Review of the public induced seismic earthquake catalogue from the Groningen field

KEM-11a

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NORSAR
Exploring the Earth

Overview

- review of metadata
- review of existing data
- review of data processing
- review of advanced data analyses

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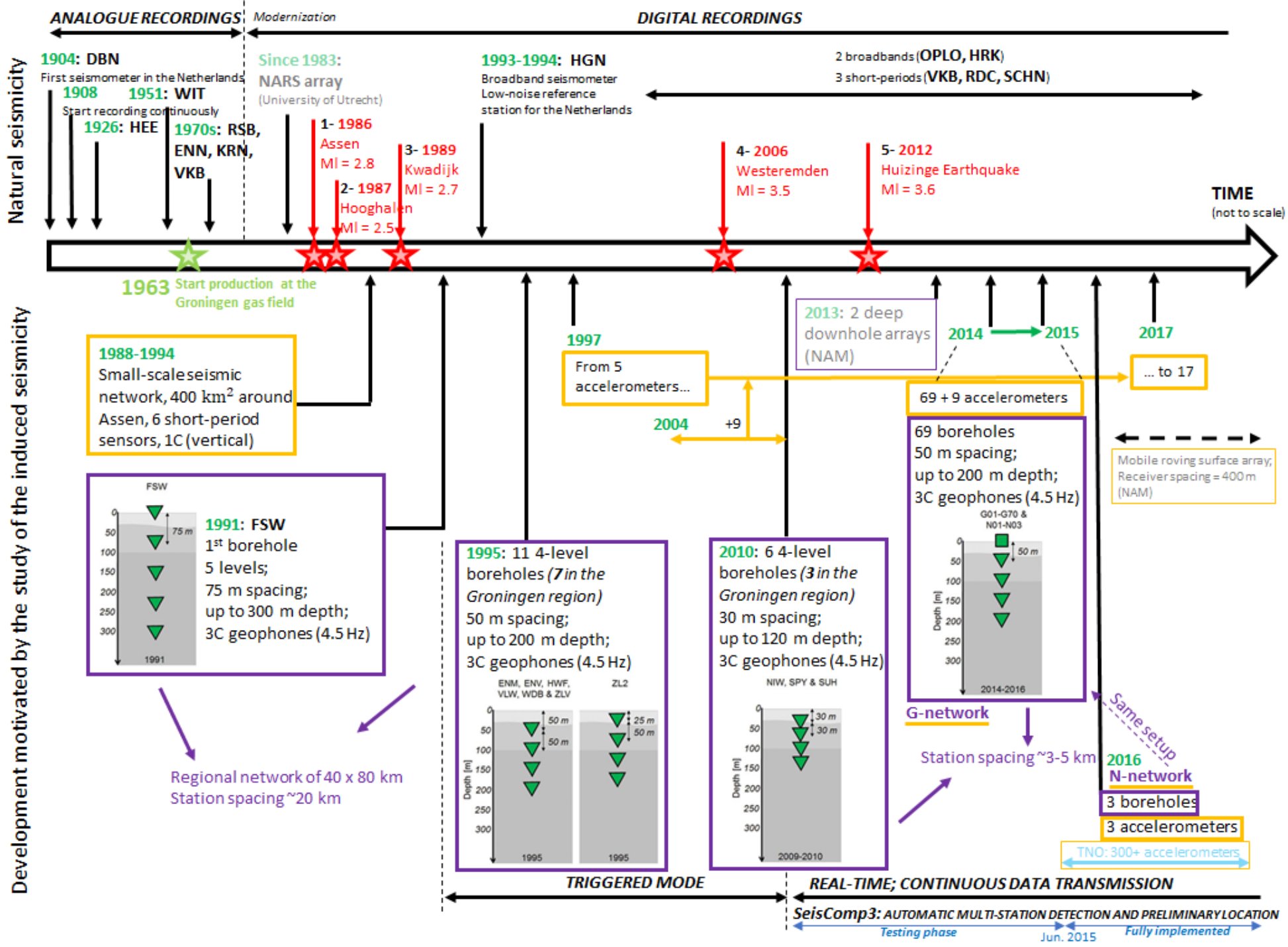
Station network development

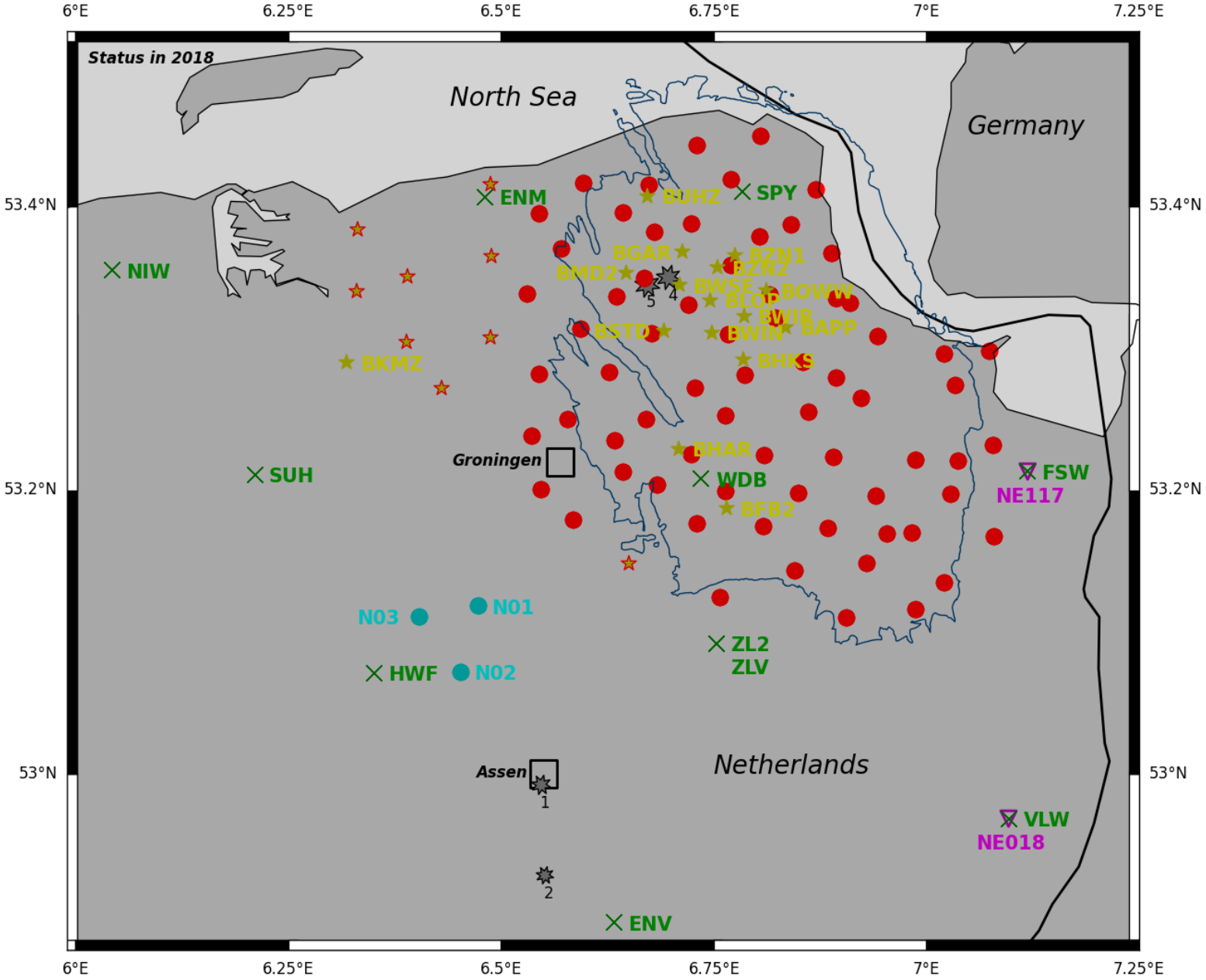


Station network

The borehole network underwent 3 major upgrades in 1995, 2010 as well as 2015 and contains 84 stations nowadays.

Before 2013, accelerometers have been deployed temporarily in various configurations. Today, 95 accelerometers are installed as part of the B- and G-networks.

With by far more than 100 seismic stations operated by KNMI and an interstation distance smaller than 5 km, the Groningen area is one of the most thoroughly instrumented sites in the world for the monitoring of induced seismicity.



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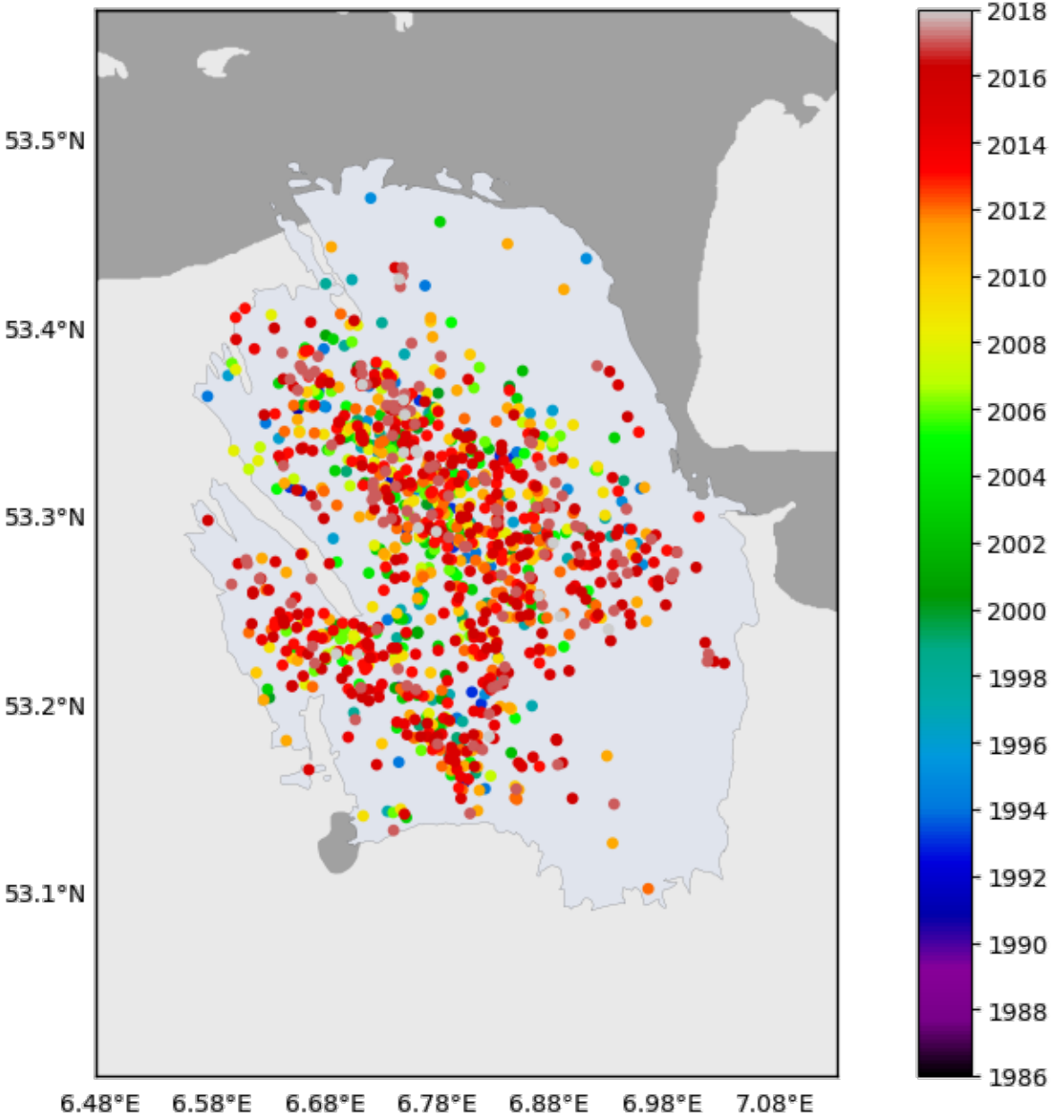
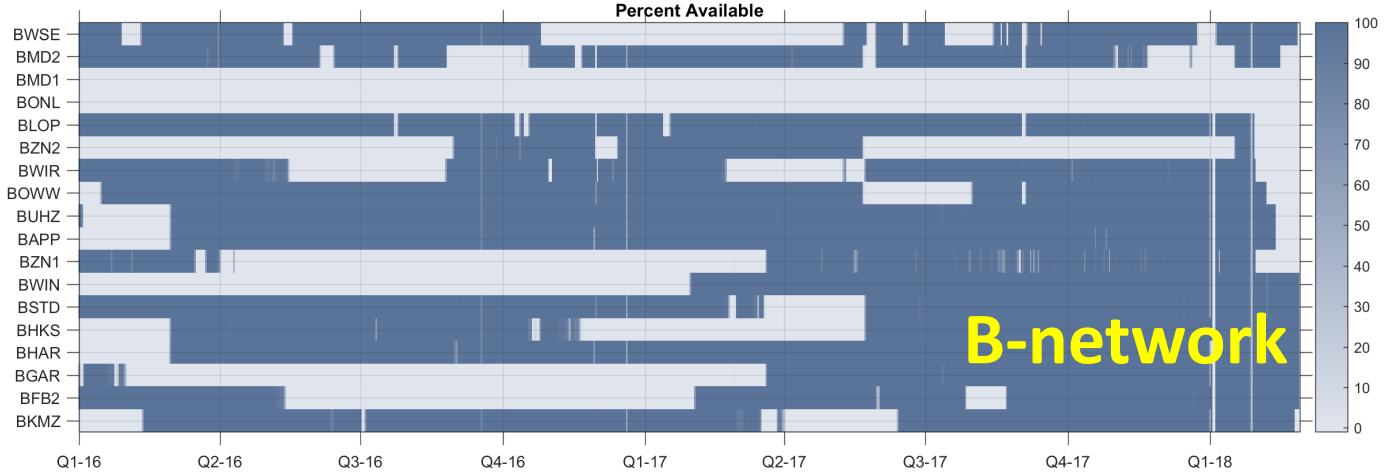
Induced seismicity catalogue

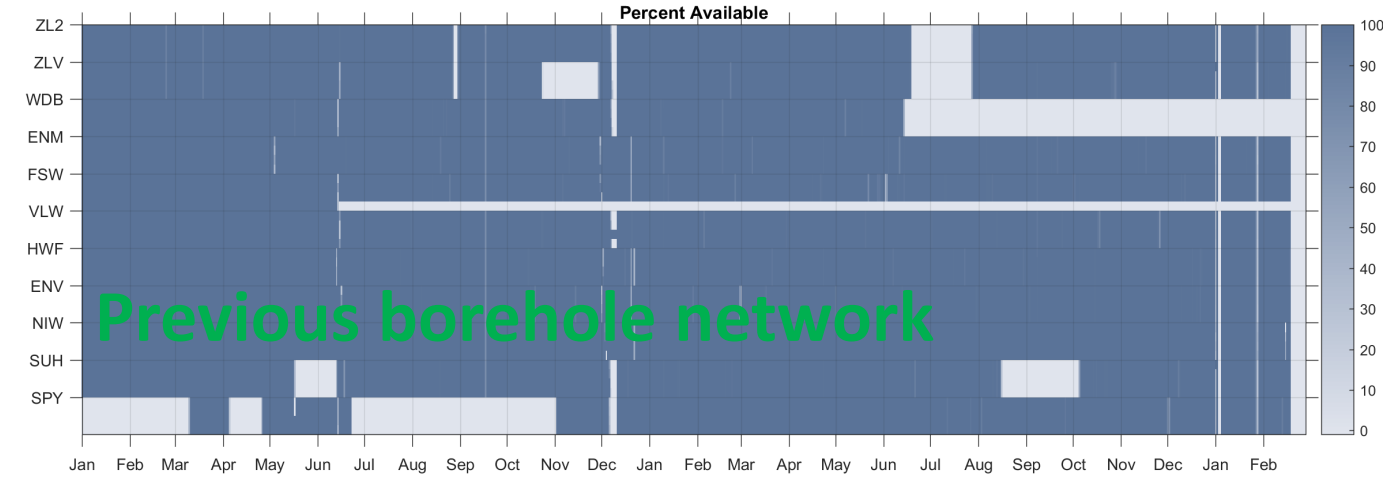
Catalogue contains 1126 events from 05/12/1991 to 20/02/2018 for Groningen field.

Parametric data for events (the bulletin) and stations as well as waveform data are available from rdsa.knmi.nl.



Data completeness





Good completeness with only few longer data gaps.

Majority of problems fixed within 2 days.

For borehole strings, typically all sensors show simultaneous gap indicating problem with data transmission.

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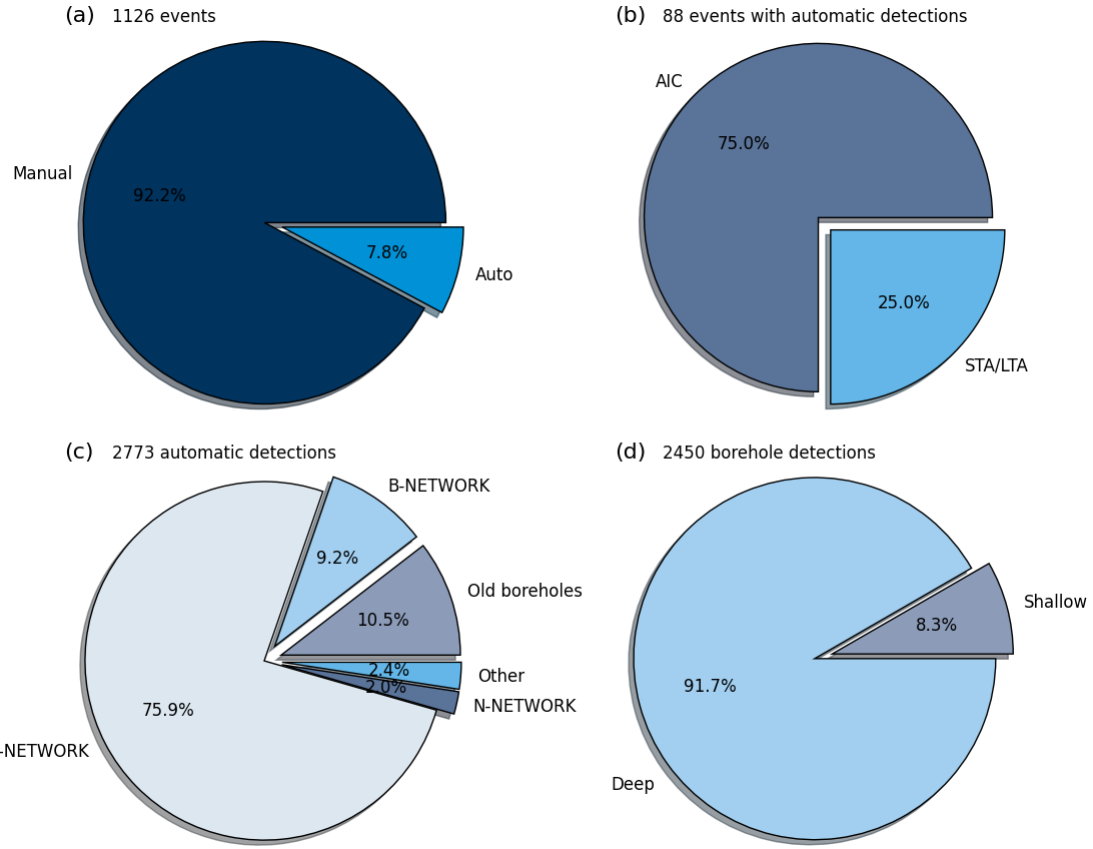
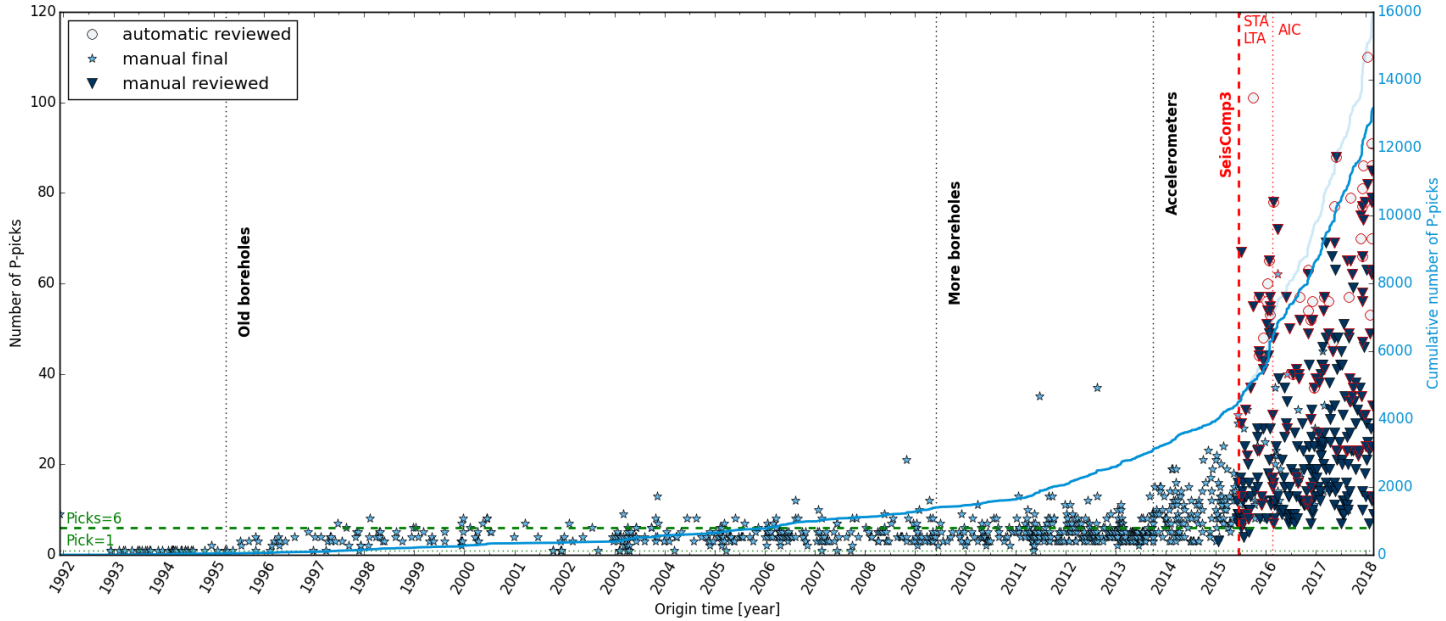
Event detection

The transition to the SeisComp3 system and its automated detection process did not result in a change in the number of events, implying that the new implementation has been a done in accordance and in continuation of the previous one, ensuring a certain homogeneity in the catalogue.

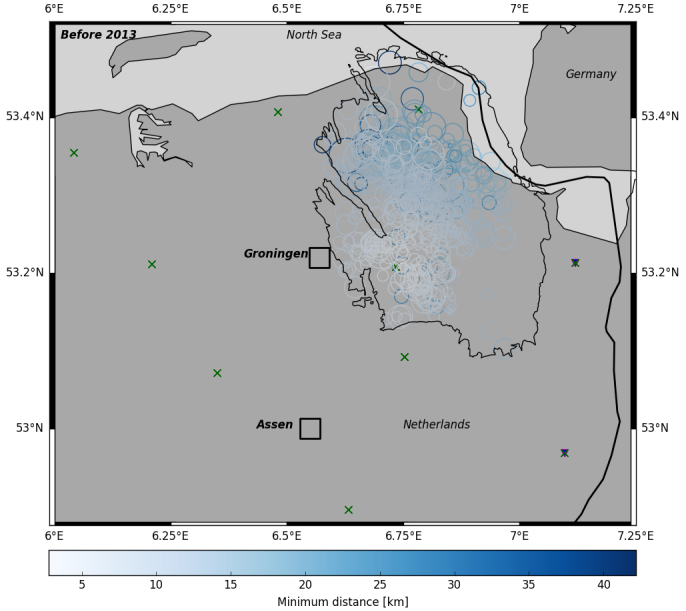


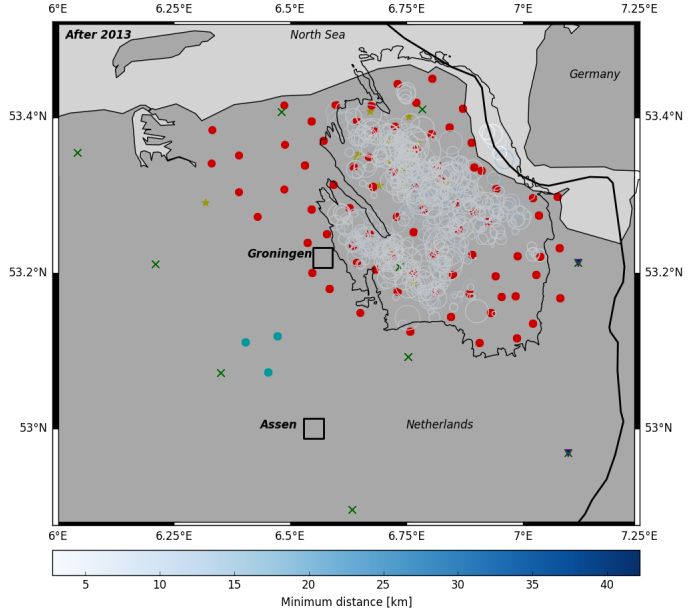


- data was recorded in triggered mode until 2010
- before 2015, only borehole stations were used for detection and a detection on a single station was sufficient to assign an event
- since the installation of the G-network, more restrictive parameters needed: SeisComp3 (Hanka et al., 2010)
- detections performed on the vertical component (P-wave expected to be strongest)
- deepest sensors most sensitive: 90% of detections

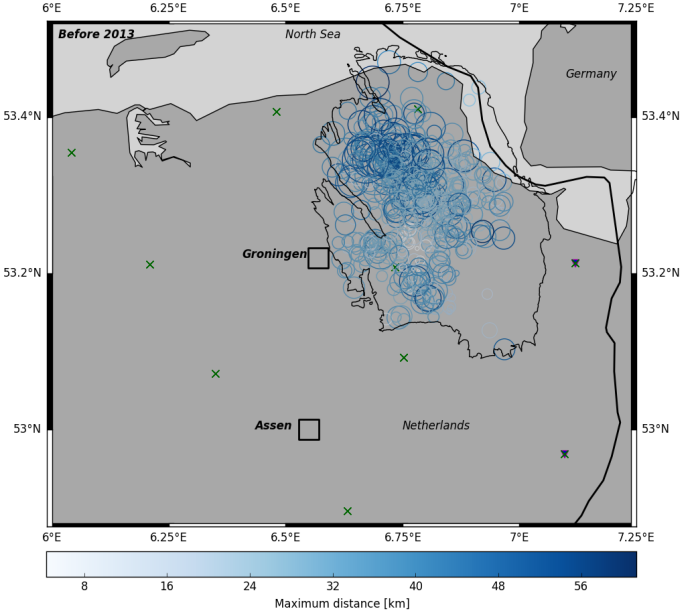
➢ **highlights importance of borehole stations for event detection in Groningen field**

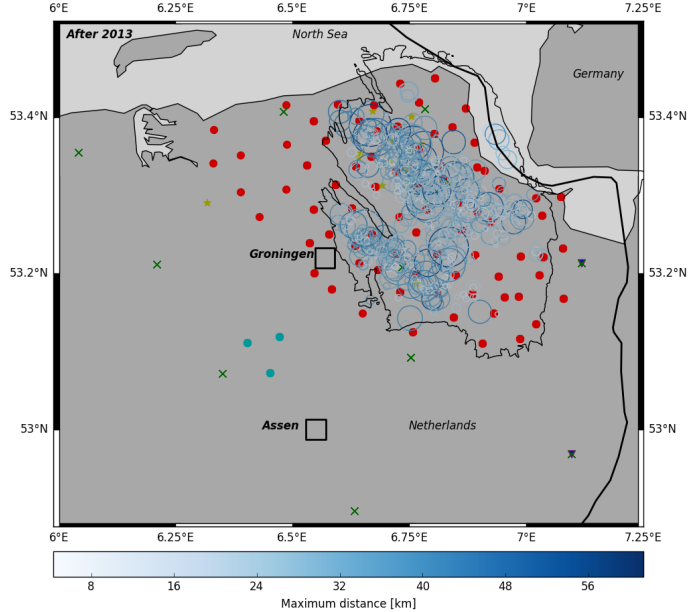
Event detectability





- minimum distance at which event is detected
- left: before 2013
- right: after 2013
- circle colour: distance
- circle size: magnitude





- same, but for maximum distance at which event is detected
- decrease in maximum distance after 2013:
  - more selective choice of stations for picking (only high quality data used)?

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Event location

- crucial for:
  - basis for understanding the seismicity
  - links between seismicity and structural features
  - basis for further analysis
- multiple influencing factors:
  - station distribution
  - data quality
  - velocity model
  - choice of event location algorithm
    - direct search:
      - deterministic searches
      - directed searches
    - iteratively linearized solution

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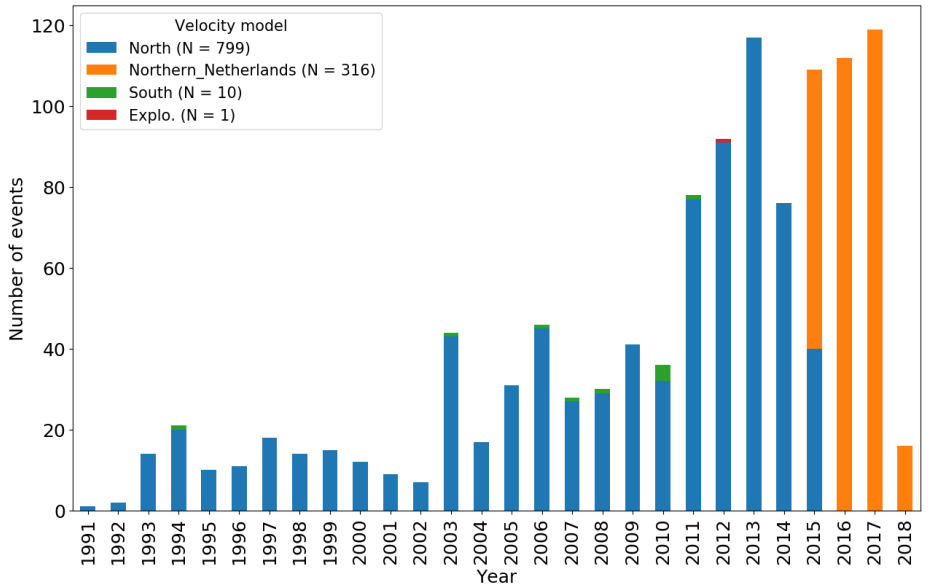
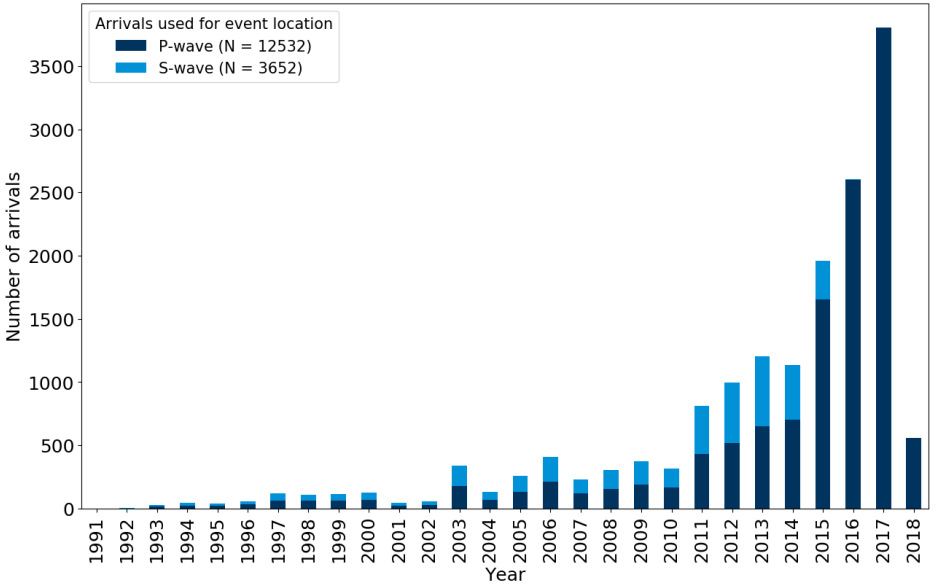
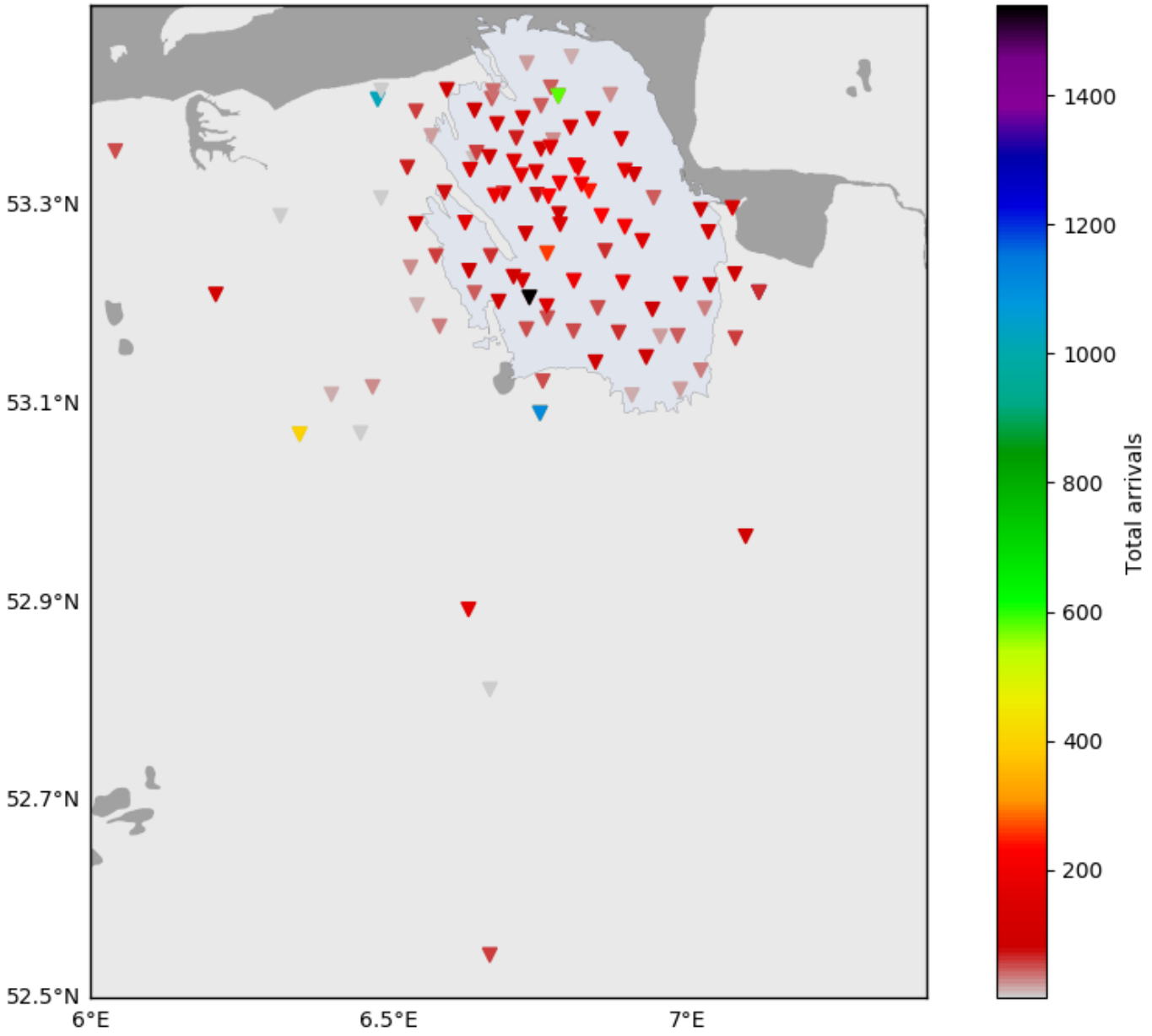
Velocity model



Arrival-time data



Station contributions



Station count

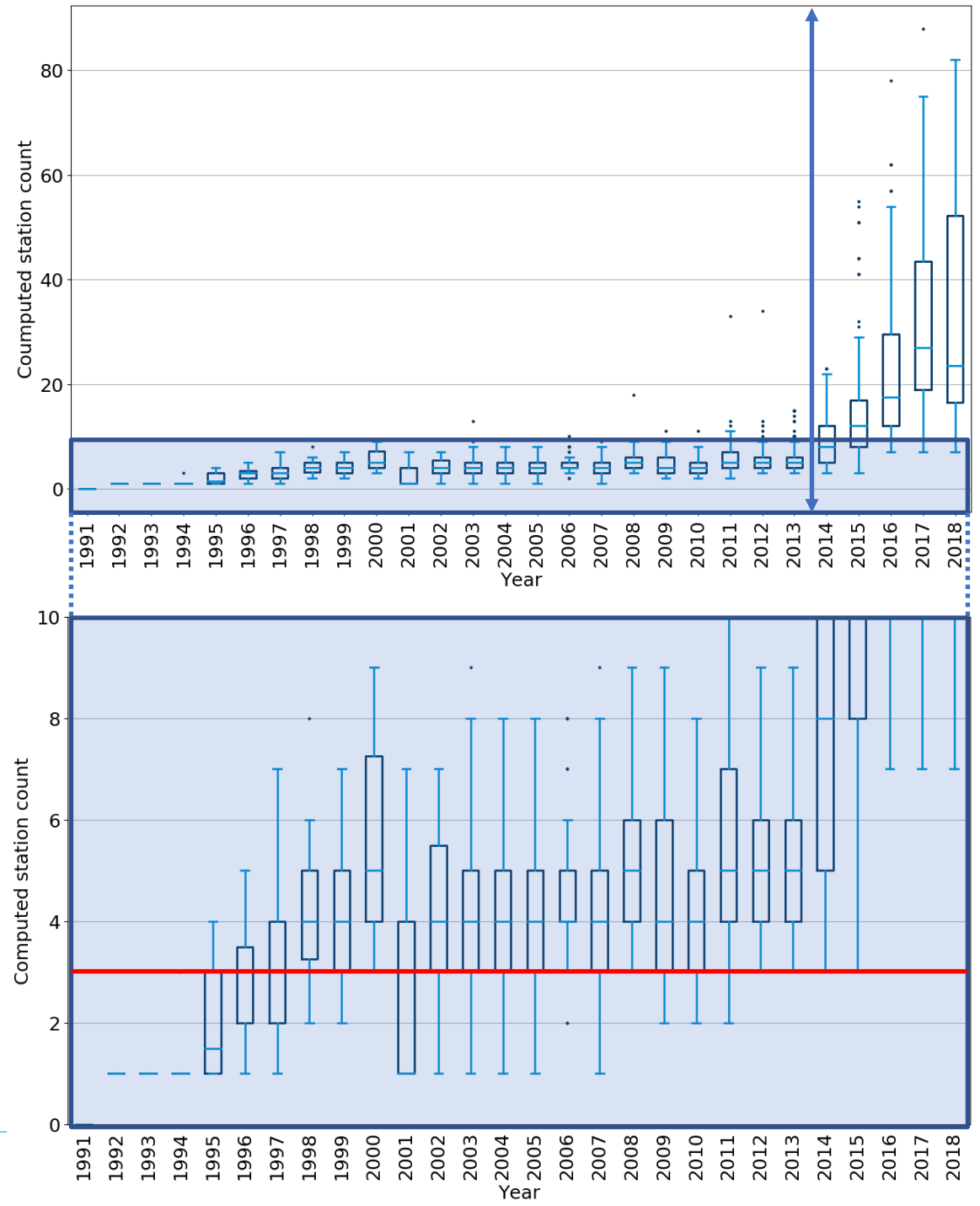
Station count, azimuthal gap and event-station distance are all important metrics for determining the quality of the event location.

85 events with station counts of less than 3 deemed unreliable.

Bondár et al. (2014) recommendations for location uncertainties less than 5 km:

- minimum 10 stations within 250 km radius (reached in 2014).

* event azimuth has been used in addition for event location

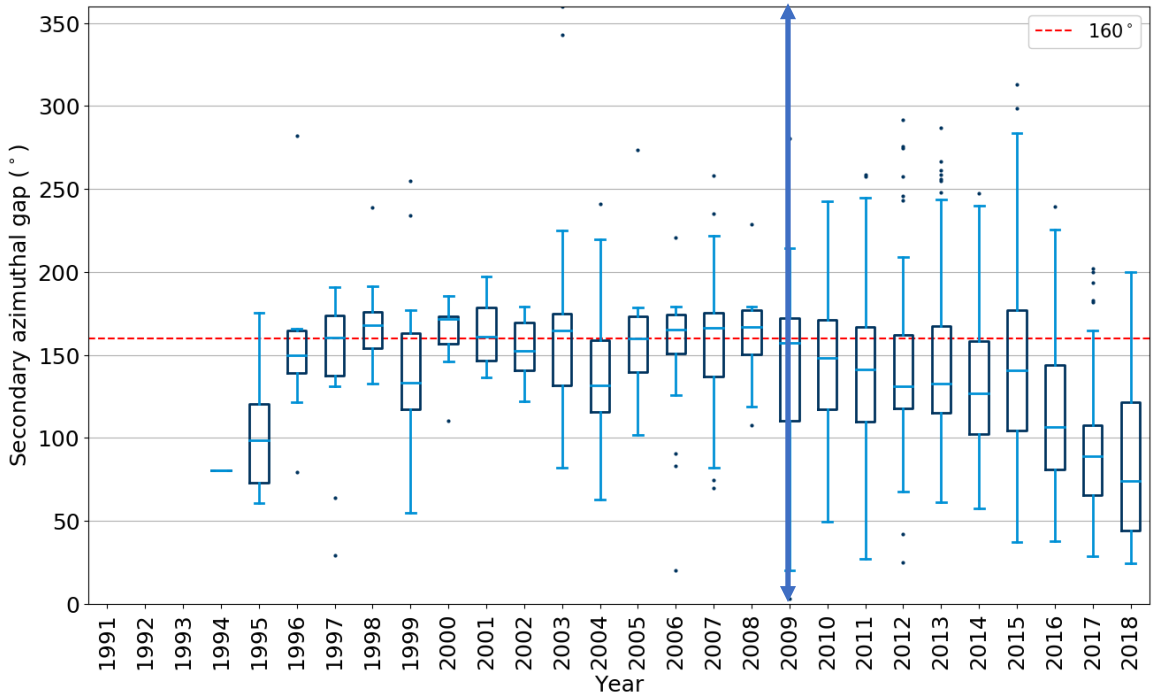


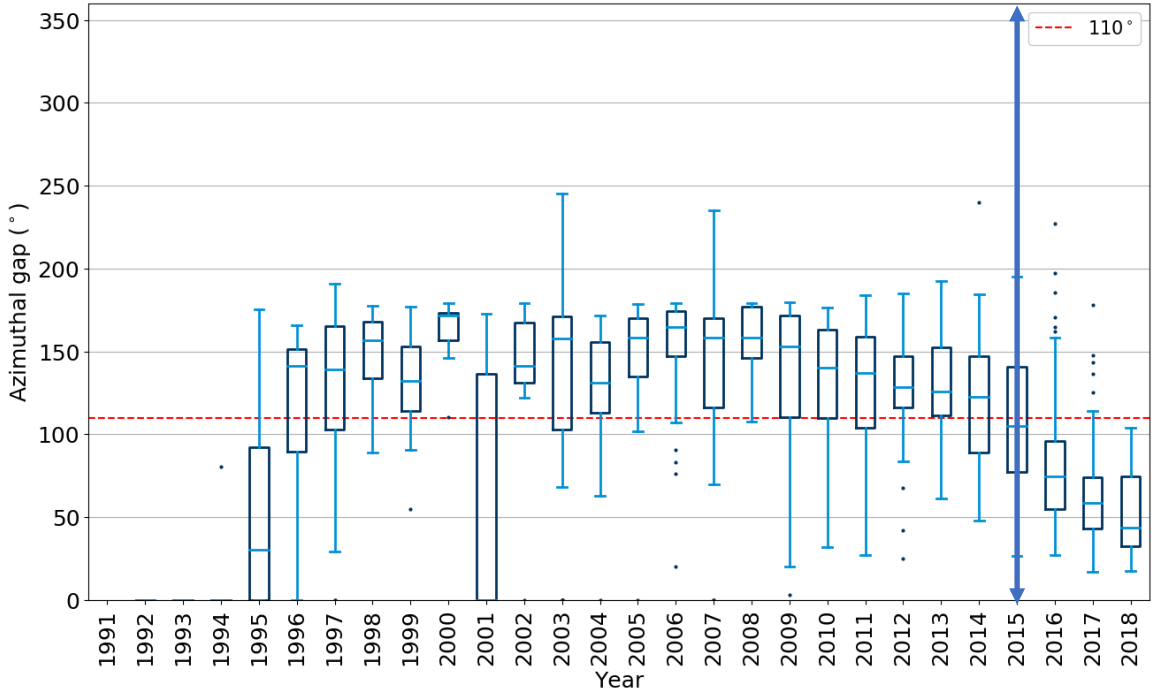
Azimuthal gap

Station count, azimuthal gap and event-station distance are all important metrics for determining the quality of the event location.

Bondár et al. (2014) recommendations for location uncertainties less than 5 km:

- secondary azimuthal gap of less than 160° (reached in 2009)
- azimuthal gap of less than 110° (reached in 2015).



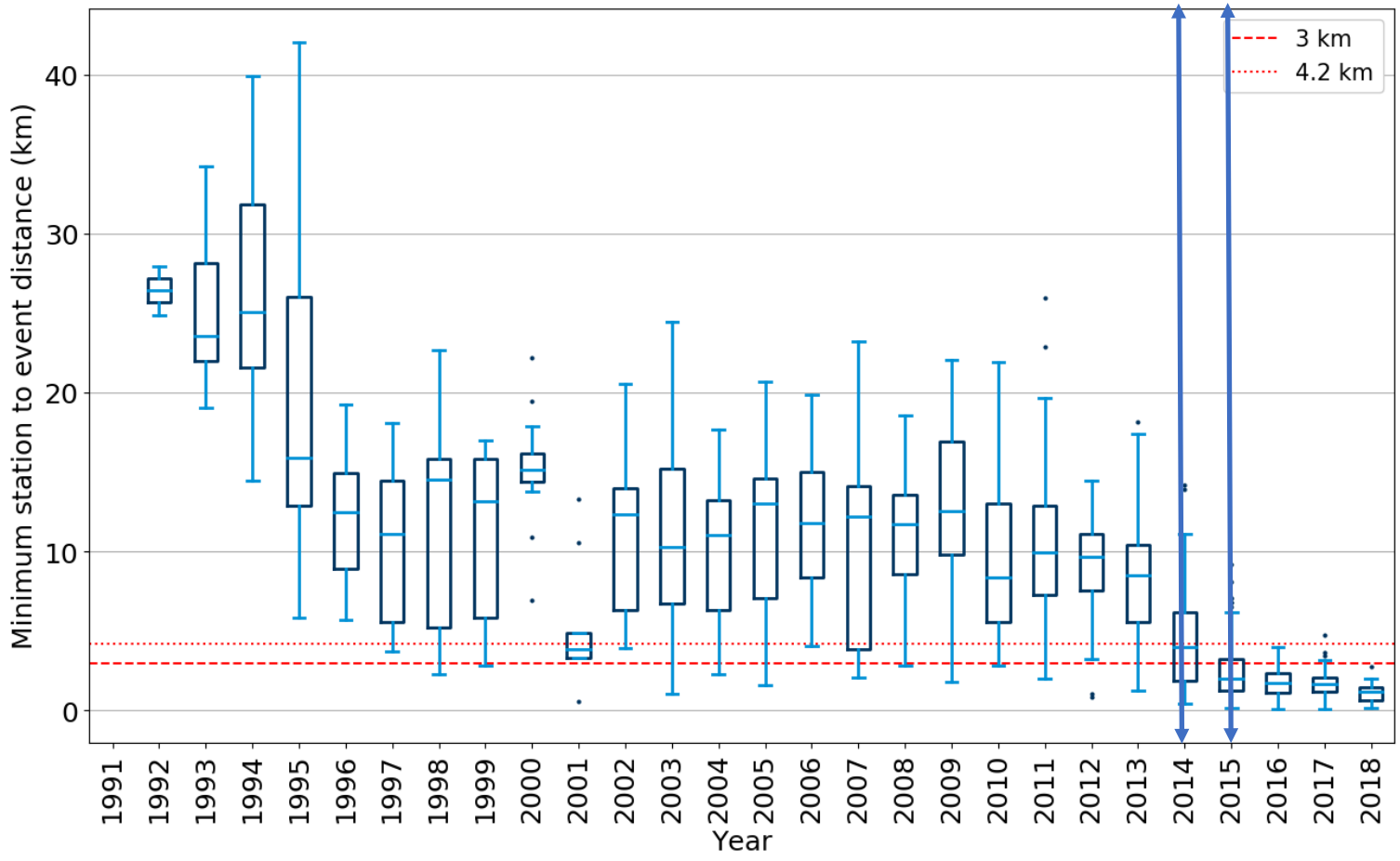


Event-station distance

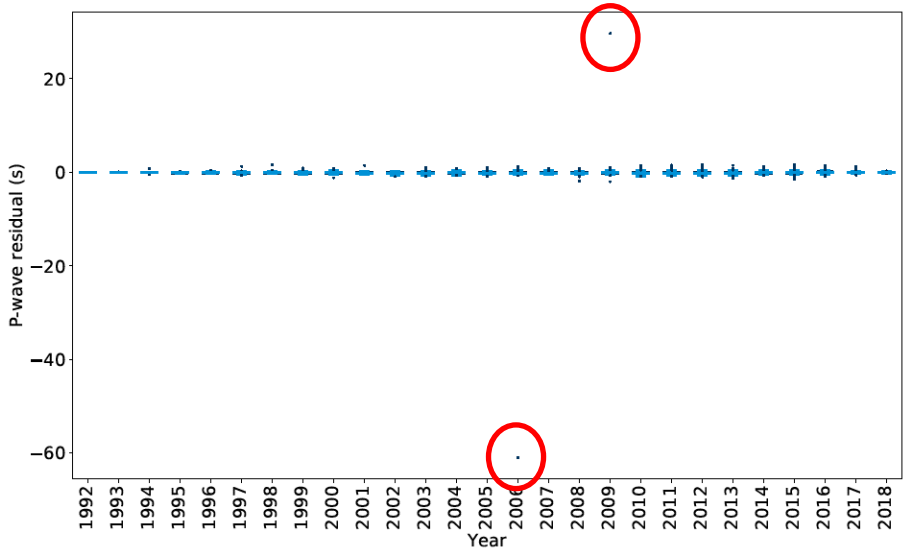
Station count, azimuthal gap and event-station distance are all important metrics for determining the quality of the event location.

Key metrics to constrain focal depth are given by Chatelain et al. (1980) and Gomberg et al. (1990) as:

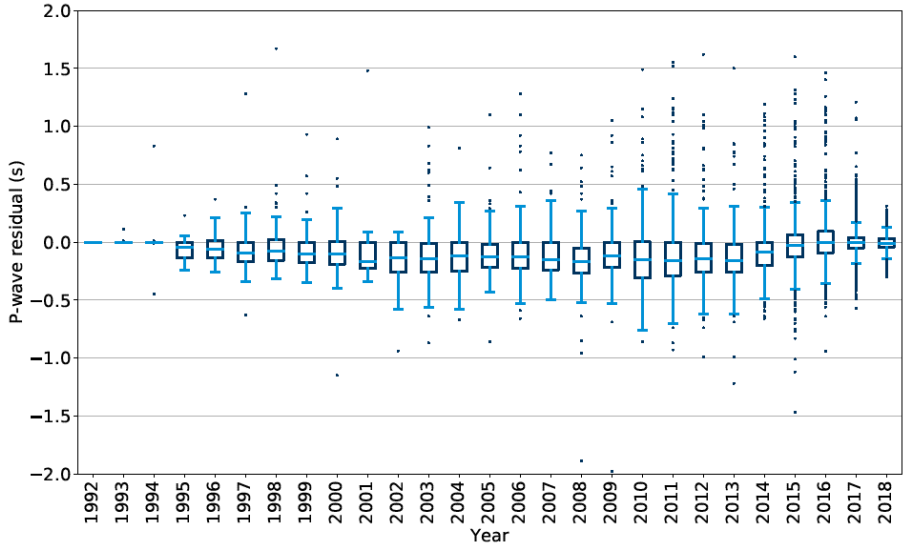
- at least one station within a focal depth's distance from the epicentre (dashed line – reached in 2015)
- an S-wave recorded within 1.4 focal depths' distance from epicentre (dotted line – reached in 2014.

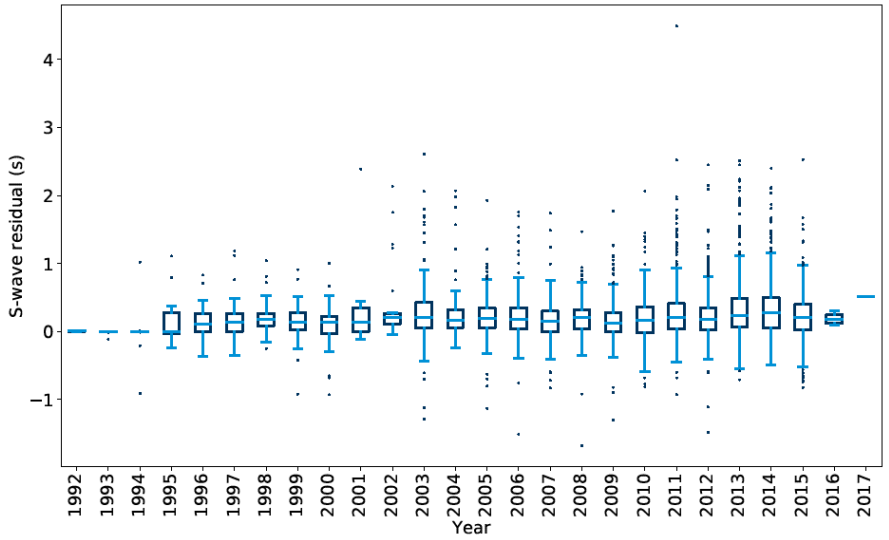


Pick residuals: how well do locations fit velocity model?



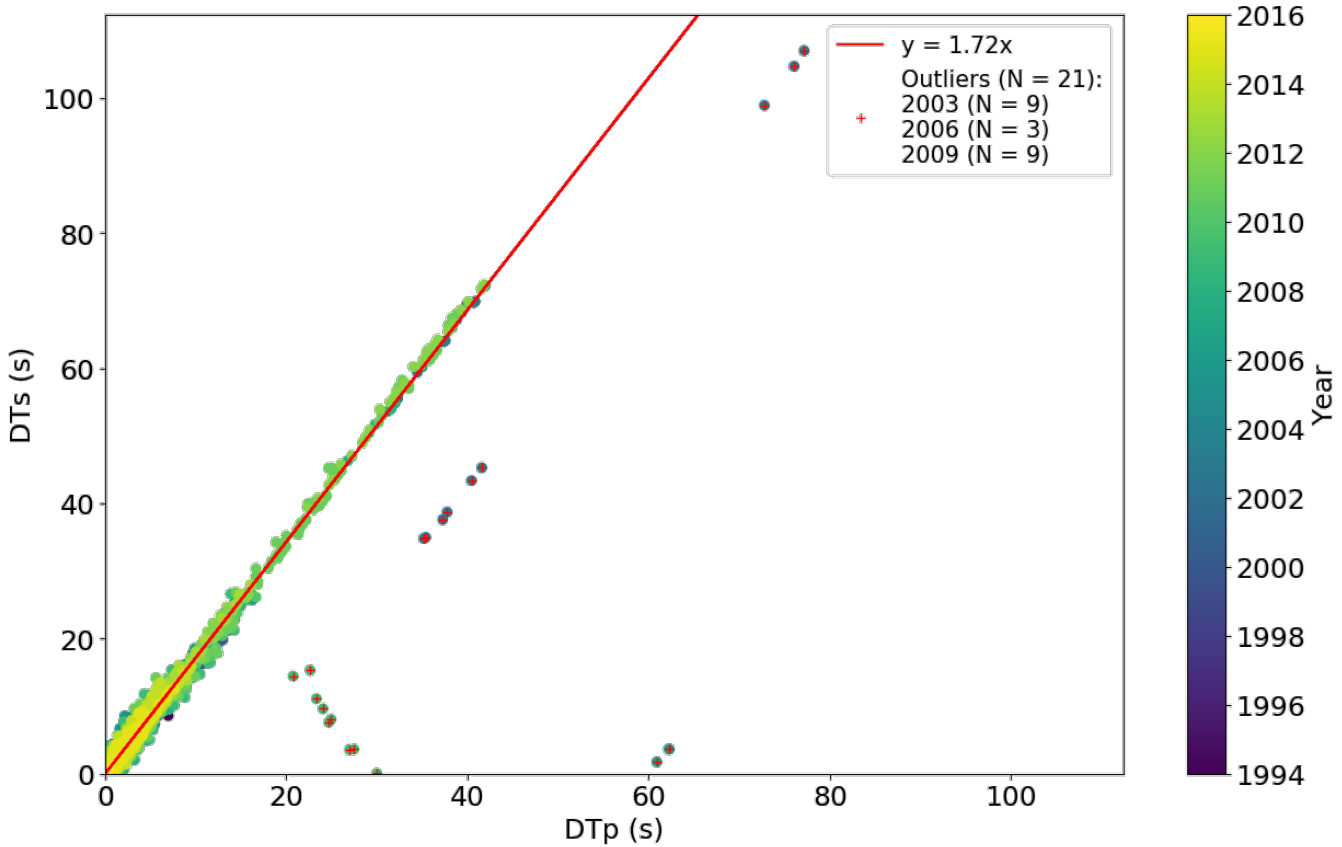
P-wave residuals: only two significant outliers, otherwise predominantly negative residuals, tending towards zero seconds from 2015 on.

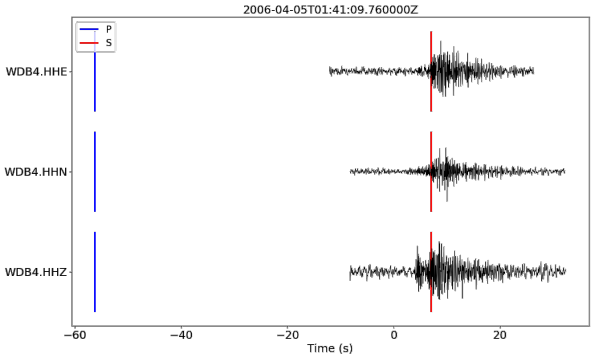


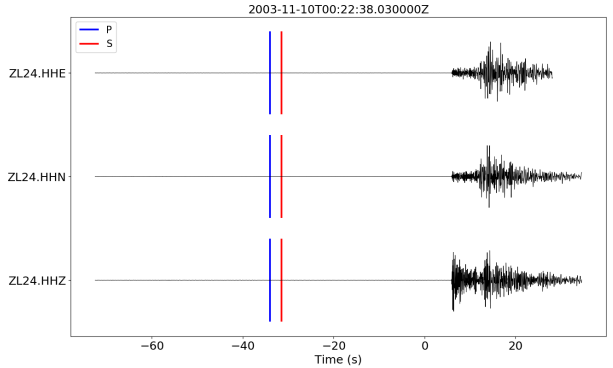


S-wave residuals: no significant outliers, predominantly positive residual, S-wave arrival data phasing out from 2015 on.

Pick consistency: S- and P-wave arrival times







- modified Wadati plot to check pick consistency (Chatelain et al., 1980)
- compares time difference of P- and S-wave arrivals recorded by pairs of stations
- deviations from linear trend reveal potential pick errors (small variations due to velocity heterogeneities)
- requires P- and S-picks, therefore applicable only to subset of events until end of 2015

➢ 21 outliers corresponding to 3 events
  - whereof only 2 picks used during event location, leading to the large P-wave residuals shown previously
  - implying they had no negative effect on event location

Impressive pick consistency!

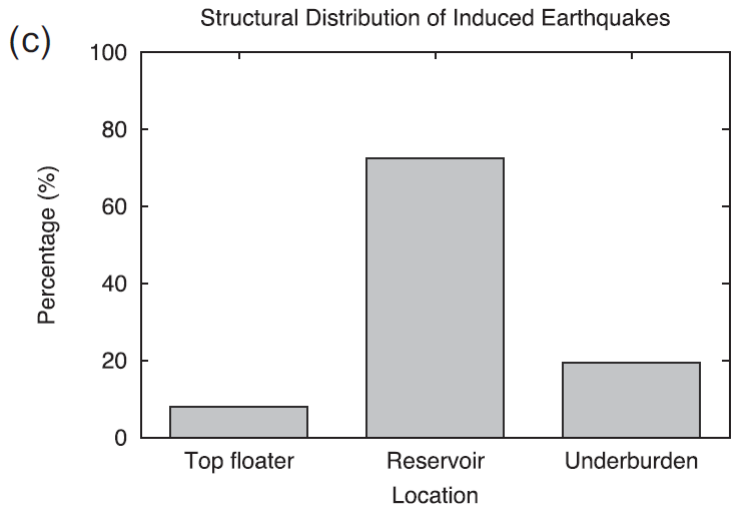
Focal depth

- KNMI currently fix event depths at 3 km - the average reservoir depth location
- increase in station density: improved ability to constrain focal depth
- difficulty to determine S-wave arrival times

- Spetzler and Dost (2017) use EDT method and NAM 3-D velocity model:
  - in first version, minority of events occurring both above and below the reservoir
  - correction: artefact, no events above reservoir found

Establishing correct event depth is important for understanding the seismic hazard at Groningen. Without multiple phases (e.g. P and S-waves), and without arrival-time observations from stations close to the epicentre (i.e. at a distance less than the earthquake depth), the depth will not be resolvable.

Fixing event depth is common practice by seismological observatories and understandable given the difficulties in resolving the depth.



Spetzler & Dost (2017)

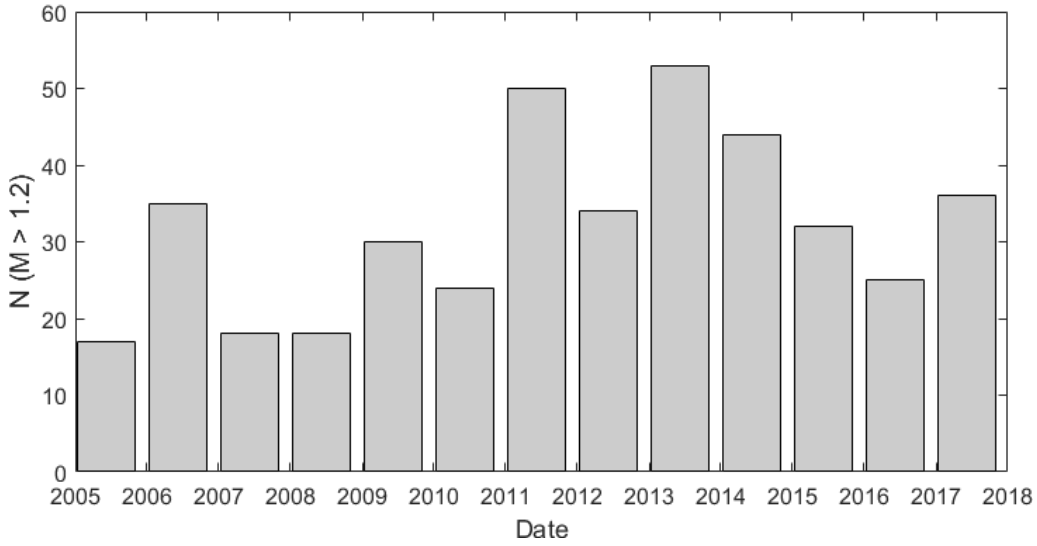
Magnitude computation:

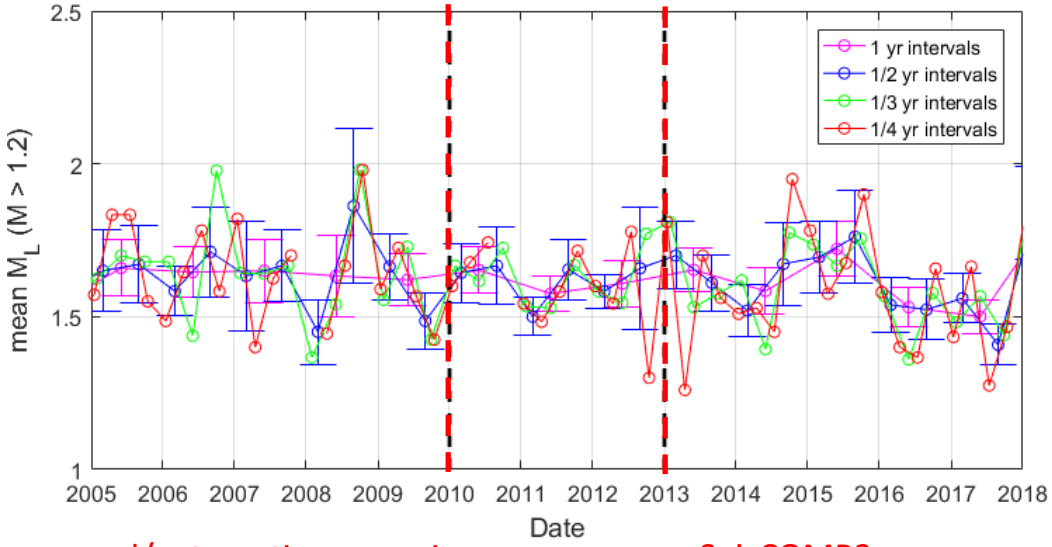
evaluate if changes in data processing or recent extensions of the borehole network potentially led to magnitude inconsistency

- local Magnitude M_L is part of standard processing for all induced events
- M_L is basis for Groningen seismic hazard and risk models
- for larger events ($M_L \geq 2.5$), moment magnitudes M_W determined in addition
- scaling relations by e.g. Dost et al. (2018)

Due to an update of the catalogue following the change of the attenuation function in 2004, the resulting catalogue is consistent.

All applied methods to estimate M_L and M_W are state of the art and consider recent theoretical and empirical publications on scaling relations elsewhere.





manual/automatic processing

SeisCOMP3

Overview

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Source mechanisms - update

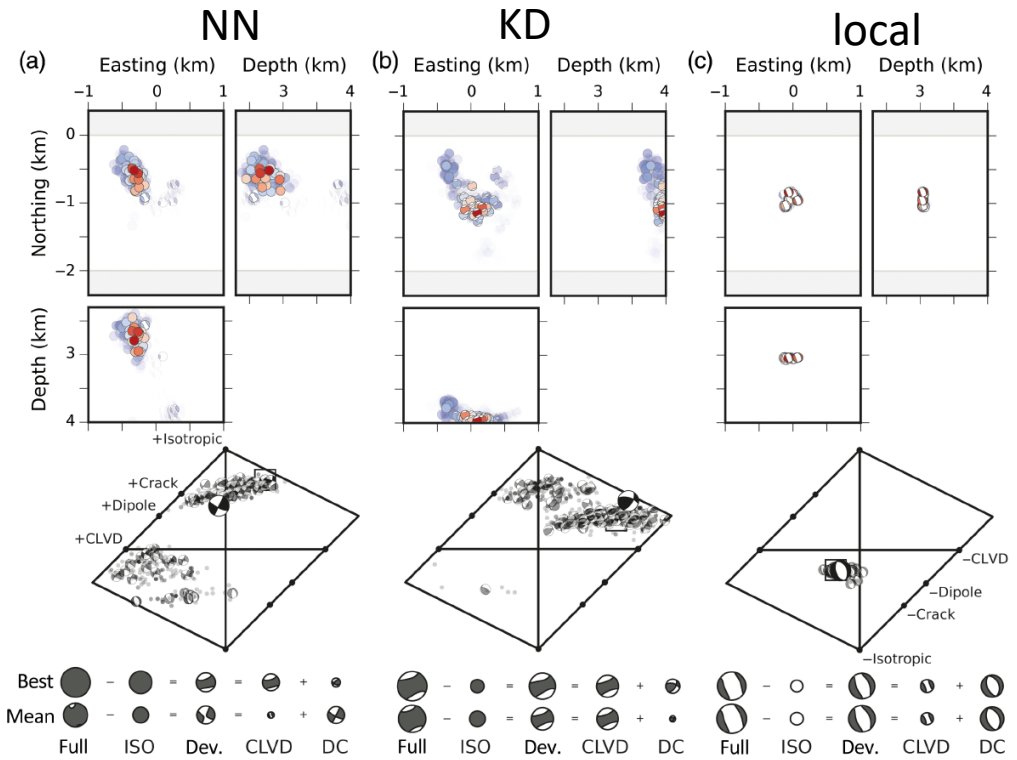
Kühn et al. (2020)

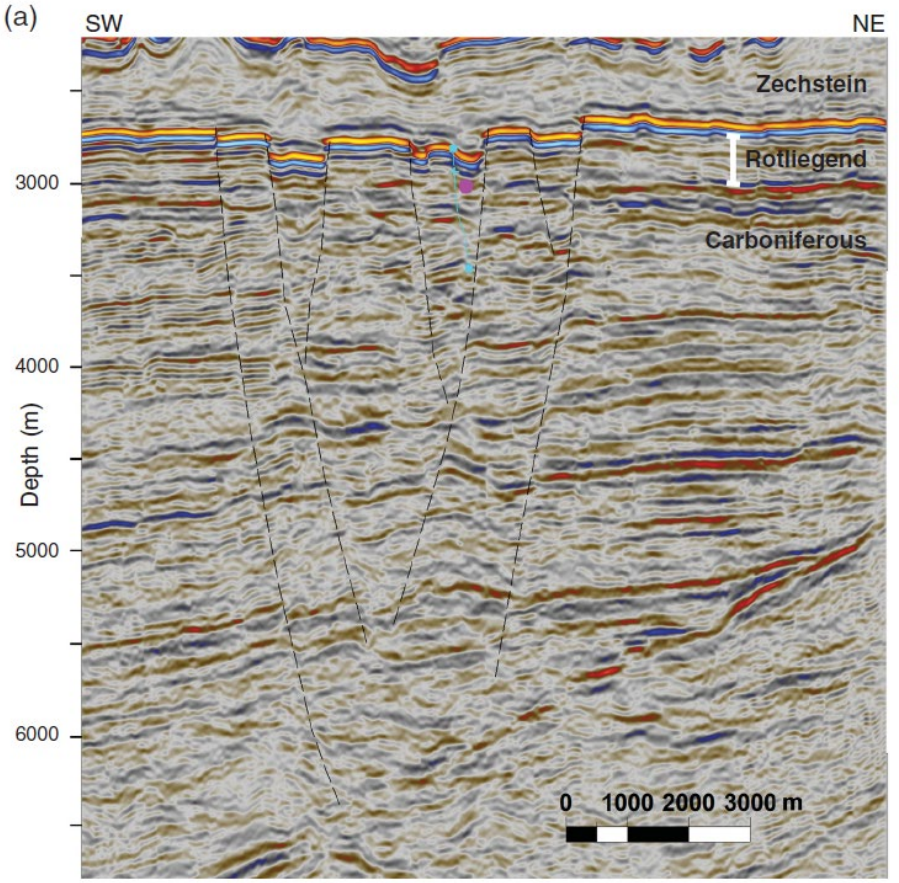
- testing:
  - velocity models
  - input data
  - station depths

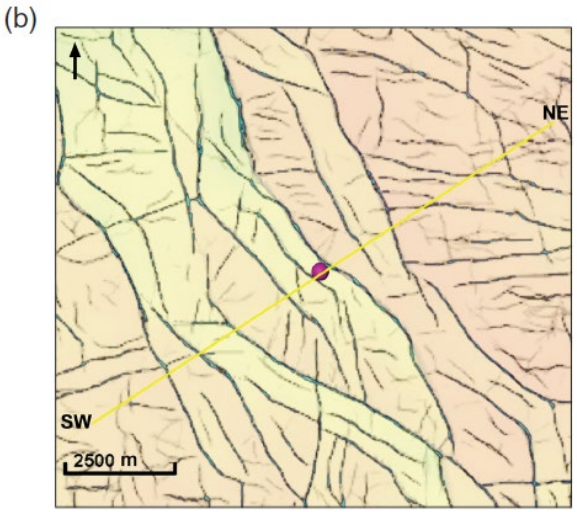
Probabilistic Moment Tensor Inversion for Hydrocarbon-Induced Seismicity in the Groningen Gas Field, The Netherlands,
Part 1: Testing
Part 2: Application

Dost et al. (2020)

- application:
  - M ≥ 2, 2016-2019
  - fault structures
  - 3D seismic sections interpretation of isotropic component







Summary

- metadata:
  - by far more than 100 seismic stations operated by KNMI, interstation distance smaller than 5 km: Groningen area is one of the most thoroughly instrumented sites in the world for monitoring induced seismicity
- data completeness:
  - only few longer data gaps, problems fixed quickly
  - for borehole strings, typically problem with data transmission
- event detection:
  - 90% of automatic detections on deepest sensors: importance of borehole stations
  - transition to the SeisComp3 system and automated detection process sustained catalogue homogeneity
- outstanding pick consistency
- station count, azimuthal gap, event-station distance:
  - important metrics for quality of the event location
  - majority of general recommendations fulfilled after completion of G-network
- focal depth:
  - fixing event depth to 3 km for the Groningen field justified
- magnitude computation:
  - all applied methods to estimate M_L and M_W are state of the art
  - due to an update of the catalogue following the change of the attenuation function in 2004, the resulting catalogue is consistent

NORSAR

Thank you for your attention!

NORSAR report available from:

https://www.norsar.no/r-d/publications/2018/review-of-the-public-knmi-induced-earthquake-catalogue-from-the-groningen-gas-field-report-project-phase-1-wp1-catalogue-review

doi: 10.21348/p.2018.0001