

Statistical mechanics-based forecasting of induced seismicity magnitudes within the Groningen gas field

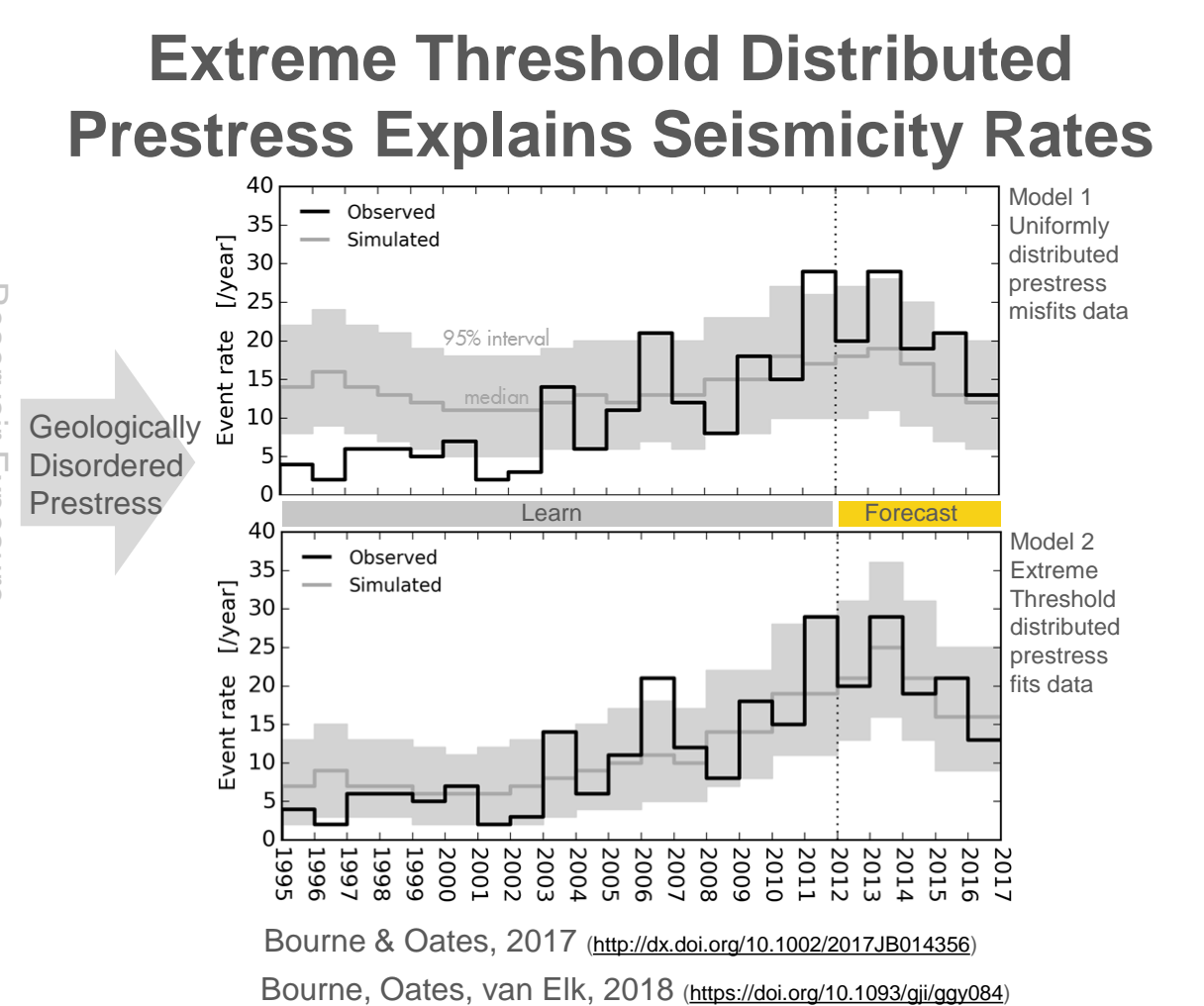
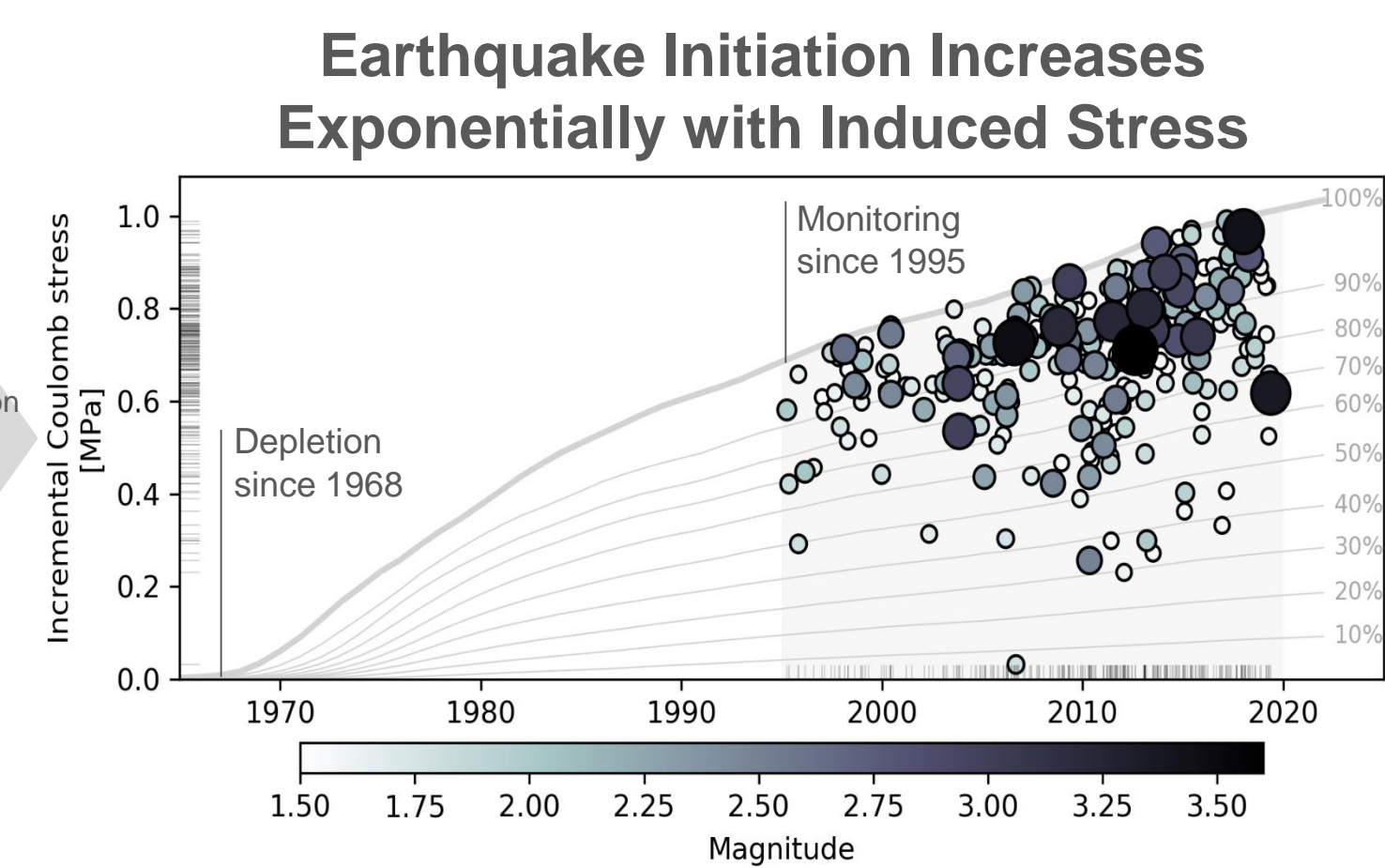
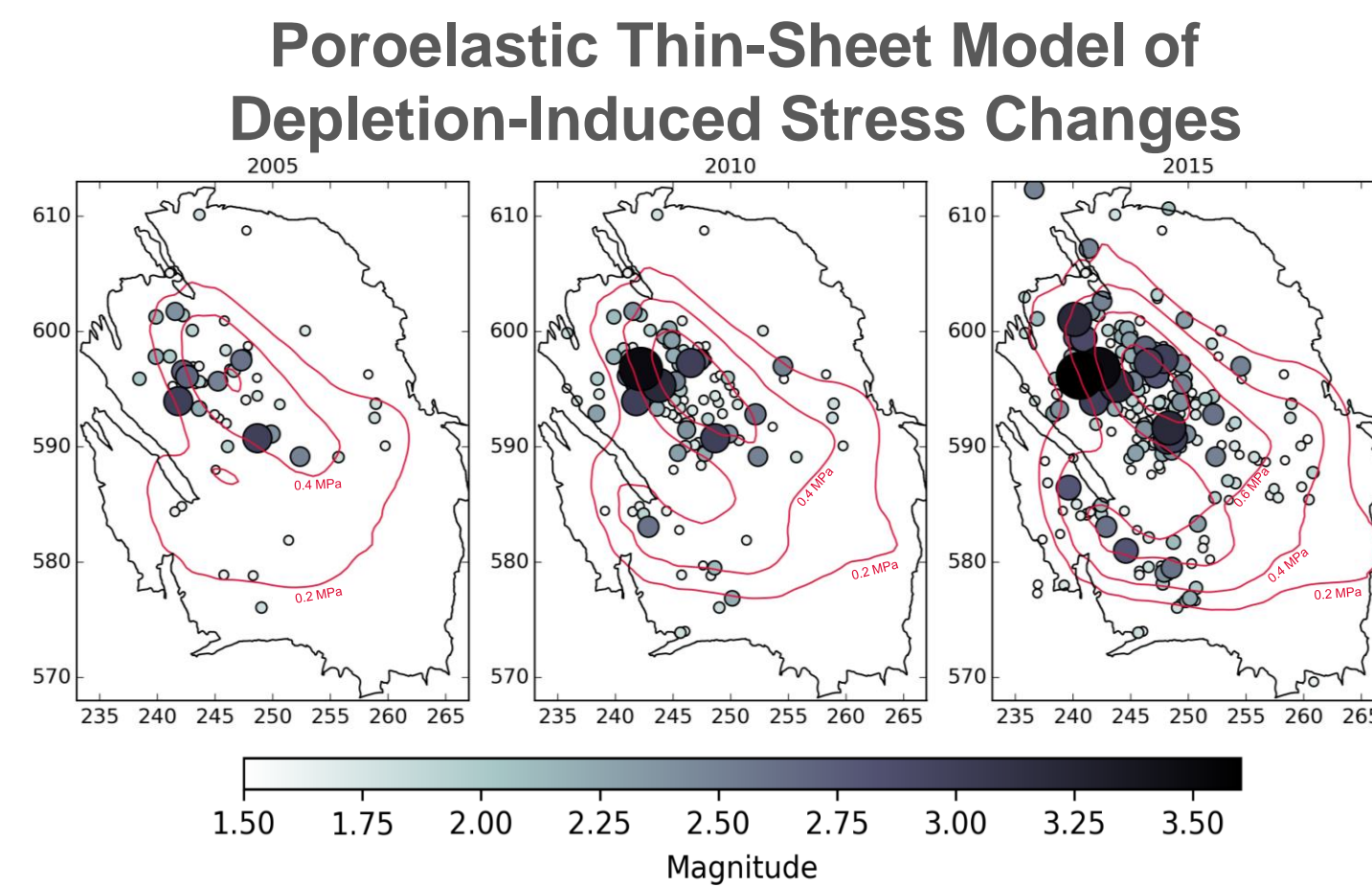


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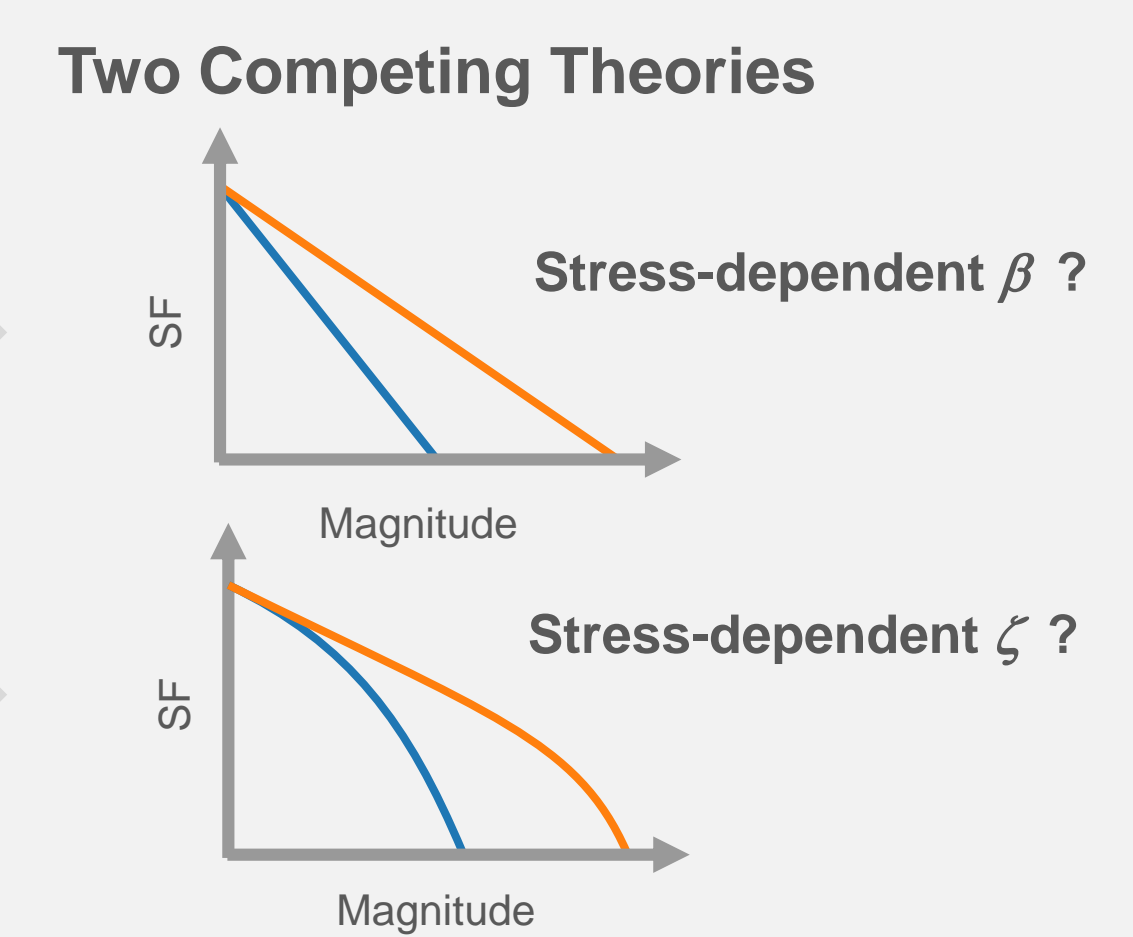
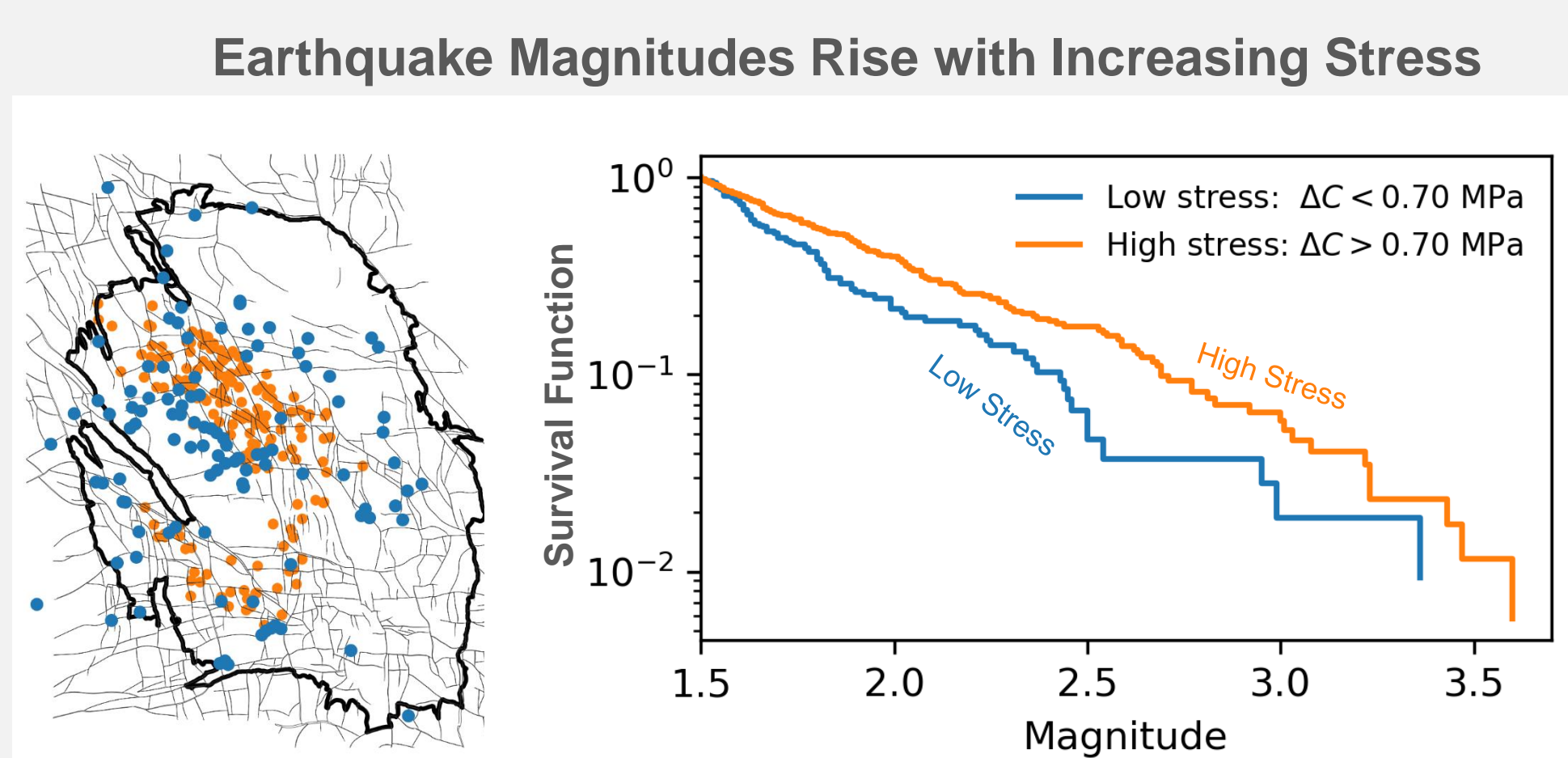
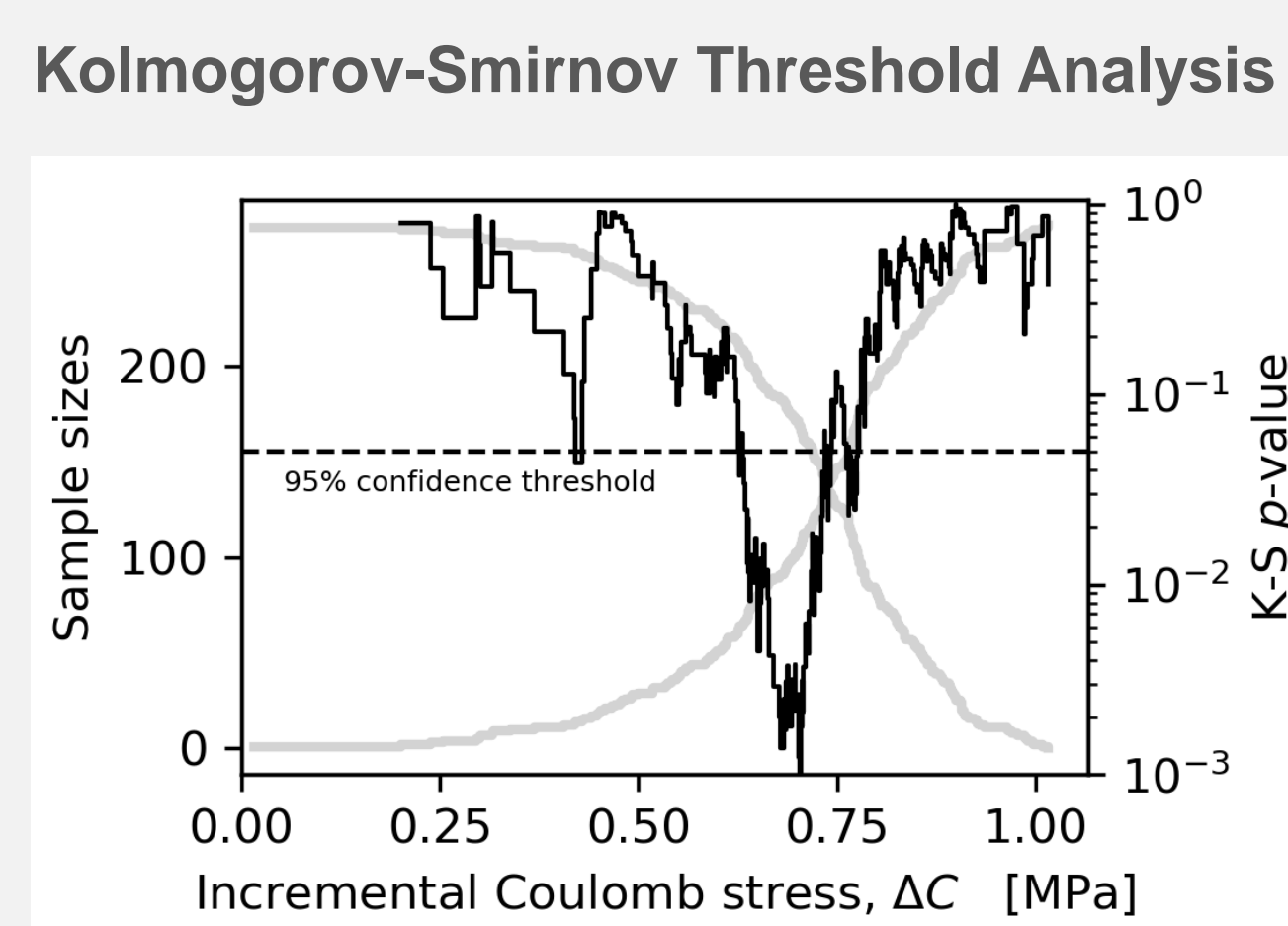
Summary

- Geological faults are vulnerable to frictional failure, and induced seismicity under rising stress loads due to hydrocarbon recovery or CO₂ storage.
- Risks to containment of subsurface fluids and to the integrity of the built environment critically depends on earthquake magnitudes.
- Statistical geomechanics motivates modifying the standard power-law magnitude distribution to include a stress-dependent exponential taper.
- Under Bayesian inference these physics-based statistical models improve fault re-activation forecasts & greatly lower expected seismic risks.

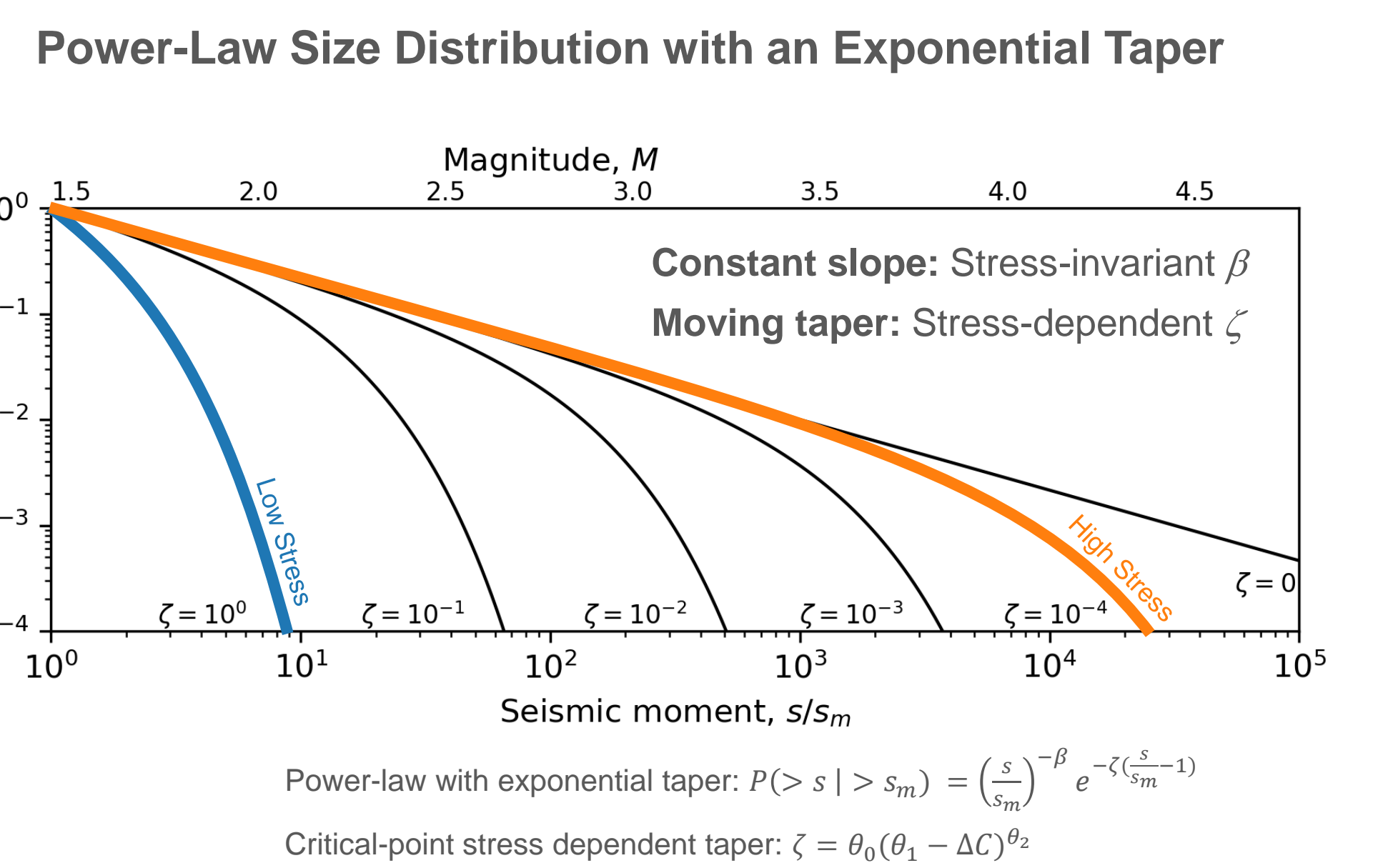
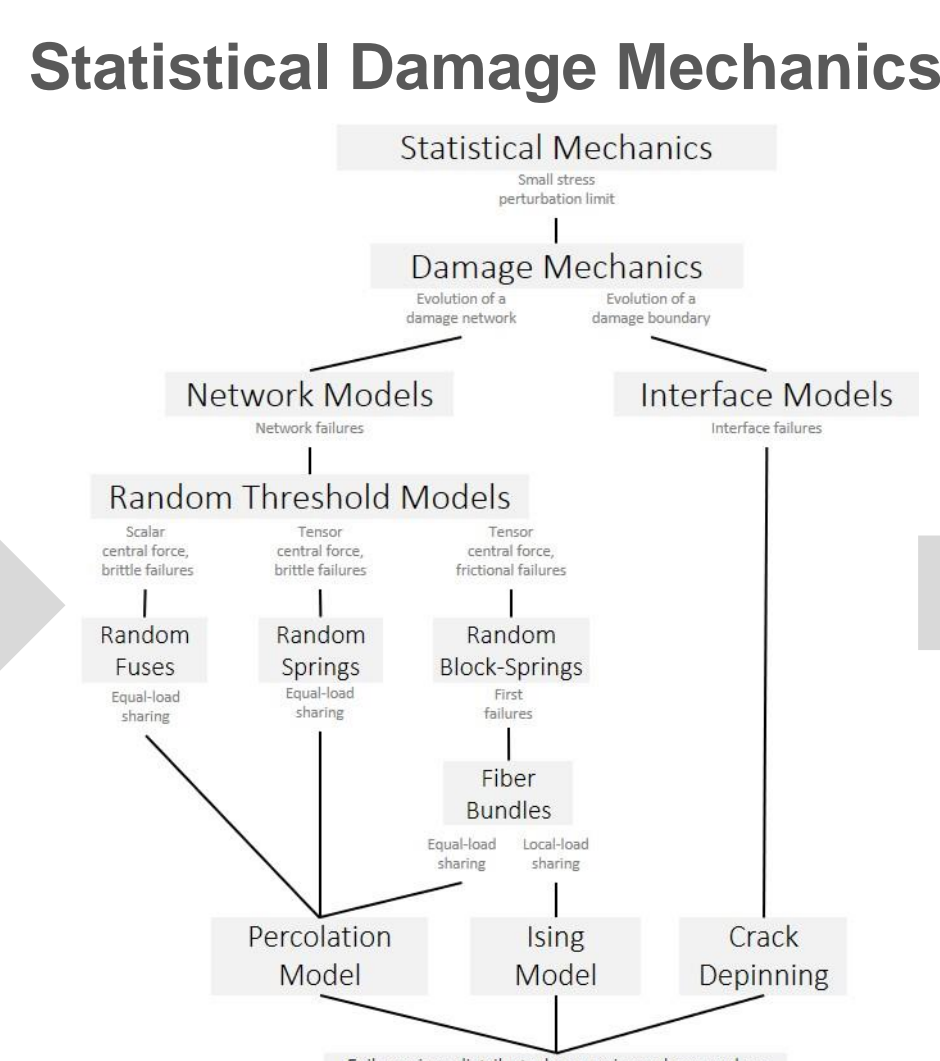
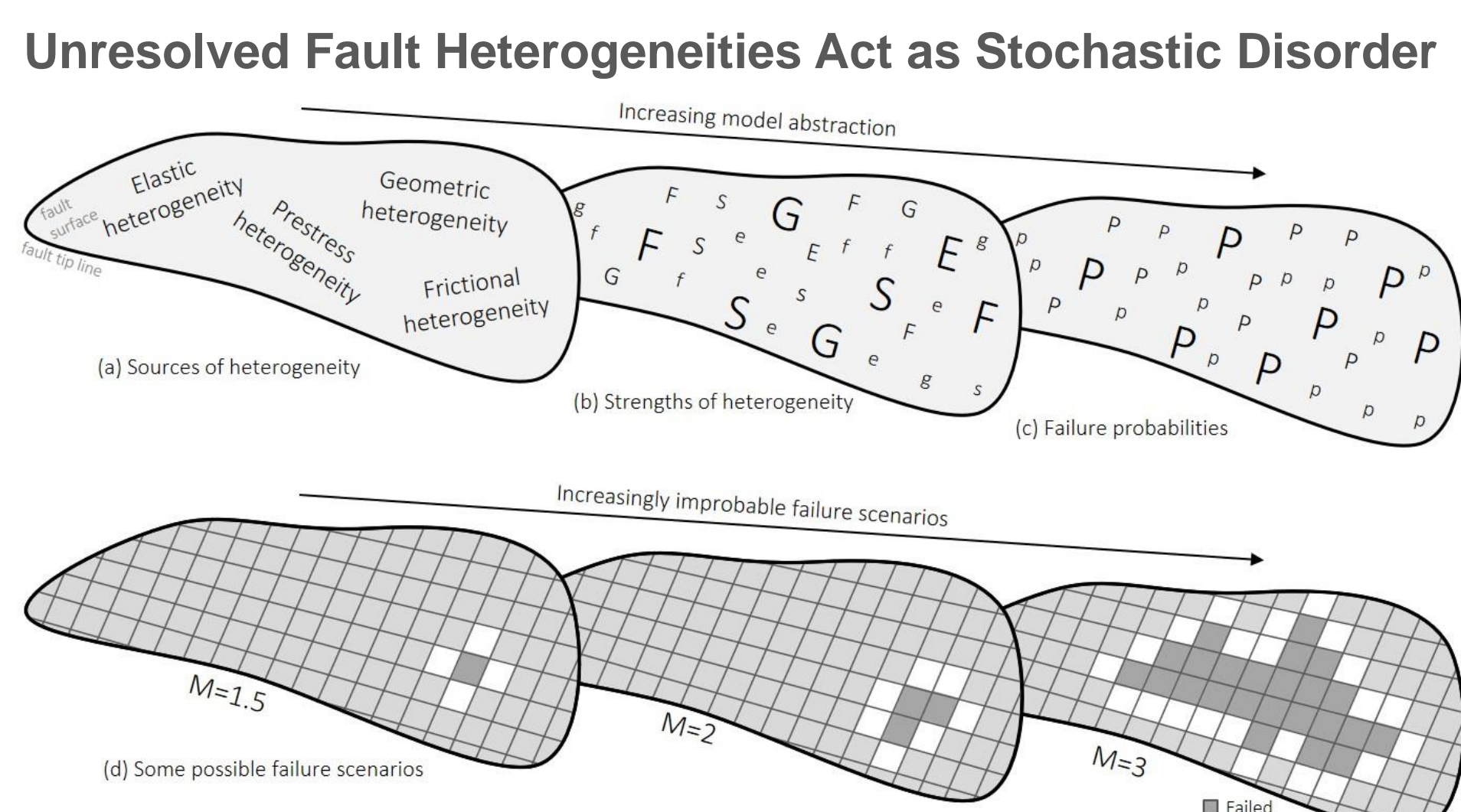
Induced Stresses & Earthquake Occurrences



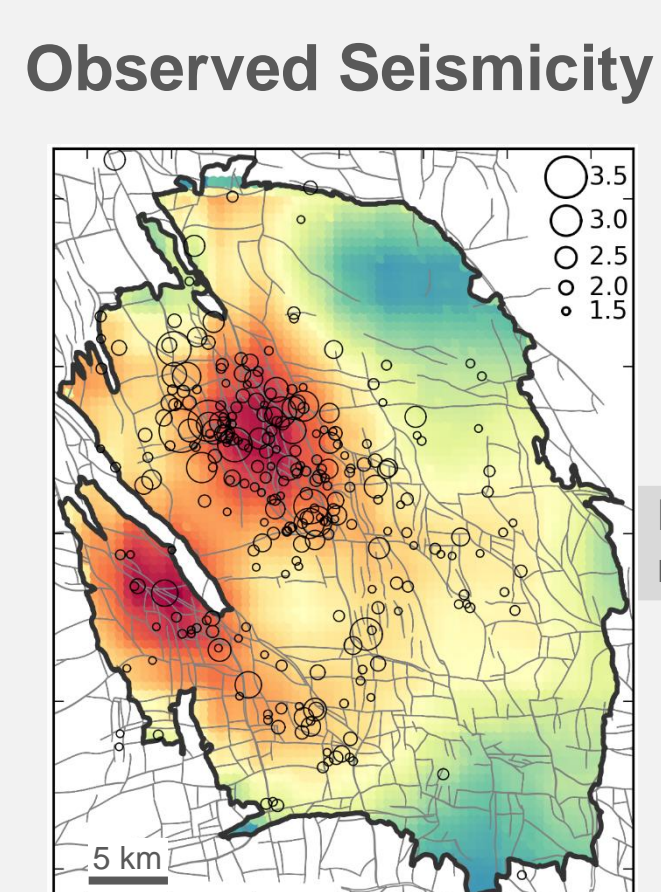
Observed magnitude distribution is also stress-sensitive



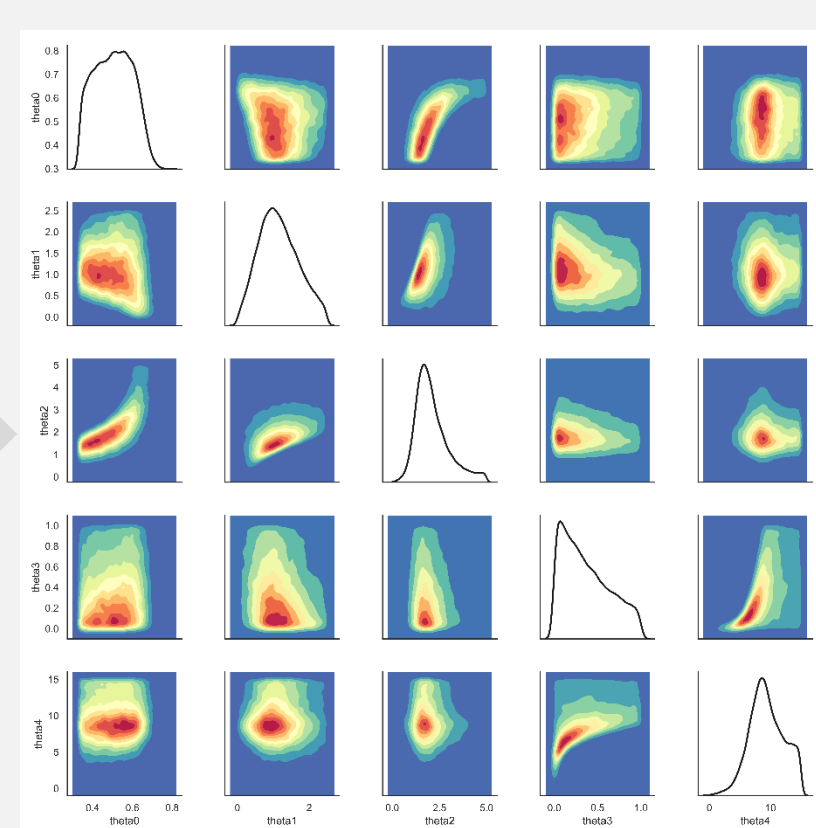
Statistical mechanics of disordered fault re-activation



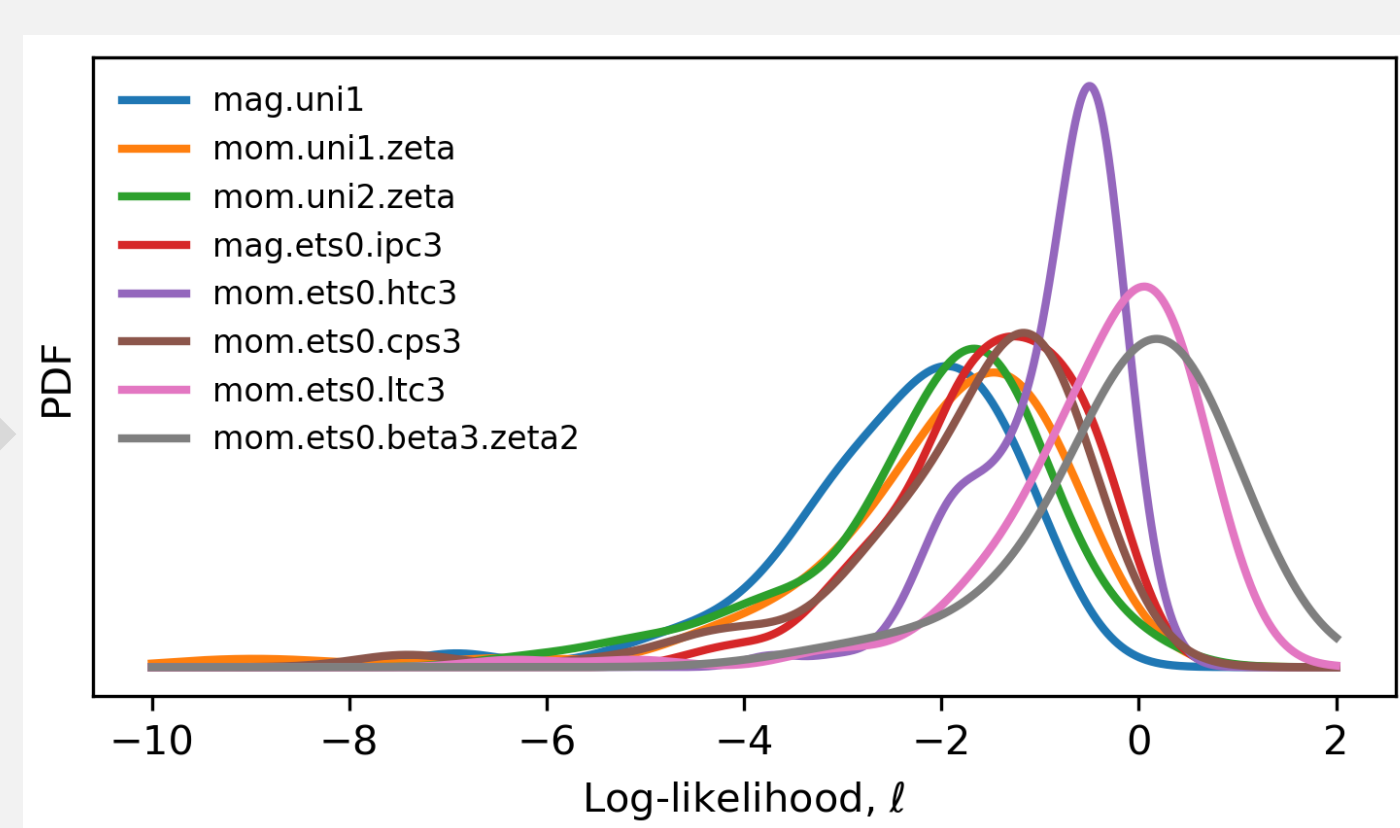
Forecast performance favours stress-dependent ζ models



Bayesian Inference



Out-of-sample Posterior Predictive Analysis



Model Ranking

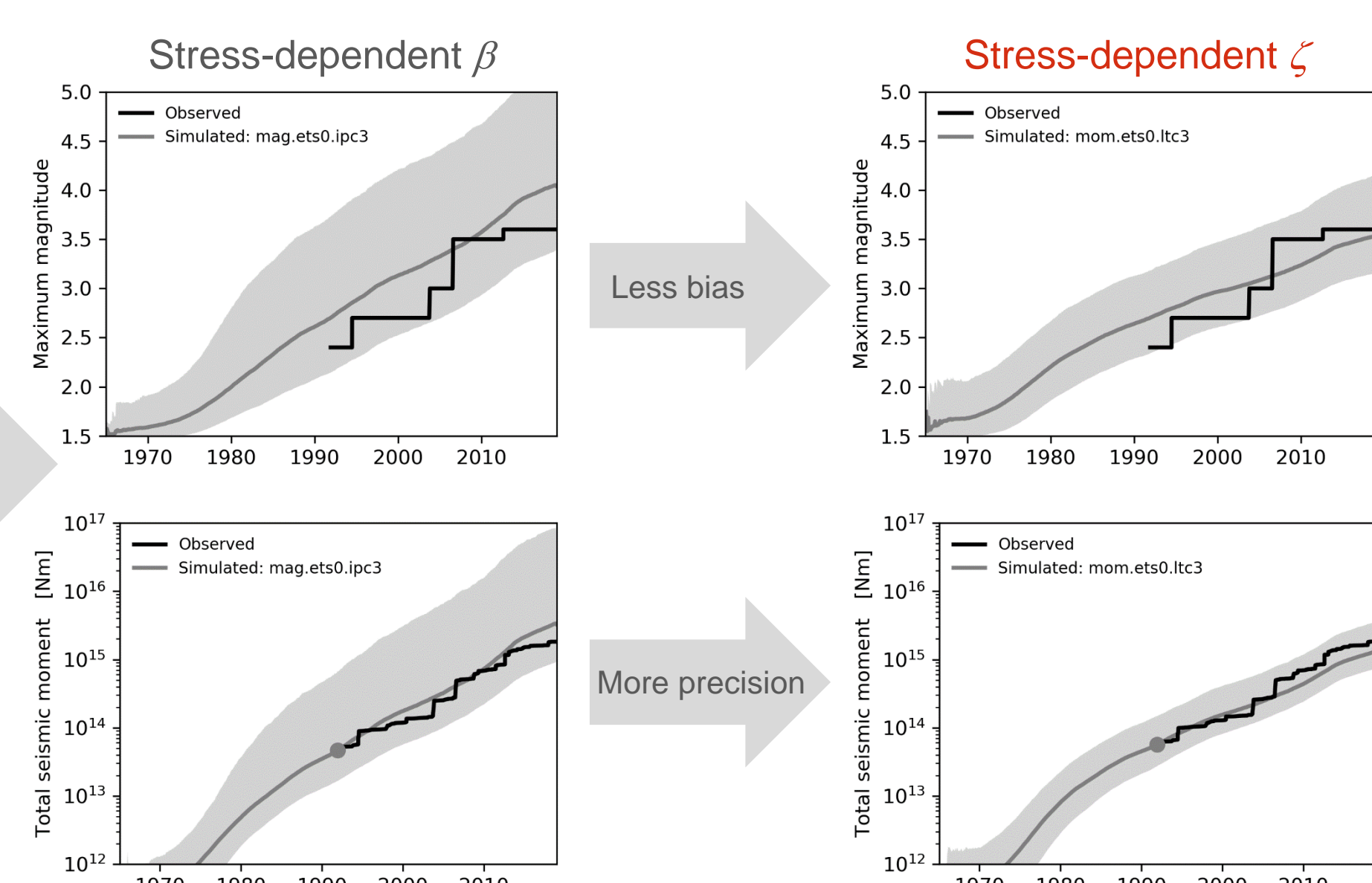
Model class	M _i	P _{ij} Probability of M _i out-performing M _j											
Stress invariant	uni1 M ₁	0.500	0.400	0.370	0.283	0.091	0.343	0.060	0.060				
	uni1.zeta M ₂	0.600	0.500	0.580	0.374	0.192	0.424	0.110	0.080				
	uni2.zeta M ₃	0.630	0.420	0.500	0.364	0.162	0.394	0.110	0.120				
Stress-dependent β	ets0.ipc3 M ₅	0.717	0.626	0.636	0.500	0.273	0.576	0.152	0.111				
	ets0.htc3 M ₇	0.909	0.808	0.838	0.727	0.500	0.727	0.253	0.192				
Stress-dependent ζ	ets0.cps3 M ₁₀	0.657	0.576	0.606	0.424	0.273	0.500	0.141	0.121				
	ets0.ltc3 M ₁₁	0.940	0.890	0.890	0.848	0.747	0.859	0.500	0.400				
Stress-dependent β-ζ	ets0.b3.z2 M ₁₃	0.940	0.920	0.880	0.889	0.808	0.879	0.600	0.500				
		M ₁	M ₂	M ₃	M ₅	M ₇	M ₁₀	M ₁₁	M ₁₃				

Outcomes

Improved models

- Disordered fault failure is a stochastic process
- Statistical mechanics constrains this process
- Bayesian inference allows data-driven learning
- Million models out-perform single models
- Worst** models: Stress-invariant distributions
- Better** models: Stress-dependent β-values
- Best** models: Stress-dependent ζ-values

Better forecasts



Lower seismic hazard

