

Tensile earthquakes: Theory, modeling, and inversion

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[1] Tensile earthquakes are earthquakes which combine shear and tensile motions on a fault during the rupture process. The geometry of faulting is described by four angles: strike, dip, rake, and slope. The strike, dip, and rake define the orientation of the fault normal and the tangential component of the dislocation vector along the fault. The slope defines the deviation of the dislocation vector from the fault. The strike, dip, and rake are determined ambiguously from moment tensors similarly as for shear sources. The slope is determined uniquely and has the same value for both complementary solutions. The moment tensors of tensile earthquakes are characterized by significant non-double-couple (non-DC) components comprising both the compensated linear vector dipole (CLVD) and the isotropic (ISO) components. In isotropic media, the CLVD and ISO percentages should have the same sign and should depend linearly for earthquakes that occurred in the same focal area. The direction of the linear function between the CLVD and ISO defines the velocity ratio ν_P/ν_S in the focal area. The parameters of tensile earthquakes can be retrieved from their moment tensors. The procedure yields the angles describing the geometry of faulting as well as the ν_P/ν_S ratio in the focal area. The accuracy of the ν_P/ν_S ratio can be increased if a set of moment tensors of earthquakes that occurred in the same focal area is analyzed. The calculation of the ν_P/ν_S ratio from moment tensors is an auspicious method which might find applications in tomography of the focal area or in monitoring fluid flow during seismic activity. If the ν_P/ν_S ratio is found and well constrained, the parameters of tensile earthquakes can be inverted directly from observed data using a constrained nonlinear inversion. In this inversion, the parameter space can be limited by fixing the ν_P/ν_S ratio or forcing the ν_P/ν_S ratio to lie within some physically reasonable limits.

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1. Introduction

[2] The increasing amount of seismic data and their quality allow resolving details of the earthquake source process. From this viewpoint, a simple model of shear planar faulting represented by the double-couple (DC) moment tensor often appears too rough and simplistic. Accurately determined moment tensors frequently reveal the presence of non-double-couple (non-DC) components originating in complexities in the earthquake source [Frohlich, 1994; Julian *et al.*, 1998; Miller *et al.*, 1998]. One of the models describing the earthquake source more adequately and predicting significant non-DC components is the general dislocation model, or equivalently the model of tensile earthquakes [Vavryčuk, 2001; Ou, 2008]. This model allows the dislocation vector defining the displacement discontinuity on the fault to deviate from the fault plane. Faulting can thus combine both shear

and tensile motions. Consequently, the fault can possibly be opened or closed during the rupture process. Tensile earthquakes are reported, in particular, in geothermal and volcanic areas rich in fluids under overpressure conditions [Ross *et al.*, 1996; Julian *et al.*, 1997; Vavryčuk, 2002; Templeton and Dreger, 2006; Shuler and Ekröm, 2009; Davi *et al.*, 2010; Sarao *et al.*, 2010], or in hydraulic fracturing and fluid injection experiments [Zoback, 2007; Vavryčuk *et al.*, 2008; Šílený *et al.*, 2009; Baig and Urbancic, 2010; Fischer and Guest, 2011]. Tensile motions can also be produced during shear rupturing when tensile wing cracks develop at the tip of the fracture [Dalguer *et al.*, 2003; Griffith *et al.*, 2009; Misra *et al.*, 2009].

[3] The basic mathematical description of the general dislocation model is well known being a straightforward generalization of the shear model [Ben-Menahem and Singh, 1981; Aki and Richards, 2002]. However, specific properties of the general dislocation model and the accuracy and efficiency of the inversion for parameters of this model are not yet well understood. In this paper, theory of tensile sources situated in an isotropic medium is presented. The eigenvalues and eigenvectors of the source and moment tensors are studied. The so-called source lines are introduced

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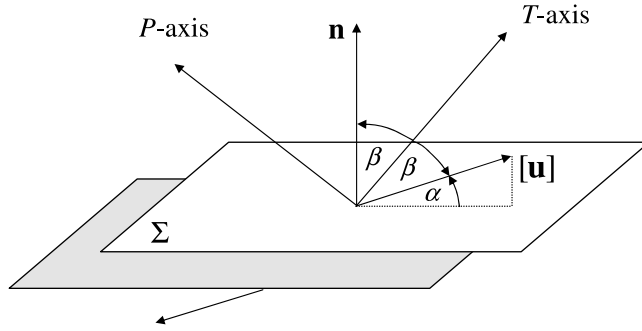


Figure 1. Model of a tensile earthquake. Σ is the fault plane, $[\mathbf{u}]$ is the dislocation vector, $\mathbf{n}$ is the fault normal, and α is the slope. Angle β is defined as $\beta = (90^\circ - \alpha)/2$.

for plotting the focal mechanisms, and their relation to standard nodal lines is discussed. Attention is paid to the inversion for the ν_P/ν_S ratio in the focal area using a set of moment tensors. The accuracy of the presented formulas is tested using numerical modeling. An application of the formulas is exemplified on observations of microearthquakes in the West Bohemia/Vogtland region.

2. Tensile Source Model

2.1. Geometrical Description

[4] For a tensile source, displacement discontinuity $[\mathbf{u}]$ (dislocation vector) does not generally lie in the fault. The source is described by four angles: strike ϕ , dip δ , rake λ and slope α . Strike ϕ and dip δ define the orientation of the fault, rake λ and slope α define the orientation of the dislocation vector. Strike ϕ , dip δ and rake λ have been introduced for describing the shear sources [Aki and Richards, 2002, Figure 4.20]. Slope α describes the tensility of the source and it is defined as the deviation of the dislocation vector from the fault (see Figure 1). Hence, $\alpha = 90^\circ$ for pure extensive sources, $\alpha = 0^\circ$ for shear sources, and $\alpha = -90^\circ$ for pure compressive sources. The projection of the dislocation vector into the fault is called the slip. The plane normal to the dislocation vector is called the dislocation plane.

[5] The fault normal $\mathbf{n}$ and the dislocation direction $\boldsymbol{\nu}$ are expressed for the tensile source in terms of angles ϕ , δ , λ and α as follows:

$$\begin{aligned} n_1 &= -\sin \delta \sin \phi, \\ n_2 &= \sin \delta \cos \phi, \\ n_3 &= -\cos \delta, \end{aligned} \quad (1)$$

$$\begin{aligned} \nu_1 &= (\cos \lambda \cos \phi + \cos \delta \sin \lambda \sin \phi) \cos \alpha - \sin \delta \sin \phi \sin \alpha, \\ \nu_2 &= (\cos \lambda \sin \phi - \cos \delta \sin \lambda \cos \phi) \cos \alpha + \sin \delta \cos \phi \sin \alpha, \\ \nu_3 &= -\sin \lambda \sin \delta \cos \alpha - \cos \delta \sin \alpha. \end{aligned} \quad (2)$$

The coordinate system $\mathbf{x}$, $\mathbf{y}$, and $\mathbf{z}$ is directed to the North, East and downward, respectively. Angles ϕ , δ , λ and α are, in general, functions of spatial coordinates and time. For simplicity, this spatiotemporal variation will be neglected in the next. It means that we focus on the point source approximation of tensile faulting on a planar fault with a constant slope in time.

2.2. Source Tensor

[6] Source tensor $\mathbf{D}$ of the tensile source is defined as follows [Vavryčuk, 2005, equation (32)]:

$$\begin{aligned} \mathbf{D} &= \frac{uS}{2} (\mathbf{n}\boldsymbol{\nu} + \boldsymbol{\nu}\mathbf{n}) \\ &= \frac{uS}{2} \begin{bmatrix} 2n_1\nu_1 & n_1\nu_2 + n_2\nu_1 & n_1\nu_3 + n_3\nu_1 \\ n_1\nu_2 + n_2\nu_1 & 2n_2\nu_2 & n_2\nu_3 + n_3\nu_2 \\ n_1\nu_3 + n_3\nu_1 & n_2\nu_3 + n_3\nu_2 & 2n_3\nu_3 \end{bmatrix}, \end{aligned} \quad (3)$$

where u is the dislocation (the magnitude of the dislocation vector $[\mathbf{u}]$), and S is the fault area. Product uS is called the “source strength” or the “potency” [Ben-Menahem and Singh, 1981]. Therefore, source tensor $\mathbf{D}$ is sometimes called the potency tensor [Ben-Zion, 2003; Ampuero and Dahlen, 2005]. Vectors $\mathbf{n}$ and $\boldsymbol{\nu}$ are perpendicular for shear sources but parallel for pure tensile (extensive or compressive) sources. For a general tensile source, vectors $\mathbf{n}$ and $\boldsymbol{\nu}$ form angle $\gamma = 90^\circ - \alpha$ ranging between 0° and 180° .

[7] Source tensor $\mathbf{D}$ has the following diagonal form [Vavryčuk, 2005, Appendix B]:

$$\mathbf{D}^{diag} = \begin{bmatrix} D_1 & 0 & 0 \\ 0 & D_2 & 0 \\ 0 & 0 & D_3 \end{bmatrix} = \frac{uS}{2} \begin{bmatrix} \mathbf{n} \cdot \boldsymbol{\nu} + 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \mathbf{n} \cdot \boldsymbol{\nu} - 1 \end{bmatrix}, \quad (4)$$

where $D_1 \geq D_2 \geq D_3$, and $\mathbf{n} \cdot \boldsymbol{\nu}$ is the scalar product of vectors $\mathbf{n}$ and $\boldsymbol{\nu}$. The determinant of $\mathbf{D}$ is zero. The source strength is $uS = D_1 - D_3$. The trace of $\mathbf{D}$

$$D_{kk} = uS (\mathbf{n} \cdot \boldsymbol{\nu}) = uS \sin \alpha, \quad (5)$$

is positive for extensive sources ($\alpha > 0$) but negative for compressive sources ($\alpha < 0$). The maximum eigenvalue D_1 is positive or zero, the minimum eigenvalue D_3 is negative or zero. The eigenvectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ of $\mathbf{D}$ are

$$\mathbf{e}_1 = \frac{\mathbf{n} + \boldsymbol{\nu}}{|\mathbf{n} + \boldsymbol{\nu}|}, \quad \mathbf{e}_2 = \frac{\mathbf{n} \times \boldsymbol{\nu}}{|\mathbf{n} \times \boldsymbol{\nu}|}, \quad \mathbf{e}_3 = \frac{\mathbf{n} - \boldsymbol{\nu}}{|\mathbf{n} - \boldsymbol{\nu}|}, \quad (6)$$

where symbol $\times$ denotes the vector product. Vectors $\mathbf{n}$ and $\boldsymbol{\nu}$, and slope α can be determined from the eigenvalues and eigenvectors of $\mathbf{D}$ by the following formulas:

$$\mathbf{n} = \sqrt{\frac{D_1}{D_1 - D_3}} \mathbf{e}_1 + \sqrt{\frac{D_3}{D_3 - D_1}} \mathbf{e}_3, \quad (7)$$

$$\boldsymbol{\nu} = \sqrt{\frac{D_1}{D_1 - D_3}} \mathbf{e}_1 - \sqrt{\frac{D_3}{D_3 - D_1}} \mathbf{e}_3, \quad (8)$$

$$\sin \alpha = \frac{D_1 + D_3}{D_1 - D_3}. \quad (9)$$

2.3. Moment Tensor

[8] Moment tensor $\mathbf{M}$ of the tensile source is expressed in anisotropic media as follows [Vavryčuk, 2005, equation (4)]:

$$M_{ij} = c_{ijkl} D_{kl}, \quad (10)$$

where c_{ijkl} are the elastic parameters of the medium surrounding the fault, and $\mathbf{D}$ is the source tensor. For isotropic media, the moment tensor $\mathbf{M}$ reads

$$M_{ij} = \lambda D_{kk} \delta_{ij} + 2\mu D_{ij}, \quad (11)$$

where λ and μ are the Lamé's coefficients. Consequently, $\mathbf{M}$ has the following diagonal form:

$$\begin{aligned} \mathbf{M}^{diag} &= \begin{bmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{bmatrix} \\ &= uS \begin{bmatrix} (\lambda + \mu) \mathbf{n} \cdot \mathbf{v} + \mu & 0 & 0 \\ 0 & \lambda \mathbf{n} \cdot \mathbf{v} & 0 \\ 0 & 0 & (\lambda + \mu) \mathbf{n} \cdot \mathbf{v} - \mu \end{bmatrix}. \end{aligned} \quad (12)$$

[9] The stability conditions imposed on an isotropic medium

$$\lambda \geq -\frac{2}{3}\mu, \quad \mu \geq 0, \quad (13)$$

imply that the following terms

$$M_1 + M_2 + M_3 = uS(3\lambda + 2\mu) \sin \alpha, \quad (14)$$

$$M_1 + M_3 - 2M_2 = 2uS\mu \sin \alpha, \quad (15)$$

must be positive for extensive sources ($\alpha > 0$) but negative for compressive sources ($\alpha < 0$). The stability conditions exclude the case when equations (14) and (15) are of opposite signs.

[10] The eigenvectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ of $\mathbf{M}$ define the T , B and P axes, respectively. Since the deviatoric parts of the source and moment tensors differ just by a multiplication factor in isotropic media, see equation (11), the eigenvectors of $\mathbf{M}$ coincide with the eigenvectors of $\mathbf{D}$, see equation (6). The P and T axes bisect the angle between fault normal $\mathbf{n}$ and dislocation direction $\mathbf{v}$ (see Figure 1). The B axis is perpendicular to vectors $\mathbf{n}$ and $\mathbf{v}$. Hence, vectors $\mathbf{n}$ and $\mathbf{v}$ are expressed in terms of $\mathbf{M}$ as follows:

$$\mathbf{n} = \sqrt{\frac{M_1 - M_2}{M_1 - M_3}} \mathbf{e}_1 + \sqrt{\frac{M_3 - M_2}{M_3 - M_1}} \mathbf{e}_3, \quad (16)$$

$$\mathbf{v} = \sqrt{\frac{M_1 - M_2}{M_1 - M_3}} \mathbf{e}_1 - \sqrt{\frac{M_3 - M_2}{M_3 - M_1}} \mathbf{e}_3, \quad (17)$$

where the eigenvalues of $\mathbf{M}$ are denoted as $M_1 \geq M_2 \geq M_3$, and $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ are the corresponding eigenvectors. Eigenvectors $\mathbf{e}_1$ and $\mathbf{e}_3$ should have a negative vertical component for equations (16) and (17) to work properly. If we interchange vectors $\mathbf{n}$ and $\mathbf{v}$ in formulas (16) and (17), we get the complementary solution. Slope α characterizing the tensility of the source is determined from equation (12) as follows:

$$\sin \alpha = \frac{M_1 + M_3 - 2M_2}{M_1 - M_3} \quad (18)$$

having the same value for both the complementary solutions.

2.4. Radiation Pattern, Nodal Lines, and Source Lines

[11] The 3-D P wave radiation patterns for tensile sources are shown in Figure 2. They form two lobes for the pure compressive or extensive sources, but four lobes for the shear sources. For higher slopes, the patterns lack directions with no radiation, hence no nodal lines are observed. The uniform P wave polarity over the focal sphere does not, however, mean a uniform radiation.

[12] A focal mechanism is usually represented by the P wave radiation pattern plotted on the focal sphere. For shear sources, the zero radiation directions form two nodal lines, one of them corresponding to the fault plane, and the other to the plane normal to the slip direction. The area of the positive P wave polarity is highlighted being delimited by the nodal lines. For tensile sources, the zero radiation directions need not correspond to the fault plane or they even need not exist. Therefore, the area of the positive P wave polarity is highlighted for the tensile sources and the nodal lines corresponding to the DC part of the moment tensor are additionally plotted. The differences between the nodal lines of the full P wave radiation pattern and of its DC part quantify how much non-DC the moment tensor is (see Figure 3, left-hand plots).

[13] The standard plots of the focal mechanisms are not, however, very appropriate for tensile sources. Plotting of the DC nodal lines might be confusing because they have no relation to geometry of faulting and do not correspond to the orientation of the fault or of the dislocation plane. A more appropriate representation is to show the so-called "source lines." The source lines are defined as the projections of two source planes: the fault plane and the dislocation plane on the focal sphere (see Figure 3, right-hand plots). The identification of the source lines with the fault or with the dislocation plane is ambiguous similarly as for the nodal lines of the shear sources. The only exception is the pure extensive/compressive source ($\alpha = \pm 90^\circ$), when the two source lines merge and form one line corresponding to both the fault and the dislocation planes. Obviously, the source lines become standard nodal lines for the shear sources ($\alpha = 0^\circ$).

[14] Figure 4 shows plots of tensile sources with strike slip, normal and reverse focal mechanisms for a variety of slopes α . Figure 4 shows the well-known standard patterns for the shear sources ($\alpha = 0^\circ$) but quite new patterns for the nonshear sources, when the source lines significantly deviate from the DC nodal lines.

2.5. Decomposition of the Source and Moment Tensors

[15] The source and moment tensors can be decomposed into the isotropic (ISO), double-couple (DC) and compensated linear dipole (CLVD) components [Knopoff and Randall, 1970]. If the ISO, DC and CLVD components are calculated in percentages according to Vavryčuk [2001, 2005], these components can directly be related to slope α . For $\alpha = 90^\circ$, the DC is zero and the ISO and CLVD are positive and maximum. For $\alpha = 0^\circ$, the DC is 100% and the ISO and CLVD are zero. And for $\alpha = -90^\circ$, the DC is zero and the ISO and CLVD are negative and minimum. If slope α is varying, the ISO is a linear function of the CLVD (see Figure 5). This function has always the same direction for the source tensors, the ISO/CLVD ratio being 1/2. For the moment tensors, the direction of this line depends on the velocity ratio ν_P/ν_S in the medium around the source.

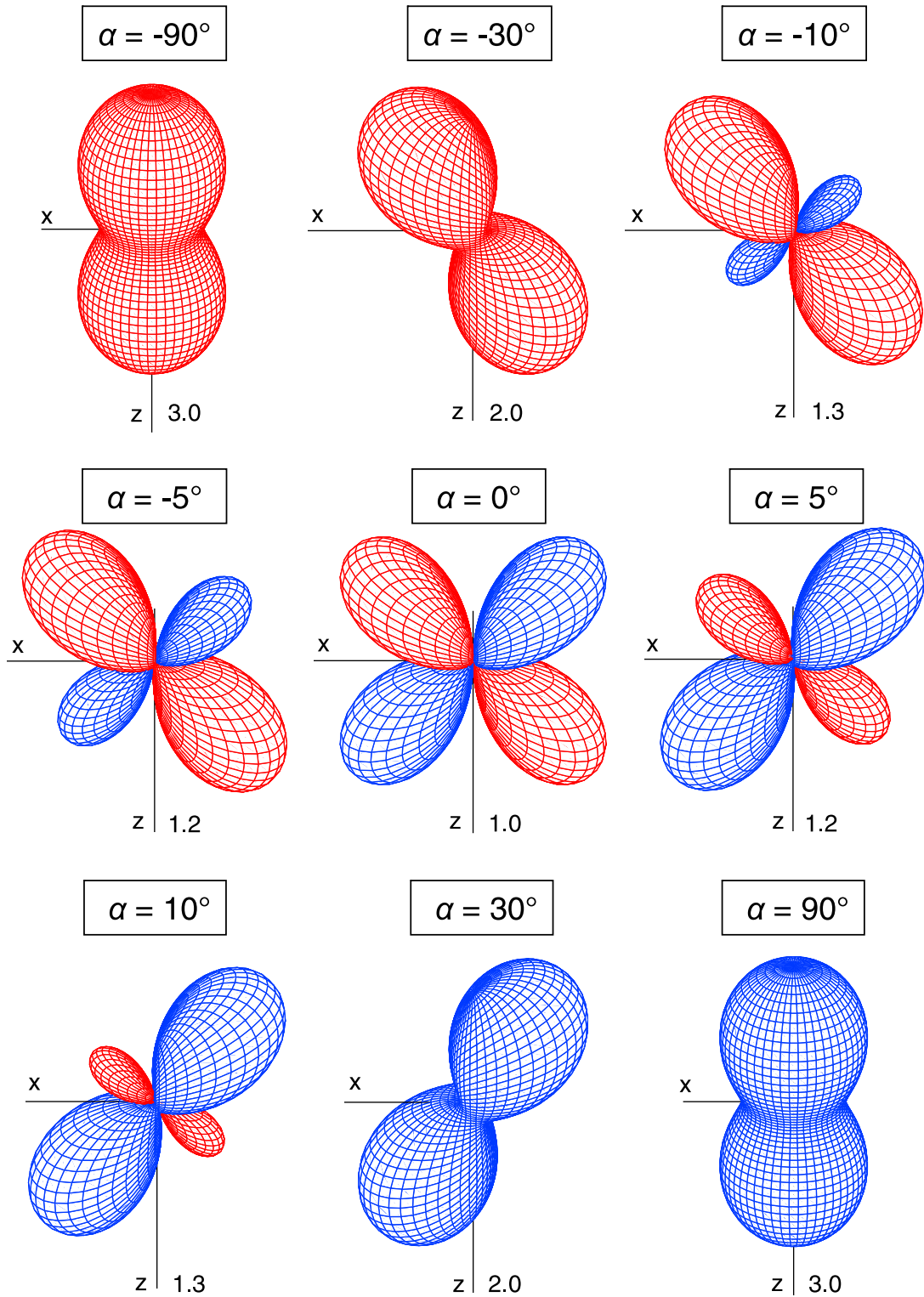


Figure 2. The P wave radiation patterns of a tensile earthquake as a function of slope α . The fault normal is along the vertical axis and the dislocation vector lies in the x_1 - x_3 plane. The blue/red color denotes the plus/minus P wave polarity. The numbers at the radiation patterns are the scale factors of the maximum amplitude. The ν_P/ν_S ratio is 1.73.

[16] Interestingly, when decomposing the source or moment tensors into the ISO, DC and CLVD components, we obtain values of different accuracy. This can easily be verified by

numerical modeling with the synthetic source tensors and moment tensors contaminated by noise. Let us assume a source with slope $\alpha = 20^\circ$, for which the source and moment tensors are contaminated by random uniformly distributed

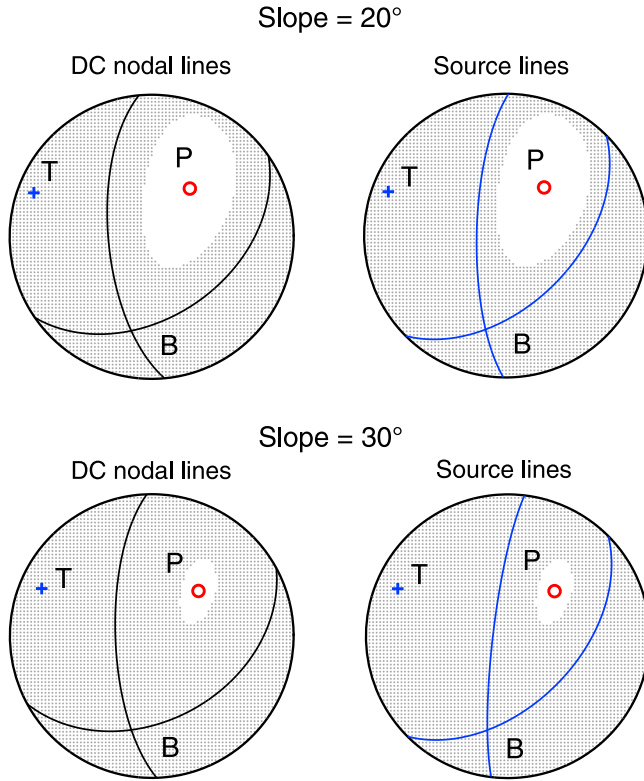


Figure 3. Focal spheres with double-couple (DC) nodal lines (black) and source lines (blue) for two tensile sources. The strike, dip, and rake have the same values for both sources: $\phi = 45^\circ$, $\delta = 50^\circ$, $\lambda = -45^\circ$. The slope is 20° and 30° , respectively.

noise with a level of 0.1 of their largest eigenvalue. Figure 6 shows a scatter of the ISO and CLVD values. The test reveals that the most accurate component is the ISO whose accuracy is about three times higher than that of the CLVD and DC. The origin of such a varying accuracy lies in the definitions of the ISO, CLVD and DC percentages [Vavryčuk, 2001].

3. Inversion for Parameters of Tensile Sources

[17] The most straightforward approach for calculating the angles of a tensile source is to perform the inversion in two steps. First, to apply a generalized linear inversion for moment tensor $\mathbf{M}$ from the observed wavefield $\mathbf{u}(\mathbf{x}, t)$ [Menke, 1989]. Subsequently, to calculate the parameters of a tensile source from $\mathbf{M}$ using (nonlinear) equations (1), (2), and (16)–(18). Since the first step of this approach is linear, the approach is called the “linear inversion.” However, the angles of the tensile source can also be calculated directly from the wavefield $\mathbf{u}(\mathbf{x}, t)$. This approach is nonlinear from its very beginning, so it is called the “nonlinear inversion.” Obviously, both approaches can be applied and the solution obtained from the linear inversion can be adopted as the initial guess for the nonlinear inversion. In general, the nonlinear inversion is more involved and more computationally demanding but it is also more flexible than the linear inversion. For example, additional constraints in the inversion can be imposed. If the ν_P/ν_S ratio is fixed or constrained to lie within some reasonable physical limits, the

parameter space can be advantageously reduced. Another merit of the nonlinear inversion is the possibility of applying a norm less sensitive to outliers than the L2 norm when calculating the misfit function. Consequently, the nonlinear inversion should be more stable and more accurate.

4. Inversion for the ν_P/ν_S Ratio in the Focal Area

[18] The ν_P/ν_S ratio in the focal area can be calculated from moment tensors and used as an additional constraint for retrieving the angles of the tensile sources by applying the nonlinear inversion.

4.1. Individual Tensile Sources

[19] The ν_P/ν_S ratio of the medium surrounding the source can be calculated from eigenvalues of $\mathbf{M}$ using the following formula:

$$\frac{\nu_P}{\nu_S} = \sqrt{\frac{\lambda + 2\mu}{\mu}} = \sqrt{1 + \frac{M_1 + M_3}{M_1 + M_3 - 2M_2}}. \quad (19)$$

The formula is applicable if stability conditions (13) are satisfied. This is taken into account by checking the following consistency criterion:

$$c > 0, \quad (20)$$

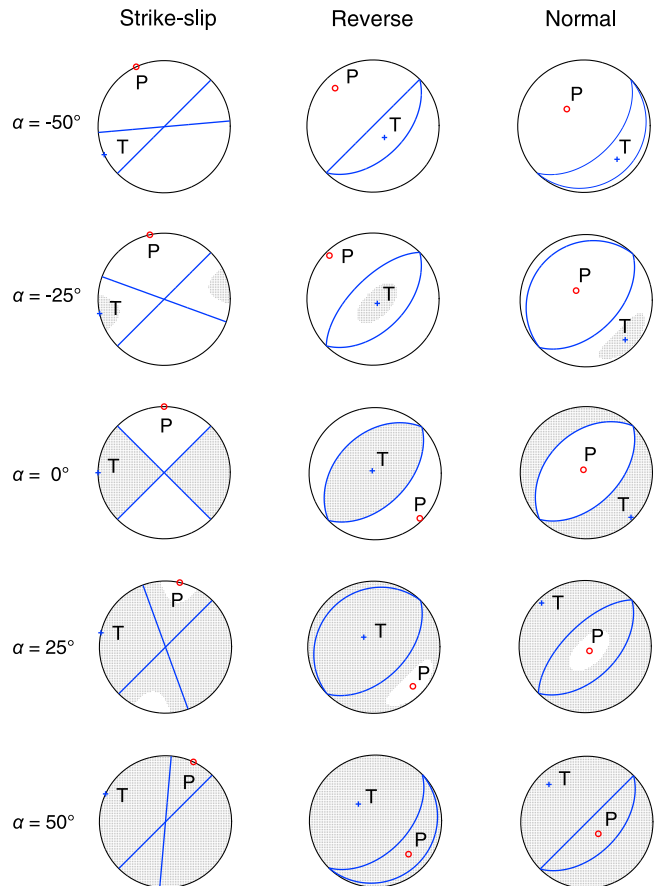


Figure 4. Focal mechanisms of tensile earthquakes as a function of slope α . The shaded area denotes the directions of the plus P wave polarity. The blue lines are the source lines.

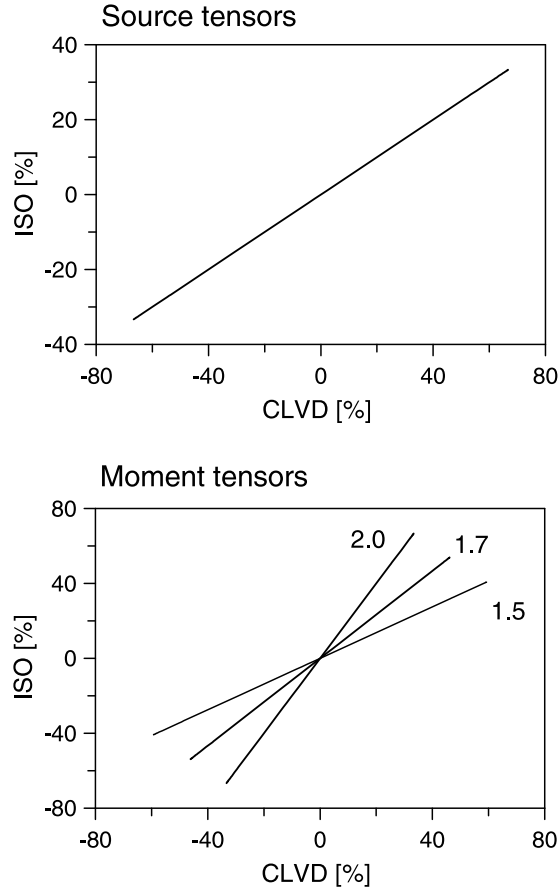


Figure 5. The dependence of the isotropic (ISO) and compensated linear vector dipole (CLVD) percentages in the source and moment tensors for varying slope α . Three different ν_P/ν_S ratios are assumed in calculating the moment tensors: 1.5, 1.7, and 2.0.

where c is the consistency coefficient

$$c = \text{sign} \left(\frac{M_1 + M_2 + M_3}{M_1 + M_3 - 2M_2} \right) \left| \frac{M_1 + M_3 - 2M_2}{M_1 - M_3} \right|, \quad (21)$$

which ranges values from -1 to 1 . Positive values of c indicate that $\mathbf{M}$ is consistent with the tensile source model. In this case, the value of c also measures the tensility of the source: c close to 1 means highly extensive/compressive sources; c close to zero means the near-shear sources. Negative values of c indicate that $\mathbf{M}$ is inconsistent with the tensile source model. The absolute value of c measures the weight of the inconsistency. If c is close to -1 the inconsistency is strong, if c is negative but close to 0 the inconsistency is weak.

[20] An equivalent way to (19) is to decompose moment tensor $\mathbf{M}$ into the ISO, DC, and CLVD components and subsequently to calculate the ν_P/ν_S ratio according to Vavryčuk [2001, equation (14)]:

$$\frac{\nu_P}{\nu_S} = \sqrt{\frac{4}{3} \left(\frac{\text{ISO}}{\text{CLVD}} + 1 \right)}. \quad (22)$$

The standard value of the ν_P/ν_S ratio, $\nu_P/\nu_S = \sqrt{3}$, corresponds to $\text{ISO}/\text{CLVD} = 5/4$. The consistency coefficient defined in terms of the DC, CLVD and ISO reads

$$c = \text{sign} \left(\frac{\text{ISO}}{\text{CLVD}} \right) \left(1 - \frac{\text{DC}}{100} \right), \quad (23)$$

implying that the ISO and CLVD for tensile sources must be of the same sign. The consistency coefficients defined by equations (21) and (23) yield slightly different values but their basic properties are the same. Both definitions give positive values of c for tensile sources ranging between 0 and 1 .

[21] Equations (19) and (22) work with the highest accuracy for events with a high tensile component. For events with a low tensile component (“near-shear” events), their accuracy becomes lower. For pure shear events, equations (19) and (22) fail because they yield undefined expressions (ratios $0/0$).

4.2. Set of Tensile Sources

[22] Similarly as for the individual sources the analyzed data set must first be checked whether it is consistent with the model of tensile sources (see equations (21) or (23)). If

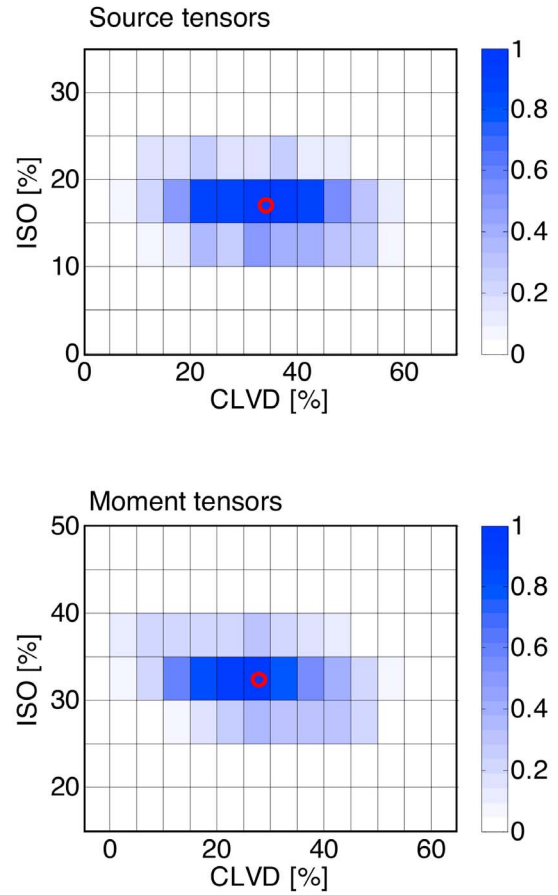


Figure 6. The probability distributions of the CLVD and ISO of the source and moment tensors contaminated by noise. Red circles show the CLVD and ISO percentages for the noise-free tensors. The probability is color coded and normalized to its maximum.

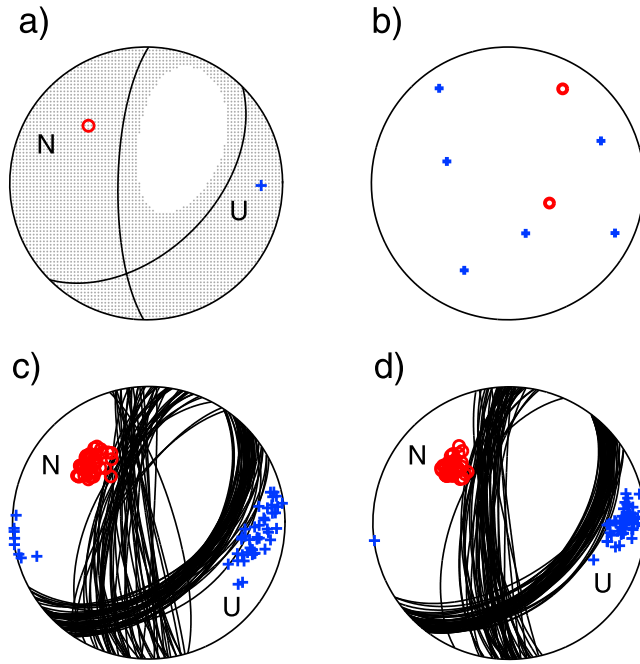


Figure 7. Linear and nonlinear inversions for a tensile source from noisy amplitudes: Coverage A. (a) True focal mechanism, (b) station configuration, (c) source lines with the U/N axes for the solutions obtained using the linear inversion from noisy amplitudes, and (d) source lines with the U/N axes for the solutions obtained using the nonlinear inversion from noisy amplitudes. The number of noise realizations was 50. The U/N axes define the direction of the dislocation vector and fault normal, respectively. Red circles and blue plus signs in Figure 7b denote the minus and plus P wave polarities at the respective stations.

the consistency criterion (20) is satisfied, an overall value of the ν_P/ν_S ratio in the focal area can be retrieved. For example, the ν_P/ν_S ratio can be calculated as the mean or median of the values obtained from equation (19) or (22) applied to the individual events. However, these formulas lose their accuracy for near-shear events when slope α is close to zero. Consequently, the accuracy of the overall ν_P/ν_S ratio can be very low. Therefore, it is more appropriate to apply more sophisticated approaches.

[23] First, Vavryčuk [2001] proposes the following formula for the overall ν_P/ν_S ratio of N events

$$\frac{\nu_P}{\nu_S} = \sqrt{\frac{4}{3} \left(\frac{\sum_1^N |\text{ISO}|}{\sum_1^N |\text{CLVD}|} + 1 \right)} \quad (24)$$

to suppress the errors in the ν_P/ν_S ratio calculated for the near-shear events.

[24] Second, since the ISO and CLVD are linearly dependent, the ν_P/ν_S ratio can be calculated using the linear regression between the ISO and CLVD constructed for all events. The regression line is forced to run through the origin of coordinates (ISO = 0, CLVD = 0); see Figure 5.

[25] Third, the overall ν_P/ν_S ratio can be inverted by applying the condition of the zero eigenvalue D_2 of source tensor $\mathbf{D}$, see equation (4). The misfit function in the inversion reads

$$\sum_1^N \left| \frac{D_2}{D_1 - D_3} \right| = \min, \quad (25)$$

being expressed in terms of the moment tensors and the ν_P/ν_S ratio:

$$\sum_1^N \left| \frac{M_2 - a \text{Tr}(\mathbf{M})}{M_1 - M_3} \right| = \min, \quad (26)$$

where

$$a = \frac{\lambda}{3\lambda + 2\mu} = \frac{(\nu_P/\nu_S)^2 - 2}{3(\nu_P/\nu_S)^2 - 4}. \quad (27)$$

The normalization by term $D_1 - D_3$ in (25) or by term $M_1 - M_3$ in (26) eliminates the dependence of the misfit on the source strength or on the scalar seismic moment of the individual events.

[26] The above formulas are valid for isotropic media. If the focal area is anisotropic, the ν_P/ν_S ratio might be directionally dependent. If we cannot treat a general anisotropic case using available observations [Vavryčuk, 2004], the anisotropy effects can be suppressed if the ν_P/ν_S ratio is studied for tensile sources with the same or similar strike, dip and rake angles.

5. Numerical Modeling

[27] In this section, the accuracy of the inversions for the parameters of tensile sources and for the ν_P/ν_S ratio in the focal area is tested numerically. The configuration of stations, velocity model and source locations are used to mimic the observations of microearthquakes in the West Bohemia/Vogtland region, the border area of the Czech Republic and Germany [Fischer *et al.*, 2010]. The focal area is at a depth of 10 km, the local seismic network homogeneously covers the focal sphere. The epicentral distances of the stations are up to 30 km. The velocity model is smooth and vertically inhomogeneous. The P wave amplitudes are inverted and the Green's functions are calculated using ray theory [Červený, 2001]. The sensitivity of the results to the number of stations used in the inversion is tested using two station configurations: Coverage A formed by 8 stations and Coverage B formed by 20 stations. The sensitivity of the results to noise in the data is tested using two noise levels: noise reaching 30% and 50% of the observed amplitude at the respective station. The noise distribution is uniform.

5.1. Inversion for Parameters of a Tensile Source

[28] The comparison of the linear and nonlinear inversions for parameters of a tensile source is shown for Coverage A in Figure 7 and for Coverage B in Figure 8. The focal mechanism is oblique normal with angles: $\phi = 45^\circ$, $\delta = 50^\circ$ and $\lambda = -45^\circ$. The source is extensive with slope α of 20° . The source planes form an angle of 70° . The ν_P/ν_S ratio in the focal area is 1.70. The DC, CLVD and ISO percentages

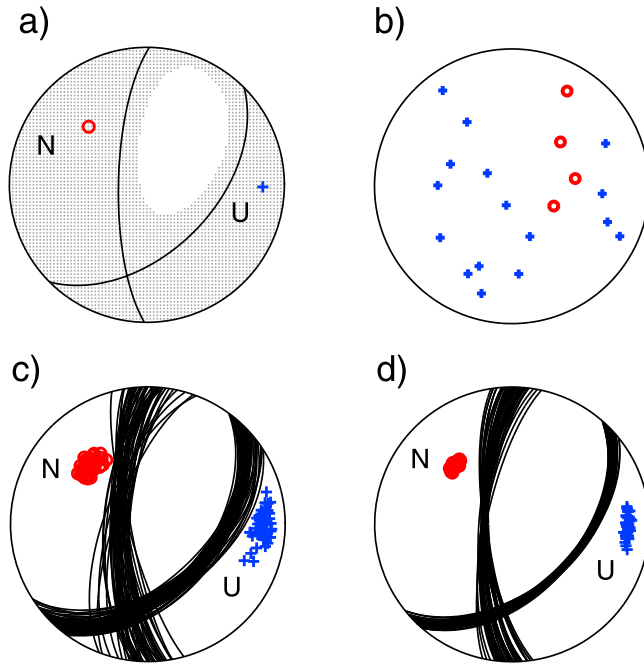


Figure 8. Linear and nonlinear inversions for a tensile source from noisy amplitudes: Coverage B. For details, see the caption of Figure 7.

of the moment tensor are 40%, 28% and 32%, respectively. The P wave amplitudes observed at the stations are contaminated by noise with a level of 50%. The inversion is performed for 50 random realizations of noise.

[29] Figures 7c and 8c show the results of the linear inversion. Figures 7d and 8d show the results of the nonlinear inversion. In the nonlinear inversion, the angles of the tensile source are calculated directly from the amplitudes, and the ν_P/ν_S ratio is fixed at the correct value of 1.70. The inverted focal mechanisms form clusters around the synthetic mechanism. The orientation of the fault plane is resolved with a higher accuracy than the orientation of the dislocation vector for both types of station coverage and in both inversions. The efficiency of the nonlinear inversion is higher than that of the linear inversion (see Table 1).

5.2. Inversion for the ν_P/ν_S Ratio

[30] In this section, the accuracy of the methods, presented in section 4.2., for calculating the ν_P/ν_S ratio in a focal area from a set of tensile sources is tested numerically. We assume 50 tensile sources at the same focus situated at a depth of 10 km. The focal mechanisms are oblique reverse with strike, dip, rake and slope randomly generated in the following intervals: $130^\circ < \phi < 180^\circ$, $40^\circ < \delta < 90^\circ$, $40^\circ < \lambda < 90^\circ$ and

$0^\circ < \alpha < 30^\circ$. We assume some theoretical value of the ν_P/ν_S ratio and calculate theoretical moment tensors. Subsequently, theoretical P wave amplitudes radiated from the sources are calculated at all stations and contaminated by noise to mimic real observations. The level of noise is alternatively 30% and 50%. The noisy amplitudes are inverted back for moment tensors using the linear inversion. The retrieved moment tensors are used to estimate the true value of the ν_P/ν_S ratio. To get statistically relevant results, the inversion for the ν_P/ν_S ratio is repeated for 100 realizations of noisy amplitudes. The whole procedure is performed for a set of theoretical ν_P/ν_S ratios to find out whether the accuracy of the inversion methods depends on the actual value of the ν_P/ν_S ratio used.

[31] Figure 9 shows the inverted ν_P/ν_S ratio as a function of the true ν_P/ν_S ratio for Coverage A and B and for noise levels 30% and 50%. The inversion is tested for a set of true ν_P/ν_S ratios in the range from 1.4 to 2.0 with a step of 0.025. Three inversion methods for the ν_P/ν_S ratio are tested. Method 1 is the inversion performed using equation (24). Method 2 calculates the ν_P/ν_S ratio using the linear regression between the CLVD and ISO (see Figure 5). Method 3 is the inversion based on equation (26). Figure 9 shows the calculated ν_P/ν_S ratios (blue dots, each dot corresponds to one noise realization), the true ν_P/ν_S ratio (red line), the average of the calculated ν_P/ν_S ratios obtained from 100 realizations of random noise (blue line), and the standard deviations of the calculated ν_P/ν_S ratios (dashed blue lines).

[32] The most accurate values of the ν_P/ν_S ratio are retrieved using Method 3. This method yields unbiased values for both types of station coverage and for both noise levels. The standard deviation of the ν_P/ν_S ratio is, however, slightly higher than that for the other two methods. Method 1 yields satisfactory results just for the dense station coverage (Coverage B) and low noise level. For sparse station coverage (Coverage A), the method yields biased results. Method 2 yields satisfactory results for all cases except for the combination of the sparse station coverage with high noise level. Interestingly, all methods work better for low ν_P/ν_S ratios. This tendency is even more visible for the sparse station coverage and high noise level.

[33] In conclusion, the tests indicate that the inversion for the ν_P/ν_S ratio is a data demanding procedure requiring good station coverage and high-quality data. For a configuration with 20 stations, the ν_P/ν_S ratio can be retrieved with an error of about ± 0.1 if a data set of 50 events with significant tensile components is analyzed.

6. Example: Microearthquakes in West Bohemia, Czech Republic

[34] The inversions for parameters of tensile sources and for the ν_P/ν_S ratio are exemplified on microearthquakes that

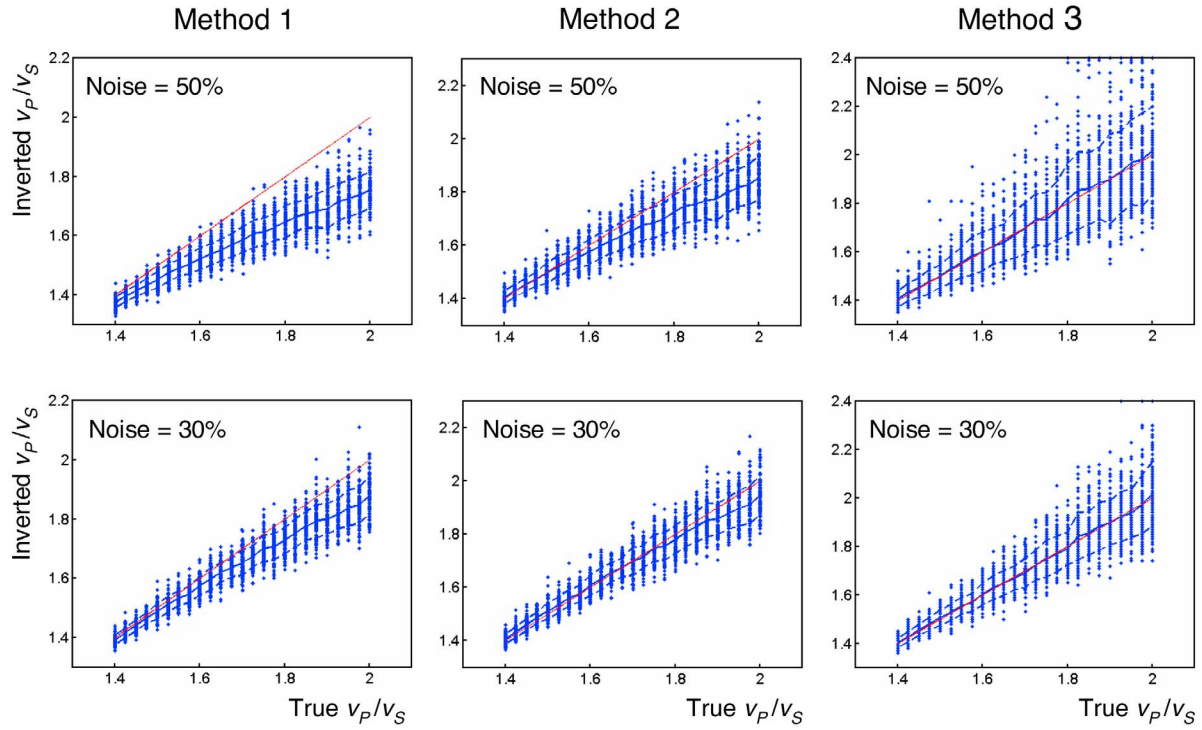
Table 1. Accuracy of the Linear and Nonlinear Inversions

Inversion Method	Station Coverage	δP^a (deg)	δT (deg)	δU (deg)	δN (deg)	δDC (%)	$\delta CLVD^b$ (%)	δISO^b (%)
Linear	A	8.4	9.2	12.7	5.3	9.8	9.9	2.6
Nonlinear	A	5.4	7.9	8.8	5.0	3.7	1.7	2.0
Linear	B	5.2	4.9	7.1	4.5	6.1	6.9	2.4
Nonlinear	B	2.9	2.9	3.8	1.8	2.6	1.2	1.4

^aSymbol δ stands for the standard deviation calculated from 50 realizations of random noise.

^bNote that the error of the compensated linear vector dipole (CLVD) is not necessarily higher than the isotropic (ISO), if the nonlinear inversion is applied.

Coverage A



Coverage B

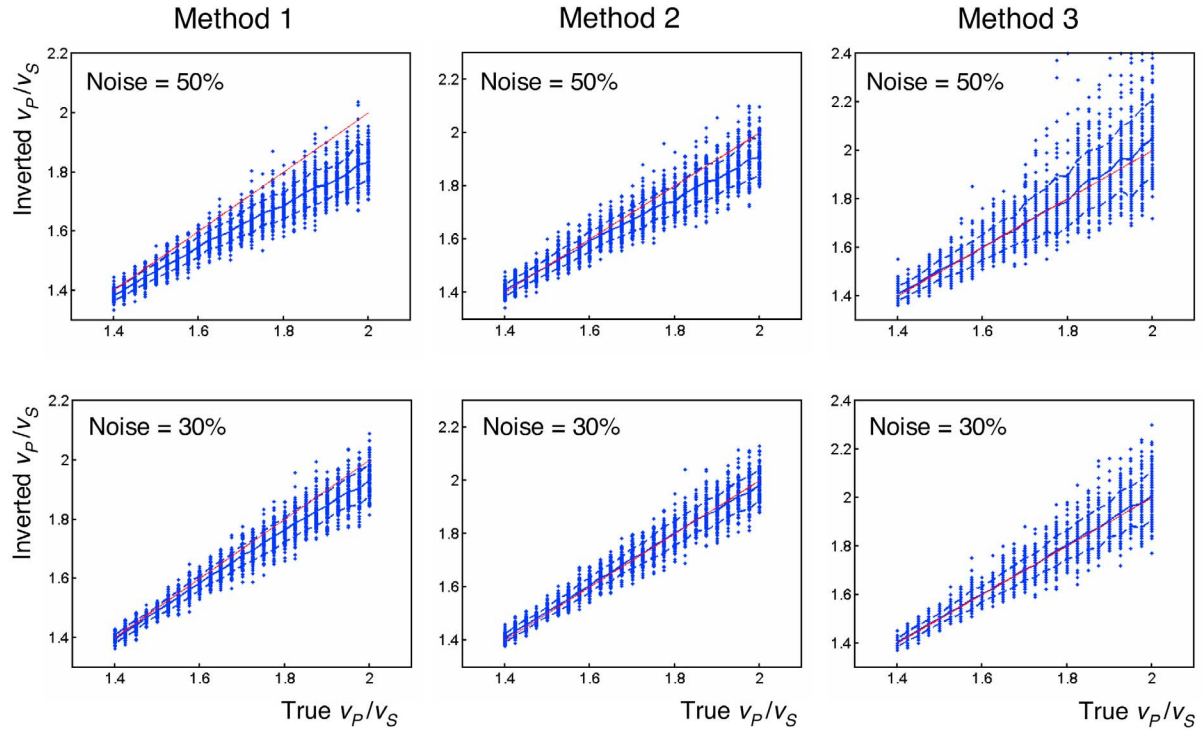


Figure 9. Inversion for the ν_p/ν_s ratio using three methods. Blue dots denote the ν_p/ν_s ratios calculated in individual inversions. Red lines denote the true ratio. Blue lines denote the mean retrieved ratio calculated from 100 repeating inversions of moment tensors of 50 tensile sources inverted from noisy amplitudes. Dashed lines show the limits of the standard deviations of the retrieved ratio.

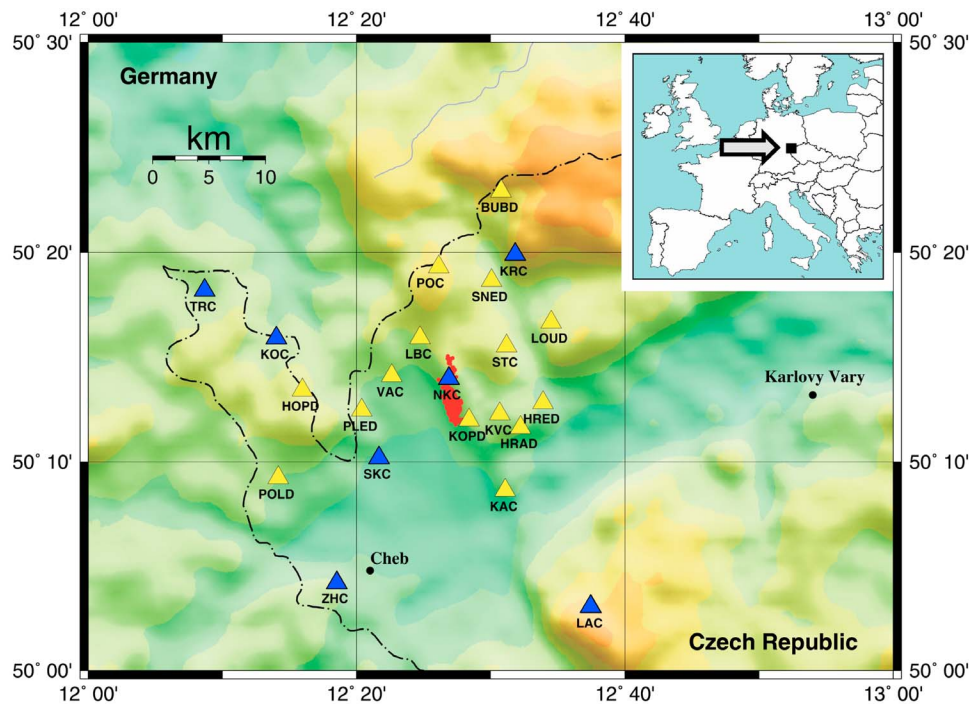


Figure 10. Topographic map of the West Bohemia/Vogtland region. The epicenters of the swarm earthquakes are marked by red circles. The WEBNET stations are marked by triangles: the blue triangles mark the stations operated in 1997 and 2008; the yellow triangles mark additional stations operated in 2008. The dashed-dotted line shows the border between the Czech Republic and Germany.

occurred in the West Bohemia/Vogtland region in the 1997 and 2008 swarms.

6.1. Seismic Activity in West Bohemia

[35] The West Bohemia region is the most seismically active region in the Bohemian Massif [Babuška *et al.*, 2007] with active tectonics being manifested by mineral springs, emanations of CO₂, presence of Tertiary or Quaternary volcanism and by frequent occurrence of earthquake swarms. The most prominent earthquake swarms occurred recently in 1985/1986, in 1997 [Vavryčuk, 2002], in 2000 [Fischer and Horálek, 2003] and in 2008 [Fischer *et al.*, 2010]. Their duration was from 2 weeks to 2 months and the activity was focused typically at depths ranging from 7 to 12 km at the focal area called the Nový Kostel focal zone (see Figure 10). The strongest instrumentally recorded earthquake was the M 4.6 earthquake on 21 December 1985.

[36] The January 1997 earthquake swarm lasted for two weeks and involved about 1800 microearthquakes with magnitudes higher than -0.5 . The strongest event was of magnitude 3.0. The hypocenters clustered within a very small volume of probably less than 1 km³ at a depth of about 9 km [Fischer and Horálek, 2000]. The 2008 October earthquake swarm was more extensive. It occurred at the same epicentral area but at depths ranging from 7 to 11 km [Fischer *et al.*, 2010]. It lasted for four weeks and involved about 25,000 microearthquakes with magnitudes higher than -0.5 . The largest earthquake had a magnitude of 3.7.

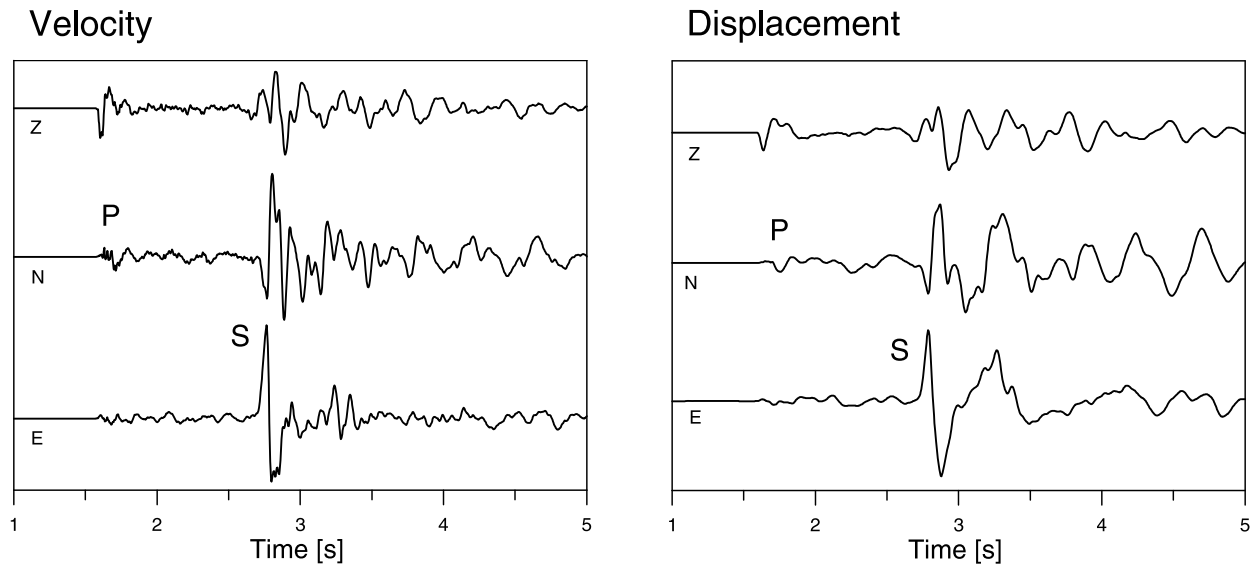
[37] Three differently oriented fault systems identified by clustering of foci and by focal mechanisms were active during the 1997 and 2008 swarms. The majority of events of

the 2008 swarm occurred along the principal fault oriented nearly in the N-S direction with strike of 169° [Vavryčuk, 2011]. This fault is characterized by occurrence of oblique left-lateral strike slips with a normal component. The other principal fault oriented in the WNW direction with strike of 304° was activated in the 1997 and 2008 swarms [Vavryčuk, 2002, 2011] displaying oblique right-lateral strike-slip mechanisms with a normal component. This fault was more active in 1997 than in 2008, when only a small portion of events occurred along this fault. The other fault active in 1997 was oriented in the N-E direction with strike of 39° with oblique left-lateral strike slips with a reverse component. In contrast to the two principal faults, optimally oriented with respect to the tectonic stress in this region, this fault is remarkably misoriented. The maximum compressive stress in the region determined from the focal mechanisms has an azimuth of N146°E [Vavryčuk, 2011].

6.2. Data and the Moment Tensor Inversion

[38] The microearthquakes were recorded by local seismic network WEBNET (Figure 10) of three-component short-period stations surrounding the swarm epicenters [Fischer *et al.*, 2010]. The network consisted of 7 stations in 1997 and of 22 stations in 2008. The sampling frequency was 250 Hz. The stations are installed mostly on hard rock with no sedimentary cover. The records are typically simple with clear P and S wave onsets (see Figure 11, left-hand plots). To suppress noise, the velocity records were filtered by a band-pass filter with corner frequencies of 1 Hz and 35 Hz and integrated into the displacement records (see Figure 11, right-hand plots). The maximum amplitudes of the direct P waves

a)



b)

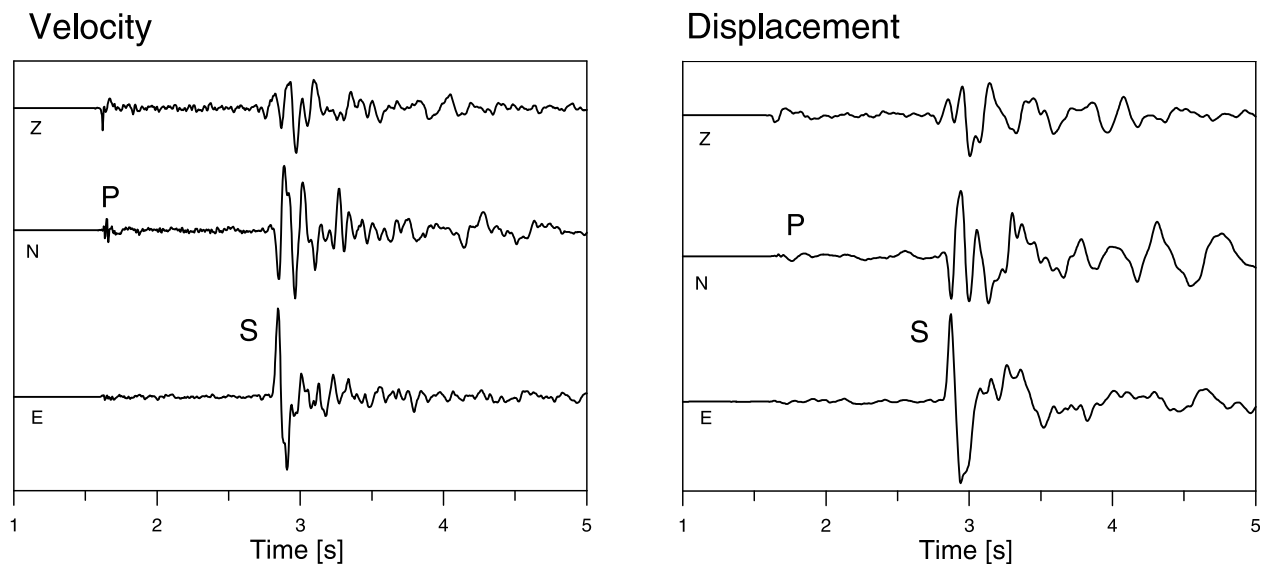


Figure 11. Velocity and displacement records of M 3.7 earthquake of (a) 14 October 2008 at 19:00:33 and of M 3.0 earthquake of (b) 14 October 2008 at 04:01:36. The records of the NKC station are displayed.

(in 2008) or of the direct P and S waves (in 1997) were measured and inverted for the full moment tensors [Horálek et al., 2000; Vavryčuk, 2011]. The Green's functions were calculated using ray theory. The velocity model was vertically inhomogeneous with a smoothly varying velocity gradient. The reliability of the moment tensors was assessed by calculating the root-mean-square (RMS) difference between the synthetic and observed amplitudes. The stability of the inversion and the accuracy of the moment tensors were tested by repeating the inversions using randomly generated noisy input data.

6.3. Parameters of Tensile Sources

[39] The parameters of the tensile sources were calculated for 38 events of the 1997 swarm and for 71 events of the

2008 swarm having the most accurate moment tensors. Since the non-DC components in moment tensors of the 2008 events were mostly very small, the selection process of the highly accurate moment tensors was particularly important. Therefore, the target moment tensors of the 2008 events were inverted from amplitudes of 20 stations or more. In order to suppress the effects of anisotropy in the focal area, we analyzed the moment tensors with a uniform focal mechanism corresponding to the principal focal mechanism in this region with angles: $\phi = 169^\circ$, $\delta = 68^\circ$, and $\lambda = -44^\circ$ [Vavryčuk, 2011]. The high accuracy of the target moment tensors was achieved by imposing the following constraints. The normalized RMS error had to be less than 0.25. The mean deviation between the P/T axes from noise-free and noisy

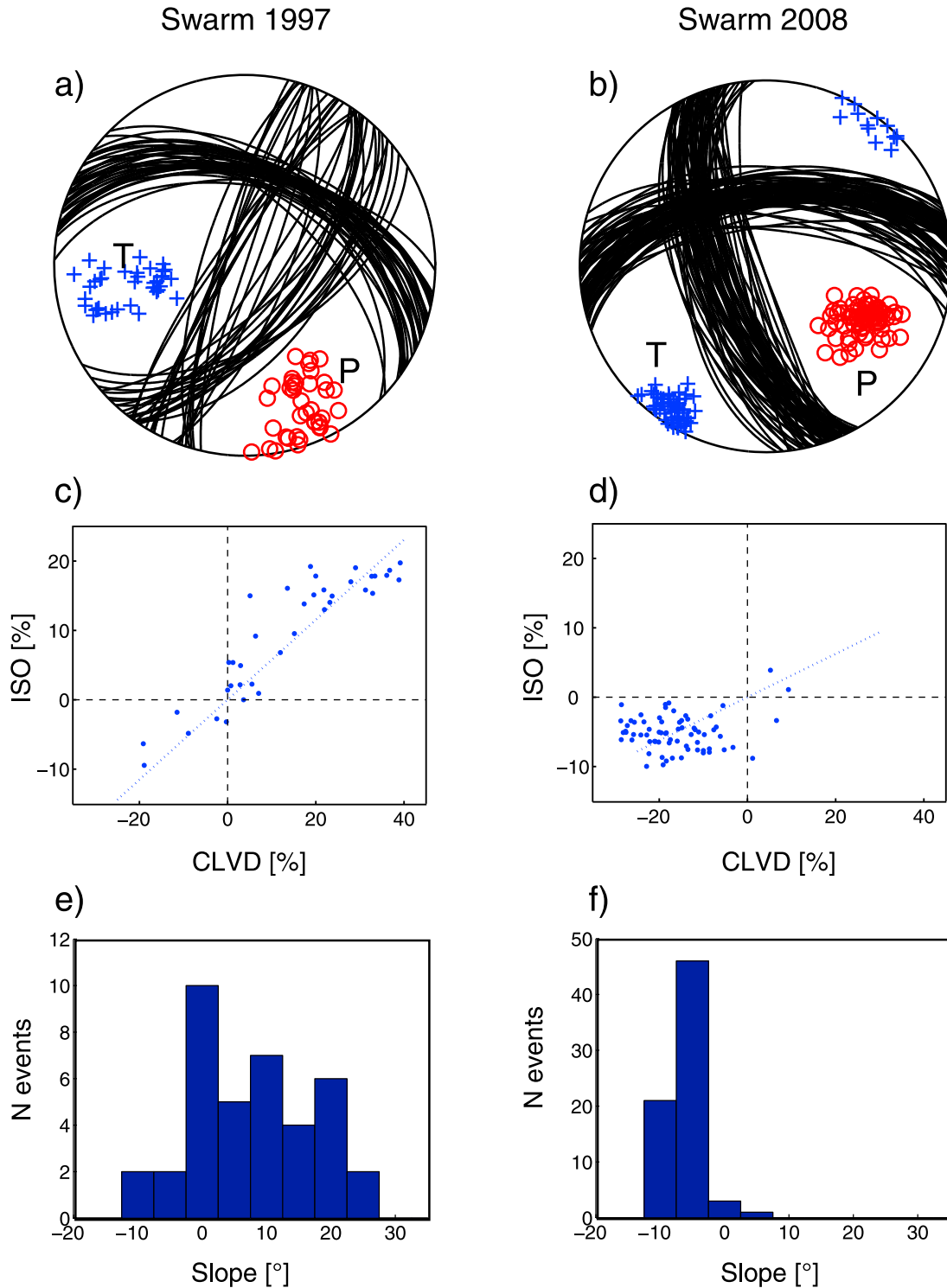


Figure 12. (a, b) Nodal lines and P/T axes, (c, d) non-DC components and (e, f) histograms of slopes for 1997 and 2008 swarm microearthquakes. The blue dotted line in the CLVD-ISO plots corresponds to the optimum ν_P/ν_S ratio obtained from the inversion of moment tensors.

amplitudes had to be less than 4° . Finally, the standard deviation of the ISO and CLVD percentages of the moment tensors retrieved from the noisy amplitudes had to be less than 3% and 6%, respectively.

[40] The focal mechanisms together with the non-DC components of the selected events are shown in Figure 12.

The behavior of the non-DC components is different for both swarms. The 1997 events contain predominantly positive and rather high ISO and CLVD, while the 2008 events are mostly low and negative. The consistency criterion (20) is satisfied for almost all events of the both data sets. This indicates that the model of the tensile source might be

Table 2. Non-Double-Couple Components and the ν_P/ν_S Ratio for the 1997 and 2008 Swarm Earthquakes^a

Data Set	Number of Events	Mean c_1	Mean c_2	Mean CLVD (%)	Mean ISO (%)	ν_P/ν_S -Method 1	ν_P/ν_S -Method 2	ν_P/ν_S -Method 3
1997	38	0.16	0.28	13.7	9.3	1.48	1.48	1.45
2008	71	0.14	0.22	−16.0	−5.3	1.33	1.36	1.32

^aQuantities c_1 and c_2 are the consistency parameters defined in equations (21) and (23), respectively.

adequate for the data under study. The ν_P/ν_S ratio calculated using the three methods proposed in section 4.2 and tested in section 5.2 is listed in Table 2. Figure 12 finally shows the histograms of the slope angle α calculated using equation (18). The 1997 events cover a broad range of slopes mostly from -5° to 20° . The 2008 events are rather uniform having slightly negative values of slope around -5° .

6.4. Interpretation of Results

[41] The striking difference in behavior of the non-DC components in the 1997 and 2008 earthquakes is likely to be caused by differently orientated fault systems activated in these swarms. The principal faults with strike of 169° (active in the 2008 swarm) and with strike of 304° (active in both 1997 and 2008 swarms) are optimally oriented with respect to the tectonic stress [Vavryčuk, 2011]. Therefore, they are associated with predominantly shear faulting with a weak compressive component. However, in contrast to the 2008 swarm, another fault with strike of 39° was activated in the 1997 swarm which is misoriented with respect to the tectonic stress and is associated with extensive tensile faulting.

[42] Since the focal mechanisms on the principal faults are not pure shear but slightly compressive, we can deduce that the rock inside the fault is weak and prone to compaction. The extensive focal mechanisms on the misoriented fault might indicate local overpressure of fluids on this fault.

[43] Anomalous low values of the ν_P/ν_S ratio retrieved from moment tensors (see Table 2) point to anomalous rheology related to highly fractured rocks in the focal zone. Since the non-DC components cover higher span of values in the 1997 swarm, the ν_P/ν_S ratio retrieved for this data set should be viewed as more reliable. The low ν_P/ν_S ratio has been detected also in other seismically active areas [Fojtíková *et al.*, 2010]. Note that the retrieved ν_P/ν_S ratio corresponds just to the fault systems activated in the studied swarms. Other, differentially oriented faults may display other values of the ν_P/ν_S ratio because the focal area might be anisotropic [Vavryčuk and Boušková, 2008]. Seismic anisotropy can also affect the mean value of the CLVD and ISO [Vavryčuk, 2004; Vavryčuk *et al.*, 2008], and subsequently, the mean value of the slope angle.

7. Conclusions

[44] The geometry of tensile sources is described by four angles: strike, dip, rake and slope. The strike, dip and rake are determined ambiguously from moment tensors similarly as for shear sources. The slope angle is determined uniquely having the same value for both complementary solutions. Since the tensile source is described by four angles, plotting its focal mechanism is more involved. Plotting the standard nodal lines is cumbersome, because their relation to the geometry of the tensile sources is not straightforward. The tensile sources can be graphically represented by plotting

source lines on the focal sphere. One of the source lines defines the fault plane, the other defines the auxiliary plane, which is normal to the dislocation vector. In general, the source lines do not correspond to the nodal lines except for the shear sources.

[45] The tensile sources are characterized by significant non-DC components in moment tensors. The accuracy of the DC, CLVD and ISO percentages is, however, different. Usually, the ISO is determined with the highest accuracy. The accuracy of the CLVD and DC is usually at least twice lower. Therefore, the interpretations based on the evaluation of the ISO component are more reliable.

[46] The tensile model can be tested whether it describes the observed data adequately or not. In isotropic media, the CLVD and ISO calculated from the moment tensors should depend linearly and should be of the same sign. The direction of the linear function between the CLVD and ISO defines the ν_P/ν_S ratio in the focal area. If the non-DC components are of another origin then their properties should be different. For example, rupturing on a nonplanar fault produces no ISO component, and anisotropy in the focal area produces ISO and CLVD with generally inconsistent signs and uncorrelated values [Vavryčuk, 2005].

[47] The parameters of tensile earthquakes can be retrieved from the moment tensors of the individual events. A more accurate approach, however, is to invert for parameters of tensile earthquakes directly from data using a constrained nonlinear inversion. The parameter space can be limited by fixing the ν_P/ν_S ratio, or forcing the ν_P/ν_S ratio to lie within some physically reasonable limits.

[48] The most accurate method for calculating the ν_P/ν_S ratio in the focal area is the inversion of a set of moment tensors of earthquakes that occurred in the same focal area. The inversion minimizes the eigenvalue D_2 of source tensor **D**. This approach can be generalized to be applicable to anisotropic media. The retrieved value of the ν_P/ν_S ratio is not directly related to rheology at the fault but rather to properties of rocks surrounding the fault. The calculation of the ν_P/ν_S ratio from moment tensors might find applications in tomography of the focal area or in monitoring fluid flow during seismic activity. Its value determined from moment tensors of real earthquakes is usually rather low pointing probably to highly fractured rocks in the focal area.

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