ISOTROPIC AND NONISOTROPIC COMPONENTS OF EARTHQUAKES AND NUCLEAR EXPLOSIONS ON THE LOP NOR TEST SITE

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ABSTRACT

We test the hypothesis that the existence of an observable isotropic component of the seismic moment tensor can be used as a discriminant to distinguish nuclear explosions from shallow earthquakes. We do this by applying the method described by Bukchin *et al.*, (2000) to a set of data recorded between 1990 and 1996 following events (seven nuclear explosions and three earthquakes) that occurred on the Lop Nor test site in Western China. We represent each source as the sum of an isotropic component at the surface and a non-isotropic, double couple component at an estimated depth. The explosions all possess a significant isotropic component, and the estimated depth of the double-couple component of the moment tensor, presumably the result of tectonic release, lies between 0 and 3 km. For the earthquakes studied, the isotropic component is indistinguishable from zero and the depths of the sources are estimated at 3, 17 and 31 km. The data set we have studied, although very small, suggests that certain source characteristics (namely, double couple depth and the ratio of the isotropic to nonisotropic components of the seismic moment tensor) may prove useful in discriminating explosions from shallow earthquakes. Further work is needed to determine whether these observations hold for explosions at other test sites, to investigate a much larger set of shallow earthquakes located in regions of interest, and to study the robustness of the estimated source parameters as source magnitude and the number of observing stations decrease.

Key words: tectonic release, seismic moment tensor, nuclear explosions, earthquakes, surface waves, discrimination

OBJECTIVE

The objective of the research is to determine if the existence of an observable non-zero isotropic component of seismic moment can be used as a discriminant to distinguish nuclear explosions from shallow earthquakes.

RESEARCH ACCOMPLISHED

Introduction

It has long been known that nearly all underground nuclear explosions have a significant component of nonisotropic seismic radiation (e.g., Press & Archambeau, 1962; Brune & Pomeroy, 1963; Aki & Tsai, 1972; Toksöz & Kehrer, 1972; Helle & Rygg, 1984; Wallace *et al.*, 1985; Walter & Patton, 1990). There appears to be general agreement that the long-period part of the nonisotropic radiation is caused by tectonic release due to existing tectonic stresses in the source region (Mueller & Murphy, 1971; Archambeau, 1972 ; Masse, 1981; Wallace *et al.*, 1985; Day & Stevens, 1986; Stevens, 1986; Day *et al.*, 1987; Patton, 1991; Stevens *et* *al.*, 1991; Harkrider *et al.*, 1994; Ekström and Richards, 1994; Li *et al.*, 1995).

Most of the experimental studies of tectonic release have concentrated on explosions at the Nevada Test Site and the test sites in Kazakhstan. Burger *et al.* (1986) described the long-period S wave radiation by tectonic release of explosions at Novaya Zemlya. Zhang (1994), Levshin & Ritzwoller (1995), and Wallace & Tinker (1996) studied Chinese nuclear explosions and found that most are accompanied by tectonic release. However, we are unaware of any detailed analysis of the source mechanisms of these events.

Several authors have estimated the relative contributions of the nonisotropic (tectonic release) and isotropic (explosion) components to the resulting seismic moment tensor of explosions (see, for example, Ekström and Richards, 1994). As a rule these estimates have been performed using the assumption that both phenomena occur in the same small volume inside the Earth.

Although the determination of the source mechanism of earthquakes is a routine operation, only a few studies have evaluated the isotropic component of earthquake radiation. This is especially true for weak events that are of the primary interest for discrimination purposes. As is well known, a pure shear dislocation does not radiate an isotropic component. Subsequently, the natural tendency is to constrain the moment tensor solution with the assumption of a zero trace. However, from the point of view of discrimination it is important to determine if a significant isotropic component could appear in unconstrained moment tensor solutions due to some physical phenomena in the source region or due to inaccuracy of measurements and underlying assumptions.

Our approach is, therefore, based on the combination of an isotropic moment tensor at the surface, which models an explosive source, and a pure double couple at an estimated depth, which models tectonic release. We find it useful to express the seismic moment of the double-couple component, M_{0qu}, and the seismic moment of the isotropic component, M_{0ex}, as the total seismic moment M_0 and an angle φ which determines the ratio of the seismic moments of the isotropic and double couple components:

$$M_{0qu} = M_0 \cos\varphi;\ M_{0ex} = M_0 \sin\varphi;\ \tan\varphi = M_{0ex}/M_{0qu}.$$

We call φ the isotropic angle, for want of a better term, because $\varphi = 0$ corresponds to a pure earthquake and $\varphi = 90^\circ$ corresponds to a pure explosion. With this notation and the assumption that the isotropic component of the source occurs at a known depth (usually at or near the surface), the source can then be characterized by six parameters: the seismic moment M_0, the isotropic angle φ, three angles (or two principal axes, **T** (tension) and **P** (compression)) determining the double couple focal mechanism, and the double-couple depth h.

We do this by applying the method described by Bukchin *et al.*, (2000) to a set of data recorded between 1990 and 1996 following events (seven nuclear explosions and three earthquakes) that occurred on the Lop Nor test site in Western China. We determine the source parameters of these events by fitting the polarities of P-wave first arrivals jointly with minimizing the misfit between synthetic and observed Love and Rayleigh surface wave amplitude spectra. We search for the optimal set of parameters by a systematic exploration of parameter space. To characterize the uncertainty of the source parameters, we calculate partial residual functions which describe the minimum misfit as a function of each varying parameter.

Data and Method

We utilized IRIS and GEOSCOPE broadband digital seismograms and the ISC bulletins for 14 events that occurred on the Lop Nor test site in China from 1990 through 1996. Eight of these events are nuclear explosions, the other six are earthquakes. However, only 10 events with high signal-to-noise surface waves recorded at several stations were selected for study. The location of the selected events (7 explosions and 3 earthquakes) is given in Figure 1. The list of stations, with their distances and azimuths from Lop Nor test site are given in Table 1.

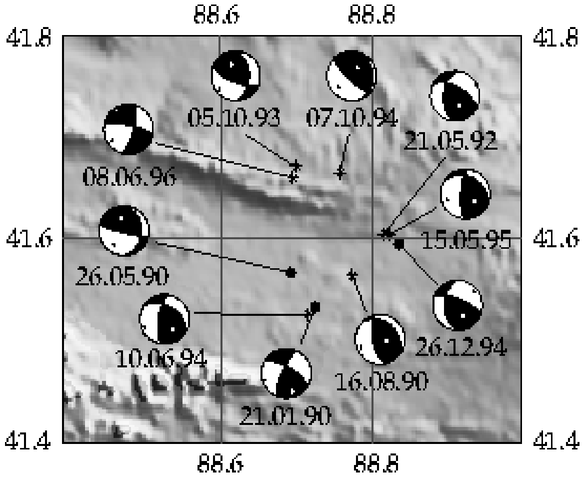

Figure 1: Epicenters and focal mechanisms of earthquakes (circles) and tectonic releases accompanying explosions (stars).

Table 1. Observed Seismograms and Models Used for
Surface Wave Calculations for Each Station

Station	Azim. (◦)	Distance (◦)	Model	Station	Azim. (◦)	Distance (◦)	Model
ABKT	271	24	Tectonic	KIV	290	34	Tectonic
ANTO	287	42	Tectonic	KMI	140	20	Tectonic
ARU	317	25	Stable	KONO	320	50	Stable
BNG	260	73	Stable	LZH	111	13	Tectonic
BRVK	319	17	Stable	MA2	43	42	Stable
CHTO	156	24	Stable	MAJO	81	38	Stable
DPC	306	49	Stable	MDJ	70	29	Stable
ENH	118	20	Stable	NIL	242	15	Tectonic
ERM	71	40	Stable	NRIL	0	28	Stable
HIA	60	23	Stable	OBN	310	37	Stable
HYB	204	26	Stable	SEY	38	42	Stable
GNI	282	33	Tectonic	TATO	111	31	Stable
INU	83	38	Stable	TLY	40	14	Tectonic
KEV	333	42	Stable	YAK	36	32	Stable

In our calculations of the theoretical surface wave spectra we used three different models for (1) the structure for the source region, (2) the stations deployed in the stable continental regimes, and (3) the stations in the tectonic regions. For brevity we will call the corresponding models ”Lop Nor”,”Stable”, and ”Tectonic”. Column 4 in Table 1 indicates the model used for each station.

We estimated the source parameters using the spectra of Love and Rayleigh fundamental waves for periods ranging from 20 s to 70 s. Love and Rayleigh fundamental modes were extracted by using frequency-time analysis (FTAN) and floating filtering (e.g., Levshin *et al.*, 1989, 1994). We also analyzed the polarization of filtered surface waves using the technique described in Levshin *et al.*, (1989), Paulssen *et al.*, (1990), Levshin *et al.* (1992, 1994), and Levshin & Ritzwoller (1995). Only records in which the surface wave polarization pattern did not exhibit significant azimuthal anomalies ($\leq 15°$) were used for further analysis.

Results of Inversions

A summary of the inversion results is given in Table 2.

Table 2. Information on the 10 Events Used in the Present Study

Date	Event type	m_b	m_s	Number of records used	Double couple depth (km)	M_0 $(N \cdot m)$	ψ (deg.)	φ (deg.)
21.01.90	earthquake	4.6	-	10	31	$0.15 \cdot 10^{17}$	72	0
26.05.90	earthquake	5.4	-	5	3	$0.42 \cdot 10^{16}$	52	0
26.12.94	earthquake	4.6	-	10	17	$0.15 \cdot 10^{16}$	56	0
16.08.90	explosion	6.2	-	7	1	$0.19 \cdot 10^{17}$	62	10-30
21.05.92	explosion	6.5	5.0	16	3	$0.62 \cdot 10^{17}$	64	10-15
05.10.93	explosion	5.9	4.7	10	0	$0.75 \cdot 10^{16}$	56	0-15
10.06.94	explosion	5.8	-	13	1	$0.52 \cdot 10^{16}$	64	20-40
07.10.94	explosion	6.0	-	11	1	$0.18 \cdot 10^{17}$	60	25-35
15.05.95	explosion	6.1	5.0	9	3	$0.15 \cdot 10^{17}$	62	40-60
08.06.96	explosion	5.9	4.3	12	3	$0.59 \cdot 10^{16}$	58	30-60

ψ is the azimuth of the horizontal compression axis, φ is the isotropic angle, which determines the ratio of the isotropic and nonisotropic (double couple) moments.

Double Couple Depths and Focal Mechanisms

The focal mechanisms for the earthquakes and for the double couple components of the explosions are shown in Figure 1. The double couple depth is well resolved for all events studied and varies from 0 to 3 km for the explosions and for the earthquakes we obtained depths of 3 km, 31 km, and 17 km. The partial residual function of double couple depth is presented in Figure 2 for all events.

The number of surface wave records that we selected for the studied events was admittedly very small (see the column 5 in Table 1), particularly for the earthquakes on the test site. For some events, only a few polarities of P wave first arrivals were available. As a result, the double-couple focal mechanism was very well resolved only for the earthquake on 21.01.90, but for half of the events the principal compression axis, which trends in the SE-NW direction, was resolved well. Fortunately, Gao and Richards (1994) estimated focal mechanisms of several earthquakes in the vicinity of Lop Nor. Considering the focal mechanisms of the studied events, and the solutions obtained by Gao and Richards, we found that while focal mechanisms vary widely, there is a moment tensor characteristic which is quite stable for all events. This characteristic is the orientation of the principal axes of the 2×2 minor of the moment tensor corresponding to the horizontal coordinates $\{M_{xx},\ M_{xy},\ M_{yx},\ M_{yy}\}$. This minor describes the horizontal deformations on the horizontal plane. We found that for all events, horizontal compression is dominant, and the principal horizontal compression axis deviates from the average direction (with an azimuth of 60°) by no more than 12°. The direction of this axis for every event is given in the eighth column in Table 1.

Isotropic Component

These observations allow us to improve the estimates of the isotropic angle φ by assuming that the orientation of the horizontal deformations is a stable characteristic for the region under study. The average direction of horizontal compression is deviated from the fault visible in Figure 1 by about 45°. With this assumption, we applied an *a priori* constraint on the possible double couple focal mechanisms. This constraint was formulated as a condition that the azimuth of the principal compression axis of the horizontal minor of the moment tensor cannot differ from 60° by more than ±45°. This constraint is weak, but reduces the number of possible focal mechanisms in half.

When we applied this constraint, the resolution of the isotropic angle φ defining the seismic moments ratio was improved for three of the seven studied explosions (16.08.90, 05.10.93, and 08.06.96) but the mean of the curves did not vary appreciably. The curves of partial residual functions of the isotropic angle φ for all explosions are shown in Figure 3. Those for the three earthquakes are displayed in Figure 4. We also applied this method to two earthquakes that occurred in the Gansu province, China (Tianzhu, 1996, $M_s = 4.9$, depth 12 km, and Yongden, 1995, $M_s = 5.4$, depth 6 km). The partial residual functions of the isotropic angle φ are also shown in Figure 4. The explosions, with perhaps one exception (05.10.93), all display substantial non-zero isotropic angles φ ranging from about 10° to 50°, corresponding to M_{0ex}/M_{0qu} ranging from about 20% to 120%. In contrast, the isotropic angles for the earthquakes are all estimated to be approximately 0.

Figure 5 illustrates the effect of adding an isotropic component to the double couple source model for an explosion (on June 10 1994). Theoretical Rayleigh wave amplitude spectra and P wave first arrival polarities are compared here with observations for two different moment tensors. One (a,b) was obtained by minimizing the joint residual for a fixed zero isotropic angle (double couple source model). The other (c, d) is a result of a similar minimization, but for varying isotropic angle (30° is the estimated optimal value). The fit to P wave first arrival polarities is good for both source models, but the fit to Rayleigh wave amplitude spectra is much better in the case of a non-zero isotropic component.

Figure 6 illustrates the effect of adding an isotropic component for the Youngden earthquake. Similar Figure 5, the results for two different moment tensors are presented here. One (a,b) was obtained by minimizing the joint residual for a varying isotropic angle. The other (c, d) is a result of a similar minimization but for a fixed (30°) isotropic angle. In contrast with the previous case the fit is better for a pure double couple source.

CONCLUSIONS AND RECOMMENDATIONS

The results above are consistent with the hypothesis that motivates this study. Namely, that for the events we analyzed on the Lop Nor test site surface wave amplitude spectra combined with polarities of P wave first arrivals can be used to discriminate explosions from earthquakes based on source characteristics alone (a combination of the double couple depth and the ratio of the isotropic to nonisotropic moments). Our recommendations for the further studies are:

- To estimate the applicability of the method for smaller events in the same region based on data from regional networks alone.
- To evaluate if the method is transportable to other regions (Novaya Zemlya, Kazakstan, India and Pakistan).
- In particular, it is important to determine the false alarm rate for earthquakes; that is the percentage of earthquakes that demonstrate a substantial shallow isotropic component.

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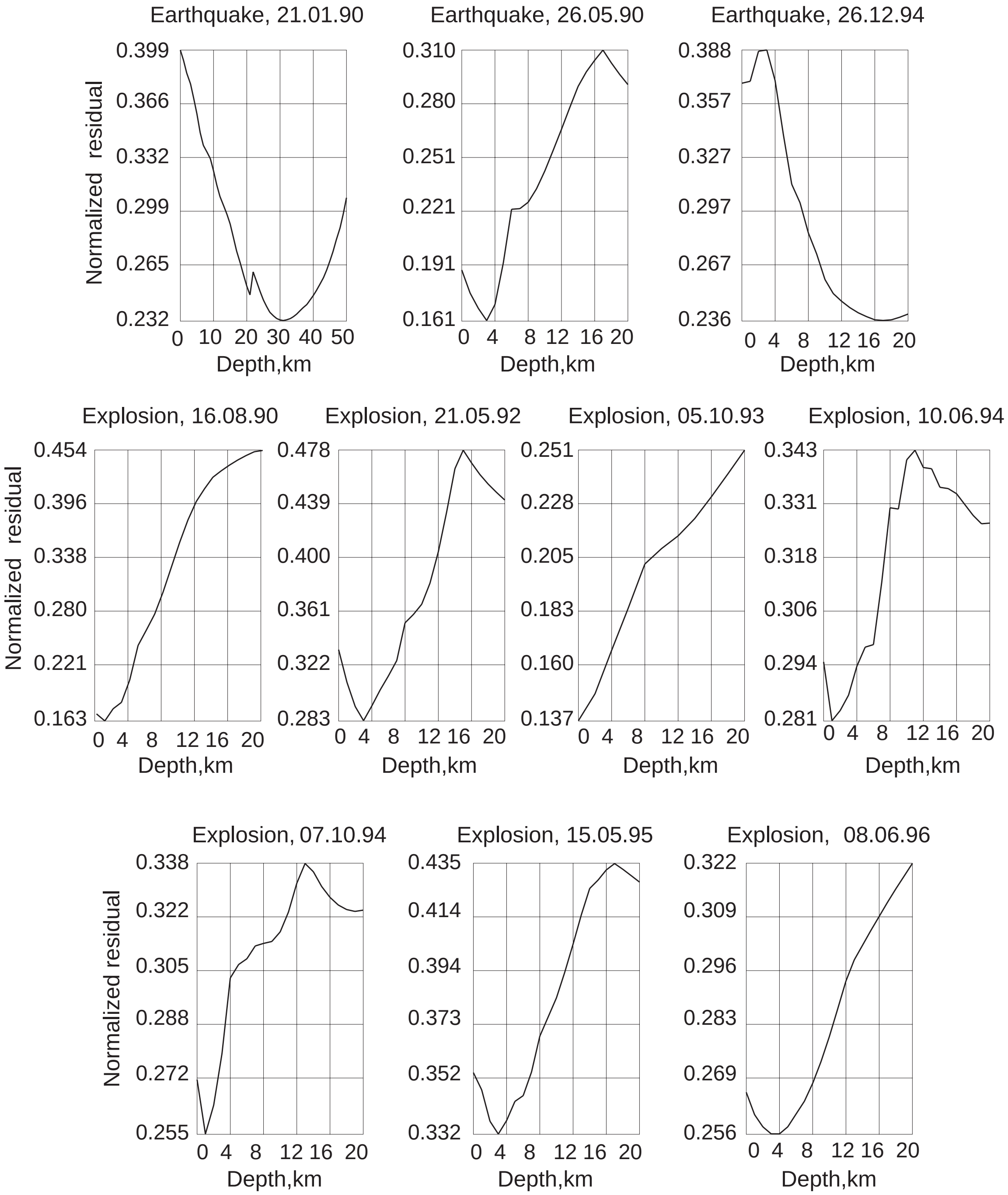

Figure 2. Partial residual functions of the double couple depth *h*.

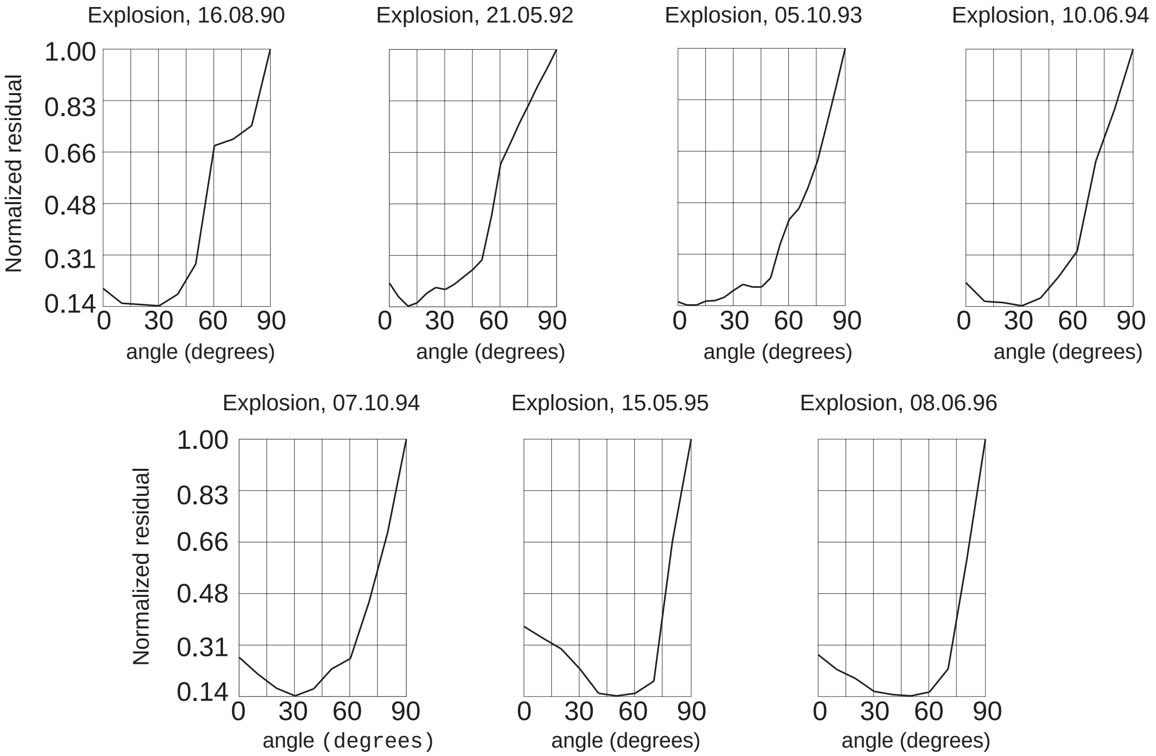

Figure 3. Partial residual functions of isotropic angle for studied explosions.

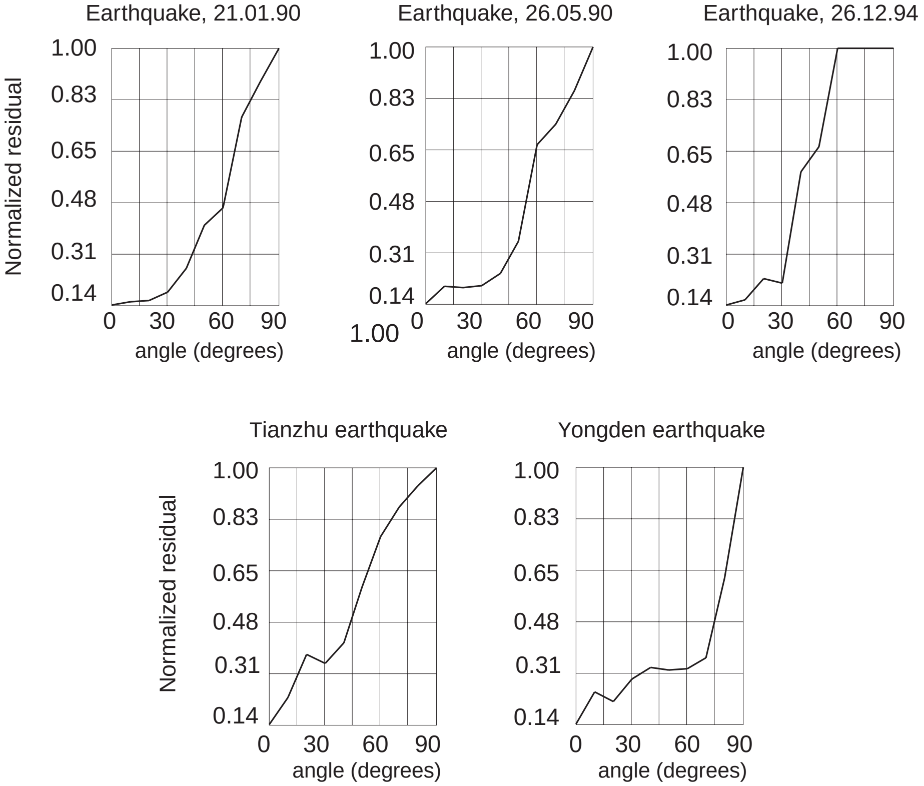

Figure 4. The same as Figure 3, but for the studied earthquakes.

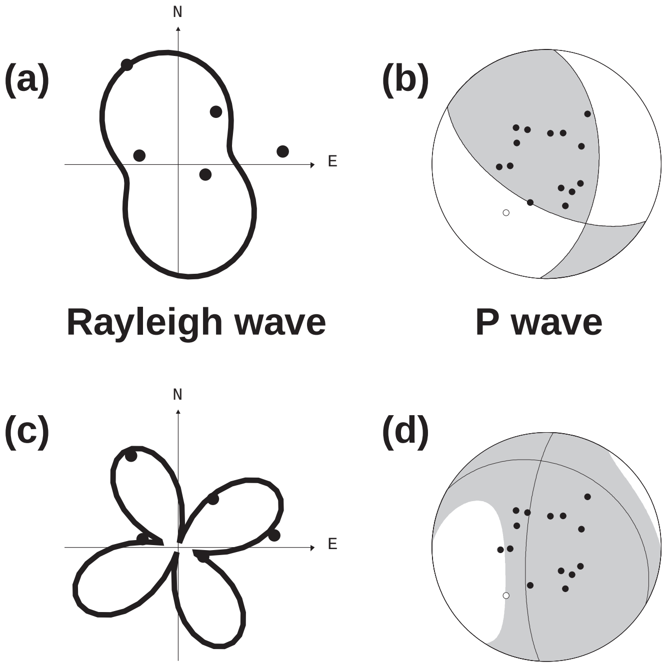

Figure 5. Comparison of observed Rayleigh wave spectral amplitudes at 26 sec period and polarities of first arrivals for the explosion on June 10, 1994 with those predicted for two different source models: (a,b) pure double couple; (c,d) non-zero isotropic component is added.

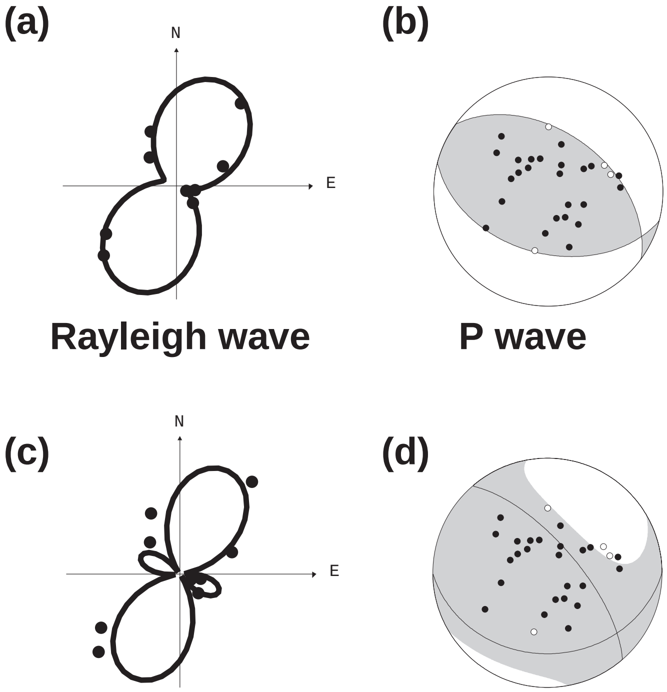

Figure 6. Same as Figure 5, but for the Yongden earthquake in Gansu province, China, on July 21, 1995 and the 50 s period.