Hydrocarbon induced seismicity in Northern Netherlands

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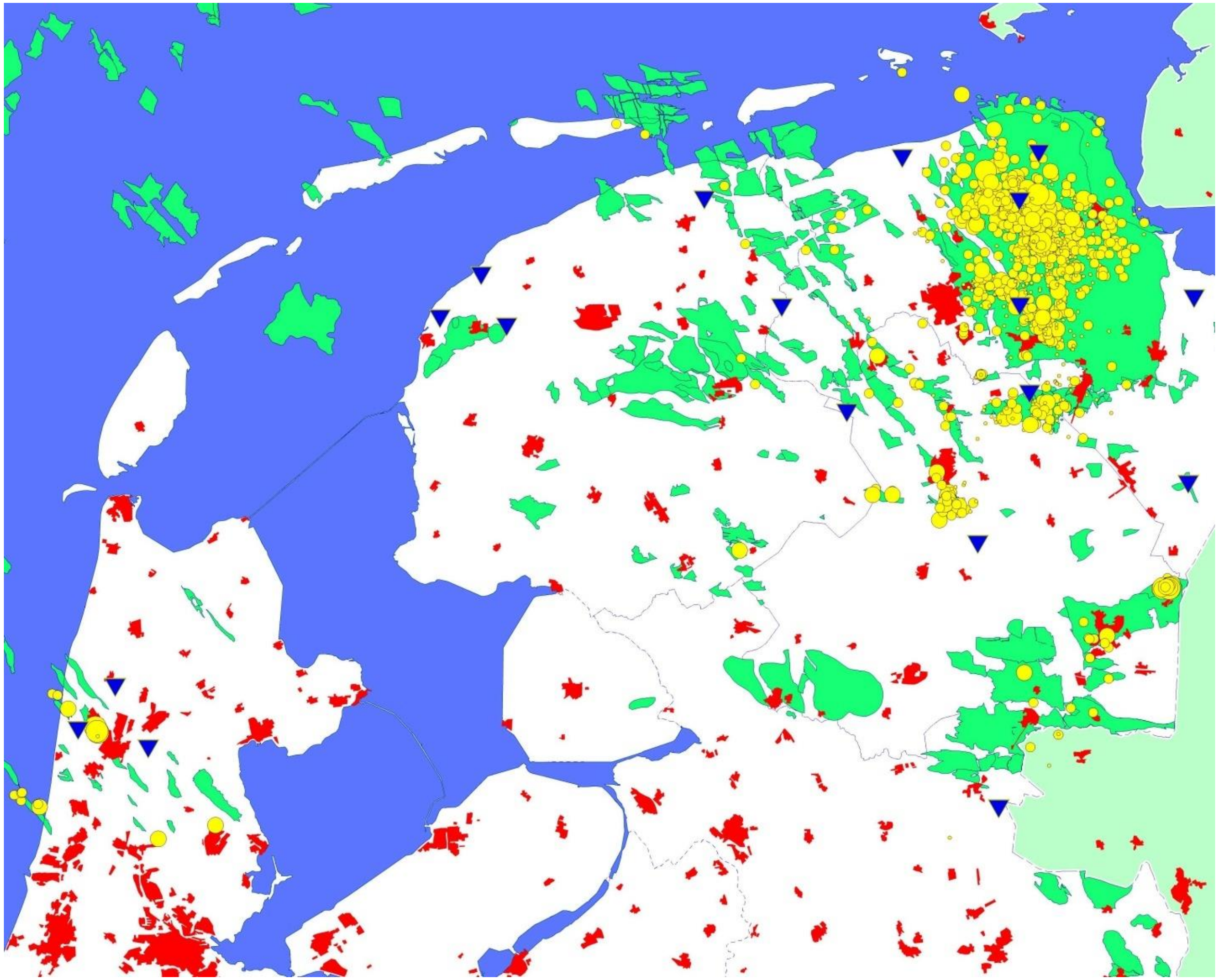
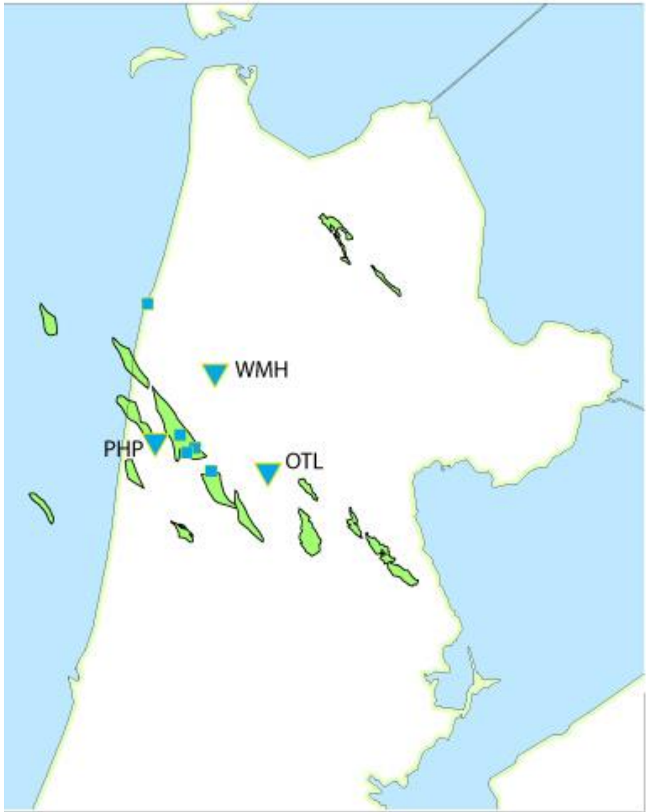
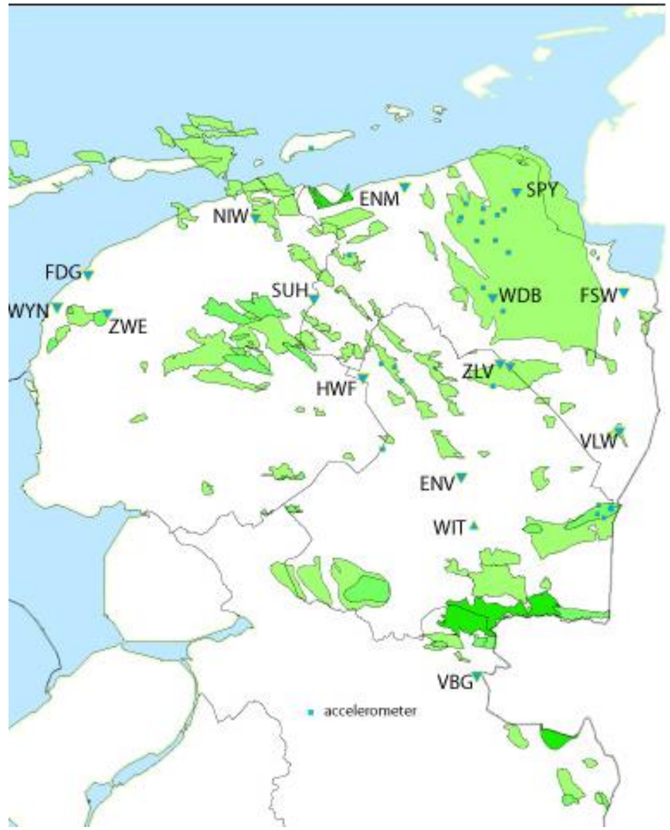
KNMI

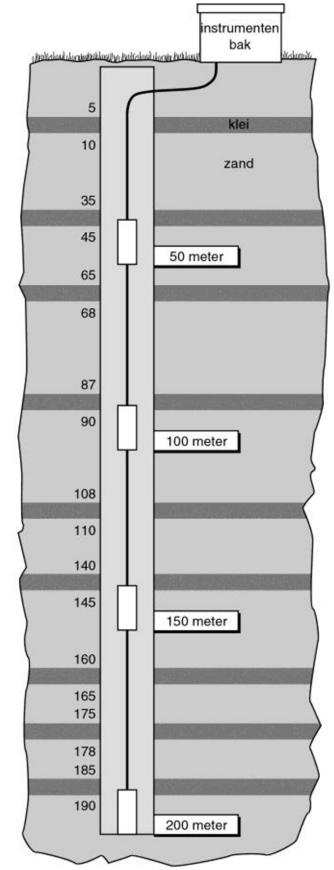


- Induced seismicity 1986-2015
- Since 2003 Groningen field is most active (~ 3000 bcm initial volume, 30*40 km)
- >1100 events recorded since 1986; Groningen 800 events, 250 M> 1,5
- Largest event recorded M=3,6; reservoir at 3 km depth
- >30000 damage claims over the last few years; population Groningen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

Monitoring network and instrumentation





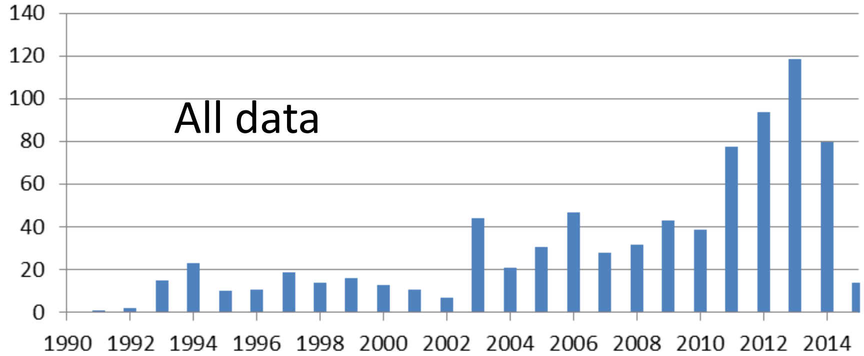


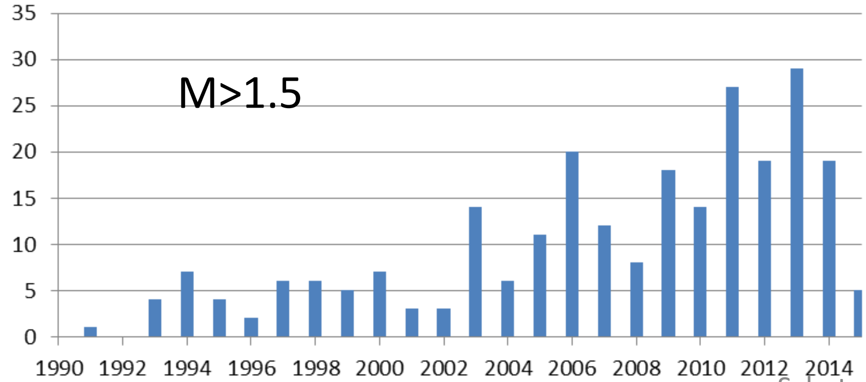
Borehole network (17) designed to detect and locate induced events in the region. Accelerometer network (23) used to provide insight in PGA&PGV values needed for evaluation of damage. KNMI is owner of the network and data.

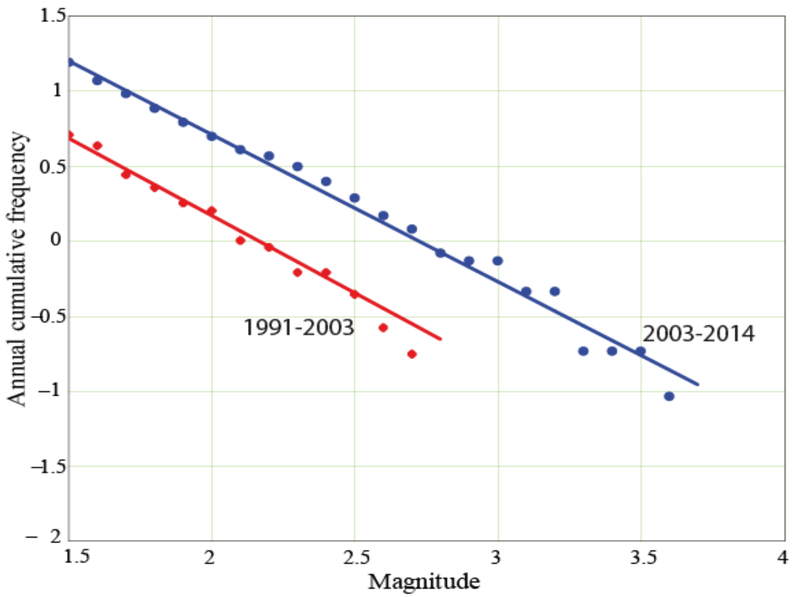
One downhole tool (2km depth) at Bergermeer (since 2010) and two downhole tools (3km depth) at Groningen (since end 2013). Data ownership at mining companies

Groningen seismicity

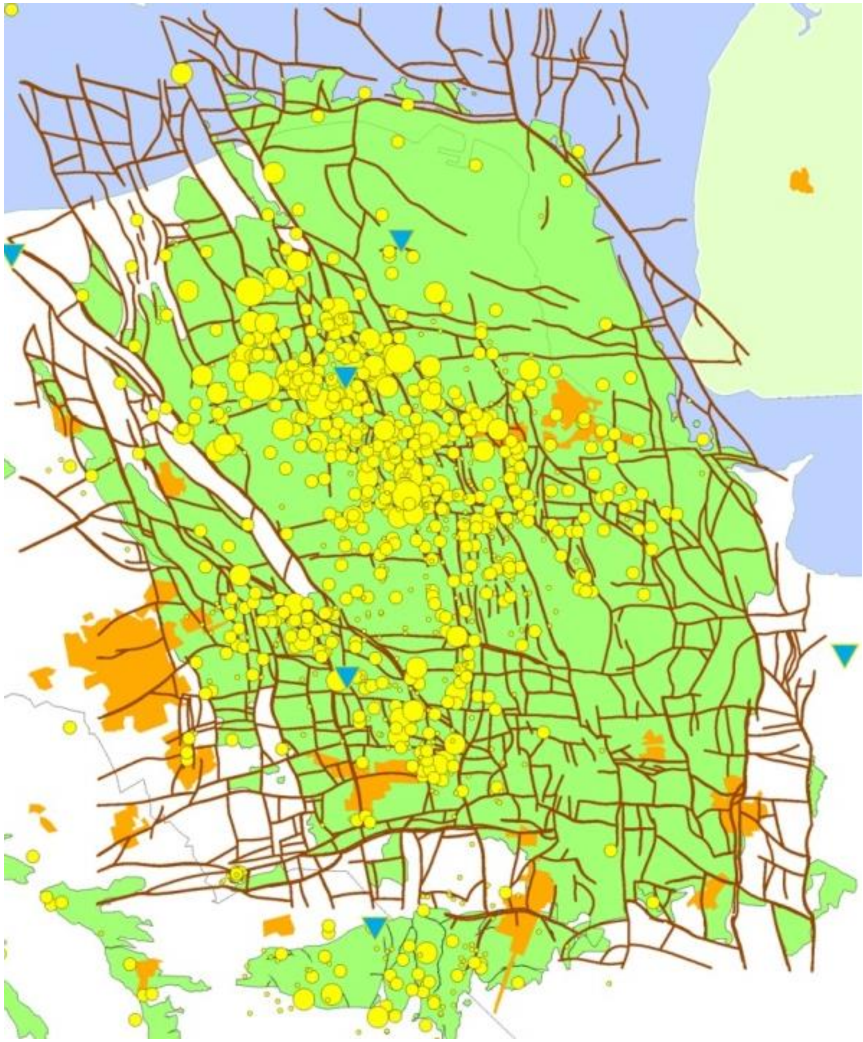
- First event in 1991, moderate activity until 2003
- Since 2003 increase in activity rate, no significant change in b-value
- No reliable M_{max} could be determined for the Groningen field alone
- Magnitude completeness M= 1,5
- Clearly non-stationary process



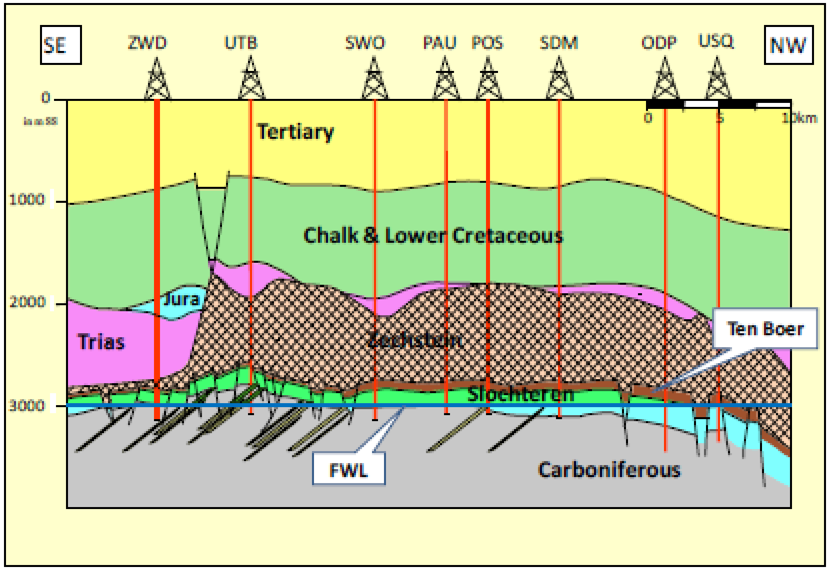




Seismicity and Geology



- 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



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)

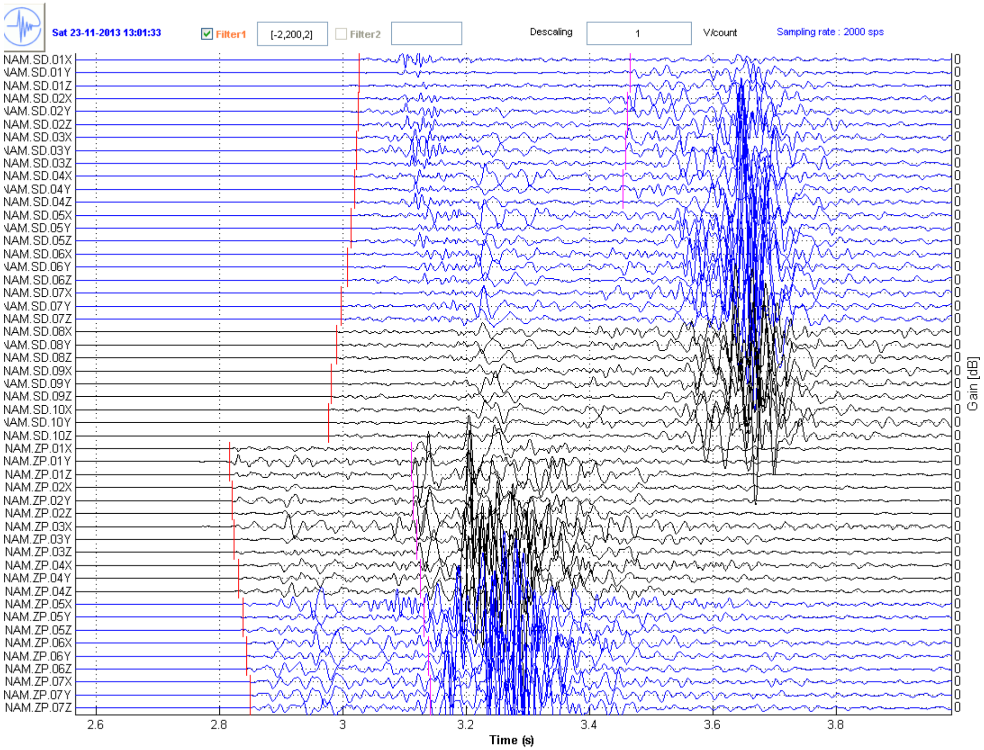
Network development:

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)

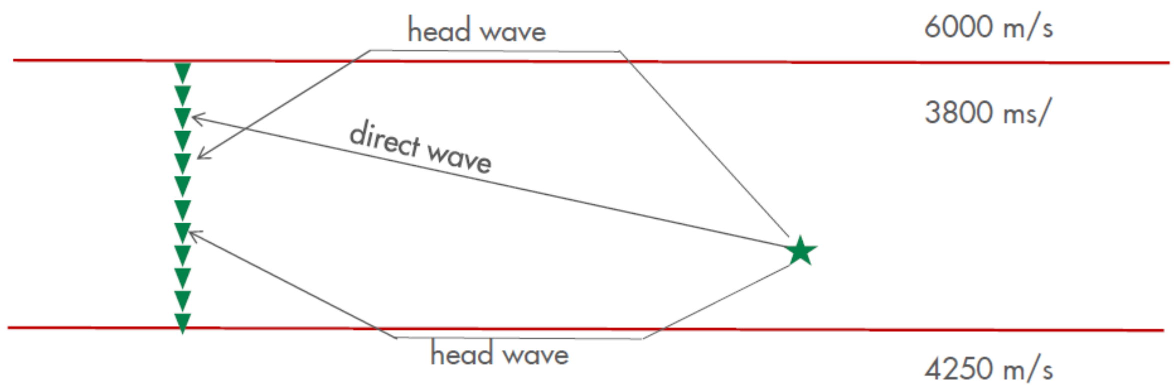
The ownership of the new shallow borehole arrays and accelerometers will be at KNMI



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

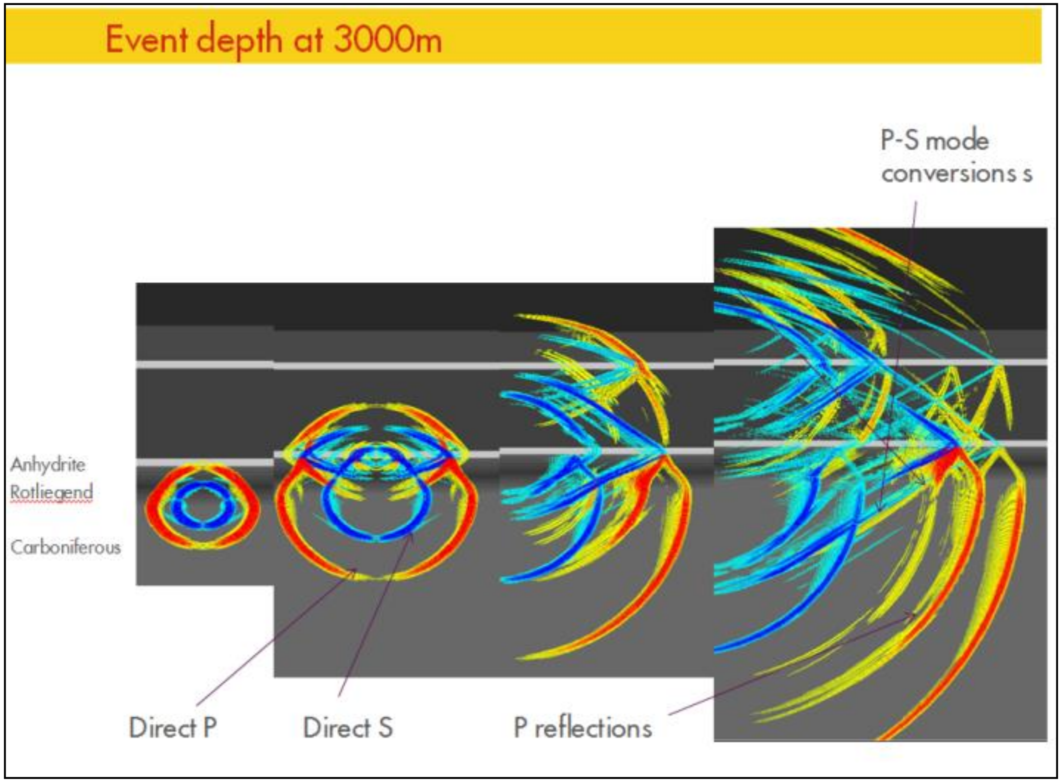
Complex pattern of arrivals

Source: magnitude

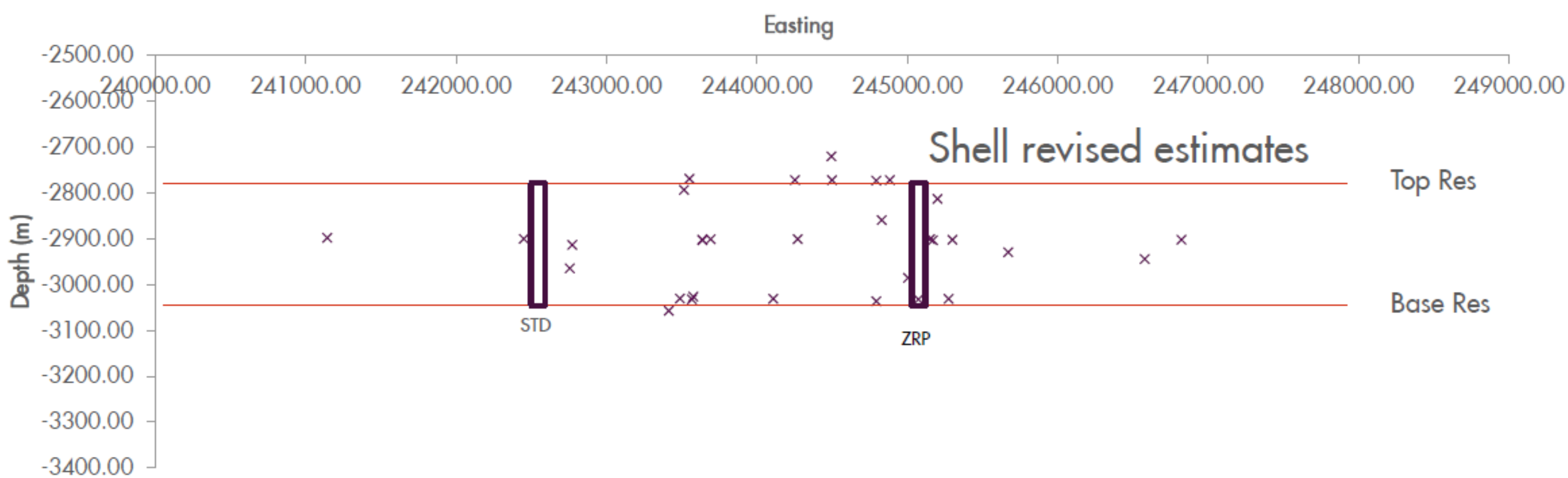


Head waves traveling through the higher velocity layers may arrive earlier than the direct waves traveling through the lower velocity layer

Source NAM



Steve Oates et al., 2014



Hazard and risk

- 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 Netherlands State Supervision of the Mines (SSM).
- KNMI and TNO asked to review the results

Hazard and risk

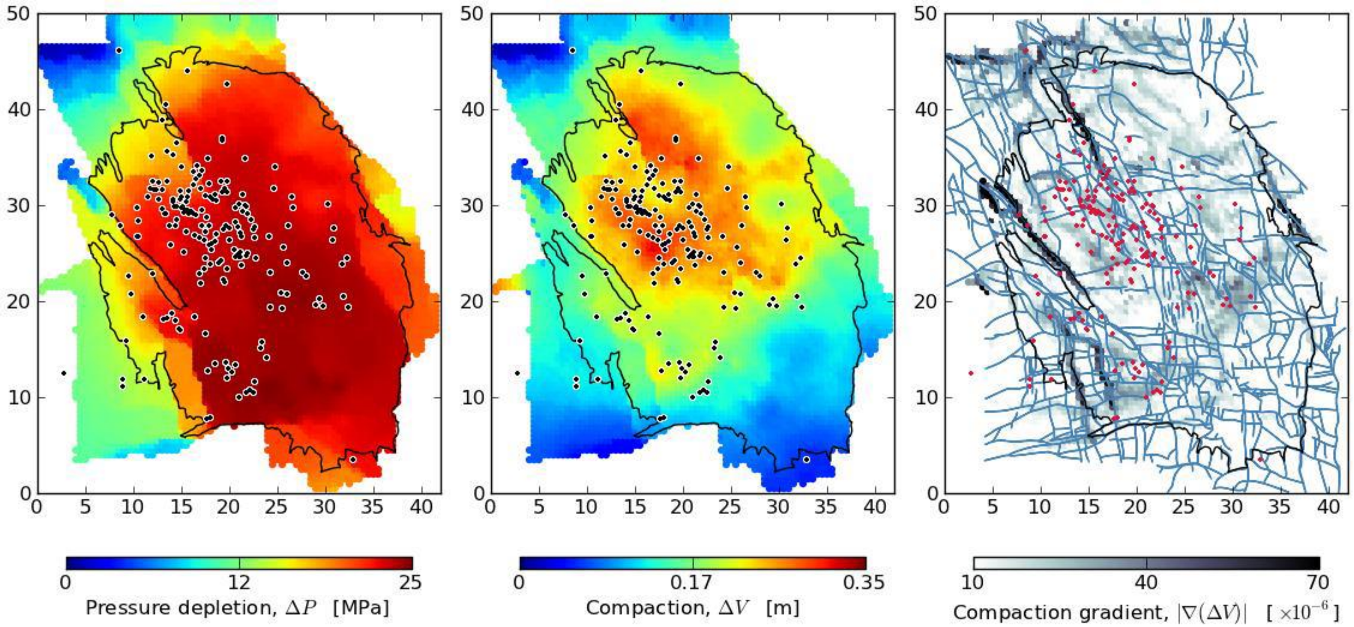
Source model → GMPE → Hazard map → vulnerability → Consequences

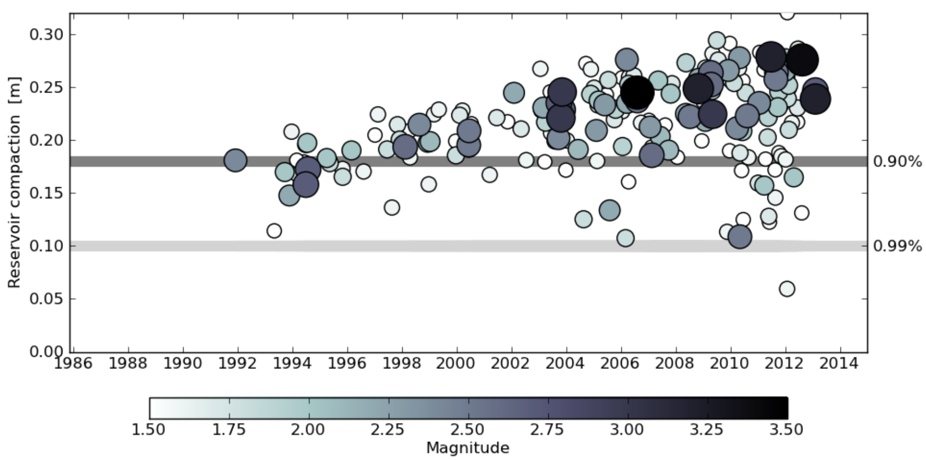
Probabilistic Seismic Hazard Analysis (PSHA) – step 1-3

- Source model: based on past seismicity or physical process (compaction; NAM/Shell, TNO)
- No GMPE for Groningen available. Hazard of small shallow induced earthquakes (M<4) is generally not well studied (Bommer, Edwards, KNMI, Deltares)

- Vulnerability: there is no building code for earthquake related damage for the Netherlands. Fragility curves are being developed (Arup, Pinho, Crowley, Bommer, TNO..).
- A national guideline for building codes induced earthquakes is being developed by the national normalization institute (NEN)

PSHA (physical) source model





Seismicity and compaction
Source: Shell/NAM

Probabilistic Seismic Hazard Analysis (PSHA)

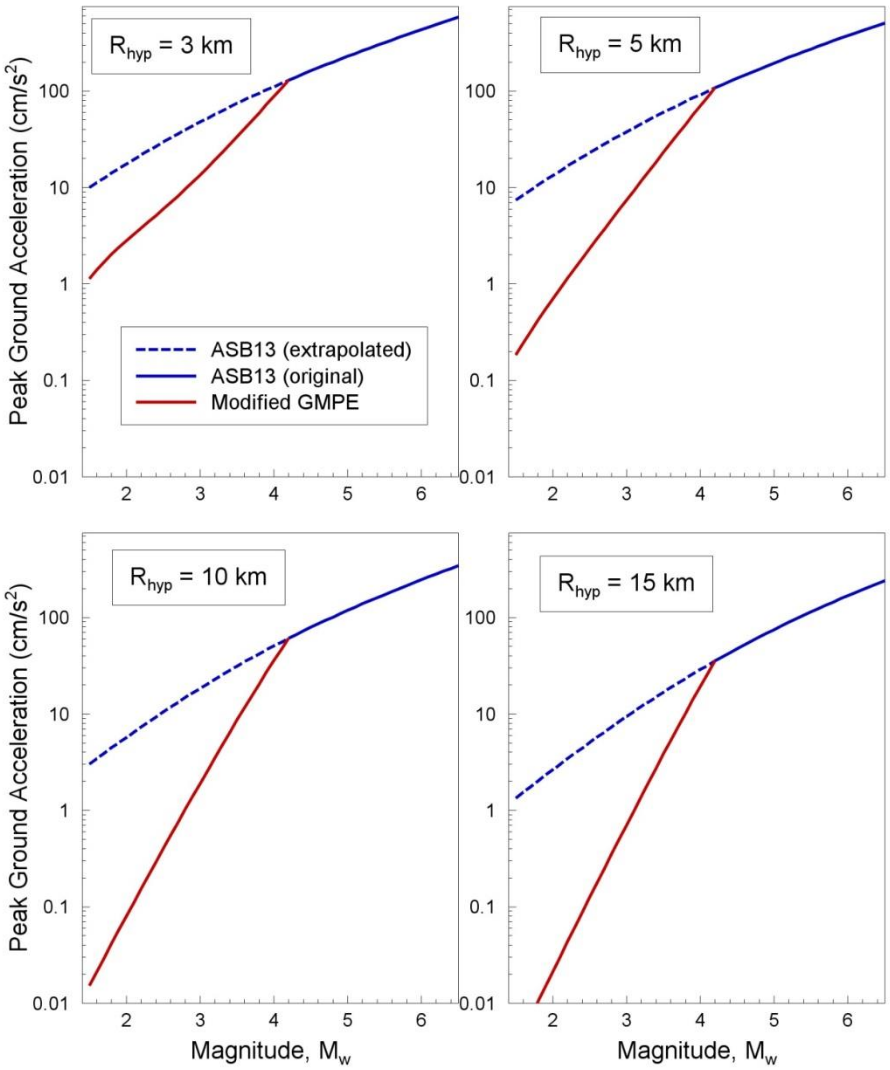
- Non stationary process
- Two approaches:
  - Conventional PSHA, based on seismic zonation and an increasing seismicity rate with time as source model
  - Monte Carlo PSHA model, based on a compaction model for the Groningen field (Bourne et al., 2014, JGR)
- Both models use the same Ground Motion Prediction 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

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

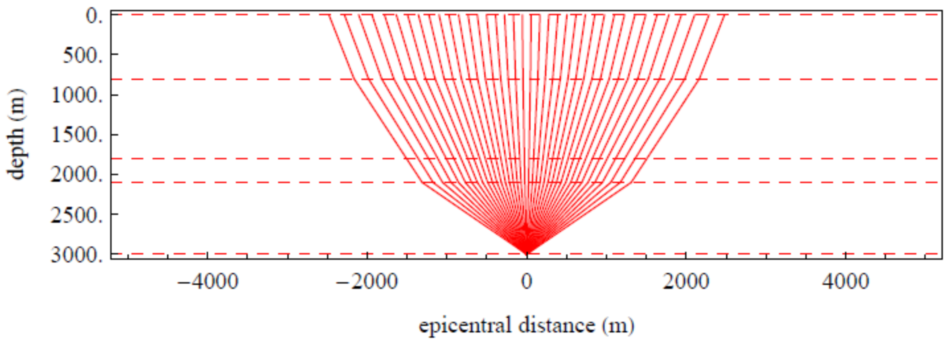
Why are the PGA and PGV values for Groningen so low?

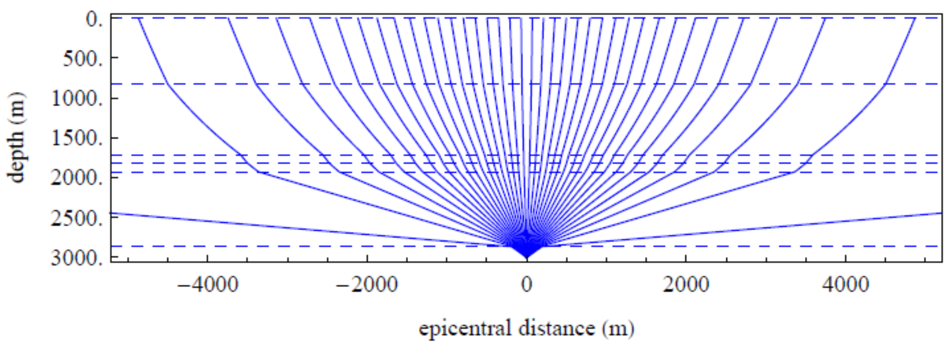
A possible explanation is the effect of the overlying Zechstein layer as high velocity layer

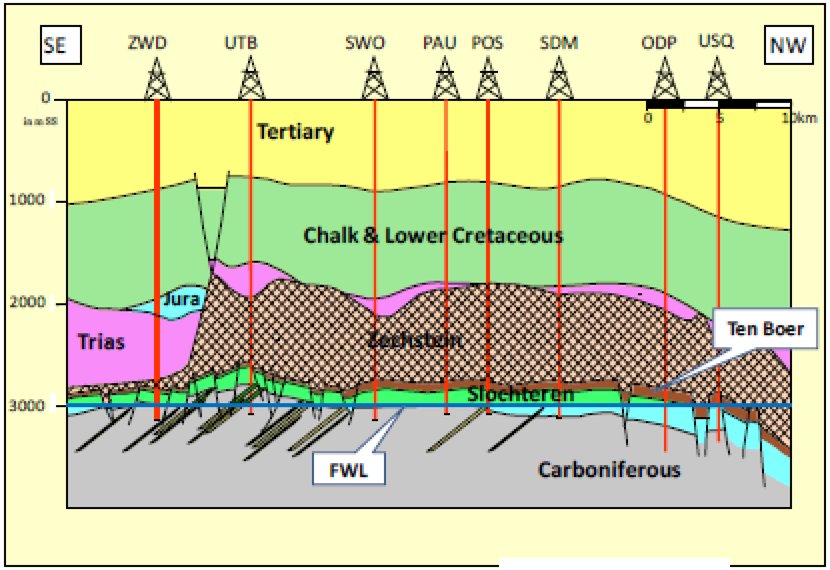


Bommer, 2013

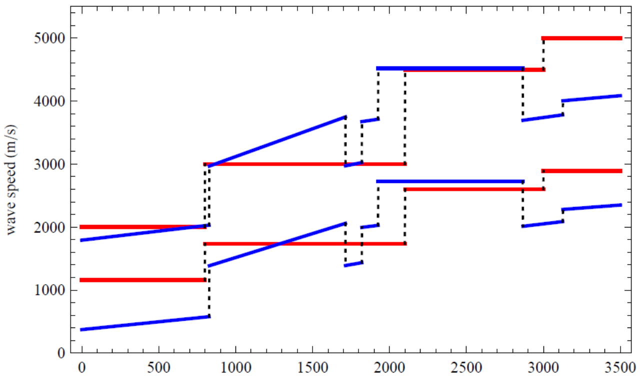
Salt influence: defocusing







source NAM



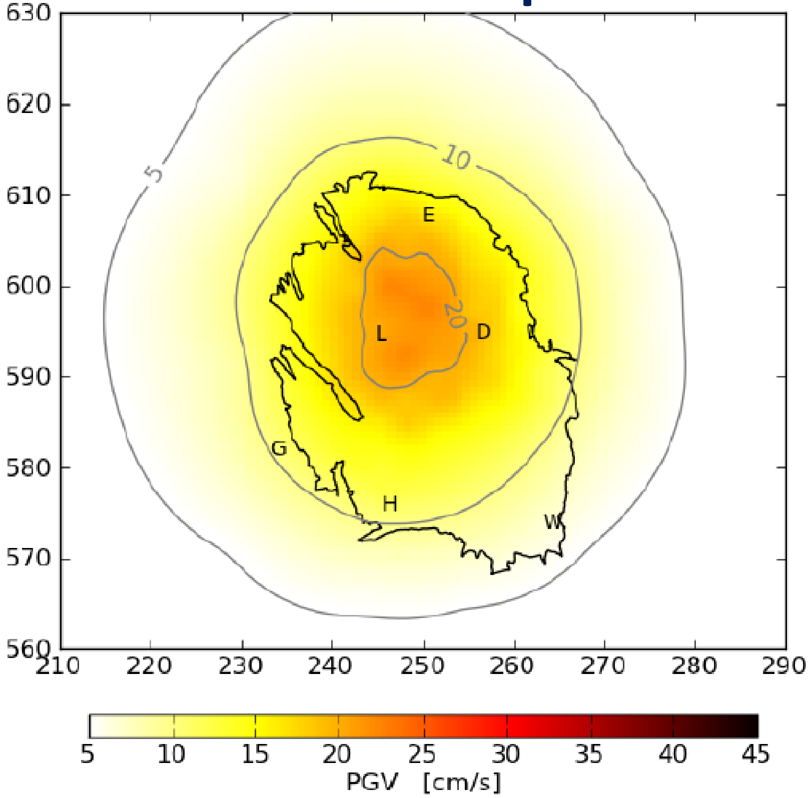
Average (regional) model

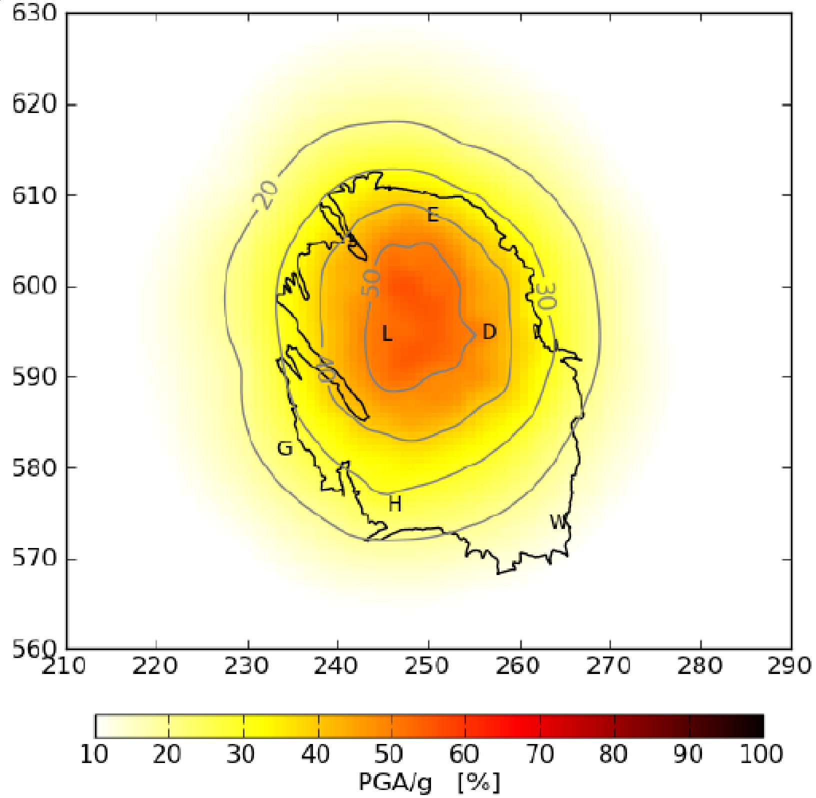
VELMOD model (1D sample)

Kraaijpoel & Dost, 2012, J. of Seism.

PSHA for the Groningen Field

PGV (max. 22 cm/s) and PGA (max. 0.57*g*) values with a 2% probability of exceedance over the period 2013-2023
Source: compaction model; method: Monte Carlo





Bourne *et al*. (2014)

Can we diminish the hazard and risk?

- 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
- Different compaction models fit the subsidence data equally well, but do have a different delays (3 months- 7 years). Which model to use?
- 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
- Ongoing research on all topics related to probabilistic risk calculations will be input for the next production plan for Groningen, that has to be submitted and evaluated in 2016.
- Improved monitoring is expected to deliver a wealth of new data and new techniques can be applied to improve location and detection.

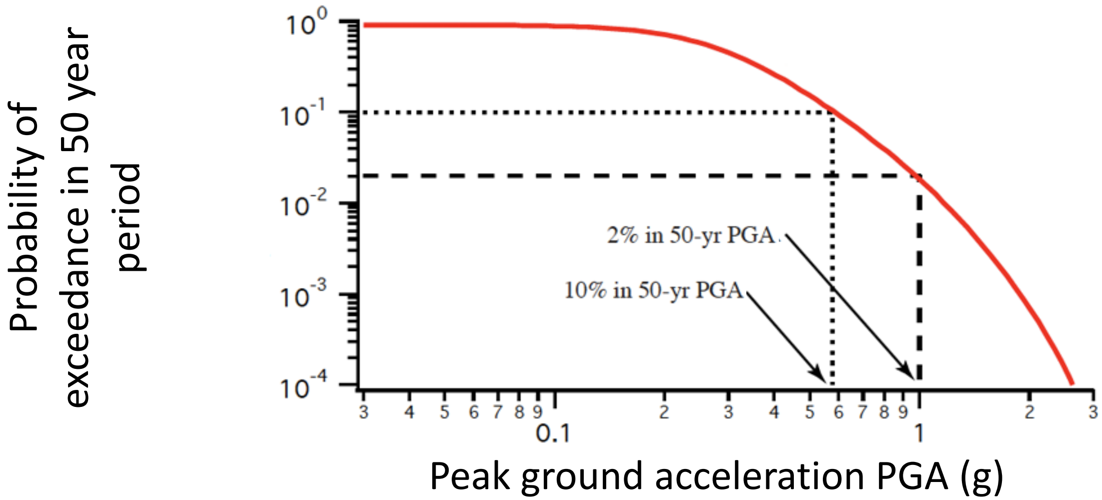
Seismic Hazard Assessment

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

HAZARD = EARTHQUAKE DISTRIBUTION * GMPE

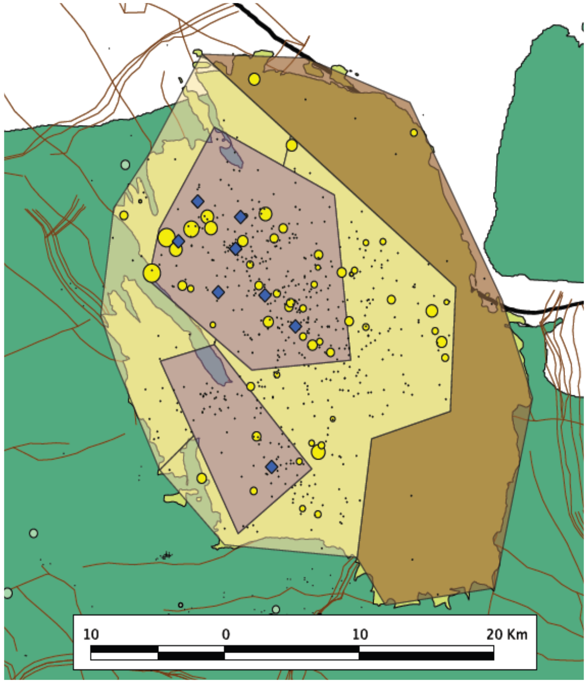
- Seismic risk: chance of exceedance of a certain damage level, such as economic loss or number of casualties

RISK = HAZARD * EXPOSURE * FRAGILITY * COST

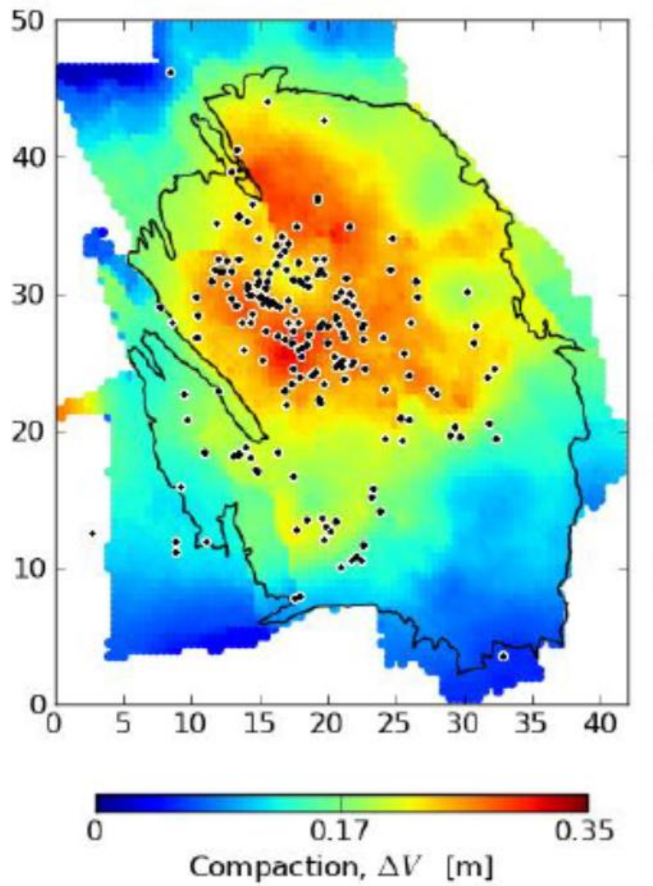


After: Kramer (1986)

Source models



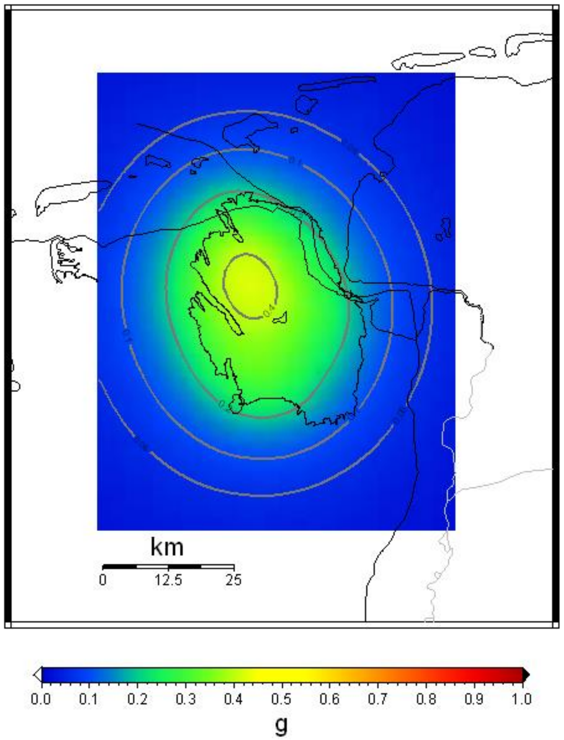
Classic zonation



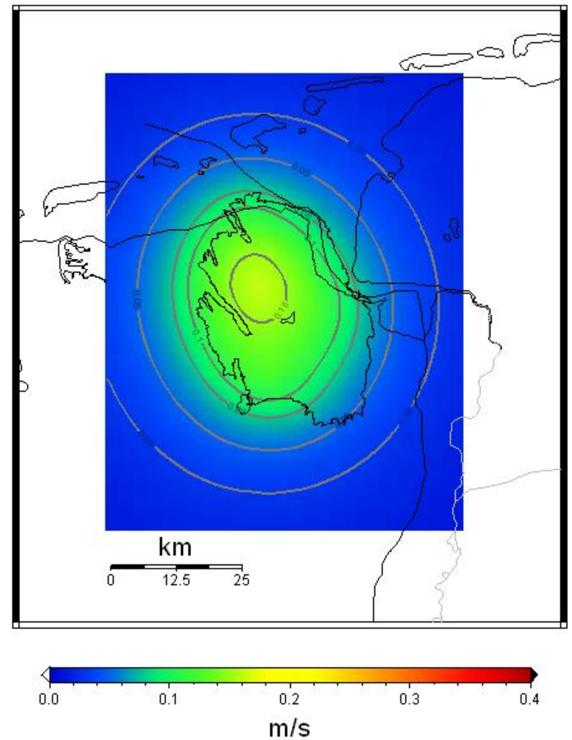
Physical model

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

PSHA results



PGA

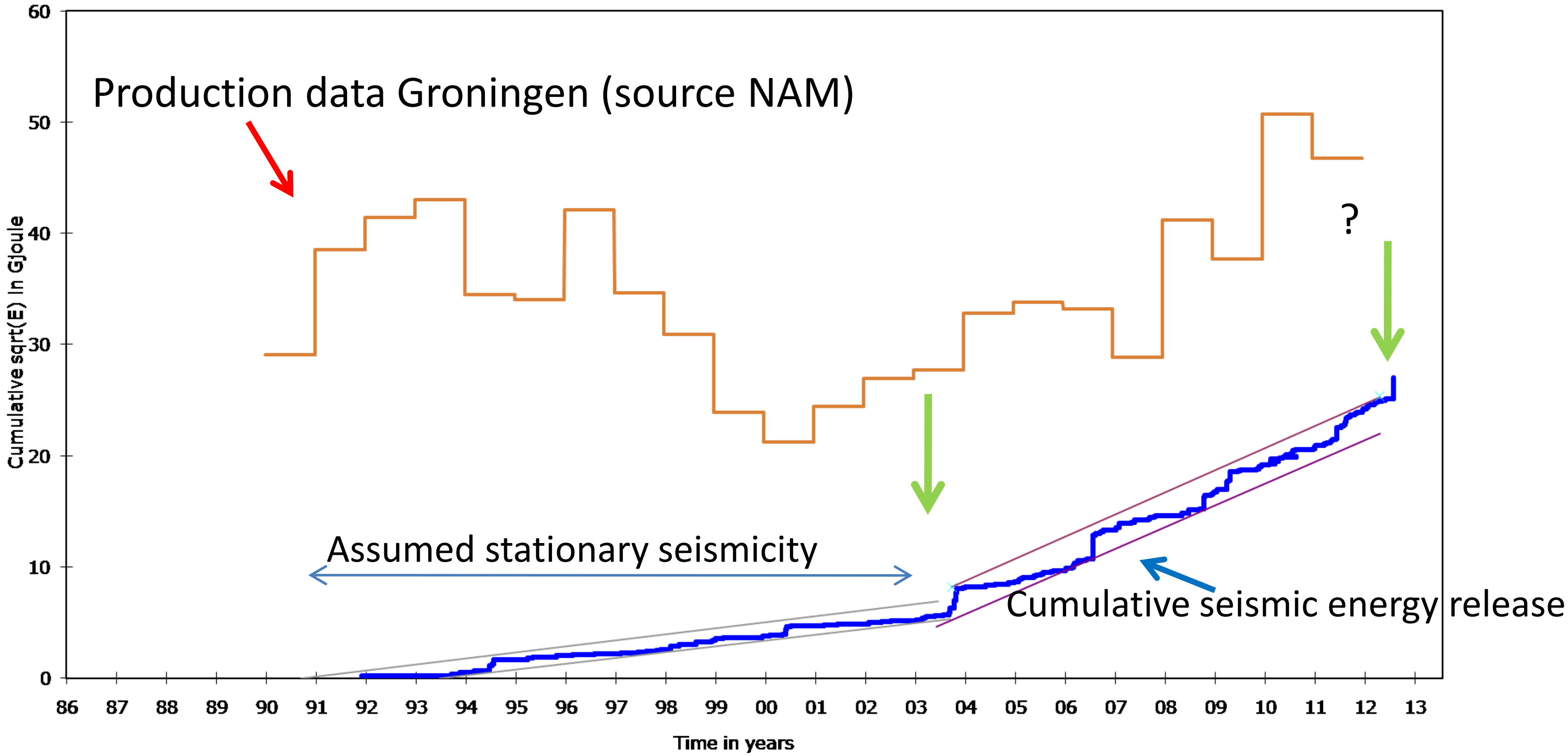


PGV

- 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)

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.