Geomechanical Analysis for investigating the occurrence of induced seismicity in small gas fields in The Netherlands

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Robert Vörös, Stefan Baisch

Geothermal reservoir engineering

Agenda

1. Summary of final report.
2. Further research
3. Discussion → questions, clarification, modifications …

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Aims & Scope

<u>Guiding Question</u>

Why do some fields produce seismicity during gas production while others do not?

→ Previous investigations focus on identifying key parameters empirically (e.g. van Eijs, 2006).

→ Can observations be explained by (simple) physics-based models?

Aims & Scope

In contrast to empirical approaches applied previously, a physics-based approach has the potential to assess the seismic hazard also in a scenario outside the range of previous experience.

→ Assemble a data base with key reservoir parameters.

→ Develop simple 2-D geomechanical models for simulating stress perturbations due to pressure depletion.

→ Develop an automatized process flow to run a large number of these models.

→ Investigate to what extent induced seismicity observations in small, onshore gas fields in the NL can be explained by these geomechanical models while requiring a low number of (free) model parameters (Occam's razor).

Data Base Compilation

Relevant parameter for the study (reservoir specific)

- Geology (reservoir, over/underburden, rock-mechanical parameter).
- Reservoir depth, thickness, compartments, depletion history.
- Mapped faults at reservoir level (classification according to strike)

No information easily available for

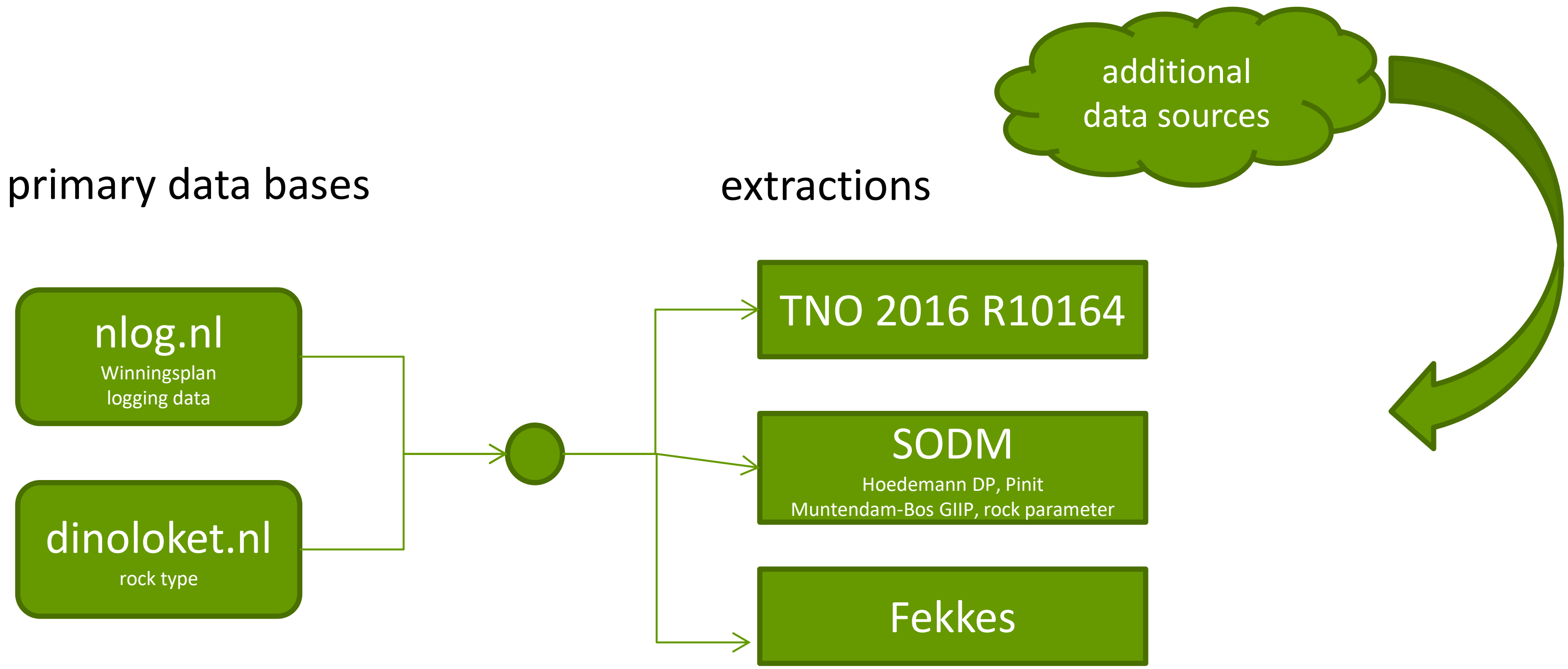
- Fault throw
- Fault dip

→ unconstrained parameter

Data Base Compilation

parameter type	parameter
ID	reservoir name (+ additional suffix for respective formation in case of multiple reservoir fields)
Geometry	reservoir depth, thickness
	over/underburden thickness
hydraulic (reservoir)	initial pressure
	depletion level • at onset of seismicity (seismically active) • current / leaving (seismically not active)
rock (reservoir, over /underburden)	Young's modulus (range) Poisson's ratio (range)
fault orientation / type	strike (discretized) / boundary (hanging wall,foot wall), internal

Data Base Compilation

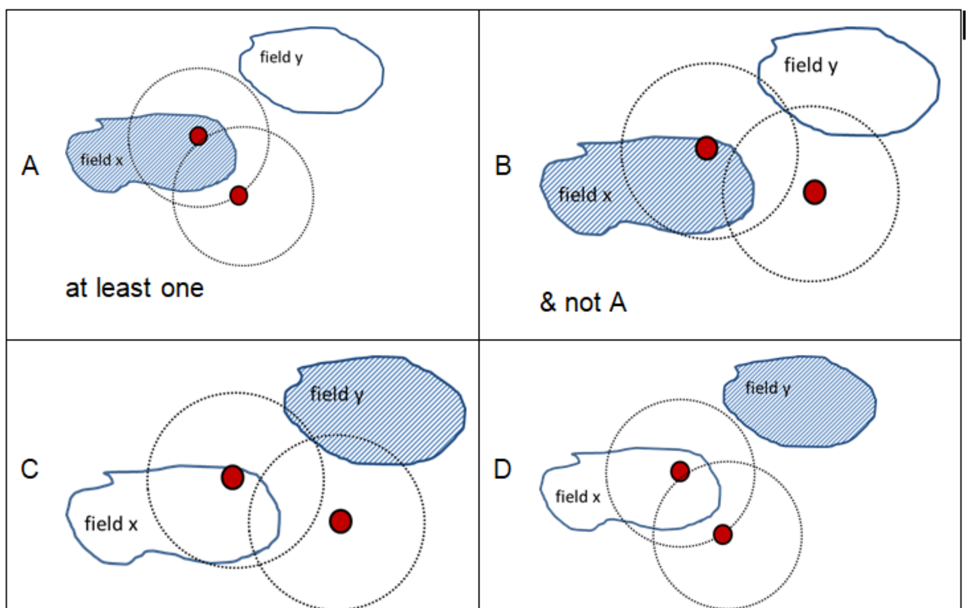


1. benefit from previous studies where information has been extracted from primary data bases
2. challenges: extractions sometimes include additional data interpretations can be contradictory

Data Base Compilation

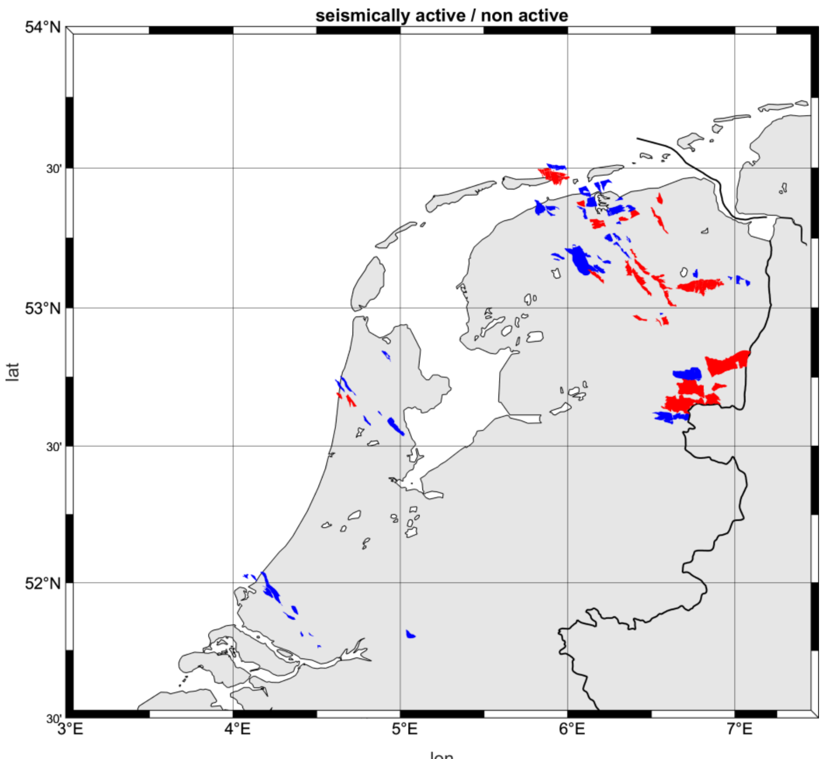
- Accounting for the location uncertainty of the earthquakes (estimated at 2.5 km)
  → Categorization of reservoirs

likely associated in catalogue	possibly associated in catalogue	possibly not associated in catalogue	likely not not associated in catalogue
A	B	C	D

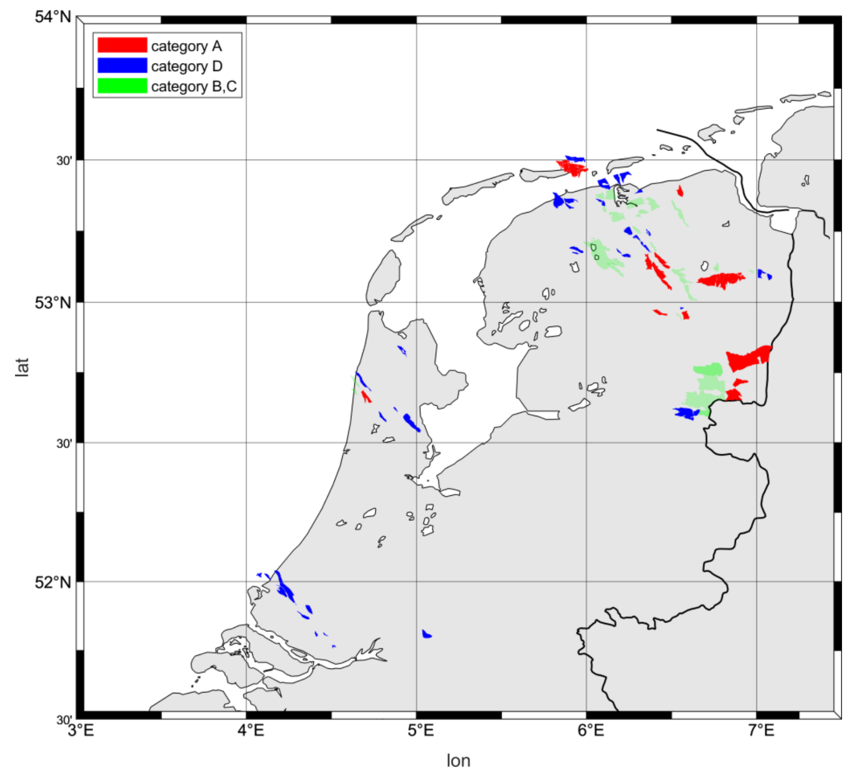


Data Base Compilation

- 81 small onshore gas fields
- 12 category A, 39 category D and 15 category B or C reservoirs each
- 374 faults (altogether), only faults > 1km considered



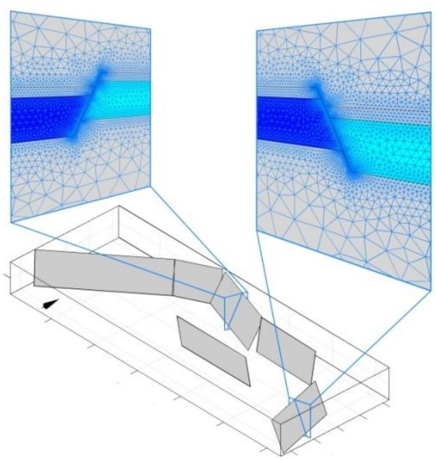
Seismically active (red) and not-active (blue) according to MDB

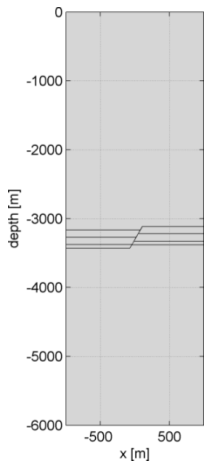


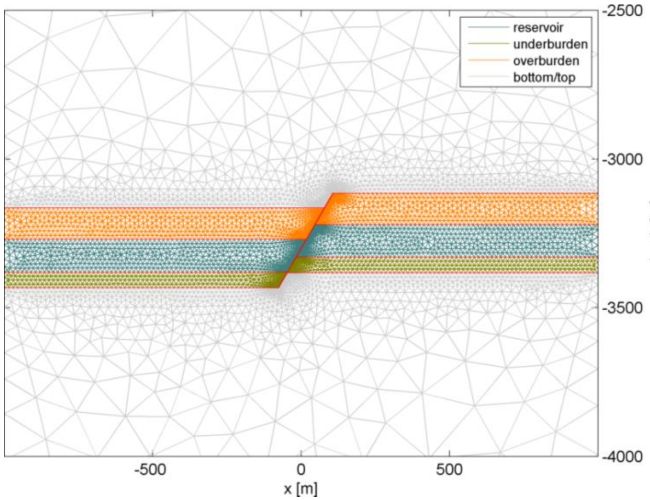
New classification

Geomechanical Simulations

- Model setup → van den Bogert type models
- Separate model for individual faults and parameter combination
- Homogeneous depletion throughout reservoir



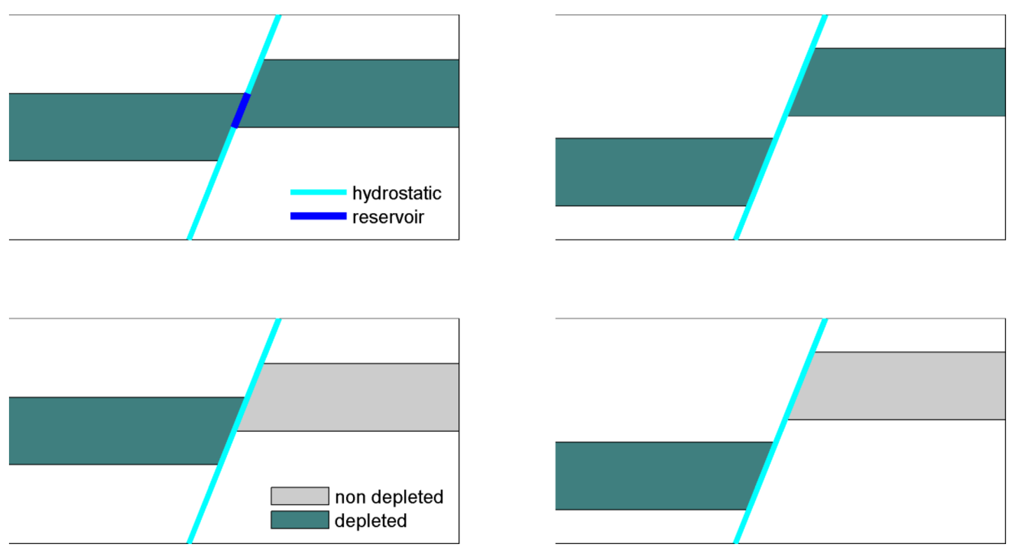




Geomechanical Simulations

Fluid pressure (inside faults)

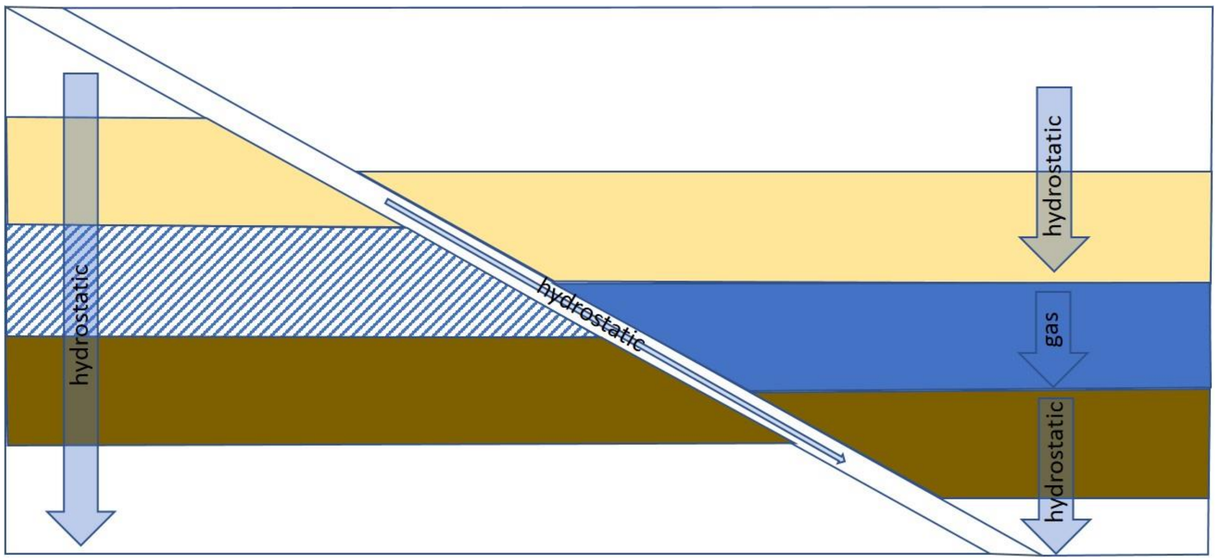
- Geomechanical simulations indicate that sealing faults might be more important than assumed previously, e.g. by van den Bogert (2016).
- In previous studies, the in situ fluid pressure inside sealing faults has been assumed to be the same as in (one side of) the reservoir. From a geomechanical perspective, alternative assumptions are reasonable (i.e. the sealed core is assumed to be the slipping area).



Geomechanical Simulations

Fluid pressure

- In the numerical model, we assume the initial reservoir pressure according to database-entries and a gas gradient inside the reservoir layer.
- Outside the reservoir and in the (sealed) fault we assume hydrostatic conditions

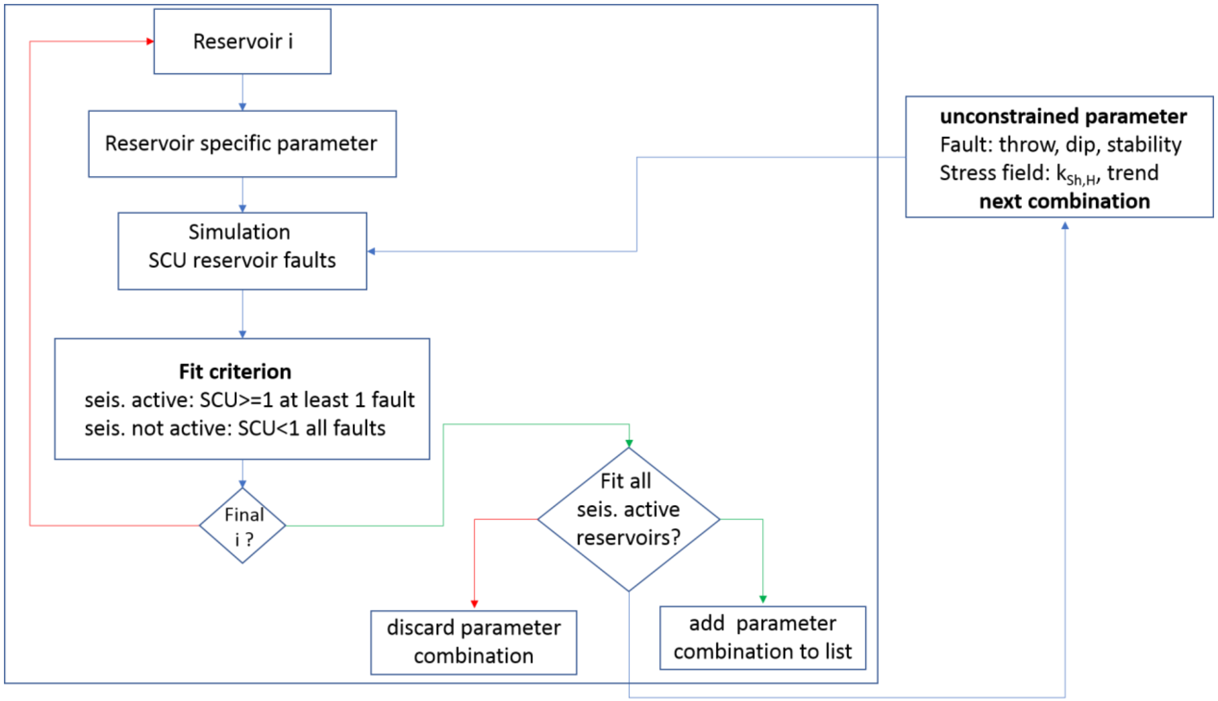


Geomechanical Simulations

- Automatized workflow to obtain a model that re-produces seismicity observations
- Key-components
  - ➢ Reservoir specific parameters (main database, ‘constrained’)
  - ➢ Parameters not generally available and subject to larger uncertainties (‘unconstrained’): stress field, fault stability, dip & throw
- Unconstrained parameter are free variables in a calibration scheme to fit seismicity observations
- In principle, all observations can be fit by introducing reservoir specific, unconstrained parameter (large degree of freedom) → no forecasting capabilities
- Ockham’s razor: Minimize number of free model parameters (ideally one global set only)
- Requirement: Fit at least all seismically active reservoirs (mandatory for SHA)

Calibration

- Identify best fit model by comparing simulation results for numerous parameter combinations scanning the expected parameter range



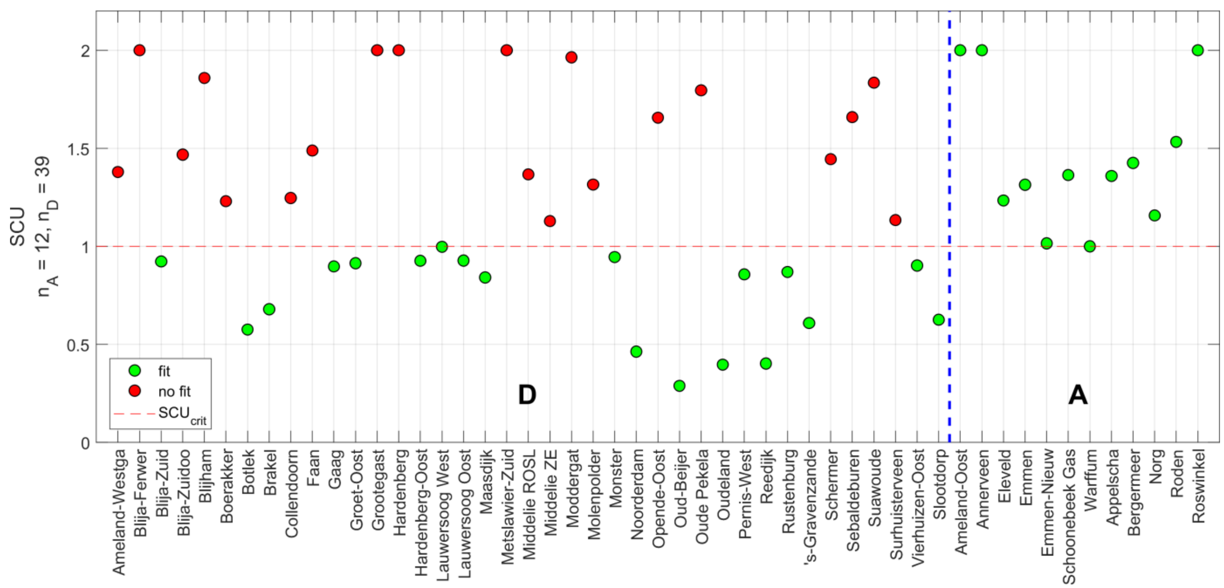
Calibration

Results of calibration procedure

- BFM-G: 100% fit category A, 28% fit category D.
  Parameter outside expected range (i.e. throw=250m & dip55°)
- BFM-P: 100% fit category A, 26% fit category D.
  Parameter within expected range
- **BFM-SW**: 100 % fit category A, 49% fit category D.
  1 additional degree of freedom → Regional Variation of unconstrained parameter k_{Sh} in the SW
- Different unconstrained parameter combinations produce equal number of observation matches
- Same sets of reservoirs tend to be matched by different best-fit combinations
  → Constrained parameter truly carry information about seismicity response of individual reservoirs

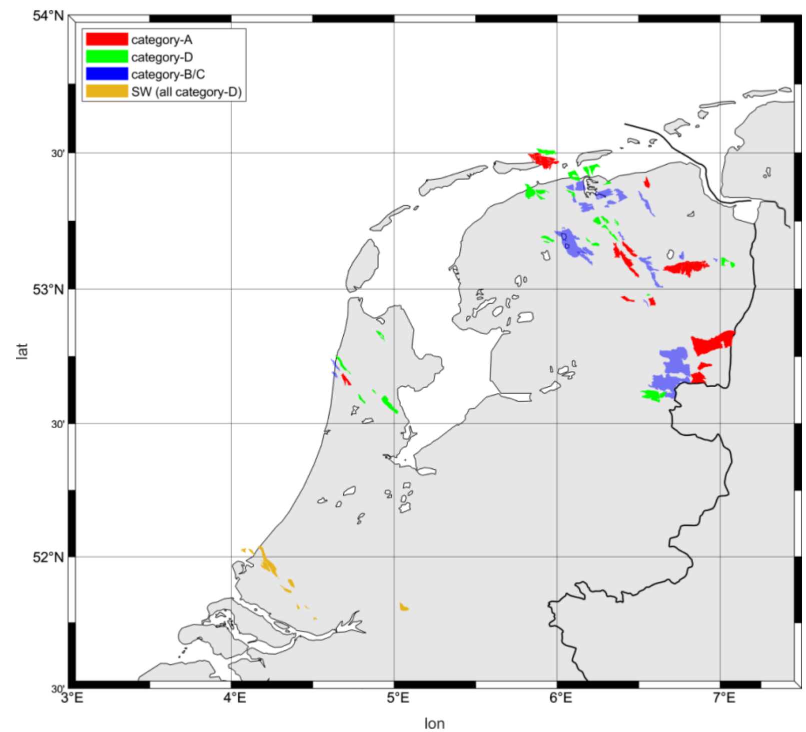
Calibration

BFM-SW: Regional variation, 11 category D reservoirs in the SW



Calibration

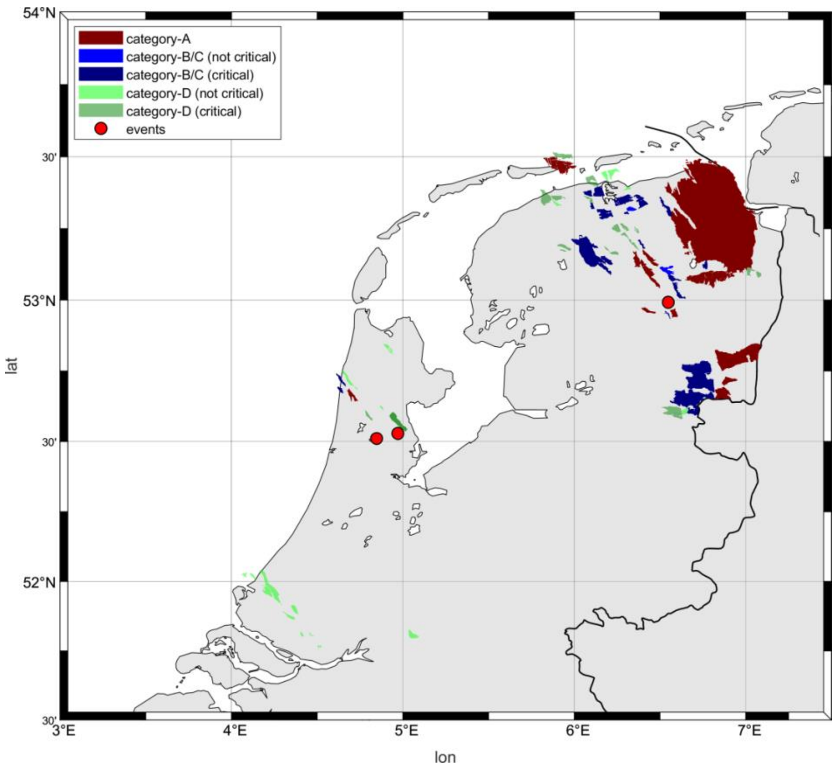
Parameter	Value	
	BFM-P	SW
throw	100 m	100 m
dip	70°	70°
μ (coeff. of friction)	0.8	0.8
C_0 (cohesion)	1.93 MPa	1.93 MPa
k_{Sh} (ratio $S_{h,eff}/S_{v,eff}$)	0.3	0.8
k_{SH} (ratio $S_{H,eff}/S_{v,eff}$)	0.85	0.85
trend SH	120°	120°
ΔSV/Δz	23 MPa/m	
Δp/Δz (fluid)	10 MPa/km	
Δp/Δz (gas)	2 MPa/km	
α (Biot coefficient)	0.8	



Consistency Check

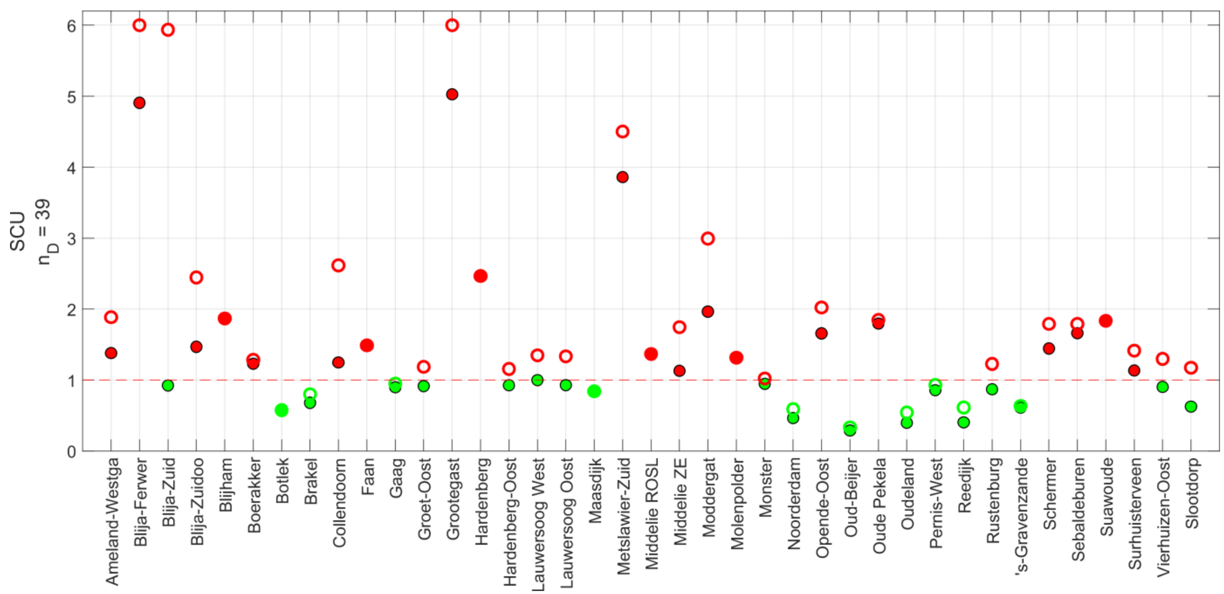
- Consideration of category B & C reservoirs for testing the calibration that was based on category A & D reservoirs
- Can BFM-SW model explain all induced seismicity in the NL?
- Model must result in at least one critical reservoir in the vicinity of an event (2.5 km estimated location uncertainty).

→ **No inconsistencies resulted**



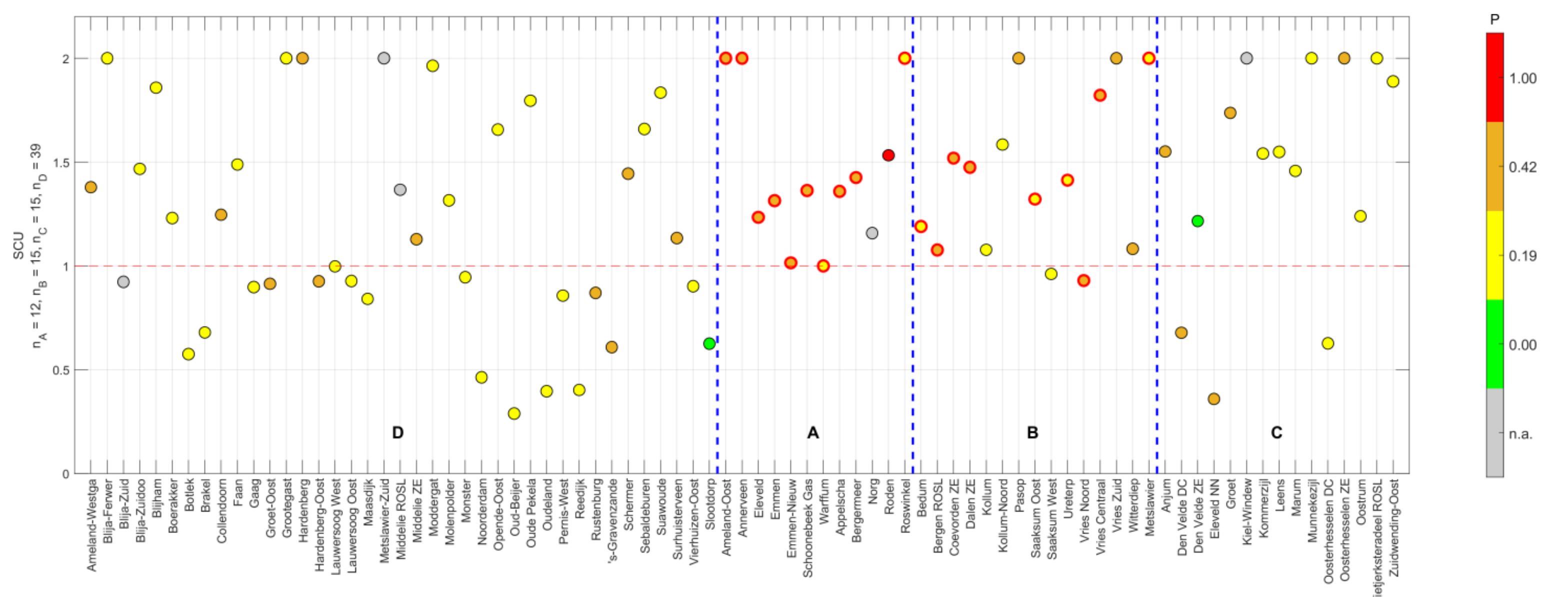
Prognosis

- Future stress evolution until the end the reservoir's lifetime
- Only 10 category D reservoirs remain at subcritical stress conditions



Comparison with DHAIS

- SHA in NL based on deterministic hazard scheme DHAIS
- Key parameters: rel. reservoir depletion, fracture surface to reservoir volume ratio & Young's modulus ratio reservoir / burden.
- DHAIS also exhibit considerable amount of mismatches but these seem to be uncorrelated with those obtained with the physics based approach.



Summary & Conclusions

- Database with reservoir specific, subsurface & operational parameter has been compiled (final version to be provided to SodM)
- Efficient, automatized simulation scheme developed & implemented for numerically simulating poro-elastic stresses associated with gas production
- Minimum complexity model for the prediction of seismic reservoir response calibrated with unconstrained parameter set
- All category A reservoirs modelled as seismically active. This is an essential prerequisite for seismic hazard assessment
- At the same time, ~50% of category D reservoirs simulated as seismically not active
- Strong indication that reservoir specific parameter carry information on seismicity response

Summary & Conclusions

- The developed tool has the potential to provide an essential component in future SHA.
- Still significant mismatch for seismically non-active reservoirs. Future research could improve prognosis.

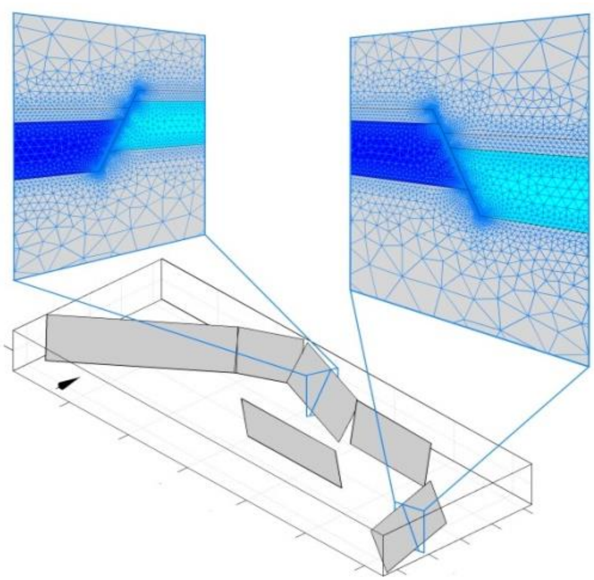
Suggestions for Future Research

How could the prognosis be improved (not part of current study)

1. Further assessment of unconstrained parameters
   - fault dip
   - fault throw
   - sealing/non-sealing faults (pressure compartiments)
2. Dynamic seismicity simulation (Block-Spring Simulator)
   - Current approach yields yes/no forecast
   - Earthquake strength can be included by dynamic simulations. This could significantly improve seismic hazard assessment.

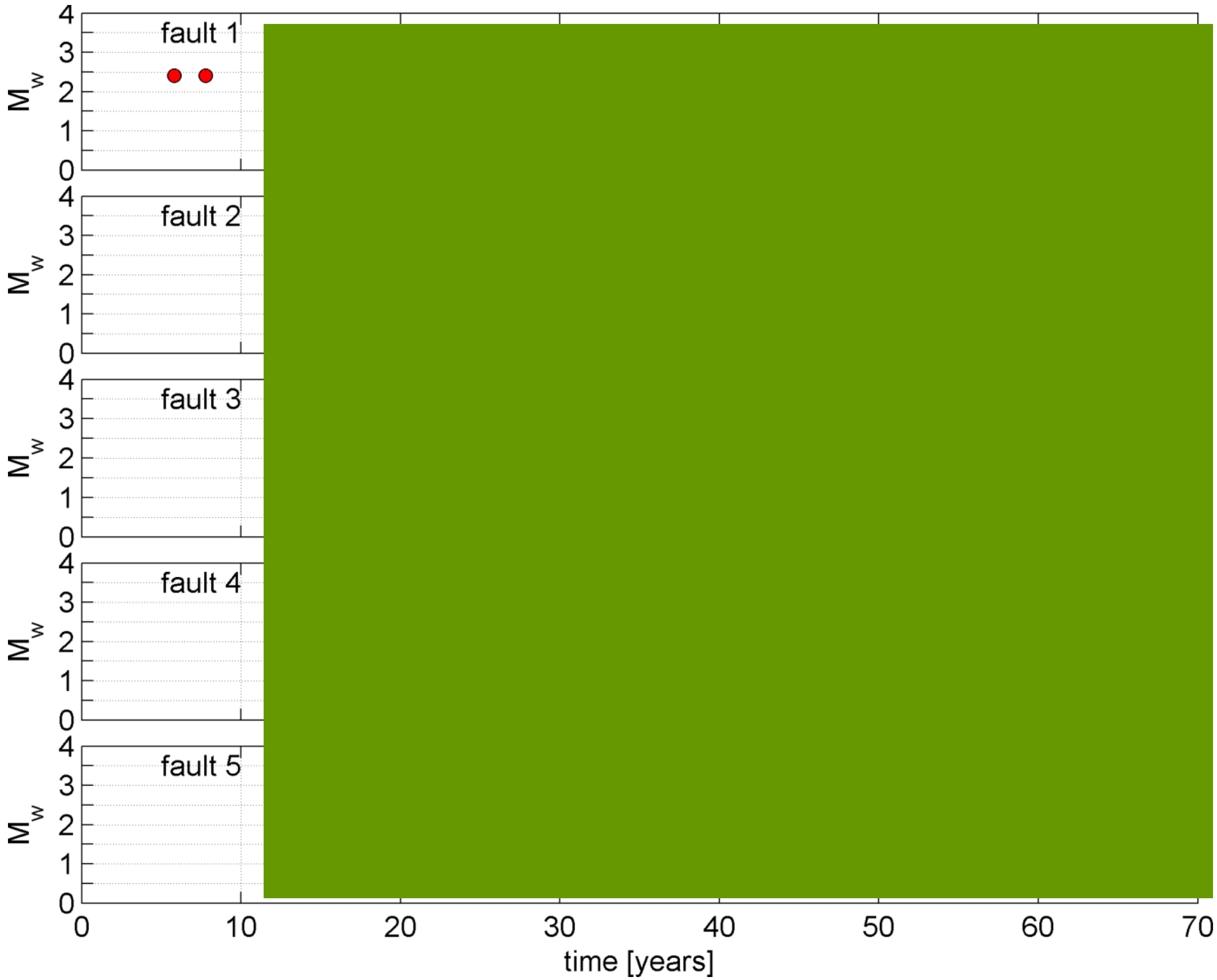
Dynamic Simulator

- Based on slider-block approach coupled with poroelastic FE simulator.
- Developed in the context of other geomechanical studies.
- Simple, physics-based models reproduce observed earthquake characteristics:

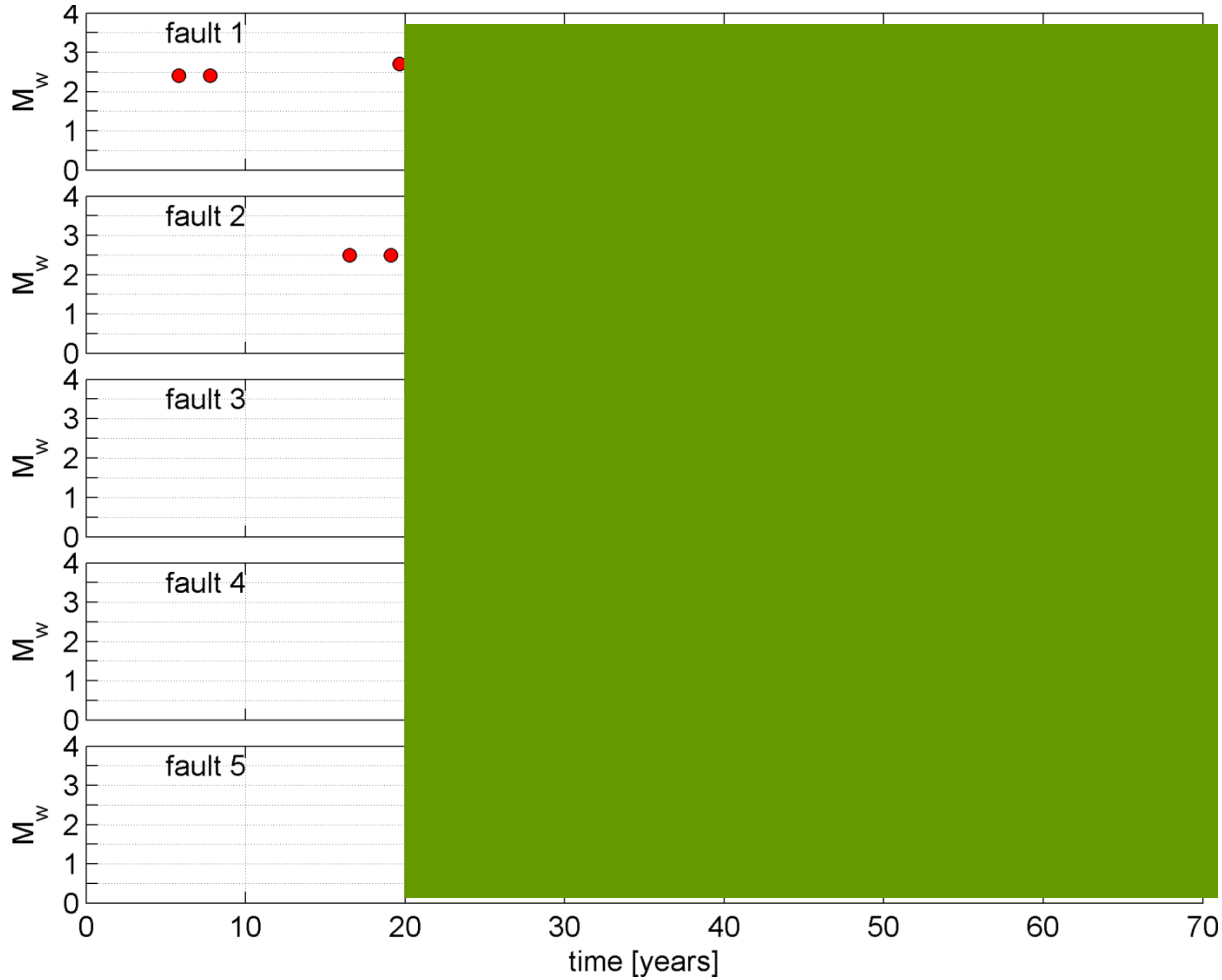


Consider a set of perfectly smooth Faults of different orientation in the same stress field.
Perform poroelastic simulations of homogeneous depletion.

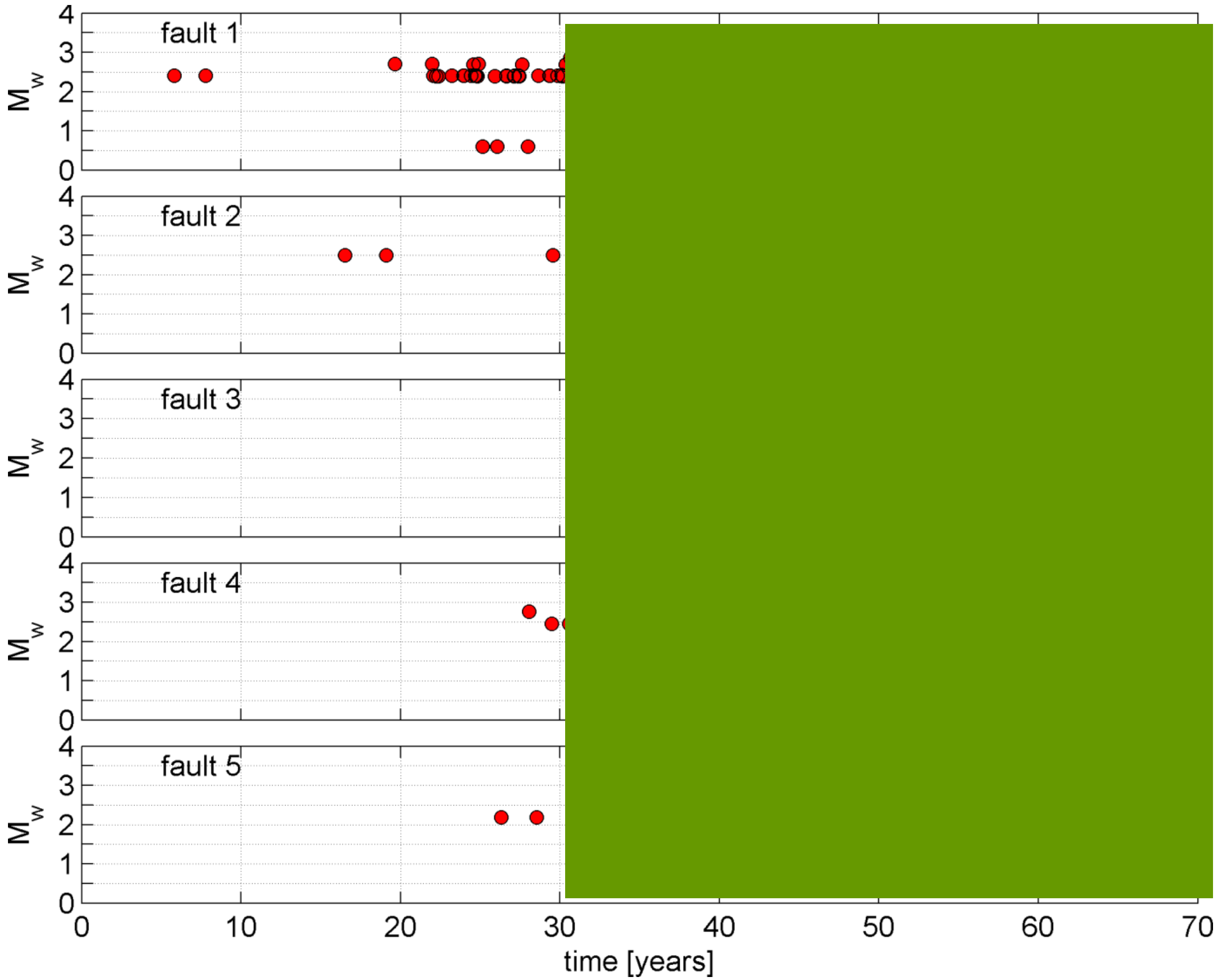
Dynamic Simulator



Dynamic Simulator



Dynamic Simulator



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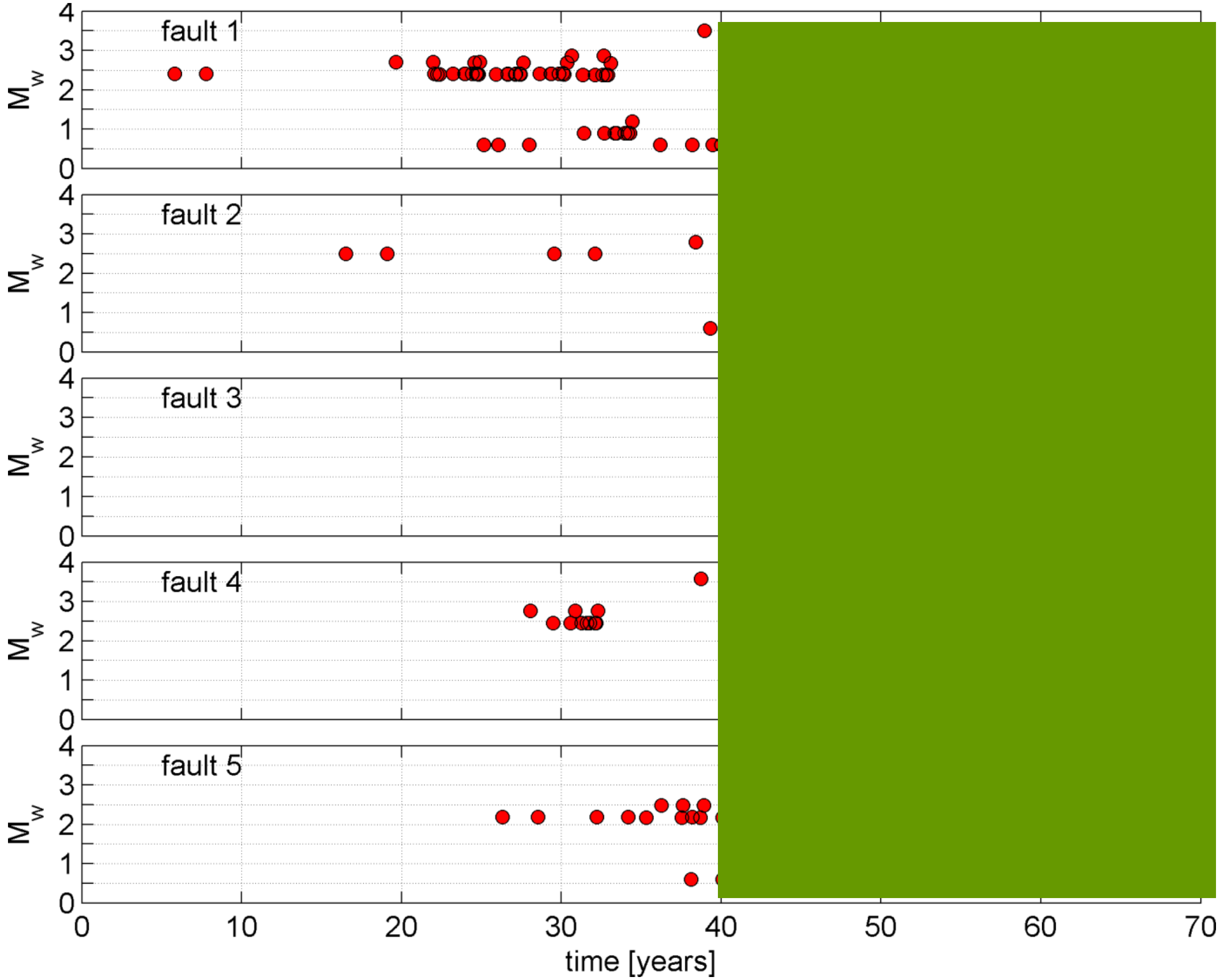
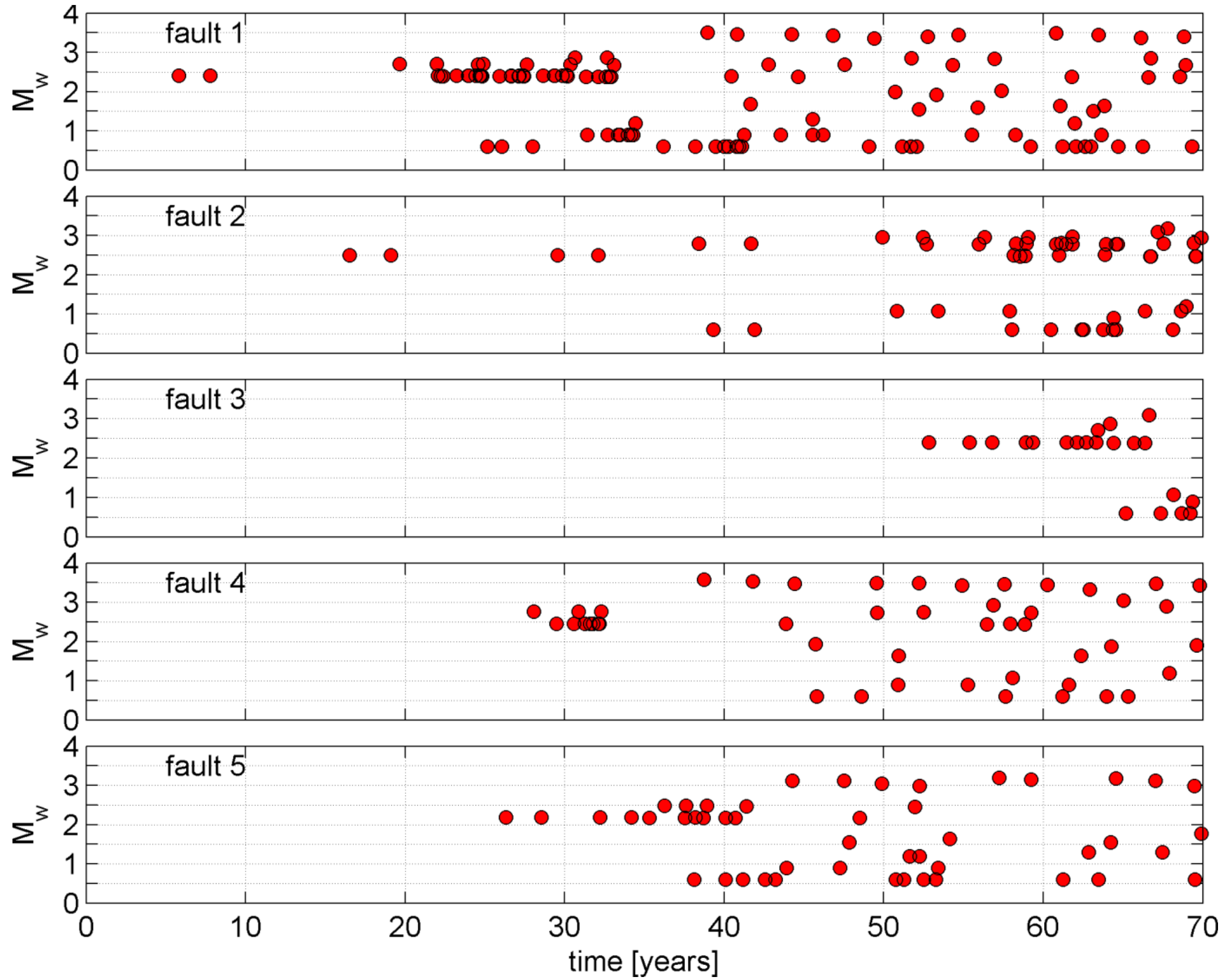


Dynamic Simulator



Further Research

What about Gutenberg-Richter?...