SCAN seismic data analysis

Insights into the acquisition data quality

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June 11, 2021

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Internship duration: 11/01/2021 - 11/06/2021

Abstract

The SCAN project is a program set up to map the Dutch subsurface as part of a geothermal exploration program. The program exists of 2D seismic acquisition, re-processing and scientific drilling. To investigate the quality of the newly acquired seismic, an analysis was done which looked at the relationship of shot data quality and acquisition parameters (e.g. charge size, height of the groundwater table). The signal-to-noise ratio (SNR), which is influenced by the acquisition parameters, is used as a measure of quality. This study investigated newly acquired lines 19, 20 and 30-34 as well as the previously shot lines (2-34). The results show that SNR is most influenced by low signal amplitudes from shots above the groundwater table. Low charge sizes or shot depths also give a low SNR, as well as a lot of noise from highways or urban areas. It is therefore advisable to shoot below the groundwater table with high charge sizes and preferably further from urban areas or parallel to highways. Besides newly acquired lines, the quality of final processed data is quantified by cross-correlation. Cross-correlation is a fairly good measure for quantifying final processed data, given that the seismic section does not contain a lot of dip and faults.

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Introduction

The energy transition and geothermal energy

The Dutch government has the goal of reducing its CO_2 emissions by 51% in 2030 compared to the emissions of 1990 and by 95% in 2050 ("Klimaatwet", 2019). Reaching this goal requires an intensive energy transition for a country which fuels itself mainly by fossil fuels. The sustainability goals can be reached by replacing fossil fuels by renewable energy sources, such as solar and wind energy. Another renewable energy source is geothermal energy.

Geothermal energy makes use of Earth's internal heat. Naturally occurring hot water in the subsurface can be used as a heat supply and an energy source in everyday life. The heat supply in e.g. urban areas, now mainly supplied by natural gas, could, at least partly, be substituted by geothermal energy.

For the use of geothermal energy knowledge of the subsurface is vital. EBN B.V. has been tasked by the Dutch government to acquire subsurface data in areas not yet extensively imaged before which led to the SCAN program.

SCAN

The SCAN (Seismische Campagne Aardwarmte Nederland) project of EBN B.V. is a program set up to research the Dutch deep subsurface as part of a geothermal exploration program. The main goal is to "fill in the blanks"; to map the deep subsurface (base Upper Rotliegend group - base North Sea supergroup) of areas which have limited seismic coverage and or limited well data (areas A-I in figure 1.1).

While other areas have been mapped extensively in the past due to oil and gas exploration, the areas A-I have not been extensively mapped due to their lack of gas and oil potential. To map the deep subsurface the research exists of three parts: acquisition of new 2D seismic lines, reprocessing of old seismic lines and scientific drilling of wells. All results and information gathered by SCAN will be made publicly available to accelerate the development of geothermal projects and the energy transition.

The focus of this report will be on the acquisition of 2D seismic lines. A seismic line is a cross-section of the subsurface over a length of tens of kilometers, in this research shot in 2D. These cross-sections provide valuable insights into the structure of the (deep) subsurface. Geothermal energy is possible from a depth of 500 m to 4000 m; below 4 km geothermal potential is called ultra deep geothermal (UDG). Targets of the SCAN program are mainly in the North Sea Supergroup until the Rotliegend for geothermal energy and the Dinantian for UDG (figure 1.2).

Seismic design	Split spread
Acquisition type	Roll On - Roll Off
Maximum offset	6997.5 m
Receiver station interval	5 m
Receiver type	5 Hz geophone
Source type	Explosive source
Source interval	60 m
Source depth	4 - 30 m
Source charge size	220 - 2200 g
Sample rate	2 ms
Record length	10 s

Table 1.1: Acquisition parameters all line, excluding the Test line. N.B. Lines SCAN019, SCAN031 and SCAN034 have a record length of 20 seconds.

In 2019 a test line was shot to test and determine the acquisition parameters (Janssen, 2020). Based on this test the acquisition parameters, as shown in table 1.1, have been determined. All but three lines, SCAN019, SCAN031 and SCAN034 have a record length of 10 seconds. The other three lines have a record length of 20 seconds which have been recorded to allow deeper research at a later stage.

Internship objectives

The internship is focused on the quality of shot data. This is done in three different ways; by analysing the quality of the data per line before processing, analysing the data of all lines together and analysing and quantifying the processed data.

The quality analysis is done for SCAN019, SCAN020 and SCAN030 - SCAN034 (Figure 1.3). The objective of the quality analysis is to answer following questions:

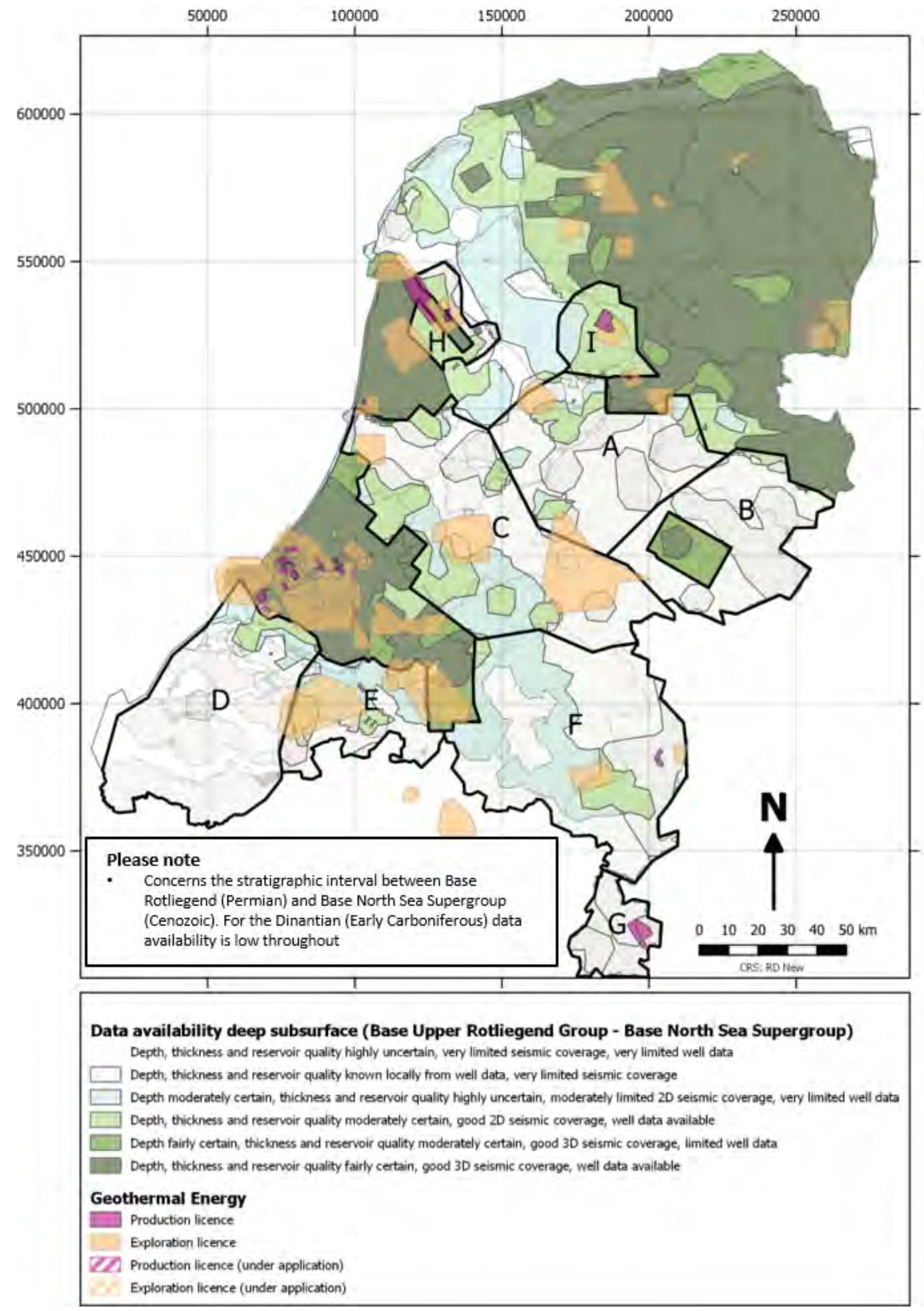


Figure 1.1: SCAN areas (EBN-TNO-AGE, 2017)

1. What is the relationship between shot data quality and weather?
2. What is the relationship between shot data quality and traffic noise?
3. What is the relationship between shot data quality and time of shooting, e.g. morning, mid-day, afternoon or evening?
4. What is the relationship between shot data quality and shot depth?
5. What is the relationship between shot data quality and charge size?
6. What is the relationship between shot data quality and near surface geology?
7. What is the relationship between shot data quality and measured uphole times?
8. What is the relationship between the measured uphole time and the near surface geology?
9. What is the relationship between shot data quality and the height of the groundwater table?
10. What is the relationship between shot data quality and time between drilling date and shot date?

The analysis between lines looks predominantly at the different parameters discussed in the aforementioned questions and also researched in previous studies (Janssen, 2020; van der Lucht, 2020; van Klaveren, 2021), but also has the objective to visualize the differences between lines, taking into account the shot depth, charge size, signal, noise (in both the shot domain and the receiver domain) and signal-to-noise ratio. For the analysis between lines, 33 lines, all but the test line, mentioned in the current report and previous reports are being taken into account (Figure 1.3).

Following the results of both the analysis of data per line as well as the analysis between lines a recommendation is done on the shot design.

Lastly, the processed data is analysed in an attempt to quantify the data quality of each line. This is done for SCAN001-011, SCAN017-018 (both combined lines), UGOU021, UGOU022, SCAN023, SCAN024, SCAN025, SCAN027, SCAN028 and SCAN029.

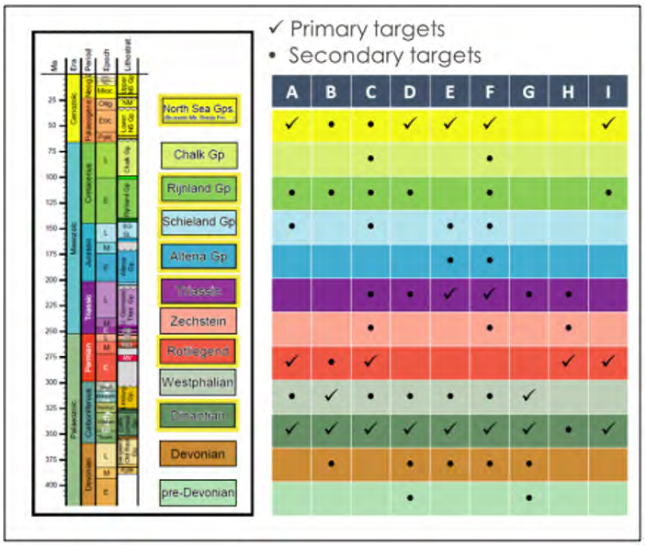


Figure 1.2: SCAN primary and secondary target areas and plays

Figure 1.3: All 34 lines researched in this report.

Method

2.1 Data quality analysis of the individual lines

The first step in assessing the data quality is analysing the acquired raw shot data of individual lines. The data is delivered in SEGY format and can be read by seismic processing software GLOBEClaritas (figure 2.1). To investigate the quality of the shots the signal-to-noise ratio (SNR) is used.

$$SNR = \frac{RMS\,signal}{RMS\,noise} \tag{2.1}$$

Both signal and noise amplitudes provide valuable insights, but looking at either alone can distort the view on shot data quality, because a high signal amplitude might turn out useless by high noise levels. A high SNR means the shot had either a high signal amplitude with reasonable noise amplitudes or reasonable signal amplitude with a low noise amplitude, both favourable, while a low SNR means a low signal amplitude and or a high noise amplitude, less favourable. Consequently, a high SNR means better shot data quality. Thus, to determine the SNR both signal and noise amplitudes need to be extracted from the raw data.

Noise amplitude analysis

To extract the noise amplitude from the raw data we looked at the ambient noise between 0-500 ms and excluding only the near offsets (-900 to +900) where the first arrival, thus shot energy, is present (figure 2.1).

The root-mean-square (RMS) noise amplitudes are gathered in GLOBEClaritas of every trace in each shot, all noise in the shot is summed and divided by the number of non-zero traces, in Python, to find the average noise amplitude per shot in the shot domain.

$$RMS\,noise = \frac{\sum RMS\,noise\,per\,trace}{\sum non-zero\,traces} \tag{2.2}$$

The same is done for the receiver domain, where the noise amplitude acquired by each receiver in every shot is gathered and an average RMS noise amplitude per receiver is calculated. Most ambient noise is produced by the surroundings, thus this is done to investigate which areas are noisy and indicate if single receivers show erratic behaviour.

Signal amplitude analysis

The signal amplitude is calculated similarly to the noise analysis, but required filtering of the data, because only shot energy of reflections is of interest (figure 2.2). First an F-k filter is applied to remove ground roll, which is frequently of high amplitude and distorts the required signal amplitude, through frequency filtering (figure 2.3). The F-k filter does not remove ground roll entirely, hence the ground roll is muted completely (tail mute) (figure 2.4), together with ambient noise visible before the first arrival (front mute) of shot energy. The F-k filter is still useful as a first filter, because it reduces the effect of ground roll energy if it is still present after the tail mute.

After muting two windows with the strongest shot energy are chosen to determine the RMS signal strength. Figure 2.5 shows the two windows: 0-1 s has a window from -1700 m to 1700 m offset and the 1-2s window goes from -3500 m to 3500 m offset. The RMS signal of the traces in each of these windows are summed and divided by the total of non-zero traces, alike the noise amplitude analysis (equation 2.2). Next, the SNR of each shot is calculated with use of the RMS signal amplitude and RMS noise amplitude (equation 2.1).

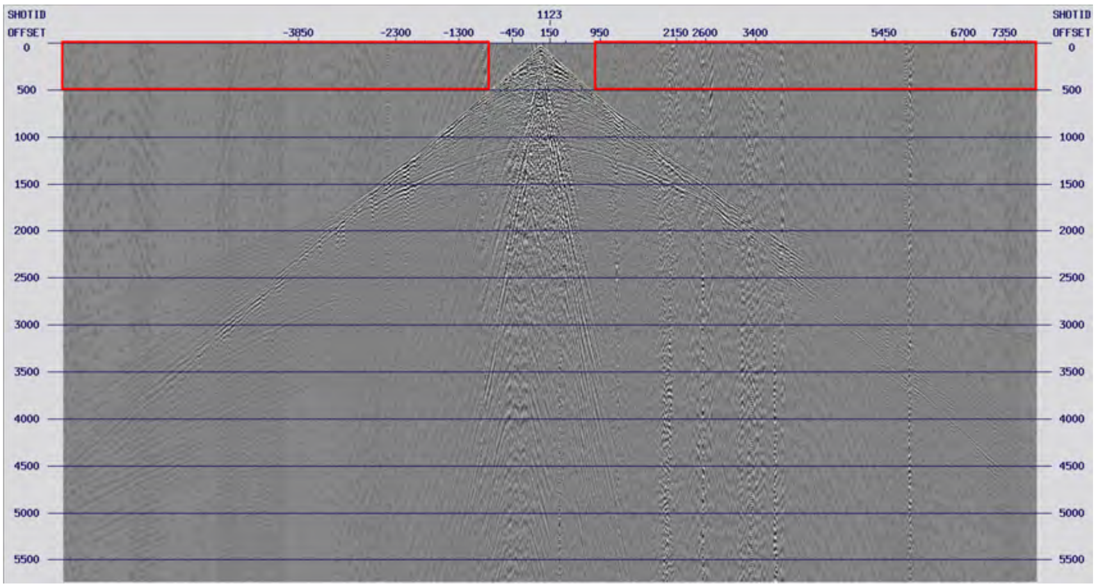


Figure 2.1: A shot in GLOBEClaritas. The red boxes indicate the areas over which noise amplitude is calculated. The boxes reach from 0-500 ms and exclude the offsets between -900m to +900m.

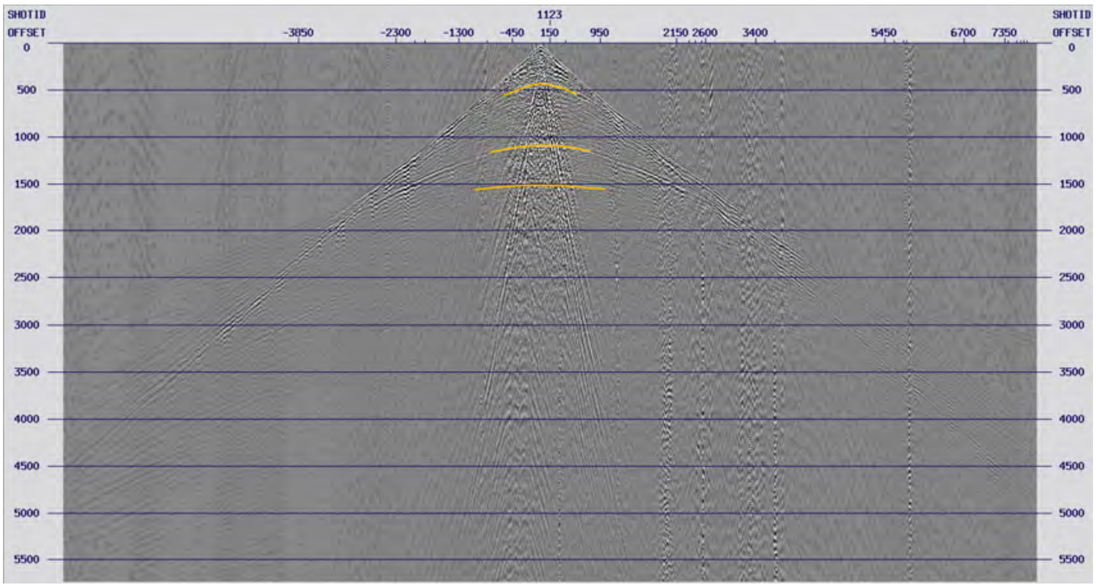


Figure 2.2: A shot in GLOBEClaritas with some of the reflections of interest highlighted.

2.2 Between lines

The SNR of each line is only one way to measure the quality of the lines. A couple of acquisition and geological parameters are investigated that have an impact on the quality of the data, as mentioned in the internship objectives; shot depth, charge size, near surface geology, the effect of the groundwater table or the time between drilling date and the shot date (or the time the explosives were underground). In previous internships (Janssen, 2020; van der Lucht, 2020; van Klaveren, 2021) most of these parameters have been investigated. This report focuses mainly on the effect of near surface geology, the groundwater table and the time between drilling and shot date and investigates these three parameters for all lines shot until date (34 lines).

The near surface geology is extracted from data from Publieke Dienstverlening Op de Kaart (PDOK, 2013), which provides public datasets on geo-information, and loaded into QGIS to extract which shots are shot in which type of geology. Using this information the effect of geology on data quality is investigated. We try to find relationships between the quality analysis of SNR and the various acquisition or geological parameters.

To investigate a possible relation between the groundwater table and SNR observed from shot records, groundwater depth information is taken from a tool of the Geologische Dienst Nederland (GDN) called grondwatertools.nl (TNO, 2021). The height of the groundwater table is plotted and compared with shot depth and topography.

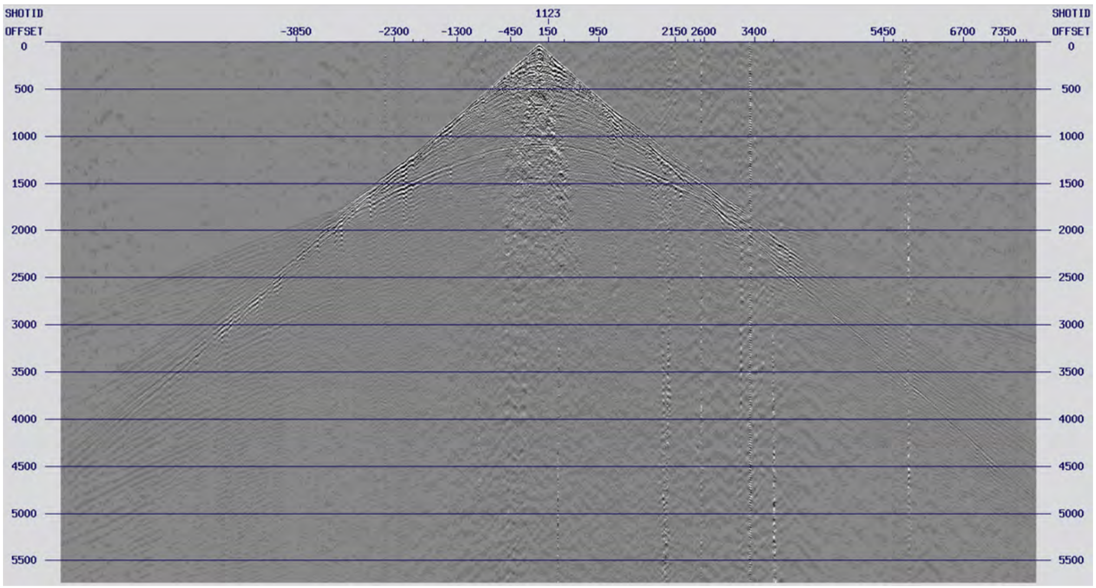


Figure 2.3: A shot in GLOBEClaritas after the F-k filter.

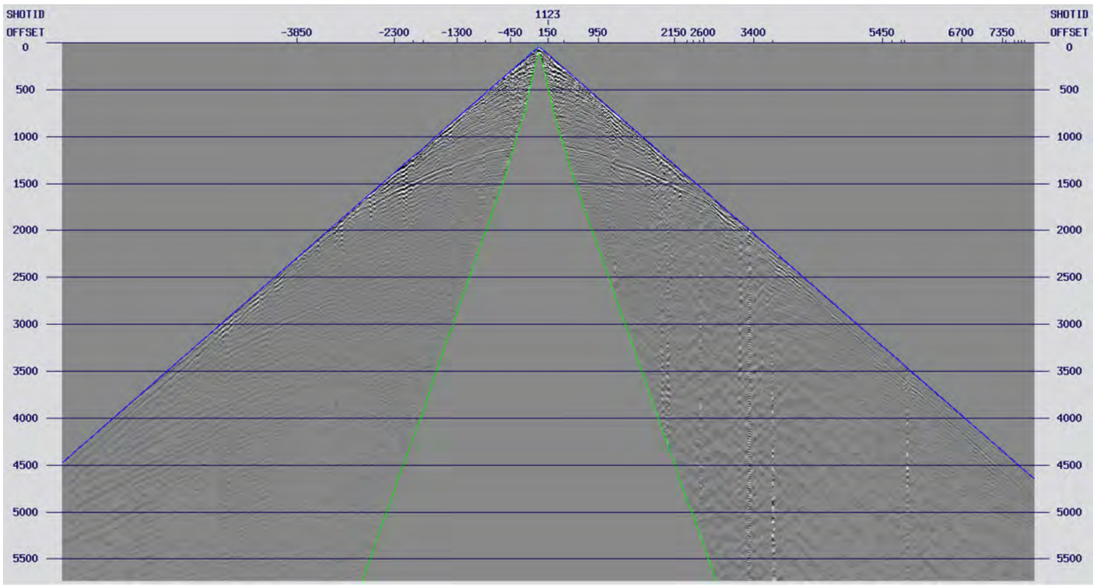


Figure 2.4: The groundroll has been muted (below the green line) as well as the ambient noise before the first arrival (above the blue line)

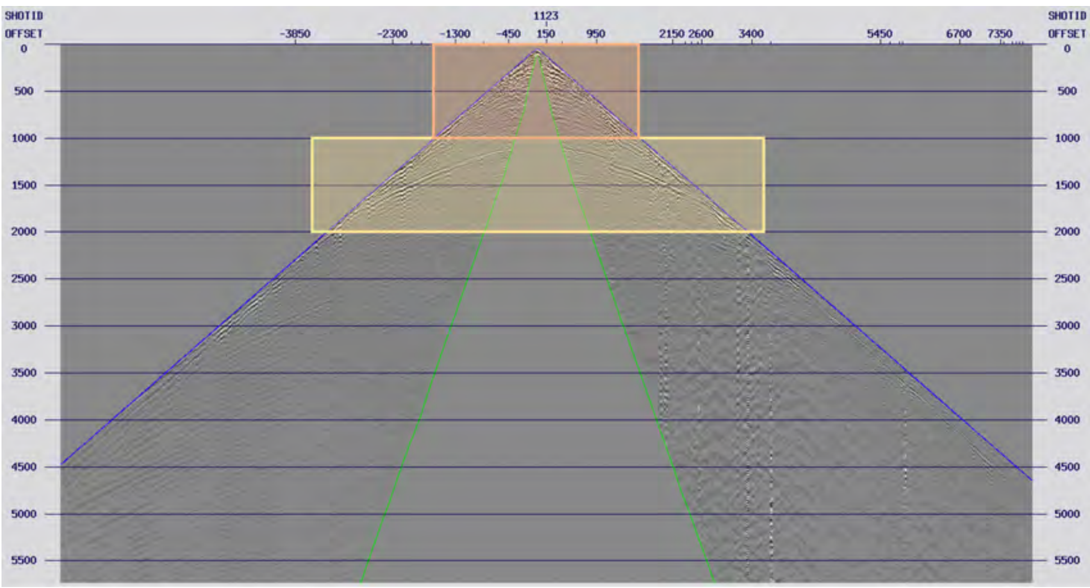


Figure 2.5: The RMS signal amplitude is extracted for 0-1s (orange box) and 1-2s (yellow box).

A parameter not yet analyzed in previous reports is the time between drilling date and shot date. The hypothesis is that the explosive could be better coupled with the subsurface, thus producing a better signal strength, if the time between drilling and shot date is longer. The time spent underground is compared to both signal strength and SNR in combination with charge size and for different geological regions.

Lastly, an overview of all lines and their average and maximum signal, SNR and noise in receiver domain, together with the average charge size and shot depth is given to distinguish between good or poor quality lines and find any outliers.

2.3 Final processing

Quantifying the final processed data is done by cross-correlation of neighbouring CDP traces. Cross-correlation looks at the similarity in shape of two traces and assigns a value from -1 to 1 to each pair. A value of 1 indicates completely similar traces, while -1 means the two traces are complete opposites and 0.5 means the two traces have some similarity (figure 2.6). A high cross-correlation value will, in our case, indicate straight continuous layers in the processed data. In previous research (van Klaveren, 2021) the choice was made to compare traces 10 steps apart from each other, representing 25 meters in the field. In this research a more robust approach was taken. The original trace is cross-correlated with 10 random traces between 1 - 20 steps further. The average of those 10 cross-correlations is then taken. The average trace step is still 10 with this approach, but this method ensures that any abrupt changes or outliers are evened out. Hence, the robustness increases. The cross-correlation is applied to both the time and frequency domain of the processed data. All processed seismic sections looked at are of true amplitude without automatic gain control applied.

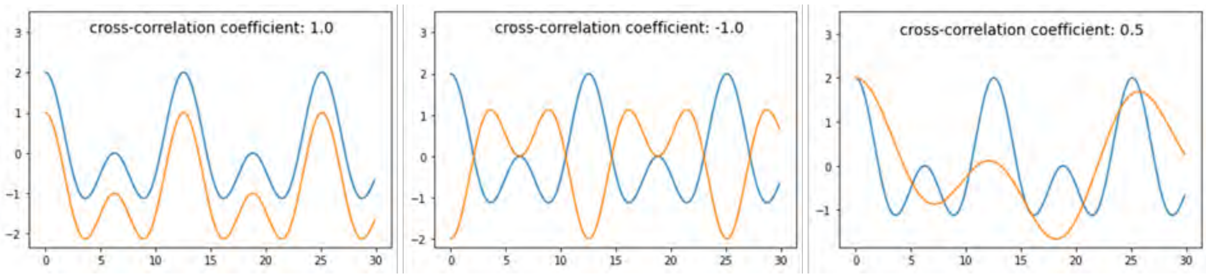


Figure 2.6: An example of cross-correlation. The left figure shows two similar wavelets with a cross-correlation coefficient of 1. The middle figure shows two opposite wavelets with a cross-correlation coefficient of -1. The right figure shows two wavelets which have cross-correlation coefficient of 0.5.

Results

3.1 SCAN019

SCAN019 is 83.305 km long and runs from north east to south west, starting in Germany, near Goch, and ending at the Dutch-Belgian border near Reusel. A summary of important acquisition parameters is shown in table 3.1. High amplitudes are mostly visible between shotpoints 14000 and 16000, where a higher charge size could be used (figure 3.1). The line was relatively noisy due to the proximity to Eindhoven (receiver numbers 10500 - 12700) and the crossing of several highways (A2, A50, A58, A73 and several N-roads)(figures 3.13 and 3.14). One receiver, station 11716, recorded particularly high noise (amplitude of 1519) compared to the average (0.178), thus this station has been removed from analysis. The noise around Eindhoven especially influenced the SNR (figures 3.3 and 3.4): the noise was so high that even with high signal strength the SNR was low. Figure 3.10 shows the groundwater level relative to the shot depth. The region around stations 14000-14100 seems to be shot above the groundwater table. Figure 3.11 shows that part of the line zoomed in. As mentioned by Klaveren (2021), shots above groundwater level give a low signal strength. Here we see that indeed a couple of shots are above the groundwater table, but it is not reflected in the signal strength. This might be due to the fact that the shots are only a couple of meters above the groundwater table, which falls within the uncertainty of the measurements of the groundwater level, as they fluctuate. The acquisition was done between 30th of November and 7th of January 2021. Between 16th of December and 4th of January there was no drilling or shooting due to Christmas holidays. This is reflected in the time the source stayed in the ground before detonation, but does not seem to influence the signal or SNR (figure 3.12).

Total acquisition length	83.305 km
Source station range	1001.5 - 17297.5
Total sources	1360
Receiver station range	1001 - 17661
Total receivers	16661

Table 3.1: Acquisition parameters SCAN019

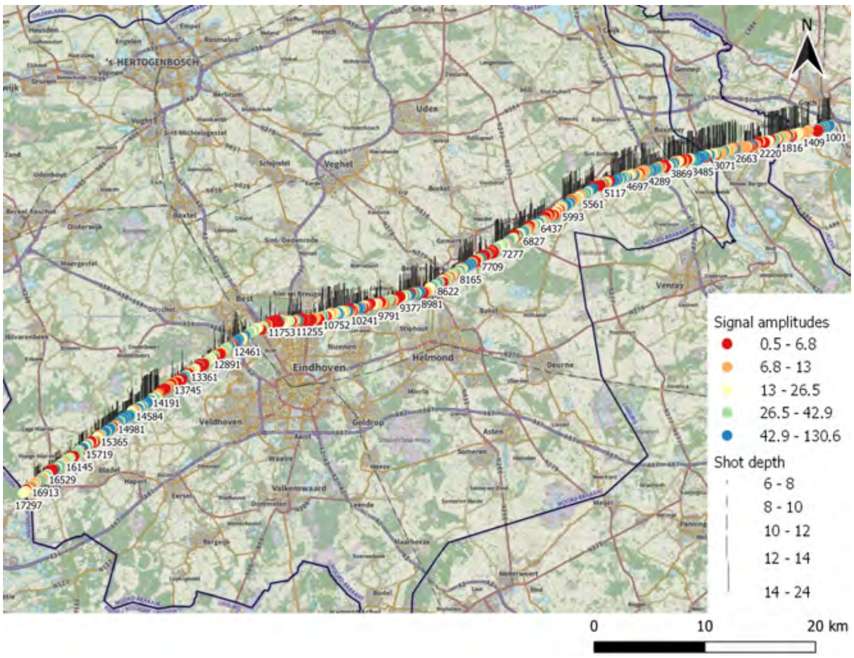


Figure 3.1: Map of the location of SCAN019. The coloured points and black lines respectively show signal amplitudes and shot depth for each station.

Shot domain:

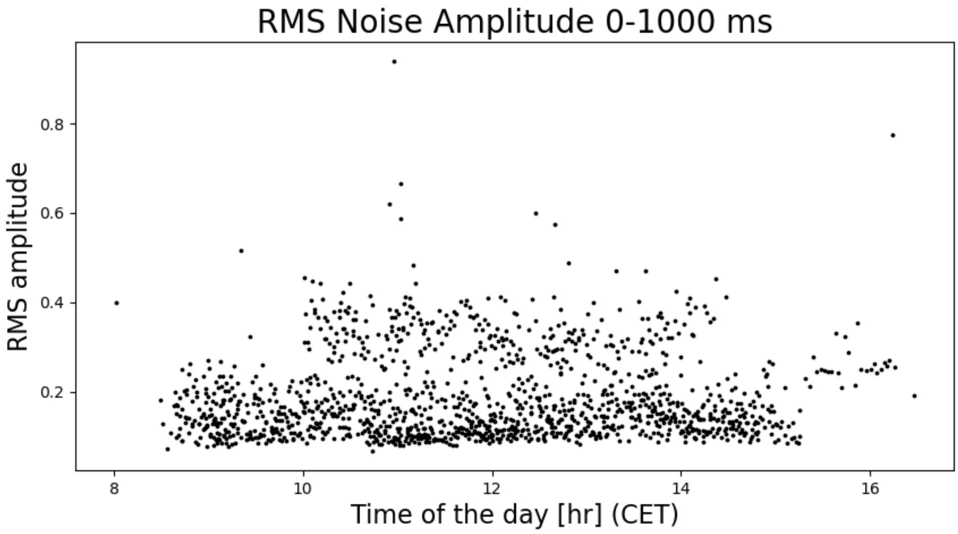


Figure 3.2: The influence of the time of the day of shooting on the noise amplitude. Shots were done between 9 am and 5 pm. For this line, the time of day does not seem to influence the noise levels. The higher noise levels (amplitudes 0.25-0.4) are due to the proximity of highways and Eindhoven.

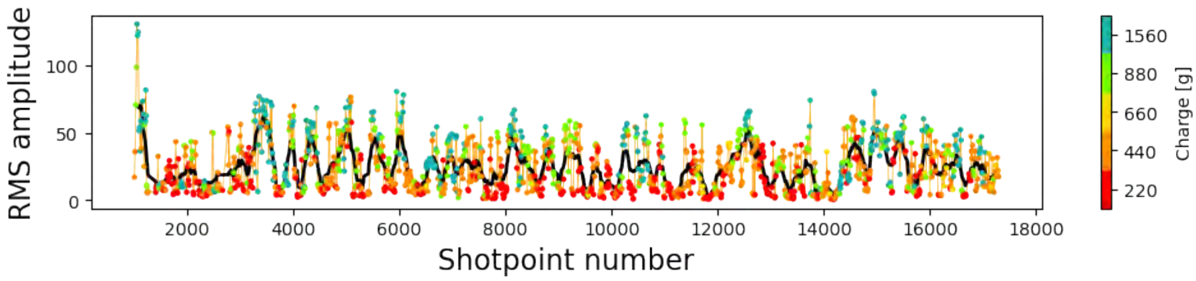


Figure 3.3: The signal amplitude per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the signal amplitude.

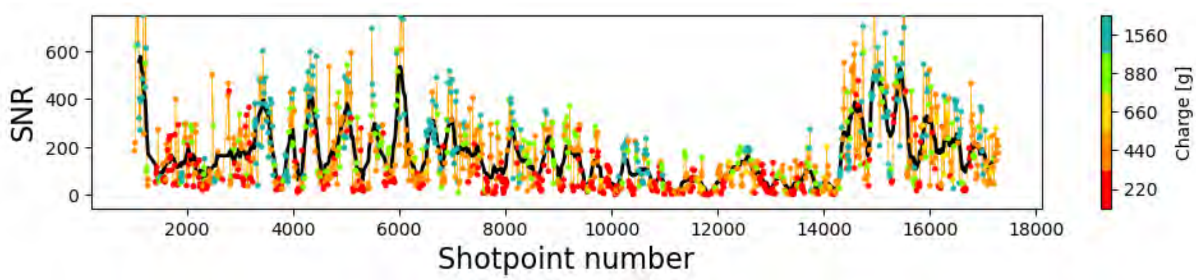


Figure 3.4: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR. Between shotpoint numbers 10500 - 12700 the line is near Eindhoven.

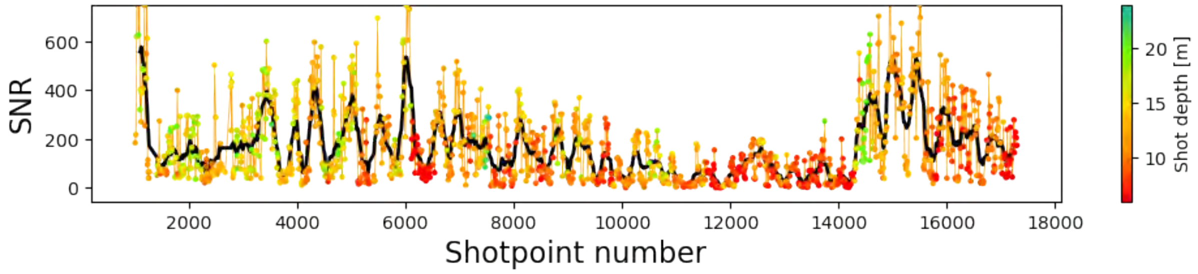


Figure 3.5: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the shot depth for each shot and the black line indicates the moving average of the SNR. Shot depths were between 4 m and 26 m. Between shotpoint numbers 10500 - 12700 the line is near Eindhoven.

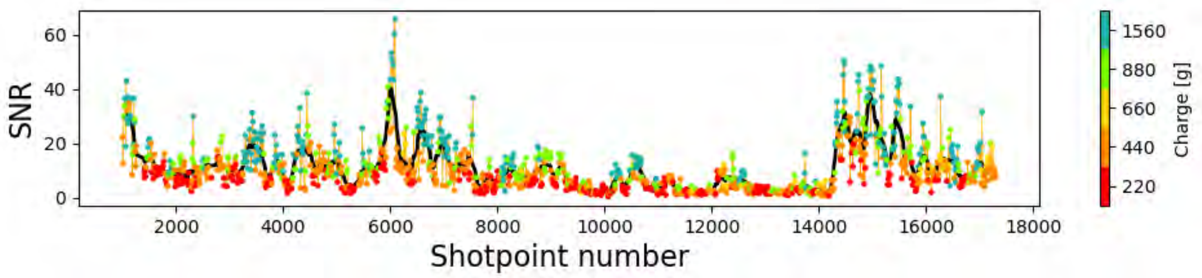


Figure 3.6: The signal-to-noise ratio per shotpoint number in the 1-2s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR. Between shotpoint numbers 10500 - 12700 the line is near Eindhoven.

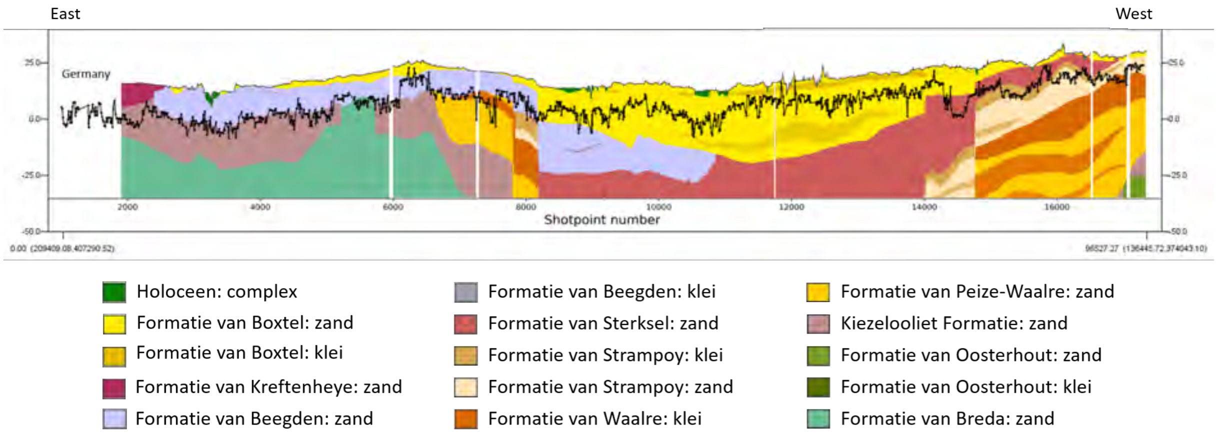


Figure 3.7: Geological profile of SCAN019 overlaid with the shot depth profile in black. The start of the line is situated in Germany of which no geological profile was available.

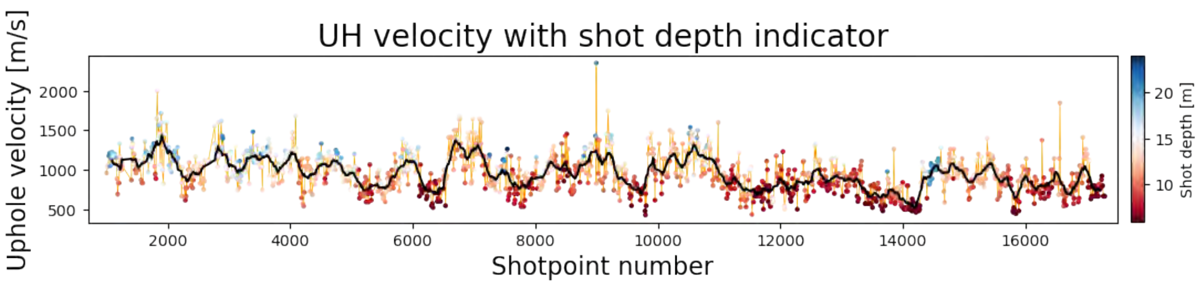


Figure 3.8: Uphole velocity. The colours indicate shot depth. The black line is the moving average of the velocity.

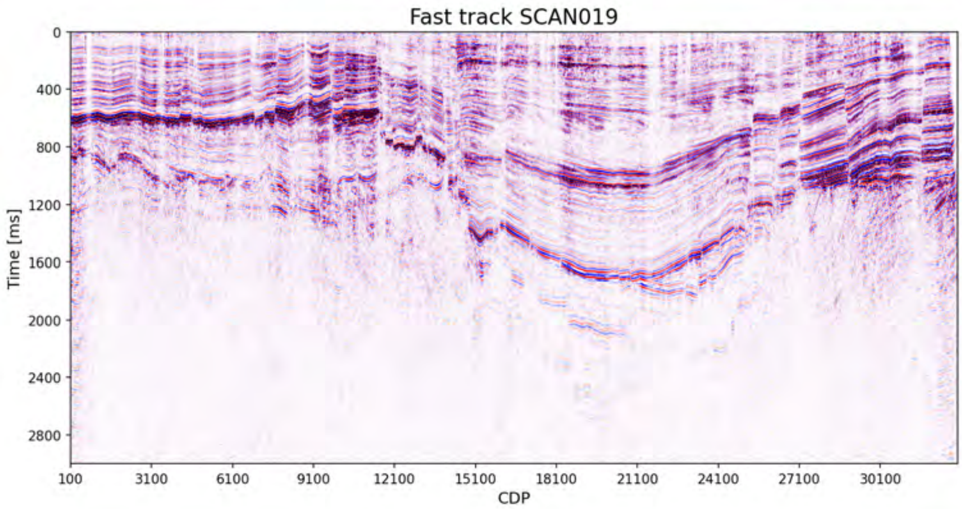


Figure 3.9: The fast track of line 19.

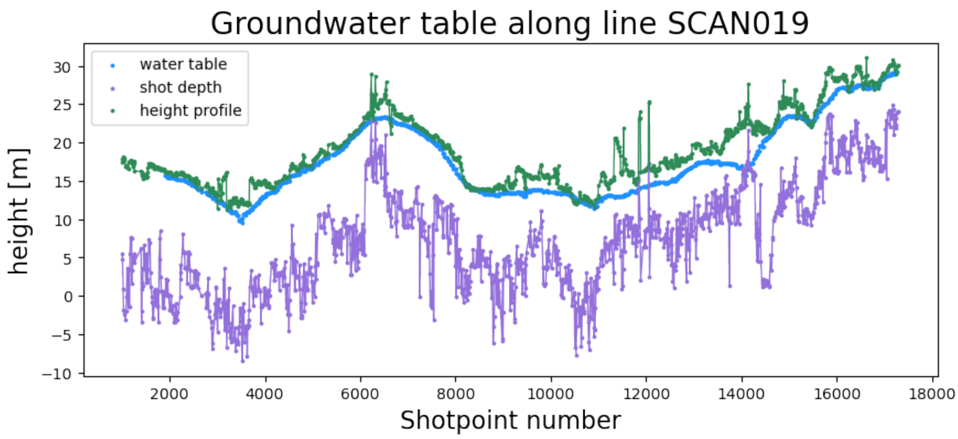


Figure 3.10: The groundwater level along SCAN019. Blue shows the groundwater table, purple the shot depth and green the surface profile.

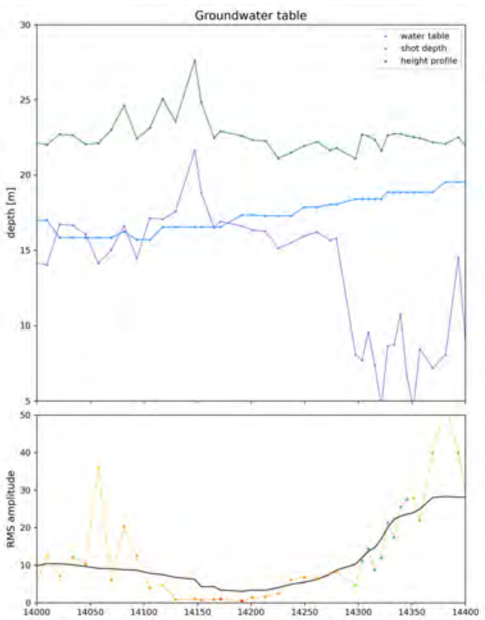


Figure 3.11: The section between stations 14000 and 14400. The shot depth here is at a couple of points higher than the groundwater level.

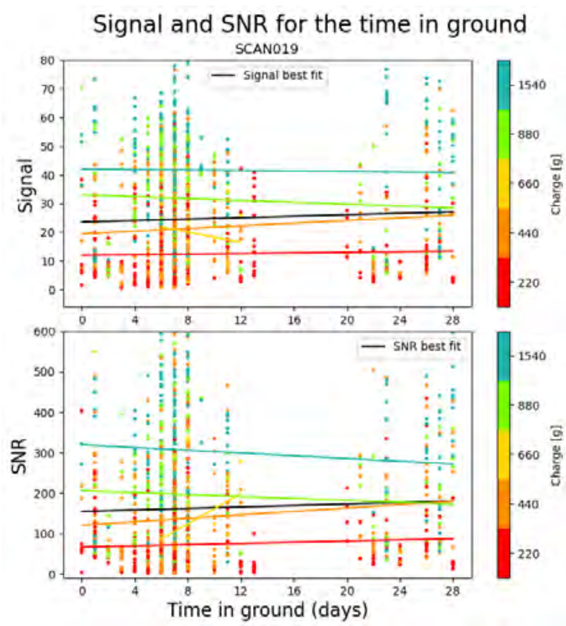


Figure 3.12: The time in days between drilling date and shot date. The colours indicate charge size. The lines are a best fit of all data (black) and per charge size (colours).

Receiver domain:

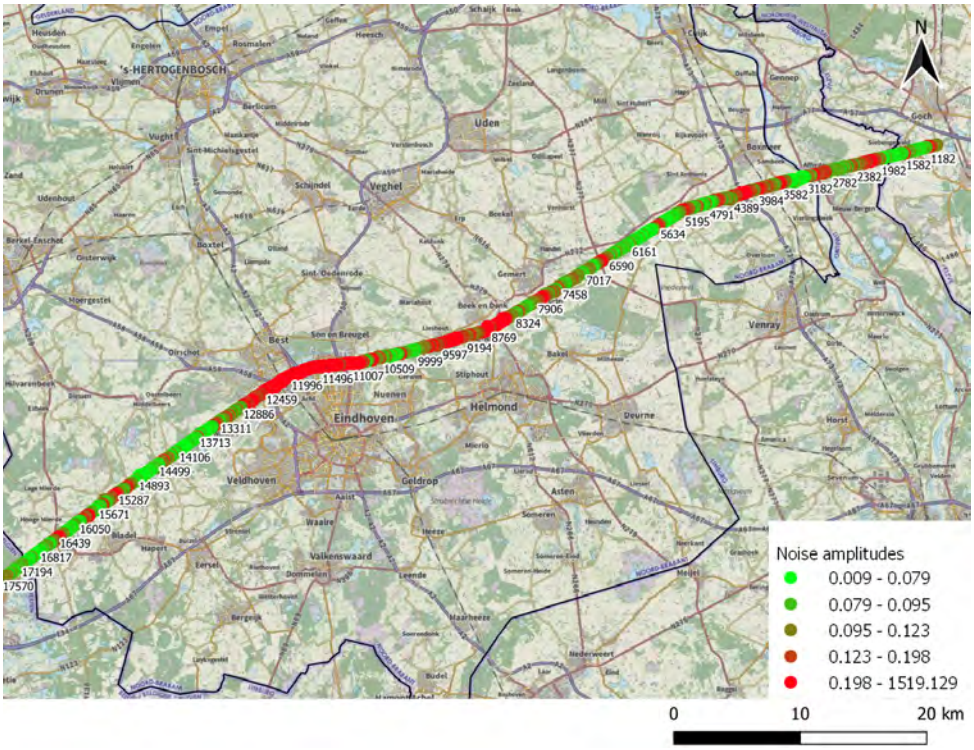


Figure 3.13: Map of the location of SCAN019. The coloured points show the noise amplitudes for each receiver. Every colour represents 20% of the noise amplitudes of this line. The brightest green are the 20% lowest noise amplitudes.

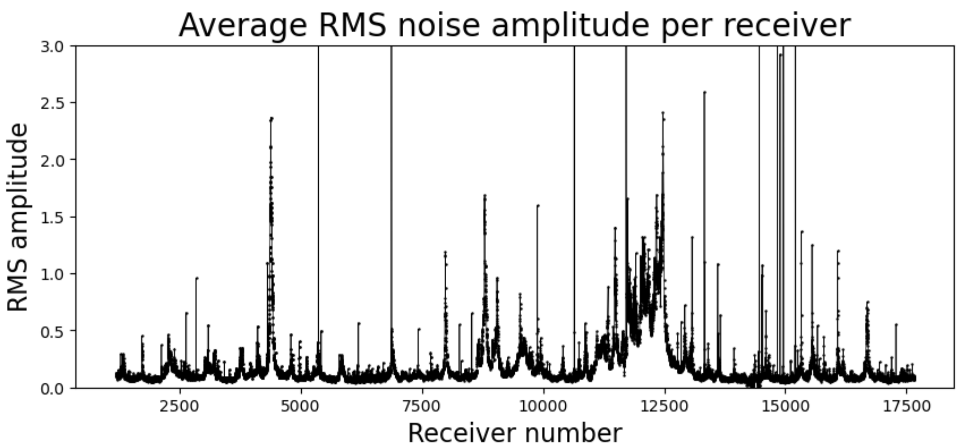


Figure 3.14: Noise amplitudes for each receiver number. High noise areas are mostly due to roads and the proximity of Eindhoven.

3.2 SCAN020

SCAN020 is 53.345 km long and runs from north west to south east, starting south of Nijmegen and ending at the German border east of Venlo (figure 3.15). A summary of important acquisition parameters is shown in table 3.2. The line is relatively quiet, running mainly through meadows and crossing few roads. High signal amplitudes seem to correlate well with higher charge size (figures 3.17 and 3.18), but less with shot depth (figure 3.19). The fact that the signal amplitude and SNR show almost similar graphs indicates that the level of noise was relatively low throughout the line. This is also visible in figures 3.26 and 3.27: the highest noise amplitude recorded is 2.666. Figure 3.24 shows the groundwater level relative to the shot depth. From shotpoint 11000 to the end of the line the shots are above groundwater level. The signal strength as well as the uphole velocity (figure 3.22) in this part of the line is also lower than average. Part of the drilling was done before Christmas holidays, while all shooting was done from the 8th of January on. This is reflected in the gap in time the source stayed in the ground before detonation (figure 3.25). A slight trend is visible between the time in the ground and signal strength and SNR, especially for higher charge sizes.

Total acquisition length	53.345 km
Source station range	1001.5 - 11657.5
Total sources	855
Receiver station range	1001 - 11669
Total receivers	10669

Table 3.2: Acquisition parameters SCAN020

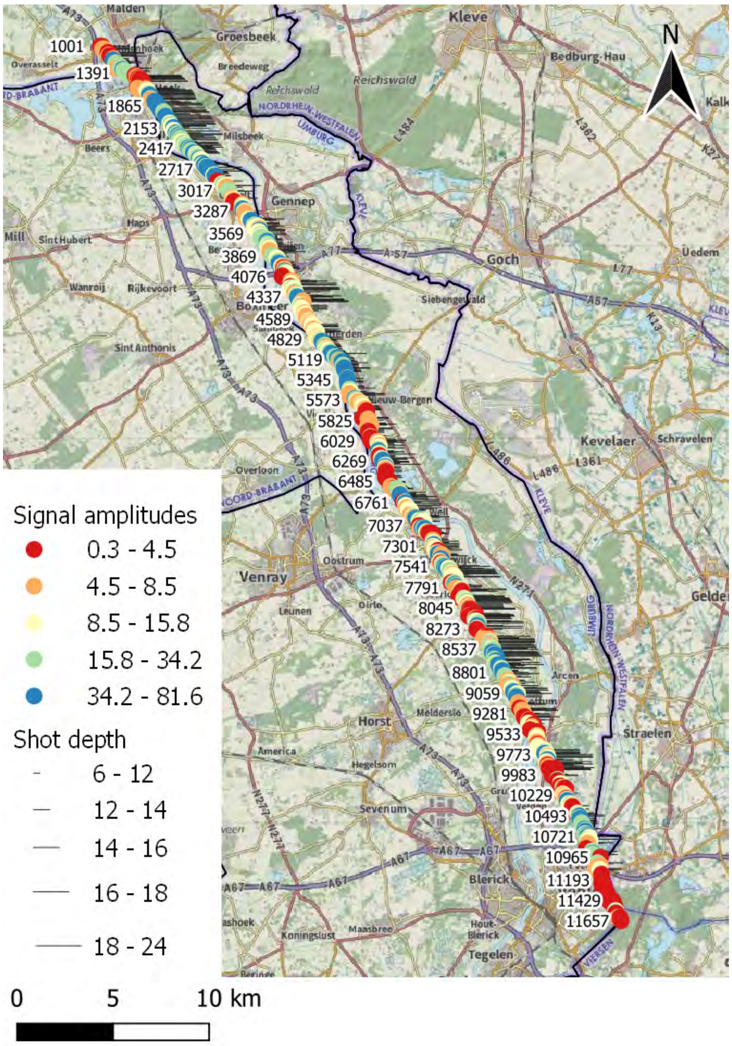


Figure 3.15: Map of the location of SCAN020. The coloured points and black lines respectively show signal amplitudes and shot depth for each station.

Shot domain:

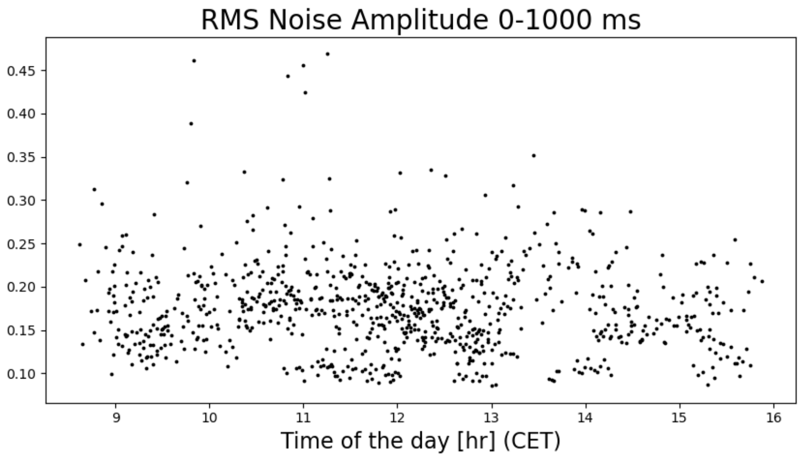


Figure 3.16: The influence of the time of the day of shooting on the noise amplitude. Acquisition was done between 8.30 am and 4 pm. For this line, the time of day does not influence the noise levels as the line does not cross any noisy main roads.

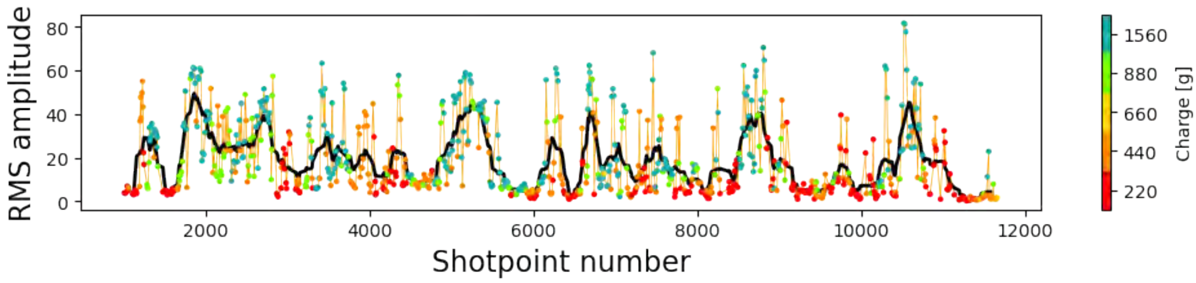


Figure 3.17: The signal amplitude per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the signal amplitude.

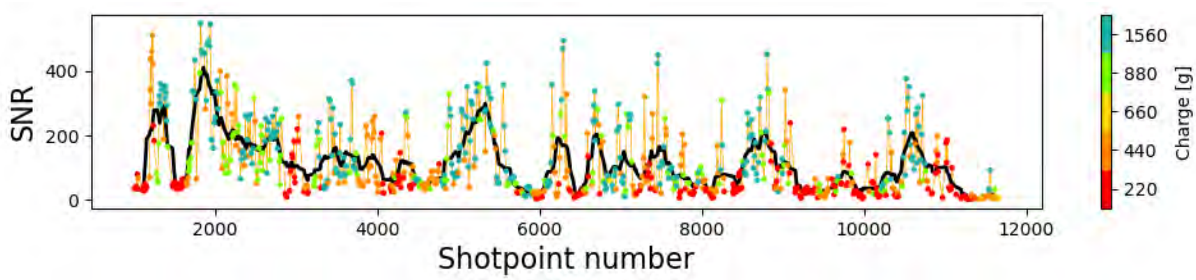


Figure 3.18: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

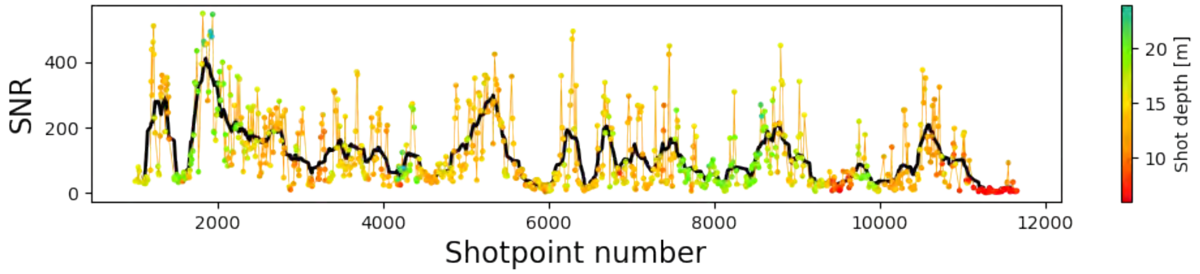


Figure 3.19: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the shot depth for each shot and the black line indicates the moving average of the SNR. Shot depths were between 4 m and 26 m.

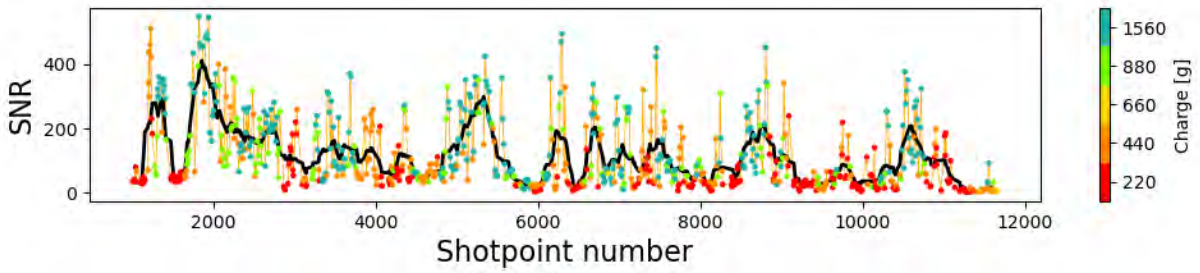


Figure 3.20: The signal-to-noise ratio per shotpoint number in the 1-2s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

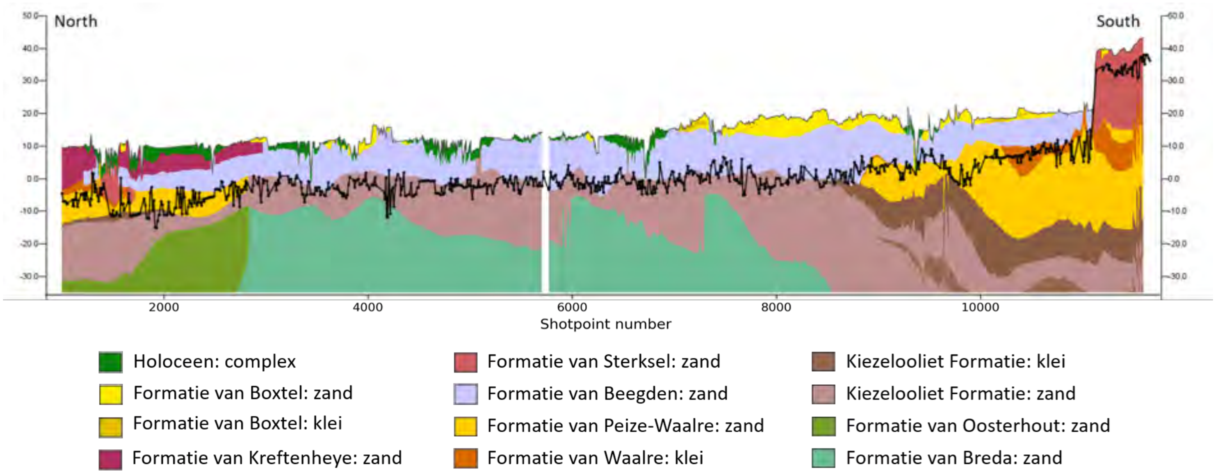


Figure 3.21: Geological profile of SCAN020 overlaid with the shot depth profile in black.

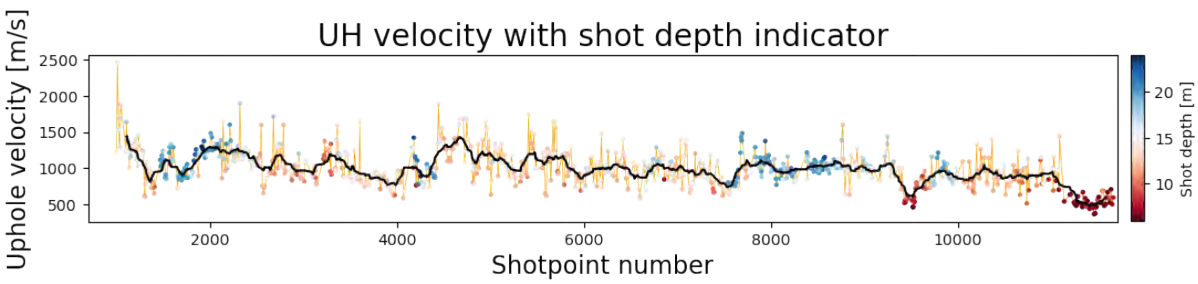


Figure 3.22: Uphole velocity. The colours indicate shot depth. The black line is the moving average of the velocity.

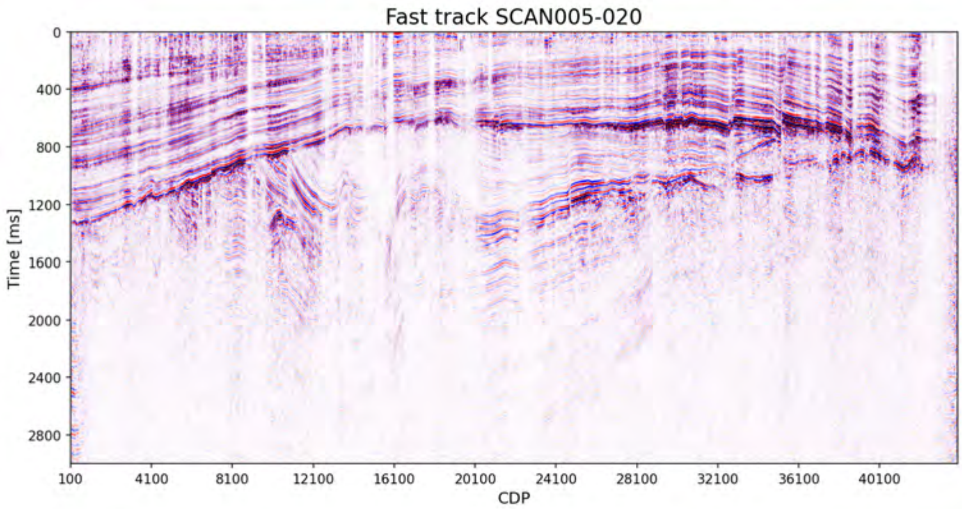


Figure 3.23: The fast track of line 20, combined with line 5.

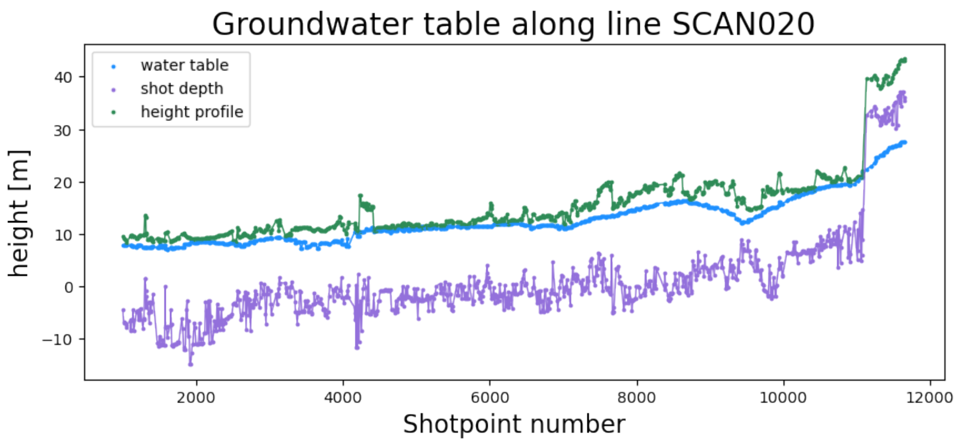


Figure 3.24: The groundwater level along SCAN020. Blue shows the groundwater table, purple the shot depth and green the surface profile.

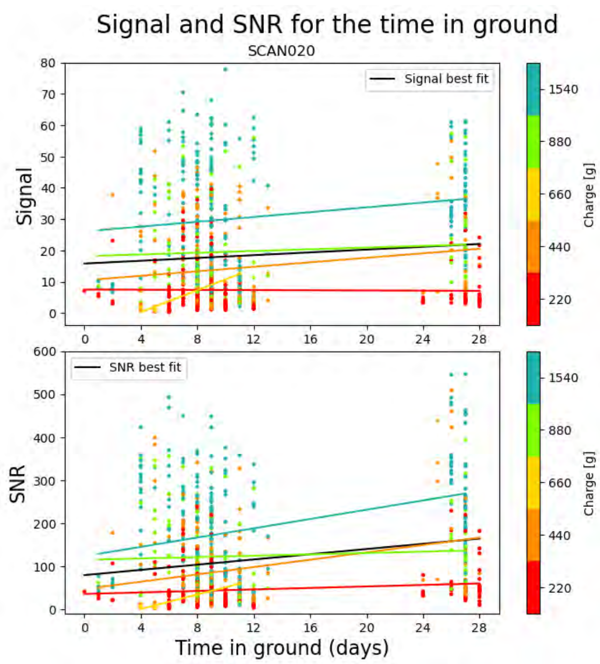


Figure 3.25: The time in days between drilling date and shot date. The colours indicate charge size. The lines are a best fit of all data (black) and per charge size (colours)

Receiver domain:

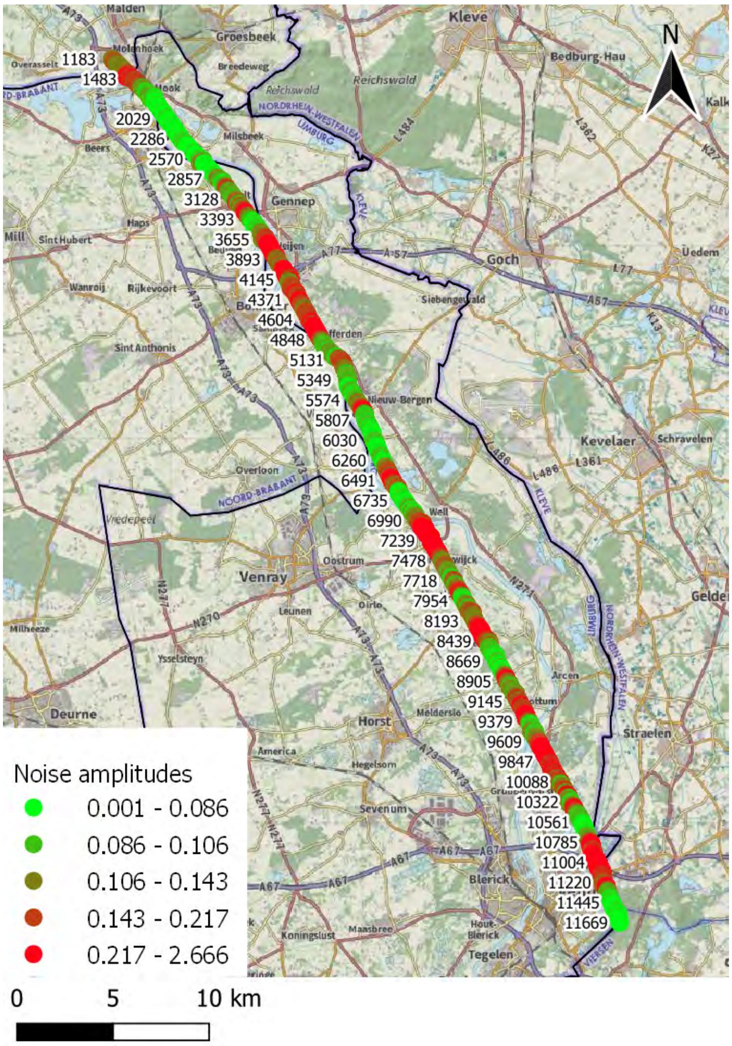


Figure 3.26: Map of the location of SCAN020. The coloured points show the noise amplitudes for each receiver. Every colour represents 20% of the noise amplitudes of this line. The brightest green are the 20% lowest noise amplitudes.

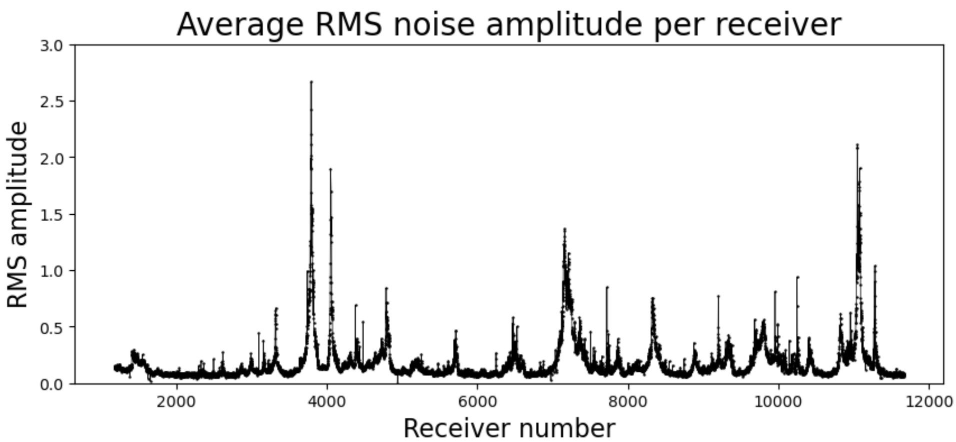


Figure 3.27: Noise amplitudes for each receiver number. The noise level is low overall, but higher noise levels are due to road crossings.

3.3 SCAN030

SCAN030 is 51.465 km long and runs from Eindhoven in the north west to Roermond and Germany in the south east. A summary of important acquisition parameters is shown in table 3.3. The line crosses the Maas around shotpoints 7000-7500 (figure 3.28). High signal amplitudes are visible between the Maas and the German border, while low signal amplitudes are mainly visible on the border and in Germany. High signal amplitudes are due to deeper shotdepths and consequently the use of higher charge size (figures 3.30, 3.31 and 3.32). The shots in Germany are all fairly shallow shots due to the fact that the geology was too hard to drill deeper (figure 3.32). The low signal amplitude shots are possibly shot above the watertable (figure 3.37). Even though no groundwater data is available of the part of the line in Germany, when extrapolating the groundwater data all shots seem to fall above the watertable. The effect of low signal amplitudes due to groundwater is visible in figure 3.36 at the end of the line. Here the quality of the data seems poorer. Overall noise levels were lower than average (0.174) compared to other lines (average of 0.244) and noise on the line was mainly due to crossing of highways (A73) or smaller roads (e.g. N280) and villages. The end of the line saw some regions with high noise (amplitudes > 3) without an obvious noise source (figure 3.40). The receivers only reported high noise values on the days it was freezing. Thus, the noise is possibly due to weather conditions (freezing over several days) affecting the receivers and reporting erroneous noise values.

Total acquisition length	51.465 km
Source station range	1005.5 - 11279.5
Total sources	813
Receiver station range	1001 - 11293
Total receivers	10312

Table 3.3: Acquisition parameters SCAN030

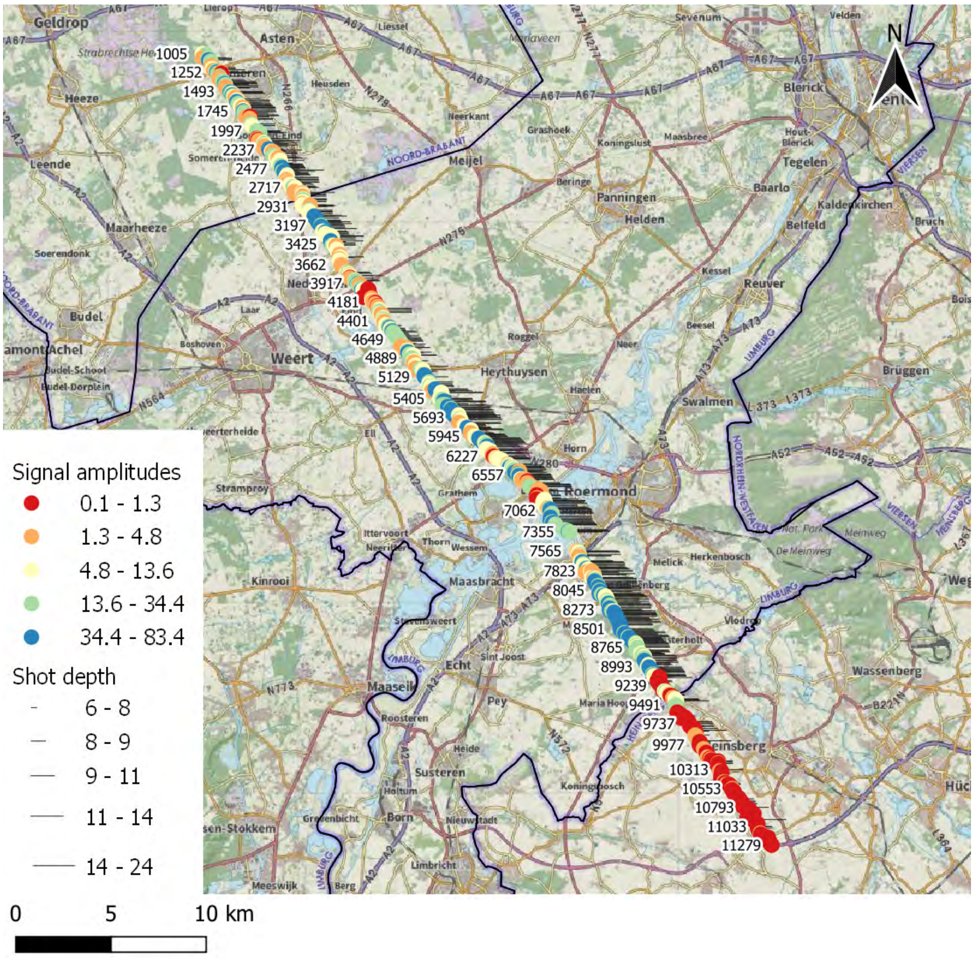


Figure 3.28: Map of the location of SCAN030. The coloured points and black lines respectively show signal amplitudes and shot depth for each station.

Shot domain:

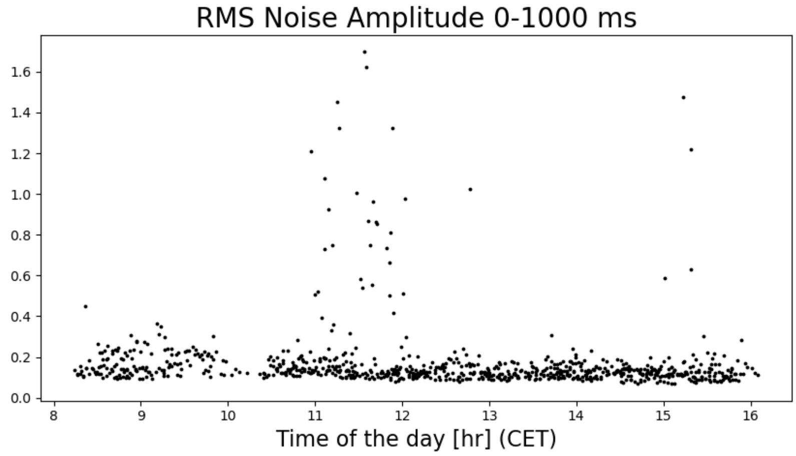


Figure 3.29: The influence of the time of the day of shooting on the noise amplitude. Acquisition was done between 8 am and 4 pm. For this line, the time of day does not influence the noise levels as the line does not cross any noisy main roads. Higher noise amplitudes (>0.3) are possibly due to weather conditions at the end of the line.

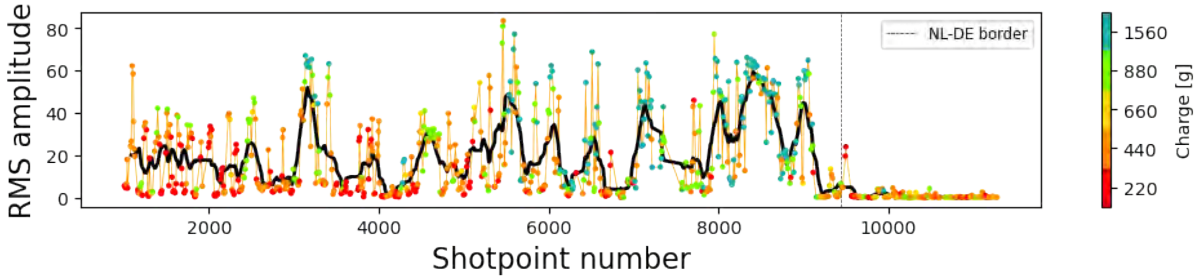


Figure 3.30: The signal amplitude per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the signal amplitude.

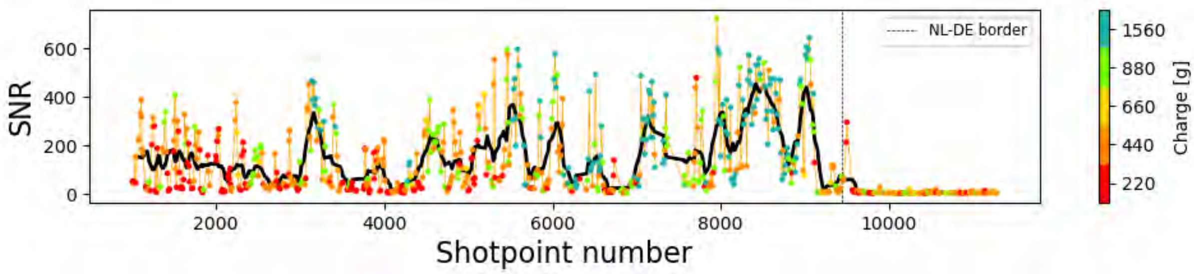


Figure 3.31: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

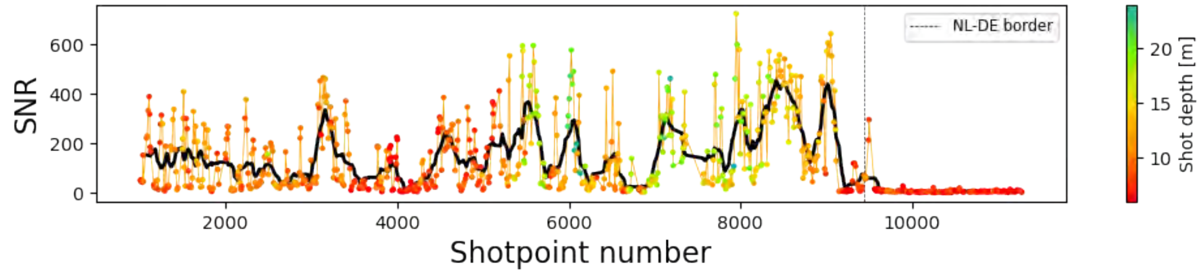


Figure 3.32: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the shot depth for each shot and the black line indicates the moving average of the SNR. Shot depths were between 4 m and 26 m.

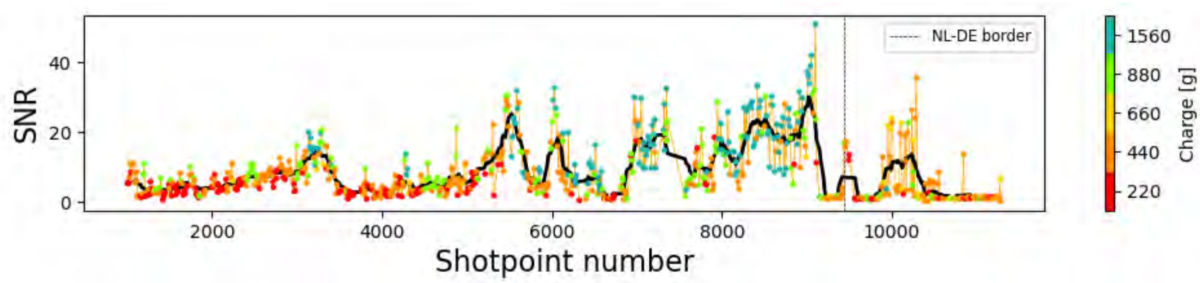


Figure 3.33: The signal-to-noise ratio per shotpoint number in the 1-2s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

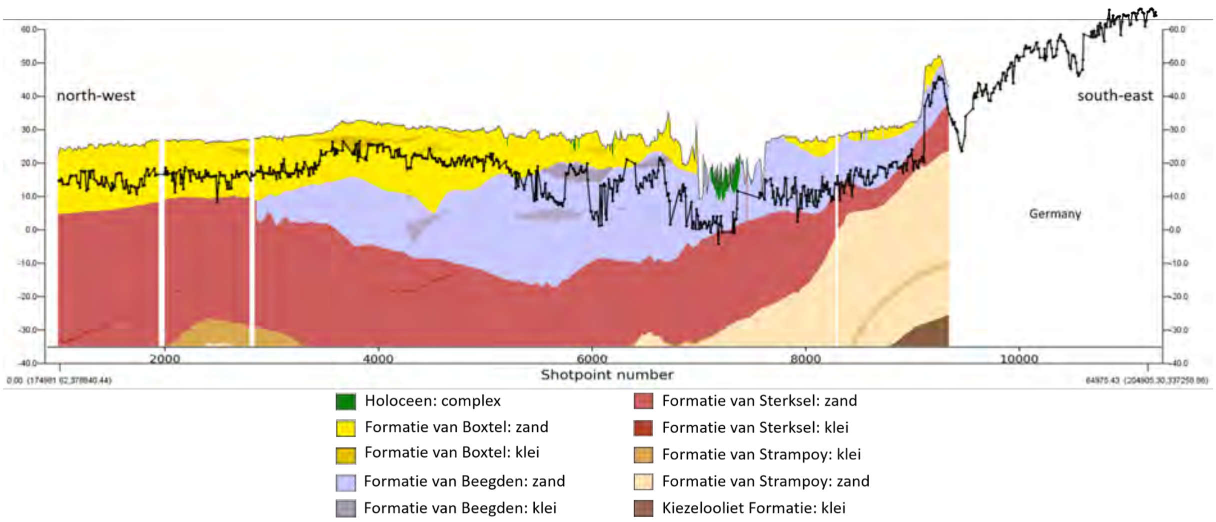


Figure 3.34: Geological profile of SCAN030 overlaid with the shot depth profile in black.

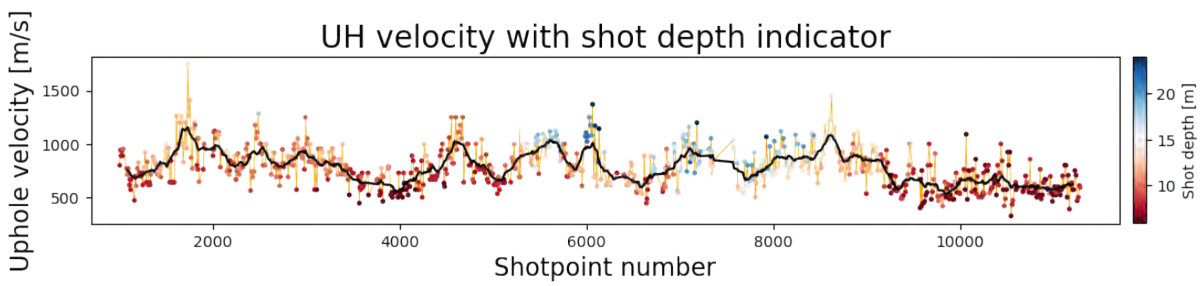


Figure 3.35: Uphole velocity. The colours indicate shot depth. The black line is the moving average of the velocity.

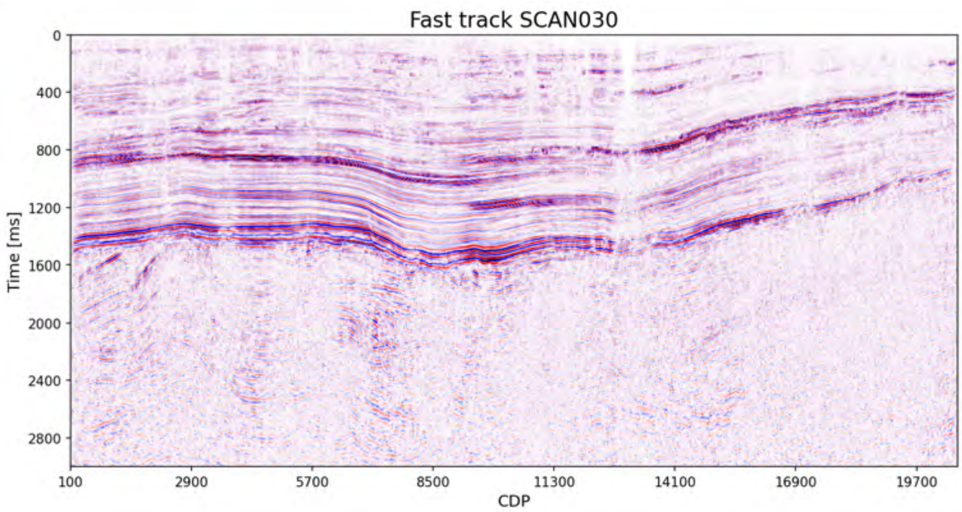


Figure 3.36: The fast track of line 30.

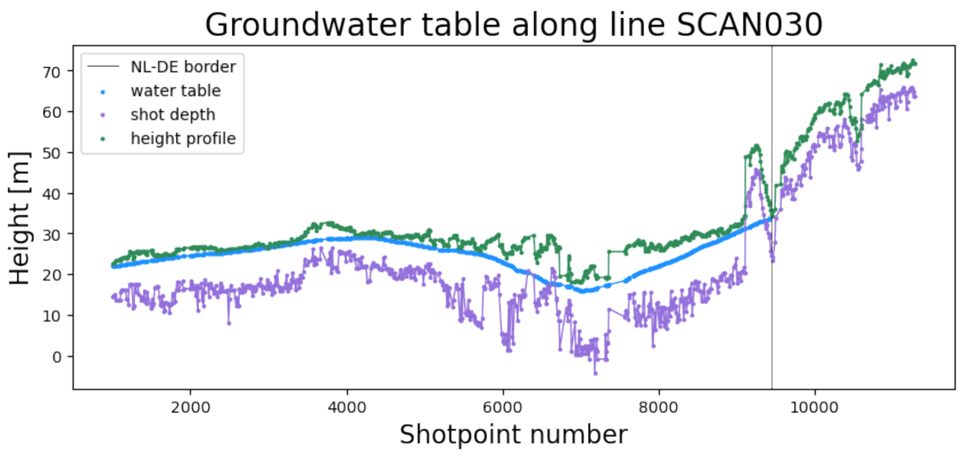


Figure 3.37: The groundwater level along SCAN030. Blue shows the groundwater table, purple the shot depth and green the surface profile.

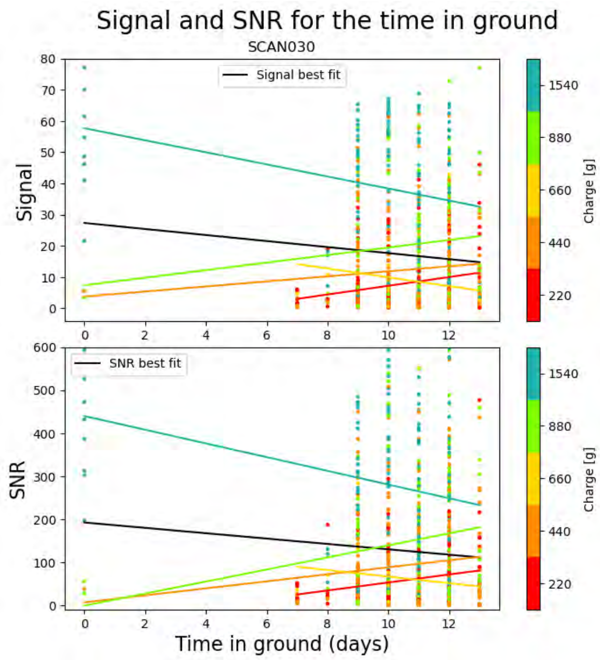


Figure 3.38: The time in days between drilling date and shot date. The colours indicate charge size. The lines are a best fit of all data (black) and per charge size (colours). No correlation is clearly visible due to a lot of scatter.

Receiver domain:

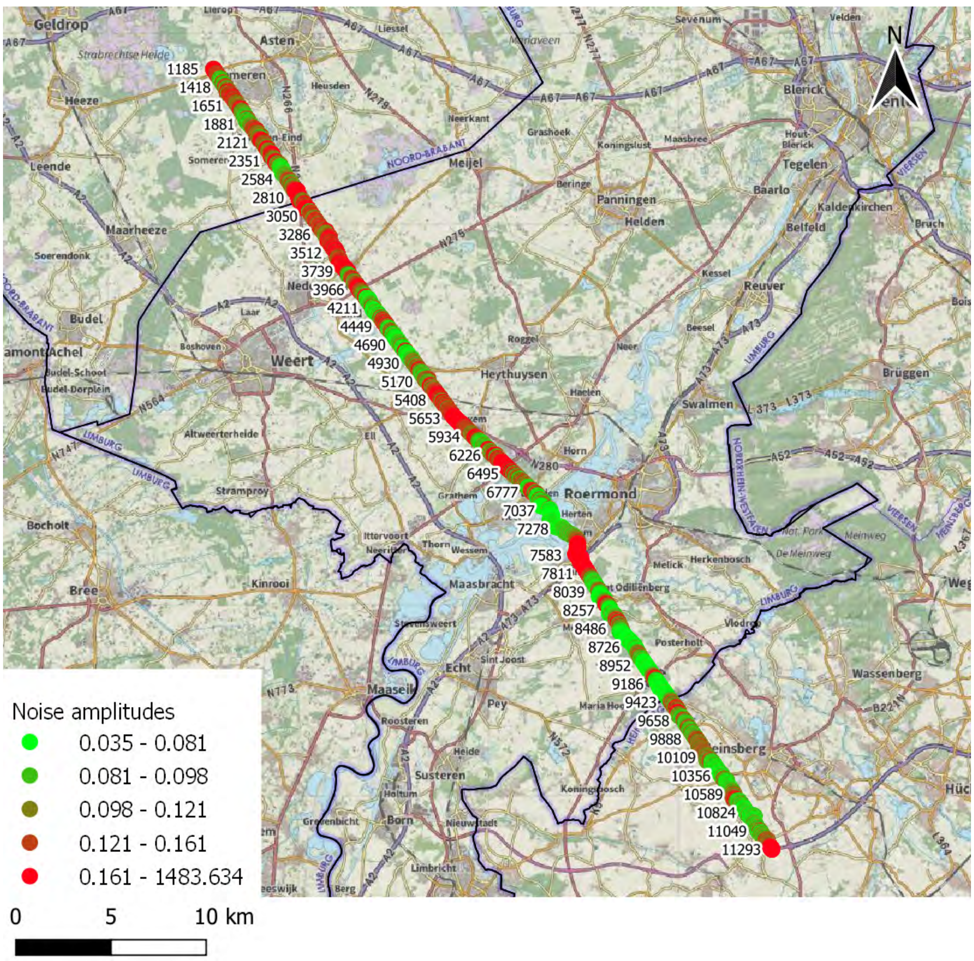


Figure 3.39: Map of the location of SCAN030. The coloured points show the noise amplitudes for each receiver. Every colour represents 20% of the noise amplitudes of this line. The brightest green are the 20% lowest noise amplitudes.

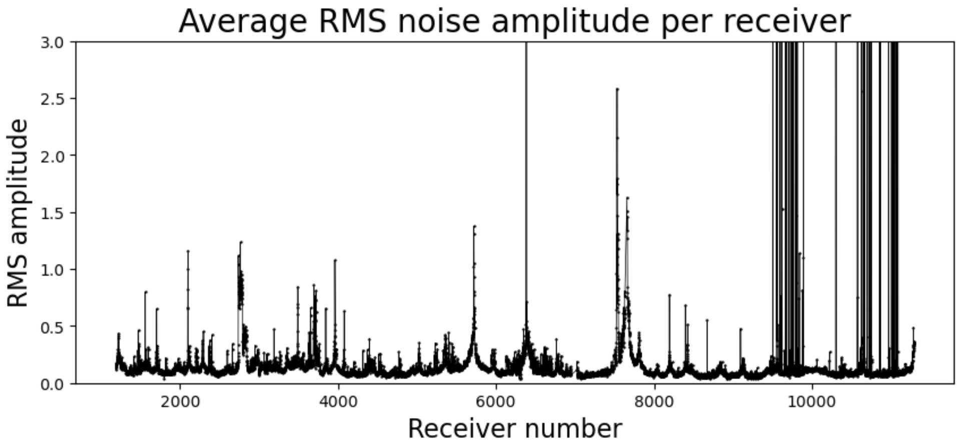


Figure 3.40: Noise amplitudes for each receiver number. The noise level is low up to receiver number 9500, except higher noise levels due to road crossings. After receiver 9500 very high noise amplitudes without an obvious noise source are visible, but are probably due to weather conditions.

3.4 SCAN031

SCAN031 is 82.240 km long and runs from the Belgian border near Heerlen in the south to Horst, near Venlo, in the north. A summary of important acquisition parameters is shown in table 3.4. The line crosses through Germany between shotpoints 6700 and 7900. It crosses the Maas around shotpoint 13000 (figure 3.41). High signal amplitudes are visible in the northern part of the line, while low signal amplitudes are visible from the start of the line in the south until shotpoint 9100 (figures 3.43, 3.44, 3.45 and 3.46). The low amplitude shots are in an area with high elevation and a different geology (e.g. shots in limestone) than other lines (figure 3.47) and are mostly shot above the groundwater table (figure 3.50). The effect of the shots above the groundwater table is clearly visible in the fast track (figure 3.49) where the start of the line until about CDP 11000 is of poor quality. The time between drilling date and shot date seems to have a positive effect on the signal and SNR for line 031 (figure 3.51). Noise is mainly due to main roads (e.g. A76 near Heerlen, around shotpoint 5000, or A67/A73 near Venlo, between shotpoints 15500 - 17200) or crossing of smaller roads (e.g. N570 near Roermond, around shotpoint 11000) (figures 3.52 and 3.53).

Total acquisition length	84.240 km
Source station range	1377.5 - 17831.5
Total sources	1299
Receiver station range	1001 - 17848
Total receivers	19581

Table 3.4: Acquisition parameters SCAN031

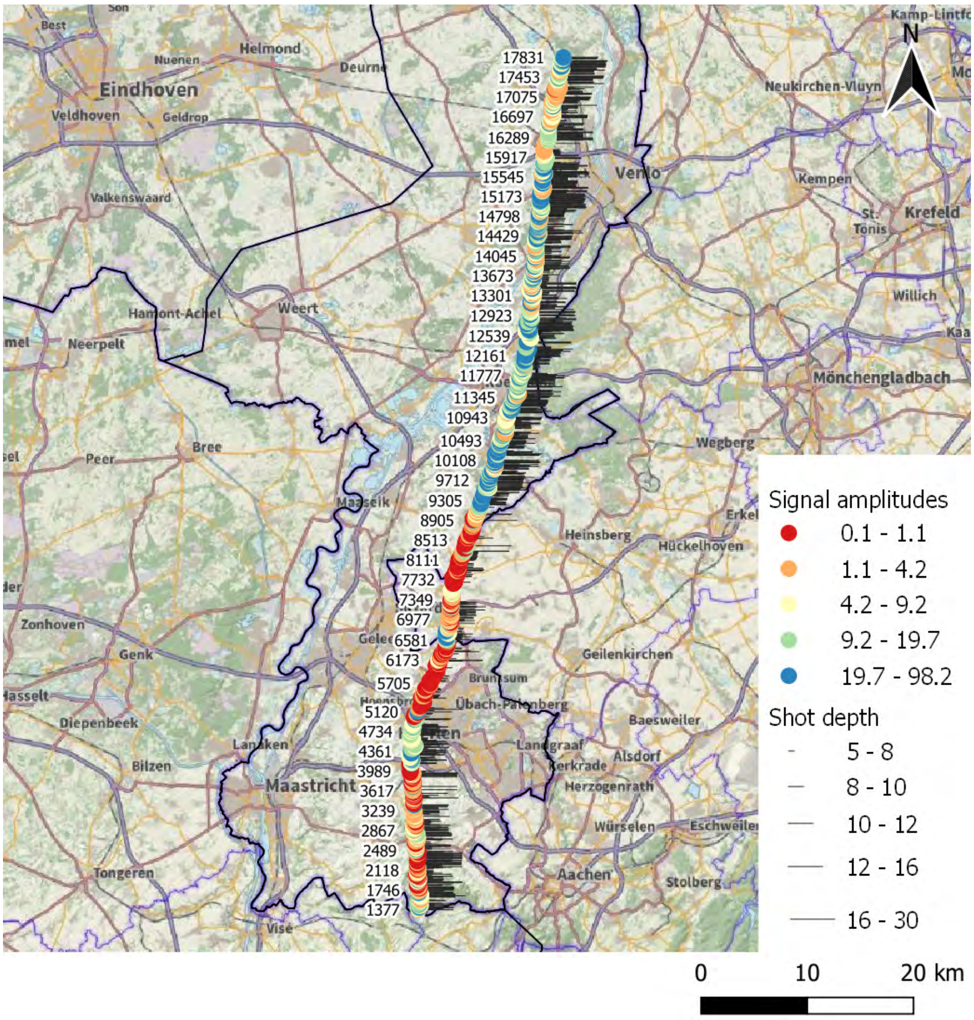


Figure 3.41: Map of the location of SCAN031. The coloured points and black lines respectively show signal amplitudes and shot depth for each station.

Shot domain:

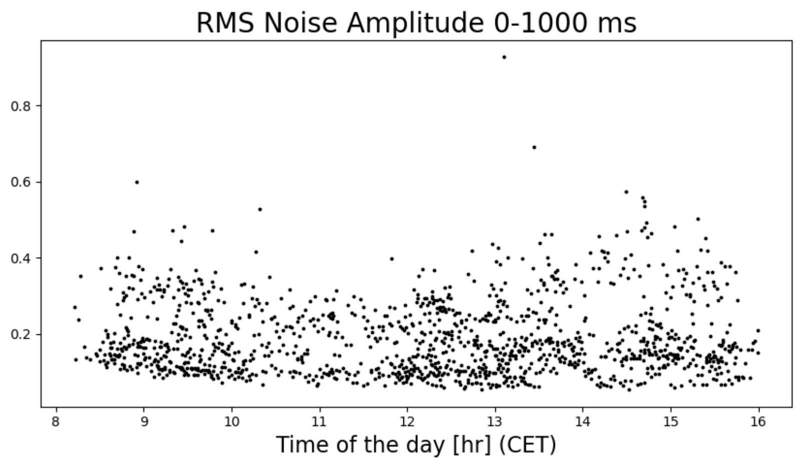


Figure 3.42: The influence of the time of the day of shooting on the noise amplitude. Acquisition was done between 8 am and 4 pm. For this line, the time of day does not influence the noise levels as the line does not cross any noisy main roads.

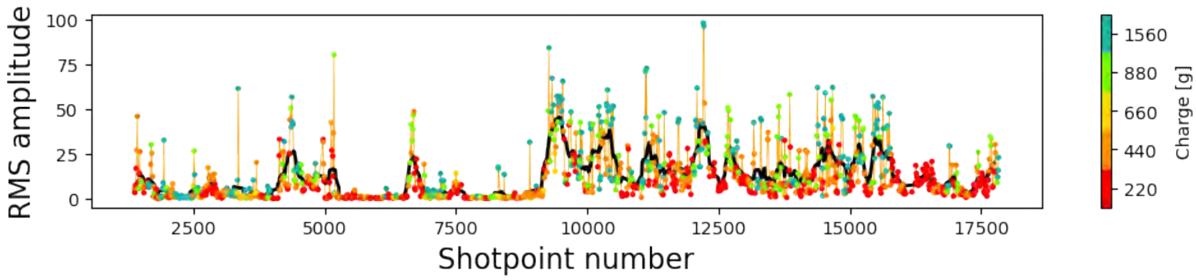


Figure 3.43: The signal amplitude per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the signal amplitude.

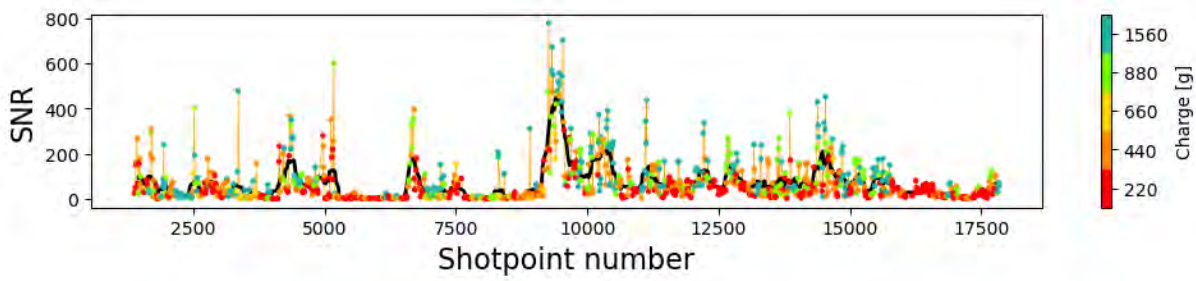


Figure 3.44: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

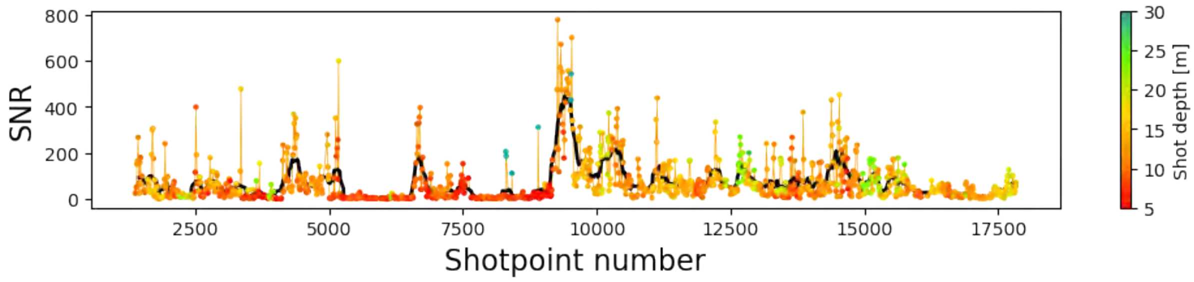


Figure 3.45: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the shot depth for each shot and the black line indicates the moving average of the SNR. Shot depths were between 4 m and 26 m.

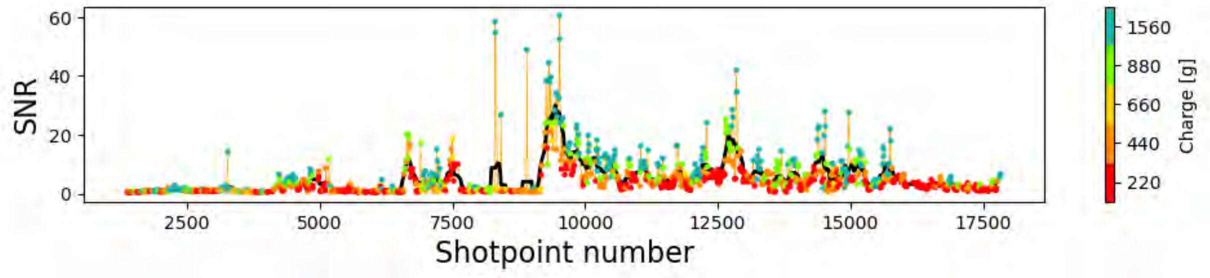


Figure 3.46: The signal-to-noise ratio per shotpoint number in the 1-2s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

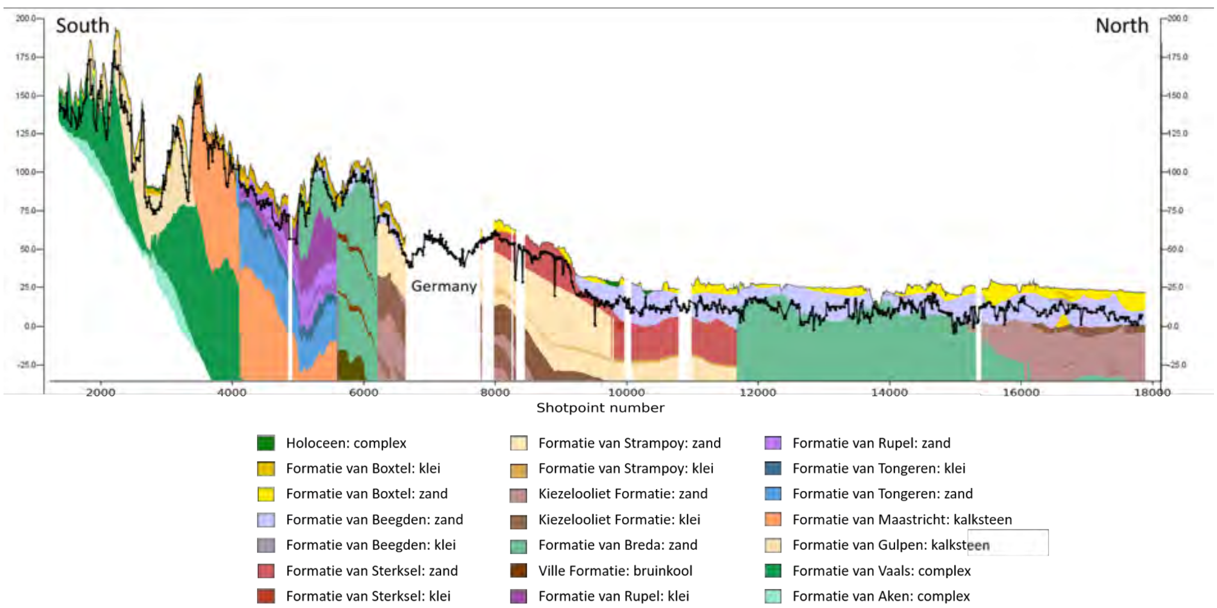


Figure 3.47: Geological profile of SCAN031 overlaid with the shot depth profile in black.

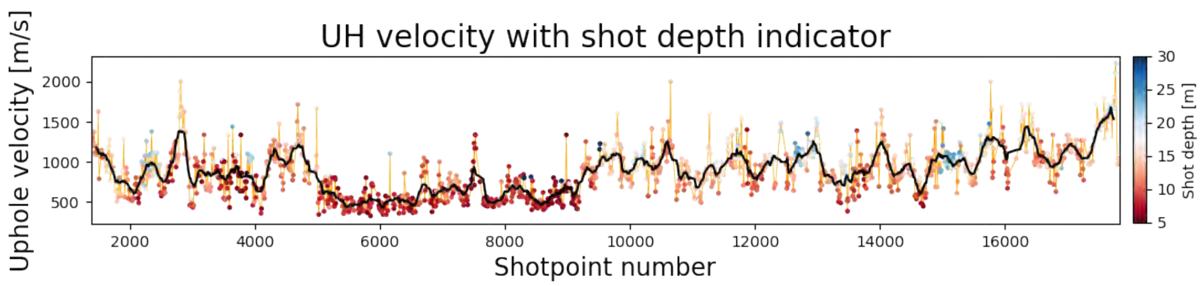


Figure 3.48: Uphole velocity. The colours indicate shot depth. The black line is the moving average of the velocity.

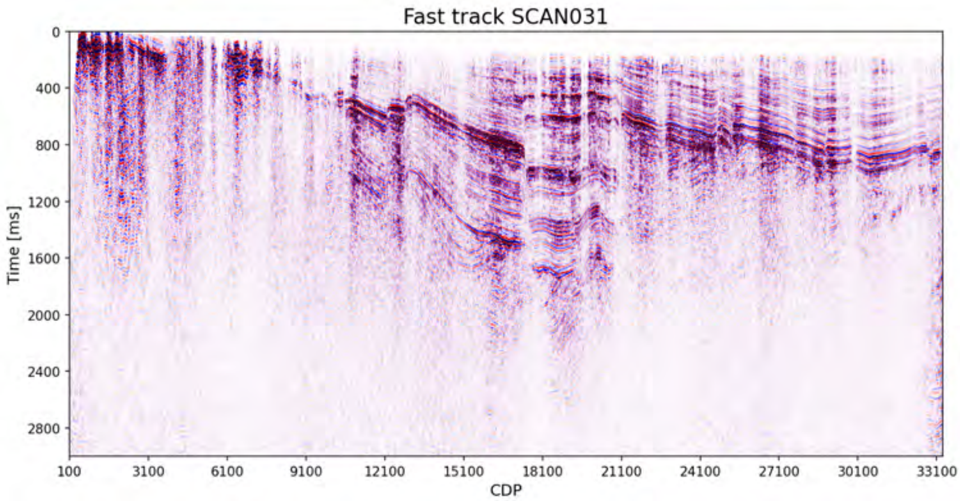


Figure 3.49: The fast track of line 31.

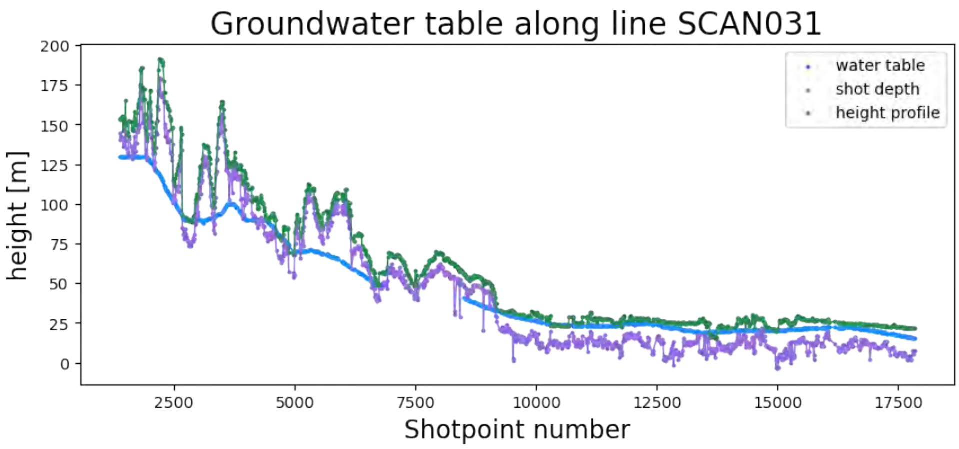


Figure 3.50: The groundwater level along SCAN031. Blue shows the groundwater table, purple the shot depth and green the surface profile.

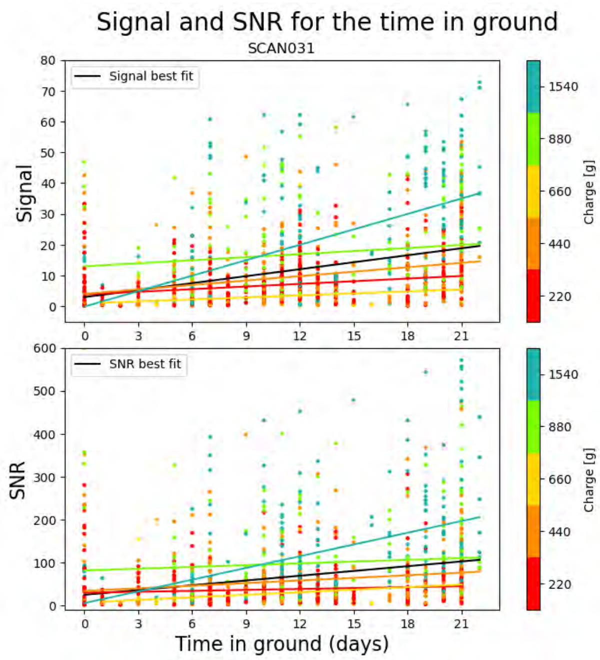


Figure 3.51: The time in days between drilling date and shot date. The colours indicate charge size. The lines are a best fit of all data (black) and per charge size (colours). No clear correlation is visible between the time in ground and signal amplitude and SNR.

Receiver domain:

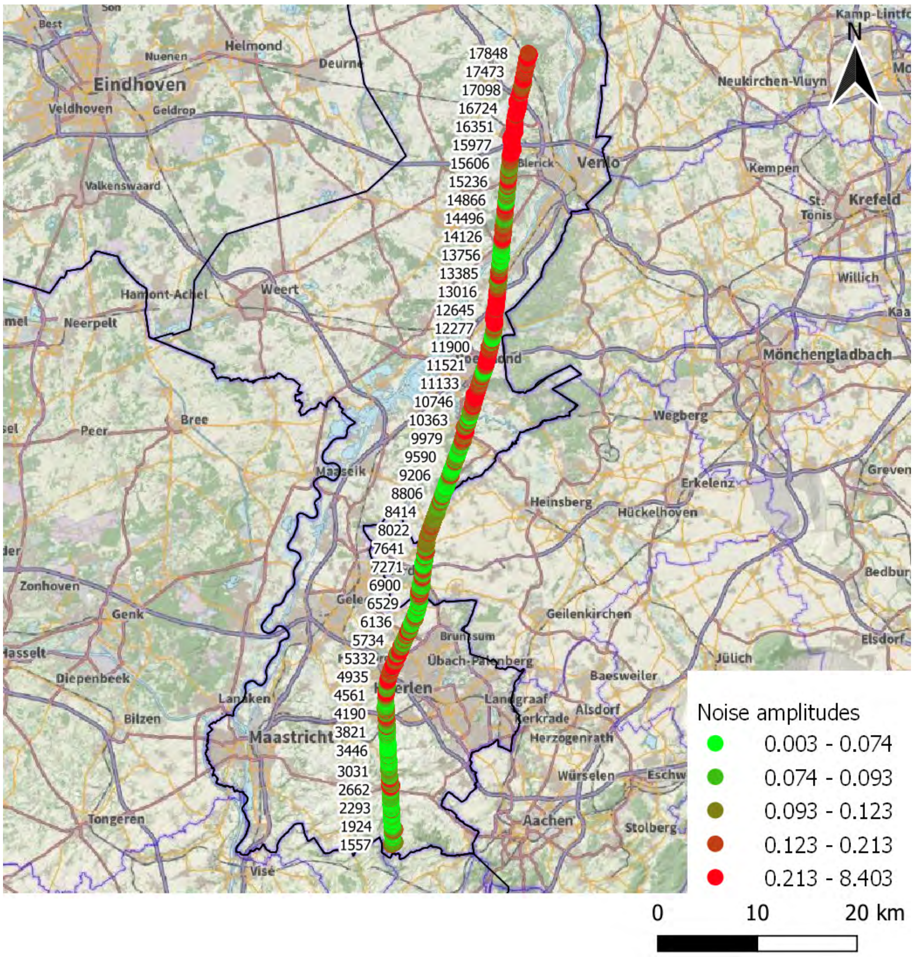


Figure 3.52: Map of the location of SCAN031. The coloured points show the noise amplitudes for each receiver. Every colour represents 20% of the noise amplitudes of this line. The brightest green are the 20% lowest noise amplitudes.

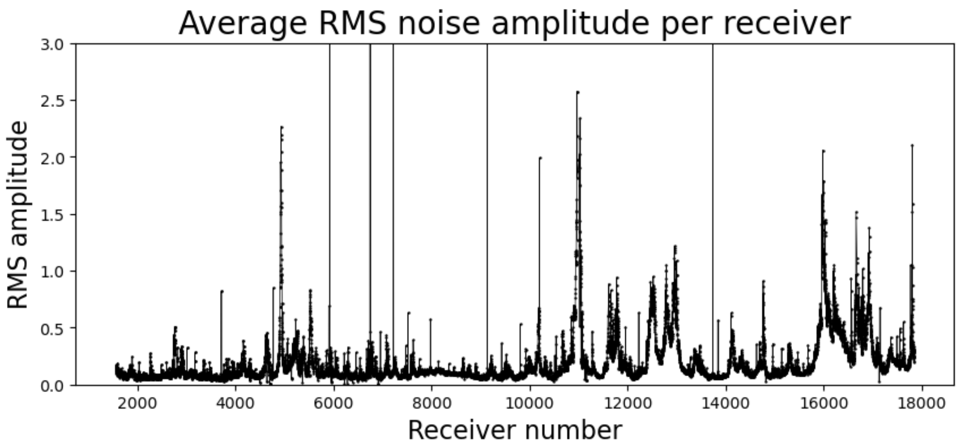


Figure 3.53: Noise amplitudes for each receiver number. The noise level is low overall, but higher noise levels are due to road crossings.

3.5 SCAN032

Total acquisition length	35.100 km
Source station range	1007.5 - 7985.5
Total sources	549
Receiver station range	1001 - 8020
Total receivers	7040

Table 3.5: Acquisition parameters SCAN032

SCAN032 is 35.1 km long and runs from Wernhoutsburg (Belgian border) in the south to Geertruidenberg in the north. A summary of important acquisition parameters is shows in table 3.5. Line 032 has an overall high signal amplitude, with an average amplitude of 21.8. Especially in the southern part of the line, approximately shotpoints 1001-2500, signal amplitude is high and correlates with the used high charge size (figures 3.54 and 3.56). Around shotpoints 4500-5500, near Breda, main roads A58 and A16 are crossed, which results in a low SNR (figures 3.57, 3.58 and 3.59) and high noise levels (figures 3.65 and 3.66). Around shotpoint 7000 the A59 is crossed resulting in another high noise peak (figure 3.66). All shots are shot below the groundwatertable (3.62.

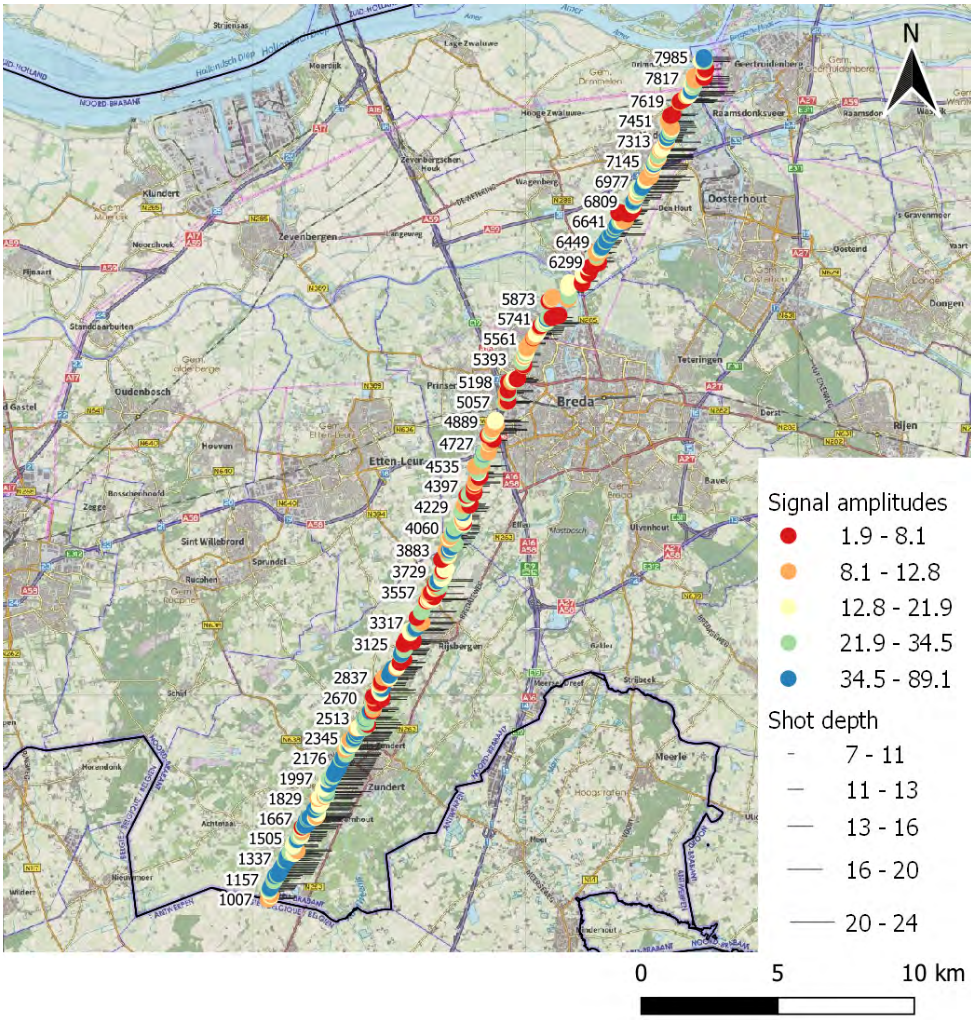


Figure 3.54: Map of the location of SCAN032. The coloured points and black lines respectively show signal amplitudes and shot depth for each station.

Shot domain:

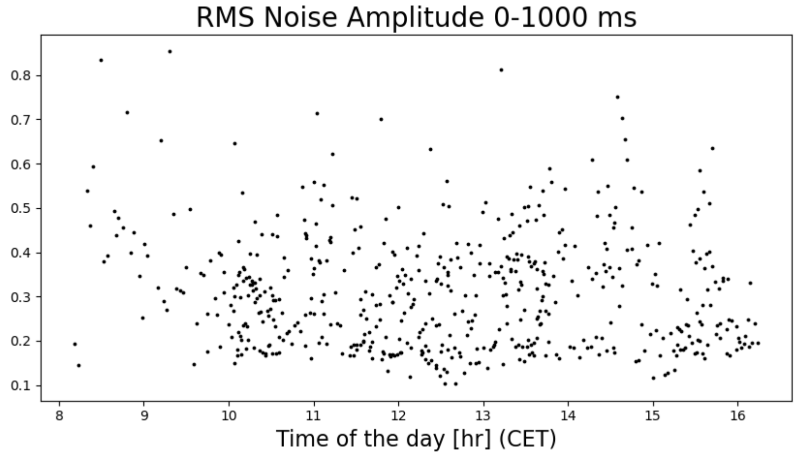


Figure 3.55: The influence of the time of the day of shooting on the noise amplitude. Acquisition was done between 8 am and 4.30 pm.

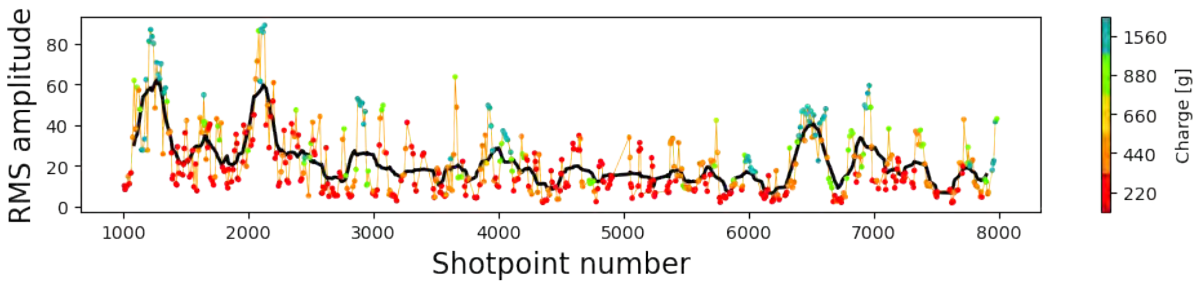


Figure 3.56: The signal amplitude per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the signal amplitude.

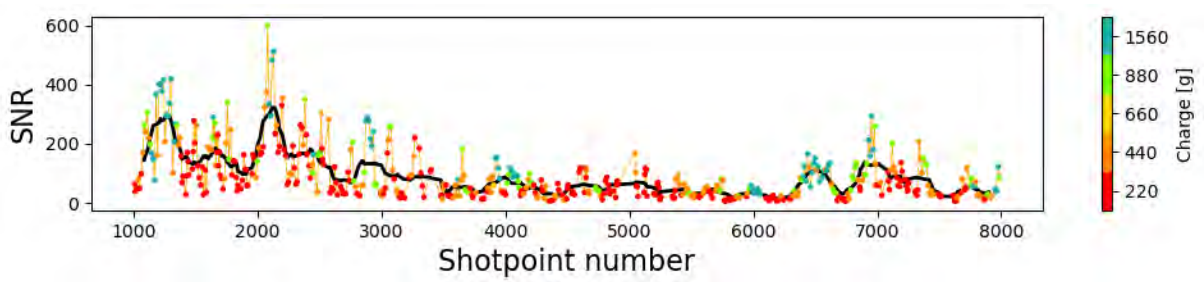


Figure 3.57: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

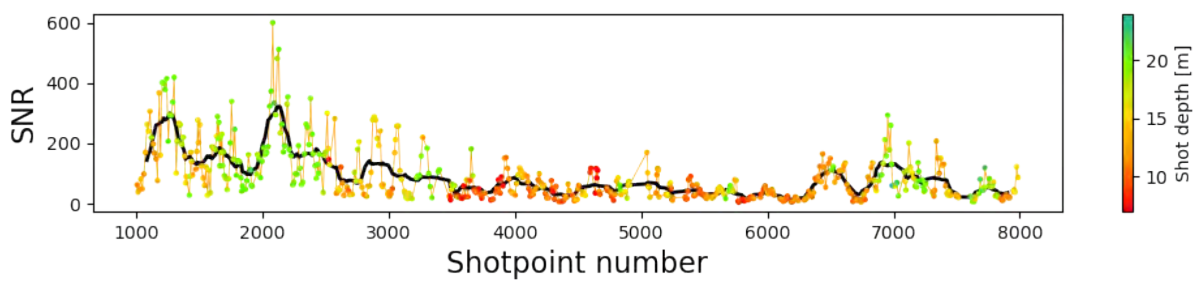


Figure 3.58: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the shot depth for each shot and the black line indicates the moving average of the SNR. Shot depths were between 4 m and 26 m.

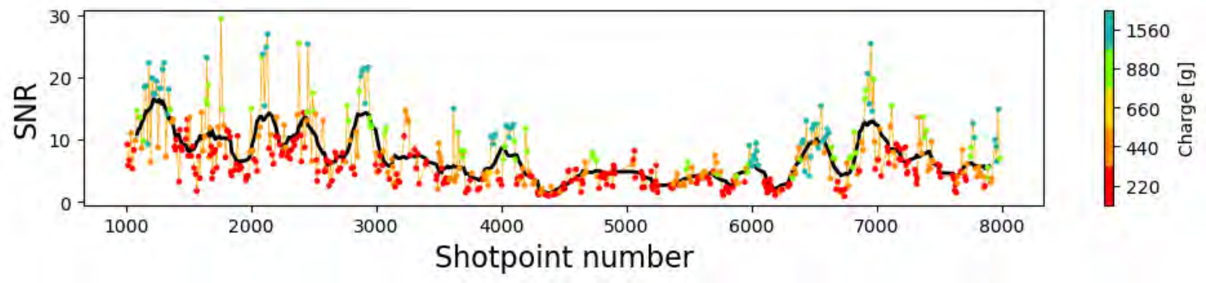


Figure 3.59: The signal-to-noise ratio per shotpoint number in the 1-2s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

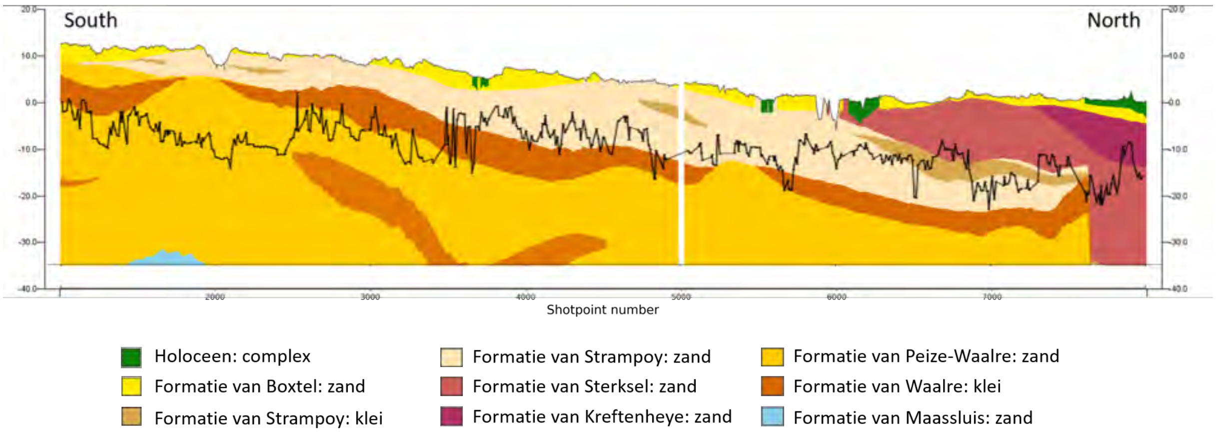


Figure 3.60: Geological profile of SCAN032 overlaid with the shot depth profile in black.

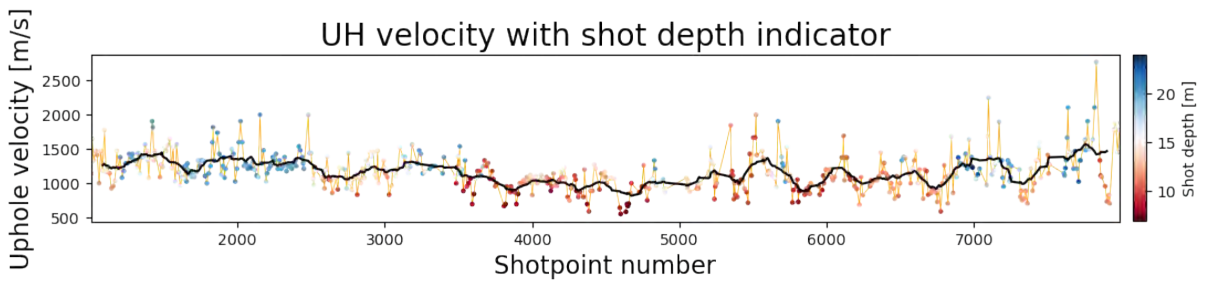


Figure 3.61: Uphole velocity. The colours indicate shot depth. The black line is the moving average of the velocity.

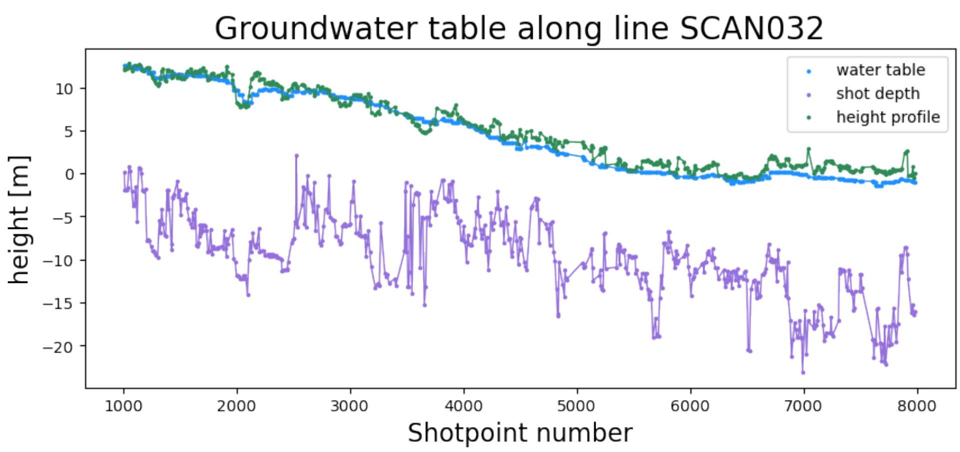


Figure 3.62: The groundwater level along SCAN032. Blue shows the groundwater table, purple the shot depth and green the surface profile.

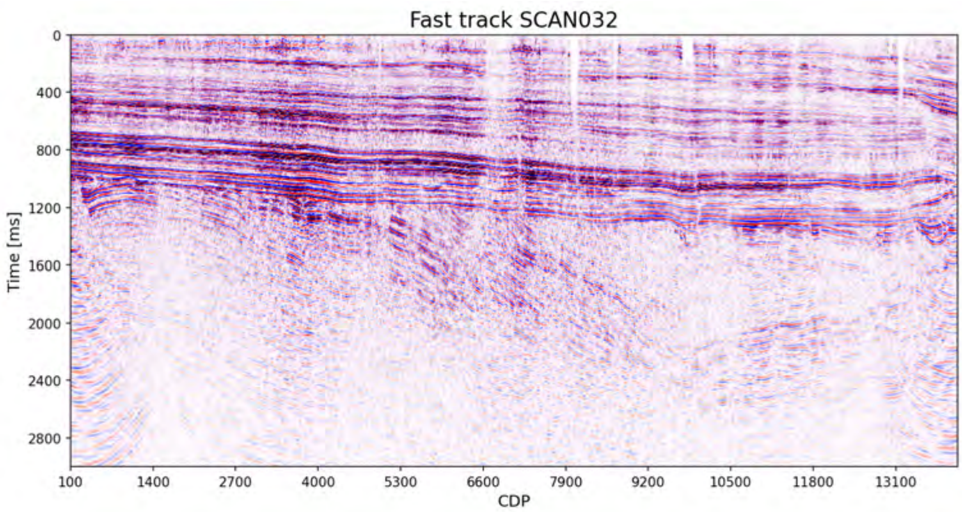


Figure 3.63: The fast track of line 32.

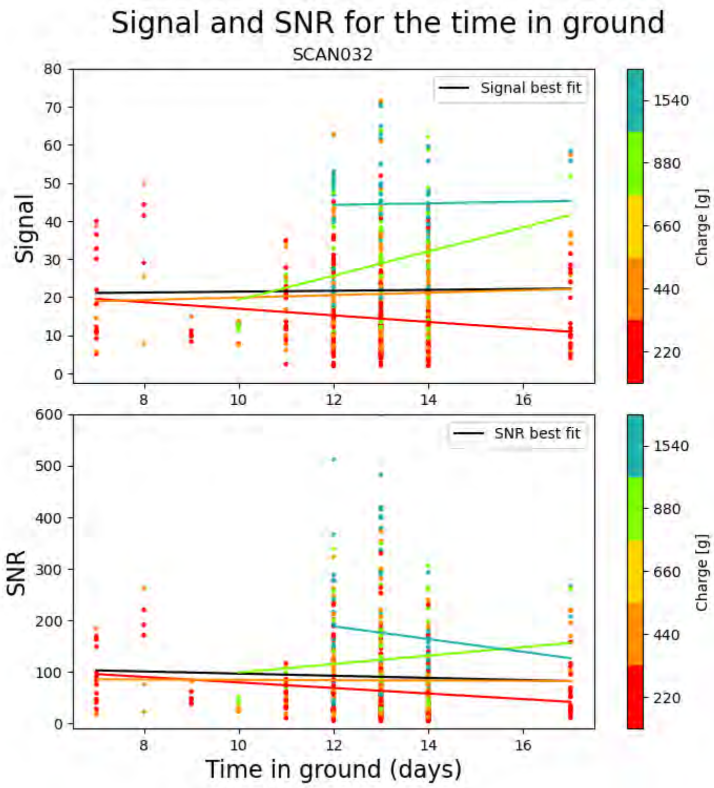


Figure 3.64: The time in days between drilling date and shot date. The colours indicate charge size. The lines are a best fit of all data (black) and per charge size (colours)

Receiver domain:

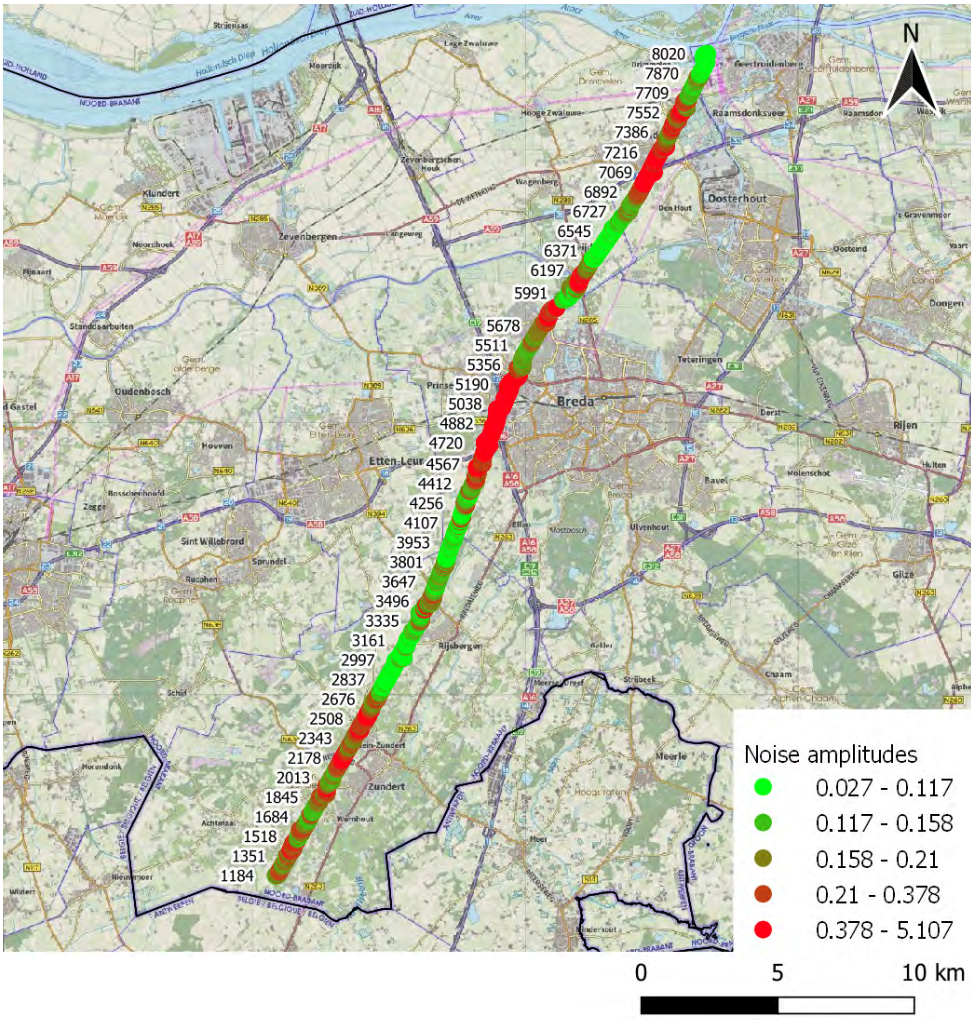


Figure 3.65: Map of the location of SCAN032. The coloured points show the noise amplitudes for each receiver. Every colour represents 20% of the noise amplitudes of this line. The brightest green are the 20% lowest noise amplitudes.

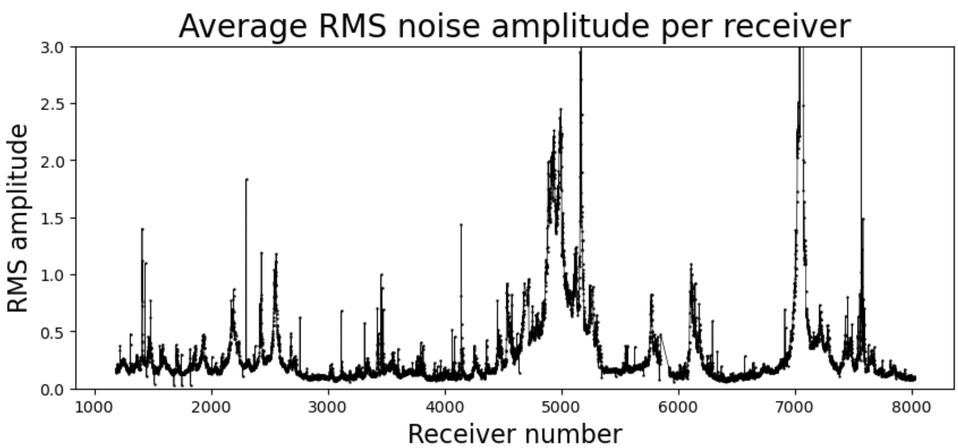


Figure 3.66: Noise amplitudes for each receiver number. The noise level is low overall, but higher noise levels are due to road crossings; e.g. around receiver number 5000 the line crosses the A16 and A58.

3.6 SCAN033

SCAN033 is 22.265 km long and runs from Lage Zwaluwe in the north west to Dongen in the south east. A summary of important acquisition parameters is shows in table 3.6. Line 033 has an overall signal amplitude of 19.8, which is higher than average. High signal amplitudes generally correlate with high charge size (figure 3.69). The signal-to-noise ratio (60.9), however, is lower than average (82.6). This is also visible in figures 3.70 and 3.71. Besides the first 500 shotpoints, SNR is low, indicating higher noise levels. The noise is mainly due to road crossings (A59, A27) and the presence of an industrial area around shotpoints 2800 - 3300 (figures 3.78 and 3.79). All shots are shot below the groundwatertable (3.76).

Total acquisition length	22.265 km
Source station range	1001.5 - 5442.5
Total sources	365
Receiver station range	1001 - 5453
Total receivers	4454

Table 3.6: Acquisition parameters SCAN033

Figure 3.67: Map of the location of SCAN033. The coloured points and black lines respectively show signal amplitudes and shot depth for each station.

Shot domain:

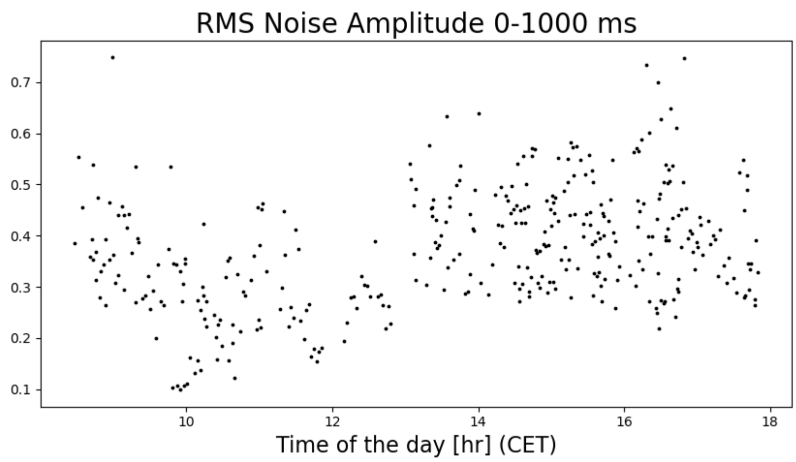


Figure 3.68: The influence of the time of the day of shooting on the noise amplitude. Acquisition was done between 9 am and 6 pm.

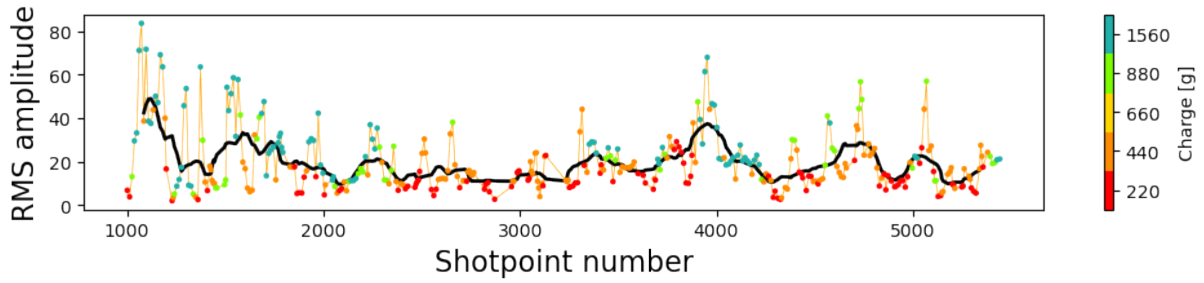


Figure 3.69: The signal amplitude per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the signal amplitude.

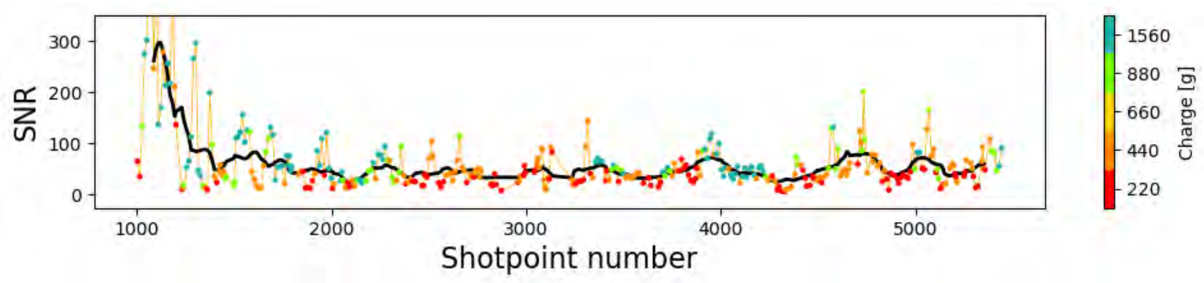


Figure 3.70: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

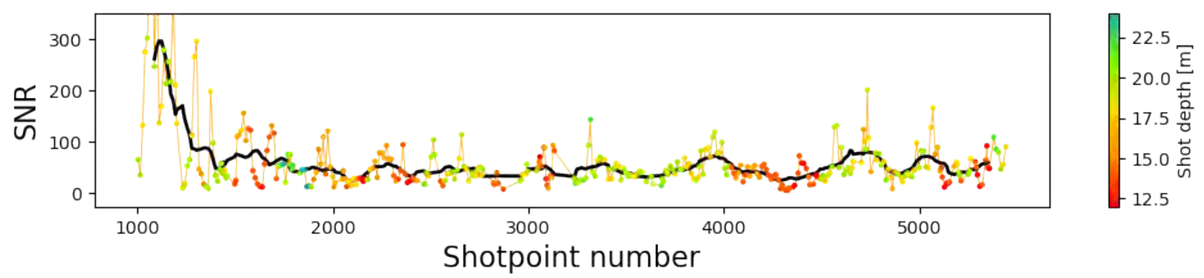


Figure 3.71: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the shot depth for each shot and the black line indicates the moving average of the SNR. Shot depths were between 12 m and 24 m.

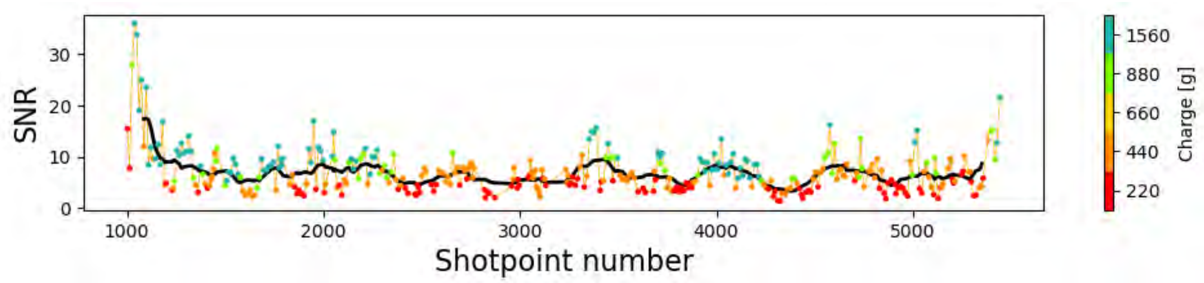


Figure 3.72: The signal-to-noise ratio per shotpoint number in the 1-2s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

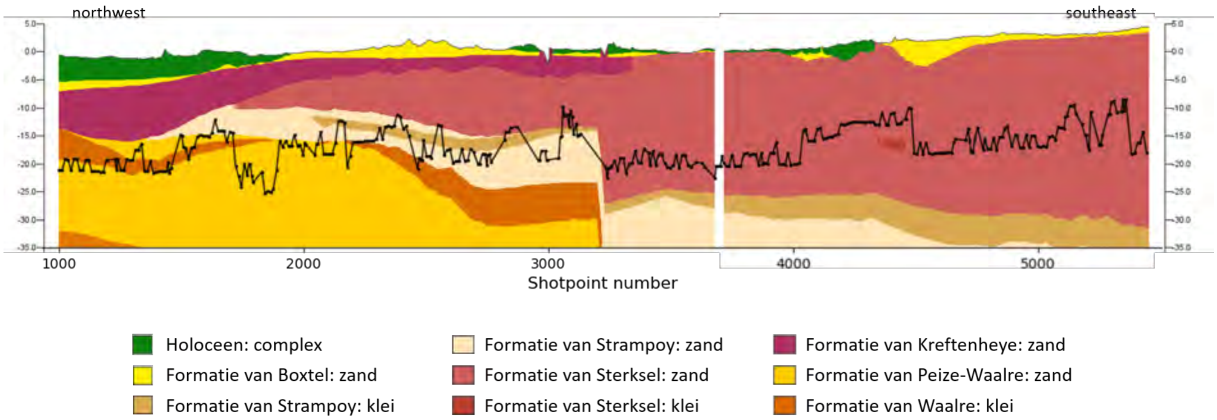


Figure 3.73: Geological profile of SCAN033 overlaid with the shot depth profile in black.

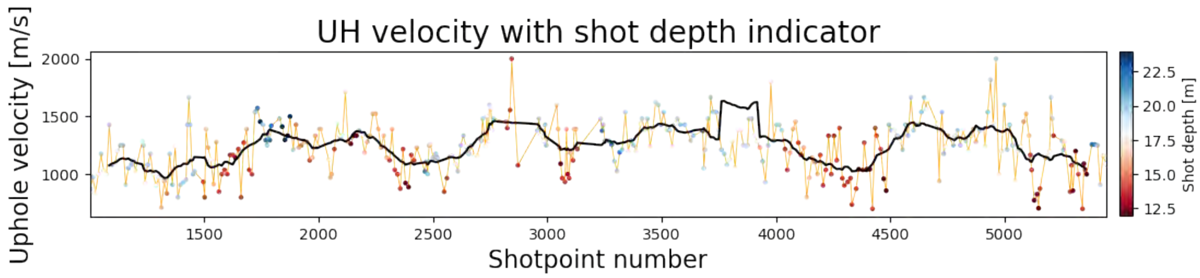


Figure 3.74: Uphole velocity. The colours indicate shot depth. The black line is the moving average of the velocity.

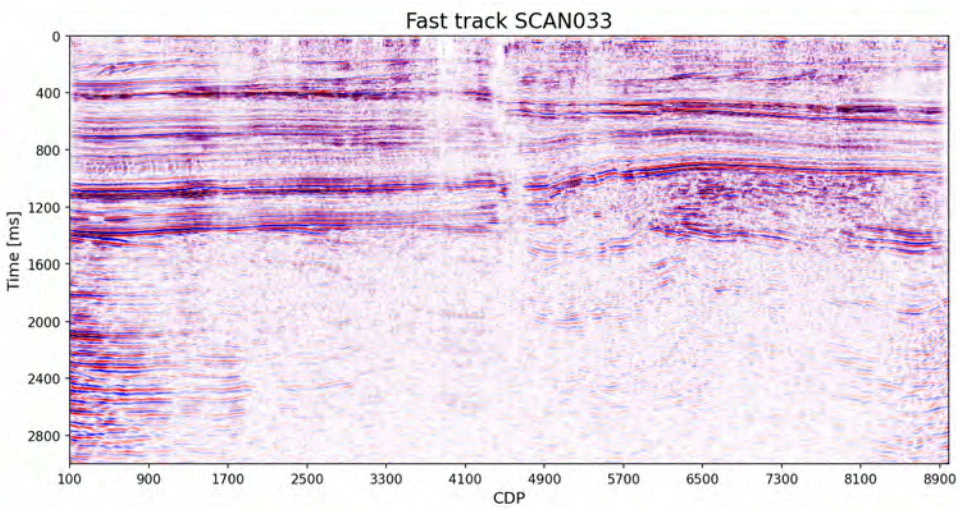


Figure 3.75: The fast track of line 33.

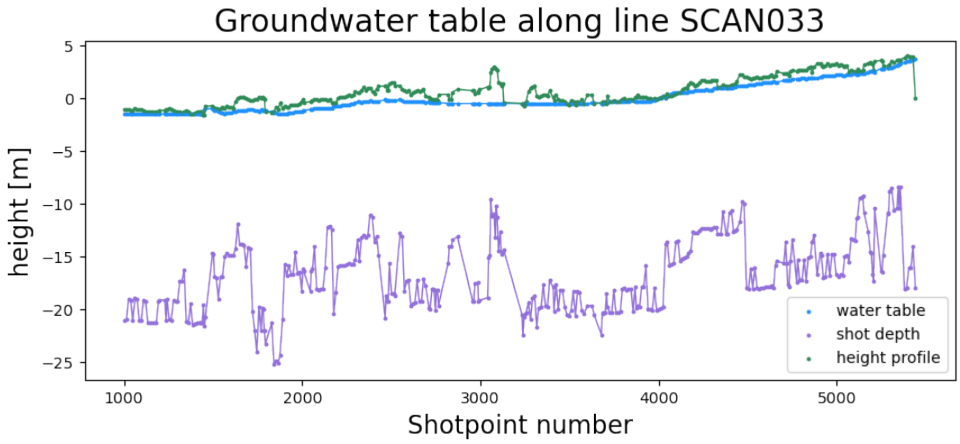


Figure 3.76: The groundwater level along SCAN033. Blue shows the groundwater table, purple the shot depth and green the surface profile.

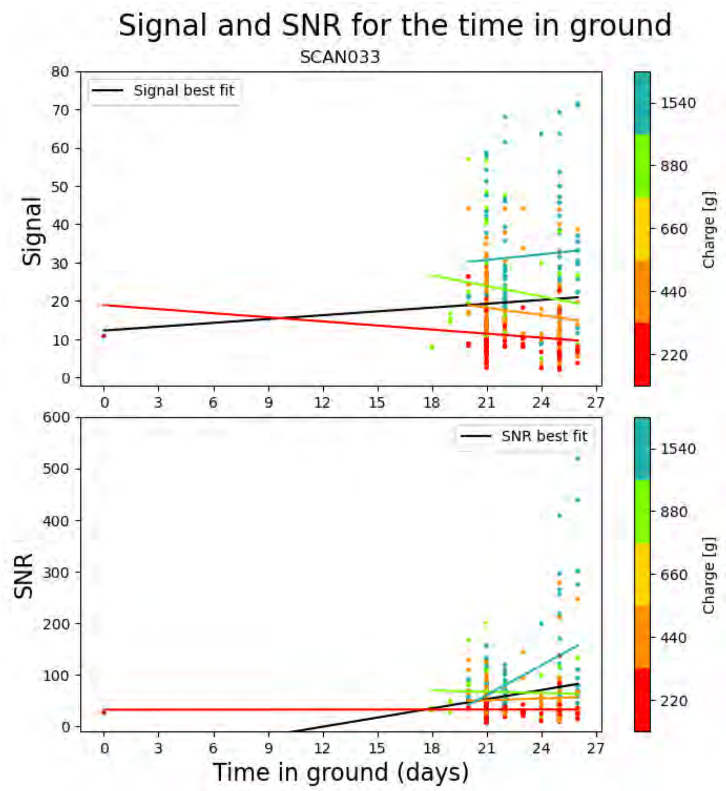


Figure 3.77: The time in days between drilling date and shot date. The colours indicate charge size. The lines are a best fit of all data (black) and per charge size (colours). No clear correlation is visible between the time in the ground and signal amplitude and SNR.

Receiver domain:

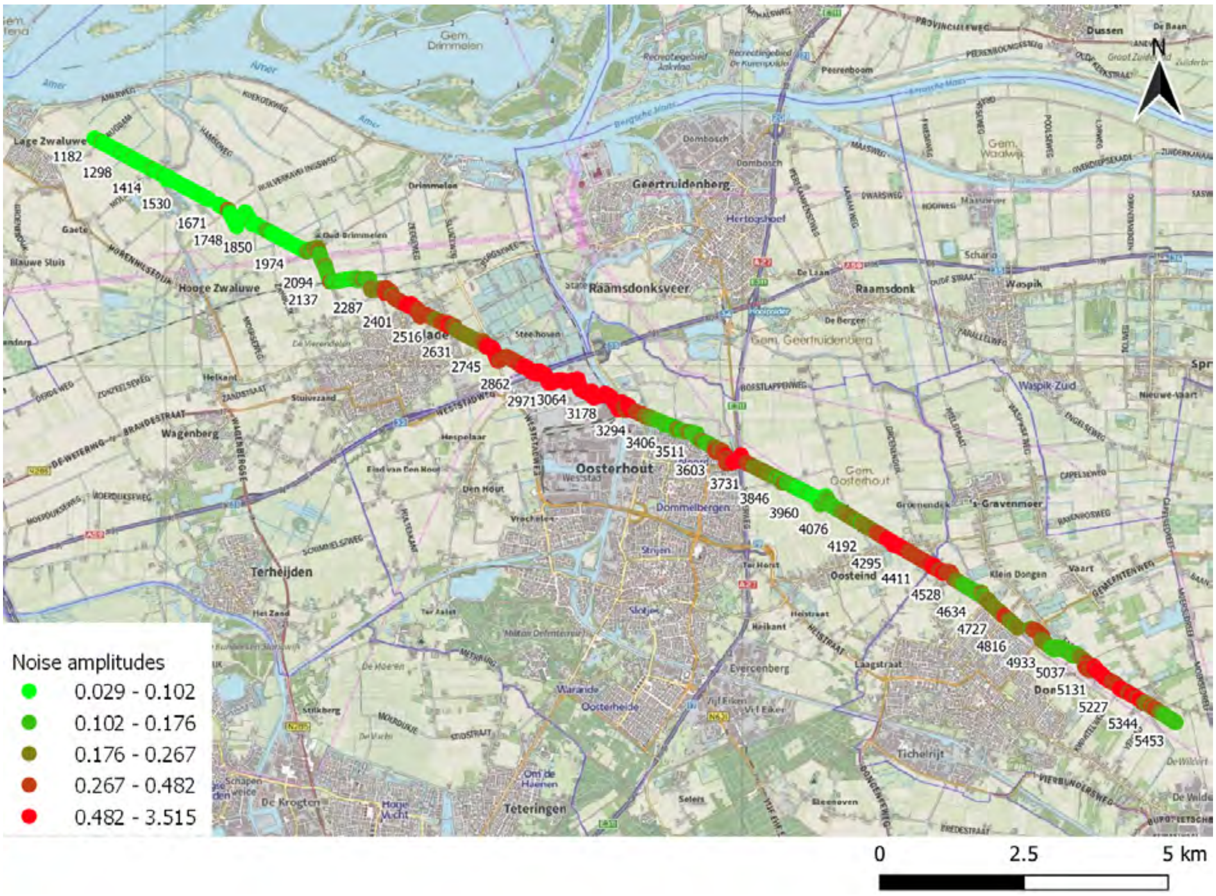


Figure 3.78: Map of the location of SCAN033. The coloured points show the noise amplitudes for each receiver. Every colour represents 20% of the noise amplitudes of this line. The brightest green are the 20% lowest noise amplitudes.

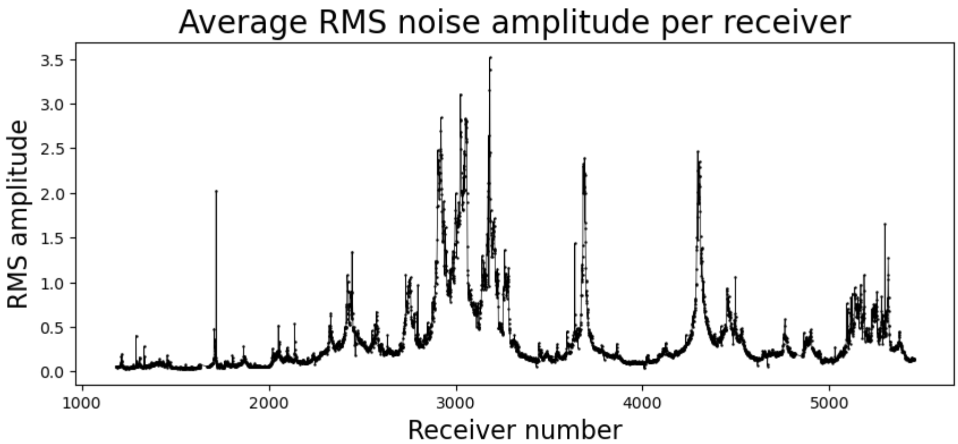


Figure 3.79: Noise amplitudes for each receiver number. The noise level is low overall, but higher noise levels are due to road crossings and an industrial area around shotpoints 2800 - 3300.

3.7 SCAN034

SCAN034 is 37.435 km long and runs from the Schelde-Rijnkanaal near the Belgian border in the south to Willemstad in the north. A summary of important acquisition parameters is shows in table 3.7. Line 034 has an overall signal amplitude of 21.2, which is higher than average. Especially between shotpoints 4000 and 6500 signal is high, which correlates with shooting in meadows (figure 3.80), consequently a higher charge size (figure 3.82) and less noise leading to high SNR (figures 3.84). Around shotpoints 6300 - 6900 the line is parallel to highway A4 leading to substantially higher noise levels (figure 3.91), also visible around Bergen op Zoom (shotpoints 3000 - 4000). Almost all shots are shot below the groundwatertable (3.89), only 4 shots (shots 2713.5-2765.5) are shot above the watertable.

Total acquisition length	37.435 km
Source station range	1091.5 - 8477.5
Total sources	621
Receiver station range	1001 - 8487
Total receivers	7487

Table 3.7: Acquisition parameters SCAN034

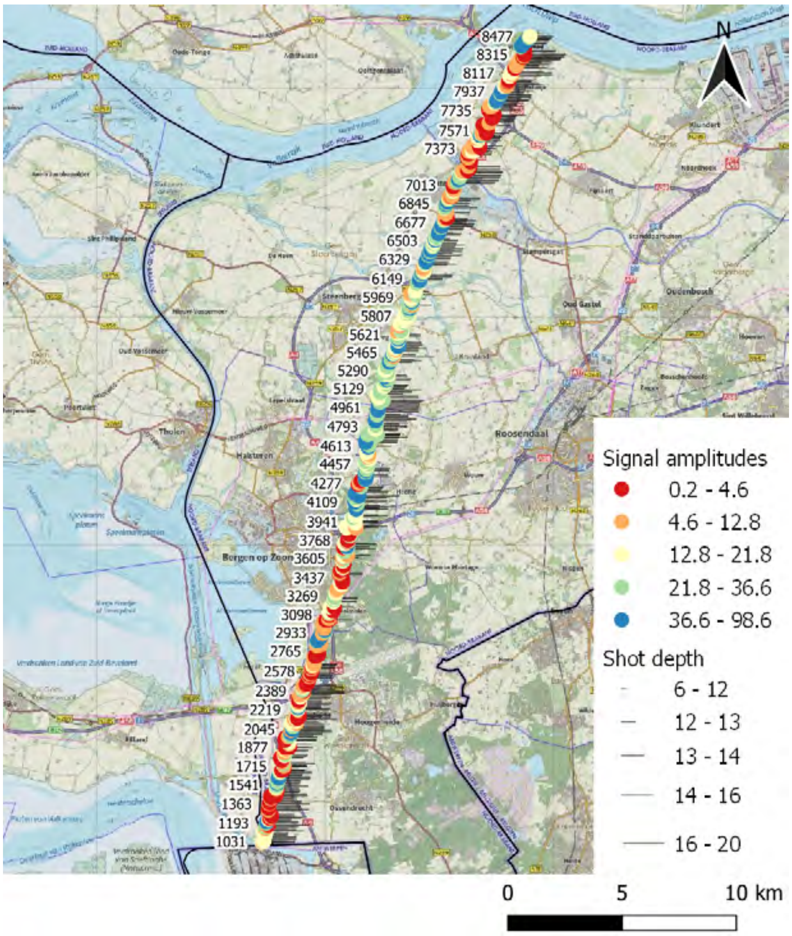


Figure 3.80: Map of the location of SCAN034. The coloured points and black lines respectively show signal amplitudes and shot depth for each station.

Shot domain:

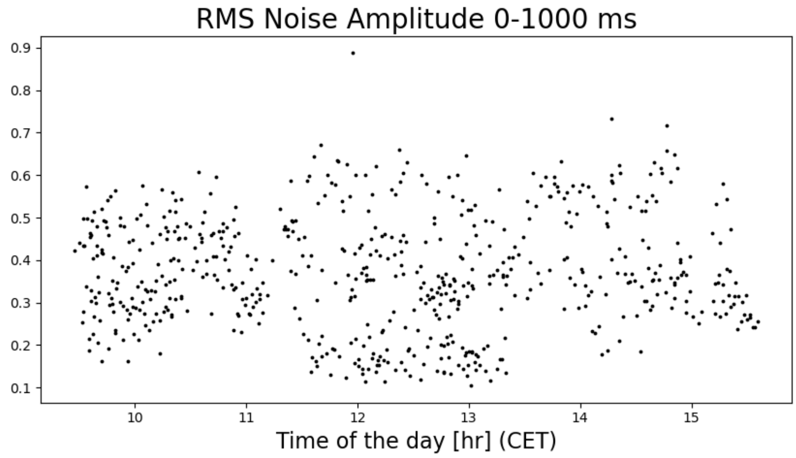


Figure 3.81: The influence of the time of the day of shooting on the noise amplitude. Acquisition was done between 9 am and 4 pm.

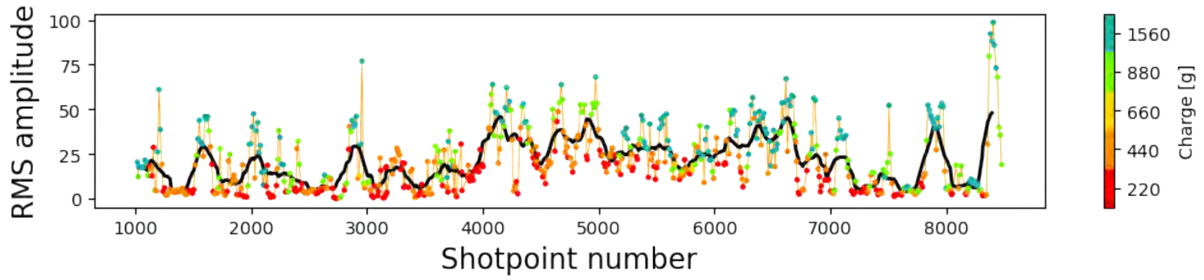


Figure 3.82: The signal amplitude per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the signal amplitude.

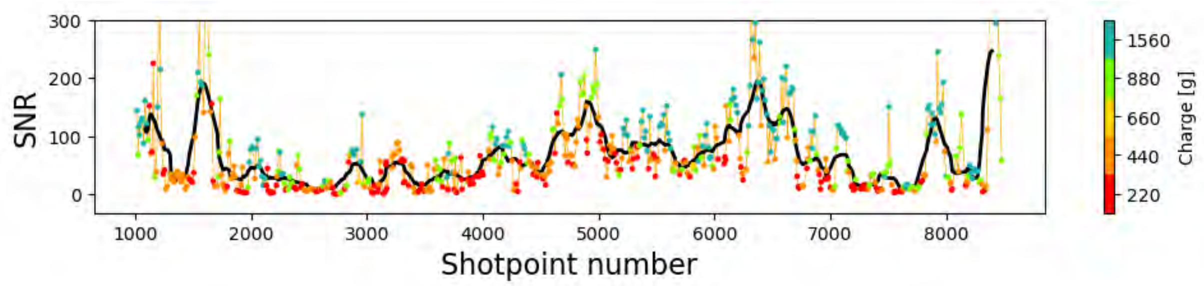


Figure 3.83: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

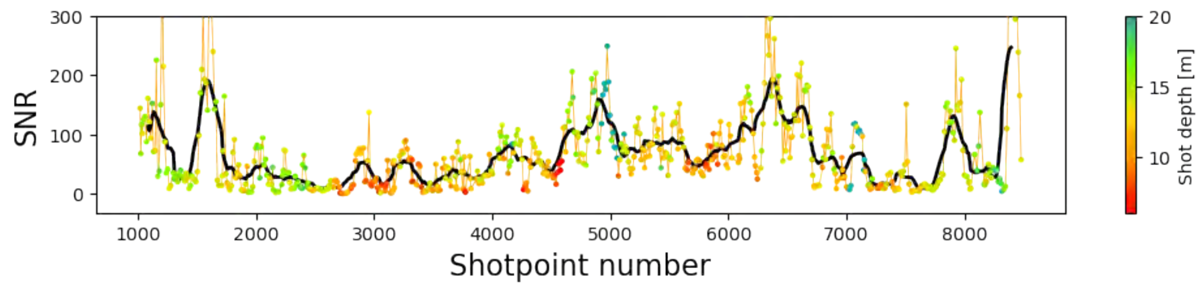


Figure 3.84: The signal-to-noise ratio per shotpoint number in the 0-1s window. The colours indicate the shot depth for each shot and the black line indicates the moving average of the SNR. Shot depths were between 12 m and 20 m.

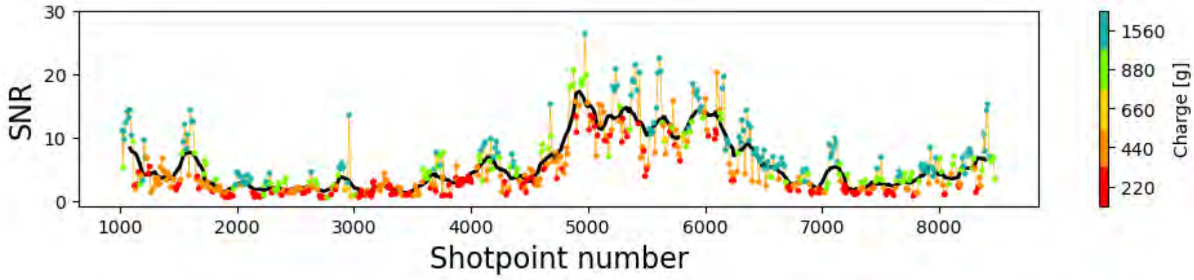


Figure 3.85: The signal-to-noise ratio per shotpoint number in the 1-2s window. The colours indicate the charge size for each shot and the black line indicates the moving average of the SNR.

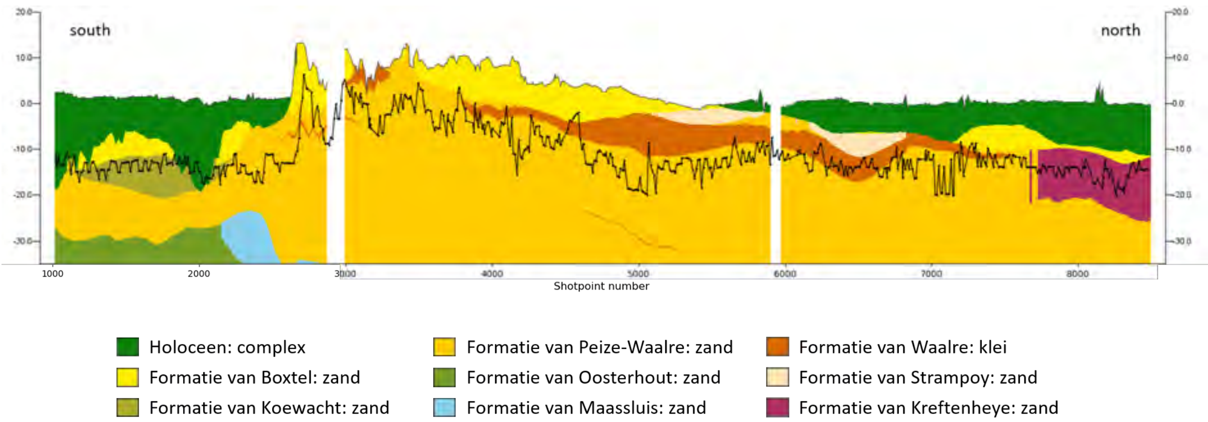


Figure 3.86: Geological profile of SCAN034 overlaid with the shot depth profile in black.

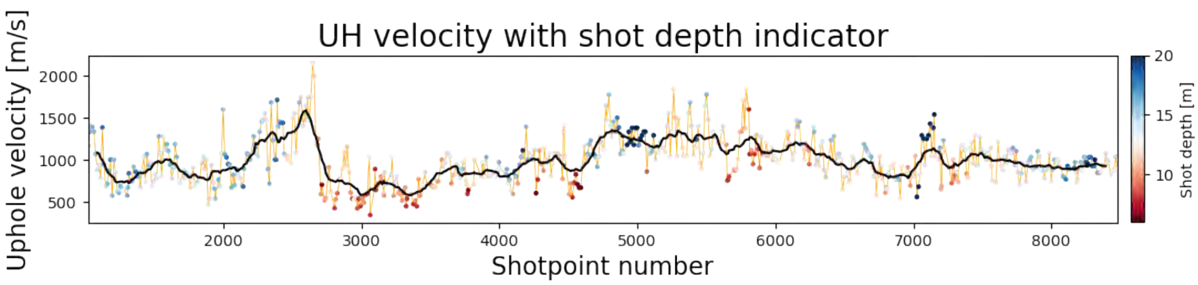


Figure 3.87: Uphole velocity. The colours indicate shot depth. The black line is the moving average of the velocity.

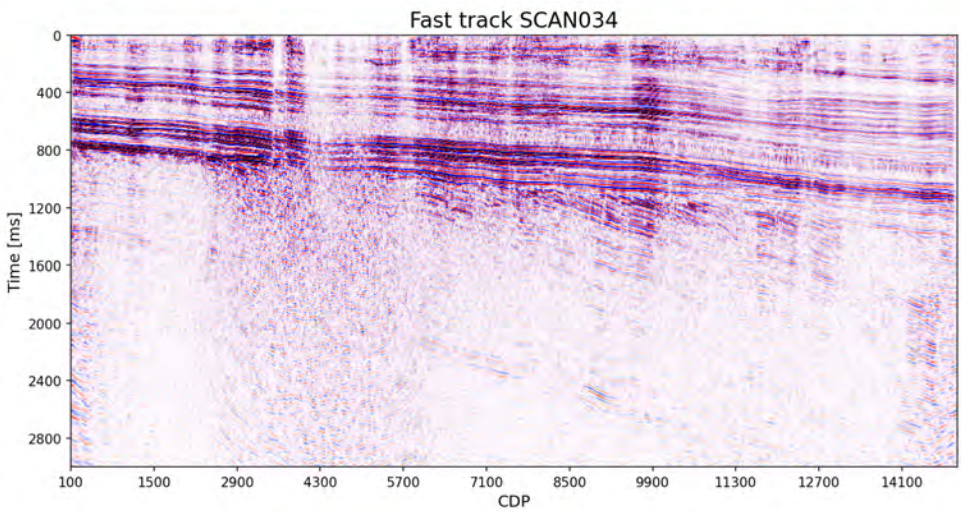


Figure 3.88: The fast track of line 34.

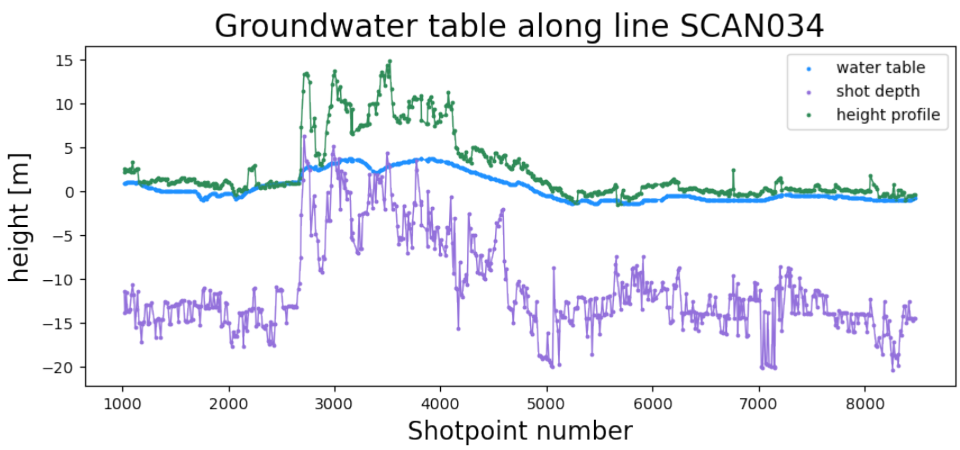


Figure 3.89: The groundwater level along SCAN034. Blue shows the groundwater table, purple the shot depth and green the surface profile.

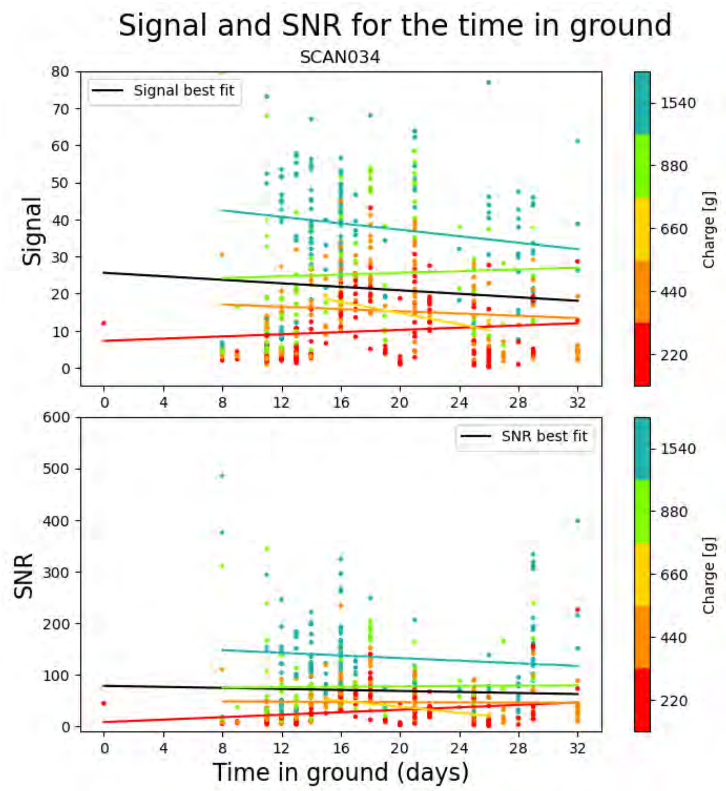


Figure 3.90: The time in days between drilling date and shot date. The colours indicate charge size. The lines are a best fit of all data (black) and per charge size (colours). No clear correlation is visible between the time in the ground and signal amplitude and SNR.

Receiver domain:

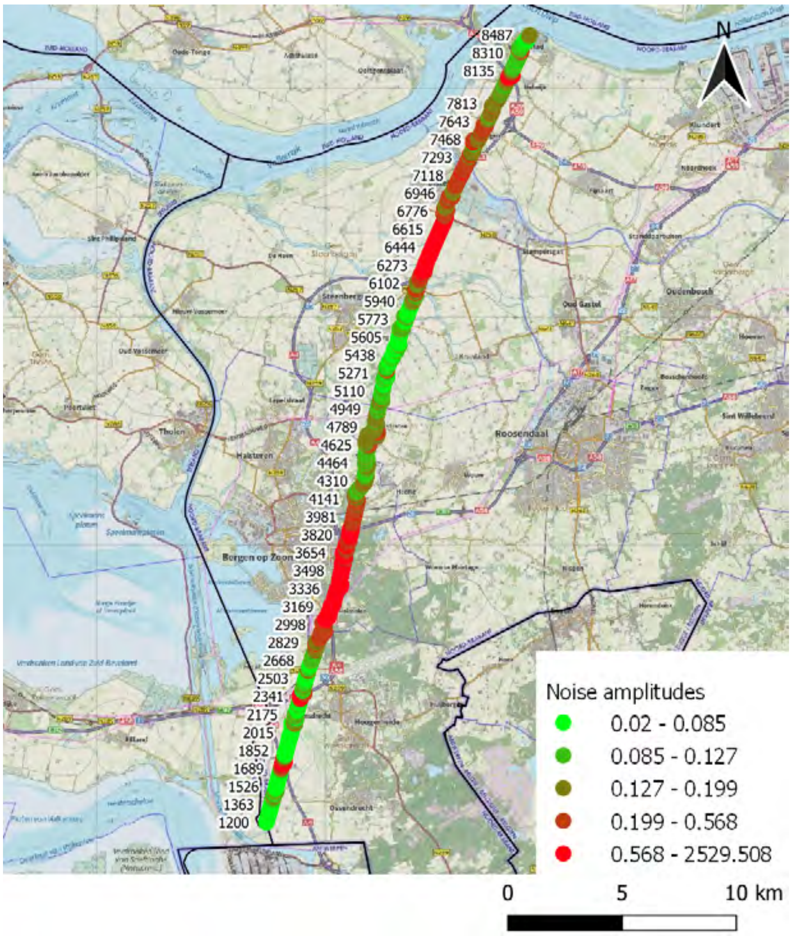


Figure 3.91: Map of the location of SCAN034. The coloured points show the noise amplitudes for each receiver. Every colour represents 20% of the noise amplitudes of this line. The brightest green are the 20% lowest noise amplitudes.

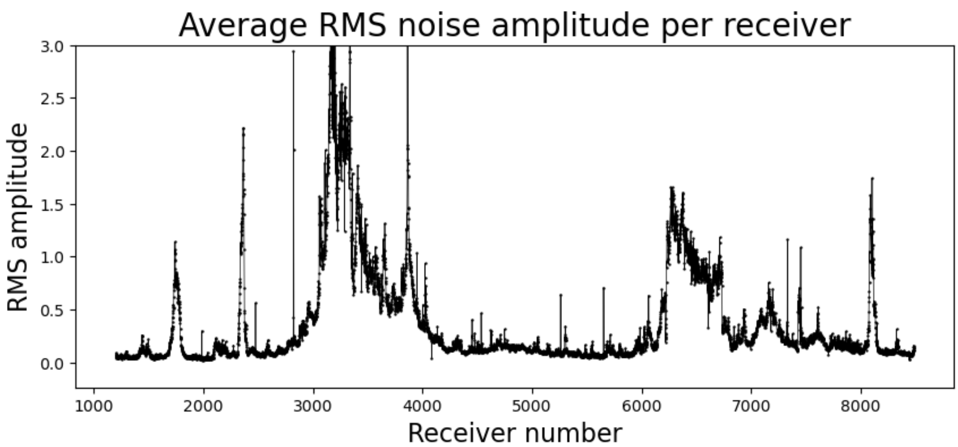


Figure 3.92: Noise amplitudes for each receiver number. The noise level is low overall, but higher noise levels are due to road crossings; e.g. around receiver numbers 3000-4000 the line is shot near Bergen op Zoom and is parallel to the A4..

3.8 Analysis between lines

At the time of writing 34 lines are shot, which all together total to more than 20000 shots. In this results section a couple of analyses have been done between those lines and shots.

3.8.1 Near surface geology

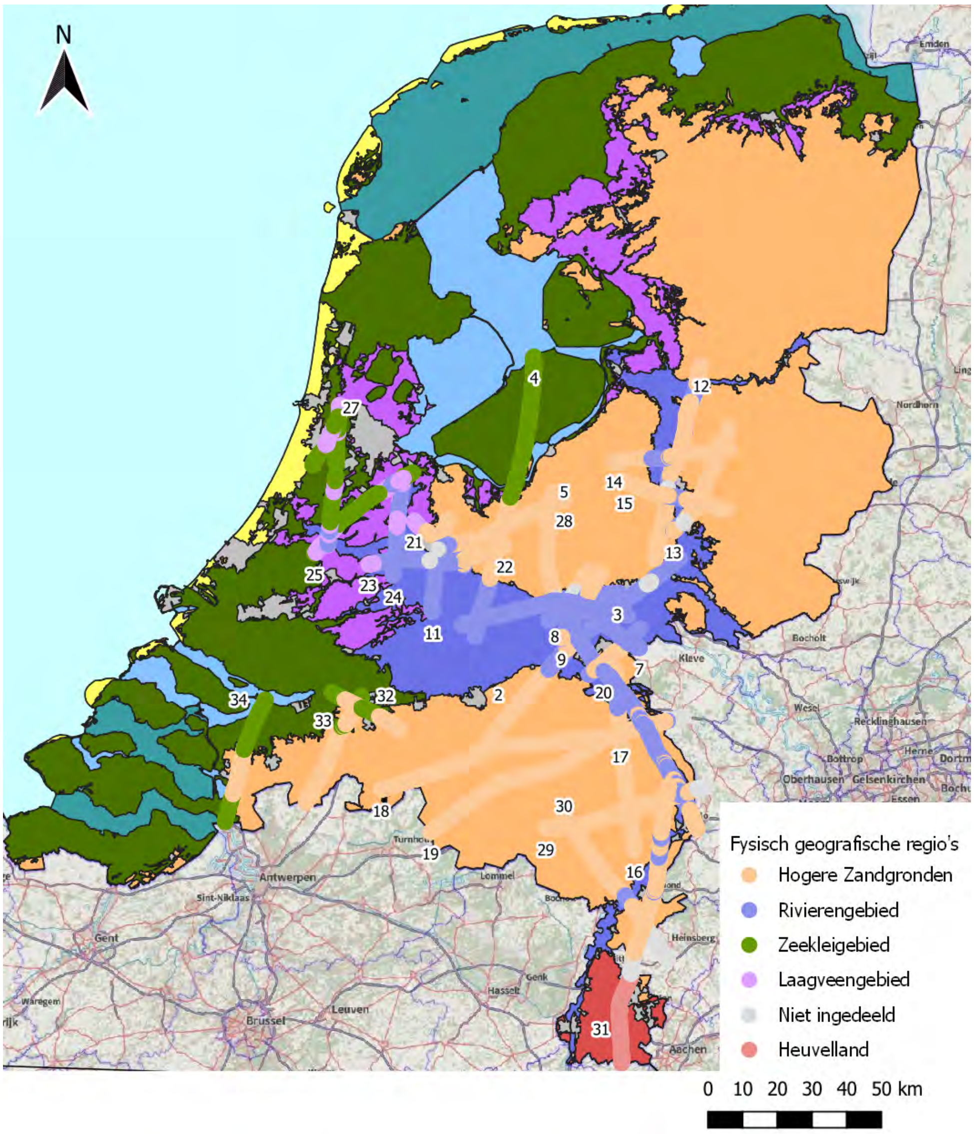
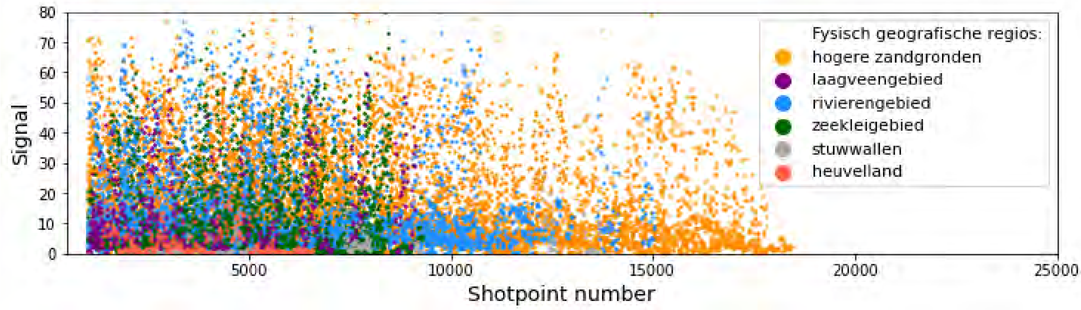


Figure 3.93: All lines and the physical geographical region each shot falls in.

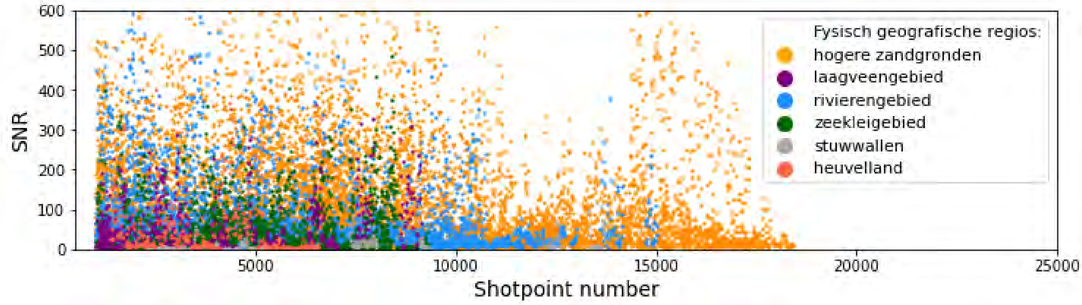
Near surface geology might be of influence on the signal strength and consequently the SNR. All shots have been mapped and assigned to a physical geographical region. They are visualized in figure 3.93. To research the dependence of signal strength on the geology as well as the SNR, all shots are plot against the shotpoint with the region as colour (figure 3.94). In this plot it is hard to distinguish which geology produces better or worse signal, but it is already clear that in the stowed deposits (grey) and hills (red) signal and SNR are slightly lower than in sand (orange) or in clay (blue and green). To better distinguish this difference another approach was taken. The average and standard deviation of both the signal strength (figure 3.95a) and SNR (figure 3.95b) show that the shots in sand give the highest signal and SNR, while the shots in stowed deposits give the lowest signal and SNR. However, the standard deviation for all types of geology are high enough that a shot in a stowed deposit can still result in better signal strength than one in sand.

3.8.2 Groundwater

It was previously shown that the groundwater table is of influence on the signal strength (van Klaveren, 2021). In this research were again a couple of lines with shots above the groundwater table. The influence hereof is seen in figure 3.96. Lines 19, 20, 30 and 31 all contained one or more shots above the groundwater



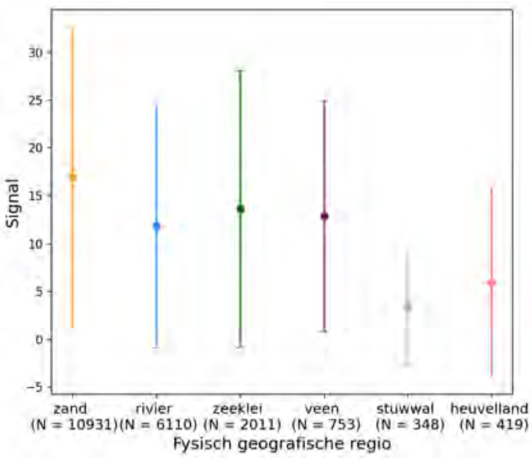
(a)



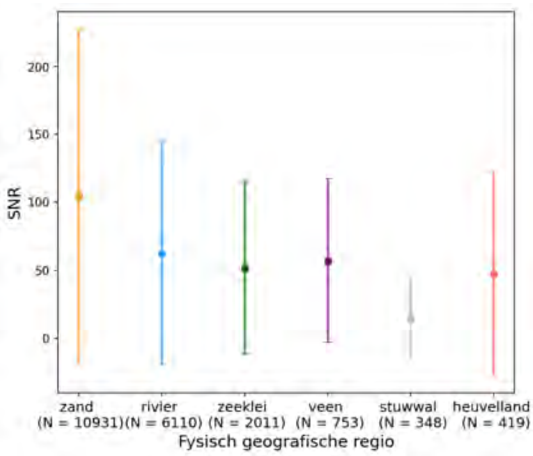
(b)

Figure 3.94: (a) The signal strength of each shot. (b) The SNR of each shot. For both (a) and (b) the shots are coloured as the region they were shot in.

table. In line 19 these were only 3 or 4 shots, of which the influence on the final data remained minimal. In lines 30 and 31, however, a substantial part of the line was shot above the groundwater table. For line 30 the majority of the shots shot above groundwater fall in Germany, of which no groundwater data was available. The extrapolated groundwater line in the upper figure of figure 3.96c, however, does correspond with the expected low signal amplitudes corresponding to shots above the water table seen in the lower figure. If any of these shots were below the groundwater table similar spikes in amplitude would have been seen as in the lower figure of figure 3.96d (at e.g. shotpoint 5000 a large spike is visible, which correlates with a shot below the groundwater table). To illustrate the difference in shot, figure 3.97a shows a shot below and figure 3.97b shows a shot above the watertable. The charge size used is larger for the shot above the watertable, but the signal is significantly lower than for the shot below the watertable.

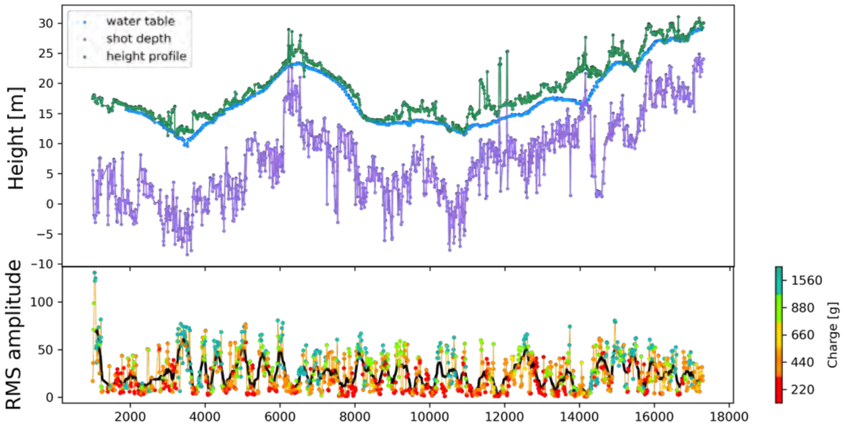


(a)

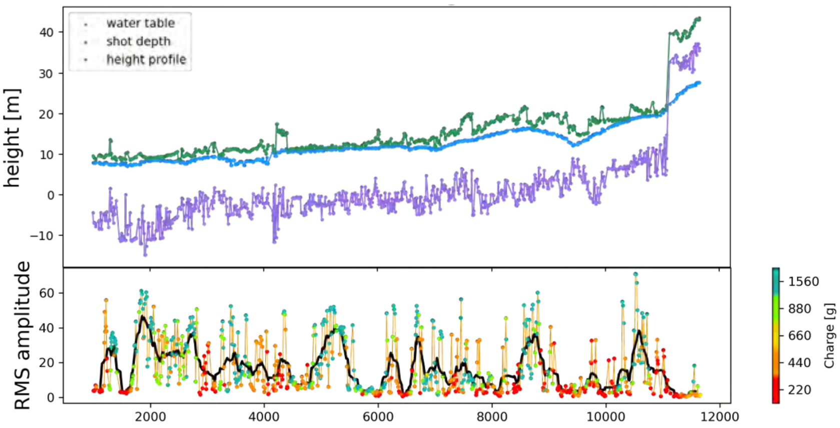


(b)

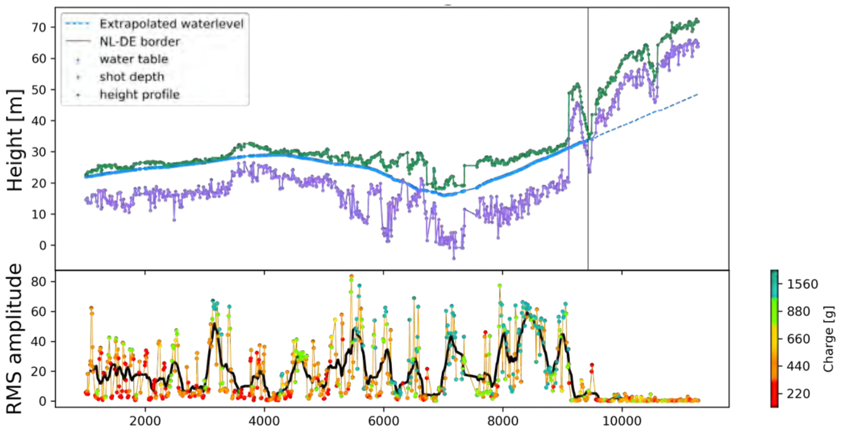
Figure 3.95: The average and standard deviation of (a) signal amplitude and (b) SNR for each physical geographical region.



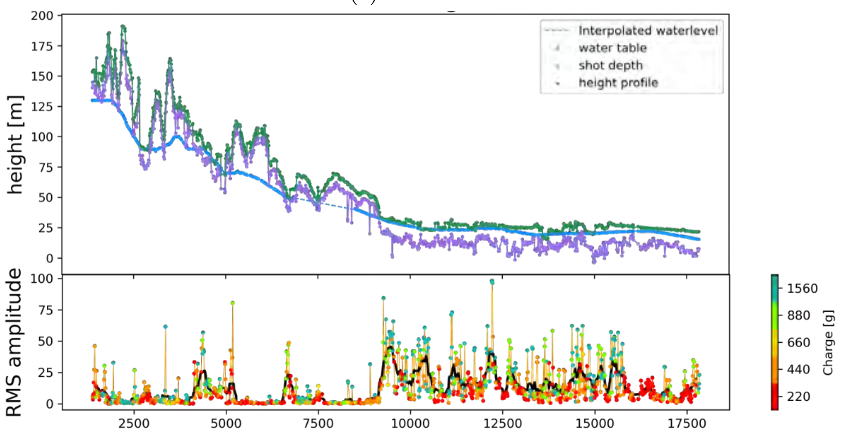
(a) SCAN019



(b) SCAN020

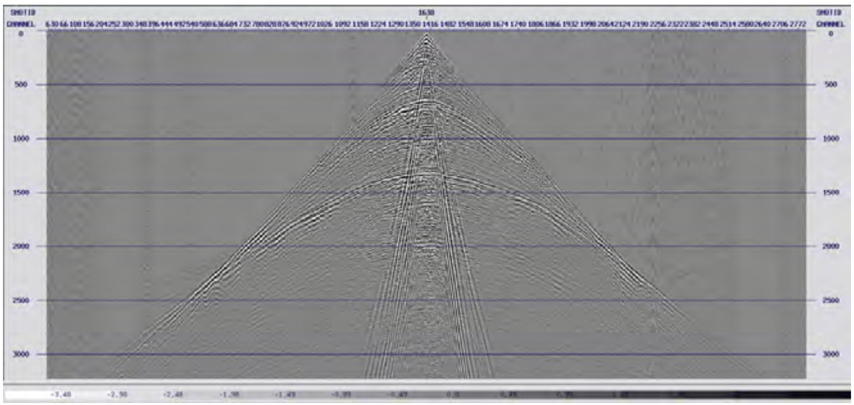


(c) SCAN030

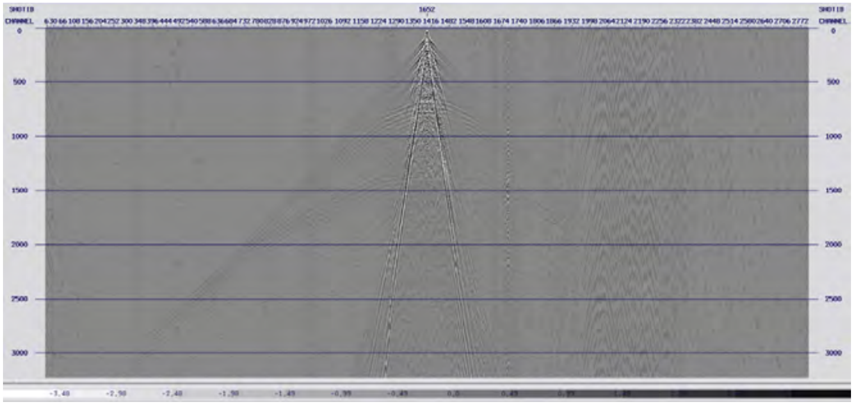


(d) SCAN031

Figure 3.96: Four lines of which part of the shots are shot above the groundwater table. Shots above the groundwater table are for (a) 13950 - 14100, for (b) 11000 - 11660, for (c) 9300 - 11900 and for (d) 1001 - 9100 with some shots below groundwater in between.



(a)



(b)

Figure 3.97: Two shots of SCAN030. (a) shotpoint 9071.5 with a charge size of 440g shot below the groundwater table and (b) shotpoint 9257.5 with a charge size of 660g shot above the groundwater table.

3.8.3 Time in ground

The time between the drilling date and the shot date (time in ground) might be of influence for the signal strength due to better coupling of the explosive to the ground. To investigate this, for each shot the time in ground is calculated and compared to the signal amplitude as well as the SNR (figure 3.98).

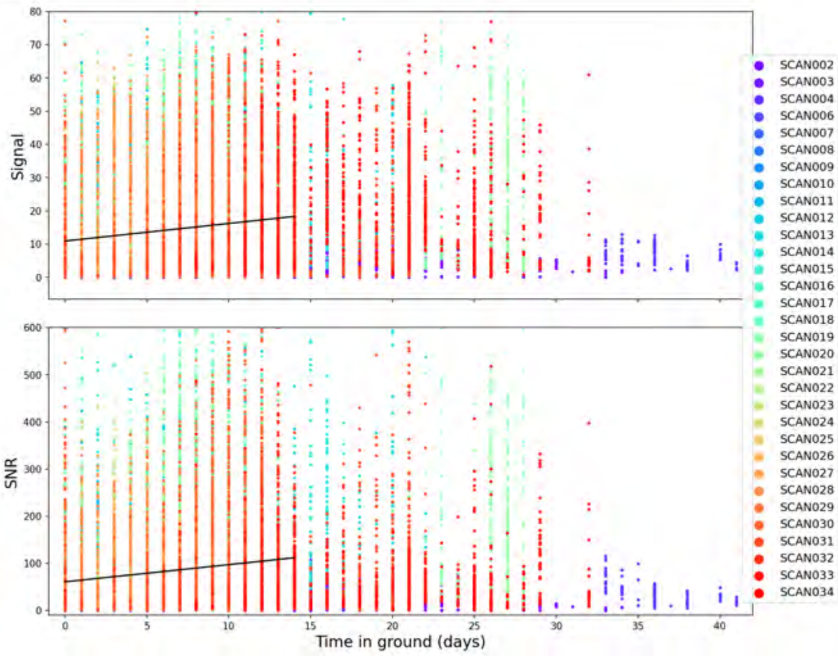


Figure 3.98: The time between drilling date and shot date in days and the correlation with signal (upper figure) and SNR (bottom figure). Every line has a different colour. The black line is the trend over the first 2 weeks.

There is a lot of scatter and a trend is only visible when looking at the first 14 days. This is only a weak trend due to large scatter. The fact that the shots were shot with different charge sizes and in different geologies could also make a difference. Coupling might be better in different geologies or different charge sizes. Figure 3.99 again shows all shots, but subdivided in charge sizes. Here we see a distinct difference between lower charge size (220 g) and higher charge sizes (1540g). The latter gives a stronger trend than the first, but there is still a lot of scatter visible. To distinguish the different geologies figure 3.93 was used and combined with the time in ground. Figure 3.100 shows all different physical geographical areas separately. The marine clay shows the strongest trend, while the stowed deposits and hills show the weakest trend. Overall there is again a lot of scatter.

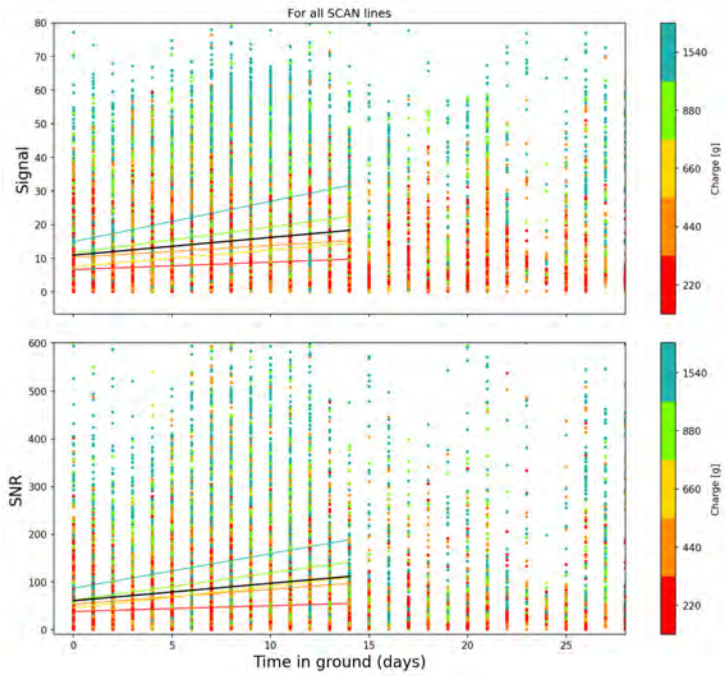


Figure 3.99: The time between drilling date and shot date in days and the correlation with signal (upper figure), SNR (bottom figure) and the charge size (in different colours). The black line is the trend over the first 2 weeks.

3.8.4 Overview of all lines

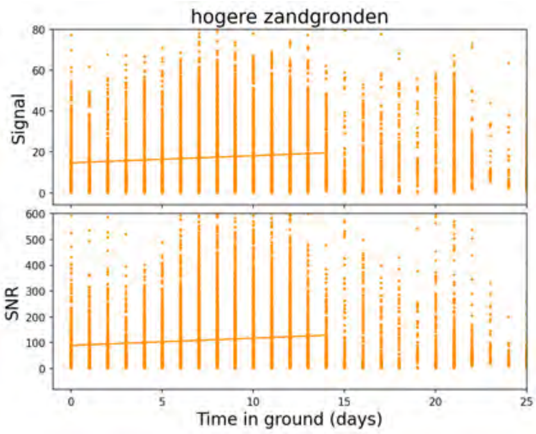
An overview is given of the signal amplitudes (figure 3.101), noise amplitudes (figure 3.102 and SNR (figure 3.103) to distinguish better or poorer quality lines. The choice has been made to look at the 1-2s window due to a difference in method for obtaining the signal amplitude in the 0-1s window between the first 9 lines (van der Lucht, 2020) and subsequent lines (van Klaveren, 2021 and this report). This resulted in substantially lower signal amplitudes and SNR for the first 9 lines (table 3.8), even though they were not of poorer quality. In the 1-2s window the method used was the same, hence this window was more suitable to compare the lines. In figure 3.101 a couple things stand out; the southern part of Limburg shows very low signal amplitudes as well as areas around Nijmegen, between Ede and Arnhem and the southeast of Flevoland. Higher amplitudes are more scattered, but almost all further away from large urban areas

Line	Signal	SNR	Line	Signal	SNR
SCAN002	3.14	15.58	SCAN019	24.63	162.08
SCAN003	6.43	36.37	SCAN020	18.35	113.54
SCAN004	4.81	26.76	UGOU021	11.30	44.38
SCAN005	6.95	26.46	UGOU022	16.53	66.43
URKM006	5.87	35.57	SCAN023	12.08	57.94
URKM007	7.70	41.64	SCAN024	13.23	67.74
URKM008	5.10	17.73	SCAN025	14.56	68.10
URKM009	4.43	14.99	SCAN026	13.58	69.04
URKM010	6.93	37.39	SCAN027	20.61	74.04
SCAN011	16.38	79.45	SCAN028	24.51	86.30
SCAN012	18.71	107.92	SCAN029	19.16	134.66
SCAN013	16.64	149.36	SCAN030	17.12	126.04
SCAN014	20.71	177.43	SCAN031	11.94	68.36
SCAN015	19.11	128.66	SCAN032	21.79	89.81
SCAN016	17.65	113.21	SCAN033	19.75	60.92
UBRO017	10.59	78.83	SCAN034	21.25	68.55
SCAN018	19.15	155.30			
Average all lines				**14.37**	**82.55**

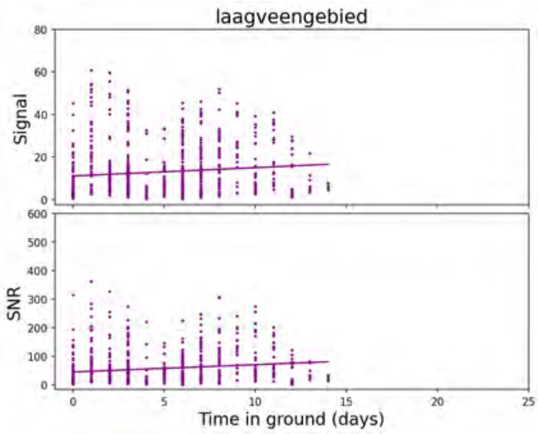
Table 3.8: The signal amplitudes and SNR in the 0-1s window for all lines.

or highways. The noise distribution shows the highest levels around highways, urban and industrial areas. Line 28 parallel to highway A28 is such an example. Lowest noise levels are found in rural areas. The SNR shows the combination of the signal and noise figures, with again a clear difference between rural and urban regions. An exception is the south of Limburg, which is not urban nor industrial but gives a very low SNR overall. This might be an indication of other factors playing a role such as groundwater levels and other near surface geological variations (section 3.8.2).

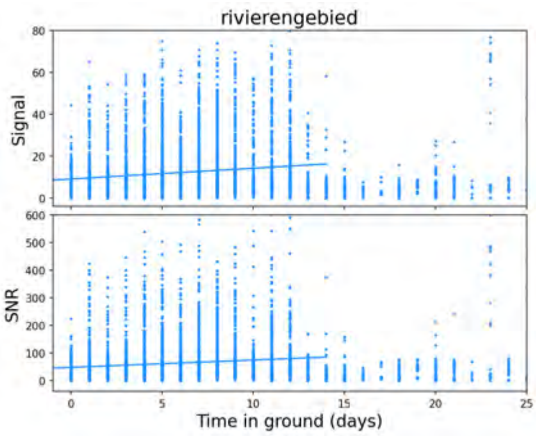
Figures 3.104-3.107 show the average and max signal, noise and SNR and the average charge size and shot depth respectively. The choice is made again to look at the 1-2s window for better comparison. Table 3.8 also includes the average values for the 0-1s window.



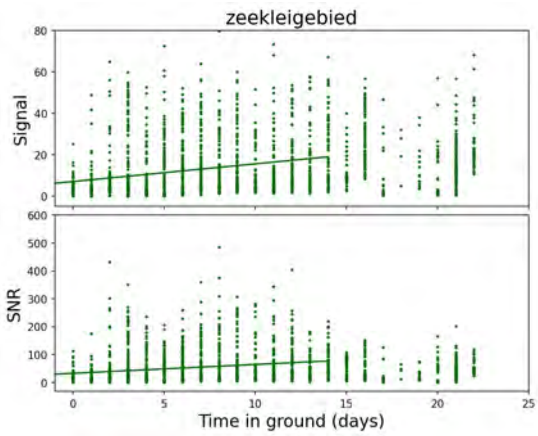
(a)



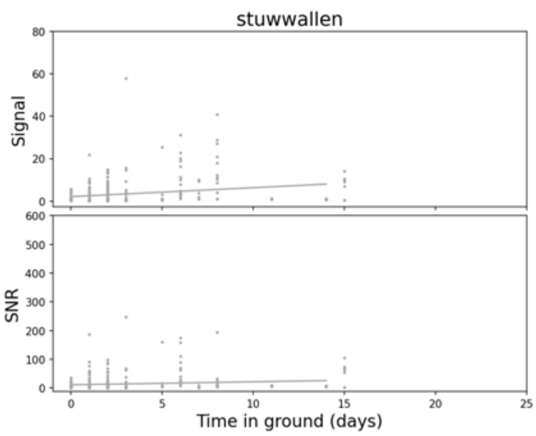
(b)



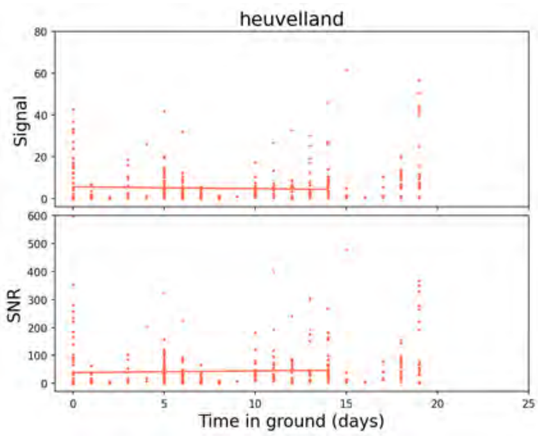
(c)



(d)



(e)



(f)

Figure 3.100: The time between drilling and shot date of (a) higher sandy soils, (b) fen area, (c) fluvial clay, (d) marine clay, (e) stowed deposits and (f) Dutch hills.

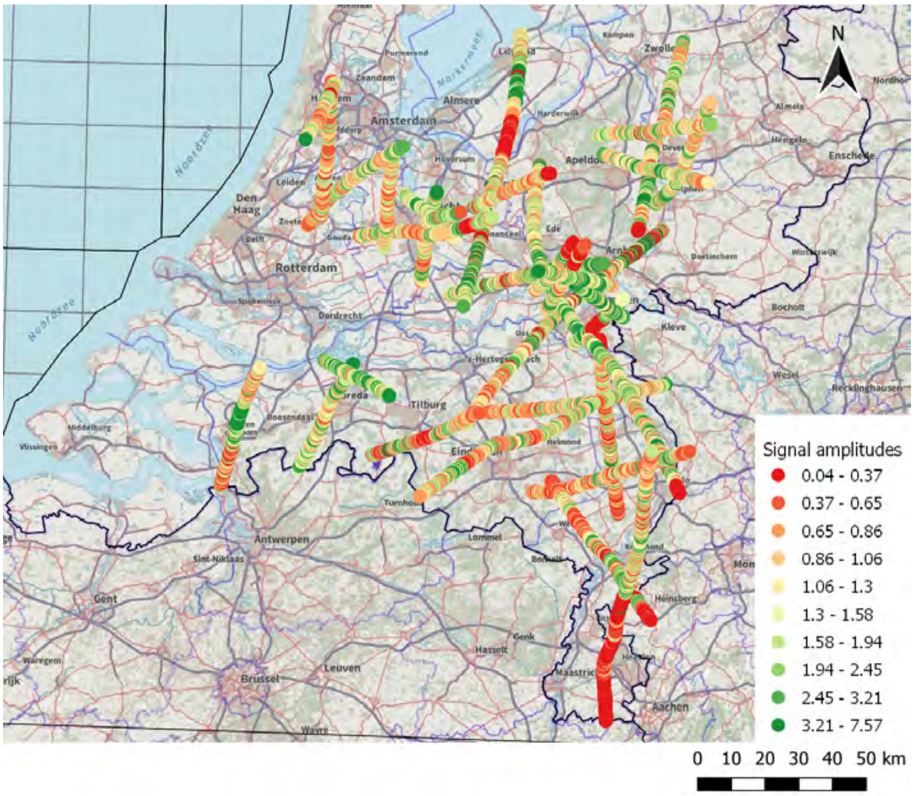


Figure 3.101: The signal amplitude of all shots for the 1-2s window. Each colour represents 10% of the total amplitude points. The green points are the 10% highest signal amplitudes, while the red points show the 10% lowest signal amplitudes.

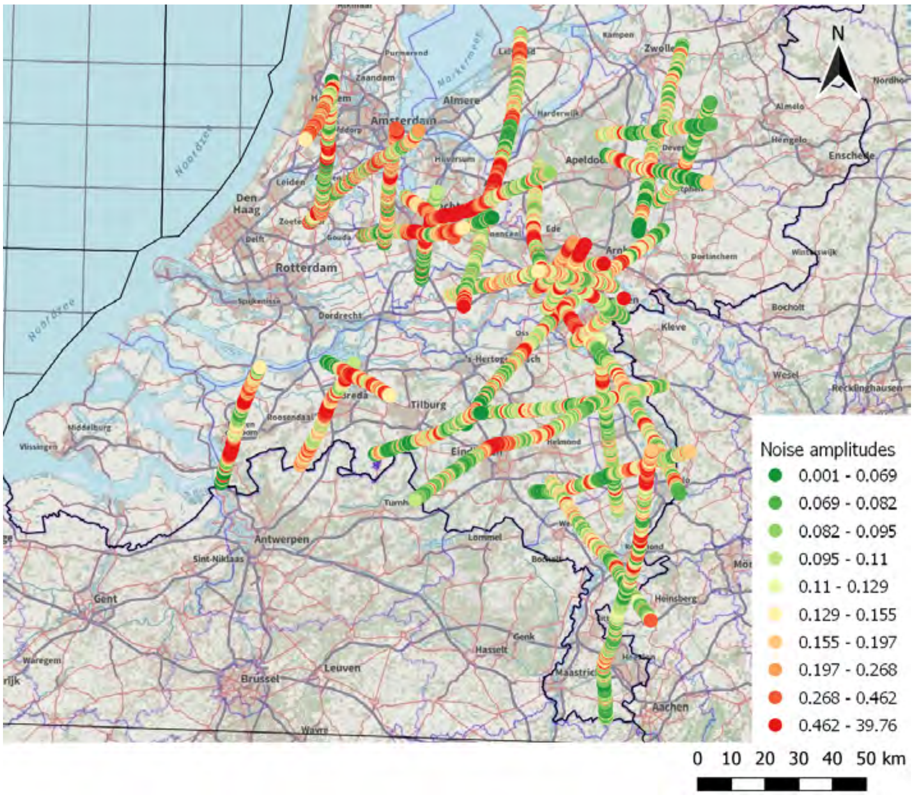


Figure 3.102: The noise amplitudes of all shots in the receiver domain.

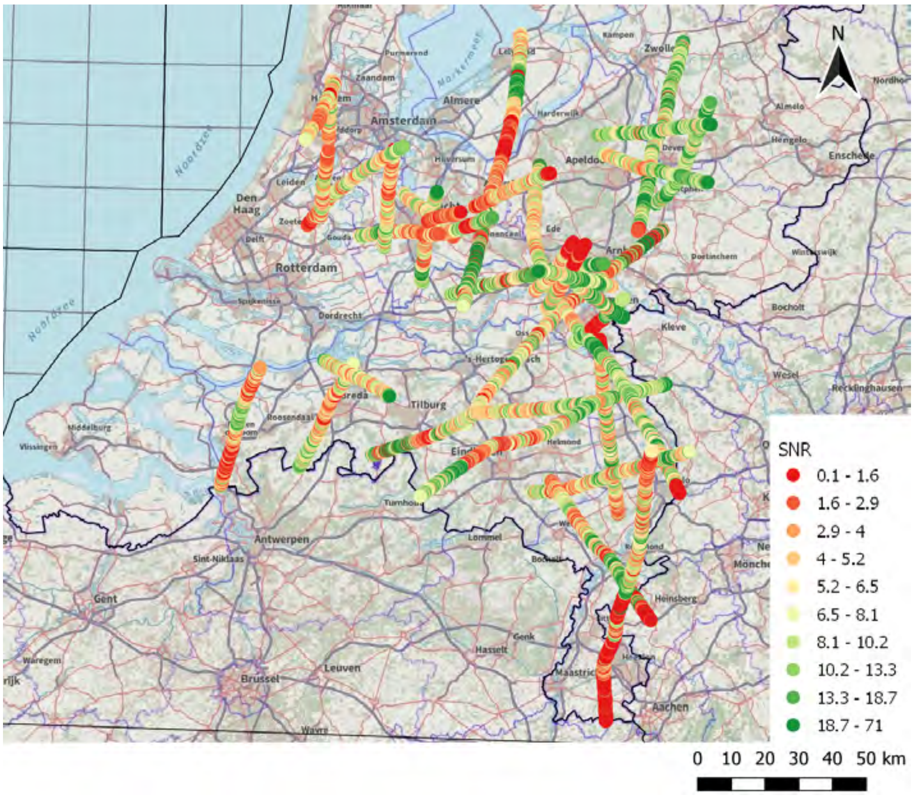
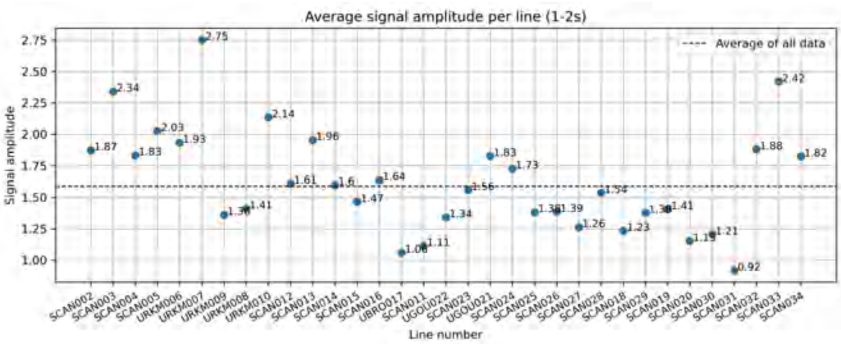
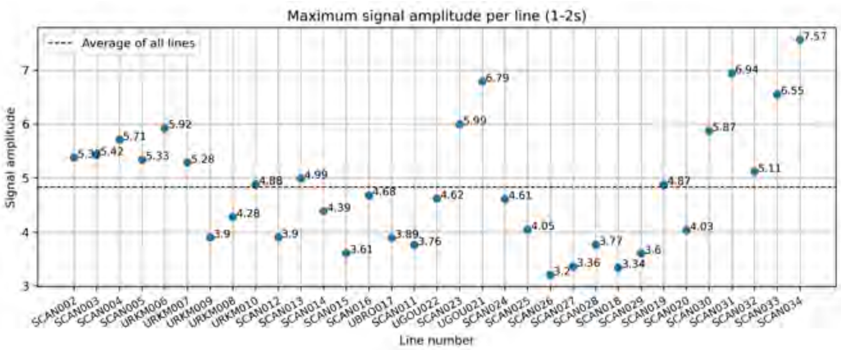


Figure 3.103: The signal-to-noise ratio of all shots in the 1-2s window

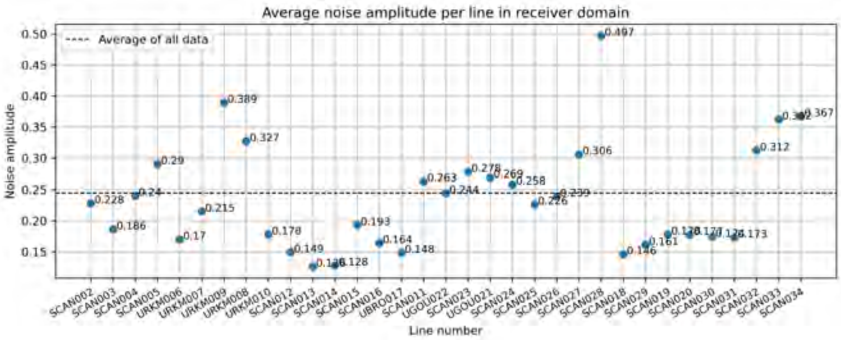


(a)

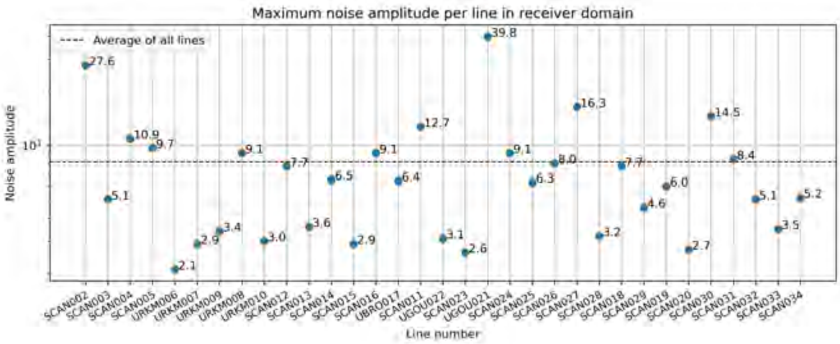


(b)

Figure 3.104: The (a) average signal amplitudes and (b) maximum signal amplitudes per line for the 1-2s window. The dotted line represents the average value of all points to better distinguish between higher than average or lower than average amplitude. The order of lines is the order in which the acquisition was done.

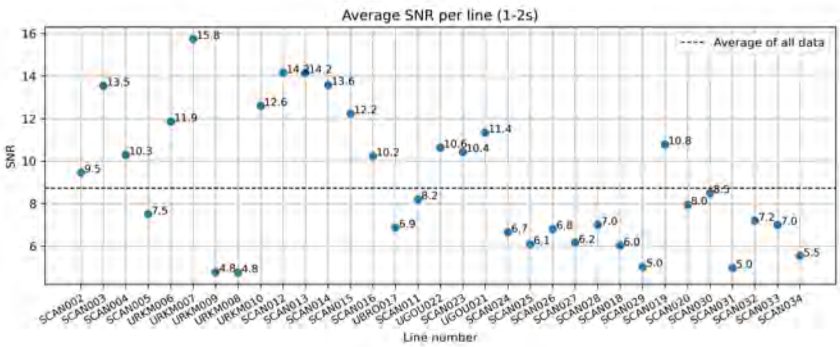


(a)

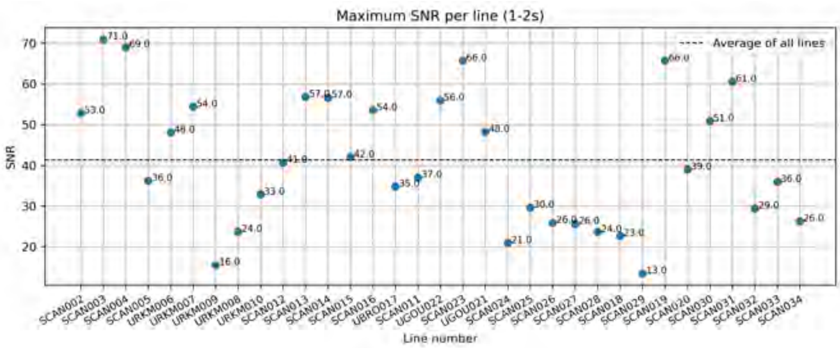


(b)

Figure 3.105: The (a) average noise amplitudes and (b) maximum noise amplitudes per line in the receiver domain. The y-axis of (b) is exponential. The dotted line represents the average value of all points to better distinguish between higher than average or lower than average amplitude. The order of lines is the order in which the acquisition was done.

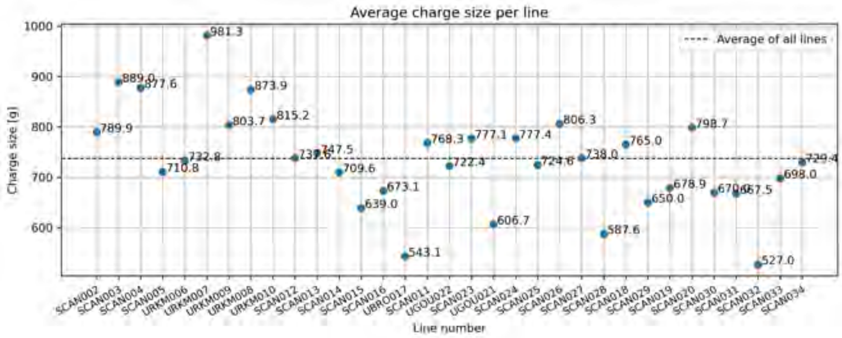


(a)

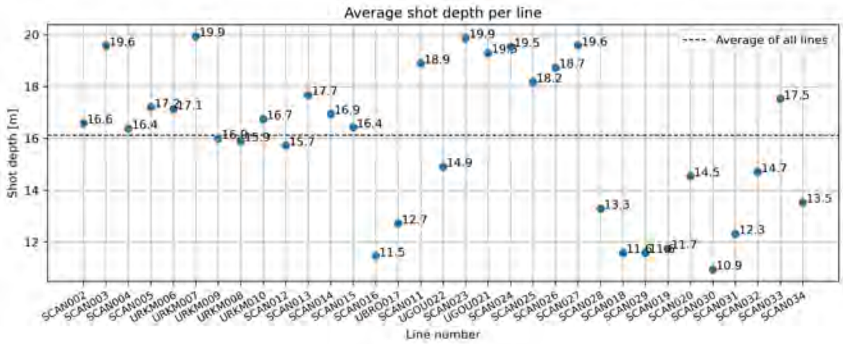


(b)

Figure 3.106: The (a) average SNR and (b) maximum SNR per line for the 1-2s window. The dotted line represents the average value of all points to better distinguish between higher than average or lower than average amplitude. The order of lines is the order in which the acquisition was done.



(a)



(b)

Figure 3.107: The average (a) charge size and (b) shot depth per line. The dotted line represents the average value of all points to better distinguish between higher than average or lower than average amplitude. The order of lines is the order in which the acquisition was done.

3.9 Final processing

The final seismic sections investigated in this research are SCAN001-011, SCAN017-018 (both combined lines), UGOU021, UGOU022, SCAN023, SCAN024, SCAN025, SCAN027, SCAN028 and SCAN029. Figures 3.108 - 3.118 show the cross-correlation in the time domain, the final processed section and the cross-correlation in the frequency domain.

SCAN001-011 is a combined line (figure 3.108). SCAN001 is the test line and had a couple different acquisition parameters than SCAN011, such as a source interval of 20 m, resulting in a higher fold (upper figure 3.109). When solely looking the the cross-correlation coefficients in figure 3.109 of the part of SCAN011 and SCAN001, the part with the higher fold shows a higher cross-correlation coefficient, but when also taking the seismic section in account it is clear that the fold is not the only parameter influencing the coefficient. The thickness of the relatively flat layers is larger, thus traces are more similar, in the final quarter of the combined line, which is again visible in the coefficient (0.935) for that quarter. In the seismic section (middle figure 3.108) the fold has some influence on the quality of the data, especially when comparing the two middle quarters (bottom figure 3.109). The left has a cross-correlation coefficient of 0.766 and seems of poorer quality than the right with a coefficient of 0.866. Thus, the fold does seem to have an influence on the quality, although it is not decisive for the overall quality, because the seismic section of lower fold also seems like a decent seismic section.

	Time	Frequency	Combined
SCAN001-011	0.853	0.928	0.891
SCAN017-018	0.856	0.944	0.900
SCAN021	0.843	0.908	0.876
SCAN022	0.808	0.901	0.855
SCAN023	0.872	0.930	0.901
SCAN024	0.822	0.904	0.863
SCAN025	0.838	0.923	0.881
SCAN027	0.824	0.914	0.869
SCAN028	0.843	0.924	0.884
SCAN029	0.855	0.932	0.894
Average	**0.841**	**0.921**	**0.881**

Table 3.9: Cross-correlation coefficients of each section in the time domain, frequency domain and combined and the average off all lines.

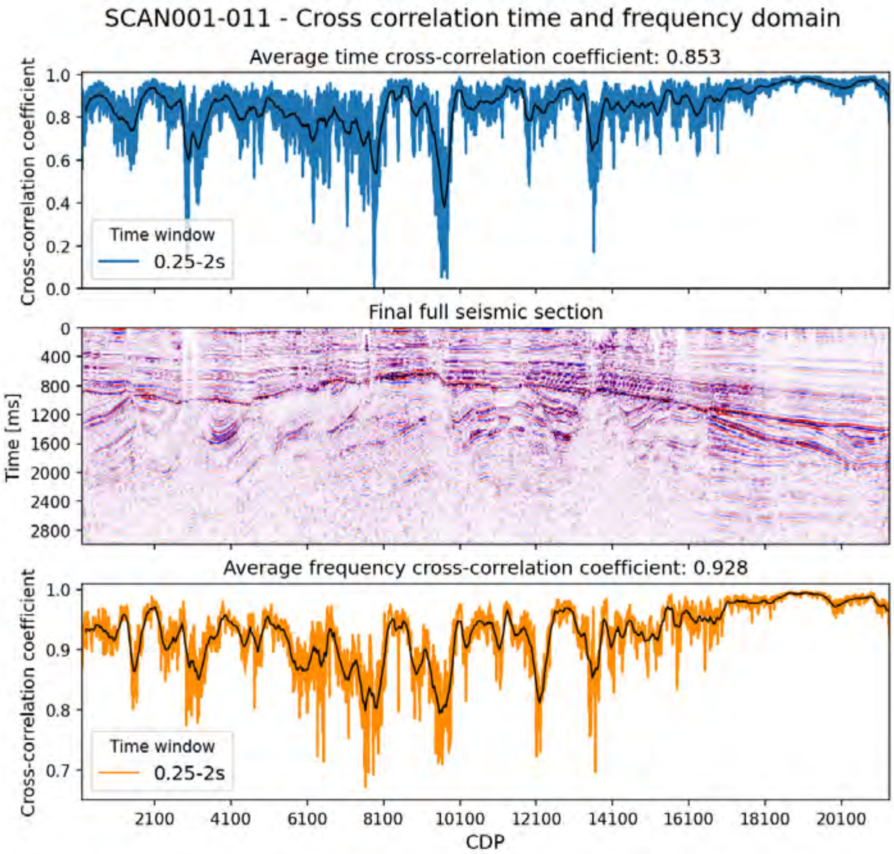


Figure 3.108: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

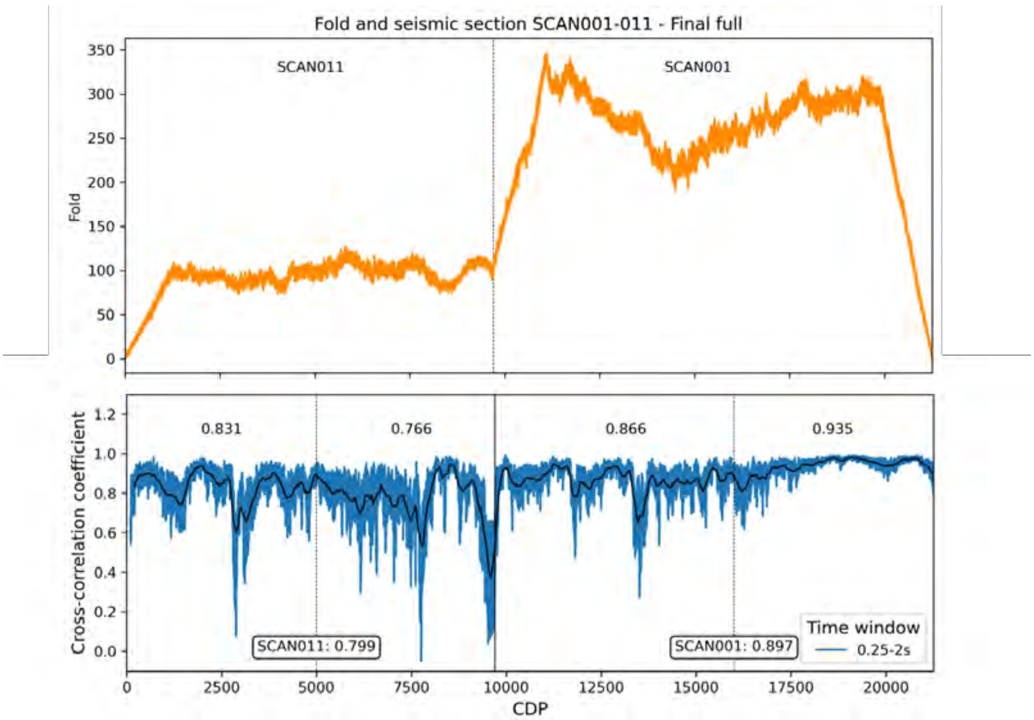


Figure 3.109: The fold (upper figure) of combined line SCAN001-011 and the cross-correlation coefficient in the time domain (bottom figure) of the two lines seperately (in boxes) and of four different parts of the line.

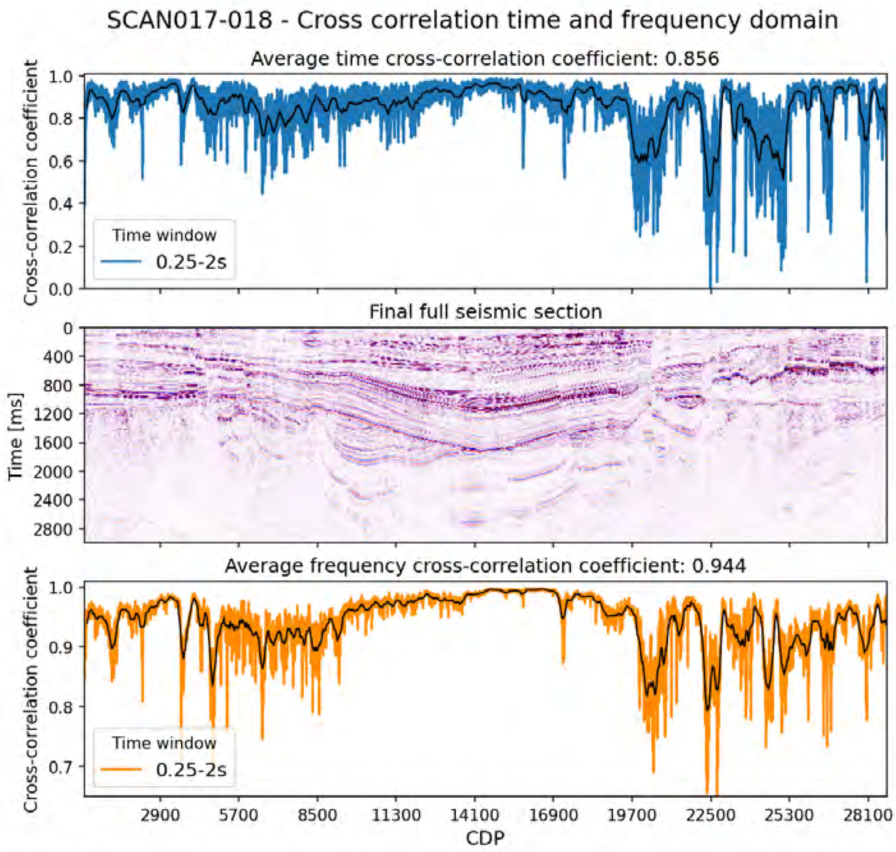


Figure 3.110: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

SCAN017-018 (figure 3.110) is also a combined line, but both parts have the same fold. The coefficient in both time and frequency domain are high compared to other lines. This is mainly due to the thick flat or very slowly dipping layers in the middle of the line. Around CDPs 20000, 22000 and 24500 some faults are visible, resulting in dips in the cross-correlation in both the time and frequency domain. Overall the section is of good quality.

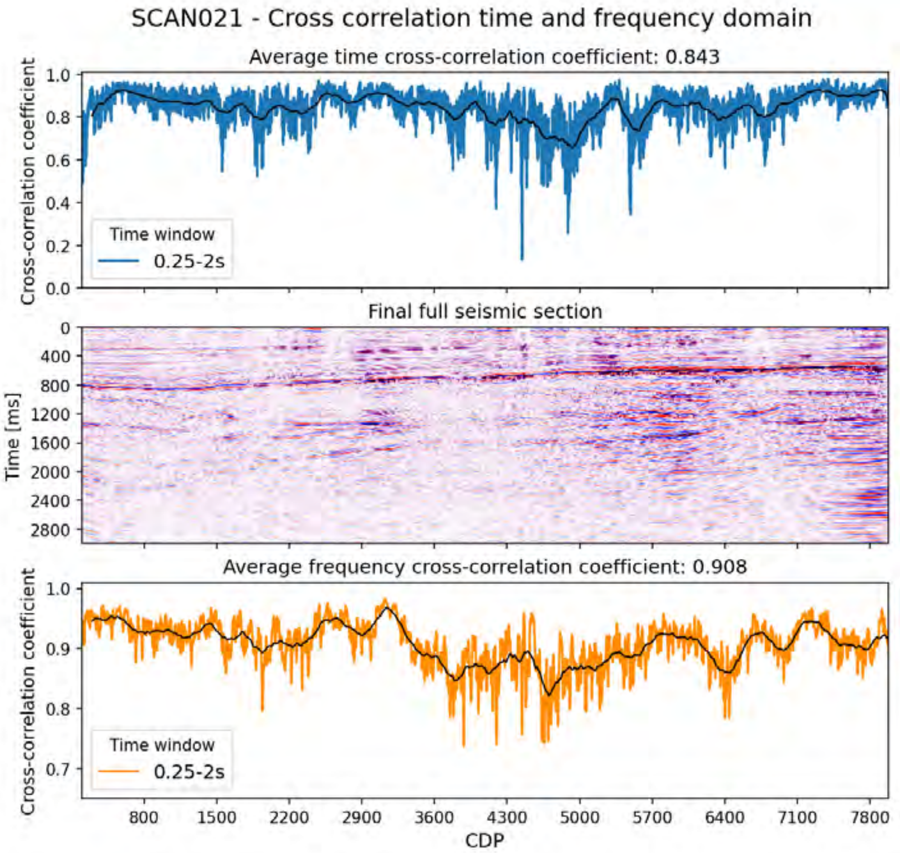


Figure 3.111: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

SCAN021 (figure 3.111) has an average coefficient in the time domain, even though part of the line is of lesser quality (CDP 0-2000), but the layers are flat so the similarity of traces might be the reason the cross-correlation is higher than expected.

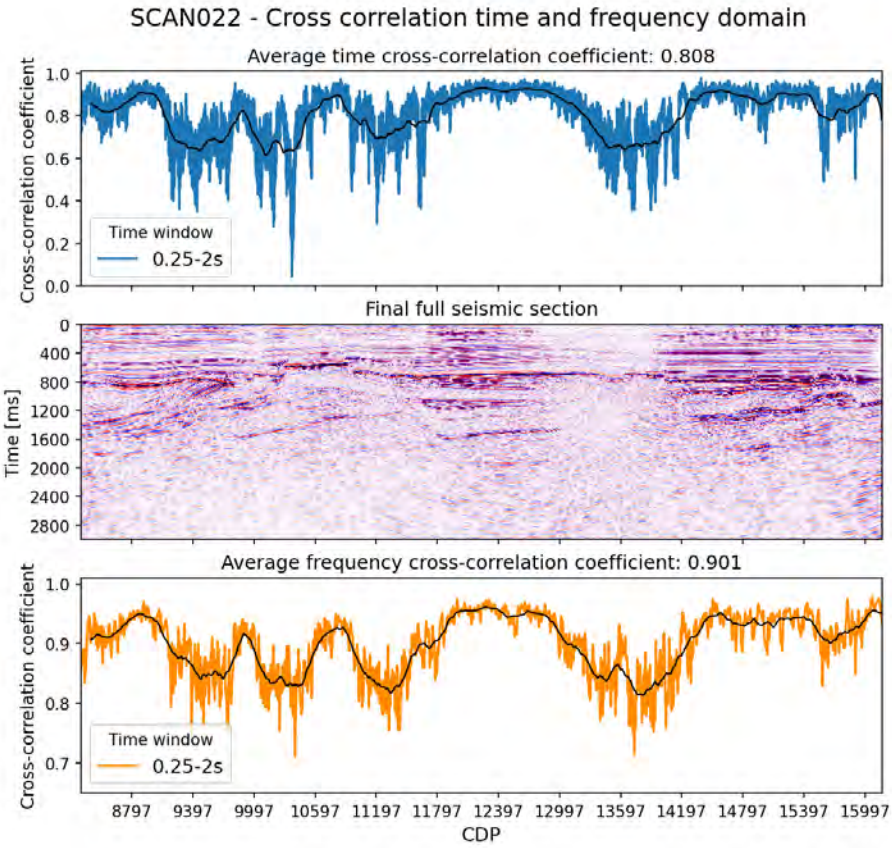


Figure 3.112: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

SCAN022 (figure 3.112) has both the lowest cross-correlation coefficient in the time and in the frequency domain. There are quite some areas of lesser quality, especially between CDP 4500 - 5750. Below the base of the North Sea Supergroup (base of the flat layers around 800ms) even more bad quality data is visible in which almost no layers are distinguishable.

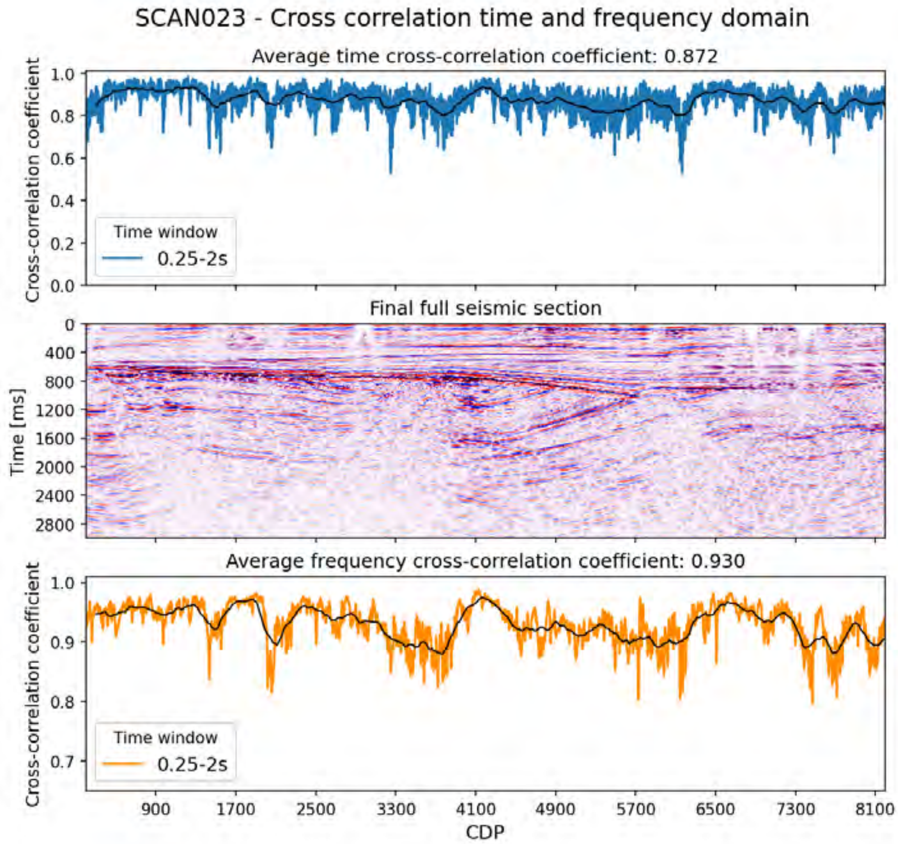


Figure 3.113: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

SCAN023 (figure 3.113) has the highest cross-correlation coefficient in the time domain of the processed sections. This is mainly due to the clear flat upper layers and almost no dipping layers below, besides a large slightly dipping lens between CDP 0-5500, but this has little effect on the correlation. There are some small gaps visible in the upper 400ms, but these are again of little influence.

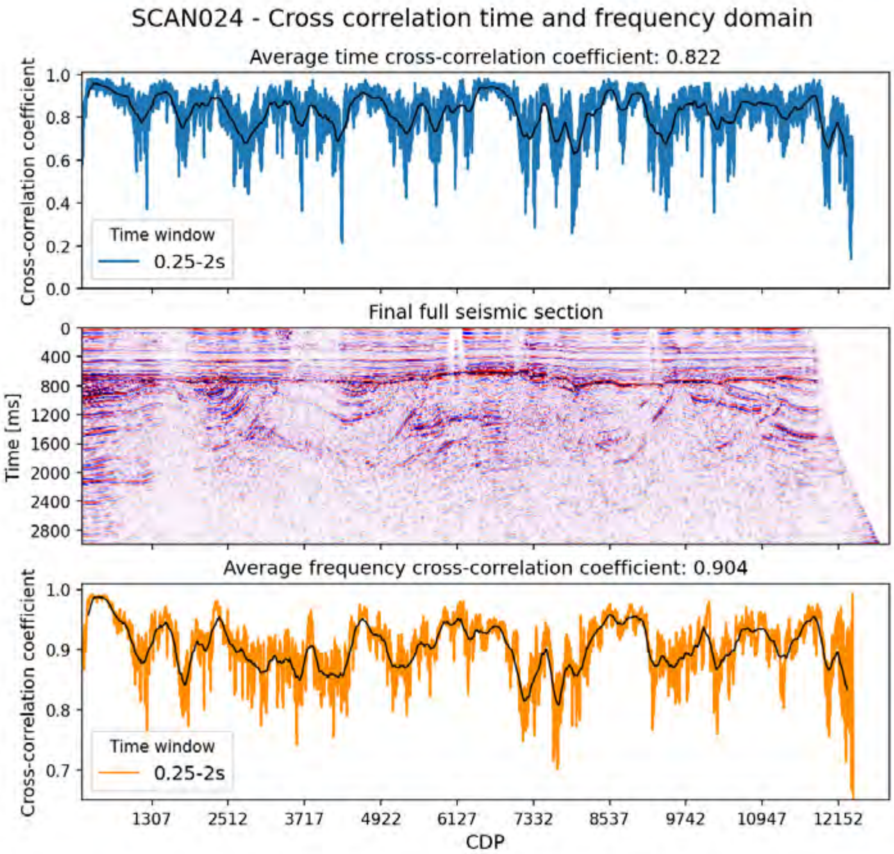


Figure 3.114: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

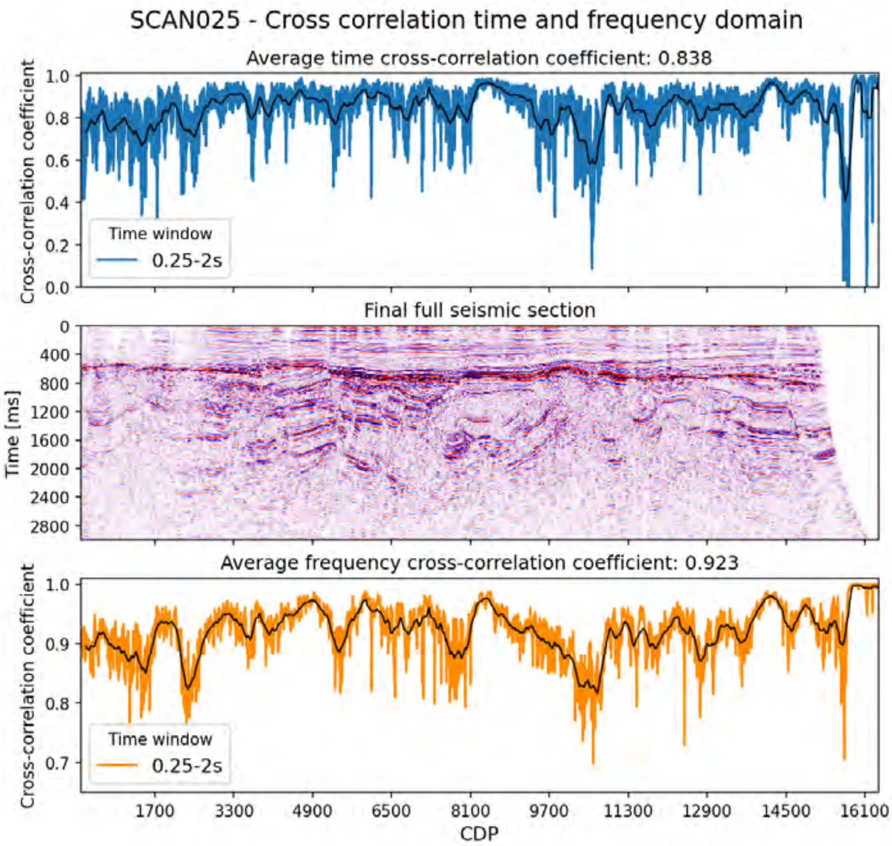


Figure 3.115: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

For SCAN024 (figure 3.114) as well as SCAN025 (figure 3.115) there is still a part to be acquired later in the year, hence the gaps at the right-hand side. Both have lower than average cross-correlation coefficients in the time domain, which in both cases could be due to the thinner North Sea Supergroup and the faults and dips below. When combining the time and frequency cross-correlation coefficients the section of line 25 is better than line 24. When judging the section by eye the same conclusion can be made.

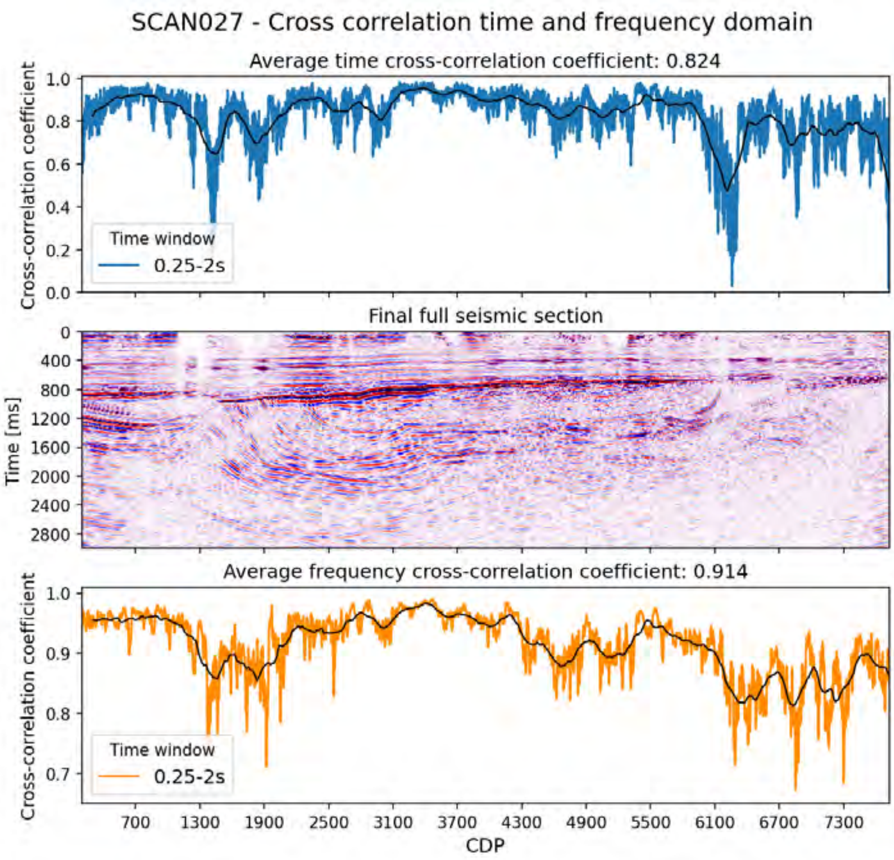


Figure 3.116: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

SCAN027 (figure 3.116) has both a lower than average cross-correlation coefficient in the time domain as well as in the frequency domain. The main causes would be the gaps at the top and dips below the base North Sea around CDP 1000-2000 and the lesser quality data at the end of the line.

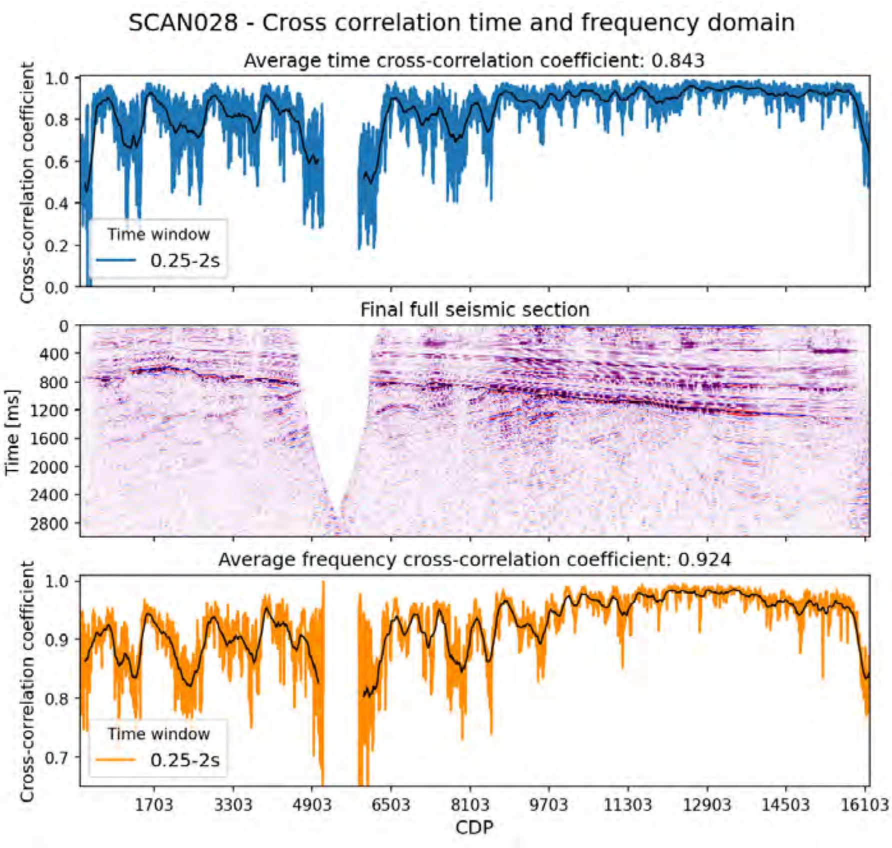


Figure 3.117: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

SCAN028 (figure 3.117), even though there is a large gap in the data, has an average cross-correlation coefficient in both time and frequency domain. The flat layers from halfway to the end of the line are of great influence for this result. The absence or nearly invisible dipping layers below the base North Sea also contribute to this average coefficient.

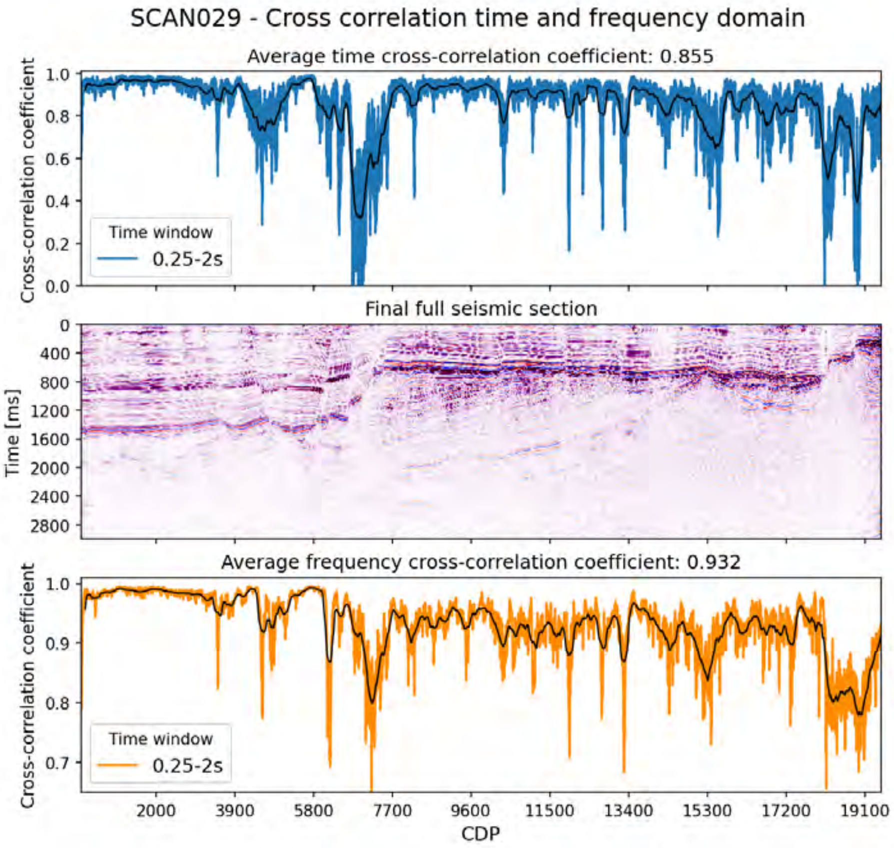


Figure 3.118: The cross-correlation in the time domain (upper), the processed seismic section (middle) and the cross-correlation in the frequency domain (bottom).

Lastly, SCAN029 (figure 3.118) has a higher than average cross-correlation coefficient in the time and frequency domain. The line has several faults in the North Sea Supergroup of which the largest around CDP 7500. Below the base North Sea the layers are again barely distinguishable, which contribute more to a high cross-correlation than clear distinguishable dipping and faulting layers.

Discussion

In the results section seven newly acquired lines were presented separately (sections 3.1-3.7) and subsequently together with results from previous lines (section 3.8). In the last section (3.9) the final processed data for ten lines were discussed. In the following section the newly acquired lines will be discussed in more depth, whereafter they will be placed in context with the rest of the previously acquired lines. Finally, The final processed data will be discussed in detail.

Newly acquired lines

A couple things stood out in the newly acquired lines; the effect of highways, nearby urban or industrial areas, the effect of the geology and the groundwater table and the effect of time spent in the ground on the coupling of the source.

The effect of crossing highways is fairly clear when looking at the receiver domain; the highest noise levels appear there where highways or even national roads are crossed (e.g. figure 3.65, the crossing with the A59). In the shot domain however, these peaks are spread over hundreds of receivers and the effect of several noisy receivers is minimal. The effect increases when acquisition is not crossing a highway but rather stays parallel to it, which can happen often in urban areas. Line 19 displays this effect between shot and receiver points 11000 - 12700 (figures 3.3, 3.4 and 3.13) where the acquisition was close to Eindhoven and parallel to highway A50. The SNR is significantly lower in this region due to the high noise levels. In the fast track this results in slighly lower quality of the data (figure 3.9). A similar effect is visible in industrial areas. An example is line 33 between shot and receiver point 2900 and 3300 near Oosterhout. Due to the constant high noise levels the signal is harder to receive and the seismic section is of poorer quality (section 3.6 and 3.75).

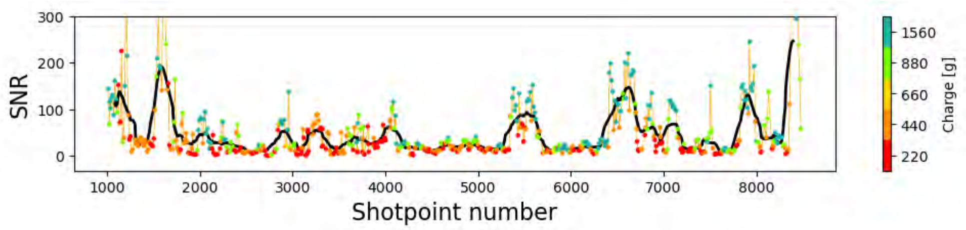
The largest geological impact on the data quality can be found in the Dutch Hills in southern Limburg, where acquisition was done in limestone (section 3.4). The SNR is very low and the effect on the final data is expected to be substantial. The fast track already shows a decrease in quality between CDP 100 - 10000 (figure 3.49). However, the effect is not solely the shooting in limestone. The hard surface made it tougher to drill to depths below the groundwater table. Rotary drilling has been tried in several locations on line 31 to be able to increase the shot depth, and it gives better results, mostly due to the fact that ground roll is less present, but when the shot was above the groundwater the signal amplitude was still low. Shooting above the groundwater table, like previously shot in stowed deposits (van Klaveren, 2021), is shown to decrease the signal amplitude significantly. The fact that the decrease in signal amplitude is both visible in limestone as well as in sand (e.g. figures 3.21 and 3.24) indicates that not just geology, but groundwater table is a major cause of low signal amplitudes. The effect on the seismic section is clearly visible in the fast track of line 30, where the end of line has been shot above the groundwater table (figure 3.36).

The time between drilling and shot date does not seem to influence the signal strength or SNR for individual lines. The results vary from a slightly positive (figure 3.25), to a negative trend (figure 3.38), to no trend at all (figure 3.12).

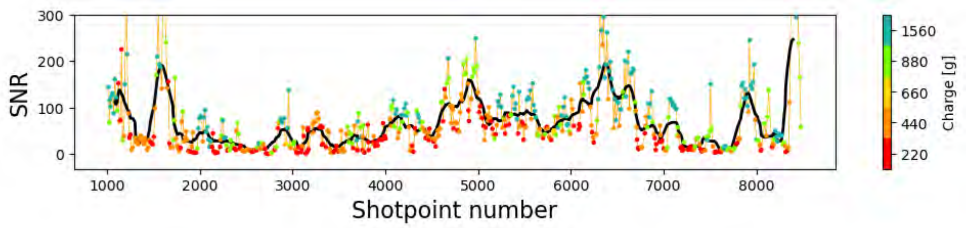
A final thing on the newly acquired lines; the effect of broken receivers. In three cases (lines 19, 30 and 34) a receiver reported constant noise levels 10000 times higher than average for the rest of the receivers. The effect of this is shown in figure 4.1. The SNR surrounding the faulty receiver is lowered significantly, only due to one receiver. Fortunately, one faulty receiver is relatively easy to erase in processing, thus the effect of the receiver is only visible in the research conducted here. It is important to discover and remove faulty receivers as they change the outcome such that different, sometimes incorrect, conclusions could be made.

Analysis of all data

When looking at the entire dataset of all lines previously acquired (Janssen, 2020; van der Lucht, 2020; van Klaveren, 2021) the effect of whether the shots were above or below the water table seems to be the main factor whether signal amplitude is low or high. Lines 4 (not the part situated in the south of



(a)



(b)

Figure 4.1: The SNR with charge size of SCAN034. (a) with the faulty receiver at station 5521.5 the average noise is 0.714 and SNR is 49.9 and (b) without the faulty receiver the average noise is 0.367 and SNR is 68.6.

Flevoland; for a full explanation of that part see Janssen (2020) and van der Lucht (2020)), 6, 9, 16, 20, 22, 30 and 31 all have a part of the line shot above the groundwater table and among these lines are also most of the lowest signal amplitudes found (figure 3.101). Even though most of these points are also situated in two physical geographical regions (stowed deposits and hills, figure 3.95), the low signal amplitude can be attributed to the groundwater table rather than to the geology, considering both regions also contain high amplitude shots whenever they are shot below the groundwater table. The cause of this low signal amplitude above the groundwater table might be that waves travel much slower and are scattered more in a surface when pores are filled with air than pores filled with water. Another cause might be that shot charges placed below the groundwater level seem to have much better coupling, allowing more seismic energy to be transmitted into the subsurface.

The time between drilling date and shot date when considering all lines, does show a trend overall, but only when considering the first 14 days or shorter. Splitting the data into different charge sizes or geologies does not seem to show a much clearer trend, apart from the highest charge sizes and in marine clay. The scatter, however, is large enough that any trends visible may be disregarded. Leaving the source in the ground for multiple days will not or not significantly improve the signal amplitude nor the SNR.

The high noise levels near highways and urban areas, mentioned in the newly acquired lines, are also visible in the previously shot lines. Even though it is clear these areas should be avoided for the optimal result, this is not always achievable, because the areas of interest are mostly situated close to urban areas as the goal is to stimulate the realisation of geothermal energy, which is mainly used by the population living in the cities. The advice is still to avoid shooting along highways as much as possible.

Quality measure of the final processed data

The use of a cross-correlation coefficient in both the time and frequency domain has both advantages and disadvantages. When layers are flat the time domain cross-correlation coefficient gives a good indication whether the line is of good quality or not. However, when layers are dipping or faults are present, but the quality of the layers is good the time domain correlation will indicate that the section is of bad quality, even though it is clear by eye that the section is not. This is also what we see in the investigated sections. The sections with the highest cross-correlation coefficients are either sections with thick flat layers of the North Sea Supergroup (e.g. line 017-018; figure 3.110) or sections without much faulting and dipping layers (e.g. line 23; figure 3.113). On average the cross-correlation in time domain does detect small gaps in the data as long as they do not cover the entire length of the traces, which happens in line 28 (figure 3.117).

The frequency cross-correlation can be used as a more complementary measure. The quality of the data cannot be solely predicted by the frequency cross-correlation as the entire section could be of lesser quality but still have a fairly constant frequency content (e.g. line 21, CDP 0-2000). The combination of frequency and time domain cross-correlation, however, can give a fairly good approximation of better and poorer quality sections. As mentioned in section 3.9, sections SCAN024 and SCAN025 have similar time domain cross-correlation coefficients, both less than average, but if the sections are investigated by eye SCAN024 has more areas of lesser quality (e.g. CDPs 1500-2000 and 3500-4000 and on average below the base North Sea) than SCAN025. The difference in frequency cross-correlation (lower than average for SCAN024, higher than average for SCAN025) then is decisive for the overall quality measure.

The effect of shooting above groundwater is visible in section SCAN022 (figure 3.112). Between CDP 5000 and 6000 the line was shot in stowed deposits, above the groundwater table. This resulted in low signal amplitudes and low SNR (van Klaveren, 2021) and here we can see the effect on the final processed data. the effect on the final processed data is also visible. There is a low quality zone in both the time and frequency domain, resulting in the lowest coefficients of all sections. In this report a few other lines with large parts shot above the groundwater table were researched (lines 30 and 31) and it will be interesting to see what quality those final sections will have.

Conclusion

The newly acquired lines SCAN019, SCAN020 and SCAN030 - SCAN034 were investigated in this report and, together with the lines previously acquired, they were analysed. After analysing several conclusions and recommendations on shot design were made. Together with the final processed sections of lines SCAN001-011, SCAN017-018, UGOU021, UGOU022, SCAN023, SCAN024, SCAN025, SCAN027, SCAN028 and SCAN029 a quality measure was proposed to be able to quantify the final sections.

The conclusions from the acquired lines are firstly, high noise levels, as produced by highways or industrial and urban areas, should be avoided. This can be done by crossing a highway instead of shooting parallel to a highway and at times when traffic is less. Urban and industrial areas might be harder to avoid since these are the areas of interest. Still, it is advisable to divert around an industrial area instead of shooting straight across. Second, drilling should be deep enough to be able to shoot below the groundwater table. The results from both newly acquired lines and final processed data show quality of the data has a large dependency on whether the shots were below or above groundwater. The groundwater levels are dependent on the geology of the area. High elevations or a certain type of geology might influence groundwater levels. It is advisable to check beforehand, whenever there is doubt on groundwater levels, at approximately what depth the groundwater table is and try to drill below this level. Moreover, previous recommendations about the charge size still stand. A higher charge size will produce higher signal amplitudes, thus it is advisable to use the highest charge sizes possible and permitted. Finally, the fact that shot depth is of influence is confirmed by rotary drilling on line 31, where an increased shot depth showed a better result due to ground roll being less present in the shot data.

One parameter which did not contribute to nor reduce the signal amplitude significantly was the time between drilling date and shot date. Even though there were exceptions, it would not be necessary to take this into account during acquisition.

The quality measure of the final processed data turned out to be a solid quantification tool as long as the time and frequency domain cross-correlation coefficient are both taken into account. However, it can be improved. Dips and faults still produce a low coefficient, even though they are correctly processed and visible. A better quality measure would also take these dips and faults into account in a correct way, thus an improvement in quality measure could be researched in later studies. The cross-correlation coefficient per line could also be researched geographically to see whether for instance physical geographical regions influence the data in any way.

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