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Regional distance seismic moment tensors of nuclear explosions

Douglas Dreger [a,*], Bradley Woods [b]

[a]UC Berkeley, Seismological Laboratory, Berkeley, CA, USA
[b]URS, Pasadena, CA, USA

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Abstract

Nuclear explosions, because of their known location, depth and theoretical source mechanism, provide a means to explore the resolution of non-double-couple and isotropic seismic moment tensors. We perform seismic moment tensor inversions on long-period (50–20 s), three-component velocity seismograms from the Caltech TERRAscope network and the Berkeley Digital Seismic Network (BDSN) to determine best-fitting double-couple, isotropic plus double-couple, deviatoric and full-moment tensor source mechanisms for the Little Skull Mountain Earthquake and three large ($M_L \geq 5.5$, $M_W \geq 4.5$) Nevada Test Site (NTS) nuclear explosions (JUNCTION, MONTELLO and BEXAR). The significance of solutions with higher degrees of freedom is evaluated using the *F*-test. The stability of the moment tensor solutions for variations in station configuration is investigated using a cross-validation method. Our results show that strongly non-double-couple seismic moment tensors and shallow source depth characterize the nuclear explosions. The full-moment tensor inversions recover a volume increase. However, our analysis indicates that the improvement in fit afforded by the extra degree of freedom is not statistically significant due to the similarity of the vertical compensated linear vector dipole (CLVD) and isotropic surface wave Green's functions at these periods. An isotropic plus double-couple source model was found to provide the same level of fit as the deviatoric moment tensor inversions. Determination of the nonisotropic source mechanism is not unique and we discuss our results with respect to the proposed source models for NTS. While the results of this study indicate that regional distance seismic moment tensor analysis is not suitable for directly discriminating nuclear explosions from earthquakes, the shallow source depth and non-double-couple seismic moment tensors obtained for these events suggest that it may be useful for identifying suspect events for further screening.

Keywords: Moment tensor; Nuclear explosion; Seismic inversion

1. Introduction

The discrimination of nuclear explosions from naturally occurring earthquakes at regional distances remains a difficult problem, particularly for the small to moderate magnitude range. Moderate-sized events will have few teleseismic recordings from the International Monitoring System (IMS) and, therefore, emphasis will necessarily be placed on studying data from the few stations that record a given event at regional to far-regional distances. Discriminants such as m_b:M_S, M_0:M_L and various spectral ratios do show

* Corresponding author.
E-mail address: dreger@seismo.berkeley.edu (D. Dreger).

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promise in many instances. For example, Denny et al. (1987) and Taylor et al. (1989) show that m_b:M_S for NTS works well down to $m_b = 4$. However, deep earthquakes can cause problems with m_b:M_S because they can result in relatively high m_b:M_S differentials and sampling of Rayleigh waves near radiation nodes can bias the M_S estimates. Additionally, all nuclear explosions produce some nonisotropic radiation (Wallace, 1991) and the mode of the nonisotropic radiation (strike-slip vs. dip-slip) can have quite different effects on Rayleigh wave amplitudes and, hence, M_S (Patton, 1991). As shown by Patton (1991), the degree of such bias is a strong function of the F-factor, f=($\alpha^2 M_0 / 2\beta^2 M_I$) (Toksöz and Kehrer, 1972), where α and β are the compressional and shear wave velocities at the source, and M_0 and M_I are the nonisotropic and isotropic scalar seismic moments, respectively. m_b:M_0 (Patton and Walter, 1993) and M_L:M_0 (Woods et al., 1993) discriminants are based on the same principle as the m_b:M_S method with the exception that M_0 is determined by waveform modeling to account for source depth and radiation pattern influences. Routine application of waveform modeling in the form of seismic moment tensor inversions is an additional tool that can help resolve possible biases in the identification of an explosion.

Near-field recordings of NTS explosions have been studied using the moment tensor formalism (Stump and Johnson, 1984; Vasco and Johnson, 1989), and it was found that it was possible to determine the explosive nature of the source, however, off-diagonal elements of the moment tensor were needed to explain observed SH radiation. Theoretically, it should be possible to determine isotropic moment tensors from regionally recorded surface and body waveform data, however, they are difficult to resolve (e.g., Patton, 1988; Kawakatsu, 1996; Julian et al., 1998). In particular, Patton (1988) examined long-period surface waveforms for the HARZER explosion and concluded that the isotropic component was not resolvable because of similarity of the basis surface wave Green's functions, particularly for shallow source depth. Dufumier and Rivera (1997) have raised concerns on full-moment tensor stability, and suggest a number of constraints that should be applied to teleseismic and regional distance full-moment tensor studies. Only a few studies have reported significant isotropic components (e.g., Zheng et al., 1995; Campus et al., 1996; Hara et al., 1996; Miller et al., 1998; Dreger et al., 2000). Obviously, when studying nuclear explosions, it is desirable that a general seismic moment tensor representation or other formalism that allows for isotropic components be used.

As pointed out by Wallace (1991), all nuclear explosions contain some degree of nonisotropic radiation, commonly referred to as tectonic release, which is evident from observed teleseismic and regional distance SH waves. The shear radiation complicates the determination of the isotropic scalar moment and can be due to a variety of mechanisms that are well described in the review articles by Massé (1981), Patton (1991) and Wallace (1991). Some of the mechanisms that have been proposed for such tectonic release include nonspherical wave propagation due to material heterogeneity near the source, explosion induced block motions, relaxation of tectonic stress due to deformation of a blast cavity or region of reduced shear strength in the fractured rock, spall slap down and relaxation of tectonic stress due to triggering of fault motions. All of these processes may be important to varying degrees in each explosive event, and can lead to difficulty in explaining observed long-period seismograms. Most studies investigating nonisotropic radiation from NTS shots have focused on the mechanisms of triggered tectonic release (e.g., Wallace et al., 1983, 1985), driven block motion primarily in the form of reverse faulting (e.g., Patton, 1988) and spall (Patton and Taylor, 1995). A recent mine collapse in southwestern Wyoming produced complex regional waveforms that are best modeled with a vertically oriented tension crack (Pechmann et al., 1995) and this type of mechanism could also be a source of seismic radiation from nuclear test sites either during the test or afterward.

Our goal in this paper is to examine the resolution of routinely and automatically applied regional distance seismic moment tensor methods (e.g., Romanowicz et al., 1993; Pasyanos et al., 1996; Fukuyama and Dreger, 2000) in terms of characterizing the nature of isotropic and nonisotropic radiation, and the source depth of NTS nuclear explosions. Of particular interest is the examination of the capability of such methods as they are routinely applied under sparse monitoring conditions. We are not proposing, and do not find that seismic moment tensor analysis can uniquely discriminate a nuclear explosion from an earthquake, but we do show that typical methods are capable of identifying a signature of anomalous non-double-couple radiation.

2. Data

The TERRAscope network began in 1988 with the deployment of station PAS, and the modern BDSN began in 1991. These new stations have Weilandt–Streckeisen STS-1 velocity sensors, colocated accelerometers and 24-bit digital recording. The nominal dynamic range of the system is 200 db and the weak motion instruments are flat to velocity from 360- to 0.10-s period. During this time, the testing program at NTS was ramping down, however, these new broadband instruments did record a number of explosions. LLNL broadband stations operating at this time did not have the low frequency band width that we require for application of our routine method. Thus, we utilize the TERRAscope stations ISA, PAS, and PFO for the explosions BEXAR, MONTELLO and JUNCTION. As a reference, we also present results for the nearby Little Skull Mountain Earthquake, which occurred on June 29, 1992. For the Little Skull Mountain event, we include BDSN station CMB, which was fortuitously deployed on June 25, 1992. Unfortunately, the very broadband station was not operating at the time of the three NTS explosions. However, we demonstrate that the three TERRAscope stations are sufficient for the recovery of the seismic moment tensor.

Hypocental information for the study events is provided in Table 1. The *F*-factors, *f*, range between 0.45 and 0.90, indicating that the explosions have a moderate level of tectonic release. The values for the study events reflect that the deviatoric moment is 1/3–3/5 of the explosive moment, and for MONTELLO the long-period Love waves have amplitudes larger than the Rayleigh waves. The locations of the events and the broadband stations are shown in Fig. 1. Although the earthquake and explosions are not located in the same place, at long periods, the source-station paths are likely to be similar (e.g., Wallace et al., 1983, 1985; Dreger and Helmberger, 1993; Song et al., 1996).

The broadband data was processed by removing the mean offset, deconvolving the instrument response to yield ground velocity in centimeters per second, application of a four-pole, two-pass butterworth filter with corners at 50- and 20-s periods, and decimation to one sample per second. We limit our analysis to TERRAscope and BDSN stations because the paths from NTS to southern California have been well studied and calibrated (e.g., Woods and Harkrider, 1995; Song et al., 1996), and because these instruments have low instrument noise and well calibrated responses at the long-periods (50–20 s) that we use.

3. Method

We employ the moment tensor inversion method outlined in Dreger et al. (2000). This method linearly inverts complete, three-component, long-period seismograms from several regional distance stations for the seismic moment tensor. The seismic moment tensor, M_{ij}, is a second rank symmetric tensor that describes a generalized system of forces at the seismic source. The indices *i* and *j* refer to the orientations of the component force vector dipoles. The trace of the

Table 1
List of events

Event name	Year/day	OT (UTC)	Latitude	Longitude	M_L	M_W	f[a]
Skull Mountain	1992/181	10:14:20.1	36.638	– 116.171	6.2[b]	5.6	–
BEXAR	1991/094	19:00:00.0	37.296	– 116.313	5.6	4.3[c]	0.89
MONTELLO	1991/106	15:30:00.0	37.245	– 116.442	5.4	4.5[c]	0.90
JUNCTION	1992/086	16:30:00.0	37.272	– 116.360	5.5	4.4[c]	0.45

[a] The *F*-factor, *f*, is defined as $f = 3/2 * M_0/M_I$ for a Poisson's ratio of 0.25, where M_0 is the double-couple scalar moment and the M_I is the explosion moment from the ISO + DC inversions.

[b] A 5.6 coda magnitude is reported in the Council of the National Seismic System catalog for this event.

[c] M_W was determined from the scalar moment obtained from the DEVMT inversions.

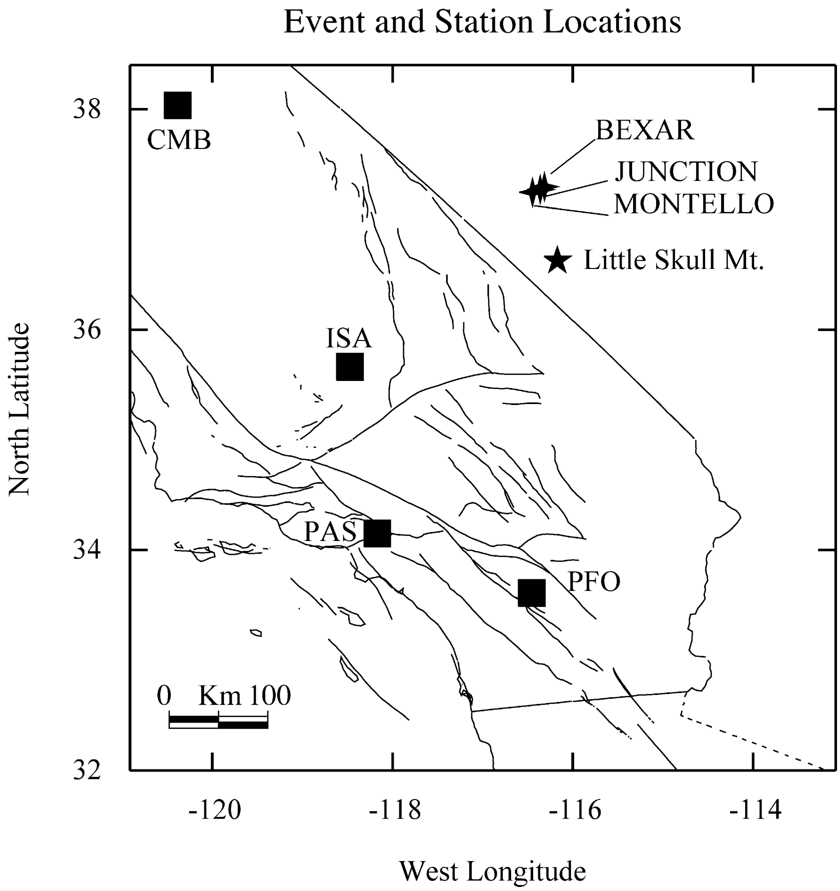


Fig. 1. Location map showing the TERRAscope and Berkeley Digital Seismic Network stations (squares), the reference Little Skull Mountain Earthquake (star) and the three NTS explosions (four-pointed stars).

seismic moment tensor describes volume change at the source, and the off-diagonal elements; the deviatoric portion of the moment tensor describes non-volumetric disturbances. The moment tensor is the most general description of source radiation although there are some mechanisms such as a single force which cannot be represented (e.g., Kanamori and Given, 1982; Kawakatsu, 1989, 1996). In this study, both deviatoric (DEVMT) and full-moment (FULLMT) tensor solutions are obtained. In addition, pure double-couple (DC) and double-couple plus isotropic (ISO + DC) solutions are obtained using a grid search over five parameters, the isotropic seismic moment (M_I), the double-couple seismic moment (M_0), and the strike, rake and dip.

The general seismic moment tensor is usually decomposed into a series of component moment tensors to facilitate interpretation (e.g., Jost and Herrmann, 1989; Julian et al., 1998). There is no unique decomposition of the seismic moment tensor, but the one we use is commonly employed, and requires that the individual component moment tensors share the orientation of the principal eigenvector. This decomposition includes double-couple, compensated linear vector dipole (CLVD: Knopoff and Randall, 1970), and isotropic terms. The isotropic component is composed of three orthogonal force dipoles of equal strength and the same sign. The double couple is composed of two equal-strength, opposite-signed force dipoles that are oriented 45° to the two orthogonal nodal planes. The CLVD is composed of three orthogonal vector dipoles. There is a major dipole, which has twice the strength of two opposite signed minor dipoles. The CLVD has been interpreted as a volume-compensated opening crack (Julian and Sipkin, 1985), and has been argued to be a good model for spall (Patton and Taylor, 1995). The results are also presented for a major plus minor double-couple decomposition (e.g., Jost and Herrmann, 1989).

The basis Green's functions used in our analysis were computed using a frequency-wave number integration code written by Chandan Saikia of URS, and the seismic velocity model (Table 2) derived by Song et al. (1996) for paths through eastern California and western Nevada. This model was shown to be effective in the determination of earthquake source parameters (e.g., Zhu and Helmberger, 1996).

Two objective functions are used to assess the goodness of fit. The first is a simple variance estimate, where for each inversion the variance is computed as follows:

$$\sigma = \sum_i \sum_j \sum_k (d_{ijk} - s_{ijk})^2 / (N - M).$$

The indices i, j, k, refer to station, component and time sample, respectively. d and s are the observed and estimated time series, N is the total number of data points and M is the total number of free parameters ($M=5$ for DC, $M=6$ for DEVMT and ISO + DC and $M=7$ for FULLMT source inversions). In each case, the source depth is one of the free parameters. This measure is used when applying the F-test, which is described in Section 4.

Table 2
Song et al. (1996) velocity model[a]

Thickness (km)	P velocity (km/s)	S velocity (km/s)	Density (g/cc)	Q_α[b]	Q_β[b]
2.5	3.6	2.05	2.2	100.0	40.0
32.5	6.1	3.57	2.8	286.0	172.0
∞	7.85	4.53	3.3	600.0	300.0

[a] Modified from the Priestly and Brune (1978) model.
[b] Q values are from Patton and Taylor (1984).

The second measure of fit is normalized by the data power to yield a percent variance reduction as defined below:

$$\mathrm{VR} = \left[1.0 - \frac{\sum_i \sum_j \sum_k (d_{ijk} - s_{ijk})^2}{\sum_i \sum_j \sum_k d_{ijk}^2} \right] 100.$$

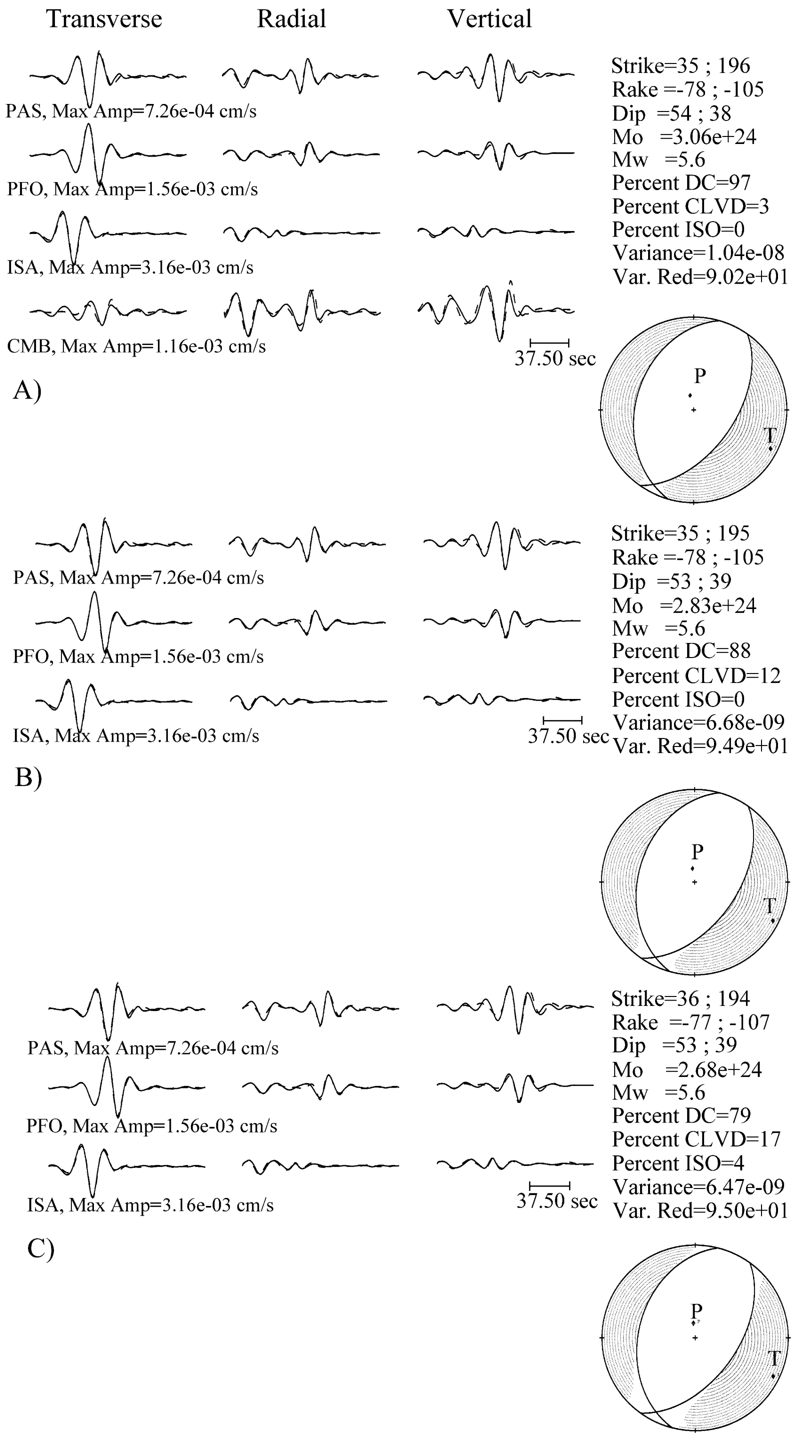
The variance reduction, VR, is used to determine the optimal source depth. The source depth is not directly inverted for, but is found by grid search in which the optimal depth maximizes the VR. Source depths from 1 to 17 km in 2-km intervals were tested.

4. Modeling results

4.1. Reference earthquake inversion

We begin by testing the inversion procedures on the reference Little Skull Mountain Earthquake. Fig. 2A shows that given four broadband stations with good azimuthal coverage, it is possible to recover the moment tensor quite well. Fig. 2B demonstrates that essentially the same result is obtained using only three stations, PAS, PFO, and ISA. These are the stations available for the study of the nuclear explosions. In fact, robust, primarily double-couple solutions are obtained with combinations of only two of the stations, and Walter (1993) showed that it was possible to obtain a stable moment tensor result using only a single station. The three-station inversion obtained a solution that agreed well with the four-station reference inversion, demonstrating that even with the sparse very broadband network that was operating at the time of the nuclear tests, the coverage is adequate for the recovery of the seismic moment tensor.

The DEVMT inversion (Fig. 2B) yielded a moment tensor that is 88% double couple for an optimal source depth of 9 km with VR = 94.9%. The resolution of the source depth is given in Fig. 3. For the FULLMT solution (Fig. 2C), the double-couple component reduces to 79%, with a 17% CLVD and a nominal 4% isotropic component, and VR = 95.0%. Thus, with only the three stations we were able to obtain a moment tensor solution which is predominantly double couple as expected for a tectonic earthquake of



Transverse
Radial
Vertical
PAS, Max Amp=7.26e-04 cm/s
PFO, Max Amp=1.56e-03 cm/s
ISA, Max Amp=3.16e-03 cm/s
CMB, Max Amp=1.16e-03 cm/s
37.50 sec
Strike=35 ; 196
Rake =-78 ; -105
Dip =54 ; 38
Mo =3.06e+24
Mw =5.6
Percent DC=97
Percent CLVD=3
Percent ISO=0
Variance=1.04e-08
Var. Red=9.02e+01
P
T
A)
PAS, Max Amp=7.26e-04 cm/s
PFO, Max Amp=1.56e-03 cm/s
ISA, Max Amp=3.16e-03 cm/s
37.50 sec
Strike=35 ; 195
Rake =-78 ; -105
Dip =53 ; 39
Mo =2.83e+24
Mw =5.6
Percent DC=88
Percent CLVD=12
Percent ISO=0
Variance=6.68e-09
Var. Red=9.49e+01
B)
P
T
PAS, Max Amp=7.26e-04 cm/s
PFO, Max Amp=1.56e-03 cm/s
ISA, Max Amp=3.16e-03 cm/s
37.50 sec
Strike=36 ; 194
Rake =-77 ; -107
Dip =53 ; 39
Mo =2.68e+24
Mw =5.6
Percent DC=79
Percent CLVD=17
Percent ISO=4
Variance=6.47e-09
Var. Red=9.50e+01
C)
P
T

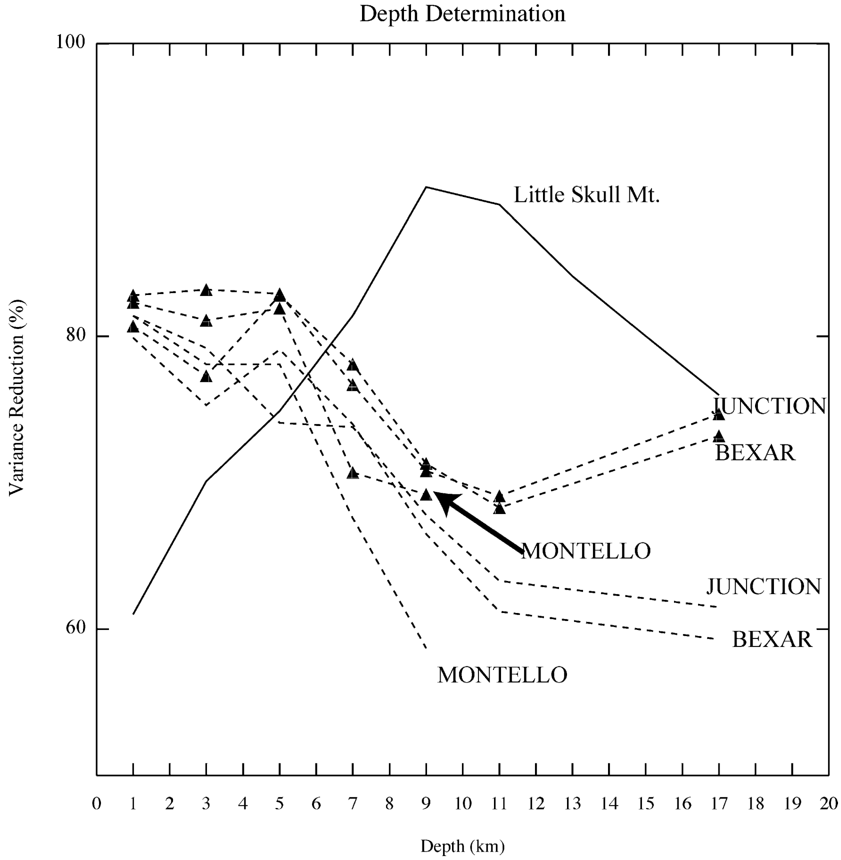


Fig. 3. The variance reduction vs. source depth for the deviatoric inversions are compared for the Little Skull Mountain Earthquake (solid line), and the JUNCTION, MONTELLO and BEXAR nuclear explosions (dashed curves). The dashed curves with symbols show the variance reduction vs. source depth for the full-moment tensor inversions for the three nuclear explosions.

this size. As Panning et al. (2001) demonstrated in a numerical study, not accounting for 3D earth structure can lead to small spurious isotropic components.

The DC solution for the Little Skull Mountain Earthquake is provided in Table 3 and is essentially the same as the double-couple component of the moment tensor inversions (Fig. 2). The F-statistic, F (defined as the ratio of the variances of models with different degrees of freedom for identical input data), is used to assess solution significance. Values of F are listed in Table 3. Since it is possible to fit the data better with models that have a greater number of unknowns, the F-test is used to determine whether a model with more unknowns fits the data significantly better than may be expected from random fluctuations in the data (e.g., Menke, 1989). Critical values of F for different levels of confidence are estimated from the F distribution. If the observed value of F is greater than the critical value, then the improvement in fit afforded by the additional parameters may be argued to be significant. The critical values of F depend on the degrees of freedom of each inversion. If we assume

Fig. 2. Deviatoric seismic moment tensor inversions for the Little Skull Mountain Earthquake using (A) four broadband stations with good azimuthal coverage, (B) using only three of the stations, which were also operating at the time of the three NTS explosions under study and (C) 6 *df*, full-moment tensor inversion results for the Little Skull Mountain Earthquake. Note that in this case, the solution remains primarily a double couple, and only a nominal isotropic component is recovered. The data and synthetics are velocity seismograms and have been band pass filtered between 0.02 and 0.05 Hz with a zero phase butterworth filter. The synthetics were computed using the PB model of Song et al. (1996).

Table 3
Inversion results

Event	DC		DEVMT[a]			FULLMT[b]	
	Strike/rake/dip	M_0 (dyn cm)	mxx/mxy/mxz/myy/myz/mzz (dyn cm)	Depth (km)	F^c	mxx/mxy/mxz/myy/myz/mzz (dyn cm)	F^d
Little Skull Mountain	196/ – 106/38	2.88E + 24	(0.320/ – 1.198/ – 0.672/ 2.273/0.397/ – 2.593) $\times 10^{24}$	9	1.15	(0.112/ – 1.183/ – 0.669/ 2.049/0.397/ – 2.513) $\times 10^{24}$	1.03
JUNCTION	117/ – 93/52	1.80E + 22	(1.284/ – 0.169/ – 1.116/ 2.212/0.834/ – 3.406) $\times 10^{22}$	1	1.85	(1.028/0.036/ – 0.070/ 1.114/0.287/ – 0.317) $\times 10^{23}$	1.09
MONTELLO	205/ – 110/45	5.40E + 22	(1.938/ – 2.413/ – 2.765/ 2.959/ – 3.032/ – 4.897) $\times 10^{22}$	1	1.13	(1.009/ – 0.243/ – 0.197/ 1.112/ – 0.265/ – 0.513) $\times 10^{22}$	1.06
BEXAR	100/ – 95/20	3.00E + 22	(1.728/ – 1.037/ – 0.962/ 2.468/ – 0.590/ – 4.196) $\times 10^{22}$	1	2.79	(8.332/ – 1.050/ – 0.036/ 9.084/ – 0.029/ – 0.438) $\times 10^{22}$	1.06

[a] Aki and Richards (1980) moment tensor convention for a deviatoric moment tensor. The scalar seismic moment for the Skull Mountain, JUNCTION, MONTELLO and BEXAR events are 2.83×10^{24}, 3.07×10^{22}, 6.09×10^{22} and 3.82×10^{22}, respectively.

[b] The Aki and Richards (1980) moment tensor convention for a full-moment tensor. The scalar seismic moment for the Skull Mountain, JUNCTION, MONTELLO and BEXAR events are 2.68×10^{24}, 6.89×10^{22}, 9.51×10^{22} and 7.11×10^{22}, respectively, with isotropic moments of 1.17×10^{22}, 5.09×10^{22}, 5.36×10^{22} and 4.34×10^{22}.

[c] Ratio of double couple to deviatoric moment tensor variance estimates. Values of F greater than 1.82 represent an improvement in fit that is statistically significant with better than 99% confidence.

[d] Ratio of deviatoric to full-moment tensor variance estimates. Values of F greater than 1.82 represent an improvement in fit that is statistically significant with better than 99% confidence. Note that the F-statistics comparing the FULLMT to the DC are the product of F^c and F^d.

that each time sample of the data are uncorrelated then N is large and the corresponding critical F-value is small. In a seismic moment tensor inversion, the sample data are clearly correlated. We assume that they are correlated over 20 s corresponding to the corner frequency of the bandpass filter. This reduces N from 1350 to 68. In this case, critical values of 1.39, 1.54 and 1.82 corresponding to 90%, 95% and 99% confidence are obtained. The values of F for the Little Skull Mountain Earthquake are only slightly greater than one and therefore, the non-double-couple components of the DEVMT and FULLMT inversions cannot be argued to be statistically significant.

4.2. Nuclear explosion inversions

Anomalous radiation patterns were obtained for the three explosions from the DEVMT and FULLMT inversions. The parameter $\varepsilon = |(\lambda_1/\lambda_3)|$, where λ_1 and λ_3 are the minimum and maximum eigenvalues of the seismic moment tensor ($|\lambda_1| < |\lambda_2| < |\lambda_3|$), is a measure of the non-double-couple nature of the tensor. For a pure double couple $\lambda_1 = 0$, and $\varepsilon = 0$, and for a pure CLVD $\varepsilon = 0.5$ (e.g., Jost and Herrmann, 1989). The percent double couple may then be defined as PDC = 100 – 200ε. ε for JUNCTION, MONTELLO and BEXAR were found to be 0.36, 0.31, and 0.28, respectively, compared to 0.06 for the Little Skull Mountain Earthquake. The F-values comparing the DEVMT to the DC result are 1.85, 1.13, and 2.79, respectively, indicating that the DEVMT inversion yields an improved fit to the data for two of the events that is significant at greater than the 99% level. For MONTELLO, although the DEVMT and FULLMT solutions improved the fit to the data over that provided by the DC solution, the improvement cannot be argued to be statistically significant. It is interesting to note that the double-couple solution obtained for MONTELLO is very similar to that obtained for the Little Skull Mountain Earthquake, which is consistent with regional stress (Patton and Zandt, 1991), but not with previous studies of tectonic release. In the following, the inversion results for the three explosions are examined in more detail.

The waveform fit and DEVMT and FULLMT solutions for JUNCTION are provided in Fig. 4. The waveform fits are quite good with VR = 81.4% and 82.8% for the DEVMT and FULLMT solutions, respectively. In comparison, the VR of the DC solution (Table 3) is only 67.3%. In the DEVMT inversion, the percent double couple (PDC) is only 26%, and the solution is largely a near-vertically oriented CLVD with a compressive major axis. In the FULLMT inversion, the PDC is a mere 7%, and the solution is characterized by a near-vertically oriented CLVD with a major compressive axis, and an isotropic component that consists of 43% of the total scalar moment. The sign of the isotropic component indicates a volume increase, which is consistent with the explosive nature of the source. The scalar moment of the FULLMT

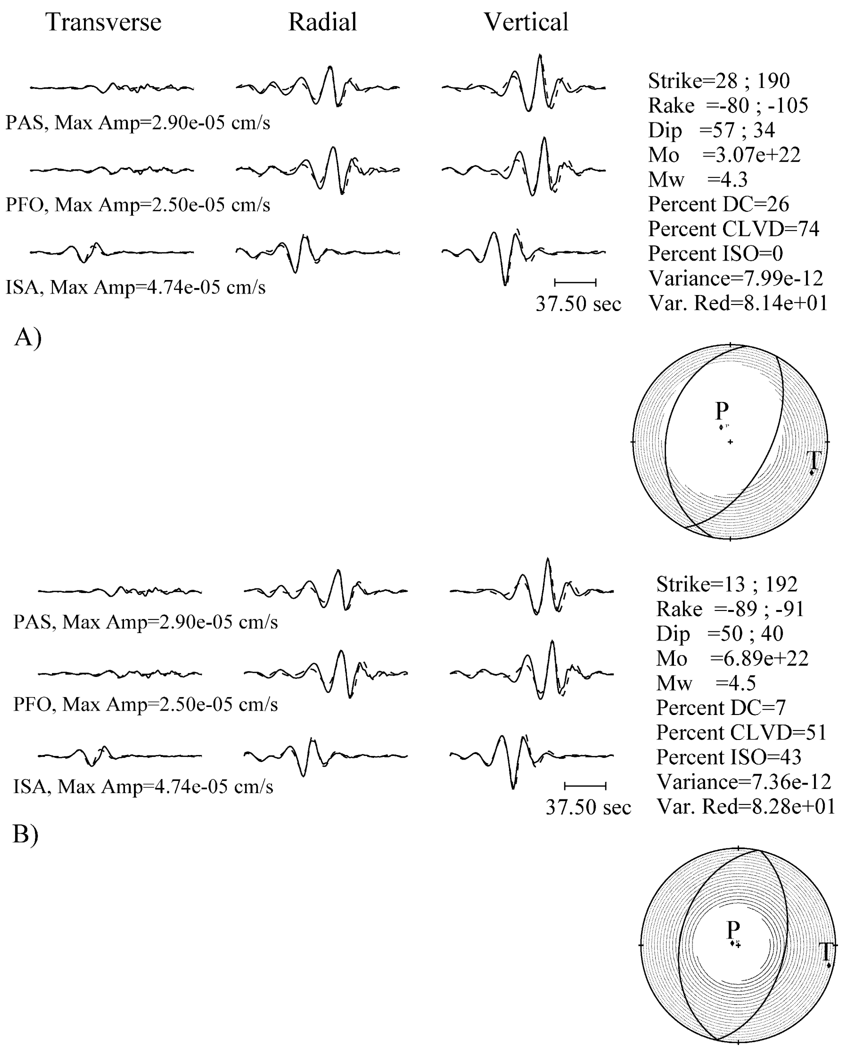


Fig. 4. Deviatoric (A) and full-moment tensor (B) inversion results for JUNCTION. The data is processed in the same manner as in Fig. 3. The P-wave first-motion focal mechanisms with the location of P and T axes are plotted. The strike, rake and dip for the double-couple component is listed together with the scalar seismic moment, the moment magnitude, the percent double couple (DC), the percent CLVD, the percent isotropic (ISO), the variance and the variance reduction. The percent DC, CLVD and ISO are computed as described in the text.

inversion is more than twice the value from the DEVMT inversion suggesting that the individual moment tensor components may be trading off.

The derived off-vertical-axis CLVD for JUNCTION explains the Love waves observed on the transverse components. However, the moment tensor may also be decomposed in terms of component double-couple mechanisms. Table 4 shows the major/minor double-couple decomposition for the FULLMT results. In the case of JUNCTION, the major double couple is a north-striking normal mechanism. The ratio of the scalar seismic moment of the minor double couple to that for the major double couple is 0.43 indicating that if triggered, faulting is the cause of the nonisotropic radiation; it is complex involving shear failure on more than one fault plane based on this source parameterization. On the other hand, it is tempting to interpret the CLVD to be due to spall slap down. However, as Day et al. (1983) have shown, the long-period excitation for such a mechanism is predicted to be too small. The value of F comparing the FULLMT and the DEVMT solutions is only 1.09 (Table 3), indicating that the improvement in fit is not statistically significant. This is consistent with Patton (1988), who showed that the resolution of a pure isotropic seismic moment tensor from a vertically oriented CLVD is not possible at low frequency using surface wave data. Although we are inverting complete three-component, long-period waveforms that contain body waves, and fundamental and higher mode surface waves, the largest signals are from the fundamental mode surface waves. Despite this lack of resolution of the isotropic component, the shallow depth of the event (Fig. 3), and the relatively large ε identifies this explosion as a suspect seismic event.

The results for MONTELLO (Fig. 5) were found to be similar to those for JUNCTION, although, MONTELLO is a larger F-factor event as evidenced by the significantly larger amplitude Love waves. The DEVMT inversion yielded only a 38% double-couple component ($\varepsilon = 0.31$). The FULLMT solution has only a 24% double couple with the remainder of the moment tensor being composed equally of a near-vertically oriented CLVD (in compression) and a tensional isotropic component. The scalar seismic moment was found to increase from 6.09×10^{22} to 9.51×10^{22} dyn cm for the DEVMT and FULLMT inversions, respectively. As was the case for JUNCTION, when the FULLMT solution is decomposed in terms of a major and minor double couple, the major double couple is a normal mechanism that is consistent with the result for the Little Skull Mountain Earthquake and the regional stress field (e.g., Patton and Zandt, 1991). However, the ratio of the scalar seismic moments of the minor and major double couples (0.31) indicates that if the mechanism of the nonisotropic radiation is triggered faulting, then it involves more than one fault plane. The level of fit obtained from the DC inversion is fairly high (VR = 71.3%), and neither the DEVMT nor FULLMT inversions provided an improvement in fit that can be argued to be statistically significant with respect to the F-test (Table 3). As was the case for JUNCTION, shallow source depths were found to better fit the data (Fig. 3).

The results for BEXAR (Fig. 6) were also found to be similar to those for JUNCTION. The scalar seismic moment was found to increase from 3.8×10^{22} dyn cm for the DEVMT inversion to 7.1×10^{22} dyn cm for the FULLMT inversion. The amplitude of the Love waves is larger for BEXAR than for JUNCTION but not as large as observed for MONTELLO. ε for BEXAR is also large (0.28). The FULLMT, however, fits the data with only a 16% double couple indicating that the nonisotropic radiation is well modeled by a near-vertically oriented CLVD. However, as before

Table 4
Focal parameters of major/minor moment tensor decomposition

Event	M_I/M_0 [a]	Strike/rake/dip major DC	M_{0min}/M_{0maj} [b]	Strike/rake/dip minor DC
Skull Mountain	0.04	193/ – 106/43	0.07	310/105/31
JUNCTION	0.62	355/ – 84/56	0.43	217/ – 176/79
MONTELLO	0.48	205/ – 107/49	0.31	353/7/79
BEXAR	0.88	215/ – 90/45	0.32	350/2/88

[a] M_I and M_0 are the explosion and deviatoric scalar moments of the FULLMT inversions.
[b] M_{0min} and M_{0maj} are the scalar moments of the major and minor double-couples of the FULLMT inversions.

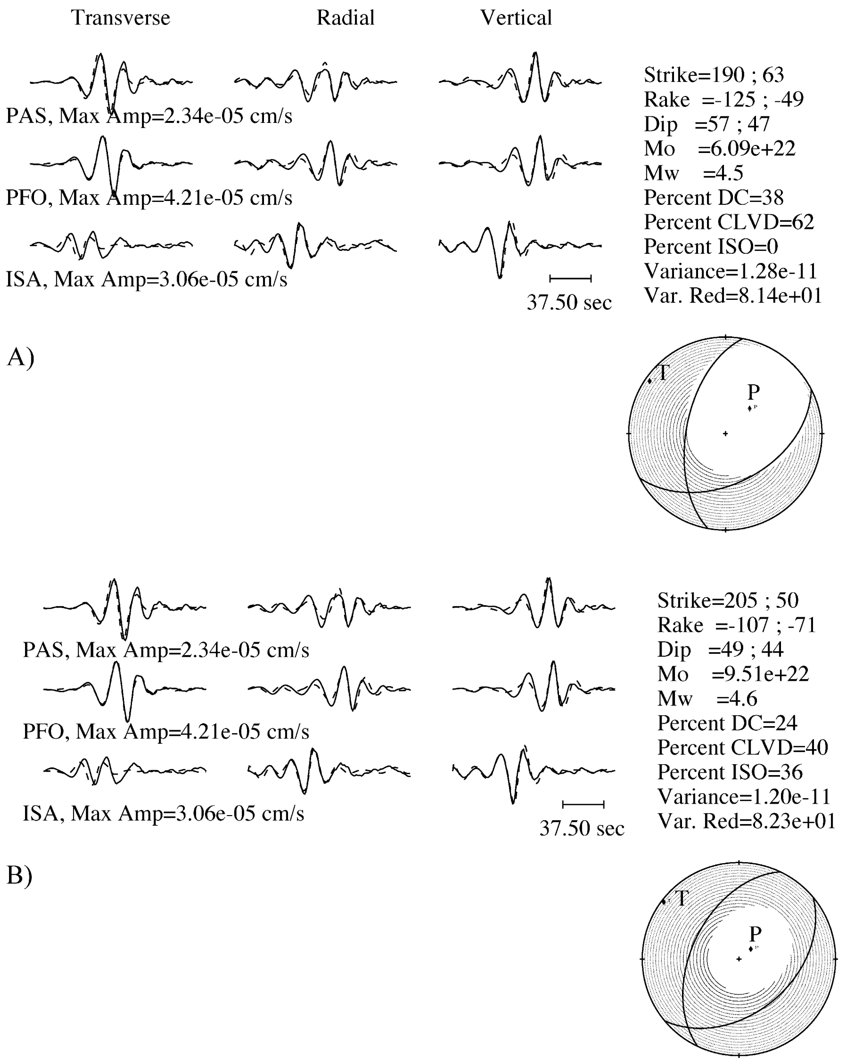


Fig. 5. Same as Fig. 4 for the MONTELLO explosion.

the F-value comparing the FULLMT to the DEVMT is only 1.06 indicating that the improvement in fit afforded by the greater number of parameters is not statistically significant. As was the case for JUNCTION, shallow source depths were found to better fit the data (Fig. 3).

The F-test has revealed that the FULLMT inversion results are not statistically significant with respect to the DEVMT results. Furthermore, in each case the total seismic moment of the FULLMT inversion was nearly double that of the DEVMT inversion indicating that there is a tradeoff between the vertical CLVD and isotropic components. We performed another series of inversions in which the solution was restrained to be composed of a double couple and an isotropic component (ISO + DC) as proposed by Ekström and Richards (1994) as a suitable model for nuclear explosions. Dufumier and Rivera (1997) concur that this is a suitable model to study nuclear explosions and is one that should improve upon ill-conditioned full-moment tensor inverse problems. To solve this nonlinear problem, we performed a grid search over the isotropic moment, the double-couple moment, and the double-couple focal parameters. The source depth

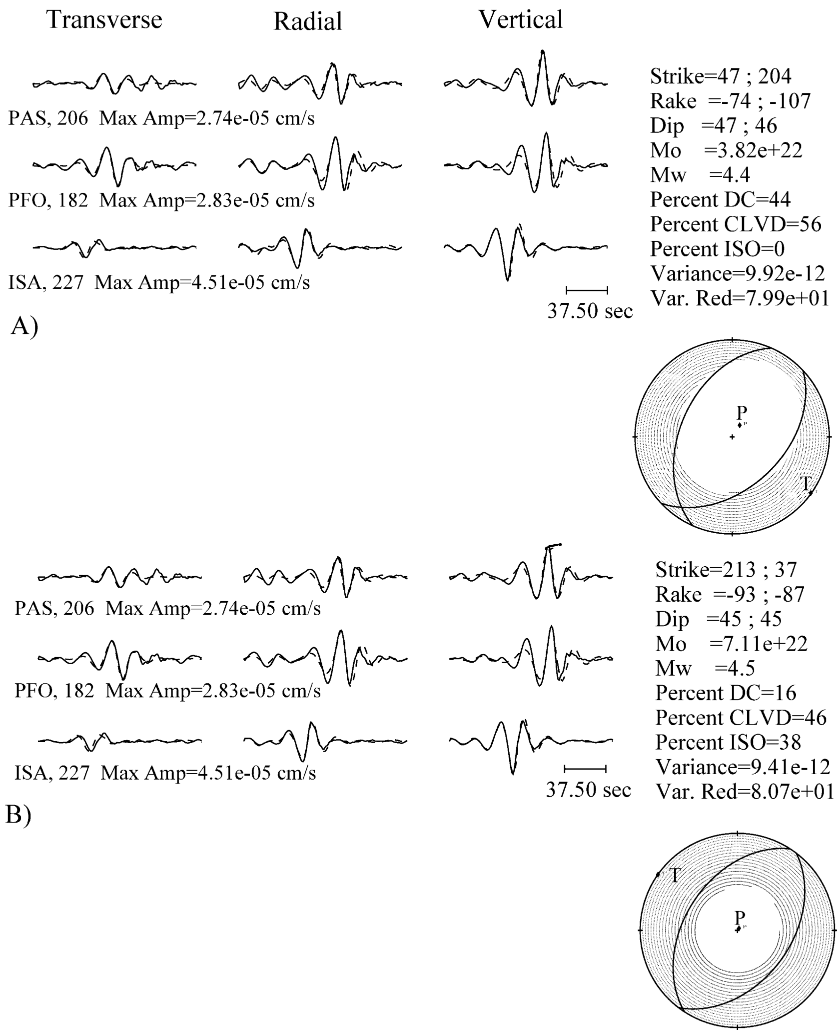


Fig. 6. Same as Fig. 4 for the BEXAR explosion.

obtained from the previous moment tensor analysis was assumed. For the Little Skull Mountain Earthquake the same results as shown in Table 3 were obtained. Table 5 lists the results for the three explosions.

For JUNCTION and BEXAR, the F-statistics are greater than 1.82 indicating a significant improvement in fit (>99% confidence) over that obtained from a pure double couple. In fact, the F-statistics for these two events are nearly the same as those obtained from the DEVMT inversions (Table 3) indicating that the ISO + DC source model provides as good of a fit to the data. For MONTELLO, the F-statistic is a mere 1.03 indicating that the ISO + DC model produces only a marginal improvement in fit over the DC model. These results indicate that for some events with a large component of tectonic release the regional distance approach described here, whether a DEVMT, FULLMT or ISO + DC inversion, cannot determine the explosive nature of the source with statistical certainty. However, this may depend on the style of the tectonic release. The ISO + DC inversions for both JUNCTION and BEXAR have double couples that have a significant amount of dip-slip. The grid search results indicate that the orientation of the double couple for BEXAR is well-constrained, how-

Table 5
ISO + DC results

Event	Isotropic moment	Double-couple moment	Strike/rake/dip	F^{a}
JUNCTION	3.6×10^{22}	1.2×10^{22}	140/170/20	1.97
MONTELLO	5.0×10^{22}	3.0×10^{22}	175/ − 170/80	1.03
BEXAR	6.4×10^{22}	3.8×10^{22}	315/105/20	2.40

[a] F is the ratio of the variances from the DC and ISO + DC inversions.

ever, for JUNCTION the distribution of P-axes is bimodal. The dip-slip mechanisms are consistent with the block driven reverse faulting model of Massé (1981) and also with the results that Patton (1988) obtained for the HARZER explosion. For MONTELLO, the orientation of the double-couple component is not unique, but the best fits are obtained for a north-striking right-lateral strike-slip mechanism that is consistent with the faulting model of tectonic release for larger NTS explosions (e.g., Wallace et al., 1983, 1985). Finally, it is interesting to note that the isotropic moment obtained from the ISO + DC inversions (Table 5) is comparable to within a factor of two of the values obtained in the FULLMT inversions (ratios of M_I from the ISO + DC and FULLMT inversions are 1.41, 1.07 and 0.68 for the JUNCTION, MONTELLO and BEXAR events, respectively).

This analysis reveals that care must be exercised when inverting regional distance data to determine the source parameters of nuclear explosions. It seems that for the three events studied, stable estimates of the explosion moment can be obtained. However, the various parameterizations resulted in different models to explain the nonisotropic radiation. In addition, the ISO + DC model satisfied a significance test for only two of the three explosions. All hope is not lost, however, as the routine procedures demonstrated here do result in large ε for all three events, which identify them as anomalous, requiring further study.

4.3. Resolution of source depth

As Fig. 3 shows, the explosions have optimal source depths of 1 km, the shallowest of the range tested. The VR is seen to decrease systematically with increasing source depth, and curves for the explosions are significantly different than for the reference Little Skull Mountain Earthquake, which has an optimal source depth of 9 km. It is important to note that the explosions were found to be strongly non-double-couple in nature over the entire range of source depths tested indicating that there is no tradeoff between non-double-couple components and source depth. The VR vs. depth curves are also plotted for the FULLMT inversions for the explosions. These curves do show that the resolution of source depth is not as good, indicating that there is some tradeoff when the isotropic component is included. Nevertheless, the combination of shallow depth and the strong non-double-couple nature of the seismic radiation identifies these events as suspect, thereby, warranting closer examination.

4.4. Surface wave radiation patterns

To help illustrate the azimuthal sensitivity of so few stations, Fig. 7 compares the Love and Rayleigh wave radiation patterns for the DC, ISO + DC, DEVMT, and FULLMT inversions for JUNCTION. The radiation patterns were constructed using Green's functions for a distance of 300 km. The triangles show the positions of the stations for illustrative purposes, and do not represent the fit to the data, which of course requires Green's functions for different distances. The azimuthal coverage of the three stations is approximately 45°, and with three-component data, this provides good sampling of the focal sphere. These diagrams show that the best fitting DC mechanism predicts that the polarity of the Love waves at PFO are opposite that of PAS and ISA, and their amplitude should be large. This comes about because the inversion is attempting to fit the large amplitude Rayleigh waves. The non-double-couple solutions (ISO + DC, DEVMT, and FULLMT) better explain the Rayleigh waves and also succeed in explaining the relative strength of the Love waves. It is evident from this diagram that the surface wave radiation patterns for the ISO + DC, DEVMT and FULLMT solutions are nearly identical, and that improved azimuthal cover-

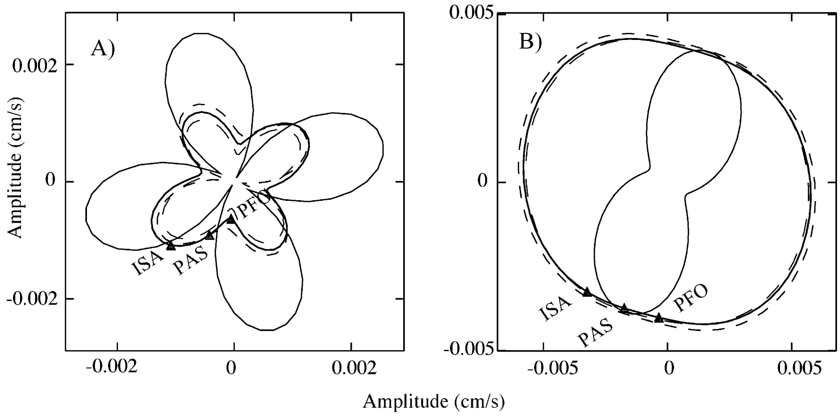


Fig. 7. Love wave (A) and Rayleigh wave (B) radiation patterns for the DC (thin solid lines), DEVMT (thick solid lines), ISO + DC (long dashed lines) and FULLMT (short dashed lines) inversions for JUNCTION are compared. The triangles show positions of the three broadband stations to illustrate the azimuthal coverage.

age would not help to resolve the actual mechanism. In order to improve the resolution, shorter period body waves must be modeled, which of course requires very well calibrated paths.

4.5. Cross-validation analysis

To investigate the stability of the deviatoric inversion, we performed a cross-validation analysis in which all combinations of single-, two- and three-station inversions were computed. Solutions from inversions that utilized fewer than the total of three stations were used to predict the three-component waveforms for the stations left out of the inversion. This test was done to determine if any station specific biases exist, and to investigate the sensitivity of the obtained non-double-couple moment tensors to the numbers and geometry of stations used in the inversion. The results for JUNCTION are summarized in Fig. 8. The three-station and two-station inversions yield near-vertically oriented CLVD solutions, as previously discussed. The two-station inversions are generally consistent with the three-station results, however, when ISA is not used, the orientation of the CLVD is rotated. The waveform prediction for each of the unused stations is very good as indicated by relatively high VR. Interestingly, the two-station inversions all yield strongly non-double-couple solutions that are consistent with the three-station result, although the double-couple components are seen to vary significantly.

Two of the single-station inversions also yield non-double-couple solutions, and only the single-station inversion of PFO yielded a double-couple result. While this double-couple solution slightly increases the PFO fit compared to the three-station inversion, it produces the worst fits to the PAS and ISA data.

The results for BEXAR indicate that the three- and two-station permutations yield small double-couple components ranging from PDC = 38–52%. The one-station permutations yield PDC = 44–76%. For MONTELLO, the two-station permutations yield PDC = 13–95%, and the one-station permutations PDC = 36–92%. The PDC = 95% for MONTELLO using two stations was the case when ISA was omitted and the large Love waves at stations PAS and PFO are well fit by a pure double-couple mechanism. These tests generally show that our using an approximate model of the actual earth structure does not introduce an azimuthal bias in the results towards non-double-couple solutions. Of course, the predominantly double-couple solutions obtained for the Little Skull Mountain Earthquake is also a demonstration of this. It also shows that station coverage is a factor and care should be exercised under very sparse monitoring conditions. Finally, it should be noted, however, that certain degenerative cases do exist with respect to station coverage. For example, if two stations are

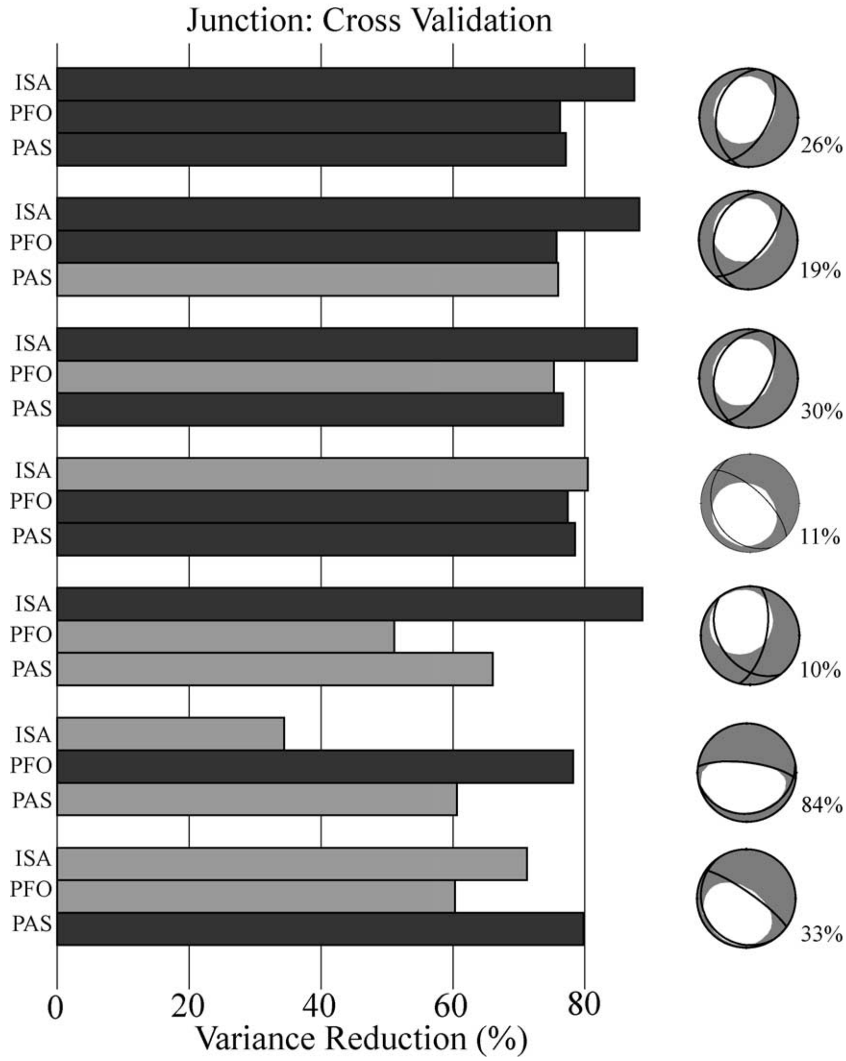


Fig. 8. Cross-validation results. The variance reduction for each three-component station is plotted for single-, two- and three-station DEVMT inversions. The black bars show the variance reduction for the stations used in the inversion, and the gray bars show the variance reduction for stations whose waveforms were predicted by the derived solution. On the right, the P-wave radiation pattern is plotted together with the percent double couple.

located at the azimuths of Love wave radiation lobes, it is not possible to distinguish between vertical strike-slip or dip-slip mechanisms. Such degeneration in terms of constraining the double-couple component of radiation could lead to problems in recovering other non-double-couple components. In the cases presented here, 45° coverage of the focal sphere is sufficient for distinguishing the characteristics of non-double-couple radiation, and they do not suffer from such degenerative cases.

5. Discussion and conclusions

We have analyzed the Little Skull Mountain Earthquake and three nuclear explosions located at NTS, using constrained double-couple, isotropic + double-couple, deviatoric and full-moment tensor source inversions of long-period, three-component, velocity waveforms. The seismic stations cover 45° of the focal sphere and range in distance from 234 to 406 km. The inversions determined shallow source depths for the explosions compared to the reference Little Skull Mountain Earthquake. Although the VR vs. depth curves for the explosions are relatively flat at shallow depth, they clearly show that the events are shallower than 5 km signaling that the events may need closer scrutiny. Event source depth is one of the most important parameters when attempting to screen seismicity to discriminate earthquakes from explosions.

All of the DEVMT inversions for the explosions yielded anomalous non-double-couple seismic moment tensors with ε-values of 0.28–0.36. This observation together with the shallow depth identifies these events as suspect warranting further analysis. We found that for two of the explosions, namely JUNCTION and BEXAR, significant (>99%) improvements in fit were accomplished with the DEVMT, FULLMT, or ISO + DC source representations compared to a single DC representation. When the FULLMT solutions are decomposed in terms of a major and minor double couple for each event, the major double couple is a northeast striking normal-slip mechanism that is consistent with the solution for the Little Skull Mountain Earthquake and regional tectonic stress (e.g., Patton and Zandt, 1991). Unfortunately, the improvement in fit provided by the FULLMT over the DEVMT is not statistically significant, which is consistent with the findings of Patton (1988). This is in contrast to the results of Dreger et al. (2000), who obtained statistically significant isotropic components for four Long Valley Caldera seismic events. In that study, the orientation of the principal axis of the CLVD was horizontal and did not tradeoff with the isotropic component.

For MONTELLO, we found that both the DEVMT and FULLMT are not statistically significant, and that this event is well modeled by a double couple. The *F*-factors, *f*, determined from the isotropic and double-couple scalar moments from the ISO + DC inversions are 0.45, 0.90 and 0.89 for JUNCTION, MONTELLO and BEXAR, respectively. It is interesting that while the *f* for MONTELLO and BEXAR are similar, the ISO + DC solutions are quite different, which is also indicated by the observed differences in the Love wave radiation, suggesting differences in the secondary explosion-induced source.

The solutions obtained using the ISO + DC source model are generally consistent with observations for other NTS nuclear explosions. Both JUNCTION and BEXAR yielded dip-slip double-couple mechanisms consistent with the model of shock driven reverse faulting proposed by Massé (1981), and observed for the HARZER explosion (Patton, 1988). MONTELLO on the other hand yielded a north–south striking strike-slip mechanism that is consistent with observations for larger NTS explosions (e.g., Wallace et al., 1983, 1985).

Clearly, the moment tensor analysis described in this study is an optimal situation in the context of the CTBT, where travel paths are short (order of 400 km), and the region has been well calibrated by waveform modeling. The results of this study demonstrate, however, that under these circumstances it is possible to identify the anomalous seismic radiation of explosive events with as few as two stations, although, uniquely determining the true mechanism of the non-isotropic radiation remains elusive. Future work will investigate the sensitivity of source parameter determinations with respect to velocity model uncertainty and degraded signal-to-noise levels. The methods we used require relatively long-period regional waveform information, which is generally only available with good signal-to-noise for M_W>4 events at regional distances, and new methods of retrieving moment-tensor information at shorter periods should be developed to potentially provide a useful means of source-type identification.

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