Quantifying the heterogeneity of the stress field derived from local and global borehole data

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WSM Quality Ranking

Stress Indicator	A Quality S_{Hmax} believed to be within ± 15°	B Quality S_{Hmax} believed to be within ± 15-20°	C Quality S_{Hmax} believed to be within ± 20-25°	D Quality Questionable S_{Hmax} orientation (± 25-40°)	E Quality no reliable information (> ± 40°)
Borehole breakout	≥ 10 distinct breakout zones and combined length ≥ 100 m in a single well with s.d. ≤ 12°	≥ 6 distinct breakout zones and combined length > 40 m in a single well with s.d. ≤ 20°	≥ 4 distinct breakouts and combined length ≥ 20 m with s.d. ≤ 25°	< 4 distinct breakouts or < 20 m combined length in a single well with s.d. ≤40°	Wells without reliable breakouts or s.d. > 40°
Drilling induced fracture	≥ 10 distinct fra... zones in a singl... with a combined length ≥ 100 m and s.d. ≤ 12°	with a combined length ≥ 40 m and s.d. ≤ 20°	with a combined length ≥ 20 m and s.d. ≤ 25°	zones in a single well or a combined length < 20 m and s.d. ≤ 40°	wells without fracture zones or s.d. > 40°

Two entangled concepts:
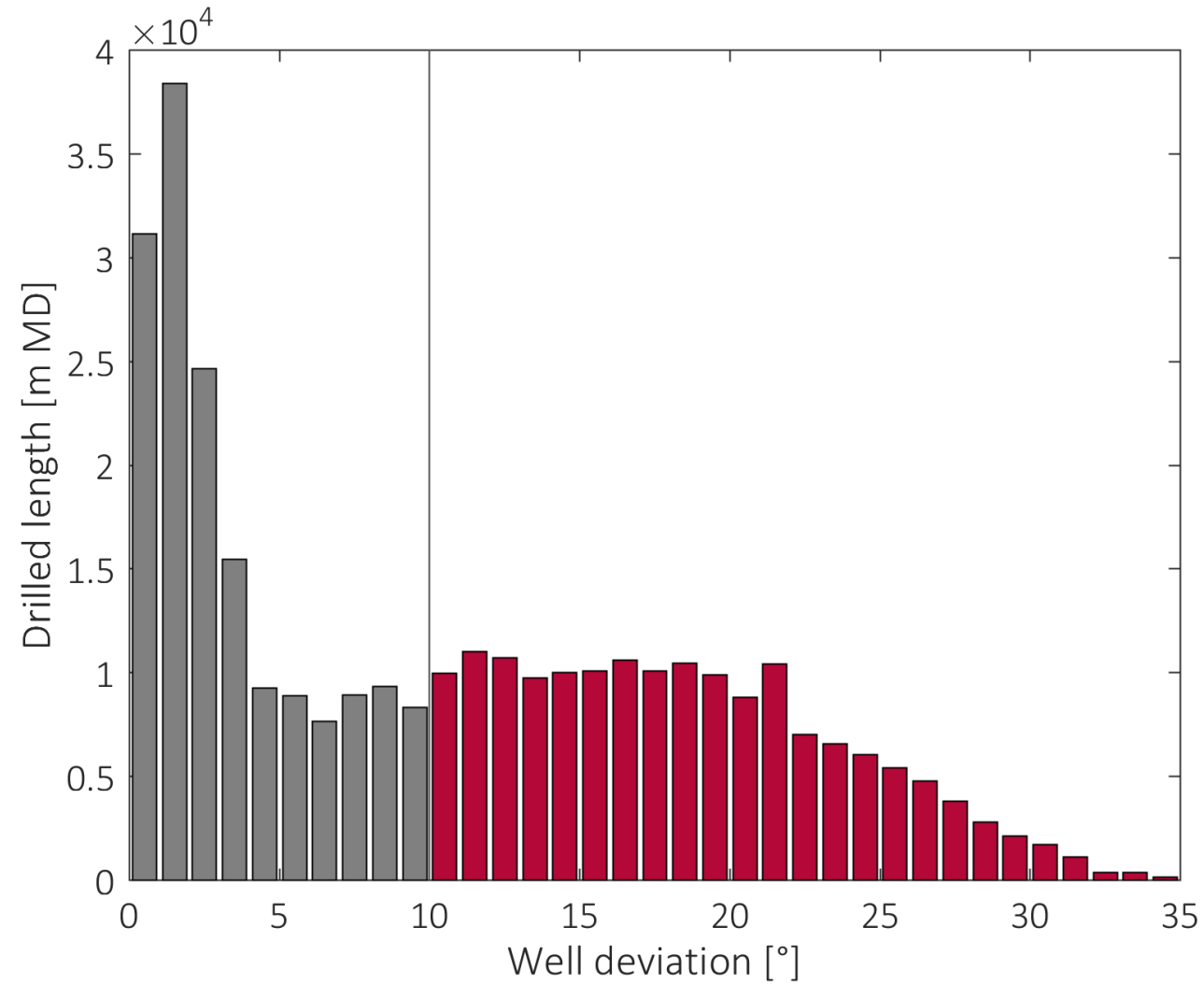Measurement Quality vs. Stress Heterogeneity

(from Heidbach et al., 2010)

Stress around wellbores
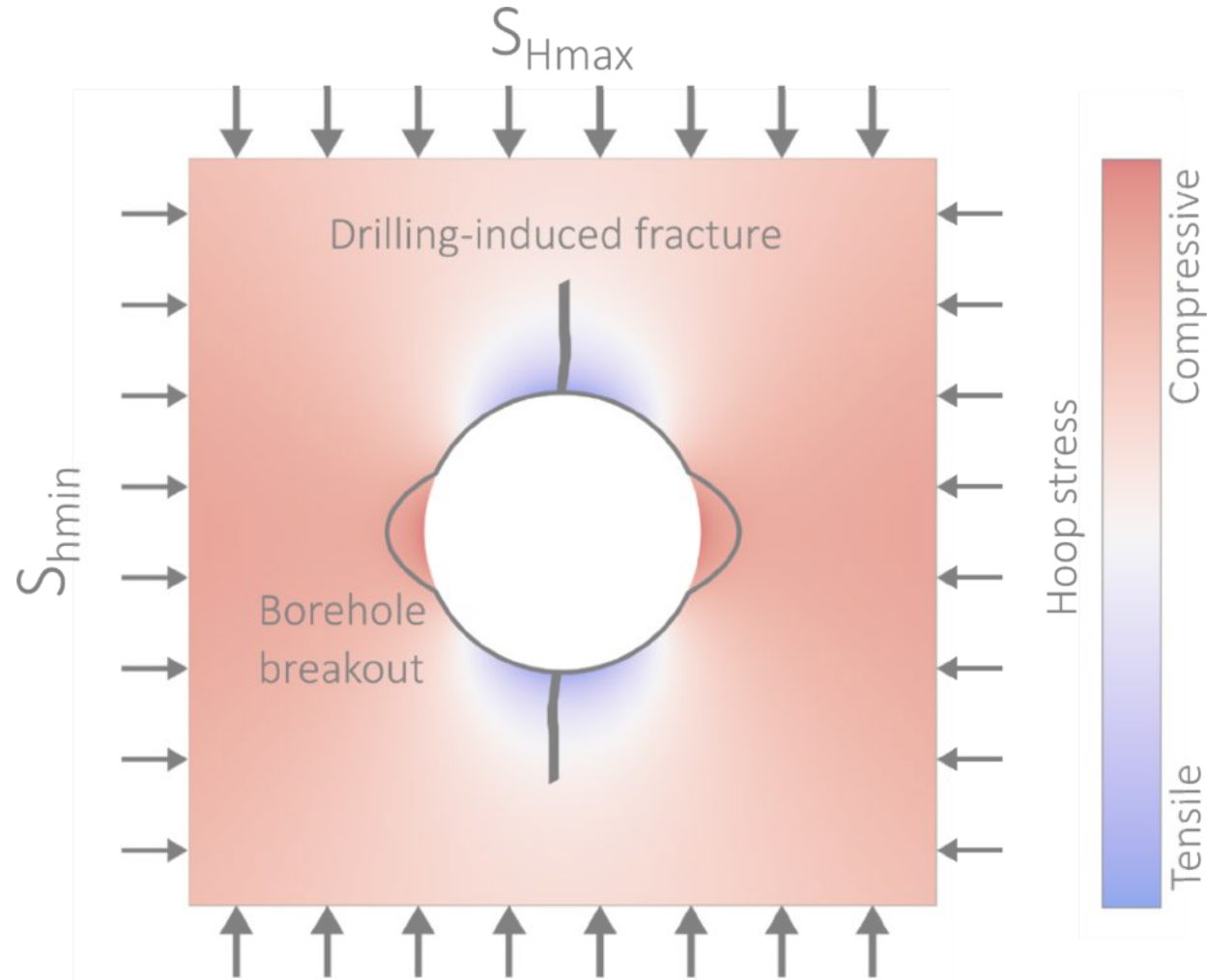
Good for near-vertical wells (DEVI<10°)
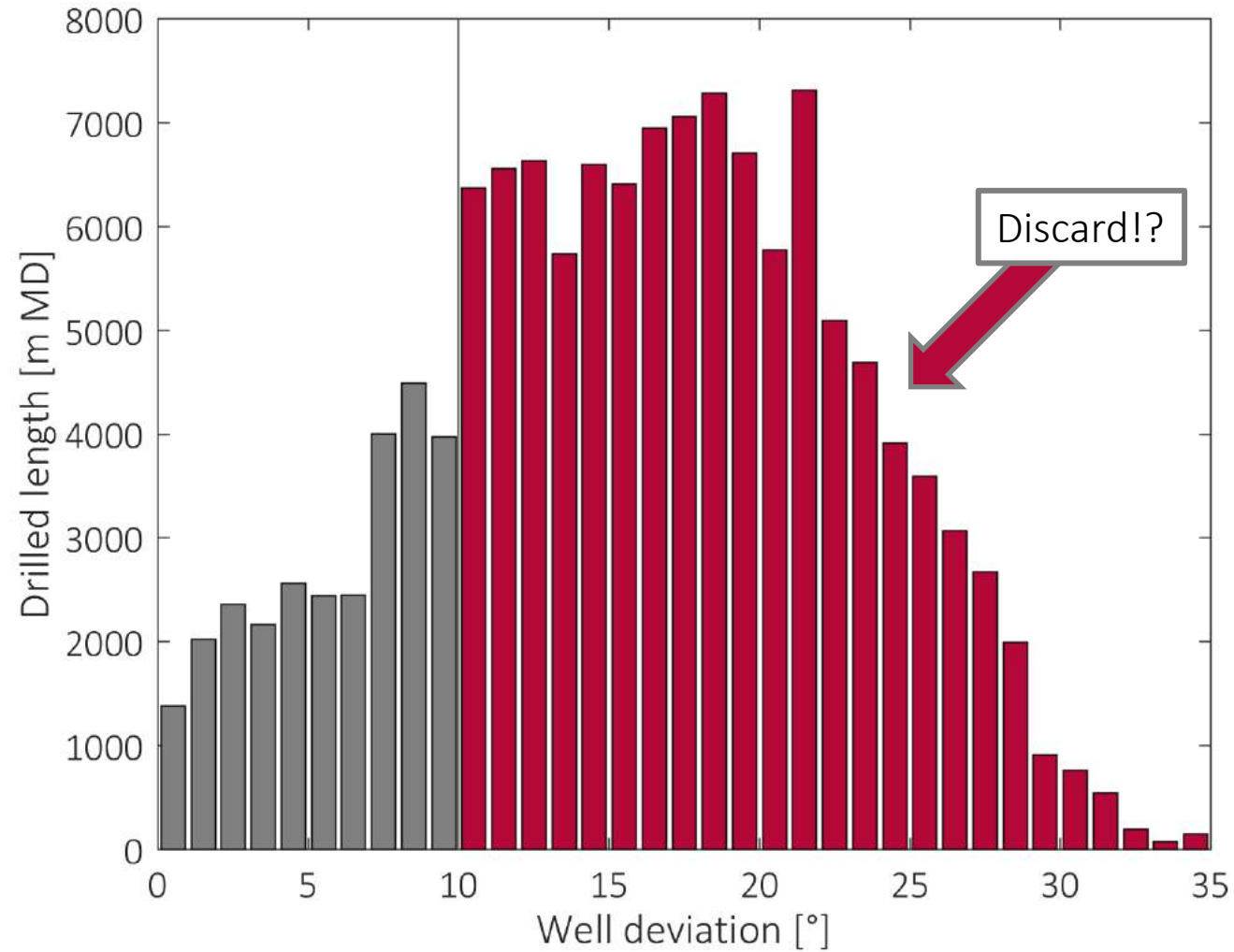Non-linear and non-unique problem for larger deviations

Well deviations at Coso Geothermal Field

- 50 % of well sections are deviated by more than 10° from vertical
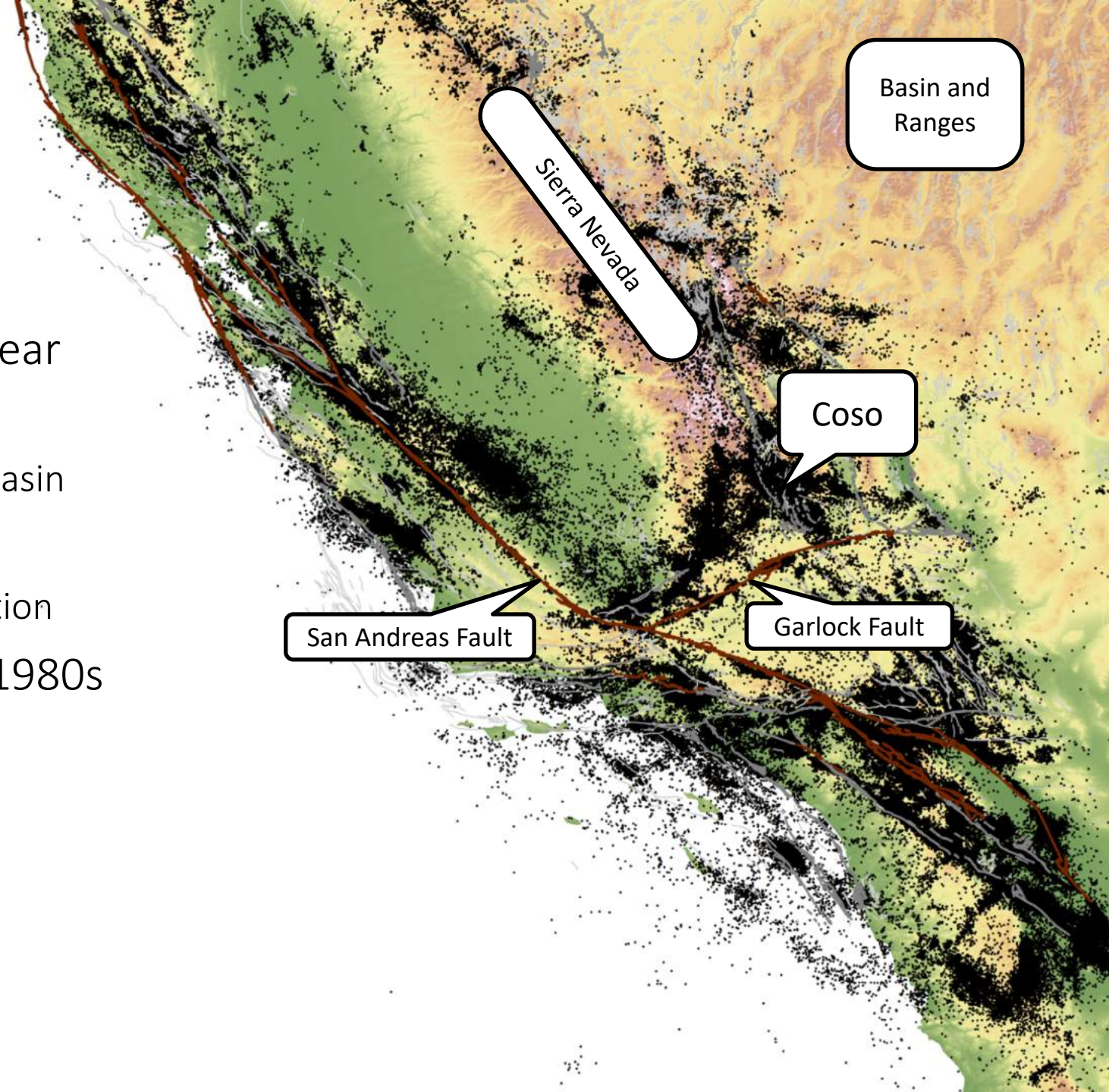
Well deviations at Coso Geothermal Field

- 80 % of deep* well sections are deviated by more than 10° from vertical
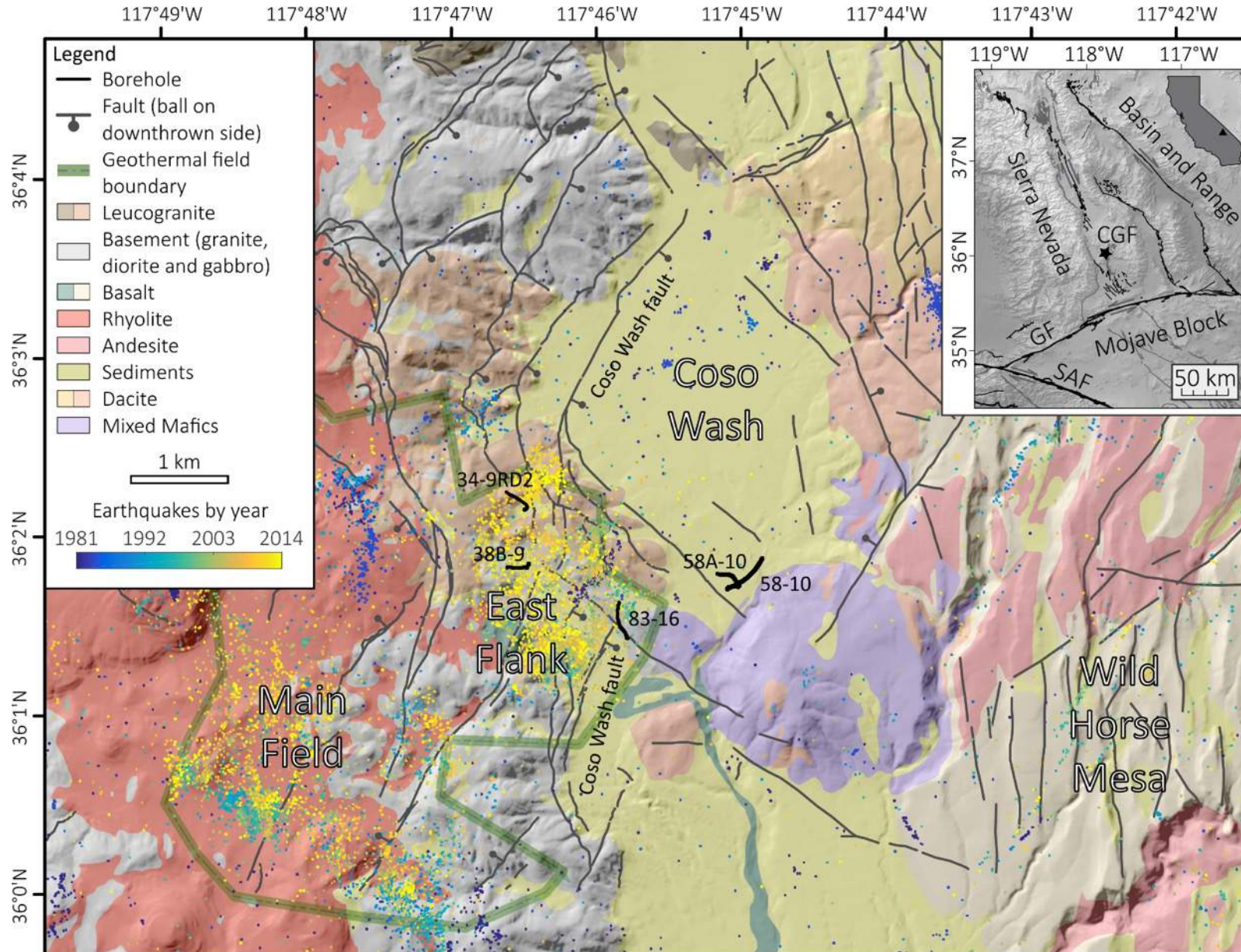
* below sea level

Coso Geothermal Field

- Young volcanic system
  - Most recent eruptions ~40 kyr ago
- Situated in the Eastern California Shear Zone
  - Transition from San Andreas Fault to Basin and Ranges systems
  - Accommodates ¼ of relative plate motion
- Geothermal exploration in 1970s – 1980s
  - 270 MW capacity online since 1990
  - > 170 wells drilled

# Coso Geothermal Field

Well trajectories
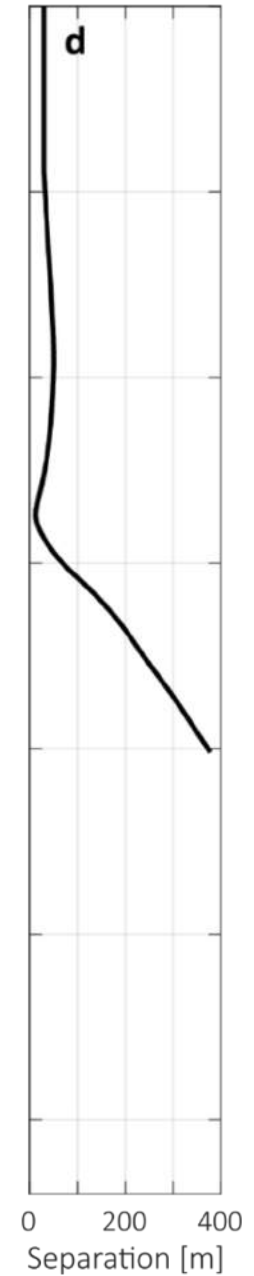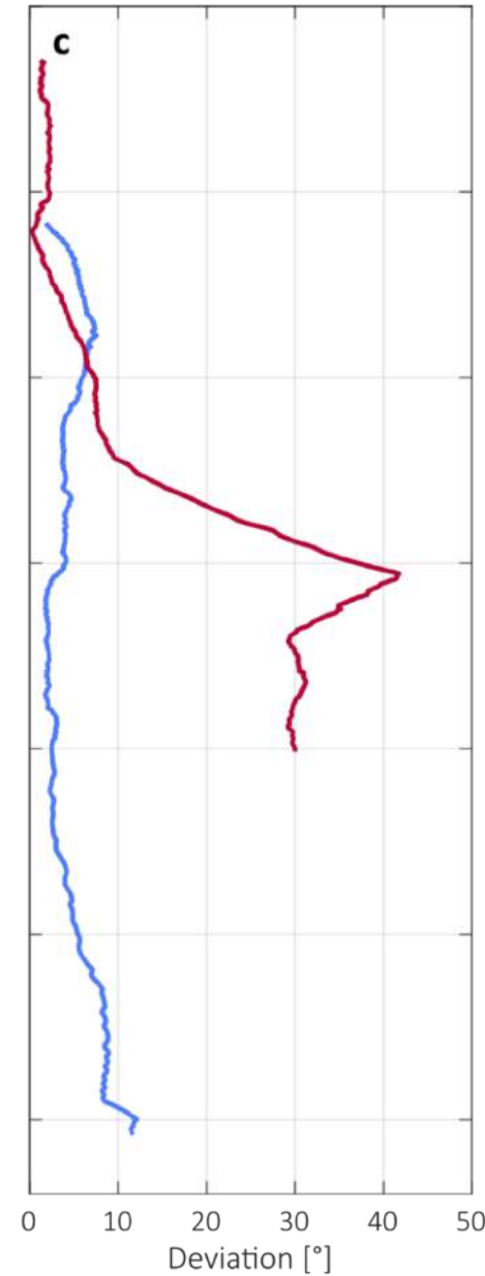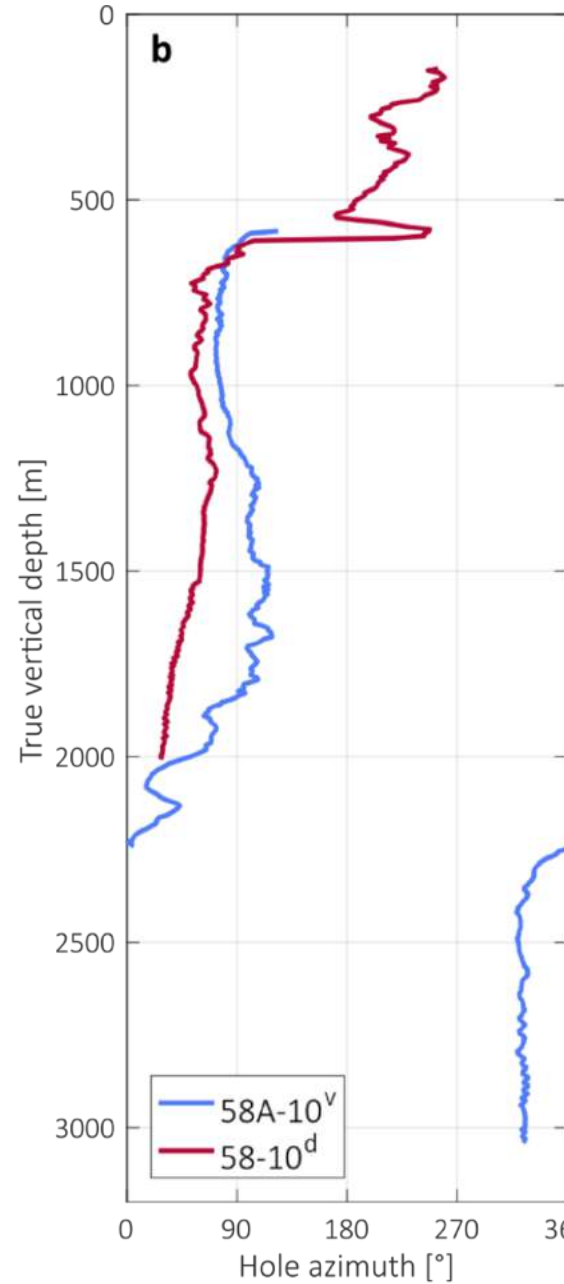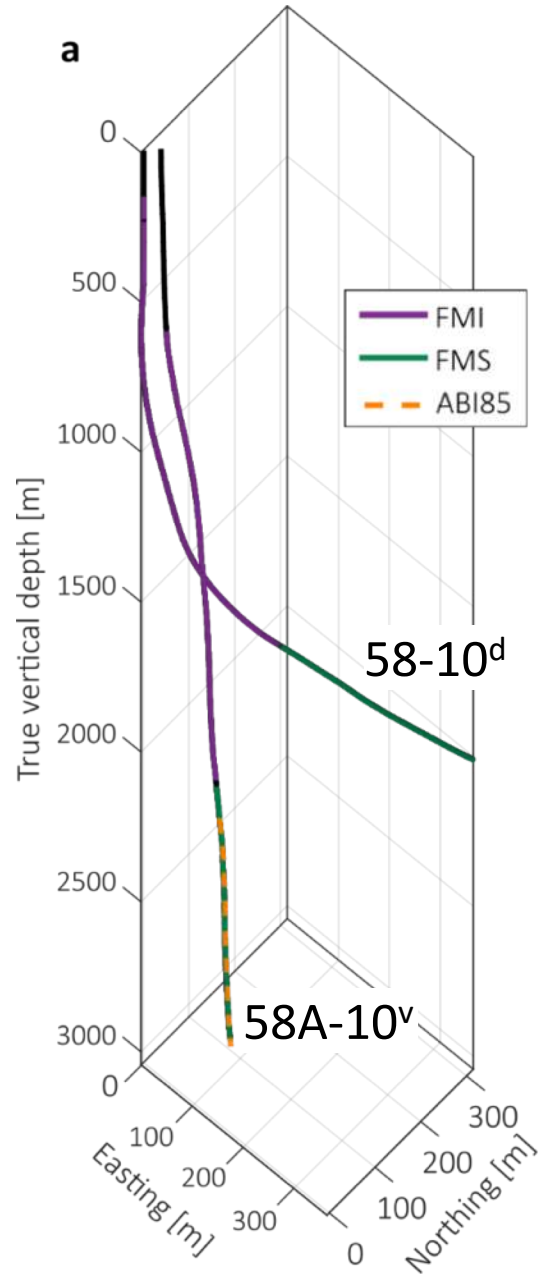
Approach to deviated wells

- Forward problem solved by Mastin (1988), Peška & Zoback (1995)
- Full inversion schemes do not provide details on non-uniqueness of best solution
  - Use a grid search instead
- Interpretation of stress indicators
  - Stress indicators in deviated wells do not coincide with stresses in geographic coordinates
  - Measure orientation relative to high side of well
- Assumptions
  - S_v is a principal stress (same as with standard analysis of vertical wells)
  - Constant ratio of S_{Hmax}, S_{hmin} and p_p to S_v
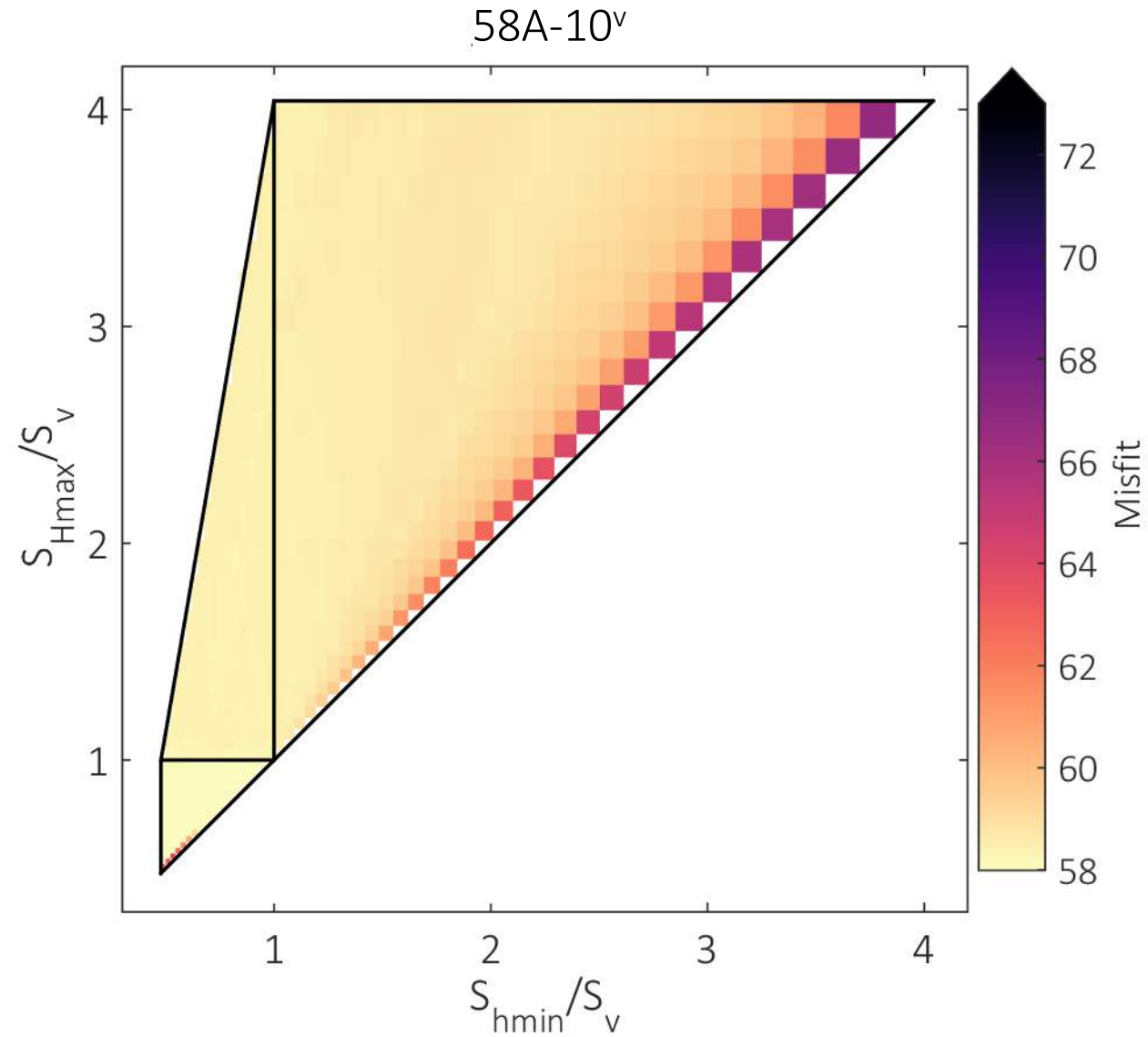
Grid search

- Perform grid search for best-fitting stress state
  - For each stress magnitude state given by S_{Hmax}/S_v, S_{hmin}/S_v
  - For each orientation of S_{Hmax}
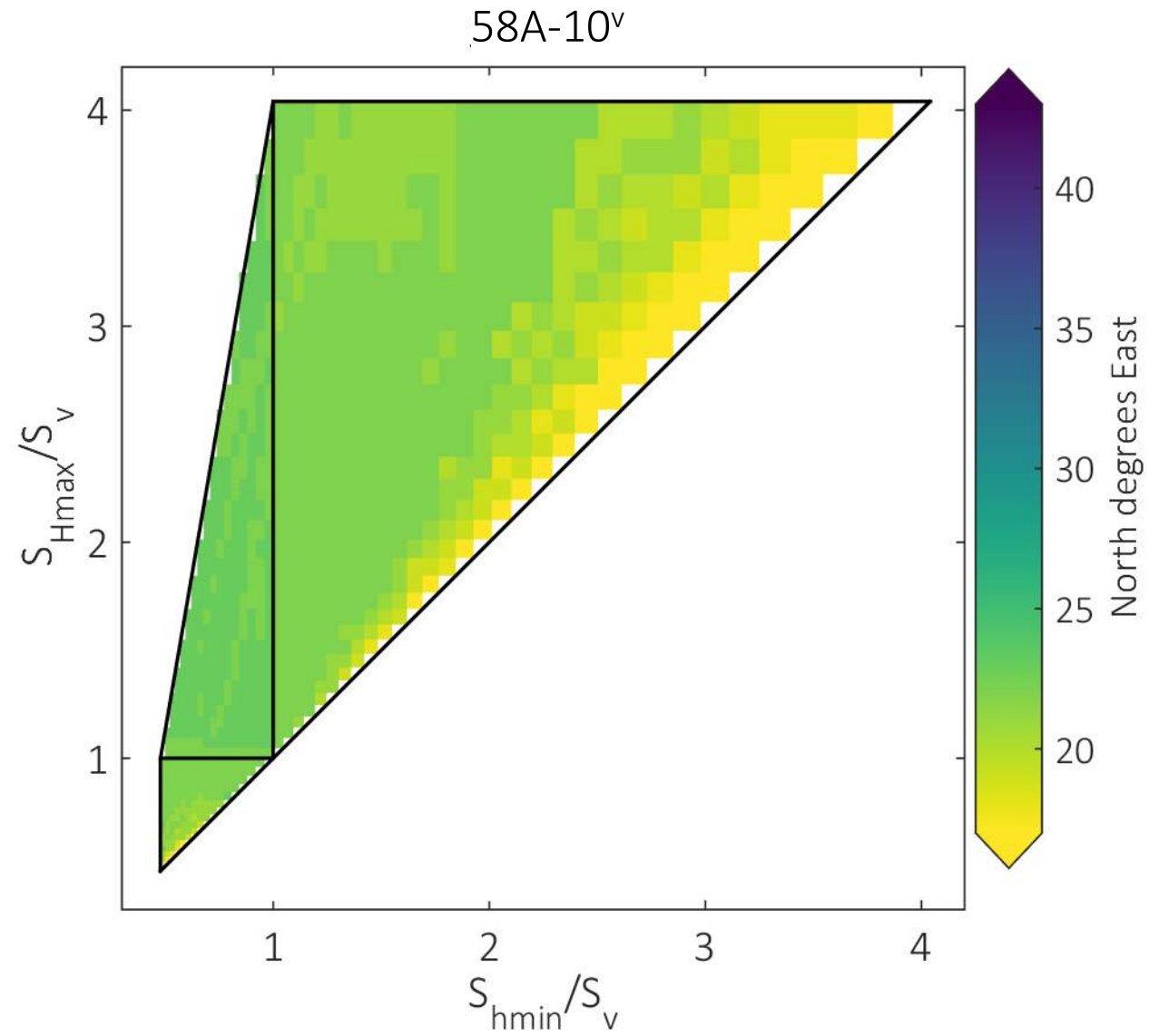 - For each failure stress indicator
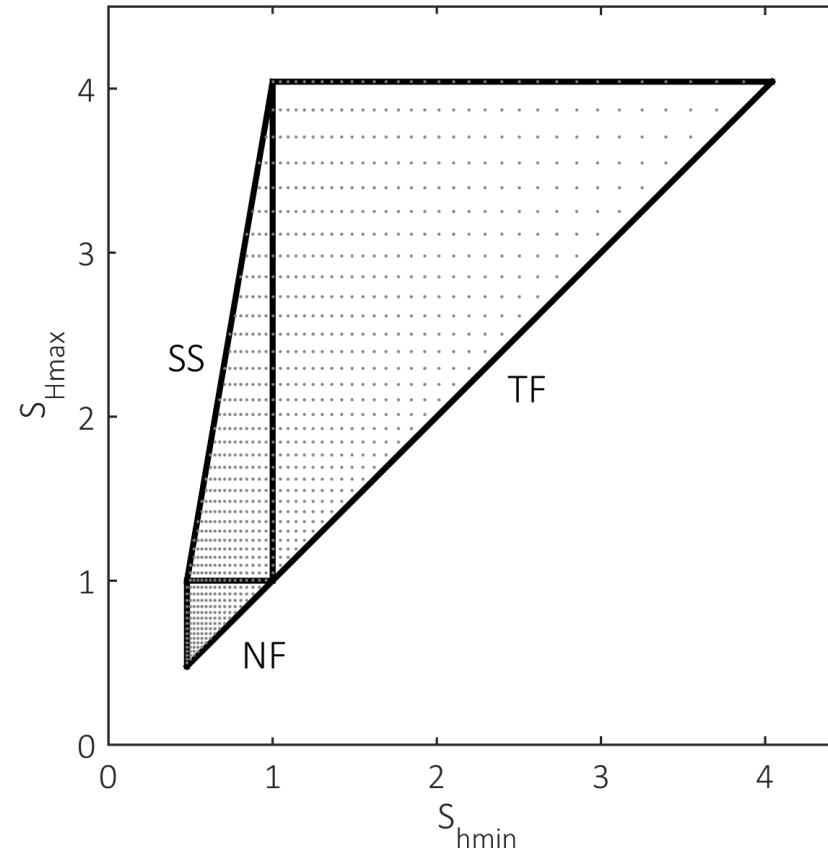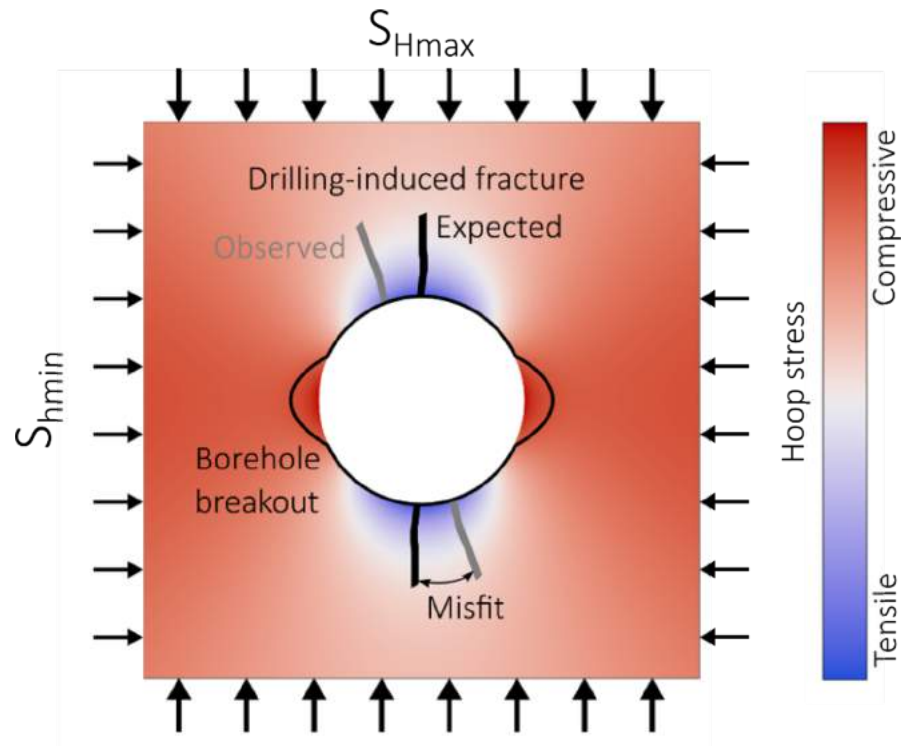
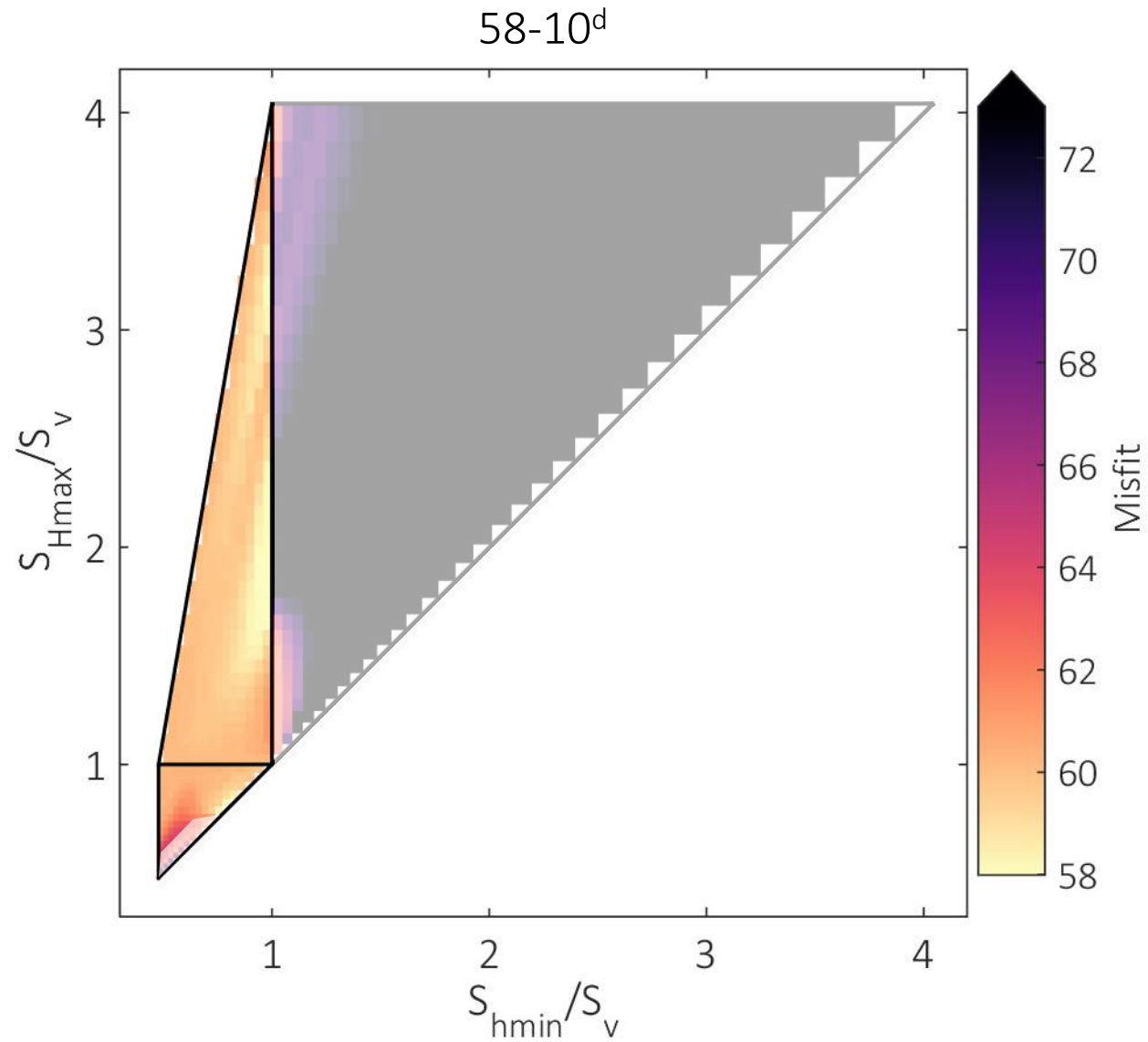> ➤ Sum *misfit* between observed and expected location

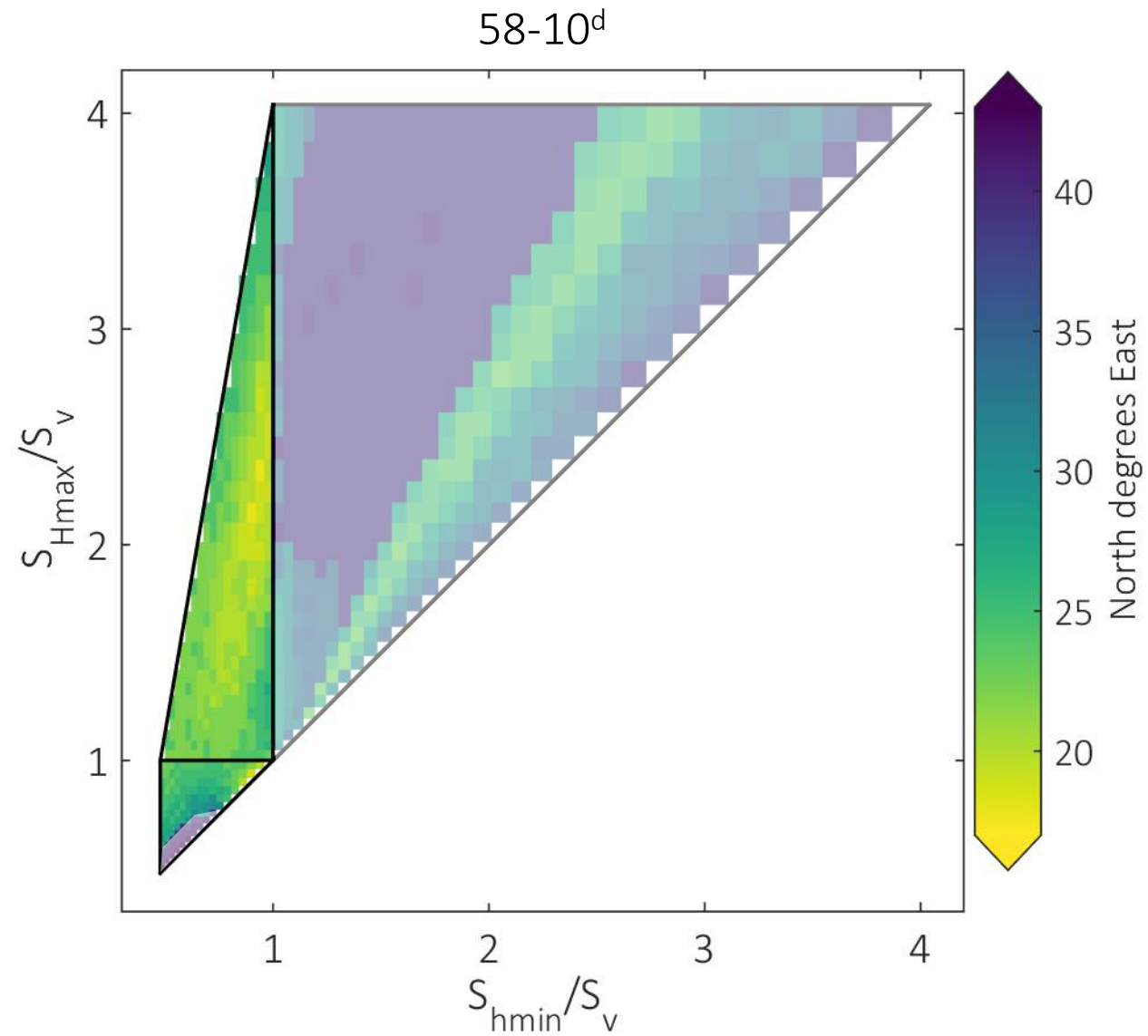# Best-fitting stress magnitude state – for any orientation of S_{Hmax}

58A-10[v]

Which S_{Hmax} orientation for best-fitting stress state?

58A-10^{v}

Best-fitting stress magnitude state – for any orientation of S_{Hmax}
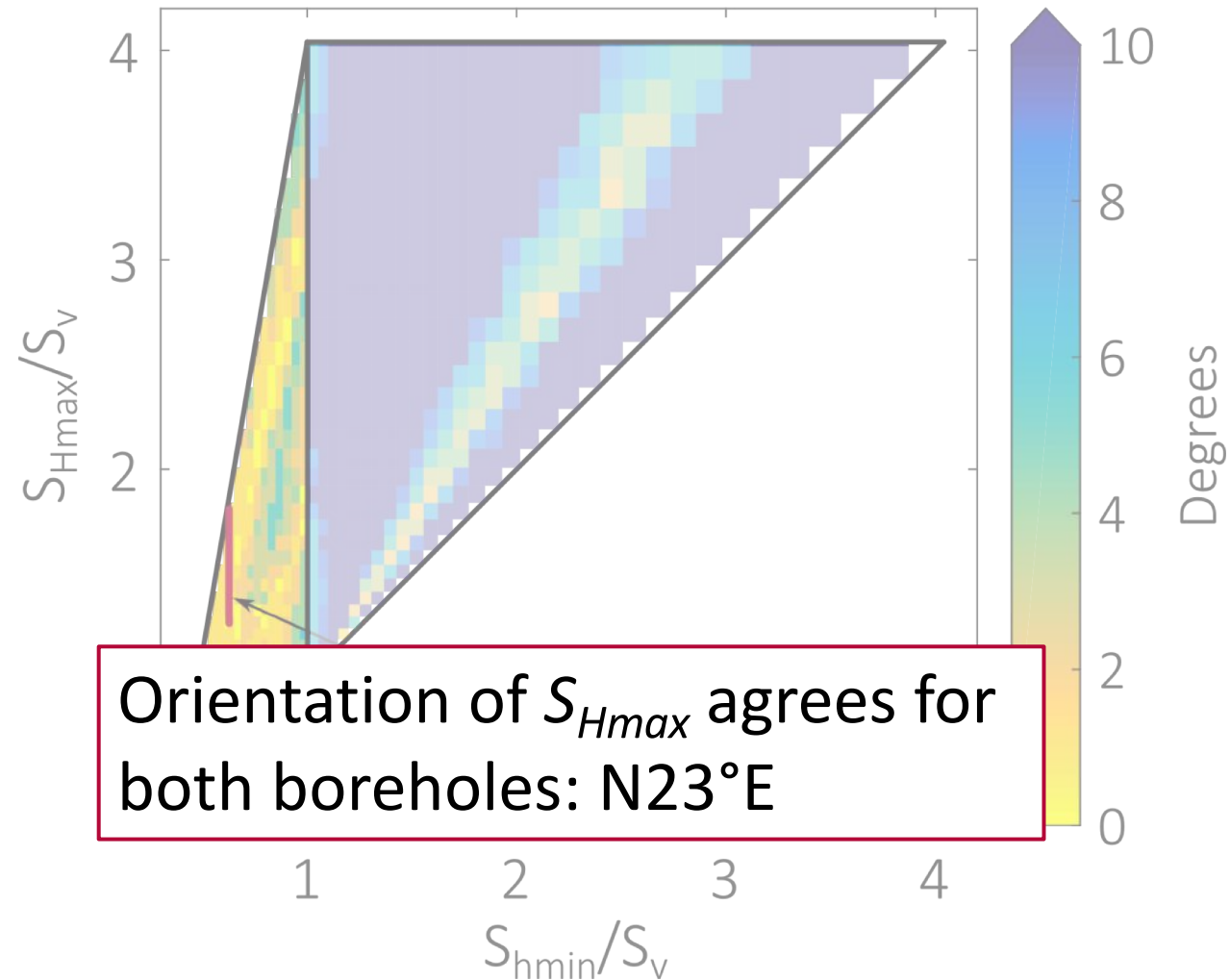

58-10^d

Which S_{Hmax} orientation for best-fitting stress state?
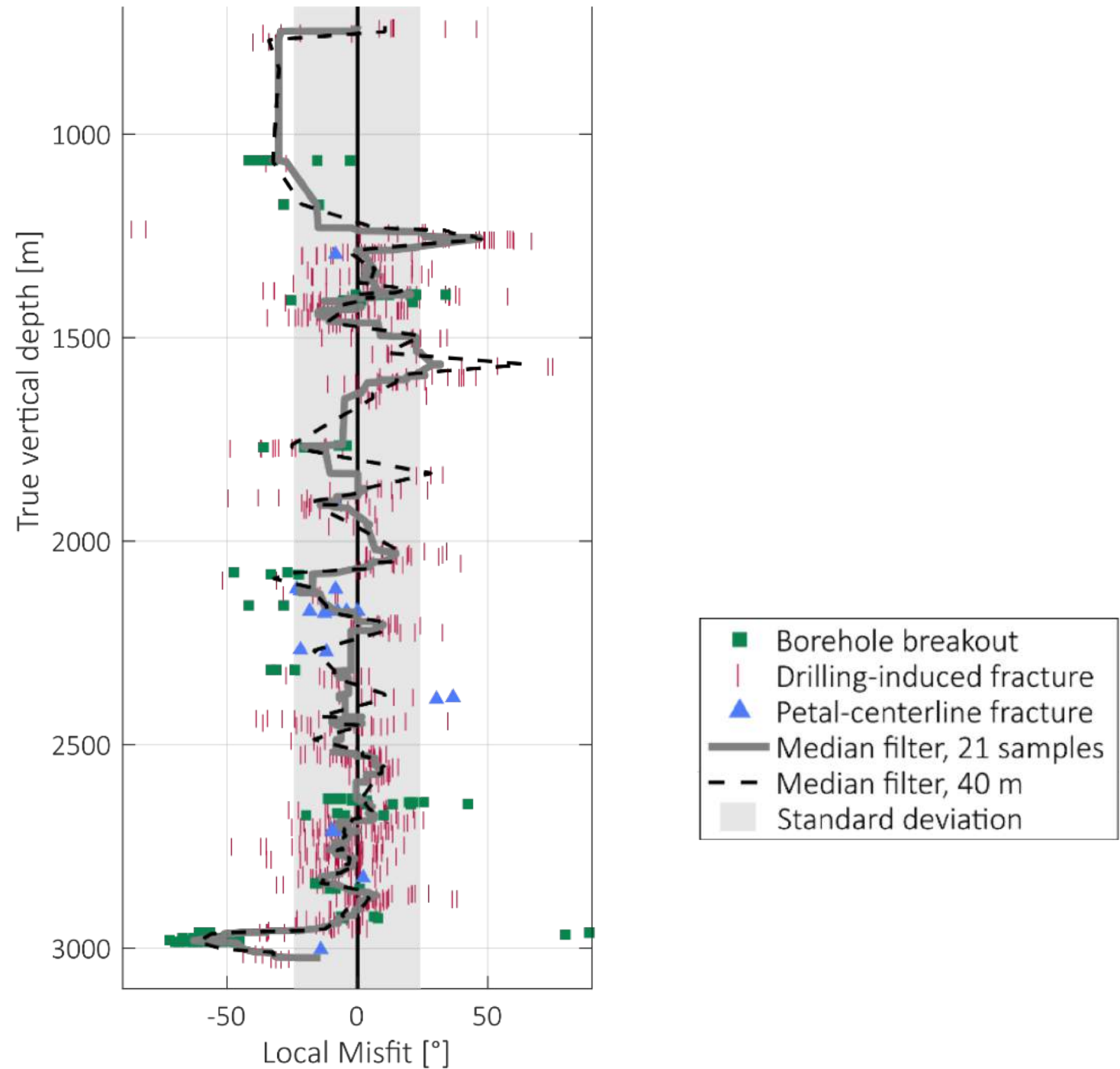

58-10^d

How do best-fitting stress orientations compare?

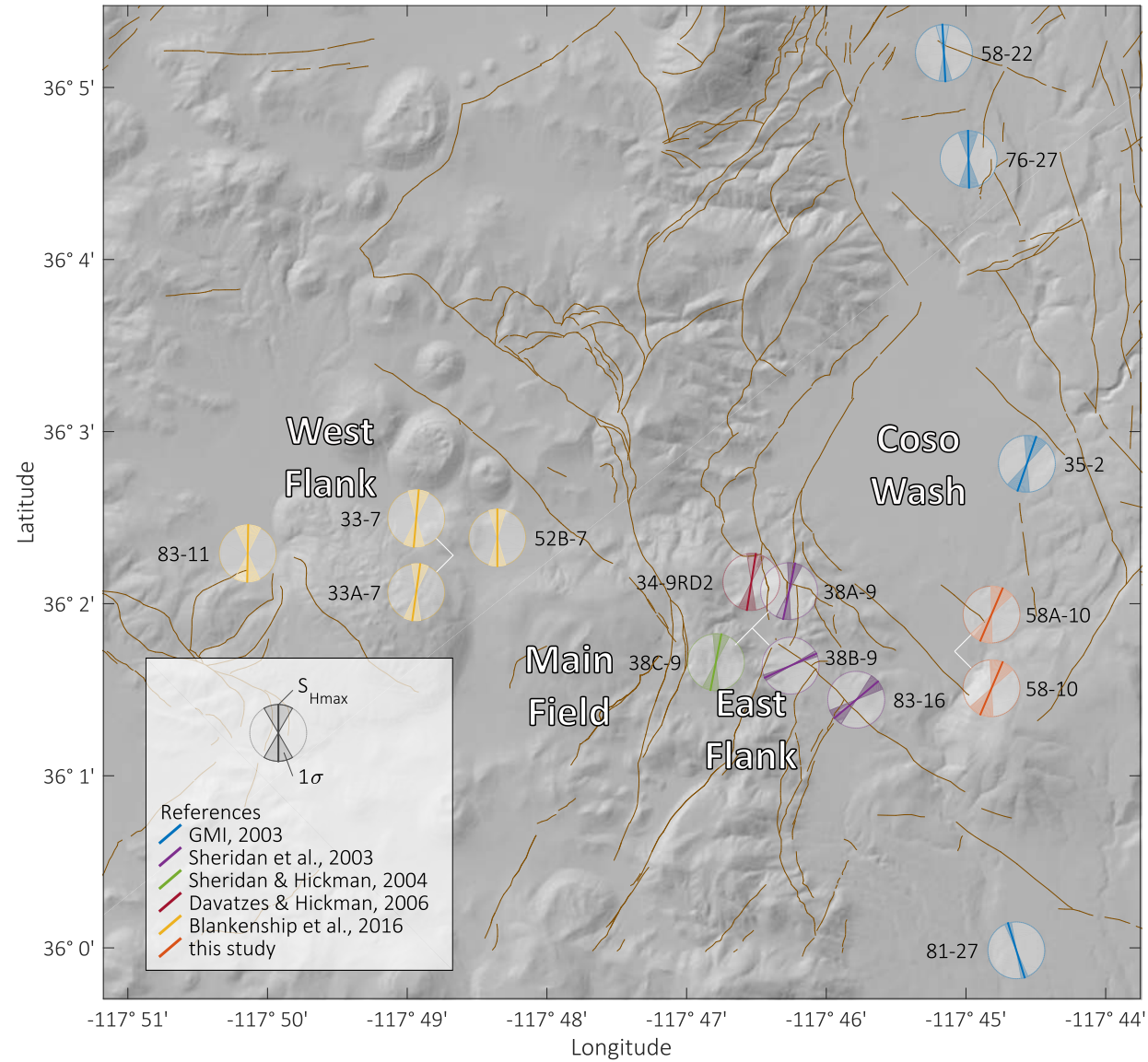- Difference of preferred orientations $|azi(S_{Hmax,58A\text{-}10}) - azi(S_{Hmax,58\text{-}10})|$
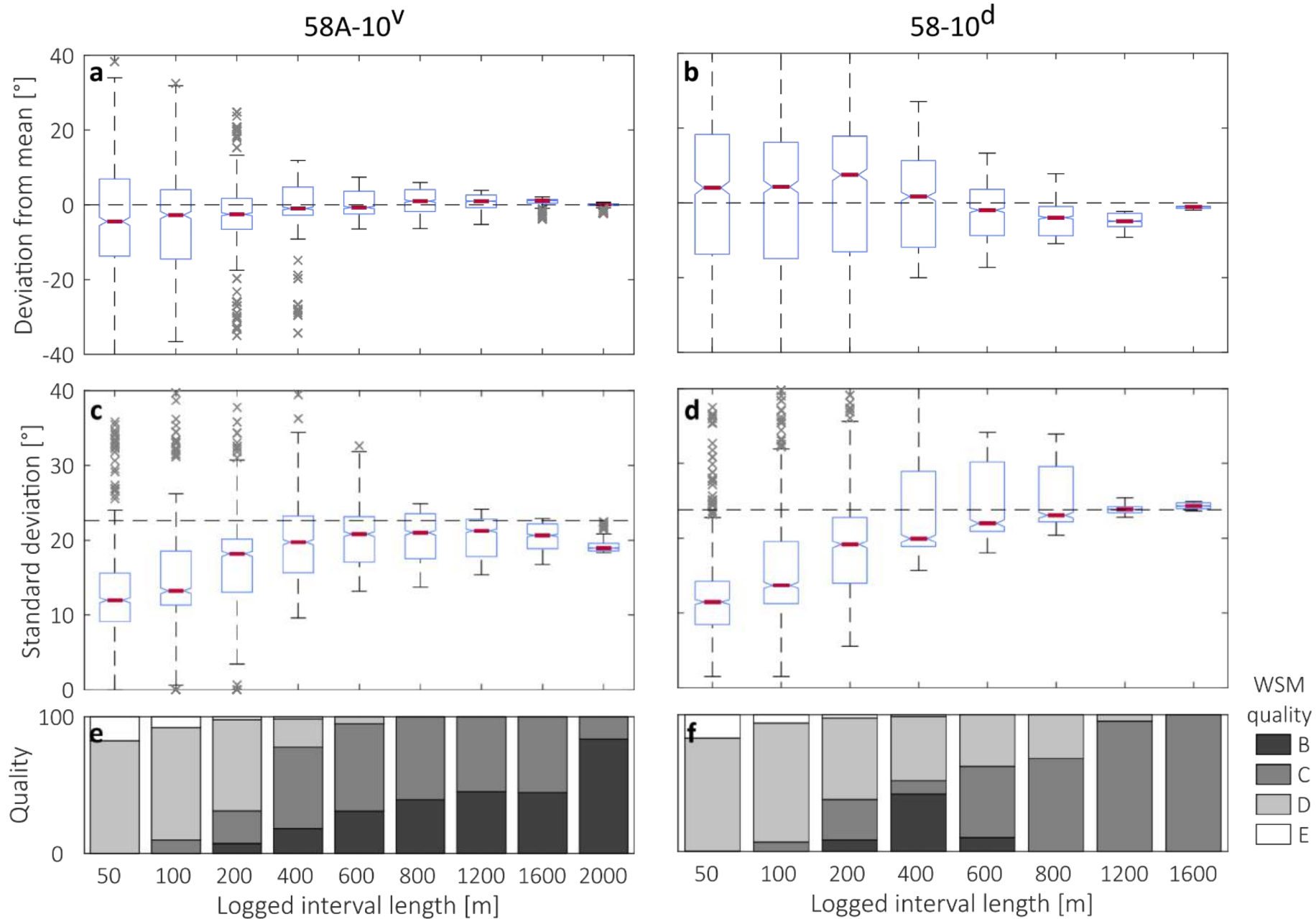

Orientation of S_{Hmax} agrees for both boreholes: N23°E

Local stress orientation

Local stress orientation

Standard deviations for both boreholes agree as well: SD=23°
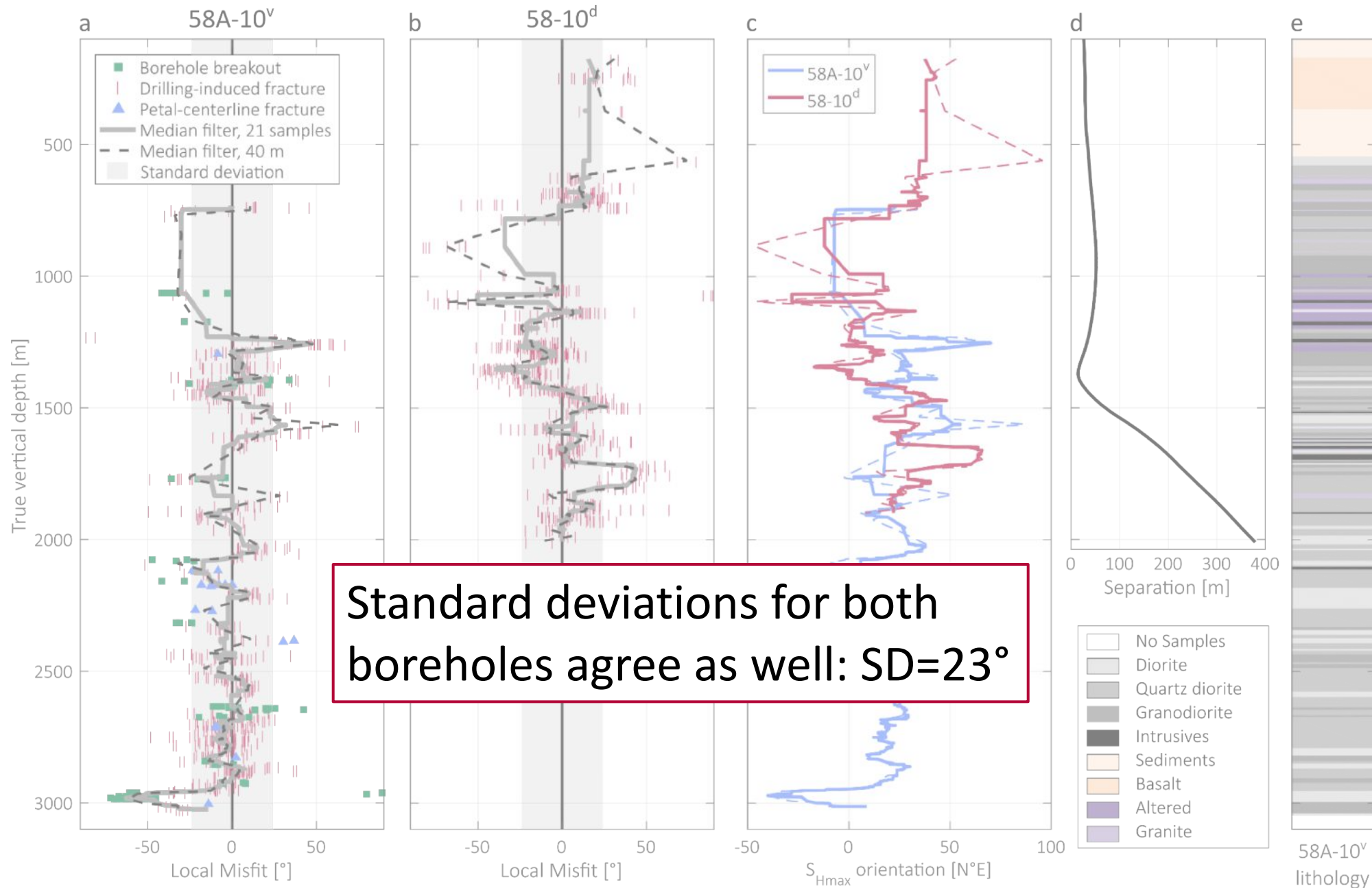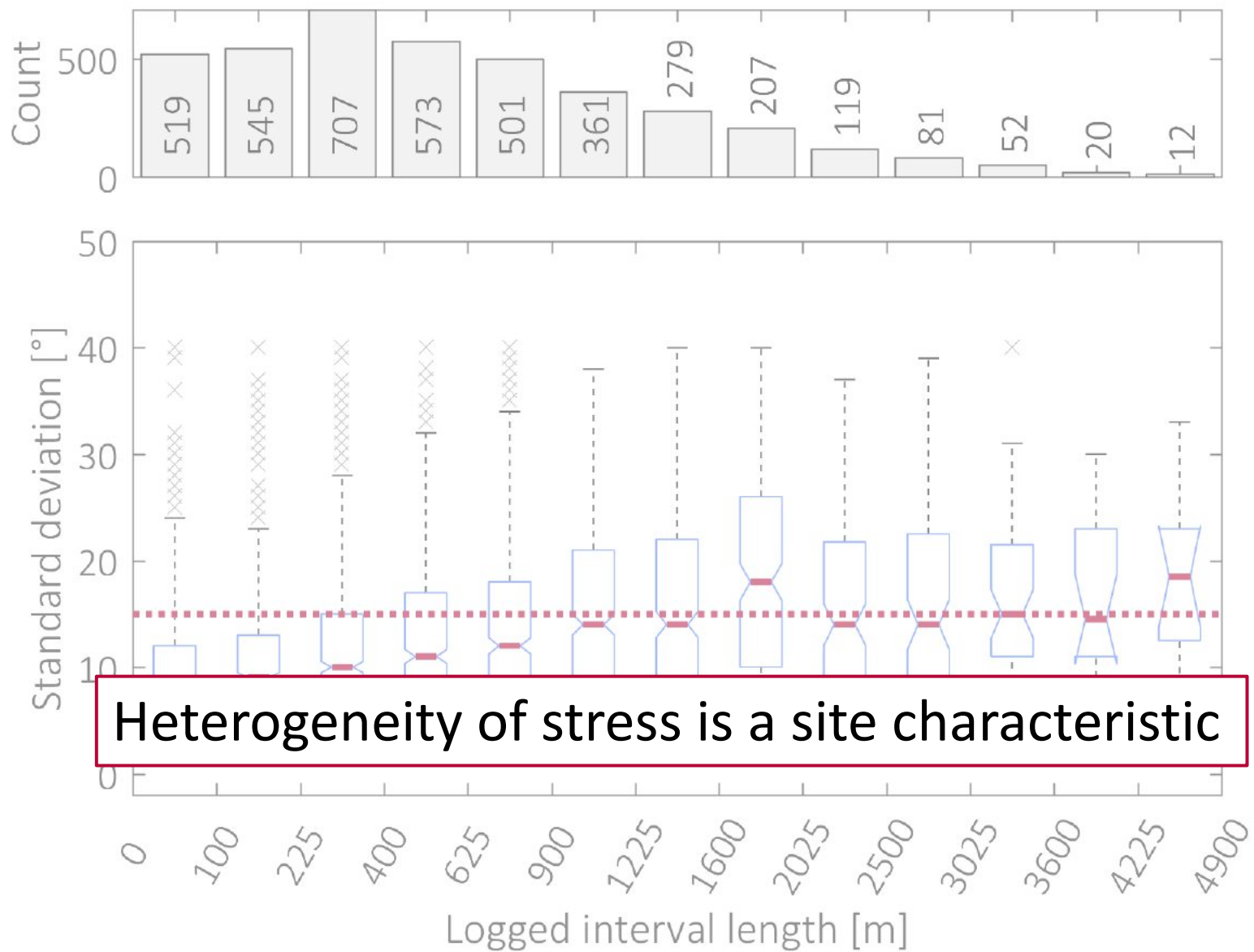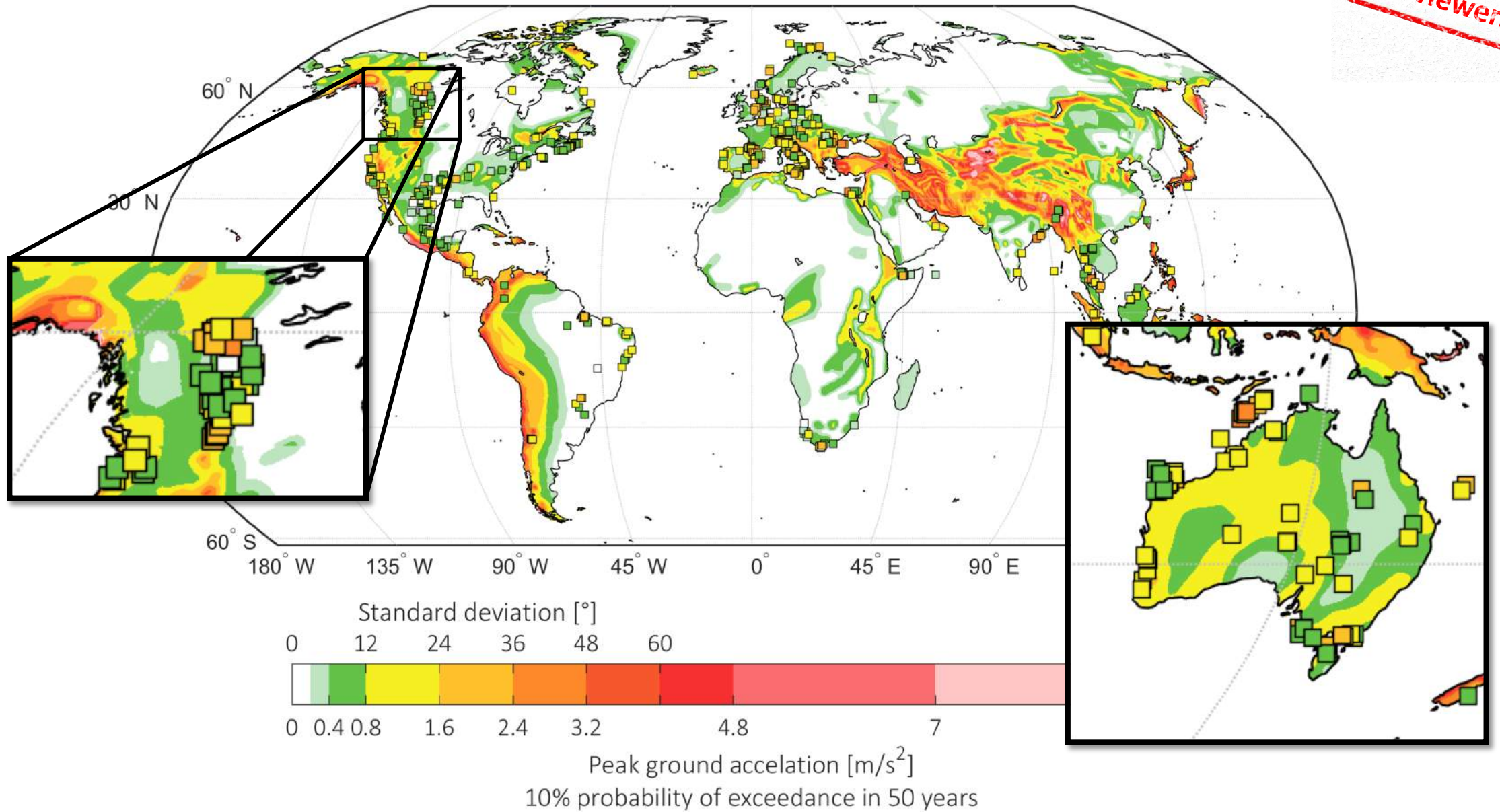
Local stress map

Derived stress orientation vs. logged interval

Global World Stress Map borehole data

Heterogeneity of stress is a site characteristic
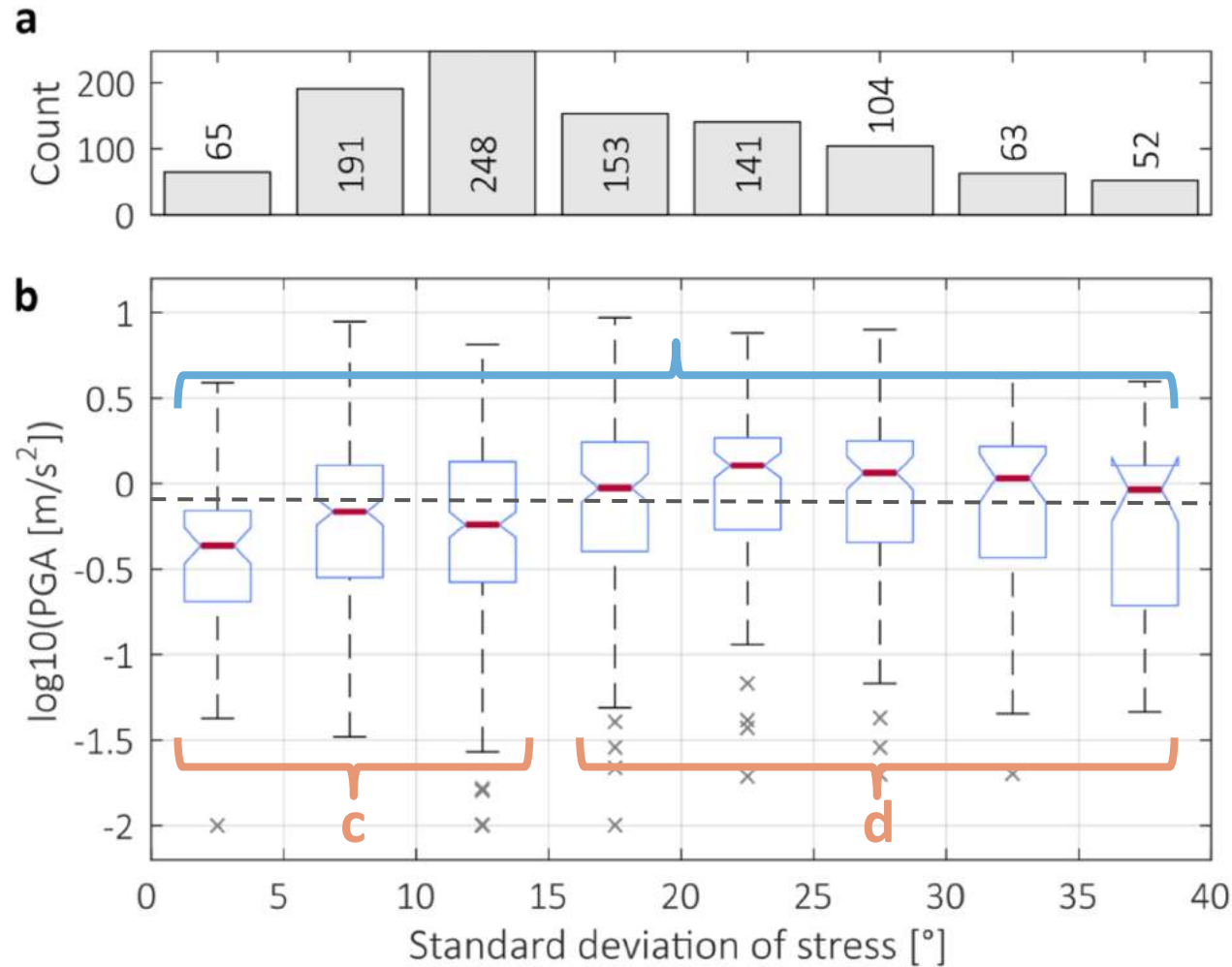
Stress heterogeneity vs. GSHAP

Standard deviation [°]

0 12 24 36 48 60

0 0.4 0.8 1.6 2.4 3.2 4.8 7

Peak ground accelation [m/s^2]
10% probability of exceedance in 50 years

Stress heterogeneity vs. GSHAP
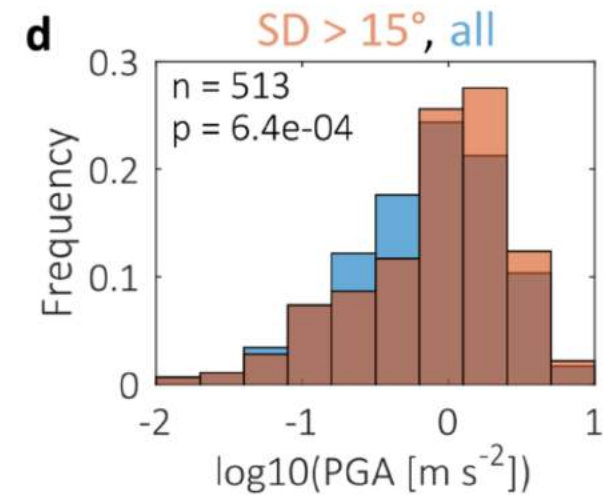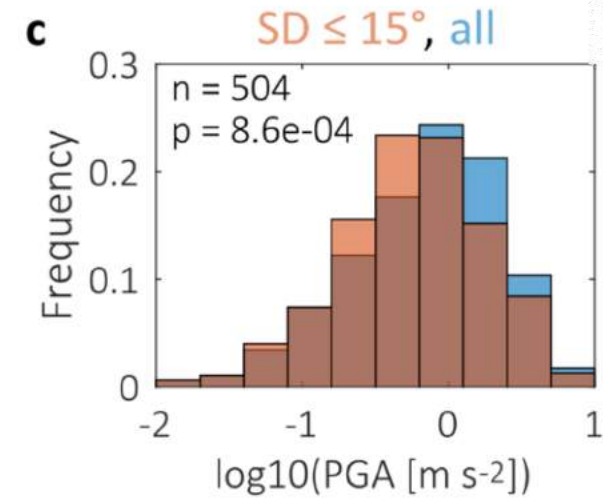
Conclusions

- Deviated wells sample the stress field in different directions
  - Gather information about stress tensor in various orientations
  - Results can be non-unique
- Heterogeneity of stress is a site characteristic
  - Large standard deviation of about 23° at Coso
  - Stress indicators spanning ≳600 m needed for a reliable stress characterization (orientation and standard deviation)
  - Correlation between stress heterogeneity and seismic activity suggested

(Almost) full story:

Schoenball, M., & Davatzes, N. C. (2017). Quantifying the heterogeneity of the tectonic stress field using borehole data. *Journal of Geophysical Research: Solid Earth*, *122*(8), 6737–6756. https://doi.org/10.1002/2017JB014370

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