Interpretation of non-DC components of MTs: A review

Václav Vavryčuk

Institute of Geophysics, Prague

Definition
and
basic characteristics

Significance of moment tensor

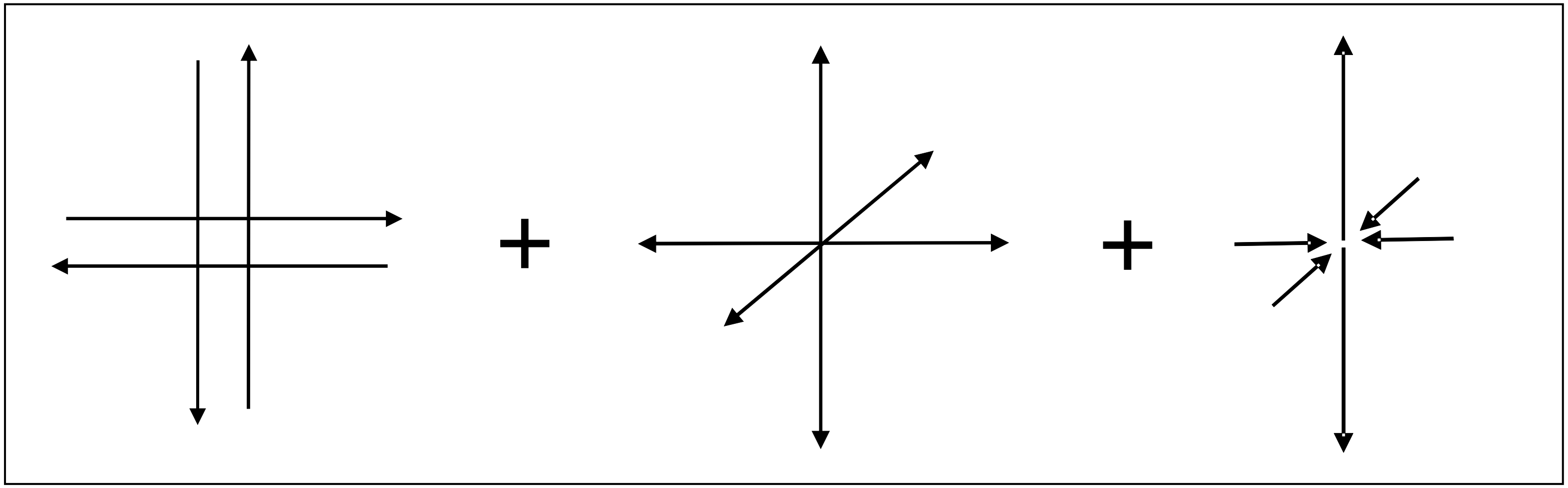
Representation theorem

$$u_i(\mathbf{x}, t) = M_{nk} * G_{in,k}$$

displacement — moment tensor — Green's function

MT decomposition

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



DC — **shear**

ISO — **non-shear**

CLVD — **non-shear**

Moment tensor in isotropic media

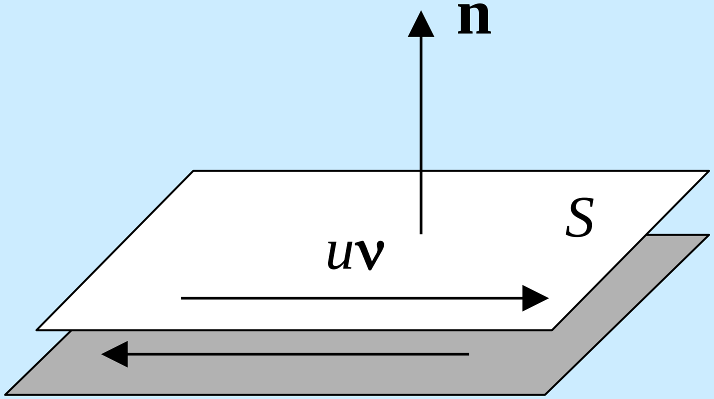
Shear earthquakes in isotropy

(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 (DC)

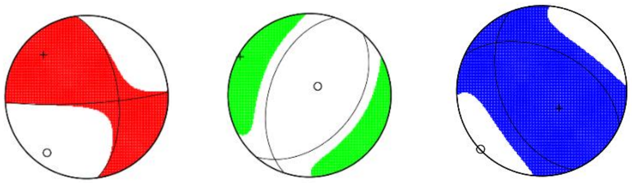


u – slip
S – fault area
μ – shear modulus
$\boldsymbol{\nu}$ – slip direction
$\mathbf{n}$ – fault normal
c_{ijkl} – elastic parameters

Basic characteristics of non-DC components

Indications of non-DC:

- P-wave radiation pattern
- anomalous P/S amplitude ratio



Areas with non-DC seismicity:

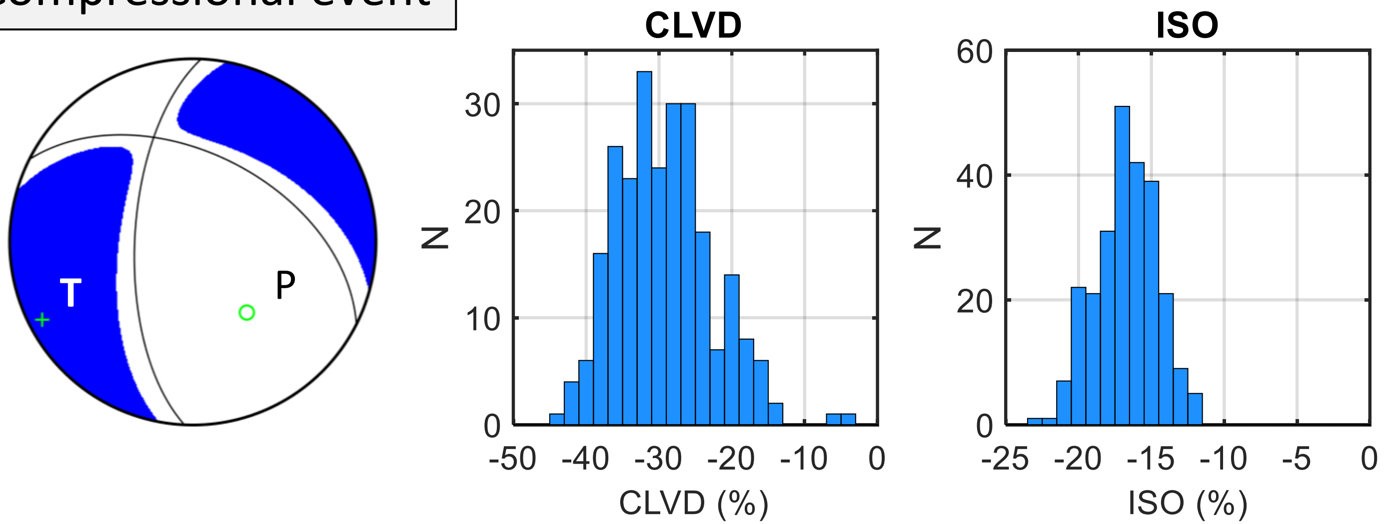
- geothermal and volcanic regions,
- complex fractured zone with interacting fault segments
- steep slopes with landslides
- subducting slabs
- mines, oil and gas fields

Physical processes

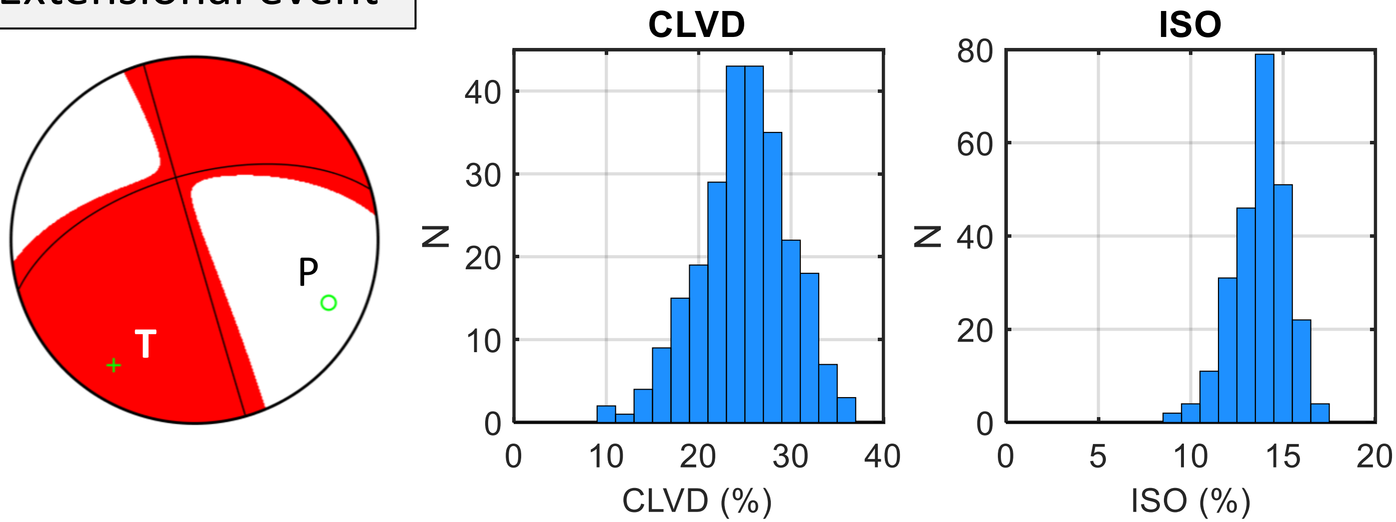
- magma and fluid flow in rocks
- stress anomalies related to complex fault geometry
- tensile stress regime
- shear faulting in anisotropic focal zone
- anthropogenic activities (hydrofracking, fluid injection, fluid extraction, mining, chemical and nuclear explosions)

Example 1: non-DC earthquakes in West Bohemia

Compressional event



Extensional event

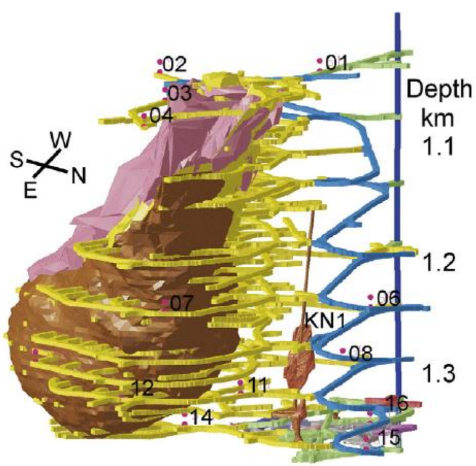


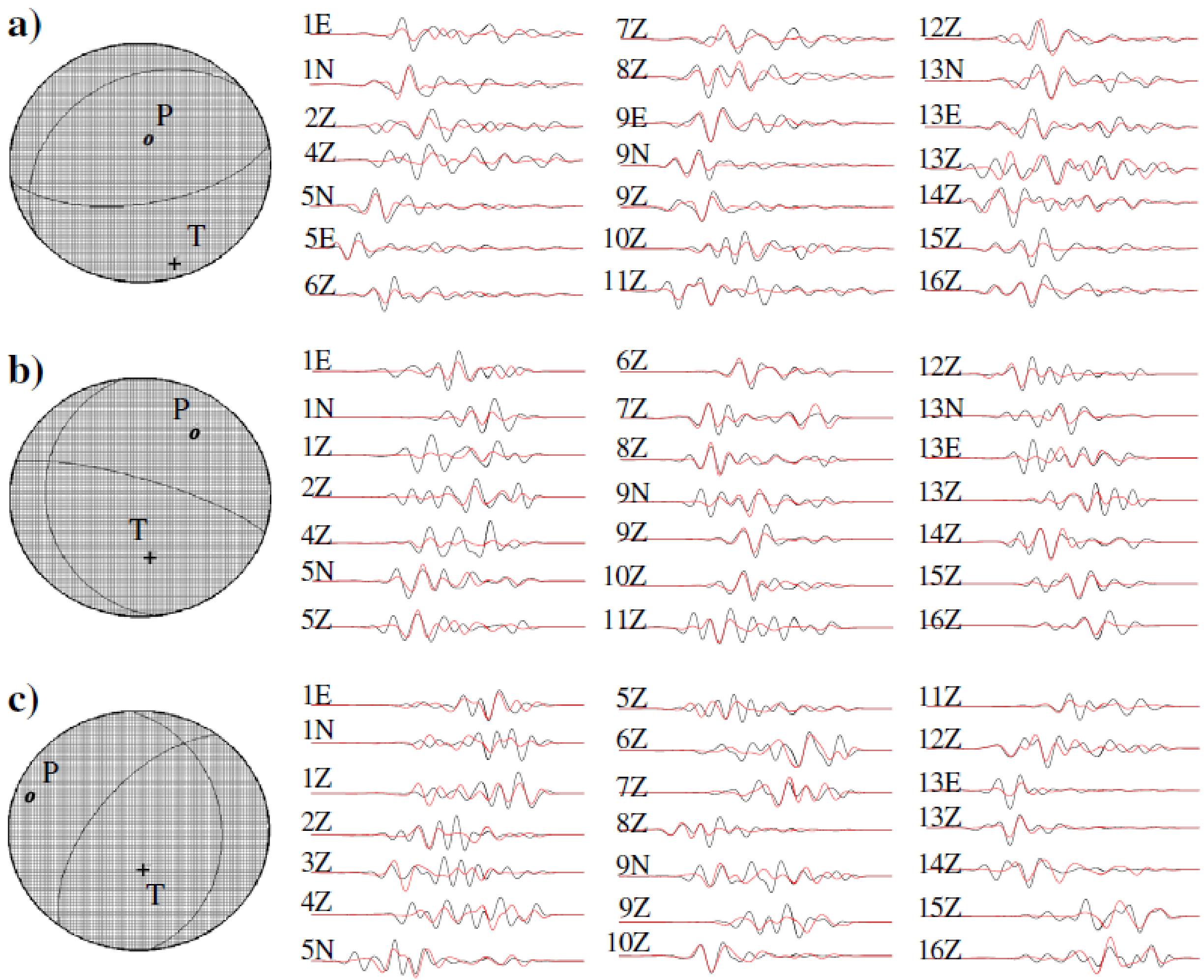
Example 2: Non-DC events in mines

Explosions in mines

Pyhasalmi ore mine, Findland

- depth of 1.4 km
- ore forms a potato-shaped body
- 16 geophones (4.5 Hz)
- sampling rate - 3000 Hz



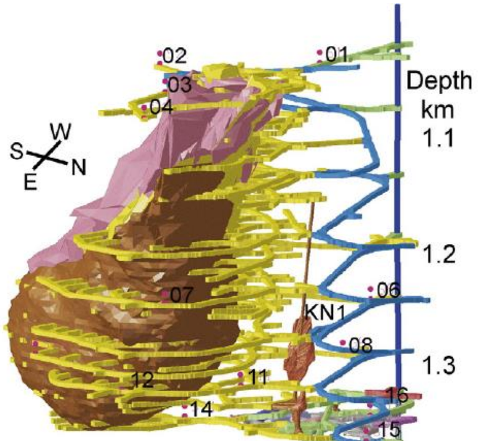


Kuehn & Vavryčuk, Tectonophysics, 2013

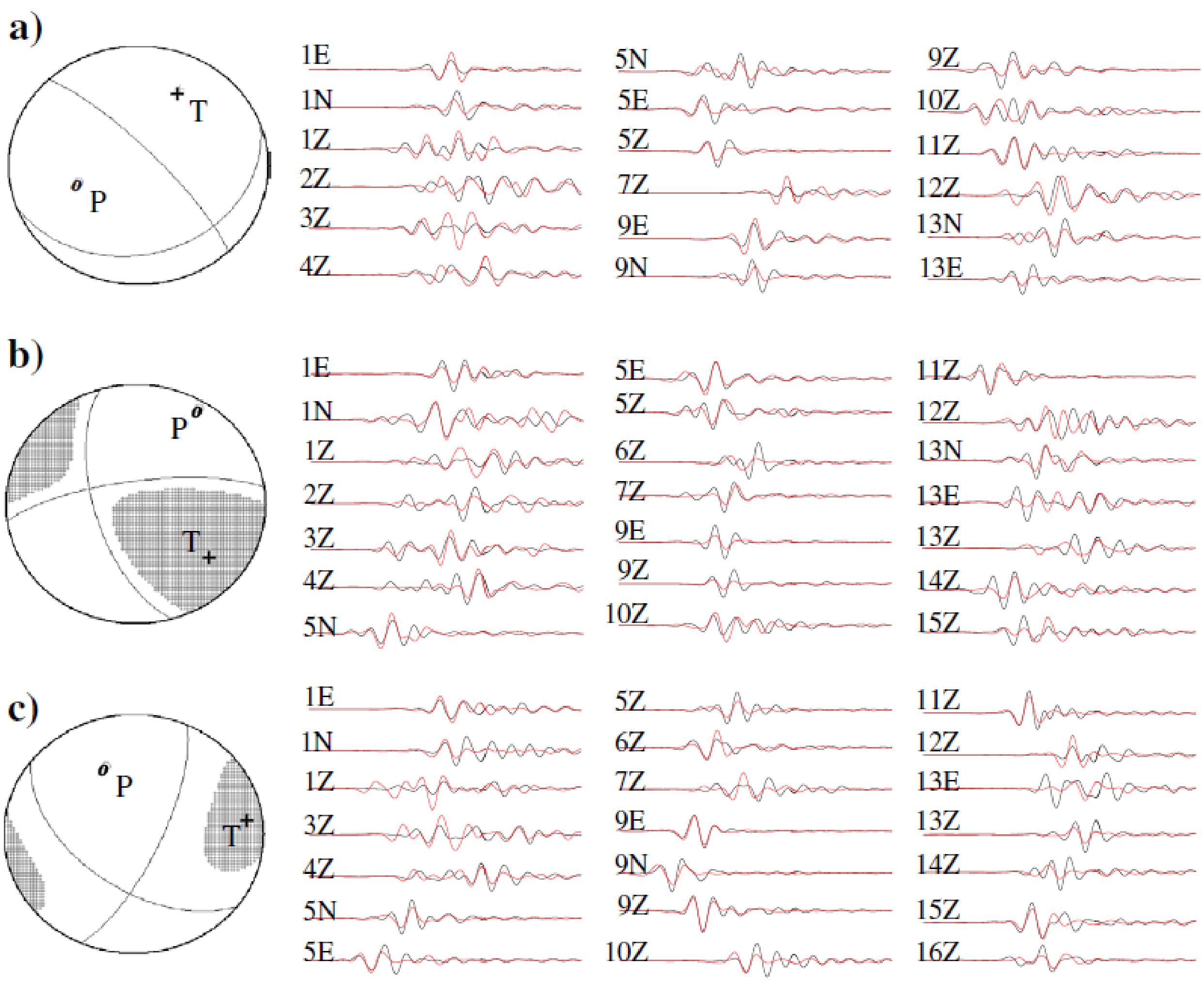
Example 3: Non-DC events in mines

Pyhasalmi ore mine, Findland

- depth of 1.4 km
- ore forms a potato-shaped body
- 16 geophones (4.5 Hz)
- sampling rate - 3000 Hz



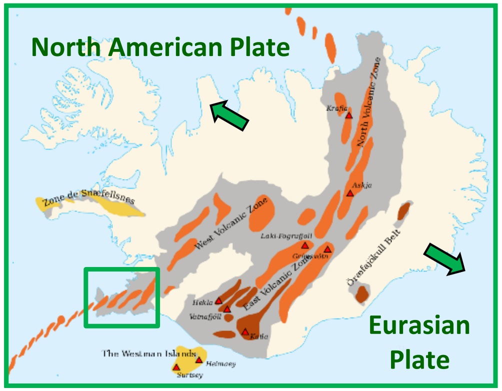
Rockbursts in mines



Kuehn & Vavryčuk (Tectonophysics, 2013)

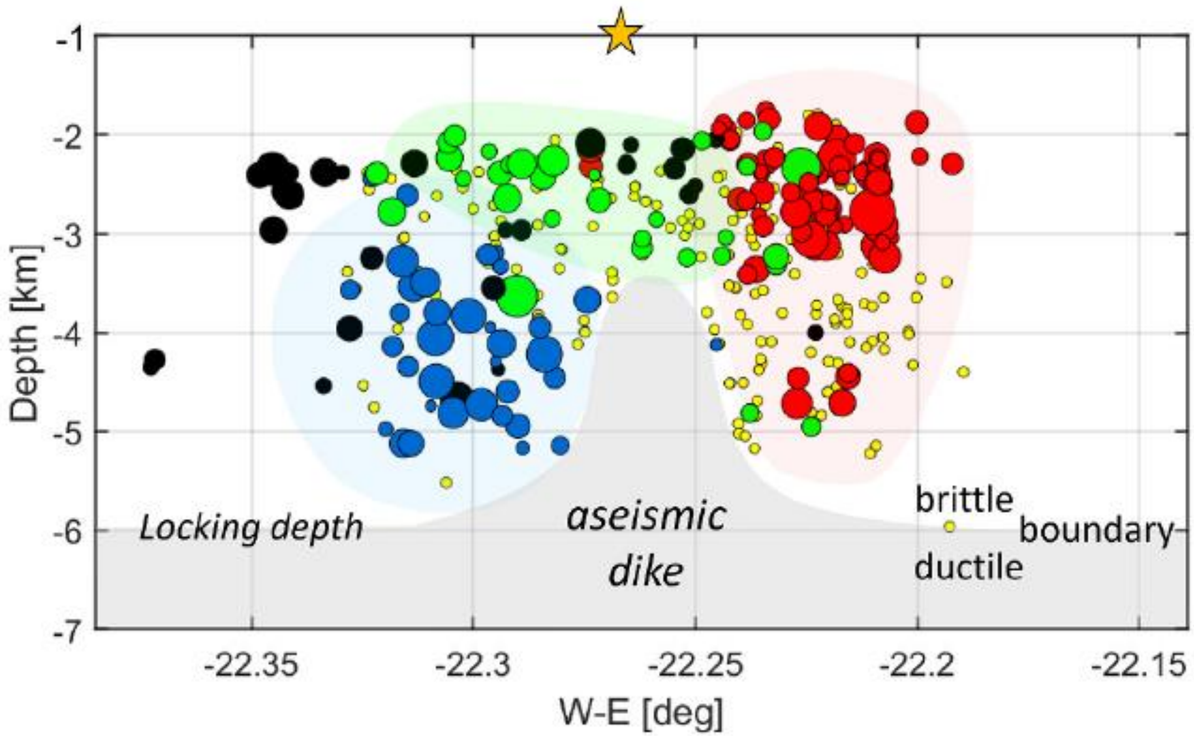
Example 4: Non-DC events in Iceland volcanic region

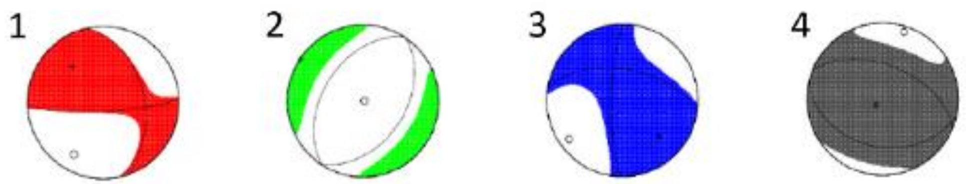
Seismicity in Reykjanes Penninsula before the 2021 Fagradalsfjall volcano eruption



Mid-Atlantic Ridge – slow-spreading rift

REYKJANET network
16 BB local seismic stations
sampling rate 250 Hz
epicentral distance:
up to 20-25 km





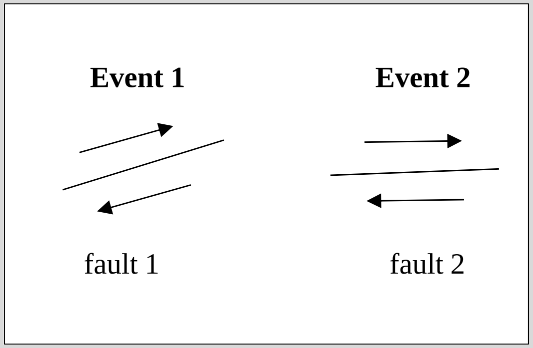
Hrubcová & Vavryčuk (EPSL, 2022; Tectonophysics, 2023)

Non-DC components: irregular fault geometry

Complex shear faulting: schemes

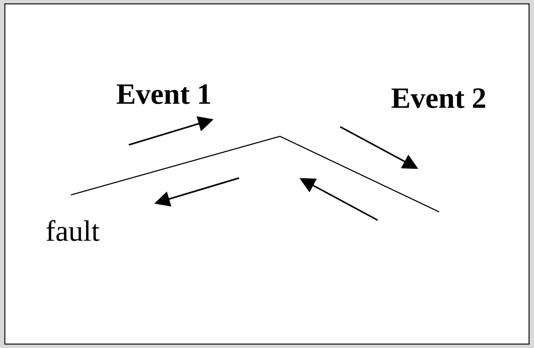
Multiple (non-interacting) events

- subsequent independent events
- simultaneous occurrence in time
- different faults



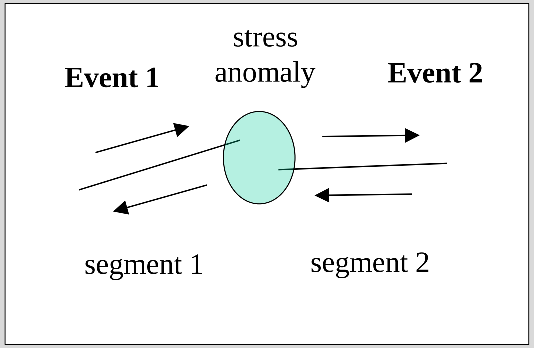
Irregular fault geometry

- smooth bending of faults
- sharp bending of faults
- differently oriented segments

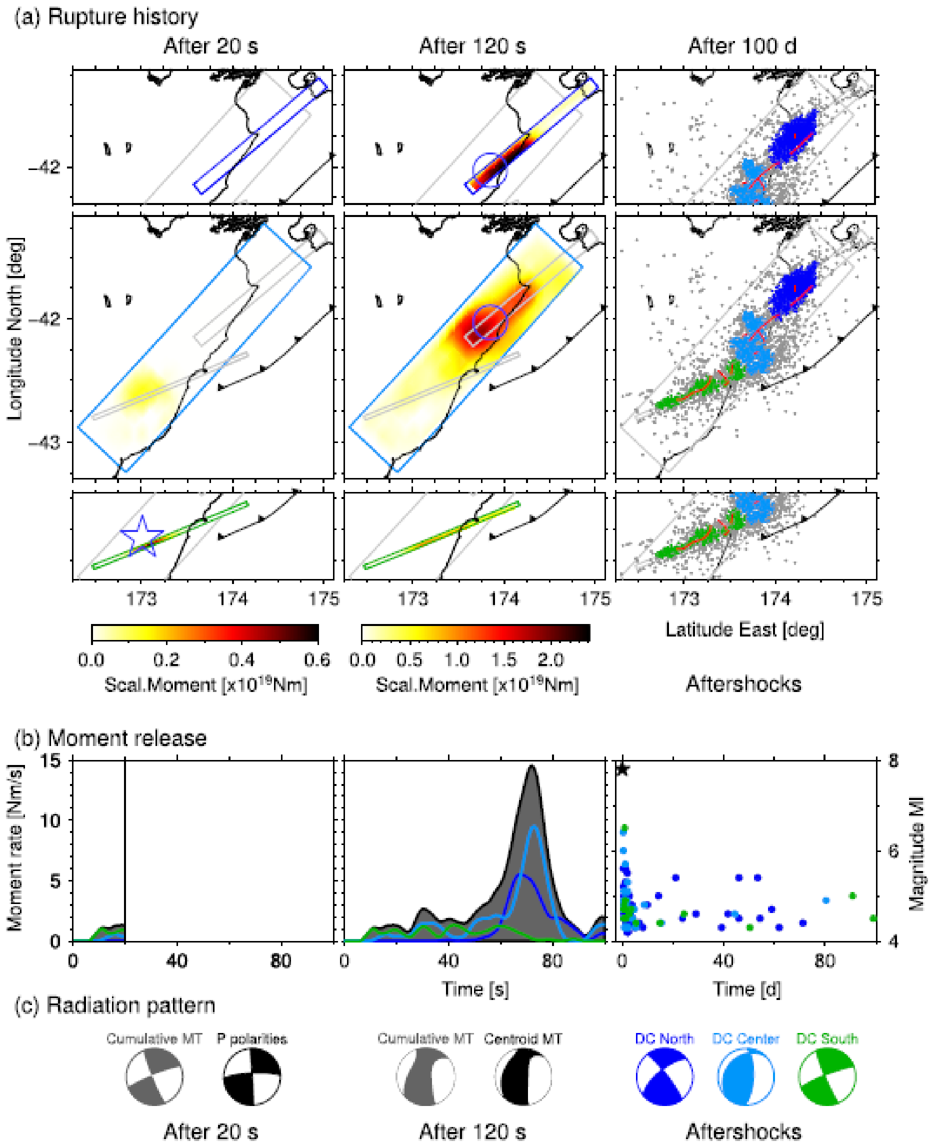


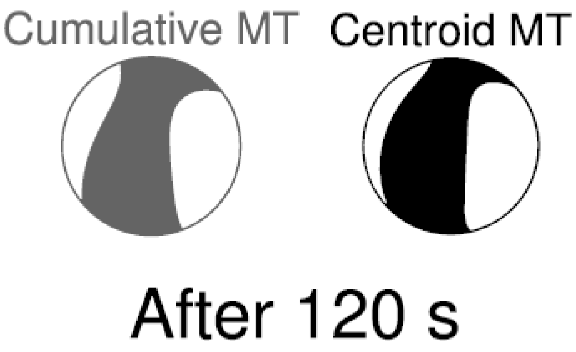
Fault segment interaction

- isolated interacting segments
- fault steps
- local stress anomaly due to interaction



Complex shear faulting: fault steps





Mw 7.8 2016 Kaikoura earthquake, New Zealand

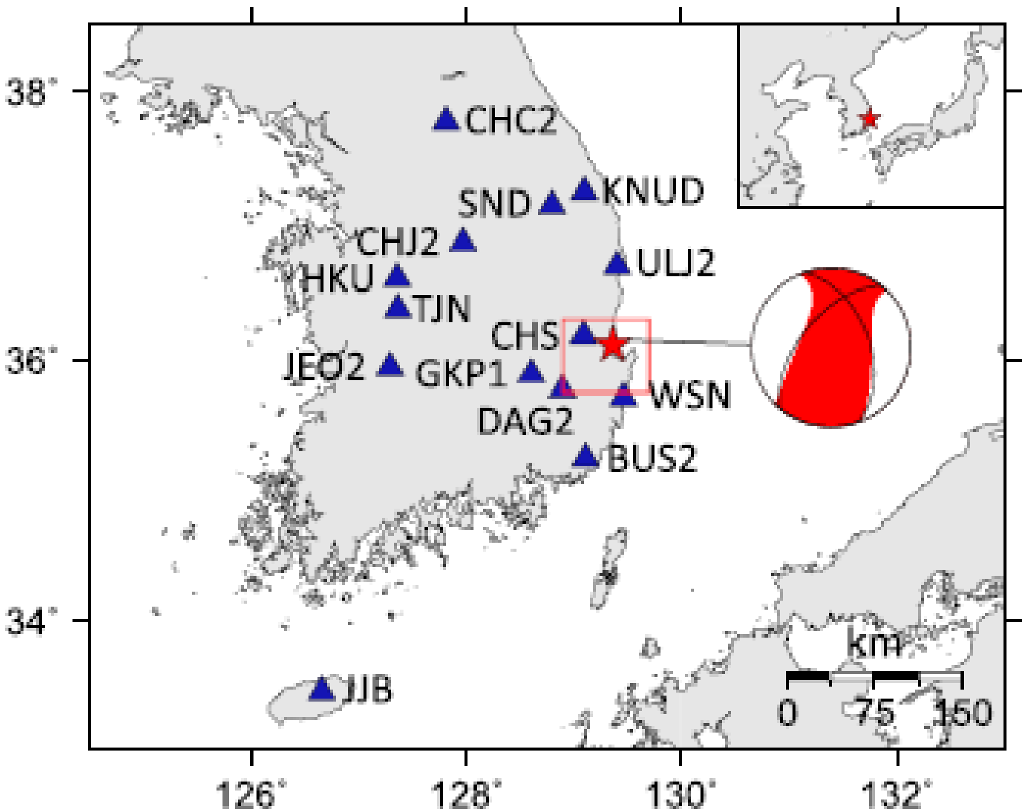
- depth of 15 km
- surface deformations
- uplift up to 8 m
- interaction of two faults

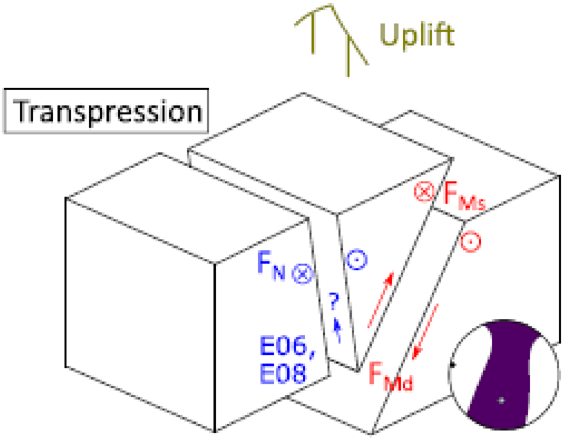
Cesca et al. (EPSL, 2017)

Complex shear faulting: activation of several fault segments

2017 Pohang earthquake (Mw 5.4)

- triggered by fluid injections in a geothermal reservoir



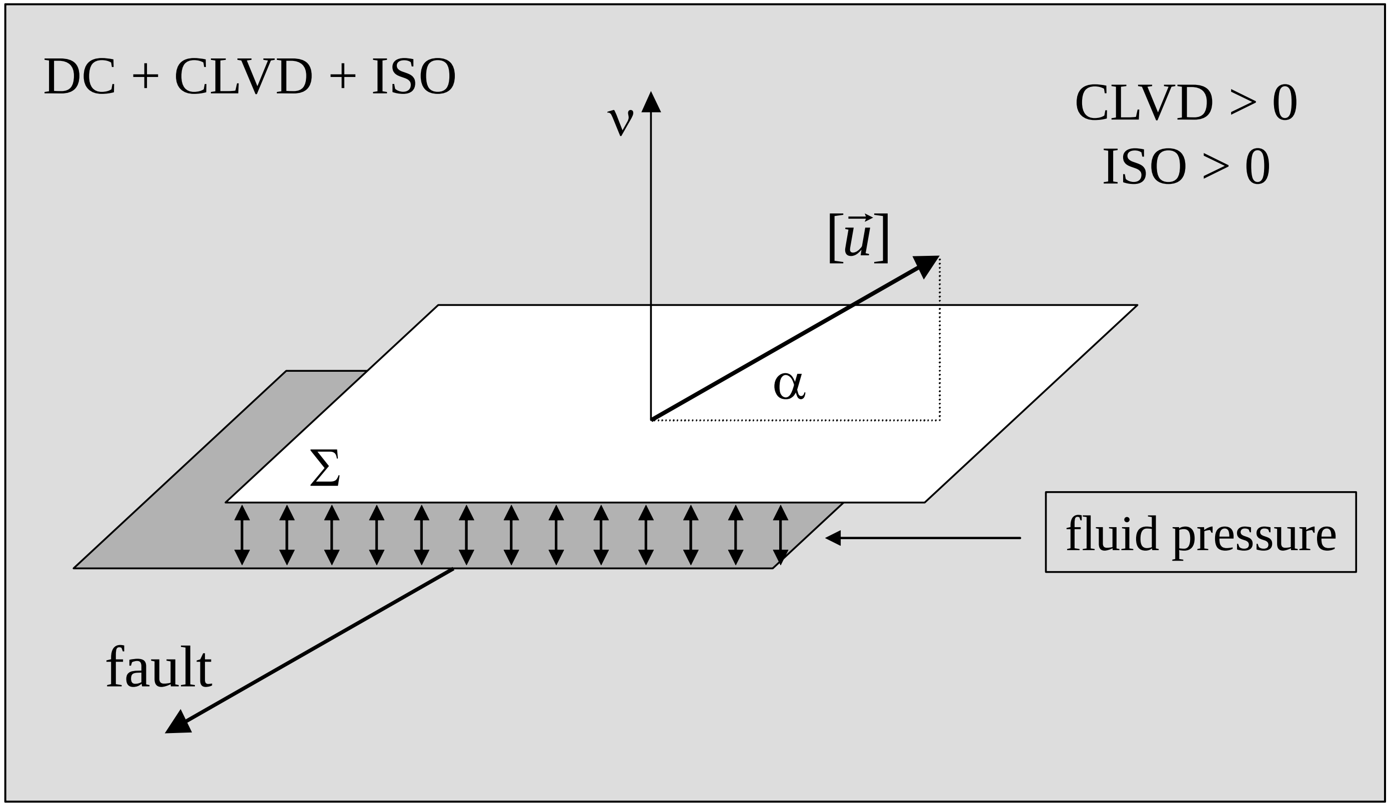


- oblique contraction
- joint movement of two intersecting faults
- reverse and strike slip movements

Son et al. (JGR, 2020)

Non-DC components: tensile/compressive faulting

Opening or closing of a fault during shear rupture

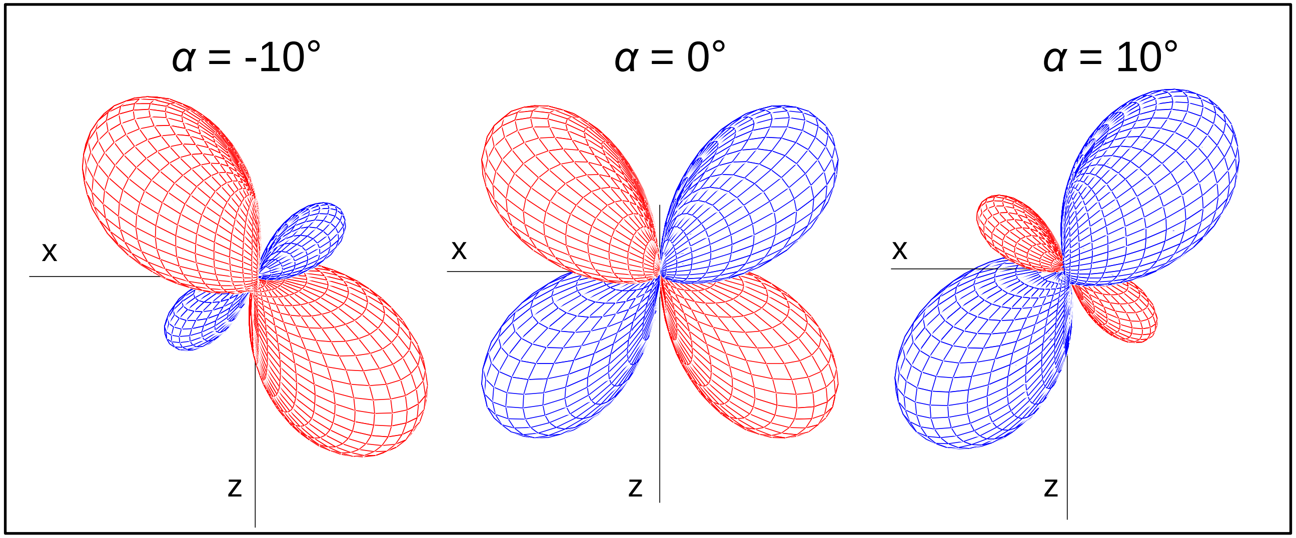


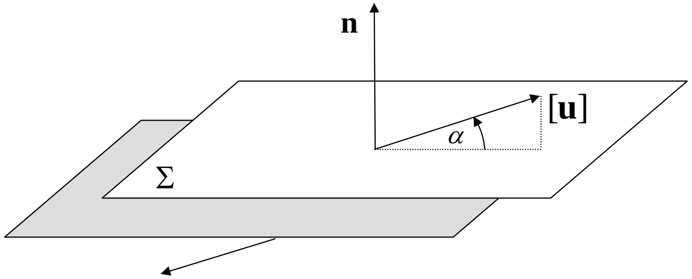
Example: hydrofracturing

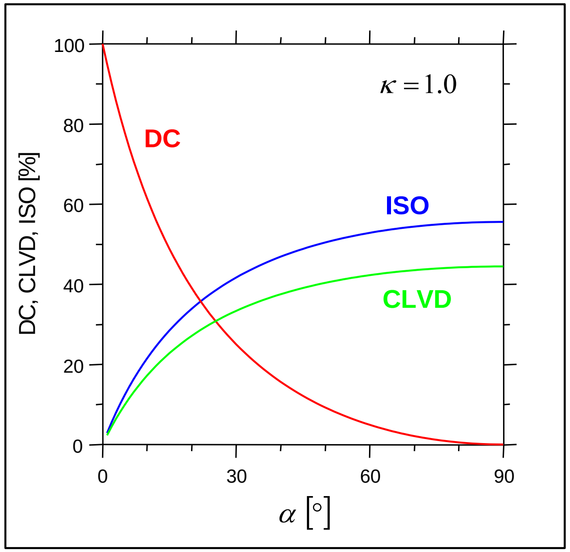
- high pore pressure can cause opening faults during the rupture process
- CLVD and ISO are positive

Shear-tensile faulting: radiation pattern

Radiation psttern as a function of the slip deviation α





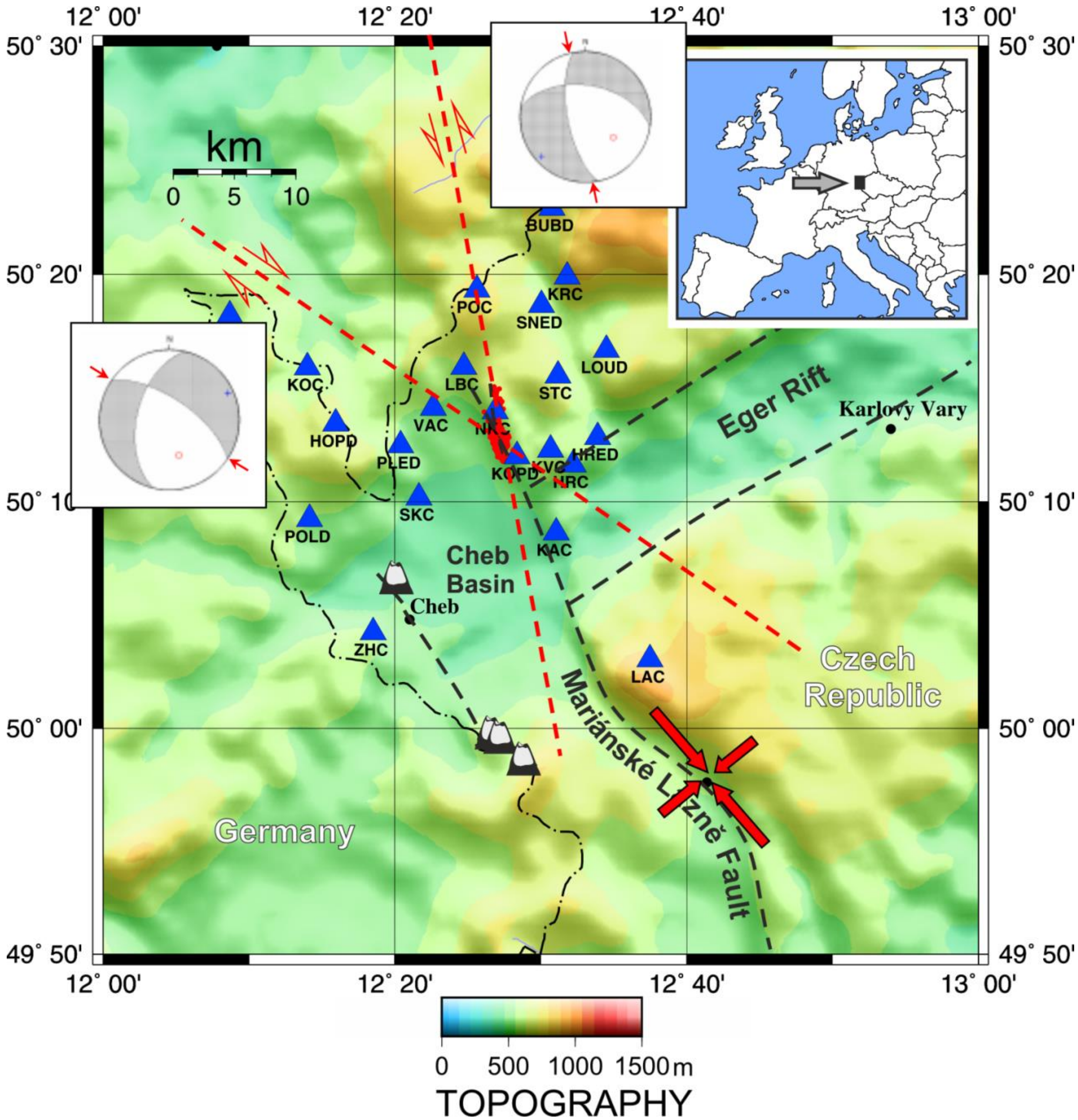


$\alpha = 10^{o}$

DC = 60 %
non-DC = 40 %

Vavryčuk (JGR, 2001, 2011)

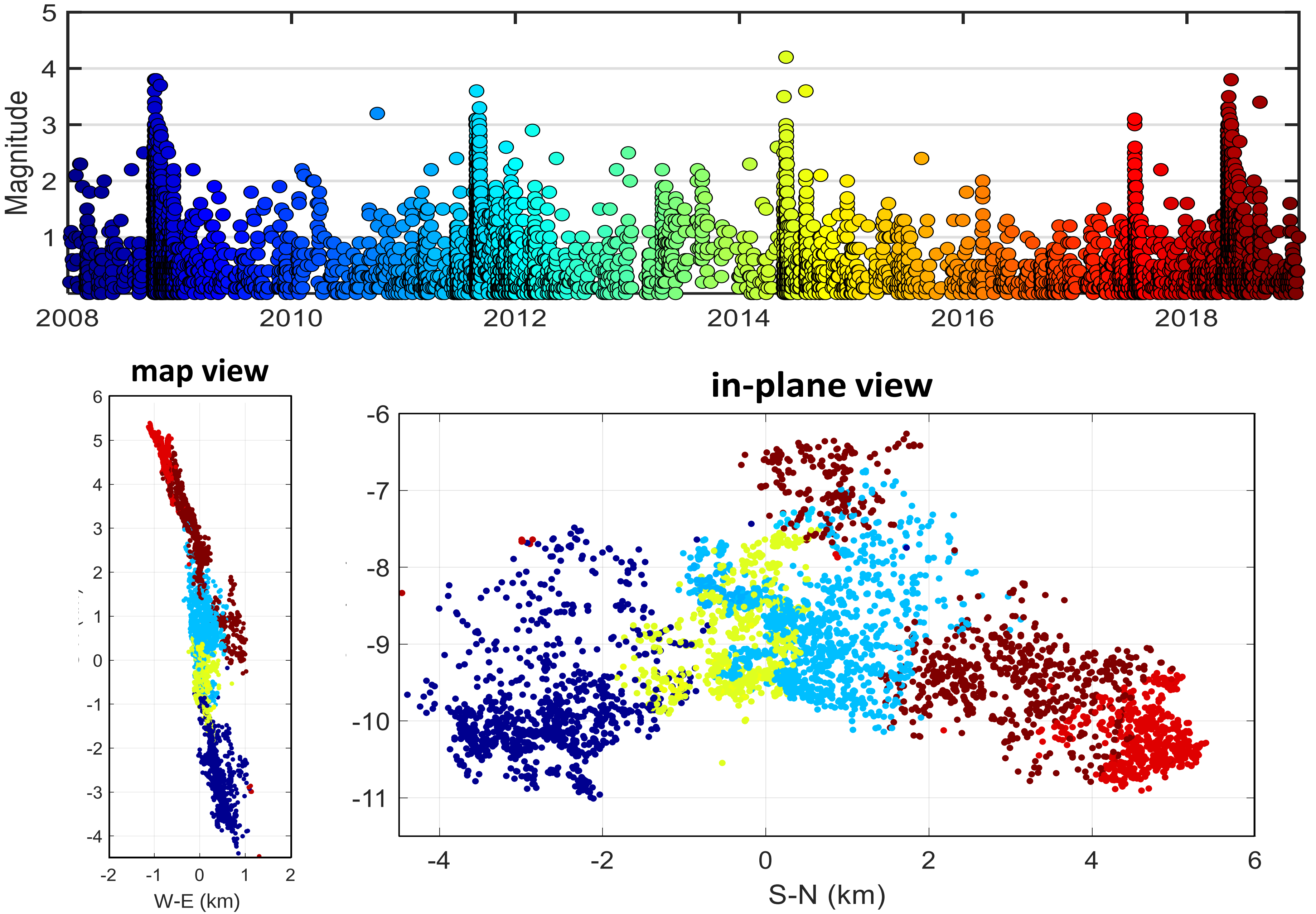
Swarm area in West Bohemia, Czech Republic



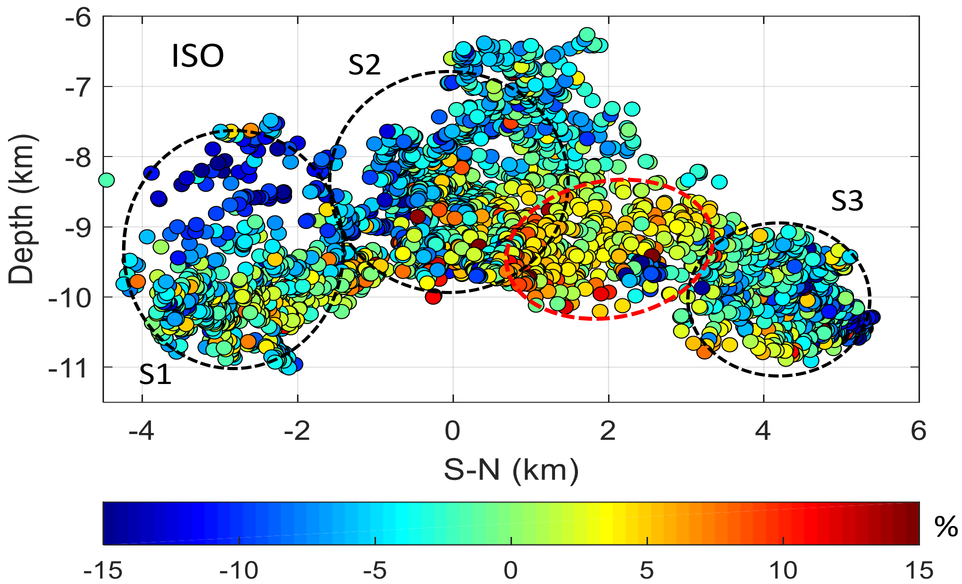
Geodynamically active area:

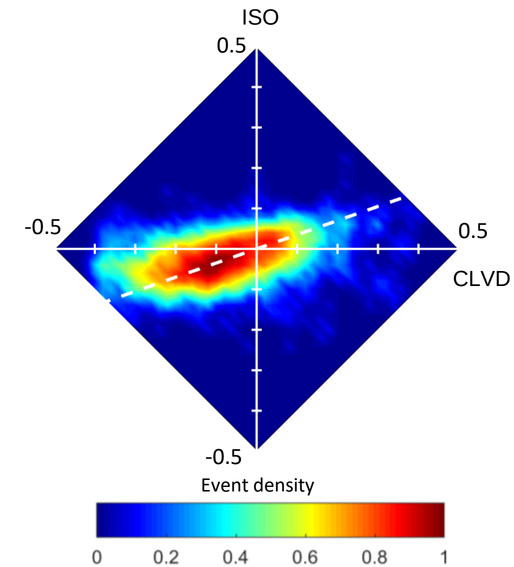
- Intersection of two major fault systems
- Persistent seismicity
- Emanations of CO_2 rich fluids
- Springs of mineral water
- Quaternary volcanoes

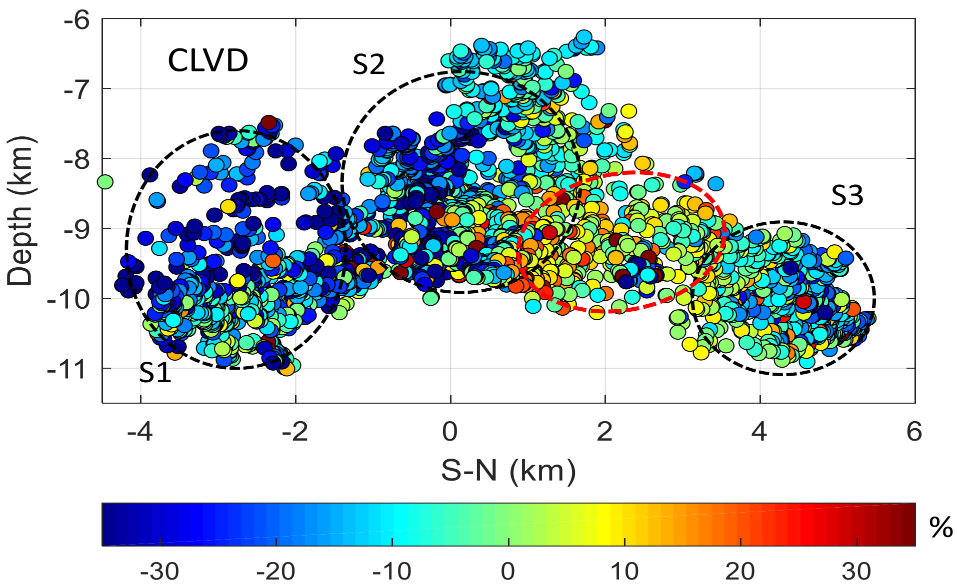
West Bohemia earthquake locations: period 2008-2018

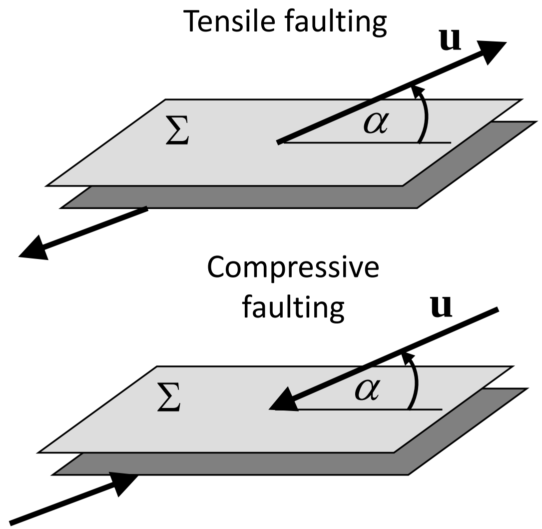


Non-DC components for shear-tensile faulting







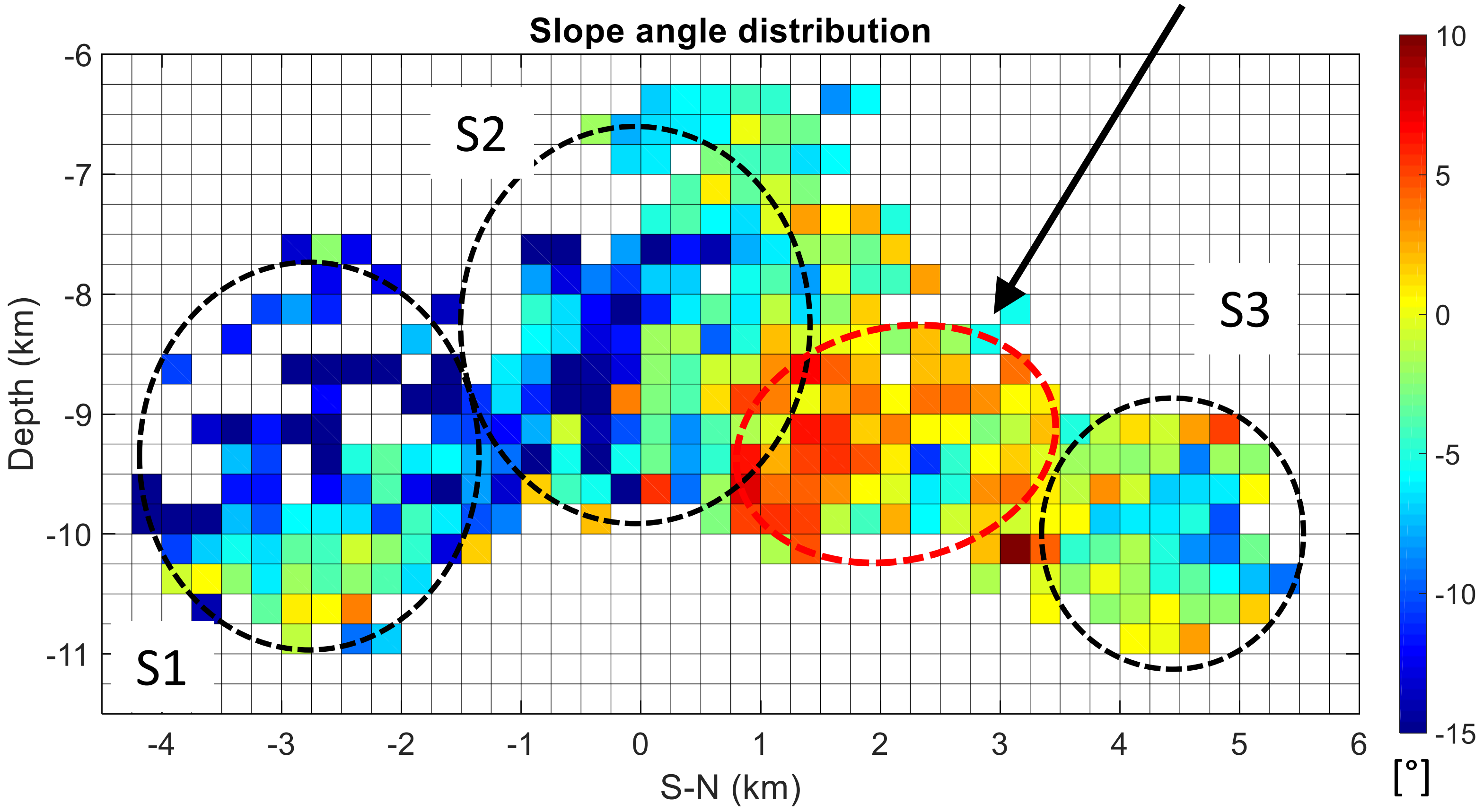


Vavryčuk et al. (JGR, 2021)

Opening/closing of a fault: West Bohemia

Mapping of fluid flow

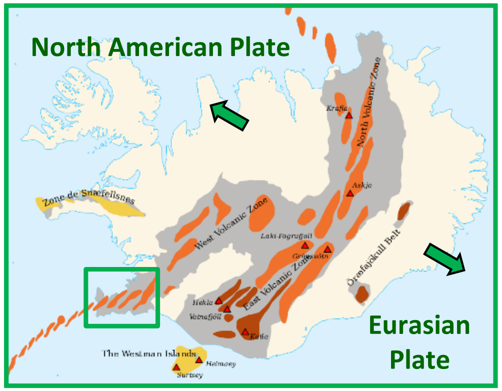
tensile stress anomaly



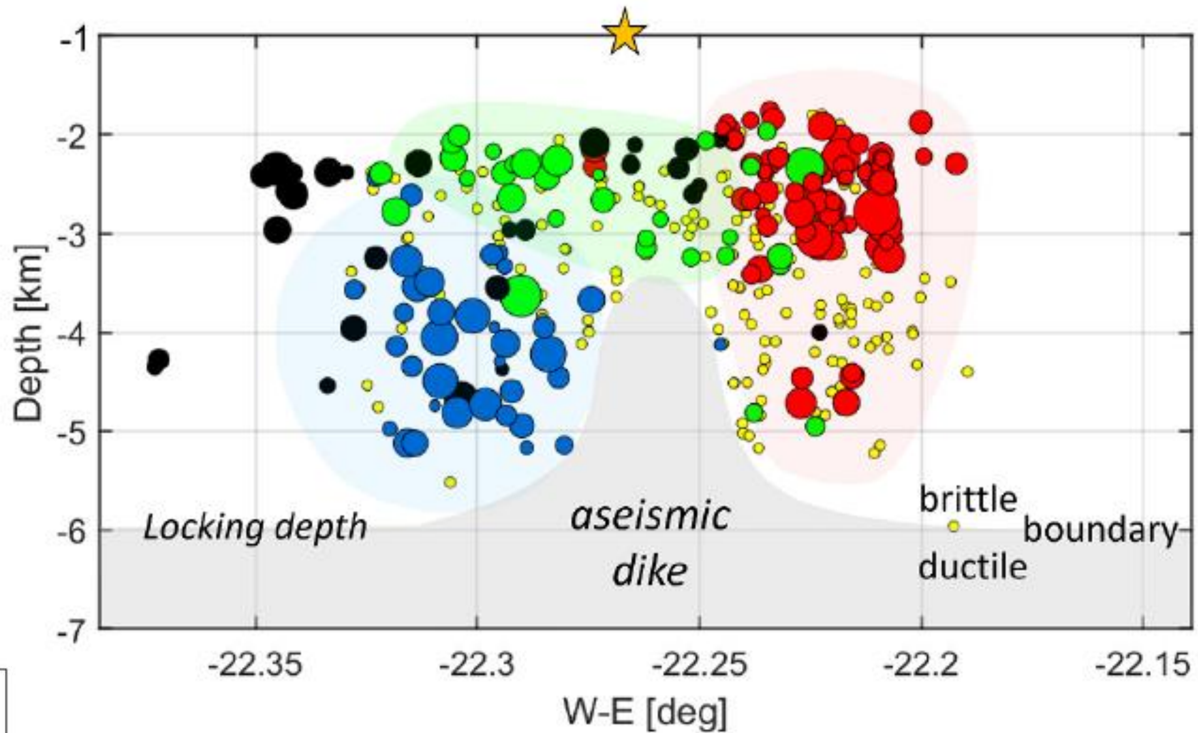
Vavryčuk et al. (JGR, 2021)

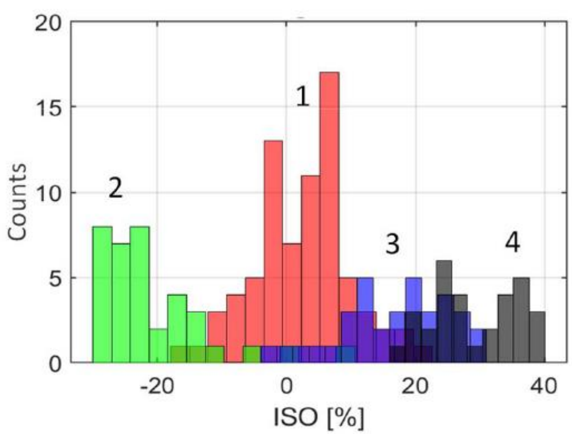
Tensile/compressive faulting in Iceland volcanic region

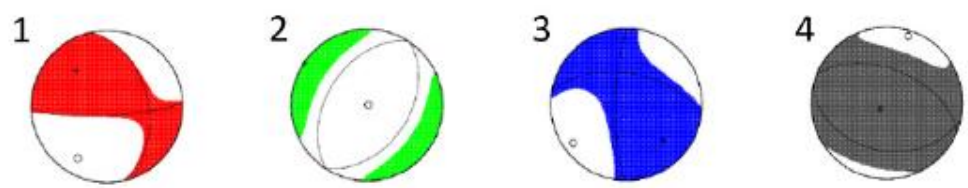
Seismicity in Reykjanes Penninsula before the 2021 Fagradalsfjall volcano eruption



Mid-Atlantic Ridge – slow-spreading rift







Hrubcová & Vavryčuk (EPSL, 2022; Tectonophysics, 2023)

Non-DC components: seismic anisotropy

Shear faulting in anisotropic media

Shear earthquakes in anisotropy

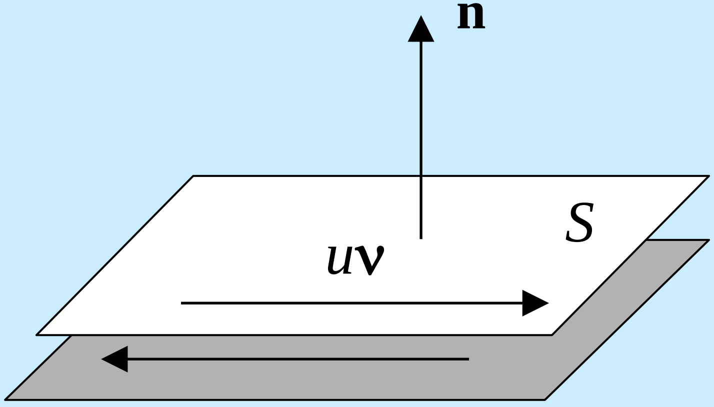
(Aki & Richards 2002, Eq. 3.19):

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

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

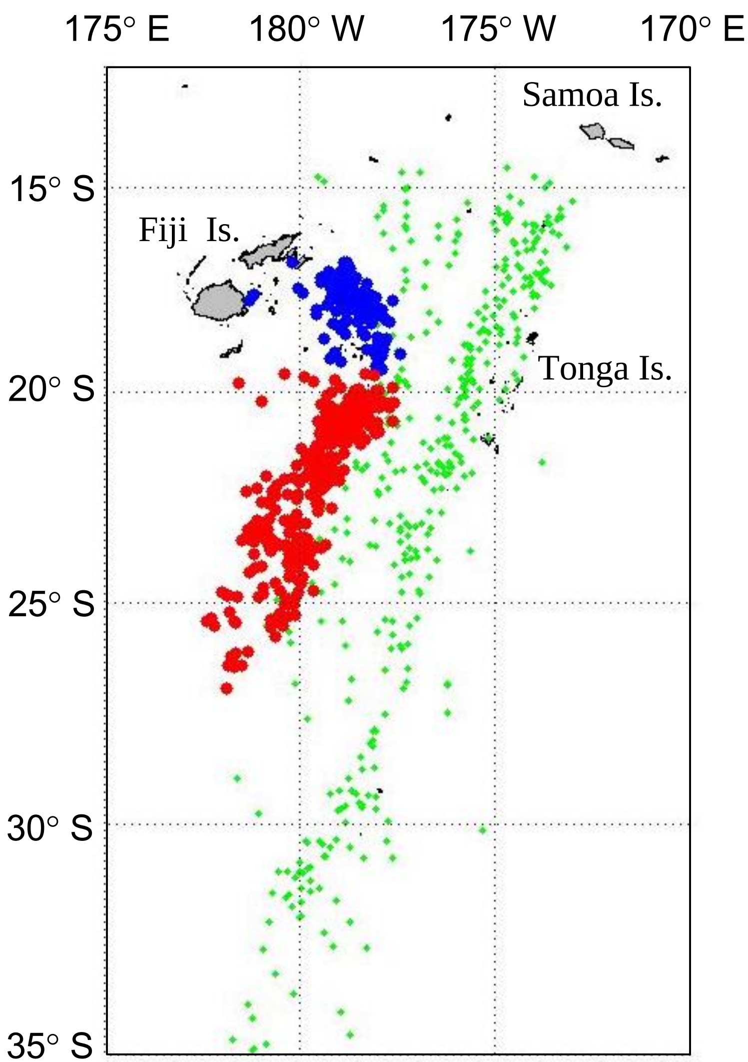
full (non-DC) moment tensor

DC + CLVD + ISO



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

Deep earthquakes in the Tonga subduction slab



Harvard MT solutions
(M>5, 1980-2002)

Tonga subduction

Pacific Plate subducts under the Australian Plate

Plate velocity is 10.5 cm/yr

Azimuth of the Tonga Trench is N210°E

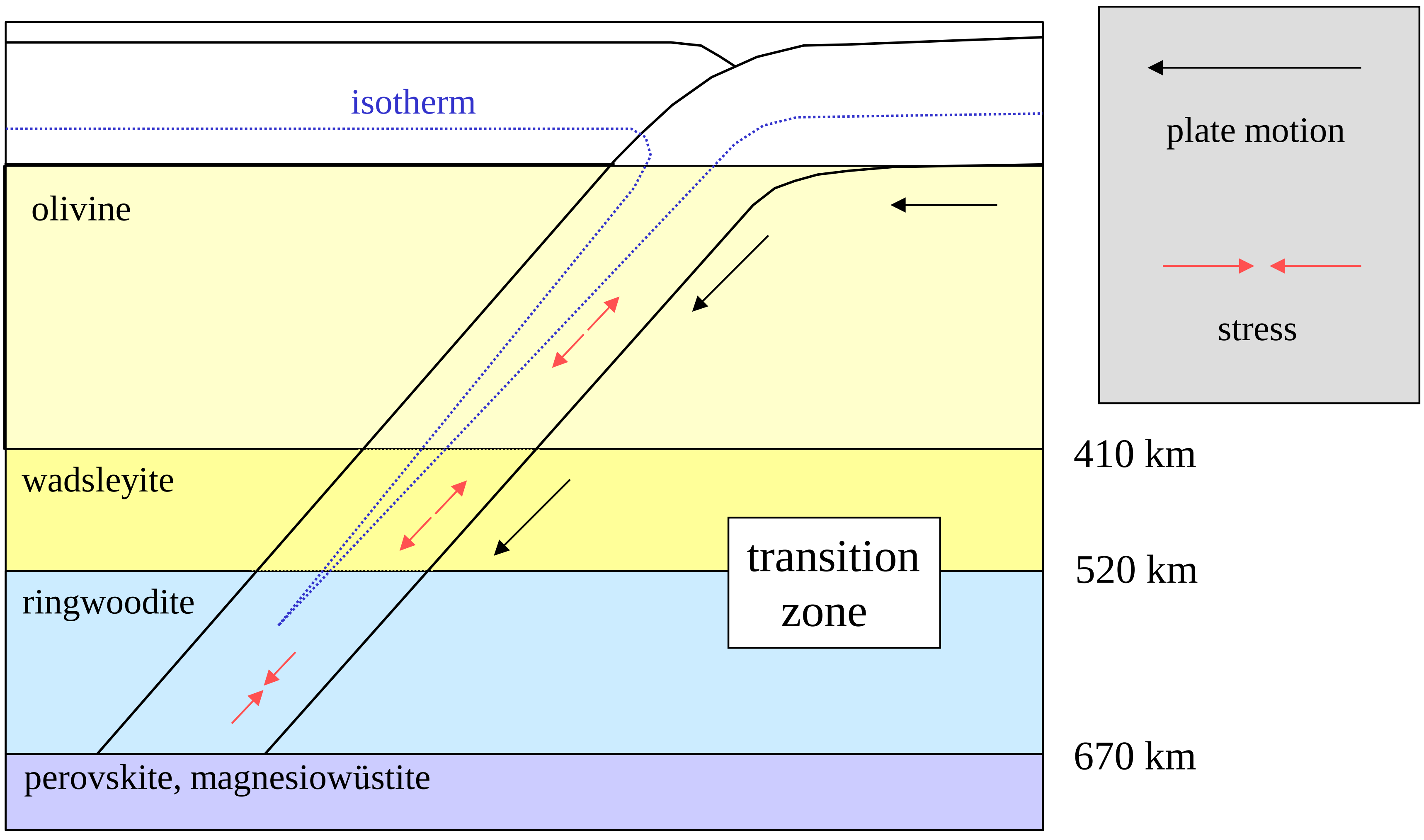
Dip of the subducting slab is 60°

The highest deep seismicity in the world

- depth 100-500 km
- **depth 500-700 km, southern cluster** ⬅
- depth 500-700 km, northern cluster

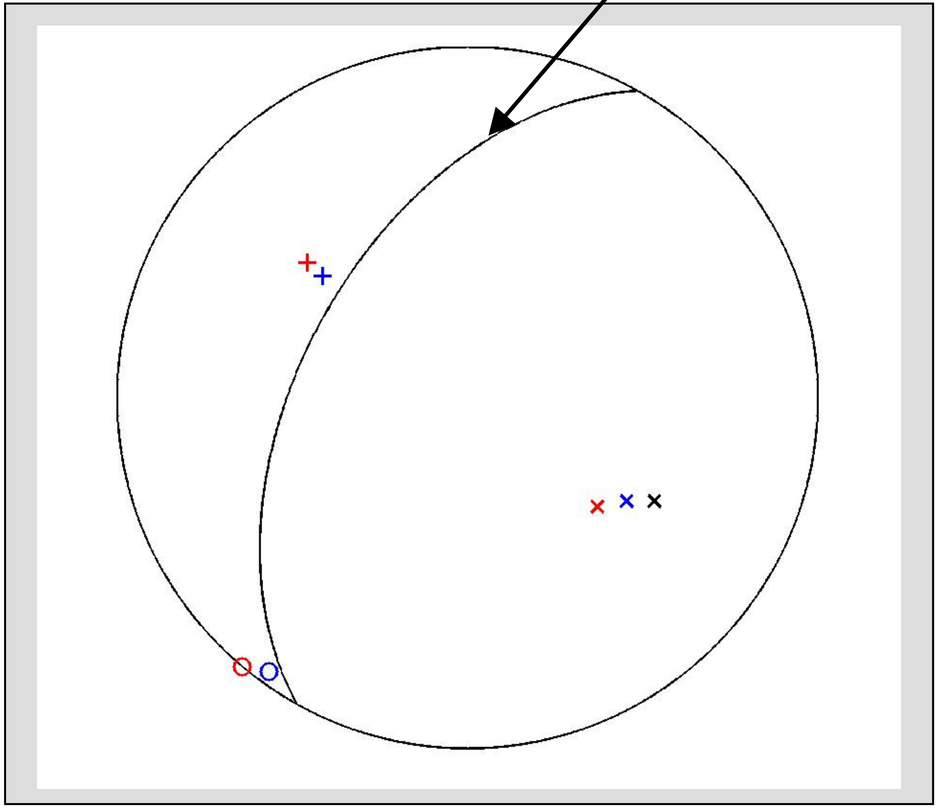
Vavryčuk (JGR, 2004; PEPI, 2008)

Slab geometry and mantle composition



Orientation of slab, stress and anisotropy

slab projection



x - normal of slab
x - stress
x - anisotropy

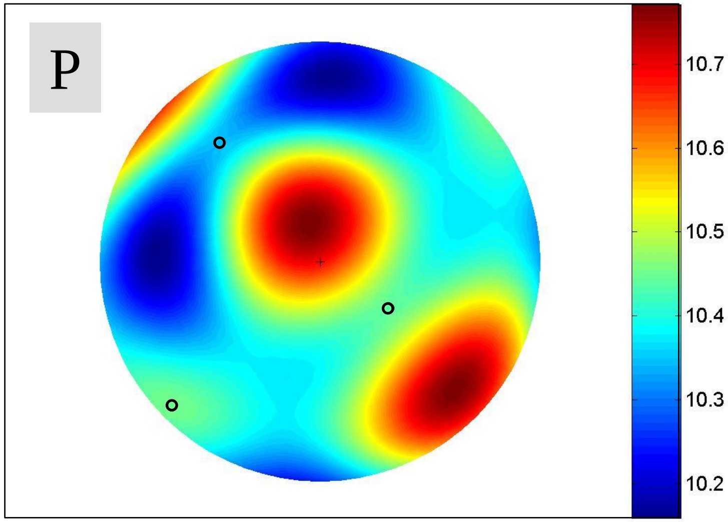
Maximum compression is along the slab ("down-dip compression")

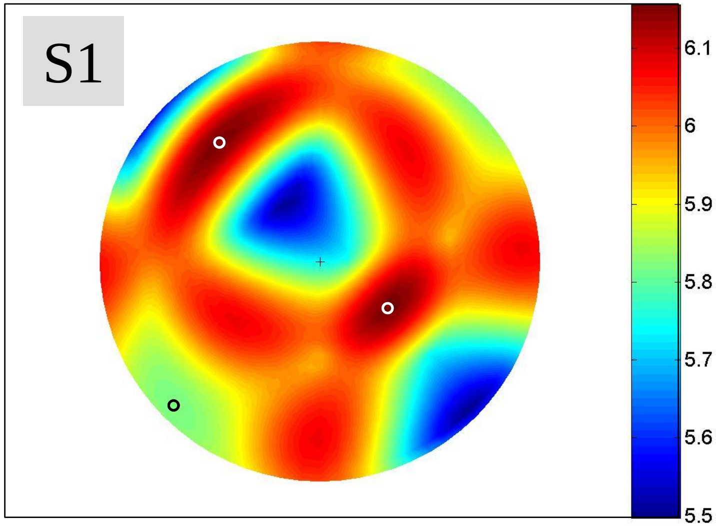
Stress and anisotropy orientations coincide

Anisotropy is stress induced!

Vavryčuk (JGR, 2004; PEPI, 2008)

Predicted velocities in the slab

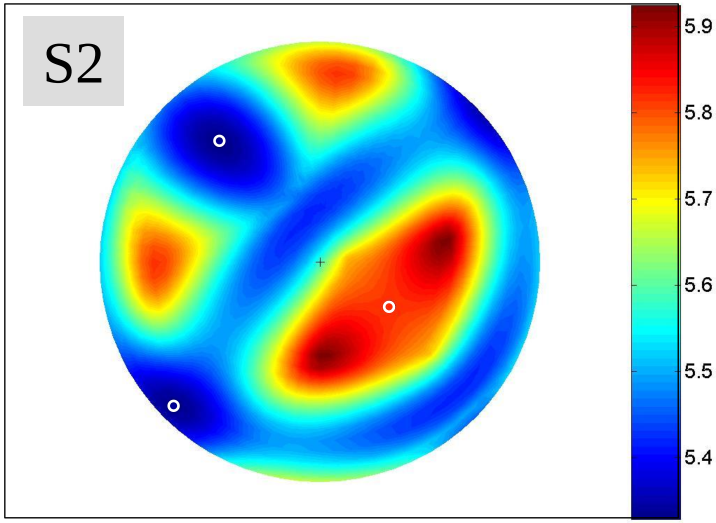




P-wave anisotropy: 6%,

S1-wave anisotropy: 11%

S2-wave anisotropy: 10%

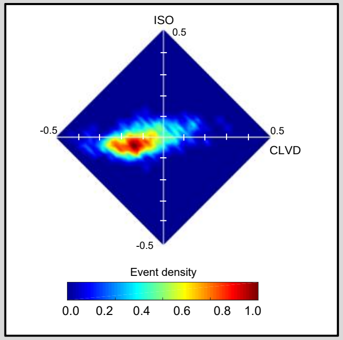


Vavryčuk (JGR, 2004; PEPI, 2008)

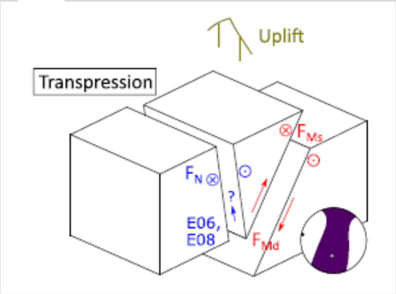
Summary

Summary

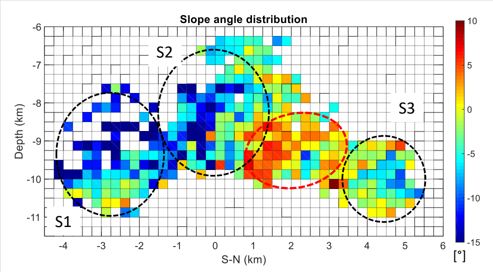
Non-DC components provide essential information about faulting, tectonic stress and physical properties of material in the focal zone



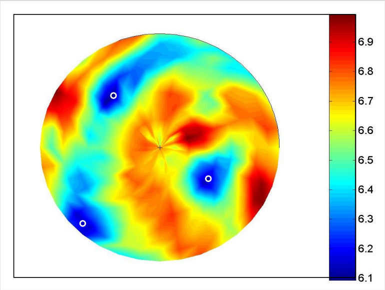
Shear-tensile faulting



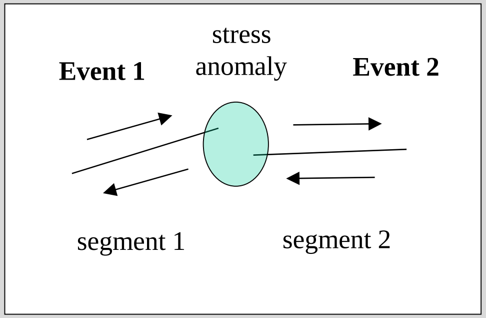
Understanding complexities of fracturing



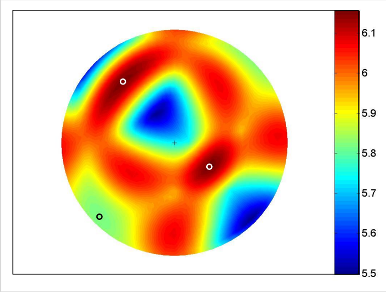
Mapping of fluid flow and rock compaction



Orientation of anisotropy in focal area



Detection of stress anomalies and fault nteractions



Velocities of P, S1 and S2 waves in focal area