ANALYSIS OF NEAR-SOURCE CONTRIBUTIONS TO EARLY $P$-WAVE CODA FOR UNDERGROUND EXPLOSIONS. III. INVERSION FOR ISOTROPIC SCATTERERS

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ABSTRACT

A systematic array processing analysis is applied to 916 teleseismic short-period $P$-wave signals from 25 underground explosions at Pahute Mesa in order to establish whether coherent arrivals scattered from near-source velocity heterogeneity can be identified. The signal coherence is measured using semblance, which can be statistically evaluated using the noncentral $F$-distribution if the noise properties are suitable. The effects of unsuitable correlated noise due to common path and receiver contributions are suppressed by applying station weighting functions obtained by stacking all observations at a given receiver. Similar corrections for individual events are applied to reduce biases due to variations in surface reflection times and spall effects. The characteristics of the spatial and phase velocity resolution of the semblance analysis are established by a series of synthetic calculations, including cases with random arrivals in the $P$-wave coda. The procedure is applied to the actual data under the assumption that any scattering structures present radiate isotropically, although this constraint could be relaxed given independent knowledge of a particular scatterer's nature. The Pahute Mesa data show some evidence for enhanced scattering contributions to the first 15 sec of the $P$-wave signals from the western edge of the Silent Canyon Caldera. The overall confidence level in this interpretation is fairly low because simulations with random scattering in the $P$ coda successfully match many features observed in the stacked data.

INTRODUCTION

Many recent investigations have attempted to extract either source or earth structure information by analysis of the short-period scattered wave field in regional and teleseismic signals. This seismic coda is generally considered to consist of randomly scattered arrivals generated near the source, along the travel path, and near the receiver (e.g., Aki, 1989). Consequently, statistical treatments of the scattered wave field are usually adopted, yielding statistical characterizations of the source spectrum or of the scale lengths of the velocity heterogeneities producing the scattering. Given the known complexity of the crust and the increasing evidence for small-scale heterogeneity throughout the mantle, such statistical characterizations of the transmitting medium are probably the best that can usually be expected. In a few instances, however, it is possible to attempt to provide a more deterministic interpretation of some components of the seismic coda. One example is the analysis of the Eskdalemuir array data by Key (1967) in which an azimuth and velocity search through the coda of incoming $P$ waves revealed the presence of a strong isolated arrival produced by $P$ to Rayleigh wave conversion at a particular location in the near-receiver crust. In this study, a reciprocal analysis is conducted, using an array of sources to seek near-source scattering structures.

Several different procedures have been developed for remotely extracting information about the velocity structure in an earthquake or explosion source region. The most common involves analysis of travel-time anomalies recorded at large distances, which are back-projected to the source region. This has been useful for
imaging subducting slab structure (e.g., Cleary, 1967; Creager and Jordan, 1986), as well as crust and upper mantle structure beneath the Nevada Test Site (NTS) (Spence, 1974; Minster et al., 1981; Taylor, 1983). A few studies have jointly analyzed first-arrival amplitude and travel-time anomalies for subduction zones (e.g., Sleep, 1973) as well as for NTS (Lynnes and Lay, 1987). The scattered wave field in the \( P \)-wave coda has received less attention due to the difficulties of isolating the near-source contributions and because of our limited knowledge of the dominant scattering processes. Attempts to extract near-source information from teleseismic coda for explosions have been presented by Greenfield (1971), Gupta et al. (1975), Douglas (1984), Baumgardt (1985), Lay and Welc (1987), and Lay (1987). These studies have been statistical in nature, in that measurements of the energy flux in the seismic coda were used rather than attempting to isolate and explain discrete arrivals.

Boucher (1973) attempted to interpret specific secondary arrivals in the coda of several NTS explosions by analyzing accelerograms within 100 km of the shotpoints. He considered only the first 3 sec of the signals and was principally concerned with identifying tectonic release radiation within a few kilometers of each explosion. Array processing techniques were used to search areas of 16 km\(^2\) around each event for secondary sources. The procedure did not yield convincing results, partly due to the complexity of the regional signals and partly due to the limited number of stations available for each event. The analysis conducted in this study is similar to that of Boucher (1973); however, a much larger data set of teleseismic recordings is used, and observations from a suite of events are combined in order to obtain better spatial resolution and to suppress contaminating propagation effects. By combining events, our attention is restricted to common scattering structures rather than event-specific processes such as tectonic release.

The actual scattering processes involved in generating the near-source contribution to teleseismic coda are poorly understood. It is generally suggested that fundamental and higher mode Rayleigh waves scatter to \( P \) waves from surface topography and lateral discontinuities in structure (e.g., Greenfield, 1971; Gupta et al., 1975; Lay, 1987). In the early \( P \) coda of explosions (within the first 15 sec of the direct arrival) significant \( P \) to \( P \) and \( P \) to \( P \) scattering may also occur. Each scattering mechanism will have a specific radiation pattern and energy partitioning [see Aki (1982) for examples], which cannot be predicted without knowledge of the scattering configuration. Given information about specific candidate scattering structures, one can try to include such radiation patterns, as Greenfield (1971) attempted to do for the cliffs around the Novaya Zemlya test site. However, such information is seldom available, and it is not known whether the scattering is more strongly influenced by concealed structures. The search for scattering structures near the Pahute Mesa (NTS) test site described later is performed for the assumption that the scattering structures radiate isotropically, or at least without a significant change in polarity or wave shape. Given this simple assumption, the search for scatterers becomes a tractable problem. Future work on the nature of crustal scattering mechanisms may provide justification for more complex scattering parameterizations.

**DATA ANALYSIS**

The basic scattering model used in this study is depicted in Figure 1. We assume that there is velocity heterogeneity in the vicinity of a suite of sources (stars) that produces scattered arrivals at each recording station (triangles). If the scattered
arrivals have a coherent pulse shape, it should be possible to locate the scatterer’s position by directivity analysis as well as to identify the type of waves scattered on the basis of the velocity of the waves from the sources to the scatterer. Given teleseismic recordings of \( j \) stations with azimuths, \( \Phi_j \), and ray parameters, \( p_j \), from a tightly clustered group of \( i \) sources, the lag times relative to each direct P wave for arrivals radiated from a point scatterer are given to first order by

\[
\tau_{ij} = r_i/V_s - \cos[\theta_i - \Phi_j]p_j r_i
\]

(1)

where \( r_i \) is the distance from each source to the scatterer with corresponding azimuth, \( \theta_i \), and \( V_s \) is the velocity of the wave from the source which scatters into the P-wave field. We assume that the sources and scatterers lie in a common plane for simplicity, since any vertical directivity will be much less than the horizontal directivity given by (1). If the scattered arrivals all have the same polarity and wave shape and could be identified as discrete arrivals at the receivers, directly measured values of \( \tau_{ij} \) could be processed to locate the scatterer using the same directivity techniques used in earthquake rupture studies. However, teleseismic P waves have significant contributions from path and receiver scattering that make it impossible to pick any coherent arrival between stations. In addition, the near-source scattering may involve numerous scattered phases with low amplitudes that will produce a
complex interference. Thus, a slant-stacking operation on the teleseismic signals is required if any coherent scattered arrivals are to be detected. Since the scatterer locations are unknown, it is necessary to search a two-dimensional grid of potential scattering locations. This results in a cumbersome four-dimensional array involving a slant stack trace at each grid location. The slant stacks must be examined to identify any specific moveout velocities producing coherent arrivals.

In order to simplify the stacking analysis for the large data set used in this study, the measure of signal coherence called semblance (Neidell and Taner, 1971) is used. The semblance for a suite of $N_e$ events and $N_s$ stations is given by

$$S(\tau_{ij}) = \frac{\sum_t \left( \sum_{i} \sum_{j} f_{ij}(t + \tau_{ij}) \right)^2}{N_s N_e \left( \sum_t \sum_{i} \sum_{j} f_{ij}^2(t) \right)}$$

where $f_{ij}(t)$ is the recording of the $i$th event at the $j$th station, and $t_g$ is the time gate over which the signal powers are computed. The semblance is a time domain coherence measure of the ratio of the power in the stacked trace to the total power of the individual traces, having a maximum value of 1.0. For a prescribed stacking or moveout velocity, $V_s$, computing the semblance at each grid location provides a measure of signal coherence over a hyperbolic trajectory through the full four-dimensional slant stack. The semblance is much more convenient to analyze than the complete set of slant stacks, and it has the additional advantage that the significance of any particular semblance value can be appraised using the well-defined $F$-statistic, $F(N_1, N_2, \lambda)$, where the degrees of freedom, $N_1$ and $N_2$, and the noncentrality parameter, $\lambda$, are defined as (Blandford, 1974)

$$N_1 = 2Bt_g$$
$$N_2 = N_1(M - 1)$$
$$\lambda = MN_1(S/N)^2$$

where $M = N_e N_s$, $S^2$ and $N^2$ are the mean signal and noise power in the frequency band respectively, and $B$ is the bandwidth in Hertz. The semblance value is related to the $F$-statistic by (Douze and Laster, 1979)

$$S = F/(F + M - 1).$$

Thus, the noncentral $F$-distribution can be used to appraise whether a particular value of semblance indicates a signal-to-noise ratio above or below a specified level. Blandford (1974) applied to the $F$-statistic in an event detection algorithm. The statistical properties of the noise must be such that it is uncorrelated from signal to signal, which introduces some problems when using multiple recordings from a given station, as addressed below.

The data set analyzed in this study is comprised of 916 teleseismic short-period $P$ waves digitized from WWSSN and Canadian Seismic Network (CSN) recordings of 25 underground explosions at the NTS subsite on Pahute Mesa. The events are closely clustered, lying within a 10 km radius of the center of the site. All but two of the events are located within the Silent Canyon Caldera. The waveforms each
have a total duration of 15 sec and were all filtered with a three-pole Butterworth bandpass filter from 0.2 to 2.0 Hz to eliminate digitizing and long-period noise. This filtering also suppresses any differences in wave shapes due to variations among the WWSSN and CSN instruments, which differ in response at frequencies greater than 1.5 Hz, and equalizes the dominant period of the waveforms for events of different yields. Signals with particularly high noise levels were removed from the complete data set digitized by Lay (1985), leaving an average of 36 recordings for each event out of a total of 71 stations. Given the nonuniform data coverage and the particular spatial distribution of the sources and receivers, it was necessary to explore the “array response” characteristics of the semblance analysis by processing synthetic data sets. The results of such simulations will be described in the next section, followed by the results for the actual observations.

**Synthetic Data Simulations**

Given the assumption of isotropic point scatterers in the vicinity of the source region, it is straightforward to construct a synthetic data set with appropriately lagged secondary arrivals. Using the explosion source parameters for event ALMENDRO given by Lay (1985), synthetic P waves were computed for the same set of 916 source-receiver combinations for which actual data were available. Scattered arrivals, with delay times given by (1), were added to each direct P wave for different specified scattering configurations, and the semblance analysis was applied to the synthetic data set to establish the resolution of this procedure.

A simulation under the optimal conditions of a strong scatterer and no noise is shown in Figure 2. The spatial search grid used throughout this paper has 361 nodes over a 30 x 30 km² area centered at the middle of the test site. The actual event locations within this grid are shown along with the position of the isotropic point scatterer lying just north of the test site. This scatterer was assigned a radiation coefficient of 0.5, and only incident waves with velocities of 2.5 km/sec were scattered, approximating a strong body-wave scattering mechanism. Thus, every synthetic had two arrivals, with the second arrival having half the amplitude of the first and an appropriate lag time. The semblance value at each grid point was computed for discrete stacking velocities of 2.0, 2.5, and 3.0 km/sec, with the

![Figure 2](image)

**FIG. 2.** Application of the semblance analysis to a synthetic data set with an isotropic point scatterer that scatters waves with velocities of 2.5 km/sec. The search grid, source distribution, and scatterer location are shown on the left. The semblance surface and maximum semblance values for several stacking velocities obtained without source or receiver weighting are shown in the middle column. Surfaces obtained by including source and receiver weighting are shown on the right.
resulting semblance surfaces being shown in Figure 2. A time gate of $t_g = 3.0$ sec was used in each case, which corresponds to the total duration of the synthetic pulses. The middle column of Figure 2 shows the results of applying the stacking process to the signals directly, with the peak value of the semblance for each case being shown. The peak value for the correct stacking velocity is less than 1.0 because the stacking procedure is slightly contaminated by the direct arrivals. Note that small semblance peaks are distributed over the portion of the grid where the events are located, indicating strong, but incomplete destructive interference.

It is reasonable to expect that suppressing the common features in each event should improve the resolution of the procedure. Similarly, in anticipation of applying the semblance analysis to real data with correlated noise from receiver and path effects, it is desirable to suppress effects common to a given station. This was accomplished by separately stacking the zero-lagged traces for each station and for each event, then computing the analytic envelope of the mean traces. The envelopes were normalized to have a peak amplitude of 1.0. This set of functions was then used as time-dependent weighting filters in the stacking operation. Each trace, $f_{ij}(t)$, was multiplied by

$$[[1 - W_1 \cdot E_i(t)] \cdot [1 - W_2 \cdot O_j(t)]],$$

where $W_1$ and $W_2$ are constants, $E_i(t)$ is the normalized envelope of the stacked traces for the $i$th event, and $O_j(t)$ is the normalized envelope of the stacked traces for the $j$th station. These smooth filters modify the relative amplitude distribution within the trace, but do not change the frequency content or polarity, which control the semblance measurement. For example, the $E_i(t)$ weighting simply suppresses the first few cycles of the waveforms, which consist of the common direct $P$ arrival at all stations for that event. Examples of actual average event envelopes are shown in Lay and Welc (1986). The right-hand column in Figure 2 shows the semblance surfaces obtained after applying station and event weighting with $W_1 = W_2 = 0.75$ to the data before stacking. The peak semblance value is enhanced and small features away from the true scatterer location (at the maximum peak) are suppressed. Alternate weighting procedures, such as subtracting off a mean signal (Boucher, 1973), can be used; however, the present scheme is attractive in that the changes in wave shape are not severe.

The example in Figure 2 shows that the semblance procedure has imperfect spatial and stacking velocity resolutions. The overall resolution is constrained by the configuration of the source and receiver distribution and by the limited bandwidth of the data. Numerous calculations with point scatterers at different locations about the test site were conducted to explore the nature of the "point spread function," or varying spatial resolution at each position. Figure 3 shows examples of the results for point scatterers similar to that in Figure 2. In each case, the peak value of the semblance surface is at the actual scatterer location. The best spatial resolution is attained for centrally located scatterers; however, the overall coherence diminishes for these locations due to contamination by direct arrivals for very nearby events. Scatterers near the edges of the grid tend to result in high coherence, but poorer spatial resolution. Overall, the spatial resolution across the entire grid is fairly uniform for moveout velocities greater than or equal to 2.0 km/sec for the 15 sec of signal energy available. Lower moveout velocities tend to have less resolution around the perimeter of the grid because the data windows are too short.

It is, of course, unlikely that only a single point scatterer would be present in any
actual case, and as the number of scatterers increases the realizable spatial and moveout velocity resolution must decrease, even in a noise-free situation. A simulation with four-point scatterers distributed around the source region is shown in Figure 4. The scatterers have varying radiation coefficients of 0.3, 0.4, 0.5, and 0.5 moving from left to right across the grid, with two scatterers having associated moveout velocities of 2.5 km/sec and two having moveout velocities of 3.0 km/sec. The semblance analysis is quite successful in detecting the discrete scatterers, and even in reflecting their respective radiation coefficients by the relative maxima of the semblance peaks. Note that the semblance surface for a moveout velocity of 3.0 km/sec is particularly successful at eliminating the lower moveout velocity arrivals. The synthetic waveforms for this simulation all have five arrivals, and inspection of the traces established that, even in this simple case, it would be very difficult to reliably track the signals from one station to the next without a systematic stacking procedure.

A much more complicated scattering situation was explored with a line of 7-point scatterers, each with a radiation coefficient of 0.4 for discrete moveout velocities of 2.0, 2.5, and 3.0 km/sec. The geometry for this calculation is shown in Figure 5, along with resulting semblance surfaces obtained with station and event weighting ($W_1 = W_2 = 0.75$). This situation can be considered to approximate scattering of $P$, $S$, and Rayleigh waves from a cliff or fault to the north of the test site. The waveforms for each synthetic $P$ wave consist of 22 arrivals with significant overlap, that were in fact similar in qualitative appearance to actual $P$-wave data. The semblance procedure performs well in spatially locating the edges of the scattering structure for lower moveout velocities, and the full row of scatterers is quite well defined at the higher velocities. The peak semblance values are significantly lower than for discrete scatterer situations due to the complex interference effects, and there is some artificial structure for the highest stacking velocity of 3.5 km/sec.

The preceding calculations were performed without any noise in the synthetics other than discretization effects. A more realistic calculation is shown in Figure 6, where a point scatterer that radiates with a coefficient of 0.3 for all incident wave speeds was combined with direct $P$ arrivals with random noise in the coda of the
Fig. 4. Application of the semblance analysis to a synthetic data set with four isotropic scatterers with discrete scattering velocities. The search grid, source distribution, scatterer locations, and corresponding scattering velocities are indicated on the left. The semblance surfaces and maximum semblance values for several stacking velocities are shown on the right.

Fig. 5. Application of the semblance analysis to a synthetic data set for a line of isotropic scatterers with scattering velocities of 2.0 to 3.0 km/sec. The scatterer locations relative to the search grid and source locations are shown at the top left. Semblance surfaces and maximum semblance values are shown for several stacking velocities.

direct signal. The noise was produced by adding 15 extra arrivals with random times in the first 15 sec of the waveforms with random amplitudes ranging from 0.0 to 0.5. These arrivals had identical shape to the direct and scattered arrivals, and the resulting scatterer signal-to-noise ratio was about 1.0. While the location of the scatterer is correctly determined for all stacking velocities, the degree of coherence is highly variable, being best at the lowest and highest stacking velocities. These calculations included station and event weighting functions, without which the spatial resolution would have been further degraded.
The preceding calculations demonstrate that if a moderate number of isotropic scattering structures are present near the source array, it should be possible to detect them as long as the noise levels are not excessive. However, for applications to real data, it is important to establish what effects would be observed if there are no coherent scattered arrivals at all. To do this, the semblance analysis was applied to synthetic $P$-wave signals with a direct arrival and 15 random secondary arrivals in the coda, with no coherent scattered energy. The semblance surfaces obtained for one simulation for a stacking velocity of 2.5 km/sec are shown in Figure 7. The surface on the left was obtained with no station or source weighting being applied, while that in the middle is the result for the same simulation with $W_1 = W_2 = 0.75$. The surface on the right resulted from applying the station and event weighting as well as additional azimuthal averaging of the data for each event using a 15° azimuth window. The azimuthal averaging was performed to give more uniform azimuthal coverage than is intrinsic to the actual data distribution. For the latter two cases, the overall coherence level is down to a few per cent, with only a few spikes left in the surface. These small peaks represent spurious coherence associated with the nonuniform event distribution. Most of the reduction in spurious coherence results from the event weighting, which tapers the early portions of the waveforms, since for these random coda cases there is no coherent station character apart from the direct arrivals.

A large number of such random coda simulations were performed, with the semblance surfaces for 10 different cases being averaged for discrete stacking velocities to give the surfaces in Figure 8. In each case, station and event weighting and azimuthal averaging were included, as in Figure 7. These surfaces provide a characterization of the spatial distribution function of spurious random noise effects for the semblance analysis for the actual data configuration to be examined next.
FIG. 7. Semblance surfaces and maximum semblance values obtained for a synthetic data set with random arrivals in the coda. The results with no receiver or station weights are shown on the left, while those including such weights are shown in the middle and on the right. The semblance surface on the right was obtained with an additional azimuthal averaging of the data for each event.

FIG. 8. Semblance surfaces for several stacking velocities obtained by analysis of synthetic data sets with random arrivals in the coda. The surfaces are averages of separate analyses of 10 random simulations, thereby indicating the intrinsic spatial characteristics of the noise properties of the array configuration.

Note that it is possible for isolated peaks to result from purely spurious constructive interference. The absolute amplitude of these surfaces is strongly influenced by the choice of random distributions, number of arrivals, and uniformity of bandwidth of the signals; so, these results are intended only to serve as a guide for interpreting the spatial variations in the semblance surfaces obtained using real data. This is a necessary complement to direct statistical analysis using the F-statistic, which does not incorporate information about the spatial configuration of the stacking procedure.

RESULTS FOR PAHUTE MESA DATA

The semblance analysis was applied to the 916 Pahute Mesa event recordings after normalizing each signal peak amplitude to unity. The resulting semblance surfaces are shown in Figure 9 for five stacking velocities. The column on the left gives results obtained with no station or event weighting, while the column on the right is for $W_1 = W_2 = 0.75$ and an azimuthal averaging window of 15°. The signals were renormalized after applying the station and event weighting to ensure a maximum potential semblance value of 1.0. The differences between the two columns reflect the degree to which biases from correlated noise appear to influence the stacking procedure. In both cases, there is a general tendency for larger peaks to be concentrated near the center of the grid, with the two peaks that develop in
the unweighted results being located near the centroids of eastern and western clusters of events (see Figure 6 for the event distribution). These peaks are suppressed by the weighting procedure, but the low maximum semblance values indicating 1 per cent coherence of the stacked traces clearly requires cautious interpretation. The semblance results for a stacking velocity of 3.0 km/sec for the weighted data appear to be the most promising, defining a line of relatively high coherence in the west-central part of the test site. The time gate used in Figure 9 was 3 sec, but this choice does not strongly affect the results, as shown in Figure 10.

In order to seek any coherence in the semblance patterns between different stacking velocities, the semblance surfaces in Figure 9 were averaged for the weighted and unweighted cases separately. These stacked surfaces are compared with corresponding stacks for random noise simulations in Figure 11. The unweighted cases are shown on the left, where there is a clear correspondence between the principal peaks in the data and major peaks in the simulation results. The corresponding stacked surfaces for the cases with station and event weighting are shown on the right, and while a few of the data peaks are located in areas that lack peaks for the simulation, the overall decay of coherence away from the center of coherence.

**Fig. 9.** Application of the semblance analysis to the actual Pahute Mesa data set, showing semblance surfaces and peak semblance values for several stacking velocities. The results on the left are for no station or event weighting of the data, while those on the right are for station and event weighting and azimuthal averaging of the data prior to stacking. The value for $t_g$ in every case is 3.0 sec.
FIG. 10. Comparison of the semblance surfaces obtained for the Pahute Mesa data using different time gates, $t_g$. Event and station weights were applied in each case.

FIG. 11. Comparison of stacked semblance surfaces for actual data (top row) and random simulations (bottom row). The column on the left is for analyses without any station or event weighting, while the column on the right includes both station and event weighting as well as azimuthal averaging.

the grid is well-matched. This indicates that much of the topography on the semblance surfaces for the actual data is consistent with a coda comprised of random arrivals. The peak values of the semblance surfaces for the simulation results are higher than those of the data, but this should not be interpreted as indicating that none of the data peaks are significant. The simulations do not
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exactly match the observed spectra, nor do they have identical noise properties; so, we are principally interested in using the simulations to characterize the intrinsic noise effects on the semblance procedure.

The semblance analysis was applied to subsets of the data population in order to explore the stability of the results. Three separate subsets of data yielded the results in Figure 12. Set (A) included the 13 westernmost events, set (B) included the 12 easternmost events, and set (C) included the 14 largest ($m_b \geq 5.8$) events. Station and event weights and 15° azimuthal averaging were applied for each case, with the station weights being derived from the entire 25 event data set. Simulations with random arrivals in the coda for similar subsets of events were also processed, with the corresponding semblance surfaces being shown in Figure 13. While the simulations again have higher peak coherence, the spatial patterns match many of the stronger features in the data, diminishing confidence in their significance as real isotropic scatterer effects. The subset of westernmost events does show a double peak that is not predicted by the simulations, and the subset of large events shows a ridge of peaks for a stacking velocity of 3.0 km/sec, which is only partially matched by the simulations.

The question arises as to whether any of the semblance peaks in the data can be interpreted as true geological scattering structures. For the large number of observations used, simple appraisal of the results using the $F$-statistic attaches high significance to many of the semblance peaks in Figure 9; however, the simulations indicate that the subtle spatial biases due to the array configuration need to be accounted for before a reliable statistical interpretation can be made. One procedure that is reasonable is to strip off the predictable component of the semblance surface which can be attributed to spurious coherence for random coda and then to apply the statistical test to the residual peaks. This conservative procedure was adopted for the Pahute Mesa data set given the overall low coherence values. Figure 14 illustrates the procedure followed. The Pahute Mesa source distribution is shown in map view along with the perimeter of the Silent Canyon Caldera, surface outcrops

![Figure 12](image-url)  
**Fig. 12.** Semblance surfaces obtained from the Pahute Mesa data set for three subdivisions of the data set. The **leftmost column** is for events in the western half of the Mesa. The **middle column** is for events in the eastern half. The **right column** is for the largest 14 events.
FIG. 13. Semblance surfaces obtained for synthetic data sets with random arrivals in the coda for the same three event subdivisions used in Figure 12, with the corresponding order from left to right.

FIG. 14. Comparison of semblance analysis results and known source region geological structure. (a) The Pahute Mesa source locations, outcrops of shallow crustal faults, perimeter of the Silent Canyon Caldera, and contours of the local Bouguer gravity anomaly. (b) The semblance values for discrete locations for the actual data for a stacking velocity of 3.0 km/sec are superimposed on the caldera outline. (c) The semblance values in (b) after removing the surface obtained from the corresponding random simulations. (d) The semblance values obtained from the data by stacking semblance surfaces for stacking velocities of 2.5, 3.0, and 3.5 km/sec and removing the averaged semblance surfaces from corresponding random simulations.
of crustal faults in the caldera, and local Bouguer anomaly contours (Ferguson, 1986) in Figure 14a. The location of the $-25$ mgal anomaly indicates that the deep structural walls of the caldera slope inward slightly. Figure 14b superimposes the semblance surface from Figure 9 on the base map for the case with the weighted data and a stacking velocity of 3.0 km/sec. Note that the points of strongest coherence are centrally located, as is true for the random noise simulations in Figure 8. The spatial biases were removed by subtracting the average semblance surface for a stacking velocity of 3.0 km/sec for the random noise simulations in Figure 8 from the data surface. The surfaces were scaled so that they had the same root mean square amplitude over the 361 grid points before the differencing operation. After masking out the negative values, the resulting corrected surface is shown in Figure 14c. The residual semblance peaks tend to lie along the western caldera rim, with some centrally located values as well. A similar result was obtained by applying the same procedure to a stack of semblance surfaces with stacking velocities of 2.0 to 3.5 km/sec, as shown in Figure 14d. This stripping procedure probably tends to undercorrect the values near the grid perimeter, but it does appear that more scattering is produced near the western edge of the caldera.

For an assumed signal-to-noise ratio for the scattered energy of 0.05, application of the $F$-statistic indicates that there is a 9 per cent probability that the largest residual semblance value in Figure 14c would result from random noise, while there is a 50 per cent probability that the largest value in Figure 14d would result from spurious noise coherence. If the actual signal-to-noise ratio is lower than 0.05, the significance of these peaks increases rapidly; however, if it is higher the significance decreases rapidly. Very low signal-to-noise ratios should certainly be anticipated, given that any actual scatterer will not radiate isotropically and that the downward scattering coefficients are intrinsically quite small (Aki, 1982).

**DISCUSSION**

The semblance procedure developed in this paper is essentially a standard array processing procedure adapted to the reciprocal problem of seeking coherent arrivals produced by near-source scattering. The synthetic calculations indicate that there is a good potential for spatially locating and characterizing isotropic scatterers. Such a procedure is desirable for detailed investigations of velocity heterogeneity in complex tectonic environments such as subducting slabs, or for the present application to the caldera complex at the NTS.

The actual data application described above has not resolved the presence of deterministic near-source scatterers unambiguously, and the simulations with random scattering actually provide support for the statistical approaches to analysis of the early $P$-wave coda like those adopted by Lay and Welc (1987) and Lay (1987). However, there is some indication that coherent scattering off the western perimeter of the Silent Canyon Caldera does occur, providing encouragement for attempting additional analyses of this type in other regions. Should reliable coherent features be detected in a particular data set, a straightforward pulse stripping operation can be applied to remove from the complete slant stack all of the robust coherent features. This was not attempted in the present application due to the relatively low confidence level of the semblance results. Ideally, this procedure should be applied to large data sets of broadband, digitally recorded signals, which are beginning to accumulate. It is possible to extend the analysis to scattered phases with pulse distortions or phase reversals by stacking the analytic envelopes of the signals rather than the actual seismograms. This procedure was attempted for the
Pahute Mesa data, but the results were quite ambiguous as a result of the limited bandwidth of the signals (very smooth semblance surfaces were obtained). The statistical properties of the stacking procedure for one-sided signals must be developed separately if such a procedure is adopted.

Some additional calculations were performed for individual event data in an attempt to detect event-specific secondary events. For the relatively small data sets available for any given event, spurious coherence is often observed, as confirmed by simulations with random noise. However, increased signal bandwidth, which will give additional degrees of freedom, may stabilize this procedure in future applications. Analysis of the short-period signals radiated from large earthquakes may be conducted using a similar formalism, with the intent of isolating concentrated regions of high-frequency radiation on the fault.

CONCLUSIONS

A slant stacking operation has been applied to teleseismic P-wave signals from a suite of underground explosions in an effort to detect near-source scattering structures. Application of the procedure to synthetic data sets indicates that there is good potential resolution of isotropic scatterers in the vicinity of the sources even in the presence of high noise levels. However, the simulations also indicate that spatial resolution biases and spurious coherence for random signals need to be taken into account when applying the procedure to real data. For 25 explosions in the Pahute Mesa test site, there is some evidence for coherent scattered energy from the western perimeter of the Silent Canyon Caldera, particularly for moveout velocities near 3 km/sec, indicating P- to P-wave scattering. However, the confidence in this interpretation is not particularly high because many characteristics of the data coherence can be qualitatively matched with random distributions of arrivals in the coda. Additional data applications are needed to establish the full potential of this procedure for remote interrogation of the near-source environment.

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**PART III. INVERSION FOR ISOTROPIC SCATTERERS**

**DEPARTMENT OF GEOLOGICAL SCIENCES**
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