Using Quarry Blasts to Image the Crust: Deconvolution and Migration of Wide-Angle Data

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Today, most crustal refraction/wide-angle reflection experiments are carried out with hundreds of instruments, large field crews, and specially drilled shots. Where resources are more limited, however, one can still obtain useful information about the crust by using quarry blasts and multiple deployments of much smaller arrays.

Deconvolution

Quarry blasts can be effective, low-cost energy sources for seismic imaging, provided that one can deconvolve the extended source signatures produced by ripple firing. This is especially important for composite refraction profiles constructed from multiple deployments of a small-aperture array because it allows the equalization of source waveforms for different ripple-fired blasts as well as enhanced resolution of structure. Unfortunately, because quarry-blast source signatures in general are not minimum delay, standard industry methods like predictive deconvolution are not always effective. This study uses real and synthetic data to compare the performance of several methods for deconvolving mixed-delay signals.

The problem considered here is the recovery of the effective source-time function along a given azimuth from traces in a shot gather. Tests building on the work of *Oldenburg et al. (1981)* focused particularly on design criteria for minimum-entropy filters and optimization of source-wavelet estimates derived by inversion of minimum-entropy filter coefficients. Predictive deconvolution reduces ringing but can generate coherent artifacts when the source wavelet is not minimum phase. Wiener filtering using source wavelet estimates derived by least-squares inversion of minimum-entropy filter coefficients preserves relative amplitudes, allows the user to specify the degree of spiking, and avoids delays in the output (Figs. 1, 2). Of 47 blasts recorded in Georgia and Tennessee with 15- to 19-channel arrays, 37 yielded a localized wavelet estimate with a duration for the most energetic portion of the wavelet estimate trace that was close to the reported duration of the blast (Fig. 3). In general, extraction of the source wavelet directly from quarry-site recordings is complicated by nonlinear effects, interference from S and Rayleigh waves, and by the variation of the source wavelet with azimuth. In spite of those complications, waveforms observed at quarry sites were similar to wavelets derived from field traces for about 10 of the blasts studied.

Wavelet estimates derived from minimum-entropy filter coefficients are not affected by static shifts between traces. Where statics have been effectively removed and where recording arrays are long enough to resolve differences in ray parameter for overlapping events, localized slant stacks can be a useful alternative for estimating the source wavelet.

Migration

Migration of very small-aperture recordings using conventional algorithms produces images dominated by smiles. The migration algorithm described here is an extension of the method developed by *Hawman & Phinney (1992)* for migrating travel-time picks in common-source gathers. We have found it to be useful for migrating data recorded with isolated, short-aperture arrays. Like the methods described by *Phinney and Jurdy (1979)* and *Milkereit (1987)*, it uses the localized slant stack of the source gather as an intermediate data set. Measurements of ray parameters fix the incidence angles, allowing separation and correct positioning of overlapping reflections. Unlike those methods, however, it assumes that all coherent energy in the slant stack consists of reflections from planar dipping interfaces; possible contributions of diffractions are ignored.

Briefly, the algorithm maps every sample in the coherency-filtered slant stack into a planar, dipping segment with a length that is a function of the length of the recording spread and the migrated dip. The method uses ray tracing to determine the position and dip of reflecting interfaces. Each sample in a given ray parameter trace (where the time axis corresponds to the travel time to the center of the recording spread) is downward continued until it intersects a ray traveling downward from the source which yields a combined two-way travel time that matches the observed time. The dip is determined from the ray parameters of the upgoing and downgoing rays. Once the subsurface position of the reflector midpoint is determined, a planar interface is generated by assigning the value of that slant-stack sample to all subsurface points along a linear segment with the appropriate dip. A separate subsurface section is generated for each ray parameter trace. Each trace in a given section is linearly interpolated over depth. The individual sections then are stacked to construct the final image of reflectors as recorded for that shot gather.

Although the method is not a true wavefield migration, it does incorporate some useful information from the input wavefield into the migrated image. The thickness and lateral extent of migration smiles are controlled by the degree of smearing in the slant stack, which in turn is controlled by the array aperture and signal bandwidth. The dimensions of these smiles thus serve as measures of the resolving power of the input gather.

The method is being used to migrate a set of roughly 110 blasts recorded in several provinces of the southern Appalachians, including 44 blasts recorded in 2002-2003 in the Blue Ridge Mountains. Preliminary results (Fig. 4) show an increase in crustal thickness from 38 km for the Carolina Terrane (and associated regional gravity high) to about 50 km along a regional gravity low associated with the foothills of the southeastern Blue Ridge. Pg-PmP travel-time differences for blasts not yet migrated suggest even greater crustal thicknesses within the central Blue Ridge.

Summary

The goal of the work described above is to more effectively utilize recordings of industrial explosions (and earthquakes) made with isolated, small-aperture arrays. These recordings can provide useful reconnaissance information prior to the deployment of large-scale, controlled-source experiments.

References

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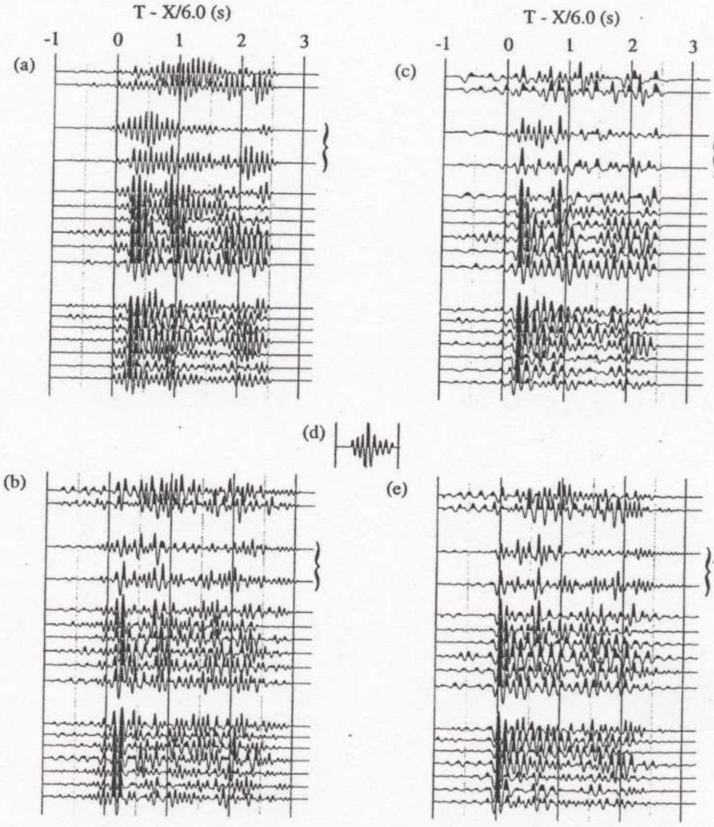

Fig. 1. Deconvolution results for a blast recorded in the Charlotte Belt, Georgia. Source-receiver offsets: 20.9 - 28.0 km. Reported source duration: 0.334 s. **(a)** Input gather after high-cut filtering with a linear taper from 10 to 15 Hz and correction for elevation and residual statics. **(b)** Predictive deconvolution of the gather in (a) using a prediction distance of one sample (spiking deconvolution) and a filter length of 80 samples (0.4 s). **(c)** Minimum-entropy deconvolution of the gather in (a) using a filter length of 20 samples (0.1 s). The minimum-entropy filter output for this blast was very similar for filter lengths between 20 and 200 samples. **(d)** Source wavelet estimate, which clearly is not minimum-delay. **(e)** Wiener deconvolution of the gather in (a) using the source wavelet in (d) and a Gaussian with dominant frequency of 10 Hz for the desired output wavelet. Similar to (c) except that energy is shifted to the beginning of each event in the gather.

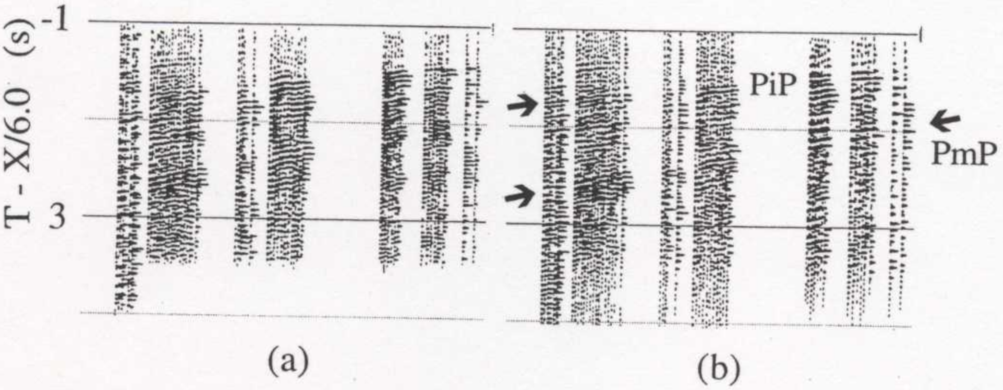

Fig. 2. Deconvolution results for a composite section consisting of 4 blasts recorded at distances from 104 to 139 km along strike within the Carolina Terrane, north Georgia. Blasts were at two quarries 3 km apart. **(a)** Input gathers after applying a high-cut filter with a linear taper from 10 to 15 Hz. **(b)** Wiener deconvolution of gathers in (a) using estimates of source wavelets derived by least-squares inversion of the minimum-entropy filter coefficients for each blast and a Gaussian with dominant frequency of 10 Hz for the desired output wavelet, followed by spectral whitening.

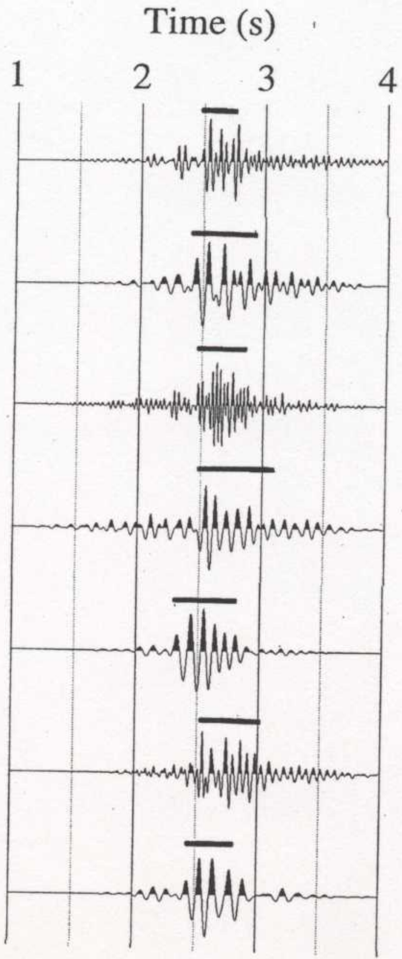

Fig. 3. Source wavelet estimates for a sampling of delay-fired quarry blasts recorded with 17-channel arrays in the Carolina Terrane of north Georgia. Wavelet estimates were generated by least-squares inversion of minimum-entropy filter coefficients. The source gather for each blast was high-cut filtered prior to minimum-entropy deconvolution; high-frequency cutoff settings ranged from 10 to 40 Hz. The reported source durations are indicated by the width of the heavy bars.

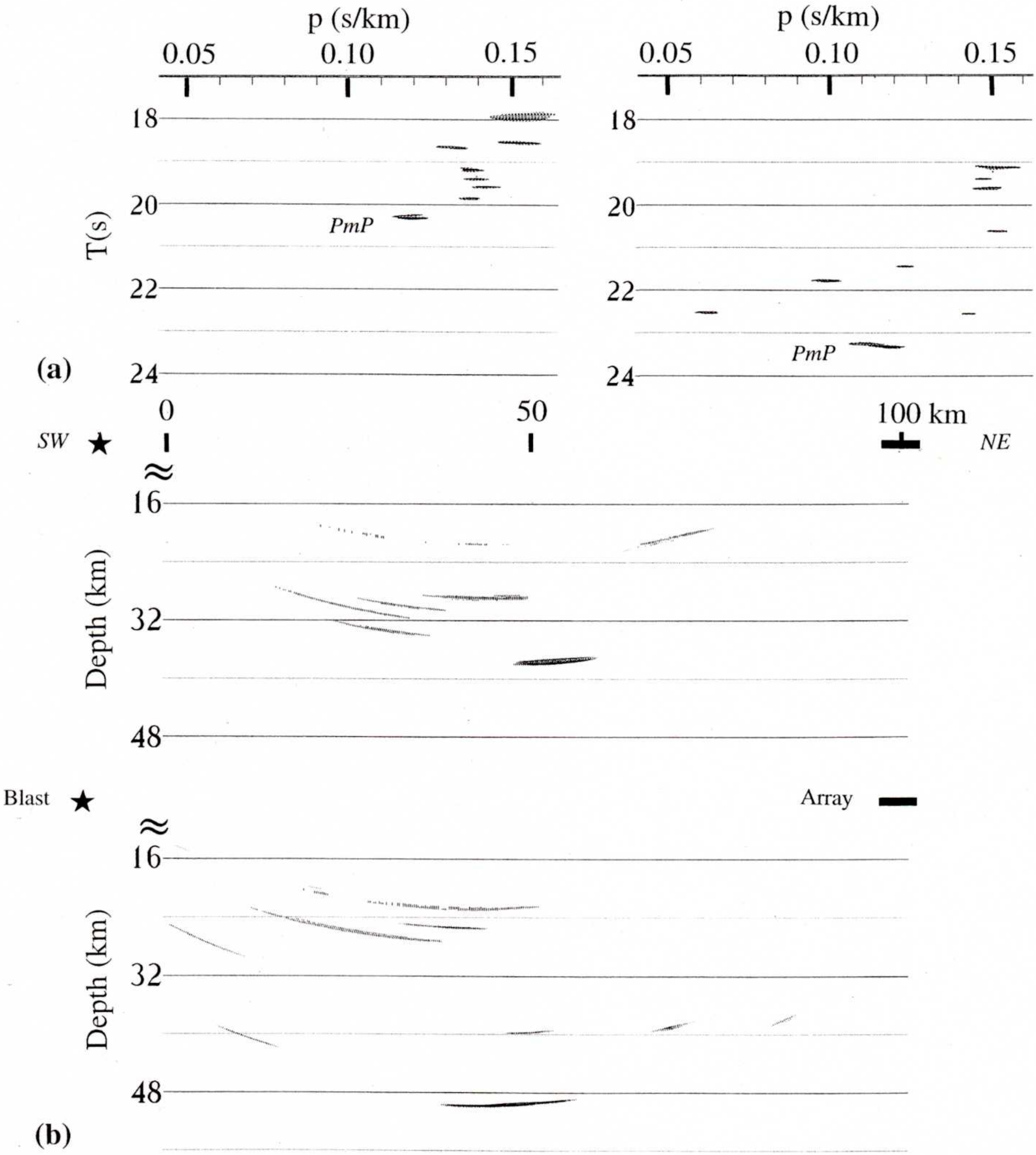

Fig. 4. Migration of single shot gathers (19-channel array) for quarry blasts recorded within the southern Appalachians. **(a)** Coherency-filtered slant stacks of deconvolved gathers; vertical axis corresponds to travel time referred to the center of the array. PmP: arrival interpreted as near-critical reflection from the Moho. Left: for blast recorded along strike within the Carolina Terrane (offsets: 106-111 km); direct arrival at 18 s not included in the migration. Right: for blast recorded along the southeast flank of the Blue Ridge Mountains (offsets: 109-113 km); noisy direct arrival at about 18.5 in the shot gather was not passed by the coherency filter. **(b)** Migrated sections. Top: Carolina Terrane. Bottom: Blue Ridge.