ENSURING SAFE GEOTHERMAL OPERATIONS: MODELING OF INDUCED SEISMICITY AND THE IMPORTANCE OF MODEL VALIDATION THROUGH FIELD-SCALE MONITORING

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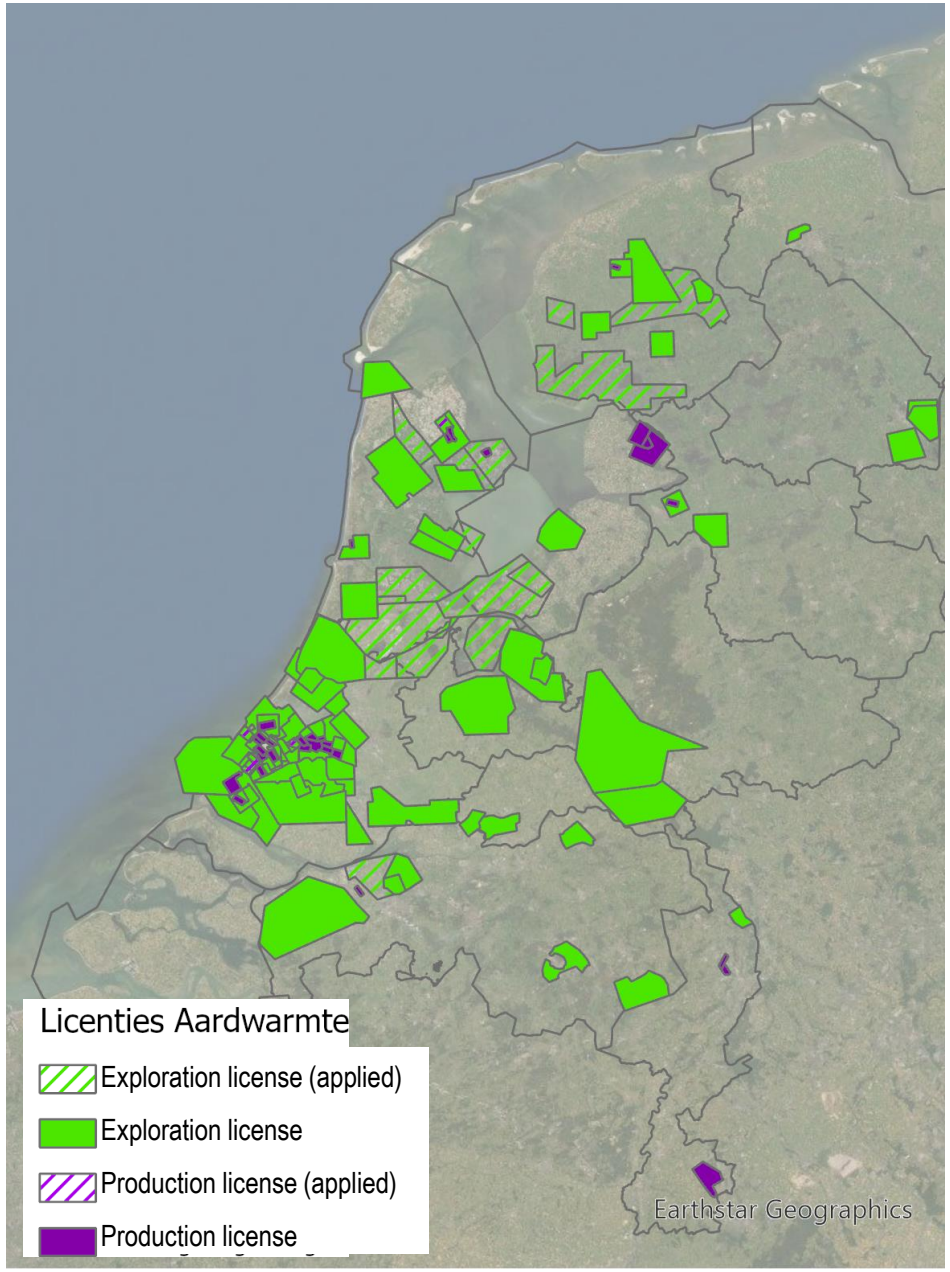
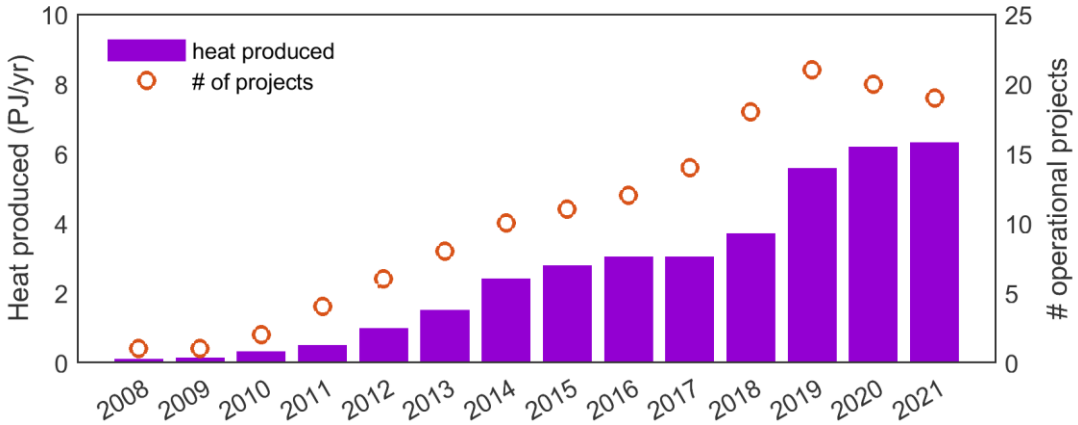


GEOTHERMAL IN THE NETHERLANDS

- First project: 2008 operational
- 2021: 19 projects operational
- 6.2 PJ heat produced
  - Total energy demand NLD ~3,000 PJ/yr
- 2030: 11 – 50 PJ expected

Jaarverslag Delfstoffen 2021, PBL 2021



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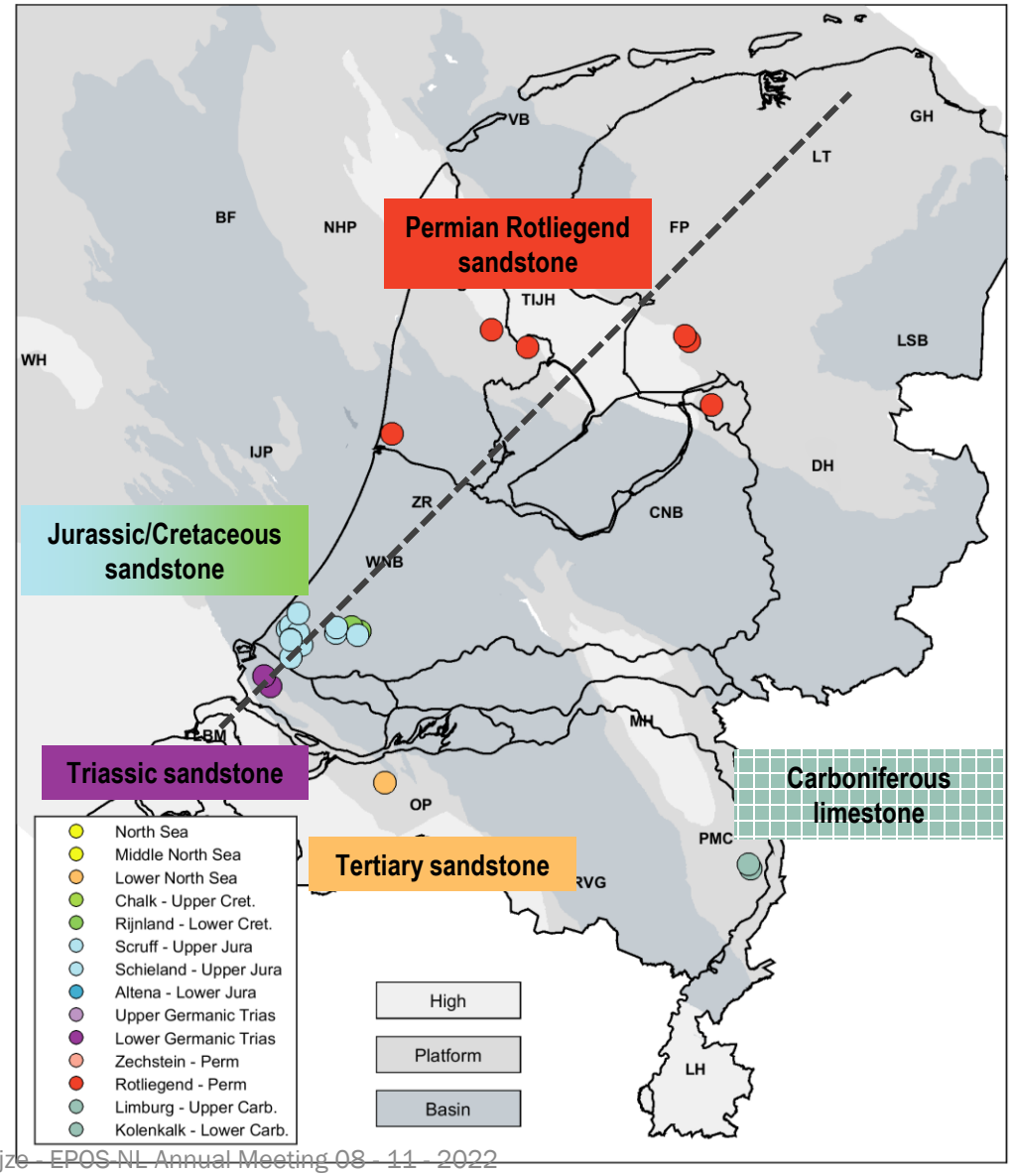
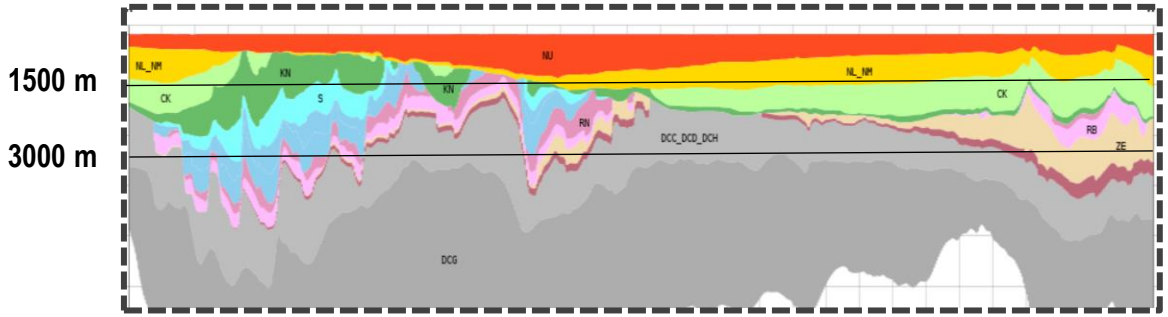
TWO TYPES OF GEOTHERMAL IN THE NETHERLANDS





Optimal window porous sandstone reservoirs: good porosity + good T

- Porous sandstone aquifers
  - Jurassic/Cretaceous: West NLD Basin (WNB)
  - Triassic: WNB
  - Permian: center of NLD
- Fractured carbonates – fracture-driven flow
  - Limburg
- Operations: balanced circulation, direct-use for agriculture
- Fracking, stimulation, not done

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INCREASING AWARENESS OF INDUCED SEISMICITY IN NLD

- Potential risk related to geothermal:
  - Induced seismic events
    (that can be felt and/or cause damage)
- No felt earthquakes registered near geothermal sites in Netherlands

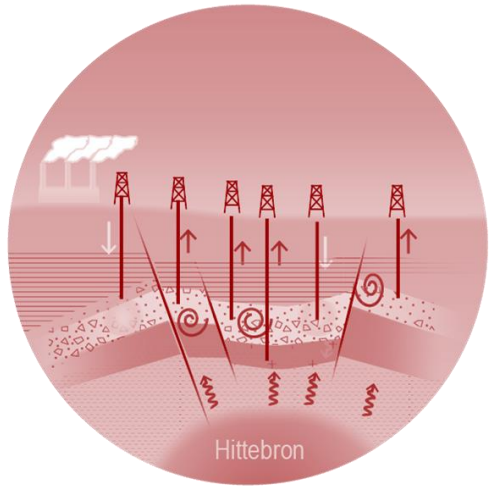
- Still, concerns about induced earthquakes exist:
  - 1) Earthquakes induced by geothermal abroad
  - 2) Earthquakes induced by gas production from similar reservoirs. Groningen.

- Showstopper for geothermal

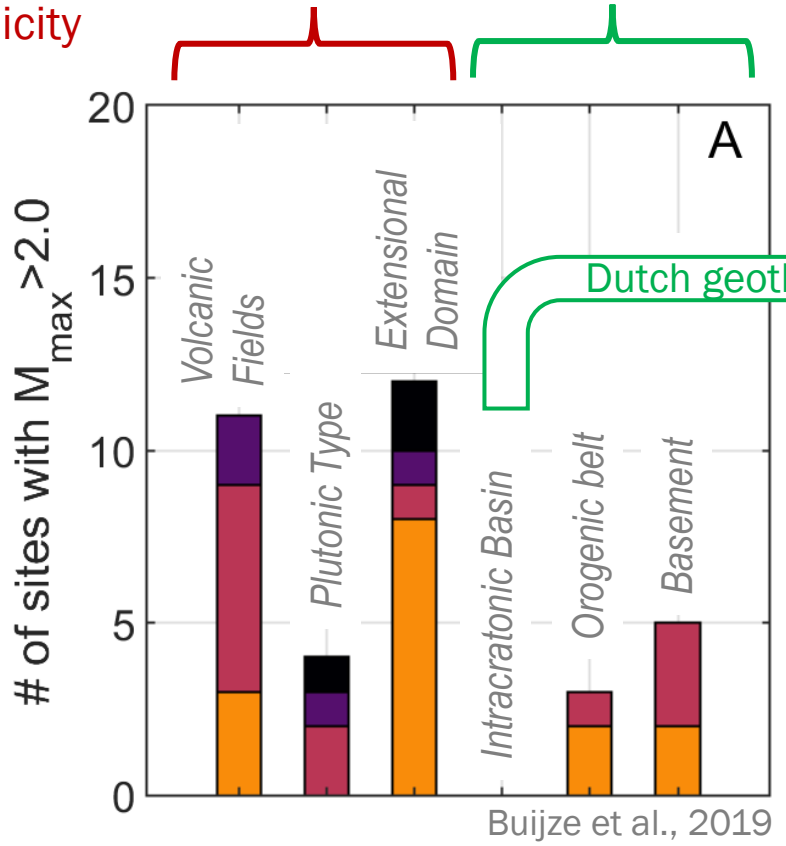
- Current seismic risk analysis protocol conservative, not region specific
- What can we learn from 1 & 2?

REVIEW GEOTHERMAL-INDUCED SEISMICITY ABROAD

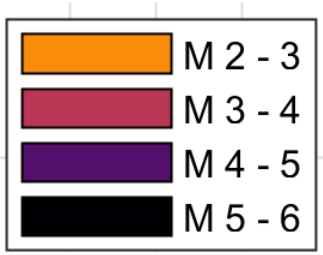
High tectonic loading
Close to plate boundaries
High natural seismicity



Low tectonic loading
Stable regions
Low natural seismicity



Dutch geothermal



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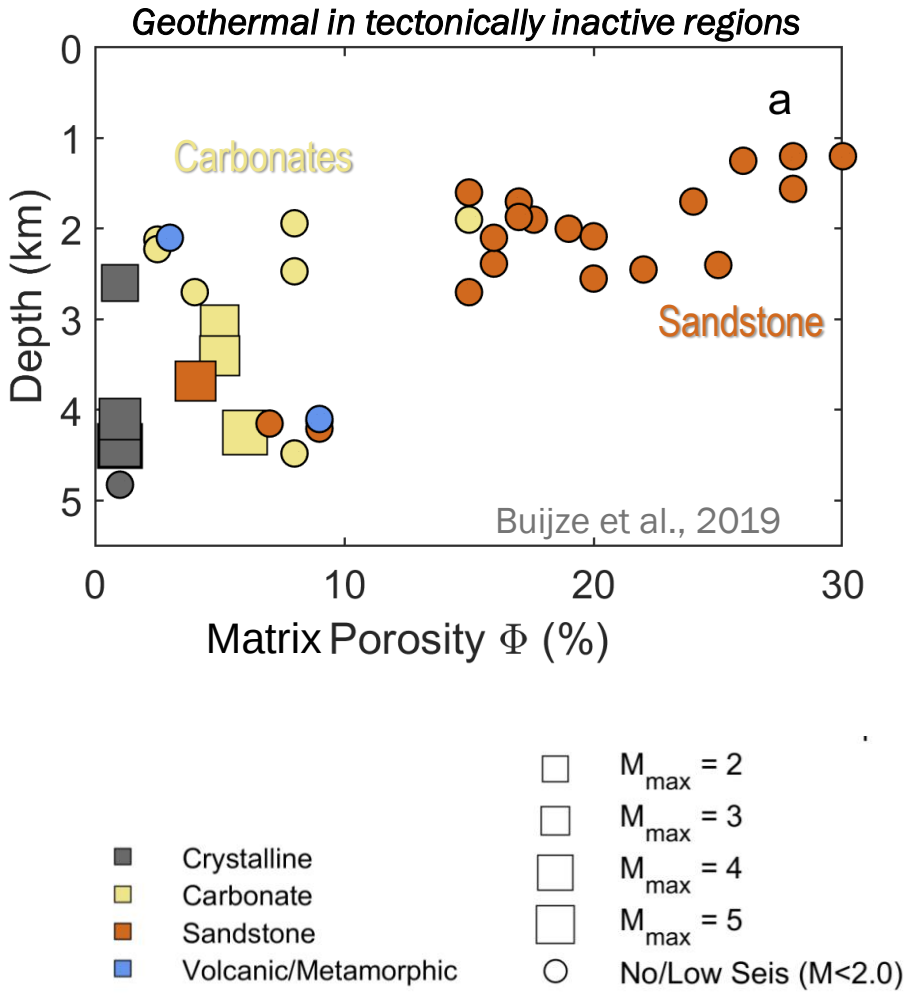
LOW SEISMIC POTENTIAL POROUS SANDSTONE RESERVOIRS

- Some events near doublets in fractured carbonates
  - Balmatt 2.1. Munich area 2.7
  - Netherlands (Californië) M 1.7

- No seismic events M > 2.0 doublets in porous sandstone
  - In Netherlands or abroad *(Buijze et al., 2019)*
- → suggests lower risk

- But:
  - Monitoring limited, # of projects and duration limited
  - Gas production events in similar rocks.

    Why? Differences/similarities?



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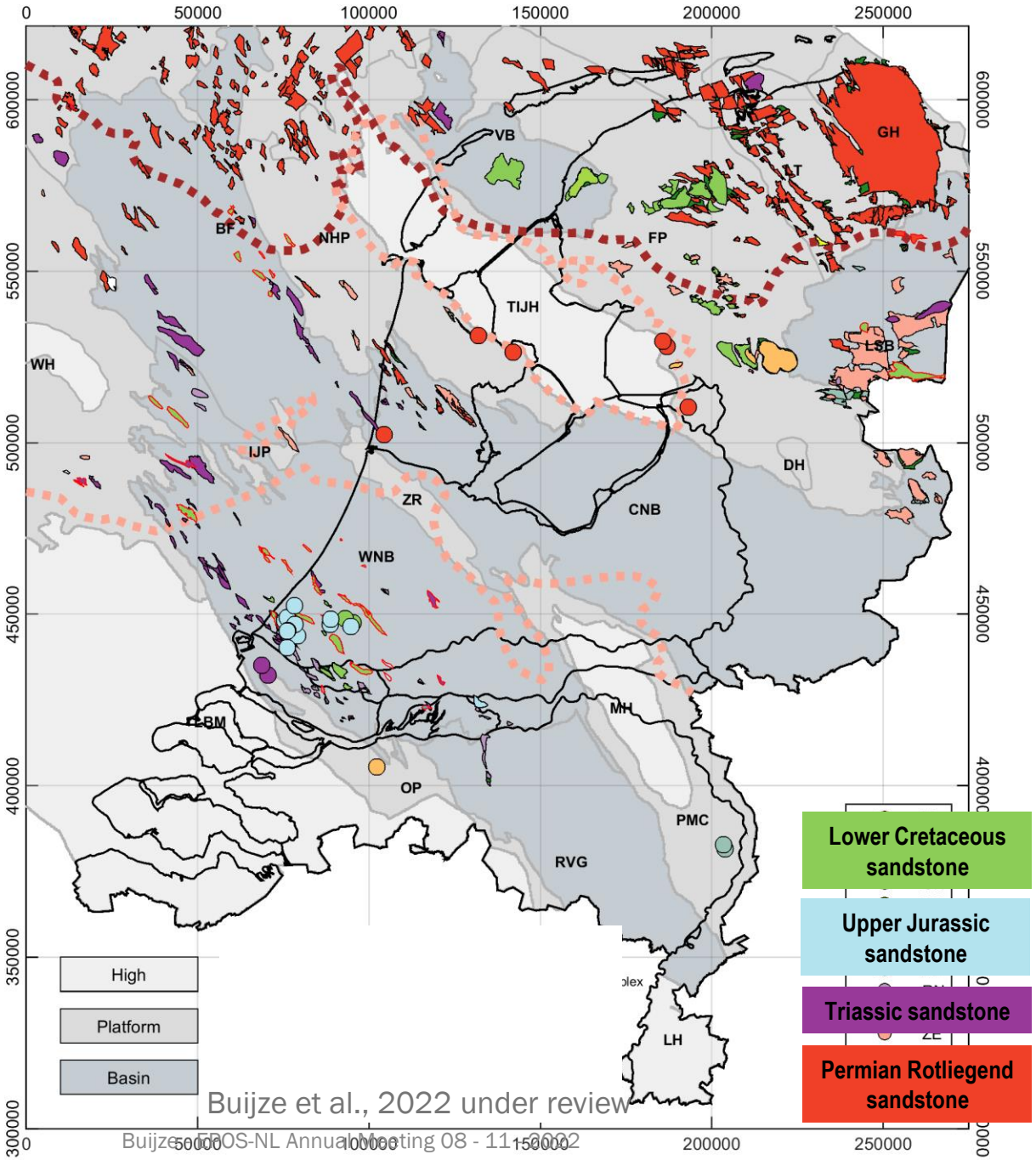


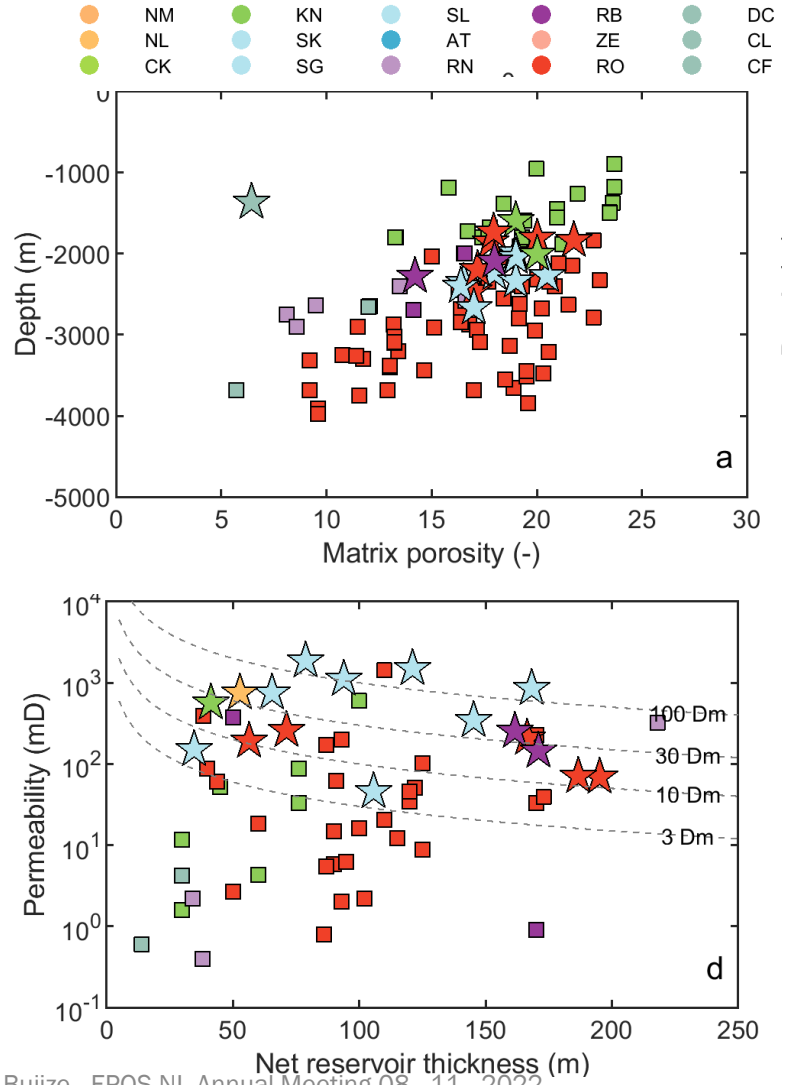
Buijze et al., 2022 under review

SIMILARITIES & DIFFERENCES GAS PRODUCTION

- Similar sandstone reservoirs are targeted by hydrocarbon and geothermal operations
- Partially in the same regions
  - West Netherlands Basin
  - Central/West Netherlands

Geothermal projects

COMPARISON OF GEOLOGICAL CHARACTERSTICS



- Similar reservoir depths and thicknesses
- Geothermal: depths < 3 km
- Also, relatively porous and permeable
- Why?
- Geothermal energy production depends on ΔT and transmissivity
  - (= permeability x net thickness)
- Viable from ~5 Dm

☐ Hydrocarbon fields ☆ Geothermal projects

Buijze et al., 2022 under review

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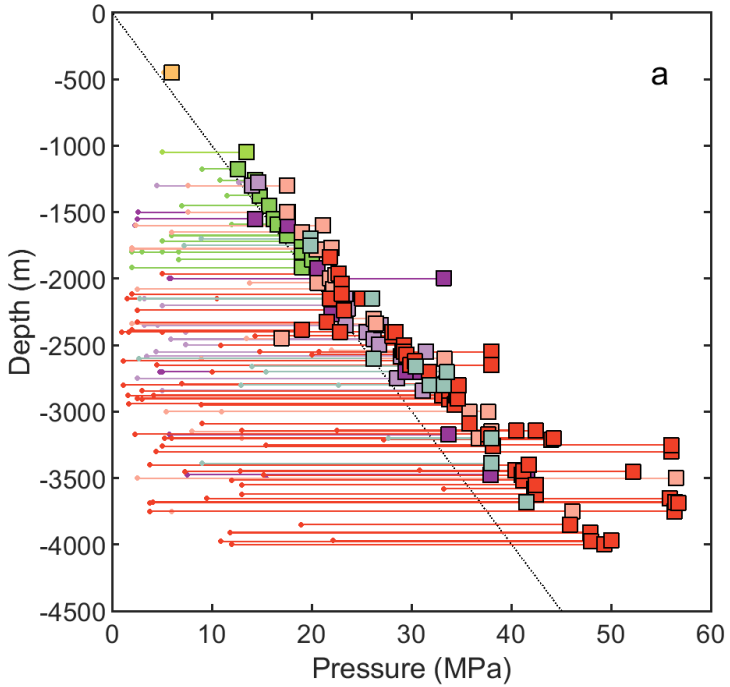
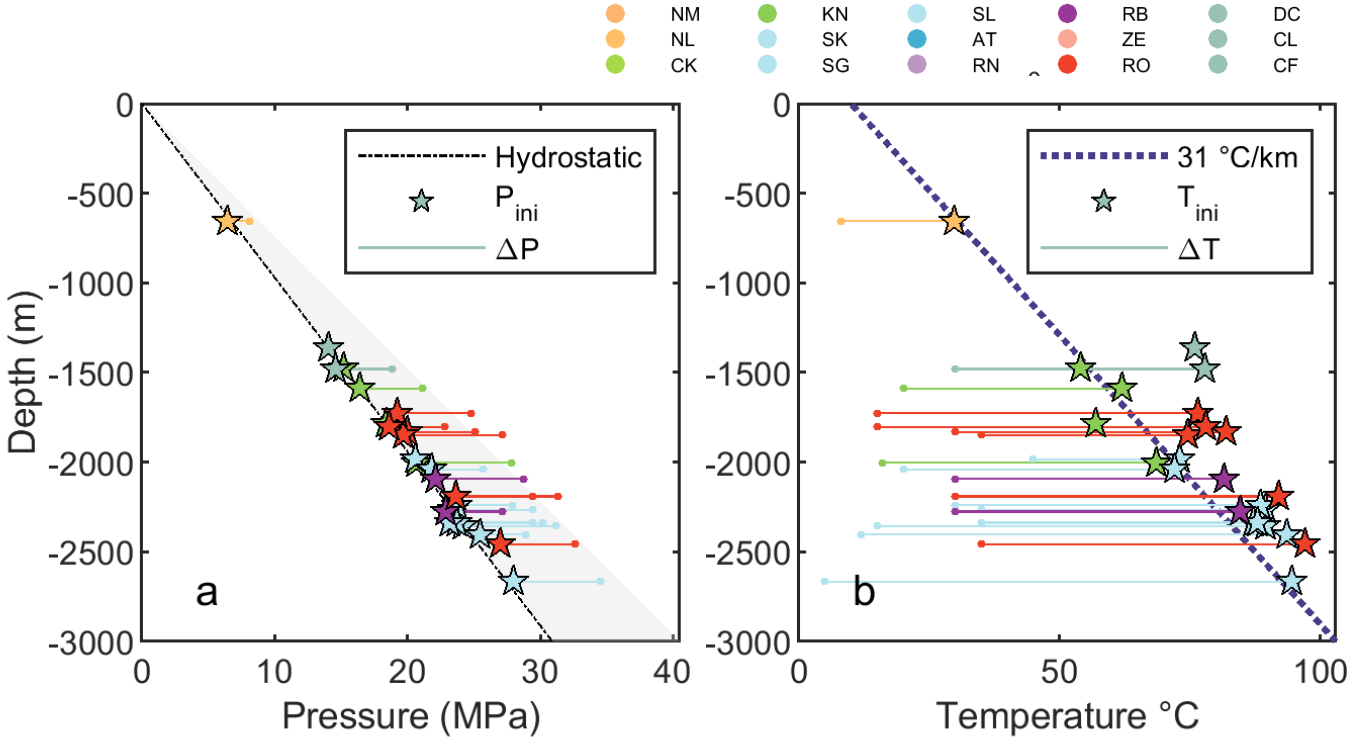
COMPARISON OF ΔP AND ΔT MAGNITUDES





Buijze et al., 2022 under review

Gas production
- ΔP is negative
- ΔP up to 95% of initial pressure
- (up to 10's of Mpa)

Geothermal
- ΔP is positive at injection well
- ΔP is limited (SodM protocol)
- ΔT is negative, up to several 10 degrees of cooling

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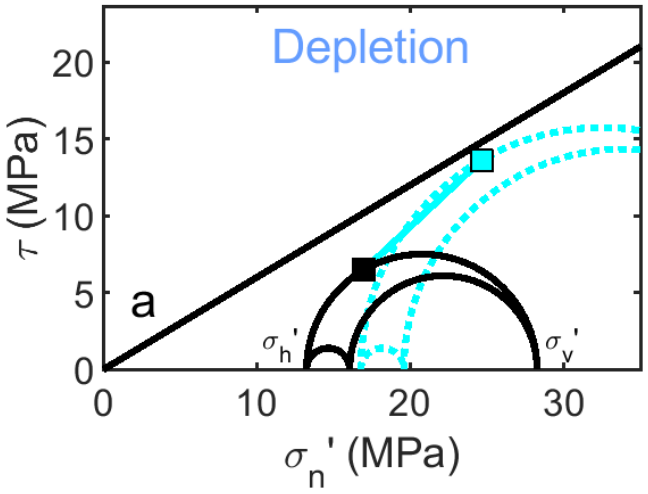
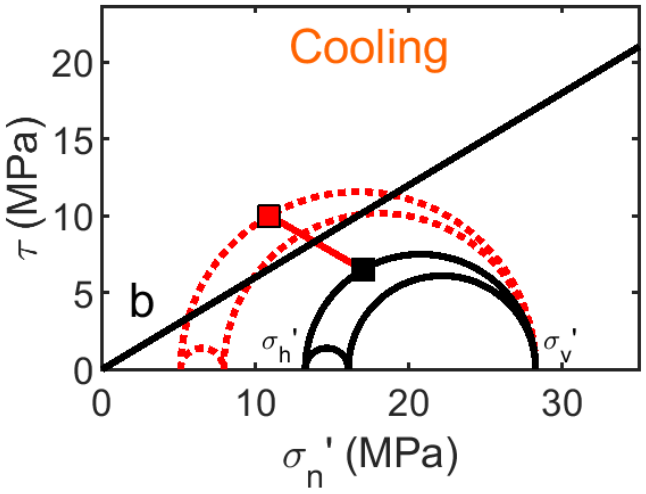
IMPLICATIONS FOR STRESS CHANGES





Pressure change dominates stress response
Poro-elasticity ~v,α
More compressive stress state with depletion

Temperature change dominates stress response
Thermo-elasticity ~E, η_T
Less compressive stress state with depletion

- Stress path cooling is quite destabilizing, and Coulomb stress changes can be substantial 1s to 10s of Mpa
  - Why no seismicity registered near geothermal sites in NLD?

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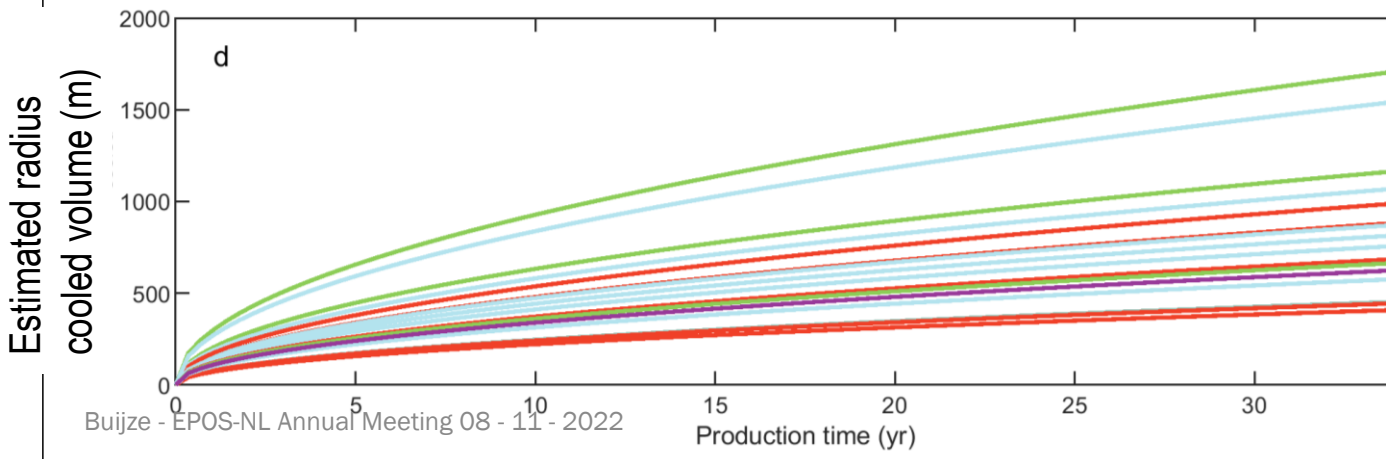
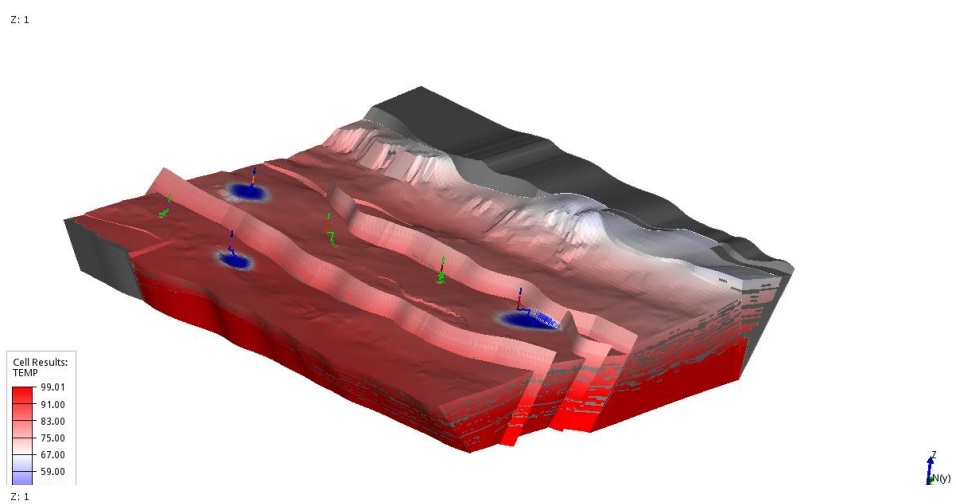
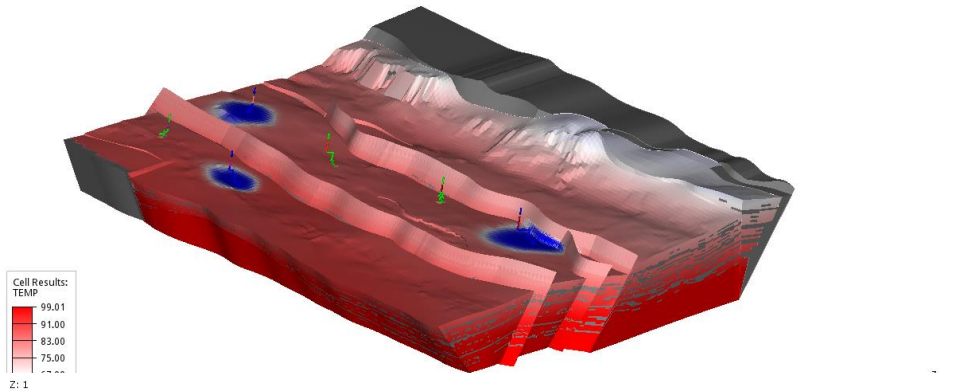
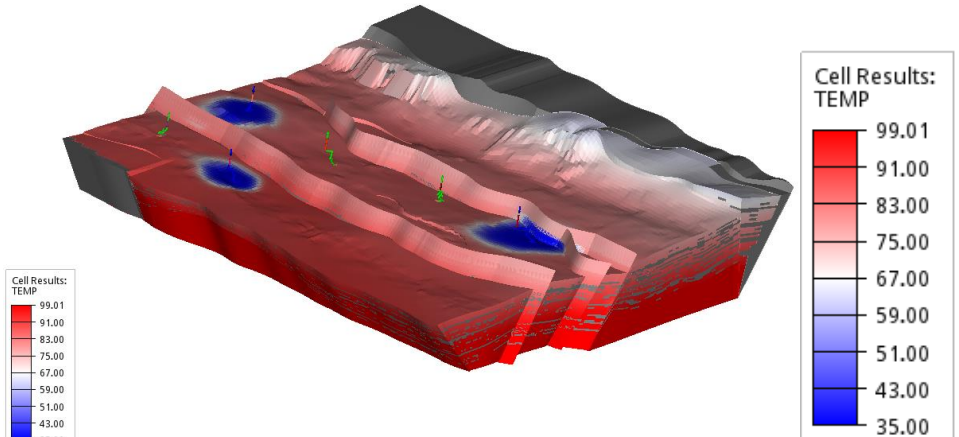
SPATIO-TEMPORAL ΔP AND ΔT GEOTHERMAL

- Cooled volume around injection well increases with time
- Nearby faults: an increasingly large fault area will experience cooling (and stressing)
- Doublets are placed typically > 100s m from faults
- Production time limited, potentially cooled area did not reach faults yet. But we know in some places it did.
- Or events may remain small
- <u>But many other factors may play a role!</u>

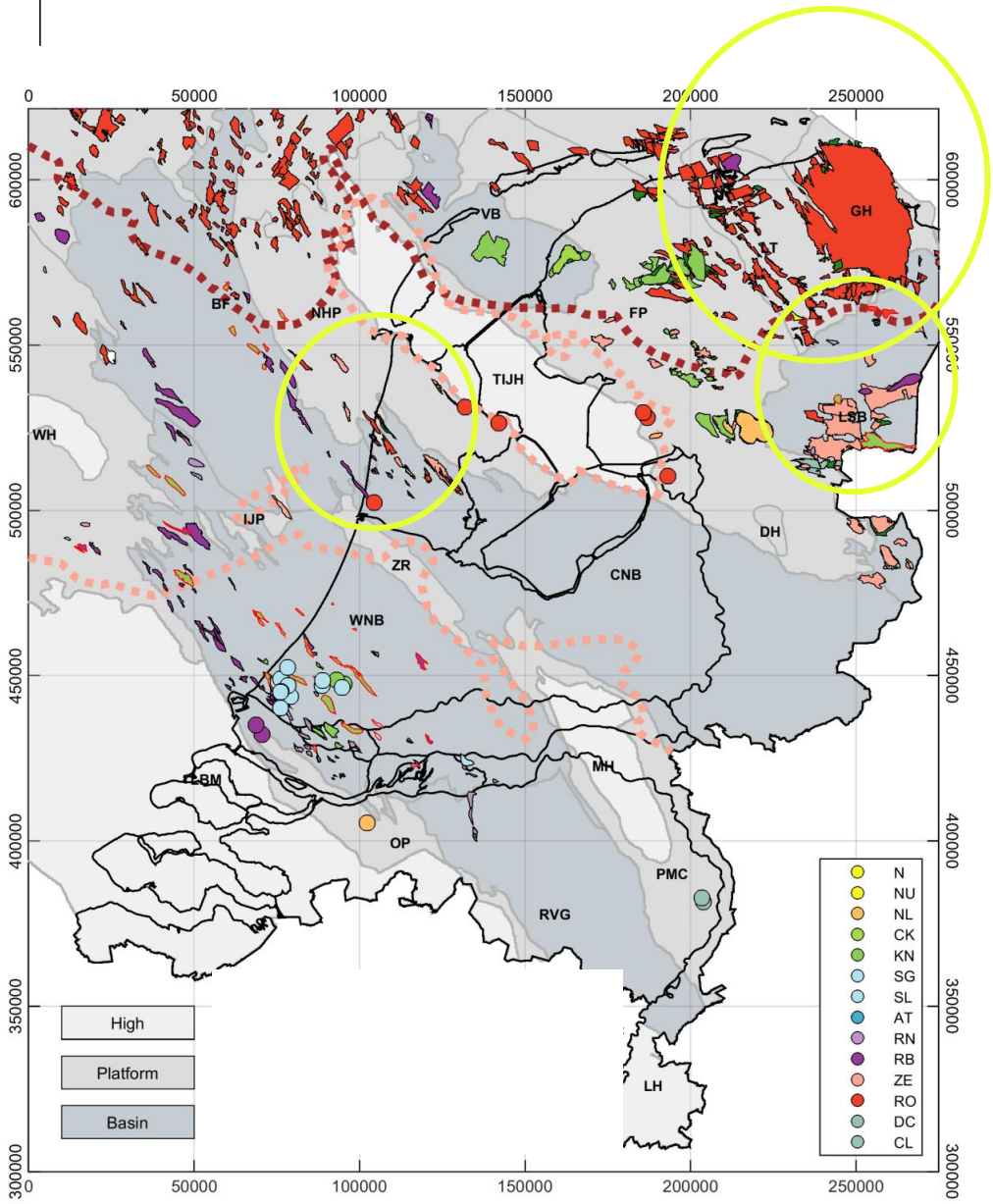


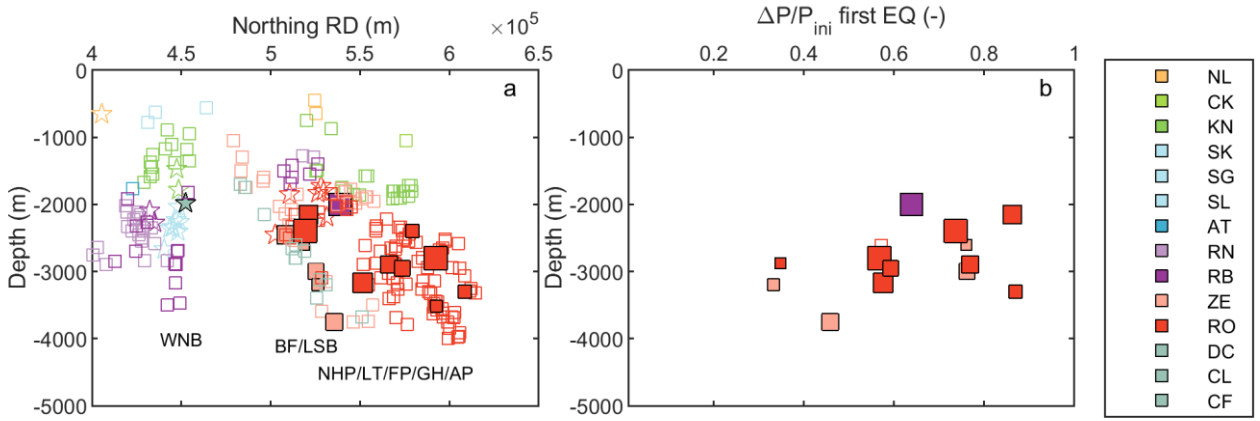






SEISMICITY IN HYDROCARBON FIELDS: WHAT CAN WE LEARN FROM THESE OBSERVATIONS?





- (Felt) Seismicity hydrocarbon fields limited to
  - North of Amsterdam-Arnhem line (salt present)
  - Permian, Zechstein or Triassic fields
  - > 2 km depth
  - After substantial depletion
- Why? Why this spatial clustering? What does it mean for geothermal?

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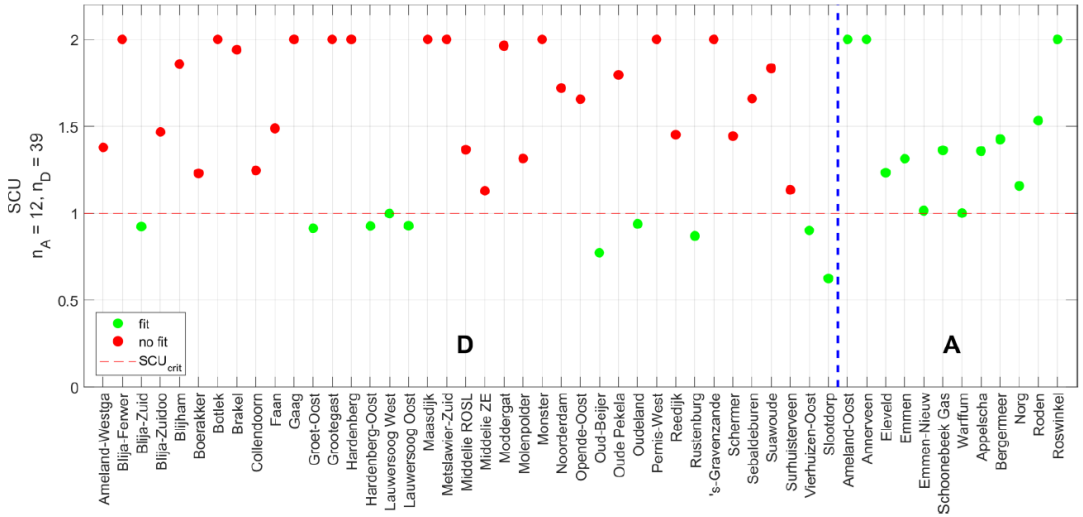
EXPLANATIONS FOR SEISMIC / ASEISMIC HYDROCARBON FIELDS

- Deterministic Seismic Hazard Analysis → **Elasticity contrasts, fault density, dP/Pini**
- KEM study Vörös & Baisch 2018
  - 2D Modeling 'predicts' seismically active fields, not does not predict aseismic fields
- **Heterogeneous initial stress?** Muntendam-Bos et al. 2021
  - Cannot explain the difference
  - → **Effect of salt creep (?)** cf e.g. Orlic et al., 2013
- Effect of fault properties? De Pater et al., 2021
- Dependency on fault properties, depositional environment?
- Monitoring bias?

- Still unclear what are the exact mechanisms!
- Process understanding lacking
- SRA Geothermal: Model validation needed

Vörös & Baisch 2018



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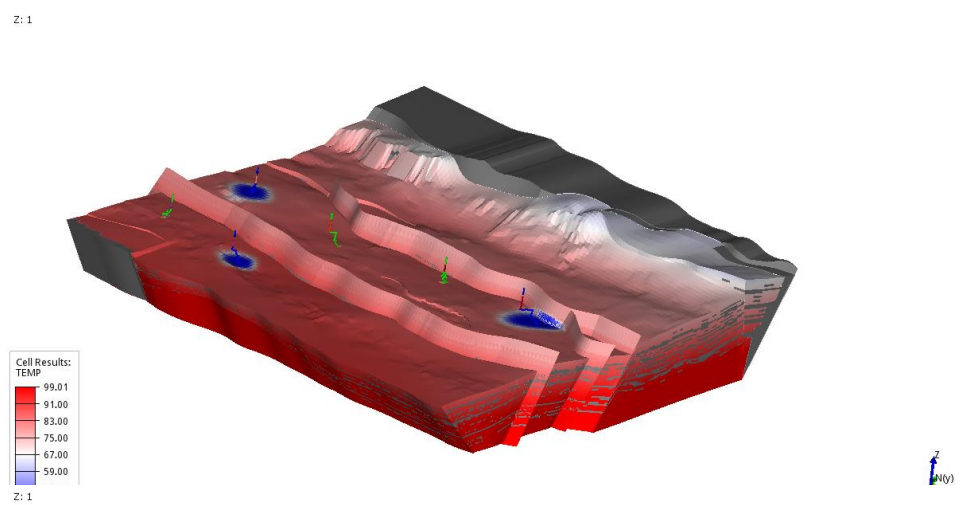
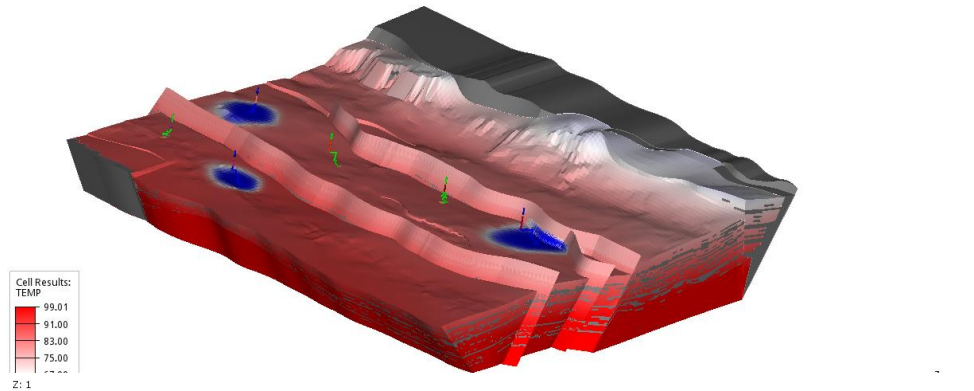
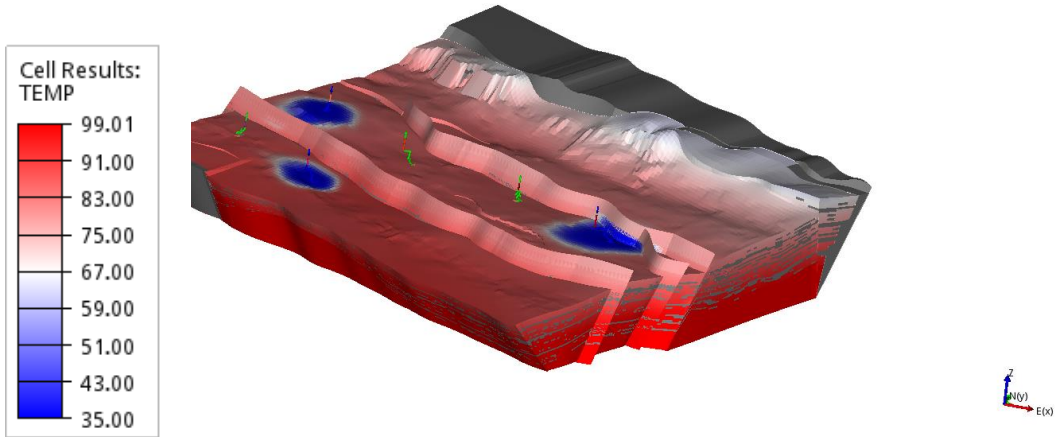
NEED FOR MONITORING!

- Process understanding is lacking
  - What are the key mechanisms for seismic fault slip?
  - Aseismic/seismic deformation? Lower normal stress → lower stress drop, more stable?
  - Effect of depositional environment on fault strength and stability, in-situ stress, seismic/aseismic behavior?
- We really need monitoring for process understanding
- Both seismic (geophones) and aseismic (FO, tilt)
- Key for model validation, design of SRA, mitigation measures, causality and early detection







NEED FOR MONITORING!

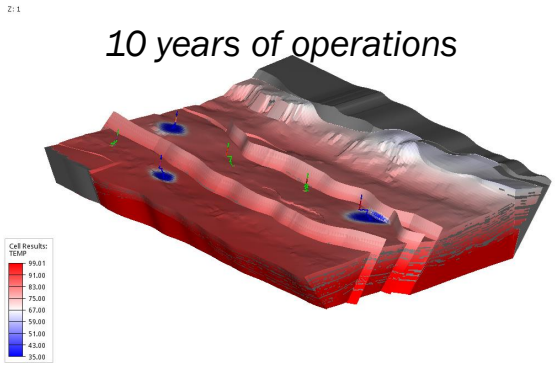
- Spatio-temporal signature PT changes and stress changes geothermal is fundamentally different from depletion
- Gas production: uniform dP over large area
- Geothermal: Gradual interaction cooled front with faults

- Early detection of (seismic) fault reactivation may be possible.

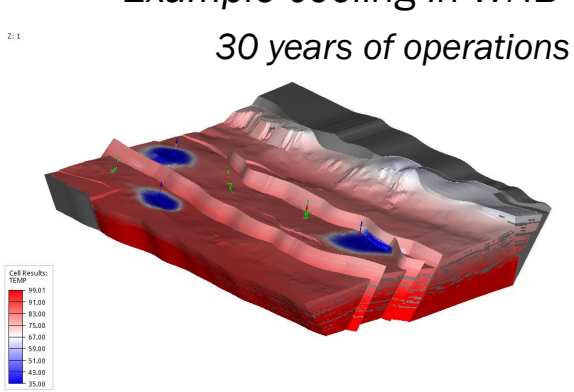
- Adequate mitigation & response
- Region-based seismic risk assessment based on understanding of the process

Example cooling in WNB

10 years of operations

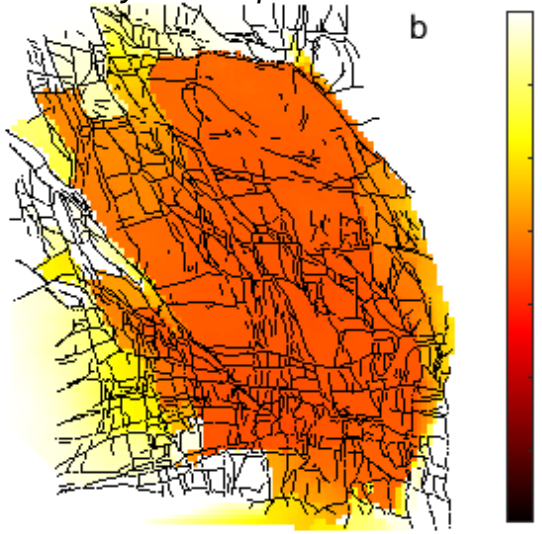
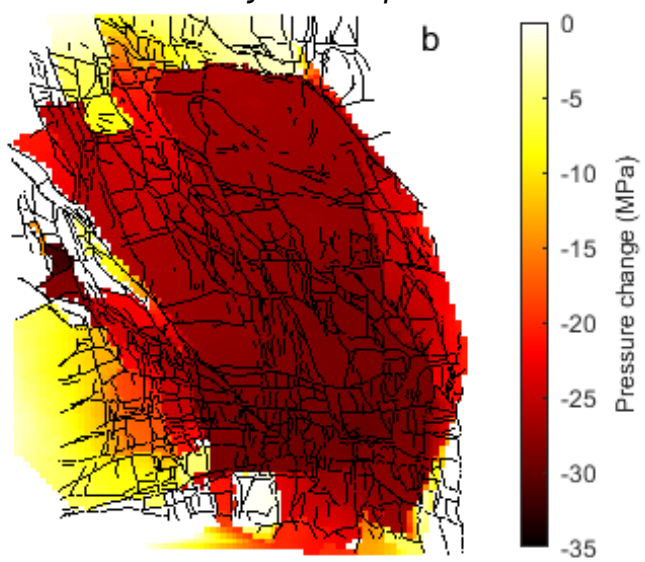


30 years of operations



Example pressure model Groningen

35 years of production



65 years of production