Seismic Anisotropy as a Measure of *In Situ* Stress for Safe CO_2 Storage

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13:40-17:30

Background

Borehole measurements of stress (breakout, overcoring etc.,) have limited spatial resolution.

Seismic anisotropy has been used to interpret S_{Hmax} in tectonic and volcanic settings (e.g., Crampin et al.,1999, Baird et al., 2015, Illesley-Kemp et al., 2019).

This project, part of the ACT3 funded SHARP Storage consortium, tests if microseismic shear-wave splitting can be used to monitor stress state and changes.

We use data recorded across the UK and data recorded by Permanent Reservoir Monitoring (PRM) systems at the Snorre field.

Summary

Shear-wave splitting measured for microseismicity can be used to interpret S_{Hmax} orientation.

PRMs are suitable for measuring microseismic shear-wave splitting.

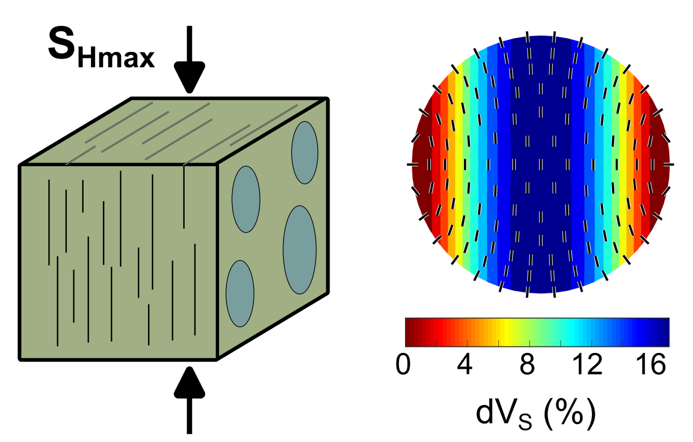
Temporal variations in shear-wave splitting can be used to infer stress changes during fault activation.

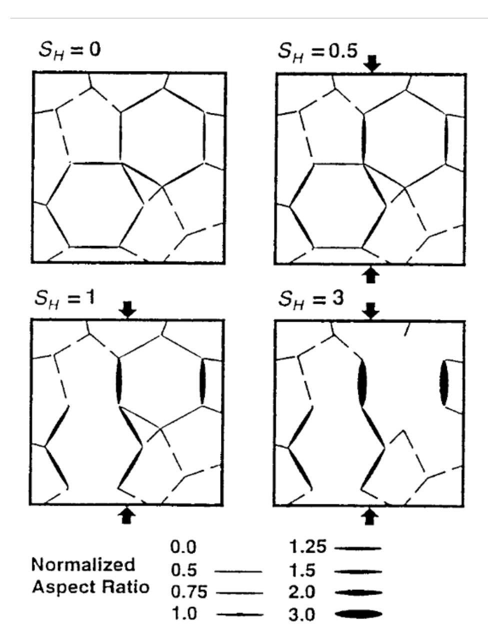
If offshore microseismic monitoring is implemented for an offshore CO_2 site then shear-wave splitting is an useful "free" added value.

Stress-induced anisotropy

Fractures and microcracks preferentially align with S_{Hmax} when there are differential horizontal stresses (Crampin, 1999).

This generates a shape preferred orientation (SPO) anisotropic fabric.

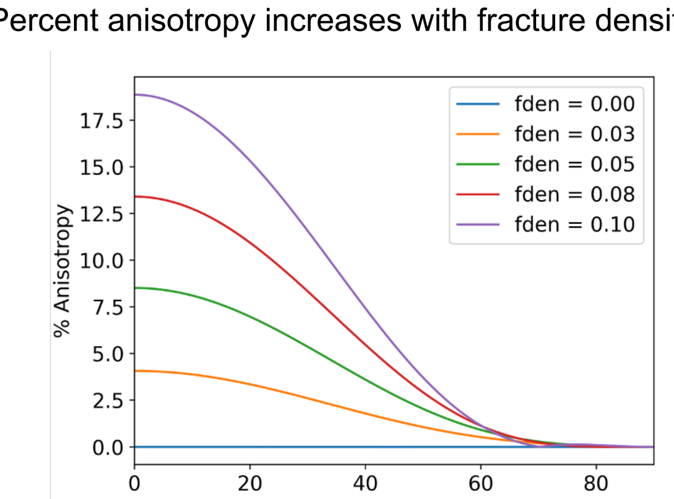




Crampin, 1999

Anisotropy develops when the maximum differential horizontal stress $S_{Hmax} > S_C$, the critical stress where cracks begin to close.

Percent anisotropy increases with fracture density.



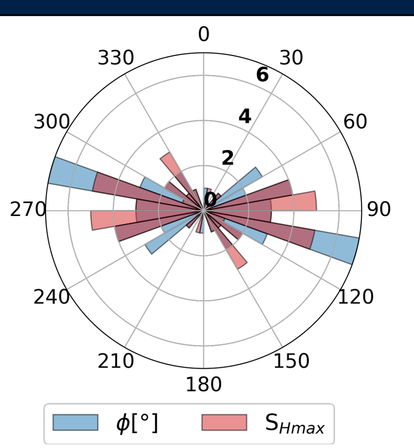
Offshore shear-wave splitting

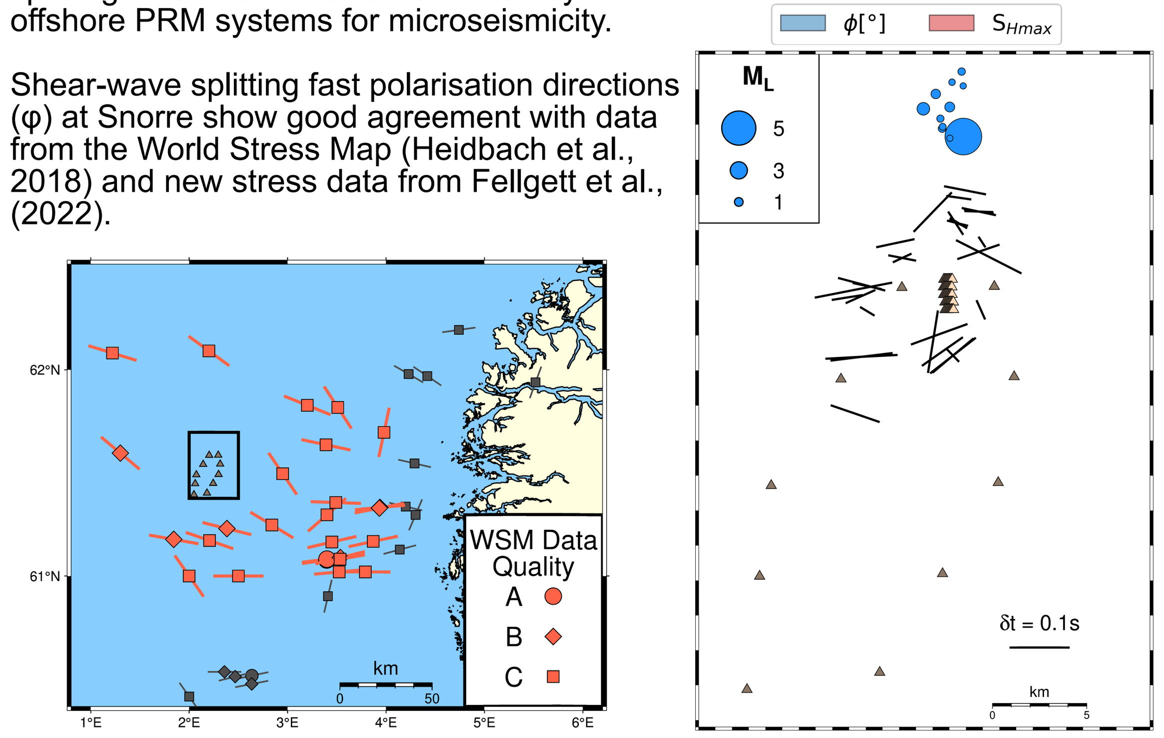
Data recorded by 60 Permanent Reservoir Monitoring (PRM) stations at the Snorre field, Northern North Sea.

Shear-wave splitting measured for the 2022 M_W 5.1 Tampen Spur earthquake and 16 aftershocks with local magnitudes in the range $0.1 < M_L < 2.6$ (Jerkins et al., 2024).

Results show that high-quality shear-wave splitting measurements can be made by offshore PRM systems for microseismicity.

Shear-wave splitting fast polarisation directions (φ) at Snorre show good agreement with data from the World Stress Map (Heidbach et al., 2018) and new stress data from Fellgett et al., (2022).



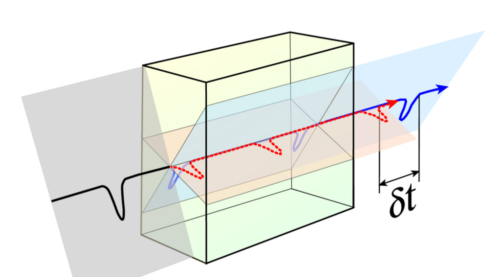


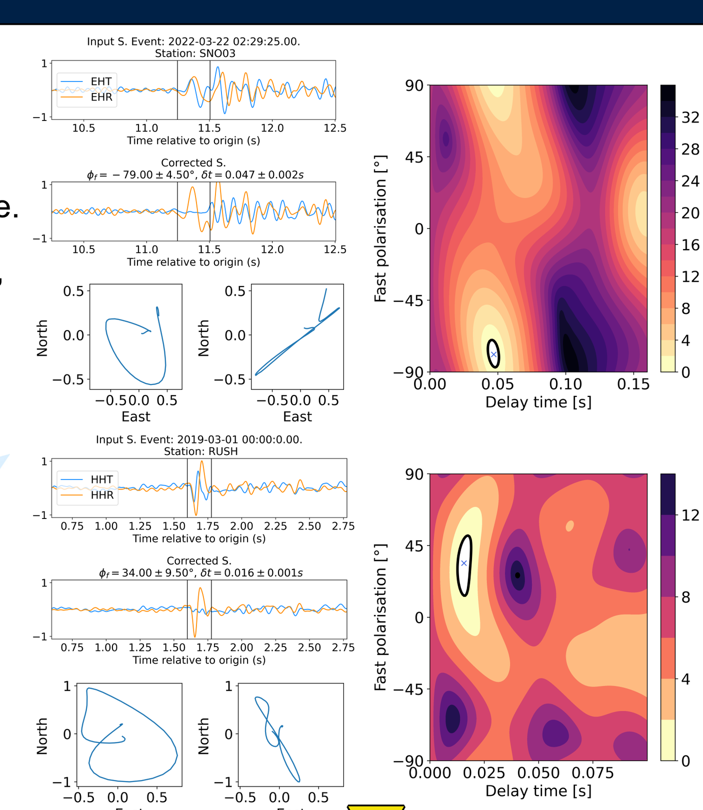
Shear-wave splitting

Shear-wave splitting is a clear indicator of seismic anisotropy.

Incident shear-waves are split into a **fast** and **slow** shear-wave.

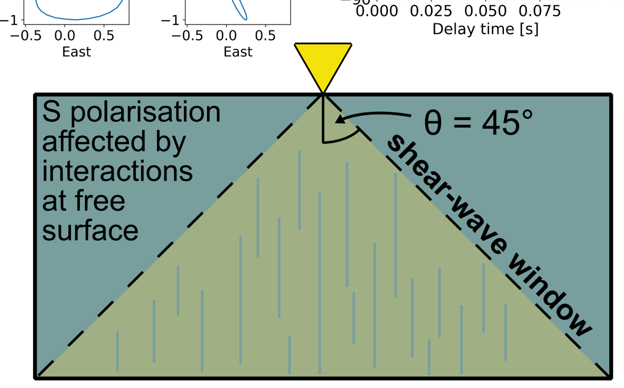
We measure the polarisation, φ, of the **fast** shear-wave and the delay time δt between **fast** and **slow** shear-waves.





Splitting measured using eigenvalue minimisation (Silver and Chan, 1991).

For shallow, local, seismicity the **shear-wave window** limits where shear-wave splitting measurements can be made.



Shear-wave splitting as a proxy for S_{Hmax} across the UK

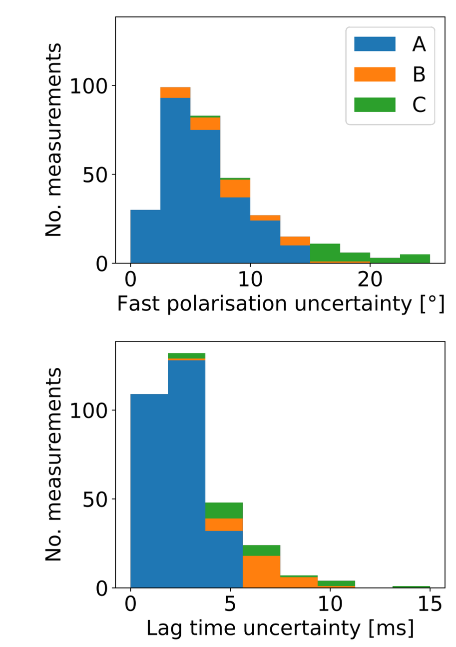
Shear-wave splitting is measured for 902 earthquake-station pairs across the UK.

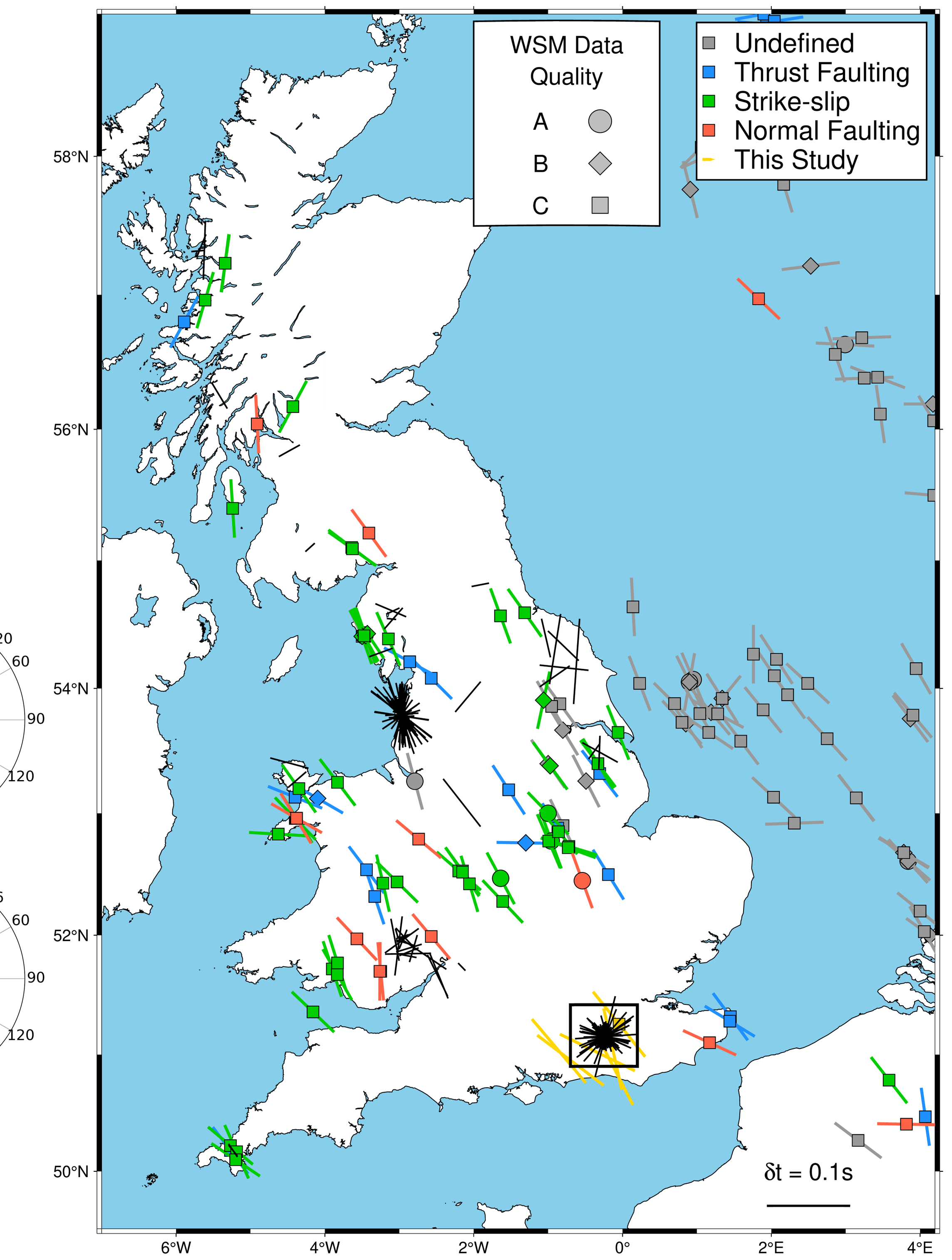
The 329 measurements with uncertainty in φ and δt equivalent to World Stress Map data qualities A-C are analysed.

The majority of the results are at two localities:

1. **Preston New Road, Lancashire**
2. **Newdigate, Surrey**

At Newdigate, temporal variations in seismic anisotropy **(3)** are also observed.





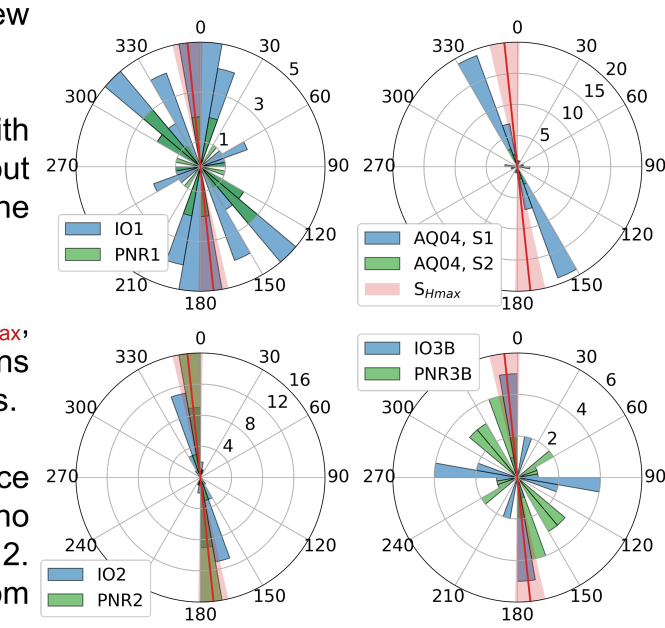
1. Preston New Road

Shear-wave splitting is measured for 173 earthquake-station pairs using microseismic events ($-1.7 \leq M_L \leq 2.9$) recorded by stations monitoring two stages of hydraulic fracturing at Preston New Road, Lancashire.

We are able to directly compare measured φ with S_{Hmax} (173 ± 7°) interpreted from borehole breakout and drilling-induced tensile fractures from the nearby Preese Hall 1 well (Clarke et al., 2019).

Shear-wave splitting generally agrees with S_{Hmax}, with local stress rotation at AQ04. Some stations (IO1, IO3B) show evidence of secondary fractures.

Anisotropy shows no signs depth dependence (event depths range from 1.6 to 2.9km) and no temporal variation between Stage 1 and Stage 2. Stations IOXX were renamed to PNRXX from Stage 1 to Stage 2

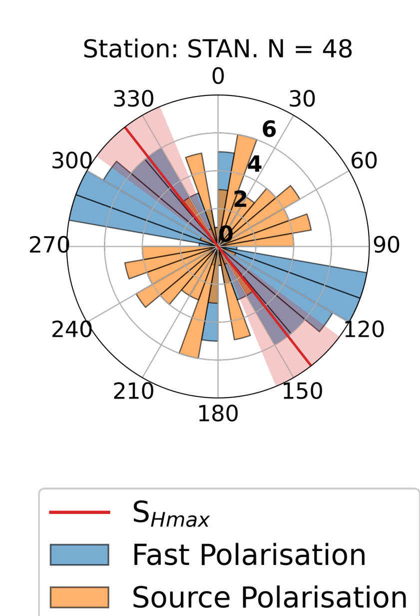


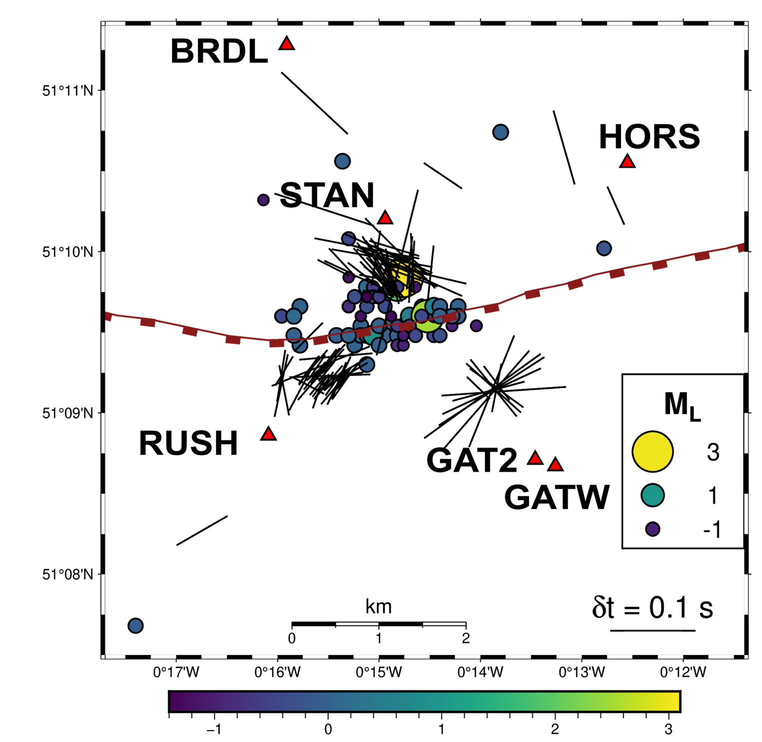
2. Newdigate

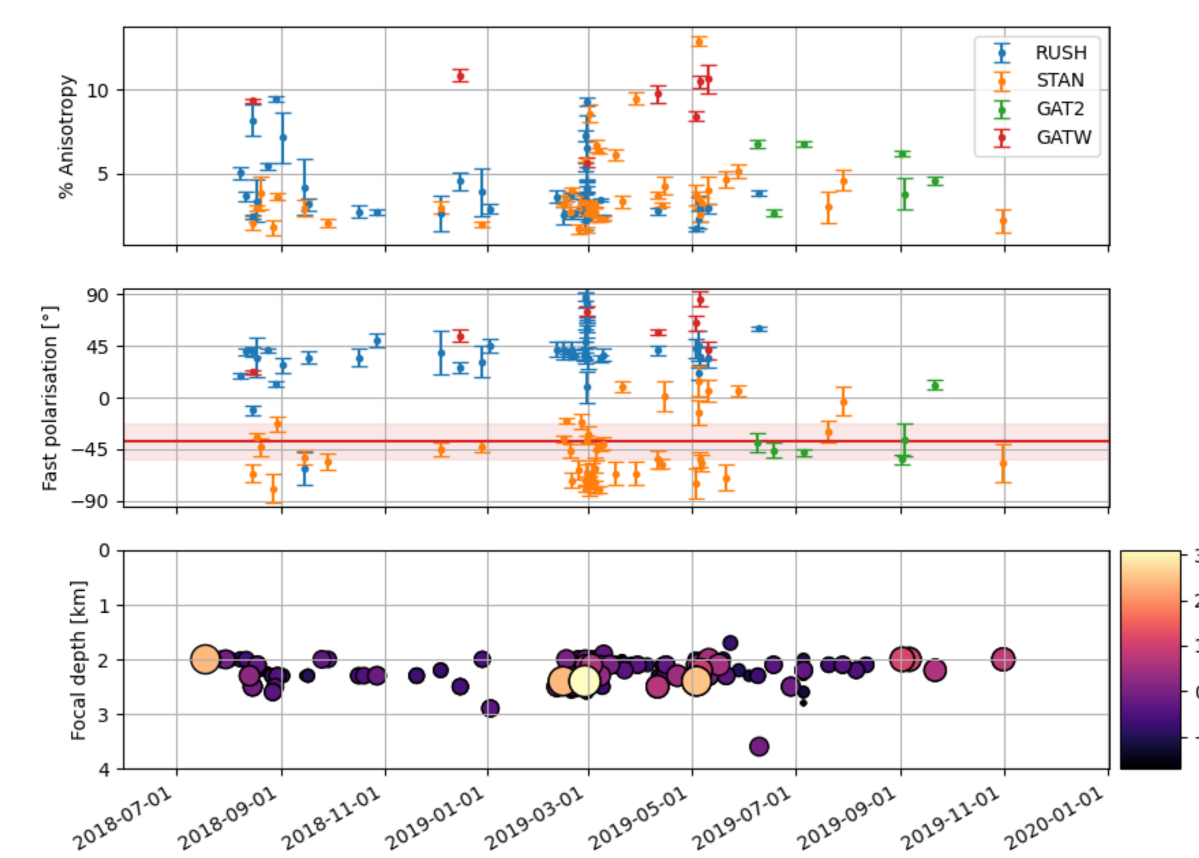
In 2018-9 an earthquake swarm occured in Southeast England near Newdigate, Surrey.

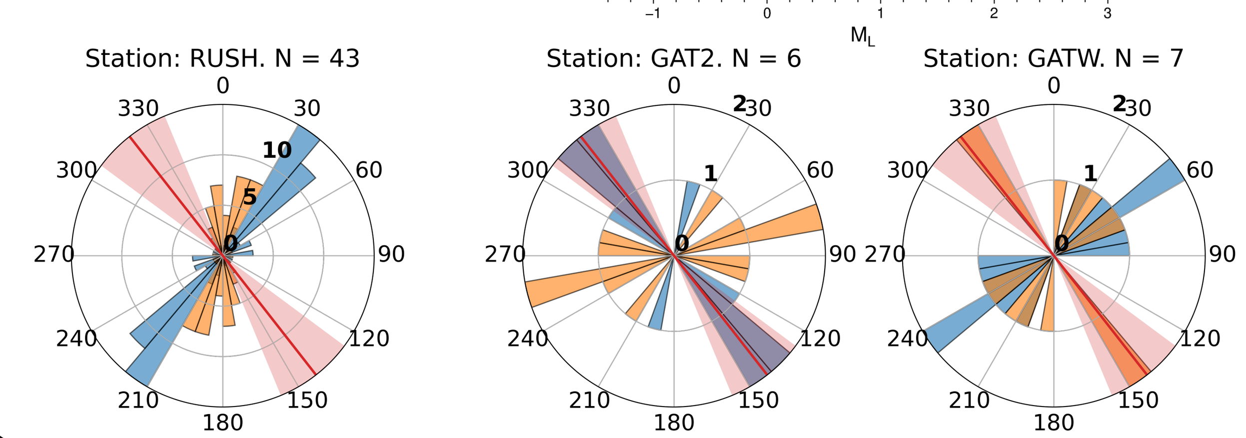
108 quality A-C shear-wave splitting measurements made for events with depths in the range 2 - 3.6 km and magnitudes in the range $-1.6 \leq M_L \leq 3.1$ (Hicks et al., 2019).

We see a large local scale rotation in φ North and South of the Newdigate fault, particularly at stations STAN and RUSH. Results North of the fault agree with S_{Hmax} = 142 ± 15° interpreted from borehole breakout across the Weald Basin.









3. Time varying anisotropy at Newdigate

For the Newdigate sequence, we also see evidence for temporal changes in seismic anisotropy. The figure above shows shear-wave splitting fast polarisation directions (φ) and percentage anisotropy plotted over time, along with earthquakes in the Newdigate sequence.

We can see that the anisotropy rises and falls during the sequence, with the most noticable build up ahead of the May 5th 2019 M_L 2.5 earthquake, before dropping back to approximately 5% anisotropy as the sequence ends.

Temporal variations can be most starkly seen at closely located stations GATW and GAT2 (left), where a ca. 90° rotation in φ is observed after June 2019.

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