



Royal Netherlands
Meteorological Institute
*Ministry of Infrastructure and the
Environment*

PSHA for seismicity induced by gas extraction in the Groningen Field

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Groningen Field

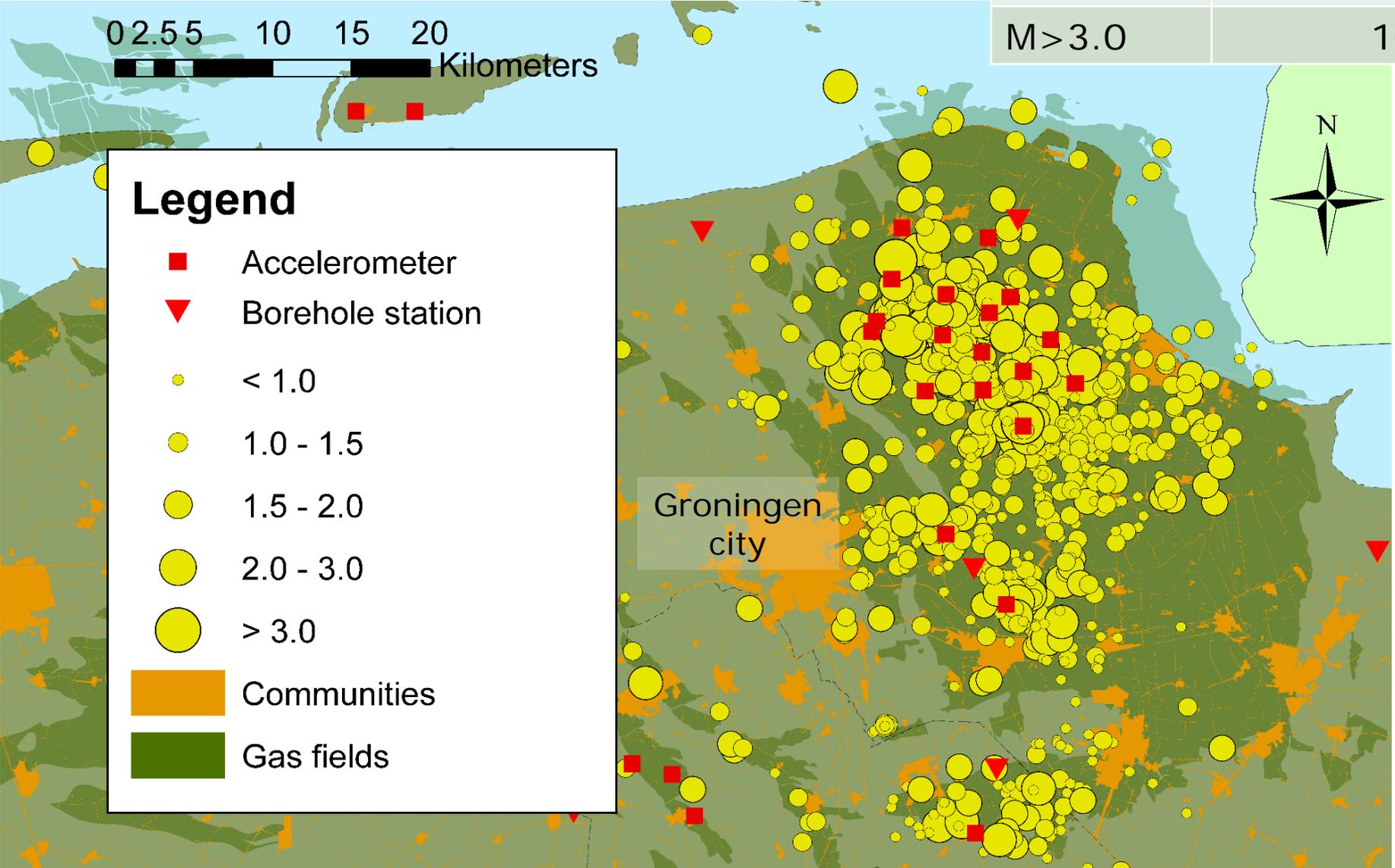
| | # events |
|---------|----------|
| Total | 815 |
| M > 1.5 | 251 |
| M > 3.0 | 10 |

0 2.5 5 10 15 20
Kilometers

Legend

- Accelerometer
- ▼ Borehole station
- < 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 3.0
- > 3.0
- Communities
- Gas fields

Groningen
city



Groningen Field

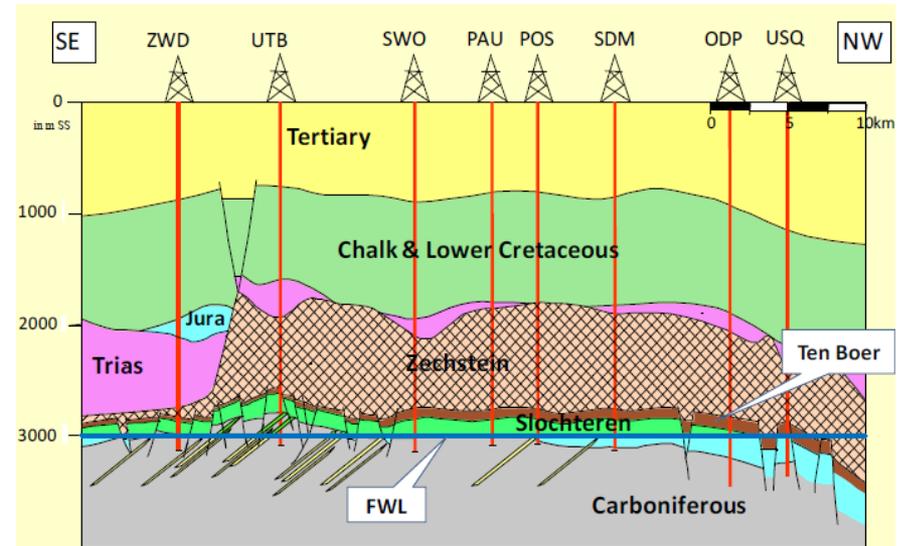


Figure: NAM

- Main driver: reservoir compaction due to pressure reduction

- Mechanism: earthquakes on existing faults due to "differential compaction"

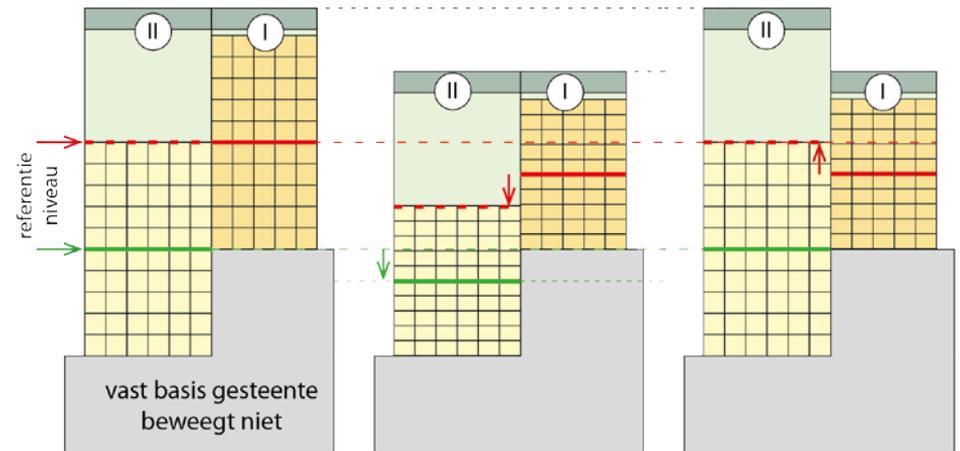
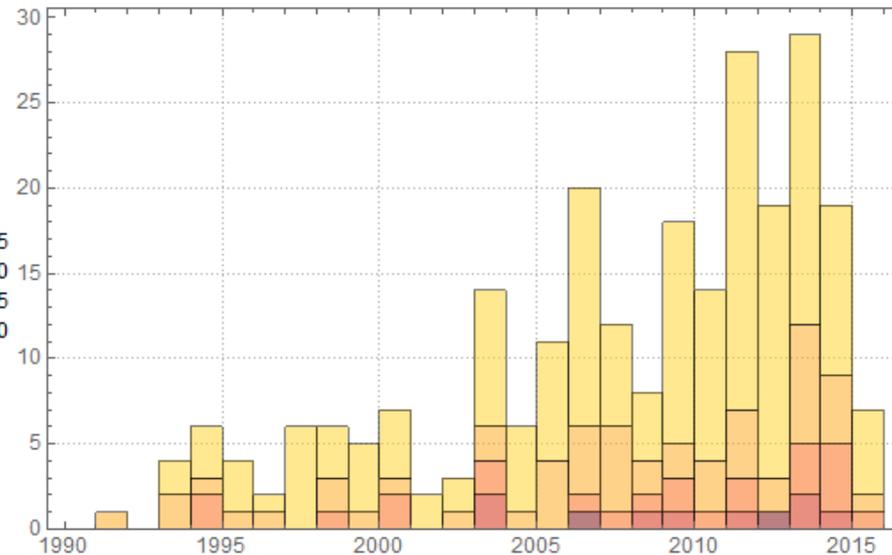
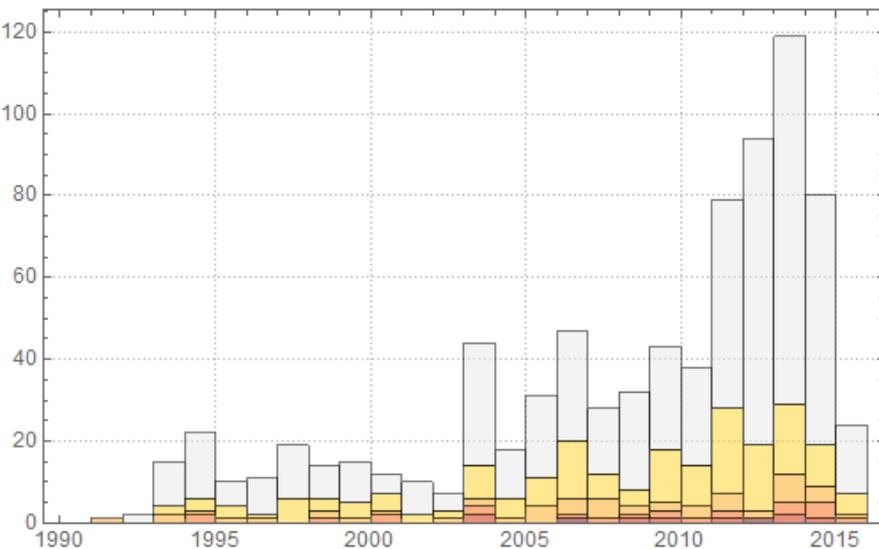
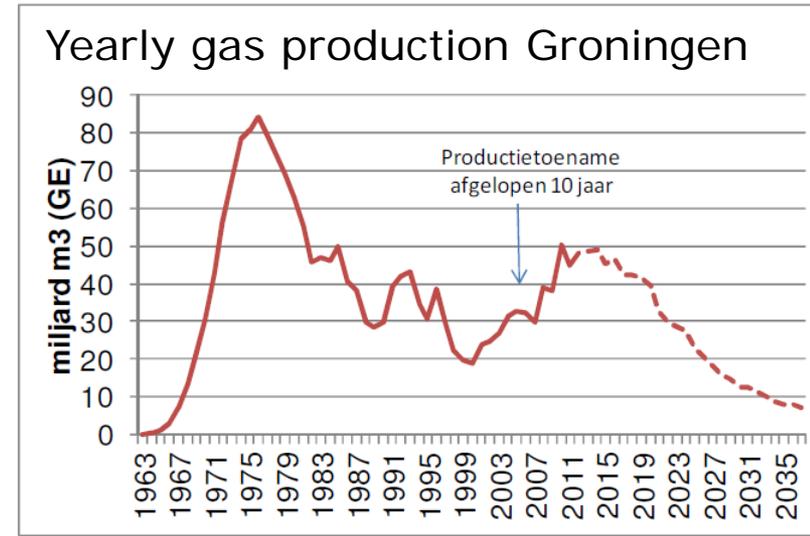


Figure: D. Nieuwland

Groningen Field

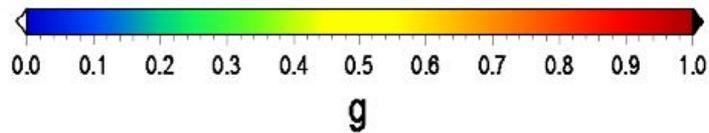
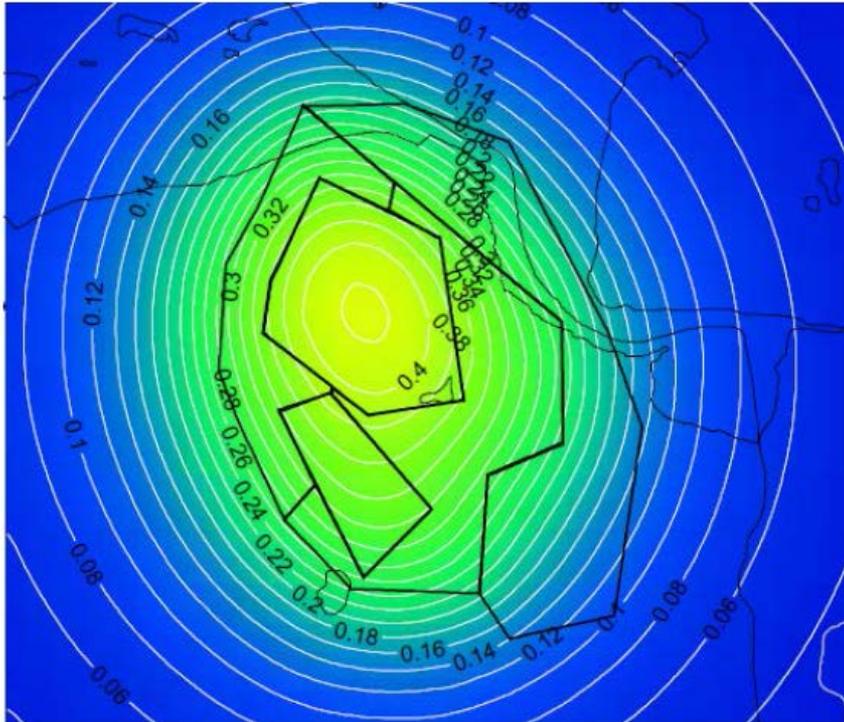
- Start gas production: 1963
- First detected seismicity: 1991
- Catalogue completeness from $M=2.5$, reduced to $M=1.5$ in 1995
- Time / compaction required to build up critical stresses



PSHA Groningen

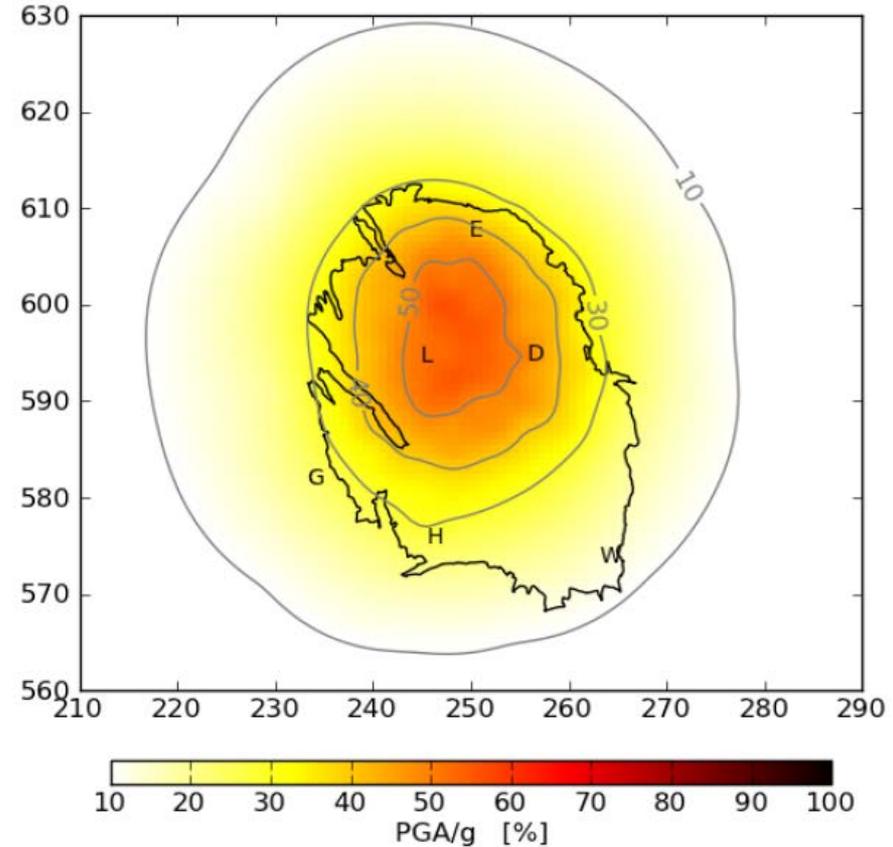
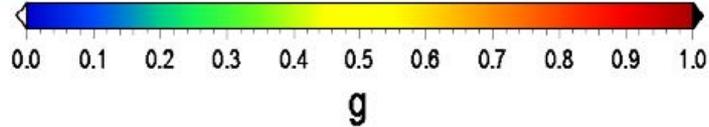
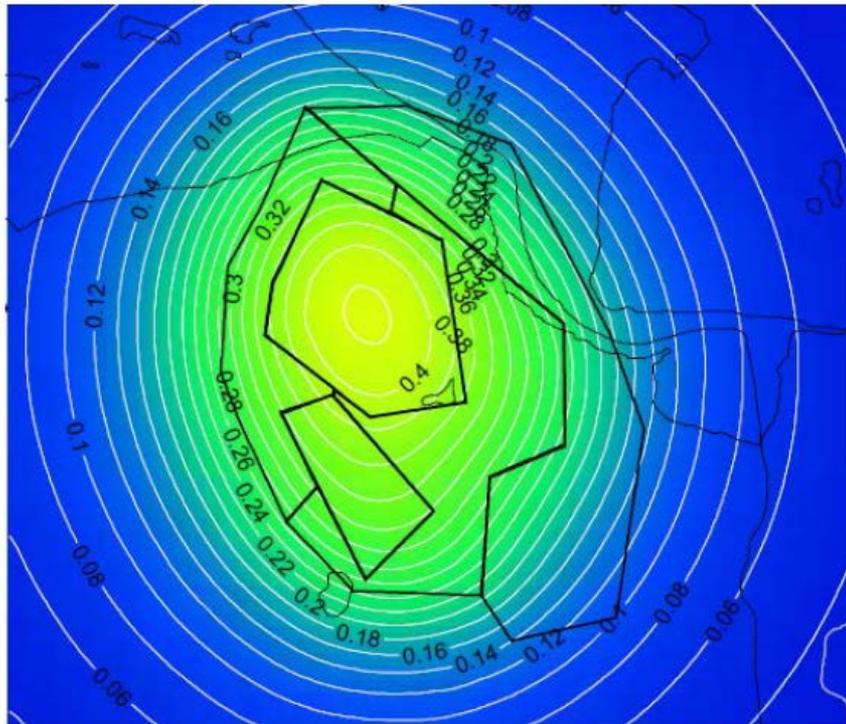
- The Netherlands started work towards National Annex Eurocode 8
- Urgent: National Practical Guideline (NPR) for the Groningen area
- Made public in January in draft status, open for comments
- Purpose: both new and existing buildings, only DS5: near collapse
- KNMI responsible for the forcing specification: hazard map, UHS
- Regular updates planned in path towards Eurocode 8

PSHA Groningen



- PGA (g) exceedance 0.2% per year
- KNMI max: **0.42 g**
- Impact huge: 35.000 – 100.000 houses don't comply

PSHA Groningen



Bourne et al., BSSA 2015

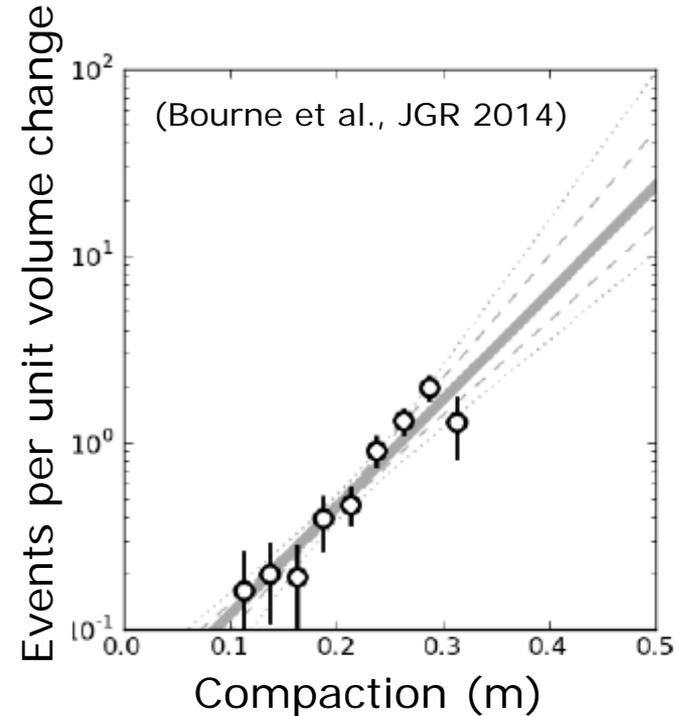
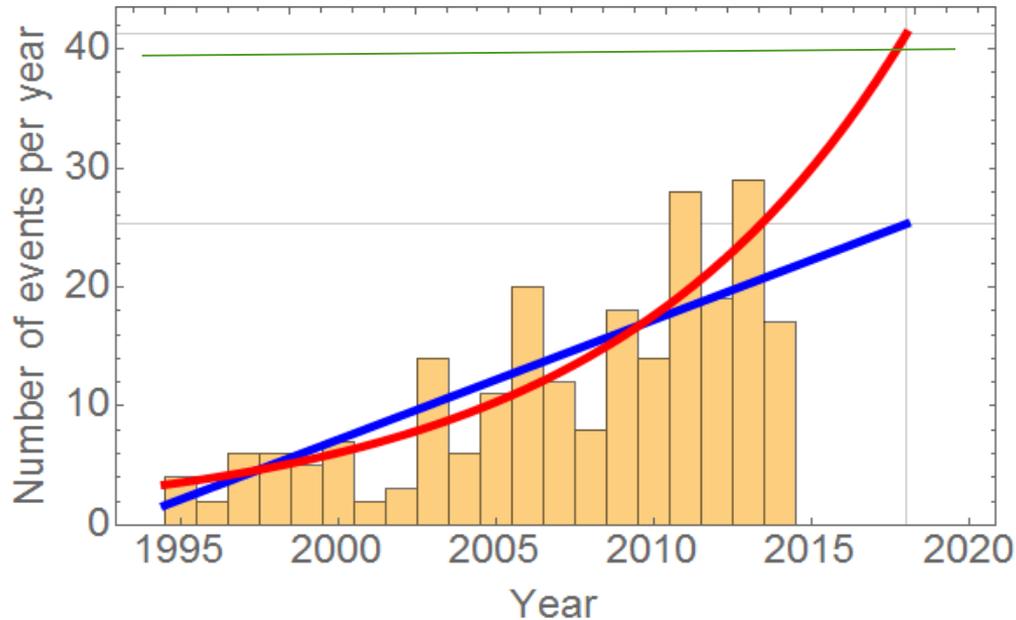
- PGA (g) exceedance 0.2% per year
- KNMI max: **0.42 g**, B&O max: **0.57 g**
- Impact huge: 35.000 – 100.000 houses don't comply

PSHA Groningen

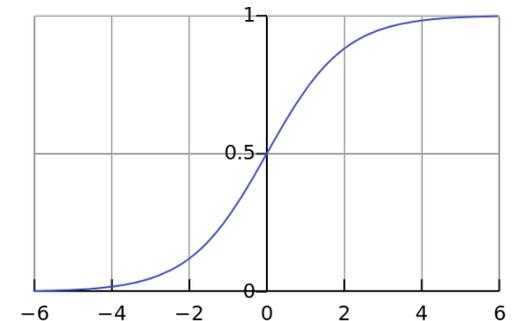
- If this is a false warning, it is an expensive one (~ 5 bln EUR).
- Hazard assessment should be as sharp as possible: both under- and overestimation are harmful
- Try to remove conservatism but don't play down an inconvenient truth
- PSHA probabilistic model ingredients:
 1. Temporal distribution: seismicity rates
 2. Spatial distribution
 3. Magnitude distributen
 4. Ground motion distribution: GMPE

PSHA ingredients (1/4): seismicity rate

- Extrapolation in time / compaction

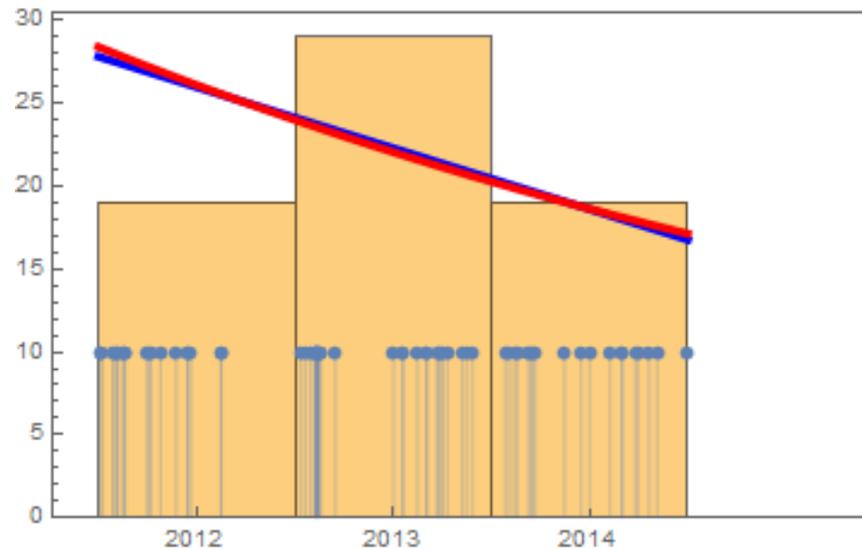


- Is there an exponential proces going on?
- More likely: activation process
- Exponential growth is worst case



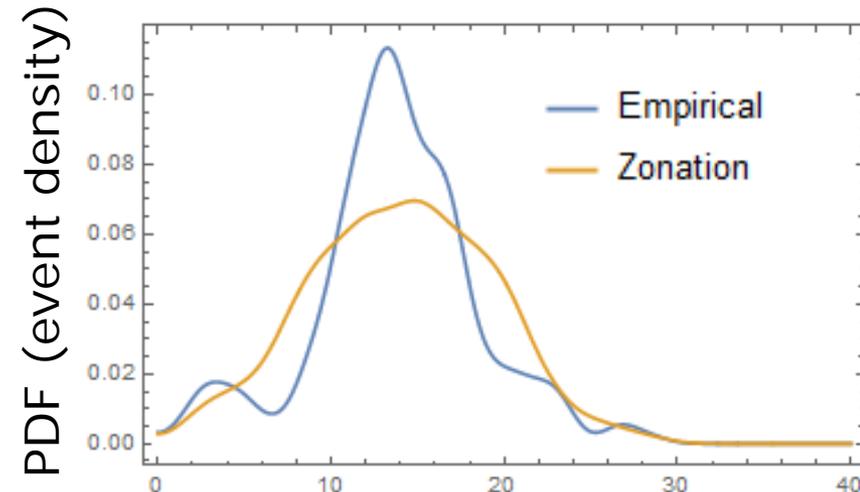
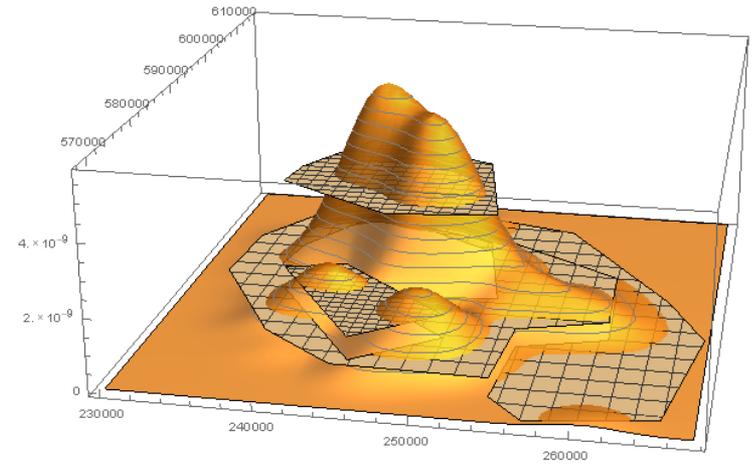
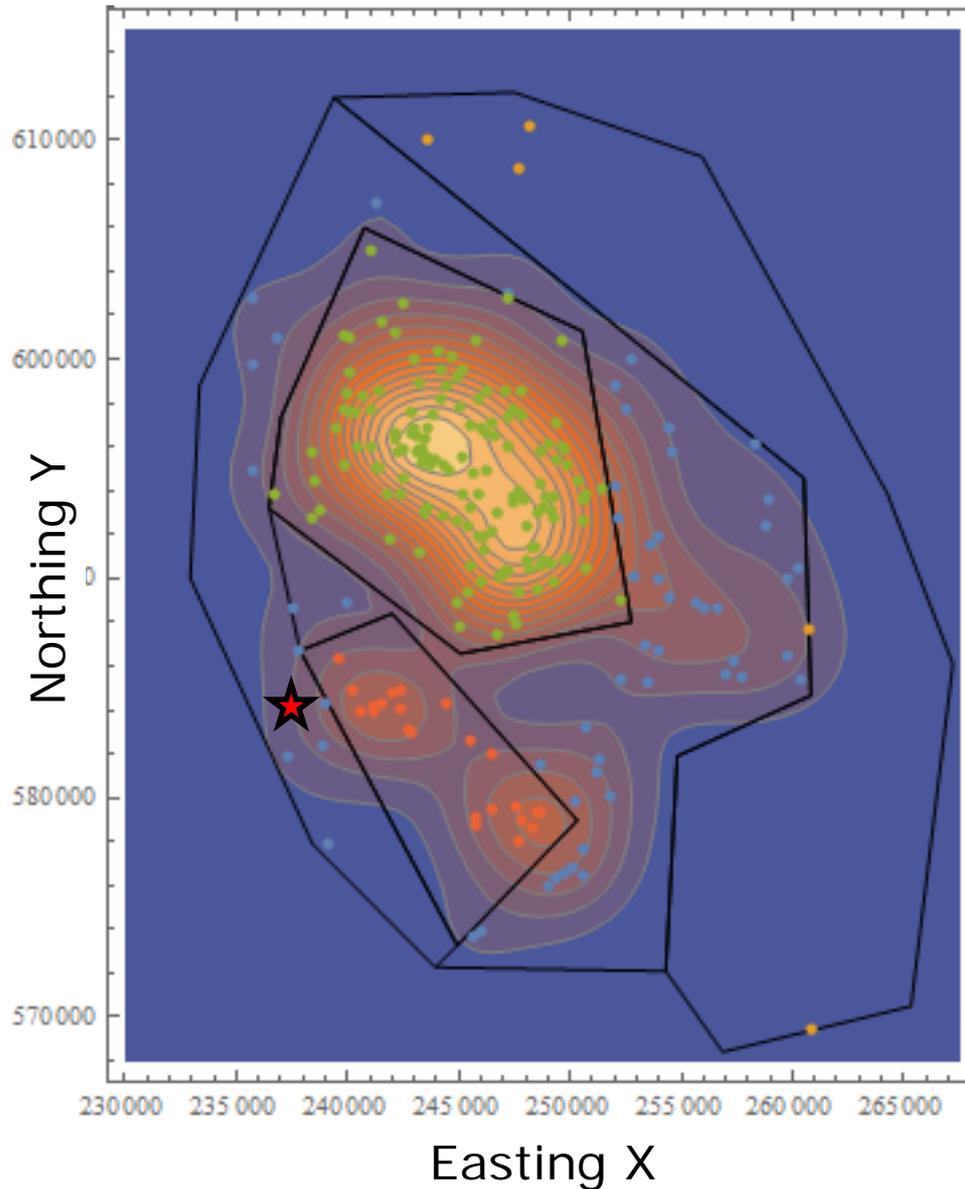
PSHA ingredients (1/4): seismicity rate

- For short term hazard forecasting: use shorter period to constrain seismicity rate model



- May help to take into account possible effects of production measures
- Reduces annual rate for assessment from 40 to ~20

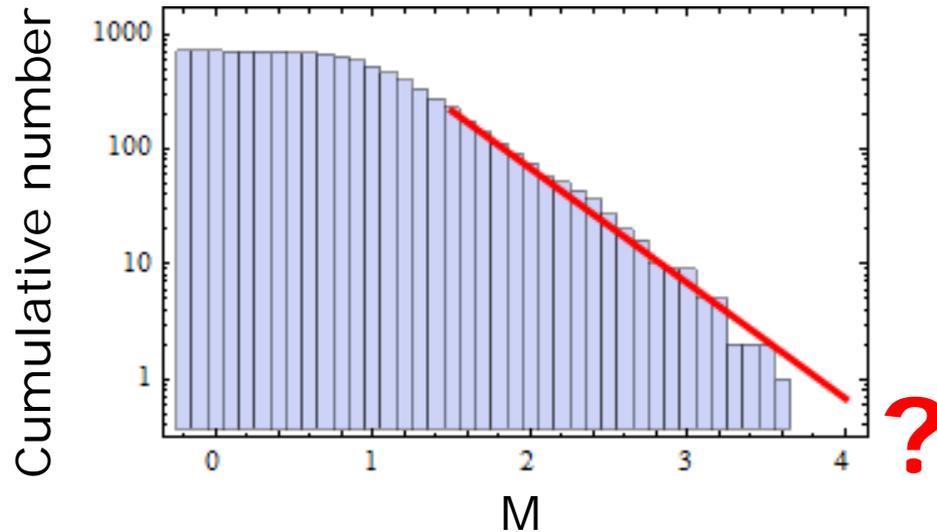
PSHA ingredients (2/4): spatial distribution



★ Epicentral distance

Not a large impact on hazard

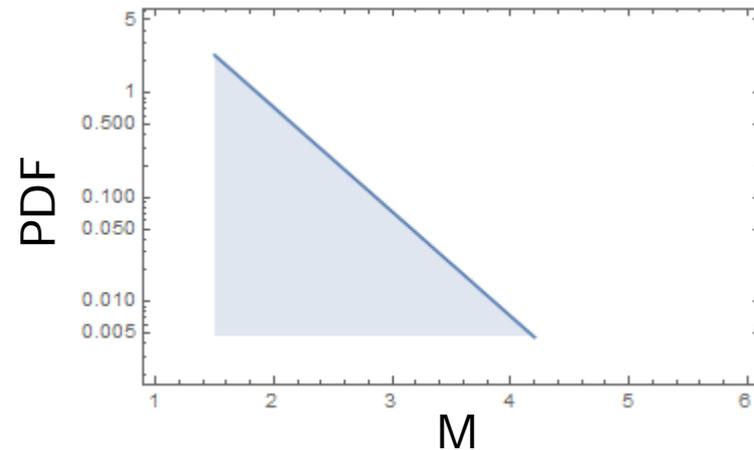
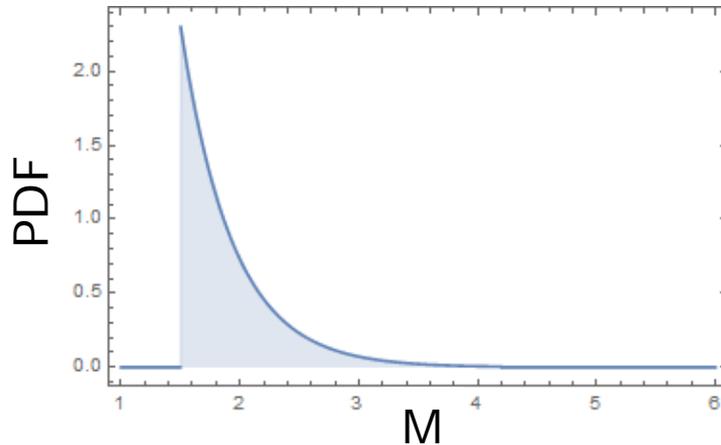
PSHA ingredients (3/4): magnitude distribution



b-value: ~ 1.0

How to extrapolate in M ?

Assume truncated exponential (Gutenberg-Richter) model:



Parameters: b-value and M_{\max}

PSHA ingredients (3/4): magnitude distribution

How to constrain M_{\max} ?

No evidence from statistics.

What can geomechanics do?

- Determine
 - Local medium properties (shear modulus)
 - Maximum fault area
 - Maximum slip

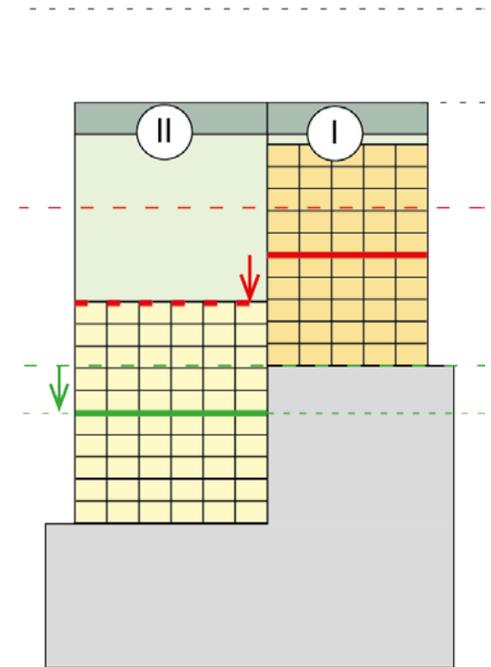
But:

- Larger faults: extend in depth, laterally or both?
- What stress drops can we expect?

Practical choices:

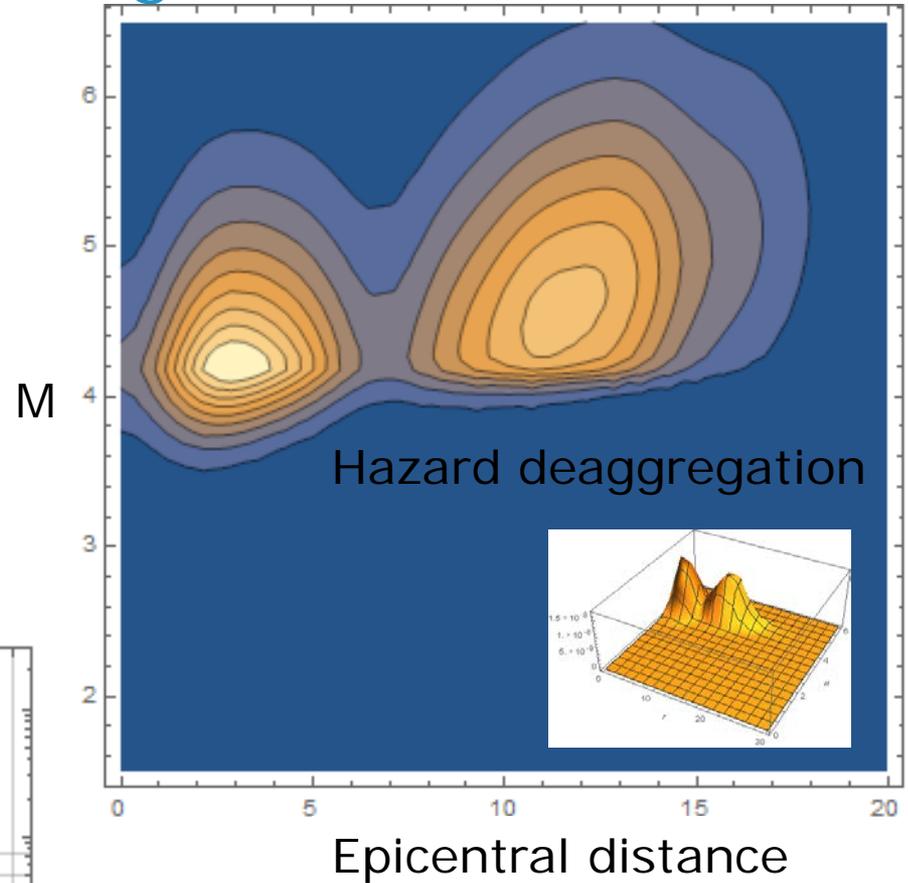
KNMI: $M_{\max} = 5$ from literature study

Bourne et al.: $M_{\max} = 6.5$ from total compaction volume

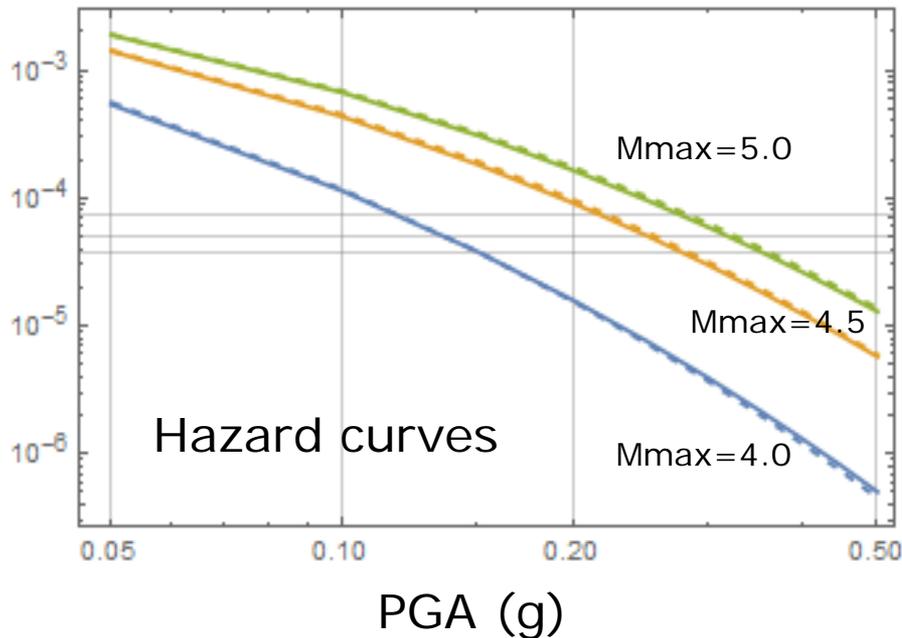


PSHA ingredients (3/4): magnitude distribution

Choice of M_{\max} can be critical

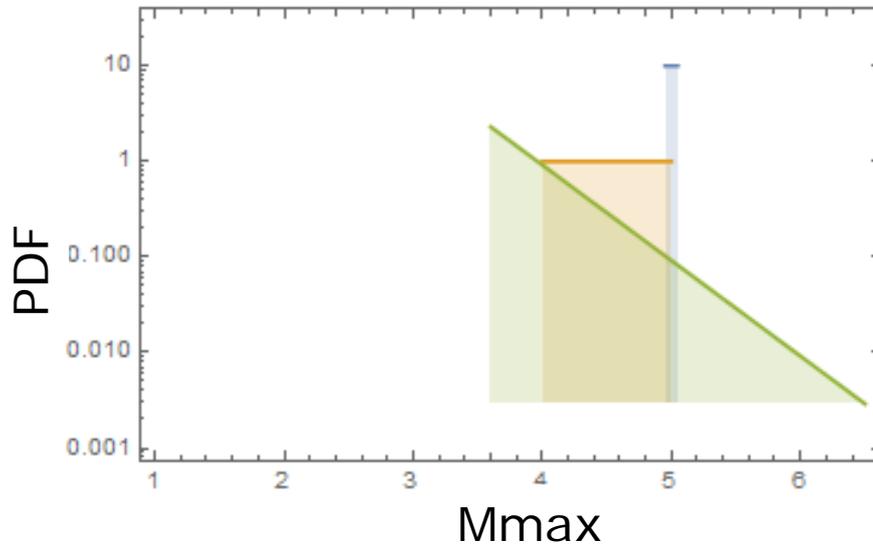


Probability of exceedance



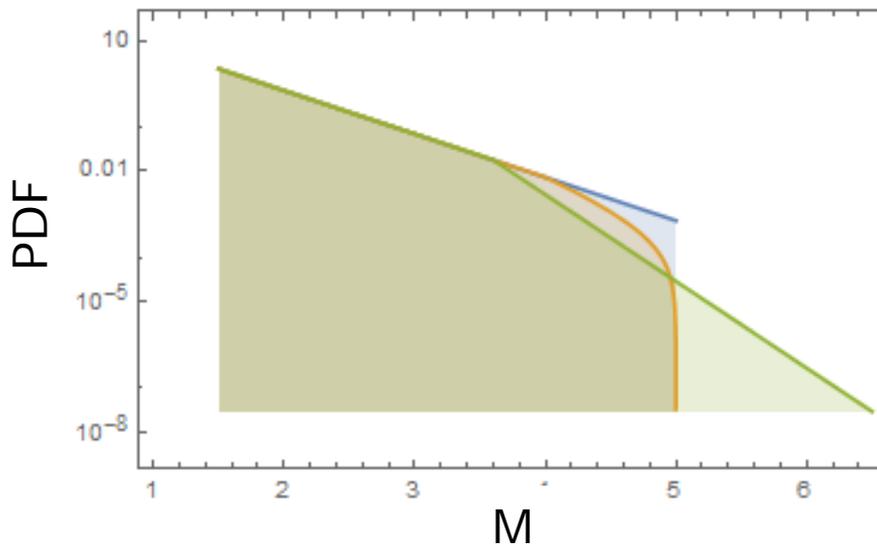
PSHA ingredients (3/4): magnitude distribution

Use distributions of M_{\max} :



M_{\max} distributions

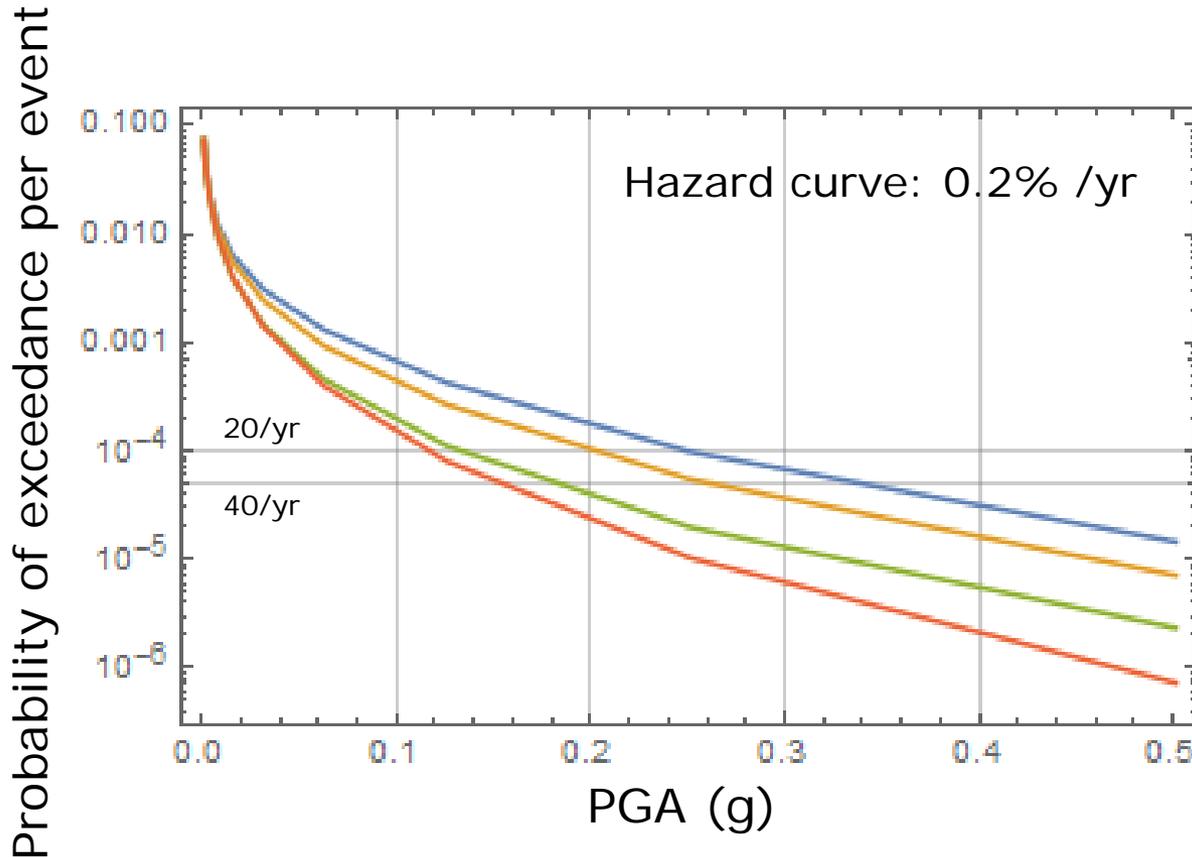
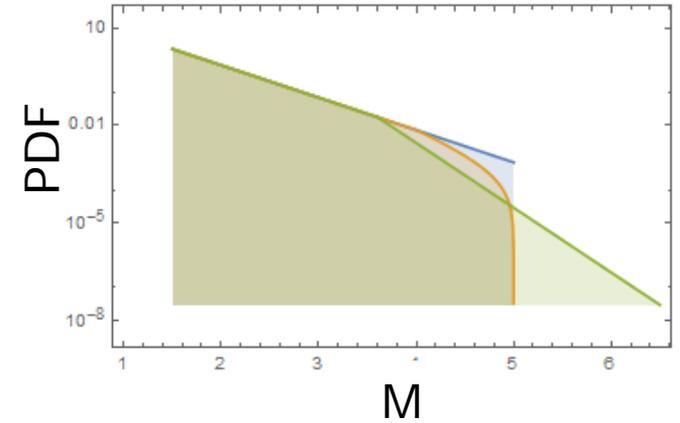
- PDF for $M_{\max}=5$
- PDF for M_{\max} uniform in $[4,5]$
- PDF for M_{\max} exponential ($b=1$) above $M=3.6$



effective
M distributions

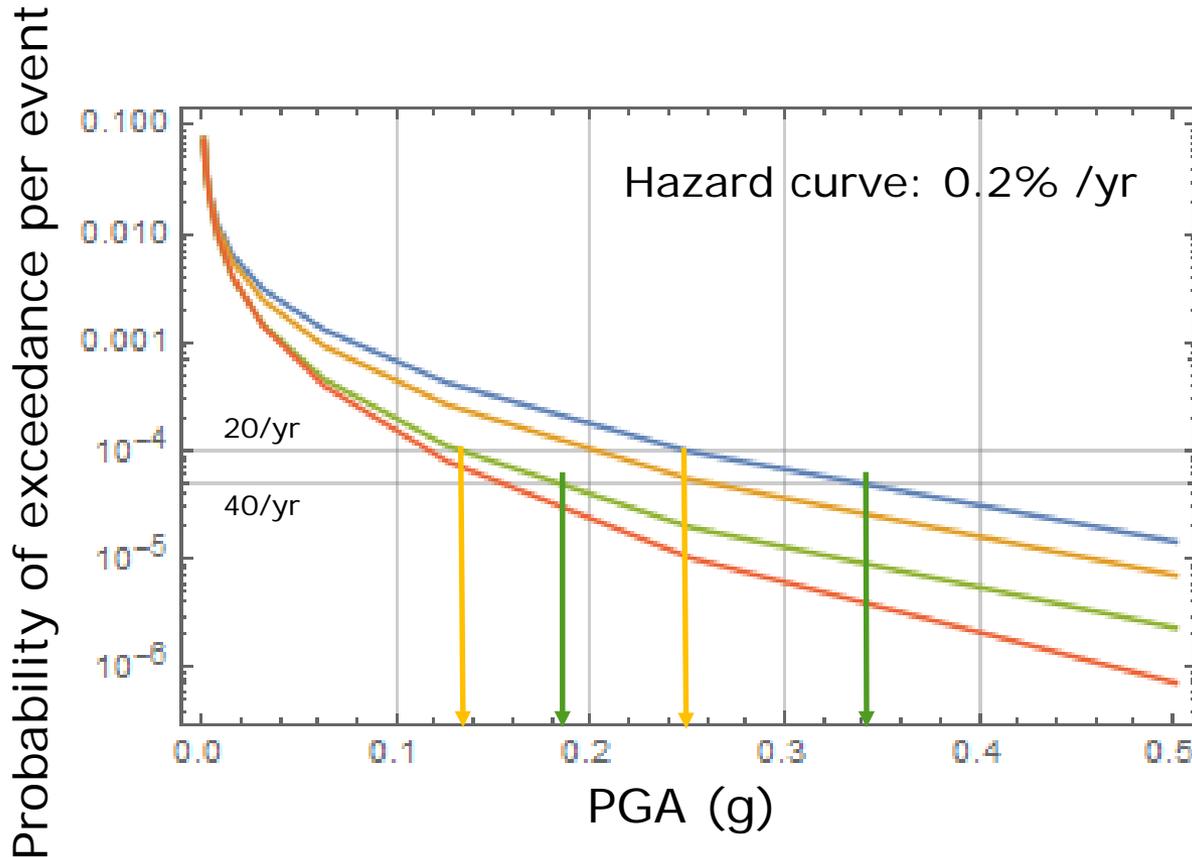
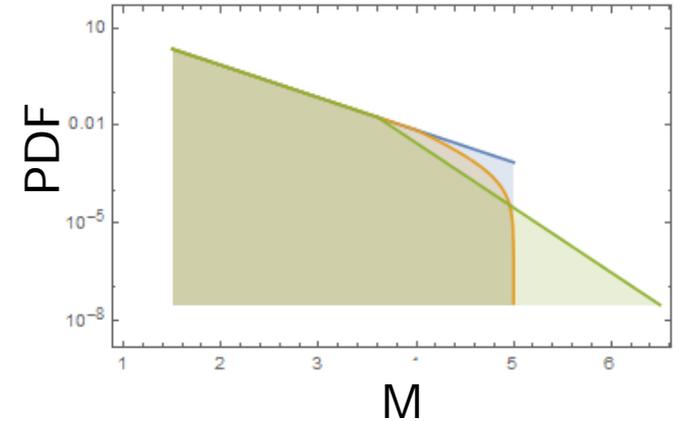
PSHA ingredients (3/4): magnitude distribution

Effect of using Mmax distributions



PSHA ingredients (3/4): magnitude distribution

Effect of using Mmax distributions



PSHA ingredients (3/4): magnitude distribution

Motivation for exponential distribution:

- Based on scale-independence: seismogenic systems with larger M_{\max} are rarer than those with smaller M_{\max}
- Requires no (arbitrary / debatable) upper bound

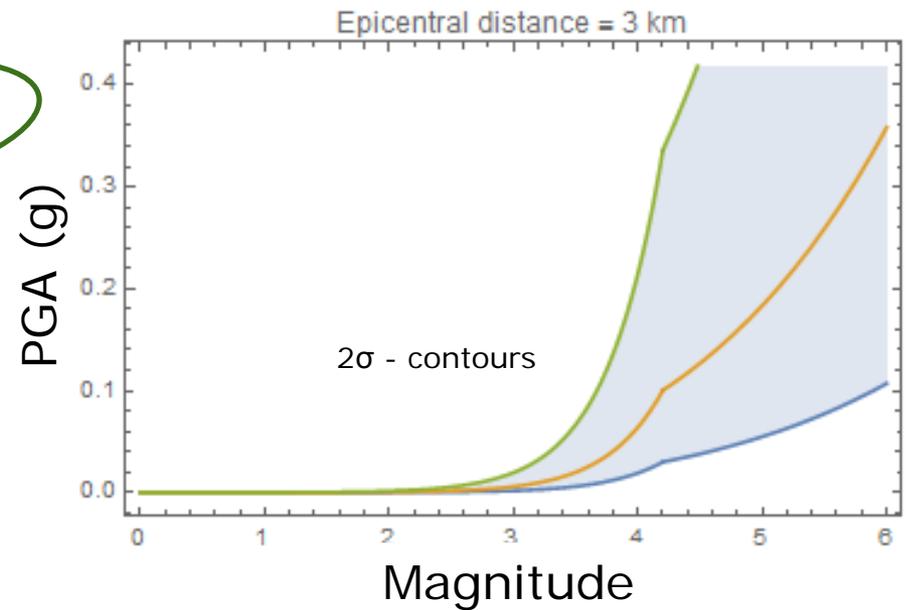
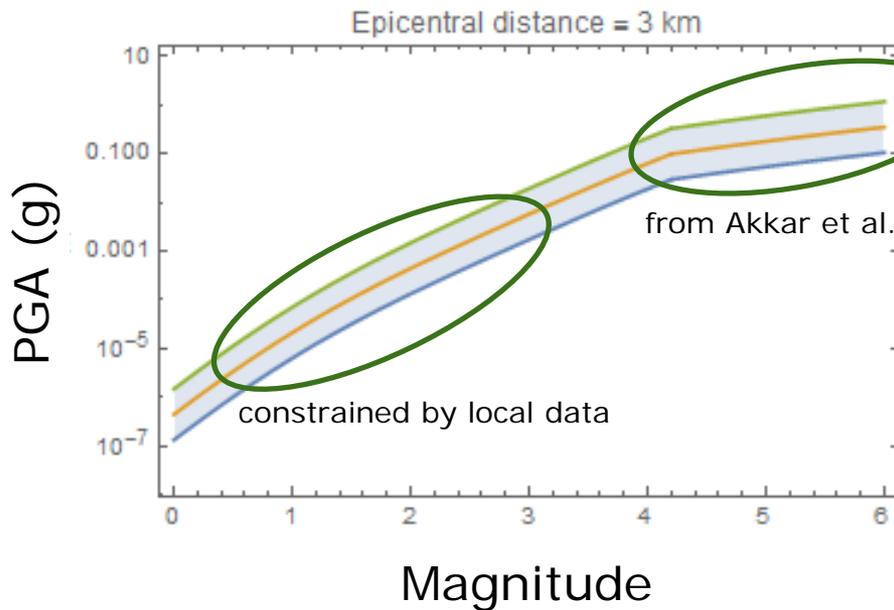
Bayesian perspective:

- Posterior = Likelihood * Prior
- Prior / null information: exponential distribution over infinite range
- Likelihood:
 - Here: simplified as step function for $M_{\max} > 3.6$ (max observed)
 - Based on catalogue
 - Other (external) empirical evidence may be included

Open issue: scale parameter = 1?

PSHA ingredients (4/4): GMPE

- Ground motion prediction equation: modification of pan-European GMPE by Akkar et al. (2014)



- Bulk of hazard comes from imported range ($M > 4$)
- The large σ has large impact
- Recent development: more local data + scaling relations for higher magnitudes

Conclusion and outlook

- PSHA for induced, non-stationary seismicity is a challenge
- Current hazard estimates for Groningen are high, with large impact
- We identify conservative choices in seismic rate and magnitude distribution that boost hazard estimates
- For short-term hazard forecasting it is better to use short period for model calibration
- Rather than a fixed M_{\max} , a distribution should be used; as a prior distribution for M_{\max} the exponential distribution seems interesting
- New monitoring network for Groningen will provide much more data to better constrain the probabilistic models and hazard

Thank you for listening!