Hydrocarbon induced seismicity in Northern Netherlands

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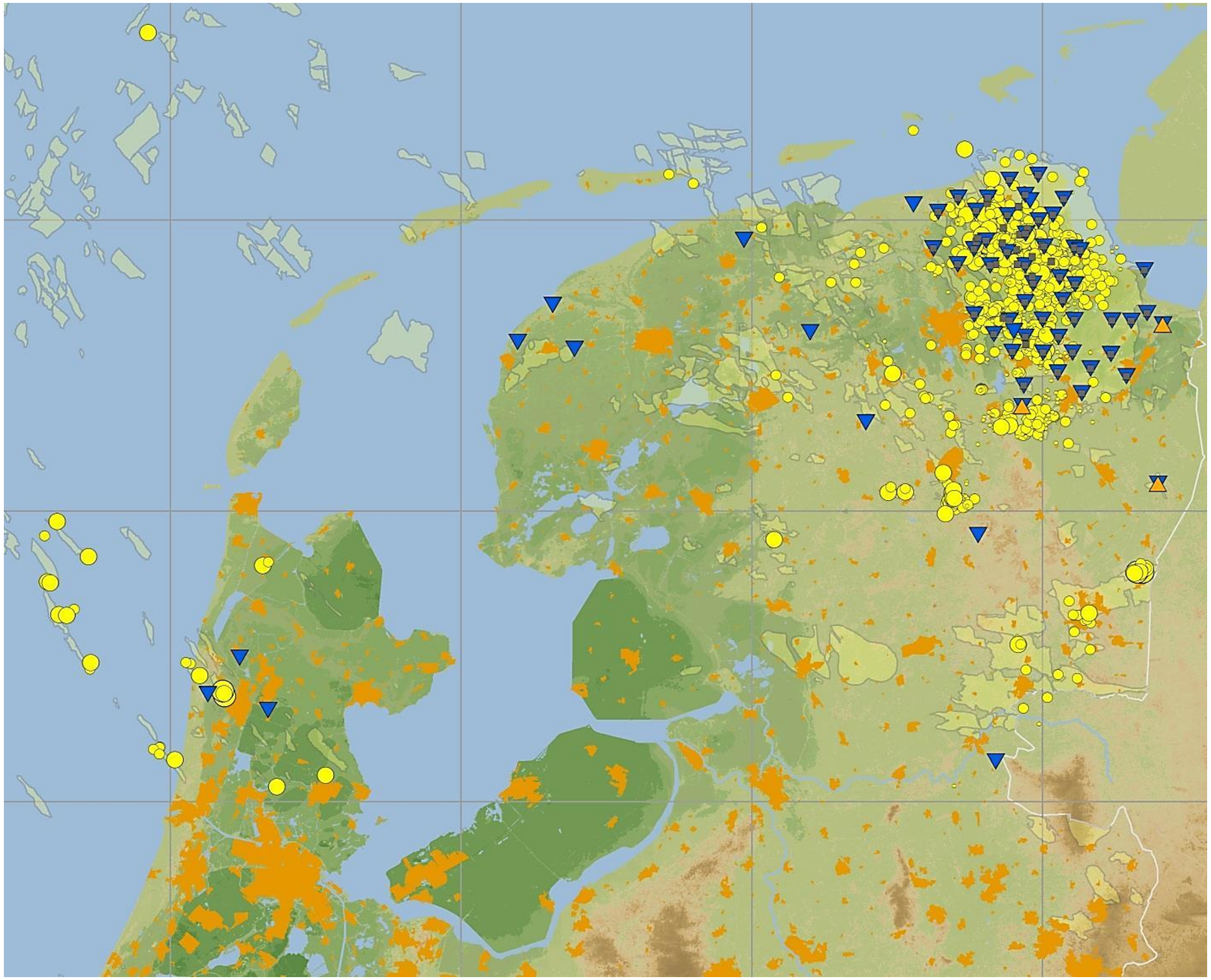

- Induced seismicity 1986-2015
- Since 2003 Groningen field is most active (~ 3000 bcm initial volume, 30*40 km)
- >1100 events recorded since 1986; Groningen 800 events, 250 M> 1,5
- Largest event recorded M=3,6; reservoir at 3 km depth
- >30000 damage claims over the last few years; population Groningen 580.000

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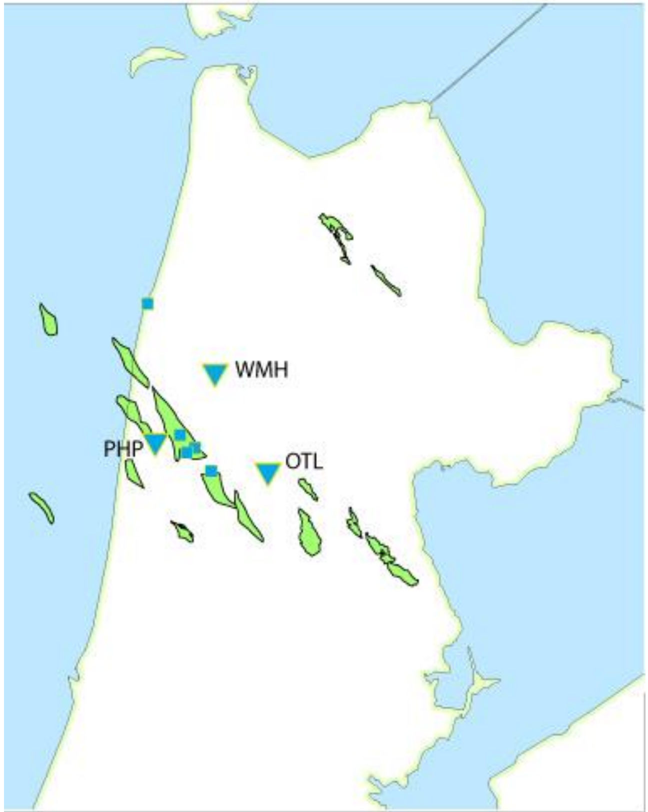
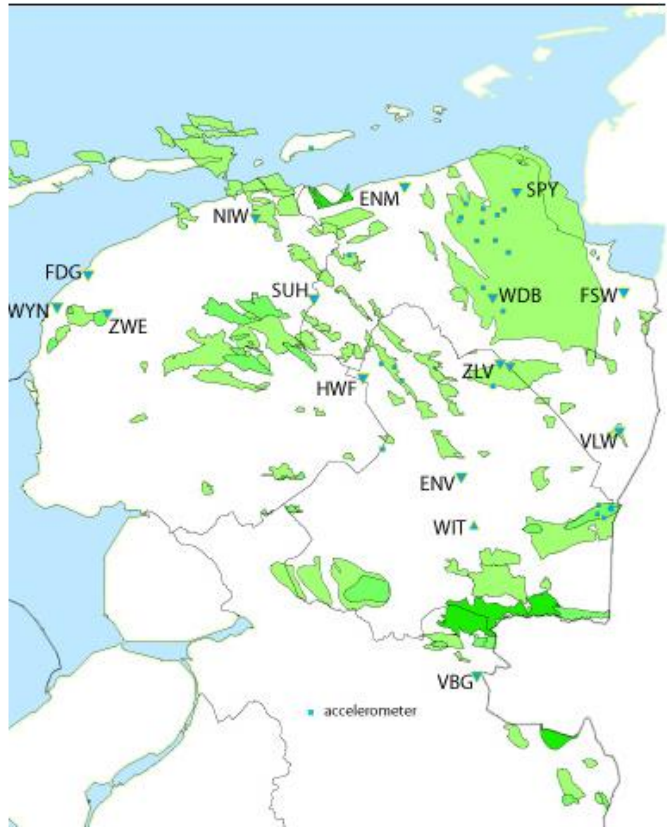
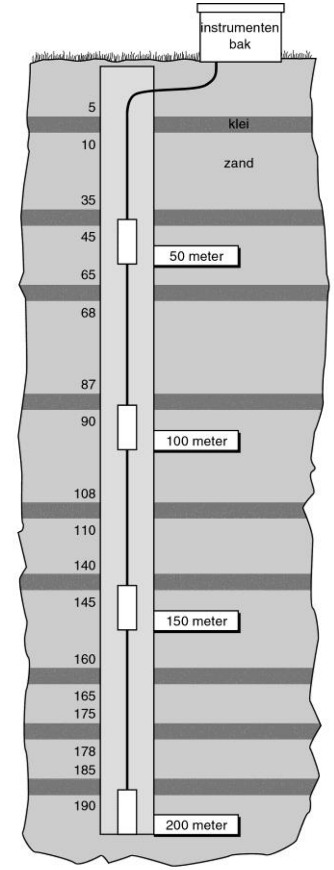
Monitoring network and instrumentation





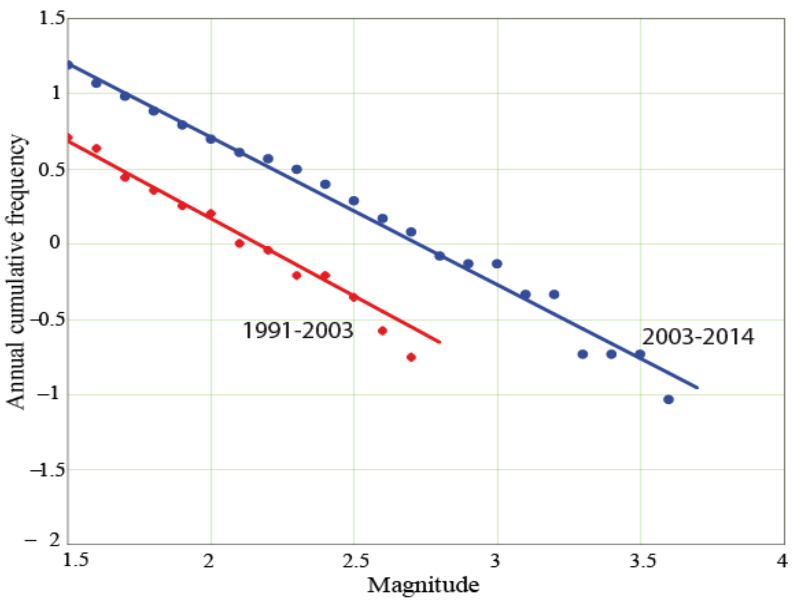


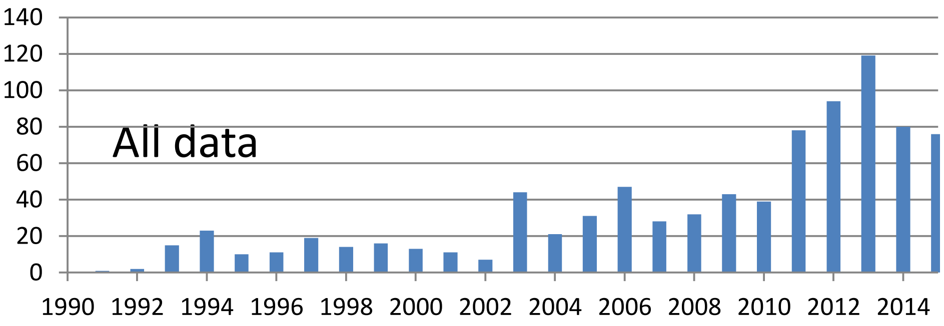
Borehole network (17) designed to detect and locate induced events in the region. Accelerometer network (23) used to provide insight in PGA&PGV values needed for evaluation of damage. KNMI is owner of the network and data.

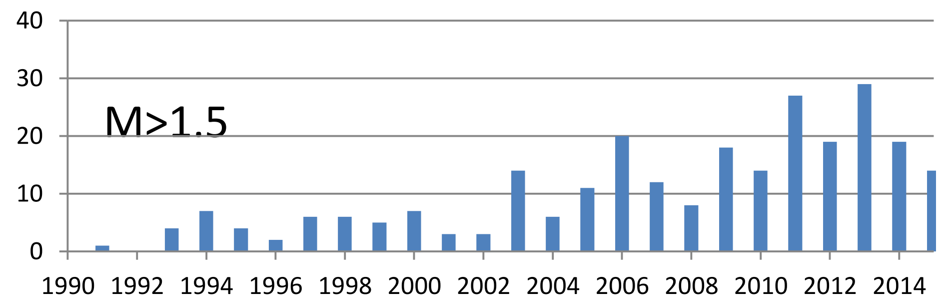
One downhole tool (2km depth) at Bergermeer (since 2010) and two downhole tools (3km depth) at Groningen (since end 2013). Data ownership of these tools at mining companies

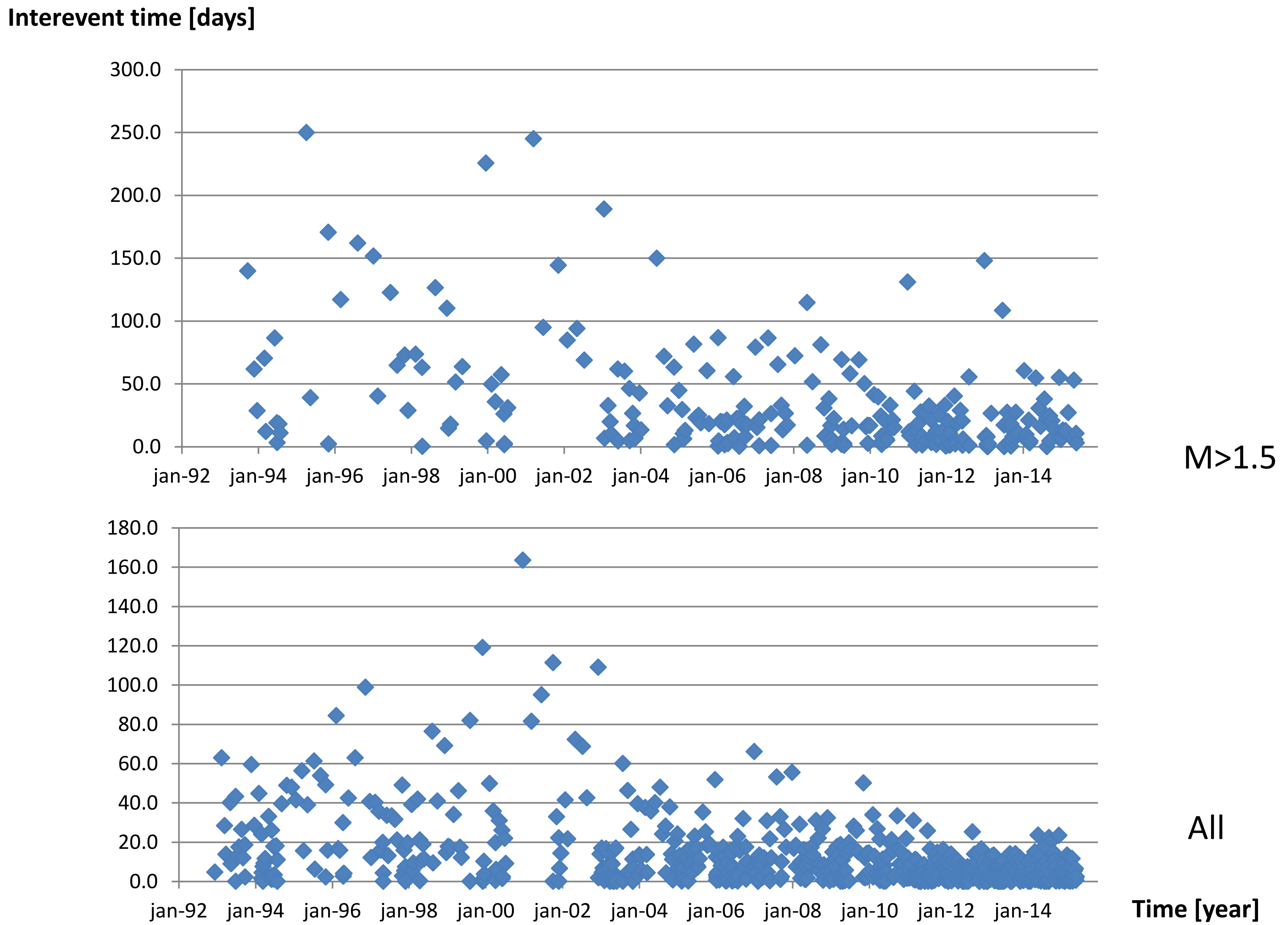
Groningen seismicity

- First event in 1991, moderate activity until 2003
- Since 2003 increase in activity rate, no significant change in b-value, although there are regional differences
- No reliable Mmax could be determined for the Groningen field alone
- Magnitude completeness M= 1,5; maximum recorded magnitude M=3.6
- A non-stationary process



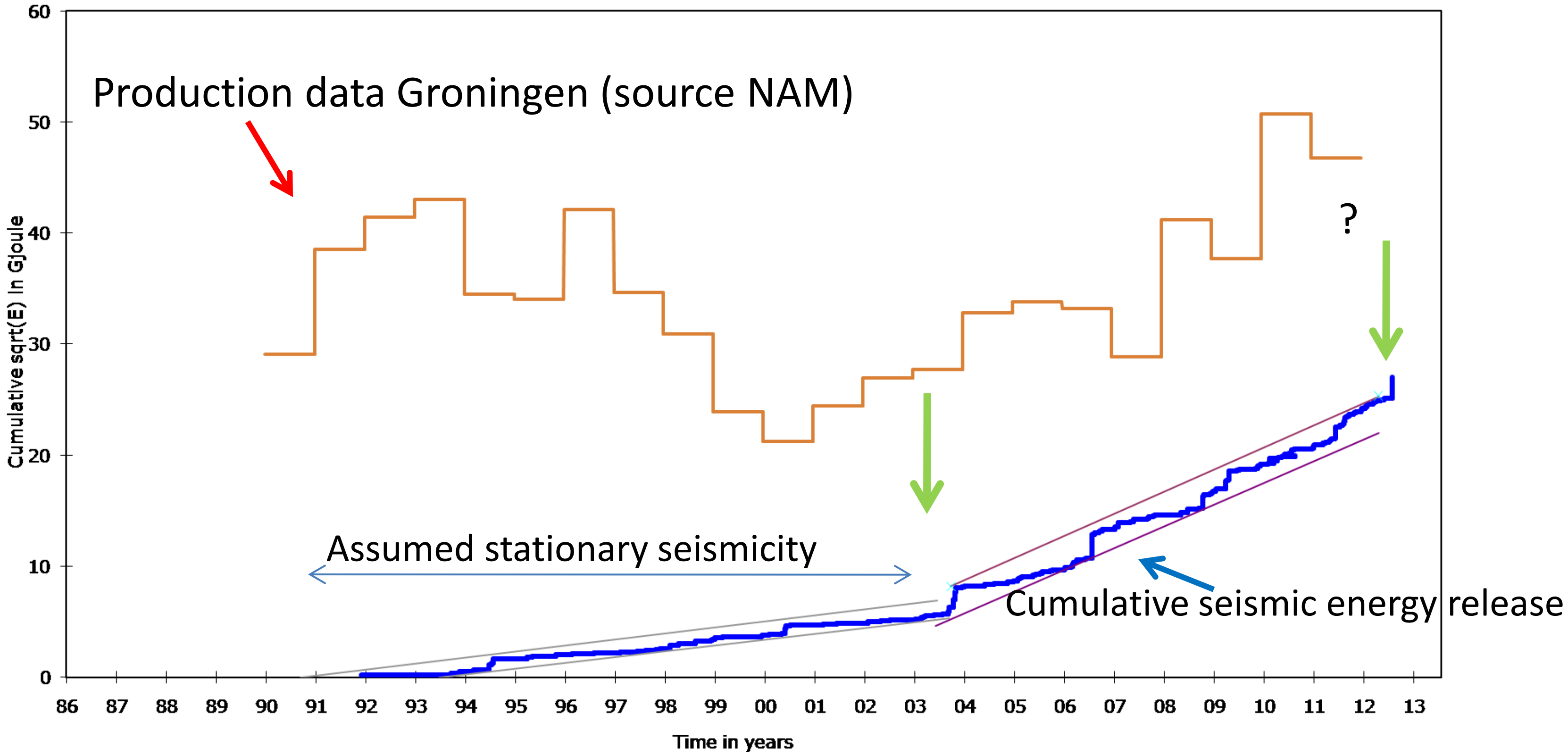






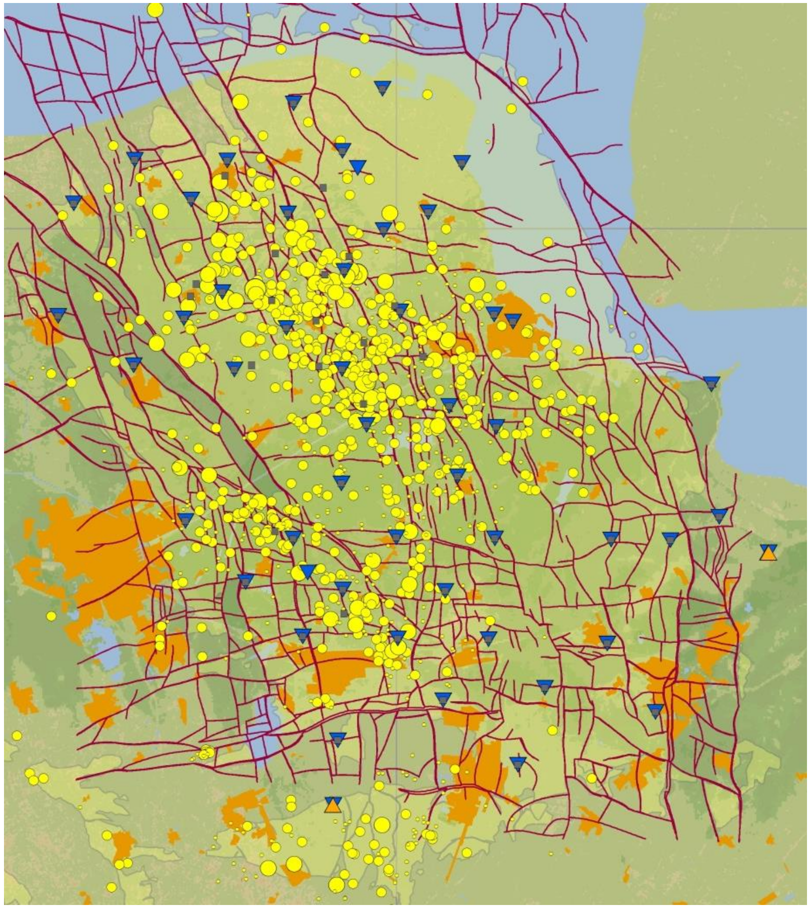
- Inter-event time shows a decrease over the period 1991-2015
- This concerns all data, not only M>1.5 (complete magnitude range)
- Statistically significant seasonal variation and correlation with production, only for M<1.3

Energy and production of the Groningen Field

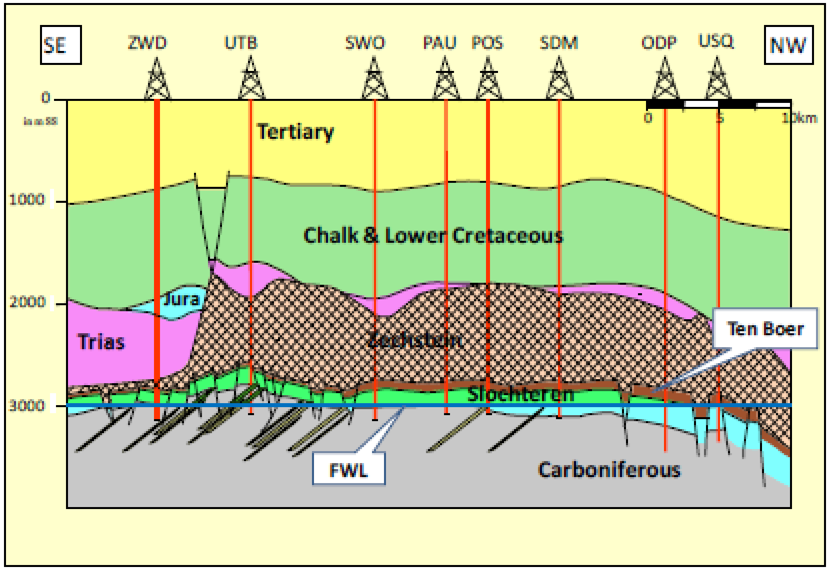


- Seismicity rate and cumulative energy changes seems to change around 2003 (2012?)
- Data has been split-up into two time intervals (1990-2003) and (2003-2012)
- Larger events occur at an interval of 2-3 years over the entire period, since 2003 the magnitude of these events increased.
- Assuming stationary seismicity, the annual frequency of M>3 is about 3 years.
- How does seismicity respond to changes in production and is there a delay?

Groningen seismicity and geology



- Location accuracy 0,5-1 km (hor) with the regional borehole network and at least 1-2 km vertical
- Deep downhole tools installed to improve depth resolution
- Horizontal location accuracy will be improved by densification of the borehole network (2015)



Examples of Damage in Groningen

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Challenges

Questions of importance to hazard models

Are all earthquakes located on existing (known) faults?

we need improved network layout, leading to the application of new techniques

Is the depth of the induced events limited to the reservoir?

we need instrumentation at reservoir depth (downhole tool) combined with an accurate velocity model of the deeper structure.

Two downhole tools are available at Zeerijp and Stedum locations (2013-present)

Network development:

January 2015:
18 accelerometers in real-time
6 boreholes near the Groningen field

New network in development

59 200m deep borehole arrays
59 surface accelerometers
4 borehole broad-band sensors
2 deep downhole arrays (3 km)

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Hypocenter estimation

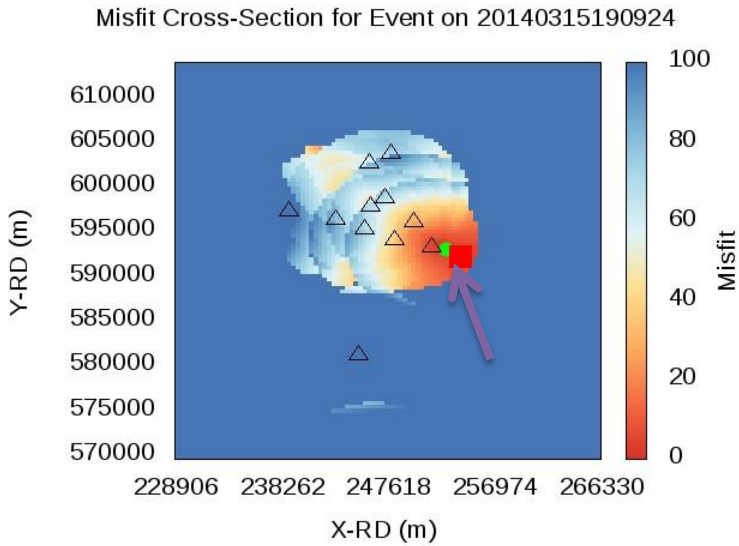
Travel time data are used in the estimation of the hypocenters of induced earthquakes in Groningen.

- The standard KNMI method is the hypocenter method by Lienert et al. (1986).

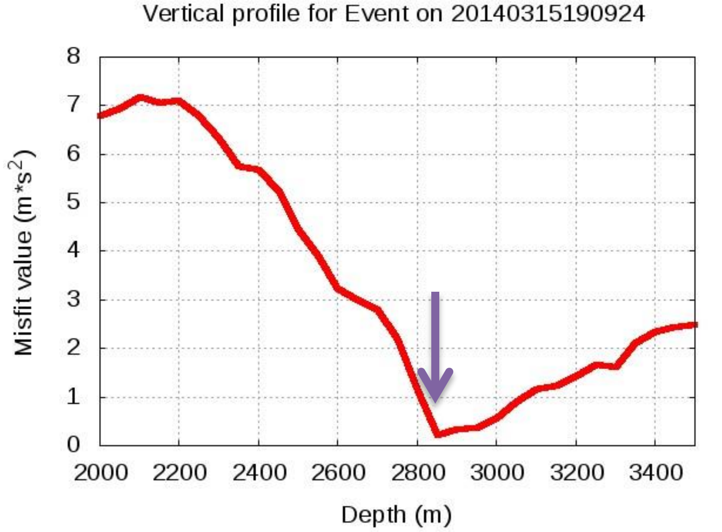
- Recently, the KNMI relocates events in Groningen using the method by Satriano et al. (2008). This approach is based on differential travel times for P-waves (dtP).

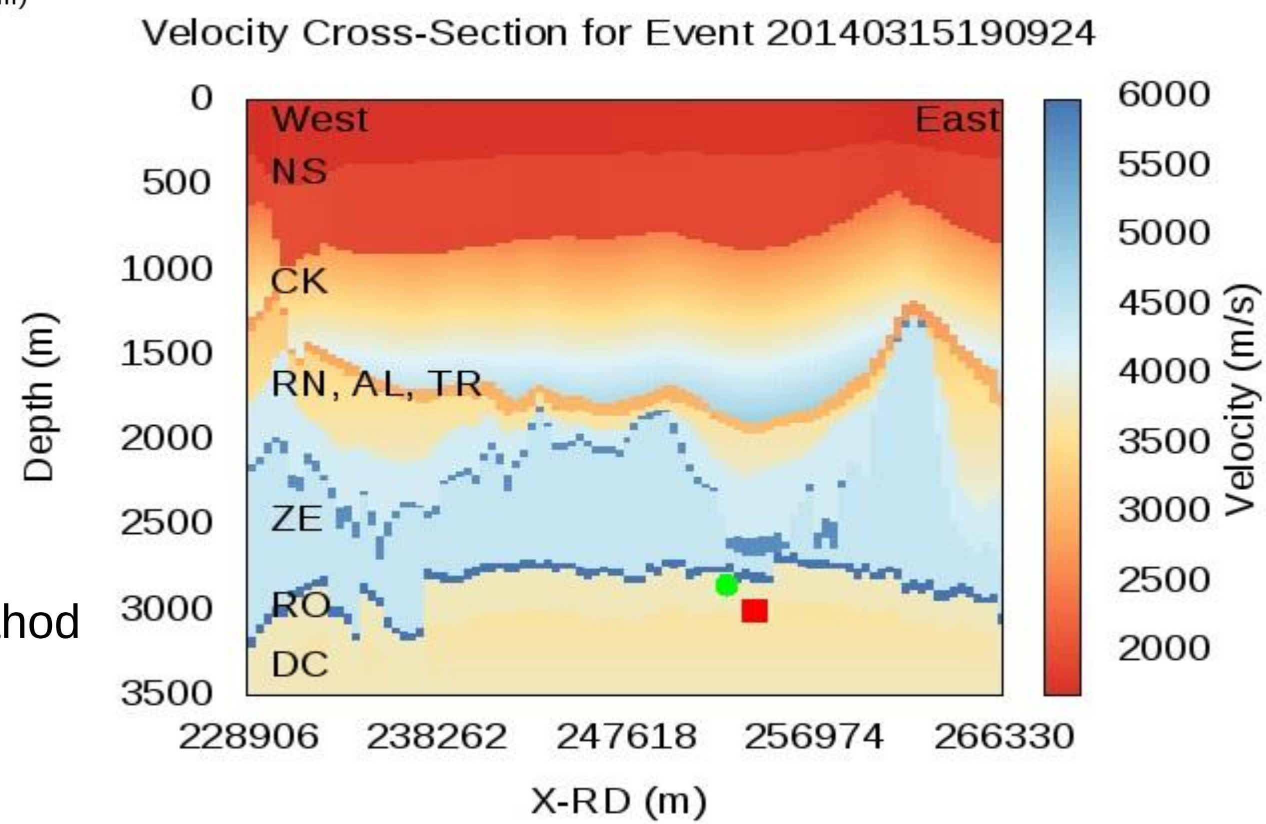
The next slide shows the result of the hypocenter estimation using the method by Satriano (2008).

Horizontal misfit function



Vertical misfit function





Focus

- dtP solution
- Hypocenter method

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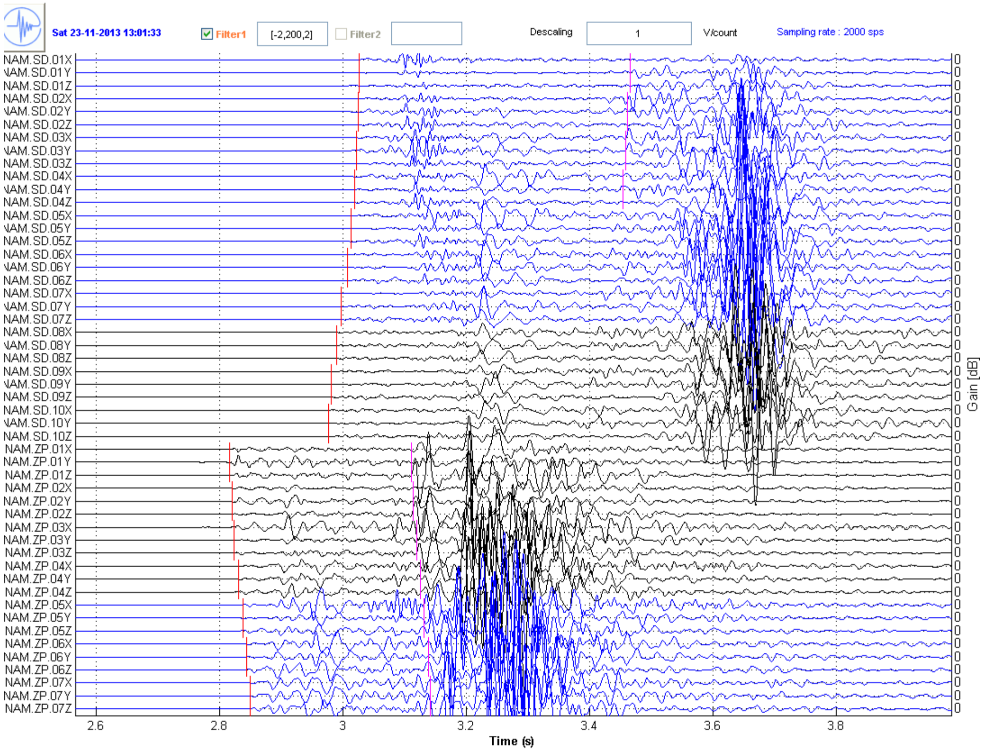
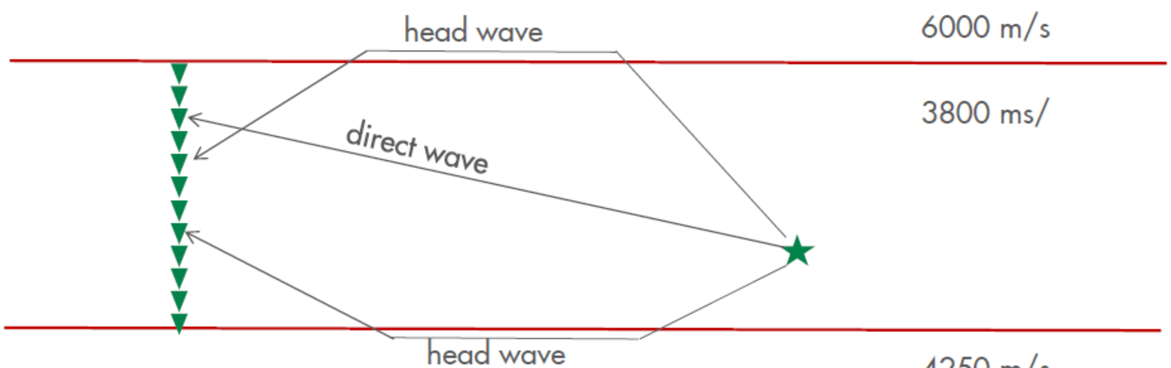


Data example, recorded in STD and ZRP Boreholes at 3 km depth

Complex pattern of arrivals

Source: magnitude



Head waves traveling through the higher velocity layers may arrive earlier than the direct waves traveling through the lower velocity layer

Source NAM

Developments

- Since 2003 a new mining law requires for each new mining prospect a production plan, including a risk evaluation.
- Until recently a general hazard assessment was sufficient, based on an evaluation of induced seismicity for all fields (limited dataset) and derived M_{max}= 3.9
- Since 2012 (M 3.6) mining companies started more research, required by the State Survey of the Mines (SSM).
- KNMI and TNO asked to review the results

Hazard and risk

Probabilistic Seismic Hazard Analysis (PSHA) – step 1-3

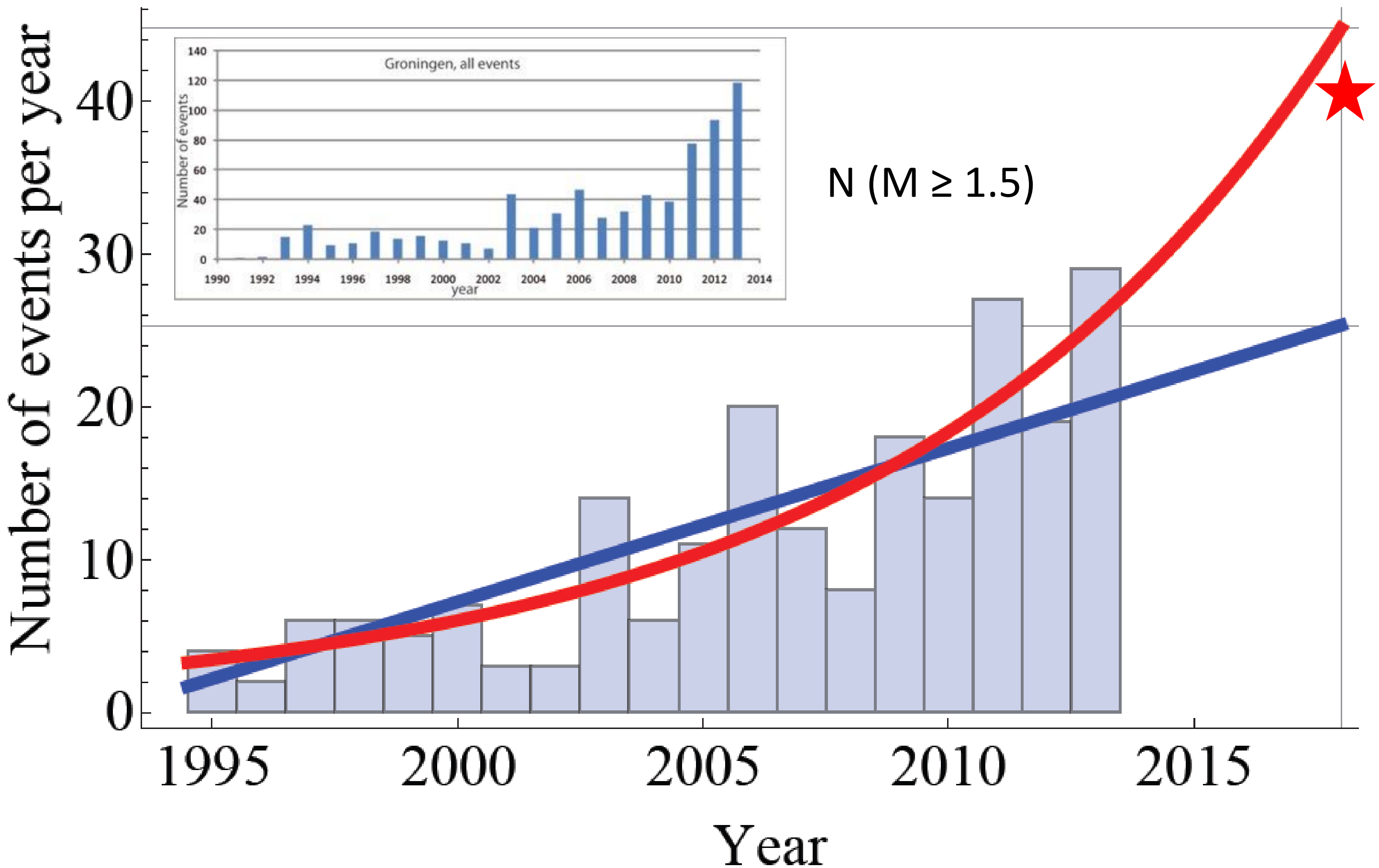
- Source model: based on past seismicity (KNMI) or physical process (compaction; NAM/Shell, TNO)
- Before 2013, no GMPE for Groningen available. Hazard of small shallow induced earthquakes (M<4) is generally not well studied (Bommer, Edwards, KNMI, Deltares)
- Vulnerability: there was no building code for earthquake related damage. Fragility curves need to be developed (Arup, Pinho, Crowley, Bommer, TNO..)

Probabilistic Seismic Hazard Analysis (PSHA)

- Non stationary process
- Two approaches:
  - Conventional PSHA, based on seismic zonation and an increasing seismicity rate with time as source model
  - Monte Carlo PSHA model, based on a compaction model for the Groningen field (Bourne et al., 2014, JGR)
- Both models use the same Ground Motion Prediction Equation (GMPE)
  - The GMPE relates magnitudes to Peak Ground Acceleration (PGA) or Peak Ground Velocity (PGV). In later versions SA are added.
  - Usually developed for M> 4-5
  - Extrapolation to lower magnitudes gives an overestimation
  - An existing relation for shallow events at 4<M< 7.5 (Akkar et al., 2014) was extrapolated to lower magnitudes and calibrated with measured accelerations in Groningen
  - New version: based on Groningen data alone and extrapolation to higher magnitudes through stochastic simulation

PSHA: Seismicity rate

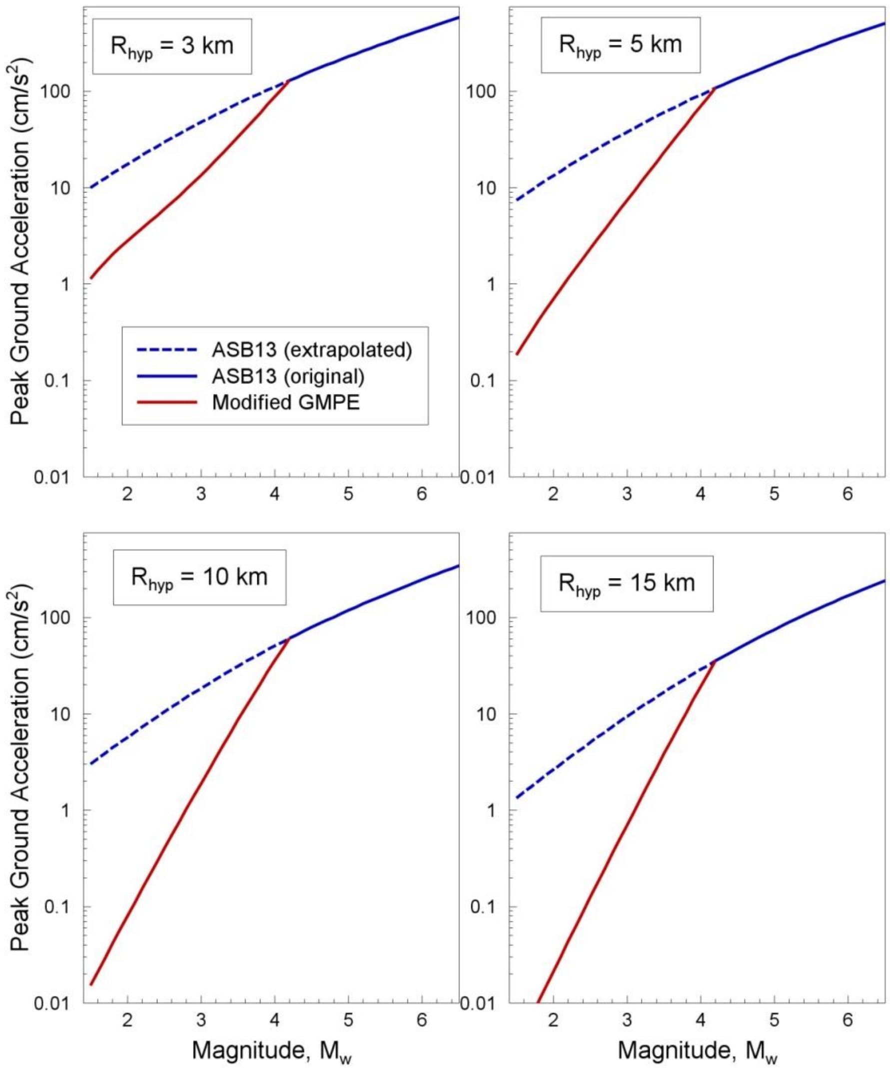
number of events/year



- Increase in seismicity rate: linear or exponential extrapolation? (equally significant) for the next five years
- N=40 was selected, based on an exponential extrapolation (Nov, 2013)
  - New model N=20, differs for each zone

Ground Motion Prediction Equation (GMPE)

PGA predictions using the modified Akkar *et al*. (2014) GMPE to match the Groningen data below M_w 4.2 at hypocentral distance of 3, 5, 10 and 15 km

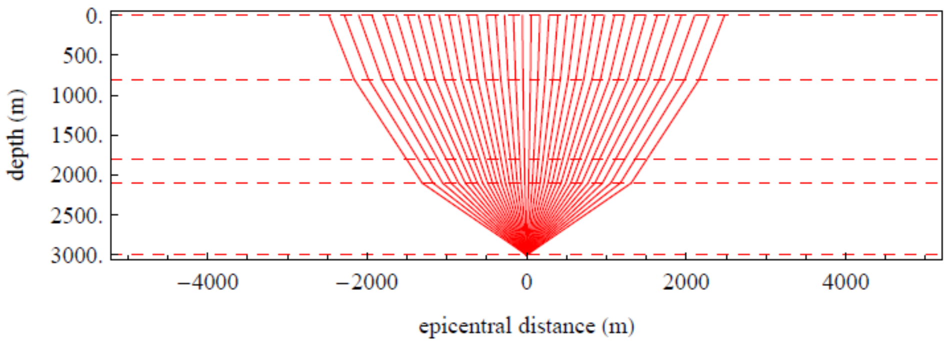


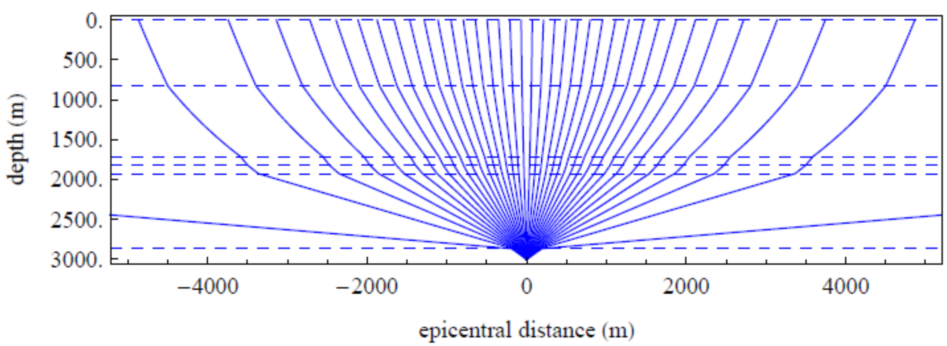
Bommer, 2013

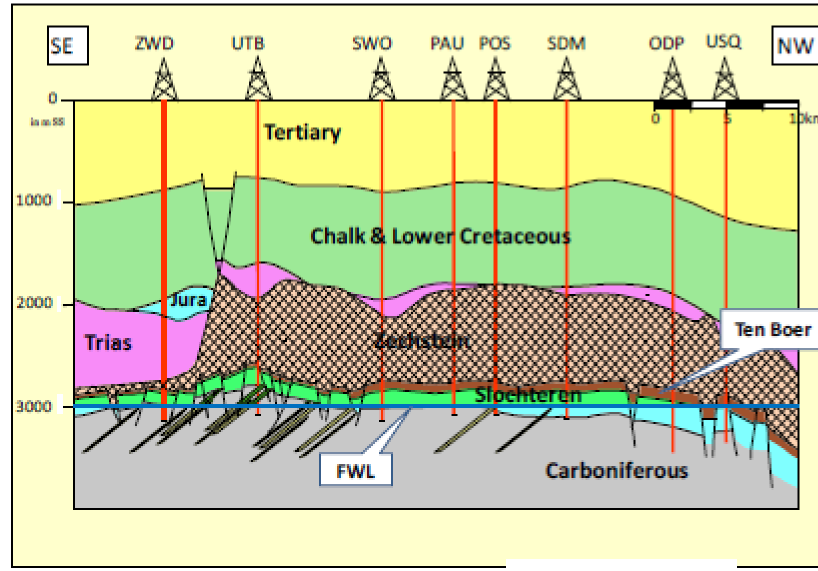
Why are the PGA and PGV values for Groningen so low?

A possible explanation is the effect of the overlying Zechstein layer as high velocity layer

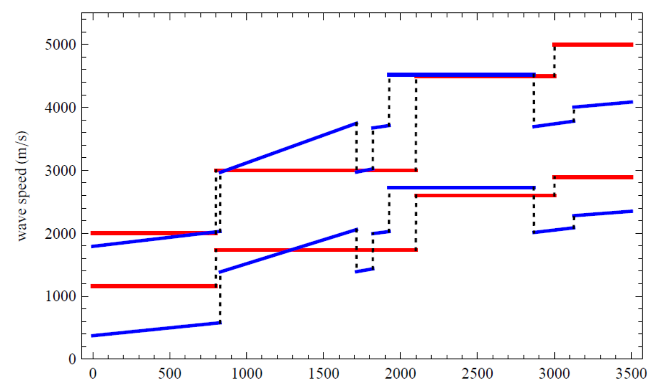
Salt influence: defocusing







source NAM



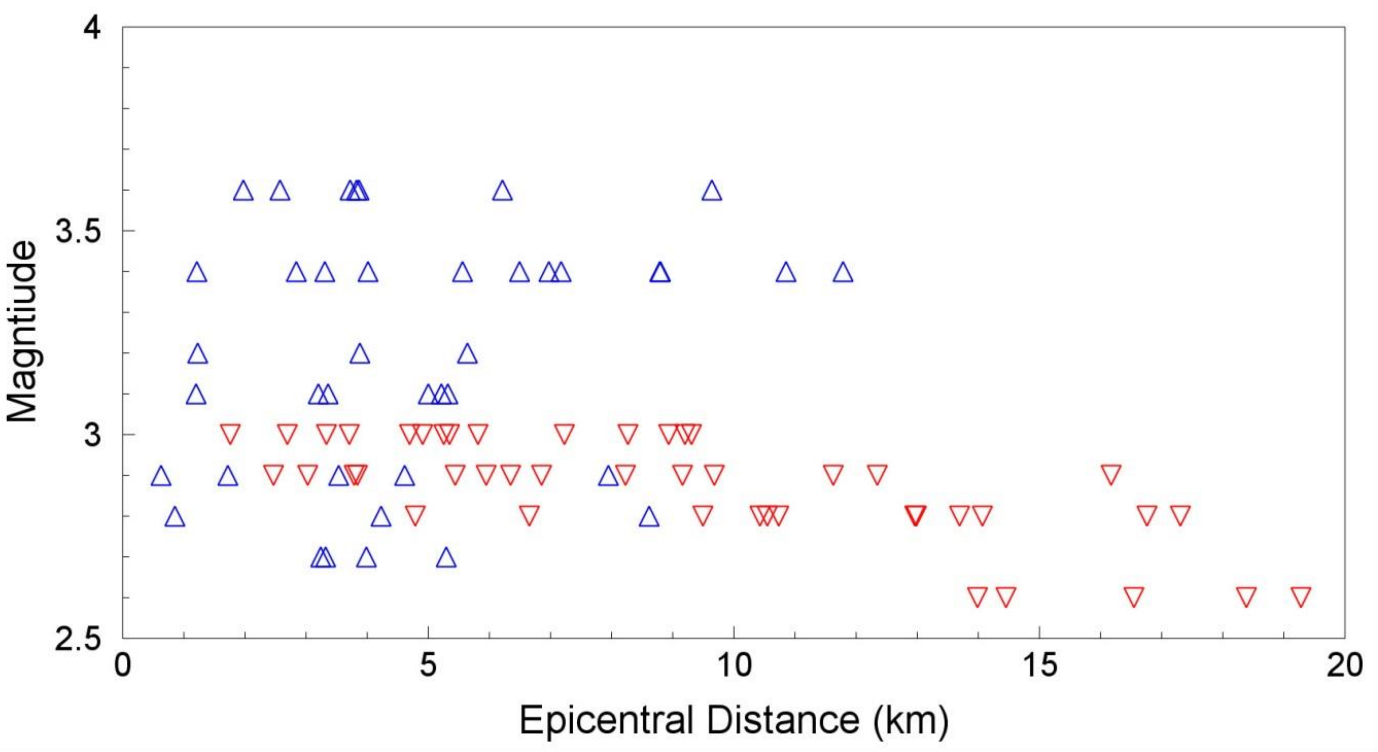
Average (regional) model

VELMOD model (1D sample)

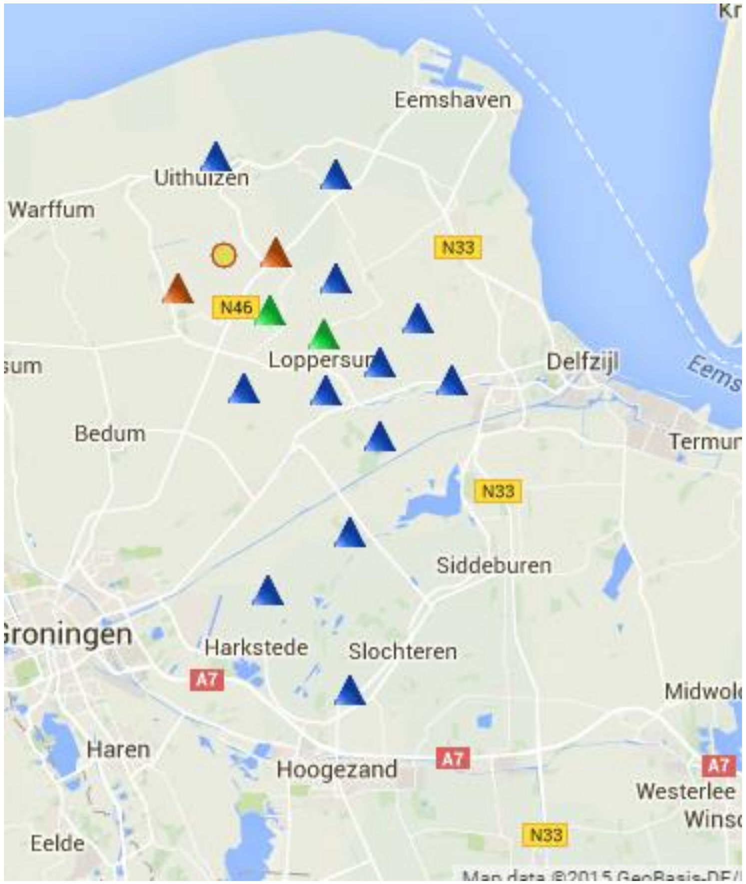
Kraaijpoel & Dost, 2012, J. of Seism.

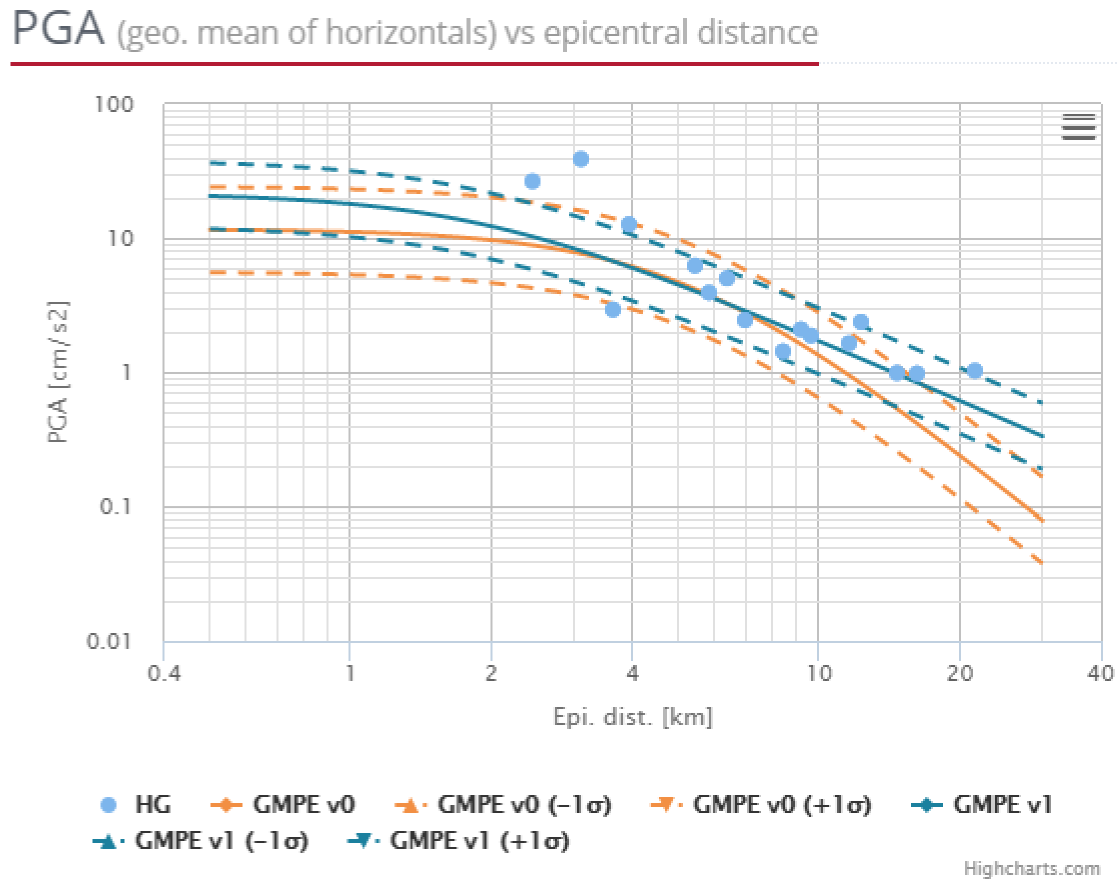
New version of the GMPE

- Based on Groningen data alone and extrapolation to higher magnitudes through stochastic simulation
- Besides PGA, also spectral acceleration at different frequencies
- Extended dataset, especially for 10-20km epicentral distance



Comparison between models and observations



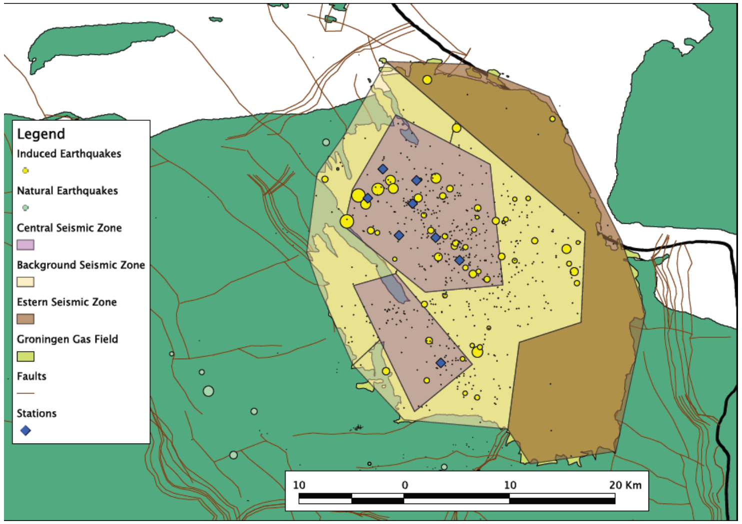


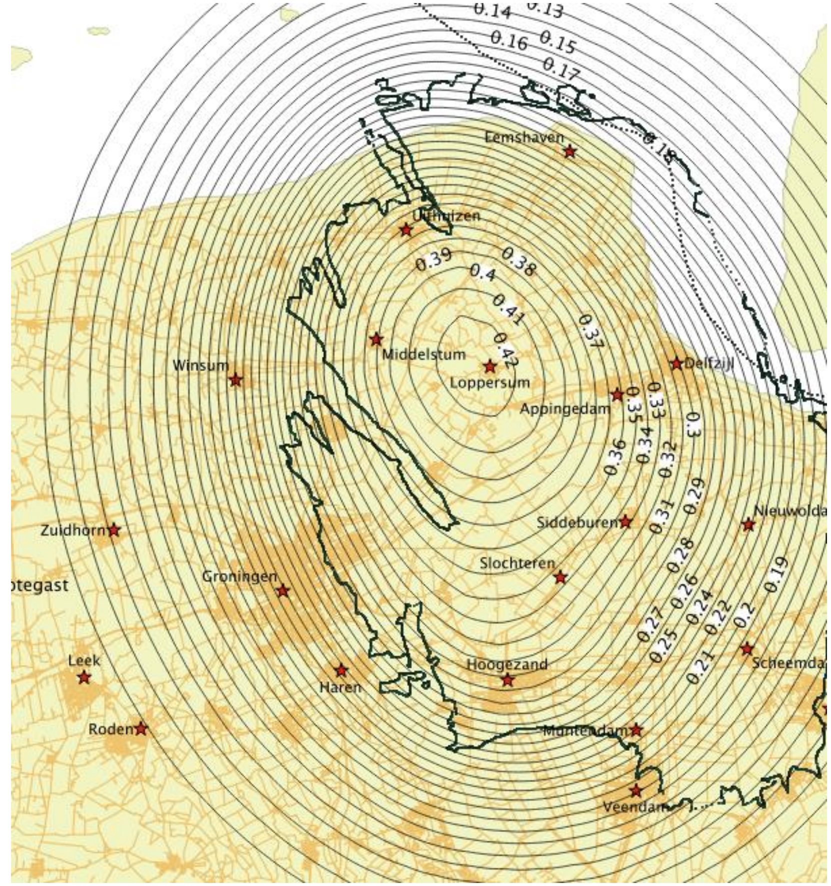
The charts only display data within certain **limits**:

$0.001 \leq PGA\ [cm/s^2] \leq 5000$

$0.0001 \leq PGV\ [cm/s] \leq 500$

PSHA results (NPR)





- Assumptions: Mmax=5, annual seism. rate: 40 (M>1.4), b=1, ASB modified GMPE, 10% probability in 50 years.
- Maximum PGA: 0.42g, maximum PGV: 16 cm/s.

Can we diminish the hazard and risk for Groningen?

- SSM advised the minister of Economic Affairs to limit production in the most active seismic area.

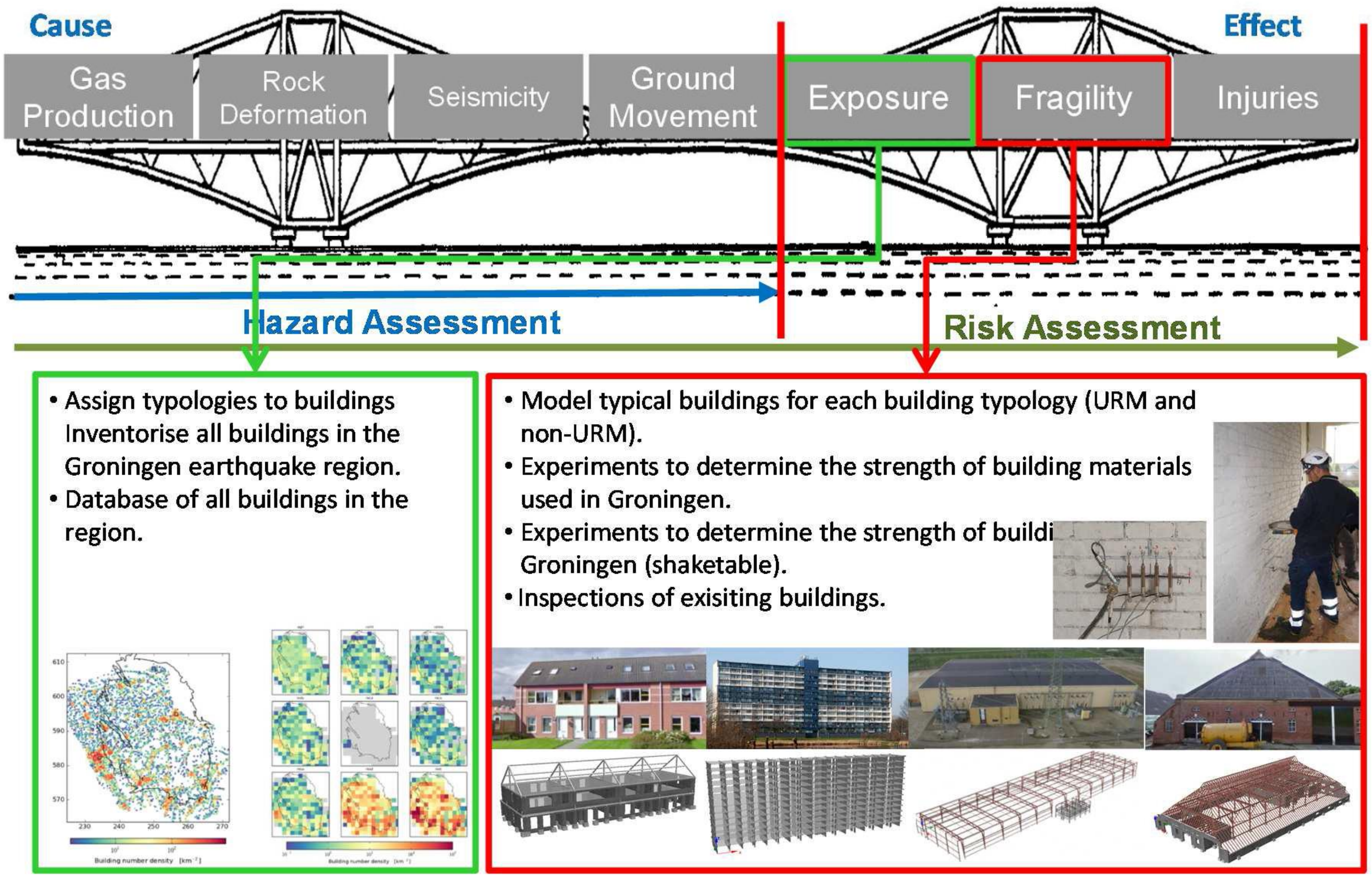
- This seems to lower activity in the region, although there is no statistically significant change observed (M>1,5).

- PSHA results show high PGA/PGV values, due to high (epistemic and aleatory) uncertainties. Improvement of e.g. GMPE for Groningen has a large influence.

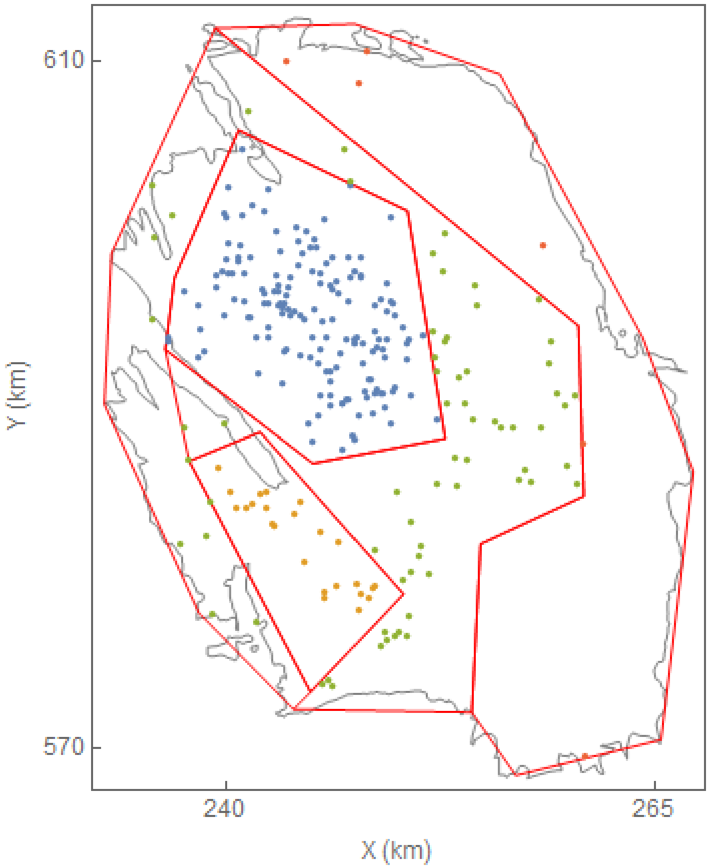
- New version GMPE (V1) is based on stochastic simulation and an extended set of acceleration records from Groningen.

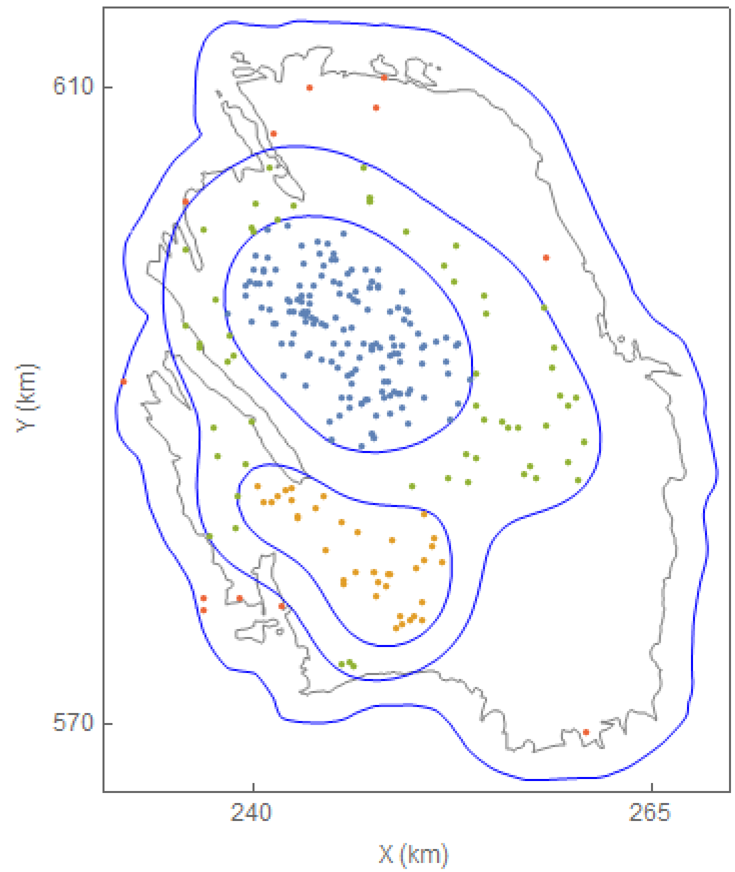
- Improved monitoring is expected to deliver new constraints on the models.

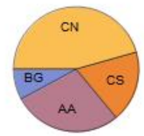
Risk

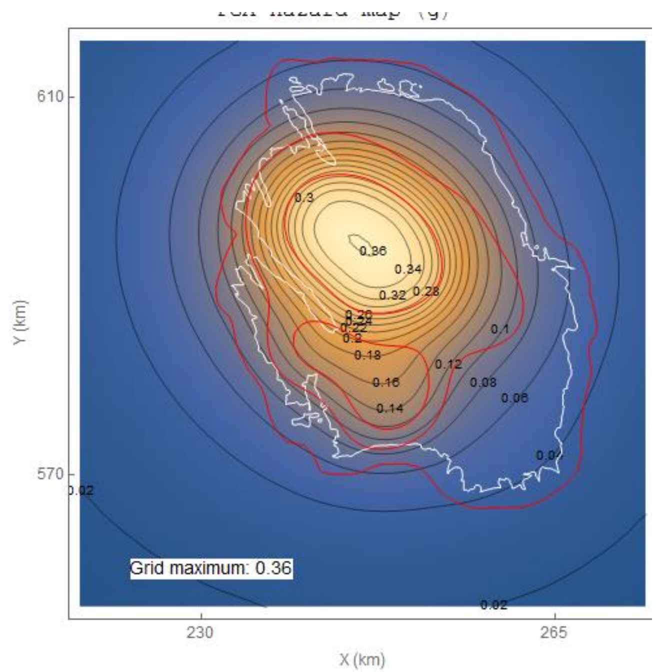


NAM: Hazard and **Risk** assessment for induced seismicity in Groningen, 2015

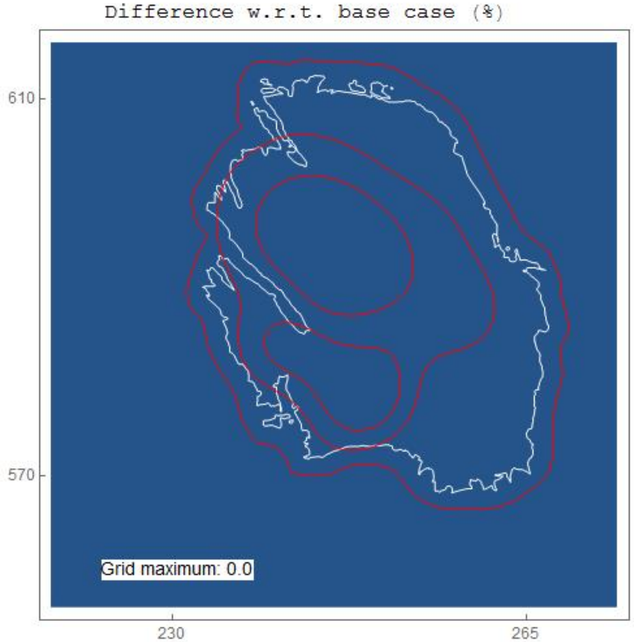

610
570
Y (km)
240
265
X (km)


610
570
Y (km)
240
265
X (km)

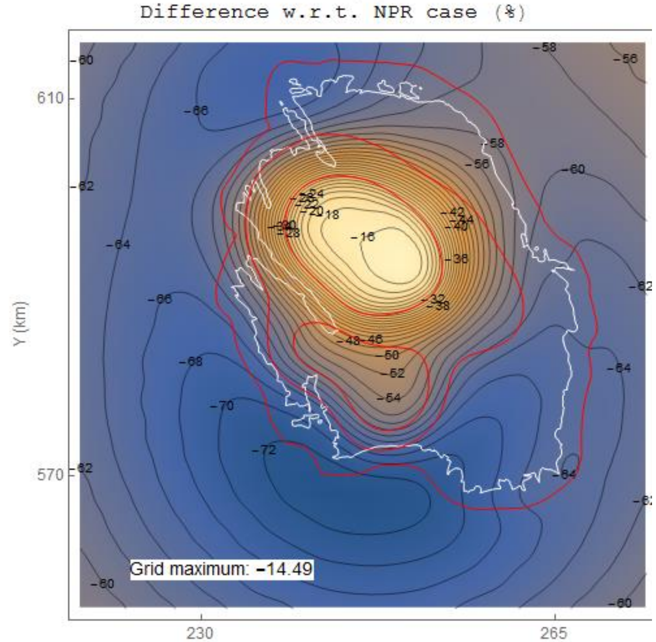
zonation	Z2
calibration time frame (years before 2015-06-01)	5
maximum magnitude model	5.0
ground motion prediction model	V1
return period (years)	475
annual number of events	22.8
b-values per zone	CN: 0.8 CS: 1.1 AA: 1.2 BG: 1.2
average distribution of events per zone (relative)	CN: 0.46 CS: 0.18 AA: 0.28 BG: 0.08 
average distribution of events per zone (annual)	CN: 10.4 CS: 4.2 AA: 6.4 BG: 1.8



Difference w.r.t. base case (%)



Difference w.r.t. NPR case (%)



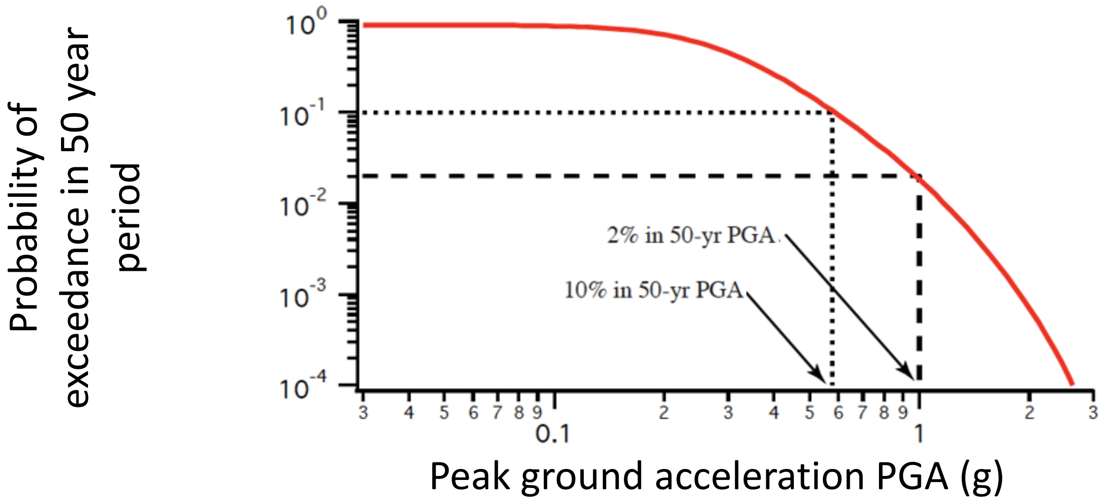
Seismic Hazard Assessment

- Seismic hazard: probability of exceedance of certain ground motion level, such as peak ground acceleration (PGA)

HAZARD = EARTHQUAKE DISTRIBUTION * GMPE

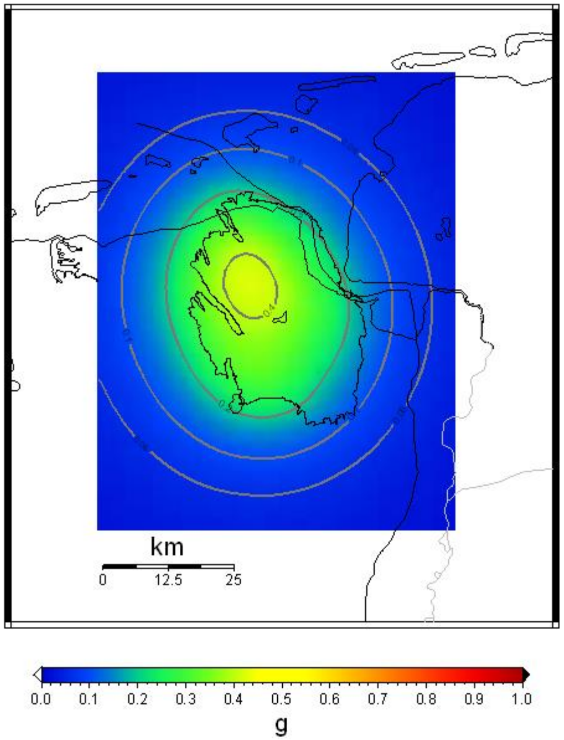
- Seismic risk: chance of exceedance of a certain damage level, such as economic loss or number of casualties

RISK = HAZARD * EXPOSURE * FRAGILITY * COST

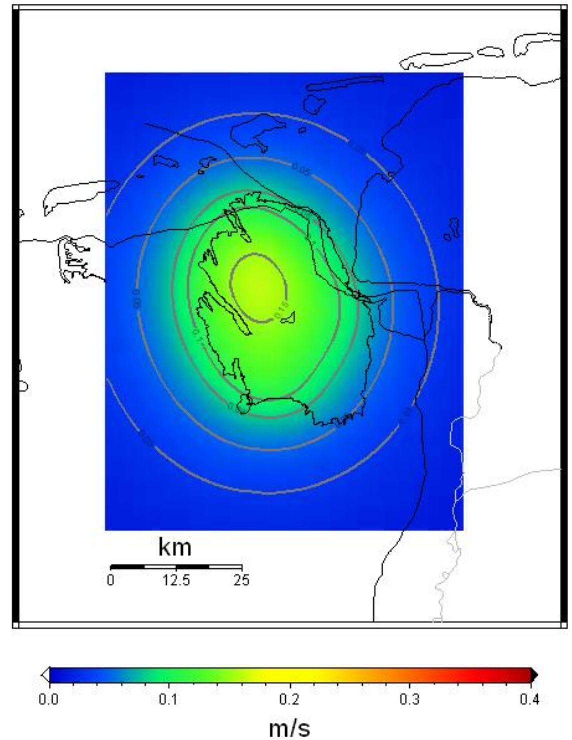


After: Kramer (1986)

PSHA results



PGA



PGV

- Assumptions: M_{max}=5, annual seism. rate: 40 (M>1.4), b=1, Akkar et al. modified GMPE, return period 475 years.
- Maximum PGA value 0.42g, maximum PGV: 16 cm/s.

Dost et al. (2014)