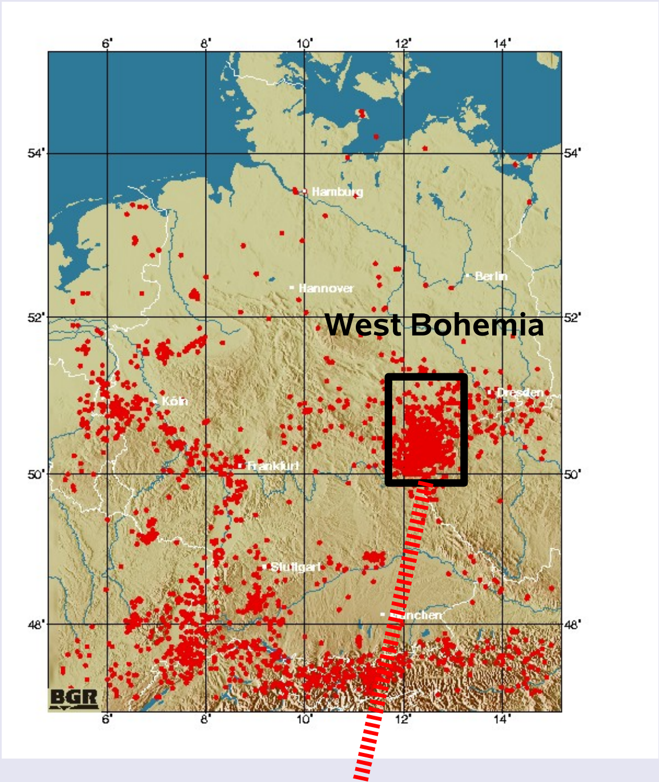
Tensile Source Components of Swarm Events in West Bohemia in 2000 by Considering Seismic Anisotropy

D. Rößler[1], F. Krüger[1], G. Rümpker[2], I. Pšenčík[3]
[1]University of Potsdam, [2]University of Frankfurt/M., FR Germany, [3]Academy of Sciences of the Czech Republic
contact: diroess@uni-potsdam.de

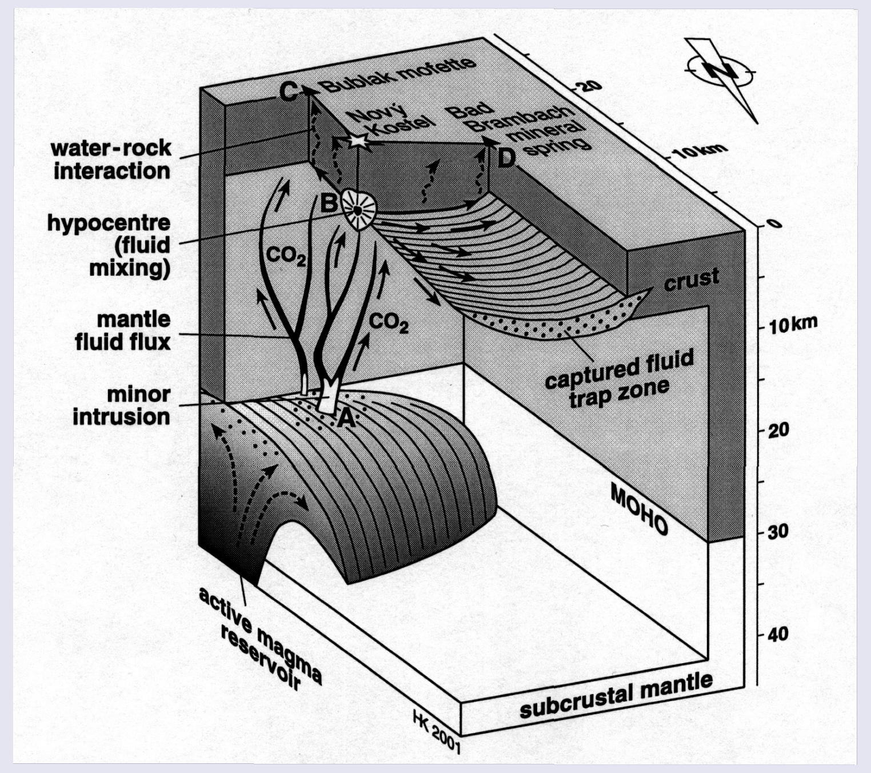
1 Motivation

Earthquake swarms occur frequently in West Bohemia, Central Europe (see below and **Fig.1**). Their occurrence is correlated with and propably triggered by fluids that escape on the earth's surface near the epicentres [7]. These fluids raise up periodically from a seemingbly deep-seated source in the upper mantle (see model sketch below and [4]).
Moment tensors for swarm events in 1997 indicate tensile faulting [1]. However, they were determined under assumption of seismic isotropy although anisotropy can be observed [6]. Anisotropy may obscure moment tensors and their interpretation [2][3].
In 2000, more than 10,000 swarm earthquakes occurred near Novy Kostel, West Bohemia (**Figs. 1, 2**). Event triggering by fluid injection is likely. Activity lasted from 28/08 until 31/12/00 (9 phases) with maximum M_L=3.2 (**Fig. 3**). High quality P-wave seismograms (**Fig. 4**) were used to retrieve the source mechanisms for 112 events (**Figs. 2, 3)** between 28/08/00 and 30/10/00 (**red stars**, phases 1-7) using > 20 stations (pink squares). We determine the source geometry using a new algorithm and different velocity models including anisotropy (**Fig. 5**).

Seismicity of Germany and adjacent areas.



Model sketch of the focal area in West Bohemia (after [4]).



West Bohemia: Background Seismicity, Stations, and Earthquakes in 2000

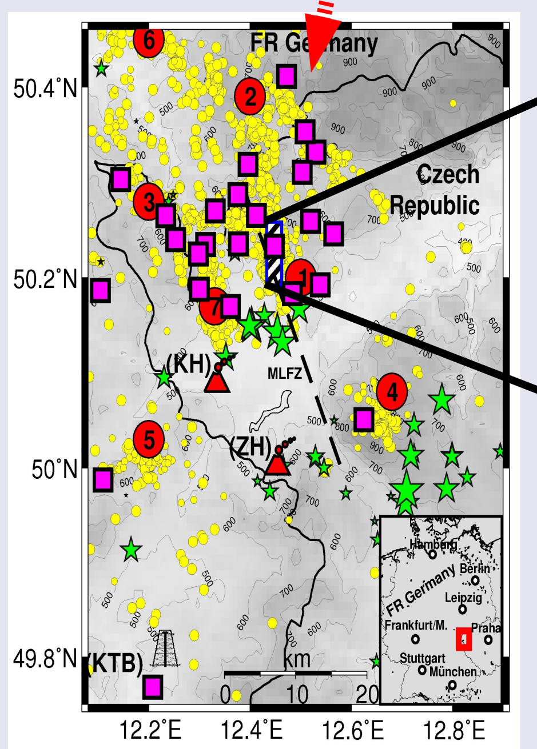


Fig. 1:
West Bohemia at the German-Czech border and adjacent area. the focal area of the earthquake swarm in 2000 is indicated by the hatched rectangle. Seismic stations are shown by **purple squares**. Background seismicity, 7 focal areas, and gas springs are shown by **yellow circles**, **red circles**, and **green stars**, respectively.

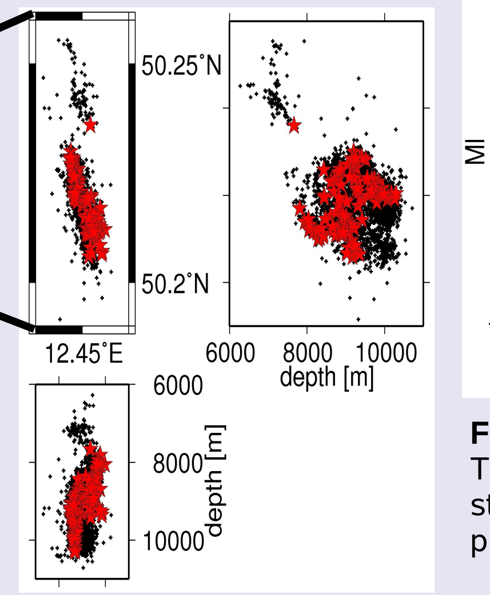


Fig. 2:
Hypocentre distribution in 2000 (28/10/00 – 31/12/00, locations by *T. Fischer*). The ruptured zone forms a near-planar N-S oriented plane. **Red stars**: considered events.

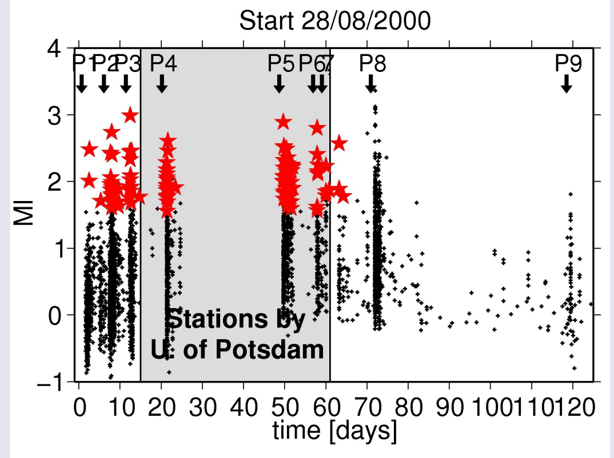


Fig. 3:
Temporal distribution of swarm events starting on 28/08/2000 forming 9 phases. **Red stars**: considered events.

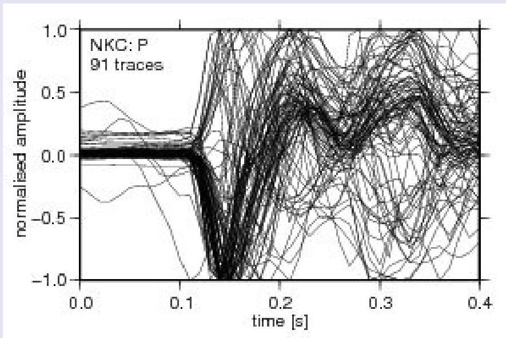


Fig. 4:
P-wave displacement records at station NKC (nearest station) show coherent waveforms but variable polarities that indicate different source mechanims.

2 Algorithm

We determine the source geometry given by the slip vector **s**, the fault normal **n**, and the fault area A_0. From the source geometry the slip inclination δ (angle between **n** and **s**) is obtained as is the moment tensor M_{jk}. δ is calculated from the eigenvalues ν_i of D_{kl}. Green's functions are calculated using the ANRAY package [5].

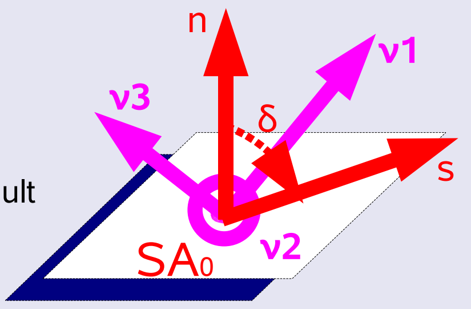
$$
\begin{aligned}
u_i &= G_{ij,k} M_{jk} \\
&= G_{ij,k} c_{jkpq} s_p n_q S A_0 \\
&= Y_{il} \sigma_l
\end{aligned}
$$

$$
\begin{aligned}
\sigma_l = (&s_1 n_1; s_1 n_2 + s_2 n_1; \\
&s_1 n_3 + s_3 n_1; \\
&s_2 n_2; s_2 n_3 + s_3 n_2; s_3 n_3) S A_0
\end{aligned}
$$

$$D_{kl} = (s_k n_l + s_l n_k) S A_0$$

$$\delta = \frac{\nu_1 + \nu_3}{\nu_1 - \nu_3}$$

Model of dislocation point sources:



n: fault normal
s: direction of the slip
δ: slip inclination
SA_0: slip length times the area of the fault
ν_i: eigenvalues of **D**

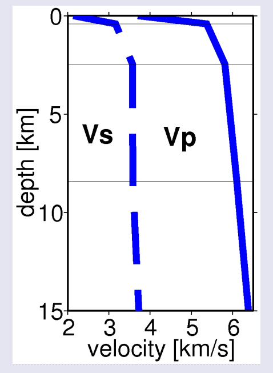


Fig. 6:
The anisotropic velocity model is a perturbation of the isotropic velocity model [6].

3 Fault-Plane Solutions

Fault-plane solutions show similar mechanisms with left-lateral strike-slip on steeply dipping N-S oriented rupture planes (**Fig. 6a**). Most events have additional normal components (**Fig. 6b**). Deepest events during the phases 1-4 may also show reverse components (**Fig. 6c**). Polarities agree well with the radiation pattern. **Red circles** indicate polarities observed at station NKC (compare **Fig.3**).

Fig. 6a: Fault-plane solutions and sense of slip.

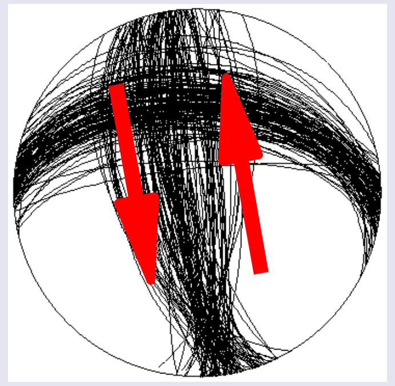


Fig. 6b: Normal oblique components occur during phases 1-7.

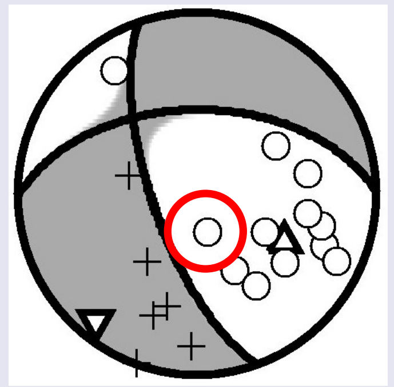
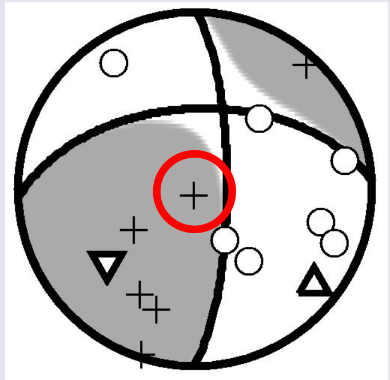


Fig. 6c: Reverse oblique components during phases 1-4.



4 Depth Dependence of Source Quantities

Retrieved quantities, e.g. seismic moment M_T / local magnitude M_L as well as dip of the rupture plane and slip inclination δ are depth-dependent.
Moment release is concentrated in 3 depth intervals (**Fig. 7a**). At depths < 8.5 km rupturing occurs on shallow and at depths > 8.5 km on steeply dipping planes (**Fig. 7b**). The majority of the events shows tensile components (δ<90°) indicating crack opening. Tensile components increase with source depth (**Fig. 7c**).

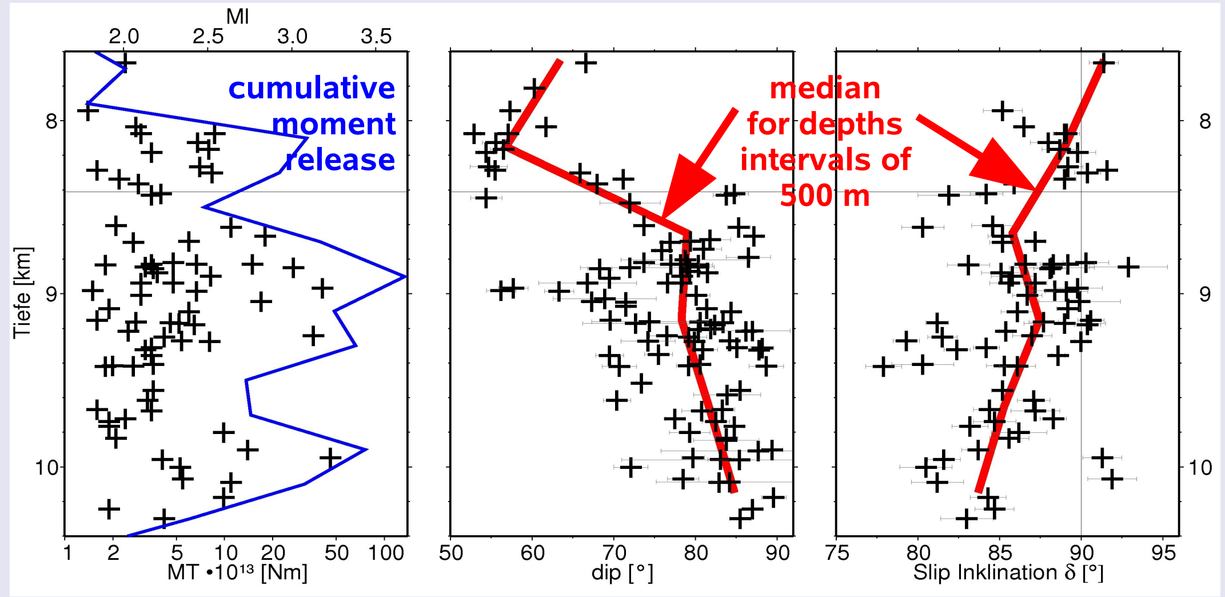


Fig. 7a: Magnitudes / seismic moments vs. source depth.

Fig. 7b: Dip of the rupture plane vs. source depth.

Fig. 7c: Slip inclination δ vs. source depth.

5 Time Variability of Tensile Components

Station coverage reached a maximum during swarm phase 4 (**Fig. 8a**). Tensile components indicated by δ<90° are observed during the swarm phases 1-7 (**Fig. 8b**). They are largest during the phases 1-4. Whereas the isotropic moment tensor components (**red cross**) are relatively stable, maximum CLVD (**green circle**) decrease and minimum DC (**blue star**) components increase during the swarm phases 1-7 (**Fig. 8c**).

Fig. 8a: No. of stations

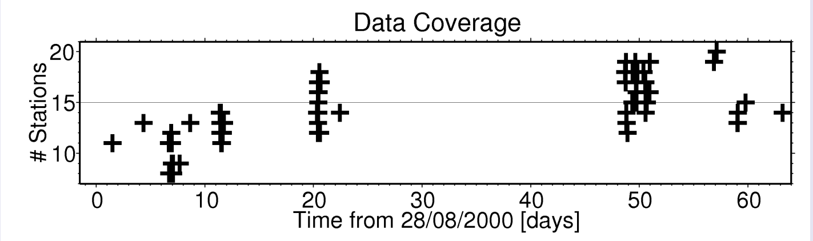


Fig. 8b: Slip incli-ations δ

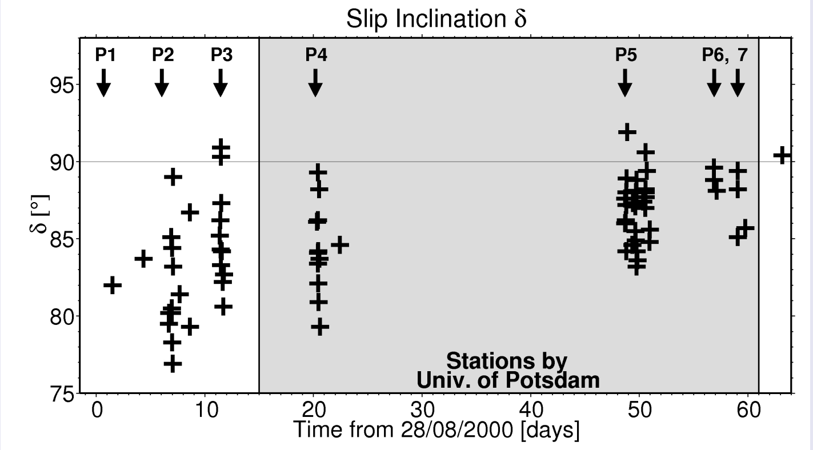
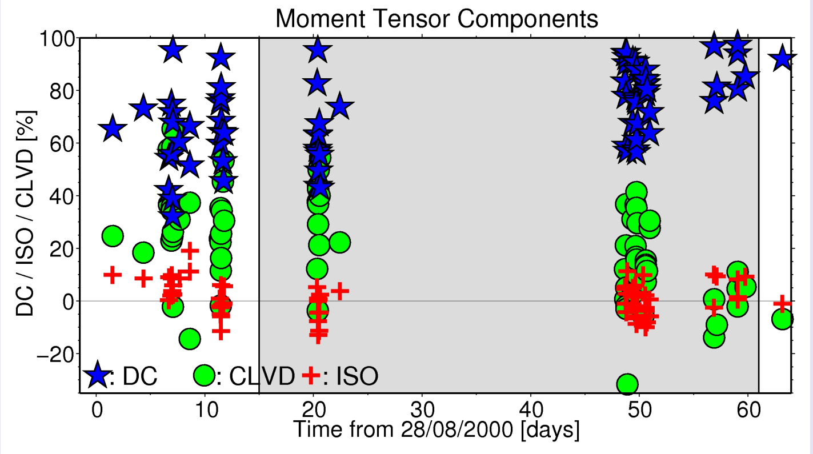


Fig. 8c: Moment tensors



6 Local Stress Field

Analysis of the P and T axes (**Fig. 9a**) indicates NW-SE and NE-SW orientation of the maximum and the minimum stress axes (**σ_1** and **σ_3**). This is in accordance with earlier studies in the region and in Central Europe. However, depth dependence is also observed (**Fig. 9b**). The dip of the P axes decreases gradually with greater depth. T axes lie almost horizontally above 8.5 km depth. Their dip angles increase to about 25° below 8.5 km.

Fig. 9a:

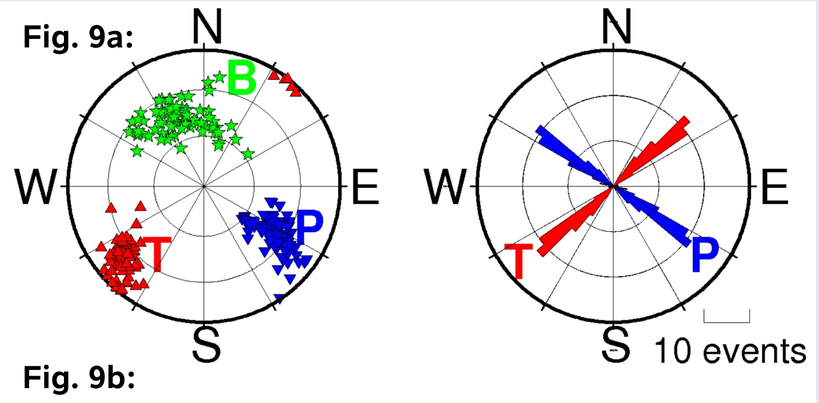
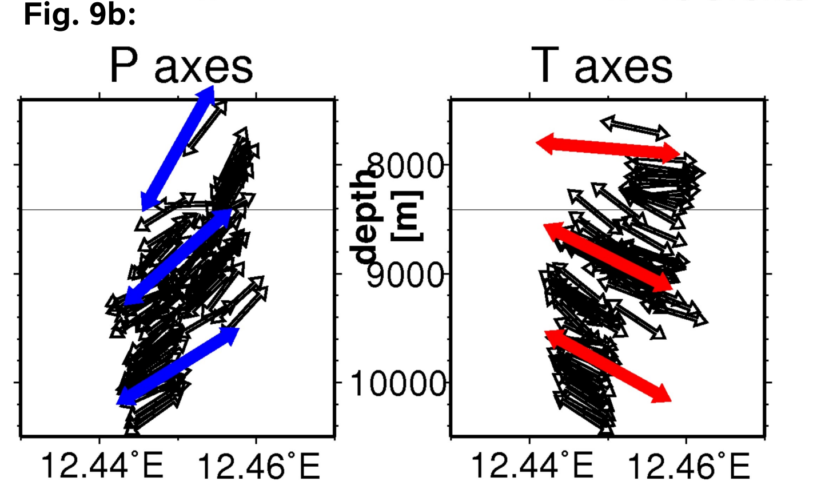


Fig. 9b:



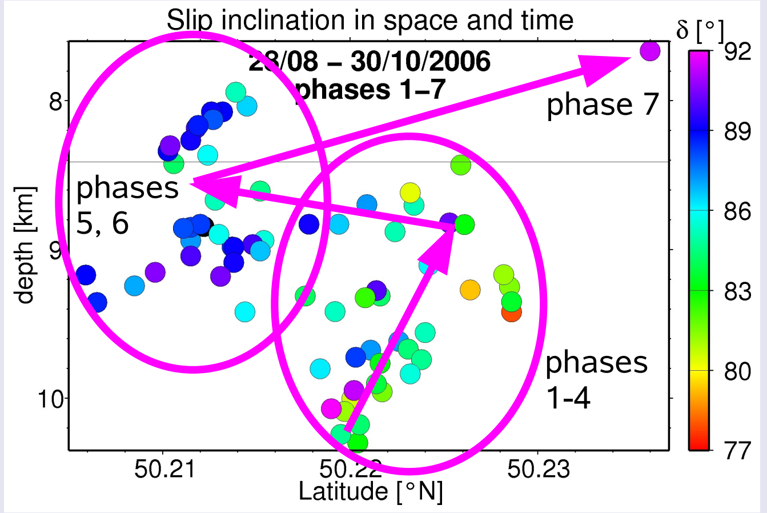
7 Slip inclination

Slip inclinations δ indicate largest volume increase for events at the beginning of the swarm and at the bottom of the foci. There, fluid injection is assumed.

Spatial overlap of events with small and large tensile components reject dependency of slip incllination on model inaccuracy.

Spatio-temporal evolution of the swarm and retrieved slip inclinations point to differences in the pore-pressure regime and / or the diffusivity in the region (see [8], [9]).

Fig. 10: Projection of hypocentres and retrieved slip inclinations δ.



8 Stability Tests

Attempts to estimate uncertainties of retrieved tensile components and source orientations included bootstrap and jackknife tests as well as different velocity models and assumptions on source mislocation. They show the significance of obtained tensile source components and their spatio-temporal variation.

Results of stability tests for one examplary event (M_L=3.1) on October 15, 2000.

Fig. 11a: Bootstrap tests.

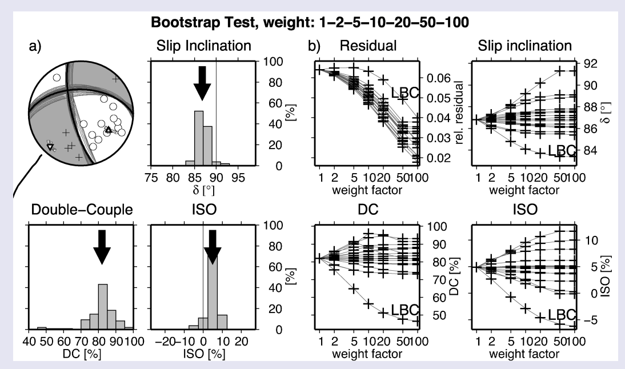


Fig. 11b: Jackknife tests.

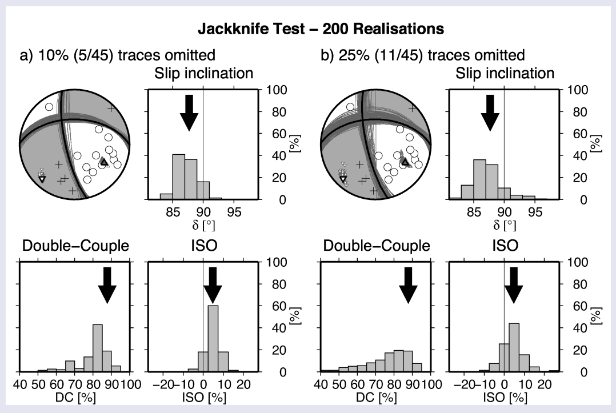
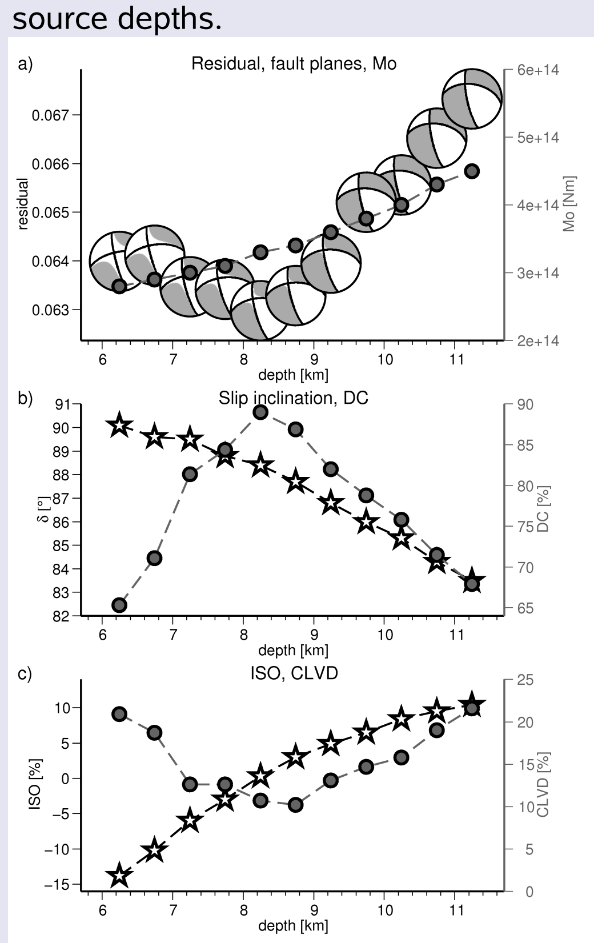


Fig. 11c: Tests assuming different source depths.



9 Conclusions

From inversions of P waves we observe M_L<3.2, strike-slip events on steep N-S oriented faults with additional normal or reverse components. Tensile components seem to be evident for more than 60% of the processed swarm events in West Bohemia during the phases 1-7. Being most significant at great depths and at phases 1-4 during the swarm they are time and location dependent (**Fig. 10**). Although tensile components are reduced when anisotropy is assumed they persist and seem to be important. They can be explained by pore-pressure changes due to the injection of fluids that raise up. Our findings agree with other observations e.g. correlation of fluid transport and seismicity [4], variations in b-value [7], forcing rate [8], and in pore pressure diffusion[9]. Tests of our results show their significance.

More information, details, and figures can be found on:
www.geo.uni-potsdam.de/forschung/Geophysik/Mominv/mominv.htm

Acknowledgments
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