ELSEVIER

Tectonophysics 356 (2002) 125–138

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Can unbiased source be retrieved from anisotropic waveforms by using an isotropic model of the medium?

Jan Šílený *, Václav Vavryčuk

Geophysical Institute, Academy of Sciences of the Czech Republic, Prague, Czech Republic

Received 4 May 2001; accepted 10 January 2002

Abstract

Anisotropy is frequently present in geological structures, but usually neglected when source parameters are determined through waveform inversion. Due to the coupling of propagation and source effects in the seismic waveforms, such neglect of anisotropy will lead to an error in the retrieved source. The distortion of the mechanism of a double-couple point source located in an anisotropic medium is investigated when inverting waveforms using isotropic Green's functions. The anisotropic medium is considered to be transversely isotropic with six levels of anisotropy ranging from a fairly weak to rather strong anisotropy, up to about 24% in P waves and 11% in S waves. Inversions are based on either only direct P waves or both direct P and S waves. Two different algorithms are employed: the direct parametrization (DIRPAR, a nonlinear algorithm) and the indirect parametrization (INPAR, a hybrid scheme including linear and nonlinear steps) of the source. The orientation of the double-couple mechanism appears to be robustly retrieved. The inclination of the resulting nodal planes is very small, within 10° and 20° from the original solution, even for the highest degree of anisotropy. However, the neglect of anisotropy results in the presence of spurious isotropic and compensated linear-vector dipole (CLVD) components in the moment tensor (MT). This questions the reliability of non-double-couple components reported for numerous earthquakes.

Keywords: Anisotropic waveforms; Direct parametrization; Indirect parametrization

1. Introduction

The source mechanism and time function of earthquakes are often determined through a waveform inversion using a point source approximation. The technique works well if the response of the medium can be accurately calculated and eliminated from the records. If the response of the medium is not known sufficiently well, the decoupling of the source and medium response is not straightforward. The problem may be expressed in the following symbolic formulation:

$$\text{observed wavefield} = \text{source} \otimes \text{medium}. \qquad (1)$$

If the accurate response of the medium were available, we could get an accurate estimate of the source.

* Corresponding author.
E-mail address: jsi@ig.cas.cz (J. Šílený).

0040-1951/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0040-1951(02)00380-3

Inaccurate knowledge of the medium introduces an inconsistency into the above problem and the equality in Eq. (1) is no more valid:

$$\text{observed wavefield} \approx \text{source} \otimes \text{simplified response of the medium.} \quad (2)$$

Replacing the approximation sign with the equality sign in Eq. (2), a biased estimate of the source is obtained:

$$\text{observed wavefield} = \text{distorted source model} \otimes \text{simplified response of the medium.} \quad (3)$$

The distortion of the source due to the simplification of the medium will affect various source parameters: the source-time function, orientation of the double-couple component in the moment tensor, scalar seismic moment and the nondouble-couple components. These parameters are differently sensitive to the type of model simplification and to the particular inversion algorithm. For example, Šílený et al. (2001) studied inaccuracies of the source parameters due to neglecting of a free surface near the source and to source mislocation. They showed that this neglect yields a systematic deviation of the double-couple orientation up to 15° and generates tens of percent of spurious nondouble-couple components.

Another possible source of the distortion of the source parameters might be neglecting of anisotropy of the medium. Anisotropy is a pervasive property of the earth's crust and the mantle caused by sediment layering, by alignments of fractures or by a preferred orientation of minerals in the rock (Babuška and Carra, 1991; Kocks et al., 1998). It can affect wave velocities, polarization and waveforms, in particular, for the S waves. For example, instead of one direct S wave propagating in isotropic media, two direct S waves propagate in anisotropic media, split in time and therefore interfering in a complicated way. Since parameters of anisotropy in the medium are not known in most cases, the waveform inversion for the source parameters must consider anisotropy in a simplified way or must be performed under neglecting anisotropy at all. The former case is studied by Šílený and Vavryčuk (2000), who proposed a special procedure, which approximately takes into account the anisotropic splitting of S waves. The aim of this paper is to study also the latter case demonstrating how the mechanism may be distorted if just a standard isotropic inversion scheme is used and anisotropy is completely ignored.

2. Inversion methods

2.1. Direct parametrization of the source

The symbolic formulation (3) can be specified in the following form:

$$u_k(x_j,t) = G_{ki,j}(x_j,t) \otimes \dot{m}(t)M_{ij}, \quad (4)$$

where $u_k(x_j,t)$ is the displacement of the observed wavefield at the observation point $\mathbf{x}$, M_{ij} is the seismic moment tensor, $\dot{m}(t)$ is the source-time function, $G_{ki,j}(x_j,t)$ is the space-derivative of the Green's function and symbol $\otimes$ means the time convolution. The source characteristics of interest are the moment tensor (MT) and the source-time function (STF).

Eq. (4) is used in a traditional approach to the inversion of source parameters. This approach is denoted in the following as the direct parametrization (DIRPAR) of a point source. If the STF is described by N parameters (e.g., weights of N overlapping triangles accepted as a set of base functions as proposed by Nábělek, 1984), the DIRPAR approach represents a nonlinear inverse problem with $N+6$ parameters. The minimization problem can be solved for the function χ^2_{D} of $N+6$ variables defined as

$$\chi^2_{\mathrm{D}} = \sum_t \frac{1}{\sigma^2(t)} \left[u_{\mathrm{obs}}(t) - u_{\mathrm{pred}}(t)\right]^2, \quad (5)$$

where $\sigma(t)$ is the standard deviation of the observed data $u_{\mathrm{obs}}(t)$. The vectors of observed data u_{obs}, predicted data u_{pred} and σ are understood as sampled values of the continuous quantity concatenated for all the stations and components at each station. It is possible to reduce advantageously the number of the model parameters by considering χ^2_{D} as a function of N variables describing the STF only, and determine the remaining six parameters corresponding to the MT from the condition of local minimization of χ^2_{D} with STF fixed.

2.2. Indirect parametrization of the source

The alternative approach to DIRPAR is indirect parametrization of a point source (INPAR), where the search for the MT and STF is carried out as follows (Šílený et al., 1992; Šílený, 1997): (i) seismograms are inverted into independent moment tensor rate functions (MTRFs) $\dot{M}_{ij}(t)$ according to Sipkin (1982):

$$u_k(x_j,t) = G_{ki,j}(x_j,t) \otimes \dot{M}_{ij}(t), \tag{6}$$

and (ii) independent MTRFs are split into MT and STF (Šílený, 1998)

$$\dot{M}_{ij}(t) = M_{ij}\dot{m}(t), \tag{7}$$

through the minimization of the following function

$$\chi_{\mathrm{I}}^2 = \sum_{i,j}\sum_{t}\frac{1}{\sigma_{ij}^2(t)}\left[\dot{M}_{ij}(t) - M_{ij}\dot{m}(t)\right]^2. \tag{8}$$

Quantity $\sigma_{ij}(t)$ is the standard deviation of the MTRFs yielded immediately by solving Eq. (6). The sampling of the MTRFs and STF need not necessarily be the same as the sampling of the records in Eq. (5). The time functions are parametrized by using a set of N base functions (Nábělek, 1984):

$$f(t) = \sum_{k=1}^{N} f_k T[t-(k-1)\Delta t]. \tag{9}$$

Then, summation over t in Eq (8) is replaced by summation over k from 1 to N according to Eq. (9). Similar to DIRPAR, it is possible to reduce the number of model parameters in the step (ii) of INPAR by minimizing for the N parameters of STF only and determine the MT by local minimization of χ_{I}^2 with STF fixed.

2.3. Direct versus indirect parametrizations

In order for Eq. (6) to remain linear, the MTRFs are considered to be independent functions in step (i) of the INPAR algorithm. Thus, according to Eq. (9), the linear equation (6) represents an inverse problem with $6N$ parameters. This is an 'overparametrization' of the task because at the very end, we ask for $N+6$ parameters only describing a constant MT and a common STF. The independent MTRFs represent a source with a time variable mechanism. The source with a constant mechanism is sought by searching for correlated parts of the MTRFs in step (ii). The overparametrization in (i) is inconvenient from the viewpoint of increasing the condition number of the matrix of the system (6) but the splitting of the inversion for the MT and STF brings a great advantage in saving calculation time. The first step (i) is linear and iterations are required only in the second, nonlinear step (ii), where 'observed' MTRFs yielded in (i) are matched by synthetic MTRFs, $M_{ij}m(t)$. Contrary to that, the DIRPAR algorithm is nonlinear from the very beginning and iterations are needed to match observed records with synthetic waveforms. Depending on the number of stations and components to be inverted, this procedure may be lengthy. However, there are only six MTRFs, the length of which is usually shorter than the length of the input records. Thus, the nonlinear part of INPAR is much less demanding than the nonlinear DIRPAR. This allows for much more iterations per time unit, finally leading to a more reliable solution.

2.4. Synchronous and asynchronous alignments of waveforms

P- and S-wave arrival times of synthetic seismograms always differ from those of observed records due to hypocentral mislocation and/or inaccurate modelling of the medium affecting wave kinematics. Therefore, a proper alignment is required by matching the observed and synthetic seismograms. This may be done manually by visual inspection or automatically by searching for the time shift that correlates best the data and synthetics. If the alignment is performed for all components of a three-component station simultaneously, then the alignment is *synchronous*. If the alignment is performed for all individual components separately, then it is *asynchronous*. The asynchronous alignment is particularly advantageous in the case of anisotropic data. One of the most prominent effects of anisotropy is the S-wave splitting: instead of a single S wave with polarization controlled by the source, two S waves are apparent, with different propagation velocities and different polarizations controlled by the orientation of anisotropy of the medium. Each S wave can be dominant in various cases (Fig. 1) and

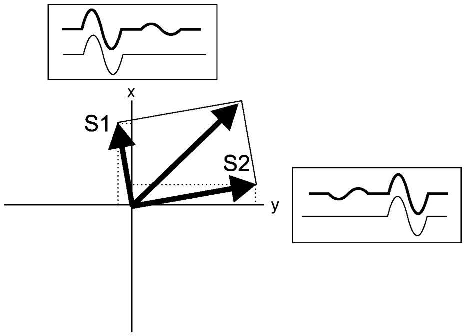


Fig. 1. Schematic representation of the fit between the split S waves in an anisotropic medium and isotropic Green's function. S_1 and S_2 are the directions of polarization of the fast and slow S wave, respectively, and x and y are the coordinate axes in the plane of the S-wave motion. The thick lines in the seismogram windows represent the observed anisotropic waveforms, whereas the thin lines denote synthetic seismograms calculated for an isotropic medium.

therefore it is necessary to align each component, independently, with a single S wave calculated using the isotropic Green's function.

3. Synthetic data

Synthetic seismograms are calculated at 10 three-component station network. The network is designed to simulate a random but good coverage of the focal sphere (Fig. 2). Hypocentral distances were chosen from 14 to 47 times larger than the characteristic wavelengths of modelled waves, hence the near-field effects can be neglected, but they span both the distances for which the S-wave splitting is small and large, respectively.

The medium was considered homogeneous, transversely isotropic, simulating a system of parallel dry cracks (Hudson, 1981). We designed 6 levels of anisotropy corresponding to an increasing density of cracks: 1%, 2%, 4%, 6%, 8% and 10%. The background P- and S-wave velocities are 6.0 and 3.5 km/s, respectively, and density of the medium is 3300 kg/m^3. The studied medium models include both fairly weak anisotropy (2.4% in the P wave and 1.1% in the S wave) as well as strong anisotropy (24% in P wave and 11% in S wave; see Fig. 3). The latter case assumes higher values than those observed in earth, but it is considered as an extreme situation for testing the maximum possible bias in the retrieved source due to a neglect of anisotropy.

The synthetic seismograms were generated for a double-couple (DC) source, which is the most important type of source for seismological applications. This source corresponds to a pure shear under isotropy. Under anisotropy, however, the shear source can also generate non-DC components. For simplicity, however, these effects are not considered here, and the study will continue to refer to DC source only.

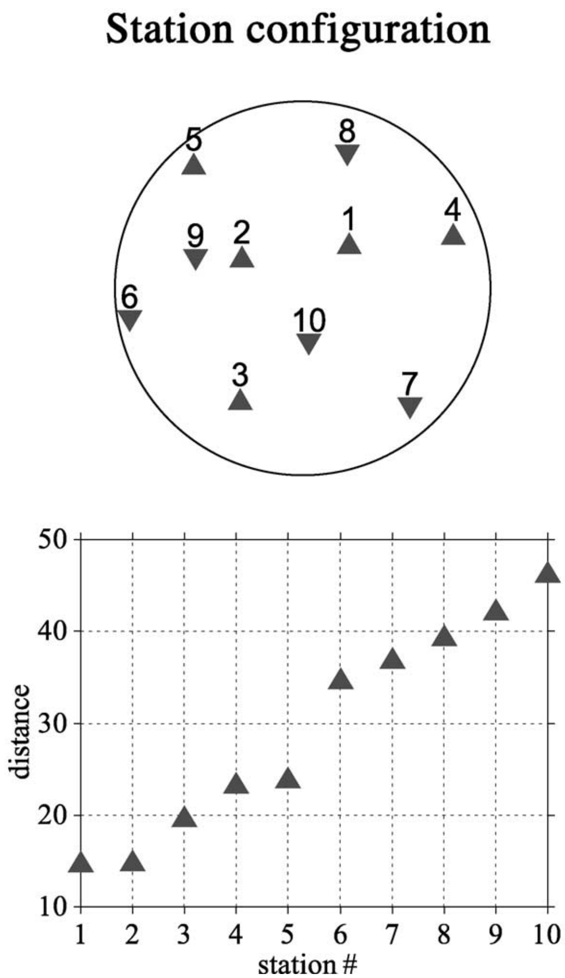


Fig. 2. The distribution of stations used in the synthetic experiments: (top) lower hemisphere equal area projection (▲—stations projected to lower hemisphere, ▼—stations projected to upper hemisphere with the projection converted to the lower hemisphere; (bottom) distribution of hypocentral distances of stations #1–#10 in units of the characteristic wavelength.

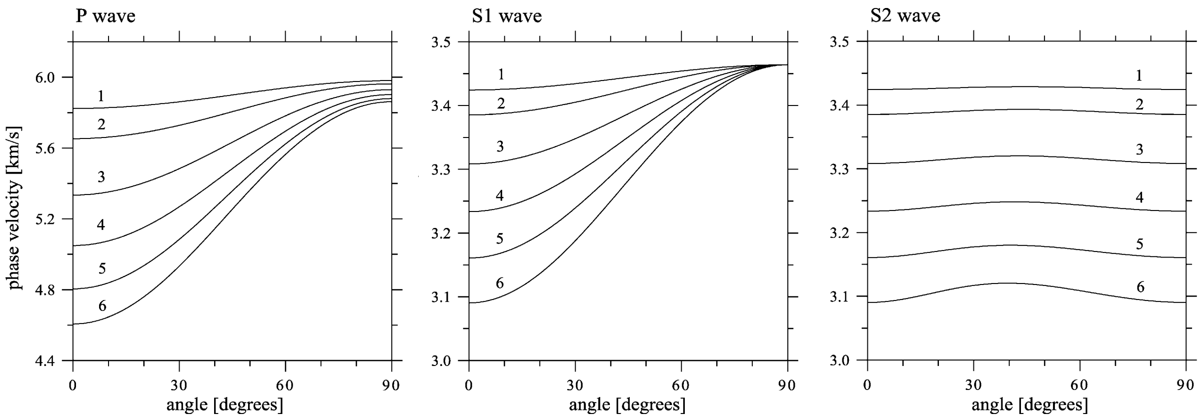


Fig. 3. P-, S1- and S2-wave phase velocities as a function of the angle between the direction of propagation and the symmetry axis for medium models under study. Models 1–6 correspond to values of the crack density of 1%, 2%, 4%, 6%, 8% and 10%. See text for the other medium parameters.

The anisotropic Green's functions were calculated by using the following formula (Červený, 2001; Vavryčuk, 2001, Eq. 3):

$$G_{kl}(x_j,t) = \frac{1}{4\pi\rho}\frac{1}{v^2\sqrt{K_\mathrm{p}}}\frac{g_k g_l}{\tau}\delta(t-\tau(x_j)), \tag{10}$$

where v is the wave group velocity, K_p is the Gaussian curvature of the slowness surface, $\mathbf{g}$ is the polarization vector, τ is the travel time and $\delta(t)$ is the Dirac delta function. Since this formula represents the Green's function for each particular type of wave, the complete Green's function is obtained by summing this formula over P, S1 and S2 waves. The obtained Green's function is valid for all directions in the far field except for caustics ($K_\mathrm{p}=0$) and the kiss singularity (Vavryčuk, 1999), which coincides with the symmetry axis in transverse isotropy. To fulfil this condition, we study media with no caustics, and an array configuration with no station located near the symmetry axis direction.

4. Synthetic experiments

The error in the source parameters retrieved from anisotropic waveforms by using isotropic medium model depends on the station array configuration. We can identify distinct directions within each anisotropy for which the propagation of seismic waves is significantly different from the isotropic case. If the radiation maxima from the source are related to these prominent directions, the mismodelling due to the neglect of anisotropy is more pronounced. As an example, the double S pulse generated by the anisotropic splitting should be fit by the single S pulse modelled using the isotropic Green's function. If one of these two S waves clearly dominates in a component to be inverted, the fit with isotropic synthetics is straightforward and the retrieved source is only little distorted. If both split S waves appear with comparable amplitudes, the fit is not unique and the retrieved source will be more biased. The result depends on the orientation of anisotropy with respect to the propagation direction and source mechanism. In order to assess the dependence of our tests on the source mechanism, a series of about 400 inversion experiments were performed, randomly varying the source orientation, and the error histograms were constructed.

Apart from the distorted orientation of the retrieved DC source, the neglect of anisotropy results in an appearance of spurious source components (Šílený and Vavryčuk, 2000), such as the isotropic component (ISO) and the compensated linear-vector dipole (CLVD). To assess these effects, histograms of the average inclination of principal axes, and the percentage of the spurious ISO and CLVD components are calculated. In addition, the quality of the reconstruction of the STF is evaluated by the histogram of the correlation coefficient between the retrieved and theoretical STF (10-point smooth pulse). Finally, the reconstruction of the scalar moment M_0 is presented in terms of the histogram of the ratio of retrieved to true value of M_0.

The quality of the source parameter inversions was evaluated for the DIRPAR algorithm with synchronous and asynchronous alignments of synthetics to the data, and the INPAR algorithm with an asynchronous alignment. From the histograms representing approximate statistical distributions of source parameters, the error in each parameter can be estimated as the width corresponding to half of the histogram peak value.

4.1. Inclination of the retrieved DC

The inversion of records with both P and S waves yields the DC inclined from the theoretical value as presented in Fig. 4. The values of the inclination are significantly larger when the synchronous alignment was applied. The distribution of the inclination values is rather broad even at the anisotropy level 4 (corresponding to the 6% density of dry cracks) with the peak value at about 15°. When the asynchronous alignment is applied to both DIRPAR and INPAR methods, the distribution is much narrower with the peak value below 10°. The error in the orientation of the retrieved DC from anisotropic records using both P and S waves is below 20°.

Limiting the data set to P waves only, a smaller error is expected in the retrieved source, as we avoid employing split S waves. As such, the inclination of the reconstructed DC is much smaller (Fig. 5). A pronounced difference in the performance of the algorithms applied is encountered under strong anisotropy, when the synchronous alignment gives a broad distribution of the inclination angles with the peak at 15°, whereas the values obtained with an asynchronous alignment are very narrowly distributed around 5°. Thus, the results are strongly affected by the type of alignment. As shown schematically in Fig. 1, the necessity of asynchronous alignment arises due to the S-wave splitting into two pulses mutually shifted in time. The anisotropic P wave is generally deviated from the direction of the ray path but the P wave is not split, and thus it should be synchronous in all components. Despite this fact, the asynchronous alignment allows for a significantly better retrieval of the source orientation than the synchronous alignment.

4.2. Spurious isotropic component

In all levels of anisotropy, the ISO component fluctuates around zero if asynchronous alignment is applied (Fig. 6). The distribution is wider for the synchronous alignment but its peak remains at zero. Note that from the half-width of the histogram, it results that the asynchronous alignment keeps the spurious ISO component below about 2% regardless of the inversion algorithm applied.

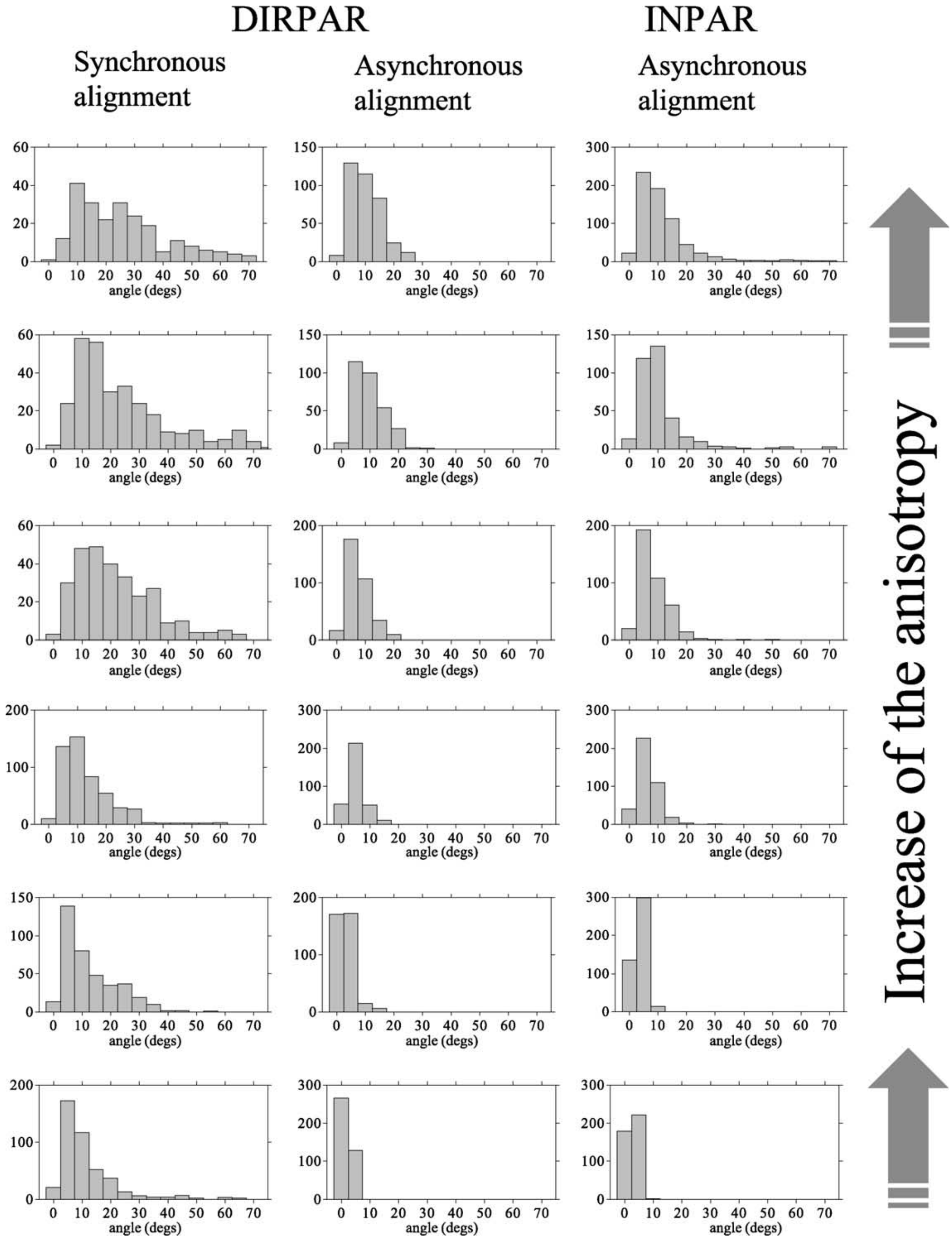
4.3. Spurious CLVD component

The spurious CLVD component is more pronounced in the inversions than the ISO component regardless of the type of algorithm applied (Fig . 7). Both inversion algorithms give very similar distributions provided that the asynchronous alignment is applied. A statistically significant nonzero component appears even at the lowest anisotropy level and can reach as much as about 30% (estimated from the half-width of the distribution). Bad results are obtained using the synchronous alignment, which gives several tens of percent of spurious CLVD at high anisotropy levels.

4.4. Reconstruction of the STF

The success in the retrieval of the STF is described by the value of the correlation coefficient between the reconstructed and theoretical STF. The fitting of these functions allows for a time shift to be employed in order to obtain the best correlation. The INPAR algorithm works significantly better than DIRPAR

Fig. 4. Errors in the orientation of the reconstructed DC. Histograms show statistics of the inclination of the retrieved DC from the theoretical solution. Orientation of the theoretical DC is chosen randomly (400 trials). For each DC, anisotropic 'observed' waveforms are generated and inverted with the isotropic Green's functions. The records consist of both P and S waves. The angle of inclination is the sum of differences of the orientation of principal axes. The histograms are constructed for six degrees of anisotropy starting from fairly weak to strong. Three methods of inversion are applied: DIRPAR with a synchronous alignment (left column), DIRPAR with an asynchronous alignment (middle) and INPAR with an asynchronous alignment (right column).


DIRPAR
INPAR
Synchronous alignment
Asynchronous alignment
Asynchronous alignment
angle (degs)
Increase of the anisotropy

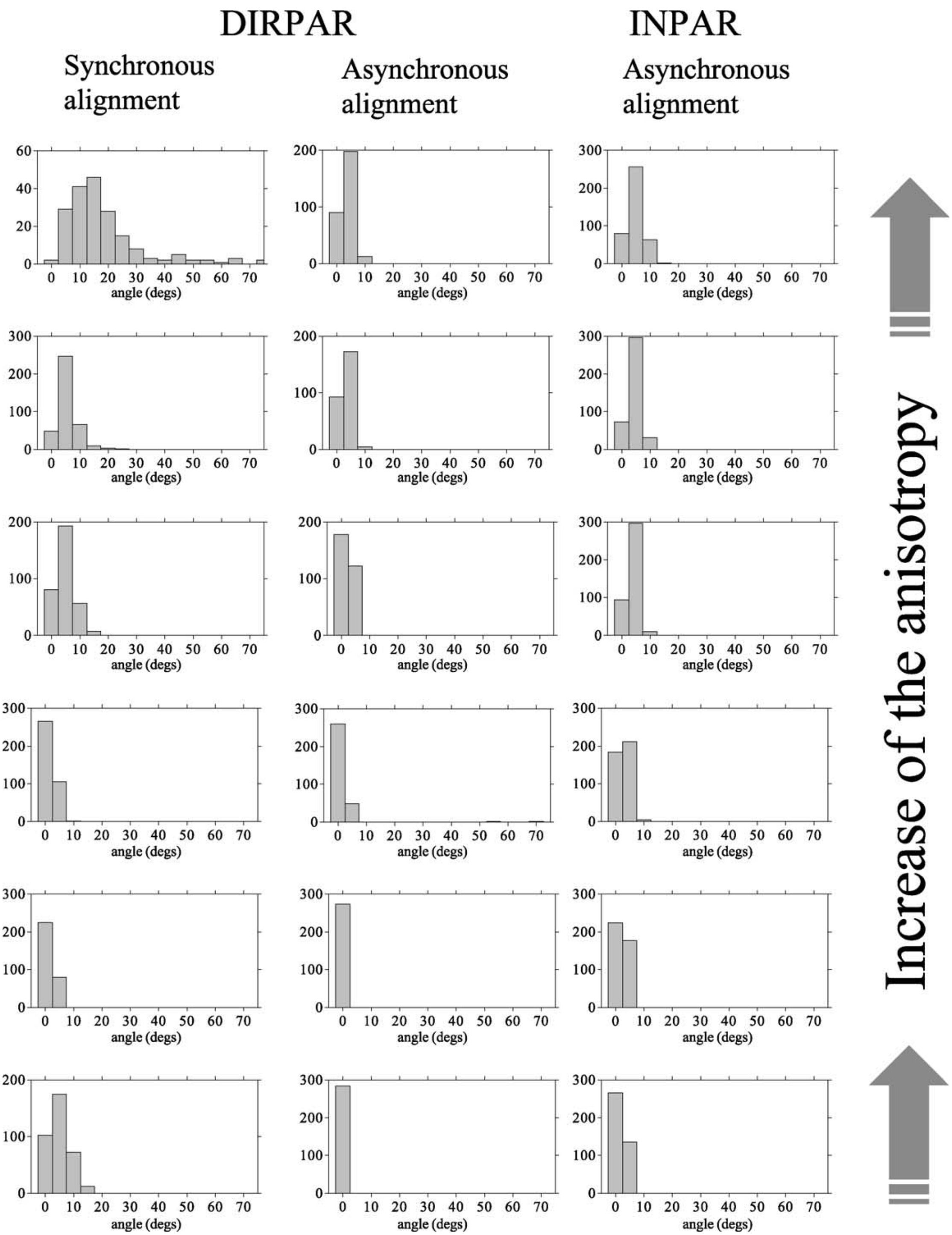


Fig. 5. Errors in the orientation of the reconstructed DC based on the inversion of P waves only. For details see the caption of Fig. 4.

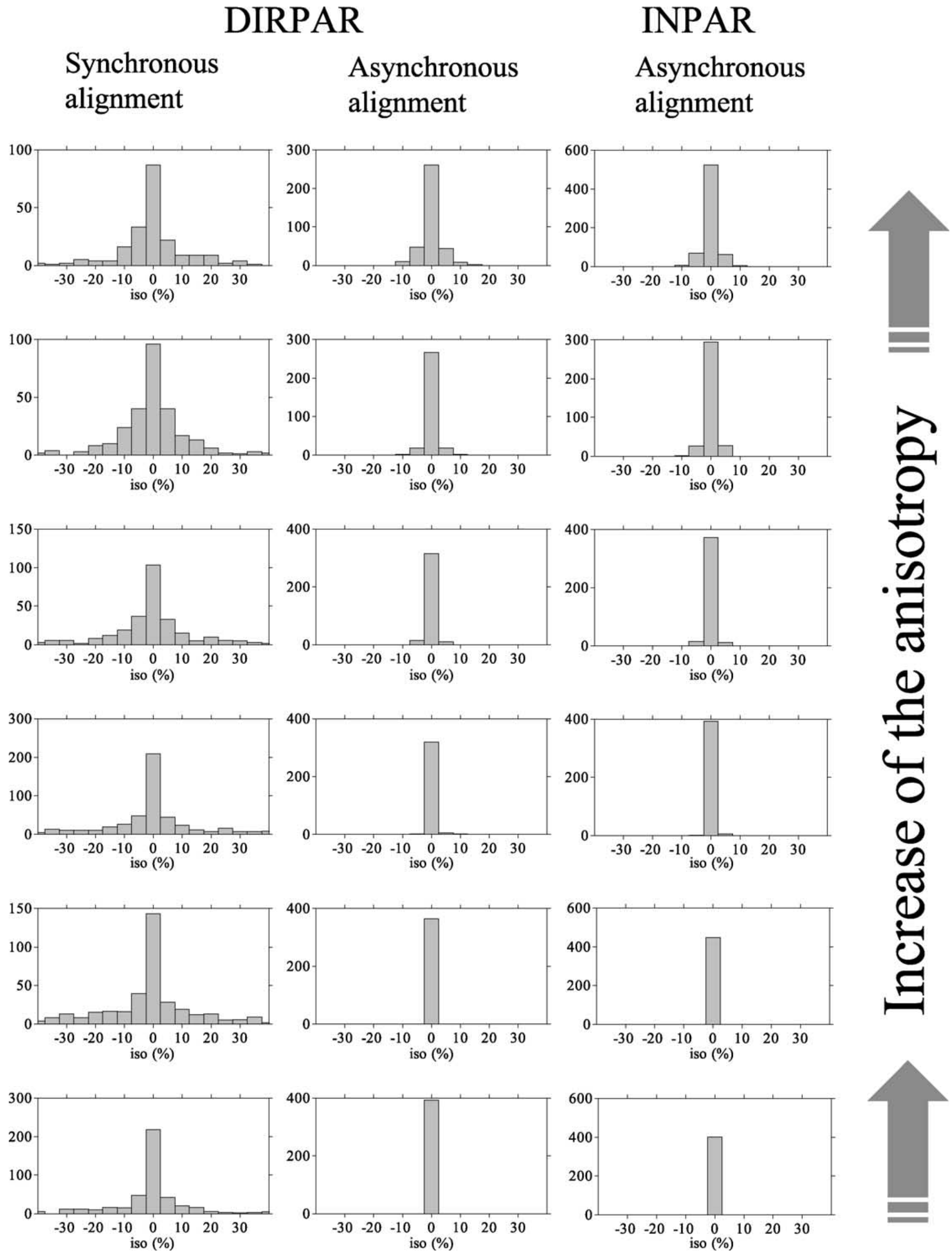


Fig. 6. Spurious isotropic component (ISO) from the inversion of both P and S waves. The percentage of the isotropic part is determined as the ratio of the squared moments of the isotropic component to the total seismic moment, ISO[%] = $100 \times M_0^2$(isotropic)/M_0^2(total), based on the relation M_0^2(total) = M_0^2(isotropic) + M_0^2(deviatoric) by Silver and Jordan (1982). For other details see the caption of Fig. 4.

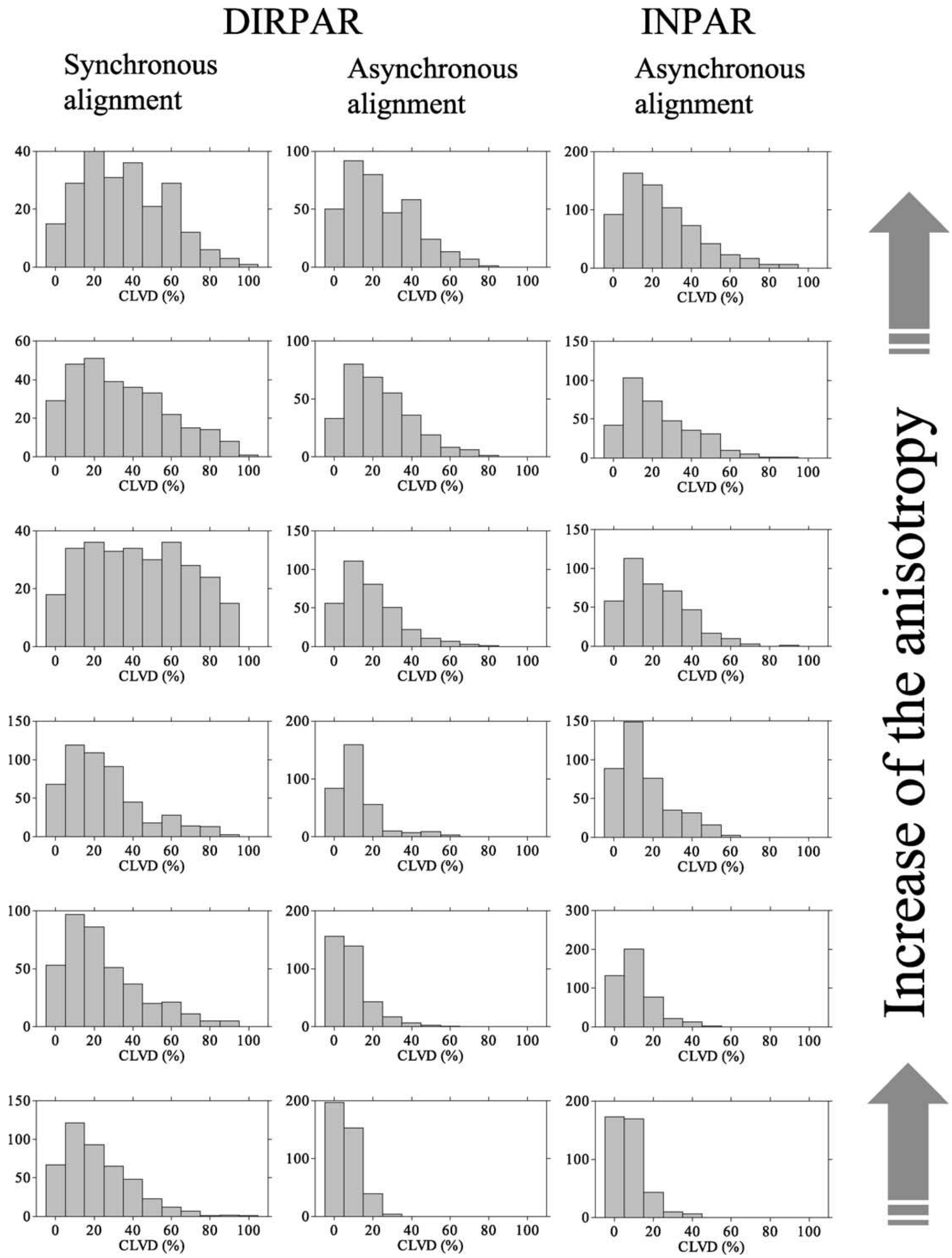


Fig. 7. Spurious compensated linear-vector dipole (CLVD) from the inversion of both P and S waves. The percentage of the CLVD is determined as CLVD[%] = $200 \times \min|\lambda_i|/\max|\lambda_i|$, where λ_i (i = 1,2,3) are the eigenvalues of the deviatoric part of the retrieved full moment tensor (Dziewonski et al., 1981). For other details, see the caption of Fig. 4.

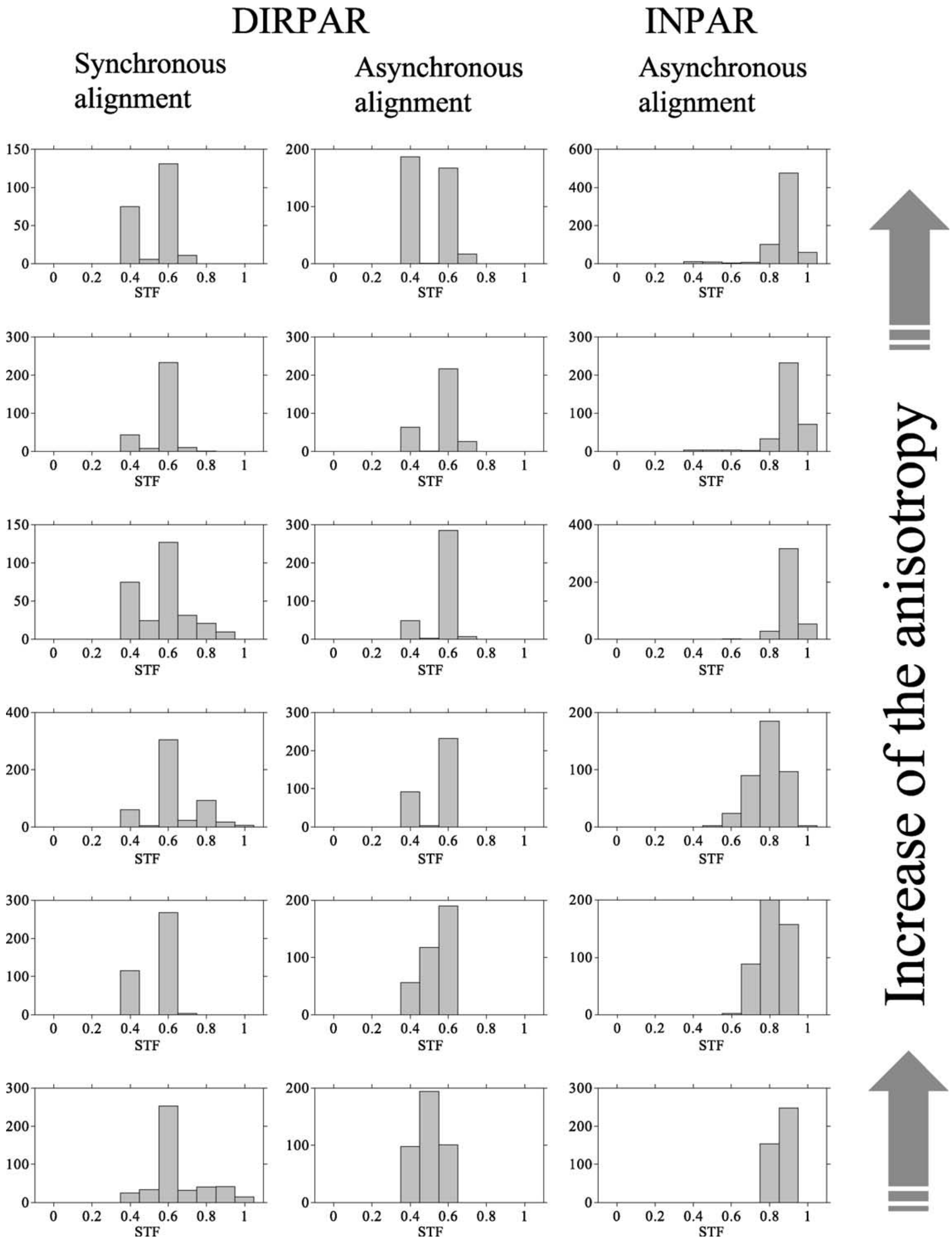


Fig. 8. Correlation between the retrieved and theoretical source-time functions (STF) from the inversion of both P and S waves. The theoretical STF was a simple smooth peak sampled by 10 points. For details, see the caption of Fig. 4.

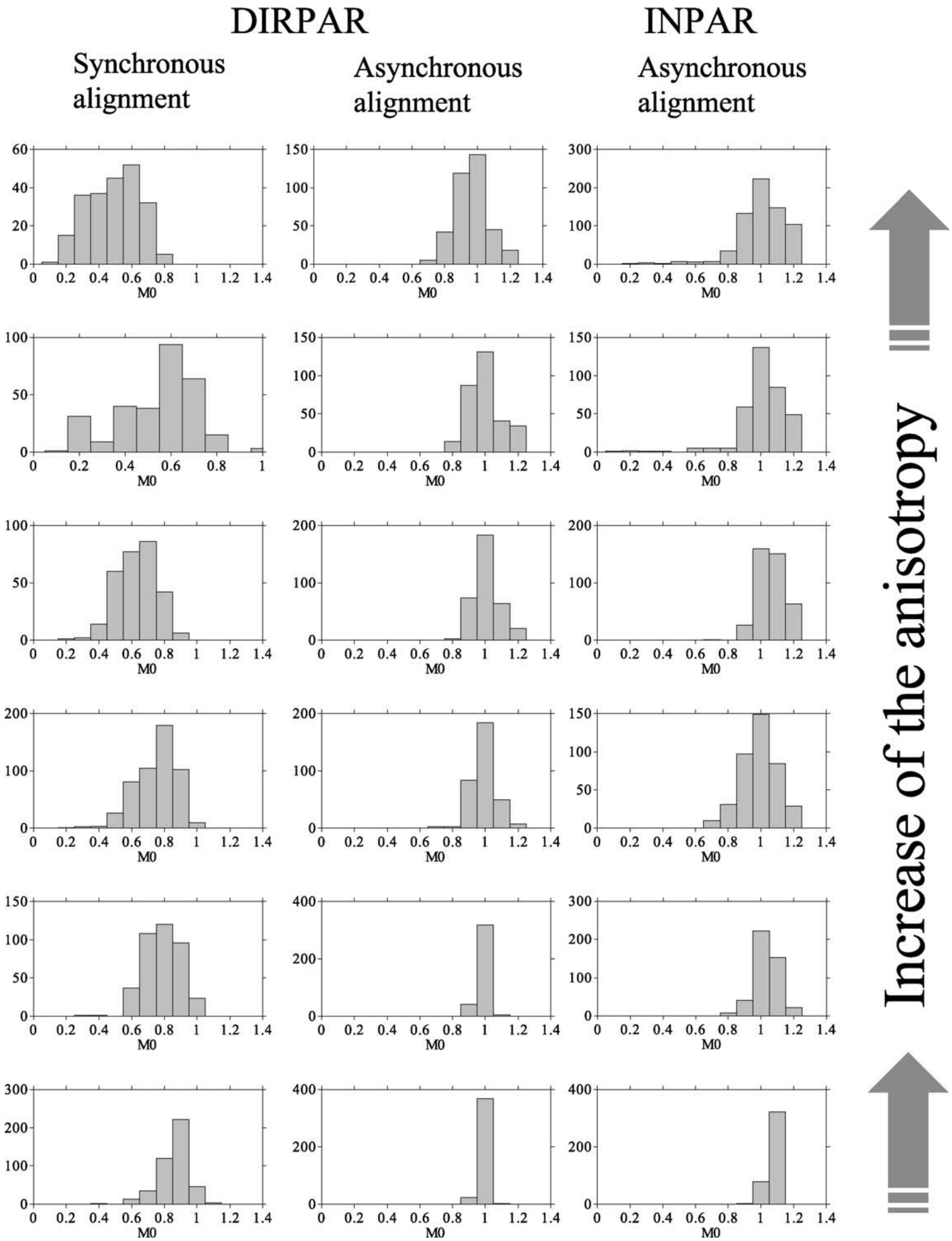


Fig. 9. Ratio of the retrieved to the theoretical scalar moment using an inversion of both P and S waves. For details, see the caption of Fig. 4.

(Fig. 8). This is because the INPAR is able to perform much more iterations in the same CPU time than DIRPAR and thus can better reach the minimum of the misfit function. In fact, DIRPAR never reaches a correlation coefficient greater than 0.6, which represents a very poor fit between the retrieved and theoretical STF. The scattering of the results obtained suggests that this algorithm would evidently need much more iterations than currently allowed (about 500), which was not feasible in this study.

4.5. Reconstruction of the scalar moment

The scalar moment, M_0, is estimated as the integral of the STF over its length. Thanks to the integration, which is basically a 'smoothing' operation, the reconstruction of the scalar moment is much more successful than the determination of the STF (Fig. 9). No difference between the M_0 retrieved by DIRPAR and INPAR algorithms is observed when using an asynchronous alignment. The histograms of the ratios of the retrieved to theoretical value exhibit a maximum at value 1, which represents a perfect reconstruction of the scalar moment. These distributions are fairly narrow even at high anisotropy levels, indicating that the error in M_0 is not larger than about 10%. Contrary to the success with the asynchronous alignment, the synchronous alignment leads to a severe underestimation of the scalar moment with the error amounting to several tens of percent.

5. Conclusion

It has been valuated that a neglect of anisotropy of the medium can have considerable effect on the retrieval of the source parameters through waveform inversion. If the source is a pure DC, spurious non-DC components appear. The magnitude of the non-DC components increases with the degree of anisotropy. Simultaneously, the orientation of the retrieved DC degrades. The source parameters are more biased if determined from both P and S waves than from P waves alone (Table 1). This is caused by peculiarities of S-wave propagation in anisotropic media, especially by the S-wave splitting. Note that the algorithm employed in the waveform inversion can control and reduce the errors. Two methods

Table 1
A summary of error estimates due to the neglect of anisotropy

Retrieved source characteristics	Error		Technique
	P waves	P and S waves	
DC orientation	< 10°	< 20°	DIRPAR, INPAR
Spurious ISO	< 2%	< 2%	DIRPAR, INPAR
Spurious CLVD	< 20%	< 30%	DIRPAR, INPAR
Source-time function	correlation about 0.8	correlation above 0.8	INPAR
Scalar moment ratio	20%	20%	DIRPAR, INPAR

Inversion of P waves, and combined P and S waves, using DIRPAR and INPAR techniques with asynchronous alignment of synthetic seismograms to the data. See the captions of Figs. 6 and 7 for the definition of the percentage of ISO and CLVD components, respectively.

were tested: an algorithm with the traditional direct parametrization of the source (DIRPAR) and an algorithm with the indirect parametrization (INPAR). Their performance in the reconstruction of the orientation of the DC component is essentially the same as they introduce very similar percentages of spurious ISO and CLVD components. The robustness of INPAR is manifested in the success of retrieving the source-time function, whereas DIRPAR fails completely. This is due to the high computational efficiency of INPAR, which advantageously combines linear and nonlinear techniques, different to DIRPAR, which incorporates only a nonlinear inverse scheme. Both algorithms act with similar success in the reconstruction of the scalar moment M_0 of the source.

A crucial role in the inversion plays the fitting of the synthetic seismograms to the observed three-component records. The traditional way of aligning all three components simultaneously (synchronous alignment) leads to substantially larger errors than the alignment of each component independently of the others (asynchronous alignment). This is due to the S-wave splitting that is present in the anisotropic waveforms. The single isotropic S wave should be matched to the dominant pulse of the split S waves by the asynchronous alignment because it takes into account different S wave arrivals of the splitting at individual components. Thus, the split S waves are joined together in the vector sum and reconstruct the total S wave in the medium, from which the anisotropy is removed (Karnassopoulou et al., 1996).

Surprisingly, the asynchronous alignment is preferred also in the inversion of P waves.

The present study provides additional evidence to the unreliability of non-DC components retrieved in the mechanisms of some earthquakes. Several authors have already pointed out that the non-DC components may be doubtful due to the inaccurate modelling of the medium and imperfect location of the source (Kuge and Lay, 1994) due to the mismodelling of the inhomogeneous medium (Kravanja et al., 1999), oversimplification of the seismic source (Frohlich, 1994) and neglect of the reflected phases at an interface next to the hypocentre (Šílený et al., 2001). Based on this analysis, the non-DC components may be also the consequence of neglecting the effects of anisotropy.

Acknowledgements

The authors thank C. Trifu and two anonymous reviewers for their constructive reviews. The study was supported by the Acad. Sci. Czech Rep. Grant Agency, Grant #A3012904, and by the Czech Rep. Grant Agency, Grants #205/00/1350 and #205/02/0383. Part of the study was carried out when J.S. was at the Abdus Salam ICTP at Trieste, Italy within the scope of the Associate Membership Scheme.

References

Babuška, V., Carra, M., 1991. Seismic Anisotropy in the Earth. Kluwer Academic Publishing, London.

Červený, V., 2001. Seismic Ray Theory. Cambridge Univ. Press, Cambridge.

Dziewonski, A.M., Chou, T.A., Woodhouse, J.H., 1981. Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. J. Geophys. Res. 86, 2825–2852.

Frohlich, C., 1994. Earthquakes with non-double-couple mechanisms. Science 264, 804–809.

Hudson, J.A., 1981. Wave speeds and attenuation of elastic waves in material containing cracks. Geophys. J. R. Astron. Soc. 64, 133–150.

Karnassopoulou, A., Pierce, R.G., Booth, D.C., 1996. A method to determine microearthquake focal mechanism in the presence of seismic anisotropy. Tectonophysics 261, 115–126.

Kravanja, S., Panza, G.F., Šílený, J., 1999. Robust retrieval of a seismic point-source time function. Geophys. J. Int. 136, 385–394.

Kocks, U.F., Tome, C.N., Wenk, H.R. (Eds.), 1998. Texture and Anisotropy: Preferred Orientations in Polycrystals and Their Effect on Materials Properties. Cambridge Univ. Press, Cambridge.

Kuge, K., Lay, T., 1994. Data-dependent non-double-couple components of shallow earthquake source mechanisms: effects of waveform inversion instability. Geophys. Res. Lett. 21, 9–12.

Nábělek, J.L., 1984. Determination of earthquake source parameters from inversion of body waves, PhD thesis, MIT.

Šílený, J., 1997. Moment tensor rate functions from waveforms with non-homogeneous variance. Geophys. J. Int. 131, 767–769.

Šílený, J., 1998. Earthquake source parameters and their confidence regions by a genetic algorithm with a "memory". Geophys. J. Int. 134, 228–242.

Šílený, J., Vavryčuk, V., 2000. Approximate retrieval of the point source in anisotropic media: numerical modelling by indirect parametrization of the source. Geophys. J. Int. 143, 700–708.

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

Šílený, J., Pšenčík, I., Young, R.P., 2001. Point-source inversion neglecting nearby free surface: simulation of Underground Research Laboratory, Canada. Geophys. J. Int. 146, 171–180.

Silver, P.G., Jordan, T.H., 1982. Optimal estimation of scalar seismic moment. Geophys. J. R. Astron. Soc. 70, 755–787.

Sipkin, S.A., 1982. Estimation of earthquake source parameters by the inversion of waveform data: synthetic waveforms. Phys. Earth Planet. Inter. 30, 242–259.

Vavryčuk, V., 1999. Properties of S waves near a kiss singularity: a comparison of exact and ray solutions. Geophys. J. Int. 130, 786–800.

Vavryčuk, V., 2001. Exact elastodynamic Green functions for simple types of anisotropy derived from higher-order ray theory. Stud. Geophys. Geod. 45, 67–84.