Royal Netherlands
Meteorological Institute
*Ministry of Infrastructure
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Hypocenter Estimation of Detected Event near Venlo on September 3rd 2018

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Summary

The hypocenter of the recorded earthquake on September 3rd 2018 close to Venlo has been determined. Data from a local network, managed by the seismic contractor Q-con, were used in the seismological analysis. Several hypocenter methods and velocity models were used in the analysis of the source location of the earthquake. The epicenter of the event is found to be close to the geothermal field which is operated by Californië Wijnen Geothermie. The event is confined to depths between 3.2 km and 9.2 km which are depth values coming from the usage of different hypocenter methods and velocity models. Previously the Royal Netherlands Meteorological Institute reported a depth of 1 km, based on the routine analysis of data from a regional network. Using the local network, such a shallow depth can be ruled out.

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1. Introduction

An earthquake was recorded near Venlo on September 3rd 2018 at the local time 20:20:34. The event was felt by a number of people near Venlo. Earthquake reports were submitted to the Royal Netherlands Meteorological Institute (KNMI) in the following days by people who had felt ground motions at the recording time of the event.

The KNMI station network in the southern part of the Netherlands is sparse. The shortest distance from nearby stations to Venlo is about 24 km. For a determination of the epicenter of the event near Venlo at least 5-6 stations distributed over Limburg at much longer distances (24-75 km) were used. The best epicenter solution using these data was at Velden (51.403N, 6.156E), a city near Venlo . Depth was found to be shallow and reported at 1 km depth. The uncertainty in the estimation of the depth of the event is rather large (possibly up to 5 km or even more) due to the sparseness of the KNMI station network in the southern part of the Netherlands.

To estimate the depth of the event in more detail, local recordings of the seismic signal are required. The seismic contractor Q-con has installed a local network consisting of five stations at the Californië Wijnen Geothermie (CWG) field close to Venlo. Event data of the event on September 3rd 2018 were recorded in the Q-con network and have been delivered to the KNMI. The epicenter of the event is within the local network coverage. The recorded data from Q-con could be used to make an estimate of the depth of the event and an improved location of the epicenter.

This report describes the hypocenter estimation scheme used on the event data for the M1.7 event close to Venlo. First, the available velocity models are presented. Next, several hypocenter methods are applied to the data. The methods are briefly explained. Then follows a section with the estimation of the hypocenter of the M1.7 event and the uncertainty in the measurement. Finally, the conclusions are given.

2. Data from Local Station Network

The event data from Q-con were loaded into the operational seismological hypocenter software (seiscomp3, in short sc3) at the KNMI. The data were recorded at five stations with the indexes K01, K02, K03, K04 and K05 which are located above or near the geothermal field operated by CWG. See Figure 1 for a lateral view of the station locations.

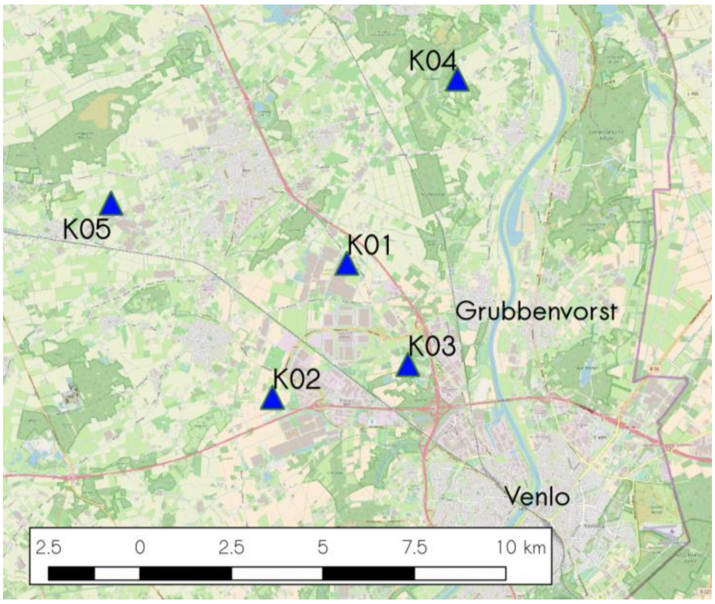


Figure 1: Location of the local stations K01, K02, K03, K04 and K05. All stations are northwest of the city Venlo and west of the river Maas.

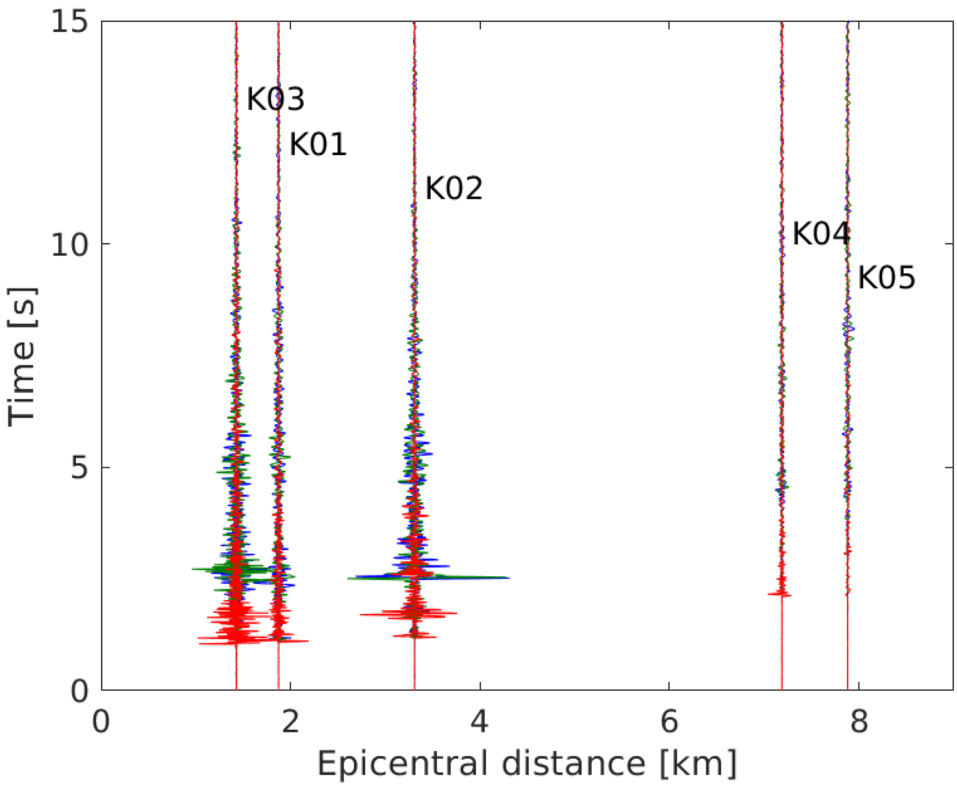


Figure 2: Event data from the local stations K01, K02, K03, K04 and K05. The red traces show vertical movement, the green traces show north-south movement and the blue traces show east-west movement.

Figure 2 shows the 3-component recordings as function of distance from the (preliminary) epicenter. The first arrival of the P-wave and S-wave phase at the five stations were picked. There can be no discussion about the accuracy of the times for the P-wave picks which are clear strong waveforms. It is more difficult to estimate the S-wave waveform and hence the uncertainly of the S-wave arrival time may be larger. Different filter combinations were used to identify a strong waveform on the horizontal components which would be defined as the S-wave waveform. Two seismologists did the travel time picking of the P-wave and S-wave arrival times. Figure 3 shows the waveform data with the picked arrival times for the P-waves and S-waves. Table 1 shows the values of the picked arrival times.

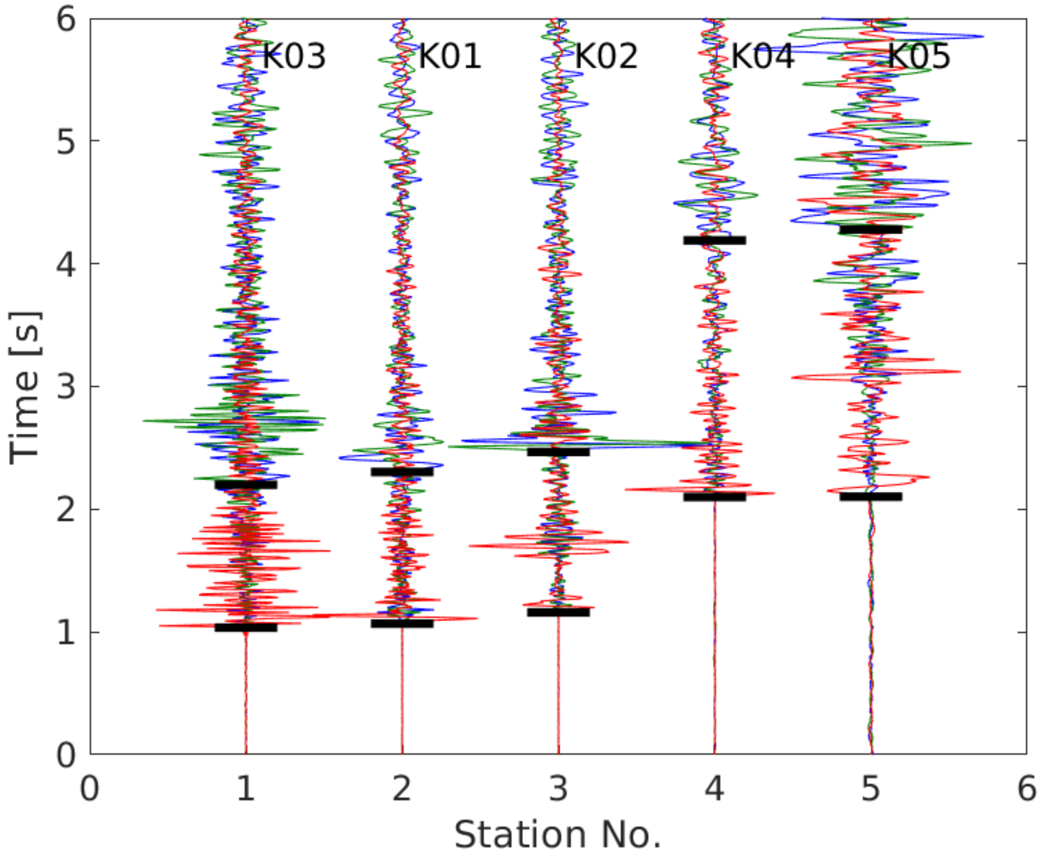


Figure 3: Event data from the local stations K01, K02, K03, K04 and K05. The black horizontal bars denote the P-wave and S-wave arrival time picks with respect to earthquake origin time 20:20:34.

Table 1: Picked arrival times for P-wave and S-waves (local time).

Station	P-wave arrival time	S-wave arrival time
K01	20:20:35.068	20:20:36.303
K02	20:20:35.159	20:20:36.467
K03	20:20:35.035	20:20:36.200
K04	20:20:36.099	20:20:38.191
K05	20:20:36.102	20:20:38.279

2. Velocity Models

Accurate information about the local velocity structure is necessary for a good hypocenter location. Three velocity models are used in the seismological analysis. All three velocity models are 1D. Table 2,3 and 4 shows the three velocity models defined as Model 1, Model 2 and Model 3, respectively. The first two velocity models are extracted from reflection seismic data for two lines going through the area with the local Q-con stations. Model 1 is provided by CWG (Broothaers & Ferket, 2011), while model 2 is the result of a MSc-thesis by Dominique Reith at TU-Delft (Reith, 2018). The depths for the lower interface of geological layers in model 1 is also used in model 2. The third model is the 1D regional velocity model for the south of the Netherlands used by the KNMI in the operational hypocenter estimation approach of earthquakes in that region. Please note that the KNMI velocity model defines a velocity profile going much deeper than Model 1 and Model 2. Model 3 is supplemented to Model 1 and 2 for depths lower than 2810 m.

Table 2: Model 1 (Source: Geological Drilling CWG).

Stratigraphical unit	P-wave velocity (m/s)	Depth of lower interface (m)
North Sea group	1850	720
Chalk	2830	780
Trias	3400	1000
Zechstein	4100	1055
Limburg	4000	1525
Coal-chalk	5000	2810

Table 3: Model 2 (Source: MSc-thesis Dominique Reith at TU-Delft).

Horizon	Velocity (m/s)
North sea	2088
Chalk	3086
PU	3224
Limburg	4228
Zeeland	6086

Table 4: Model 3 (Source: The KNMI).

Velocity (m/s)	Depth of lower interface (km)
5000	2
5800	3
6000	10
6250	19
6500	30

The Vp/Vs ratio is equal to 1.73 in the regional velocity model for the southern part of the Netherlands which is used in the automatic hypocenter method at the KNMI. In a first test, this depth-independent Vp/Vs ratio is used for Models 1, 2 and 3. In a second test, a depth-dependent Vp/Vs ratio is used for Model 1. With stratigraphic information about the Vp and Vs velocity ratio in Groningen, an educated guess for a depth dependent Vp/Vs ratio is proposed. The depth dependent Vp/Vs ratio profile is given in Table 5.

Table 5: Velocity model 3 (Source: Groningen model 2017).

Stratigraphical unit	Vp/Vs-ratio	Depth of lower interface (m)
North Sea group	3	720
Chalk	2.5	780
Trias	2.5	1000
Zechstein	1.79	1055
Limburg	1.7	1525
Coal-chalk	1.7	2810
Carboniferous	1.7	30000

3. Hypocenter Methods

Several hypocenter methods are available at the KNMI. Different methodologies are tested on the Q-con data to make an estimate of the location and depth of the earthquake near Venlo and the associated error. The operational sc3 program, used to routinely locate earthquakes in the Netherlands, has implemented the well-documented method by Lienert *et al* (1986). This approach is applicable for layered media, hence the hypocenter method is valid for the three velocity models in Section 2.

A new generation of methods for source location of earthquakes is under development at the KNMI. The new hypocenter methodology by Spetzler and Dost (2017) which was explicitly developed to estimate the depth of induced earthquakes in Groningen, has been reconfigured to be used for the Q-con stations at the CWG field. In addition, the same KNMI in-house software in Spetzler and Dost (2017) has again been modified to include the standard hypocenter basis principle of using the traveltime difference between P-wave and S-wave phases in source location of earthquakes (Aki and Richards, 1980). The two latter methods are using a 3D ray tracer to calculate traveltimes for P-waves and S-waves.

4. Hypocenter Estimation of Earthquake

The Q-con data were loaded into the KNMI operation software. The picked P-wave and S-wave arrivals were used as data with velocity Model 1 for Venlo in the hypocenter method by Lienert *et. al.* (1986). The earthquake is located near Grubbenvorst inbetween station K01 and K03. The depth of the event is 4 km. Figure 4 is a screen shot with the result of the hypocenter analysis in sc3. The residual of the data fit is equal to 0.1 s. The error in location is 2-3 km.

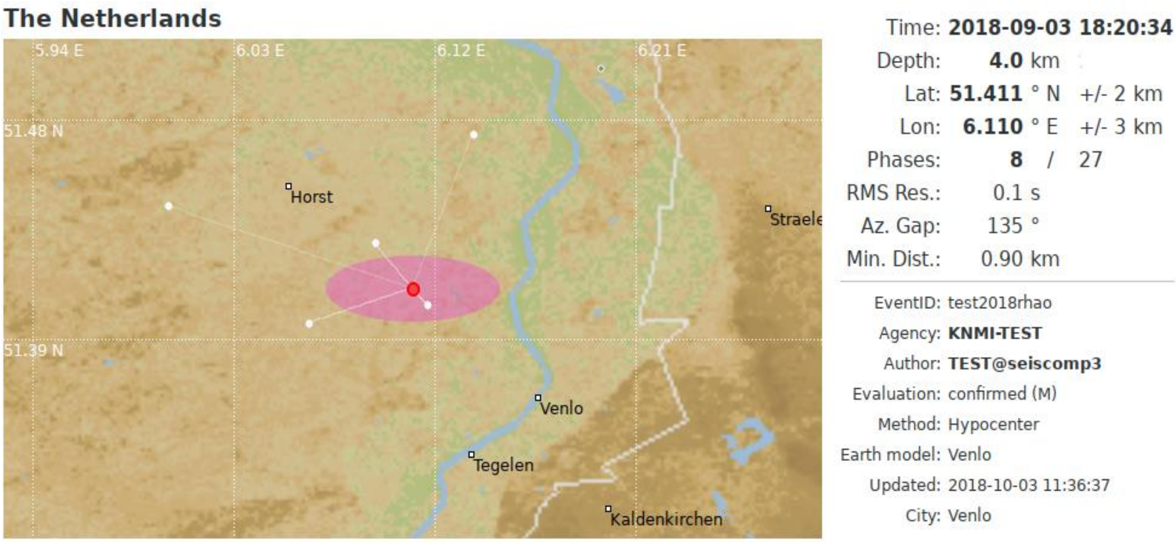
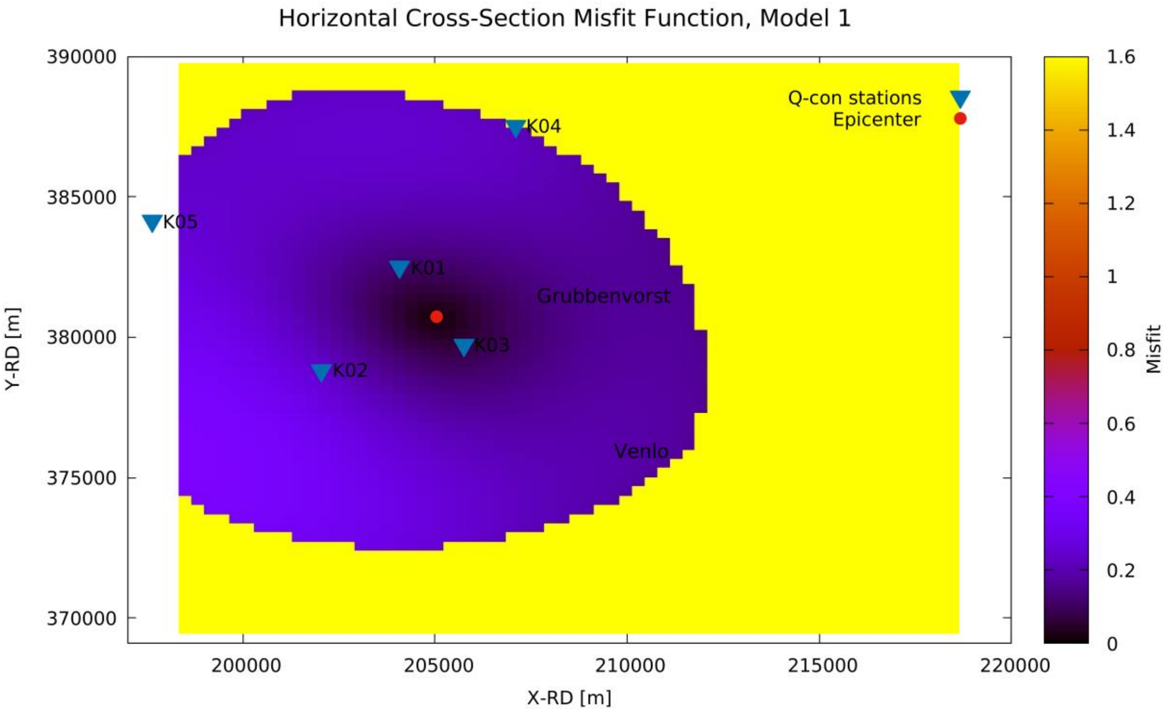


Figure 4: Screen shot of sc3 result window.

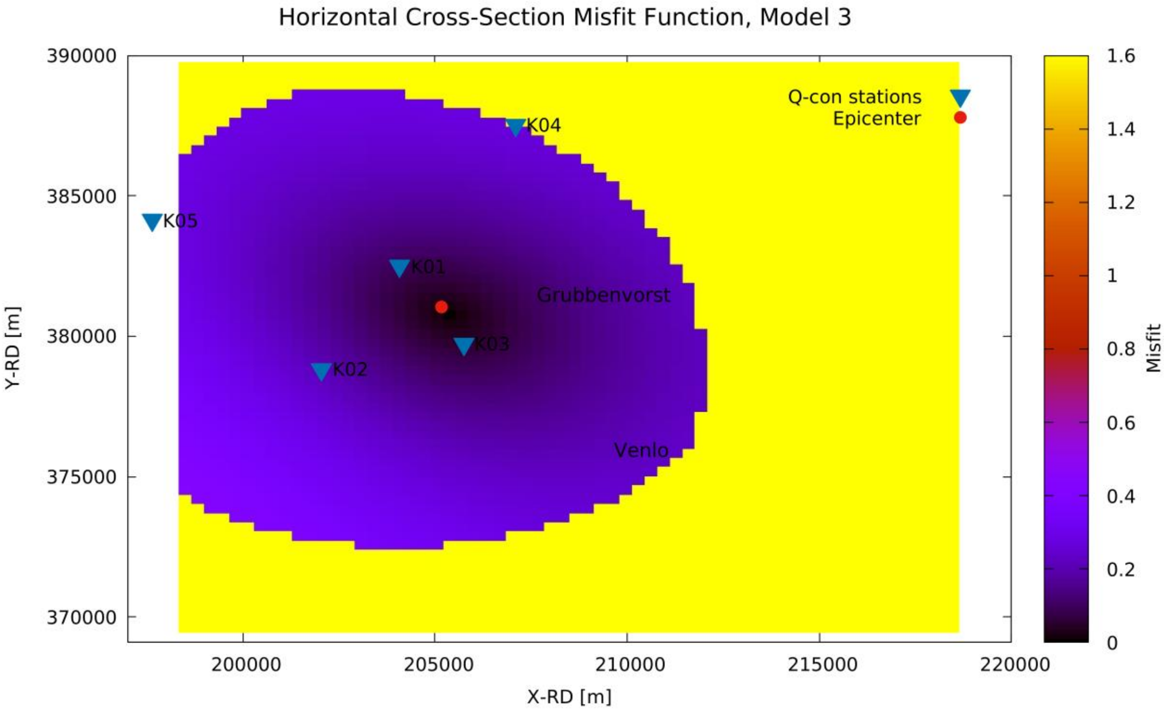
Next, the new KNMI in-house hypocenter software for P-wave arrival times and for differences between P-wave and S-wave times has been used to make an estimate of the location and depth of the Venlo event. This time the three velocity models in section 2 with constant Vp/Vs and depth dependent Vp/Vs have been used in the analysis. In Figure 5 subplots with the cross-section of the data misfit function are presented for several velocity models. The first two subplots are similar, showing that the different velocity models are pointing towards a similar location of the event. The event has taken place close by Grubbenvorst between station K01 and K03. The third sub plot with the misfit function for Model 1 with a depth dependent Vp/Vs. This time the misfit function is less well-behaved. The estimated epicenter is more to the west of the ones in the two other subplots in Figure 5. Table 6 gives the coordinates for the estimated epicenters in the hypocenter analysis for the three velocity models and possibilities for Vp/Vs ratio. The misfit function and estimated epicenter for Model 1 and Model 2 for a constant Vp/Vs ratio are identical.

A)



Horizontal Cross-Section Misfit Function, Model 1
Q-con stations
Epicenter
K01
K02
K03
K04
K05
Grubbenvorst
Venlo
390000
385000
380000
375000
370000
Y-RD [m]
200000
205000
210000
215000
220000
X-RD [m]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Misfit

B)



Horizontal Cross-Section Misfit Function, Model 3
Q-con stations
Epicenter
K01
K02
K03
K04
K05
Grubbenvorst
Venlo
390000
385000
380000
375000
370000
Y-RD [m]
200000
205000
210000
215000
220000
X-RD [m]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Misfit

C)

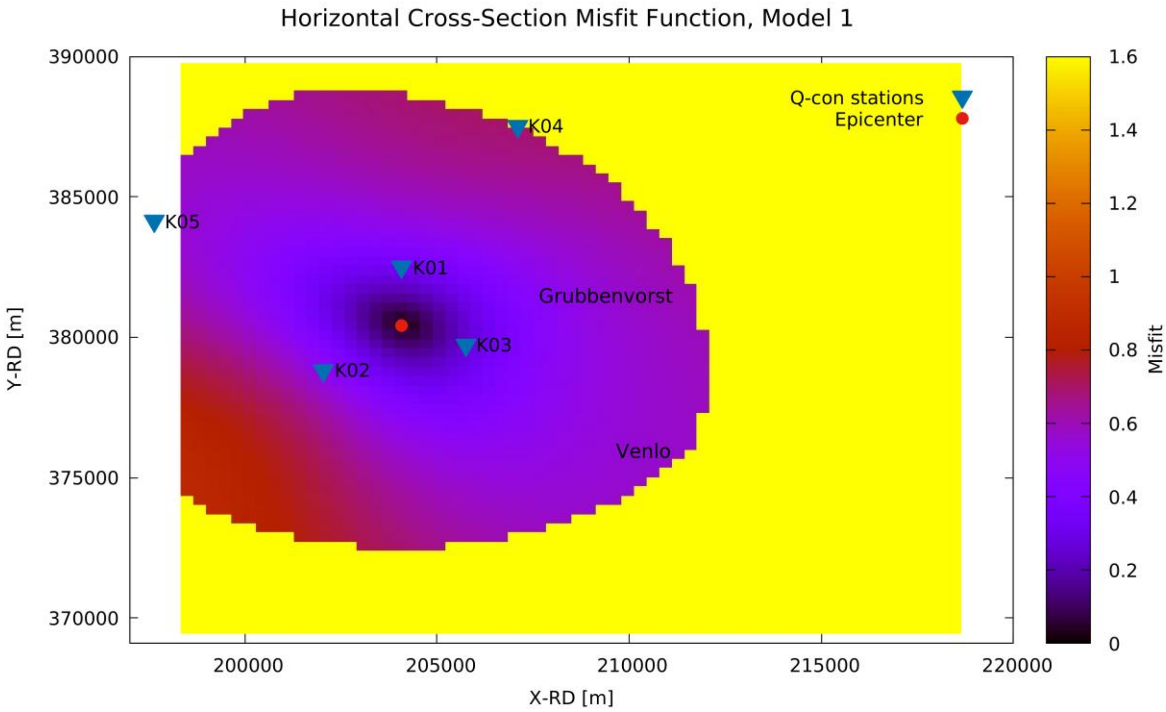


Figure 5: Horizontal cross-section of misfit function to determine the location of the event applying the different velocity models. A) Model 1 with constant Vp/Vs ratio, B) Model 2 with constant Vp/Vs ratio and C) Model 1 with depth dependent Vp/Vs ratio.

Table 6: Estimated epicenters.

Model description	Vp/Vs-ratio	X-RD [m]	Y-RD [m]
Model 1	1.73	205053	380746
Model 2	1.73	205053	380746
Model 3	1.73	205162	381027
Model 1	Depth dependent	204069	380418

To determine the depth of the Venlo event, the misfit is computed as a function of depth, for vertical profiles through the epicenters as established in Figure 5. Figure 6 is a plot of the four profiles of the misfit function. Model 1 and Model 2 are extracted from locally recorded data at the geothermal field and are considered to be most representative for the structure of the subsurface. The estimated depth based on these two velocity models with constant Vp/Vs ratio is around 7200-7300 m. Model 3 is an averaged velocity model for the south of the Netherlands and again the Vp/Vs ratio is constant. This latter model does not account for local velocity structures in the geothermal field. The estimated depth is 9300 m which is deeper than the estimates using Model 1 and Model 2. Model 3 has a higher velocity in the top layer, hence to predict the difference between P-waves and S-waves measured at the Q-con stations, the hypocenter depth must accordingly be deeper. The last test case is the investigation of a depth dependent Vp/Vs ratio for Model 1. This time the estimated depth is 3.2 km due to the higher Vp/Vs ratio in the shallower part of the elastic model. However, the misfit function for the case of Model 1 with a depth dependent Vp/Vs ratio is less well behaved and the misfit value at the estimation of the depth of the earthquake is larger than for the three other profiles. This is an indication that the data fit is much more poor and the solution may not be optimal.

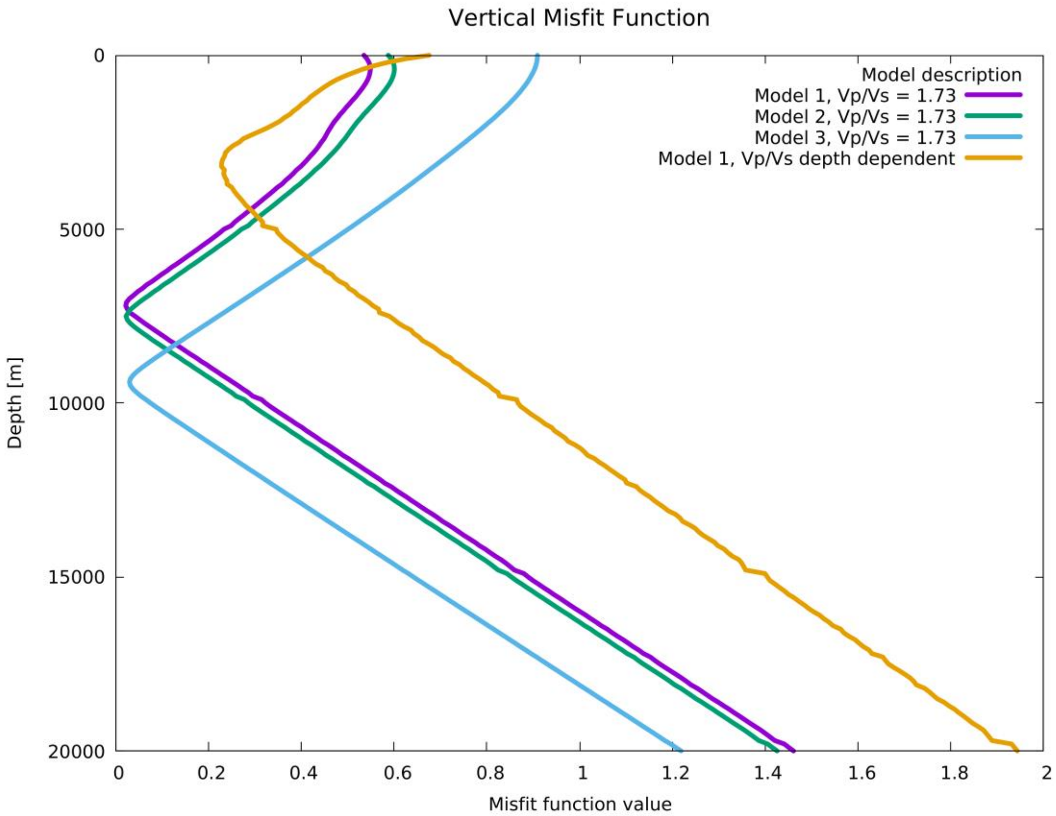


Figure 6: Vertical profile of the misfit function at the estimated epicenter.

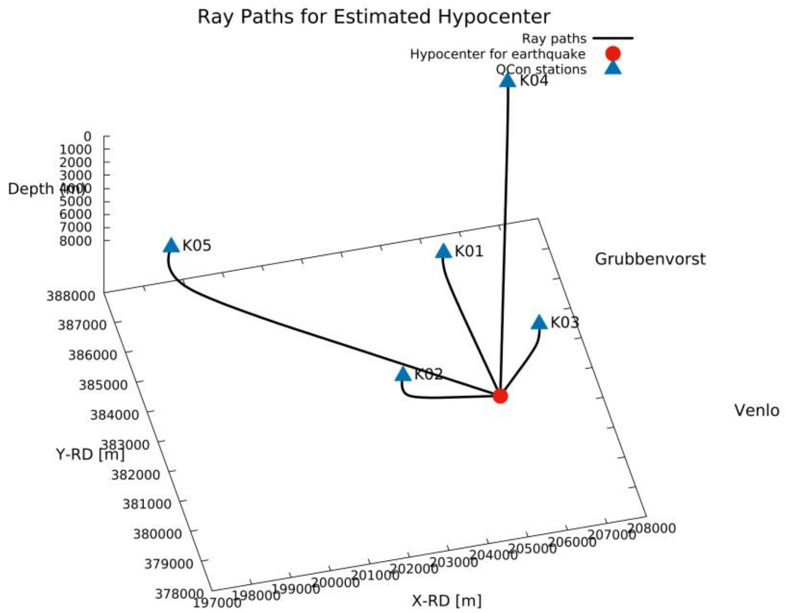


Figure 7: Quality control of the estimated hypocenter. Ray paths from the hypocenter to the five Q-con stations.

A final figure in this section is the ray path plot in Figure 7. The rays (i.e., path of seismic energy) from the estimated hypocenter to the Q-con stations are smooth lines without odd discontinuities along the ray paths. The smooth ray paths shows that the KNMI hypocenter software is producing a realistic result.

5. Conclusions

The event data with the earthquake recorded at the Q-con stations on September 3rd 2018 at the local time 20:20:34 have been analysed with several hypocenter methods and velocity models of the subsurface northwest of Venlo, close to Californië Wijnen Geothermie. The hypocenter analysis shows that the event took place under the geothermal field at a depth between 3.2 km and 9.2 km with two cases pointing towards a depth around 7.2-7.3 km. The solution in the KNMI operation hypocenter method estimates the depth to 4.0 km. The estimated depth at 9.2 km was obtained with the 1D region velocity model for Limburg which is not representative for the subsurface structure near Venlo. This means that the deeper estimate may be an overestimation of the hypocenter depth. The more shallow depth at 3.2 km comes from a solution with a much poorer data fit. For all the case studies, it is found that the event took place at a location near Grubbervorst. This location is in agreement with observations: 1) The seismic event data show the first arriving P-wave phases and the smallest differences between P-wave and S-waves at the two stations K01 and K03. These two stations are the ones near Grubbenvorst. 2) Ground motion reports come from addresses close to station K03.

Routine analysis of the earthquake data recorded over a sparse regional network yielded a depth estimate of 1 km, with a very large uncertainty. This depth estimate is superseded with the new analysis, yielding a depth between 3.2 and 9.2 km.

The lack of knowledge on the actual S velocity in the region prevents an accurate depth estimate. It is recommended to measure this parameter in the region.

Acknowledgements

Q-con is acknowledged for the delivery of the event data recorded at the local station network dedicated to monitor the CWG field near Venlo.

6. References

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