Physics-based, operational forecasting of production induced seismicity within the Groningen gas field

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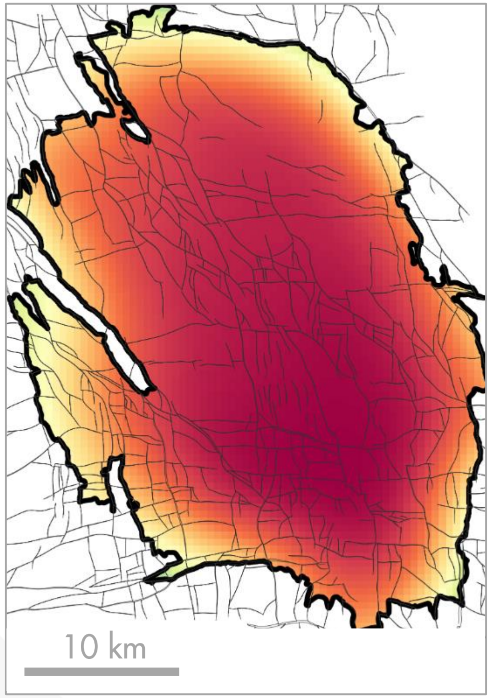
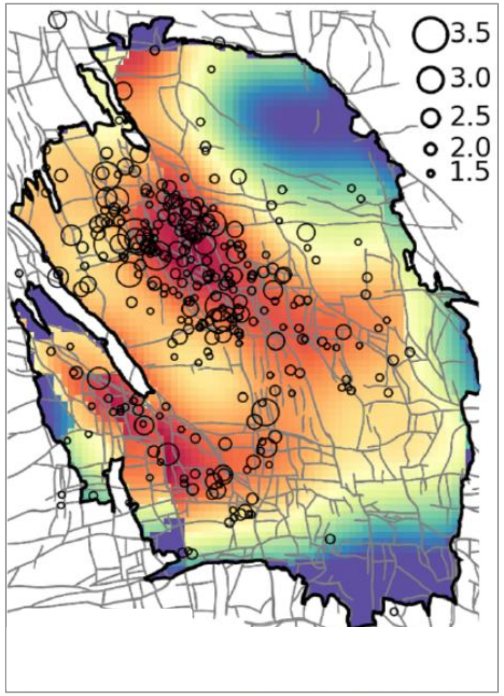
Groningen production induces depletion, seismicity, hazard, and risk

Depletion



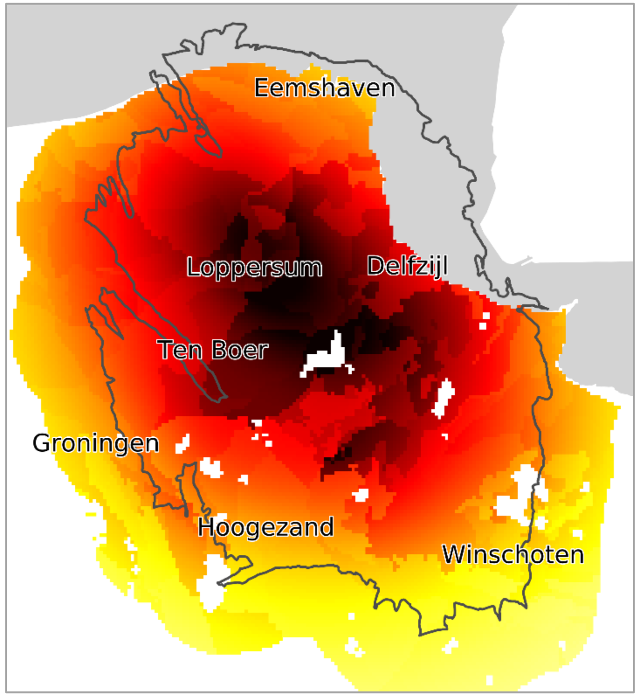
Uniform reservoir depletion reflects hydraulic connectivity

Seismicity



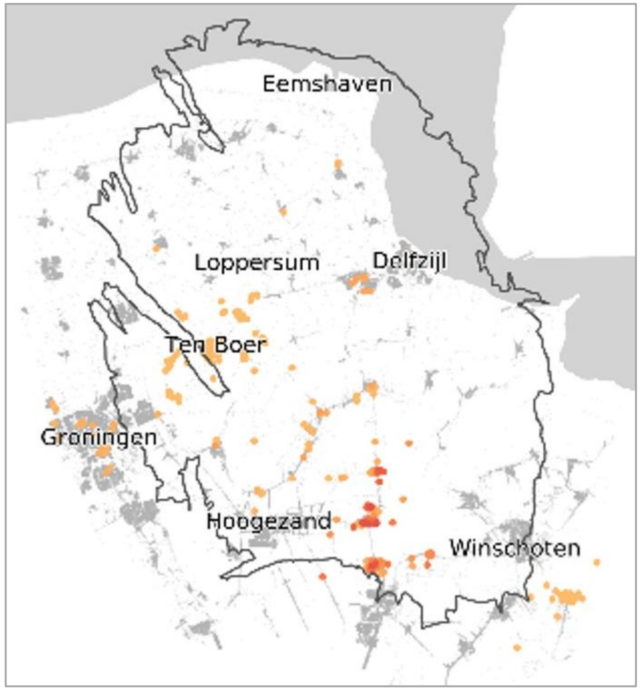
Heterogeneous reservoir seismicity reflects poroelastic Coulomb stress

Hazard



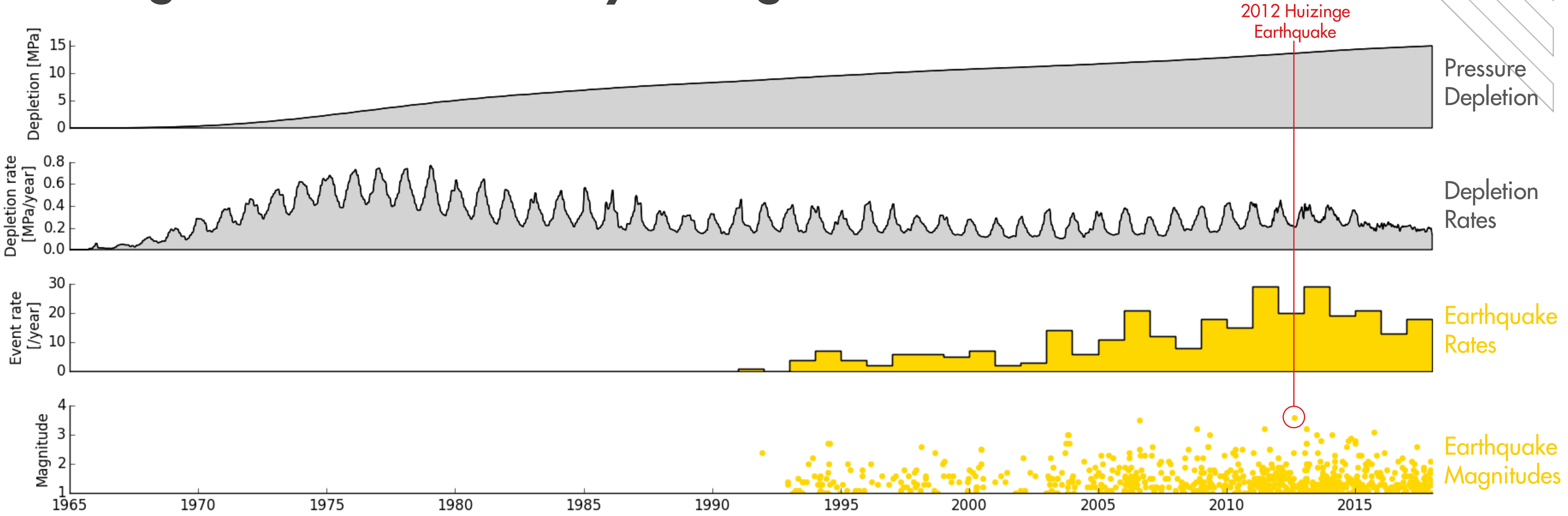
Heterogeneous ground motion hazard reflects seismicity and near-surface geology

Risk



Distributed risk clustering reflects building exposure to hazard

Groningen induced seismicity emerges over decades



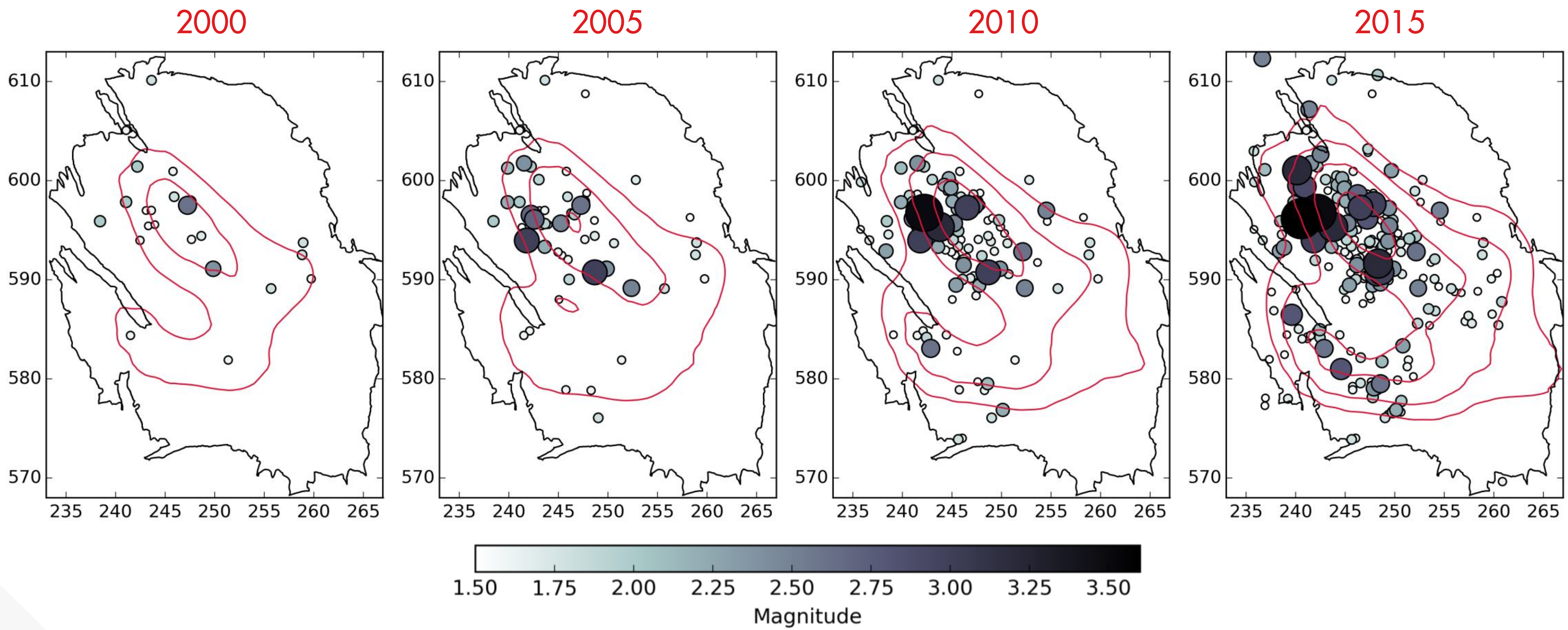
Induced seismicity increases slowly

- Earthquake rates *slowly* increased with time
- Earthquake magnitudes *slowly* increased with time

Expertise in producing gas not earthquakes

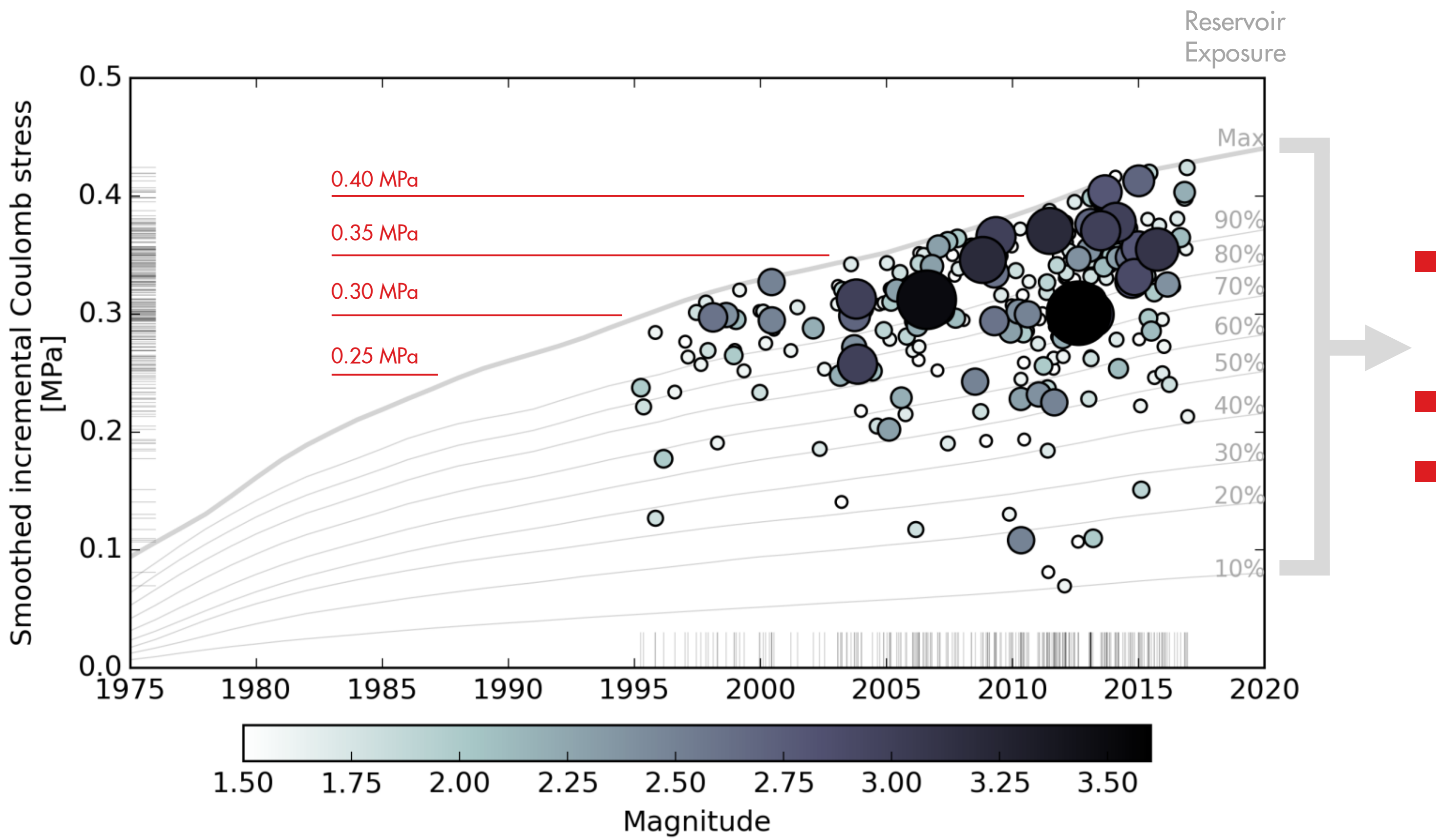
- Forecasting gas production is routine
- Forecasting earthquakes is *not* routine

Induced seismicity follows induced stress



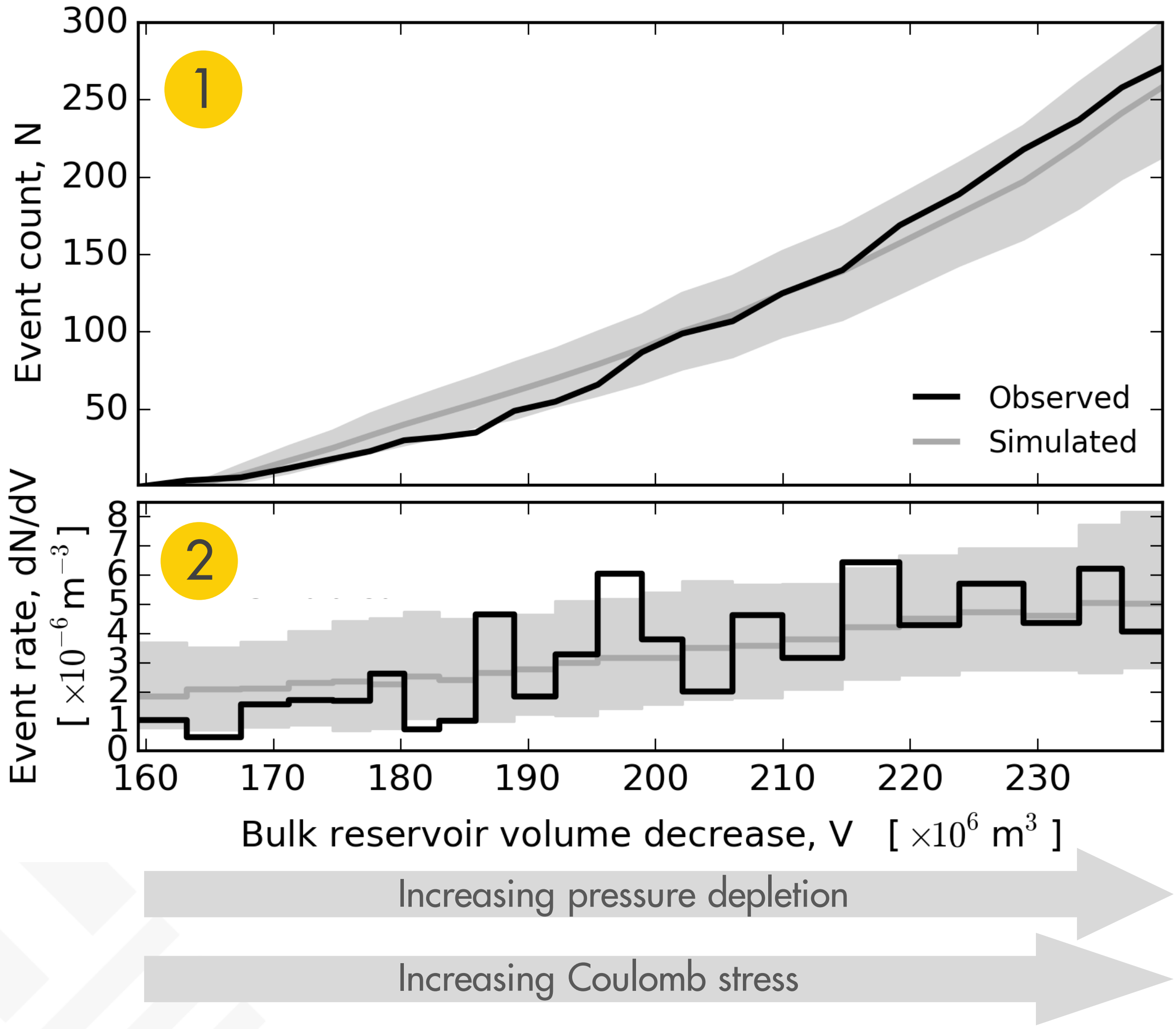
- Smoothed incremental Coulomb stress contours: 0.25, 0.30, 0.35, 0.40 MPa
- Earthquake rates and magnitudes appear to increase with incremental Coulomb stress

Induced seismicity *mostly* follows induced stress



- Significant variability of induced stress at the time and location of induced earthquakes
- Earthquakes more likely at higher stresses
- Larger magnitudes more likely at higher stresses

An exponential rise of induced seismicity with induced stress



Observations

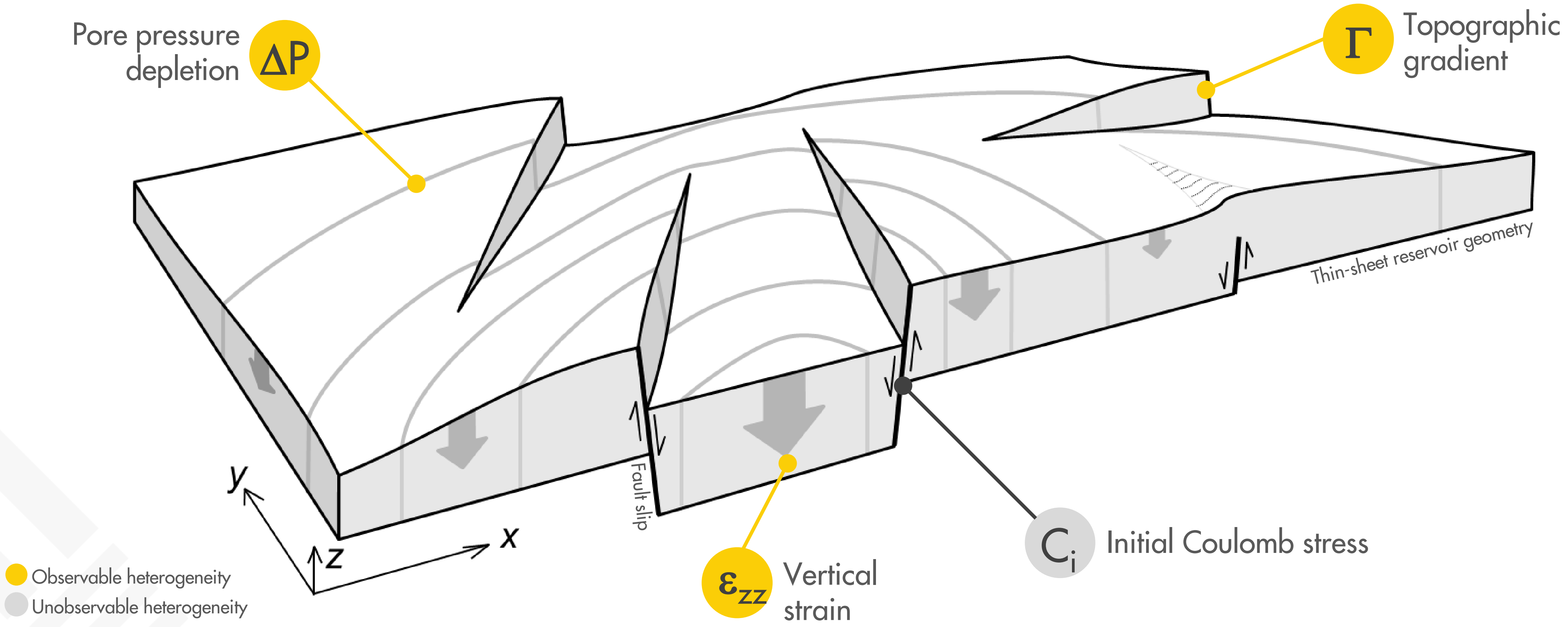
1. Numbers increase exponential-like with cumulative production
2. Numbers per unit gas production increases steadily

Interpretation

- Fault reactivations increase exponentially with increasing stress
- Fault strength is a highly-variable & disordered system
- Statistical trends emerge from large disordered systems

A simple, fast, probabilistic, reservoir stress model

Poroelastic thin-sheet with Coulomb faults

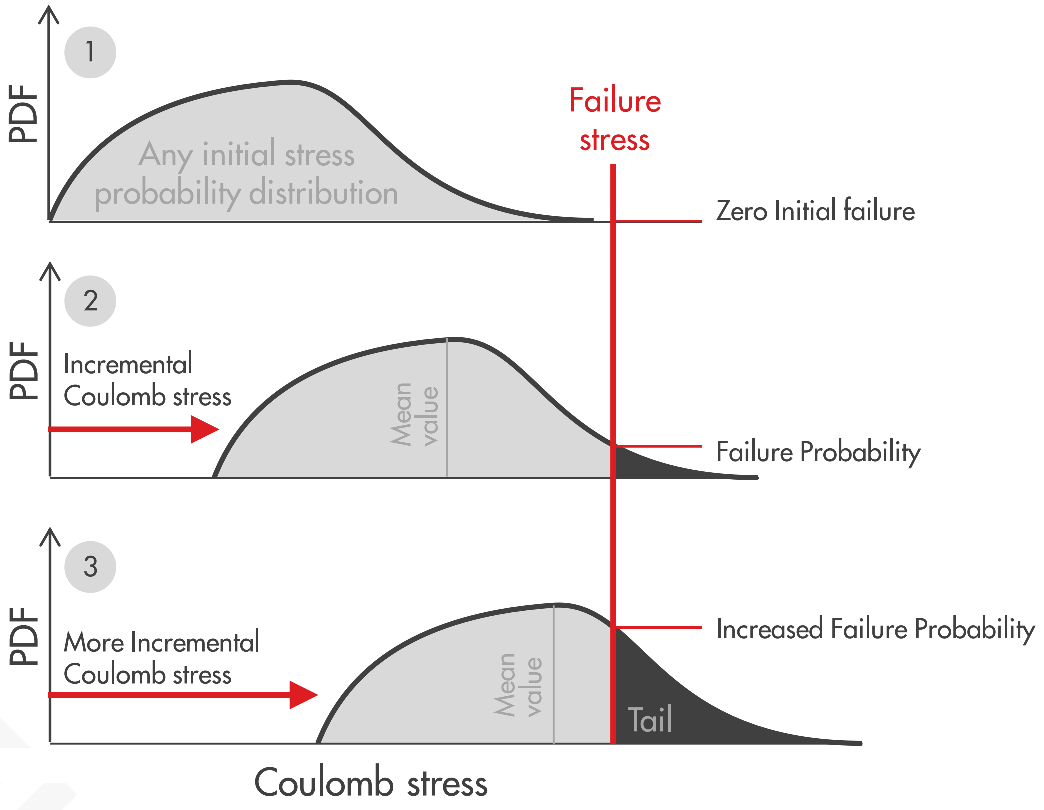


Bourne & Oates, 2017 (http://dx.doi.org/10.1002/2017JB014356)

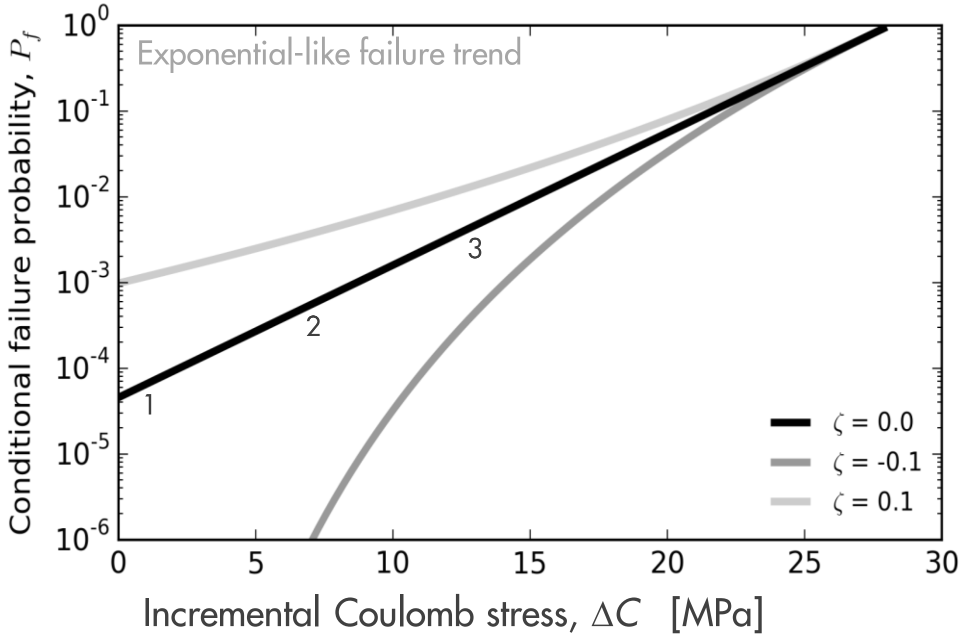
Fault Reactivation is an Extreme Threshold Failure process

Not a Mean Value Failure process

Failure Probability



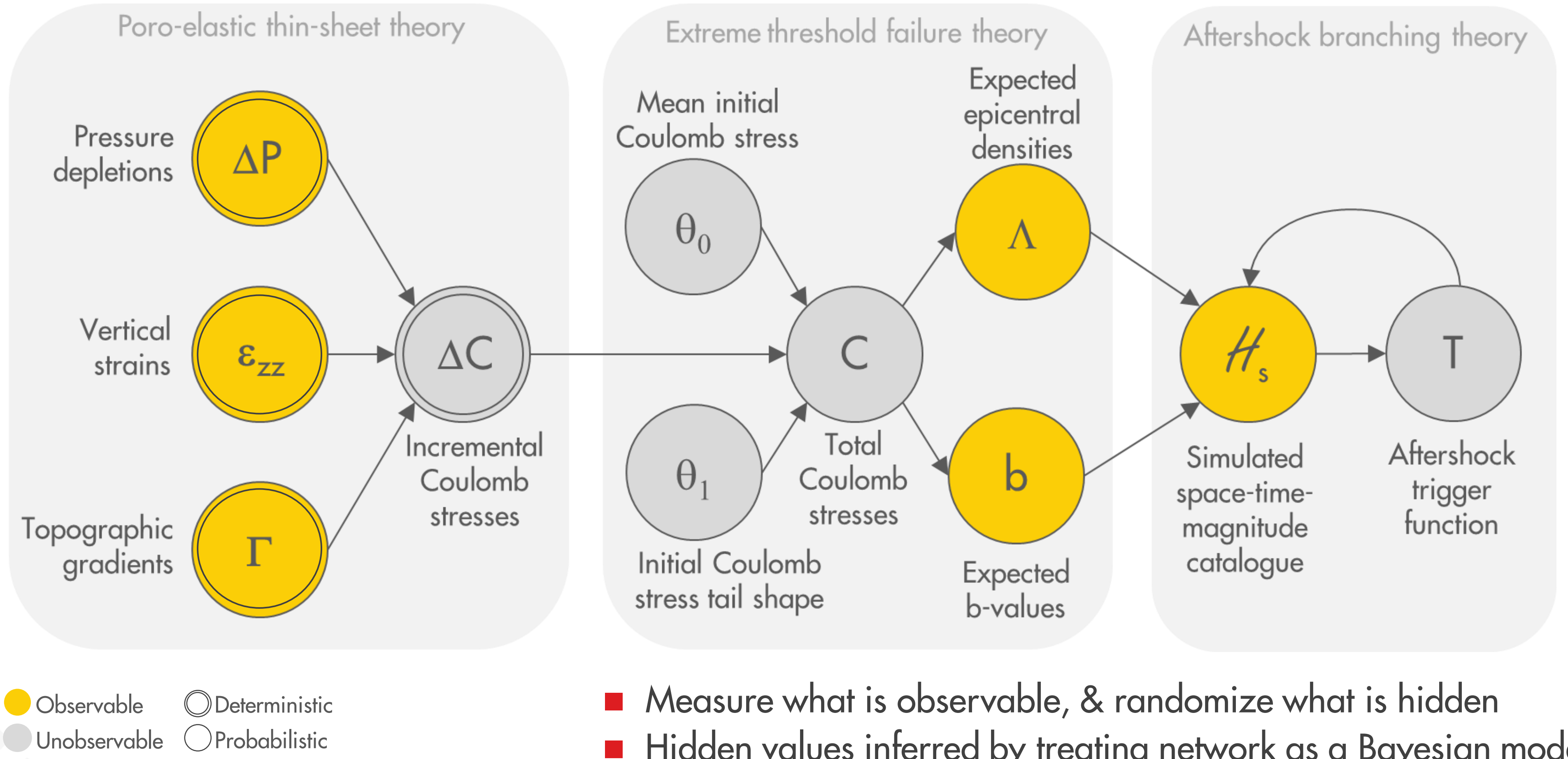
Extreme Threshold Theory



- Tail of the initial stress distribution fails first
- All probability tails follow Extreme Threshold Theory
- Mean value failure criteria are systematically optimistic

Bourne & Oates, 2017 (http://dx.doi.org/10.1002/2017JB014356)

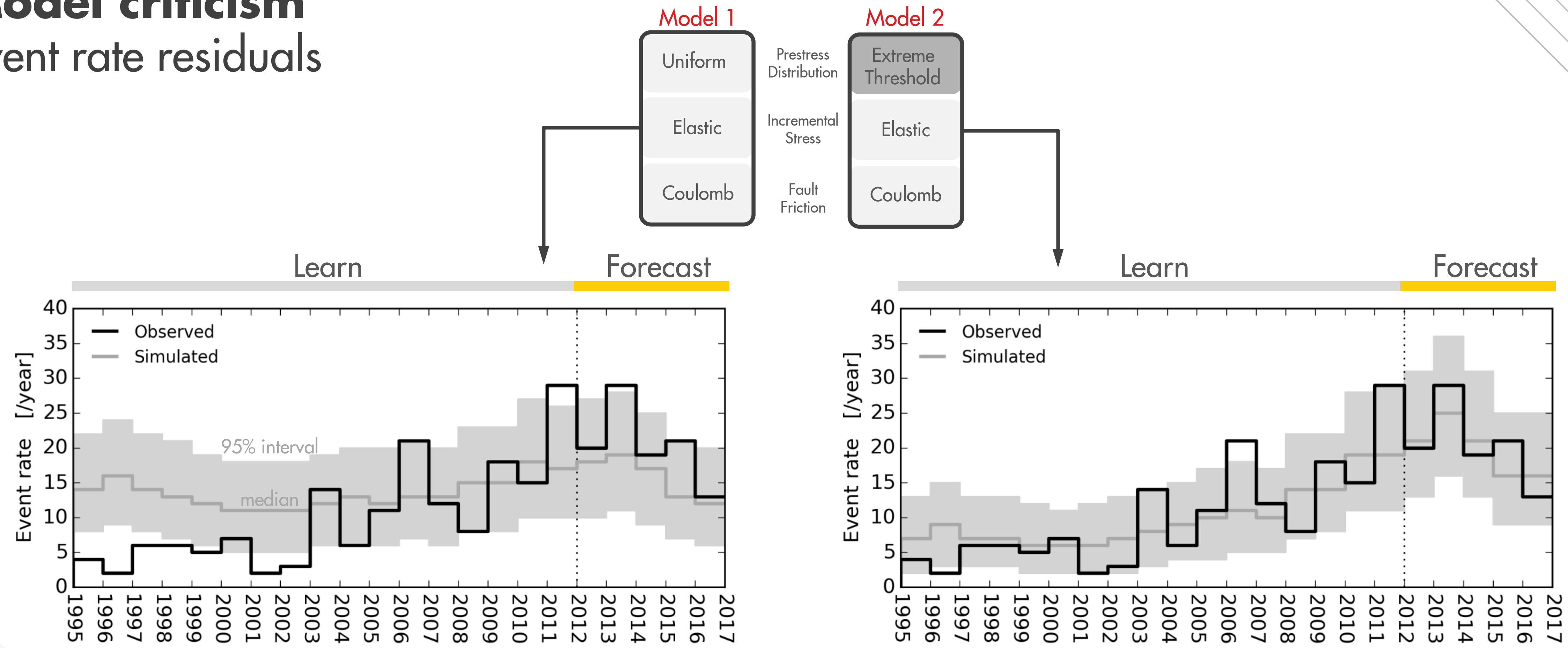
Seismological model as a probability network of physical processes



- Measure what is observable, & randomize what is hidden
- Hidden values inferred by treating network as a Bayesian model
- Yields ensemble of history-matched models

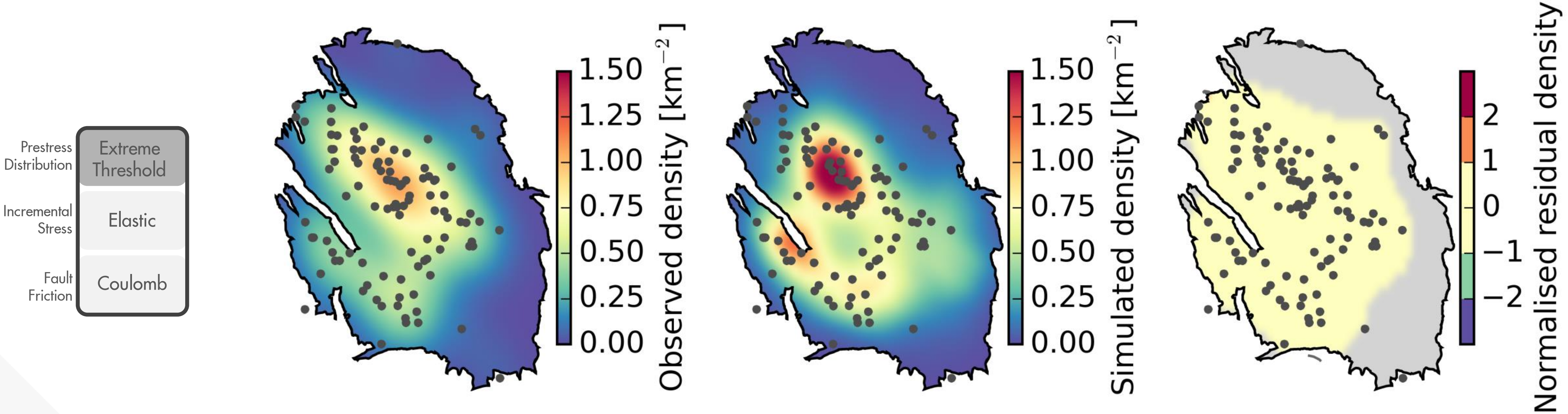
Model criticism

Event rate residuals



- Model 1: Uniform Prestress Distribution insufficient to describe increasing event rates from1995 to 2012
- Model 2: Exponential Extreme Threshold Failure trend improves performance over the learning and forecast periods

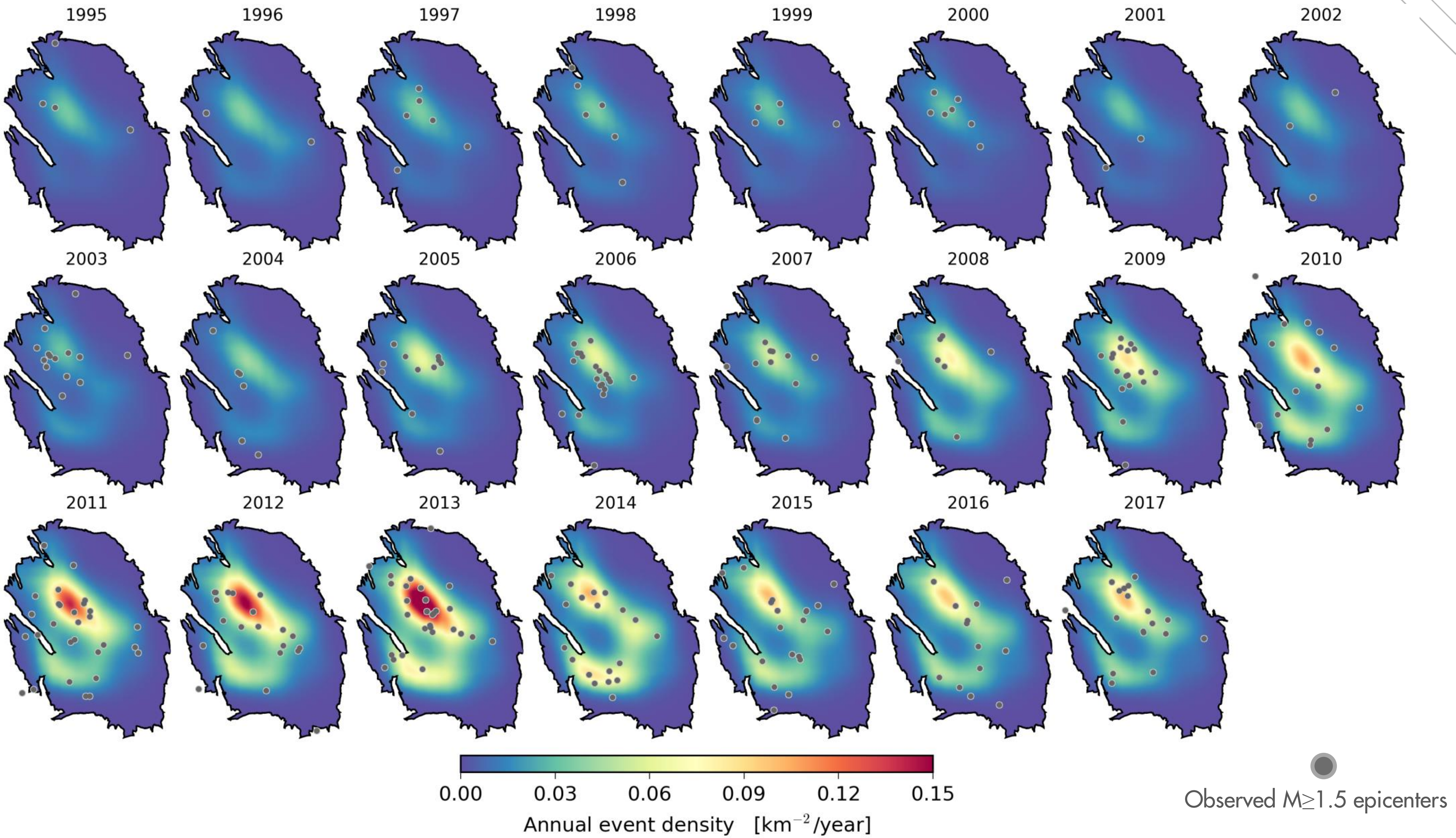
Model criticism
Epicentral density residuals

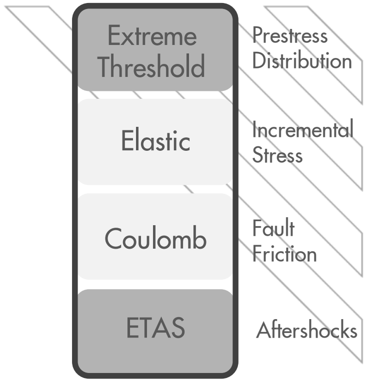


- Learning period: 1995 to 2012
- Forecast period: 2012 to 2017
- Extreme Threshold Failure model forecasts observed spatial density within stochastic variability

Expected epicentral density maps given history matched models

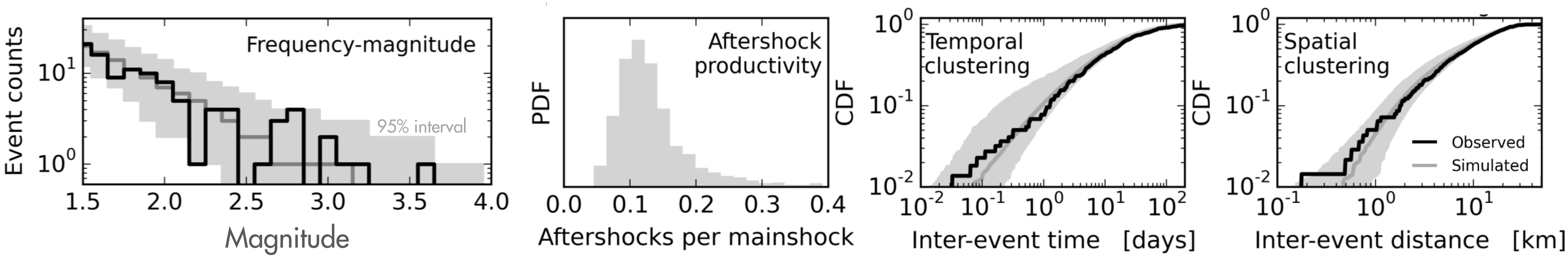
Prestress Distribution	Extreme Threshold
Incremental Stress	Elastic
Fault Friction	Coulomb





Model criticism

Magnitude distribution and aftershock clustering residuals

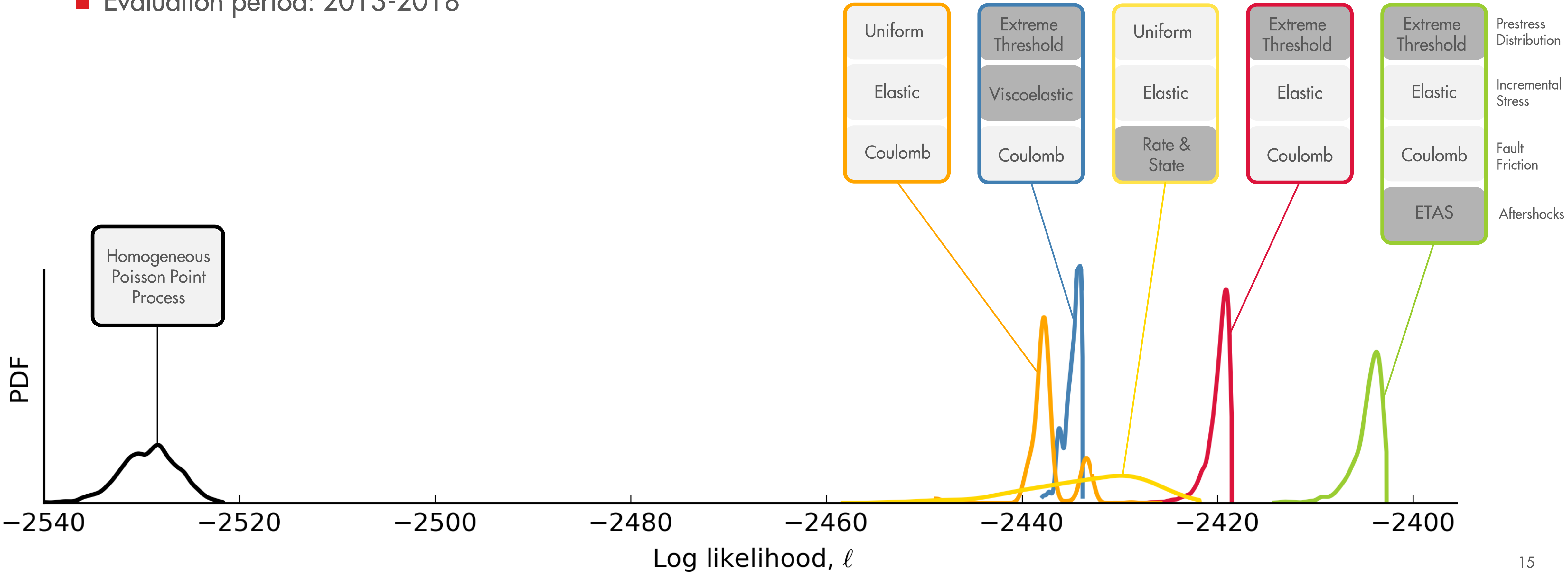


- Learning period: 1995 to 2012
- Forecast period: 2012 to 2017
- Epidemic Type Aftershock model forecasts magnitudes and aftershocks consistent with observed trends and variabilities
- 10-20% of observed earthquakes are aftershocks triggered by small stress transients induced by prior earthquakes

Bourne, Oates, van Elk, 2018 (https://doi.org/10.1093/gji/ggy084)

Blind forecast performance analysis

- Performance metric: Likelihood of observed events given the model
- Learning period: 1995-2013
- Evaluation period: 2013-2018



Summary

- Established a minimum physics-based theory for fault reactivation & induced seismicity with Groningen
- Pore-elastic thin-sheet theory
  - Computes smoothed incremental Coulomb stress according to resolvable geometric and elastic heterogeneities
- Extreme thresholds failure theory
  - Computes induced seismicity rates according to incremental Coulomb stress and the extremes of initial Coulomb stress
  - Computes the frequency-magnitude distribution and its dependence on incremental Coulomb stress
- Bayesian inference for hidden variables
  - Ensemble of realizations for each seismological model
  - Family of alternative seismological models represent different types of reservoir heterogeneity
- Model performance
  - Out-of-sample forecast testing provides objective performance ranking of alternative models
  - Analysis of residuals characterizes sources of poor model performance