, possibly due to proximity to the cliffs at the southern end of the island, resulting in scattering contributions to the entire $P$ signal. It is interesting to note that the one Novaya Zemlya event exhibiting a double pulse in the envelope stacks is the event of 18 October 1975 (see Figure 9), which Burger et al. (1986b) discovered to be a double explosion. This event also deviates from the general magnitude dependence of $C_{15}$ shown in Figure 12. Note that because the complexity due to the double explosion occurs early in the signal, this waveform anomaly is not apparent in the $\log(\text{RMS}^{5.15}/\text{RMS}^{0.5})$ complexity measures.

**Discussion**

The foregoing analysis has revealed that there are fundamental differences in the energy flux in short-period $P$ waves from underground explosions at different test sites. These differences reflect both near-source conditions, such as the effect of local rock competence on $pP$ delay time; regional conditions, such as the shallow high-velocity defocusing body beneath Pahute Mesa; and global conditions, such as the deep mantle heterogeneity producing the common pattern in the NTS $P$ waves and $P$ coda. It is clear that the early $P$ coda may vary systematically with the direct $P$ amplitudes as a result of some propagation effects, while being less sensitive to others. It is difficult to recognize the presence of these effects, much less to explain them and account for any resulting magnitude biases. Bullitt and Cormier (1984) have detected similar complex coupling of direct arrival and coda amplitudes at small arrays. Without the azimuthal coverage provided by the global WWSSN and Canadian Seismic Network, most of the patterns apparent for Pahute Mesa would not be recognized, and analysis of isolated stations or arrays in Europe, where the azimuthal patterns happen to be most pronounced, could lead to erroneous conclusions. Ideally, all of the data collected would be broadband, three-component, and digitally recorded, so that an analysis like that described above could be performed routinely.

This study has provided no evidence to support the presence of significant tectonic release contributions to the short-period signals from underground explosions. Frequency domain analysis of the same data set by Lay (1987a) also indicates that structural effects are far more important than tectonic release. This is not to say that tectonic release has no observable effects, only that the major patterns detected by our parametric measurements are unlikely to be the result of tectonic release interference.
It appears that focusing and defocusing by velocity heterogeneity produce the amplitude pattern for Pahute Mesa. The near-source contribution results from defocusing by a high-velocity body at crustal and upper mantle depths below the Mesa that was detected by travel time analyses by Spence (1974), Minster et al. (1981), Taylor (1983), and Lynnes and Lay (1984). The spatial configuration of this heterogeneity will be best resolved using joint amplitude and travel-time data. It appears that event FAULTLESS is also affected by near-source focusing by velocity heterogeneity, of a different nature than that proposed by Priestley and Chavez (1985). P waves from FAULTLESS are focused at azimuths for which P waves from Pahute Mesa events are defocused, which may account for some portion of the positive magnitude anomaly for FAULTLESS. Large-scale heterogeneity well removed from the NTS test site also produces an azimuthal pattern for the Pahute Mesa events. A better understanding of the location and nature of this heterogeneity may be provided by the three-dimensional models that are being developed for the entire mantle.

A quantitative understanding of the magnitude dependence of complexity for the Novaya Zemlya and Amchitka events is needed. It may be possible to attribute much of this observation to reverberations in shallow sedimentary layers that are preferentially excited by shallower explosions, or to depth dependence of excitation of high-frequency surface waves that scatter into the coda. Alternatively, there may be some depth-dependence in the physics of coupling at hard rock sites that has not been clearly revealed by the NTS events, for which the magnitude dependence is very weak or absent. Future deterministic modeling should address this issue to ascertain whether information about near-source velocity gradients can be obtained from the early P coda behavior.

CONCLUSIONS

A data intensive analysis of the first 15 sec of short-period P waves from underground explosions has been performed to determine the near-source contributions to the waveforms. A strong azimuthal amplitude pattern is apparent for both the Pahute Mesa and Amchitka test sites. In both cases, the direct P arrivals vary in amplitude more than the early P coda, although the overall variations are coupled. For Pahute Mesa, the amplitude pattern appears to result from a combination of near-source heterogeneity, that causes defocusing of arrivals to the north, and deep mantle heterogeneity that produces a common pattern in the P waves and P coda. Other NTS events share the latter pattern to a large degree, although the direct P waves may have different focusing effects, as is the case for FAULTLESS. Neither component of the amplitude pattern for Pahute Mesa can be realistically explained by tectonic release interference. The azimuthal pattern for the Amchitka events is probably produced by defocusing by the high-velocity anomaly of the subducting Aleutian slab. Novaya Zemlya events lack any strong slowly varying azimuthal patterns caused by comparable near-source heterogeneity, and are distinctive in their simple, impulsive average waveform character and low, early P coda levels. These events do have a strong inverse relation between magnitude and complexity which is not yet well understood.

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