Interpretation of moment tensors of induced earthquakes: a review

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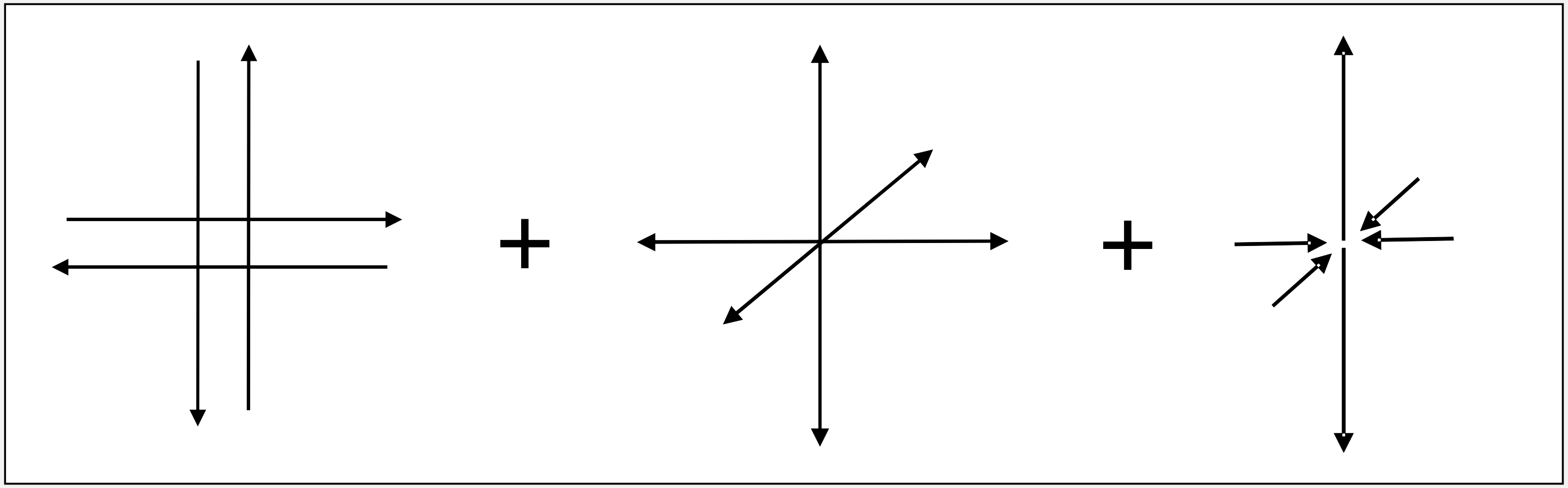
Decomposition of MT

Moment tensor represents equivalent body forces at a point source

$$\mathbf{M} = \mathbf{M}^{DC} + \mathbf{M}^{ISO} + \mathbf{M}^{CLVD}$$



DC — shear

ISO — non-shear

CLVD — non-shear

Interpretation of the DC part of the moment tensor

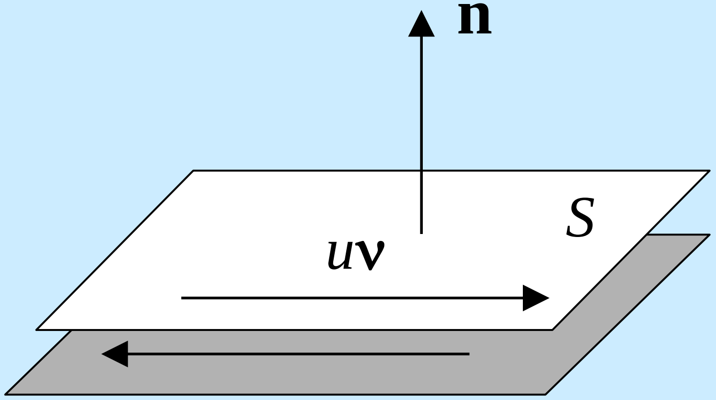
Moment tensors of shear faulting in isotropy

Shear earthquakes in isotropy
(Aki & Richards 2002, Eq. 3.22):

$$M_{kl} = \mu u S\left(\nu_k n_l + \nu_l n_k\right)$$

$$M_{kl} = M_0 \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

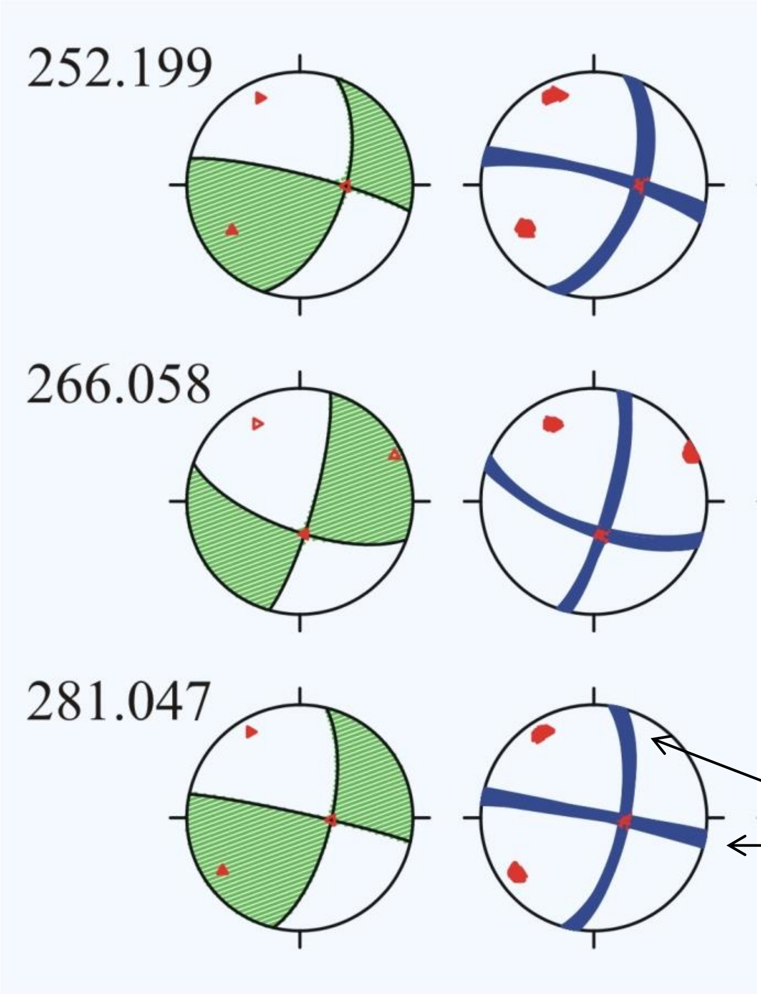
double-couple



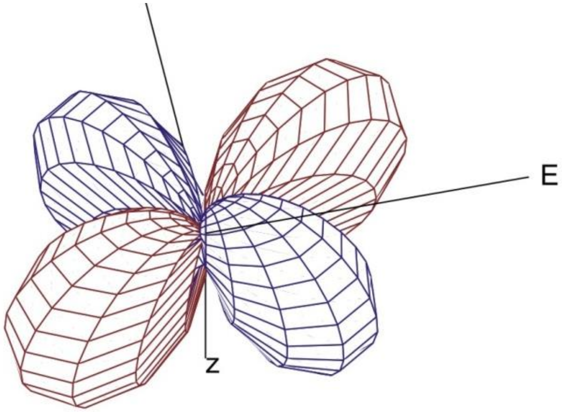
u – slip
S – fault area
μ – shear modulus
$\boldsymbol{\nu}$ – slip direction
$\mathbf{n}$ – fault normal
c_{ijkl} – elastic parameters

Focal mechanisms

Events induced in the fluid injection experiment in the KTB site in 2000



P-wave radiation



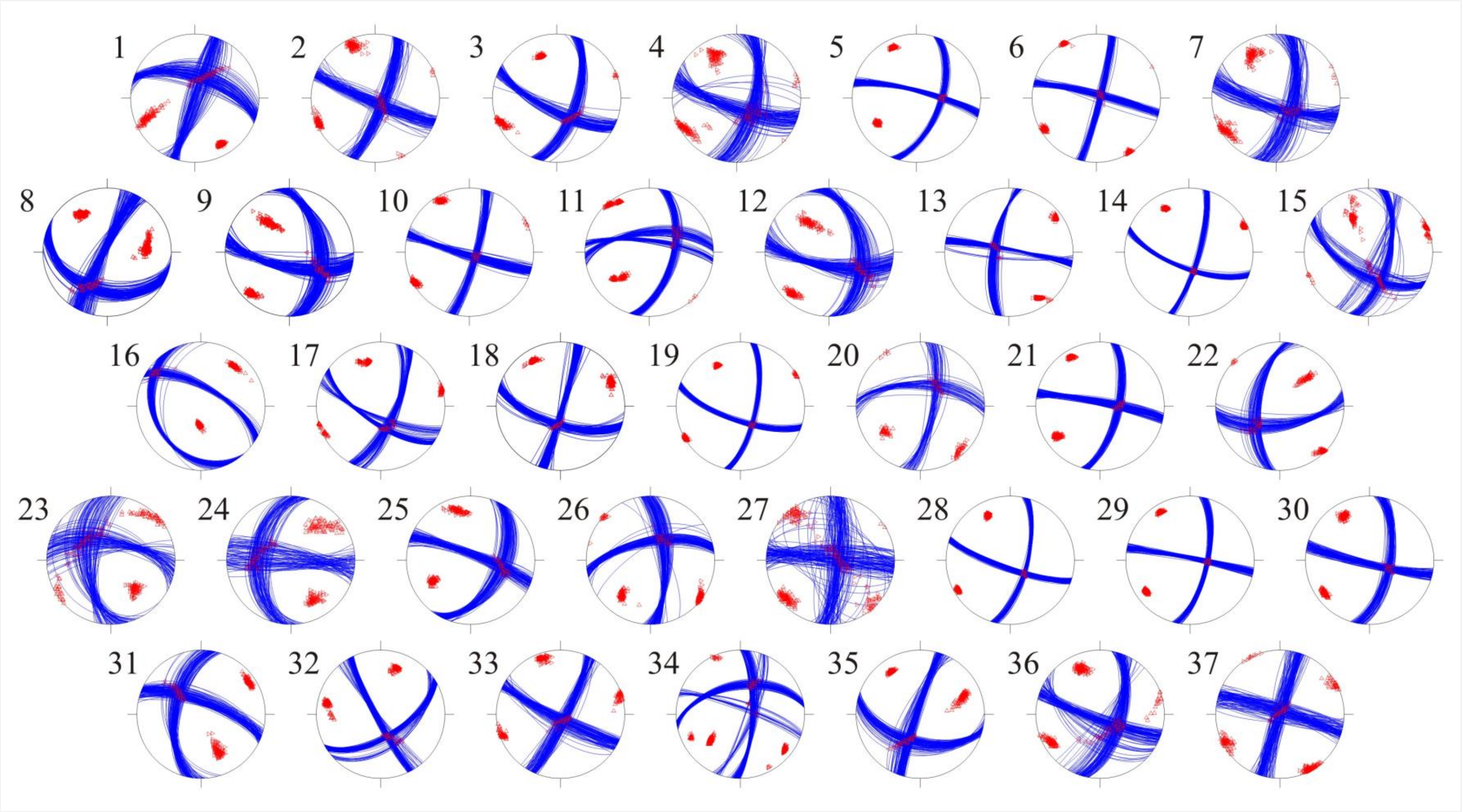
Orientation of the DC informs us about the orientation of fractures

Nodal planes:
fault plane + auxiliary plane

Vavryčuk et al., (Tectonophysics, 2008)

Inversion for stress

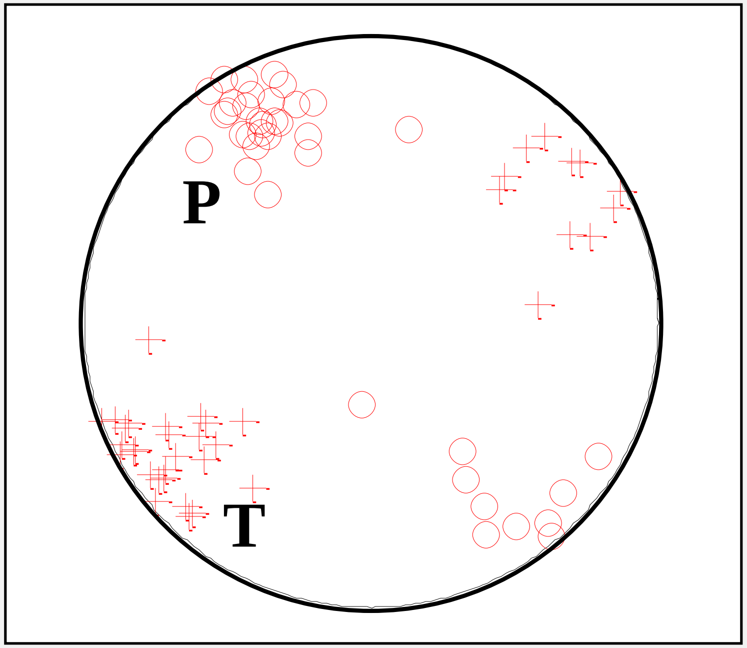
Fluid injection in KTB in 2000: focal mechanisms



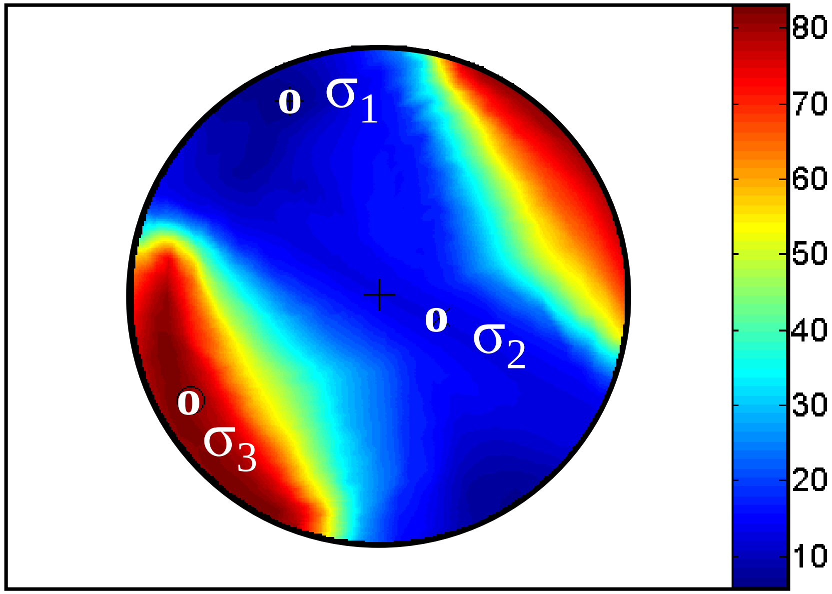
Vavryčuk et al., (Tectonophysics, 2008)

Fluid injection in KTB: stress inversion

P/T axes



stress axes



- directions of principal stress axes
- shape ratio $$R = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$$

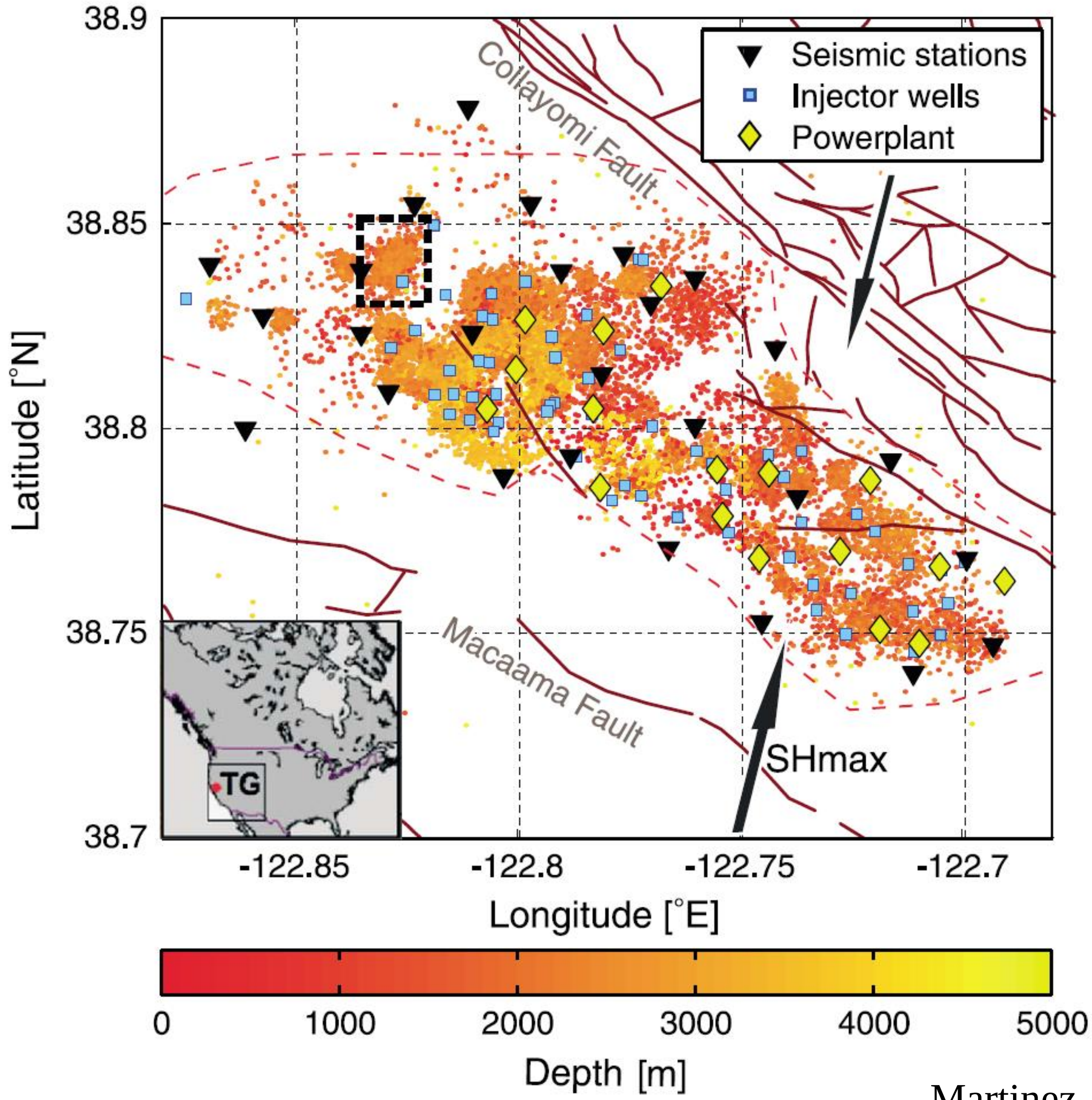
Gephart & Forsyth (1984) stress inversion

Michael (1984)

Angelier (2002)

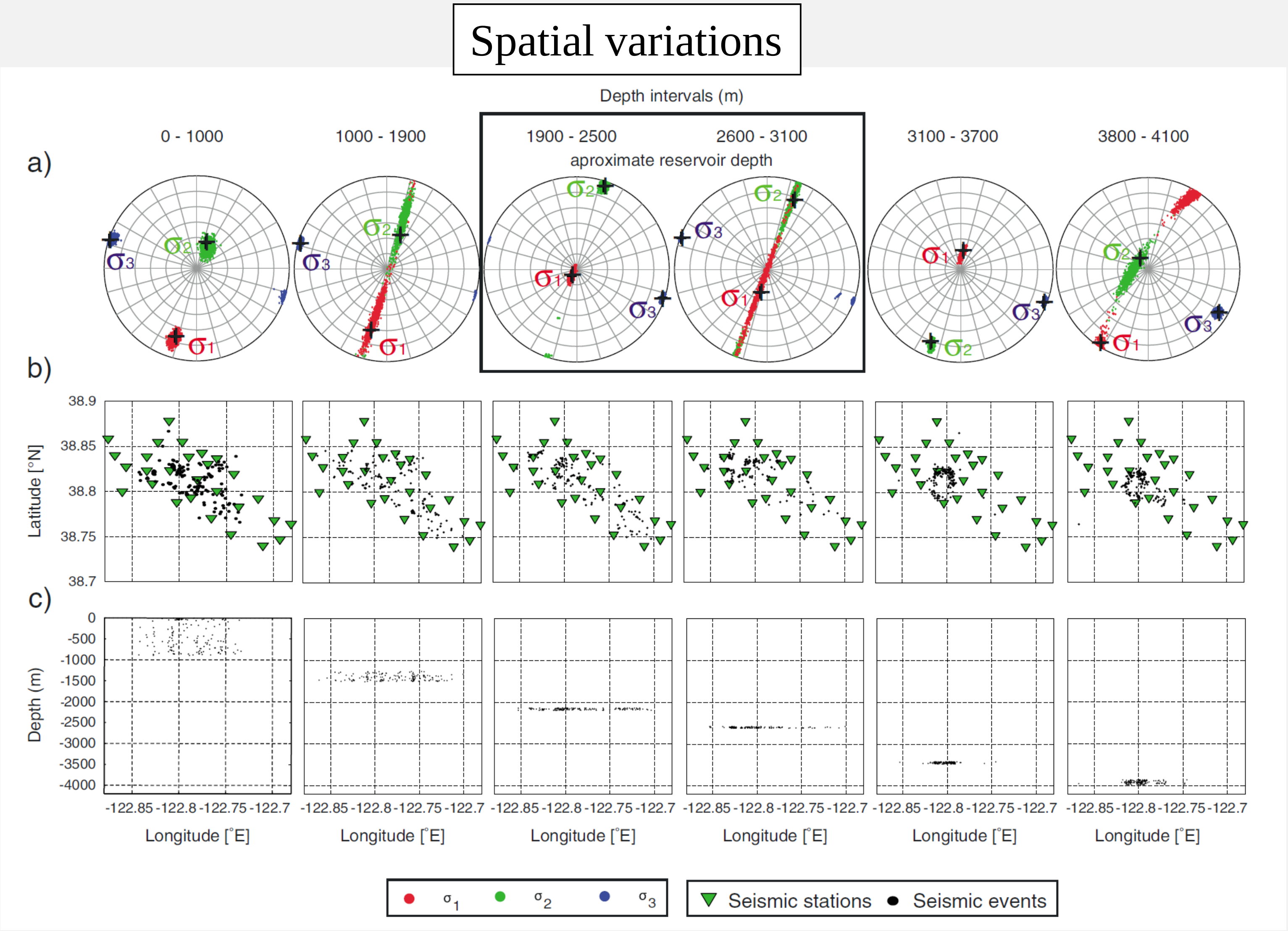
Vavryčuk et al., (Tectonophysics, 2008)

The Geysers geothermal field, CA



Martinez-Garzon et al, (GRL, 2013)

Stress variations in the Geysers geothermal field, CA

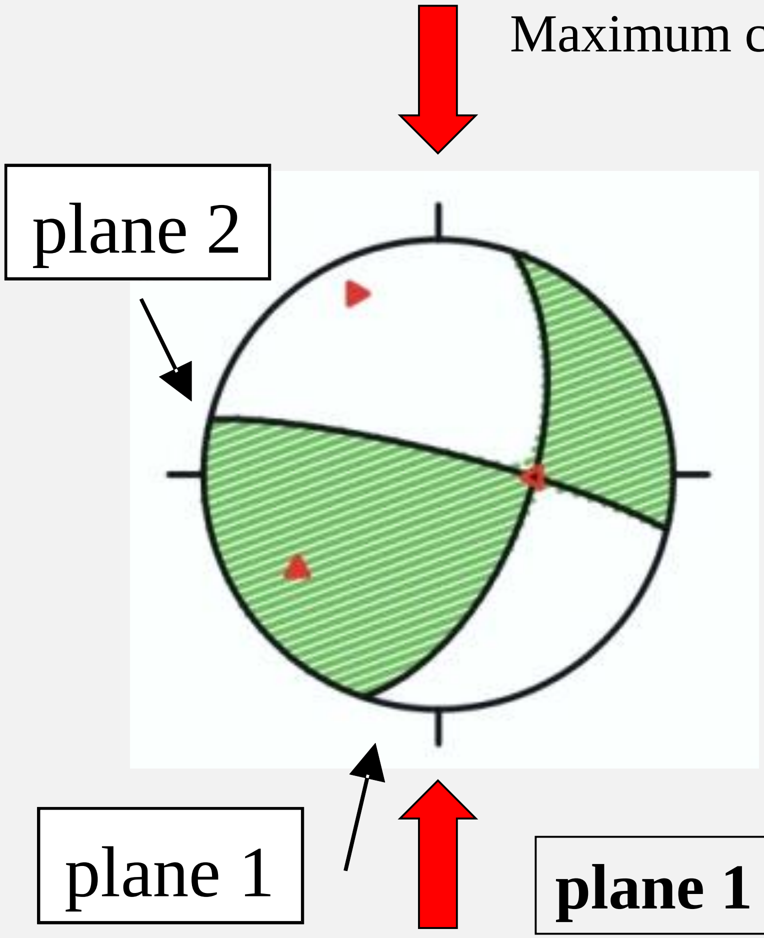


Martinez-Garzon et al, (GRL, 2013)

Fault planes indicated from stress

Fault instability concept

Maximum compression



Optimally oriented fault:

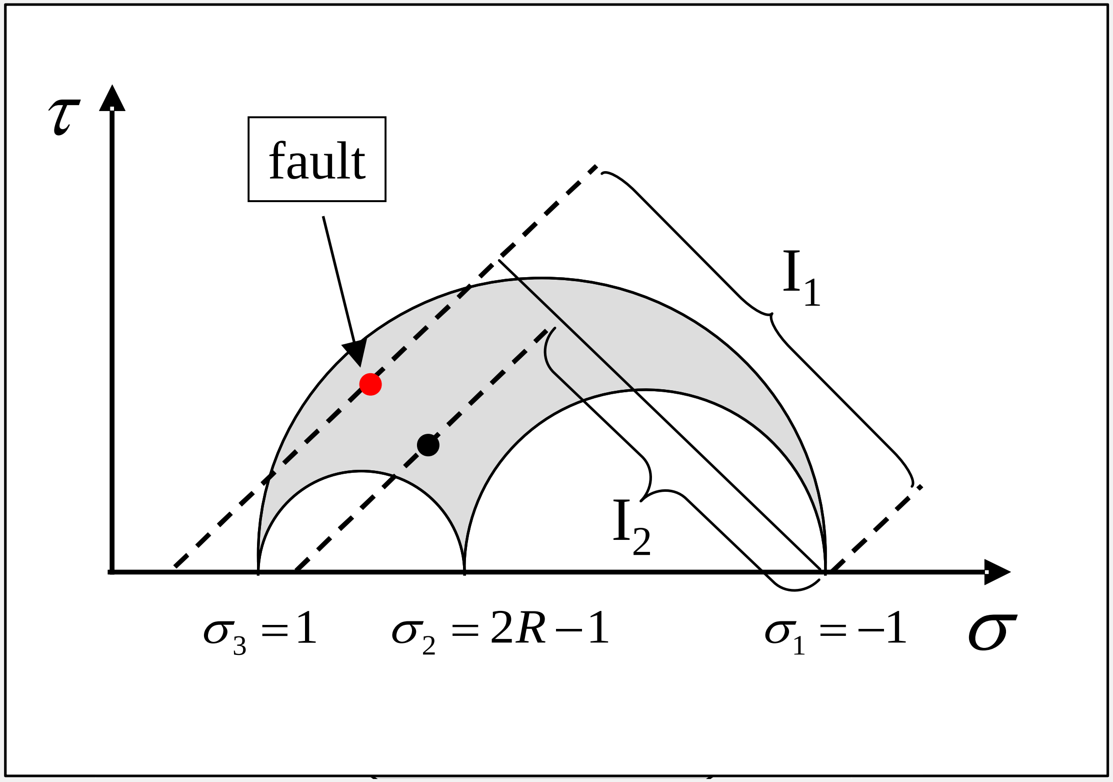
Inclination of about 30º

from the maximum compression

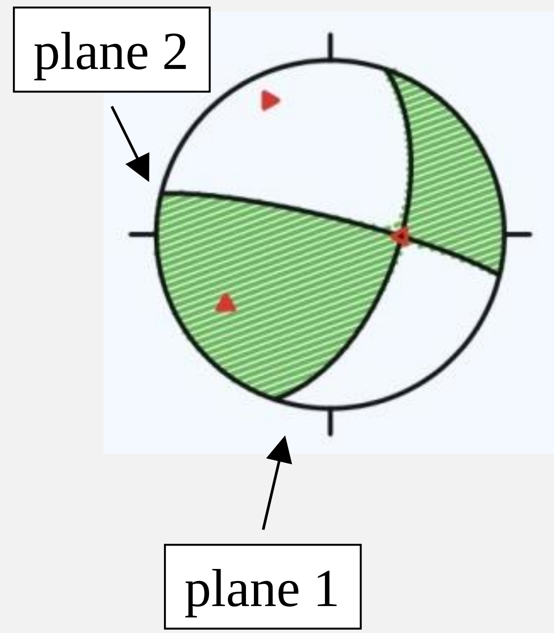
plane 1 is more unstable than plane 2

Fault instability: definition

Normalized stress tensor



$$I = \frac{\tau + \mu(\sigma + 1)}{\mu + \sqrt{1 + \mu^2}}$$

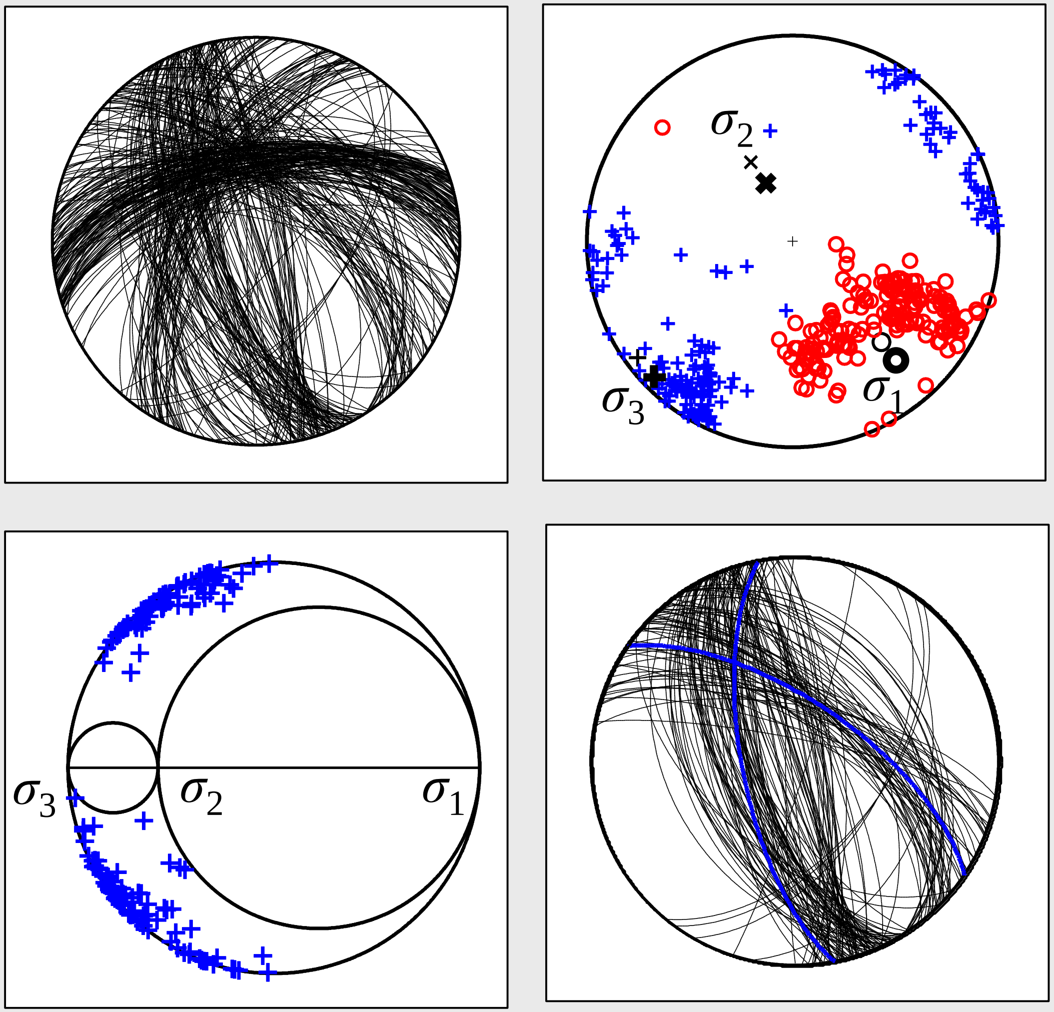


The fault is identified with the nodal plane of the **higher fault instability**

$$I_1 > I_2$$

Vavryčuk et al. (Tectonophysics, 2013)

Joint inversion for stress and fault orientations



Earthquake swarm in West Bohemia in 2008

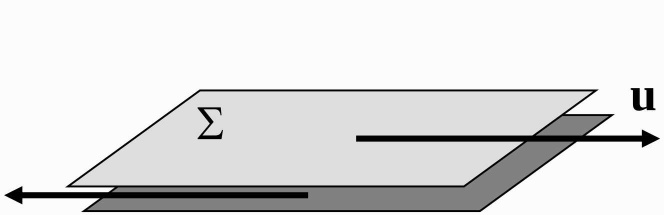
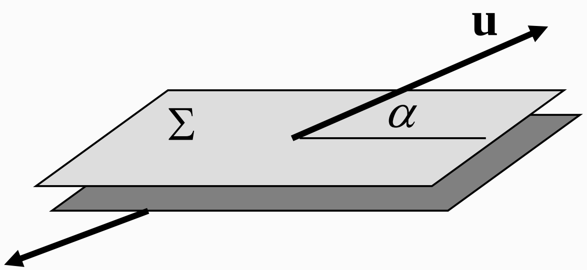
Input data:
focal mechanisms
with no knowledge about
the fault orientations

Output of the inversion:
- stress axes
- shape ratio
- fault orientations

Vavryčuk (GJI, 2014)

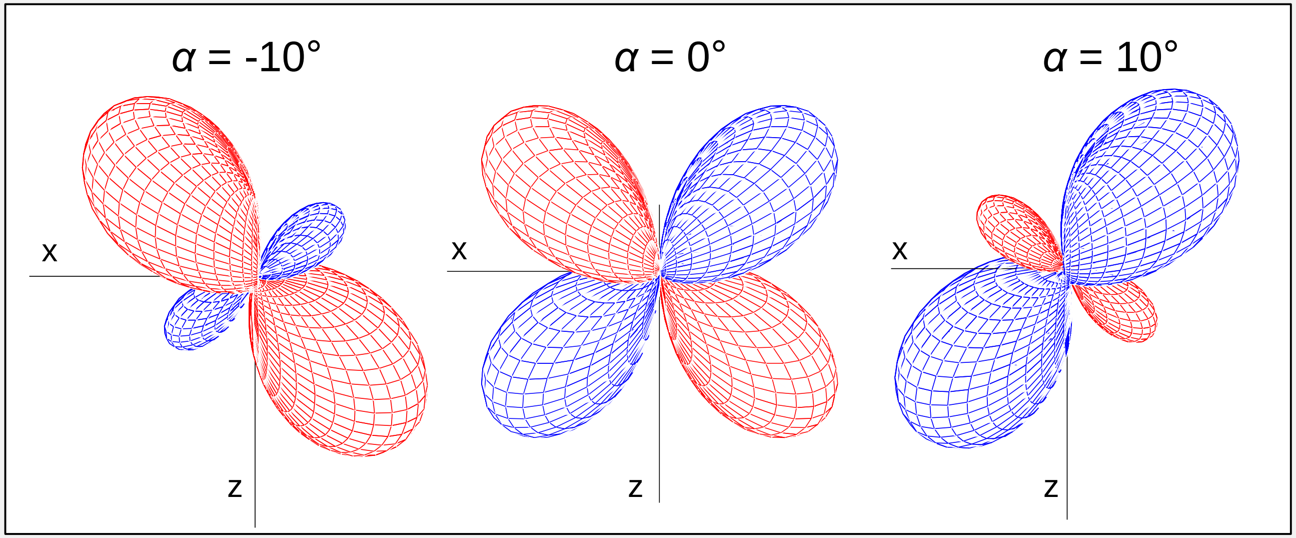
Interpretation of the non-DC part of the moment tensor

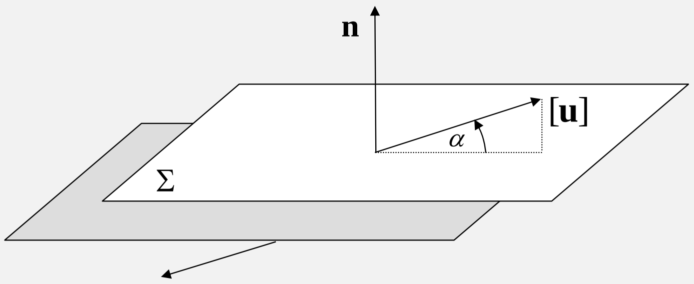
Shear & tensile faulting

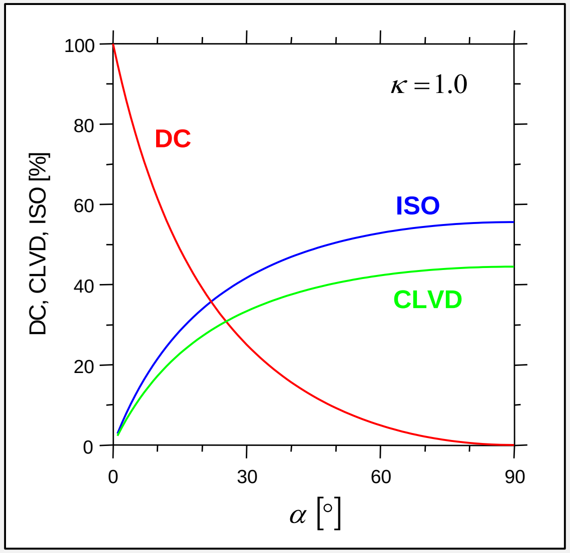
Shear faulting	Tensile faulting
	
Slip is along the fault	Slip is **<u>not</u>** along the fault
Moment tensor is **DC**	Moment tensor is **non-DC** (DC+CLVD+ISO)

Σ – fault , **u** – slip, α – slope angle (deviation of the slip from the fault)

Shear-tensile faulting: radiation patterns and DC





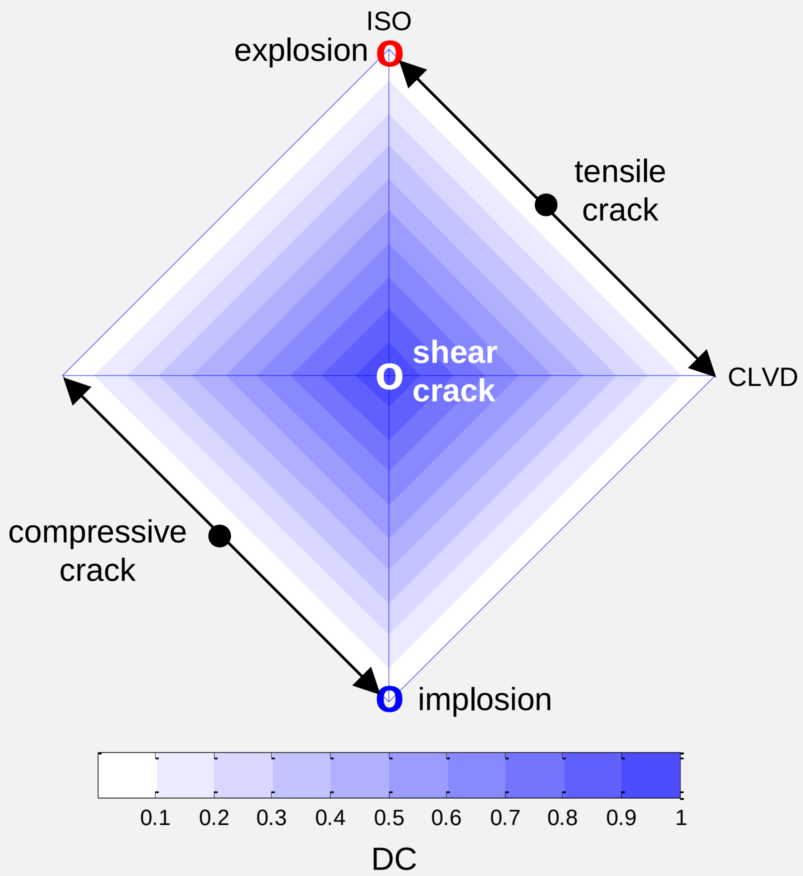


$\alpha = 10^{o}$

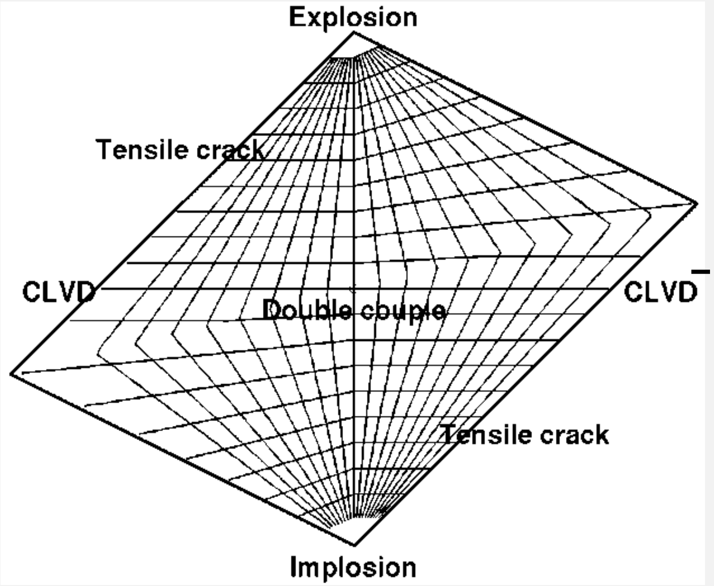
DC = 60 %
non-DC = 40 %

Vavryčuk (JGR, 2001, 2011)

Diamond and skewed diamond source-type plots

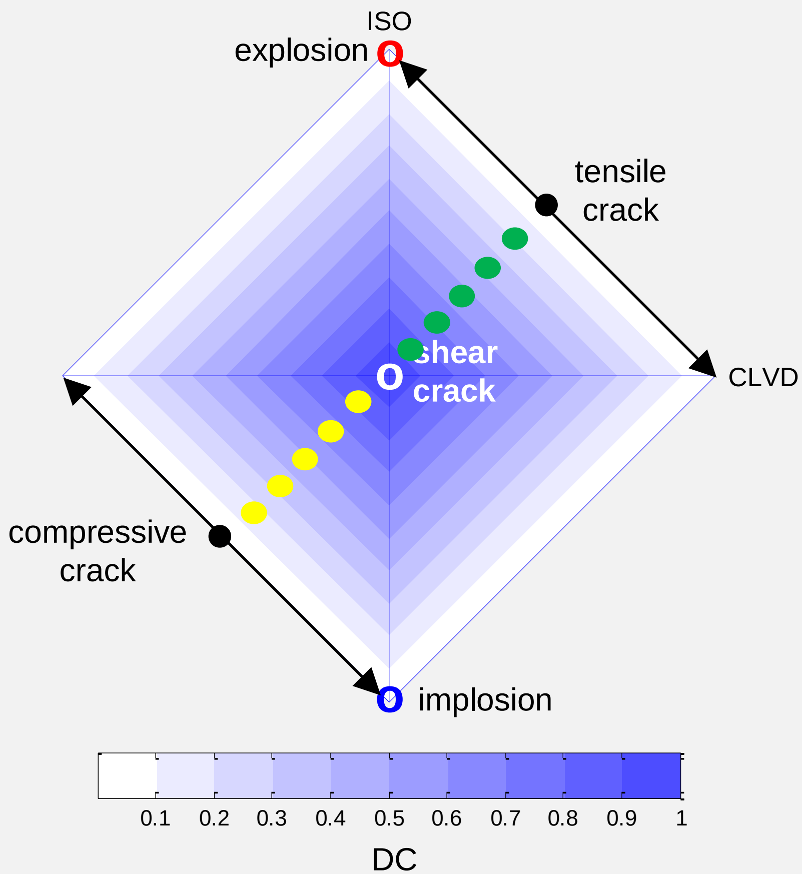


Hudson et al. (1989)

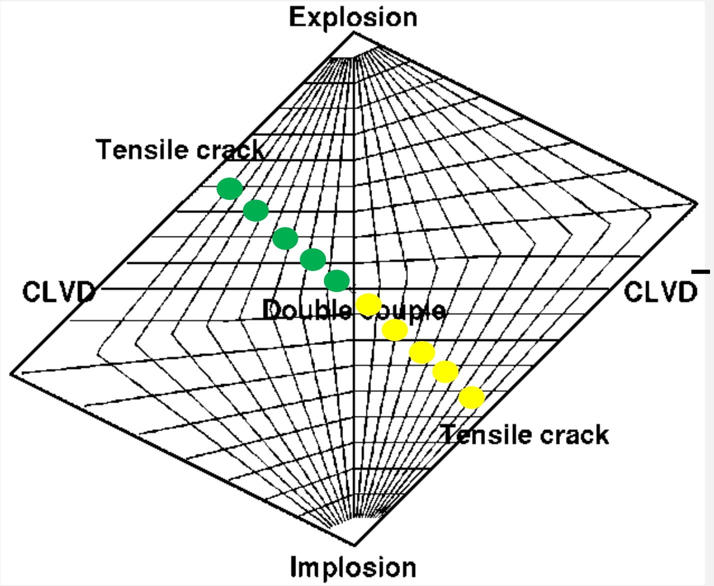


Vavryčuk (J. Seismology, 2014)

Shear-tensile faulting in source-type plots



Hudson et al. (1989)



Vavryčuk (J. Seismology, 2014)

Tensile faulting versus anisotropy

Moment tensors of shear faulting in anisotropy

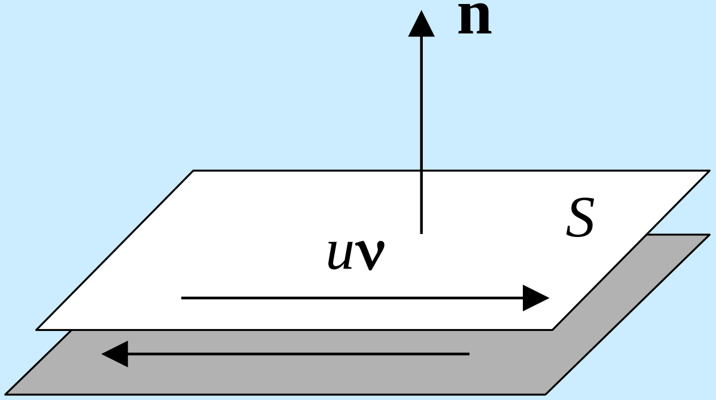
Shear earthquakes in anisotropy

(Aki & Richards 2002, Eq. 3.19):

$$M_{kl} = uSc_{ijkl}\nu_k n_l$$

$$M_{kl} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{bmatrix}$$

general mechanism with non-zero DC, CLVD and ISO!



u – slip
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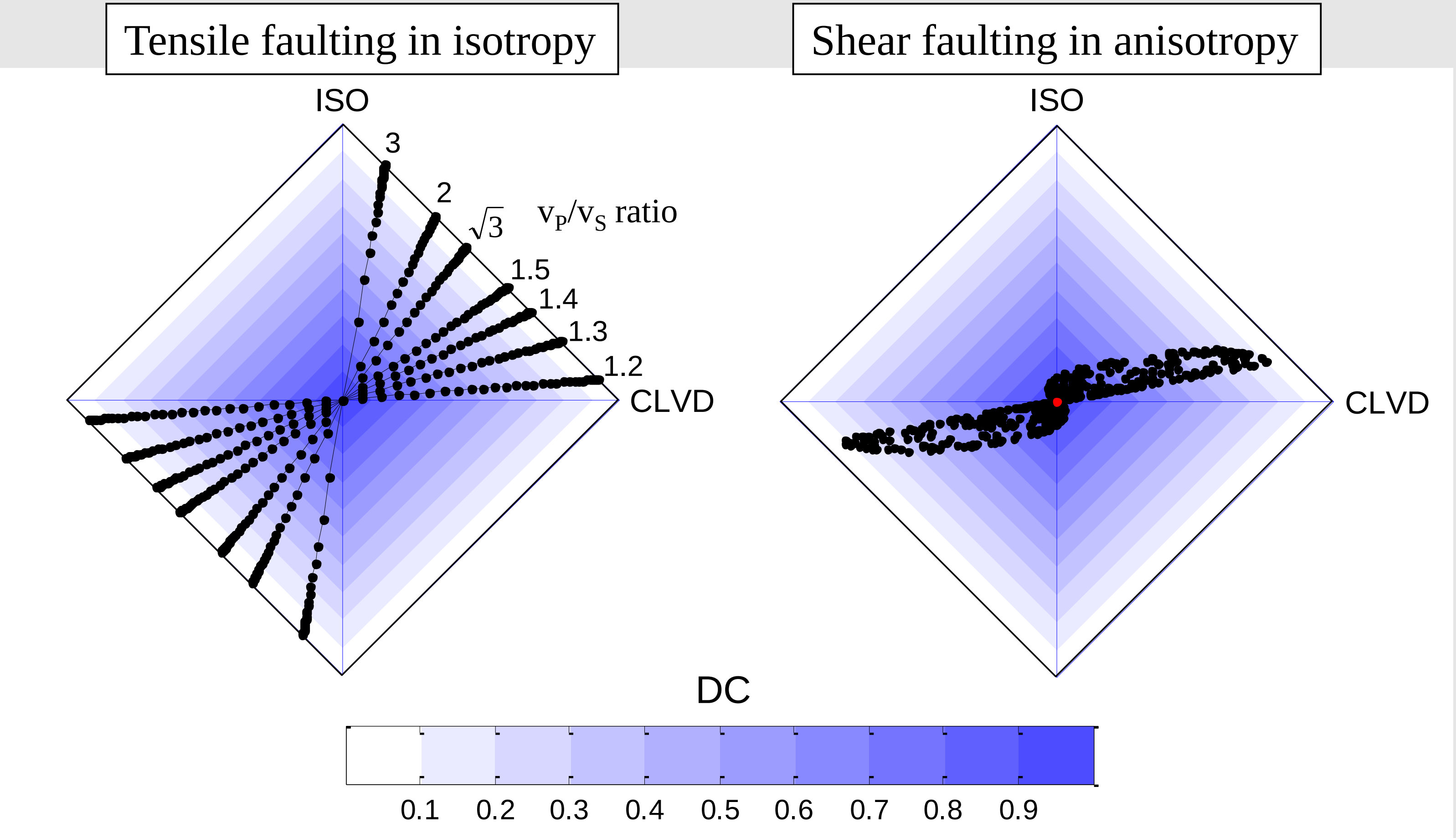
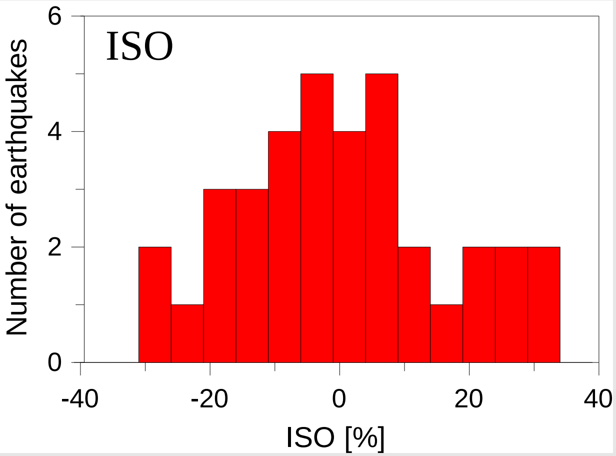
Tensile faulting in isotropic and anisotropic media

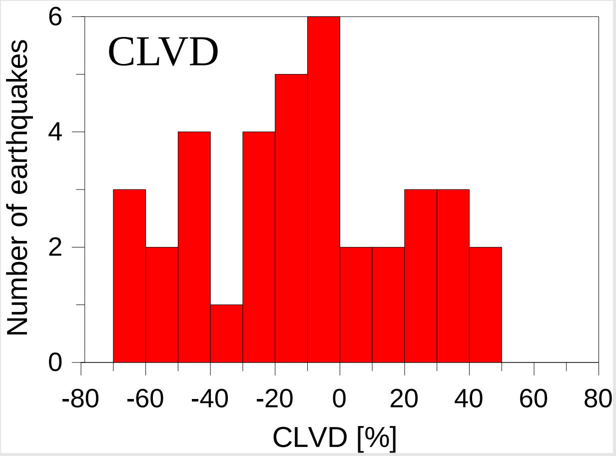


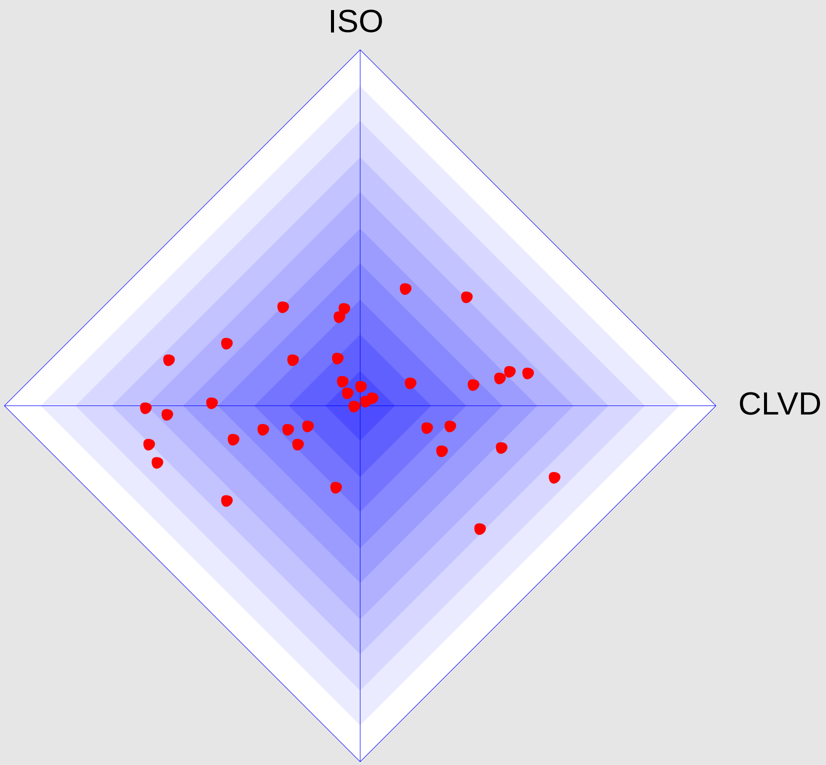
Anisotropy: Bazhenov shale, see Vernik and Liu (1997)

Vavryčuk (J. Seismology, 2014)

Non-DC components: KTB injection experiment



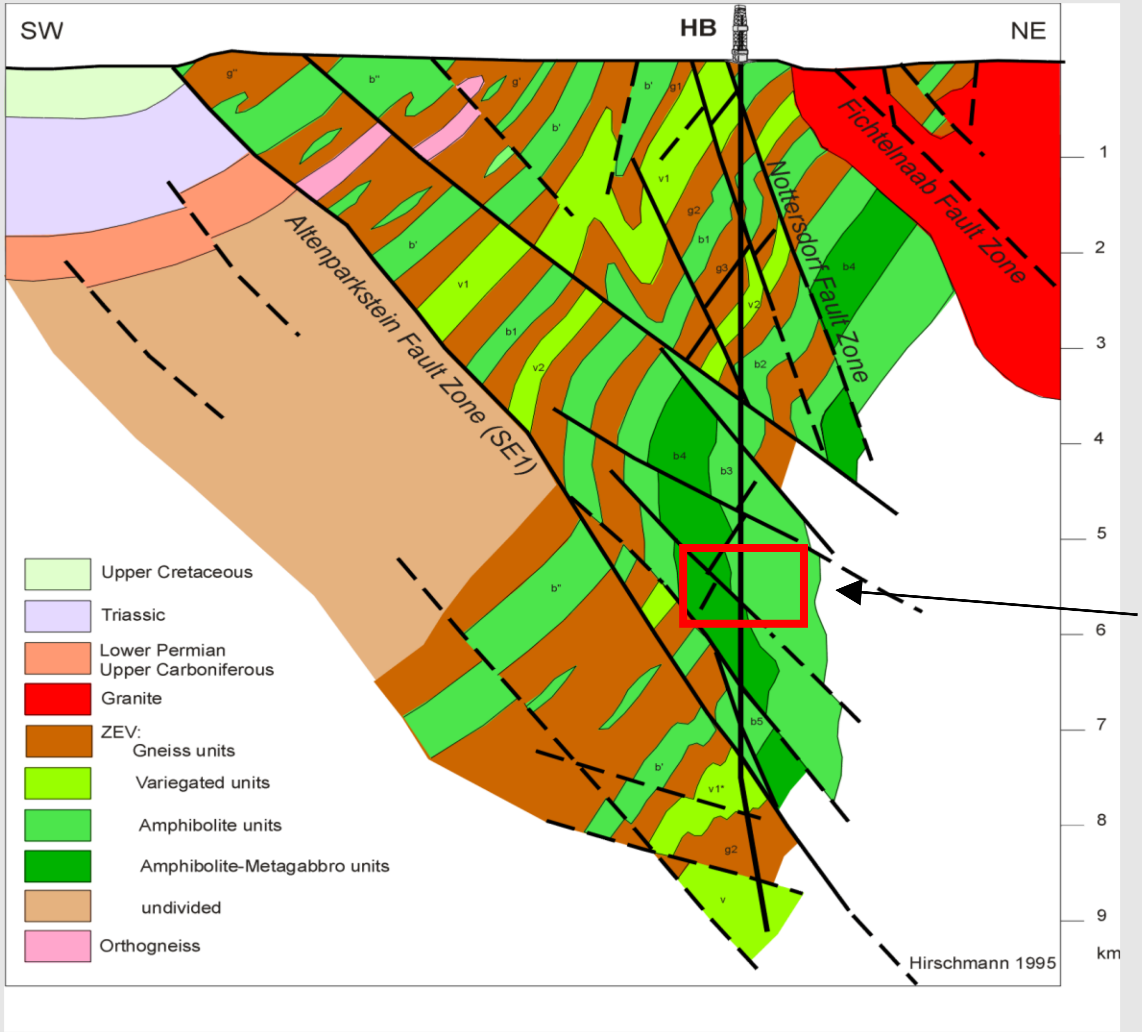




38 events from the 2000 fluid injection experiment in KTB

Vavryčuk et al., (Tectonophysics, 2008)

Geological structure in KTB

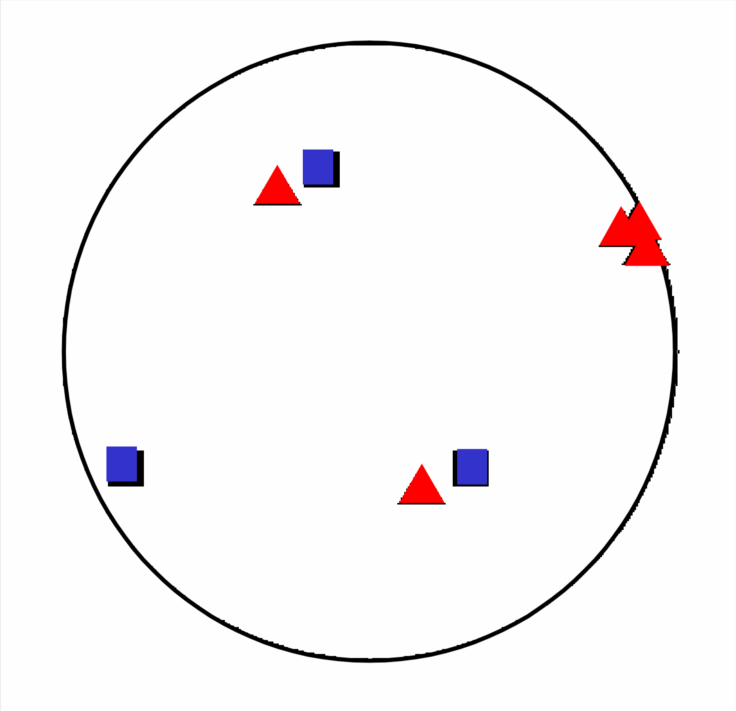


Inclined anisotropic structures:
amphibolite, gneiss

area of study

Hirschmann (Tectonophysics, 1995)

Retrieved orientation of anisotropy in KTB



▲ optimum orientation from moment tensors

■ orientation from MSP Rabbel et al. (2004)

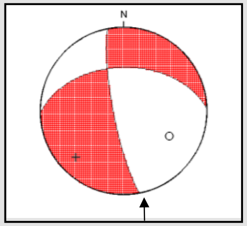
Anisotropy axes (plunge/azimuth):
Axis 1: 5º/65º, Axis 2: 50º/160º, Axis 3: 40º/330º

Vavryčuk et al., (Tectonophysics, 2008)

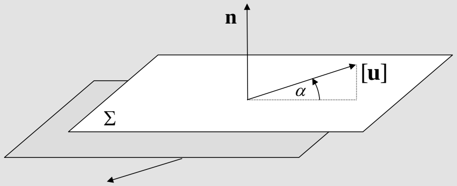
Summary

Summary

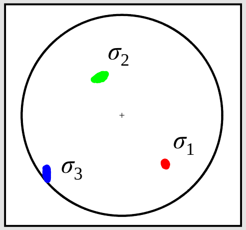
Moment tensors provide key information about induced seismicity:



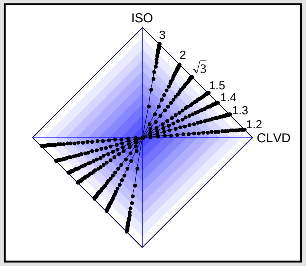
Size and orientation of fractures



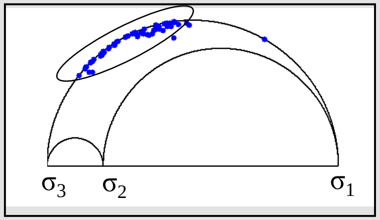
Fracture mode: shear versus tensile faulting



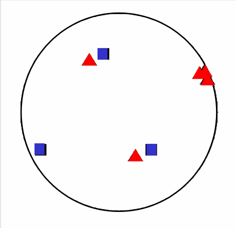
Stress regime in the source area



v_P/v_S ratio in the focal zone



Fracture instability



Orientation of anisotropy