Hypocenters for the December 2024 -January 2025 sequence of events near Kerkrade

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Introduction

Between 2024-12-13 and 2025-01-17 six events occurred near Kerkrade in Limburg, the Netherlands. The origin time of the first event is 2024-12-13T00:08:26 UTC and the local magnitude is 1.1. For the second event about 5 min 31 s later on 2024-12-13T00:14:05 UTC, the local magnitude is 1.7. The next three events all occurred on 2025-01-03. The origin times and local magnitudes are respectively 06:22:13 UTC and 0.9, 07:07:02 UTC and 2.4, and 15:26:15 UTC and 1.1. The event on 2025-01-17T20:33:47 UTC has the local magnitude 0.5. The magnitude 2.4 was felt by many people. About 140 online questionnaire earthquake forms were submitted to the KNMI. All events were detected by the KNMI network (*KNMI*, 1993) and located near-real time with the hypocenter method by *Lienert et al.* (1986). This hypocenter method uses an average 1D model for the south of the Netherlands. The hypocenters calculated with this method are published by the Royal Netherlands Meteorological Institute (KNMI) in the earthquake catalogue for tectonic events (Aardbeving catalogus, www.knmi.nl/kennis-en-datacentrum/dataset/aardbevingscatalogus).

In this report, the hypocenters are relocated using a modified methodology and velocity model for Limburg. The P-wave and S-wave traveltime picks for the events are the same ones as used in the operational KNMI hypocenter analysis. The elastic velocity model for Limburg used in the improved hypocenter estimation was derived from a seismic tomographic experiment by *Reamer and Hinzen* (2004). The refined hypocenter methodology estimates the epicenter and depth of the event by combining the classical P-S phase time difference for single stations with the EDT principle for P-phase times for pairs of stations (*Spetzler et al.*, 2024). The uncertainty of the hypocenter is estimated as well. The location error incorporates the local variations of the velocity field, modelling effects as well as picking errors.

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

GUI: http://rdsa.knmi.nl/dataportal/

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

Herzogenrath event on 2024-12-13T00:08:26

A number of stations in Limburg, Germany and Belgium detected the event on 2024-12-13 near Herzogenrath. However, stations in Germany and Belgium and for the northern part of Limburg (i.e. the accelerometer in Neeritter) have rather large distances to the event which does not add valuable information to the depth estimate. On the contrary, only proximal stations have adequate information about the depth distribution through the P-S phase differences of vertically inclined propagating wavefields. A minimum of number of stations is 3 with both picked P- and S-phases within 20 km distance of the event location is required for the hypocenter relocation method to work.

Figures 1 and 2 illustrate the hypocenter solution and uncertainty region. The first plot shows the distribution of stations and the epicenter, while the second illustration presents the

depth distribution of the event. The location with the maximum probability is assigned to be the relocated hypocenter. Both the hypocenter published in the KNMI catalogue and the relocated hypocenter are shown in the plots. Figure 1 shows that most stations are located to the west of the epicenter. The nearby station ROLD is close to the epicenter and helps to reduce the uncertainty in the depth estimate. By comparing the operational KNMI and relocated hypocenter, one finds that the epicenters are separated by approximately 1 km. The depth of the event in the KNMI earthquake catalogue is 7 km. However, no surface waves are observed in the recorded waveform data which is an indication of a deeper source location. The relocated hypocenter depth is found at 7.8 km.

The list below contains the new epicenter both in wgs84 coordinates and in the Dutch national triangulation system (RD), the depth estimate and the uncertainty in the hypocenter solution.

Epicenter in wgs84 [deg]: 6.0772, 50.8469

Epicenter in RD [m]: 203597, 317680

Depth [m]: 7800

Uncertainty in epicenter [m]: 815, 956

Uncertainty in depth [m]: 1577

Aken event on 2024-12-13T00:14:05

The results of the relocation of the event on 2024-12-13 near Aken are shown in Figures 3 and 4. The local magnitude is 1.7 which is higher than the magnitude of the earlier event on 2024-12-13T00:08:26. Figure 3 includes 4 nearby stations. The epicenter of the KNMI earthquake catalogue and the relocated hypocenter are separated more this time by 2 km. The event depth of the relocated hypocenter is found at 6.9 km and not at 5 km as indicated in the KNMI earthquake catalogue. The deeper hypocentre is in agreement with the recorded waveforms which show no surface waves.

The next list contains the new epicenter both in wgs84 coordinates and in the Dutch national triangulation system (RD), the depth estimate and the uncertainty in the hypocenter solution.

Epicenter in wgs84 [deg]: 6.07739, 50.8468

Epicenter in RD [m]: 203611, 317669

Depth [m]: 6900

Uncertainty in epicenter [m]: 753, 569

Uncertainty in depth [m]: 1905

Kerkrade event on 2025-01-03T06:22:13

The local magnitude of the event on 2025-01-03T06:22:13 is 0.9. The P- and S-arrivals are weak and often hidden under the instrument noise level. The event is relocated using the nearest stations where it is possible to pick both P- and S-wave phase times. These stations are ROLD, TERZ and HGN. The P- and S-wave phase picks in the waveforms on station VKB are difficult to see, but are added as an educated guess in order to improve the azimuth distribution. The results of relocating the event are shown in Figures 5 and 6. A visual check of the recorded waveform data shows no surface waves. The depth estimate of the relocated hypocenter is 6.9 km while the depth in the KNMI earthquake catalogue is set to 5 km. The epicenter locations of the operational KNMI and relocated solution are separated 5.1 km.

The next list contains the new epicenter both in wgs84 coordinates and in the Dutch national triangulation system (RD), the depth estimate and the uncertainty in the hypocenter solution.

Epicenter in wgs84 [deg]: 6.08358, 50.8452

Epicenter in RD [m]: 204048, 317495

Depth [m]: 6900

Uncertainty in epicenter [m]: 764, 601

Uncertainty in depth [m]: 1824

Kerkrade event on 2025-01-03T07:07:02

The event on 2025-01-03T07:07:02 is the strongest detection with a local magnitude of 2.4. The results of relocating the event are presented in Figures 7 and 8. A visual check of the recorded waveform data shows no surface waves. The relocated hypocenter depth is found to be 7.7 km and the KNMI earthquake catalogue depth is 5 km. The distance between epicenters of the operational KNMI and relocated solution is 2.5 km.

The next list contains the new epicenter both in wgs84 coordinates and in the Dutch national triangulation system (RD), the depth estimate and the uncertainty in the hypocenter solution.

Epicenter in wgs84 [deg]: 6.07243, 50.8523

Epicenter in RD [m]: 203256, 318278

Depth [m]: 7700

Uncertainty in epicenter [m]: 754, 578

Uncertainty in depth [m]: 1879

Kerkrade event on 2025-01-03T15:26:15

The event on 2025-01-03T15:26:15 has the local magnitude 1.1. The results of relocating the event are presented in Figures 9 and 10. No surface waves are observed in the waveform data. The relocated hypocenter depth is found to be 8.4 km and the depth estimate in the KNMI earthquake catalogue is 5 km. The distance between epicenters of the KNMI and relocated solution is 4.3 km.

The next list contains the new epicenter both in wgs84 coordinates and in the Dutch national triangulation system (RD), the depth estimate and the uncertainty in the hypocenter solution.

Epicenter in wgs84 [deg]: 6.0936, 50.8452

Epicenter in RD [m]: 204754, 317502

Depth [m]: 8400

Uncertainty in epicenter [m]: 871, 616

Uncertainty in depth [m]: 1408

Kerkrade event on 2025-01-17T20:33:47

The event on 2025-01-17T20:33:47 has the local magnitude 0.5. The results of relocating the event are illustrated in Figures 11 and 12. No surface waves are observed in the waveform data. The relocated hypocenter depth is 8.7 km and the depth estimate in the KNMI earthquake catalogue is 1 km. The distance between epicenters of the KNMI and relocated solution is 1.6 km.

The next list contains the new epicenter both in wgs84 coordinates and in the Dutch national triangulation system (RD), the depth estimate and the uncertainty in the hypocenter solution.

Epicenter in wgs84 [deg]: 6.0332, 50.8584

Epicenter in RD [m]: 200487, 318931

Depth [m]: 8700

Uncertainty in epicenter [m]: 729, 930

Uncertainty in depth [m]: 2234

Correlation with known tectonic faults in Limburg

The relocated hypocenters are compared with known fault structures in the HIKE European fault database (*Gessel et al.*, 2021). A few fault lines are found in Limburg and close to the east border to Germany. Figure 13 shows the fault structures and the epicenters of the five events near Kerkrade. The first two events on 2024-12-13T00:08:26 and 2024-12-13T00:14:05 with local magnitudes 1.1 and 1.7 have similar epicenters and therefore can not be discerned in the plot. The five relocated earthquakes between 2024-12-13 and 2025-01-03 are clustered in the same area with a separation of less that 2 km. The event on 2025-01-17 is located to the west of the other events. The HIKE European fault database includes faults near the epicenters of the relocated events in the Dutch side of the border area. However, the faults are not clearly seen in the HIKE data in Germany, east of Kerkrade. This does not mean that the faults are not present in Germany, but is merely an artefact in the HIKE database where faults stop at national borders. The considered faults are the Feldbiss fault and the Heerlerheide fault which have a north-west to south-east direction and is present near Kerkrade (*van Bergen et al.*, 2007).

Conclusion

The recorded events on on 2024-12-13, 2025-01-03 and 2025-01-17 near Kerkrade have been relocated with a refined hypocenter method and compared to known fault structures in Limburg and in Germany east of Limburg. The five events between 2024-12-13 and 2025-01-03 are found to cluster and all estimated depths are between 6.9 and 8.4 km. The later event on 2025-01-17 is located to the west of the other events and the depth is 8.7 km. The six events are found in an area where the Feldbiss fault and Heerlerheide fault are present. The uncertainty in epicenter locations is in the order of 800 m and in depth is around 1400-2200 m. Given the hypocenter depths and the epicenter locations relative to mapped faults, it is concluded that the six events near Kerkrade have a tectonic origin.

References

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van Bergen, F., H. J. M. Pagnier, and P. C. H. van Tongeren (2007), Peat, coal and coalbed methane, *Geology of the Netherlands*, pp. 265–282.
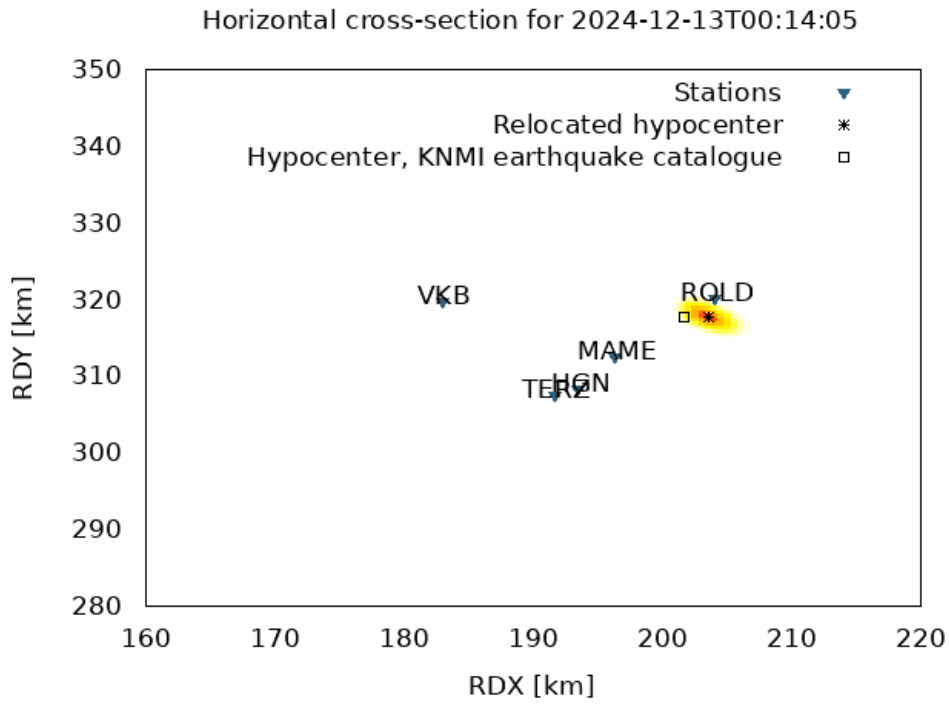
Figure 1: Overview map of the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with black square and black star, respectively.
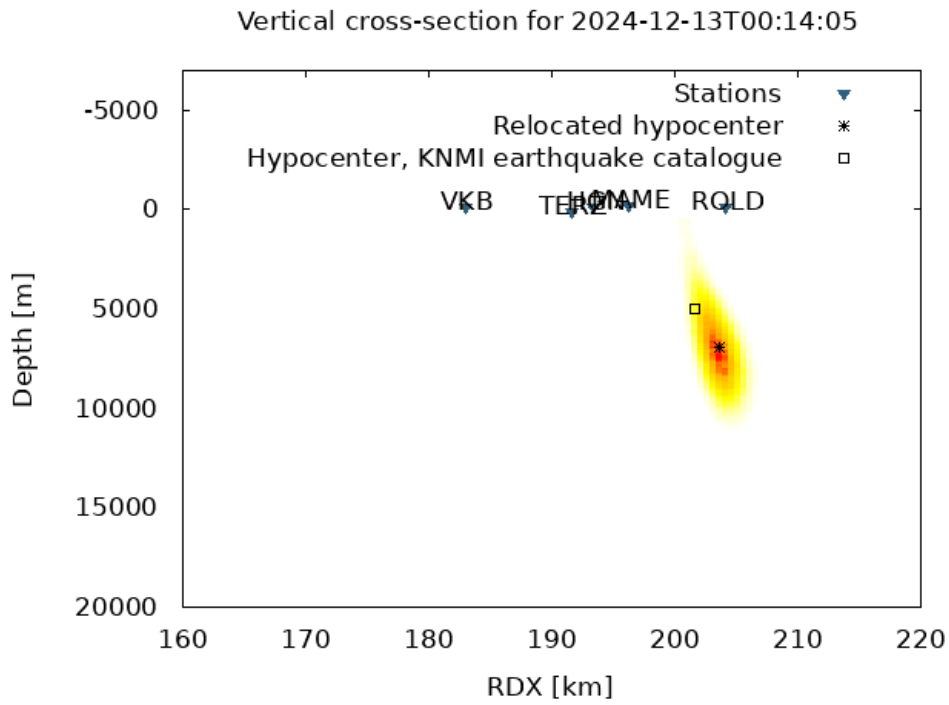

Figure 2: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI earthquake catalogue and relocated hypocenter are the black square and black star.
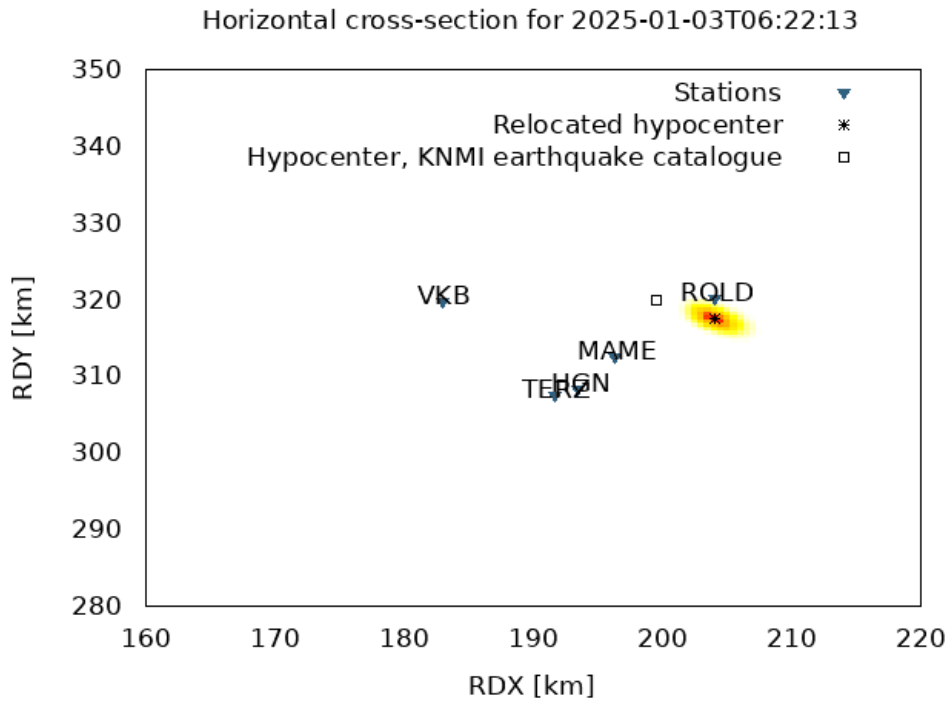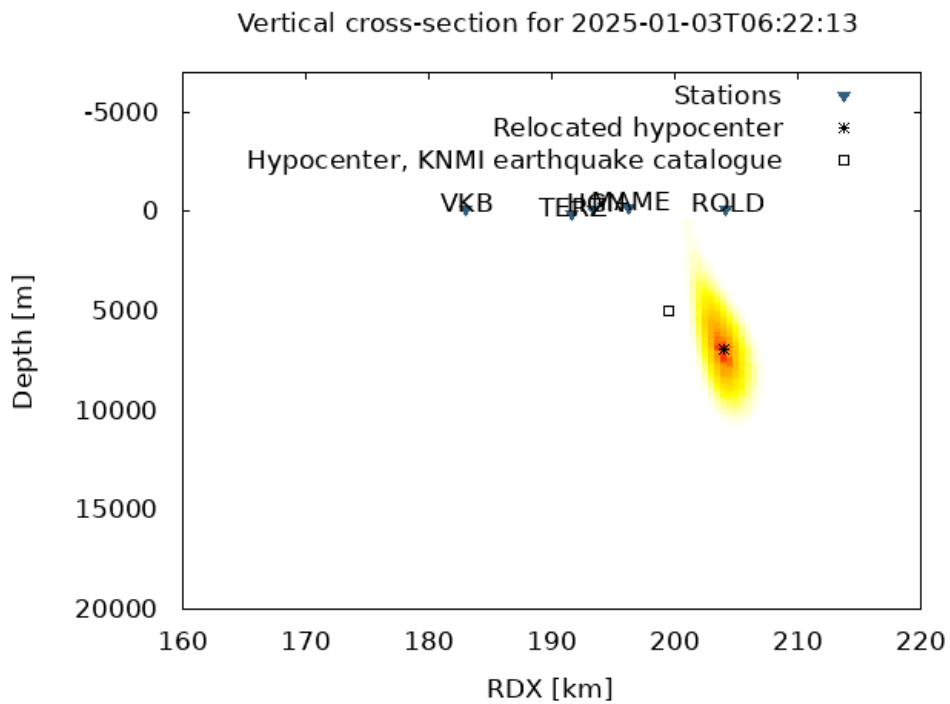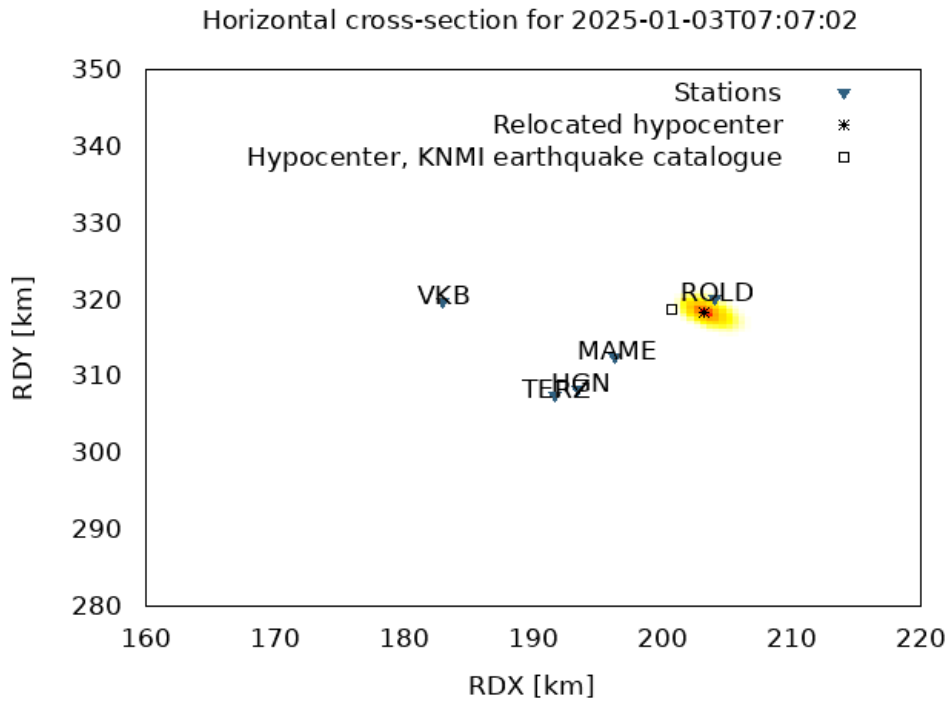
Figure 3: Map of the horizontal cross-section with the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with black square and black star, respectively.

Figure 4: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI earthquake catalogue and relocated hypocenter are the black square and black star.

Figure 5: Map of the horizontal cross-section with the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with black square and black star, respectively.
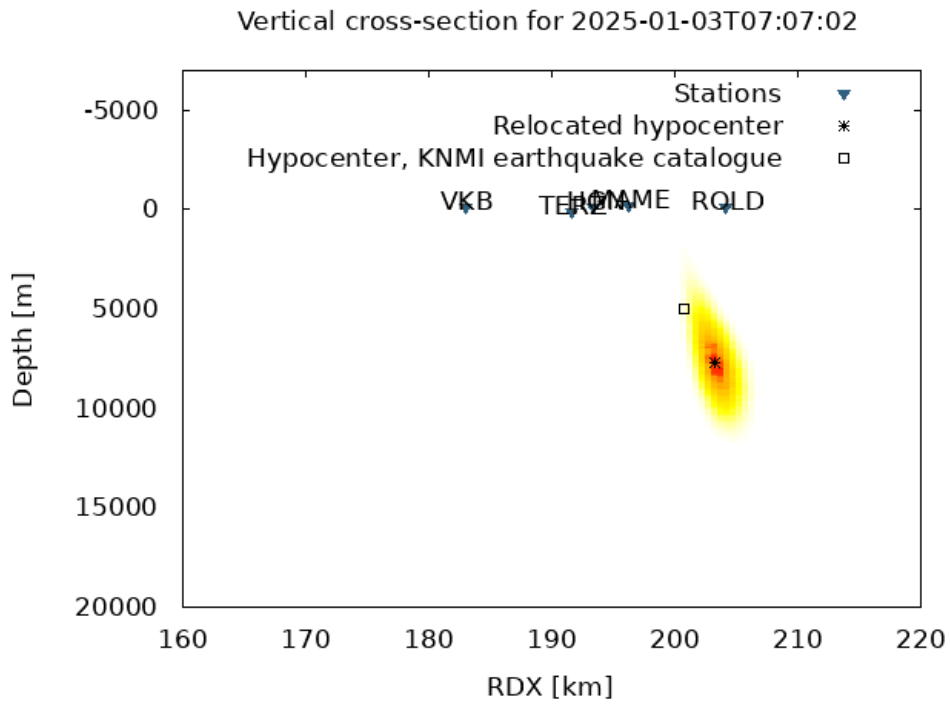

Figure 6: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI earthquake catalogue and relocated hypocenter are the black square and black star.
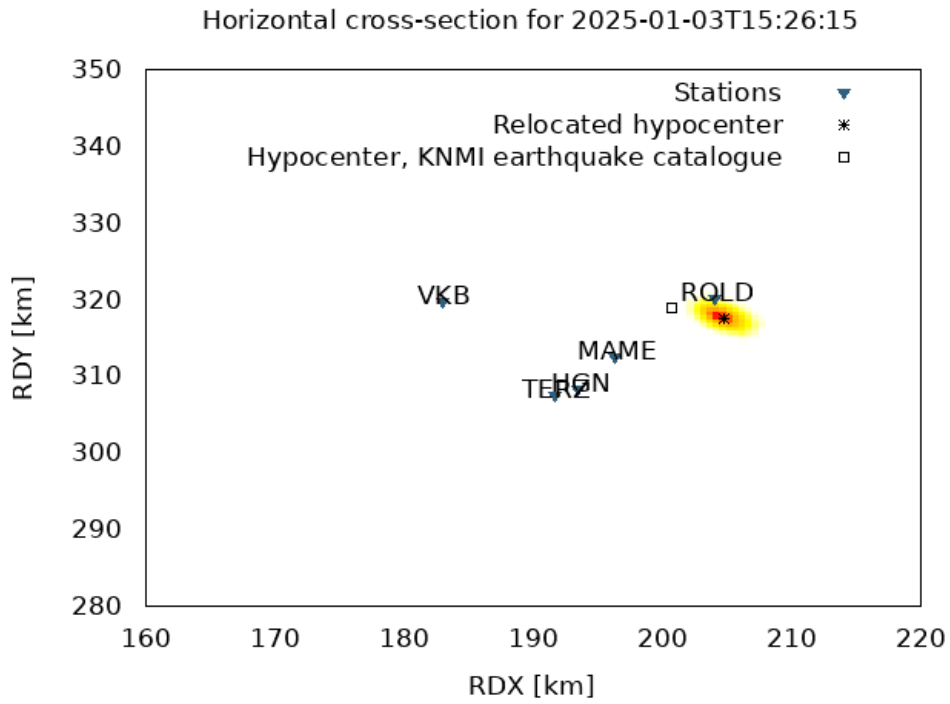
Figure 7: Map of the horizontal cross-section with the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with black square and black star, respectively.
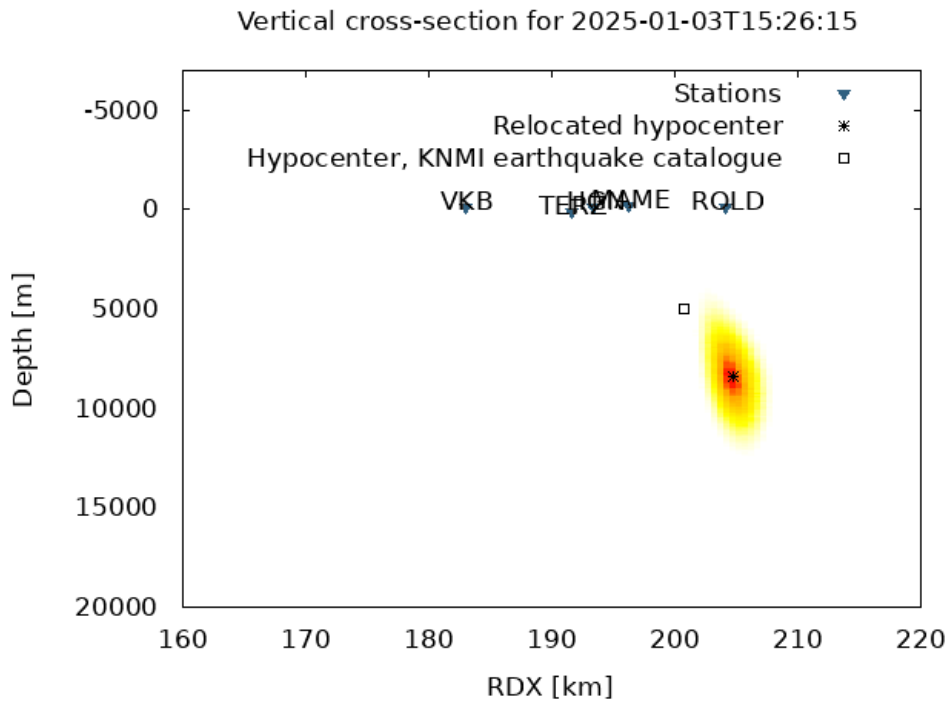

Figure 8: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI earthquake catalogue and relocated hypocenter are the black square and black star.
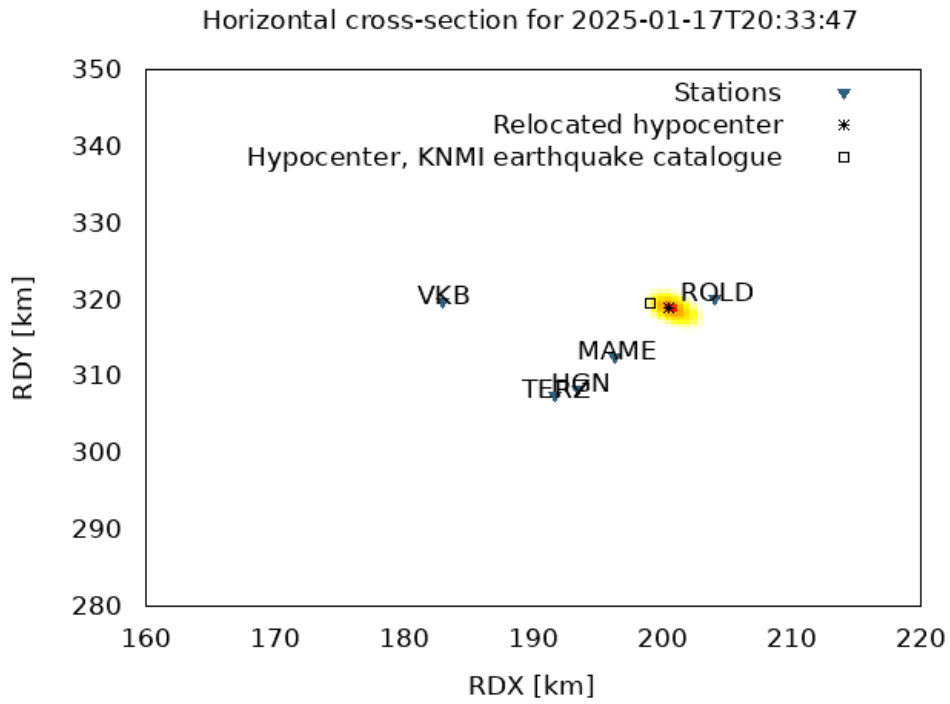
Figure 9: Map of the horizontal cross-section with the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with black square and black star, respectively.

Figure 10: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI earthquake catalogue and relocated hypocenter are the black square and black star.

Figure 11: Map of the horizontal cross-section with the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with black square and black star, respectively.
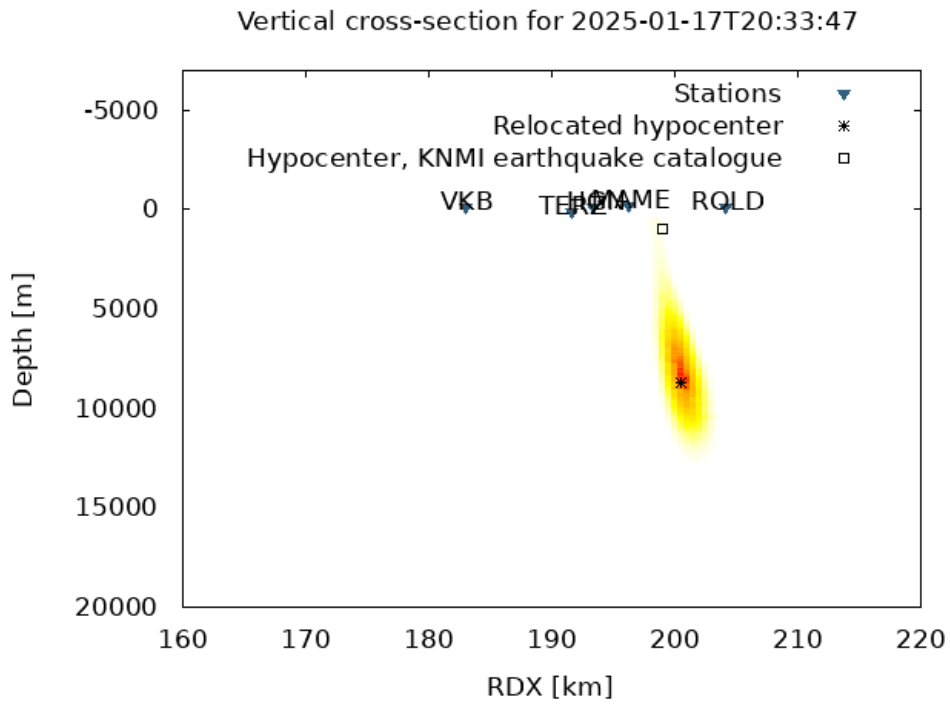

Figure 12: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI earthquake catalogue and relocated hypocenter are the black square and black star.
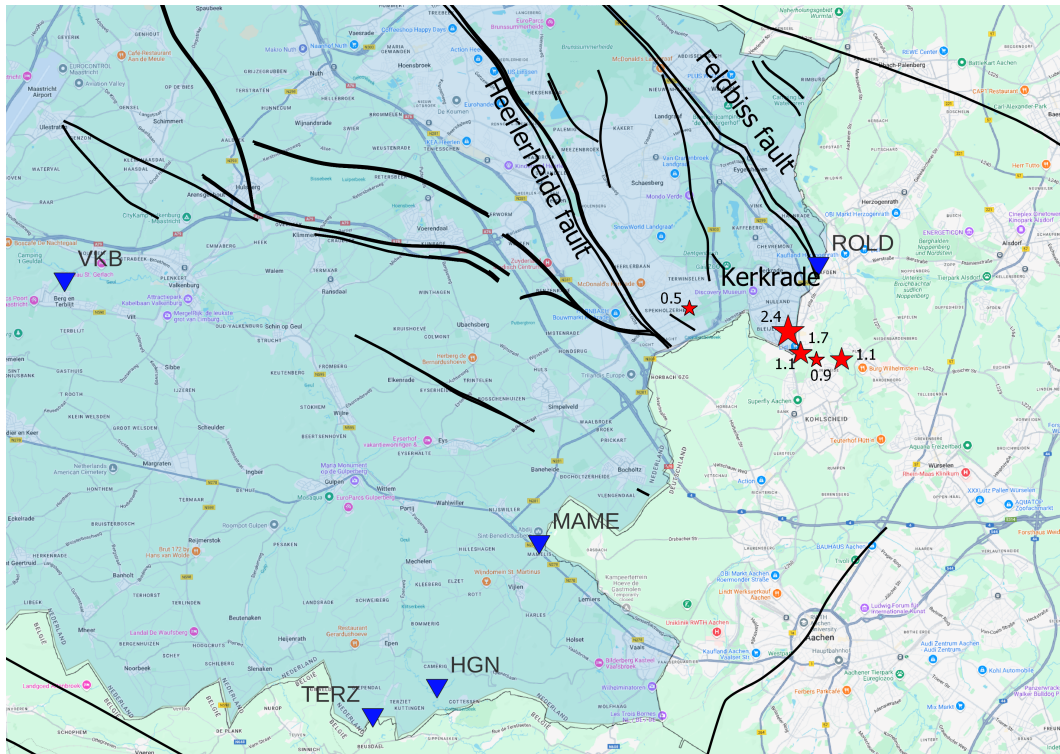
Figure 13: Comparison of relocated epicenters with known fault structures in the southern part of Limburg.