Royal Netherlands Meteorological Institute
Ministry of Infrastructure and Water Management

Analysis of the hypocenter for the Warffum 2025-05-18 earthquake

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Summary

The Warffum event on 2025-05-18T20:57:23.7 with a local magnitude of 2.1 was detected by the KNMI network and located in near-real time with the Hypocenter method. This fast solution uses an average 1D model for the north of the Netherlands. In this report, an updated location and its uncertainty are derived. The location (6.5581E, 53.4019N) with its uncertainties are consistent with a known fault in the region on which the event occurred at a depth of 3.1 km (±1.3 km).

Introduction

The Warffum event on 2025-05-18T20:57:23.7 with a local magnitude of 2.07 was detected by the KNMI network (*KNMI*, 1993) and located near-real time with the Hypocenter method (*Lienert et al.*, 1986). This fast solution uses an average 1D model for the north of the Netherlands (*Kraaijpoel and Dost*, 2013). In this report, an updated location and its uncertainty are derived.

Epicenter

The epicenter is improved by using a best-fitting traveltime versus distance model based on a database of local P-wave traveltime picks. This data-driven model incorporates actual underburden velocities and only well pickable phase arrivals. An error estimate is derived from the spread in picking times from the best-fitting model. This error incorporates both the local variations of the velocity field as well as picking errors. These errors are propagated further into the epicentral probability density function (PDF). This results into an updated epicenter and its 95% confidence region. Details of the method are described in *Ruigrok et al.* (2023).

Fig. 1 shows the seismic sensors where manual P-wave picks are available. Using the indicated stations, a grid search is performed for a region around the Hypocenter solution, as indicated by the red boxes in the figure. In the first step, Equal Differential Time (EDT, *Zhou*, 1994) residuals are computed. That is, for each grid point and for each station combination, the traveltime differences are forward modelled and tabulated. From these values, the observed traveltime differences are subtracted to obtain the EDT residuals. In the second step, the PDF is derived from the EDT residuals, using a L1 norm (*Tarantola*, 2005). Fig. 2 shows the 95% confidence area of the resulting PDF. The locations with the maximum probability is assigned to be the updated epicenter.

The following list contains the new epicenter for the Warffum 2025-05-18 event, both in wgs84 coordinates and in the Dutch national triangulation system (RD). The line that surrounds the 95% confidence zone is by approximation an ellipse. The parameters of this ellipse (major axis, minor axis and orientation) are listed, together with the standard deviations describing the epicentral PDF in the direction with the largest uncertainty σ_1 and the perpendicular direction with the smallest uncertainty σ_2.

Epicenter in wgs84 [deg]: 6.5581, 53.4019
Epicenter in RD [m]: 232880, 602360
Ellipse major and minor axes [m]: 954, 612
σ_1 and σ_2 [m]: 195, 125
Orientation of the major axis [deg]: 161

The waveform data used in the above analysis is publicly available and can be obtained through:

FDSN webservices: `http://rdsa.knmi.nl/fdsnws/dataselect/1/`

Depth

For estimating event depth, local velocity profiles are needed. KNMI obtained a 3D P-wave velocity model from the Nederlandse Aardolie Maatschappij. From this model, a profile is extracted near the location of the initial epicenter (Fig. 3). For depth estimation P-wave arrival times are used at eleven sensors within 10 km epicentral distance: G074, G034, G124, G800, G084, G780, G164, G044, G614, G174 and G134, the nearest being at 1.1 km epicentral distance. For these sensors, the P-EDT are estimated using finite-difference modelling and compared with the measured P-EDT for various locations (*Spetzler et al.*, 2024). The resulting depth estimate and 95% confidence zone is shown in Fig. 4, with the highest probability at 3.1 km depth and a depth uncertainty of σ_Z=1.3 km. The uncertainty could be reduced by including S-wave arrival times in the analysis. This was not done due to time restrictions.

References

KNMI (1993), Netherlands Seismic and Acoustic Network, Royal Netherlands Meteorological Institute (KNMI), Other/Seismic Network, `https://doi.org/10.21944/e970fd34-23b9-3411-b366-e4f72877d2c5`.

Kraaijpoel, D., and B. Dost (2013), Implications of salt-related propagation and mode conversion effects on the analysis of induced seismicity, *Journal of Seismology*, *17*(1), 95–107.

Lienert, B. R., E. Berg, and L. N. Frazer (1986), HYPOCENTER: An earthquake location method using centered, scaled, and adaptively damped least squares, *Bulletin of the Seismological Society of America*, *76*(3), 771–783.

Romijn, R. (2017), Groningen velocity model 2017, *Tech. rep.*, NAM (Nederlands Aardolie Maatschappij), `https://nam-feitenencijfers.data-app.nl/download/rapport/9a5751d9-2ff5-4b6a-9c25-e37e76976bc1?open=true`.

Ruigrok, E., P. Kruiver, and B. Dost (2023), Construction of earthquake location uncertainty maps for the Netherlands, *KNMI Technical Report*, *TR-405*, `https://cdn.knmi.nl/knmi/pdf/bibliotheek/knmipubTR/TR405.pdf`.

Spetzler, J., E. Ruigrok, and D. Bouwman (2024), Hypocenter uncertainty analysis of induced and tectonic earthquakes in the Netherlands, *Journal of Seismology*, pp. 1–23.

Tarantola, A. (2005), *Inverse Problem Theory and Methods for Model Parameter Estimation*, SIAM, Philadelphia.

Zhou, H. (1994), Rapid three-dimensional hypocentral determination using a master station method, *Journal of Geophysical Research: Solid Earth*, *99*(B8), 15,439–15,455.

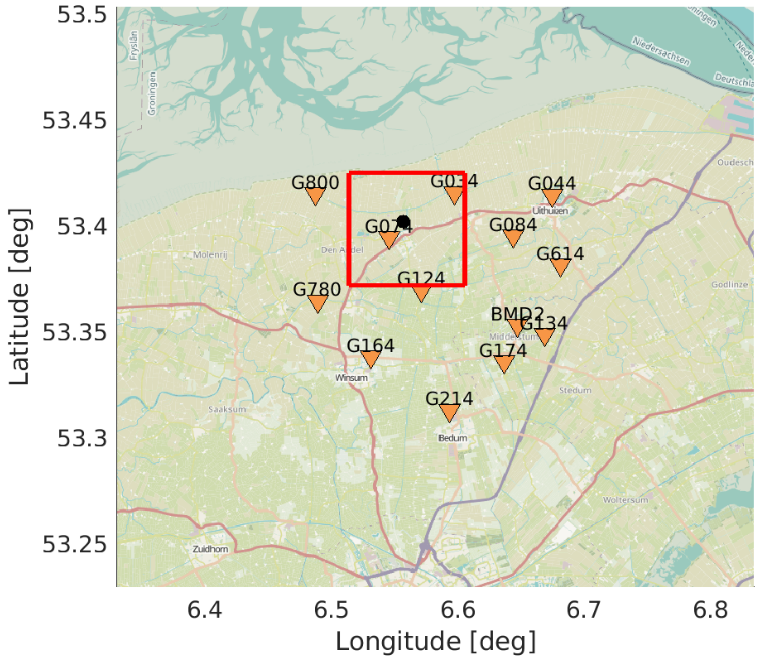

Figure 1: Overview map with locations of stations (orange triangles) where P-wave onsets were picked, the fast Hypocenter solution (black dot) and the boundary line of the area in which a grid search is done (red box). Background map is from www.openstreetmap.org.

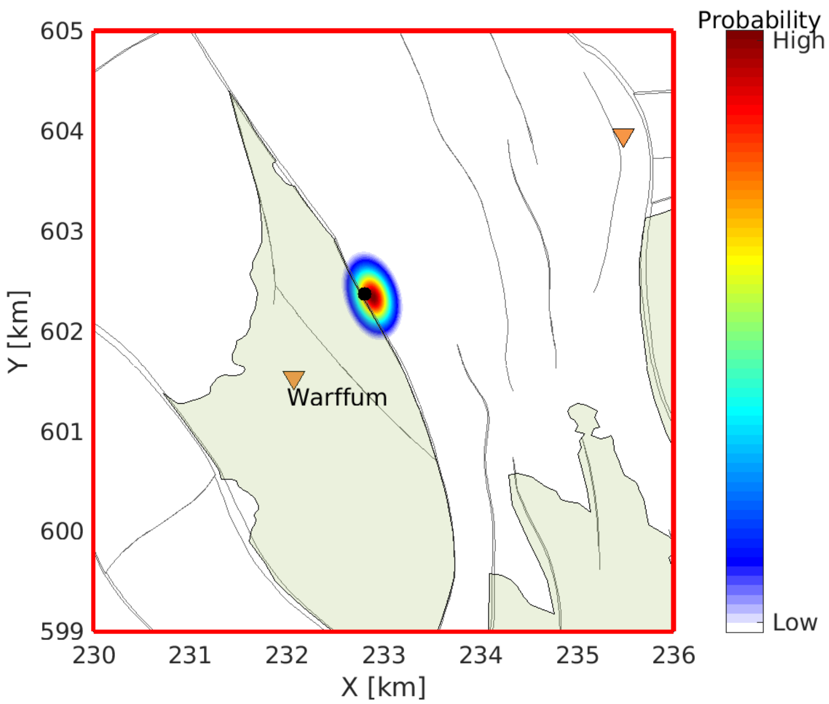

Figure 2: Map showing hydrocarbon fields (green-filled polygons), faults (black lines), the fast Hypocenter solution (black dot) and the epicentral probability density function (PDF) using measured time-differences and a traveltime model. The coloured area corresponds to the 95% confidence area of the PDF. The faults and field polygons are from www.nlog.nl, using the May 2025 update.

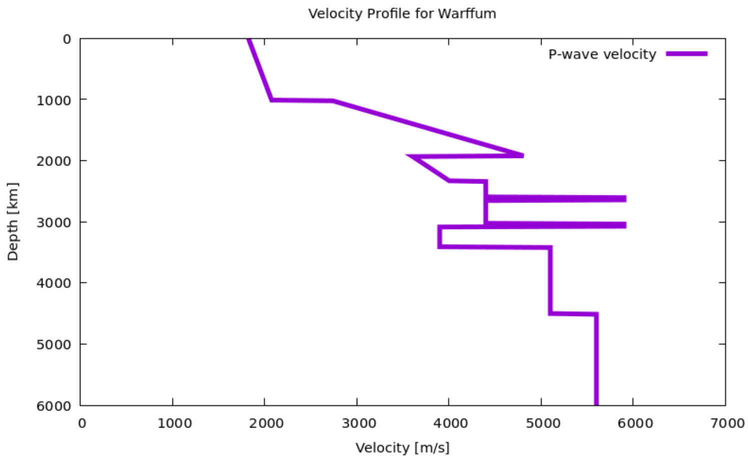

Figure 3: The P-wave (purple line) velocity model used for estimating the depth of the event. The profile has been obtained from *Romijn* (2017) at location [RDx,RDy]=[234421, 599011] m

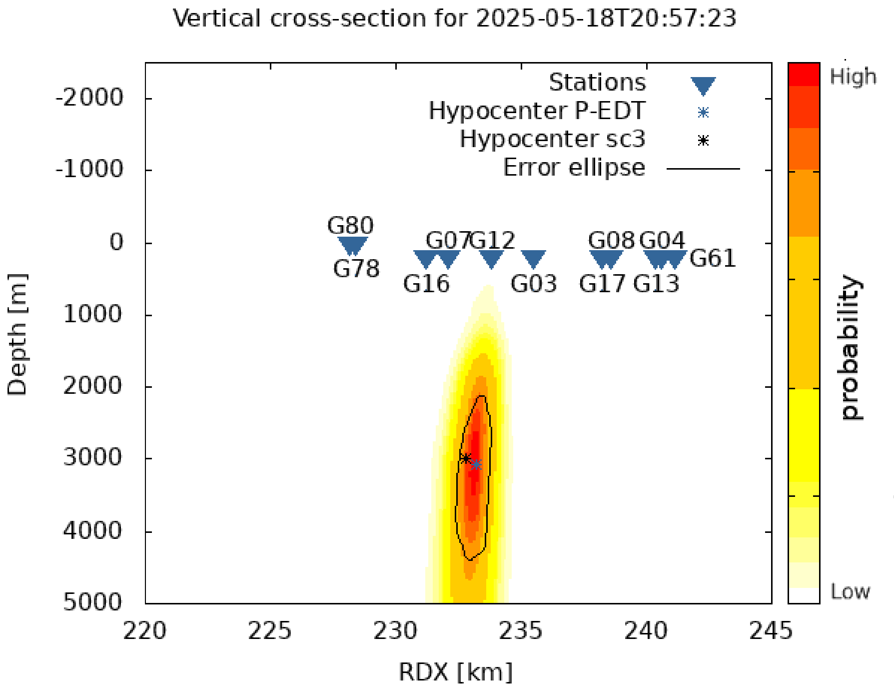

Figure 4: A depth slice through the 95% confidence zone (coloured area) that is obtained by using P-EDT at eleven nearby stations. The highest probability lies at 3.1 km depth (blue star). The black line shows the contour of the 68% confidence zone. The black star shows the solution obtained with the fast Hypocenter method (labeled 'Hypocenter sc3' in the figure) with a depth fixed at 3.0 km.

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