



RESEARCH ARTICLE

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Mapping Stress and Fluids on Faults by Nonshear Earthquakes

Key Points:

- Nondouble-couple moment tensors (MTs) show patches of compressive/tensile fracturing along the fault
- Tensile fracturing detected by MTs is produced by interaction of tensile fault steps
- Tensile patches on the fault serve as pathways for fluid escapes from the focal zone

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Abstract Fluids on faults facilitate triggering of earthquakes and affect seismic energy release. Their detection in the focal zone is, however, difficult. Here, we present mapping of stress changes and fluid flow based on determining seismic moment tensors (MTs), which describe focal mechanisms and shear/tensile/compressive fracturing modes of earthquake sources. We calculate highly accurate MTs of 4,500 microearthquakes that occurred in the West Bohemia swarm region in the period of 2008–2018. The extent and quality of the moment tensor data are unique and allow us to study detailed behavior of the nondouble-couple (nonDC) components of MTs along the fault. The nonDC components were mostly zero or negative and indicated shear/compressive fracturing. However, also a patch with positive nonDC components, indicating tensile fracturing, was revealed. The inversion for stress and modeling of the Coulomb stress change confirmed that this patch is under anomalous stress conditions. Tensile fractures in the patch were opened due to interaction of tensile fault steps and filled by overpressurized fluids. Hence, evaluating nonDC components of earthquakes might help for tracing stress variations and fault interactions, identifying pathways of fluids and locating areas with overpressure prone to being activated.

1. Introduction

Knowledge of tectonic stress, fault geometry, rheological properties of rocks and presence of fluids in the focal zone is essential for understanding earthquakes and their sequences in seismically active regions. Faults are complex systems with subfaults or fault segments of various lengths and shapes, which mutually intersect or form fault step overs (Fossen & Rotevatn, 2016; Micklethwaite et al., 2015). Fault irregularities, fault steps and fault tips become stress concentrators and interact under the stress field (Crider & Pollard, 1998; Lin & Stein, 2004; Madden et al., 2013) producing damage zones (Kim et al., 2004), and a large variety of seismic energy release such as background and clustered seismicity including foreshocks, mainshock-after-shocks or earthquake swarms (Mogi, 1963). Tectonic stress and fluids also control creation or reactivation of faults and their fracturing mode (Sibson, 1992; Vavryčuk & Hrubcová, 2017).

A detailed geometric description of complex fracturing is provided by seismic moment tensors (MTs), which characterize rupturing mode on all scales: from acoustic emissions to large-size earthquakes. The MTs consist of double-couple (DC) components, representing shear focal mechanisms, and nondouble-couple (nonDC) components. According to the commonly used decomposition, the nonDC components consist of isotropic (ISO) and compensated linear vector dipole (CLVD) components (Jost & Hermann, 1989; Julian et al., 1998; Knopoff & Randall, 1970). The DC components are prevailing, but the nonDC components are also frequently detected. The nonDC components are produced, for example, by a collapse of cavities in mines (Šílený & Milev, 2008), by shear faulting on irregular faults (Frohlich, 1994; Zahradník et al., 2008), by seismic anisotropy in the focal zone (Menke & Russell, 2020; Šílený & Vavryčuk, 2000, 2002; Vavryčuk, 2006) or by tensile faulting (Vavryčuk, 2011a), when faults are opening due to fluid injection in volcanic or geothermal regions (Miller et al., 1998). While opening of fractures is associated with positive ISO and CLVD, the negative ISO and CLVD can originate in closure of fractures due to compaction of fault gouge during rupturing (Vavryčuk & Hrubcová, 2017). Hence, the sign of the nonDC components is an indicator of tensile/compressive fracture mode along a fault (Vavryčuk, 2015).

Orientation of tectonic stress is usually determined from focal mechanisms of earthquakes. If focal mechanisms of many earthquakes are known, they can be inverted for principal stress axes and for the stress ratio $R = (\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$, where σ_1 , σ_2 , and σ_3 are the maximum, intermediate and minimum principal stresses

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(Michael, 1987; Vavryčuk, 2014). If earthquakes cover densely a fault for periods of activity before and after a large earthquake, groups of focal mechanisms belonging to the same cell or time period can be inverted to map the spatiotemporal variations of stress in the focal zone (Hardebeck & Michael, 2006; Vavryčuk, 2006; Vavryčuk & Adamová, 2018; Yu et al., 2018). However, the stress inversion is a data demanding method, when tens or hundreds of focal mechanisms are needed in each individual cell to get reliable results. Moreover, the stress inversion is rather insensitive to changes in the stress regime (tensile/compressive), because only a deviatoric part of the stress tensor is inverted.

In this paper, we propose a method of detecting changes in the stress regime along a fault by employing nonDC components of MTs. Since the nonDC components are sensitive indicators of a tensile/compressive fracturing mode, their variation should correlate with the tensile/compressive stress regime closely associated with presence of fluids on a fault. We test this idea on a high-quality data set from abundant seismicity in West Bohemia, Czech Republic, observed in the period of 2008–2018. We map high-resolution fault geometry by double-difference locations and trace a detailed variation of nonDC components along the fault. We find changes in the fracture mode that are correlated with a spatial variation of stress determined by the standard stress inversion and by modeling of the Coulomb stress change.

1.1. West-Bohemia Swarm Area

The West Bohemia region is a seismically active area with a frequent occurrence of earthquake swarms (Figure 1). The seismicity covers an area $40 \times 50 \text{ km}^2$, but the most prominent earthquake swarms are located within the $3 \times 12 \text{ km}^2$ of the Nový Kostel focal zone (Čermáková & Horálek, 2015; Fischer et al., 2014). This zone is elongated in the NNW-SSE direction (Figure 1a) and foci of microearthquakes are at depths from 6 to 11 km. The earthquake swarms last typically from several days to several months and consist of thousands of microearthquakes, which rarely exceed a local magnitude ML of 4.0. The strongest earthquake instrumentally recorded in this area was the ML 4.6 earthquake that occurred on December 21, 1985.

The area is geodynamically active being characterized by Tertiary and Quaternary volcanism associated with mineral springs, CO₂ emanations, and dry and wet mofettes (Brauer et al., 2018; Hrubcová et al., 2017; Kaempfer et al., 2013). The tectonic structure of the area is formed by two perpendicular fault systems: the Ore Mountain WSW-ENE fault and the Mariánské Lázně NW-SE fault. Recent seismic activity is, however, associated with a system of left-lateral, strike-slip faults in the NNW-SSE direction, which bound the Cheb Basin, filled by sediments up to 300 m thick, and with small echelon right-lateral, strike-slip faults in the WNW-ESE direction. Both recently active fault systems are optimally oriented for shearing with respect to the regional stress, with the azimuth of the maximum compression (SHmax) ranging between 130° and 145°.

The seismicity is monitored by local seismic stations of the West Bohemia Network (WEBNET), see Figure 1b. The WEBNET network consists of 23 three-component stations with the sampling frequency of 250 Hz. All stations are within 25 km from epicenters and station NKC is just above the foci. The stations cover the area with no significant azimuthal gaps. The magnitude threshold of completeness of the earthquake catalog based on the WEBNET observations is about -0.3 (Fischer et al., 2010).

Five major earthquake sequences occurred in the West Bohemia region during the period of 2008–2018: in 2008, 2011, 2014, 2017, and 2018 (Figures 1e and 2). All of them are typical swarm-like sequences except for the activity in 2014, which was anomalous and resembled according to the Bath's law (Bath, 1965) a main-shock-aftershock sequence (Hainzl et al., 2016; Jakoubková et al., 2017; Vavryčuk & Adamová, 2018). The 2014 activity consisted of three distinct phases with a strongest event of each phase having magnitude larger by more than one unit than the other events (Figure 2c). All observed sequences in 2008–2018 differ in their duration, in the number of phases of intense seismicity and in the microearthquake productivity (Figure 2). The strongest event in this period appeared in 2014 with magnitude ML of 4.2.

The double-difference locations of the microearthquakes were obtained by the cross-correlation of waveforms and have an accuracy of 25 m in the horizontal directions and 75 m at depth (Bouchaala et al., 2013). The locations reveal rather complex geometry of the fault system (Jakoubková et al., 2017; Vavryčuk & Adamová, 2018; Vavryčuk et al., 2013), when individual seismic sequences activated different fault segments (Figure 1d and 1e). In general, the seismicity migrated from south to north. This refers namely to the 2008,

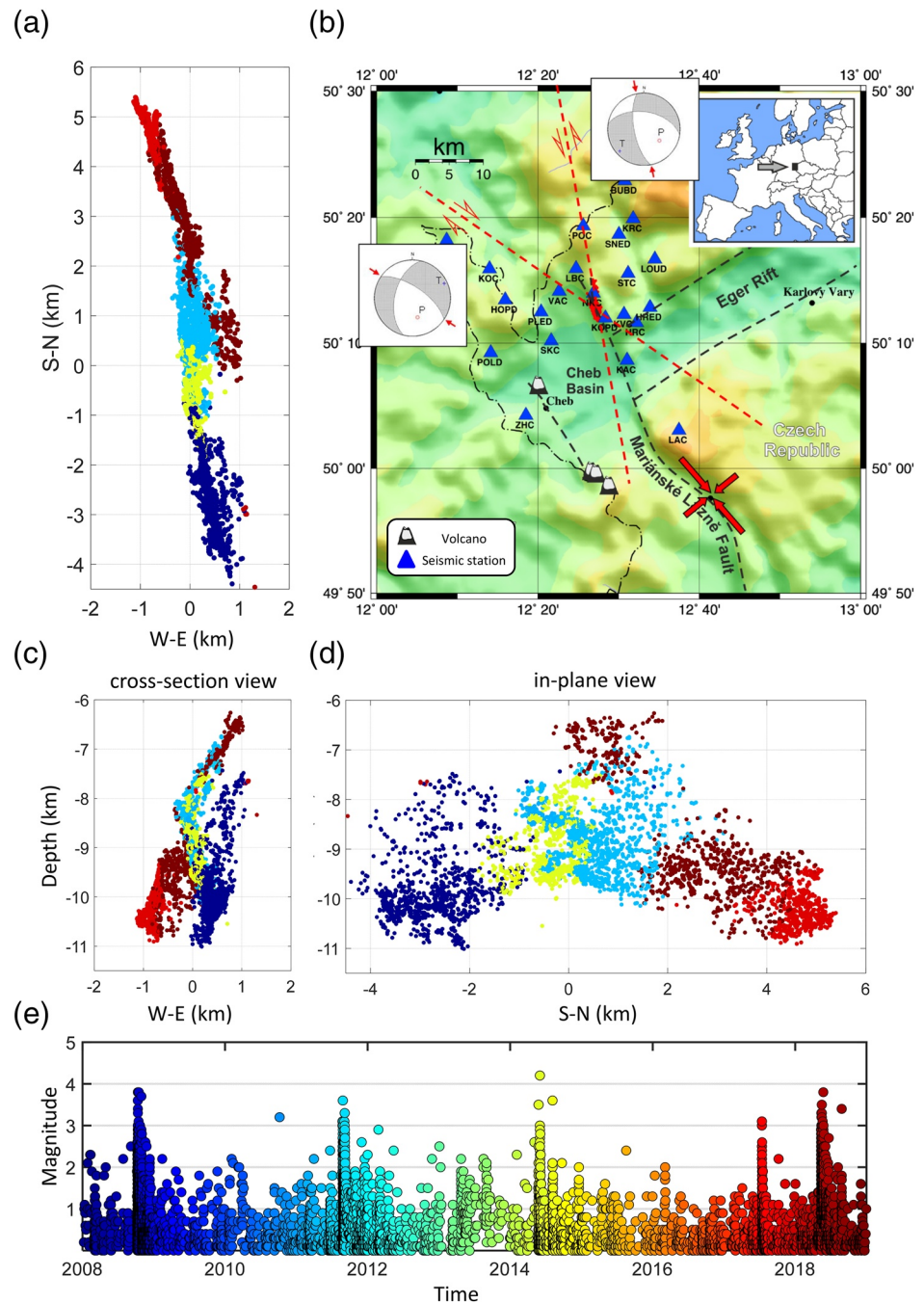


Figure 1. (a) Double-difference locations of earthquakes with local magnitude $M_L \geq 0.5$ in the period of 2008–2018 in the map view, (b) map of the West Bohemia seismoactive region, (c) cross-section view, (d) in-plane view, and (e) the magnitude-time plot of activity in the period of 2008–2018. The individual activity periods are color coded according to time: 2008 – dark blue, 2011 – light blue, 2014 – yellow, 2017 – red, and 2018 – brown. The blue triangles in (b) show the West Bohemia Network (WEBNET) stations and the red dots the locations of earthquakes. The black dashed lines indicate the main tectonic lines; the red dashed lines indicate the strikes of the active faults. The red full arrows mark the maximum and minimum compressions. The border between Germany and Czech Republic is indicated by the dashed-dotted line. The Quaternary volcanoes in the area are marked by cones. The insets show the position of the area in Europe and two typical focal mechanisms in the area.

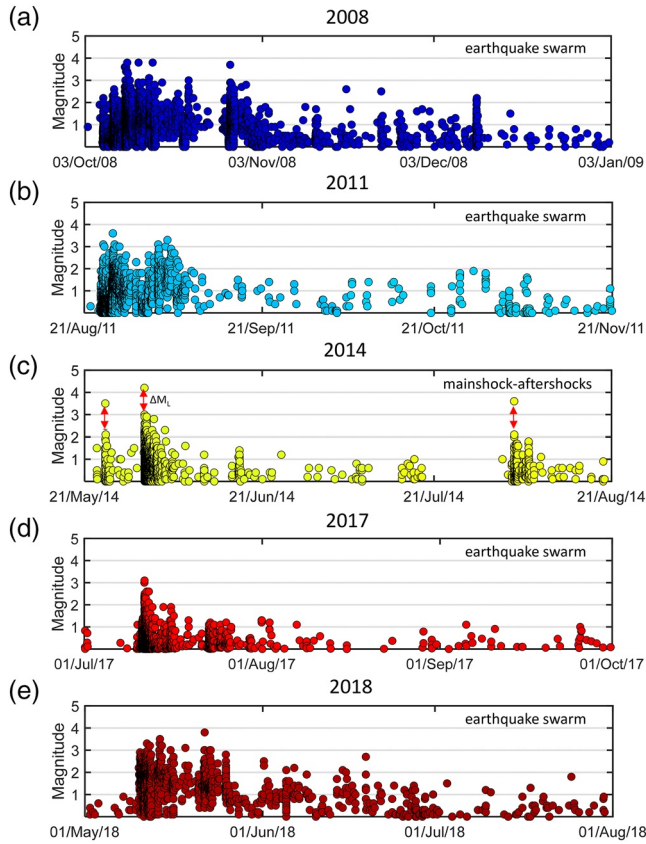


Figure 2. Magnitude-time plots of the (a) 2008, (b) 2011, (c) 2014, (d) 2017, and (e) 2018 seismic sequences. ΔM_L (red arrows in panel c) denotes the magnitude difference between the strongest and second strongest events in the three phases of the 2014 activity. The value of $\Delta M_L > 1$ indicates a mainshock-aftershock sequence rather than an earthquake swarm (Bath, 1965). Such magnitude gaps between the two strongest events are missing in the other seismic sequences.

2011, and 2017 swarms. These swarms progressively activated three isolated fault segments with a similar orientation but with offsets and gaps between them. Moreover, the subfault activated during the 2011 swarm was sharply bent in dip in its lower part. The barrier between the patches active in 2008 and 2011 was broken during the 2014 activity, and a gap between patches active in 2011 and 2017 was filled by a seismicity during the 2018 swarm. The whole fault system has an average strike of 170° and dip of 75° but some parts significantly deviate from this direction. Apart from the main fault, there are a few minor echelon fault segments with strike of 305° and dip of 65° at the deepest part of the fault—visible in the vertical sections (Figure 1d—blue dots at depth of 10.5–11 km).

1.2. NonDC Components of MTs

The inversion for MTs of microearthquakes is challenging, because: (1) the waveforms are noisy, complex, and of high frequency and (2) the datasets comprise thousands of microearthquakes, which need an automated processing. We use the inversion method proposed by Vavryčuk et al. (2017), based on the principal component analysis (PCA), see Figure 3. The method extracts a common wavelet from all vertical components of direct P waves recorded at seismic stations; effective P-wave amplitudes are determined by matching this wavelet with individual recorded traces. The obtained amplitudes are inverted for the MTs using the Green's functions calculated by the ray method. The method is fast, robust, and rather insensitive to seismic noise. Since the PCA method applies time shifting using cross-correlation of waveforms when constructing the common wavelet, the errors due to inaccurate locations and inaccurate velocity model are reduced.

The MTs are further decomposed into the DC and nonDC components. We use the commonly used moment tensor decomposition, which was originally proposed by Knopoff and Randall (1970). The moment tensor $\mathbf{M}$ is diagonalized and further restructured to form three basic types of a source: the isotropic (ISO) and DC sources, which have a clear physical interpretation, and the CLVD source, which is needed for the decomposition to be mathematically complete. The ISO, CLVD and DC components of $\mathbf{M}$ are denoted as M_{ISO} , M_{DC} and M_{CLVD} and expressed as follows:

$$M_{\text{ISO}} = \frac{1}{3}(M_1 + M_2 + M_3), \quad (1)$$

$$M_{\text{CLVD}} = \frac{2}{3}(M_1 + M_3 - 2M_2), \quad (2)$$

$$M_{\text{DC}} = \frac{1}{2}(M_1 - M_3 - |M_1 + M_3 - 2M_2|), \quad (3)$$

where M_1 , M_2 , and M_3 are ordered eigenvalues of moment tensor $\mathbf{M}$, $M_1 \geq M_2 \geq M_3$. The relative scale factors C_{ISO} , C_{DC} , and C_{CLVD} expressed in percentages are defined as:

$$\begin{bmatrix} C_{\text{ISO}} \\ C_{\text{CLVD}} \\ C_{\text{DC}} \end{bmatrix} = \frac{1}{M} \begin{bmatrix} M_{\text{ISO}} \\ M_{\text{CLVD}} \\ M_{\text{DC}} \end{bmatrix}, \quad (4)$$

where M reads

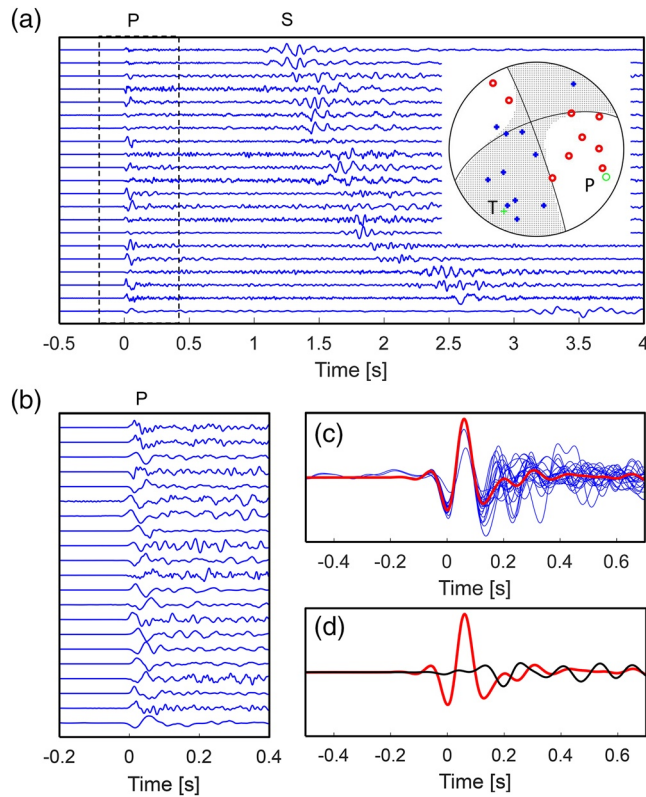


Figure 3. Principal component analysis (PCA) moment tensor inversion of the ML 2.1 earthquake on May 24, 2014 at 16:14:30. (a) Whole velocity records; (b) aligned P waves in the time window defined by dashed lines in panel (a); (c) the P waves traces (blue lines) and their common wavelet (red line); (d) the first principal component (red line) representing the common wavelet and the second principal component (black line) representing dissimilarities and noise in waveforms. P traces in panel (c) are normalized and plotted according to the polarity of the common wavelet. The inset in panel (a) shows the focal mechanism and positions of stations on the focal sphere (red circles – negative P-wave polarities, blue plus signs – positive P-wave polarities). The P/T axes are marked by the green circle and plus sign, respectively.

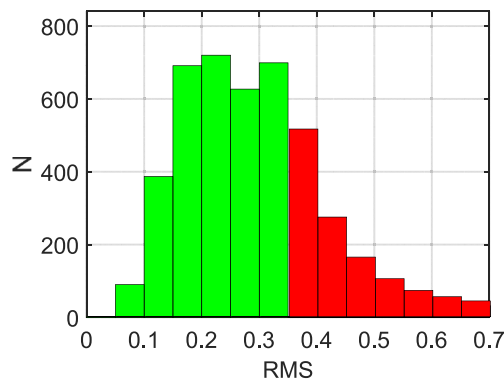


Figure 4. The histogram of root mean squares (RMS) of 4,496 moment tensors (MTs) calculated using the PCA based MT inversion. The 3,499 most accurate MTs were selected to have RMS lower than 0.35. All selected microearthquakes were recorded at least by 18 stations.

$$M = |M_{\text{ISO}}| + |M_{\text{CLVD}}| + M_{\text{DC}}. \quad (5)$$

Equations 1–5 imply that C_{DC} is always positive and in the range from 0 to 1; C_{CLVD} and C_{ISO} are in the range from –1 to 1. Let us emphasize that the above described moment tensor decomposition is unique and free of any ambiguity. For other details, see Vavryčuk (2015).

We calculated MTs of 4,496 microearthquakes with accurate double-difference locations (see Figure 1). We further selected 3,499 MTs of earthquakes recorded at least by 18 stations and with the normalized root mean square (RMS) difference between theoretical and predicted amplitudes less than 0.35 (see Figure 4). The MTs were classified by applying the k -means clustering algorithm (Jain, 2010), which finds clusters in the data space by minimizing variances of data within the predefined number of clusters. We classified the data into three clusters, each cluster being defined by its centroid (see Figure 5, Table 1). The cosine distance (Cesca et al., 2014; Vavryčuk et al., 2017; Willemann, 1993) was used to measure mutual differences between the MTs in the clustering procedure. This definition of distance is different from the frequently applied Kagan angle (Kagan, 1991), which is applicable to the DC MTs only.

The most frequent focal mechanisms (Figure 5, red color) correspond to the main activated fault. All three types of the focal mechanisms represent centroids of the clusters and are well oriented for shearing with respect to the background stress. Classifying the focal mechanisms into three clusters appeared as optimum, because a more detailed clustering produced additional centroid mechanisms quite similar to the three original focal mechanism types.

The MTs also contain nonnegligible nonDC components (Figure 6). Their variation along the fault is not random but displays systematic trends. Both ISO and CLVD are prevalently negative or close to zero (activities in 2008, 2014, 2017 and partly 2011 and 2018, see Figure 6, blue or green colors). However, a pronounced anomaly with positive ISO and CLVD is detected at a fault patch activated in 2011 and 2018 (see Figure 6, yellow and red colors, the area delineated by the red ellipse). The ISO and CLVD attained values up to 15% and 30% respectively. The ISO and CLVD are well correlated and the percentage of the CLVD is about twice higher than that of the ISO. Such behavior of the nonDC components excludes a possibility that they are numerical errors of the MT inversion. The mean errors in the ISO and CLVD were calculated by a repeating MT inversion with data contaminated by random noise with the flat probability distribution and with the noise level up to 25% of the maximum P-wave amplitude. The analysis shows that the standard ISO and CLVD errors are less than 2% and 6%, respectively (Figures 7c and 7d). Since the detected percentages (Figure 6) are much higher than their errors, the most of the nonDC components must reflect real processes. This is documented in Figure 8, which shows focal mechanisms and nonDC components for two selected microearthquakes. The first microearthquake is compressive with the focal mechanism of Type 3. The second microearthquake is tensile with the focal mechanism of Type 1. The histograms of the nonDC components are calculated from 250 realizations of random noise in P-wave amplitudes and simulate a possible scatter of the nonDC components for both events. The histograms prove that all solutions from noisy amplitudes are clearly nonshear.

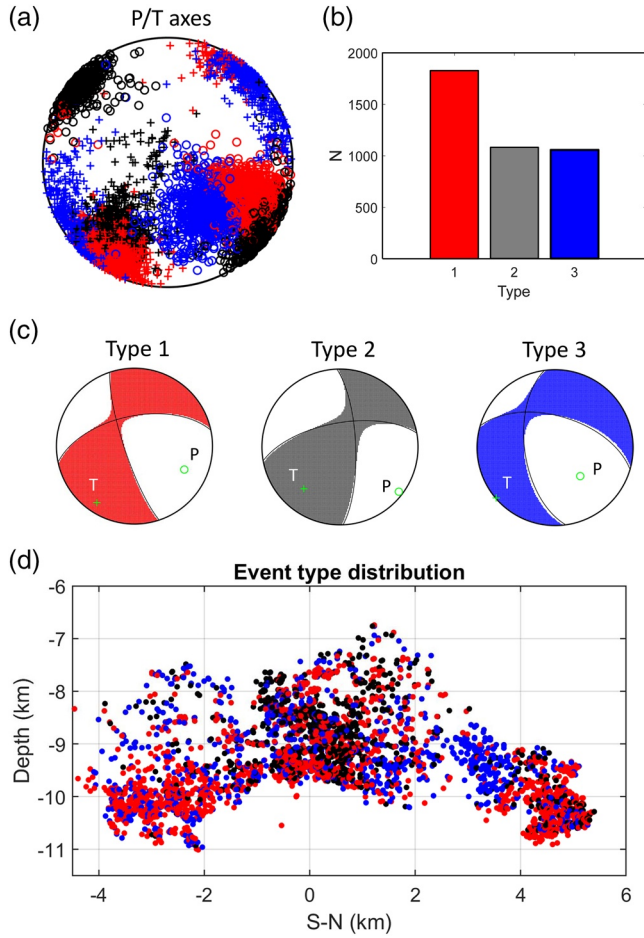


Figure 5. (a) The P/T axes, (b) histograms of the focal mechanism types, (c) centroid focal mechanisms, and (d) the distribution of 3,977 focal mechanisms along a fault. The P and T axes are indicated by circles and plus signs, respectively. All plots are color coded according to three types of the focal mechanisms: Type 1 (red), Type 2 (black or gray), and Type 3 (blue).

In order to demonstrate that the nonDC components are detected to high confidence, we also compare fits predicted by the inversions for the full MT and for the best-fitting DC solution for both the events shown in Figure 8. Figure 9 shows the beach balls for the two inversions and the relative misfits of the P-wave amplitudes at individual stations. The full MT solutions yield almost twice lower misfits than the best-fitting DC solutions. Apparently, such a reliable detection of the nonDC components was allowed by high-quality data and by dense and uniform station coverage of the focal sphere (see Figure 9). A detailed error analysis of the nonDC components detected in the target area was also presented in Vavryčuk and Hrubcová (2017).

The detected nonDC components might be produced by seismic anisotropy in this area (Růžek et al., 2003; Vavryčuk & Boušková, 2008) or by tensile/compressive fracturing of the fault. In both cases, the non-DC components behave in a different way. In seismic anisotropy, the nonDC components originate in neglecting effects of anisotropy in the Green's functions (Šílený & Vavryčuk, 2000, 2002; Vavryčuk, 1997, 2007) and in more complicated properties of MTs (Menke & Russell, 2020; Vavryčuk, 2006, 2015). As a consequence, the ISO and CLVD are mostly mutually independent and do not correlate. By contrast, the tensile/compressive fracturing in isotropic media is characterized by a simple behavior of ISO and CLVD, when ISO and CLVD are linearly correlated.

1.3. MTs of Shear/Tensile/Compressive (STC) Sources

For the STC sources, the slip vector $\mathbf{u}$ 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 direction of slip $\mathbf{u}$. The slope α is defined as the deviation of the slip vector $\mathbf{u}$ from the fault Σ (see Figure 10a and 10b). The fault normal $\mathbf{n}$ and the direction vector $\mathbf{v}$ of slip $\mathbf{u}$ are expressed for the STC sources in terms of angles ϕ , δ , λ and α as follows:

$$\begin{aligned} n_1 &= -\sin \delta \sin \phi, \\ n_2 &= \sin \delta \cos \phi, \\ n_3 &= -\cos \delta, \end{aligned} \quad (6)$$

$$\begin{aligned} v_1 &= (\cos \lambda \cos \phi + \cos \delta \sin \lambda \sin \phi) \cos \alpha - \sin \delta \sin \phi \sin \alpha, \\ v_2 &= (\cos \lambda \sin \phi - \cos \delta \sin \lambda \cos \phi) \cos \alpha + \sin \delta \cos \phi \sin \alpha, \\ v_3 &= -\sin \lambda \sin \delta \cos \alpha - \cos \delta \sin \alpha, \end{aligned} \quad (7)$$

The coordinate system x , y , and z is directed to the North, East and downwards, respectively. Moment tensor $\mathbf{M}$ is expressed in isotropic media as (Vavryčuk, 2011a)

$$M_{ij} = uS(\lambda n_k v_k \delta_{ij} + \mu n_i v_j), \quad (8)$$

where u is the slip, S is the fault area, and λ and μ are the Lamé's coefficients. Moment tensor $\mathbf{M}$ has the following diagonal form:

$$\mathbf{M}^{\text{diag}} = \begin{bmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{bmatrix} = uS \begin{bmatrix} (\lambda + \mu) \mathbf{n} \cdot \mathbf{v} + \mu & 0 & 0 \\ 0 & \lambda \mathbf{n} \cdot \mathbf{v} & 0 \\ 0 & 0 & (\lambda + \mu) \mathbf{n} \cdot \mathbf{v} - \mu \end{bmatrix}. \quad (9)$$

Table 1
Centroid Focal Mechanisms

Type	N	φ_1 (°)	δ_1 (°)	λ_1 (°)	φ_2 (°)	δ_2 (°)	λ_2 (°)
1	1,832	161.5	79.4	-32.3	258.1	58.3	-167.6
2	1,085	357.7	73.6	26.4	259.8	64.8	161.8
3	1,060	286.3	56.8	-140.6	172.1	58.0	-40.3

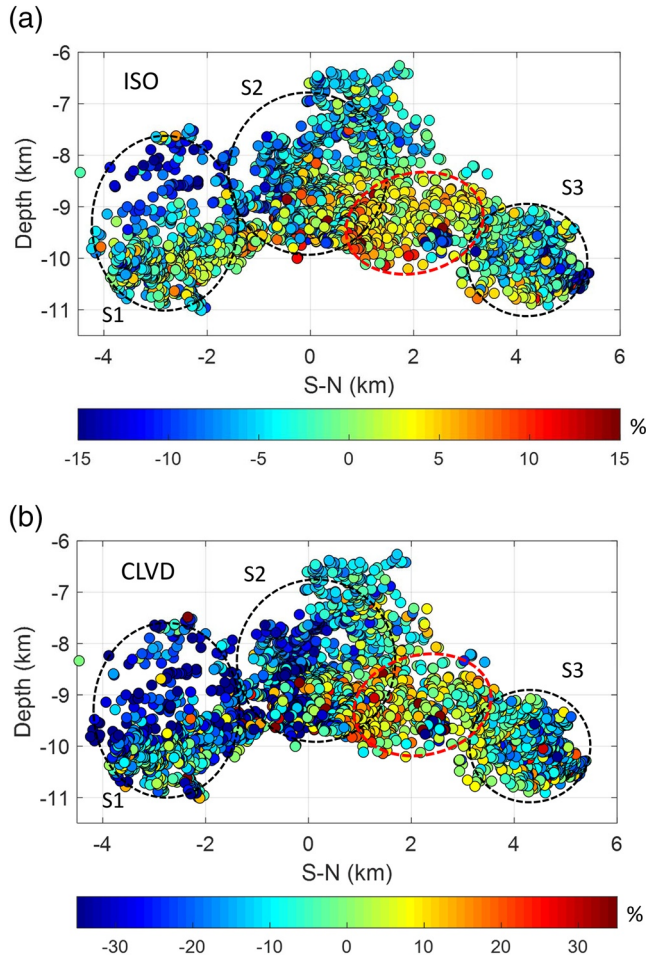


Figure 6. Distribution of the color-coded percentages of the (a) isotropic (ISO) and (b) compensated linear vector dipole (CLVD) components along the fault. The ISO and CLVD percentages are calculated using Equations 1–5. The fault segments S1, S2, and S3 delineated by black ellipses were activated during the 2008, 2011, and 2017 earthquake swarms, respectively. The red ellipse delineates the area of interaction of segments S2 and S3 activated during the 2018 swarm.

Slope α characterizing the opening of the crack is determined from Equation 9 as follows:

$$\sin \alpha = \frac{M_1 + M_3 - 2M_2}{M_1 - M_3}. \quad (10)$$

Considering Equations 1–4, 9 and 10 we readily express the $C_{\text{ISO}}/C_{\text{CLVD}}$ ratio as follows

$$\frac{C_{\text{ISO}}}{C_{\text{CLVD}}} = \frac{3\lambda}{4\mu} + \frac{1}{2}. \quad (11)$$

Hence, the ratio of the ISO and CLVD percentages is independent of the slope α , and the ISO and CLVD form a line in the Hudson's diamond CLVD-ISO plot (Hudson et al., 1989). This property characterizes the STC sources in isotropic media being not valid for other types of sources or for sources in anisotropic media (Menke & Russell, 2020; Vavryčuk, 2015). Therefore, the same signs of ISO and CLVD and their linear dependence observed in Figure 10c for our data is a strong indication that the studied sources are appropriately described by the STC model. Negative values of ISO and CLVD describe compressive fractures, which are closing, while positive ISO and CLVD describe tensile fractures, which are opening (Figure 10a and 10b). Physically, opening of fractures is facilitated by high pore pressure. Opening/closing of fractures can be mapped by the slope α , which is the angle between the slip vector and the fault plane.

Figure 10d shows a mean value of the slope angle calculated for MTs along the fault in individual cells with size of 250×250 m. Each valid (colored) cell contained at least two events described by MTs with RMS less than 0.4. The slope angle ranges between -15° and $+10^\circ$ and confirms the presence of compressive as well as tensile fracturing along the fault. The shear-compressive motions are prevailing along fault segments S1, S2, and S3 (black ellipses). The tensile motions are detected in the area of interaction of segments S2 and S3 (red ellipse).

The CLVD-ISO plot (Figure 10c) also provides information on material properties in the focal area, because it is related to the v_p/v_s ratio as follows (Vavryčuk, 2011a, Equation 22)

$$\frac{v_p}{v_s} = \sqrt{\frac{4}{3} \left(\frac{C_{\text{ISO}}}{C_{\text{CLVD}}} + 1 \right)}. \quad (12)$$

The mean $C_{\text{ISO}}/C_{\text{CLVD}}$ ratio is 0.35 ± 0.05 for the whole data set (white dashed line in Figure 10c), which corresponds to the v_p/v_s ratio of 1.34 ± 0.02 . If only MTs of the 2018 swarm are used, the v_p/v_s ratio attains a value of 1.45 ± 0.05 . Both the values are lower than the frequently assumed value of $\sqrt{3}$ valid for the Poisson solid, but they are consistent with previous works in the area under study (see Vavryčuk, 2011a, Table 2). A rather low v_p/v_s ratio determined from the MTs probably points out to highly fractured rocks in the focal area.

1.4. Inversion for Tectonic Stress

We calculated tectonic stress on the fault using the public-open Matlab code STRESSINVERSE developed by Vavryčuk (2014) (<http://www.ig.cas.cz/stress-inverse>). The code is based on the stress inversion of focal mechanisms developed by Michael (1987), modified by utilizing the fault instability criterion (Vavryčuk et al., 2013) needed to discriminate, which of the two nodal planes is the fault. The method is robust and

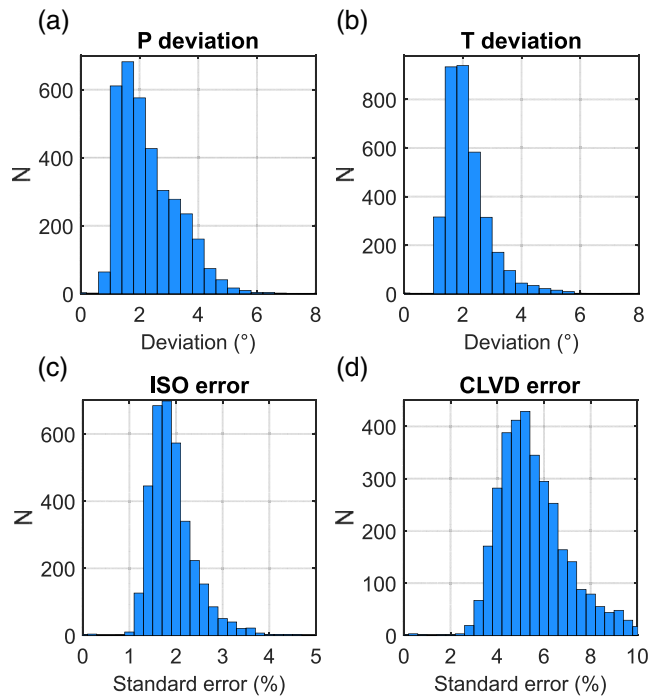


Figure 7. Histograms of mean deviations of the P/T axes (a and b) and of the standard errors of the ISO and CLVD percentages (c and d) for the 3,977 selected MTs. For each event, the mean P/T deviations and the standard errors of ISO and CLVD were calculated from 100 solutions of MTs inverted using amplitudes contaminated by random noise.

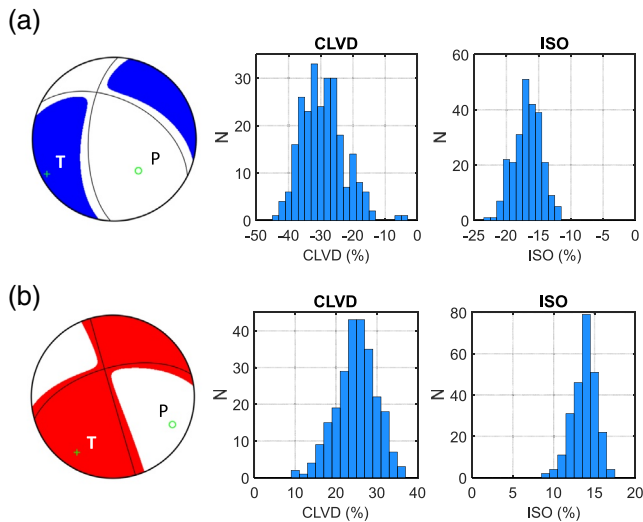


Figure 8. Focal mechanisms and the error analysis of the nonDC components for two microearthquakes that occurred: (a) on September 1, 2011 at 12:54:05.7 (ML = 0.6, depth = 9.47 km, focal mechanism of Type 3, $C_{ISO} = -16.8\%$, $C_{CLVD} = -29.5\%$) and (b) on May 11, 2018 at 06:26:09.0 (ML = 2.3, depth = 8.47 km, focal mechanism of Type 1, $C_{ISO} = 13.8\%$, $C_{CLVD} = 25.1\%$).

fast and provides uncertainties of stress axes directions and of the stress ratio. Note that the method inverts the DC part of MTs only, while an accurate stress inversion should consider also their nonDC components. However, as reported by Jia et al. (2018), the differences between both the inversions are small for events with slope angles $|\alpha|$ less than 30° . Since the slope angle $|\alpha|$ is less than 15° in our target area, applying the standard stress inversion of the DC focal mechanisms is fully satisfactory.

The stress inversion is performed in cells with size of 1×1 km. We analyzed cells, which contained at least 35 events described by MTs with RMS less than 0.35. In this way, we calculated principal stress axes and the stress ratio in 27 cells, and traced their variations along the fault. The stress ratio is mostly between 0.60 and 0.90 with slightly lower values at shallower depths (< 8.1 km). However, an anomalously low stress ratio with values between 0.1 and 0.3 is detected (Figure 11b) at the area of tensile faulting characterized by the positive ISO (Figure 11a, Region C).

The stress anomaly expressed by extremely low values of the stress ratio is well identified also in directions of the principal stress axes. Figure 12 and Table 2 summarize the stress inversion results for four regions defined in Figure 11a, which merge cells with similar properties of stress along the fault. Regions A and D (swarms in 2008 and 2017) have almost identical principal stress axes and the same stress ratio ($R = 0.65$). Region B, located at shallow depths, is characterized by a slightly steeper σ_1 -axis and by $R = 0.5$. Region C, associated with tensile fracturing, is characterized by a horizontal σ_1 -axis and almost vertical σ_2 -axis and by $R = 0.15$.

A local deviation of stress from the regional background stress detected at some patches on the fault points to fault irregularities and/or interaction of fault segments. As shown in Figure 1c and 1d, the fault has complex geometry, consisting of several isolated segments with similar but not identical orientations and with offsets between them. The fault segments were activated step by step and could mutually interact in the area close to tips of the fault segments. Such interaction can destroy the regional background stress and cause anomalies (Figure 12c) and variations of focal mechanisms and nonDC components. Moreover, the recognized tensile character of fracturing of these events indicates that the stress anomaly is associated with the presence of tensile fault steps.

1.5. Coulomb Stress Modeling

The fault interaction is modeled using the Matlab code COULOMB 3.4 (<http://www.coulombstress.org/download>), which calculates the static stress near active faults and its change caused by slip produced by an earthquake (Lin & Stein, 2004; Toda et al., 2005). Modeling of the static stress change reported by many authors has confirmed that earthquakes can change directions of the principal stress axes near the fault, indicated as well by observations of seismicity before and after large earthquakes (see, e.g., Hasegawa et al., 2012; Yoshida et al., 2012, 2014). The code is also used for studying interactions between faults on various scales (see, e.g., Fan & Shearer, 2016; Turner et al., 2013; Vavryčuk & Adamová, 2018).

We simulated fault geometry in the focal zone (Figure 1) by three fault segments with length of 3.2, 3.2 and 2 km. The depth extents of the fault segments are 7.5–11.0 km, 7.0–10.0 km, and 9.0–11.0 km, respectively. The fault segments form two fault steps: a compressive fault step

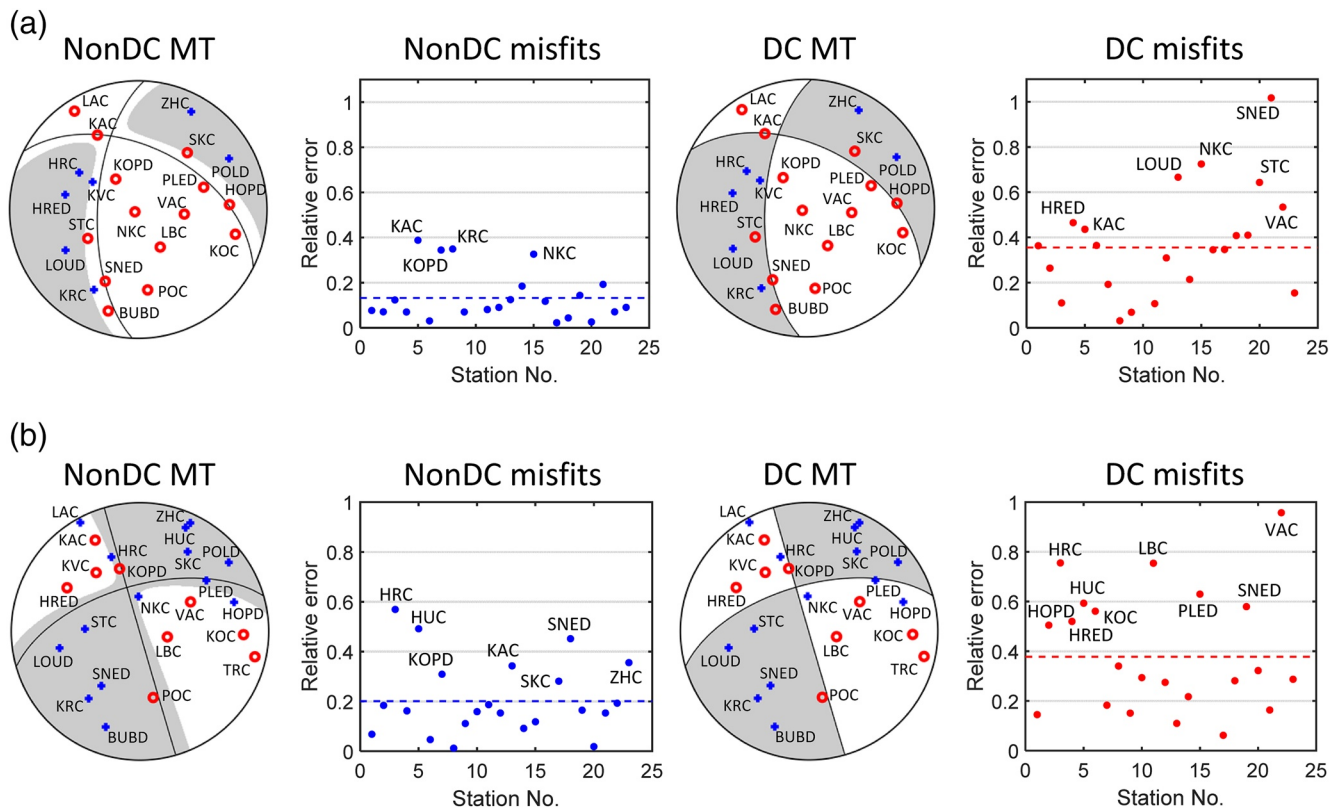


Figure 9. Focal mechanisms and amplitude misfits for the full MT solution (“nonDC MT” and “nonDC misfits”) and for the best-fitting DC solution (“DC MT” and “DC misfits”) for the two microearthquakes shown in Figure 8. The amplitude misfits are calculated as the absolute values of differences between the theoretical and observed amplitudes at individual stations normalized to the mean amplitude at all stations for a given event. The blue and red dashed lines show the average amplitude misfits for the full MT solution and for the best-fitting DC solution, respectively. Names of stations with large misfits are indicated. The positive and negative P-wave polarities of stations are marked by blue plus signs and red circles in the focal sphere plots.

between segments 1 and 2, and a tensile fault step between segments 2 and 3. For the compressive fault step, the separation distance is 300 m and the fault segments do not overlap. For the tensile fault step, the separation distance is 150 m and a gap of 1.2 km is between the tips of the fault segments (Figure 13). Segments 1, 2, and 3 were activated in 2008, 2011, and 2017, respectively. The compressive fault step between segments 1 and 2 was broken in 2014, and the tensile fault step between segment 2 and 3 in 2018.

The strike, dip and rake angles are 169° , 75° and -32° for segments 1 and 2, and 162° , 75° and -32° for segment 3, respectively. The friction on faults is 0.55, which is an optimum value valid for the whole data set. This value was also obtained in previous stress analyses in this area (Vavryčuk, 2011b). The static stress change is calculated for earthquakes on all three fault segments activated during the 2008, 2011 and 2017 swarms. We assume the cumulative slip of 35 cm on segments 1 and 2, which corresponds to the cumulative scalar moment equivalent to $M_w = 5.4$. The cumulative slip on segment 3 is 25 cm; this segment is smaller and being activated by less intense seismicity than the other fault segments. The stress change is calculated at a reference depth of 9.5 km.

The Coulomb stress change caused by the cumulative slip of the 2008, 2011, and 2017 swarms is shown in Figure 13, which nicely demonstrates a strong interaction of the fault segments. The stress change is shown for three differently oriented receiver faults characterized by the centroid focal mechanisms, see Table 1. While the typical focal mechanisms are unlikely to be activated between the fault tips of the compressive fault steps S1 and S2 (indicated by the blue color between the tips of segments S1 and S2 in Figures 13a–13c), they can occur between the fault tips of the tensile fault steps S2 and S3 (indicated by the

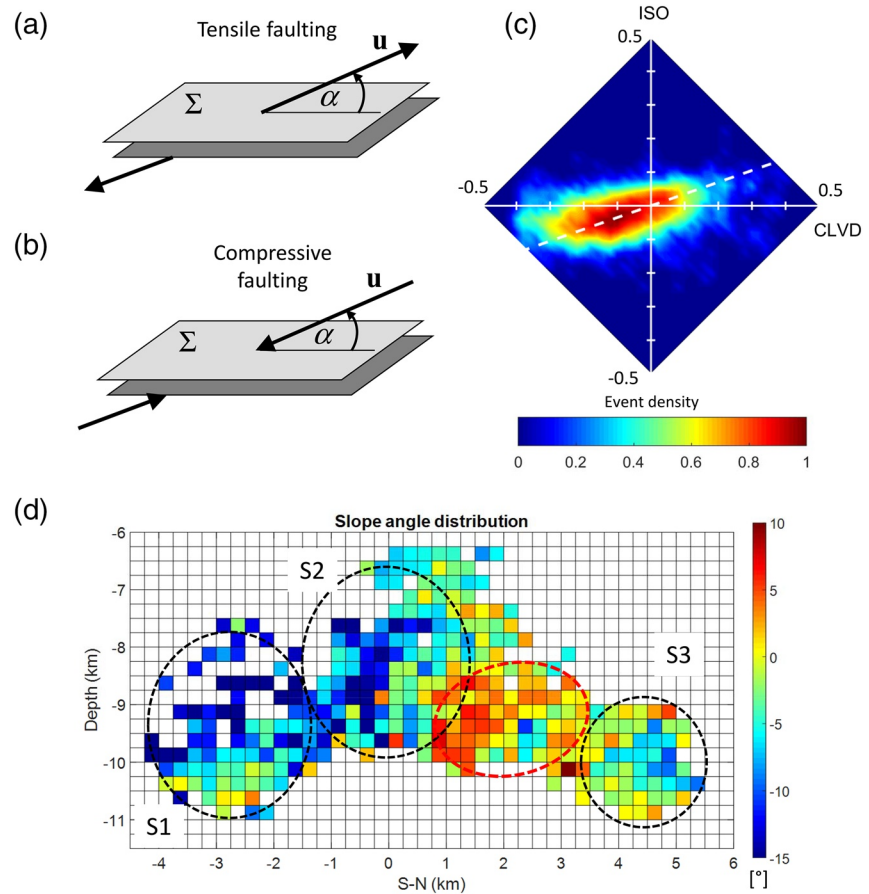


Figure 10. Mapping of shear/tensile/compressive fracturing along the fault. (a and b) The scheme of tensile/compressive fracturing, (c) the diamond CLVD-ISO plot of the event density, and (d) the distribution of the color-coded slope angle along the fault. The slope angle α (the angle between slip vector $\mathbf{u}$ and fault plane Σ) is positive for tensile fracturing and negative for compressive fracturing. The color scale in (d) is in degrees. The standard deviation of the slope angle is $\pm 4^\circ$. The fault segments S1, S2, and S3 delineated by black ellipses were activated during the 2008, 2011, and 2017 earthquake swarms, respectively. The red ellipse delineates the area of interaction of segments S2 and S3 activated during the 2018 swarm.

red color between the tips of segments S2 and S3 in Figures 13a–13c). The highest positive Coulomb stress change is predicted to occur between segments 2 and 3 for the focal mechanism of Type 3 (blue beach ball). A prevailing (but not exclusive) occurrence of this type of the focal mechanisms predicted by modeling is confirmed by observations (see Figure 5d).

Table 2
Stress Inversion Results

Region	Number of events	σ_1 -axis		σ_2 -axis		σ_3 -axis		Stress ratio R
		Azimuth	Plunge	Azimuth	Plunge	Azimuth	Plunge	
A	1,820	128.0°	27.3°	335.1°	59.9°	224.1°	11.7°	0.64
B	450	134.6°	49.2°	309.6°	40.7°	41.7°	2.5°	0.49
C	445	308.5°	14.0°	70.7°	65.0°	213.2°	20.3°	0.16
D	901	130.2°	35.8°	333.1°	52.0°	228.4°	11.2°	0.63

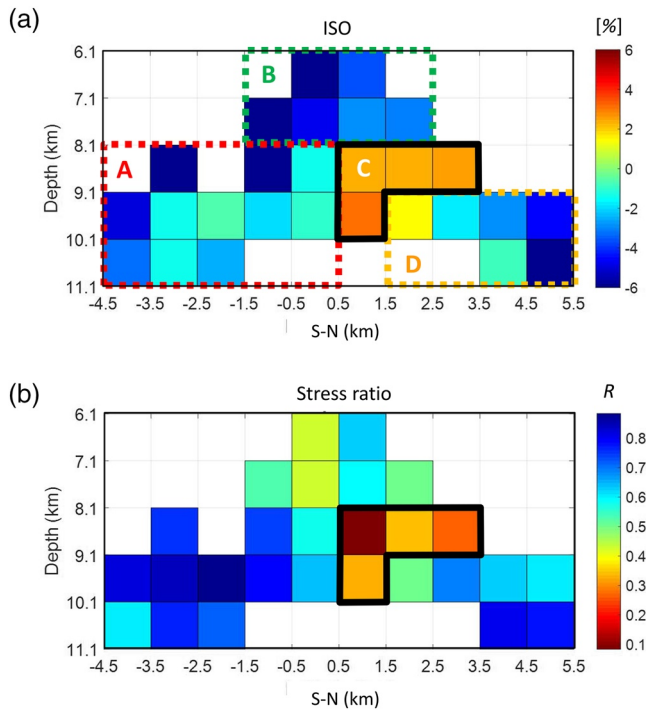


Figure 11. A comparison of the (a) ISO component and the (b) stress ratio along the fault. The minimum number of focal mechanisms in individual cells inverted for stress is 35. The full black line and dotted color lines in (a) mark four regions of a similar stress state. Region C is anomalous in both ISO and stress ratio, and it corresponds to the stress anomaly.

2. Discussion

The nonDC components of MTs are often missed in earthquake catalogs or not interpreted, because dense local networks are needed for their determination (Ren et al., 2020), and thus their uncertainties are usually high. However, once nonDC components are reliably acquired (Figures 6–9), they can help in understanding fracture processes in the focal zone (Figure 10). This is documented by studies of seismicity induced by presence of fluids or by fluid injections (Boyd et al., 2018; Shapiro, 2015; Sibson, 1992, 2000; Sibson & Scott, 1998), where positive nonDC indicate opening of fractures due to high pore fluid pressure (Martínez-Garzón et al., 2017; Yu et al., 2018; Zhao et al., 2014) and negative nonDC indicate closing fractures due to gouge compaction (Vavryčuk & Hrubcová, 2017), fluid extraction or fluid leakage (Yu et al., 2019).

The nonDC components are not just indicators of the fracture mode (Figure 10). Since they are sensitive to pore pressure and stress, they can be employed for a detailed modeling of stress regime and its variations (Figures 10d and 11a). The standard stress inversion gives the information on the deviatoric stress: the directions of the stress axes and the stress ratio. It is based on observations of shear focal mechanisms of many earthquakes under the same stress state, so it must be run in cells and its resolution is limited (Figures 11b and 12). Mapping variations of nonDC components along a fault or with time provides additional information about tensile/compressive stress regime, which is related to the isotropic part of the stress tensor. If positive nonDC components are detected, at least one principal stress must be tensile. This provides another constraint on absolute stress values in the focal area. In addition, no large datasets observed at each space-time cell are needed. The variation in stress regime can be

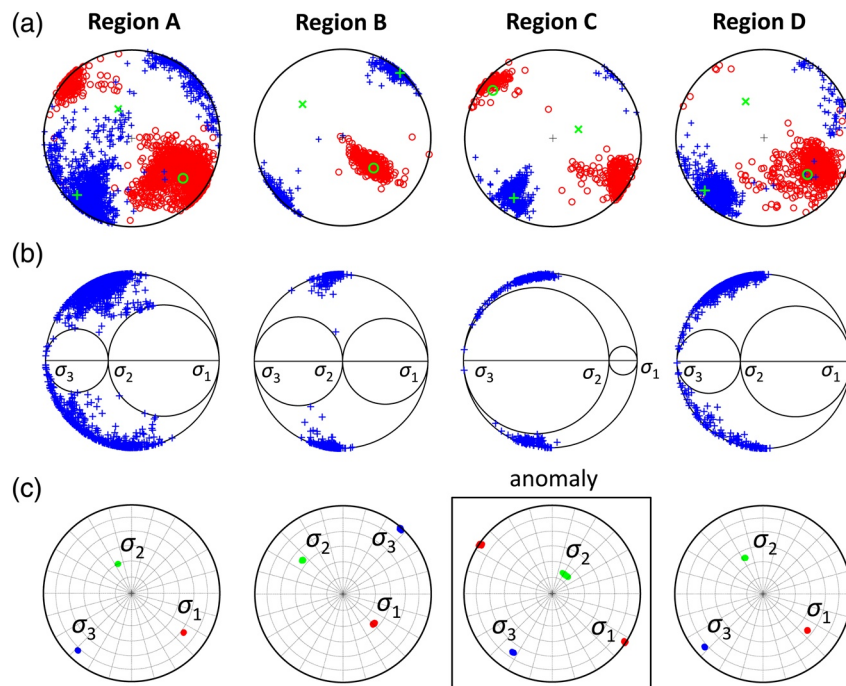


Figure 12. Inversion for stress along the fault in four regions of similar stress. (a) The P (red) and T (blue) axes, (b) the Mohr's circle diagrams, and (c) uncertainty limits of the principal stress axes on the focal sphere. For values of the retrieved stress, see Table 2.

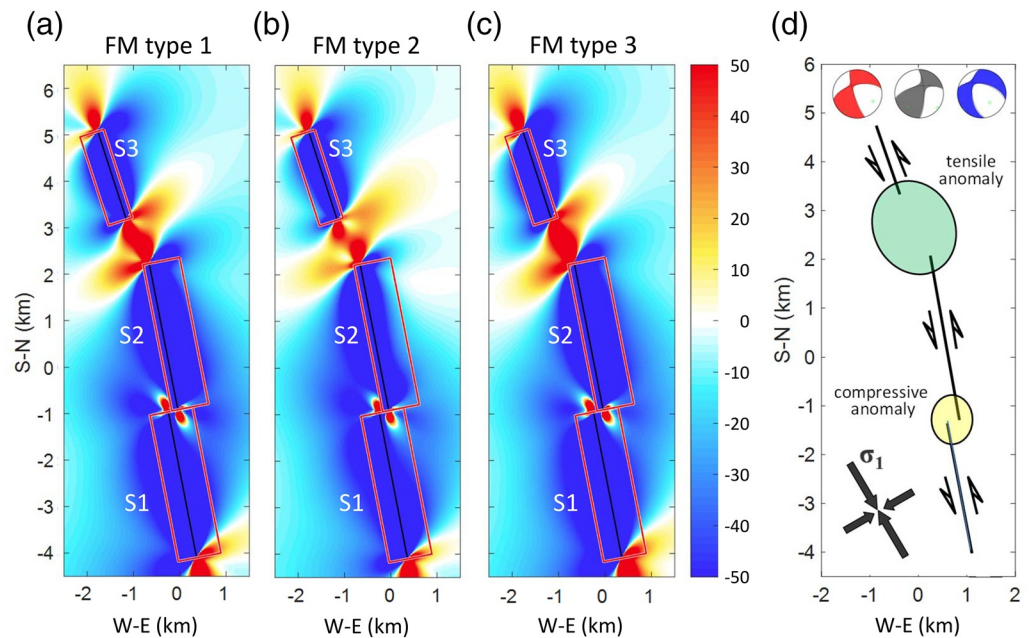


Figure 13. (a–c) Modeling of the Coulomb stress change produced by the 2008, 2011, and 2017 earthquake swarms that occurred at fault segments S1, S2, and S3, respectively. (d) The sketch of the fault system. The receiver faults in (a–c) are characterized by the focal mechanisms (FM) of Type 1 (a), Type 2 (b), and Type 3 (c), see Table 1. The red lines mark the fault margins in depth, the black lines show the faults at the target depth of 9.5 km. The color represents the Coulomb stress change in bars. For the purpose of visualization, the static stress changes are clipped close to the fault tips, because they are quite high due to the stress change instability. The yellow and green areas in (d) mark the compressive and tensile stress anomalies, respectively. The full black arrows denote the directions of the maximum and minimum compressions of the background stress. The beach balls in panel (d) define the three types of the focal mechanisms in the area.

detected with more detail and with a higher resolution (compare Figures 10d and 11b). This is important, because stress can change very rapidly along the fault and the point-like information about stress is essential for an accurate reconstruction of stress variations and anomalies in the focal zone.

Importantly, the stress variations are not limited only to variations of stress axes directions, but also to changes in the stress ratio. In the area of tensile stress regime (Figure 12c, Region C), we observe not only significantly rotated stress directions but also a remarkably different stress ratio. While the areas with the shear-compressive stress regime have stress ratio R in the range of 0.5–0.65 (Figure 12b and Table 2, Regions A, B, and D), the area with the tensile stress regime is characterized by $R = 0.15$. This indicates that the relative principal stress magnitudes are quite sensitive to the stress regime. A systematic reduction of the stress ratio in areas with fluids and high pore pressure is reported also by other authors (Boyd et al., 2018; Martínez-Garzón et al., 2016). The physical mechanism of the observed negative correlation between pore pressure and the stress ratio is not yet fully understood. However, since isotropic stress changes cannot affect ratio R , we can speculate that the effects of the overpressurized fluids are not isotropic. The fluids probably produce directional stress effects due to the presence of aligned cracks. This is supported by observed close magnitudes of σ_1 and σ_2 and by the near vertical σ_2 -axis in Region C (Figure 12), which can be interpreted as a result of (sub)vertical fluid-filled cracks parallel with the maximum compression. Consequently, we conclude that even though the fluid pore pressure is intrinsically isotropic, the response of cracked media on fluid flow might be anisotropic.

Since the nonDC components provide us with information about volumetric changes in the focal zone, their detailed maps can be utilized for detecting pore fluid overpressure and for tracing fluid flow in the focal zone. We can study pathways of fluids and predict areas with overpressure, which are prone to being activated (Proctor et al., 2020). Also, the seismic energy release as the mainshock-aftershock sequence or the swarm-like activity is affected by presence of fluids in rocks, because it affects their rheology (Ben-Zion & Lyakhovsky, 2006; Zaliapin & Ben-Zion, 2013). Areas rich in fluids, which continuously migrate through

fractures and cause their weakening, do not usually accumulate high stress and tend to release seismic energy in earthquake swarms (Vavryčuk & Hrubcová, 2017). By contrast, the role of fluids in mainshock-after-shock sequences, which produce stronger magnitudes and are thus more dangerous, is rather minor (Vavryčuk & Adamová, 2018). As demonstrated in Figure 2, the energy release can be switched during time from the swarm-like sequence to the mainshock-aftershock activity at the same seismically active zone. This points out to an extreme variability of rheology and fluid flow in complex fracture systems. Hence, any detailed detection of fluids and pore fluid pressure deduced from the nonDC maps can improve seismic hazard scenarios.

3. Conclusions

Detailed maps of the nonDC components of swarm earthquakes in West Bohemia revealed a systematic variation of fracturing mode associated with stress changes on the fault. The focal zone is formed by three fault segments, activated in different time periods and mutually interacted. The fault interaction created two stress anomalies: (1) a small-size compressive anomaly produced by compressive fault step and (2) a larger-size tensile anomaly produced by tensile fault step. While the nonDC components are mostly zero or negative along the whole fault system, the tensile anomaly is well-mapped by positive nonDC components. The slope angle between the slip and the fault ranged from -15° , characterizing fault closing, to $+10^\circ$, characterizing fault opening associated with the tensile anomaly.

The principal stress axes rotated in the area of the tensile stress anomaly and the stress ratio was distinctly different from that in the other parts of the fault system. The stress ratio attained a value of 0.15 compared to values of 0.5–0.65 outside of the anomaly. The systematic reduction of the stress ratio can be associated with fluids and high pore pressure as reported also by other authors (Boyd et al., 2018; Martínez-Garzón et al., 2016). The physical mechanism of the observed negative correlation between pore pressure and the stress ratio is still unclear, but it might indicate that the stress change due to overpressurized fluids in cracked media is not isotropic but displays a directional variation.

The presence of tensile fault step, revealed by foci clustering, was confirmed by numerical modeling of the static Coulomb stress change. The area characterized by tensile stress and associated with fault opening might form a pathway of intense fluid flow and facilitate a fluid escape from the focal zone. The fault opening and fluid escape can be sensitive to fluid pressure being realized in repeating episodes as suggested in the fault-valve model proposed by Sibson (1992). We speculate that the fluid escape resulted in a relaxation of pore pressure in the currently active zone. Consequently, we do not expect a reactivation of the same fault patch but rather a migration of the future activity to other adjacent areas exposed to unrelaxed stress conditions.

Data Availability Statement

The event catalogs and waveforms used for this research are available at <https://doi.org/10.17632/4swk36hbvz.1>.

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