Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

New developments in monitoring seismicity in the Groningen gas field

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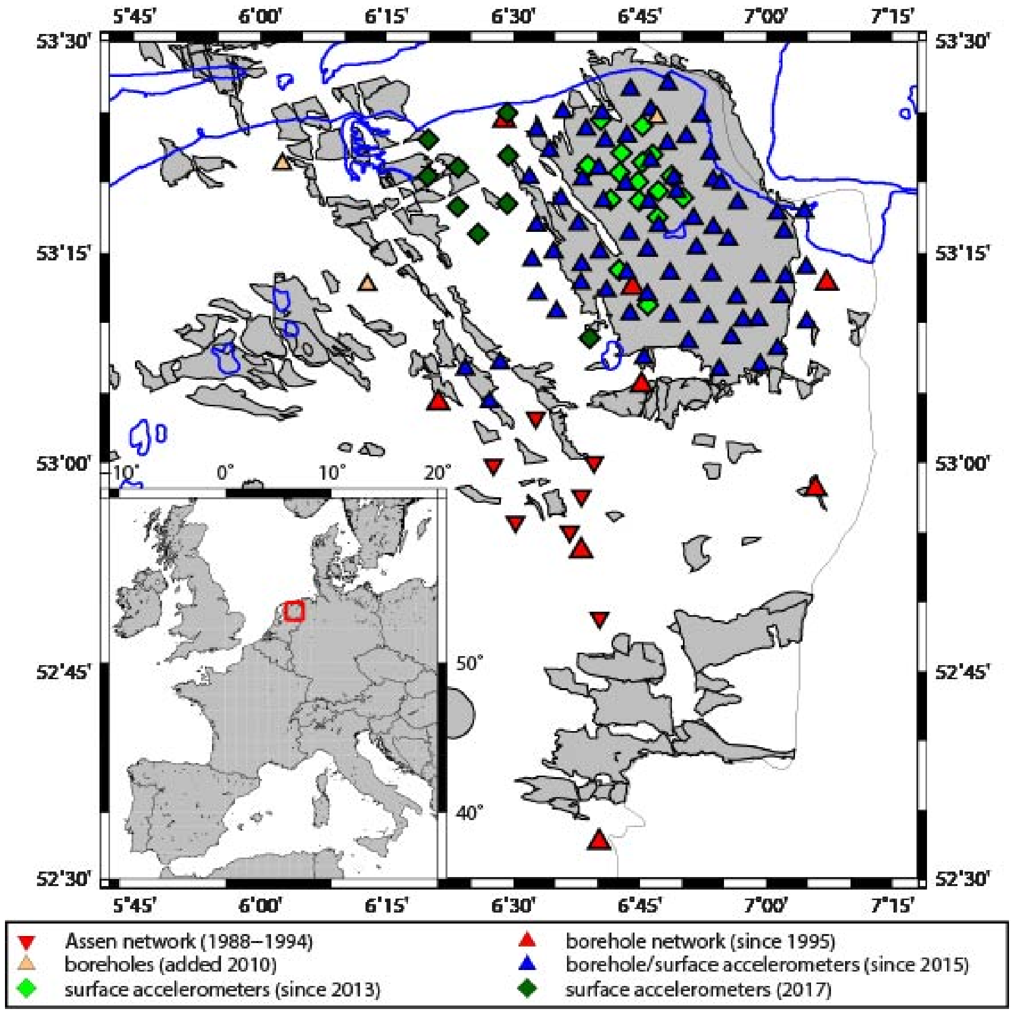
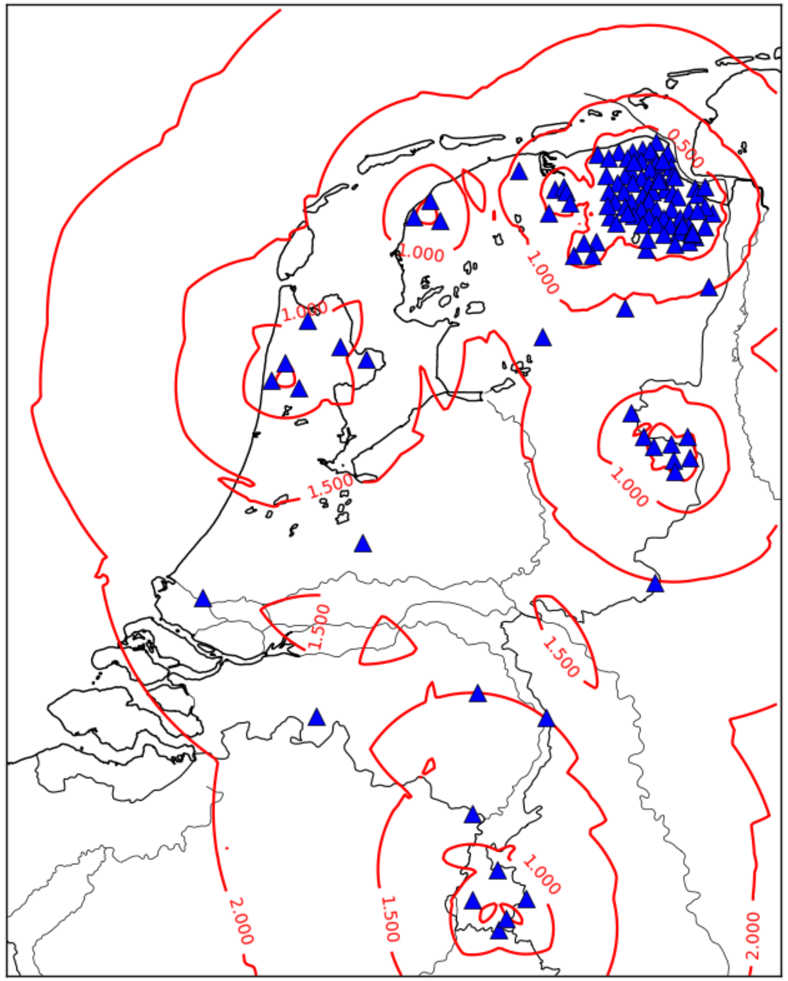
Groningen Network



Designed to
- 1995: locate M>1.5
- 2014: locate M>0.5

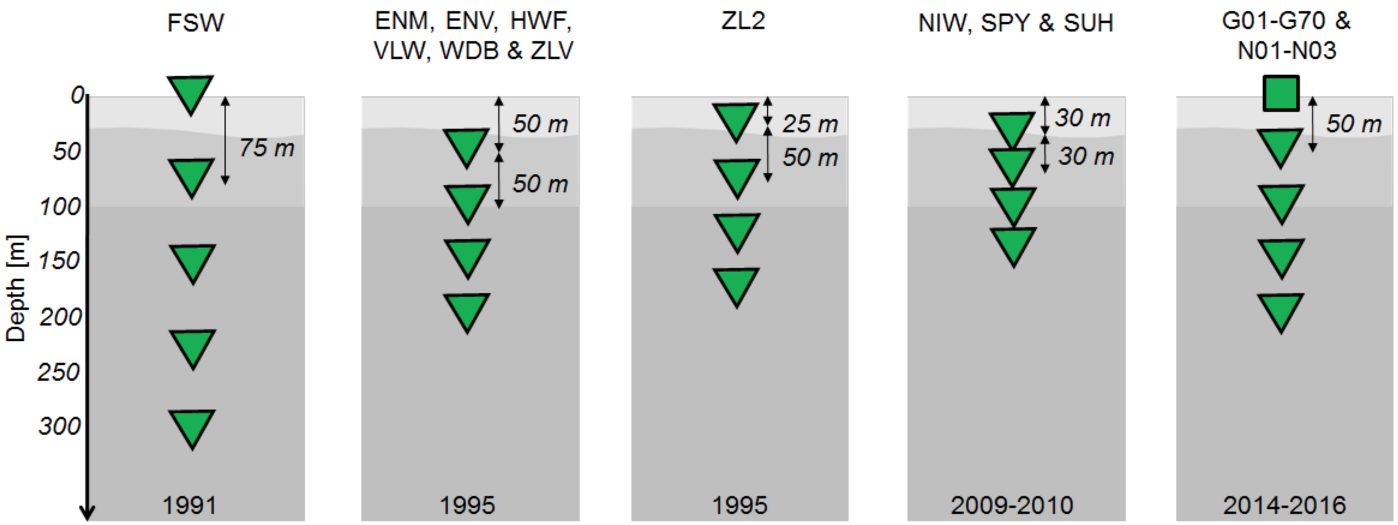
Build-up 2014-2015

In 2018: 4 broad-band (STS-5) at 100m depth, Co-located with existing borehole station



Location treshold, status 2019

Borehole instrumentation



Data availability

- Boreholes without casing, configuration changes over time
- Geophones (4.5 Hz) and surface accelerometers at G stations (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

Sensor orientations

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

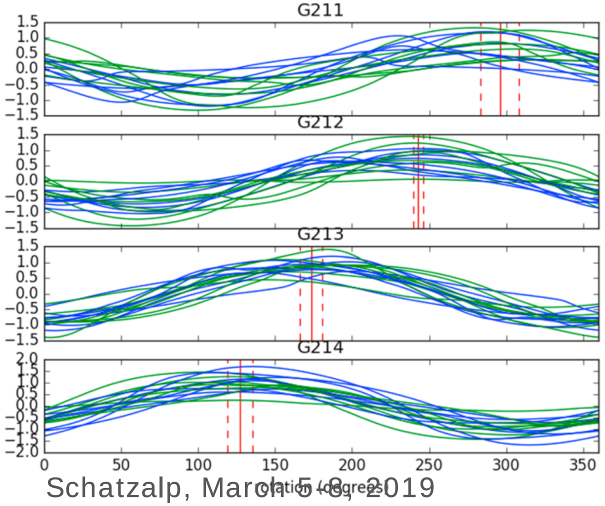
- Check-shots
- Controlled explosions
- Cross-correlation with surface sensors

Both with known location and timing

- Teleseismic events

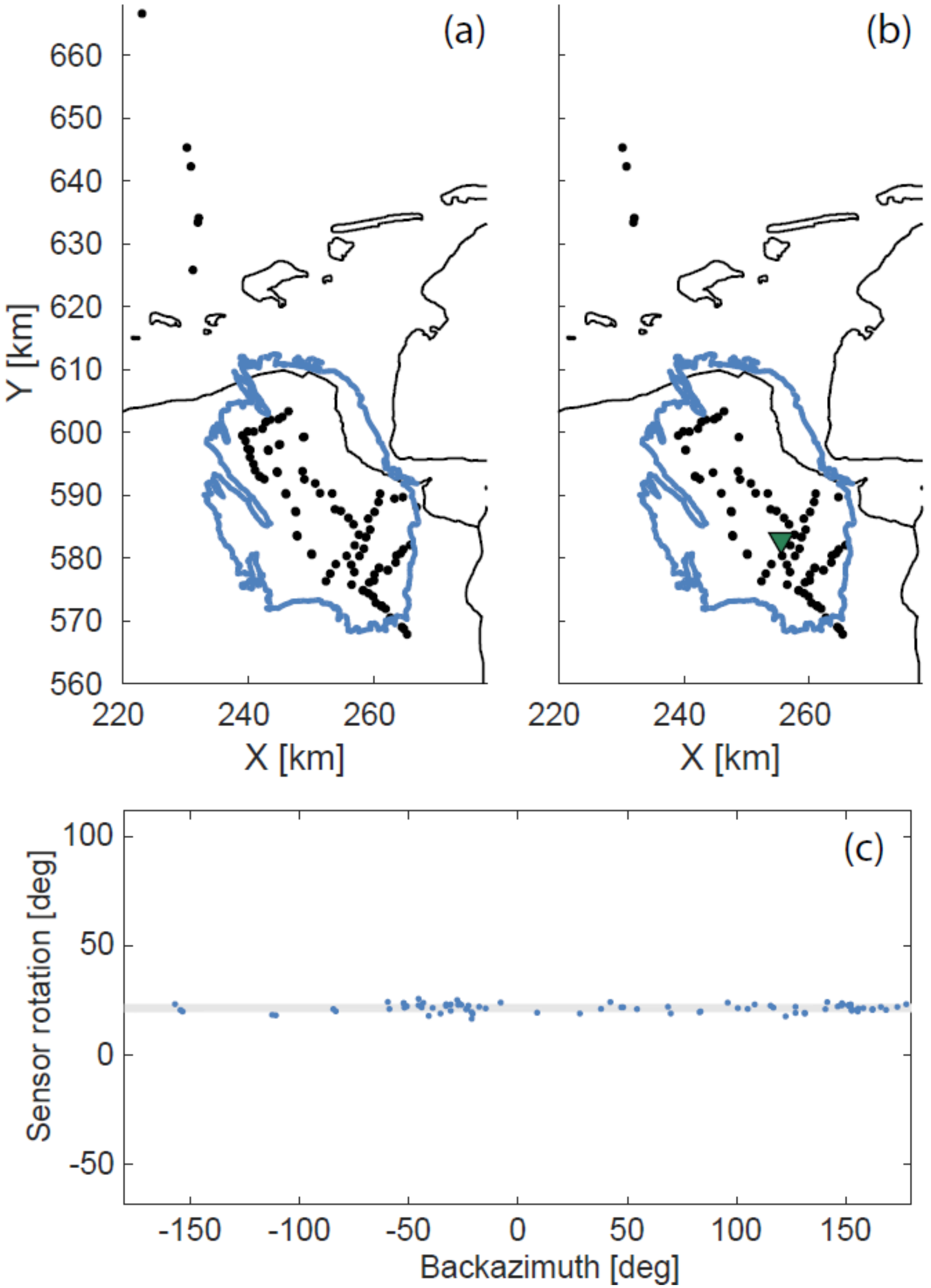
Essential information for e.g. Moment tensor inversion

- 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



Data

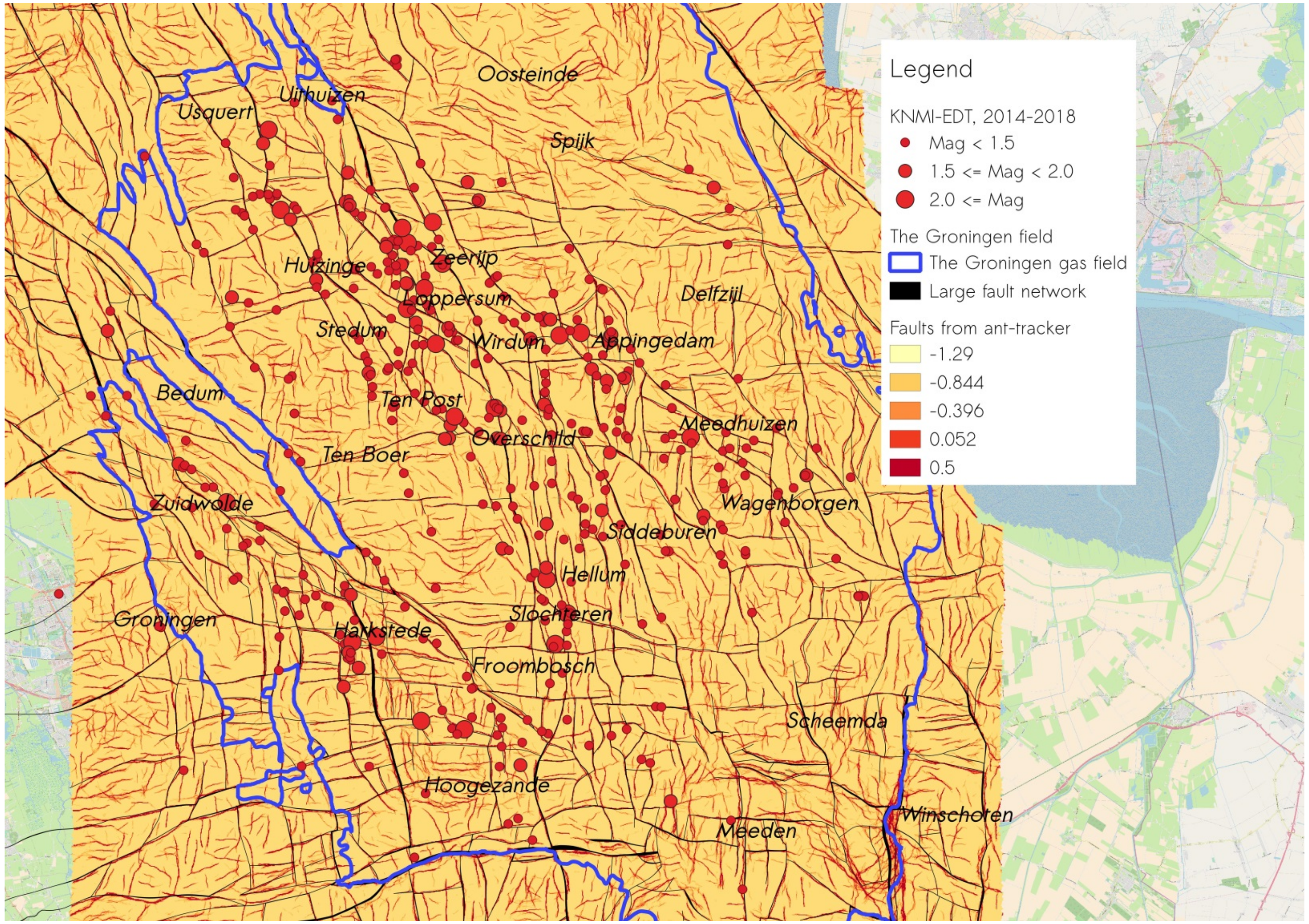
- All real-time data are available through http://rdsa.knmi.nl/dataportal or through fdsn web services.
- All meta-data is available in dataless seed headers, including sensor orientation.
- An error was detected in the gain setting of the accelerometer on top of the new borehole strings. This was corrected mid December 2018.
- Please check the metadata if you use amplitude information.

Earthquake location

- Accurate P and S velocity model (NAM 3D, Romijn, 2017)
- Rapid location using hypocenter software (uncertainty x,y,z ~0.5 km)
- Implementation of other location algorithms (EDT, NLL (Lomax))
- Re-location using:
  - Modified EDT method (Spetzler & Dost, 2017, GJI),
    based on local averaged 1D models and travel time tables
  - Updated EDT method (Spetzler & Dost, in prep)
    based on 3D raytracing, using a ray perturbation method,
    valid up to 6 km epicentral distance
  - Moment tensor inversion

- Automatic location procedures are being updated.

Relocation results



432 relocated events 2014-2018

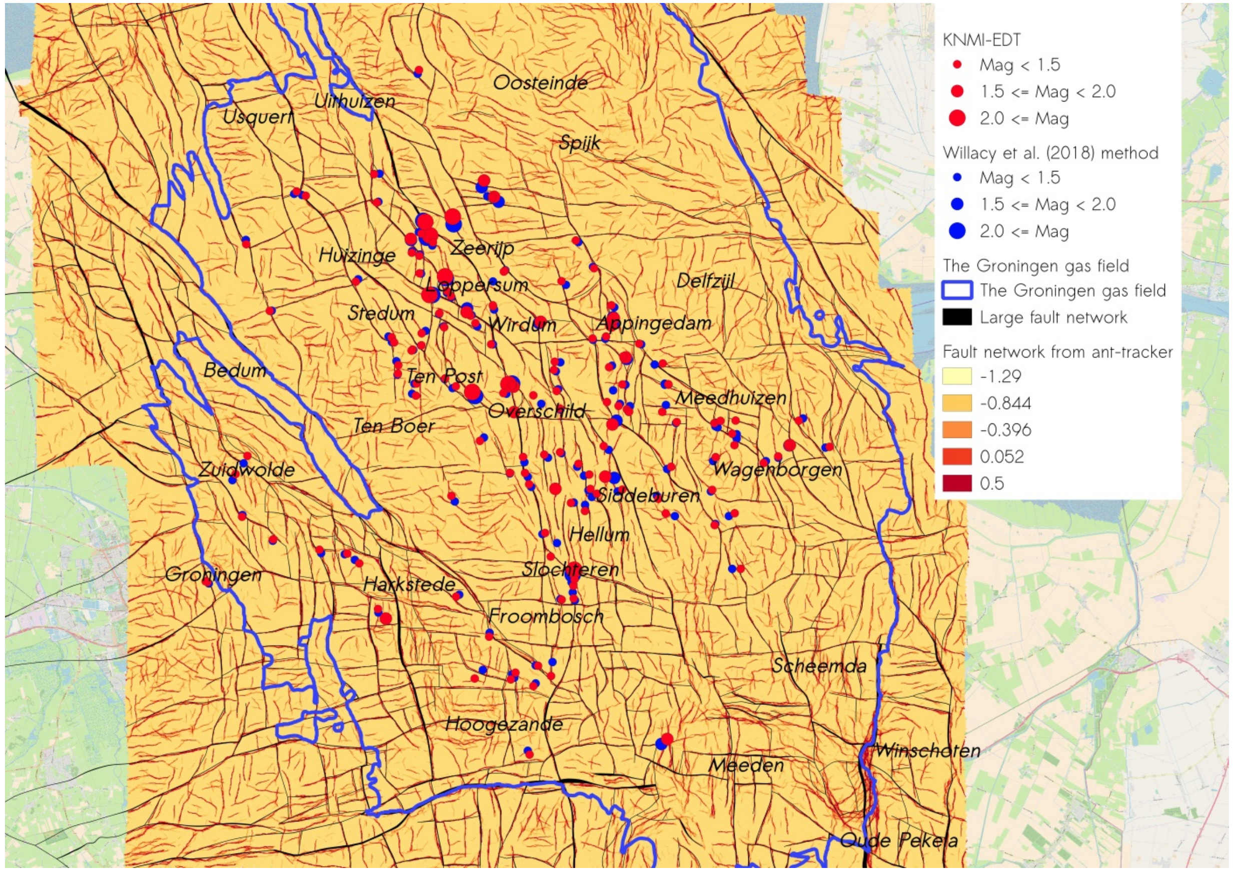
Method: EDT-2, 3D raytracing

Epicenters line-up with existing larger and smaller faults in the reservoir. Epicentral error: 100-200m

Depth estimates are at 2600-3200km (reservoir). Average error 200m.

No events associated with anhydrite layers within the Zechstein overburden

Comparison

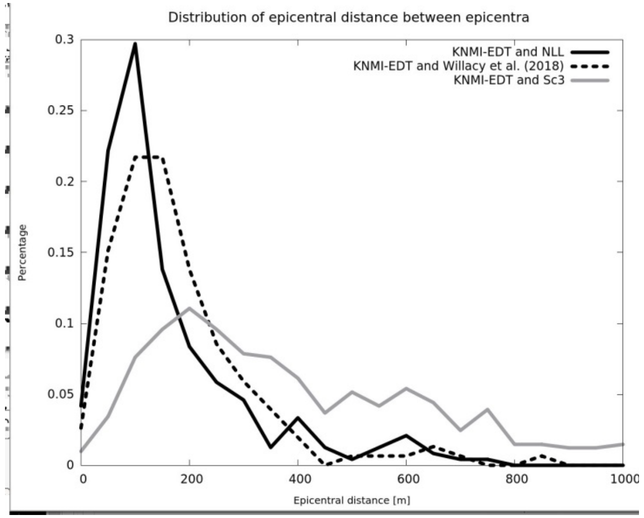


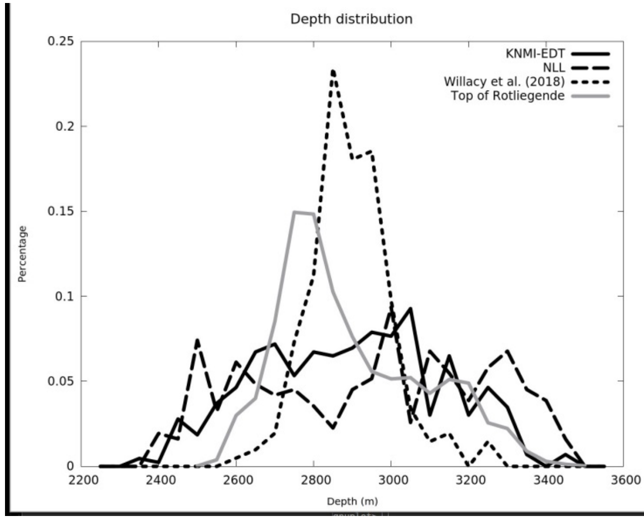
EDT – local 1D model (Spetzler&Dost, 2017)
- Now 3D model and raytracer (in prep)

NLL - implementation with a smoothed 3D model

Willacy et al. (2018) location based on full waveform modelling in the 3D Groningen model

154 events are evaluated using the 3 methods



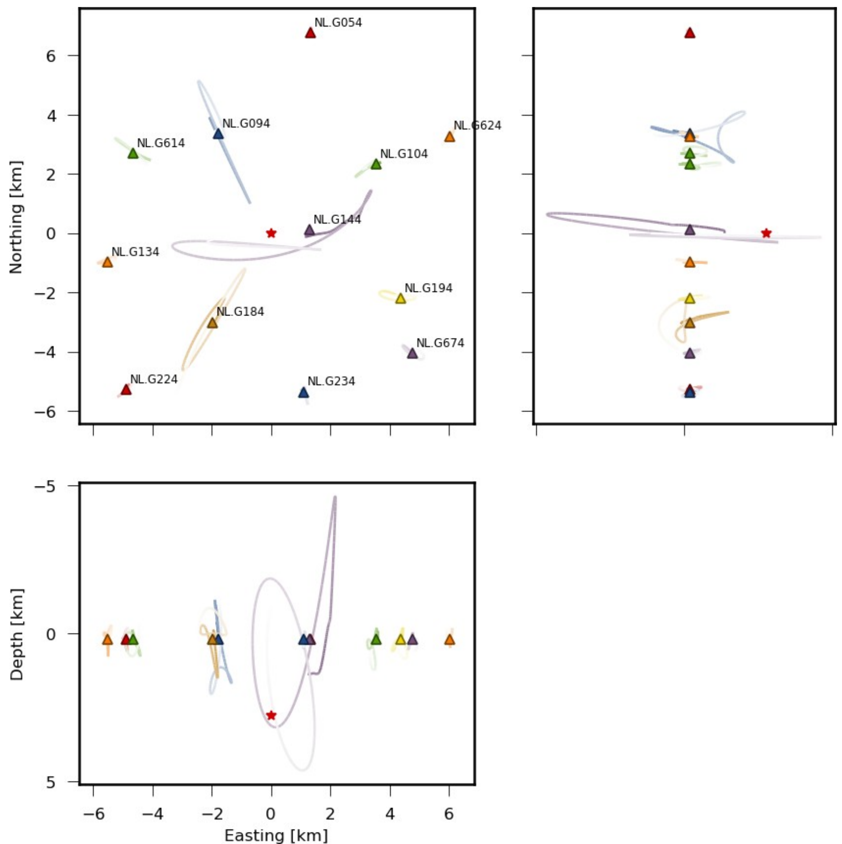


Moment tensor Inversion

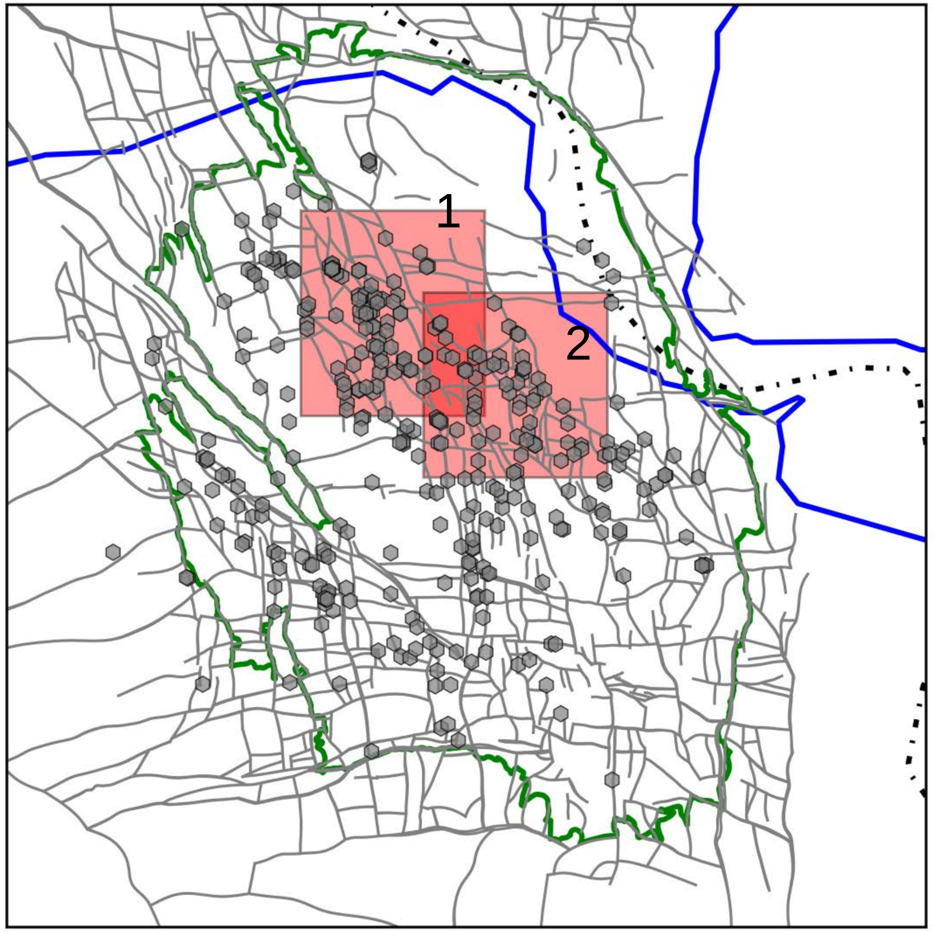
- Modelling using the pyrocko package (GFZ, S. Heimann et al.)
- Two parts:
  - 1] Create a library of Green's functions (FOMOSTO)

    Groningen: local 1D velocity models, derived from 3D model
  - 2] Calculate synthetic seismograms (qseis, Wang (1999)) and compare with data (GROND 60000 iterations)

- Data preparation
  - Focus on lowest borehole levels (150, 200m)
  - Orientations should be known (Hofman et al., JGR 2017)
  - P-polarisation plots within GROND
    - Orientation
    - Source location



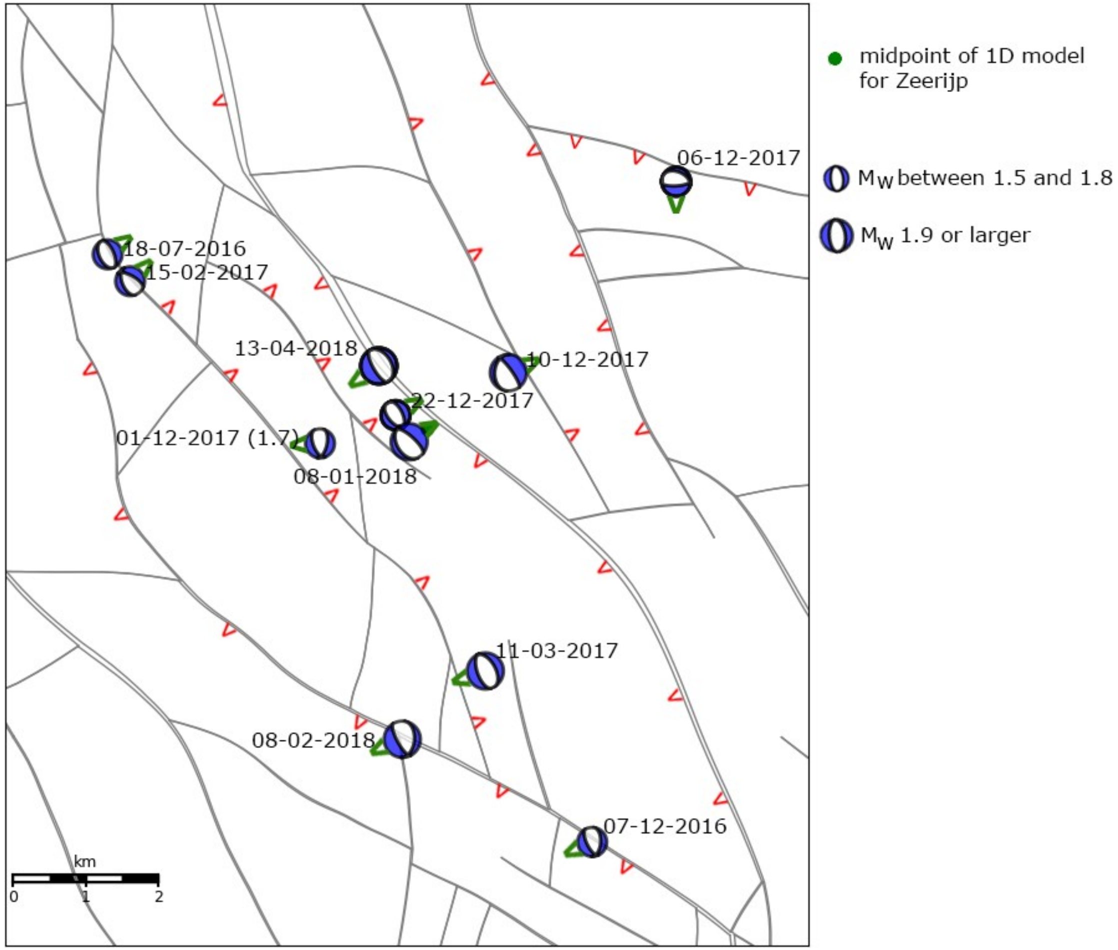
Moment tensor inversion



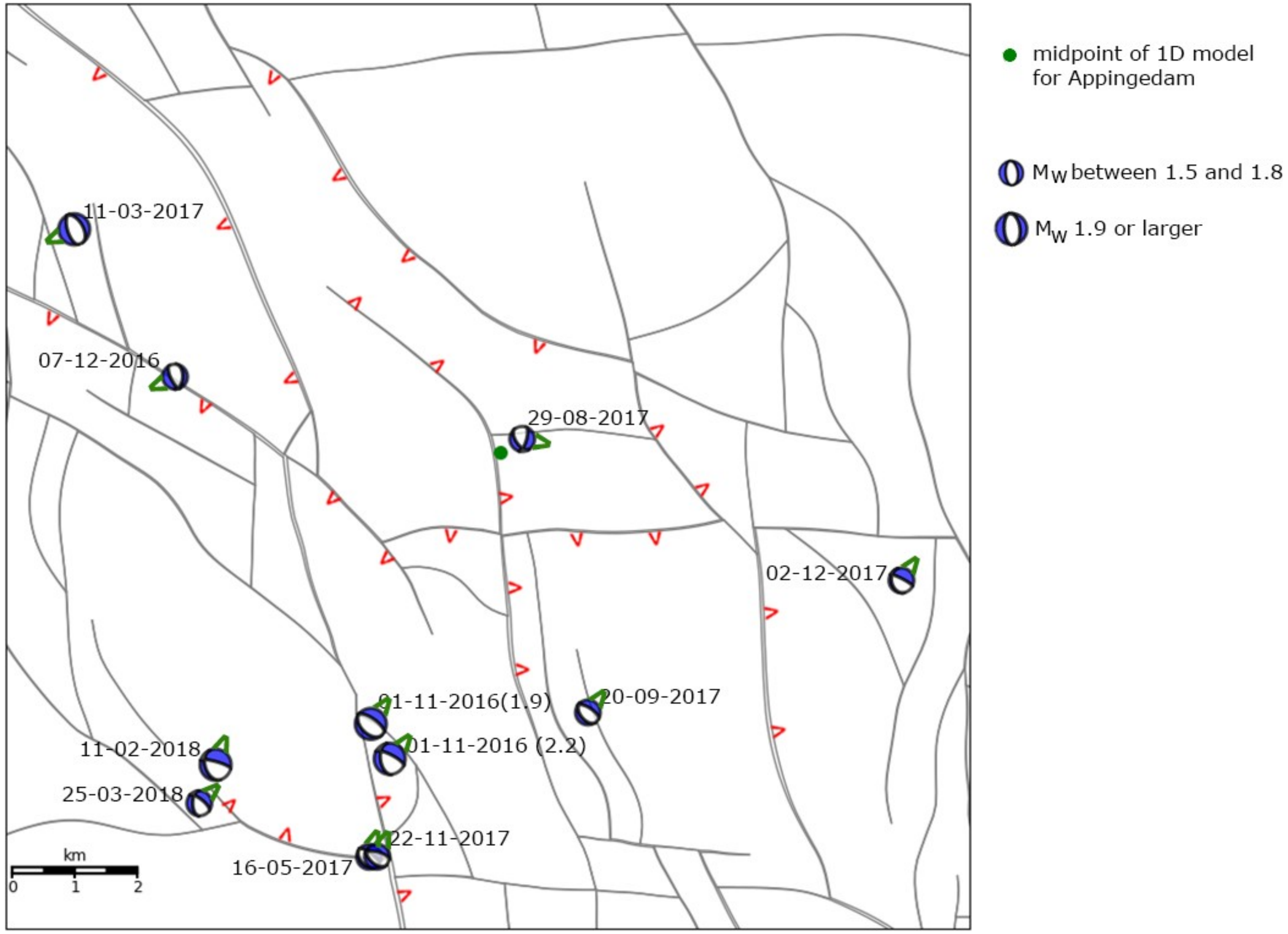
- Seismicity 2014-2018, relocated using the EDT method (Spetzler & Dost, 2017)
- Relocated events correlate well with known faults

- Two active regions: Zeerijp (1) and Appingedam (2)
- Moment tensor inversion for these partly overlapping regions

Results



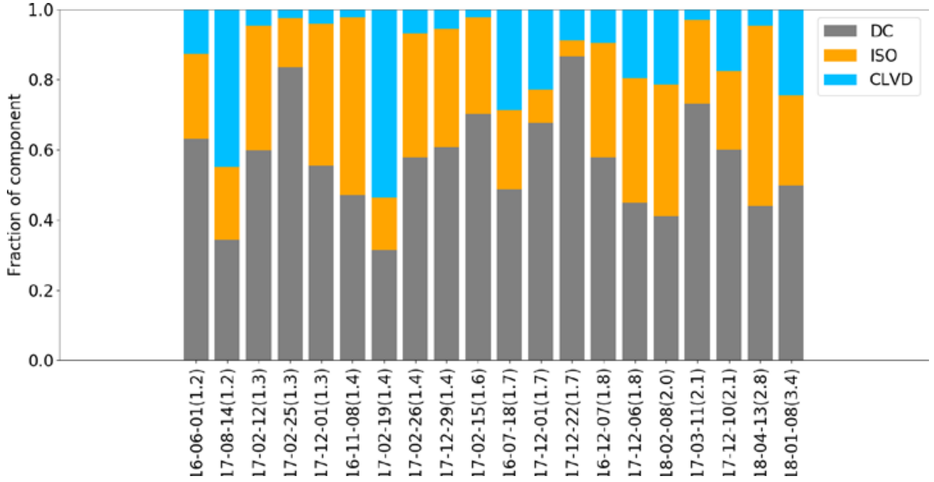
Zeerijp



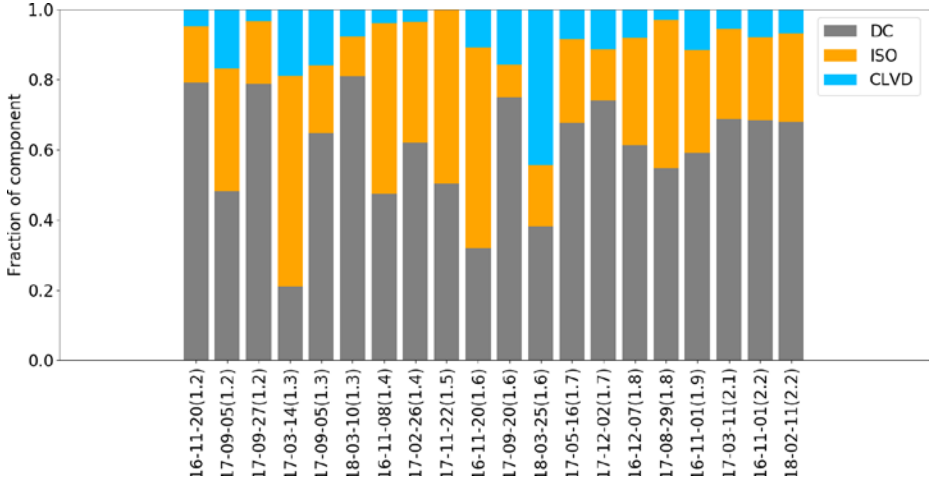
Appingedam

Full moment tensor components

Zeerijp area



Appingedam area



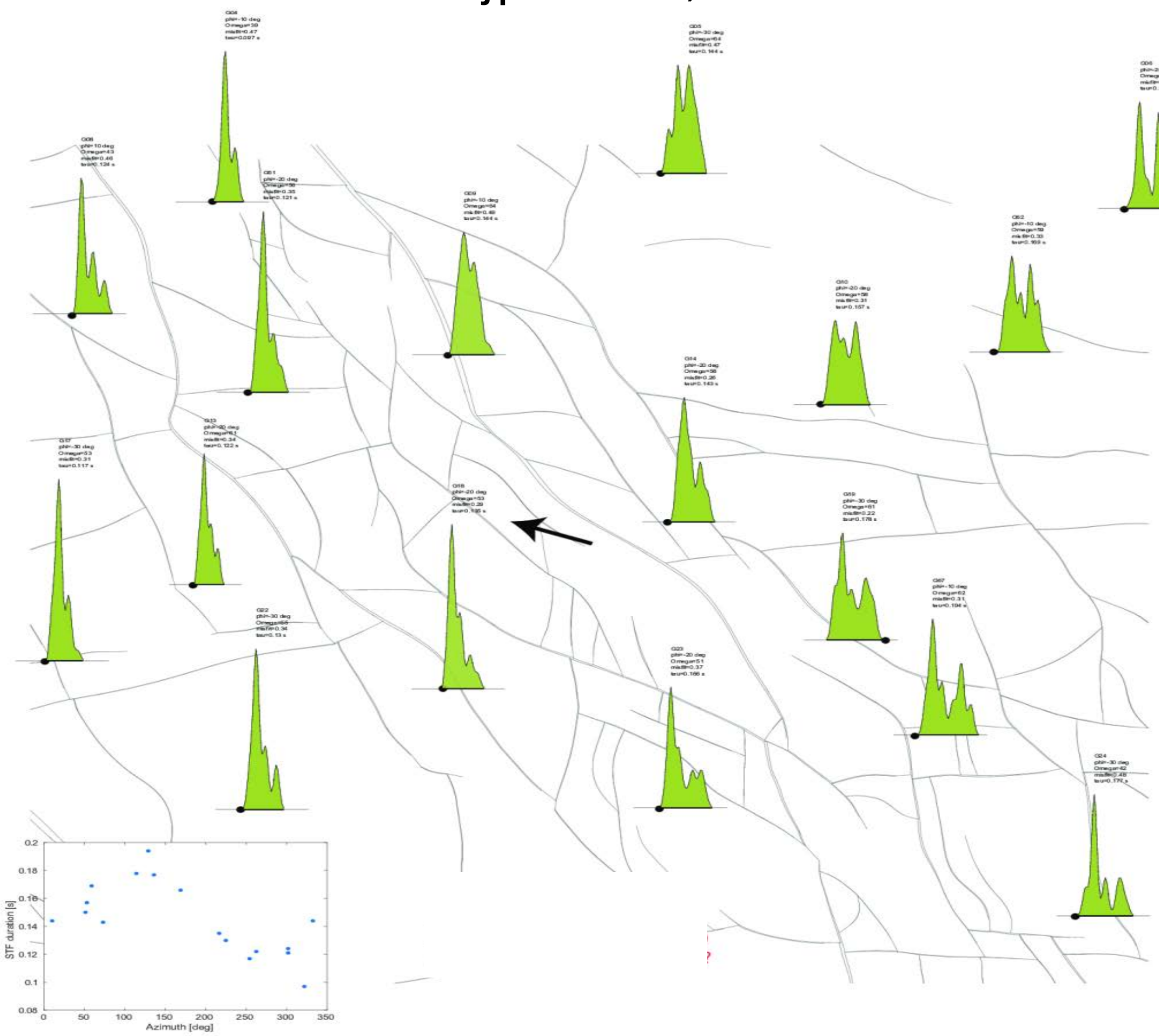
Contribution of Double Couple (DC), Isotrope (ISO) and Compensated Linear Vector Dipole (CLVD) components to the Moment Tensor solutions.

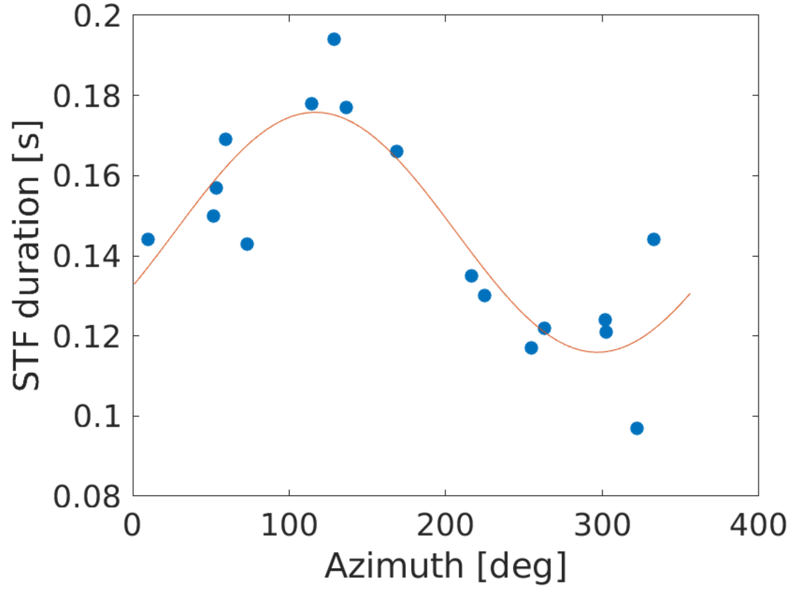
Figures are sorted on increasing magnitude (left to right)

Most events of M>1.5 have limited CLVD, larger ISO and dominant DC components

Spatial distribution STFs

Zeerijp: M3.4, 8-1-2018





$$\tau = \frac{L}{v_r} - \frac{L}{v_p}\cos(\theta - \theta_r)$$

Best fitting model:

Rupture length L: 170m
Vr = 1200 m/s
Θr = 295 degrees

DC solution from MTI

Strike: 310 degrees
Dip: 60 degrees
Rake: -110 degrees

Conclusion

- The new network is now mature and enables the calculation of hypocenter locations at a sufficient accuracy to identify re-activated faults
- Events are located in the reservoir, no clear deviations were detected.
- Moment tensor inversions show results in line with known fault movement: normal faulting along steeply dipping faults in the reservoir.
- The contribution of non-DC components is sometimes large, mainly with respect to the isotropic component (volume change).
  Only an inversion for the DC component produces erroneous results for some events.
- Interpretation of the duration of Source Time Functions for the M 3.4 Zeerijp event provides detailed insight in the rupture process