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BOPS

Bristol and Oxford Passive Seismic Research Consortium (new name for BUMPS)

Quantifying the variability in fault density across the UK Bowland Shale, with implications for induced seismicity hazard

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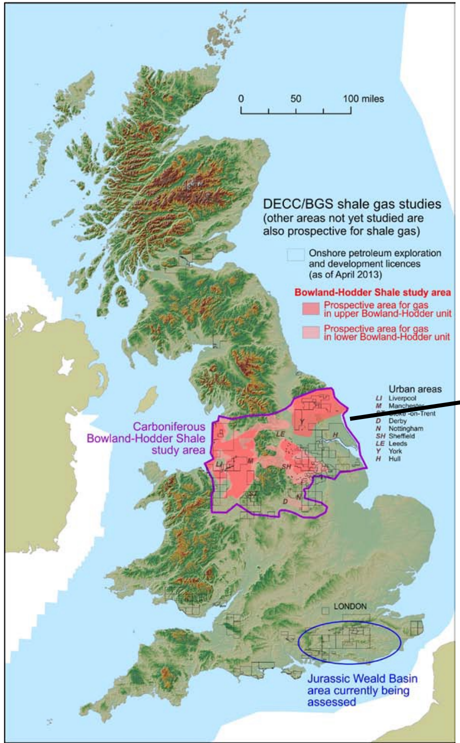
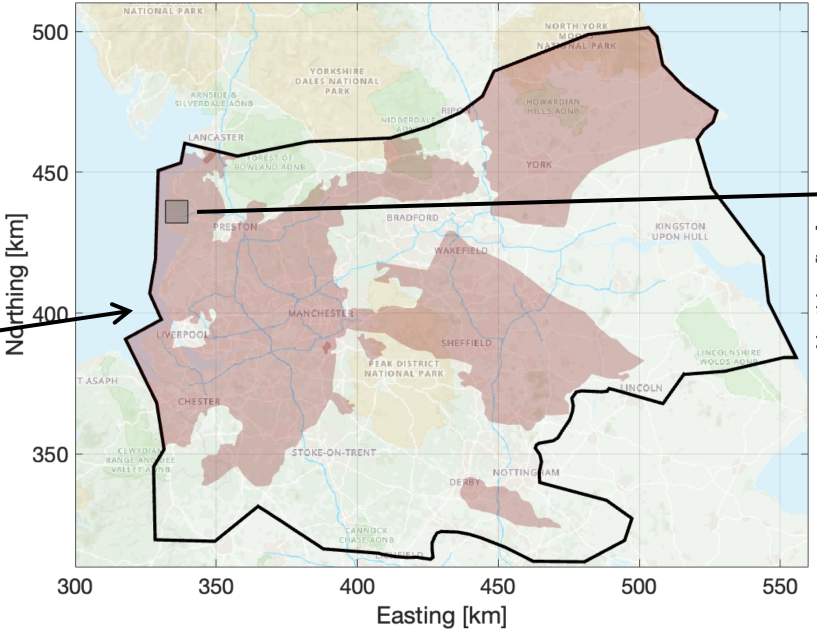
GEoREST Workshop on Induced Seismicity | *Palma, Spain, 11-13 March 2024*

1. First (and last) HF Wells in the Bowland Shale

Bowland Shale – Estimated resource of > 30 trillion cubic metres (tcm) of gas in place



Upper and Lower Bowland Shale



3 wells fracked to date in the Fylde Peninsula:

Rodríguez and Verdon, GETE (2024)

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- Preese Hall (2011) – M_{MAX} 2.3
- PNR-1 (2018) – M_{MAX} 1.5
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Moratorium imposed after 2019 seismicity

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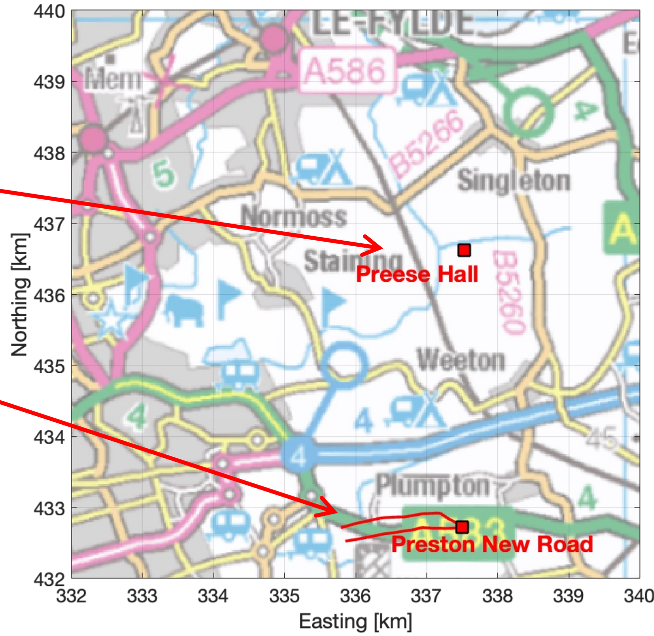

Rodríguez and Verdon, GETE (2024)

2. Motivation

Bowland Shale – estimated resource of > 30 trillion cubic metres (tcm) of gas in place

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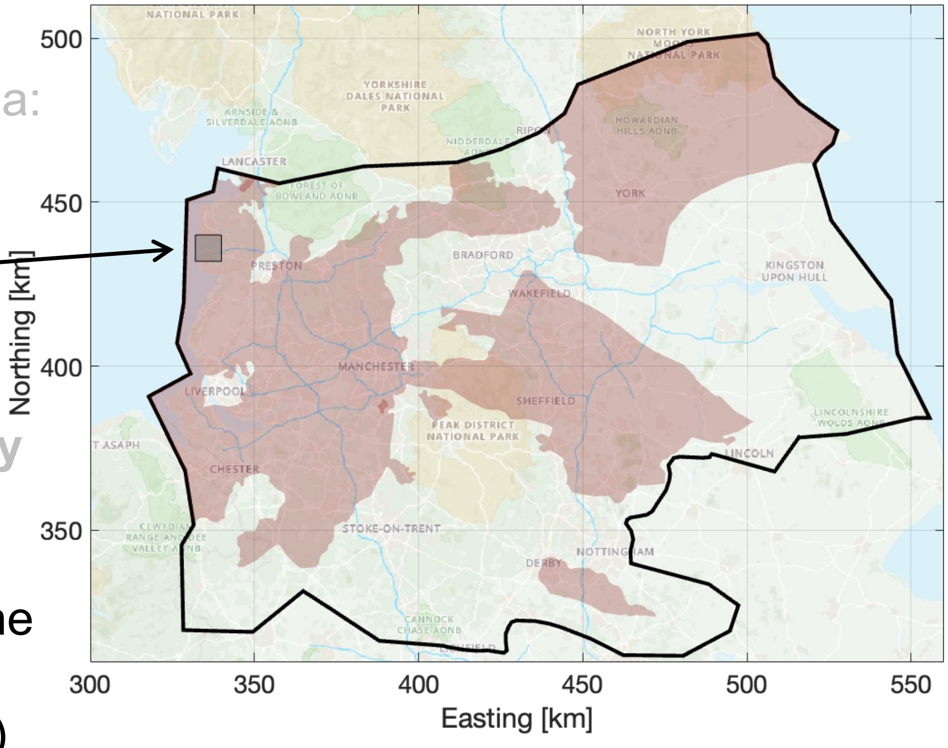

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<u>Key question:</u>
How might induced seismicity vary across the play if HF takes place elsewhere?
And other industries? (geothermal, CCS, …)

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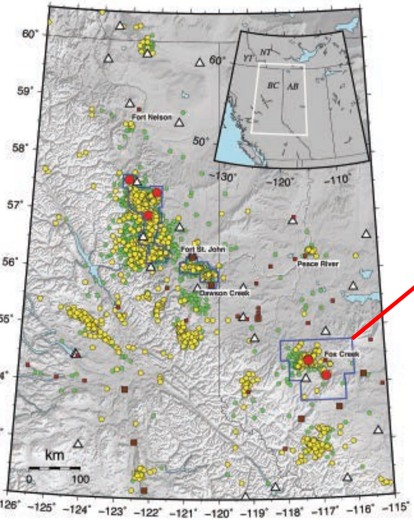
2. Motivation

Controls on induced seismicity occurrence during hydraulic fracturing?

Induced seismicity varies significantly between plays (e.g., Duvernay Shale, WCSB)

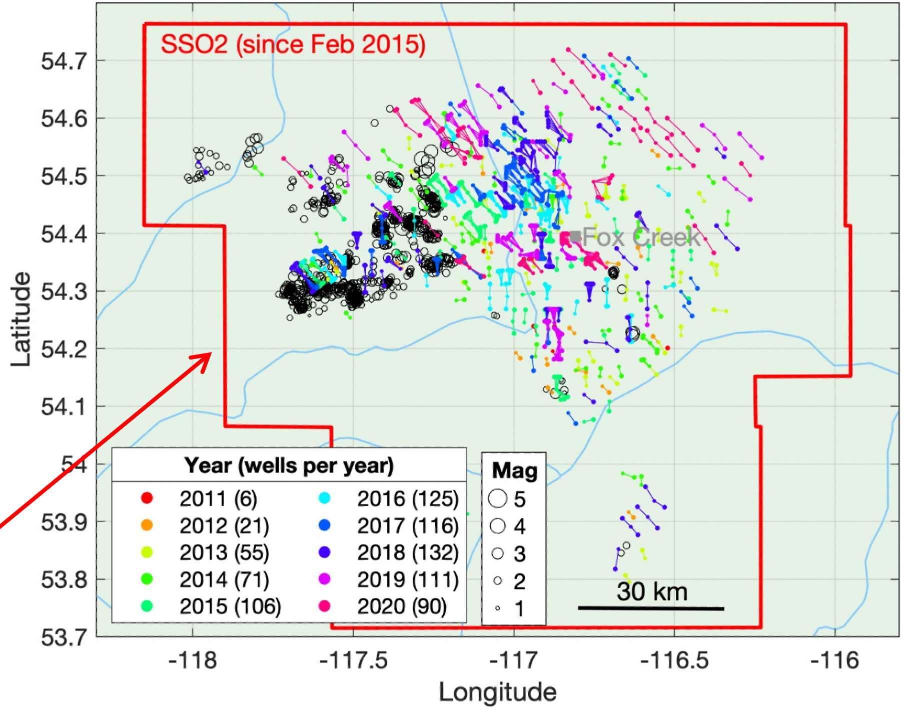
Potential controls:

- Fault density
- Stress conditions
- Pore pressures



Kao et al., TLE (2018)

Duvernay Shale zone, Western Canada Sedimentary Basin (WCSB)

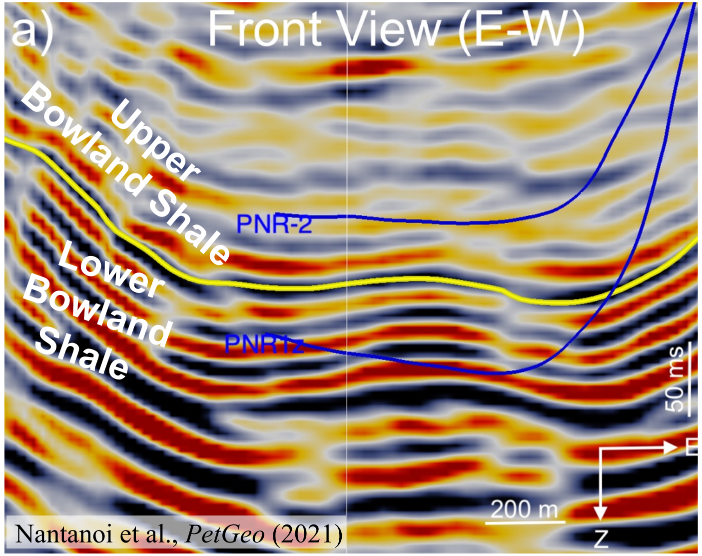


Reyes-Canales et al., JGR (2021)

3. Multi-Stage Hydraulic Fracturing in PNR

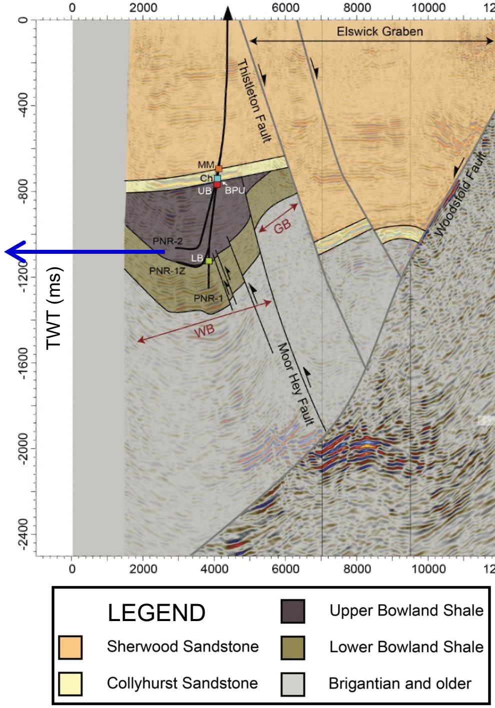
- *Deterministic methods* for fault interpretation

Bowland-12 3D seismic with Preston New Road (PNR) wells



Nantanoi et al., *PetGeo* (2021)

Interpreted cross section with PNR wells



Anderson and Underhill, *PetGeo* (2020)

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3. Multi-Stage Hydraulic Fracturing in PNR

- We cannot identify every fault.
- <u>*Deterministic methods*</u> cannot be relied on to avoid causing induced seismicity

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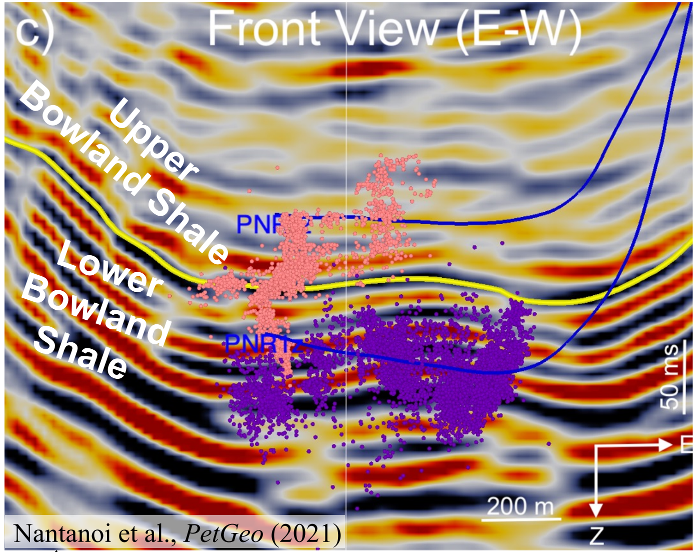
Microseismic events from HF stimulations



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- PNR-1 (2018) – M_{MAX} 1.5
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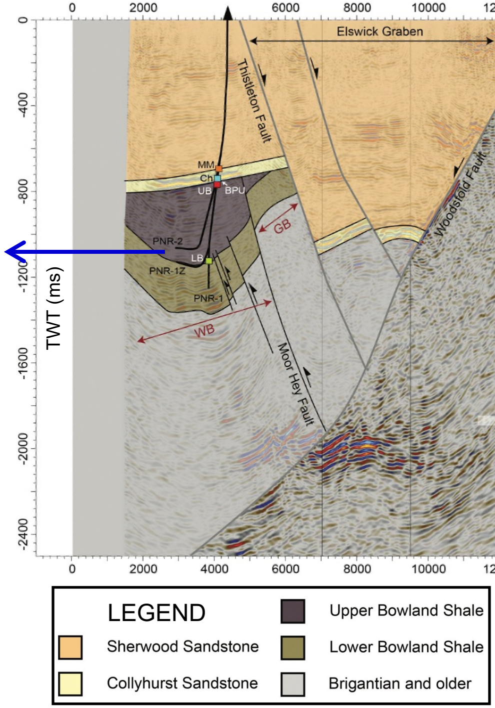

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3. Multi-Stage Hydraulic Fracturing in PNR

- We cannot identify every fault.
- *Deterministic methods* cannot be relied on to avoid causing induced seismicity

Probabilistic Method:

- We can still assess relative hazard based on fault distributions and stress data based on the *Seismogenic Index* *(Σ)*:

$$\Sigma = \log\left({}^{N}/_{V}\right) + bM$$

- Can be used to predict the largest event size:

$$M_{MAX} = \left(\Sigma - \log\left(\frac{\ln \chi}{V}\right)\right)/b$$

- *Seismogenic Index* is controlled by the number of critically-stressed faults (*N*), and the stress change required to activate them (*C*), within a given volume:

$$\Sigma = a + \log\left({}^{N}/_{C.S}\right)$$

Bowland-12 3D seismic with Preston New Road (PNR) wells

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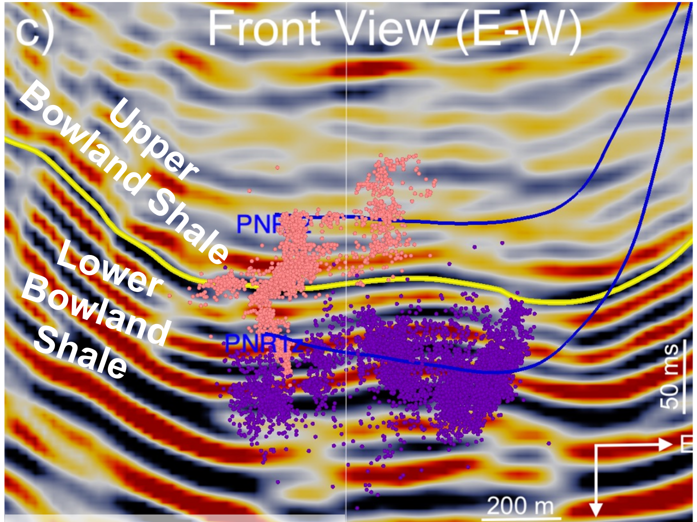

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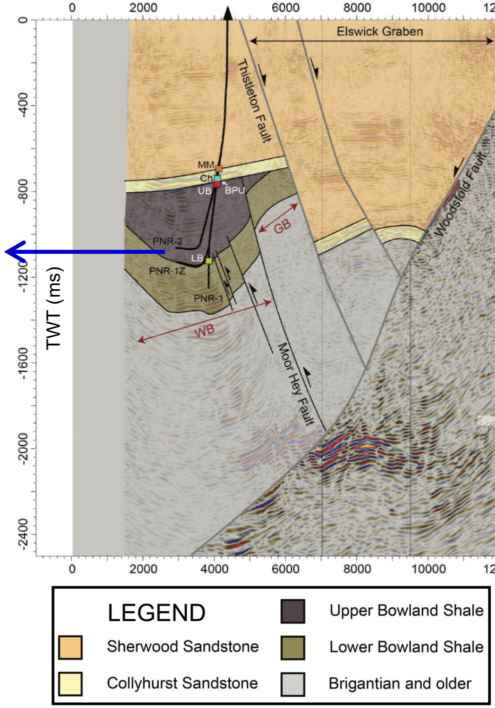

Anderson and Underhill, *PetGeo* (2020)

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4. Reflection Seismic Data

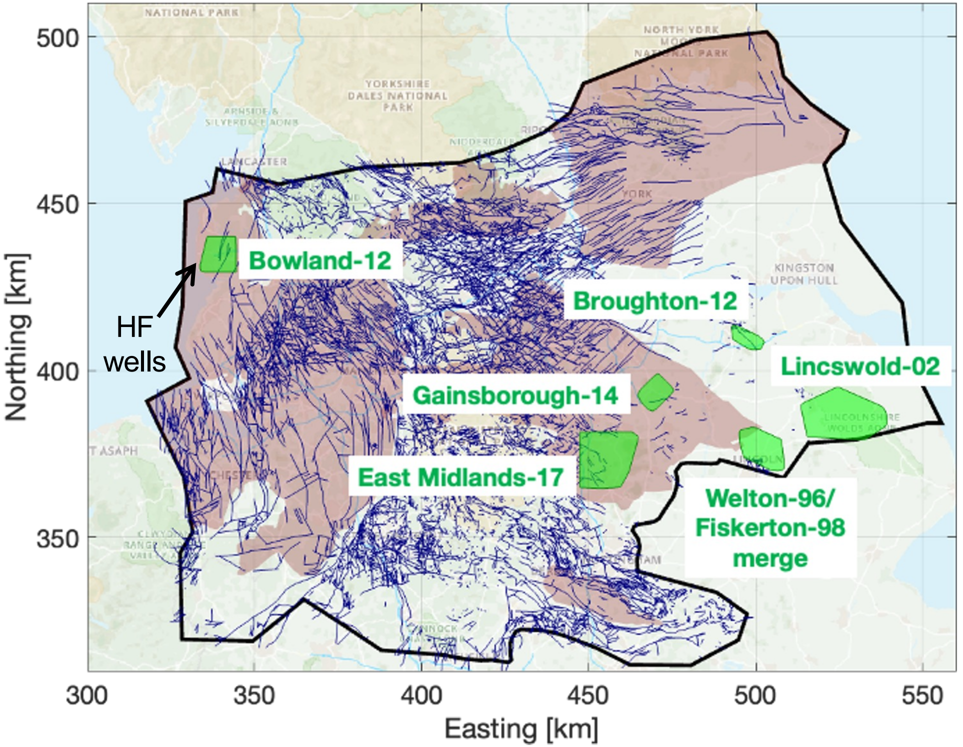
BGS Fault Mapping:

- Fault density highest in northwest, decreasing to E and S.
- However, data is from geological mapping – strongly controlled by geological exposure.
- Mapping of faults that run to surface does not image deeper faults in Carboniferous sections

Our approach:

- We use 3D reflection seismic data to image faults within horizons of interest
- 6 3D surveys used, running across a W – E axis across the play.
- Manual interpretation and automated fault detection using the Thinned Fault Likelihood attribute (TFL)

Regional faults (BGS) + 3D Seismic Datasets



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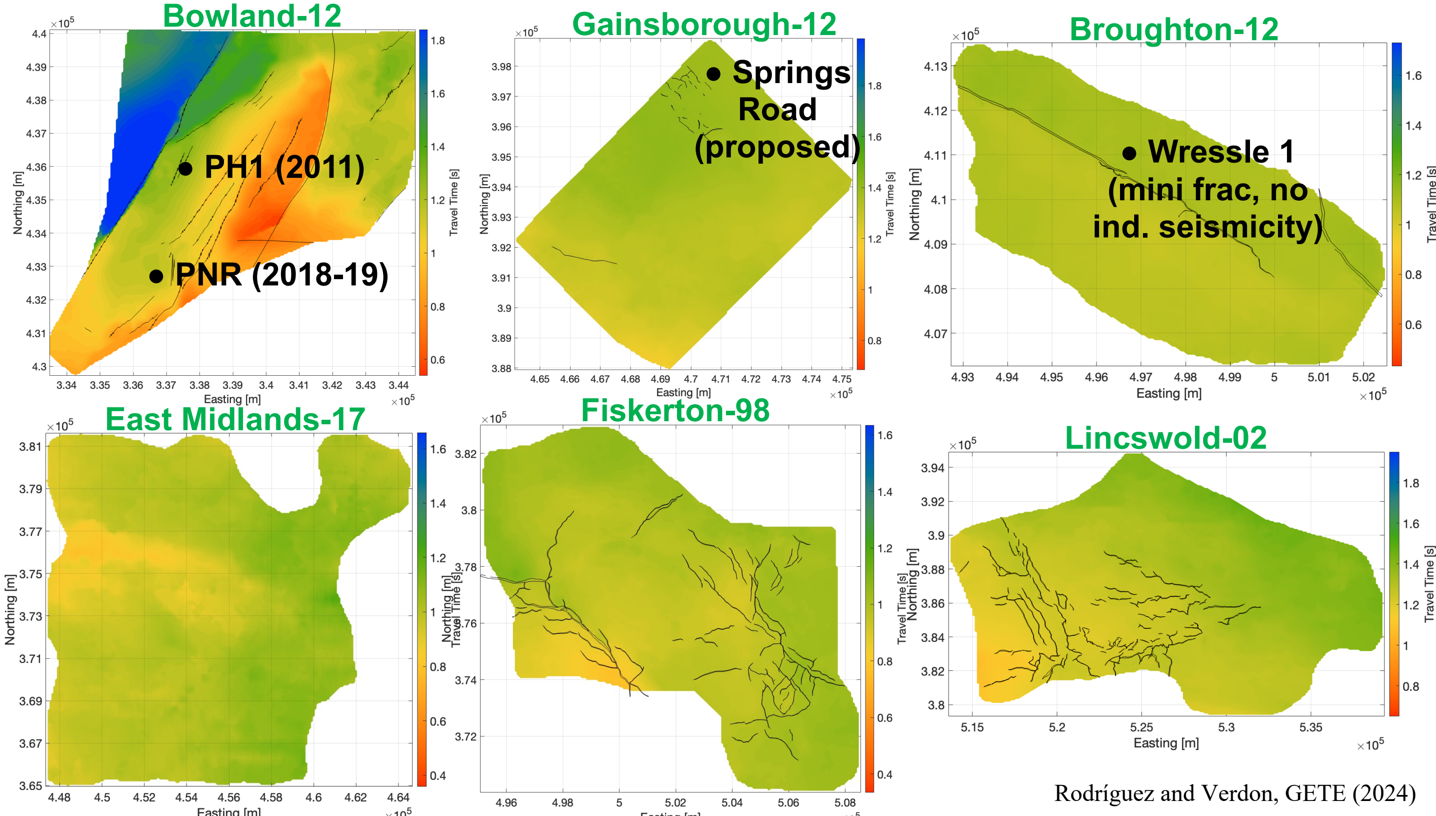
4. Reflection Seismic Data

Bowland-12 survey has significantly more ”topography” than other surveys

Bowland-12 has higher offsets across the mapped faults.

Manually interpreted faults are subject to interpreter bias, so we compare densities of automated fault maps.

Interpreted top of Lower Carboniferous (Top of Lower Bowland Sh. or Eq.) + Interpreted Faults



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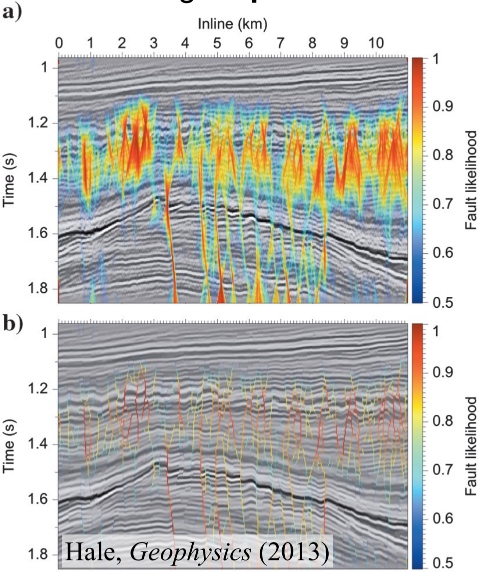
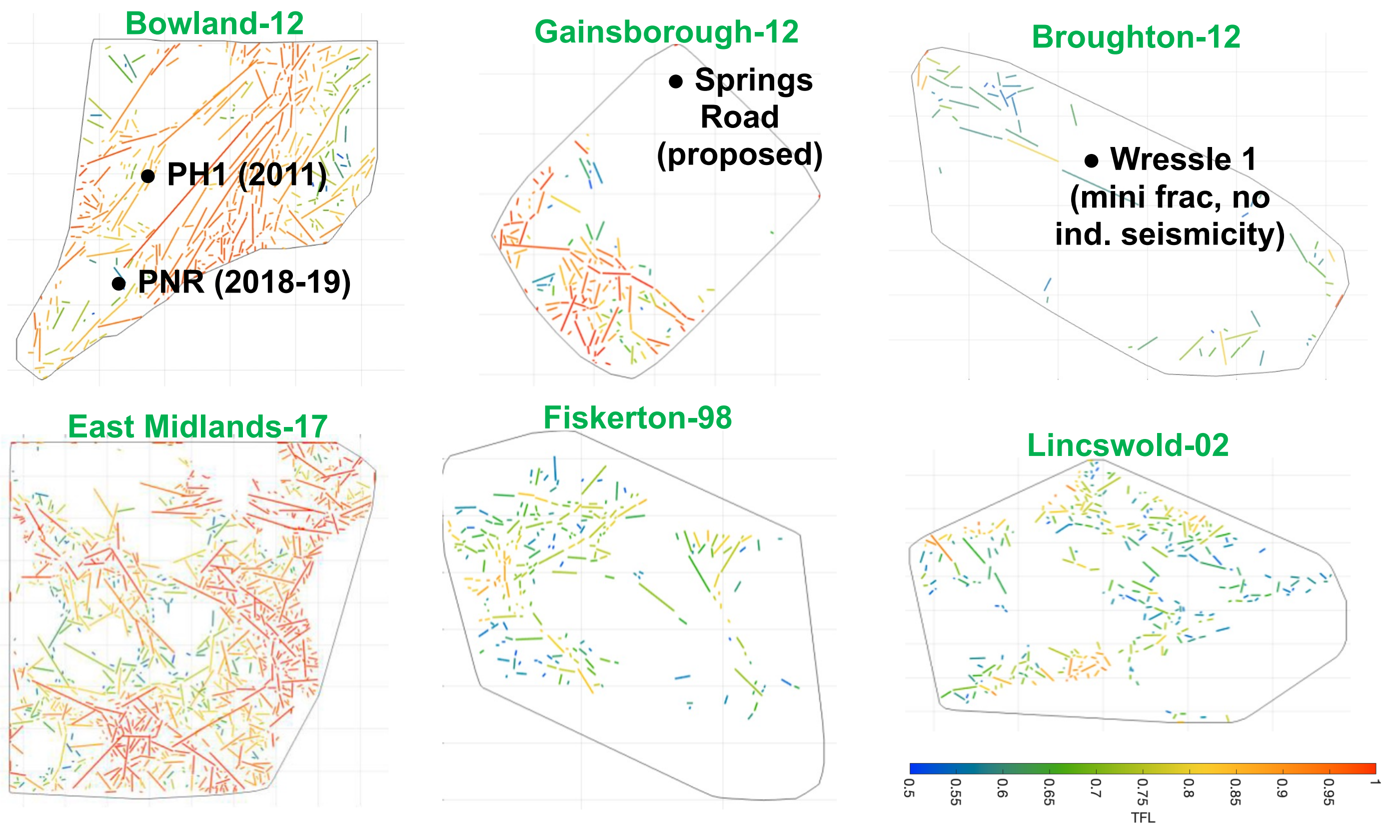
5. Automatic 3D Fault Interpretation

Thinned Fault Likelihood (TFL)

3D seismic attribute based on semblance (measure of coherence, between 0 and 1) to first compute fault images, and a structure-oriented filter for "thinning". **OpendTect V7**

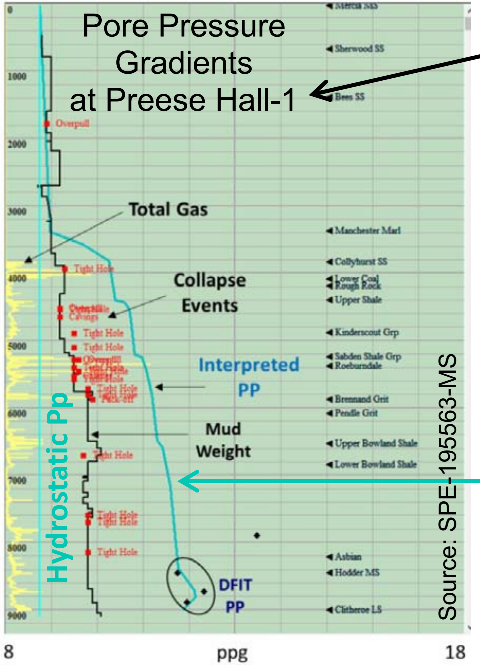


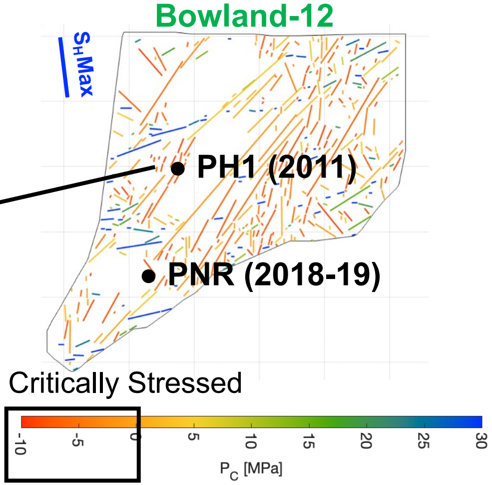
Differences in fault density are also reflected in the automated fault maps

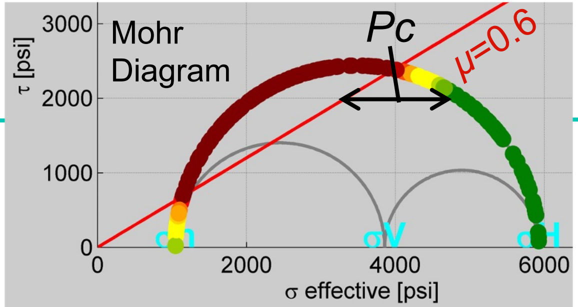


6. Stress Data and Critically Stressed Faults

Resolve normal and effective stresses to compute Pc for each fault







Critical pore pressure *Pc* (change required to reactivate faults):

$$P_C = \sigma'_n - \frac{|\tau|}{\mu_f}.$$

Robust stress and pore pressure measurements are few and far between (Fellgett et al., 2018)

Bowland Shale is significantly **overpressured**, dPp ≈ 13 kPa/m

Resolve normal and effective stresses to compute *Pc* for each fault

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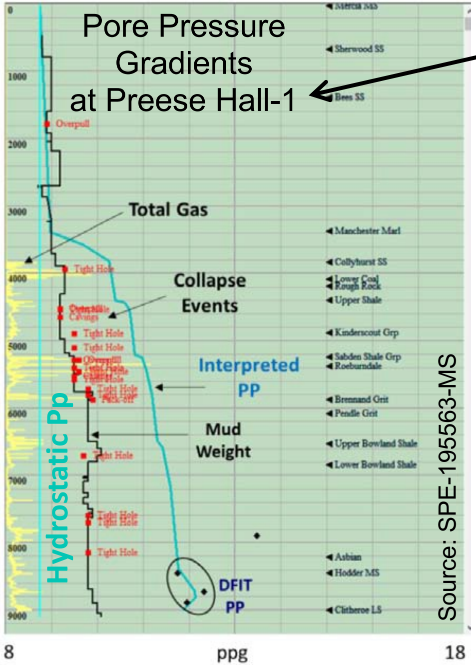
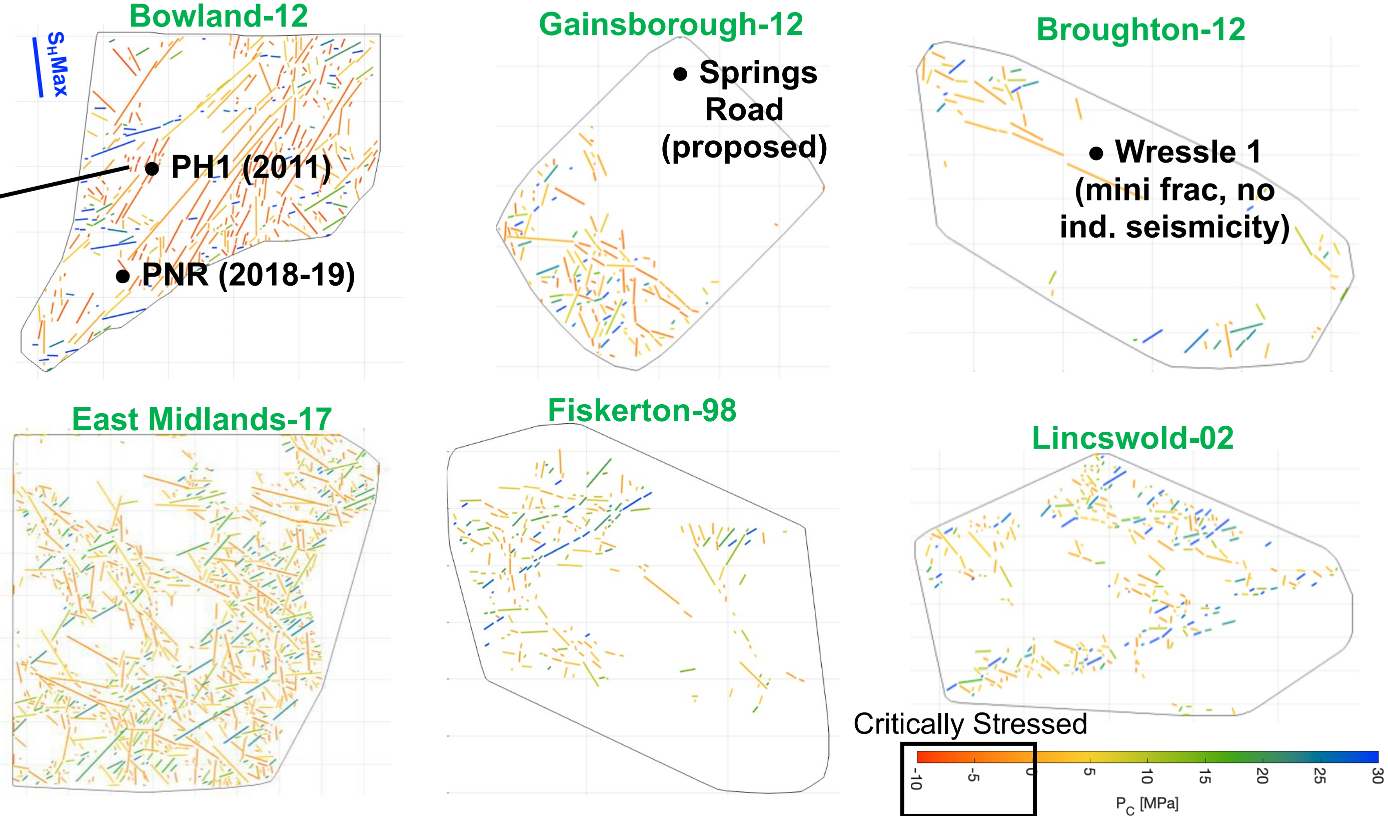
6. Stress Data and Critically Stressed Faults

Resolve normal and effective stresses to compute Pc for each fault





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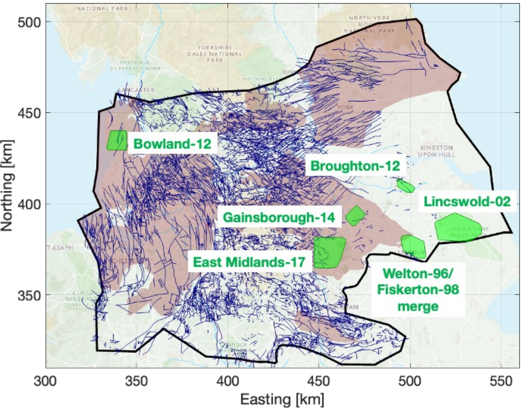
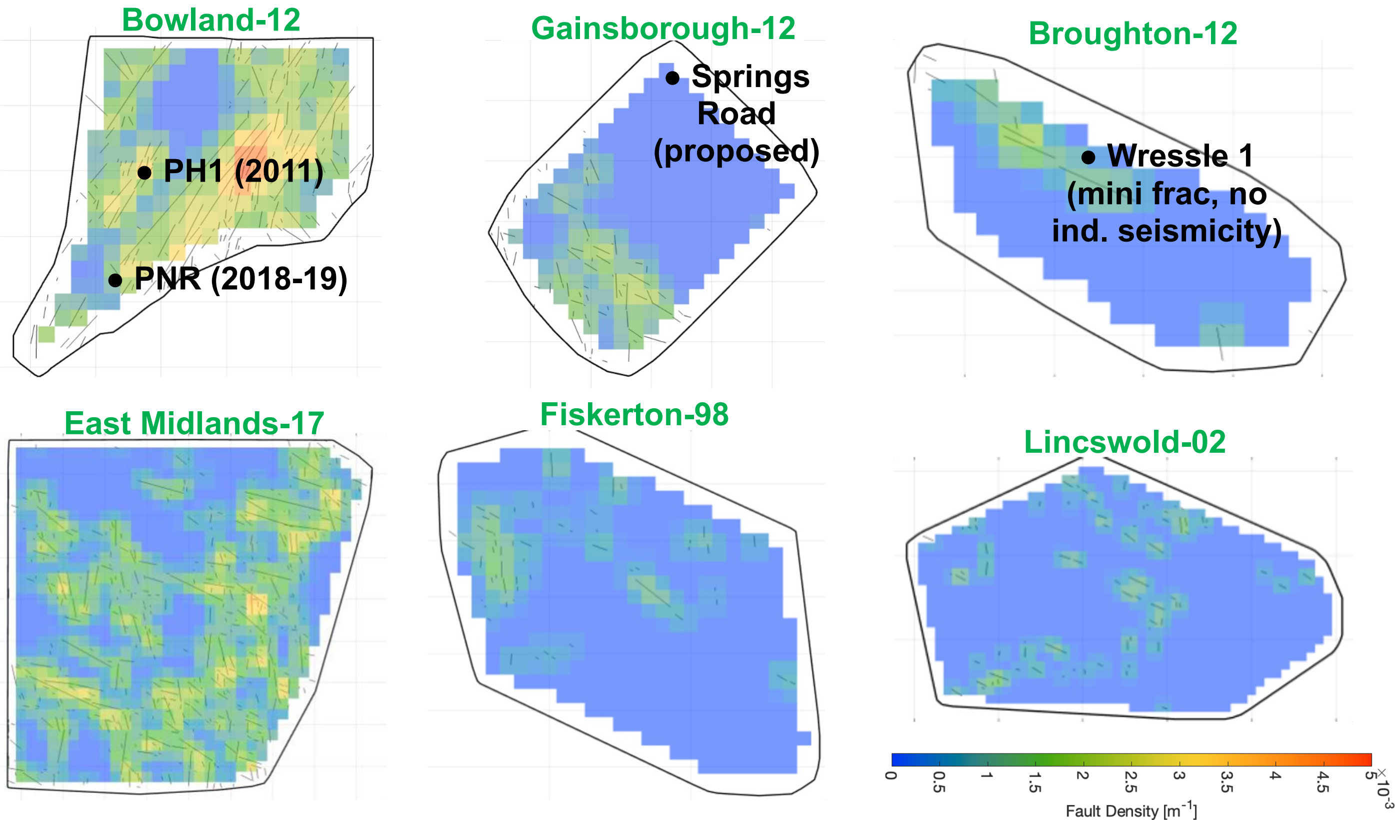
6. Stress Data and Critically Stressed Faults

Spatial variability in fault density of critically-stressed faults:

1x1 km “blocks”



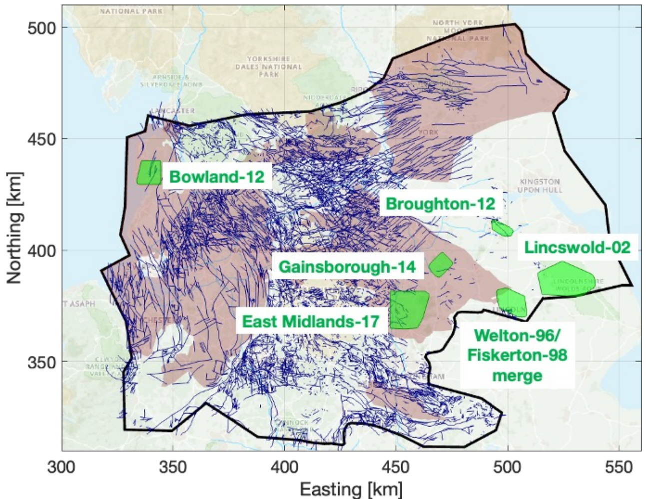


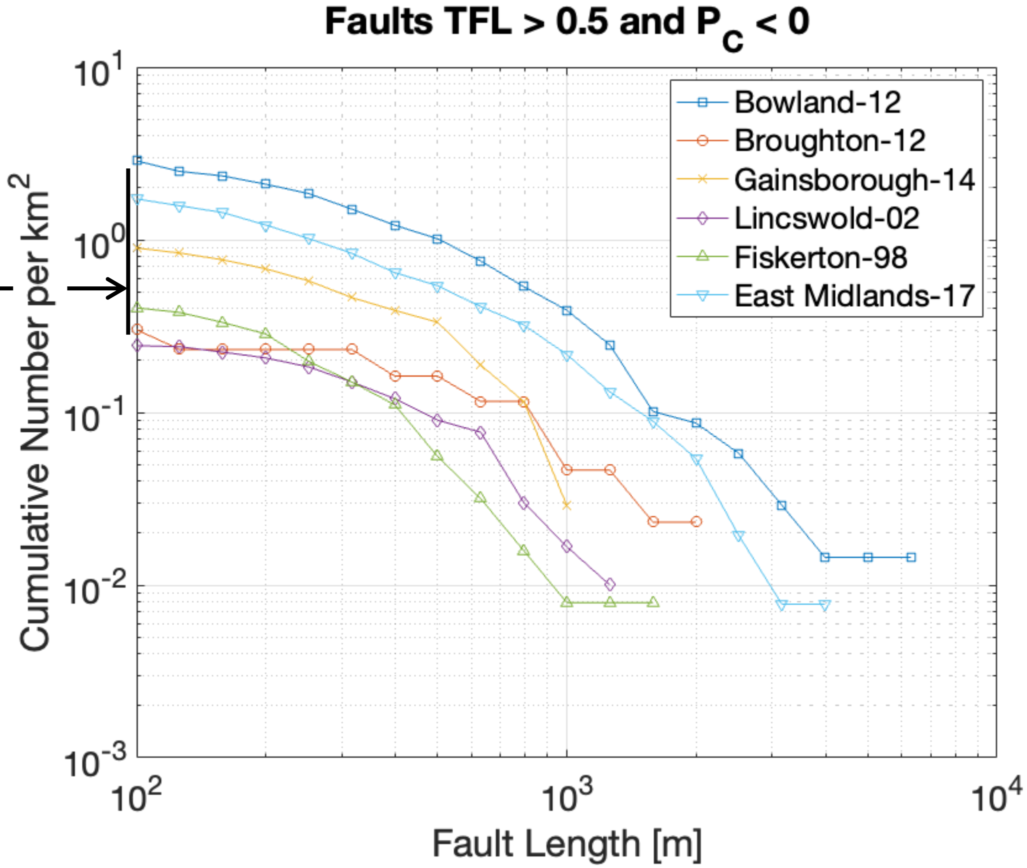
Rodríguez and Verdon, GETE 2024

6. Stress Data and Critically Stressed Faults

Density of faults that are critically stressed (Pc < 0):

Bowland-12 has an order of magnitude more critically stressed faults than regions to the SE.





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7. Implications for Seismic Hazard

Decreasing **fault density** (F) by an order of magnitude = decreasing Seismogenic Index (Σ) by 1 unit:

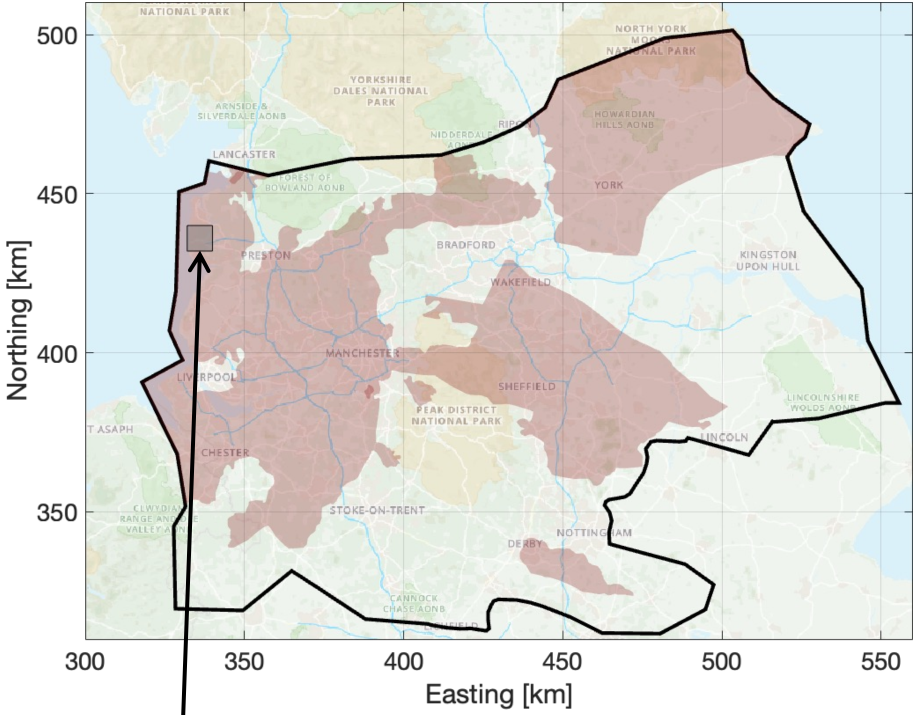
$$\Sigma = a + \log\left({}^{F}/_{C.S}\right)$$

Which means a decrease is seismic rate by 1 order of magnitude

$$N = V.10^{\Sigma - bM}$$

And a decrease in event magnitude by 1 unit

$$M_{MAX} = \left(\Sigma - \log\left(\frac{\ln \chi}{V}\right)\right)/b$$



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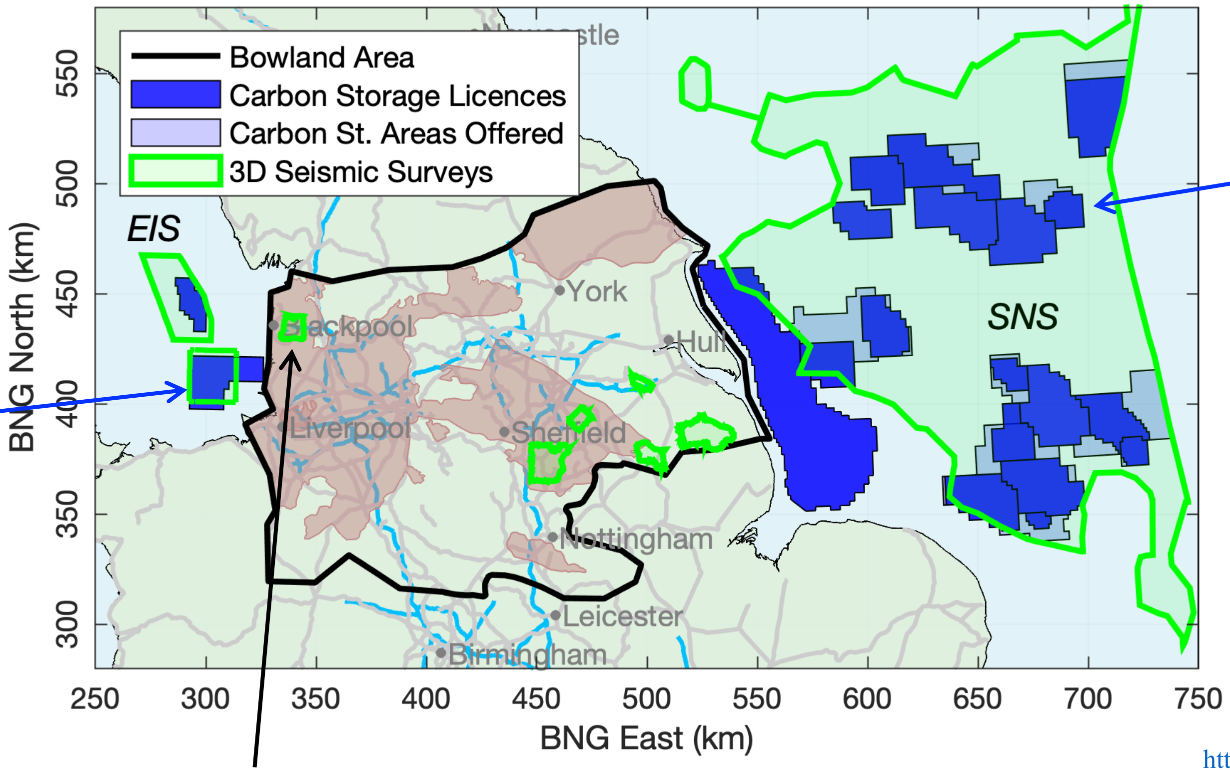
7. Implications for Seismic Hazard

Carbon Capture and Storage (CCS) licenses in the UK



EIS (HyNet): Planned CO_2 injection: Up to **10 MTPA**

https://hynet.co.uk/about/

- PNR-2 (2019) – *M_{MAX} 2.9*

SNS (Bunter Sand.): Planned CO_2 injection:

- Net Zero Teeside: Up to **10 MTPA**
- Zero Carbon Humber: **17+ MTPA**

https://www.netzeroteesside.co.uk/northern-endurance-partnership/

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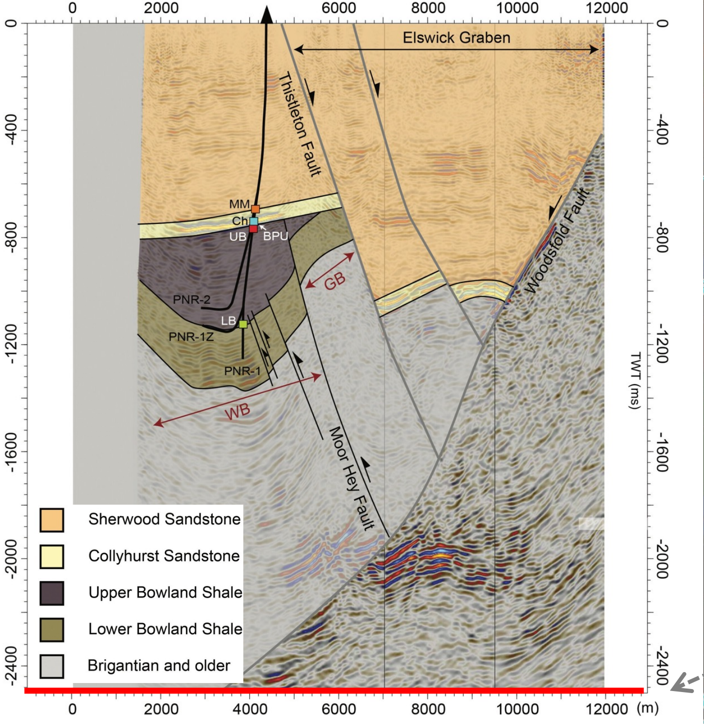
7. Implications for Seismic Hazard

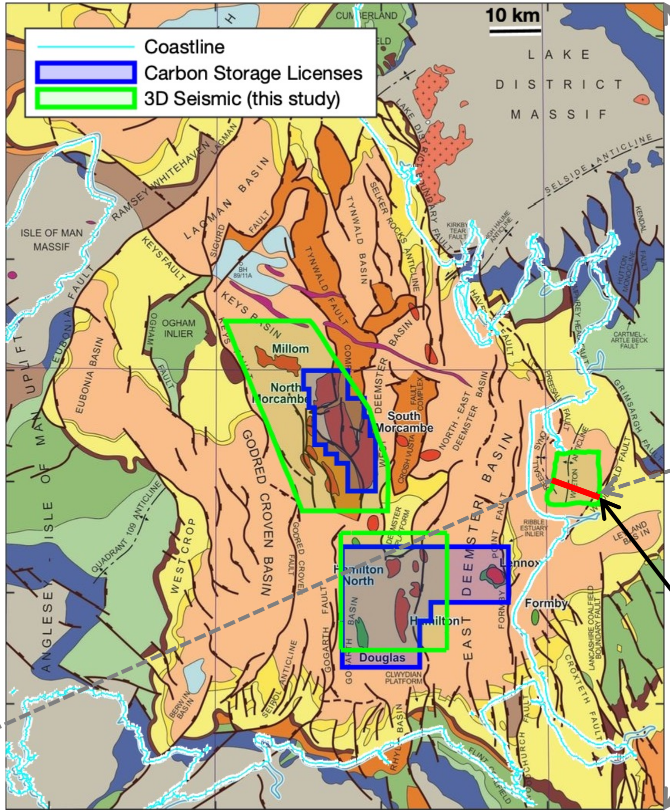
Carbon Capture and Storage (CCS) licenses in the UK

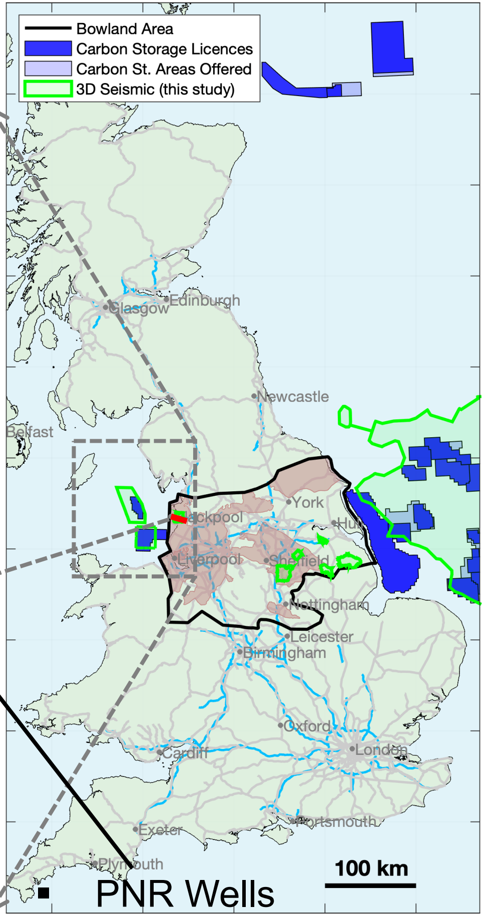
East Irish Sea Basin



Anderson and Underhill, *PetGeo* (2020)

Bunce, 2018. https://doi.org/10.1144/SP465.6





Conclusions

- Induced seismicity prevalence varies within plays by a significant amount
- No reason to assume a priori that induced seismicity across the Bowland will be the same as on the Fylde Peninsula.
- We measure fault densities across the play using an automated fault detection method applied to 3D seismic cubes.
- Significant variability in critically-stressed fault densities from west to east, decreasing by an order of magnitude
- Prevalence of induced seismicity may be significantly lower if HF operations were to take place elsewhere in the play.
- However, the continued occurrence of induced seismicity cannot be precluded.
- Similar fault mapping and slip potential analysis can be implemented in nearby CCS sites

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Acknowledgements

- 3D seismic datasets:

UK Onshore Geophysical Library

UK National Data Repository

- Reprocessed 3D seismic dataset in the Bowland area with interpreted faults and horizons:

egdon RESOURCES

IGas Energy

- Seismic interpretation software:

OpendTect V7

- Research Consortium:

BOPS

Bristol and Oxford Passive Seismic (new name for BUMPS)

Thank you!

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7. Implications for Seismic Hazard

Carbon Capture and Storage (CCS) licenses in the UK

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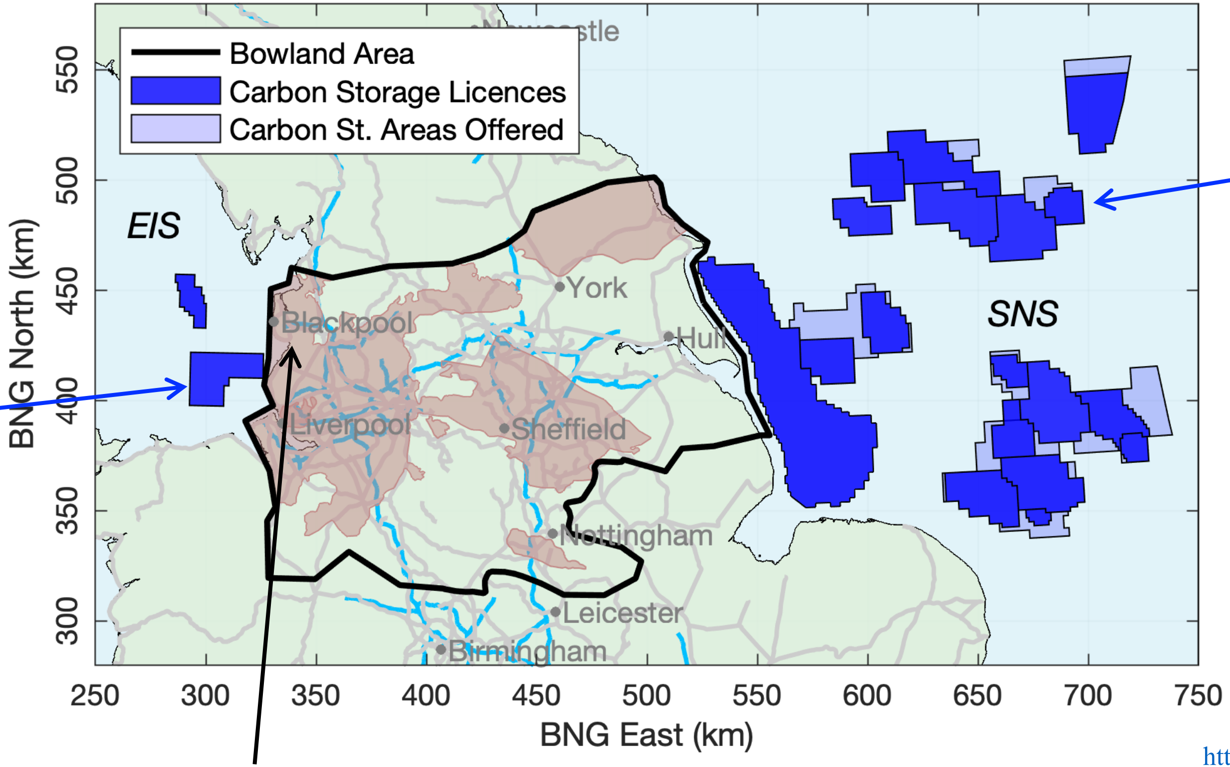
https://hynet.co.uk/about/



- PNR-2 (2019) – *M_{MAX} 2.9*

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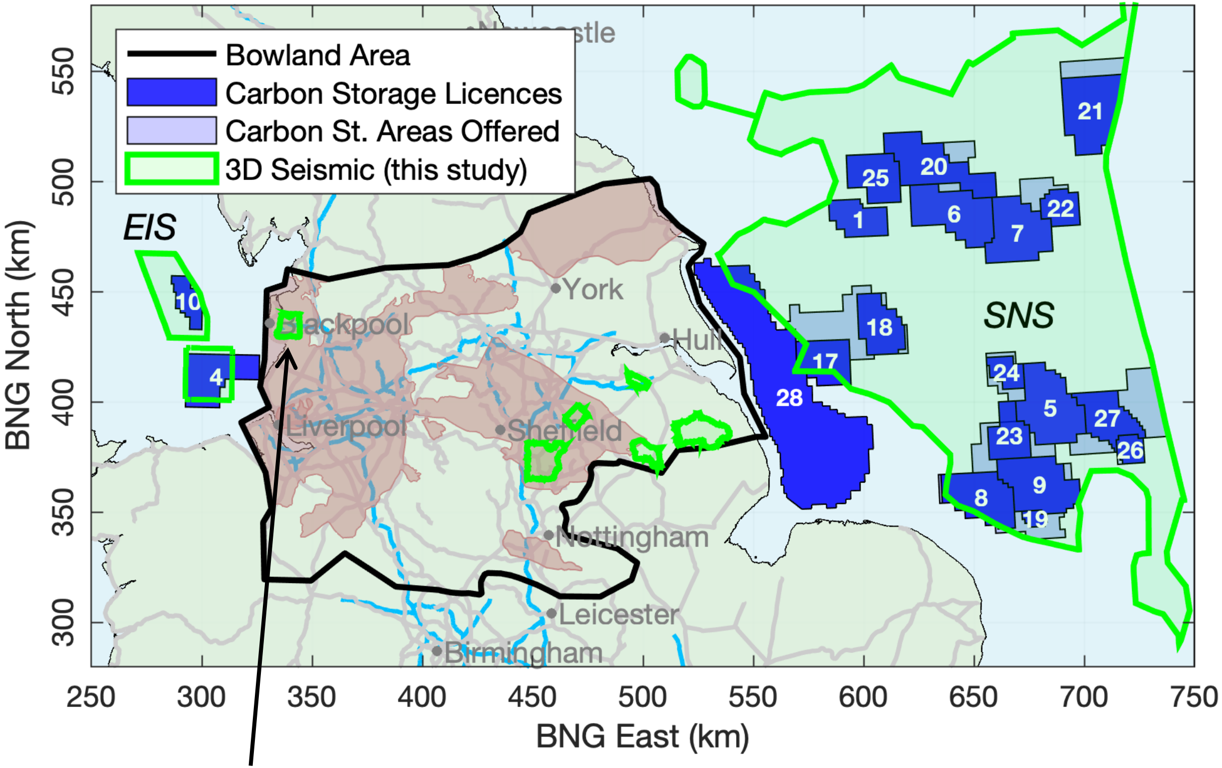
7. Implications for Seismic Hazard

Carbon Capture and Storage (CCS) licenses and 3D seismic surveys in the UK

EIS

CS#	Licensee
10	SPIRIT ENERGY
4	ENI UK



SNS

CS#	Licensee
1, 6, 7, 25	BP, EQUINOR
5	CHRYSAOR PRODUCTION
8	ENI UK
9, 17, 18	PERENCO UK, CARBON CATALYST
19	SYNERGIA ENERGY, ENERGY, WINTERSHALL DEA
20, 22	NEPTUNE ENERGY
21	NEPTUNE ENERGY, ESSO UK
23, 24	CHRYSAOR PRODUCTION, BP
26, 27, 28	SHELL UK, ESSO UK

- PNR-2 (2019) – M_{MAX} 2.9

Data sources: UKOGL, UK NDR (NSTA)

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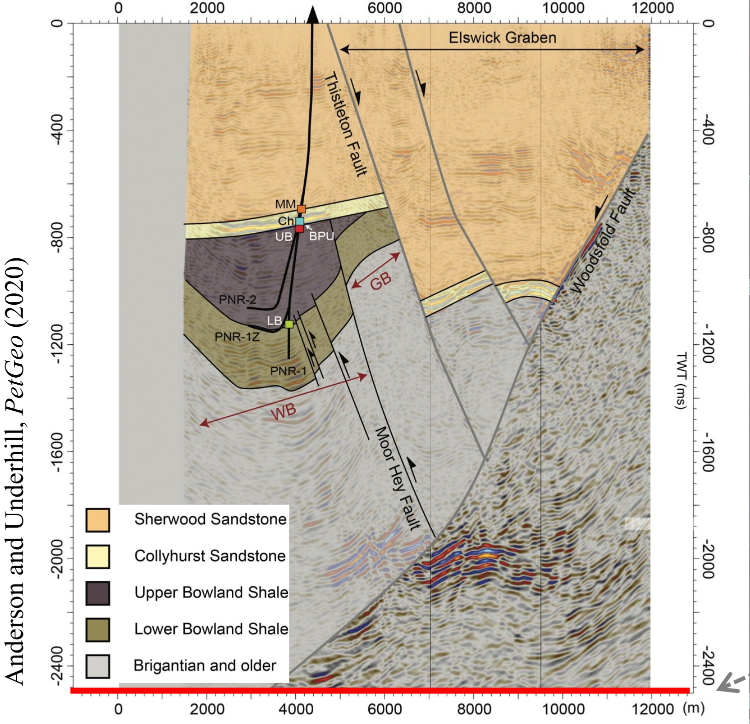
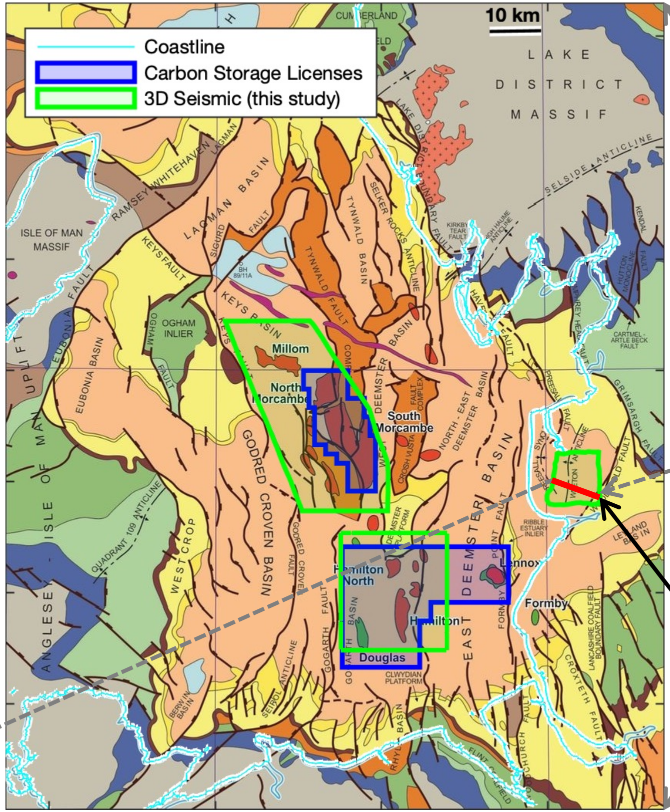
7. Implications for Seismic Hazard

Carbon Capture and Storage (CCS) licenses in the UK

East Irish Sea Basin



Anderson and Underhill, *PetGeo* (2020)



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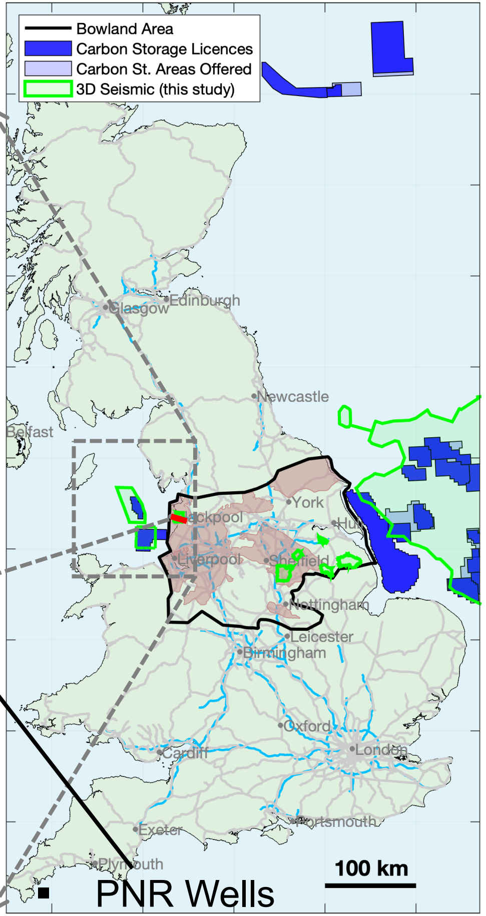

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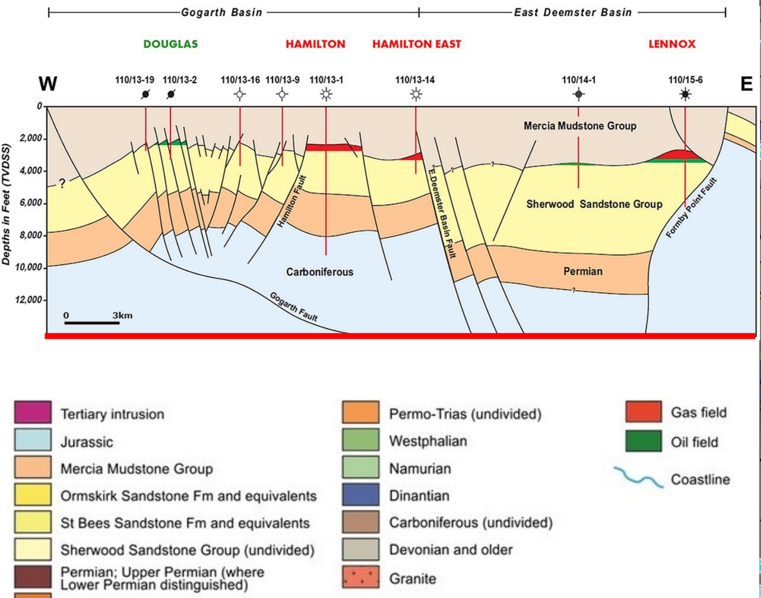
7. Implications for Seismic Hazard

Carbon Capture and Storage (CCS) licenses in the UK

East Irish Sea Basin

- Extensional grabens bounded by normal faults



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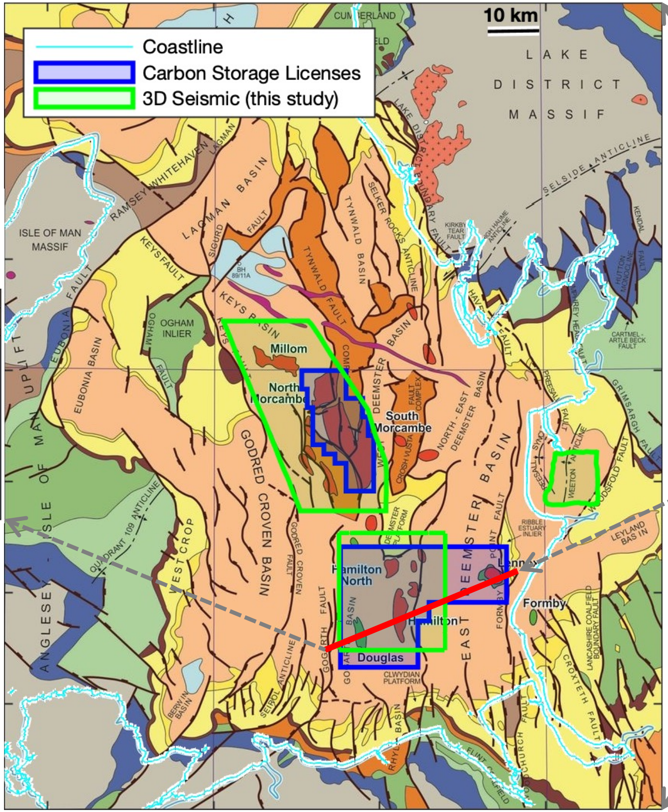

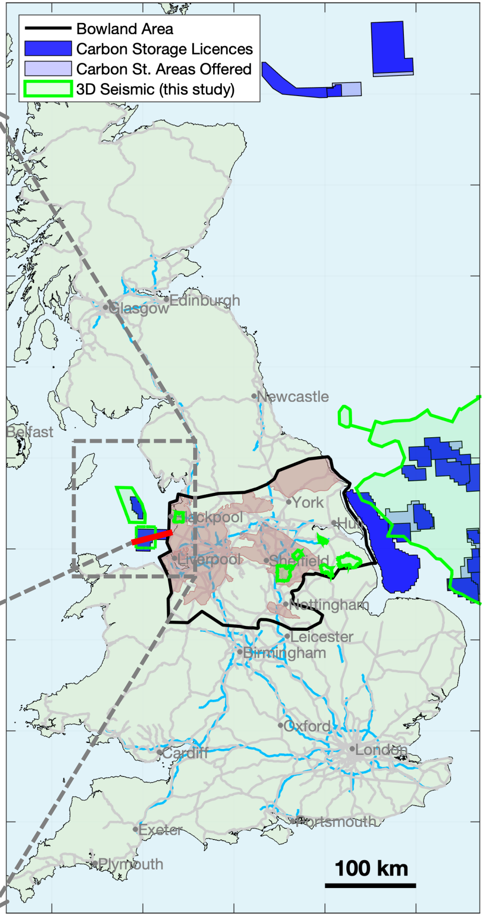

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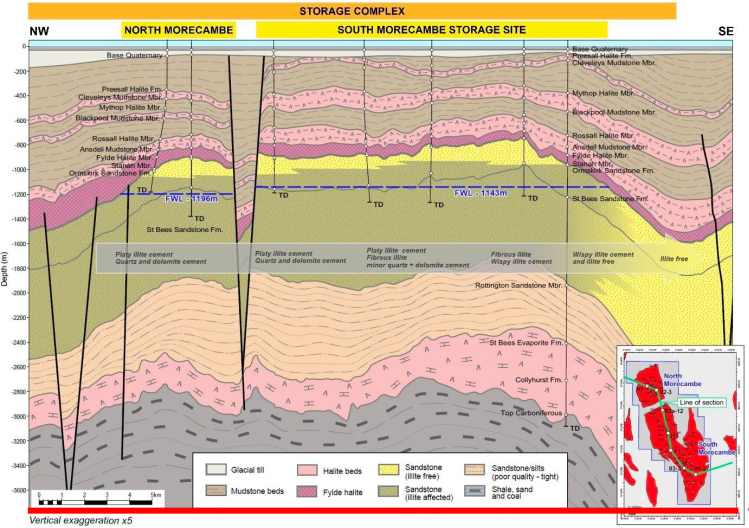
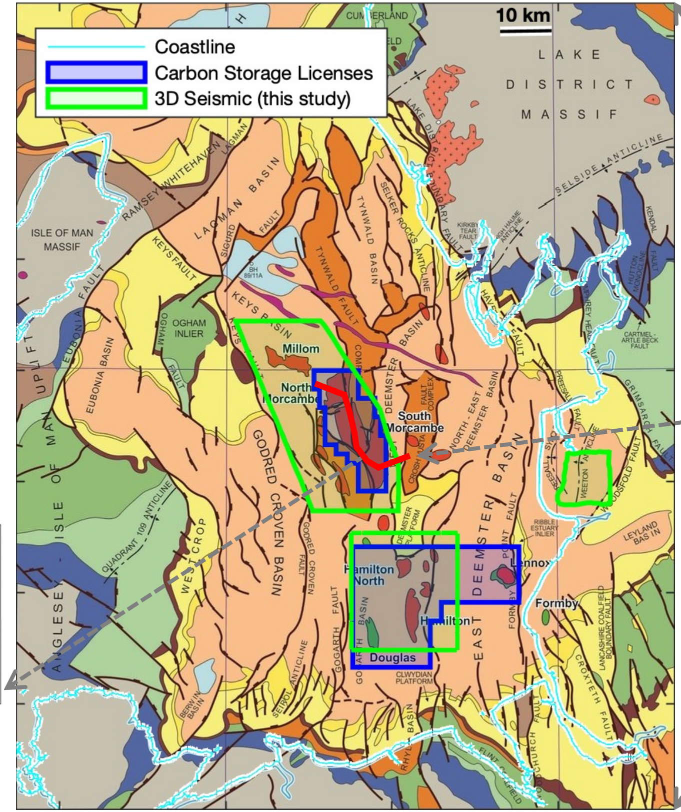
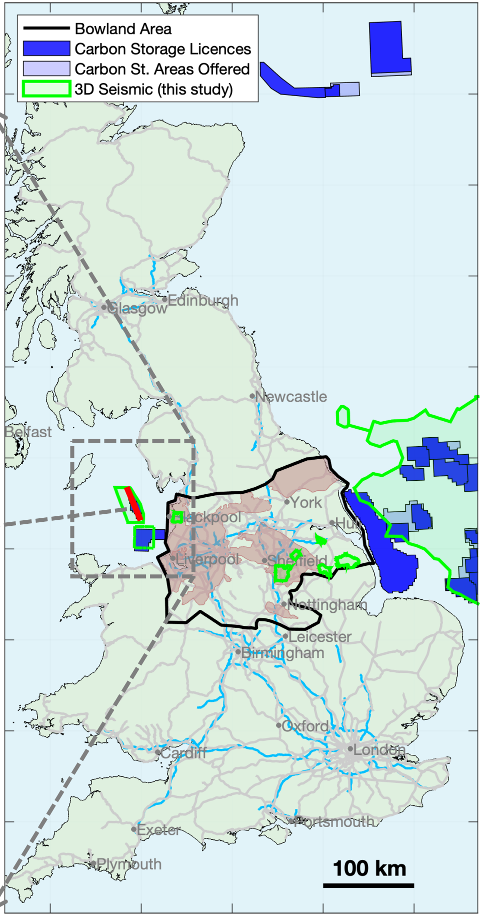


Inglis et al, 2023. https://doi.org/10.3997/2214-4609.2023101474

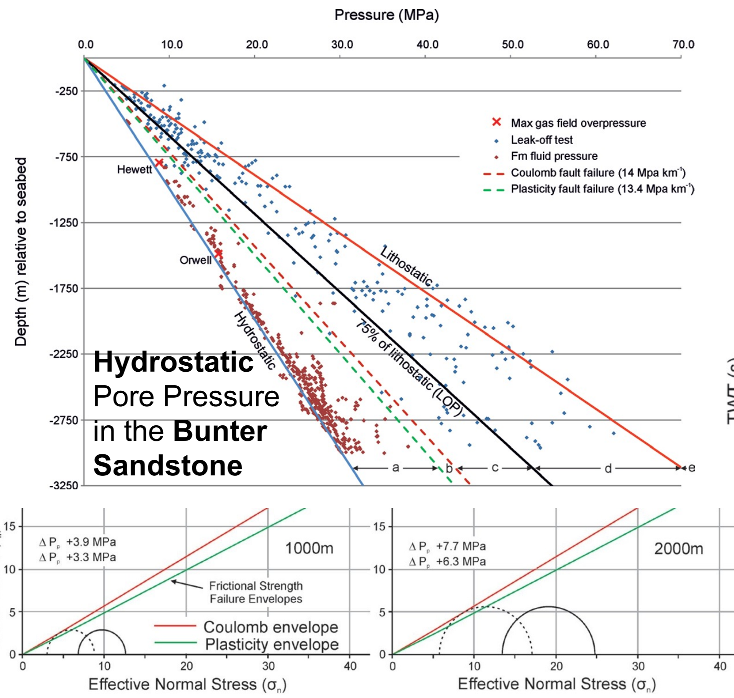




Bunce, 2018. https://doi.org/10.1144/SP465.6

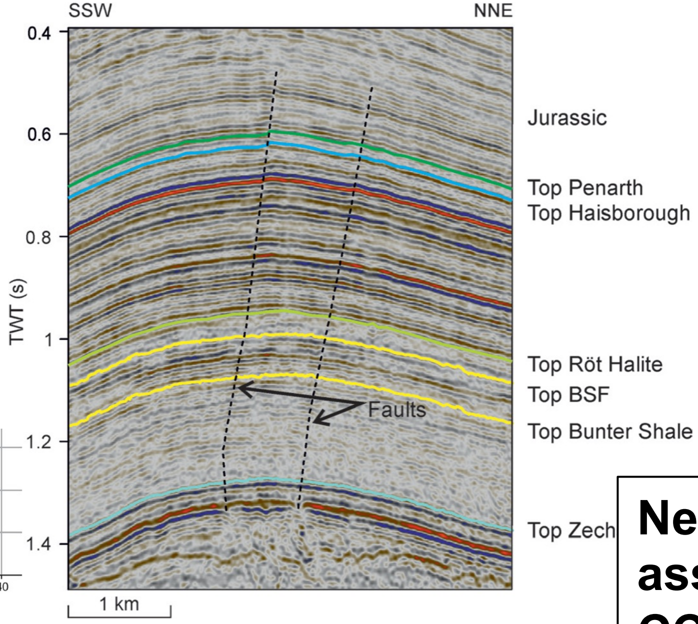
7. Implications for Seismic Hazard

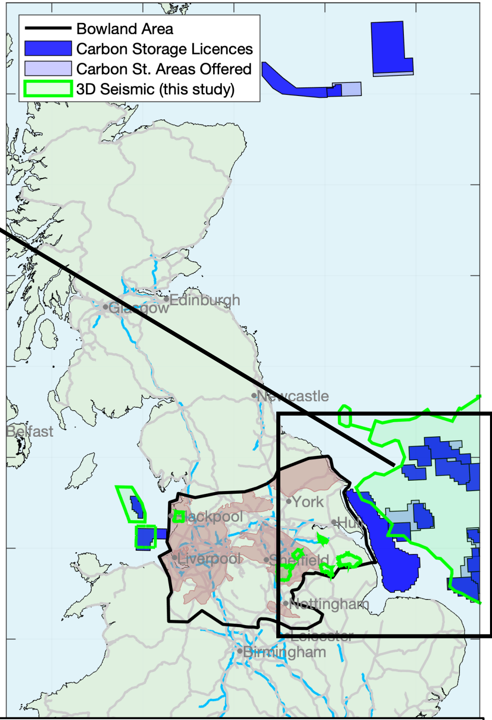
Carbon Capture and Storage (CCS) licenses in the UK Southern North Sea (Bunter Sandstone)



Williams, S. Holloway and G. A. Williams, *Pet. Geo.* (2014)

Non-gas bearing structure





Need for fault density assessments around CCS sites

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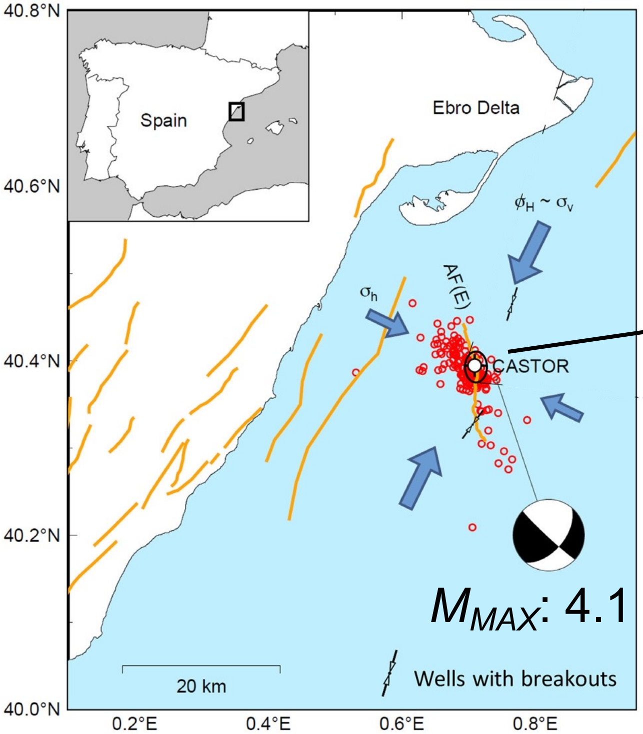
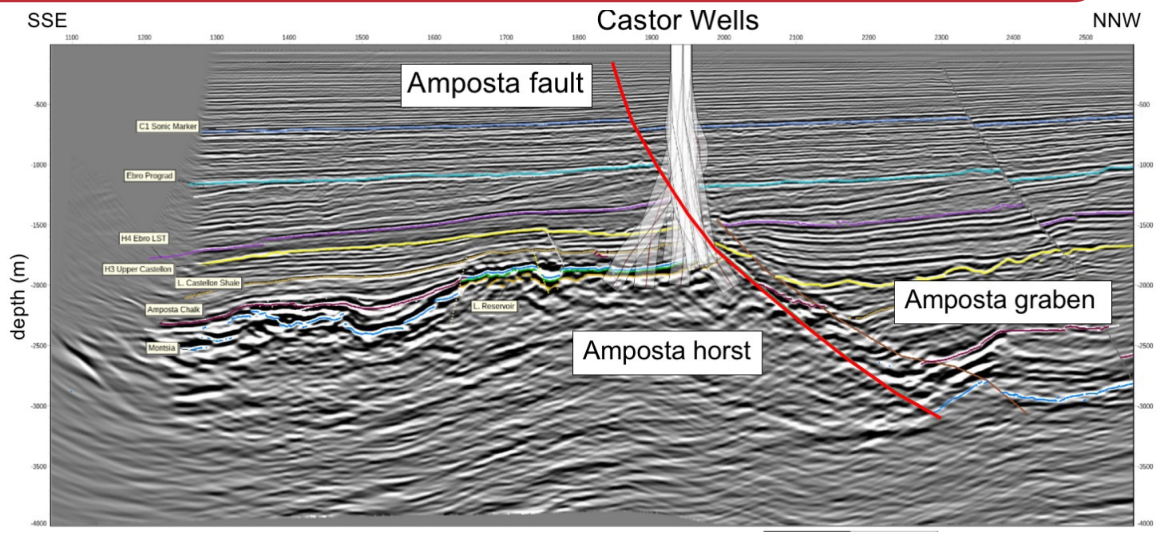
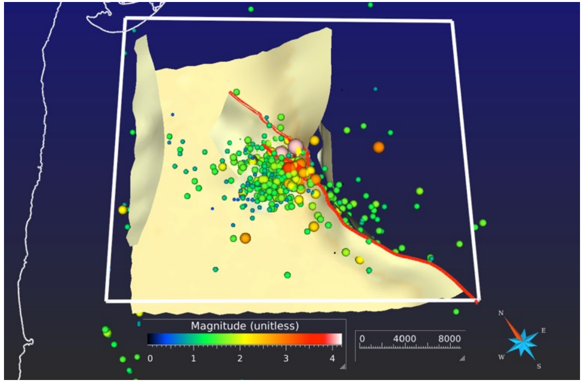
8. Induced Seismicity in CCS/Gas Storage sites

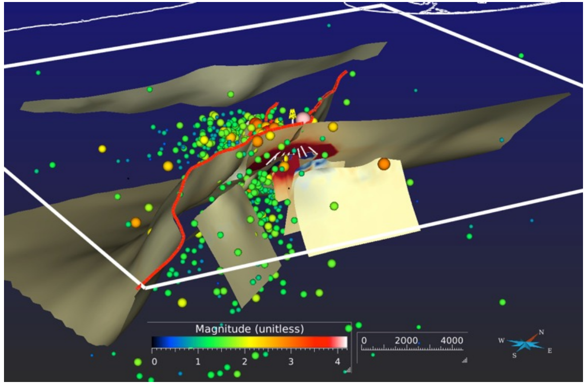
Castor, Spain (Gas Storage)



Vilarrasa et al, *JGR* (2021)







Juanes et al, (2017). Induced Seismicity at the Castor Project. Final Report.

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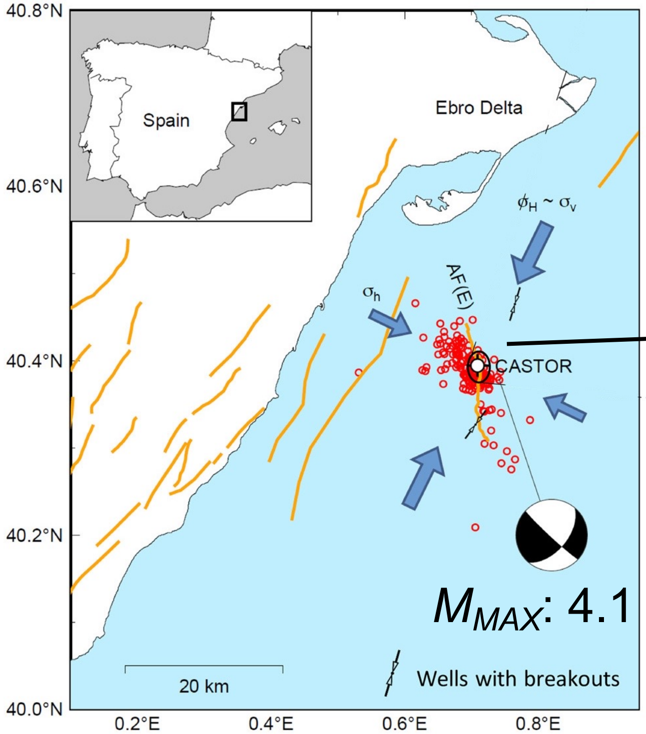
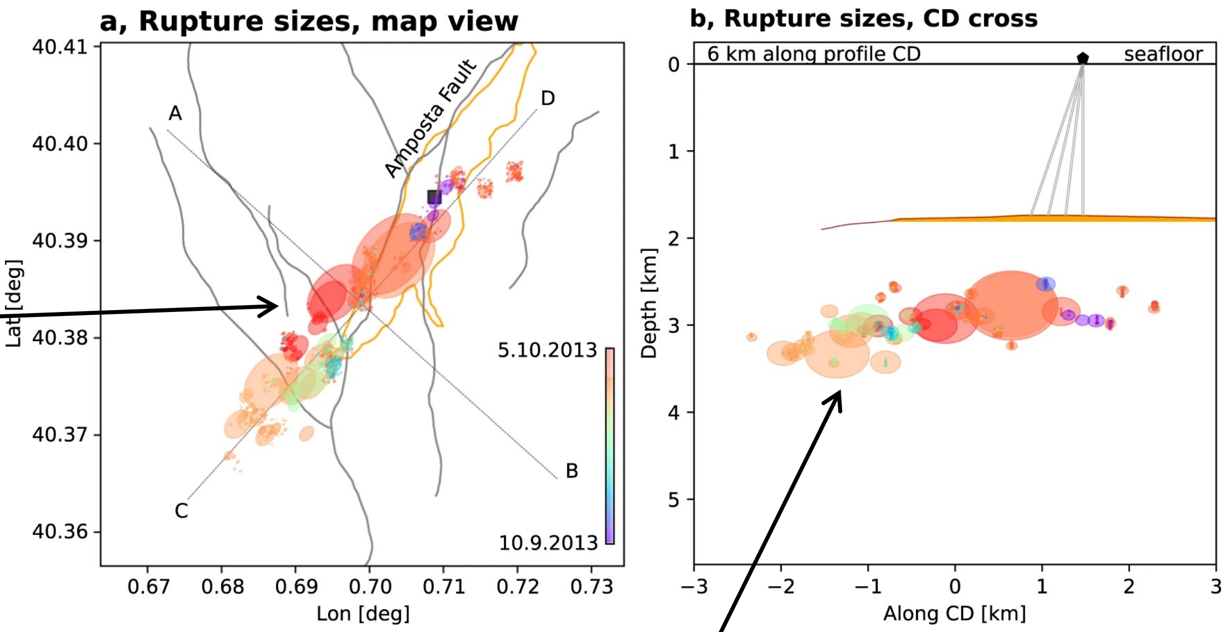
8. Induced Seismicity in CCS/Gas Storage sites

Castor, Spain (Gas Storage)





Vilarrasa et al, *JGR* (2021); Cesca et al, *Nature Comm.* (2021)

Pre-existent faults reactivated > 1km ***below*** the reservoir