Inversion of focal mechanism and events identification using an improved relative amplitude method*

Hongchun Wang Ping Jin^{*} Changzhou Pan Weiguo Xiao

Northwest Institute of Nuclear Technology, Xi'an 710024, China

Abstract The relative amplitude method (RAM) is more suitable for source inversion of low magnitude earthquakes because it avoids the modeling of short-period waveforms. We introduced an improved relative amplitude method (IRAM) which is more robust in practical cases. The IRAM uses a certain function to quantify the fitness between the observed and the predicted relative amplitudes among direct P wave, surface reflected pP and sP waves for a given focal mechanism. Using the IRAM, we got the fault-plane solutions of two earthquakes of $m_b 4.9$ and $m_b 3.8$, occurred in Issyk-Kul lake, Kyrgyzstan. For the larger event, its fault-plane solutions are consistent with the Harvard's CMT solutions. As to the smaller one, the strikes of the solution are consistent with those of the main faults near the epicenter. The synthetic long period waveforms and the predicted P wave first motions of the solutions are consistent with observations at some of regional stations. Finally, we demonstrated that fault-solutions cannot interpret the characteristics of teleseismic P waveforms of the underground nuclear explosion detonated in Democratic People's Republic of Korea (DPRK) on October 9, 2006.

Key words: improved relative amplitude method; inversion of focal mechanisms; events identification

CLC number: P315

Document code: A

1 Introduction

The difference of the focal mechanism is the intrinsic distinctions between the natural earthquakes and the underground nuclear explosions. So it is more credible to identify the events according to the focal mechanisms. Nowadays P-wave onset distribution and waveform modeling are two mainly used methods for source mechanism inversion (Dziewonski et al, 1981; Sipkin, 1994; Ford et al, 2007; Ma et al, 1997, 1998, 1999; Zhao et al, 2005). Because the former approach only uses the source's P-wave polarity information, it's difficult to get the exactly source mechanism of an event unless its P-wave onsets distribute uniformly and well-defined at stations. Most of time the waveform modeling has been using long-period signals because of the lower resolution of structure models. Low and intermediate magnitude events are the focus of seismic observation, verification and clarification in the CTBT (Comprehensive Test Ban Treaty) scenario, but these events only have

short-period waveforms at regional or some high quality teleseismic stations. In order to meet this need, some researchers have implemented approaches to invert source mechanisms from 3-component short-period waveforms (Dreger and Helmberger, 1991, 1993). However, these approaches are all based on fine velocity models of specific region. The short-period signals at teleseismic distance are simpler than that at regional distance. The direct P and the surface reflected pP, sP are the dominant part of the teleseismic P-wave trains. The relative amplitudes among direct P-arrivals and pP, sP arrivals of teleseismic short-period P-wave trains have the information of source radiation pattern in different directions. Langston and Helmberger (1975) first proposed to constrain the fault plane solution of the source by surface reflected arrivals. Pearce (1977, 1980) constrained several earthquake sources by relative amplitude among direct P and surface reflected pP, sP at teleseismic stations. Because the effect of the propagation path is eliminated by the division of the observed amplitudes and the precise waveform modeling is avoided, the short-period waveforms can be used with the absence of the high resolution medium model. The relative

* Received 2 June 2008; accepted in revised form 13 October 2008; published 10 February 2009.

^{*} Corresponding author. e-mail: jinping6608@tom.com

amplitude method (RAM) has been used to analysis many events related to the identification of the underground explosions since it was proposed. Marshall et al (1989) got the fault plane solution of an earthquake near the former Soviet Novaya Zemlya nuclear test site, and excluded the possibility of underground nuclear explosion. Clark and Pearce (1988) identified a series of multiple explosions which have depth phase arrival characteristics at teleseismic stations. Douglas et al (1999) demonstrated the event with teleseismic recordings from Kazakhstan could not be an earthquake with several kilometer depth, actually this event was a chemical explosion detonated in October 1998.

A boxcar function was used to quantify the fitness of all relative amplitudes between the observed and the predicted in above articles. The lowest and the uppermost sides of the boxcar are the lowest and the uppermost limitations of observed relative amplitudes that are “given” by seismic analysts according to seismograms. This function can select all possible fault plane-solutions in global solution space, but it excludes the plane-solutions of which the predicted relative amplitudes have little departure from the observed bounds. This may lead to unexpected results for clarifying some suspicious events because the departure of the relative amplitude is unavoidable because of noises in signal and subjective of analyst. In order to overcome this problem, an object-function that can quantify the misfits for the plane solutions with biased predicted relative amplitudes should be adopted. Rogers and Pearce (1992) constructed an object-function based on Gauss distribution. This object-function can give a “best fit” solution, but the solution is not the most reasonable one. In this article, we will introduce an object-function consisting of features of boxcar and exponential functions. This object-function can not only select all possible plane solutions within the boxcar sides, but also quantify the misfit for the plane solution beyond the boxcar side.

2 Methodology

The ray paths of pP, sP at teleseismic stations go upward from source and reflected from surface, then propagate to stations with the similar path as direct P. The time differences between the reflected arrivals and direct P-arrivals are proportional to source depths. Assuming the source structure is the same as the receiver structure, Langston and Helmberger (1975) gave the vertical P-wave displacement at teleseismic stations as,

$$u_z^p(x, t) = \frac{\dot{M}_0(t)}{4\pi\rho\alpha^3 R^p(x, \xi)} * \left[F^p \delta(t - t_p) + R^{pp} F^{pp} \delta(t - t_{pp}) + R^{sp} F^{sp} \frac{\eta_\alpha}{\eta_\beta} \frac{\alpha^3}{\beta^3} \delta(t - t_{sp}) \right] R_{pZ}, \quad (1)$$

where the star is convolution. x, ξ are coordinates of source and receiver, t_p, t_{pp}, t_{sp} are travel-times for P, pP and sP, ρ, α, β are density, P- and S-wave velocities, respectively. $\eta_\alpha = \sqrt{1/\alpha^2 - p^2}, \eta_\beta = \sqrt{1/\beta^2 - p^2}$, p is the slowness, $M_0(t)$ is the moment tensor of source. $R^p(x, \xi)$ represents the geometrical spreading from source to receiver; δ is delta function; R^{pp}, R^{sp} are the reflection coefficients of pP and sP from surface, respectively, they can be calculated for stratified structures, here we use PREM model to compute these coefficients; R_{pZ} is the P-wave receiver function; F^p, F^{pp} and F^{sp} are radiation patterns of P, pP and sP, respectively. The radiation factors of P and SV can be figured out from source's strike (ϕ_s), dip (δ), rake (λ) and earthquake's azimuth (ϕ) and the take-off angle (i_ξ) (Aki and Richards, 1980). For the shallow earthquake at teleseismic stations, the take-off angles of P, pP and sP are figured out as,

$$\begin{cases} i_p = \arcsin(\alpha p_1) \\ i_{pp} = 180^\circ - \arcsin(\alpha p_2) \\ i_{sp} = 180^\circ - \arcsin(\beta p_3) \end{cases} \quad (2)$$

where p_1, p_2 and p_3 are horizontal slowness of P, pP and sP, respectively. In general, $p = p_1 \approx p_2 \approx p_3$. Following the equations (1), the relative amplitudes of P, pP and sP at teleseismic stations may be represented as

$$\frac{A_{pp}}{A_p} = \frac{F^{pp} R^{pp}}{F^p}, \quad (3)$$

$$\frac{A_{sp}}{A_p} = \frac{\alpha^3}{\beta^3} \frac{\eta_\alpha}{\eta_\beta} \frac{F^{sp} R^{sp}}{F^p}. \quad (4)$$

We search for the fault plane solutions of earthquakes globally to fit the predicted ratios and the observations of equations (3) and (4), and then the rational solution can be selected by the object-function. The fitness here means a range, in which the predicted ratios and observations are consistent. If the bias beyond the fitness range, a number between 0 and 1 is used to quantify this bias.

3 The object-function for inversion

In this section we introduce our object-function,

which can quantify the fitness of model and observations in a continuous way. Assuming an earthquake is recorded by N stations, the amplitudes of P, pP and sP measured at i -th station are $A_i \pm \delta a_i$, $B_i \pm \delta b_i$ and $C_i \pm \delta c_i$, then the relative amplitude bounds of these phases can be presented as

$$\text{pP/P: } L_i^{(1)} = \frac{B_i - \delta b_i}{A_i + \delta a_i}, \quad U_i^{(1)} = \frac{B_i + \delta b_i}{A_i - \delta a_i}. \quad (5)$$

$$\text{sP/P: } L_i^{(2)} = \frac{C_i - \delta c_i}{A_i + \delta a_i}, \quad U_i^{(2)} = \frac{C_i + \delta c_i}{A_i - \delta a_i}. \quad (6)$$

where $L_i^{(j)}$ and $U_i^{(j)}$ are the relative amplitudes lowest and uppermost bounds for j -th phases pair ($j=1, 2$ for pP/P and sP/P, respectively) at i -th station; A_i , B_i and C_i are amplitudes of P, pP and sP; δa_i , δb_i and δc_i are noises for these phases at i -th station. The object function we want has the characteristics that it equals to 1 when the predicted relative amplitudes at all defined stations fall into the observed bounds defined by equations (5) and (6), otherwise it has a value between 0 and 1. The farther the difference between predicted and observed beyond the bounds, and the more the stations have non-consistent value between predicted and observed, the lower the value the function will have. With this function, not only could all fault solutions be figured out of which the predicted relative amplitude fit the observed relative amplitude exactly, but for solutions which cannot predict relative amplitude as observed, the function can give the bias between predicted and observed. This is very important for seismic verification. The function can be written as

$$F(\delta, \lambda, \phi_s) = \prod_i \prod_{j=1}^{M_i} f_{ij}(\delta, \lambda, \phi_s; L_i^{(j)}, U_i^{(j)}), \quad (7)$$

where M_i is the phases pair number at the i -th station ($M_i \leq 2$),

$$f_{ij}(\delta, \lambda, \phi_s; L_i^{(j)}, U_i^{(j)}) = g[h_i^{(j)}(\delta, \lambda, \phi_s); L_i^{(j)}, U_i^{(j)}], \quad (8)$$

where $h_i^{(j)}(\delta, \lambda, \phi_s)$ is the predicted relative amplitude of j -th phases pair at i -th station according to fault solution with the parameters δ , λ and ϕ_s

$$g(h_i^{(j)}; L_i^{(j)}, U_i^{(j)}) = \begin{cases} e^{-a(L_i^{(j)}/h_i^{(j)}-1)} & h_i^{(j)} < L_i^{(j)} \\ 1 & L_i^{(j)} \leq h_i^{(j)} \leq U_i^{(j)} \\ e^{-a(h_i^{(j)}/U_i^{(j)}-1)} & h_i^{(j)} > U_i^{(j)} \end{cases}, \quad (9)$$

where a is a factor related to signal to noise ratios. The shape of function g is shown in Figure 1. The abscissa of

the figure is the predicted value of the relative amplitude, and the ordinate is the value of function g . We can see the function features described above. These features will be robust for errors of amplitude measurement. For events which have first-motion constraints, the function will equal to 0 directly when the first-motion isn't consistent with the predicted value at any stations.

Figure 1 Plot of object function.

4 Examples

We apply the IRAM with the object-function we've introduced to two earthquakes occurred in Issyk-Kul lake, Kyrgyzstan to get their fault plane solutions, and demonstrate the application of IRAM in nuclear explosion monitoring taking DPRK nuclear explosion which detonated on 9th October, 2006 as an example. The parameters of two earthquake events are shown in Table 1. The locations of all events and seismic stations are shown in Figure 2.

Table 1 Catalogue of earthquakes studied in this paper (according to IDC)

No.	Date a-mo-d	Origin time (UTC)	Lat.	Long.	Depth /km	m_b
1	2004-01-16	09:06:16.6	42.53°N	75.45°E	21	4.9
2	2005-04-20	17:48:50.1	42.32°N	76.53°E		3.8

4.1 The earthquake on 16 th January, 2004 near Issyk-Kul Lake, Kyrgyzstan

The Harvard CMT solutions for this large earthquake are dip 48°, rake 90°, strike 88° or dip 42°, rake 90°, strike 267°. We retrieved seismograms of this earthquake from IMS arrays FINES, ARCES, ILAR, YKA, ASAR and IRIS stations MKAR, ULHK, KZA, UCH, EKS2, CHM, TKM2, which associated to KN network. The beamforming and correlogram (Pearce, 1977) are used to enhance the surface reflected phases

pP and sP in array recordings. The original waveforms are filtered by optimum filter proposed by Douglas (1997) to phase out the low frequency noise. The beam-formed and optimum filtered seismograms, named processed waveforms, and the correlograms are shown in Figure 3. The correlograms are the correlation of two

sub-array processed waveforms of an array. The pP phases, indicated by thin dotted lines, could be clearly seen from correlograms at each station, and sP phases, indicated by thick dotted lines, could also be clearly seen at stations of FINES and ILAR.

Figure 2 Distribution of the events studied in this paper and the corresponding stations.

Figure 3 P waveforms processed by the optimum filters (a) and the corresponding correlograms (b) of 2004-01-16 earthquake in Issyk-Kul lake, Kyrgyzstan. The thick solid lines indicate the arrivals of P, thin dashed lines for the possible pP and thick dashed lines for the sP (similar following).

The relative amplitude ranges of pP/P and sP/P at each station are given in Table 2. The ranges are obtained from signal and noise levels of P, pP and sP. Epicenters, azimuths and P-onsets, including that at MKAR station, of the earthquake are also shown in Table 2. The a in equation (9) is assigned a value of 5.0 according to the SNR at each station. We search globally for the fault plane solutions and the object-function distribution in fault plane solution space is obtained and shown in Figure 4. The lengths of the line in Figure 4 indicate the value of the object function, and the directions of the

line show the strike of the fault. Figure 4 only shows the fault planes with the rake of $0^\circ \sim 180^\circ$. Combining the relative amplitudes and P-onsets in Table 2, the fault plane solutions can be limited to a narrow band, as shown in Figure 4. The maximum of the object function in inversion is 0.97, which corresponding to two fault planes with dip 40° , rake 90° , strike 80° or dip 50° , rake 90° , strike 260° . They are similar to Harvard CMT solution.

4.2 The earthquake on 20th April, 2005 at Issyk-Kul Lake, Kyrgyzstan

The magnitude of this earthquake is lower, and its

fault plane solutions are not provided by any institution. We will figure out it by IRAM. Waveforms at IMS arrays, FINES, ARCES, ILAR, YKA, are retrieved from IDC, waveforms at KZ stations, MKAR and KN stations, ULHL, KZA, UCH, AAK, CHM, USP, TKM2, AML, are also retrieved. The procedure for data processing is the same as above, except the 3 order Butterworth band pass filters are used instead. The results are shown in

Figure 5. The parameters in Table 3 are used to invert the fault plane solutions. The meanings of each parameter are the same as that in Table 2. Here the a is assigned a value of 3.0, and two larger object function values, 0.98 and 0.97 are obtained, they correspond to the fault plane solutions dip 50° , rake 65° , strike 55° and dip 45° , rake 115° , strike 265° .

Table 2 The relative amplitude bounds among P, pP, sP at some teleseismic stations and the P first motion direction of earthquake in 16 January, 2004

Station	FINES	ARCES	ILAR	YKA	ASAR	MKAR
Distance($^\circ$)/Azimuth($^\circ$)	34.5/320	36.9/334	67.7/18	74.6/5	85.5/128	6.5/47
pP/P	0.85–1.60	0.38–1.20	0.60–1.03	0.70–2.25	0.01–0.60	
sP/P	1.36–3.50		0.36–0.75		0.01–0.50	
P wave first motion	+	+	+/-	+	+	+

Note: P first-motion “+” represent up, “-” represent down, “+/-” represent uncertainty.

Figure 4 The distribution of the object-function values in global fault space of earthquake in 16 January, 2004

Table 3 The relative amplitude bounds among P, pP, sP at some teleseismic stations and the P first-motion direction of earthquake in 20 April, 2005

Station	FINES	ARCES	ILAR	YKA	KZA	USP
Distance($^\circ$)/Azimuth($^\circ$)	34.5/320	36.9/334	67.7/18	74.6/5	1.0/250	1.7/301
pP/P	0.29–2.24	0.25–0.76	0.25–0.90	0.18–0.70		
sP/P	0.32–2.65		0.00–0.50	0.11–0.65		
P wave first motion	+/-	+/-	+	+	+	-

Note: P first-motion “+” represent up, “-” represent down, “+/-” represent uncertainty.

In order to demonstrate the rationality of the solutions in this paper, we will try to interpret the P-wave first-motions at some other regional stations according to the results. The stereographic projections (Aki and Richards, 1980) of the fault planes and corresponding stations are shown in Figure 6. We notice the predicted P first-motions are consistent with the observed ones at these stations.

We further demonstrate the rationality solutions by comparing them with the faults distribution in this region. The faults distributions (Ren, 1999) along our re-

sults are shown in Figure 7, where F_1 represents Alatau orogenic zone and F_2 represents the Tianshan orogenic zone. The strikes of the two faults are mainly ENE, which are consistent with our fault solutions. The 18~20 s period synthetic seismograms at stations CHM and AML are also computed from our results and Steven’s crust model (Stevens, 1986), the results are shown in Figure 8. We notice the seismograms synthesized and observed are consistent.

4.3 Nuclear explosion of DPRK on 9th October, 2006

We always try to identify the depth phases of pP

Figure 5 P waveforms and the corresponding correlograms at some teleseismic stations of earthquake in Issyk-Kul lake region, Kyrgyzstan in 20 April, 2005. (a) Waveforms filtered by the three order band-pass Butterworth filters; (b) Correlograms of the filtered waveforms.

Figure 6 The stereographic projections of the focal fault sphere and regional stations. (a) The fault projection of earthquake (dip 50°, rake 90°, strike 260°) in 16 January, 2004, the thin dashed lines indicate the CMT fault solution of Harvard (dip 42°, rake 90°, strike 267°); (b) The fault projection of earthquake (dip 45°, rake 115°, strike 265°) in 20 April, 2005. The positive signs indicate the positive first motions; circles indicate the negative first motions.

Figure 7 The distribution of main faults in the epicentral region (Ren, 1999).

and sP in teleseismic P-waves to determine the source depths of earthquake events. Because the depths of earthquakes are usually tens kilometers, the travel-time differences between depth phases and direct P-waves are several seconds. However, the depths of underground nuclear explosions are usually shallower than one kilometer because of the engineering limitations, so their depth phases are difficult to identify. For underground nuclear explosions, the coda waves of direct P often have characteristics of depth phases. If they are misunderstood as pP or sP, the depths of explosions may be estimated as deep as earthquakes do. With the same procedure as that in section 4.2, the seismograms of DPRK nuclear explosion at five IMS arrays are processed and illustrated in Figure 9. From the waveforms beamformed and the correlograms, the coda waves of direct P are similar to depth

phases and easily be misunderstood. If this happened, the depth of the explosion may be estimated as 3.4 km. Here, we can apply the IRAM to them and excluded the possibility of being depth phases. The source mechanism so-

lution space is searched for based on parameters in Table 4, which are obtained from Figure 9, the maximum of object function is 0.1, and this can not be the case of depth phases for an earthquake.

Figure 8 Comparison between synthetic (thick solid traces) and observed (thin dashed traces) waveforms at two regional stations of earthquake in 20 April, 2005. (a) CHM (156 km, 295°); (b) AML (232 km, 263°). All waveforms are filtered by the 0.04~0.125 Hz three order band-pass Butterworth filter and normalized by the maximum amplitudes of Z traces.

Figure 9 The teleseismic P waveforms of DPRK nuclear explosion recorded by some IMS stations and the corresponding correlograms. (a) Beamformed P waves after filtering; (b) Correlograms.

Table 4 The relative amplitude bounds assuming DPRK nuclear explosion in 9 October, 2006 to be natural earthquake with 3–4 km depth

Station	FINES	AKASG	ASAR	NVAR	PDAR
Distance(°)/Azimuth(°)	60.0/327	64.5/316	65.1/175	79.4/47	80.7/39
pP/P	0.60–0.80	0.5–0.70	0.15–0.30	0.20–0.50	0.70–0.90
sP/P	0.90–1.00	0.00–0.10	0.50–0.70	0.20–0.50	0.00–0.20
P-wave first-motion	+/-	+/-	+/-	+/-	+/-

Note: P first-motion: “+” represent up, “-” represent down, “+/-” represent uncertainty.

5 Discussion and conclusions

Although earthquake sources are not pure double-couple and that of explosions are not pure isotropic, the double-couple component is dominant (Kuge and Kawakastu, 1990) for most shallow moderate magnitude tectonic earthquakes, and the isotropic component is dominant for underground nuclear explosions. Here we further argue the partial isotropic earthquake sources may be obtained correctly and its nature can also be

identified with enough confidence by numerical simulations. First, we add the isotropic source to the source of example 2, which is dip 40°, rake 90°, strike 80°, and then synthesize the seismograms for teleseismic stations in Table 2. The technique for synthesis refers to Marson-Pidgeon and Kennet (2000). The isotropic source sizes are adjusted to get the synthetic seismograms of these sources at each station. The moment tensor percentages are computed after Bowers and Hudson (1999).

Secondly, according to different SNR, the random noises are added 50 times to each of the amplitudes of direct P and depth phases pP and sP measured from synthetic seismograms. Thirdly the relative amplitude ranges are determined as before. Finally the fault plane solution spaces are searched globally and the maximums of object function are determined. The results are shown in Figure 10. We notice the maximums of object-function are greater than 0.6, most of them greater than 0.8, when the isotropic sizes are less than 20 percent. However, when the isotropic sizes are greater than 60 percent, the maximums of the object-function are less than 0.2. These results further demonstrate the effectiveness of applying IRAM to seismic verifications.

In this paper, based on RAM of Pearce (1977, 1980), an object function, which quantify the predicted and observed relative amplitudes, was introduced, and the robustness of the RAM was improved. The improved relative amplitude method is applied to invert the sources of the two earthquakes occurred in Kyrgyzstan and identify one underground nuclear explosion in DPKR. The results show the sources of earthquakes can be derived correctly by IRAM, and the nature of the nuclear explosion can be identified with enough confidence.

Figure 10 Graph showing the relation of object function values and the percentages of explosion moments.

Acknowledgements This study is supported by Foundation of Verification Researches for Army Control Technology (513310101).

References

- Ma S T, Yao Z X and Ji C (1997). The focal mechanism solution for March 19, 1996 M_s 6.9 earthquake in Xinjiang, Jiashi region and related problems. *Chinese J Geophys* **40**(6): 782–790 (in Chinese with English abstract).
- Ma S T, Yao Z X and Ji C (1998). Preliminary estimation for the focal mechanisms of 1996 Lijiang main shock in Yunnan Province and studies of the related problems. *Acta Seismologica Sinica* **20**(1): 18–28 (in Chinese with English abstract).
- Ma S T, Yao Z X and Ji C (1999). To estimate focal mechanisms of moderate earthquakes using a long period surface waveform fitting method as well as first motion signal of P waves. *Chinese J Geophys* **42**(6): 785–799 (in Chinese with English abstract).
- Ren J S (1999). Seeing Chinese tectonic structure from globe — Brief manual for the tectonic structure map of China and neighborhood. Geological Publishing House, Beijing, 22–23 (in Chinese).
- Zhao C P, Chen Z L, Zheng S H and Liu J (2005). Moment tensor inversion and source rupture process of the September 27, 2003 M_s 7.9 earthquake occurred in the border area of China, Russia and Mongolia. *Acta Seismologica Sinica* **27**(3): 237–249 (in Chinese with English abstract).
- Aki K and Richards P G (1980). *Quantitative Seismology: Theory and Methods*. W. H. Freeman California, San Francisco, 109–155.
- Bowers D and Hudson J A (1999). Defining the scalar moment of a seismic source with a general moment tensor. *Bull Seism Soc Amer* **89**: 1 390–1 394.
- Clark R A and Pearce R G (1988). Identification of multiple underground explosions using the relative amplitude method. *Bull Seism Soc Amer* **78**: 885–897.
- Dziewonski A M, Chou T-A and Woodhouse J H (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *J Geophys Res* **86**: 2 825–2 852.
- Douglas A (1997). Bandpass filtering to reduce noise on seismograms: Is there a better way? *Bull Seism Soc Amer* **87**: 770–777.
- Douglas A, Bowers D, Marshall P D, Young J B, Porter D, Walis N J (1999). Putting nuclear-test monitoring to the test. *Nature* **398**: 474–475.
- Dreger D S and Helmberger D V (1991). Source parameter of the Sierra Madre earthquake from regional and local body waves. *Geophys Res Lett* **98**: 8 107–8 125.
- Dreger D S and Helmberger D V (1993). Determination of source parameters at regional distances with three-component sparse network data. *J Geophys Res* **98**: 8 107–8 125.
- Ford S R, Dreger D S and Walter W R (2007). Identifying isotropic events using an improved regional moment tensor inversion technique. In: *Proceedings of the 29th Monitoring Research Review: Ground-based Nuclear Explosion Monitoring Technologies*. LA-UR-07-5613, 561–570.
- Kuge K and Kawakatsu H (1990). Analysis of a deep “non double couple” earthquake using very broadband data. *Geophys Res Lett* **17**: 227–230.
- Langston C A and Helmberger D V (1975). A procedure for modeling shallow dislocations. *Geophys J R astro Soc* **42**: 117–130.
- Marshall P D, Stewart R C and Lilwall R C (1989). The seismic disturbances on 1986 August 1 near Novaya Zemlya: a source of concern? *Geophys J* **98**: 565–573.
- Marson-Pidgeon K and Kennett B L N (2000). Flexible computation of tele-seismic synthetics for source and structural studies. *Geophys J Int* **143**: 689–699.
- Pearce R G (1977). Fault plane solutions using relative amplitudes of P and pP. *Geophys J R astr Soc* **50**: 381–394.
- Pearce R G (1980). Fault plane solutions using relative amplitudes of P and surface reflections: Further studies. *Geophys J R astr Soc* **60**: 459–487.
- Pearce R G, Hudson J A and Douglas A (1988). On the use of P-wave seismograms to identify a double-couple source. *Bull Seism Soc Amer* **78**: 651–671.
- Rogers R M and Pearce P G (1992). Use of the relative amplitude method to compute “best fit” earthquake moment tensors. *J Geophys Res* **97**: 14 083–14 095.
- Sipkin S (1994). Rapid determination of global moment-tensor solutions. *Geophys Res Lett* **21**: 1 667–1 670.
- Stevens J L (1986). Estimation of scalar moments from explosion-generated surface waves. *Bull Seism Soc Amer* **76**: 121–151.