Simultaneous Inversion for Detailed Source and Structure Parameters Using Quarry Blast Data Recorded in Eastern Kazakhstan

Danny J. Harvey

University of Colorado

F49620-94-1-0109
Sponsored by AFOSR

Abstract

We have completed a study aimed at the development of a full waveform joint structure-source inversion method. We used differential seismograms to represent the linearized structure effects and perturbed source terms to represent the source effects. We found it desirable to include unbalanced force terms, in addition to an arbitrary symmetric moment tensor, to represent the source. We also found it necessary to use exact expressions for computing the differential seismograms that did not involve eigenvalue-only approximations. We applied the inversion method to a dozen local quarry blasts recorded by the NRDC network in Kazakhstan in the 0.4 to 2.0 Hz frequency range. We found that it was possible to produce very good fits between the synthetic seismograms and the observed data on all three components simultaneously and for the P-wave, Rayleigh wave and Love wave. The inclusion of the unbalanced force terms significantly improved the fits for some of the events and resulted in more reasonable structure and source parameters than were obtained without the force terms. We interpreted some of the inverted source parameters as being characteristic of several different types of industrial surface mining operations.

Key Words

local events, waveform inversion, waveform modeling, industrial explosions

1. Objective

The objective was to obtain fundamental understanding of the source physics and local wave propagation characteristics associated with industrial explosions by attempting to match synthetic seismograms with real quarry blast data. In this report we will document a study in which we developed a technique for inverting full waveform data for both detailed source parameters and structure parameters. We used seismograms from a set of industrial explosions that were analyzed in a previous study as our data. These explosions took place in Eastern Kazakhstan and were recorded by the Natural Resources Defense Council seismic network that was in operation during 1987.

2. Research Accomplished

2.1 Inversion Procedure

We started using the structure inversion technique developed in a previous work[1] which we will refer to as Harvey (1993). In this study we developed a structure inversion method, using both dispersion and full waveform data, based upon the cylindrical geometry, laterally homogeneous, elastic wave propagation methods developed by Harvey[2] that uses a normal mode superposition approach for computing synthetic seismograms. The full waveform inversion method we developed is similar to the method described in Gomberg and Masters[3] and Walter and Ammon[4] and generally consists of the usual damped steepest descent approach that utilizes differential seismograms[5] for the determination of local performance function gradients. Although our method is most similar to that of Gomberg and Masters, since we use a normal mode as opposed to a reflectivity approach, we made some substantial changes to the method developed by Gomberg and Masters which we found necessary to insure rapid and accurate matching between the synthetic and real seismograms.

In our previous work, we essentially either constrained the source terms in the inversions, or inverted for a scalar source amplitude using a simple explosion source, or we employed a "seat-of-the-pants" method for obtaining more complicated source moment tensor solutions that did not involve the use of formal inversion for the source moment tensor. In this study we have developed a complete formal inversion method that allows us to infer both structural and source parameters simultaneously. We added unbalanced force terms to the standard symmetric moment tensor terms which we found to be desirable for modeling shallow industrial explosions.

---

[1] Harvey, D., 1993, Full waveform inversion for structure and source parameters using regional data recorded in Eastern Kazakhstan, Final Report, Report no. PL-TR-93-2078, Phillips Laboratory, Air Force Materiel Command. ADA266405

[2] Harvey, D. (1981). Seismogram synthesis using normal mode superposition: the locked mode approximation. *Geophys. J. R. Astr. Soc.* **66**, 37-61.

[3] Gomberg, J. and Masters, T., 1988, Waveform modelling using locked-mode synthetic and differential seismograms: application to determination of the structure of Mexico, *Geophys. J. R. Astr. Soc.*, **94**, 193-218.

[4] Walter, W. and Ammon, C., 1993, Complete regional seismic waveform inversion for crust and upper mantle structure: The September 14, 1988 JVE explosion, Kazakhstan, Eurasia, Preprint, Lawrence Livermore National Laboratory, Report no. UCRL-JC-112844

[5] Harvey, D., 1991, Studies of regional wave propagation using differential seismograms and randomized structural models, Final Report, Report no. PL-TR-91-2126, Phillips Laboratory, Air Force Systems Command, ADA247011.

2.1.1 Source Parameter Inversion

We follow the work of Stump[6] who describes the process of formulating a synthetic Green's function as a linear sum of a special set of synthetic seismograms weighted by terms that can be directly related to the symmetric moment tensor elements. We did our inversions in the time domain after applying a bandpass filter to both data and synthetics.

In addition to the ten synthetic Green's function components that are required to represent an arbitrary symmetric moment tensor (for laterally homogeneous structures), we added five more Green's function components that are required to represent an arbitrary unbalanced force vector. The resulting 15-component Green's function was combined with the 3-component data to form a 9x9 least squared inversion matrix for the 9 source parameters (6 moment tensor elements and 3 force elements). Standard singular value decomposition was used to form the inversions. The double-couple, dipole, explosion or force terms could be independently constrained in the source inversion.

2.1.2 Source-Structure Inversion Process

In order to simultaneously invert for both structure and source parameters, it is first necessary to expand the synthetic solution in terms of a linearized joint expression of both source terms and structural perturbations. If the source terms were small perturbations like the structural terms, then the linearized synthetic representation would be a simple expression involving both source and structure perturbations. However, in the case of the source inversion, the source terms are not small perturbations, but are the actual moment and force values and the linearized synthetic expression can be considered to be exact, to the extent that the linear elastic wave equation governs the overall physics of the wave propagation process. On the other hand, the linearized synthetic solution expressed as a function of the structural perturbations is definitely an approximation to the actual relationship between the synthetic waveforms and the structural parameters, which is highly non-linear even when using a linear form of the elastic wave equation. In this situation it is necessary that the structural perturbations remain small in order for the linearized synthetic waveforms to be valid and thus the inversion to remain stable.

We can write down an expression for the synthetic waveforms as a sum of the 15-component source Green's functions weighted by the source moment and force terms. Each of these Green's functions can then be expanded as a linear perturbation involving differential Green's functions and the structural perturbations. If we put these expanded Green's functions into the original representations for the synthetic waveforms we are left with expressions that are non-linear in the source and structure model parameters and are thus not suitable for linear inversion. One way around this problem is to assume that the source terms can be expanded into zeroth order terms plus small perturbations. Using this approach we can derive a set of synthetic waveform expressions with completely linearized dependences on small source and structure perturbations. However, we are still left with the determination of the zeroth order source parameters which will require source-only inversions.

Our joint source-structure inversion procedure is iterative in nature to account for the non-linear relationship between the synthetic waveforms and the structure parameters. We fix a set of layer thicknesses based upon the applicable wavelengths. We then make a zeroth order estimate of the structure velocities, densities and Q values using observed dispersion functions, travel times and any other constraints that we can

[6] Stump, B., Investigation of seismic sources by the linear inversion of seismograms, Ph.D. Thesis, University of California, Berkeley.

reasonable use. This initial estimate of the structure is one of the more tedious and difficult parts of the inversion. At this point we typically constrain the Q values and the densities.[7] We start the iterations by doing a source-only inversion to determine the zeroth order source parameters. Using these source parameters, we then do a simultaneous source-structure inversion for small source and structure perturbations. We add a small structure perturbation constraint to the performance function to stabilize the structure part of the inversion. We add the structural perturbations to the original model and we go on to the next iteration by doing another zeroth order source-only inversion.

Note that we do not add the inverted source perturbations to the zeroth order source parameters, but instead do another zeroth order source-only inversion. If the linearized synthetic expressions were exact, then there should be no difference between the two approaches, and in the case where the linearized synthetic expressions are inexact, redoing the source-only inversion acts to stabilize the inversion by removing the source perturbations that are produced as a result of inaccuracies in the linearized structure dependent parts of the expressions. One might ask why we bother to do the joint inversion at all if we are going to ignore the source perturbation results from the joint inversion. The answer to this is that it is desirable to allow the extra degrees of freedom when doing the structure inversion so that some amount of fit can be taken up in source terms as opposed to requiring structure perturbations only. This should cause the inversion to converge more rapidly than doing source-only, structure-only iterations.

2.2 Data and Observations

We used seismic data recorded as part of the NRDC program conducted during 1987. The NRDC network was operated by the University of California, San Diego and consisted of three stations that surrounded the Shagan River and Degelen Mountain areas of the Eastern Kazakhstan Soviet test site. Although there were three stations in the NRDC network, throughout most of the year only one or two stations were operational and the most consistent station was KKL (Karkaralinsk). All of the results in this study are based upon data collected at KKL. We used as our data source the NRDC Information Product which was compiled by IRIS' Joint Seismic Program Center and distributed through the IRIS Data Management Center.

The instrumentation at KKL consisted of a surface 1 Hz 3-component seismometer, a surface 0.2 Hz 3-component seismometer and a borehole 0.2 Hz 3-component seismometer all recording at two different gain levels (on 16-bit digitizers) and at 250 sps. The site was on granitic bedrock and generally exhibited low noise characteristics. The region around KKL is an active mining area with many shallow explosions and generally exhibits low natural seismicity. Most seismicity in the area is of the "induced" type and is associated with the large nuclear explosions at the former Soviet test site.

2.2.1 Data Characterization

A total of 12 events were used in this study. These events came from the results of Harvey (1993) and consist of presumed quarry blasts all within about 25 km of Karkaralinsk. Event epicenters were determined by using the S-P distances along with back azimuth estimates that were obtained from polarization analysis. We chose a set of events that were clustered and are presumably from a few different quarries.

---

[7] For this study we were able to assume elastic propagation throughout because of the short source-receiver distances and the relatively low frequencies.

Figure 1 shows the unfiltered KKL radial, transverse and vertical components for event number 521. The time is relative to the event origin time. The label on the left of the traces shows an event id for each event, along with the distance in km and the event to station azimuth in degrees. Figure 1 also shows the same event after passing through a 0.4 to 2.0 Hz Butterworth bandpass filter. The filtered traces show high signal to noise with strong Rg excitation. The transverse component shows strong Love wave excitation as well. In the high frequency band we can see that there must be a high degree of scattering of the P-wave into the transverse component which is likely due to 3-dimensional scattering. However, in the 0.4 to 2.0 Hz passband the transverse P-wave component is very small compared to the radial P-wave components. Also in the lower frequency band the P-wave to Rayleigh wave amplitude ratio is small.

We can see from Figure 1 that there is a strong low frequency Love wave. The relative amplitude of this Love wave varies considerably from event to event. At this distance and in this frequency band there can be no more than about 10 wave cycles for the lowest velocity waves at a frequency of 2 Hz. Given the observed variations in the Love wave relative amplitudes and the small number of wave cycles along the propagation path it is unlikely that the large Love waves are caused by lateral scattering, but instead are caused by direct source excitation.

The use of a simple explosion source will obviously produce none of the Love waves that we see in the data. We can use an arbitrary symmetric moment tensor to parameterize the source which will result in non-zero Love wave components. However, if we think about the physics associated with a large surface explosion, we can see that the use of a moment tensor to represent the source, which best characterizes completely contained explosions or other relaxation sources such as earthquakes, may not be adequate.

To start with, we assume that most large industrial explosions are intended to aid in the excavation of surface material and are thus designed to be uncontained. Completely contained explosions are usually used in underground mining operations and tend to be small to avoid damaging the mining infrastructure.[8] An explosion associated with a surface mining operation is designed to pulverize large amounts of rock and, in some cases, to move the pulverized material laterally. Regardless of whether or not the actual gases associated with the explosion are well contained, the rock material around the explosion will be broken up to the surface and there will be a disruption in the elastic integrity of the rock mass that originally surrounded the explosion which will result in an effective unconstrained source term. In addition, when significant quantities of rock material are moved laterally by the explosion, we would expect an unbalanced lateral thrust vector to be applied to the elastic material.

2.3 Inversion Results

Because of the large difference between the P-wave and Rg amplitudes we found it desirable to equalize these amplitudes through the application of a time-varying gain factor before performing the inversions. This was accomplished through the following steps for each event. First, we computed a time-varying rms average of the individual data components after rotating to radial and transverse components. These rms functions were then divided into the data to give amplitude equalized data functions (these are sometimes called AGC functions). We then used the same rms functions to equalize the amplitudes of the synthetic seismograms and each of the Green's function components and the differential seismograms. The inversions were then performed with these amplitude equalized traces. All data and synthetics were put through a 0.4 to 2.0 Hz bandpass filter before the inversion.

[8] The obvious exceptions to this are underground nuclear explosions.

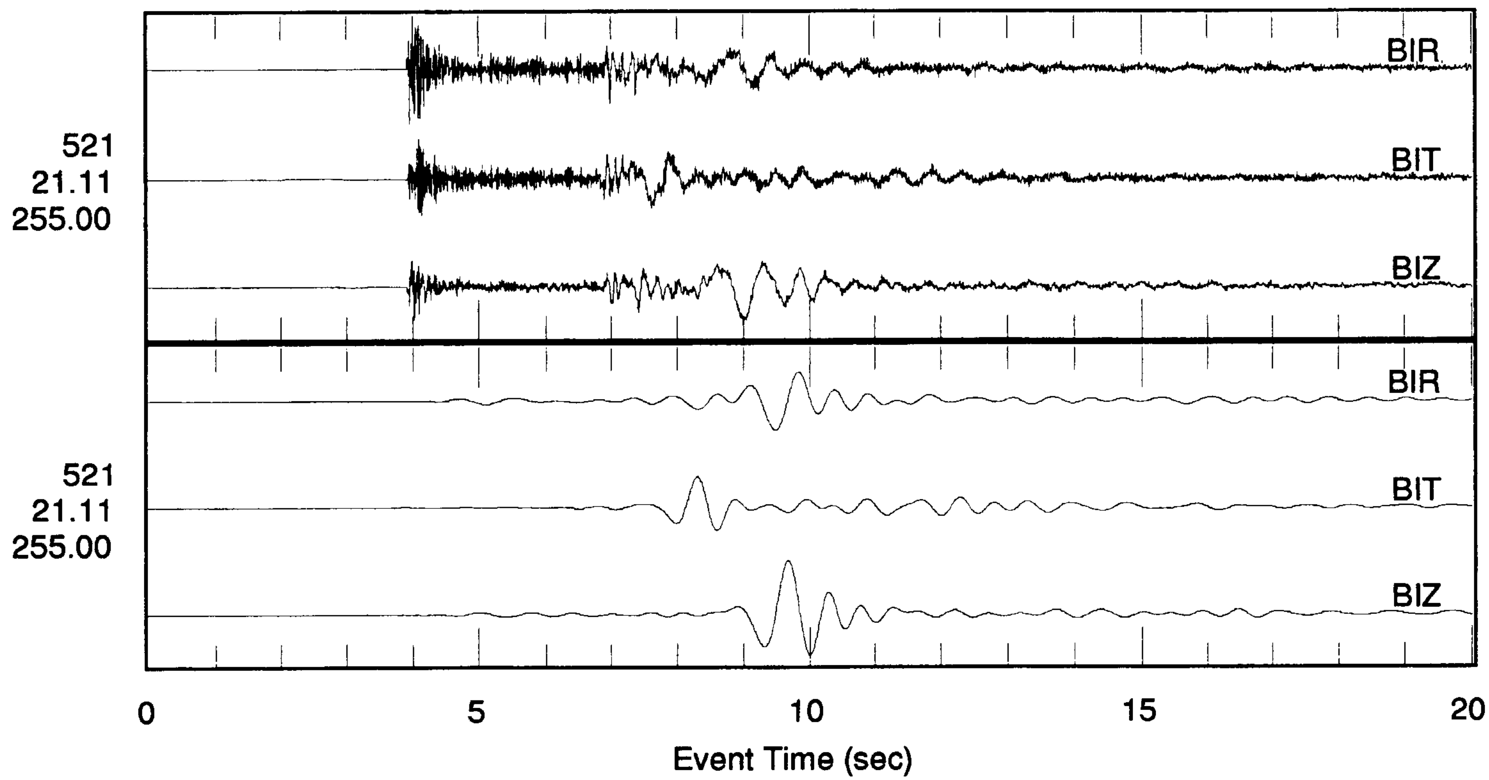

Figure 1. Unfiltered and filtered radial, transverse and vertical component seismograms for event number 521. The labels to the left refer to the event id, the distance in km and the event to station azimuth in degrees.

The results of simultaneous source-structure inversion of event number 521 are summarized in figure 2. At the bottom left hand corner are comparisons of the filtered and amplitude equalized radial, transverse and vertical component data traces and synthetic seismograms after the last inversion iteration. The data traces are shown as the thinner lines and the synthetic traces are shown as the thicker lines. At the upper left hand corner is a plot of the initial and final structure P and S velocity model. The initial model is shown with the light lines and the final model is shown with the thicker lines. At the center top is a display of the final moment tensor and force vector solution. The beachball is gray shaded according to the resulting particle motion with lighter shades representing dilitational motion and darker shades representing compressional motion. The right most panels show how the rms error and source terms changed with each inversion iteration. The panel labeled rms shows the auto scaled rms misfit error. The panel labeled mom0 shows the absolute value of the principle moment component with the bottom of the plot scaled to zero moment. The panel labeled percent shows the percentage of the moment term partitioned into explosion (darker shade), dipole (medium shade) and double-couple (lighter shade). In addition, a '+' or '-' character is put into each explosion and dipole bar to represent whether the term was compressional or dilitational in sign. The panel labeled force shows the absolute magnitude of the force vector with the bottom of the plot scaled to zero force. The panel labeled 'frc str/pl' shows the force strike and plunge angles. The force vector application angle is also shown on the beachball as the 'F' character.

We can see from this inversion that we have obtained a remarkably good fit between the data and synthetics for all three components and for the P-wave, the Rayleigh wave and the Love wave. Even more encouraging is that we obtained the fit after essentially five or six iterations. In our previous work (Harvey 1993) we found it necessary to perform as many as several hundred iterations to obtain a good fit and in some cases we were unable to adequately fit the data no matter how many iterations we performed.

In our initial attempt at fitting these events, we used the same inversion procedure as we used in our previous study (Harvey 1993) which is functionally equivalent to the procedure used by Gomberg and Masters (1988). In this approach the differential seismograms are approximated by using only the differential terms associated with eigenvalue derivatives of the modal expansion while ignoring the eigenfunction derivative terms. In another previous work (Harvey 1991), we had shown that these differential approximations broke down for body waves and that it was necessary to include the eigenfunction derivative terms to accurately compute the differential seismograms. However, we found that including the eigenfunction derivative computations increased the computer run times substantial and we decided to use the faster approximations instead. We reasoned that although the differential seismograms would not be strictly accurate, they would be good enough to move the inversion in the right direction and the use of the approximations would only effect the inversion by requiring more iterations to get to the ultimate results.

When we applied these approximations in the inversion of event 521 we found that although we could fit the Rayleigh and Love waves well, we were not able to fit the P-wave amplitudes no matter how many iterations we tried. When we put in the eigenfunction derivative terms we got the results shown in figure 4. Not only are we fitting the P-wave amplitudes well, but we are doing it in just a few iterations. We then realized that although we were able to fit the body phases in our previous study, we were doing so by adjusting Q values which directly effected the eigenvalue derivatives. In this study we are using elastic structural models and the only way we can match body wave amplitudes is through the elastic structural parameters (and the source terms). We can see that the use of eigenvalue based approximations for the differential seismograms can result in spurious Q values to overcome the inaccuracies in the differential seismogram computations.

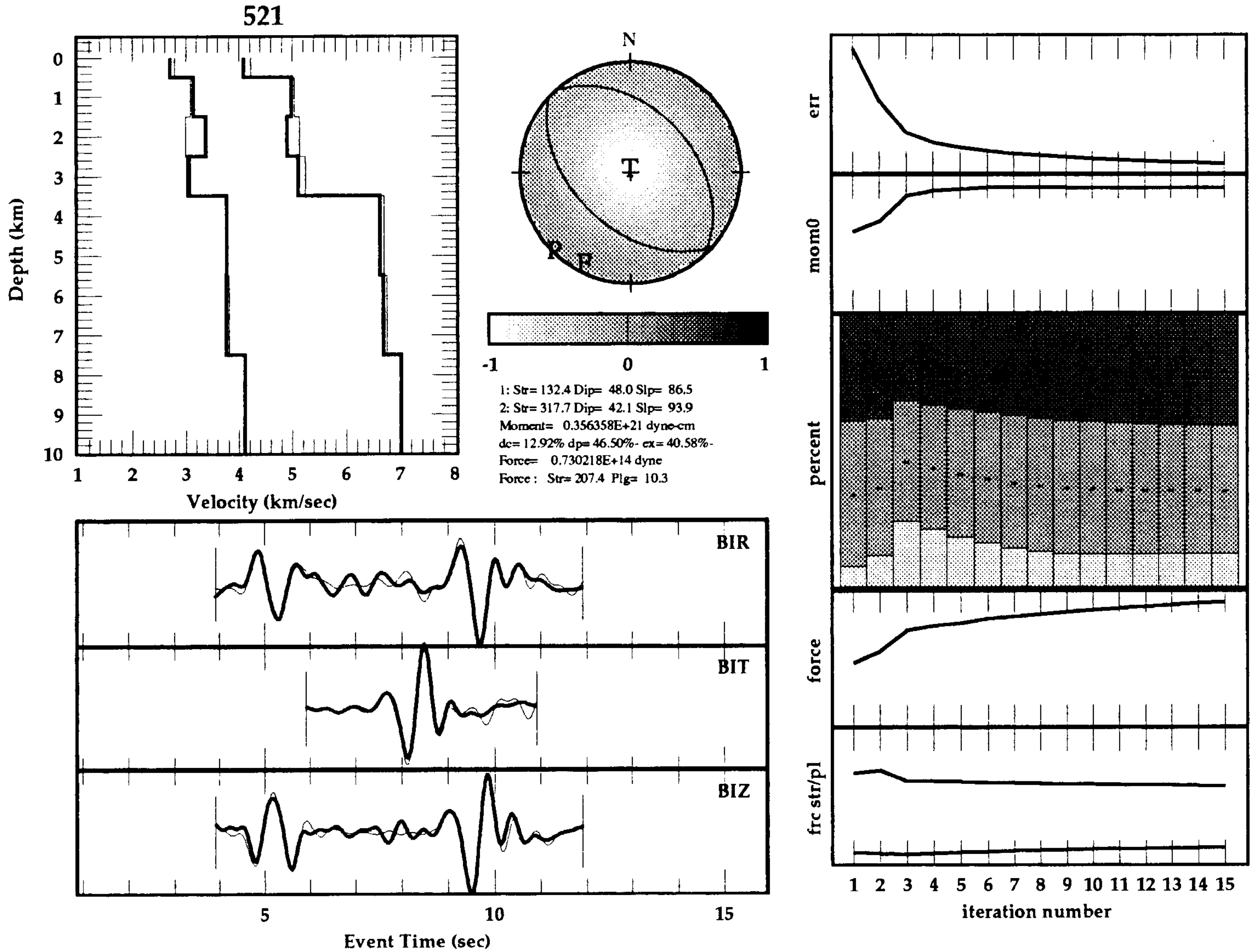

Figure 2. Summary results of full waveform inversion for source and structure parameters for event no. 521. All source terms were included in the inversion. The bold traces are the synthetic seismograms and the lighter traces are the real data.

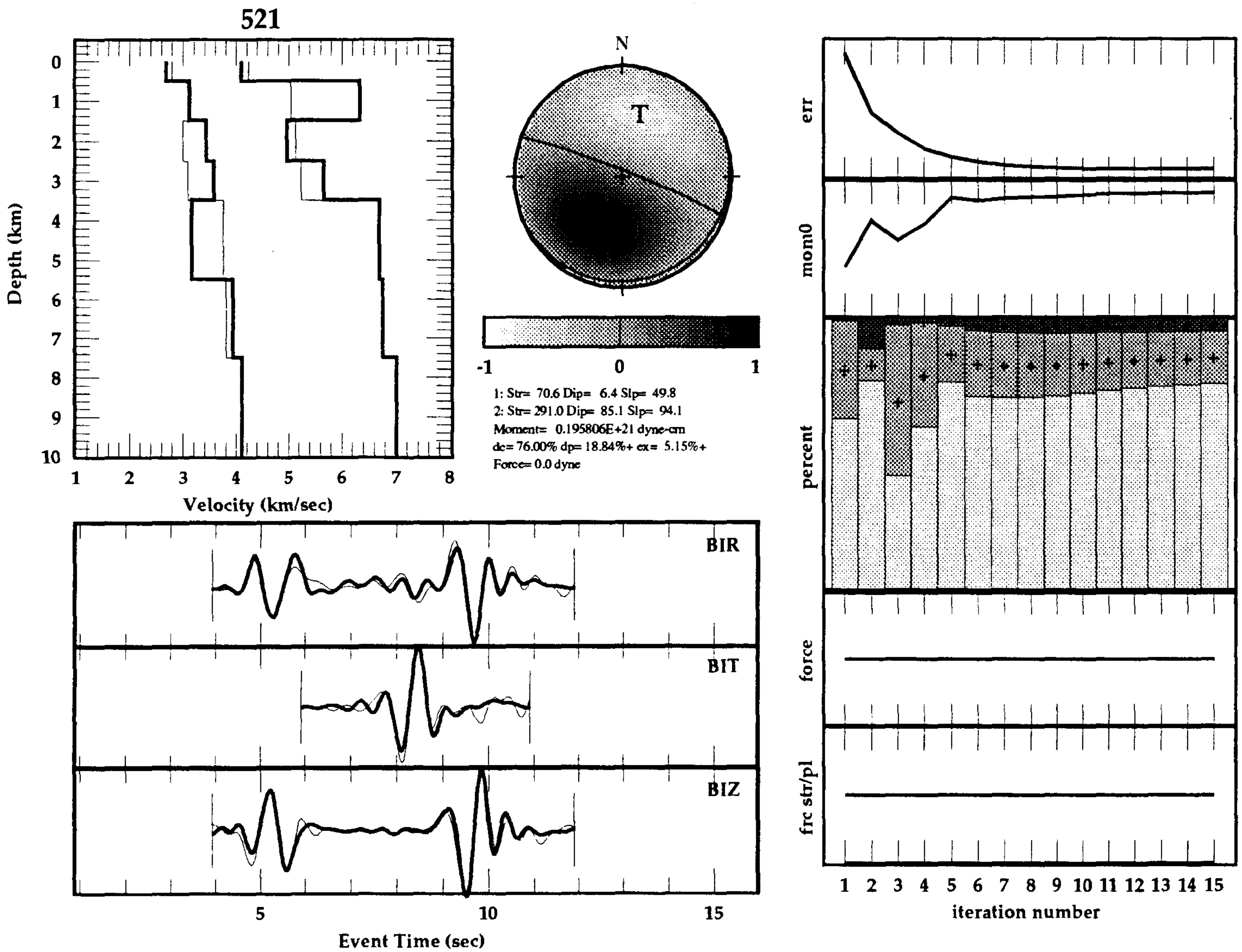

Figure 3. Summary results of full waveform inversion for source and structure parameters for event no. 521. Unbalanced force terms were excluded from the inversion. The bold traces are the synthetic seismograms and the lighter traces are the real data.

The inversion results summarized in figure 2 show a reasonable structural model that is not too much different from the starting model. Both the moment and force values would indicate a rather large explosion.[9] We can see that the moment is fundamentally implosive and vertical dilitational dipolar with a small residual amount of double-couple. The thrust vector is almost horizontal. We might expect these type of source terms for a cast shot type blast that ejects rock material laterally. The strong dilitational terms could be due to the rebound after removal of the ejected material.

In figure 3 we show the same inversion except we have constrained the source terms to only include the moment tensor (no force terms). We can see that the fit is not as good as in figure 3 especially for the Love wave. Also, the resulting structural model is less believable than the results from the original inversion. For this inversion we get a strong double-couple term which is probably necessary to fit the strong observed Love wave amplitude.

The same inversion proceedure was performed using data from the other events used in this study. The results for event 505 look very similar to those for 521. However for events 507, 510 and 509 we get somewhat opposite results in terms of the explosion and dipolar terms being compressional instead of dilitational. We suspect that some of these mines are coal mines that use surface strip mining operations to get at flat lying buried coal seams. A standard blasting technique in this case is to place charges over a horizontal spatial extent either within or slightly above the seams. The resulting blast is designed to break up the material above the seams for easy surface removal without moving it significantly. For an explosion of this type, we might expect the resulting moment tensor to be compressional due to the fact that no rebound due to removed material would occur combined with the effective gravity assisted confinement of the material above the blast.

The other events show a variety of source solutions, but we can say that in most cases the fits are very good and that in every case the resulting moment solutions are thrust fault or normal fault in nature. Also the resulting structures tend to cluster into two families; structures that look similar to the structure for event 521 and structures that show a low P-velocity zone from 1.5 to about 3.5 km depth. This may be indicative of two different quarries with slightly different average propagation characteristics.

When we compare the unconstrained with the constrained inversions, we see results similar to the comparisons of figures 2 and 3 except for event 510 in which case there appears to be no resolvable difference in the two inversions. For the other events the constrained inversions yield less believable structures and source terms that include large double-couple components to presumably fit the Love waves. We think that the inclusion of the unbalanced force terms provide realistic extra degrees of freedom in the source parameterization that generally produce more accurate inversions for the structure and moment parameters.

3. Conclusions and Future Plans

We have completed a study aimed at the development of a full waveform joint structure-source inversion method. We used differential seismograms to represent the linearized structure effects and perturbed source terms to represent the source effects. We found it desirable to include unbalanced force terms, in addition to an arbitrary symmetric moment tensor, to represent the source. We also found it necessary to use exact expressions for computing the differential seismograms that did not involve

[9] For comparison, a 10^{20} dyne-cm moment roughly corresponds to a m_l = 2.5 event in Southern California and a 10^{11} dyne force roughly corresponds to the thrust from a V-2 class rocket engine burning one ton of propellant over one second.

eigenvalue-only approximations.

We applied the inversion method to a dozen local quarry blasts recorded by the NRDC network in Kazakhstan in the 0.4 to 2.0 Hz frequency range. We found that it was possible to produce very good fits between the synthetic seismograms and the observed data on all three components simultaneously and for the P-wave, Rayleigh wave and Love wave. The inclusion of the unbalanced force terms significantly improved the fits for some of the events and resulted in more reasonable structure and source parameters than were obtained without the force terms. We interpreted some of the inverted source parameters as being characteristic of several different types of industrial surface mining operations.

The results documented in this report represent the successful conclusion of the first phase of our proposed research, as we listed in our original work statement. We found that although we obtain good fits using single station-event data, we suspect that many of the inversions are not well constrained and we expect that by combining multiple events and/or stations in simultaneous inversions we will significantly remove the ambiguities that we may have experienced in this study. In the next phase of this work, we will concentrate on doing joint inversions for several sources from the same area using a common structure and different source parameters. We have most of the tools to do this now. However, we will need to add the capability to invert for source location simultaneously with the other source parameters and the structure. This will be needed because mis-location errors could otherwise cause irreconcilable inconsistencies in the synthetic and real seismograms.