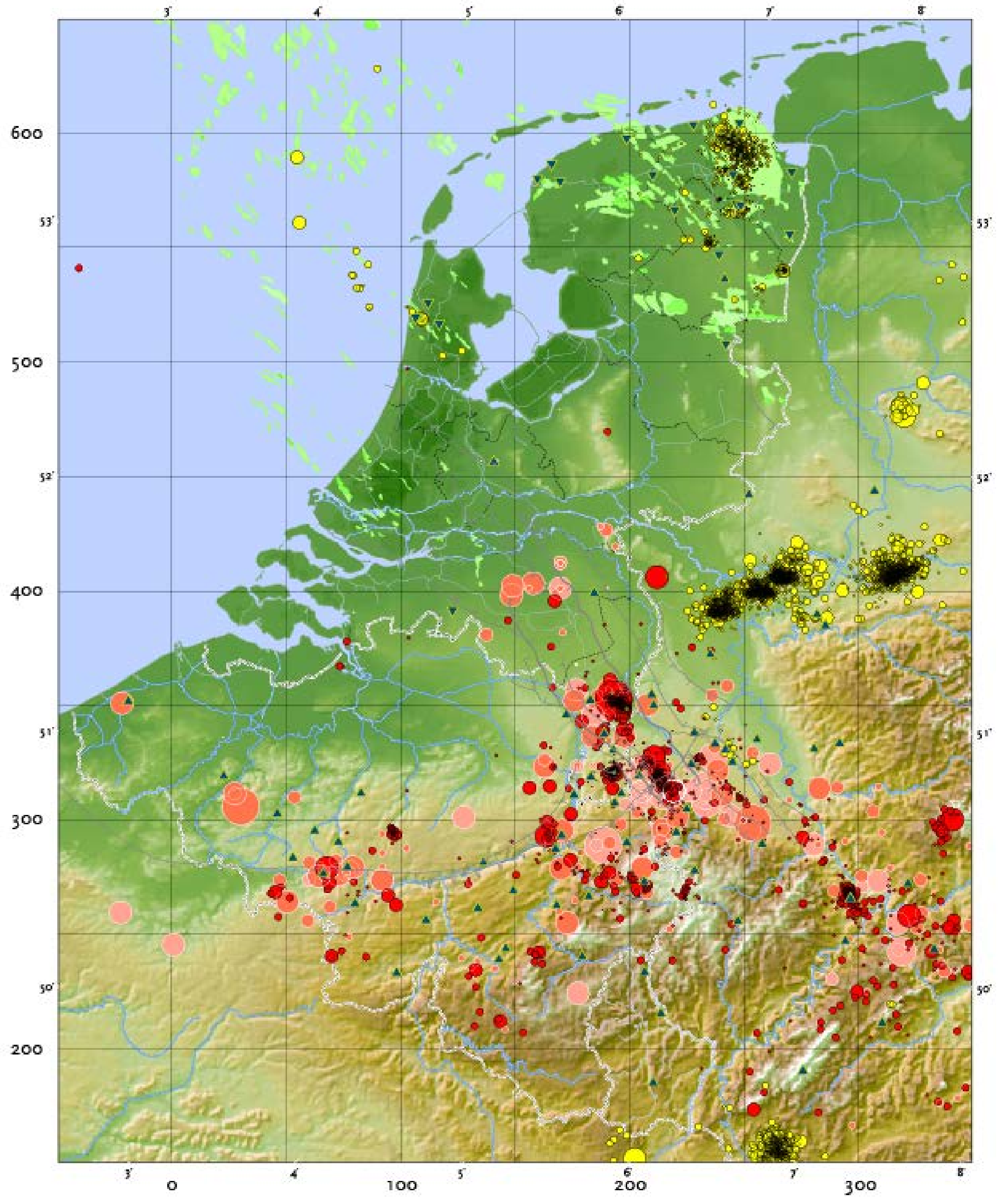
Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

Measuring seismicity in the Groningen Field

Bernard Dost, Elmer Ruigrok, Jesper Spetzler,
Gert-Jan van den Hazel, Jordi Domingo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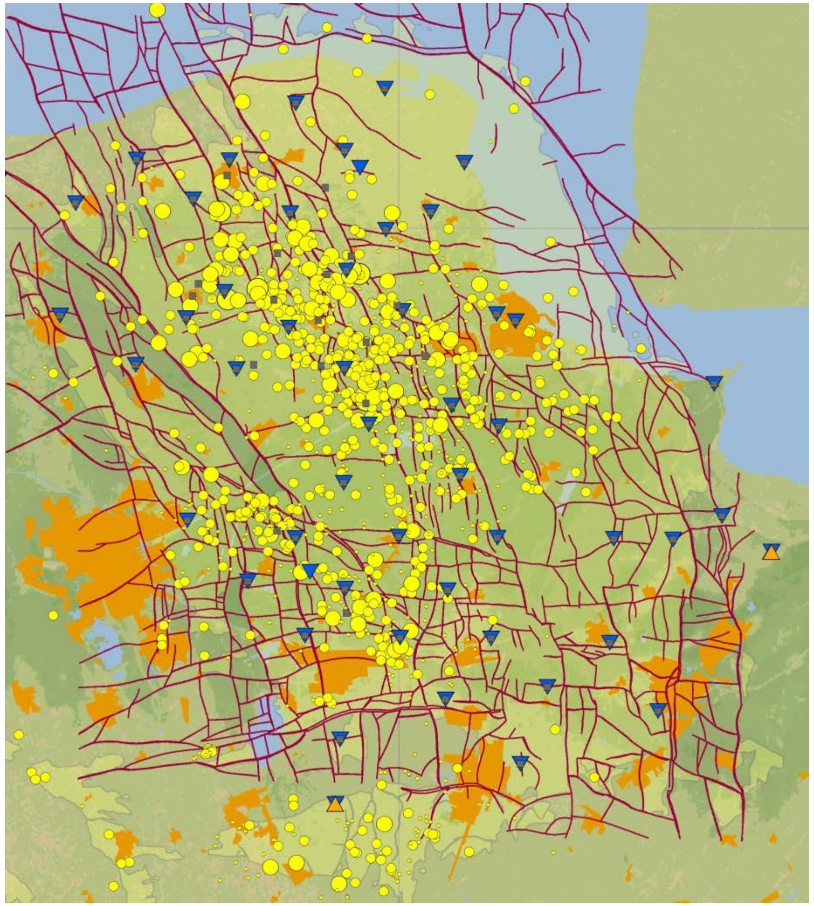
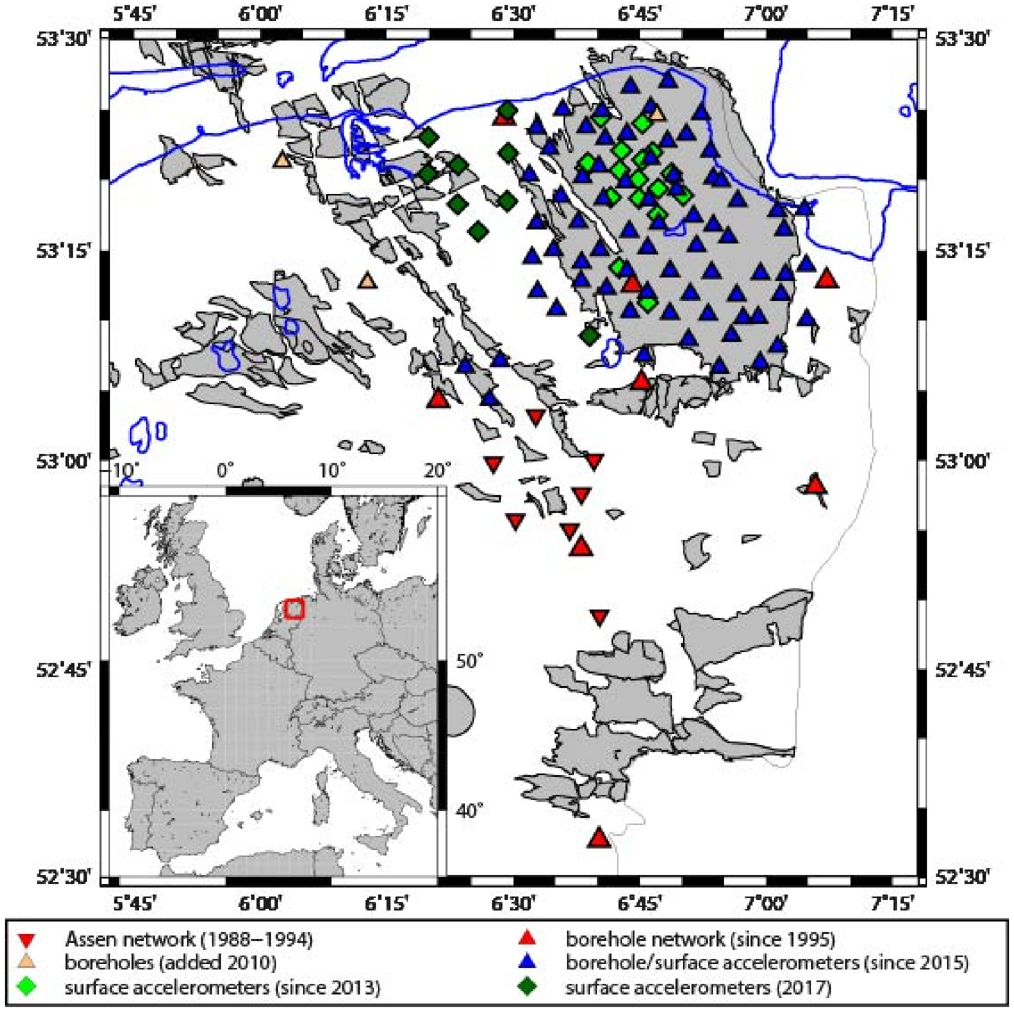


Monitoring induced seismicity in the Netherlands. Instrumentation and network design

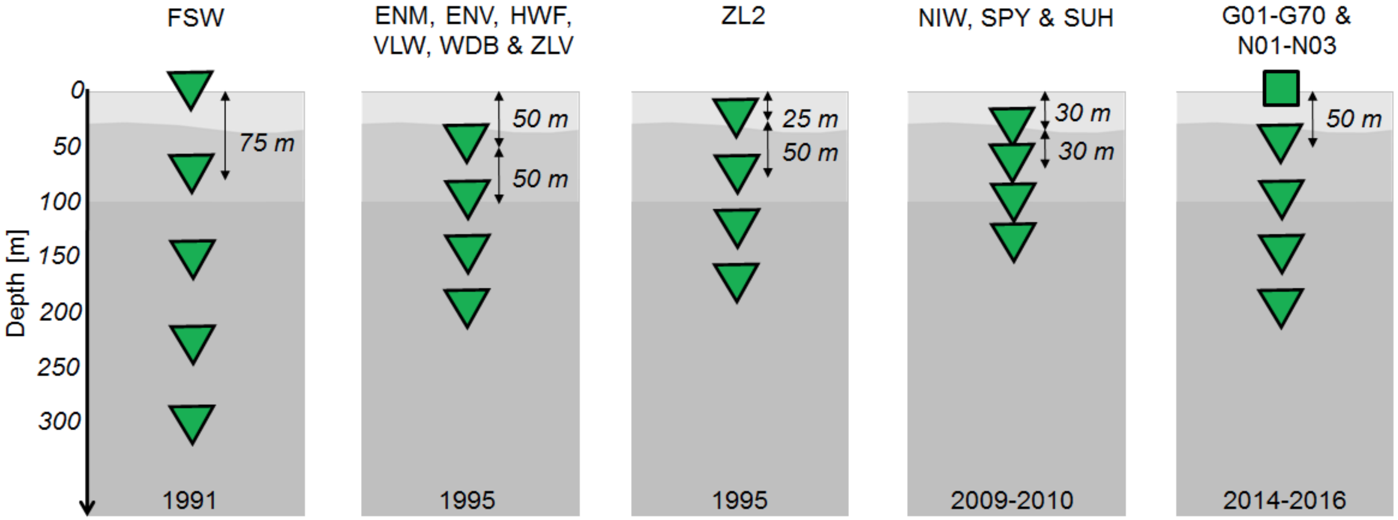
Data analysis; accuracy of earthquake locations. Are we capable to identify re-activated faults?

Magnitude relations; shallow structure; source mechanism; data availability and products

Instrumentation

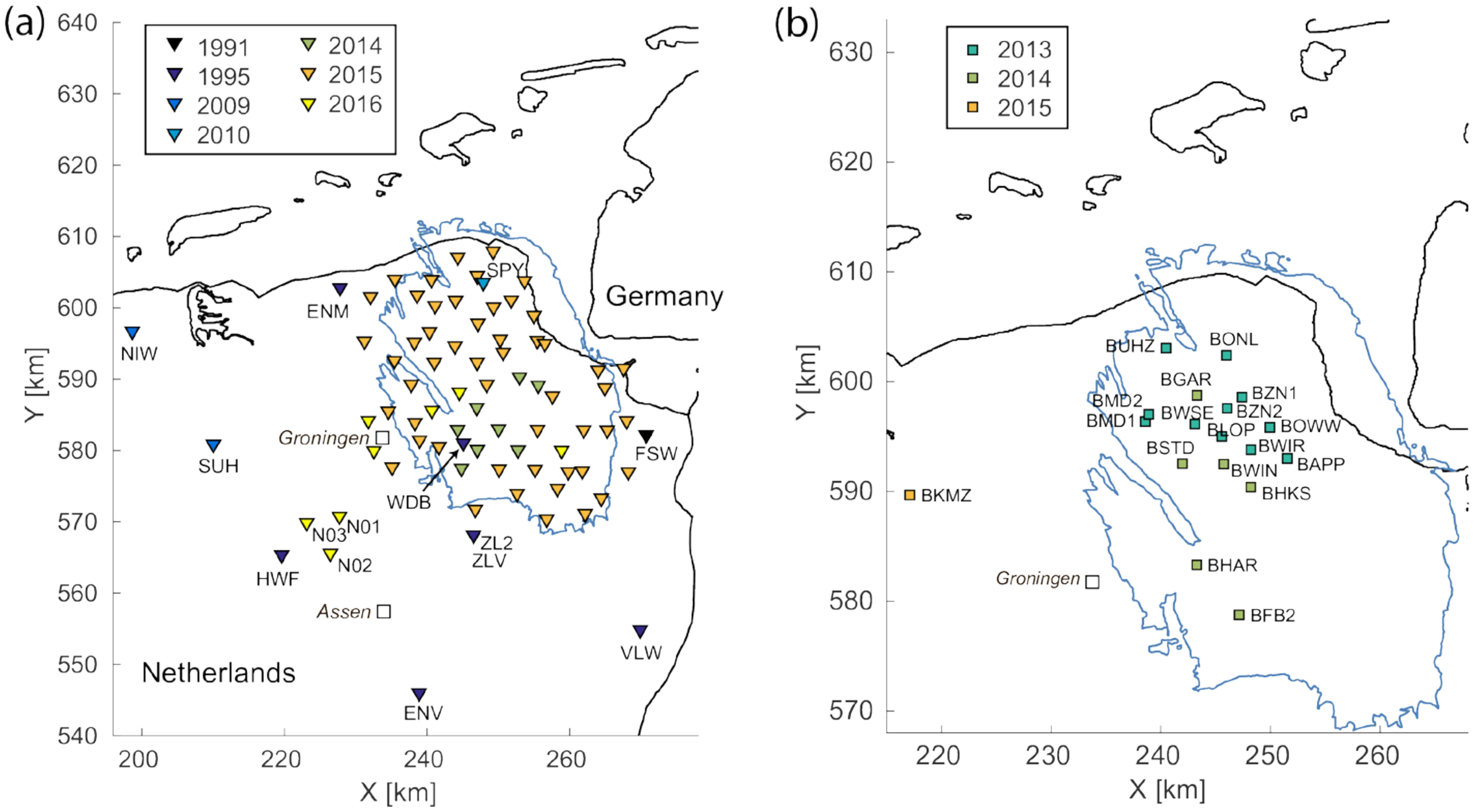


Borehole instrumentation



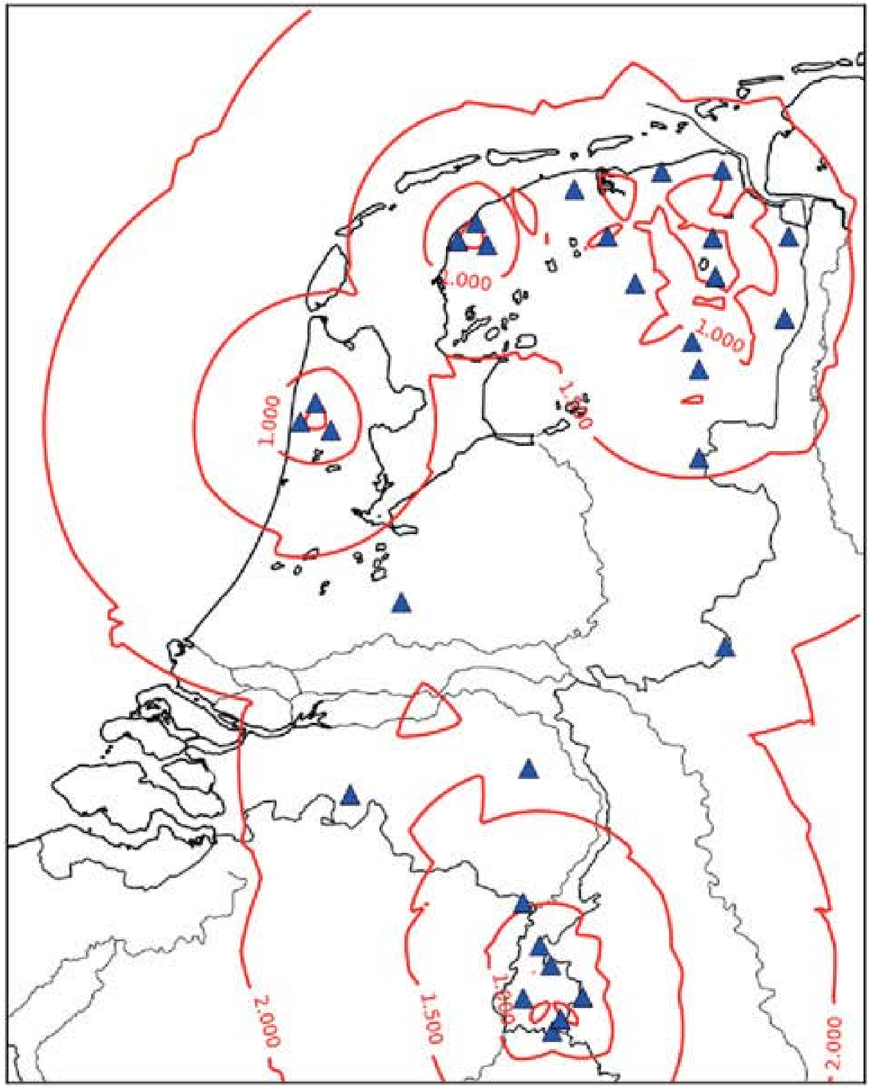
- Boreholes without casing, configuration changes over time
- Geophones (4.5 Hz) and accelerometers (episensors)
- Orientation of the sensors at depth is unknown and should be determined.
- Real time data transfer, start: mobile communication (4G), since 2017: all DSL

Network development

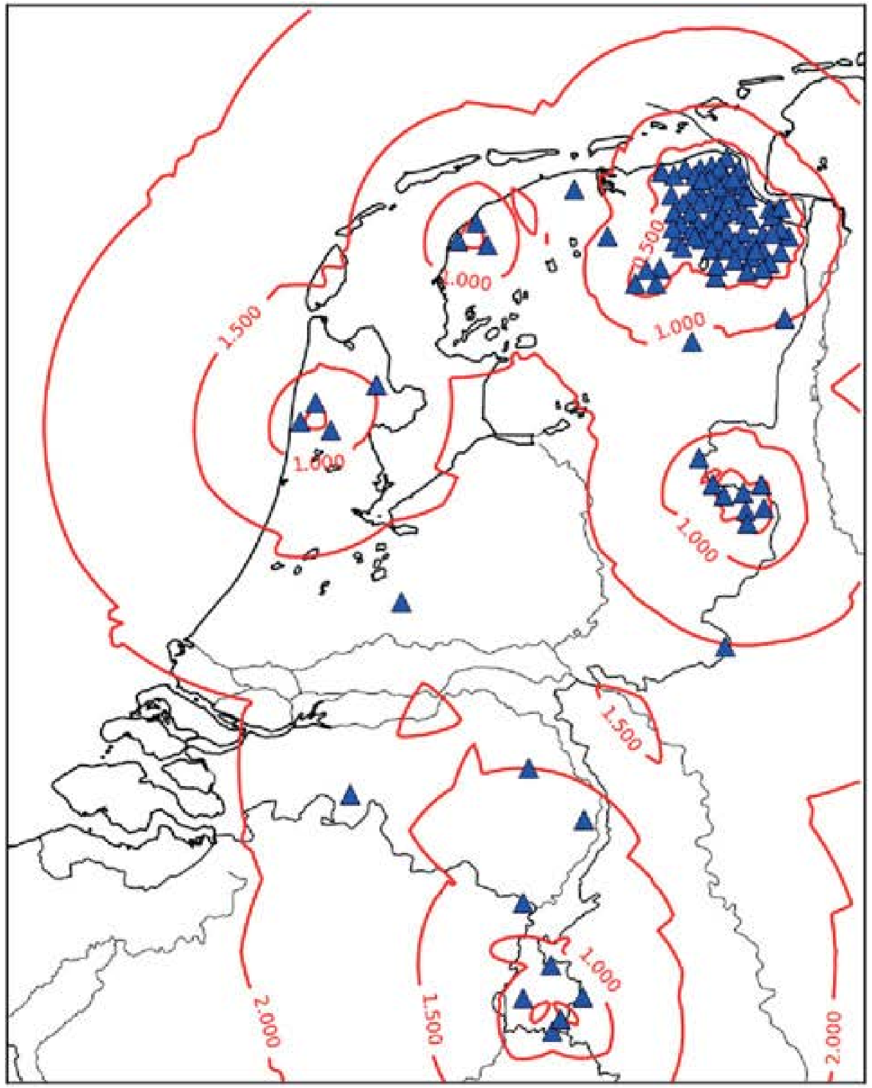


>70 multiple level borehole stations (200m deep) including accelerometers at the surface
3 deep boreholes equipped with geophones near reservoir level (3km, NAM)
4 STS-5 at 100m depth (broadband instruments, will be installed early 2018)

Network design

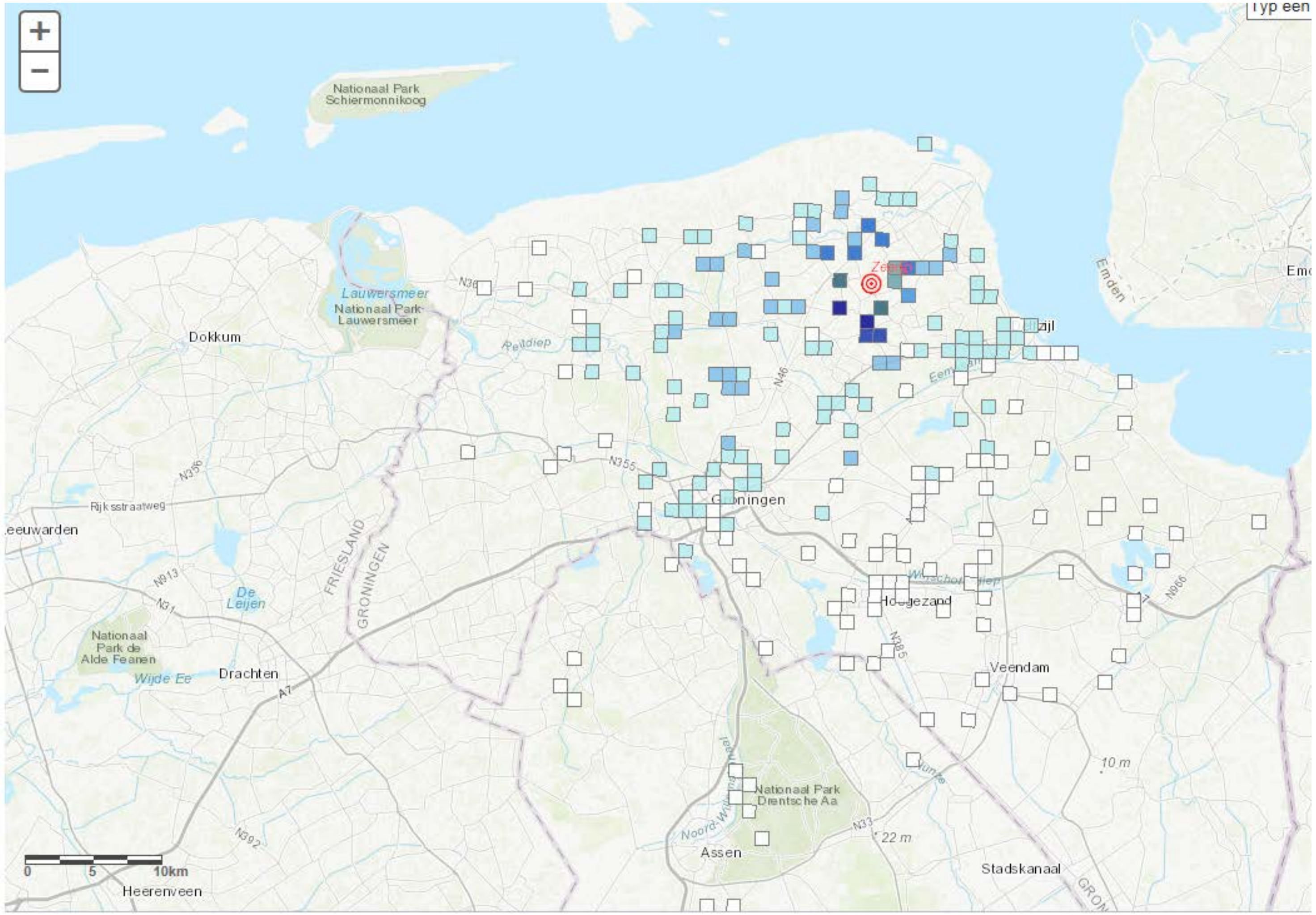


2013



2017

TNO sensor network



www.nam.nl

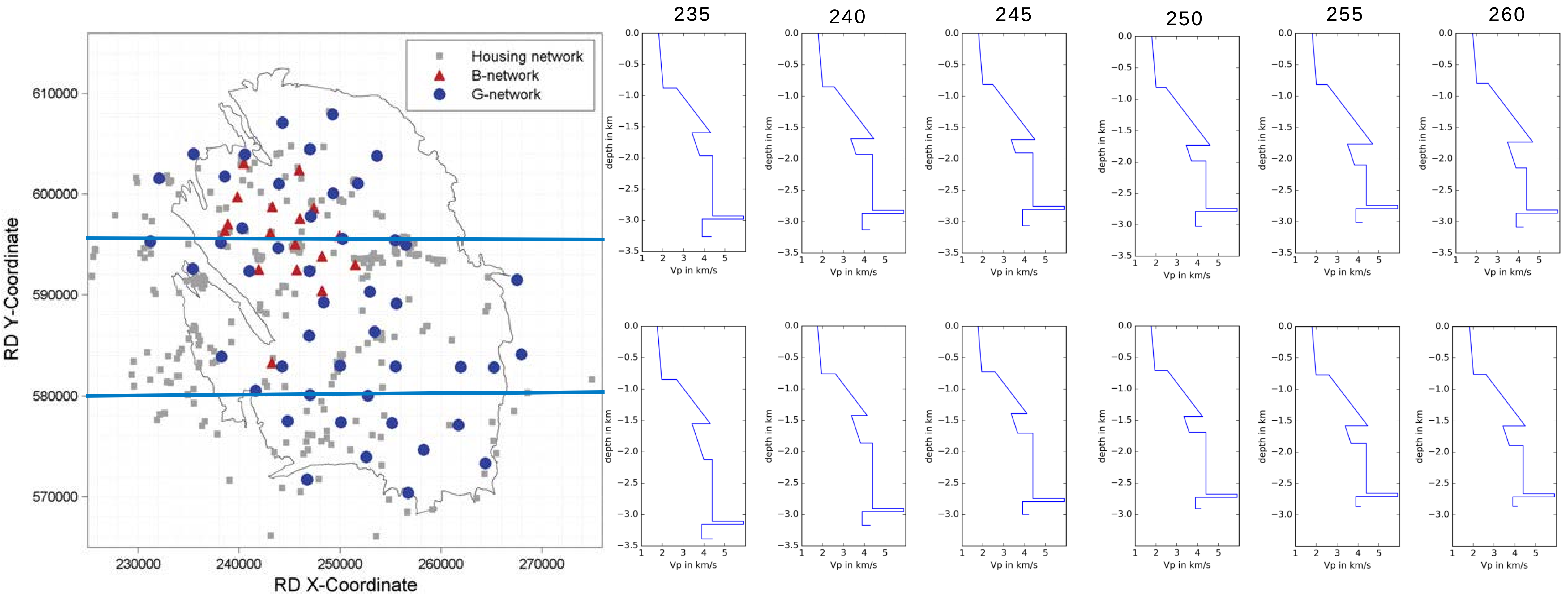
- TNO sensor network installed in buildings (>300 sensors; triggered system)
- Measured averaged PGA, resulting from the 2018-01-08 M 3.4 network

Earthquake location

- Accurate velocity model (NAM 3D)
- Rapid location using hypocenter software (uncertainty x,y,z ~0.5 km)
- Application of new location algorithms (e.g. EDT)
- Re-location using:
  - Modified EDT method (Spetzler & Dost, 2017, GJI)
  - Relative locations of clusters (Jagt et al., 2017, NJG)
  - Moment tensor inversion

- Automatic location procedures are being updated.

Velocity model



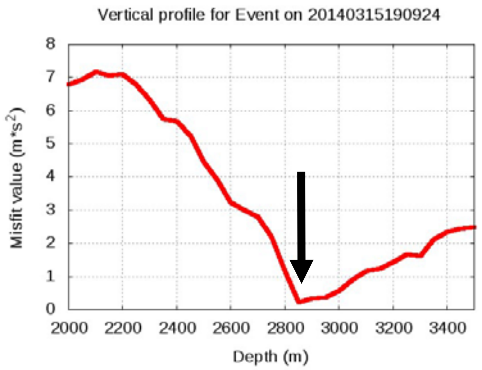
1D Vp models averaged over 5 km radius. Differences in thickness Zechstein and combined Rijnland, Jurrasic and Triassic formations.

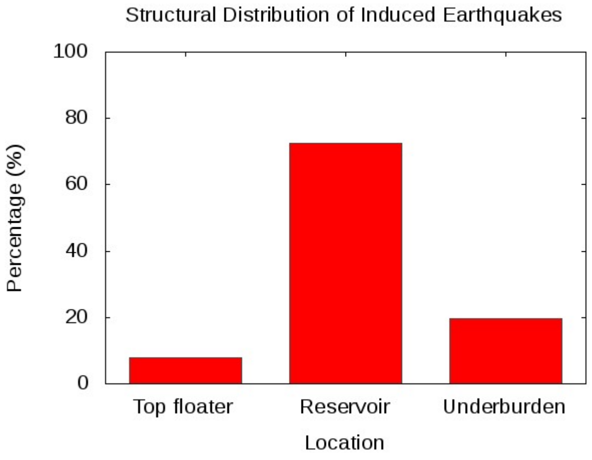
Hypocenter location

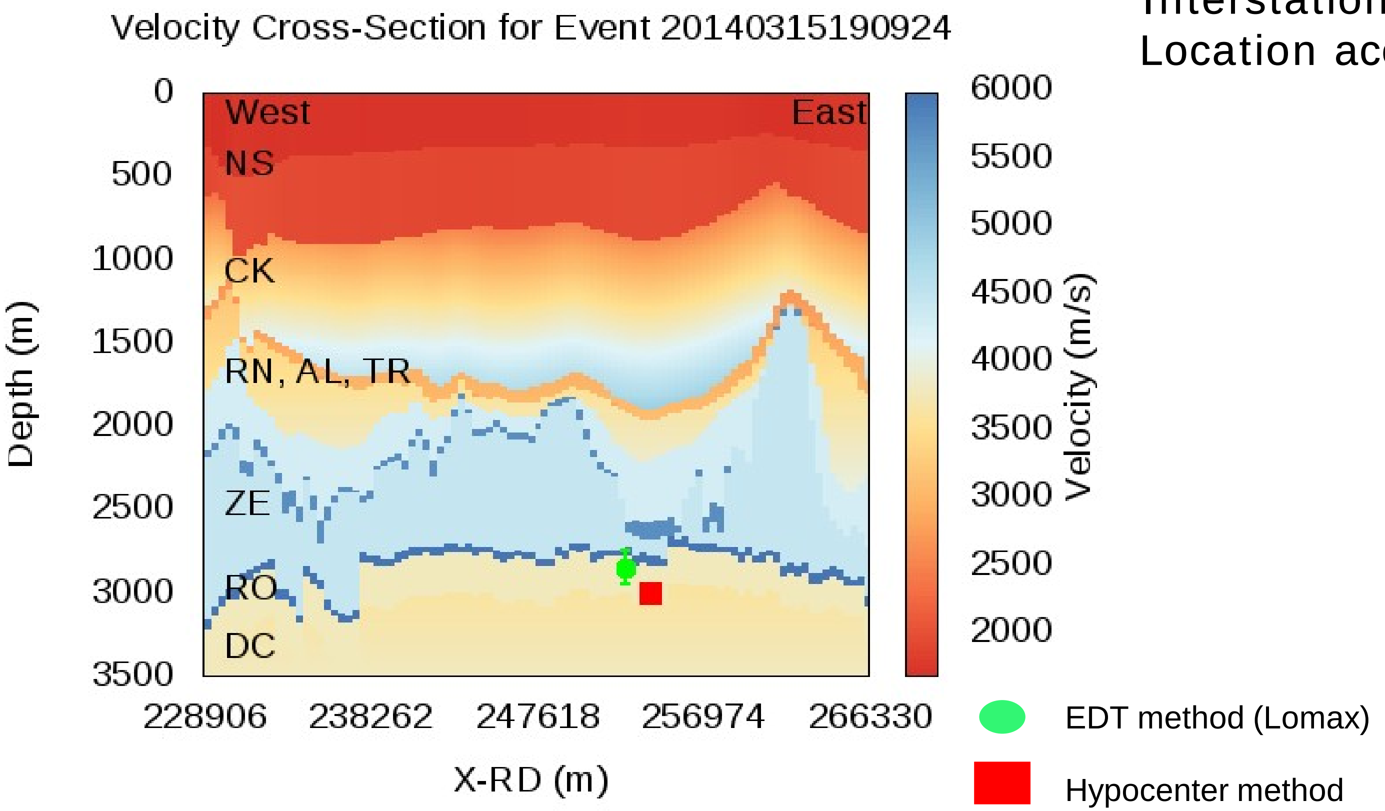
Old network:
Interstation distance ~20
Location accuracy 0.5-1 km

New network:
Interstation distance 4-5 km
Location accuracy 0.1-0.3 km

Vertical misfit function







Analysis of deep boreholes (NAM, microseismicity) shows most events are confined to the reservoir e.g. Pickering

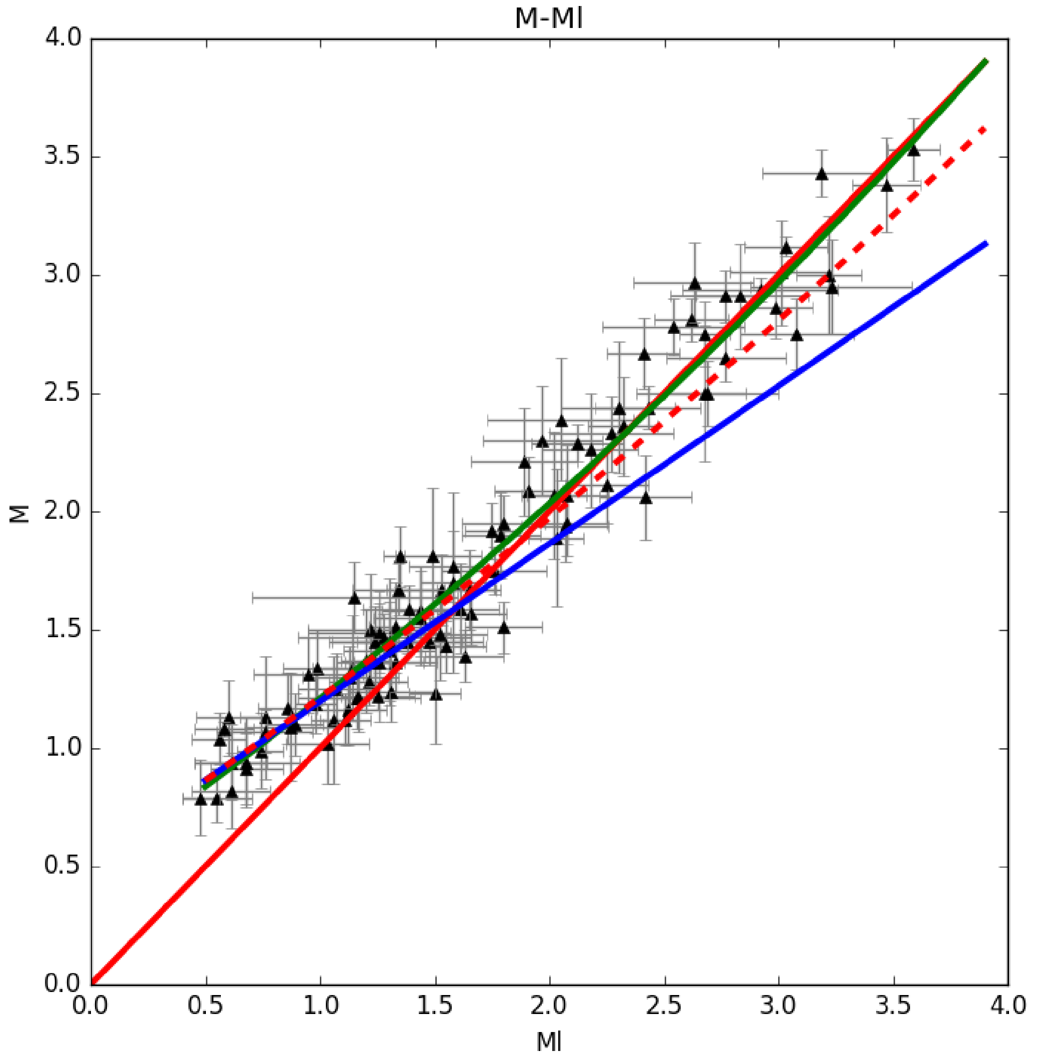
Spetzler & Dost, 2017, GJI

Magnitude

Local magnitude (ML)
- Fast calculation (max hor. comp. WA simulated signal)

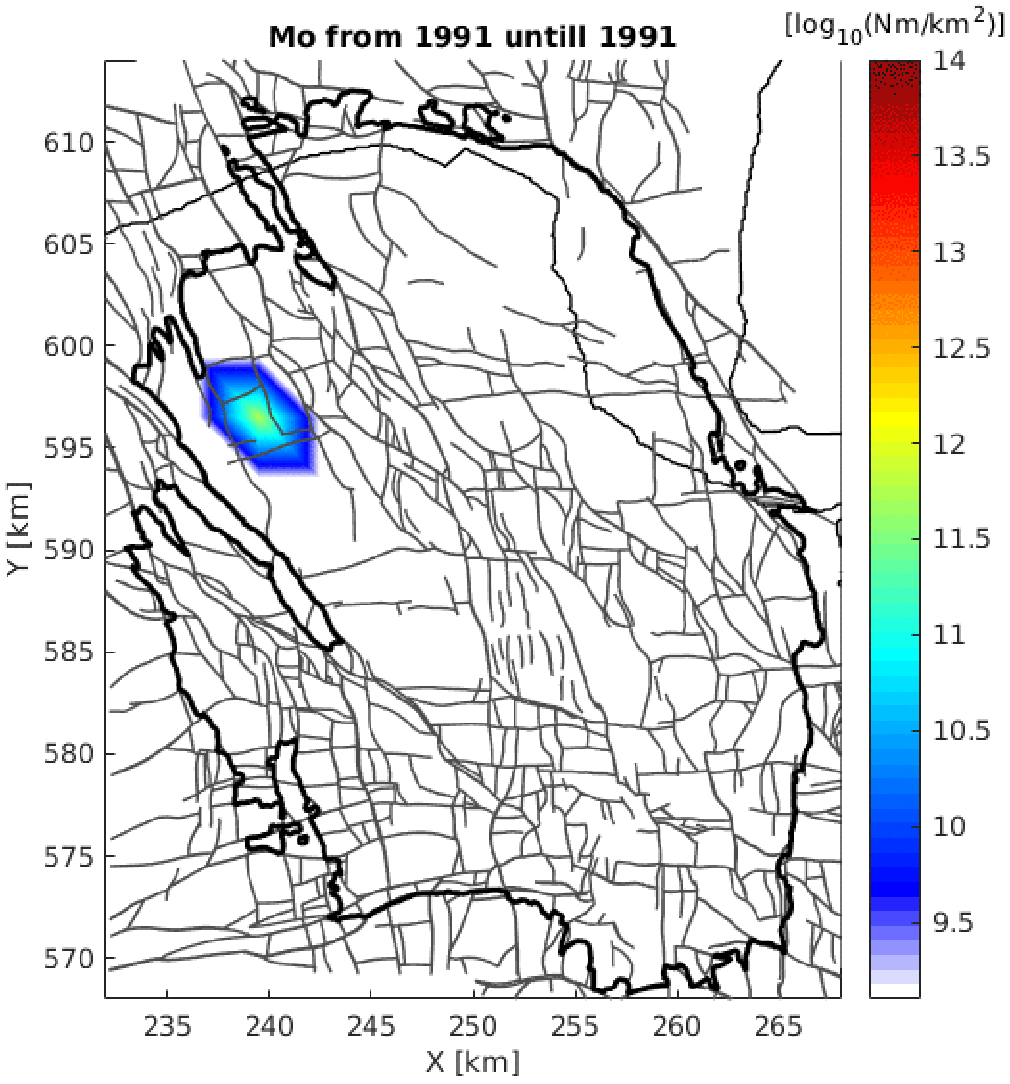
Moment magnitude (**M**)
- No saturation, based on physics
- Calculated from earthquake spectra or through moment tensor inversion

Relation between M and ML required for hazard assessment



In green the proposed quadratic relation for Groningen is shown (Dost et al., 2018). In red-dashed the Grünthal et al. (2009) and in blue the Munafò et al., (2016) relation.

Seismic moment release



Sensor orientations

The orientations of the borehole sensors were unknown and are determined using

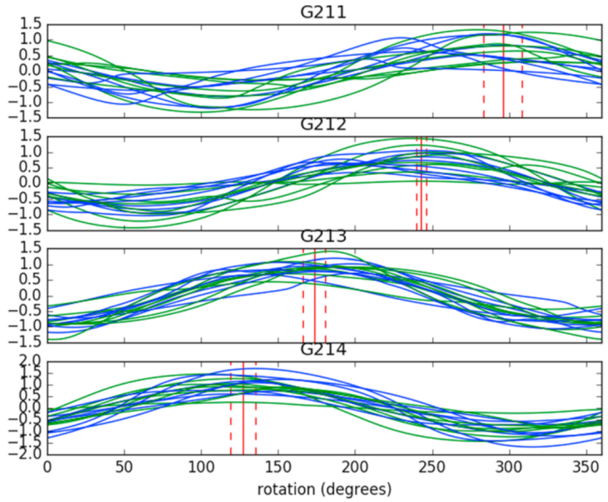
- Check-shots
- Explosions
- Cross-correlation with surface sensors

Both with known location and timing

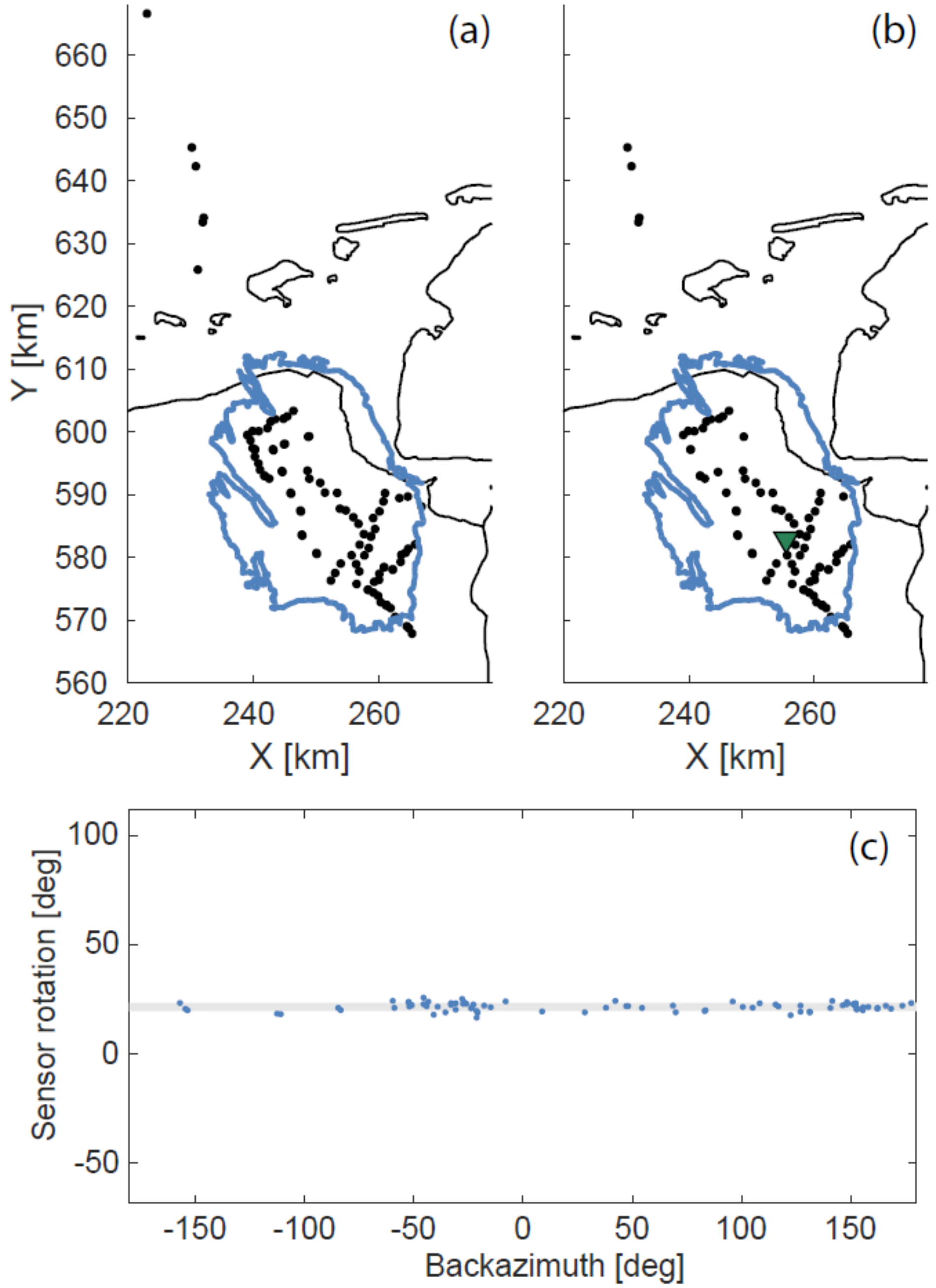
- Teleseismic events

Essential information for e.g. Moment tensor inversion

- 70*5*3 = 1050 channels

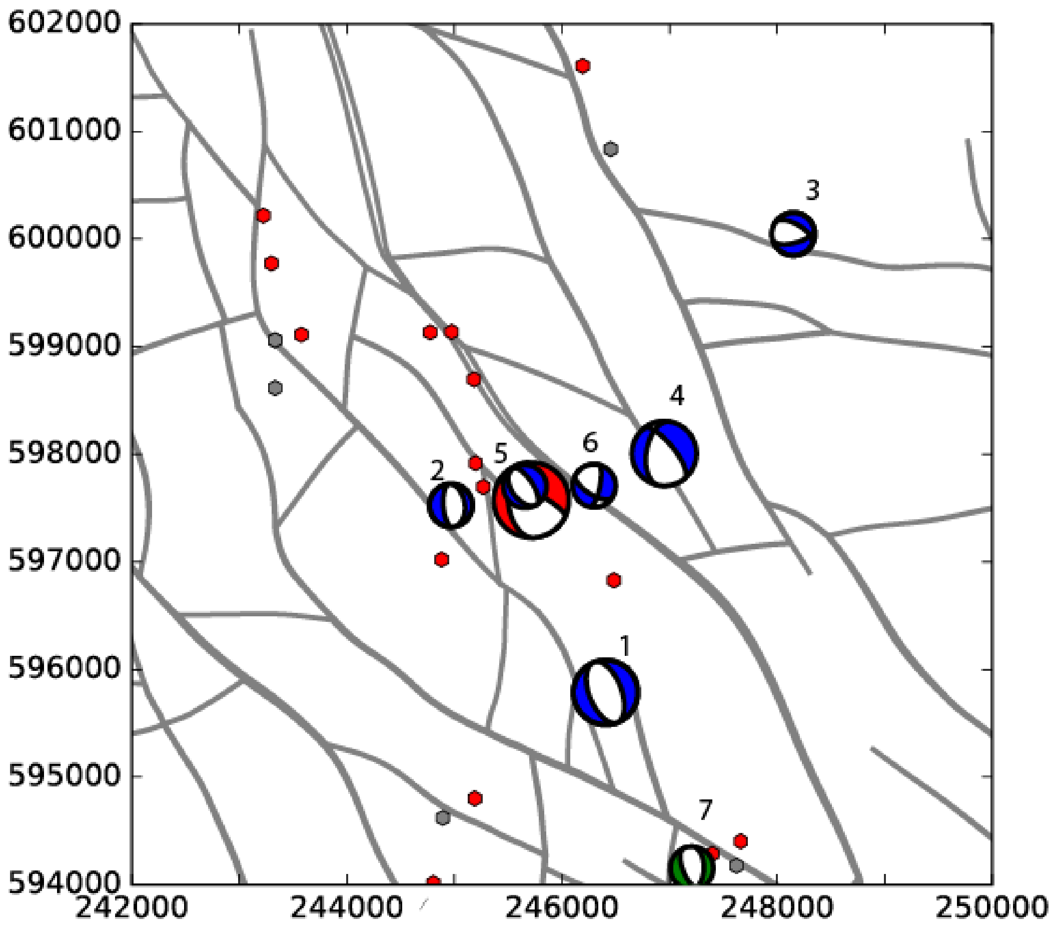


Cross-correlation coefficient as a function of the rotation of the geophone for different borehole levels.
Hofman et al., 2017, JGR



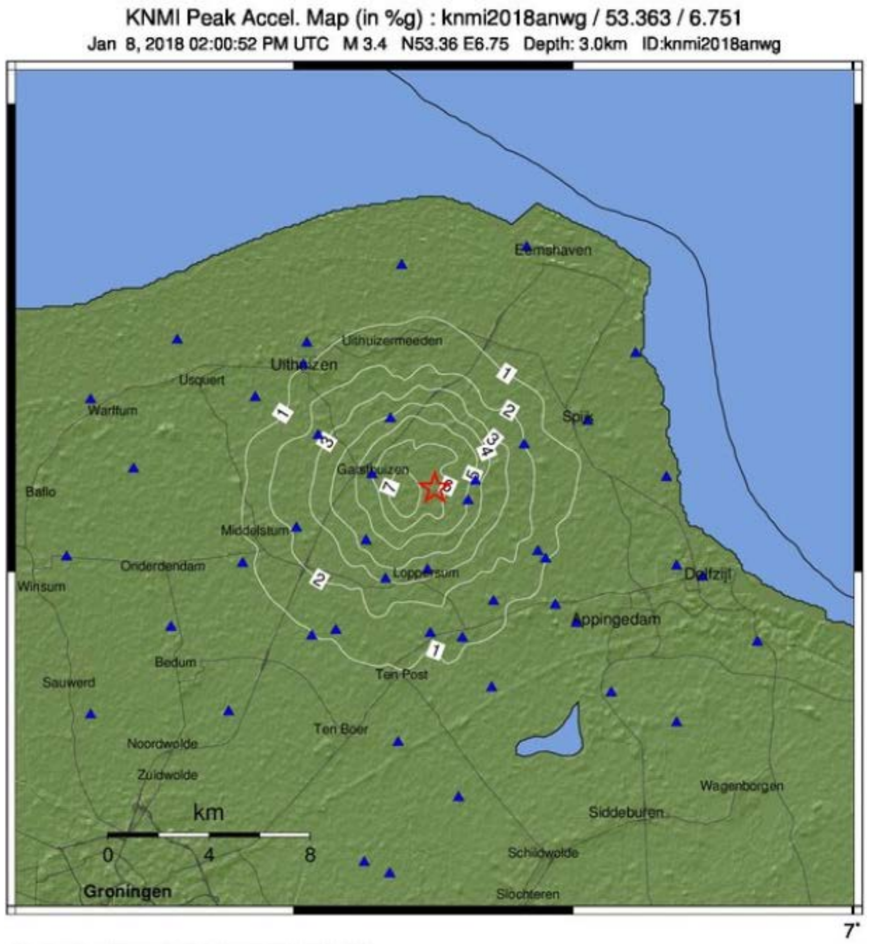
Source mechanism

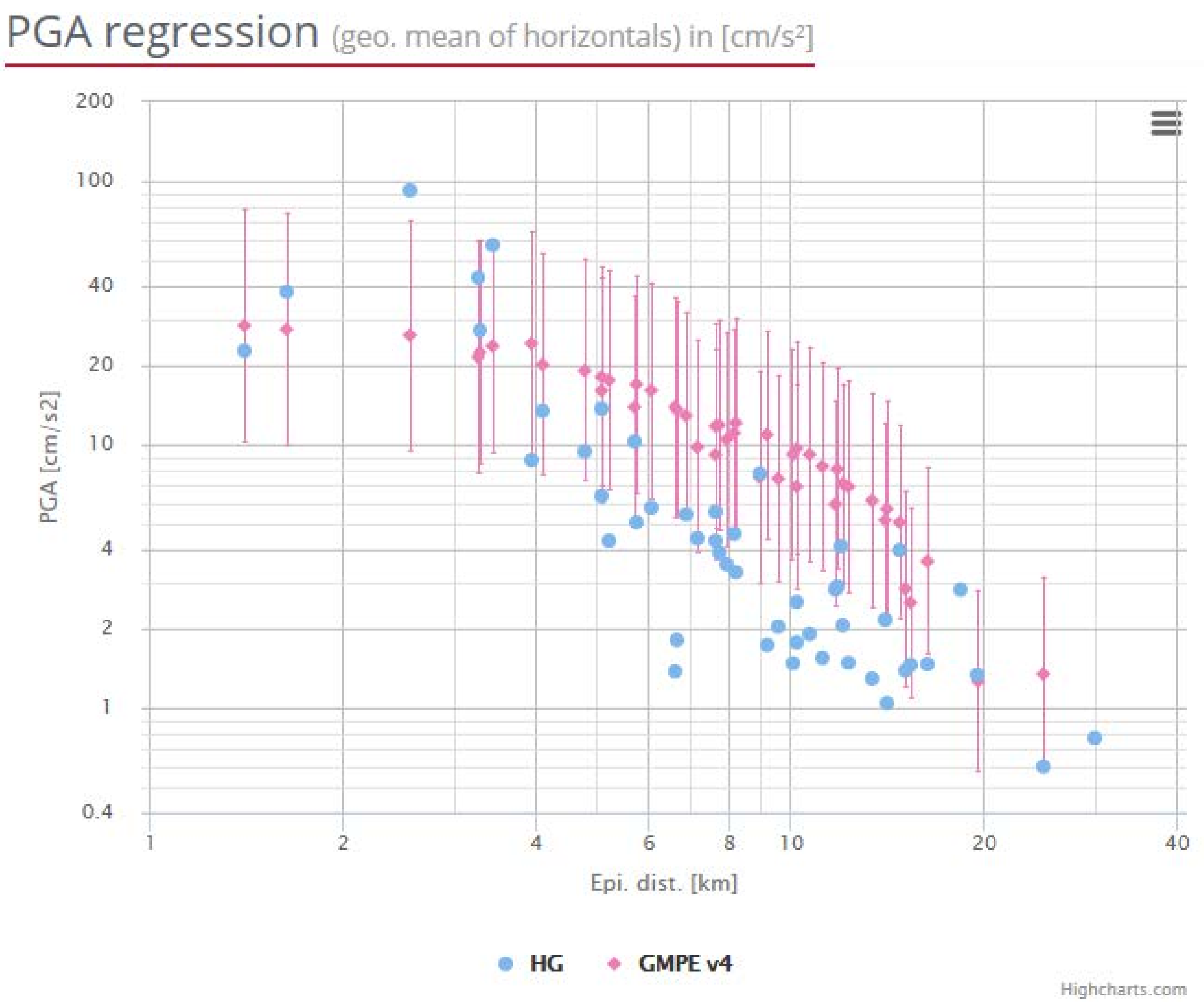
- Calculation of the Green's function for an average 1D model in the central part of the Groningen field.
- Comparison synthetic seismograms with observations
- Best fitting mechanism and a relocation of the source.
- Zeerijp (180108, M 3,4) marked in red
- Normal faulting, strike 297 degrees, dip 70 degrees, fits with known faults.
- Validation of NAM results using full waveform inversion.



1=170311 2=171201 3=171206 4=171210 5=171222 6=171229 7-161207

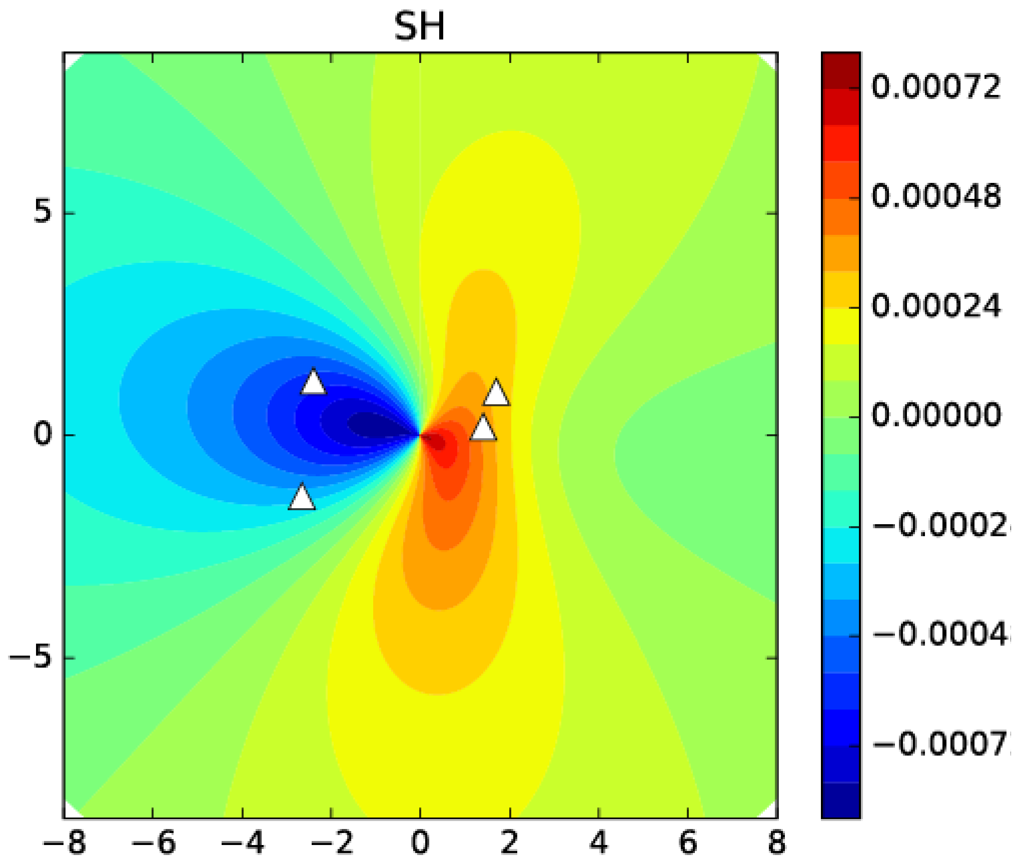
Data products: Shakemaps

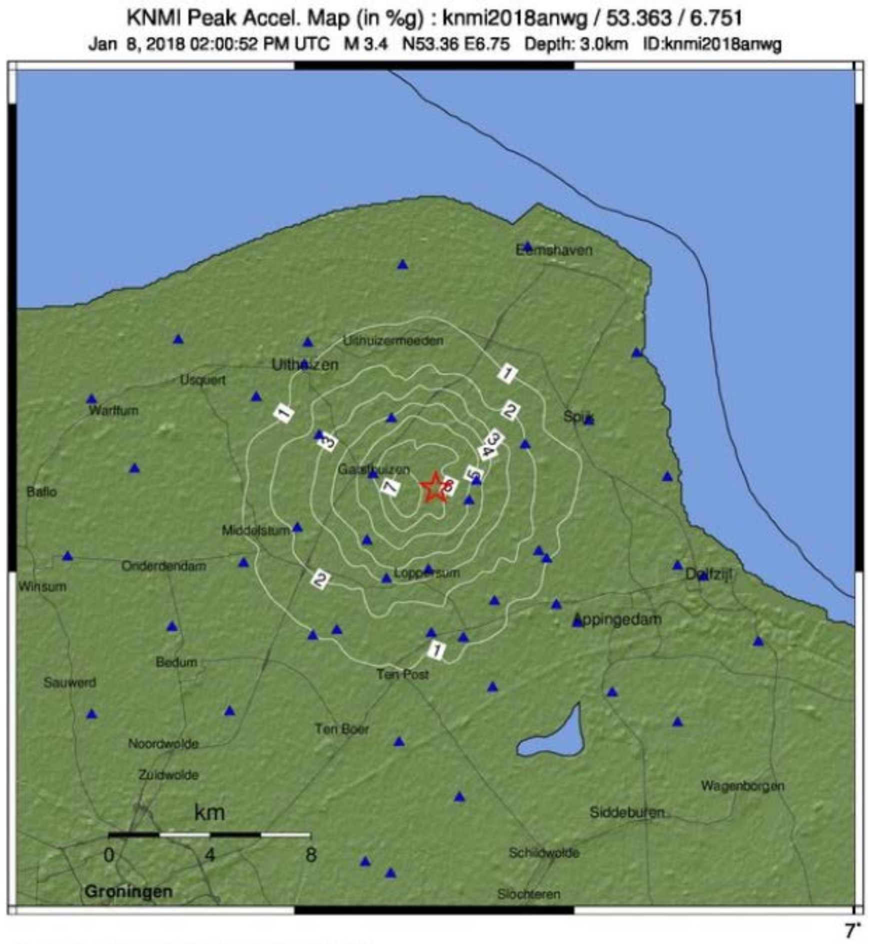




› Zeerijp, 2018-01-08, ML =3.4. Left: Shakemap shows a maximum west of the epicenter. Can this be explained? Right: Comparison of data with GMM v4.

Radiation effects





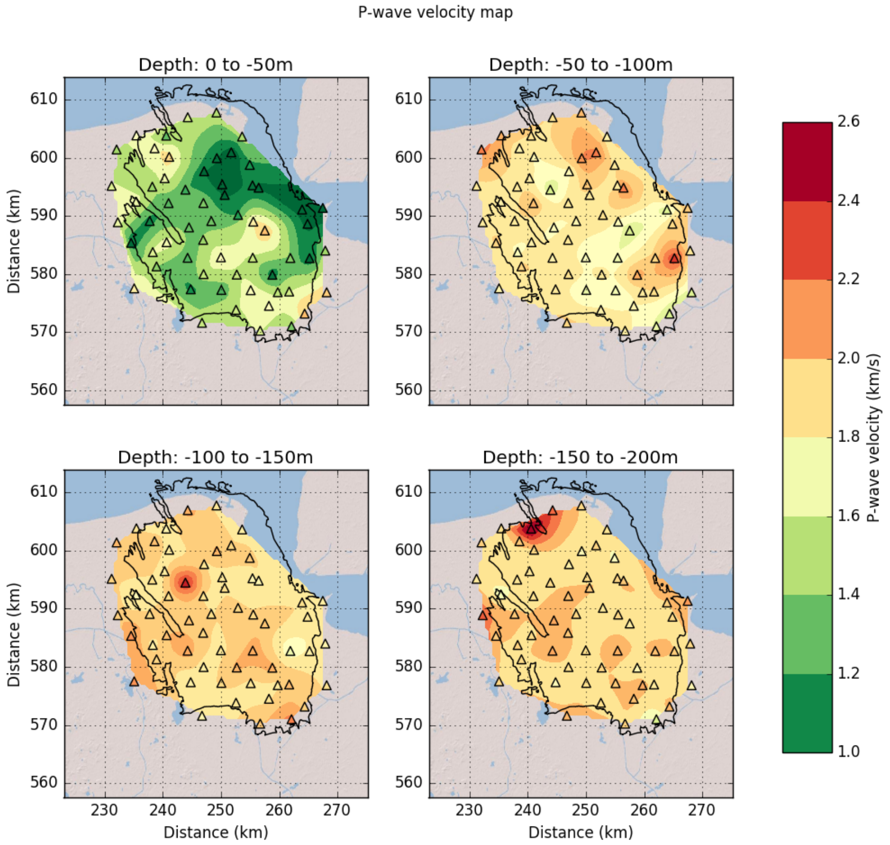
› Simulation of displacement at the surface (average 1D model)

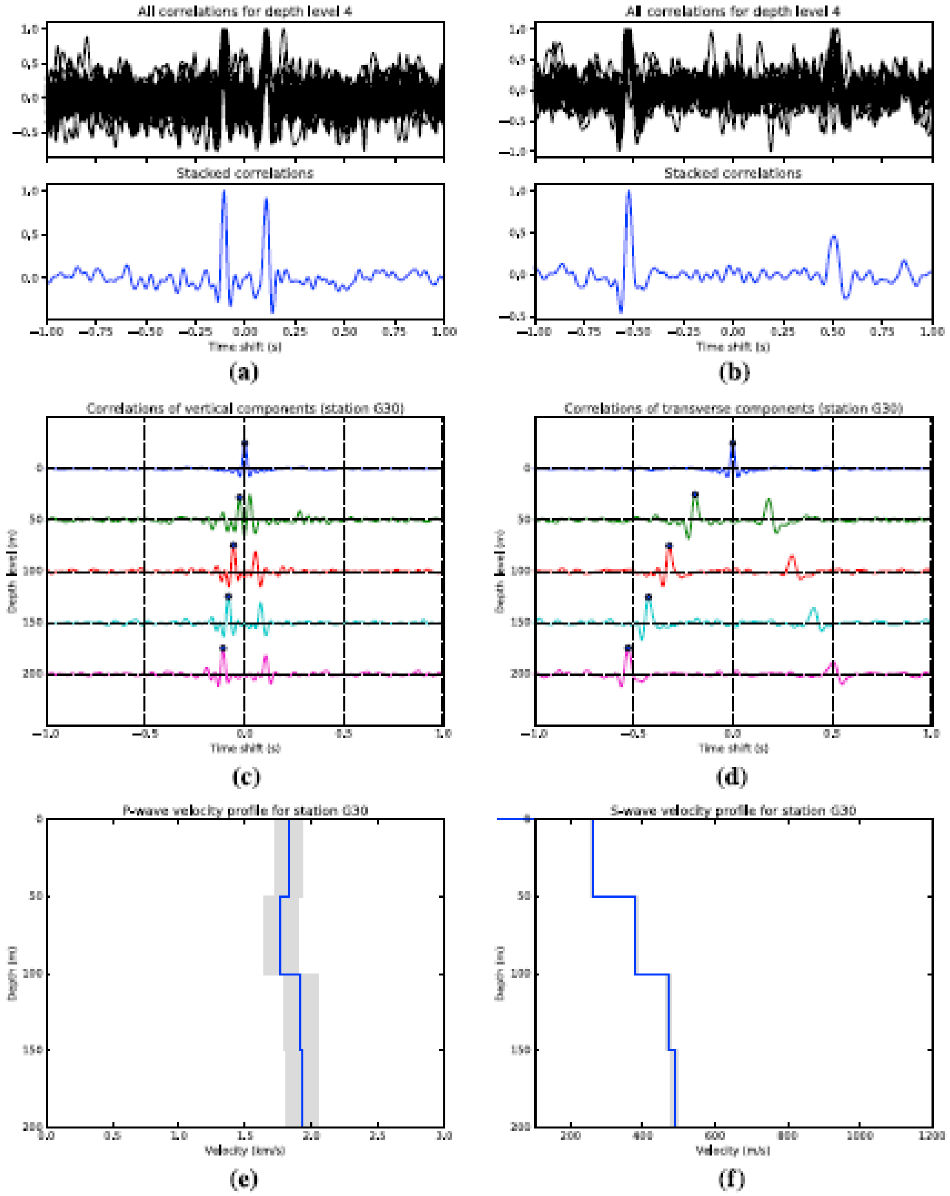
› The shakemap pattern can be explained by the (SH) radiation pattern

Shallow shear velocity model

Cross correlations between geophones at depth and surface sensor (a=P, b=S). Stacks for all levels (c=P, d=S), incl. timing

30 local events used for this example

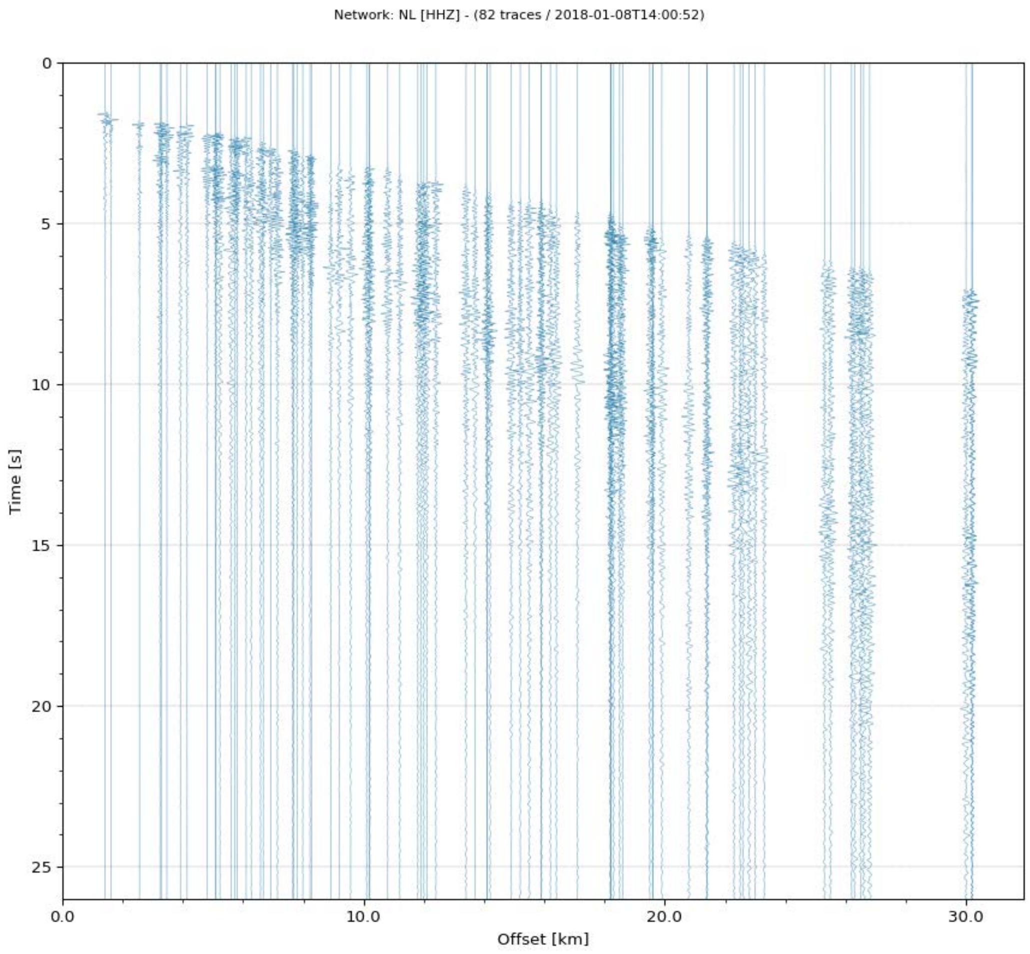


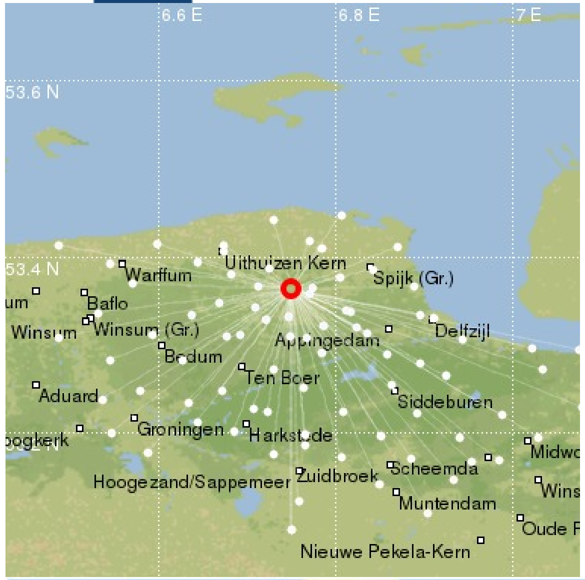


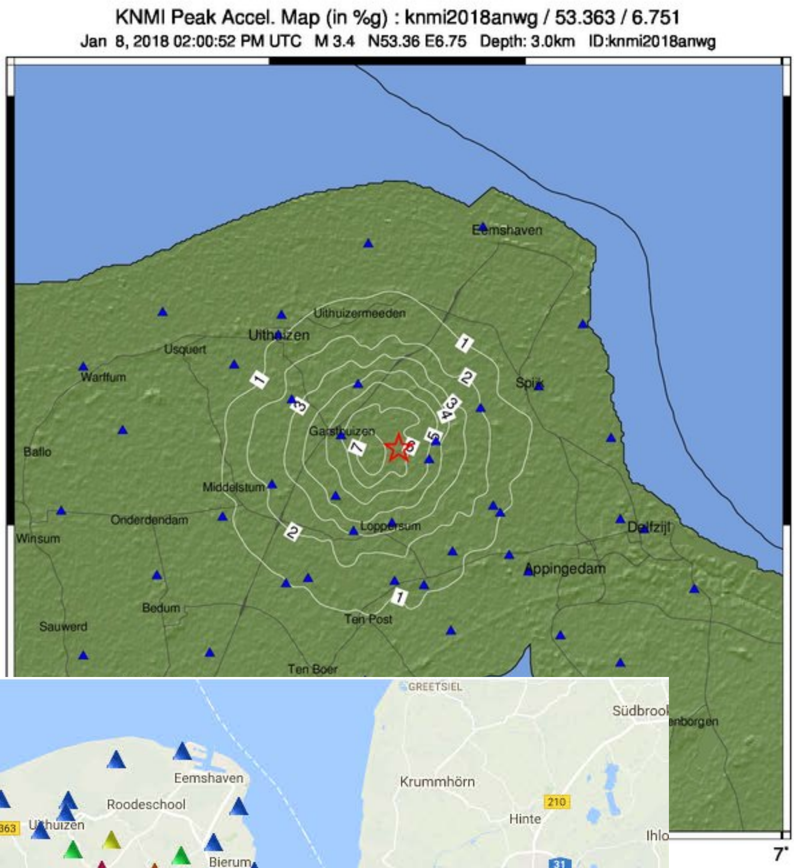
Hofman et al., JGR 2017

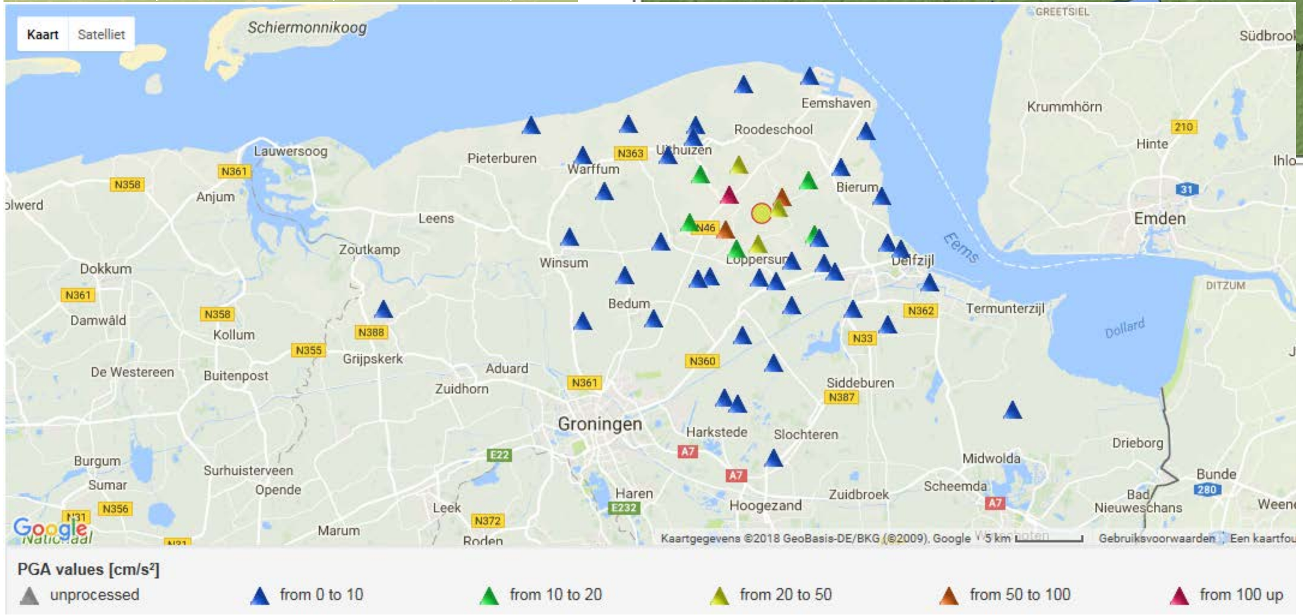
Data products

Open data policy: waveform data, Shakemaps (M>2.0), comparison with GMM

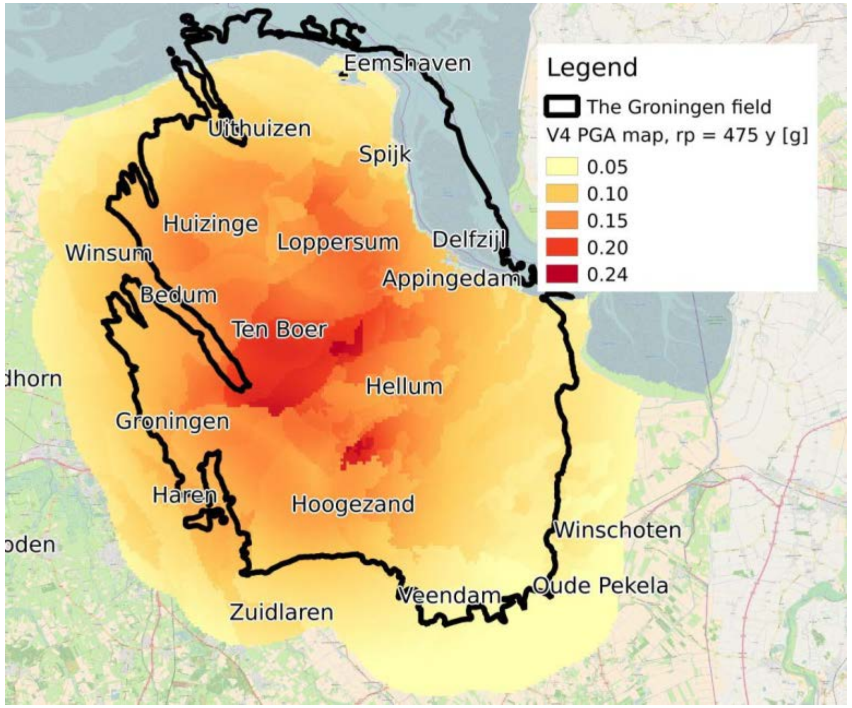








Probabilistic Seismic hazard assessment



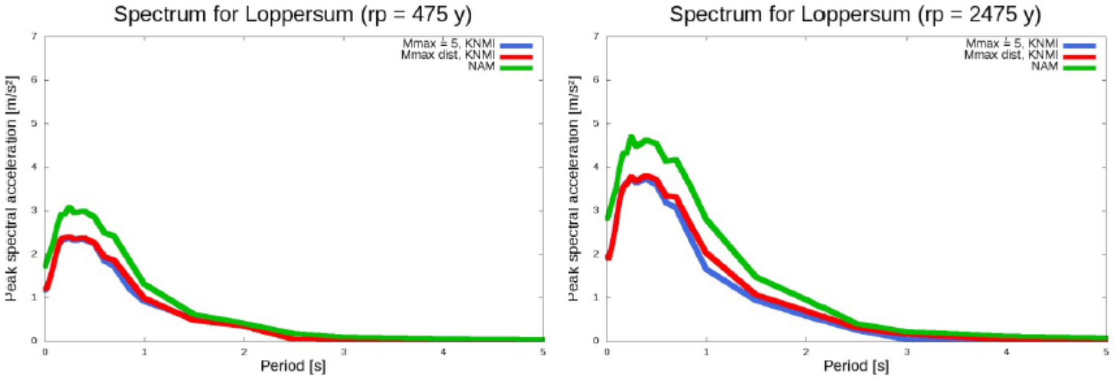


Figure 12: Comparison of spectra in Loppersum. The return period is 475 y and 2475 y.

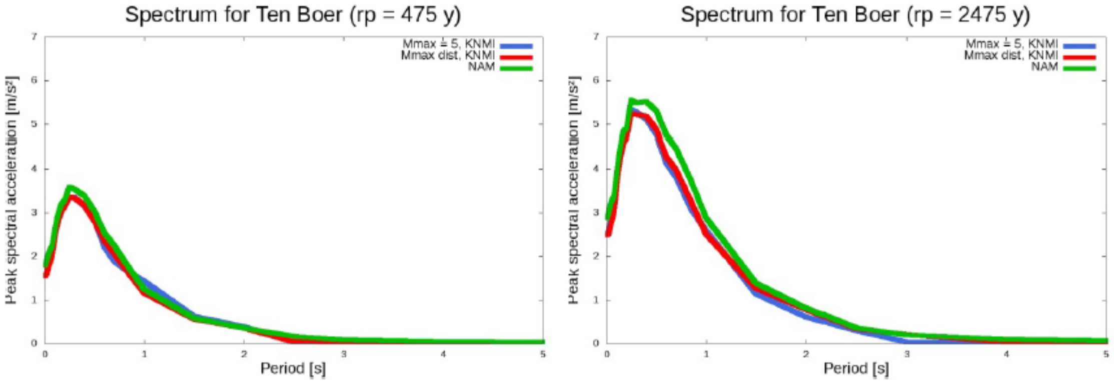


Figure 13: Comparison of spectra in Ten Boer. The return period is 475 y and 2475 y.

- Validation of NAM PSHA results
- Same Ground Motion Model (GMM) used, different assumption on the source term (KNMI based on recorded seismicity) and different calculation method (integration vs Monte Carlo simulation)

Conclusions

- New network:
  - Strong improvement in location accuracy
  - Provides essential data for GMM development
  - Enables moment tensor inversion
- Most events occur within the reservoir, which is also inferred from microseismicity recorded in the deep boreholes.
- Sensor orientation has been determined for most of the geophones and accelerometers (>1000 channels).
- Source mechanisms combined with relocated sources show a good correspondence to known faults and can be used to explain shakemap features.
- Analysis of multilevel borehole data contributes to the understanding of shallow velocity structure
- Validation of NAM results.
- All data and products are open available.