REFINEMENT OF REGIONAL DISTANCE SEISMIC MOMENT TENSOR AND UNCERTAINTY ANALYSIS FOR SOURCE-TYPE IDENTIFICATION

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ABSTRACT

We build on our earlier results (DE-FC52-06NA27324, Dreger et al., 2008; Ford et al., 2010; Ford et al., 2009a, b; Ford et al., 2008) in which it has been demonstrated that regional distance moment tensor analysis can discriminate explosions from naturally occurring earthquakes and mine collapses. In this project, as an effort to refine procedures for implementation we develop a more complete understanding of uncertainties, and define robust methods for their characterization. In Ford et al., 2008, it was found that populations of explosions, earthquakes and collapses in the Western U.S. separated on a Hudson et al. (1989) diagram enabling source-type discrimination. A question the current research addresses is whether these populations remain separated for other regions of the world. We have compiled a database of naturally occurring, and induced seismicity to examine the distribution of non-double-couple seismic moment tensors in a Hudson source-type diagram to be used as an a priori constraint. The results indicate the region of tradeoff between a pure explosion monopole and a compressional major vector dipole (CLVD) is relatively devoid of natural and induced seismicity, which is favorable for seismic moment tensor source-type discrimination. In addition, we present new results for the North Korean test combining regional and teleseismic observations to further restrict tradeoff between pure explosion and pure CLVD solutions for nuclear explosions. We are investigating the velocity model dependence of vanishing free-surface traction effects on seismic moment tensor inversion of shallow sources, and are working on developing a damped inversion to suppress these effects and reduce bias in scalar moment estimates for shallow sources. Finally, we are working toward extending the regional seismic moment tensor database for nuclear explosions and natural seismicity for the Korean Peninsula and Kazakhstan.

OBJECTIVES

In this project (FA9453-10-C-0263) we build on our earlier results (DE-FC52-06NA27324, Dreger et al., 2008; Ford et al., 2010; Ford et al., 2009; Ford et al., 2008) to investigate whether source-type populations (explosion, collapse, earthquakes) that were found to separate on a source-type plot for the Western U.S. remain separated for other regions of the world. We expand the database of studied events to include natural and man-made seismicity from the Korean Peninsula, Kazakhstan, Middle East, and European Arctic. In each region we apply regional distance seismic moment tensor analysis, investigating aleatoric and epistemic (velocity model and network configuration) uncertainties. This regional characterization is a necessary first step toward developing a decision basis for utilizing moment tensor results for source-type identification and discrimination. In addition, we present results comparing different data windowing and component goodness of fit weighting strategies using the Network Sensitivity Solution (NSS) framework (Ford et al., 2010) to improve the separation of event type, and to reduce tradeoff between non-double-couple solutions as represented on a source-type plot. We are developing a modified inverse method to damp the effect of vanishing traction on the recovery of stable seismic moment tensors and scalar seismic moment. The analysis procedures will be developed with synthetic cases and then applied to studied events.

RESEARCH ACCOMPLISHED

Introduction

Ford et al. (2009) calculated seismic moment tensors for 17 nuclear test explosions, 12 earthquakes, and 3 collapses in the vicinity of the Nevada Test Site in the Western U.S. They found that the relative amount of isotropic and deviatoric moment provided a good discriminant between the explosions, earthquakes and collapses (Figure 1). The observational work to describe the discriminant was accompanied by a theoretical study into the sensitivities of the method and it was found that the ability to resolve a well-constrained solution is dependent on station configuration, data bandwidth, and signal-to-noise ratio (SNR). To capture all these variables in a succinct way in order to assess the uncertainty in an individual discrimination result a new tool was developed called the NSS (Ford et al., 2010).

The fit of intermediate period synthetic waveforms to the observed regional distance data is used to determine the moment tensor solution for each source. Those moment tensor results are shown in the Hudson et al. (1989) source-type representation (Figure 1) solutions for western U.S. nuclear explosions, earthquakes, mining collapses as well as the recent North Korean nuclear tests, and the India nuclear tests. As shown in Figure 1, the different source type populations separate, enabling seismic moment tensor based discrimination. Importantly, the populations of explosions and cavity collapses separate dramatically whereas in traditional mb:MS and regional phase P/S ratio discriminants this separation is less clear (e.g. have inconsistent results) (Walter et al., 2007).

For the western U.S. events aleatoric uncertainties derived from a residuals bootstrap are represented by the error ellipses. There have been many attempts to understand and characterize the various sources error in seismic moment tensor inversions. Sileny and co-authors have done extensive sensitivity testing of the methods they use to calculate the moment tensor. Sileny et al. (1992; 1996), Sileny (1998), Jechumtalova and Sileny (2001), and Sileny (2004) have collectively investigated the effects of incorrect event depth, poor knowledge of the structural model including anisotropy, noise, and station configuration on the retrieved solution. They found that for only a few stations with data of SNR>5 the moments of various components were sensitive to improper source depth and velocity model, but that the mechanism remained robust, and that spurious isotropic components may manifest in the solution if an isotropic medium assumption is made incorrectly. The probabilistic inversion method by Weber (2006) inverted for hundreds of sources using a distribution of hypocentral location based on *a priori* information using a probabilistic treatment, which inspired our development of the NSS (Ford et al., 2010). Perturbations to the velocity model and noise are also added in the synthetic portion of the study. Empirical parameter distributions are then produced to assess the resolution.

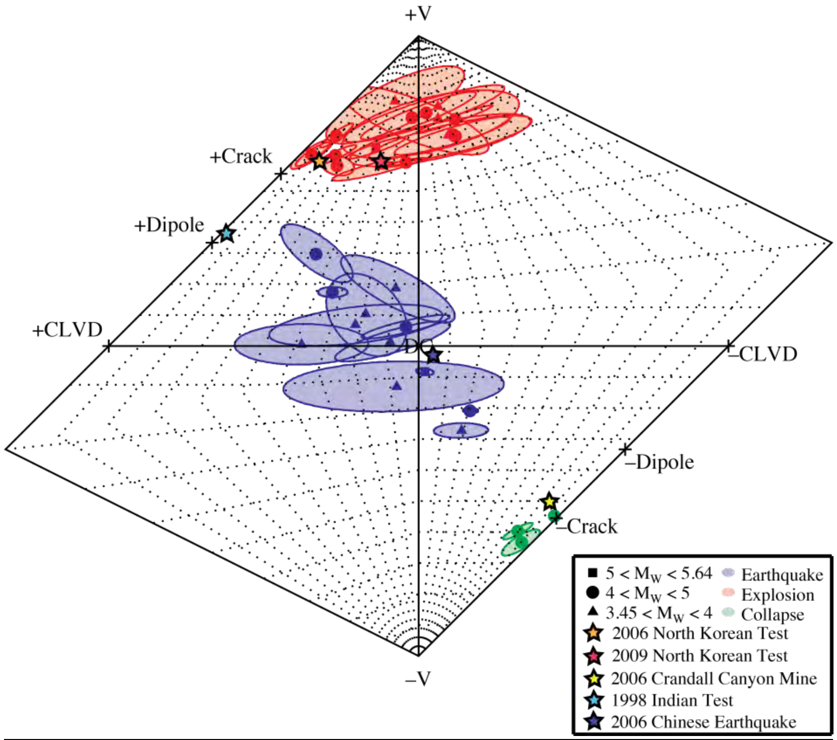

Figure 1. Compilation of regional moment tensor results for western U.S. earthquakes, nuclear explosions, mining collapses, and the North Korean and Indian nuclear explosions. Modified from Ford et al. (2009a).

Network Sensitivity Solutions (NSS) for the 2009 North Korean Nuclear Test

The theoretical NSS tries to answer the question of how well a pure earthquake or explosion can be resolved with very high SNR data for the given event scenario (i.e., data bandwidth and station distribution) using a source-type representation. The source-type parameters (Hudson et al., 1989) are calculated for each of the thousands of possible source solutions distributed uniformly on a source-type plot (Figure 2). A single set of source-type parameters (one point on the source-type plot) can represent several sources. For example, a DC source with any strike, rake, or dip, will plot in the center of the source-type plot. However, as one moves away from the center of the source-type plot (location of a DC mechanism), source orientation becomes less important to the seismic radiation so that the top and bottom of the plot are uniquely represented by an explosion or implosion, respectively.

The NSS for the 2009 North Korean test shows that the best solutions are located away from the origin and have significant positive volumetric components. The NSS also illustrates the well-known tradeoff between the pure explosion and negative CLVD (with major compressional vector dipole oriented vertically) solutions due to the similarity in Rayleigh wave radiation patterns for the two source types. As pointed out by Patton and Taylor (2011), such CLVD sources can possibly be an important component of seismic radiation from nuclear explosions and arise from damage in the source region and elastic rebound of the surrounding material. In natural seismicity such solutions would be expected to be rare due to the competition of force dipoles due to the explosive monopole and inward or compressional forces of the negative CLVD. We envision that the distribution of seismic moment tensor solutions for natural and induced seismicity can serve as a prior constraint to help characterize the anomalous nature of nuclear explosions from their NSS distributions. As shown in Dreger et al. (2010) the earthquake and explosion distributions in the NSS are complementary, and we have found that this is similarly true when non-double-couple natural and induced earthquakes are considered.

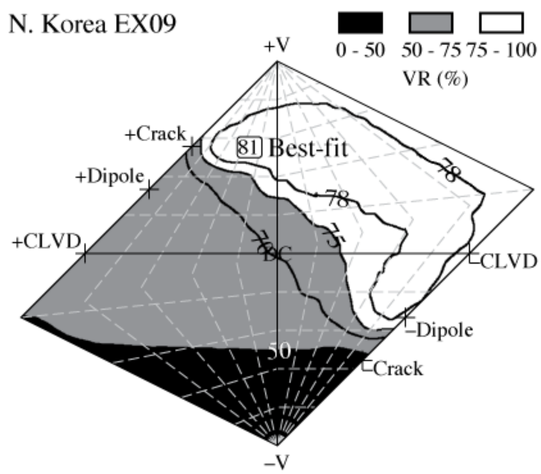

Figure 2. NSS for the 2009 North Korean nuclear test. The shading and contouring shows the level of fit measured by the variance reduction. The best fit solution is identified by the square and the corresponding fit.

For example, Figure 3 shows the distribution of Global Centroid Moment Tensor GCMT moment tensors (isotropic component is typically restrained to zero). Firstly, the GCMT catalog shows that the vast majority of events are located near the ε=0 double-couple, and that the tails toward positive and negative CLVDs are strongly attenuated. While CLVD events do occur in the GCMT catalog they are relatively rare, particularly in the -2ε range from 0.6 to 1.0 where the explosion/-CLVD tradeoff (Figure 2) occurs.

Secondly, the distribution of volcanic, geothermal, mining and induced events shown in Figure 4 shows that the majority of this anomalous seismicity is located along the line from a positive dipole to a negative dipole passing through the double-couple origin. In fact the positive explosion negative CLVD quadrant, where the explosion/CLVD tradeoff exists for nuclear explosions, has relatively few events. This is similarly true for the negative explosion positive CLVD quadrant. Thus it can be shown that background seismicity is extremely rare in the region of the tradeoff, and therefore it will be possible to use the NSS distribution in addition to an anomalous moment tensor solution in a probabilistic manner to further constrain the source-type identification or discrimination of a given event. In addition, as shown last year (Dreger et al., 2010) the 1998 Indian nuclear test has a NSS that lies in this negative explosion positive CLVD quadrant due to the large degree of tectonic release in this event that reversed the phase of the observed Rayleigh waves. While such phase reversals are problematic for interpretations of regional moment tensor solutions, the analysis of the NSS and comparison with expectations from prior background seismicity appears to be able to aid in discriminating or identifying such events as well.

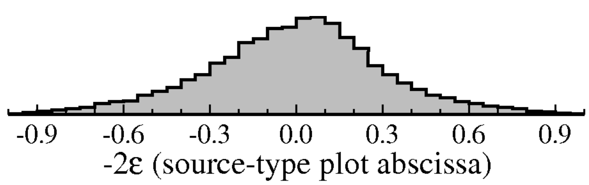

Figure 3. Distribution of -2ε from 22393 events (up to Dec. 2010) from the GCMT catalog. A pure double-couple has a value of zero, and this distribution represents the x-axis of the source-type plot. Note the exponential decay of non-double-couple solutions.

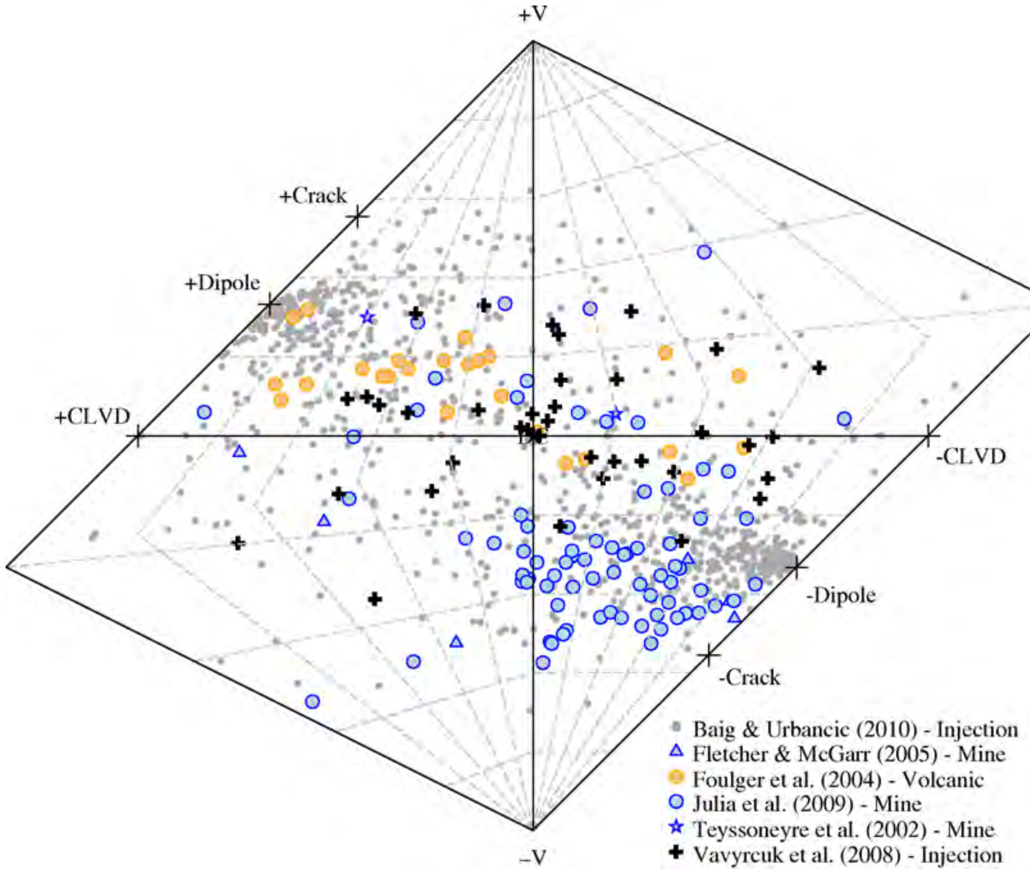

Figure 4. A compilation of moment tensor solutions for volcanic, mining and induced seismicity. The general trend is the line from the opening to closing crack, passing through the double-couple, origin. The upper right quadrant of negative CLVD and positive volumetric terms has relatively few events, as does the region of positive CLVD and negative volumetric character.

Combination of Regional Seismic Moment Tensor Solutions and Teleseismic P-waves to Further Constrain the NSS

Ford et al. (2009b) calculated a seismic moment-tensor for the announced nuclear test of the Democratic People's Republic of Korea (DPRK) on 25 May (Memorial Day) 2009 using regionally-recorded (<1500km), intermediate-period (10-50s) waveforms. The source-type derived from the seismic moment-tensor was dominantly explosive. However, the similarity in data-fit between a compensated linear-vector dipole with a vertical axis in compression (VCLVD-P) and dominantly explosive source presents a problem in discrimination between these two source-types, however additional data sensitive to different regions of the focal sphere can be incorporated and constrain the VCLVD-P/explosion trade-off. We propose to use teleseismic-P recordings that, due to the steep take-off angles, are sensitive to the lower hemisphere of a focal sphere, which is in dilation for a VCLVD-P and compression for an explosion, to constrain the moment-tensor-derived source-type. We start with the Regional NSS (Figure 5c) and then multiply the VR for each source by zero if the correlation with the teleseismic-P waveforms (Figure 5b) is negative. This results in a new NSS where sources that are inconsistent with the teleseismic-P waveform are not used in the solution. The NSS shown in Figure 5d no longer exhibits the explosion/CLVD trade-off.

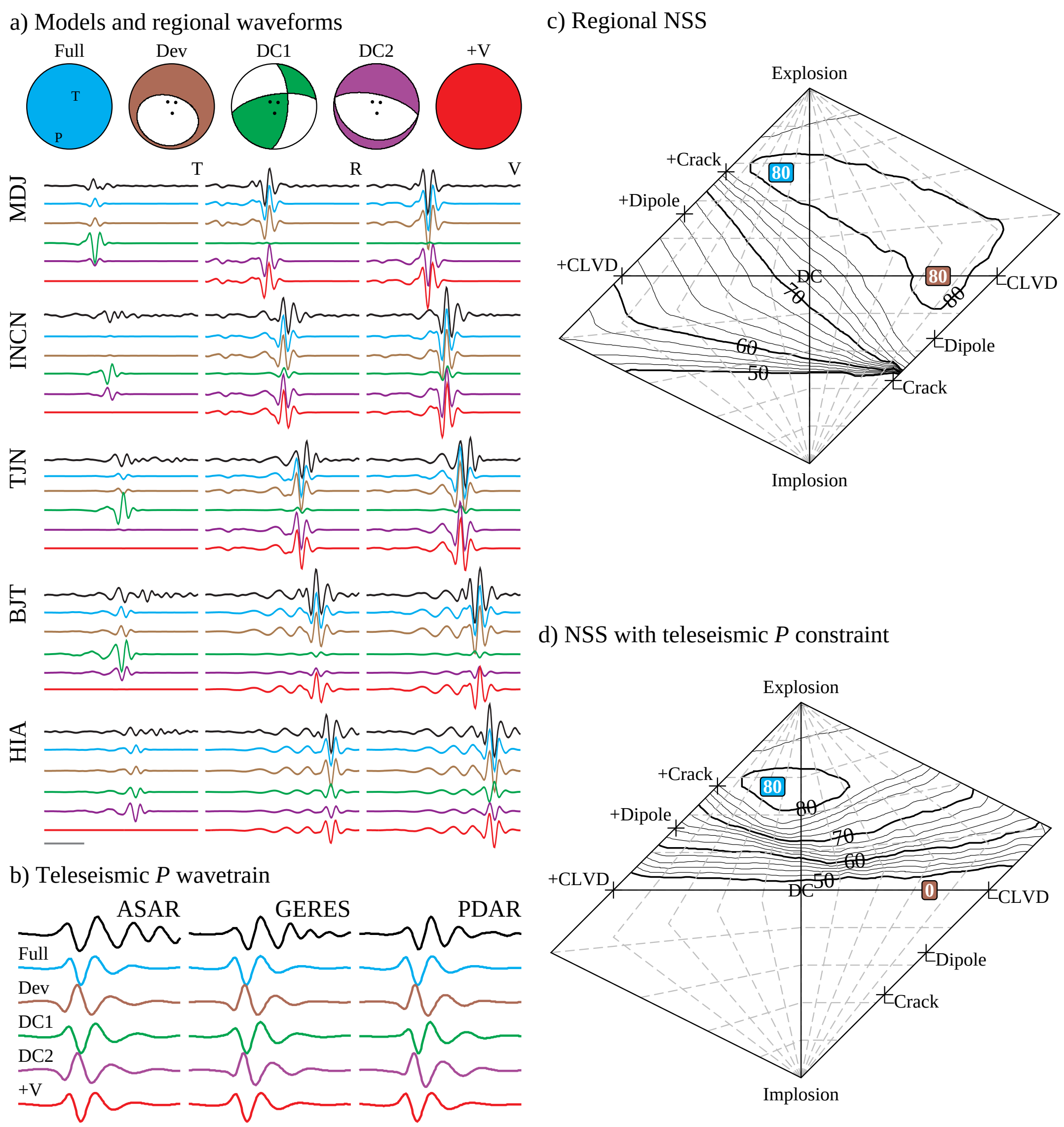

Figure 5. Teleseismic constraint to regional source-type determination for the 2009 DPRK nuclear test. a) Three-component (Tangential, Radial, and Vertical) intermediate period (10-50s) displacements (black) from regional stations and synthetic waveforms at those stations predicted by the sources shown with a lower-hemisphere equal-area focal-sphere. Amplitudes are normalized to the maximum of the three components at each station. The gray bar is 50 sec long. The color of the predicted waveform matches the color of the compressional component of the focal-sphere. The AK-135-predicted take-off angles to the teleseismic arrays are given by the small circles on the focal-spheres of the best-fit deviatoric (Dev), and two examples of double-couple solutions (DC1 and DC2). For comparison, the best-fit explosion is also given (+V). b) Array beams of high-frequency (0.8-4.5 Hz) teleseismic P-wavetrains (black), and synthetic waveforms at those arrays predicted by the sources given in a). Each trace is 4 sec long. The color of the predicted waveform matches the color of the compressional component of the focal-sphere. Note the anticorrelation of the teleseismic P predicted by the best-fit deviatoric (Dev) source. c) Contours of fit (Variance Reduction, VR) to the regional data shown in a) for a uniform distribution of sources on the source-type plot. This NSS shows comparable fit to the data for a CLVD-like source (Dev) and an explosion-like source (Full) with a similar VR of ~80%. d) The NSS given in b) but where the VR is now zero if the teleseismic P and forward-predicted synthetic data are anticorrelated, as is the case for the deviatoric source (Dev).

Effects of Vanishing Traction at the Free-Surface on Seismic Moment Tensor Scalar Seismic Moment Estimation

The vanishing traction condition has a strong effect on the mxz and myz components of the seismic moment tensor and the corresponding fundamental fault Green's functions for vertical dip-slip faults. In Figure 6 this is illustrated with bandpass filtered displacement Green's functions for the Song et al. (1996) velocity model that was used in Ford et al. (2009a). The explosion (REP and ZEP), vertical strike-slip (TSS, RSS and ZSS), and 45-degree dip-slip (RDD and ZDD) Green's functions show little to no variation with source depth over the range from 1200 m to 200 m. At higher frequencies differences in waveforms are observed in these components due to differing strengths of wave reflecting from the free-surface, but in the long-period passband (10 to 50 seconds period) employed in regional moment tensor inversion the waveforms are essentially identical over this depth range.

On the other hand, the vertical dip-slip components (TDS, RDS and ZDS) display a strong attenuative effect on the Green's functions for shallowing source depth. The importance of this effect was commented on in Given and Mellman (1986) in their analysis of fundamental model Love and Rayleigh wave amplitude and phase for nuclear and tectonic release source terms, and estimates of seismic moment for explosion yield determinations.

In a seismic moment tensor inversion the use of an incorrect source depth can therefore lead to biases in the mxz and myz elements of the seismic moment tensor due to the vanishing amplitude of the corresponding Green's functions. As Green's function amplitudes become small the related moment tensor terms can grow very large biasing both the inferred source orientation information, and the partitioning of explosive and non-explosive components, as well as the estimates of scalar seismic moment (Figure 7).

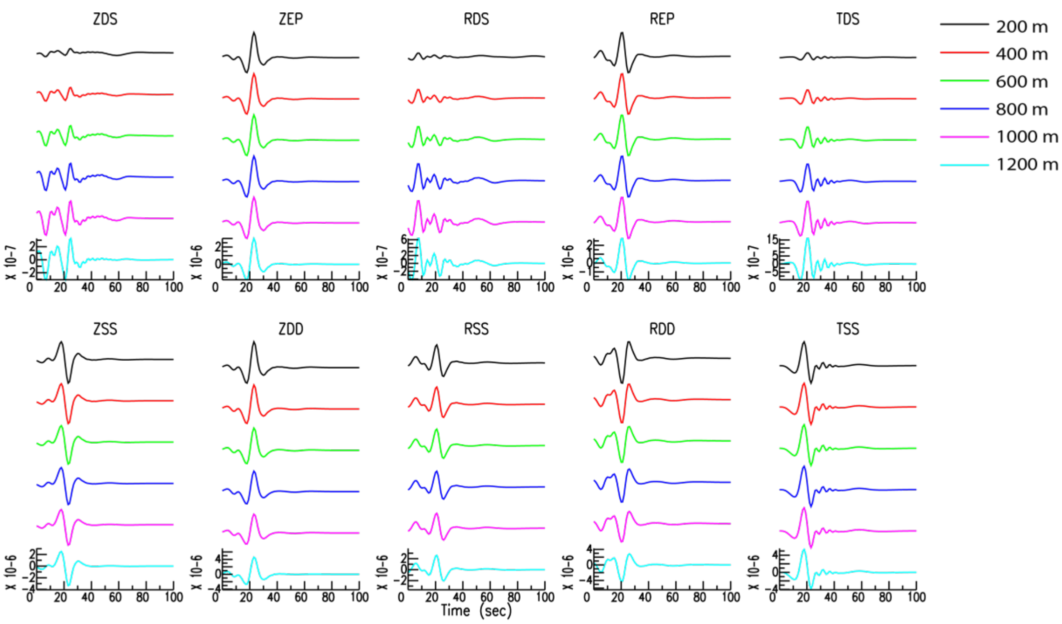

Figure 6. Fundamental fault Green's functions computed using the Song et al. (1996) velocity model for the western U.S. for a range of source depth. The displacement Green's functions have been bandpass filtered between 10 to 50 seconds period. tss and tds are the vertical strike-slip and vertical dip-slip Green's functions for the transverse component. The radial and vertical components also have their 45-degree dip-slip (rdd and zdd) and explosion (rexp and zexp) Green's functions presented. The station distance is 100 km. tds, rds, and zds show a strong reduction in amplitude due to the vanishing traction at the free-surface, where as the strike-slip and explosion components have no effect. The rdd and zdd components show little wave amplitude variation with shallowing source depth but do demonstrate differences in waveforms due to the constructive interference of waves interacting with the free-surface.

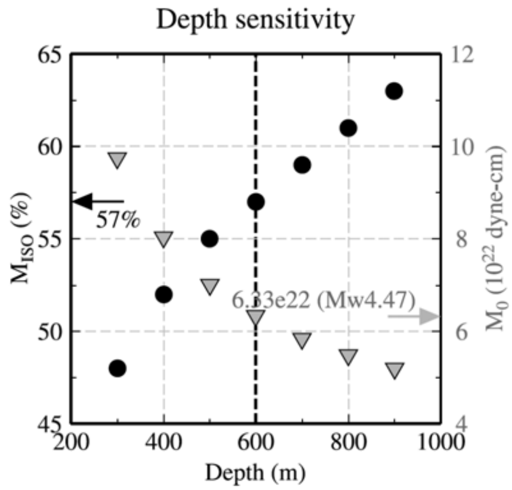

Figure 7. Source depth sensitivity on total scalar moment (triangles), and percent isotropic component (circles) in the moment tensor solution for the 2009 North Korean nuclear test from Ford et al. (2009b).

Fortunately the waveforms are seen to vary in a systematic manner for a given velocity model in which to first order the amplitude is effected, and only minor differences in waveform phase result. Therefore it is possible to either 1) employ corrected Green's functions at the time of inversion given independent depth of burial information, or 2) correct moment tensor results following inversion. We are developing both capabilities as well as a modification to the regional moment tensor inverse method to damp the moment tensor elements that are sensitive to this effect. We will present an analysis of the near-surface amplitude and phase scaling of waveforms for a suite of velocity models to examine the importance of near-surface seismic velocity gradients on the scaling. We will also document the effect on seismic moment tensor determination and scalar moment recovery accounting for errors in velocity structure and the presence of random noise. The behavior of the Green's functions in Figure 6 suggests that it will be possible to correct the non-linear trends observed in Figure 7 so that estimates of scalar moment and percent isotropic are stable over the typical emplacement depth range of nuclear devices.

CONCLUSIONS AND RECOMMENDATIONS

Our work to date indicates that our proposed refinement of a regional distance seismic moment tensor method can improve reliability of the solutions and reduce ambiguities enabling a robust regional distance method for source type discrimination of nuclear explosions.

We have additional work to perform before the above conclusion is finalized, however. Notably it is necessary to investigate the solutions of events in other regions of the world.

Nevertheless, our results do show that by combining regional distance three-component intermediate period waveforms with P-waves obtained from teleseismic array beams the well known theoretical tradeoff between a pure explosion source and a vertical CLVD with major compressional vector dipole in fitting regional intermediate period surface waves can be eliminated. As Figure 5 shows, using the teleseismic P-waves it is possible to eliminate inconsistent solutions in the NSS (Figure 2, and Ford et al., 2010) that produces a distribution distinct and complementary to those for earthquakes. Our continuing work will investigate data fit measures, strategies for differentially weighting the regional and teleseismic data, as well as the performance under degrading signal to noise conditions.

We have compiled catalogs of deviatoric and full moment tensor solutions from the GCMT as well as local and regional studies of events in volcanic, geothermal and mining environments. The GCMT catalog shows that the majority of events are classified as double-couples and importantly that the CLVD solutions are rare. This implies that while the regional surface waves of nuclear explosions can be fit with either explosion or CLVD sources are some combination of each, if such a solution is obtained for an event in question it is unlikely to be a natural event. Similarly the plot in Figure 4 for volcanic, geothermal and mining seismicity moment tensor studies demonstrates that the explosion/negative-CLVD quadrant has few natural or induced events. These catalogs can be used to determine the prior expectation of natural/induced seismicity in the context of the source-type plot and NSS, and can be used to develop a Bayesian moment tensor approach, which will be the focus of a future project.

Finally, the fact that the free-surface is a traction free boundary condition, and that for long-period and intermediate-period waves the effect of vanishing traction extends to depth can lead to biases in regional distance seismic moment estimates (e.g., Figure 7 and Ford et al., 2009b). The explosion Green's functions are unaffected by the free-surface for shallowing source depth (Figure 6). Thus pure explosion inversions are expected to be stable over the depth range where nuclear tests are commonly conducted. The transverse, radial and vertical vertical-dip-slip Green's functions corresponding to the mxz and myz moment tensor terms are subject to the effect of the free-surface in which the amplitude of Green's functions vanish for shallow source depth. The presence of noise in real data and imprecise knowledge of emplacement depth with the free-surface effect on the Green's functions can lead to biases in both the recovered moment tensor and the scalar seismic moment. As Figure 6 shows as the source becomes shallower the amplitude of the affected terms decrease however importantly the waveform phase remains relatively constant. This means that corrections can be derived for scalar moment estimates. Our ongoing work is 1) testing the effect of vanishing traction in synthetic cases with different near-surface velocity structure with varying levels of noise, 2) developing a set of correction terms with respect to a reference depth of say 1000m, and 3) developing and testing a modified moment tensor inversion designed to damp the effect of vanishing traction on the saturation of the mxz and myz terms leading to seismic moment tensor bias.

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REFERENCES

Dreger, D. S., S. R. Ford, and W. R. Walter (2008). Source Analysis of the Crandall Canyon, Utah, Mine Collapse, *Science* 321: 217.

Dreger, D. S., S. R. Ford, and W. R. Walter (2010). Identifying isotropic events using a regional moment tensor inversion technique, in *Proceedings of the* 2010 *Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-10-05578, Vol. 1, pp. 381–389.

Ford, S., D. Dreger and W. Walter (2008). Source Characterization of the August 6, 2007 Crandall Canyon Mine Seismic Event in Central Utah, *Seism. Res. Lett.*, 79: 637–644.

Ford, S. R., D. S. Dreger and W. R. Walter (2009a). Identifying isotropic events using a regional moment tensor inversion, *J. Geophys. Res*., 114, B01306, doi:10.1029/2008JB005743.

Ford, S. R., D. S. Dreger, and W. R. Walter, (2009b). Source Analysis of the Memorial Day Explosion, Kimchaek, North Korea, *Geophys. Res. Lett*. 36: 21, Citation L21304.

Ford, S. R., D. S. Dreger and W. R. Walter (2010). Network sensitivity solutions for regional moment tensor inversions, *Bull. Seismol. Soc. Am.*, 100: 1962–1970.

Given, J. W., and G. R. Mellman (1986). Estimating explosion and tectonic release source parameters of underground nuclear explosions from Rayleigh and Love wave observations, *Air Force Geophysics Laboratory Technical Report* No. AFGL-TR-86-0171(I), 79p.

Hudson, J. A., R. G. Pearce, R. G., and R. M. Rogers (1989). Source type plot for inversion of the moment tensor, *J. Geophys. Res*. 9: (B1), 765–774.

Jechumtalova, Z. and J. Sileny (2001). Point-source parameters from noisy waveforms: Error estimate by Monte-Carlo simulation, *Pure Appl. Geophys*. 158: 1639–1654.

Patton, H. and S. R. Taylor (2011). The apparent explosion moment: Inferences of volumetric moment due to source medium damage by underground nuclear explosions, *J. Geophys. Res.*, 116, doi: 10.1029/2010JB007937.

Sileny, J. (1998). Earthquake source parameters and their confidence regions by a genetic algorithm with a 'memory', *Geophys. J. Int.* 134: 228–242.

Sileny, J. (2004). Regional moment tensor uncertainty due to mismodeling of the crust, *Tectonophysics* 383: 133–147.

Sileny, J., P. Campus, and G. F. Panza (1996). Seismic moment tensor resolution by waveform inversion of a few local noisy records; I, Synthetic tests, *Geophys. J. Int.* 126: 605–619.

Sileny, J., G. F. Panza, and P. Campus (1992). Waveform inversion for point source moment tensor retrieval with variable hypocentral depth and structural model, *Geophys. J. Int.* 109: 259–274.

Song, X. J., D. V. Helmberger, and L. Zhao (1996). Broad-band modelling of regional seismograms; the basin and range crustal structure, *Geophys. J. Int*. 125: (1), 15–29.

Walter, W., E. Matzel, M. Pasyanos, D. Harris, R. Gok, and S. Ford (2007). Empirical Observations of Earthquake-Explosion Discrimination Using P/S Ratios and Implications for the Sources of Explosion S-Waves, in *Proceedings of the 30th Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-07-5613:Vol. 1, pp. 684–693, https://na22.nnsa.doe.gov/prod/researchreview/2007/PAPERS/03-20.PDF.

Weber, Z. (2006). Probabilistic local waveform inversion for moment tensor and hypocentral location, *Geophys. J. Int.* 165: 607–621.