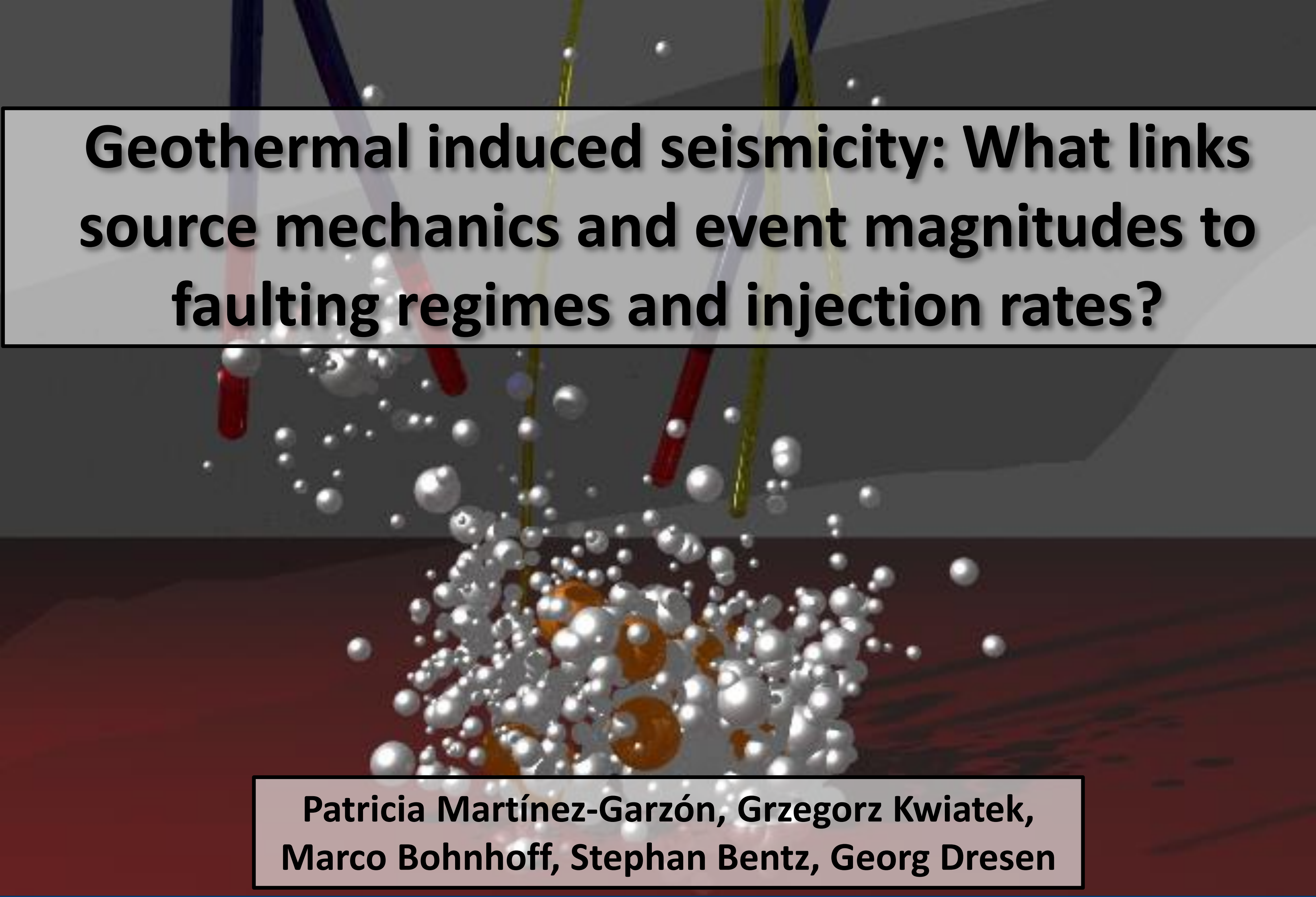
Geothermal induced seismicity: What links source mechanics and event magnitudes to faulting regimes and injection rates?



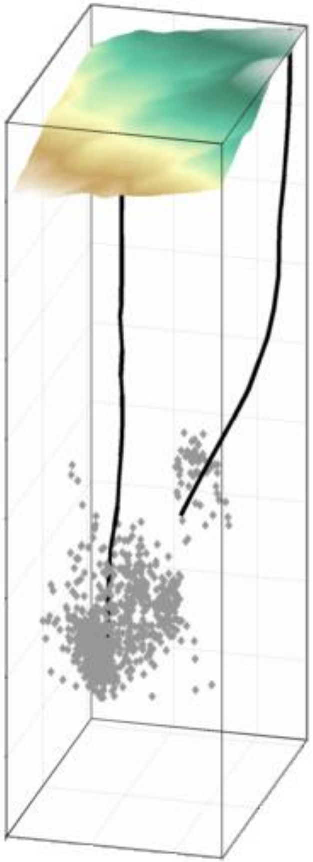
Patricia Martínez-Garzón, Grzegorz Kwiatek, Marco Bohnhoff, Stephan Bentz, Georg Dresen

Motivation

- Non Double-Couple (NDC) components describe more accurately the seismic deformation

- Identification of tensile openings allow for monitoring of the desired permeability enhancement in EGS

- NDC are difficult to detect!



Main Goal:

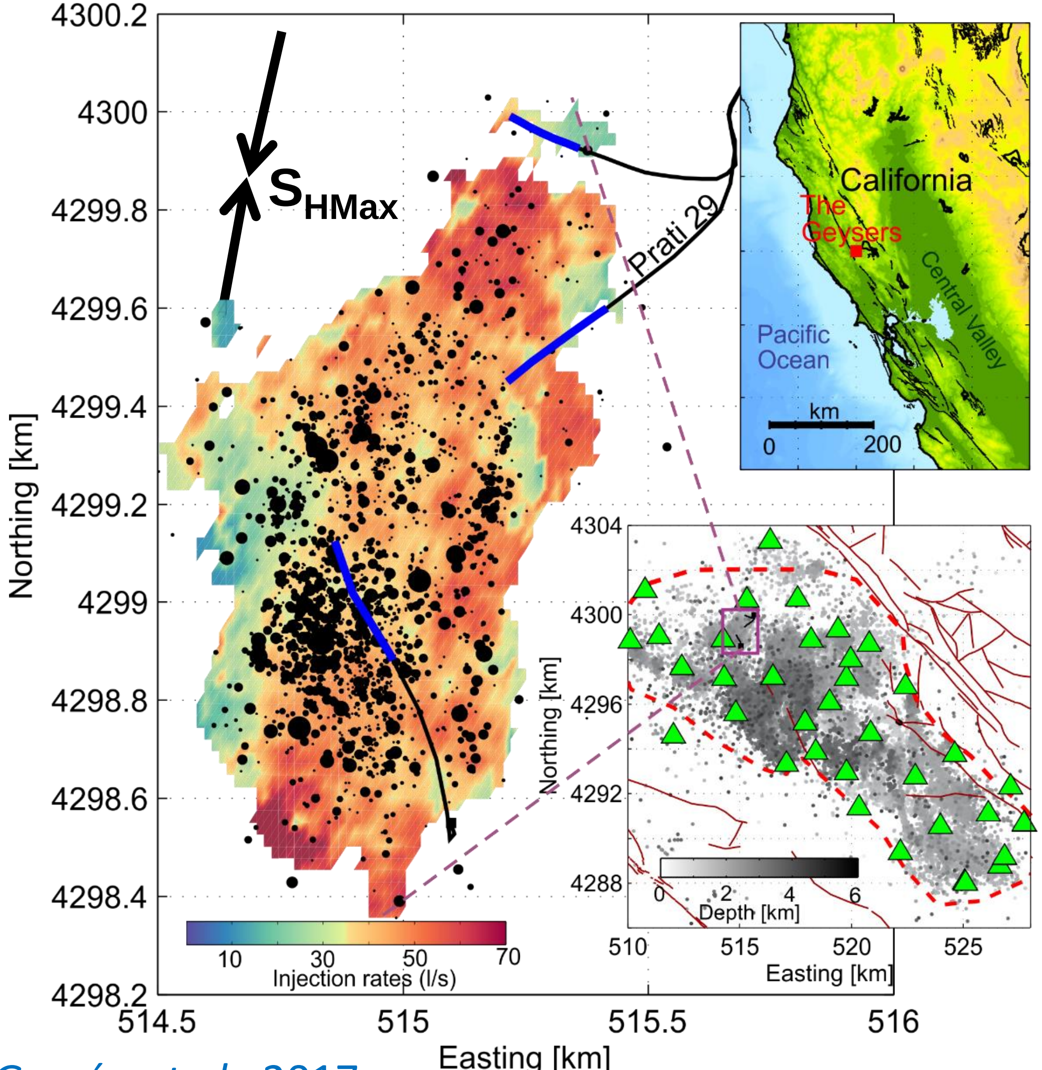
Analysis of large number of MTs to investigate earthquake source-types in relation with the local state of stress and the hydraulic activities nearby

The NW Geysers geothermal field

- ≈ 4000 EQ/yr since 1960s
  M_W (1.3 – 4.8)

- Mechanisms:
  a) Thermal fracturing
  b) Small pressure changes

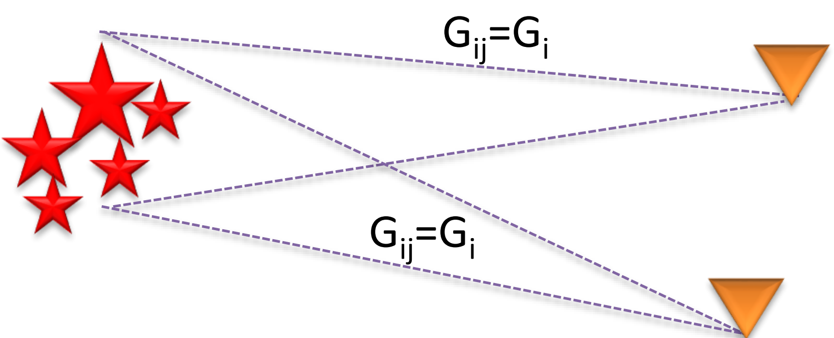
- Selected area:
  -2 injection wells
  -869 MTs M_W [0.8 3.5]
  - Input data manually processed

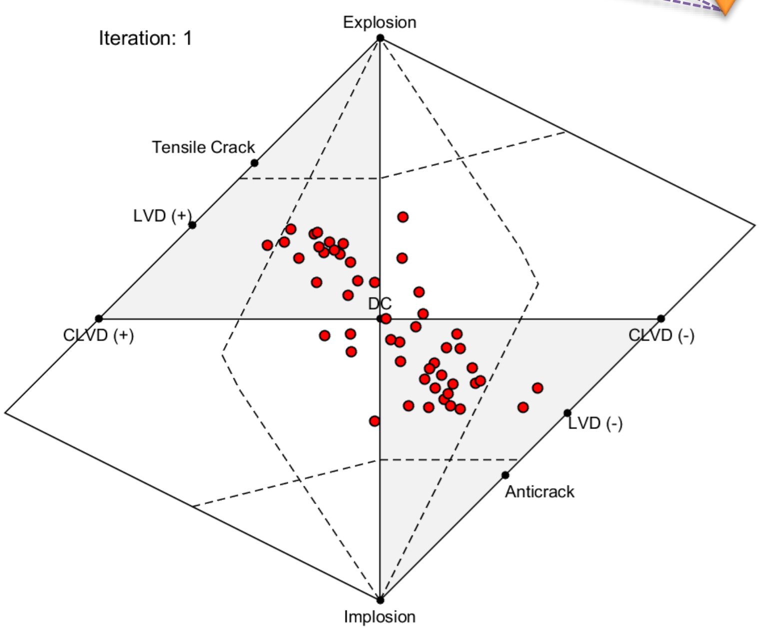


Martínez-Garzón et al., 2017

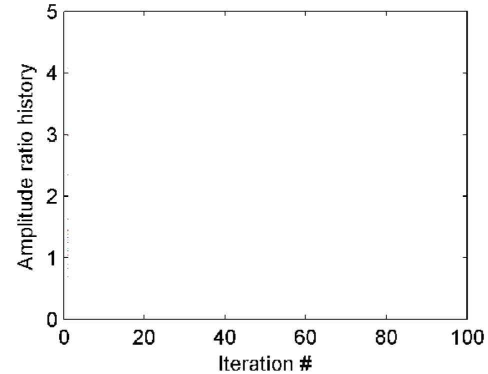
HybridMT moment tensor calculation

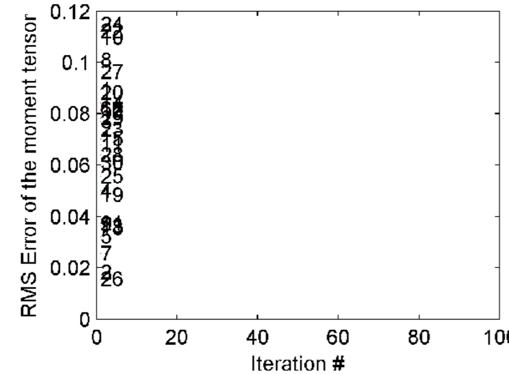
Iterative refinement of MTs by removing path effects and correcting for wrong sensor gain

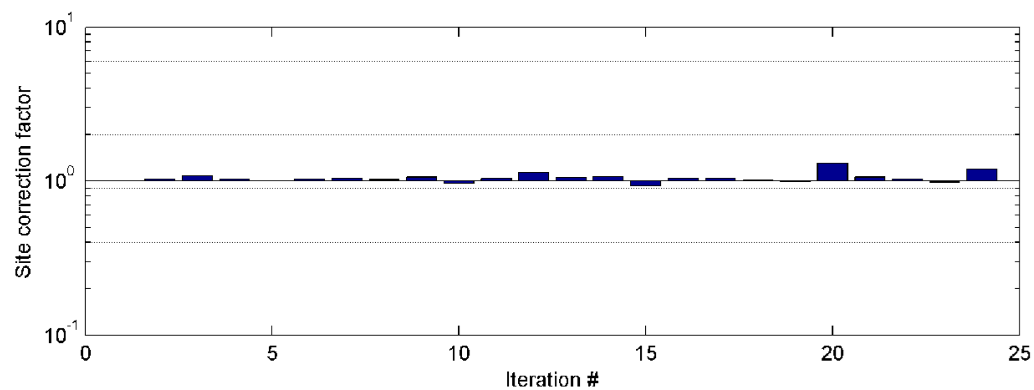




Kwiatek et al., 2016







Uncertainty assesment and results

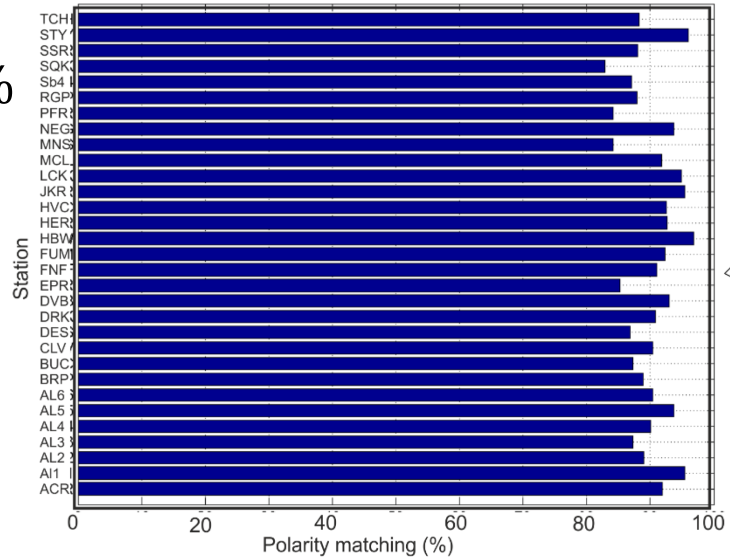
✓ 200 MTs solutions per event perturbing:
- P amplitudes → Noise
- Takeoff angles → V model
- Polarities → Pick errors

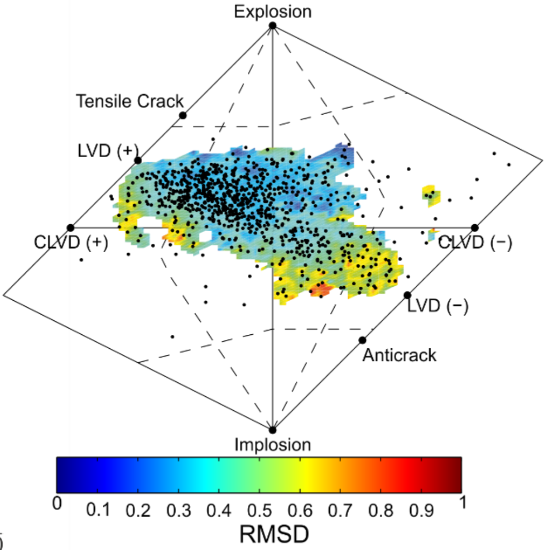
Overall NDC uncertainty: $\pm 7\%$

San Andreas (movie)

$|\%ISO| + |\%CLVD| > 25\%$
for 65% of the MTs

68% with + %ISO & %CLVD
15% with - %ISO & %CLVD





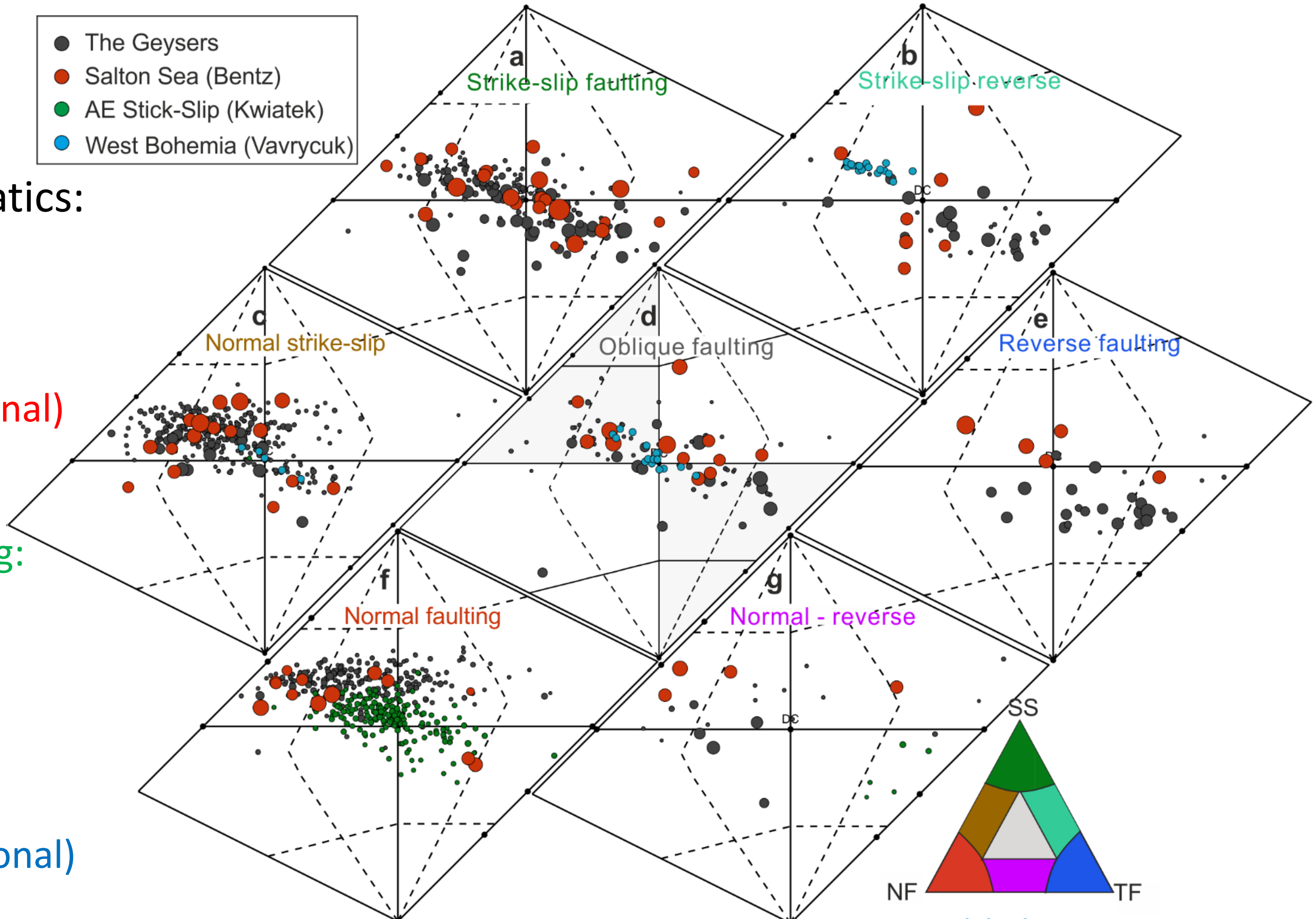
Source types and faulting kinematics

Faulting kinematics:

- Normal faulting:
  tensile opening
  (least compressional)

- Strike-slip faulting:
  DC ruptures

- Reverse faulting:
  fracture closing
  (most compressional)



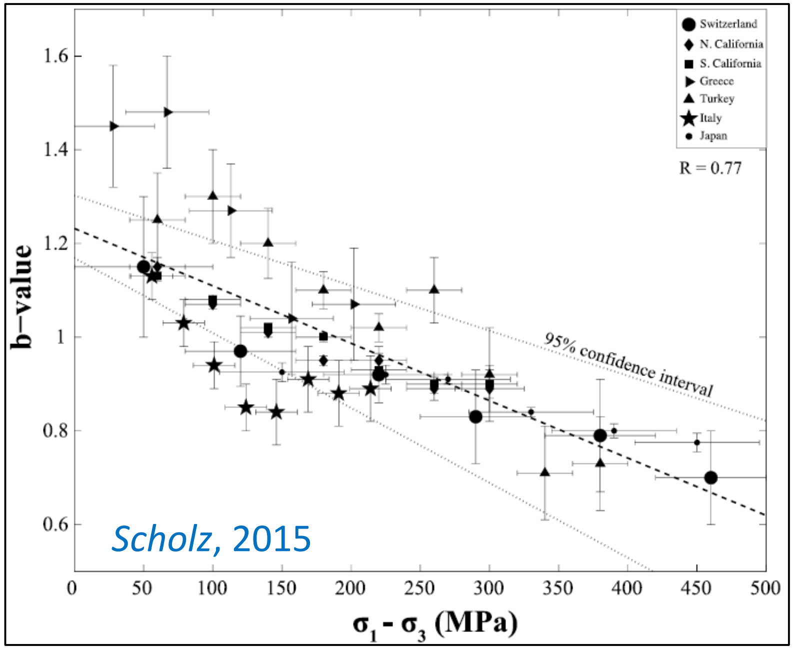
Frohlich, 1991

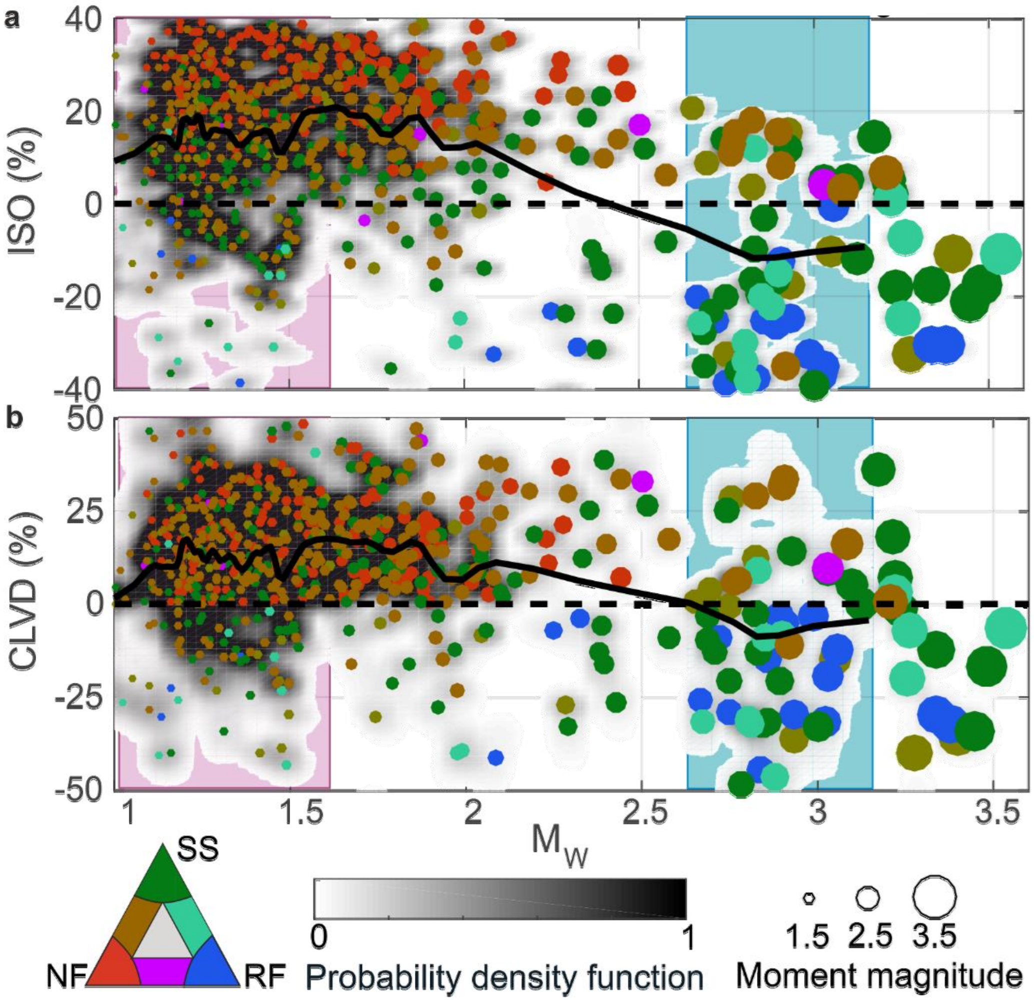
Source types and magnitudes

$$0.9 < M_W < 1.6$$
$$ISO \approx 16\%, CLVD \approx 13\%$$

$$2 < M_W < 2.5$$
$$ISO \approx 3\%, CLVD \approx 6\%$$

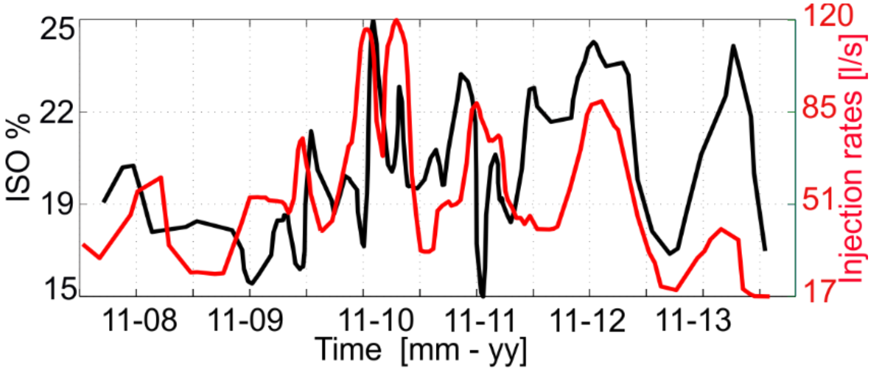
$$2.6 < M_W < 3$$
$$ISO \approx -10\%, CLVD \approx -6\%$$

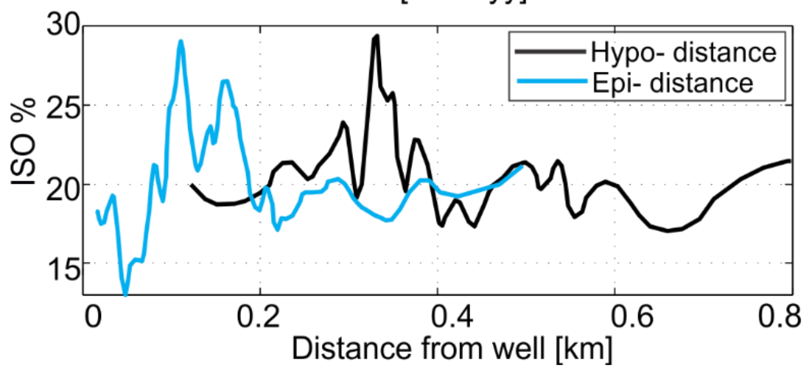




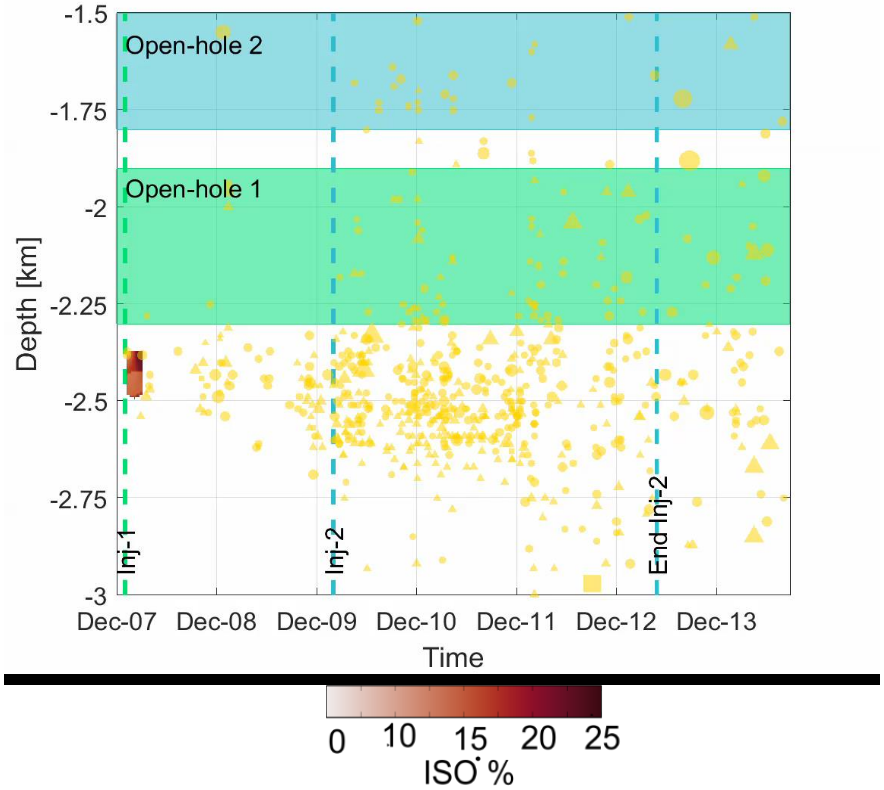
+ ISO and injection rates

- Increases during high injection rate periods
- Enhanced at smaller distances from open-hole sections



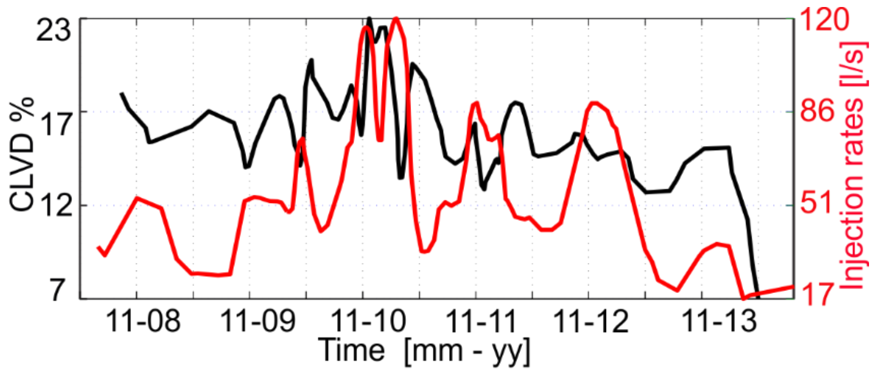


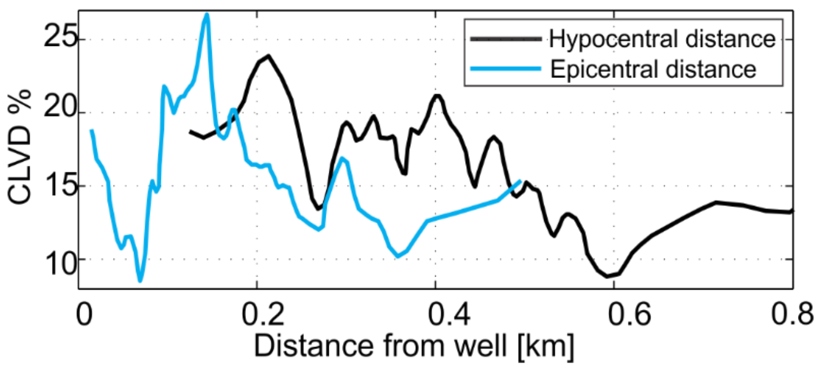
- Long-term increase
- Related to pore pressure increase?



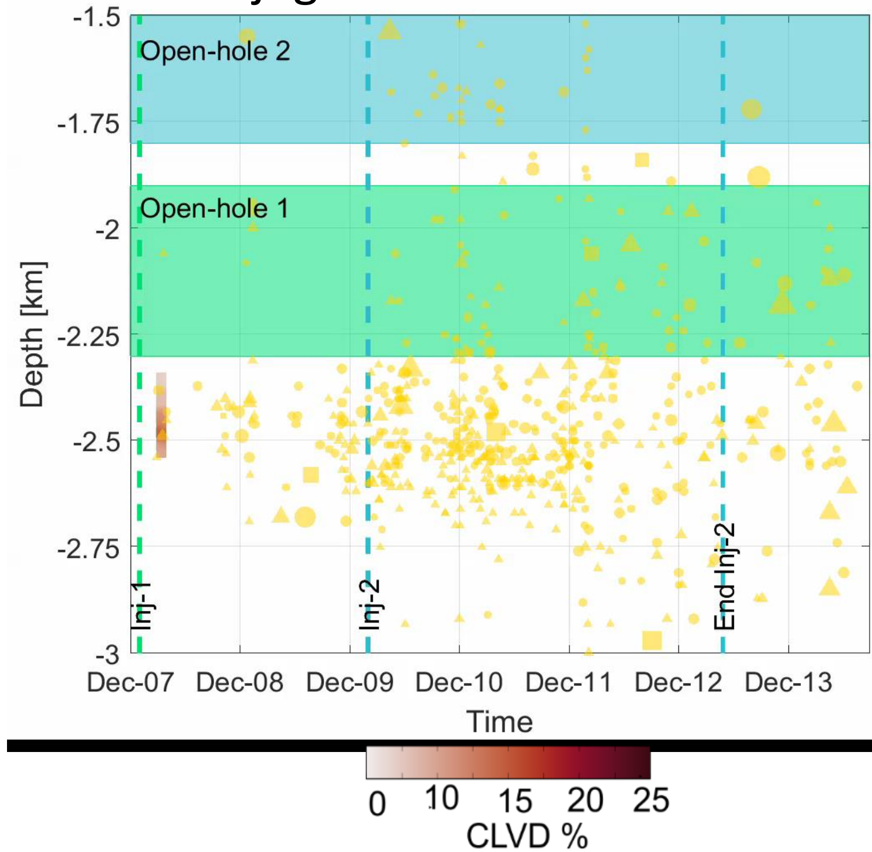
+ CLVD and injection activity

- No clear relation with injection rate
- Decreasing with distance from open-hole sections
- Long-term decrease



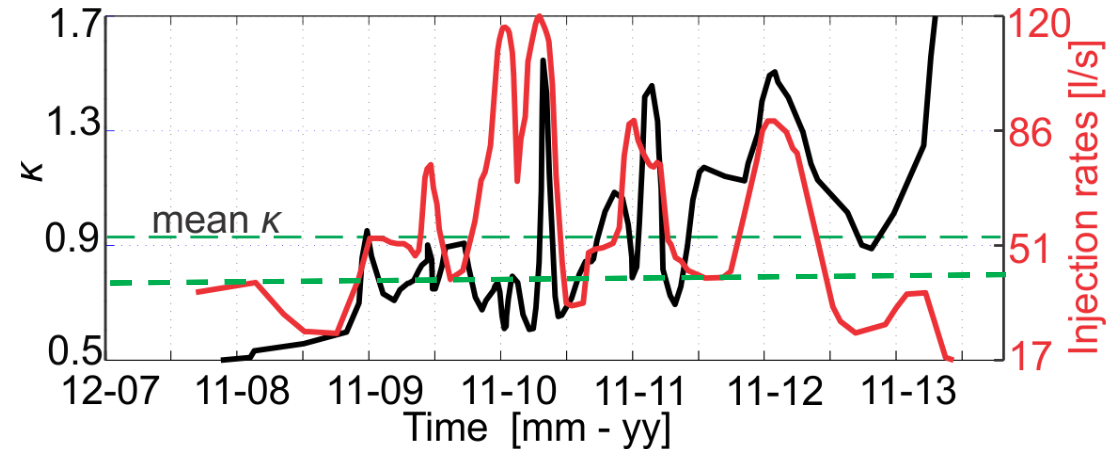


- **A** Enhanced damage around open-hole sections ?
- **B** Multiple events occurring in conjugate faults ?



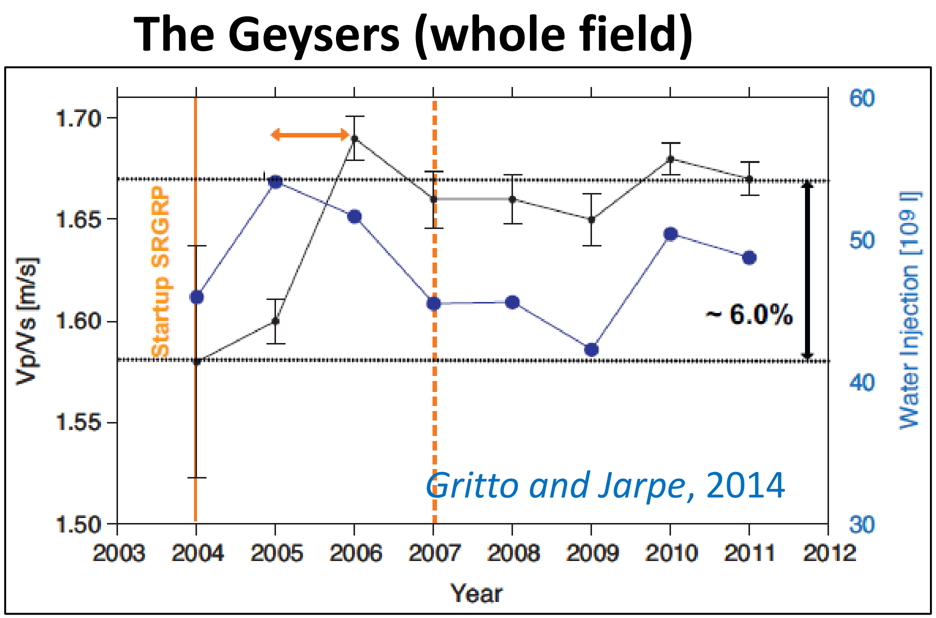
NDC components and seismic velocity

$$\kappa = \frac{4}{3}\left(\frac{\%ISO}{\%CLVD} - \frac{1}{2}\right) = \frac{\lambda}{\mu} = \frac{V_P^2 - V_S^2}{V_S^2}$$



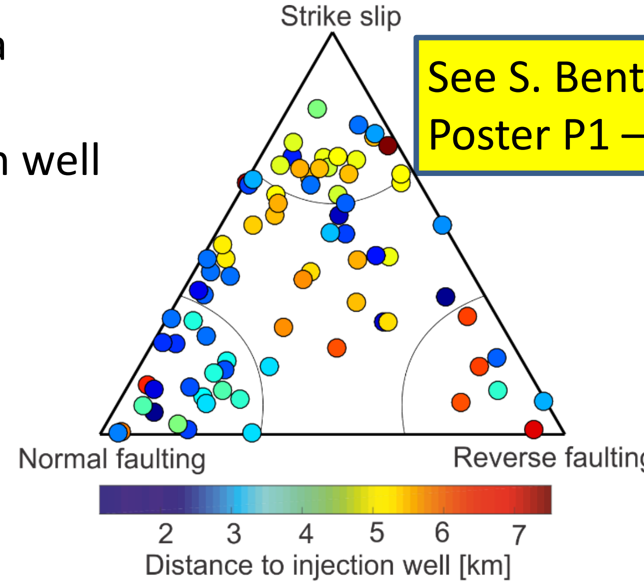
- During high injection, the elastic fault properties are different

- The ${}^{V_P}/_{V_S}$ ratio is increasing (as observed for the whole field)

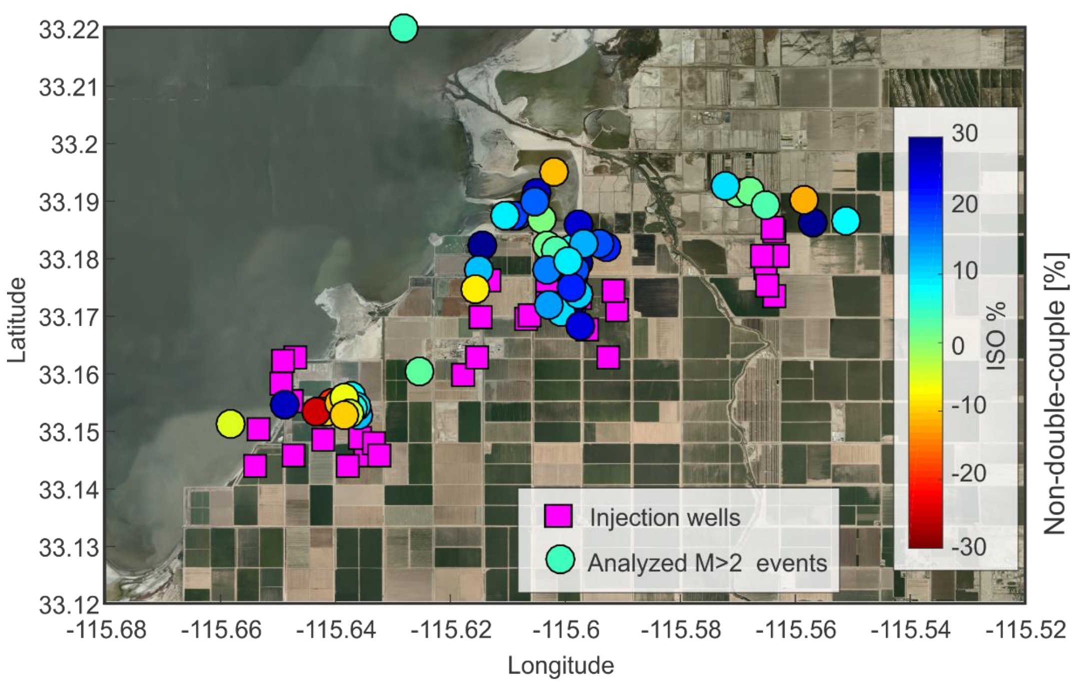


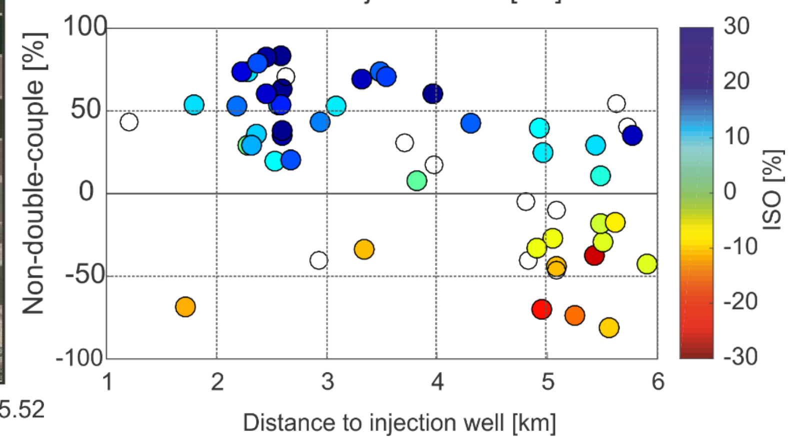
MTs of M>2 events at the Salton Sea

- MTs of 80 events M > 2 with local borehole data
- NDC components decreasing with distance from well
- NF near the wells, SS / RF at greater distance



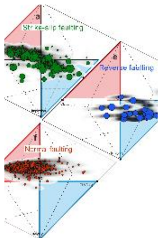
See S. Bentz et al., Poster P1 – 01 (Thu)



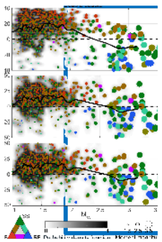


Summary of results

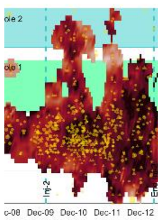
Analysis of 869 moment tensors from NW The Geysers geothermal field



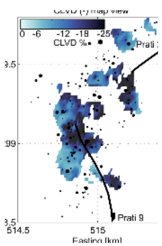
Source types dependent on local stress state: Tensile opening at low diff. stress (NF), crack closing at high diff. stress (RF)



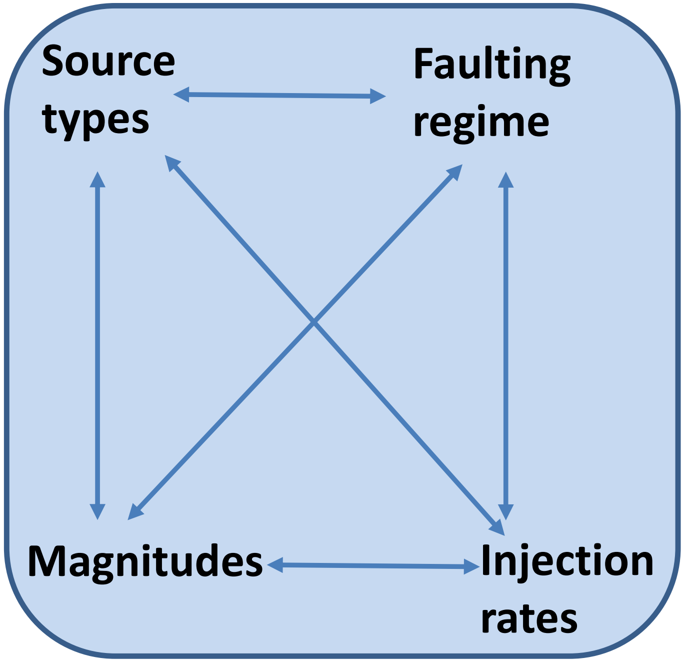
Source-types related to EQ magnitudes: Tensile opening at lower magnitudes and crack closing at larger magnitudes



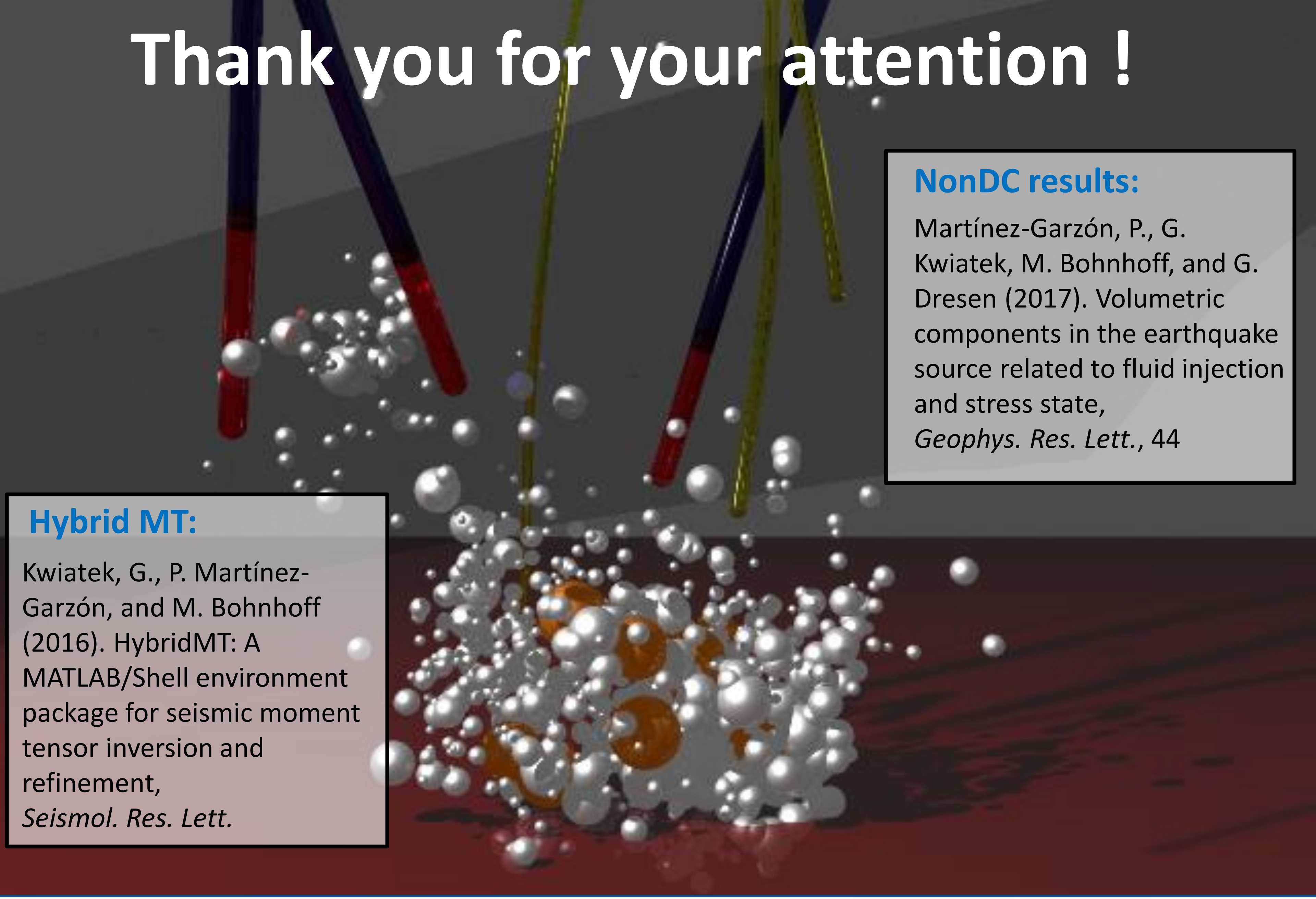
Volumetric (**ISO**) components **more responsive** than CLVD **to** temporal changes in **injection rates**



Larger NDC components near open-hole sections, suggesting their link with hydraulic operations



Thank you for your attention !



NonDC results:

Martínez-Garzón, P., G. Kwiatek, M. Bohnhoff, and G. Dresen (2017). Volumetric components in the earthquake source related to fluid injection and stress state, *Geophys. Res. Lett.*, 44

Hybrid MT:

Kwiatek, G., P. Martínez-Garzón, and M. Bohnhoff (2016). HybridMT: A MATLAB/Shell environment package for seismic moment tensor inversion and refinement, *Seismol. Res. Lett.*

GFZ Helmholtz-Zentrum Potsdam

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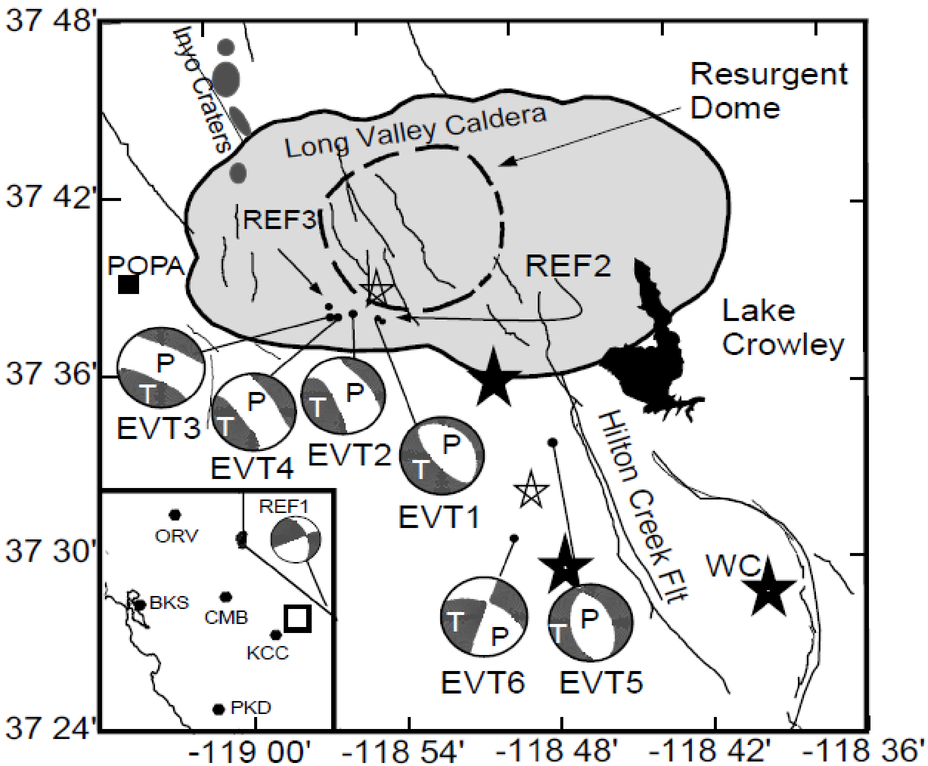
HELMHOLTZ GEMEINSCHAFT

Other slides

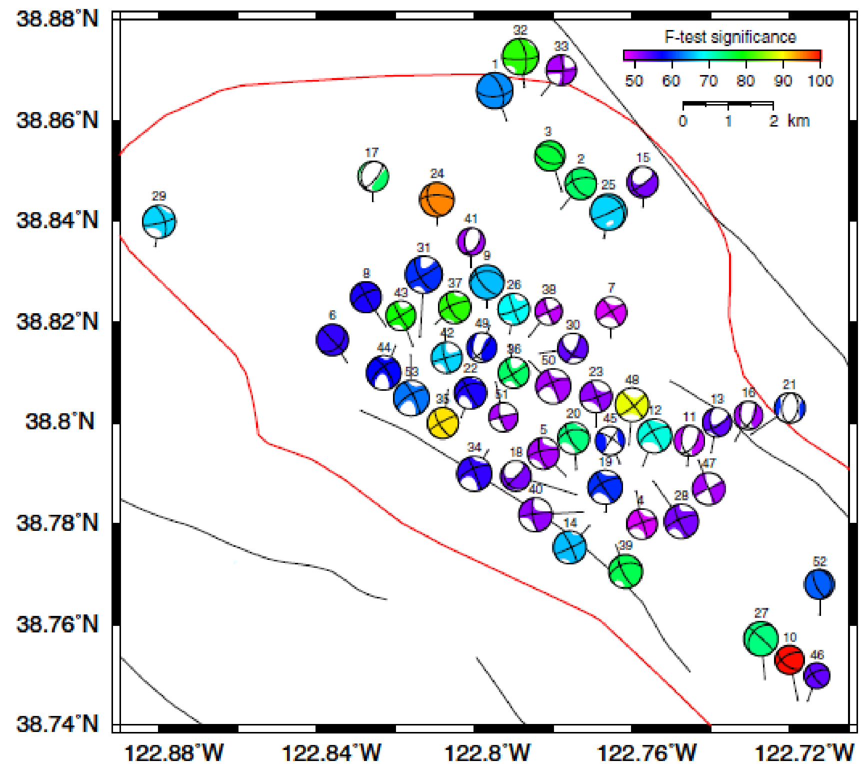
NDC in natural and induced seismicity

Natural degassing of CO_2, volcanic environments



e.g. Miller et al, 1998; Dreger et al., 2000; Vavrycuk, 2002;

Geothermal stimulation, hydraulic fracturing



e.g. Cuenot et al., 2006; Fischer and Guest, 2011; Boyd et al., 2015

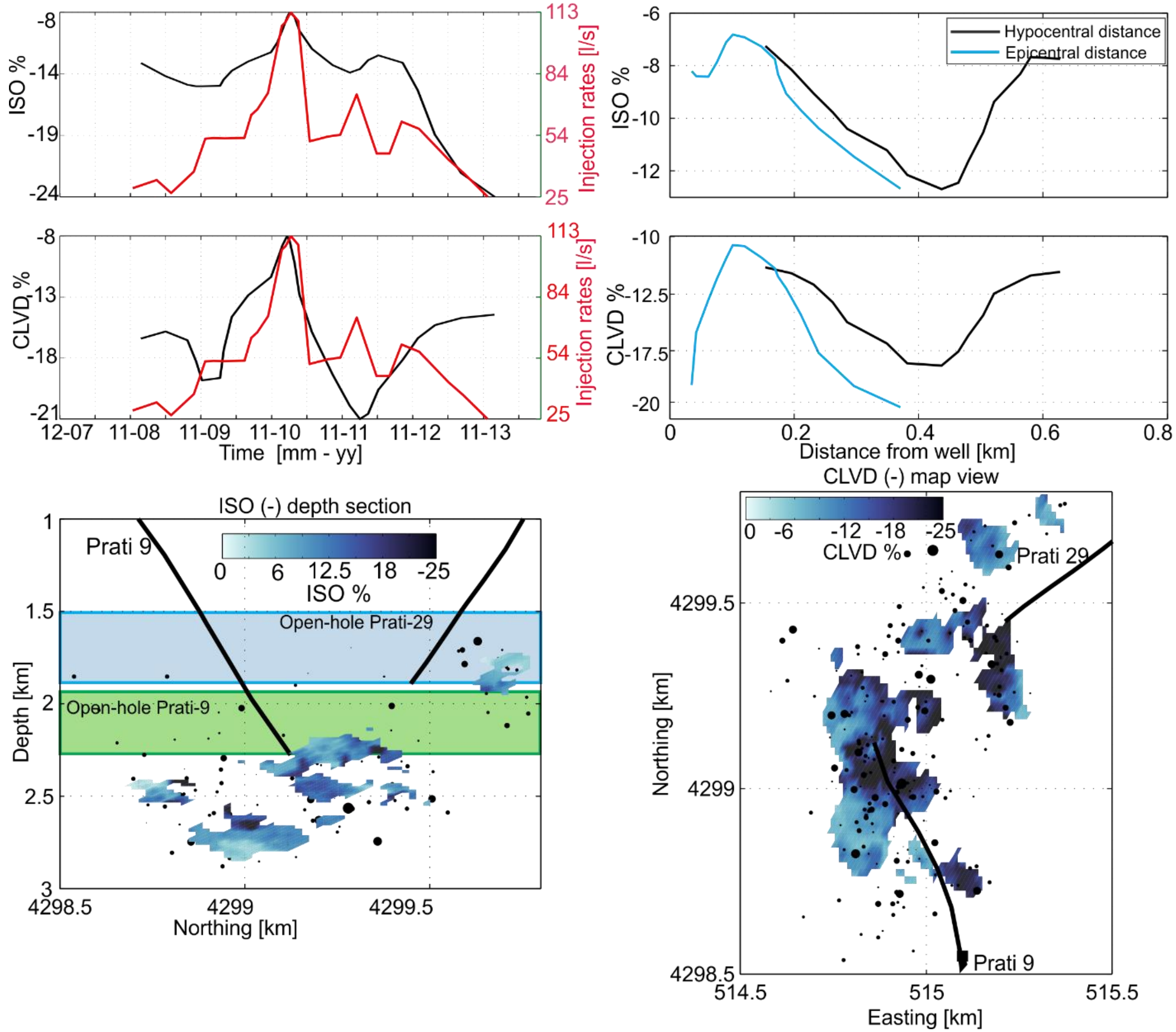
Distribution of - NDC components

- ISO and CLVD tend to decrease during high injections

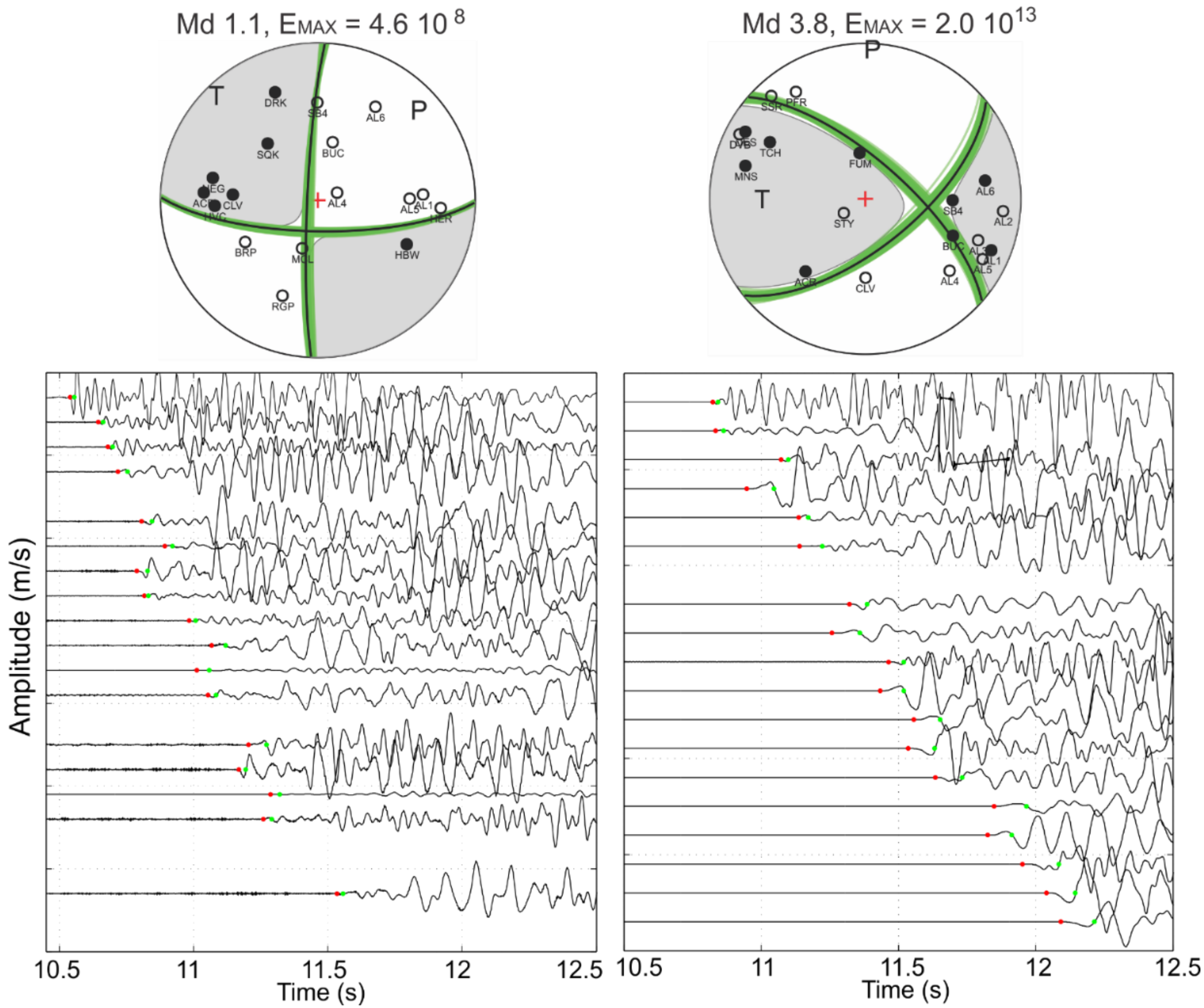
- ISO and CLVD tend to cluster around the open-holes

A Thermal shrinking?

B Other processes …?



Hybrid-MT Moment tensor calculation



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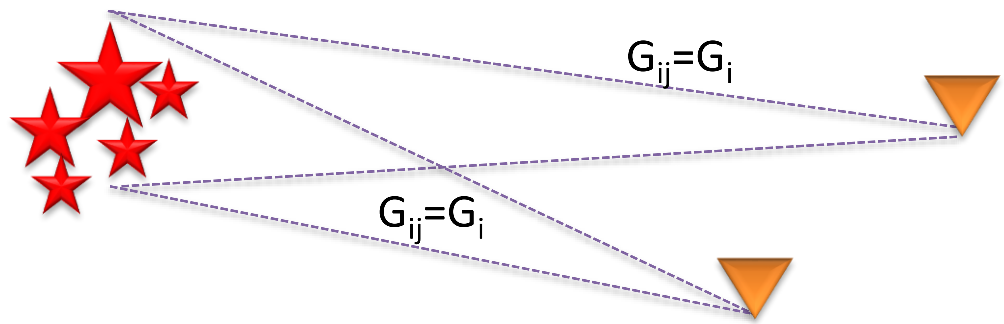
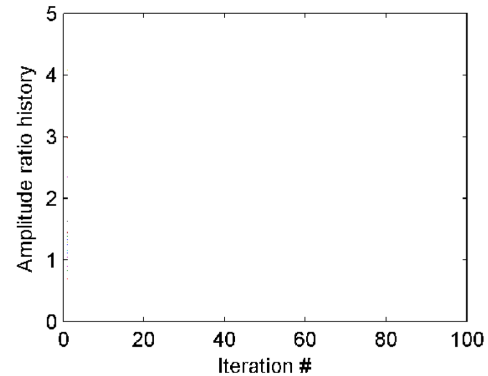
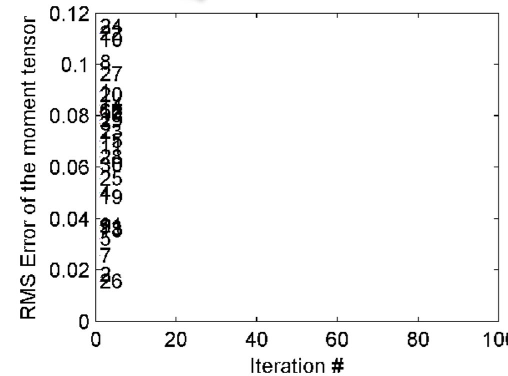
Iterative refinement of MTs by removing path effects and correcting for wrong sensor gain

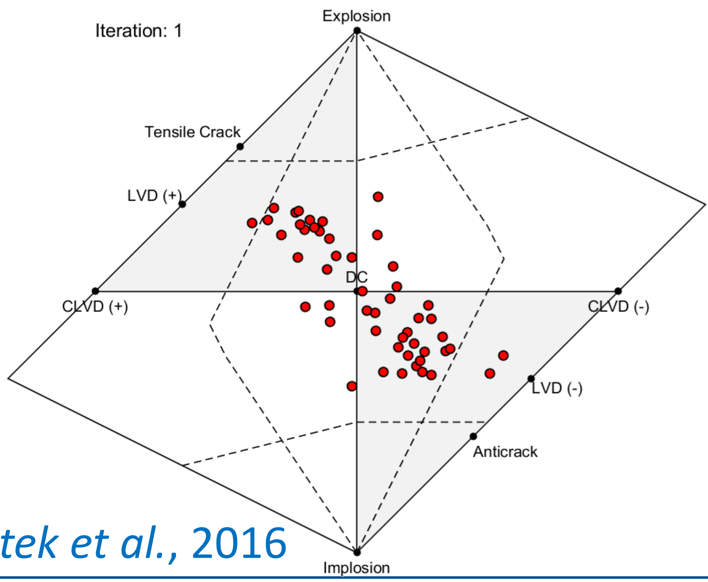


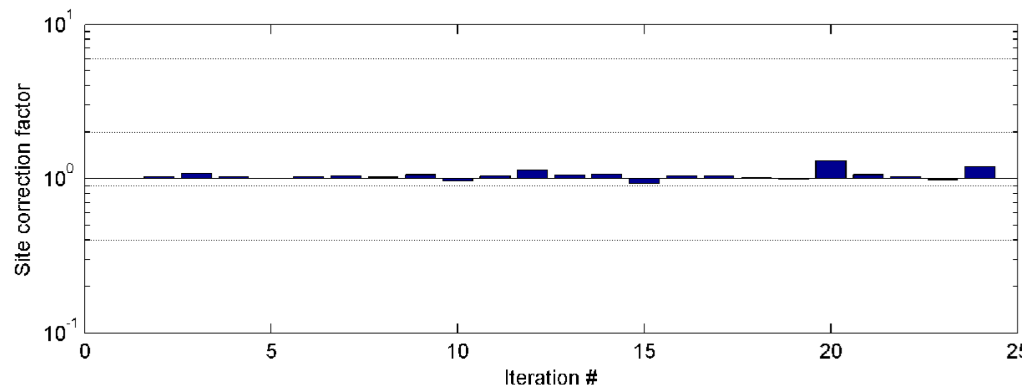
$$r_{ij} = u_{ij}^{\mathrm{th}} / u_{ij}^{\mathrm{obs}}$$

$$u_{ij}^{*,\mathrm{obs}} = u_{ij}^{\mathrm{obs}} + w_i u_{ij}^{\mathrm{obs}} (\tilde{r}_i - 1)$$



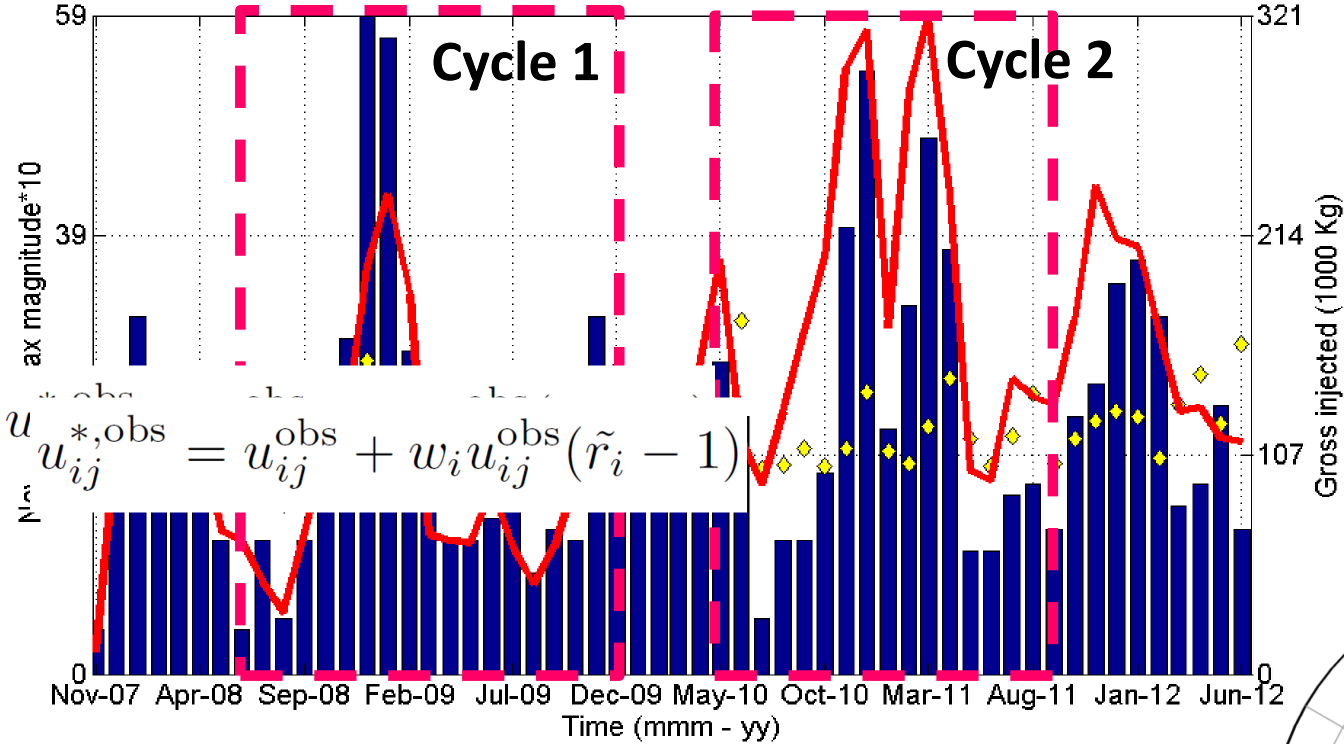




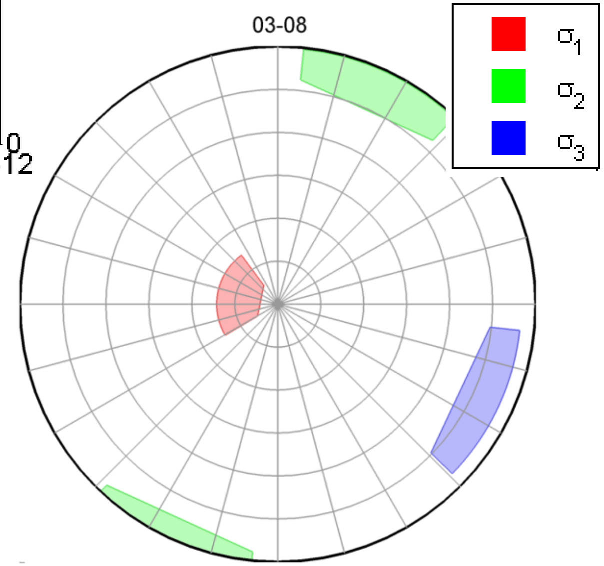


Kwiatek et al., 2016

Stress field change during peak injections



$$u_{ij}^{*,\mathrm{obs}} = u_{ij}^{\mathrm{obs}} + w_i u_{ij}^{\mathrm{obs}}(\tilde{r}_i - 1)$$



- Corelation between flow rates and changes in the stress field orientation.
- Significant changes (~ 20°) during peak injections

Martínez-Garzón et al. ,GRL, 2013

Azimuthal distribution of seismicity

- Hypocentral distance increase during peak injections
- Fracture network aligned with S_{HMax}