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Hypocenters for the events between March and May 2023 near Klimmen

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Introduction

From March to May 2023 four events occurred near Klimmen in Limburg. The origin time of the first event on 01-03-2023 is 17:58:49 UTC and the local magnitude is 2.2. For the second event on 19-03-2023, the origin time is 01:23:36 UTC and the local magnitude is 1.4. The third event on 23-02-2023 has the origin time at 05:18:54 and the local magnitude is 0.6. Lastly, the fourth event on 06-5-2023 has the low local magnitude of 0.6 and the origin time is 21:03:03 UTC. All events were detected by the KNMI network (Nederlandse stations, www.knmi.nl) and located near-real time with the hypocenter method (*Lienert et al.*, 1986). This hypocenter method uses an average 1D model for the south of the Netherlands. The hypocenter found by this method is published by KNMI in the earthquake catalogue for tectonic events (Aardbeving catalogus, www.knmi.nl).

In this report, the hypocenters are relocated using a modified hypocenter methodology and velocity model for Limburg. The P-wave and S-wave traveltime picks for the events are unchanged. 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. 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 final result is an estimate of the hypocenter of the events and the associated uncertainty in terms of the 95% confidence region. The uncertainty in epicenter and depth is the standard deviation which is the 3 dimensional 95% confidence region divided by 2.7 (*Wang B.*, 2015).

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/>

Klimmen event on 01-03-2023

A number of stations in Limburg, Germany and Belgium detected the event on 01-03-2023 near Klimmen. However, stations in Germany and Belgium and for the northern part of Limburg (i.e. the accelerometer in Neeritter) have rather large stations distances 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. Therefore the hypocenter relocation method limits the number of stations to 6 with both picked P- and S-phases within 35 km station distances.

Figures 1 and 2 illustrate the hypocenter solution and the 95% confidence region. The first plot shows the distribution of stations and the epicenter, while the second illustration presents the depths distribution for 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 the azimuth distribution is poor. However, the nearby station VKB helps constraining the depth distribution and the station ROLD reduces the uncertainty in the epicenter location. By comparing the KNMI and relocated hypocenter, one finds that the epicenters are separated by approximately 5 km. The depth of the event in the KNMI earthquake catalogue is 1 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 7.9 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]: 5.85461, 50.8927

Epicenter in RD [m]: 187888, 322646

Depth [m]: 7900

Uncertainty in epicenter [m]: 731, 923

Uncertainty in depth [m]: 1600

Klimmen events on 19-03-2023

The results of the relocation of the 19-03-2023 event near Klimmen are shown in Figures 3 and 4. The local magnitude is 1.4 of this event which is lower than the magnitude of the 01-03-2023 event. Consequently, the event was detected by fewer stations. Figure 3 includes 4 nearby stations. The epicenter of the KNMI and the relocated hypocenter are closer this time. The event depth of the relocated hypocenter is found at 7.9 km and not at 1 km as indicated in the KNMI earthquake catalogue. The deeper hypocentre is in agreement with the recorded waveforms. They show no surface waves, indicating a deeper source location.

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]: 5.90315, 50.8955

Epicenter in RD [m]: 191301, 322984

Depth [m]: 7900

Uncertainty in epicenter [m]: 1047, 1497

Uncertainty in depth [m]: 2335

Klimmen event on 23-03-2023

The local magnitude of the event on 23-03-2023 is 0.6. The P- and S-arrivals are weak and often hidden under the station noise level. The event is relocated using the nearest station where it is possible to pick both P- and S-wave phase times. These stations are VKB, TERZ and HGN. For stations farther away, especially the S-wave arrival is very difficult to identify. With only three stations and two of them virtually at the same location, the azimuth distribution is very poor for this event and may have an influence on the hypocenter solution. Therefore, it is getting more difficult to find a stable hypocenter solution, even with the modified hypocenter method. The results of relocating the event are shown in Figures 5 and 6. The 95 % confidence level is rather narrow but with a long extension between the station VKB and the stations TERZ and HGN because of the poor azimuth distribution of stations. A visual check of the recorded waveform data shows no surface waves. The depth estimate of the relocated hypocenter is 11.6 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]: 50.8663, 5.84798

Epicenter in RD [m]: 187440, 319707

Depth [m]: 11600

Uncertainty in epicenter [m]: 1137, 769

Uncertainty in depth [m]: 2180

Klimmen event on 06-05-2023

The event on 06-05-2023 has a local magnitude of 0.6. Similar to the 23-03-2023 event, only P- and S-arrivals are identified at the nearest stations. These stations are VKB, TERZ and HGN. The azimuth distribution is poor for this event. 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 10.3 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]: 50.8957, 5.80629

Epicenter in RD [m]: 184486, 322965

Depth [m]: 10300

Uncertainty in epicenter [m]: 1044, 935

Uncertainty in depth [m]: 2247

Correlation with known tectonic faults in Limburg

The relocated hypocenters are compared with known fault structures in the HIKE European fault database (geoera.eu/projects/hike10/faultdatabase/). A few fault lines are found in Limburg. Figure 9 shows the fault structures and the epicenters of the four events near Klimmen. Three of the events are found to be close to known faults in the southern part of Limburg. One event is located along on the path of the linear extension between two mapped faults.

Conclusion

The detected events on 01-03-2023, 19-03-2023, 23-03-2023 and 06-05-2023 near Klimmen in Limburg have been relocated with a refined hypocenter method and compared to known fault structures in the area. Three of the four events are found to have occurred near tectonic faults, while one is inbetween two faults. The depth of the magnitude 2.2 and 1.4 events is 7.9 km with uncertainties of approximately 2 km. The sparse network in Limburg limits the picking of P- and S-phases to the nearest stations for the two M0.6 magnitude events. The relocated hypocenter depths of these two events are between 10-12 km with uncertainties of around 2 km. Given the hypocentre depths and the epicentre locations relative to mapped faults, we conclude that the four events between March and May 2023 near Klimmen have a tectonic origin.

References

- 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.
- Reamer, S., and K.-G. Hinzen (2004), An earthquake catalog for the northern rhine area, central europe (1975-2002), *Seismological Research Letters - SEISMOL RES LETT*, 75, 713–725, doi: 10.1785/gssrl.75.6.713.
- Wang B., S. W. . Z. M. (2015), Confidence analysis of standard deviational ellipse and its extension into higher dimensional euclidean space, *The Leading Edge*, 10(3), 1–17.

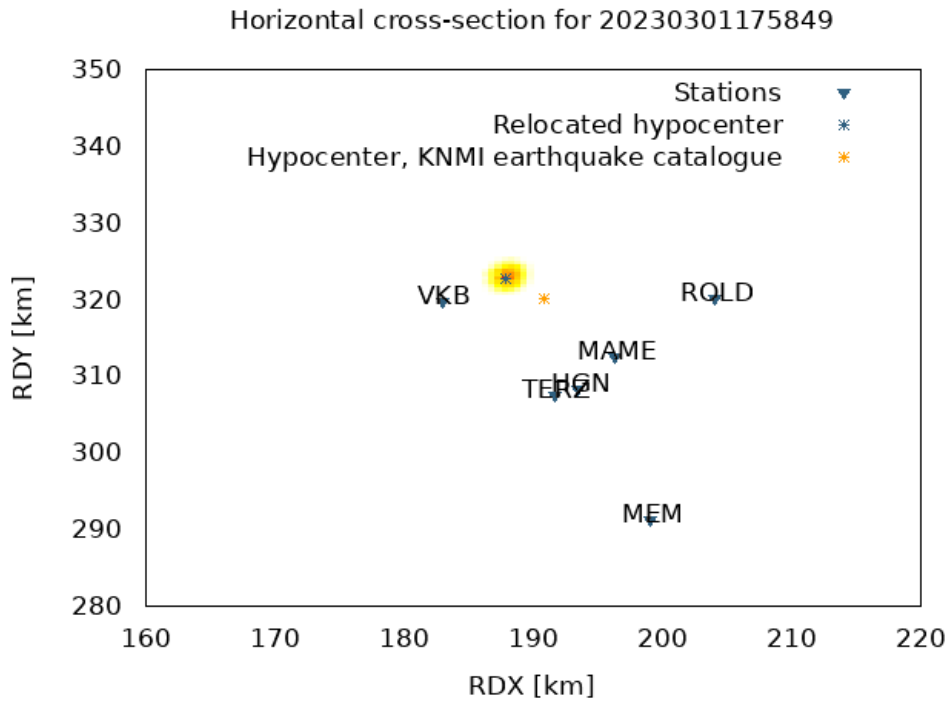


Figure 1: Overview map of the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with yellow and blue stars, respectively.

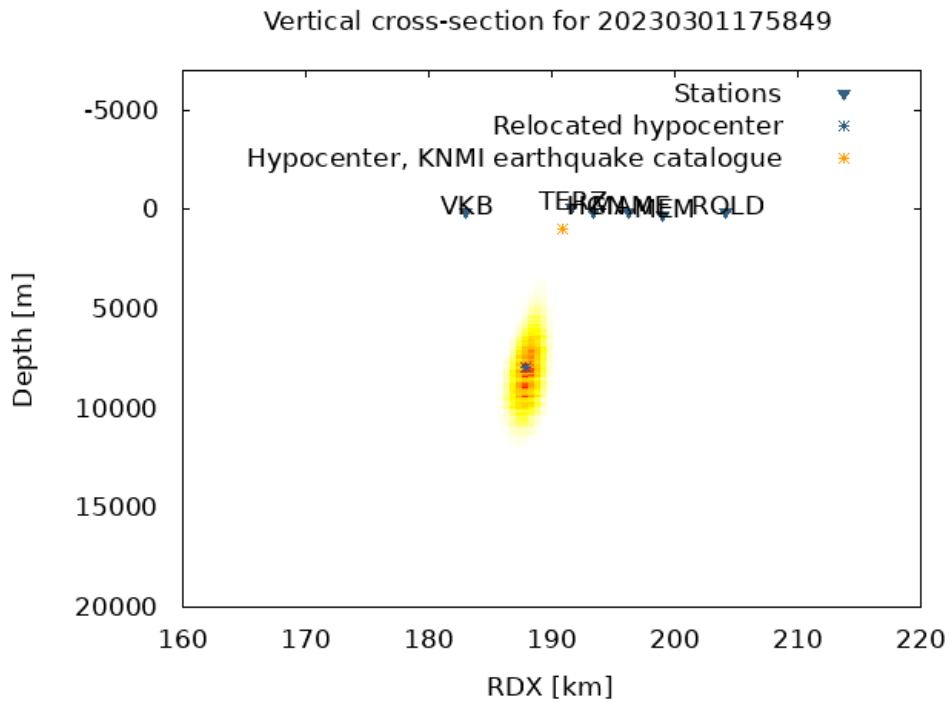


Figure 2: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI and relocated hypocenter are the yellow and blue star.

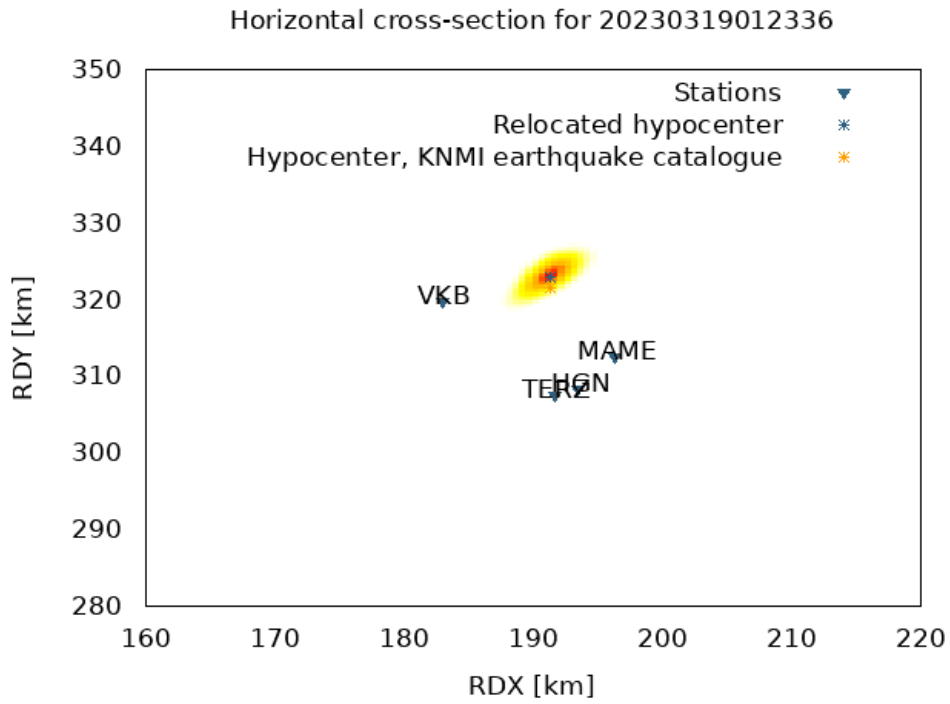


Figure 3: Map of the horizontal cross-section with the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with yellow and blue stars, respectively.

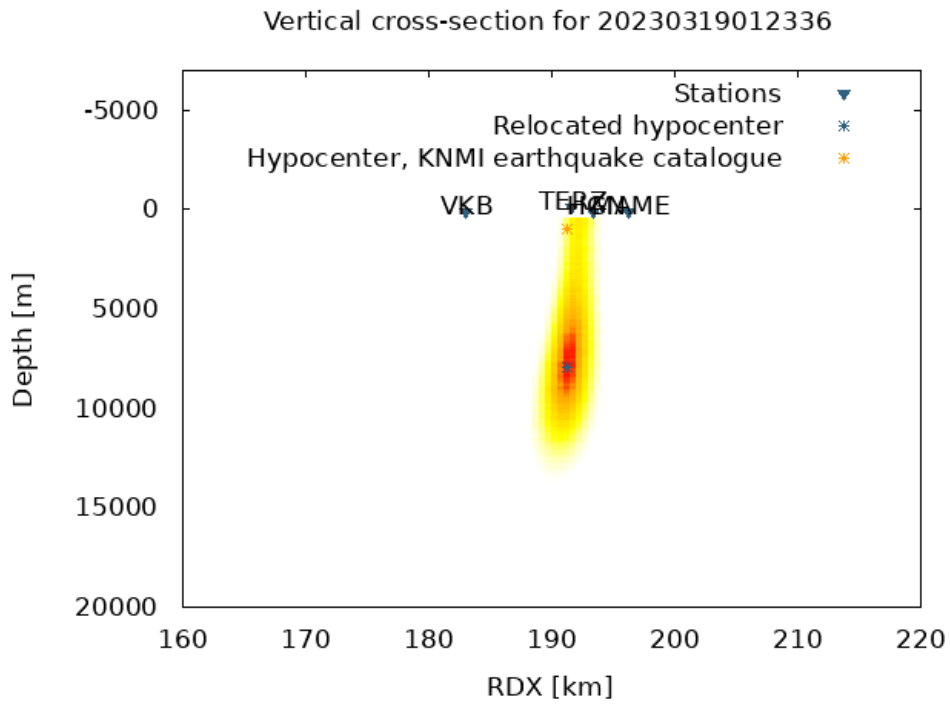


Figure 4: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI and relocated hypocenter are the yellow and blue star.

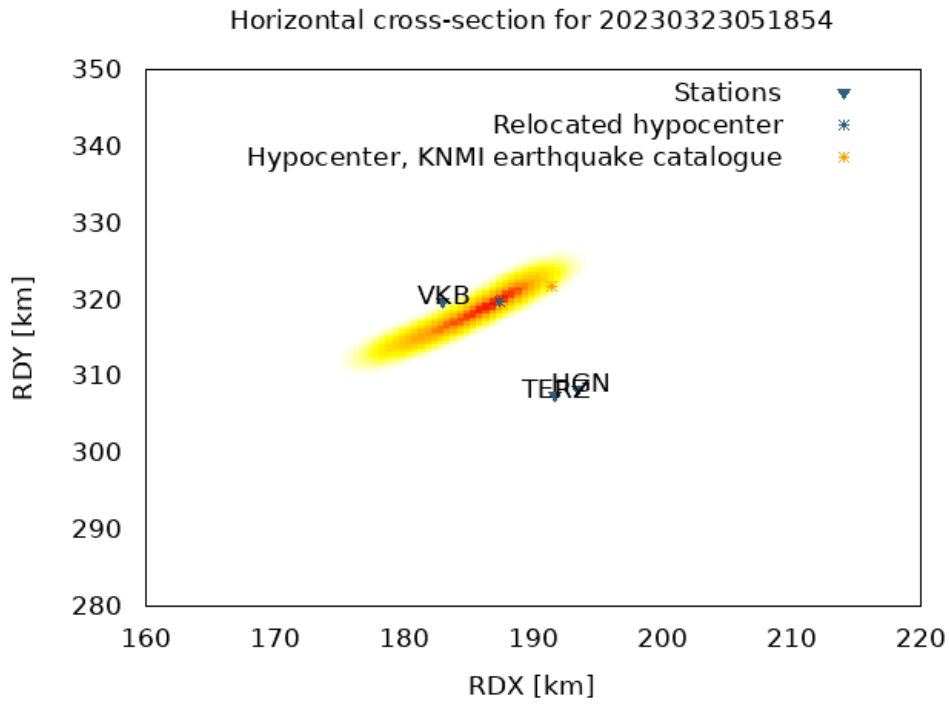


Figure 5: Map of the horizontal cross-section with the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with yellow and blue stars,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

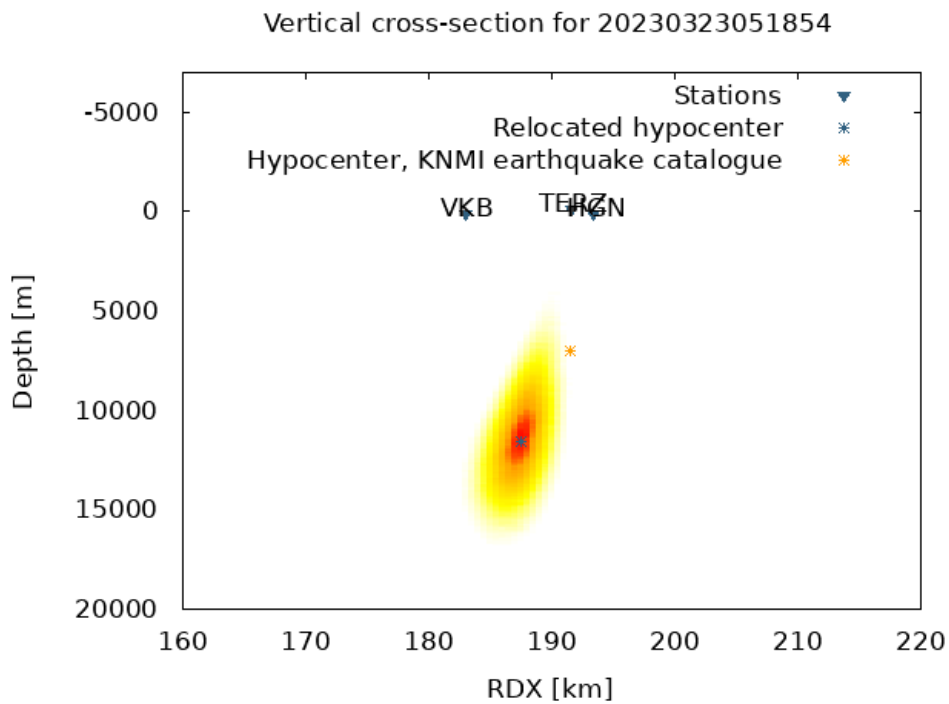


Figure 6: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI and relocated hypocenter are the yellow and blue star.

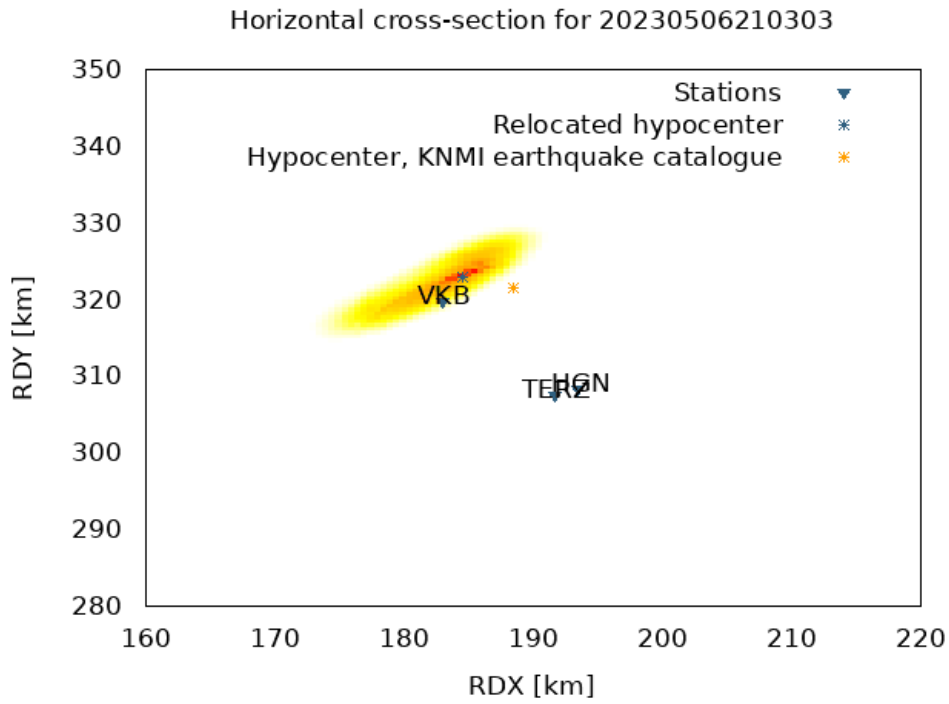


Figure 7: Map of the horizontal cross-section with the station distribution, epicenter and horizontal cross-section of the 95% confidence area (indicated with red-orange-yellow colours). The epicenters from the KNMI earthquake catalogue and from the relocation method are shown with yellow and blue stars, respectively.

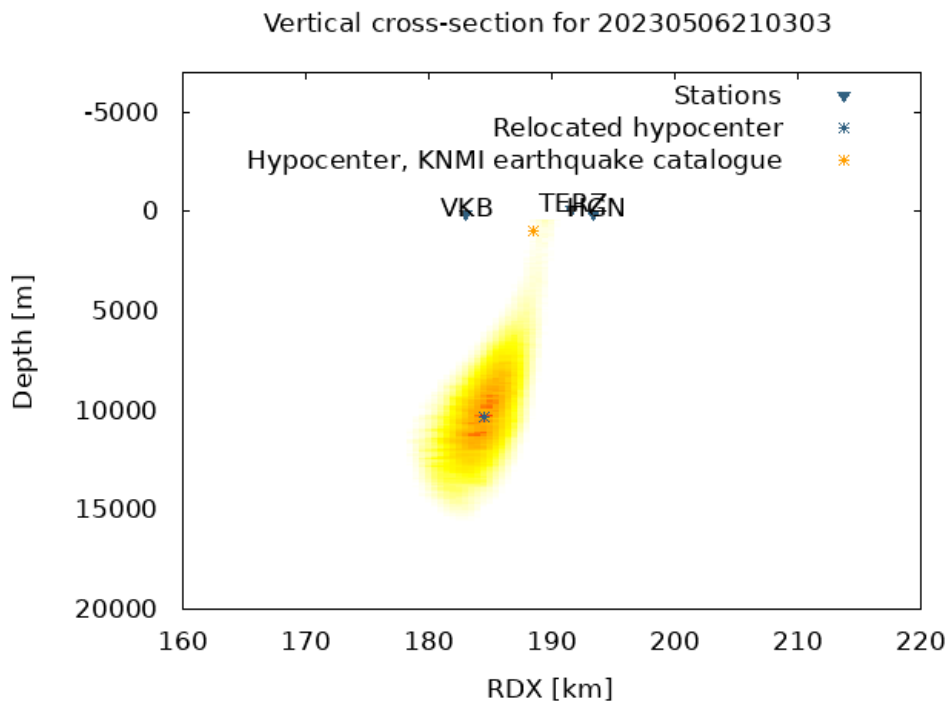


Figure 8: Vertical cross-section of epicenter location to illustrate the depth distribution of the event. The KNMI and relocated hypocenter are the yellow and blue star.

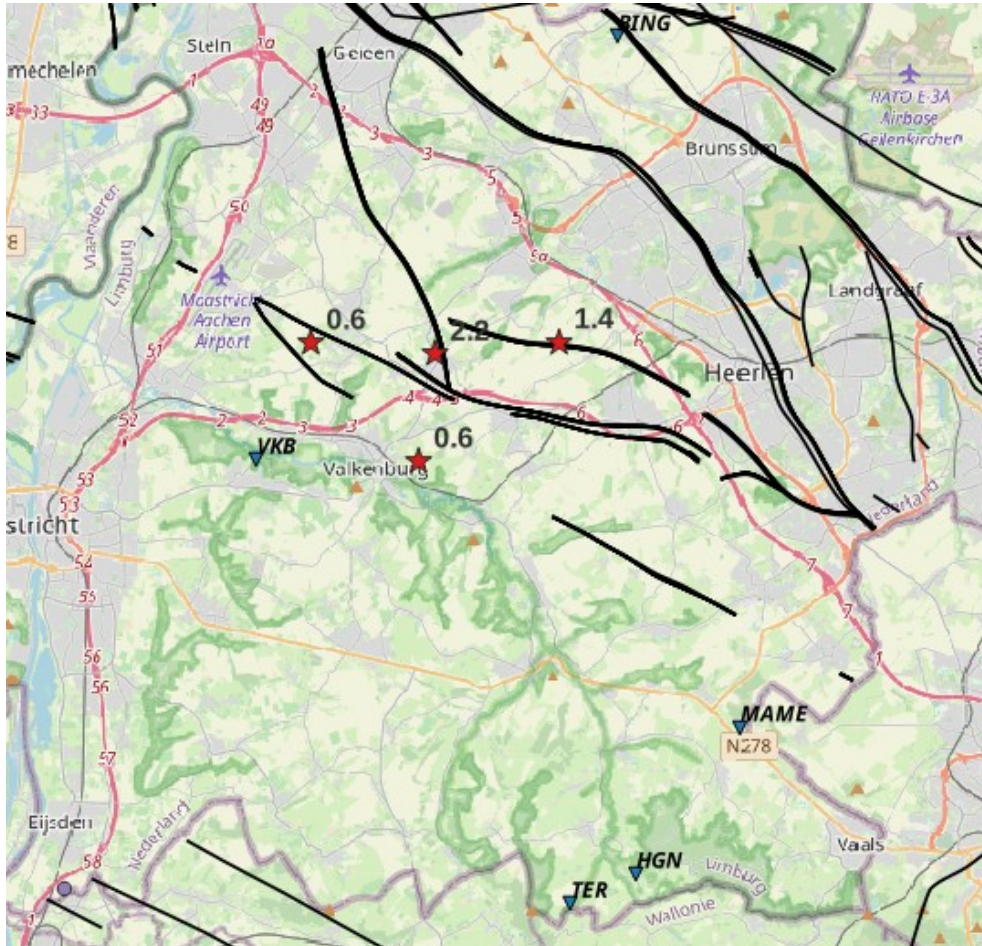


Figure 9: Comparison of relocated epicenters with known fault structures in the southern part of Limburg.

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