Insights into the quality of newly acquired SCAN data

Internship at EBN B.V.

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5 February 2021
The Netherlands

Utrecht University

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Summary

This internship is part of the SCAN project. The goal of the SCAN project is to better image the subsurface of the Netherlands to obtain a better understanding of its geothermal potential. The SCAN project consists of acquiring 2D seismic data, reprocessing old seismic data and scientific drilling. In this report we focus on the newly acquired data. This report describes the quality of the shot data for lines 11-18 and 21-29 as well as a proxi for quality of the final seismic sections of lines 2-10 and 12-16. For the shot data, the quality is determined by signal to noise ratios (SNR), high ratios correspond to high quality. We found that in general higher charge sizes and deeper shots lead to the higher SNRs. Also we found that the low quality shots in the stowed glacial deposits are fired above the ground water table. Firing shots above the ground water table seems to be the cause of this low quality data. For the final seismic sections we found that cross correlation in the time and frequency domain can be used as proxies for data quality measures. Shot gaps do effect the data quality of the final seismic sections but when the fold is kept high by replacement shots, this effect seems small.

1 Introduction

This internship is part of the SCAN project. SCAN is a large 2D seismic acquisition programme in the Netherlands, aiming to provide a better image of the subsurface in order to explore geothermal potential. The SCAN project has been established because a large part of the subsurface of the Netherlands has not been mapped well enough for a good geological understanding. In the north and west, however, we do have enough seismic data available thanks to oil and gas exploration. Figure 1 shows the amount of data that is available between the base Rotliegend and the Based North Sea Group. The white regions in figure 1 are regions where we have insufficient data for a good evaluation of the geothermal potential; the SCAN programme is designed to fill these data gaps.

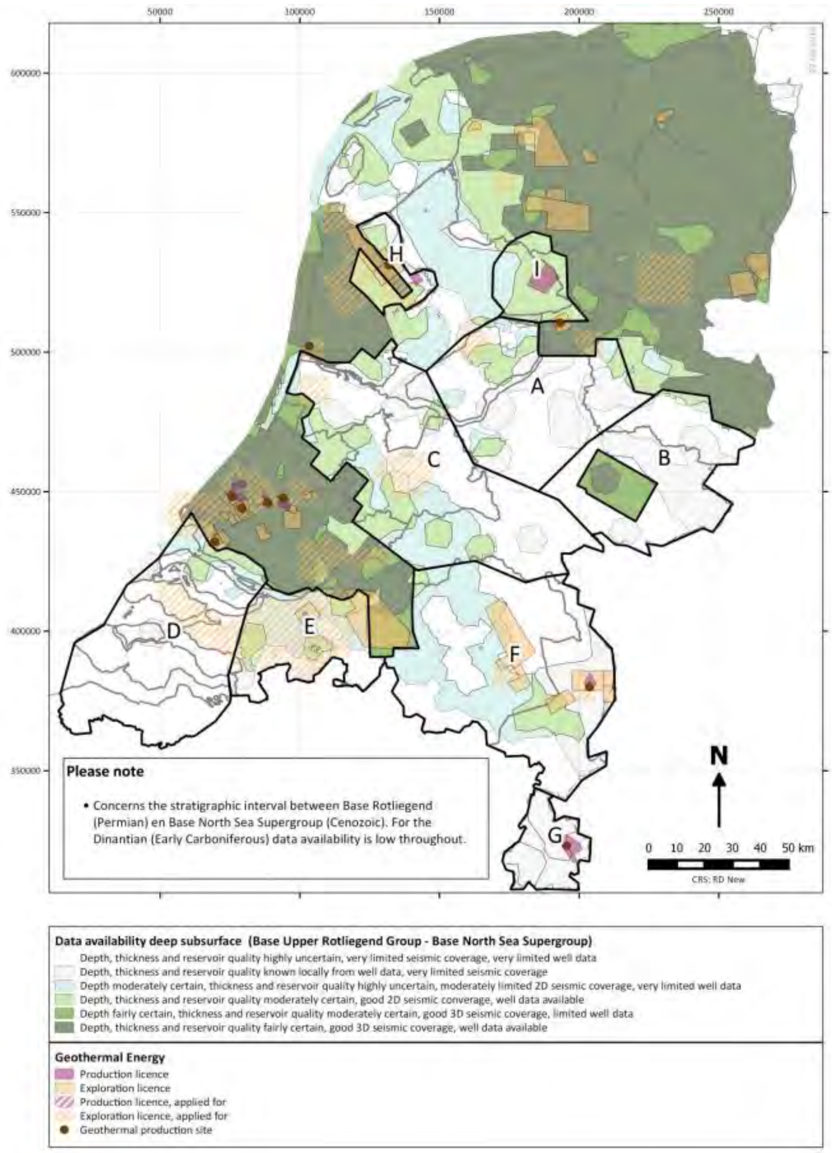


Figure 1: Data availability for the Base Rotliegend – Base North Sea Group [van Lochem et al., 2019]

EBN B.V. is conducting this project commissioned by the ministry of Economic Affairs and Climate Policy. The geotechnical operations team (GTO) of EBN B.V. is responsible for this project and outsources both acquisition and processing of the seismic data. Rossingh B.V. is the seismic acquisition contractor and acquires the seismic data throughout the Netherlands. DownUnder GeoSolutions (DUG) is the selected seismic processing contractor and the work is executed at their London based processing center. Thanks to quality control of GTO, the three companies together have successfully delivered 14 processed seismic sections at the moment of writing. In total there are 42 lines planned. The raw SEGY field data as well as the final Pre-Stack Time Migration results will be made public through TNO's NLOG website.

A seismic line represent a 2D cross section of the subsurface. This cross section provides information on layer thicknesses and structures that are present in the subsurface, like faults and fold structures. These images allow to find thicknesses of target layers that potentially contain hot water, and therefore indicate geothermal potential.

The report focuses on the newly acquired data. After this first stage of data acquisition, scientific drilling and core logging will provide information on rock properties of the target layers and will allow for calibration of the seismic images to actual depths. Most targets are located between ∼0.5-4 km depth, but the aim is to also image the Dinantian layer which in some places is located at ∼8 km depth. Figure 2 shows the primary and secondary targets. Several UDG (ultra deep geothermal) consortia participate in the data acquisition such as GOUD, Renkum and Oost-Brabant consortium. SCAN acquires regional UDG lines for those consortia.

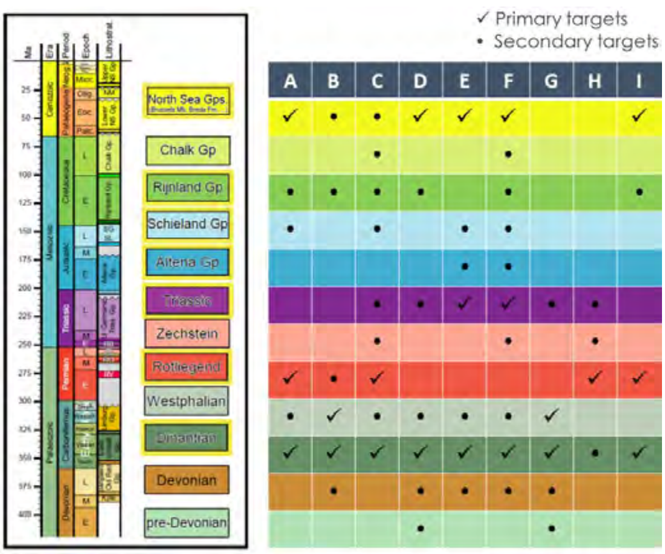


Figure 2: Overview of the primary and secondary targets in the SCAN areas [van Lochem et al., 2019]

In 2019 a test line was carried out to determine the best acquisition parameters [Janssen, 2020]. Table 1 shows the chosen parameters, used for all lines.

Table 1: Acquisition parameters

Seismic design	Split spread
Maximum offset	6997.5 m
Receiver station interval	5 m
Receiver station type	5 Hz geophone
Source type	Explosive source
Source interval	60 m
Source depth	4 - 26 m
Charge size	220 g - 1560 g
Sample rate	2 ms
Record length	10 s

This report consists of three parts:

1) Analysis of data quality of lines 11-18 & 21-29

2) Analysis per parameter between all lines

3) Analysis of the processed data

The first part is a continuation of work done by Wouter Janssen and Ingmar van der Lucht. Janssen [2020] developed the first set of workflows using the test line data. Van der Lucht [2020] analysed the effect of different parameters such as windspeed, time of the day, geology, charge size, uphole velocities and shot depth on RMS amplitudes and signal to noise ratios along lines 2-10. Section 2 describes how this analyses is done since a similar approach is used for lines 11-18 and 21-29. The lines evaluated in this report are shown in figure 3.

In the second part all the data from all lines is used to do analysis per parameter, is there a relation between the parameter (e.g. charge size) and high or low signal to noise ratios (SNR)? If so, it is best to optimize that parameter during acquisition. Three parameters are investigated that seem to contribute most to good SNRs according to earlier research of Janssen [2020] and Van der Lucht [2020]: charge size, shot depth and groundwater levels.

Figure 3: Map of the seismic lines evaluated in this report. Blue indicates SCAN lines, orange indicates GOUD lines, red indicates Renkum lines and yellow indicates the Oost Brabant line

The last part focuses on the final processed data, which was processed through a state-of-the-art broadband Kirchhoff anisotropic pre-stack time migration processing flow. This data has been processed by DUG and in this section we try to define good and bad quality data by taking cross correlations between two traces. We will also look at the influence of shot gaps along a line, when for example a river limits the acquisition, on the final product.

2 Methods

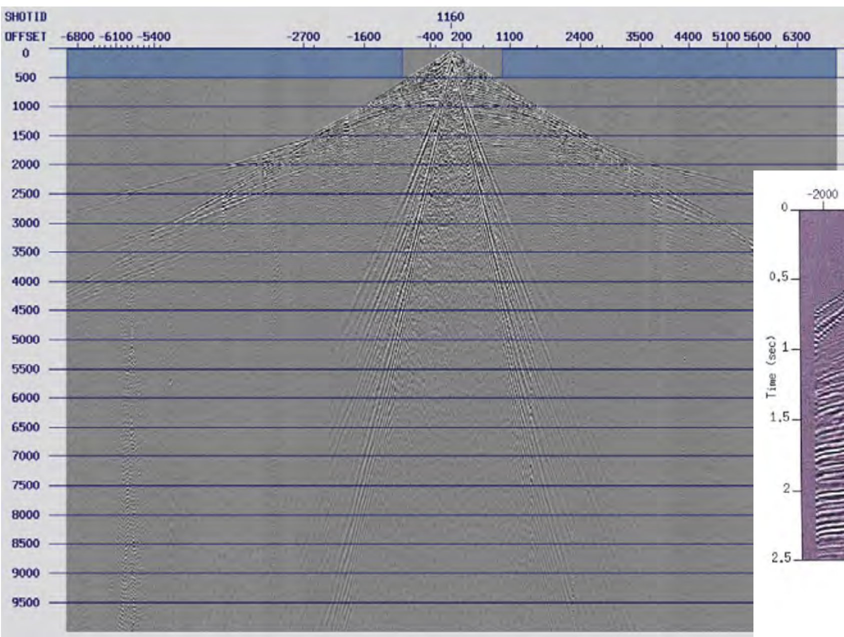
2.1 Determining data quality in shot domain

The data is delivered in SEGY format and can be read with the software *GLOBEClaritas™*. We use signal to noise ratios as a proxi for data quality. When SNR is high, it either means the RMS signal amplitude is very high or that noise is very low, both are favorable. When SNR is low, the RMS signal amplitude can be low or noise is very high. In order to determine SNRs we need to define both signal and noise levels, in the shot domain. For every shot the RMS signal is determined as well as the RMS noise. With *Python* scripts the SNRs are calculated following the formula:

$$SNR = \frac{RMS\ signal}{RMS\ noise} \tag{1}$$

Figure 4 shows a shot, as an example. Here we see the amplitudes measured by receivers 7 km north and 7 km south from this shot, for a 10 seconds long recording time. The y-axis represents two-way-travel time. In this seismic image we see all the waves that cause amplitude increases at the receiver. Not all of those amplitudes are reflections from layers, so we have to be careful in what we interpret as results and what not. Figure 5 shows the different wave types that can appear on a seismic shot record. We are only interested in the dark blue reflection waves for the determination of the signal amplitude.

The RMS noise is determined in the 0-500 ms window of the shots, for all offsets excluding -900 till 900 meters, indicated in blue in figure 4. The waves generated by the shot have not reached those receivers yet, so these amplitudes represent background noise.



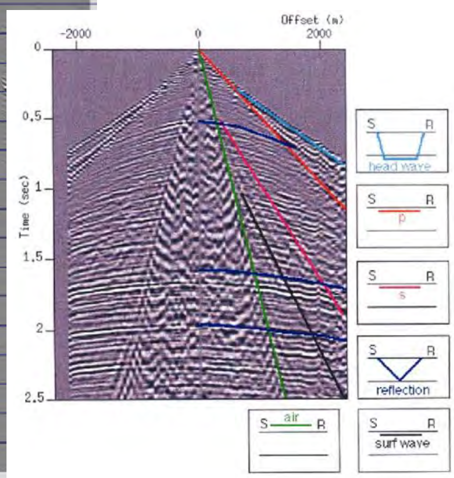


Figure 4: Example of a seismic shot record. The x-axis shows offset and the y-axis shows two way travel time. This shot is from line 12, shot id 1160.

Figure 5: Typical raw seismic record where all different types of waves are indicated [Debu, 2011]

Before the RMS signal could be determined, some processing steps are taken. An FK-mute filter is applied to mute the effect of the ground roll (i.e. surface waves), as shown in figure 6a. Since high amplitudes remain in the ground roll window, this window was muted completely. Everything above the first arrivals was muted as well to determine mainly signal, and not noise (figure 6b). The most reflections are found in the first second. We determine the signal for two windows: 0-1s and 1-2s (figure 6c). For the deeper parts the signal amplitude has declined significantly, making it more difficult to determine a reliable SNR.

a

b

c

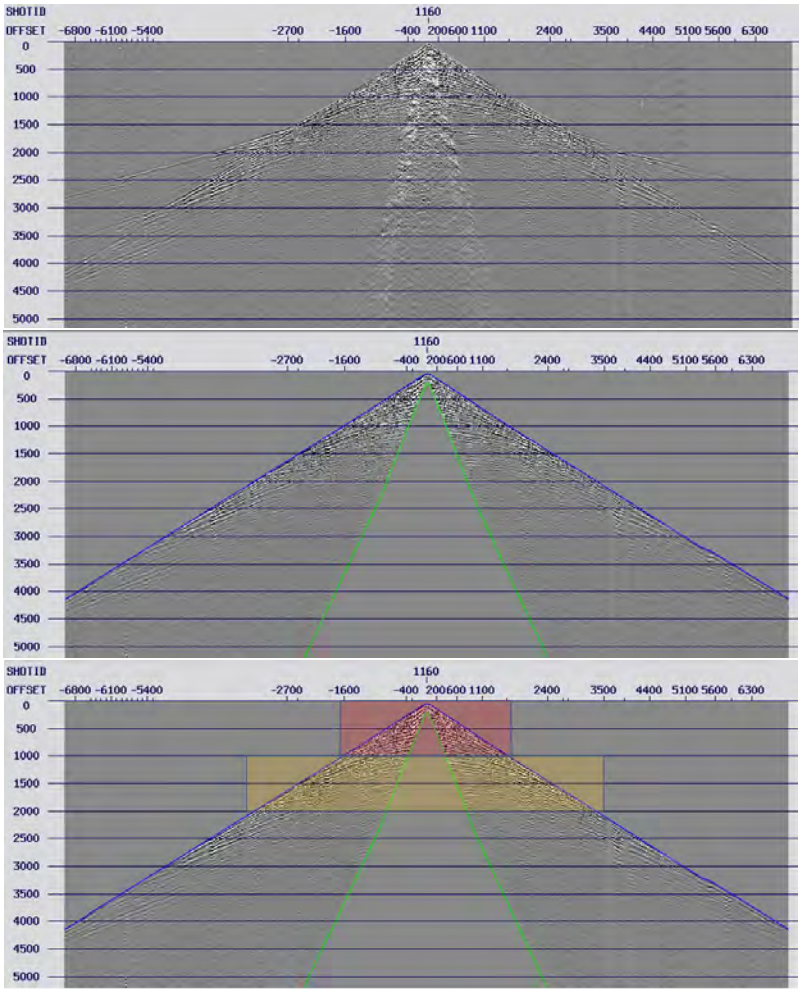


Figure 6: Processing steps to determine the RMS signal. a) Seismic shot after a FK-filter was applied. b) Seismic shot after front and tail mute was applied. c) Red box indicates the 0-1s window on which the signal is calculated, the orange box indicated the 1-2s window.

2.2 Determining noise levels in the receiver domain

Besides determining noise levels in the shot domain for SNR purposes, the noise levels are also determined per receiver, to see which receiver is noisy and why. To do so the data is sorted to the receiver domain, in this way the noise contribution of every shot can be selected per receiver. All the noise contributions of all shots are summed for that single receiver. The total summation is the RMS noise amplitude of that receiver station location. Noise is mostly generated by external sources and is observed at the receiver stations, not at the shot locations. This distinction shows where noisy surroundings exist.

2.3 Determining data quality of final processed data

One way of determining the data quality is by taking cross correlations between neighbouring CDP traces. Cross correlation assumes that all the coherent data on the seismic trace represents the seismic signal and all non-coherent data is representing noise. This assumption is not always valid as will we see in the result section (3.3.1). In this section we will explain the cross correlation method.

Cross correlation is a measure of similarity of two series. To explain this we see an example in figure 7, where two series are compared. If they are completely similar in shape the cross correlation coefficient is 1, if they are completely opposite the coefficient is -1 and if they are relatively similar in shape but not exact it will be something like 0.5. The coefficients vary between -1 and 1.

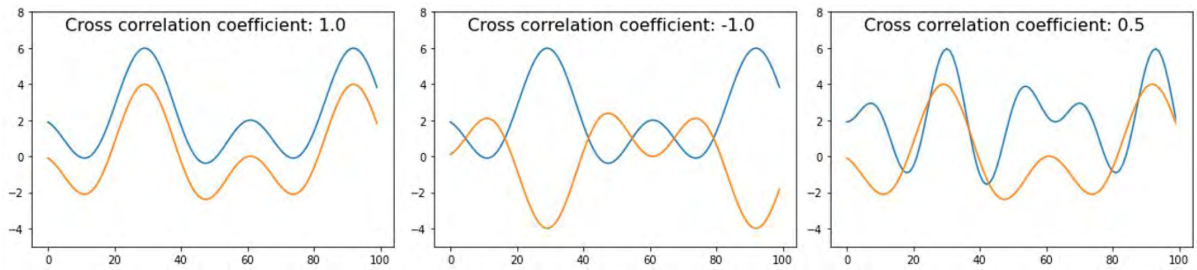


Figure 7: Cross correlation coefficient for three different comparisons between two series

We do not compare the direct neighbouring traces because they would be too similar and the cross correlation coefficient would always be very high, also when the data is of low quality. We checked different trace steps and found that a trace step of 10 distinguishes bad and good data the best (figure 8). Neighbouring shapes are still close to the original trace, but not so far that the traces are completely dissimilar. A step of 10 represents 25 meters, as the CDP spacing of the final processed data is 2.5 meter.

We compare the first CDP trace of the final product with trace 11, trace 2 with trace 12 and in this way we move through all the CDP traces to find a measure of quality. We do this in the time domain but also in the frequency domain. Of every trace the frequency spectrum is determined, those frequency series are then compared in a similar way.

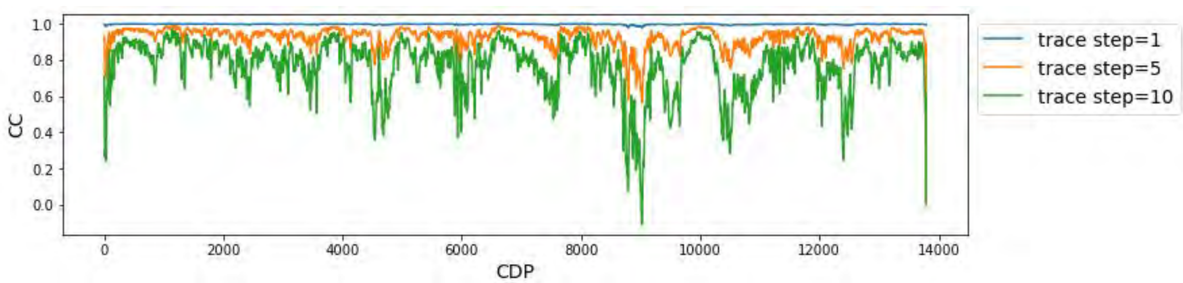


Figure 8: Cross correlation coefficient for three different trace steps

3 Results

3.1 Analysis of lines 11 - 29

For every line we show the same plots, to have an overview per line. In the text we will point out when we see something remarkable in the plots as well as acquisition details. Table 2 shows the average RMS signal and average RMS noise for all lines together, also divided in different regions and in different regions classified based on physical geography. This allows comparison of the values shown in the plots, to be able to see whether amplitudes are relatively high or low.

Table 2: Average signal and noise amplitudes for all lines, for the different regions and for different regions classified based on physical geography

	RMS signal average	RMS noise average	SNR average
all lines	12.59	0.24	74.08
mid	7.62	0.27	32.89
west	11.97	0.25	55.98
east	18.77	0.25	136.51
south	16.64	0.15	118.89
high sand area	15	0.22	99.34
river area	10.2	0.25	51.85
sea clay area	11.03	0.24	50
low peat area	12.86	0.26	57.2
stowed glacial deposits	3.34	0.36	14.91

On every signal and noise amplitude map the colours are scaled to the values of that particular line. Scaled between the minimum and maximum value of that line, to clearly see the variation between that line. Colours on other maps therefore indicate other amplitudes, shown in the legends. Every colour represents 20% of the data, data that falls within the given interval. The receiver domain noise amplitude plots are all scaled between 0 and 3. In all signal amplitudes, SNR and uphole velocity plots a black line is shown behind the data points. This is a moving average of 15pt. The average is taken from 7 points left and 7 points right of this value. In this way the trend is easier to see.

The groundwater level plots are based on data from grondwatertools.nl, a database from *TNO*. There are little data points in the west of the Netherlands so the tool was not always able to generate a water level grid for every line. However, we know that the ground water levels are around zero in the wetlands with low topography. Therefore not every line has a ground water plot, but the lines that have lots of topography and are important for our analysis (section 3.2.3) do have one.

For lines 12-16, the lines that are processed and delivered, we show plots of the final seismic sections. For the other lines the fast tracks are shown in the overview per line. The fast tracks are the seismic sections created after two weeks of processing and they give a good first order image of the subsurface. On the seismic sections the y-axis represents two-way-travel time, the time it take for waves to move downwards, reflect where a difference in impedance of layers exist and to move back.

3.1.1 SCAN011

Line 11 runs from north to south and runs east of Utrecht. High signal amplitude are reached at the end of the line, large charge size were used for those shots. Most shots are fired in the evening between 18 and 20h. Between shotpoint 3500 and 5000 SNRs are relatively low, low charges where used. Noise levels are also high in this region. There is a shot gap of 900 meter because of the Lek river between shot location 2352.5 and 2629.5. There are no shots above the ground water level.

Table 3: Acquisition parameters line 11

Number of shots	445
Range source station	1031.5-6497.5
Number of receivers	8515
Range receiver station	1047-6501
Total length	27.505 km

The noise per receiver map, figure 19, clearly shows high noise amplitudes near the A27. Line 11 is being processed by *DUG* at the moment of writing. We only have a fast track seismic section based on two weeks of processing available for lines 11 (figure 15c) and 17-29 and not a final full seismic section.

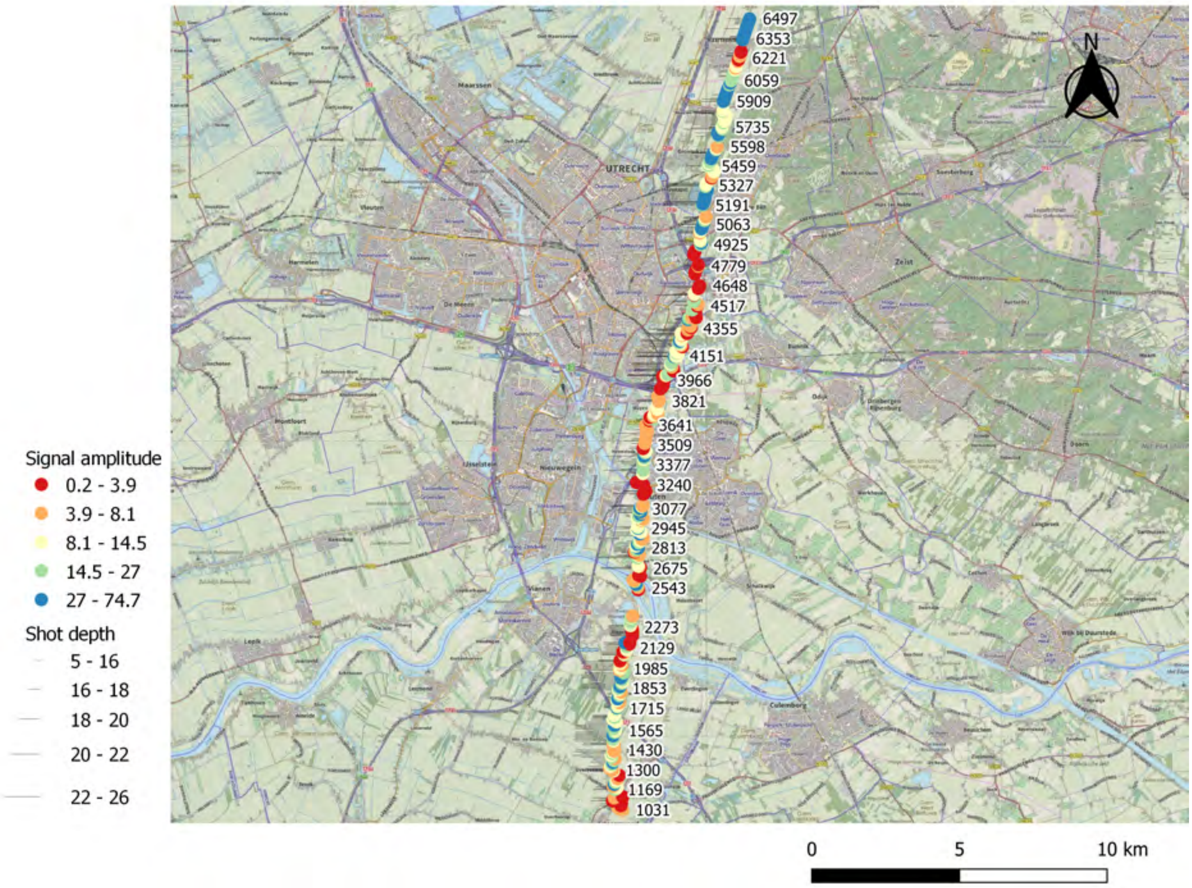


Figure 9: Regional map of line 11. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

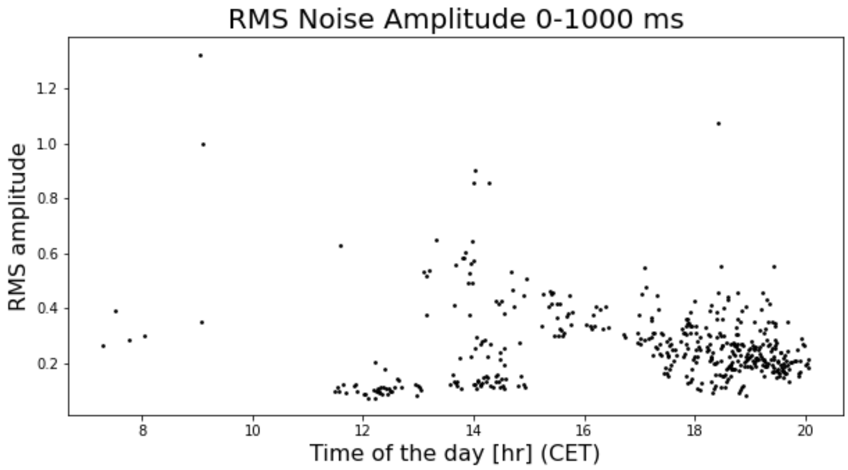


Figure 10: Noise amplitudes in the shot domain per time of the day

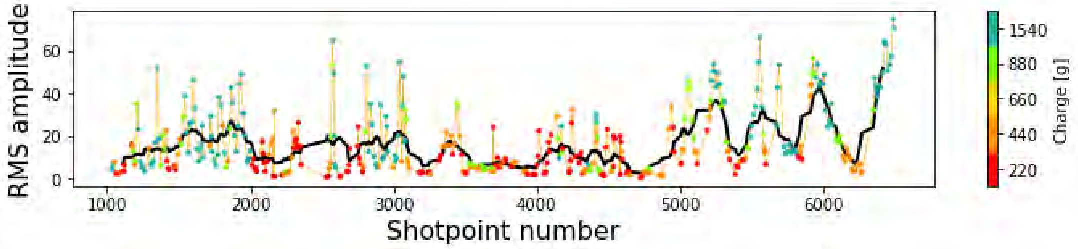


Figure 11: RMS Signal amplitudes in the 0-1s window

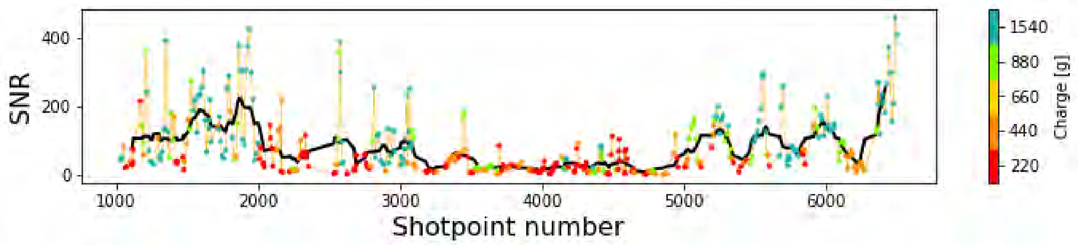


Figure 12: Signal to noise ratios in the 0-1s window with charge size indicator

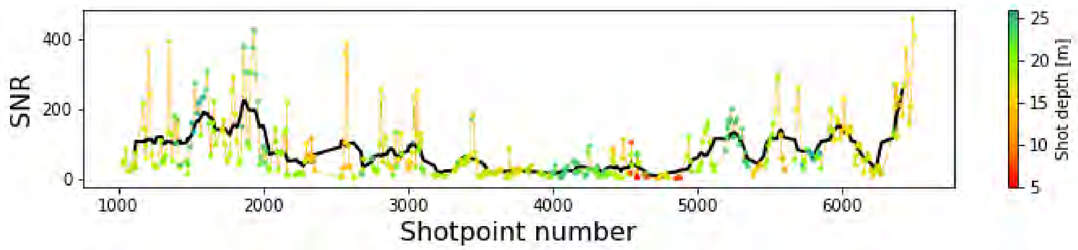


Figure 13: Signal to noise ratios in the 0-1s window with shot depth indicator

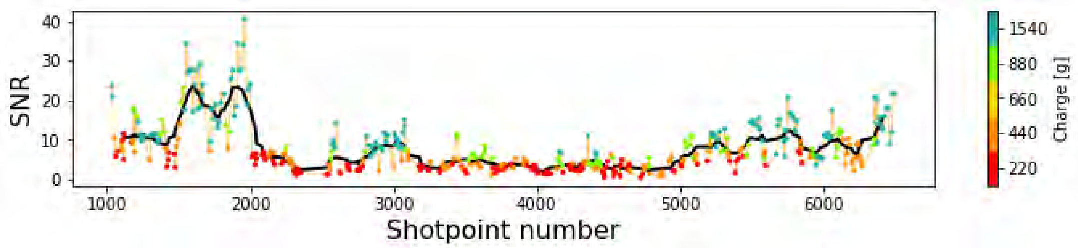


Figure 14: Signal to noise ratios in the 1-2s window with charge size indicator

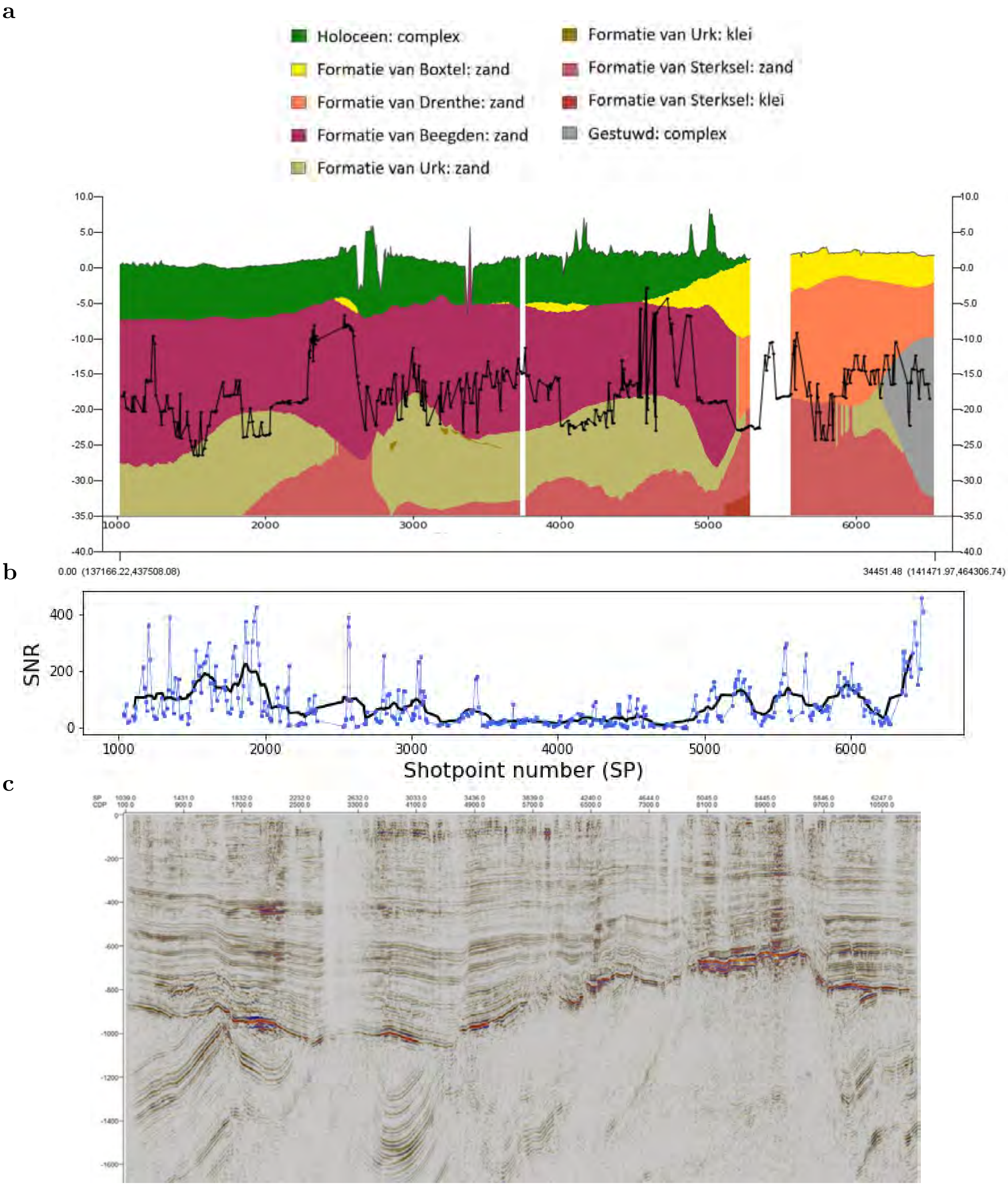


Figure 15: SCAN011. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

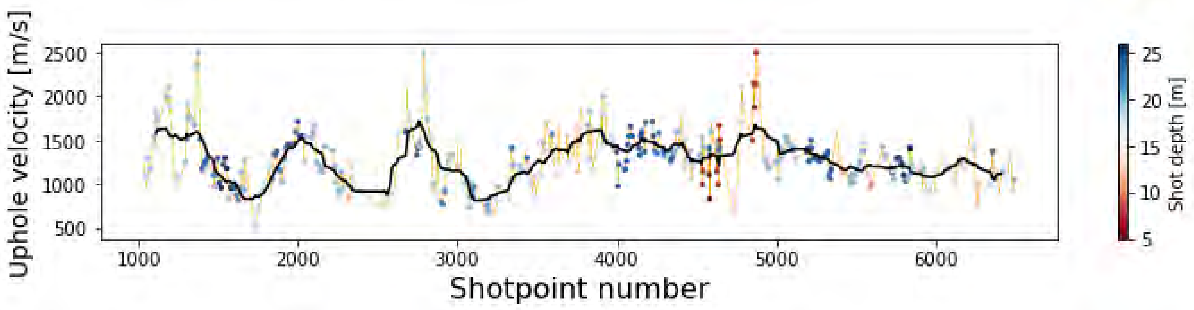


Figure 16: Uphole velocity with shot depth indicator, calculated from uphole times

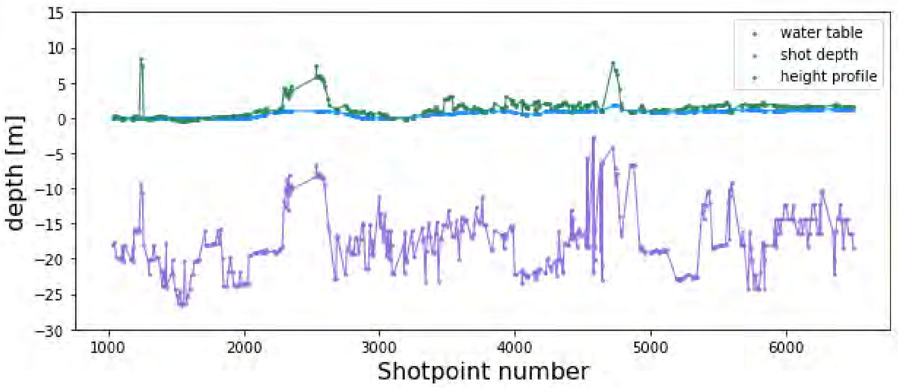


Figure 17: Ground water table along line 11

Receiver domain:

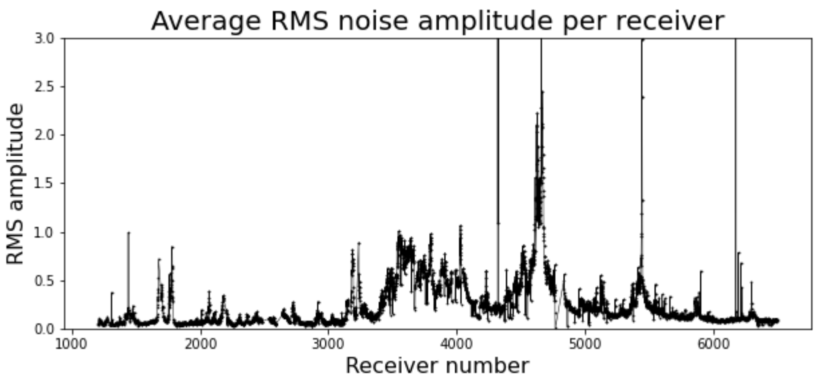


Figure 18: Noise amplitudes in the receiver domain

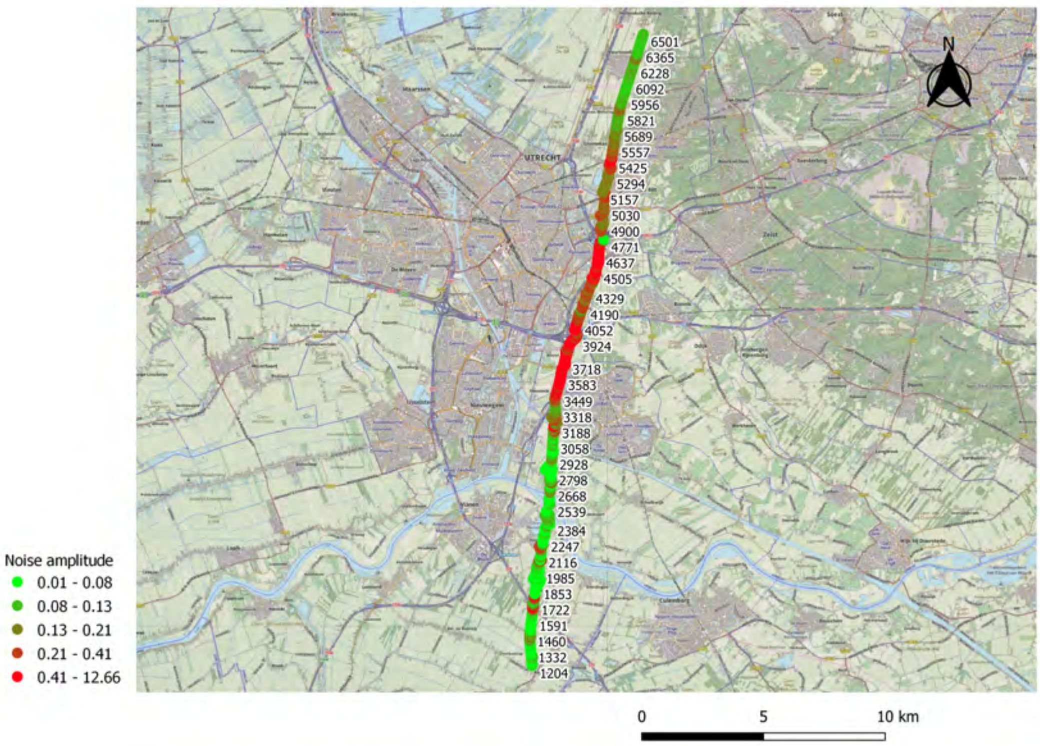


Figure 19: Regional map of line 11. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.2 SCAN012

Line 12 runs from north to south and runs east of Zwolle and Apeldoorn. In general a lot of low charge sizes were used along this line. Between shotpoint 5500 and 6000 shots are very shallow, which we also see in the geological map (figure 26). This corresponds to low uphole velocities (figure 27). In the geological map we see stowed glacial deposits in the south, near the Veluwe. The shots in those layers are shot above the water table. The noise per receiver map, figure 30, clearly shows high noise levels near the A58 and the A2.

Table 4: Acquisition parameters line 12

Number of shots	922
Range source station	1019.5-12593.5
Number of receivers	11400
Range receiver station	1001-12599
Total length	57.99 km

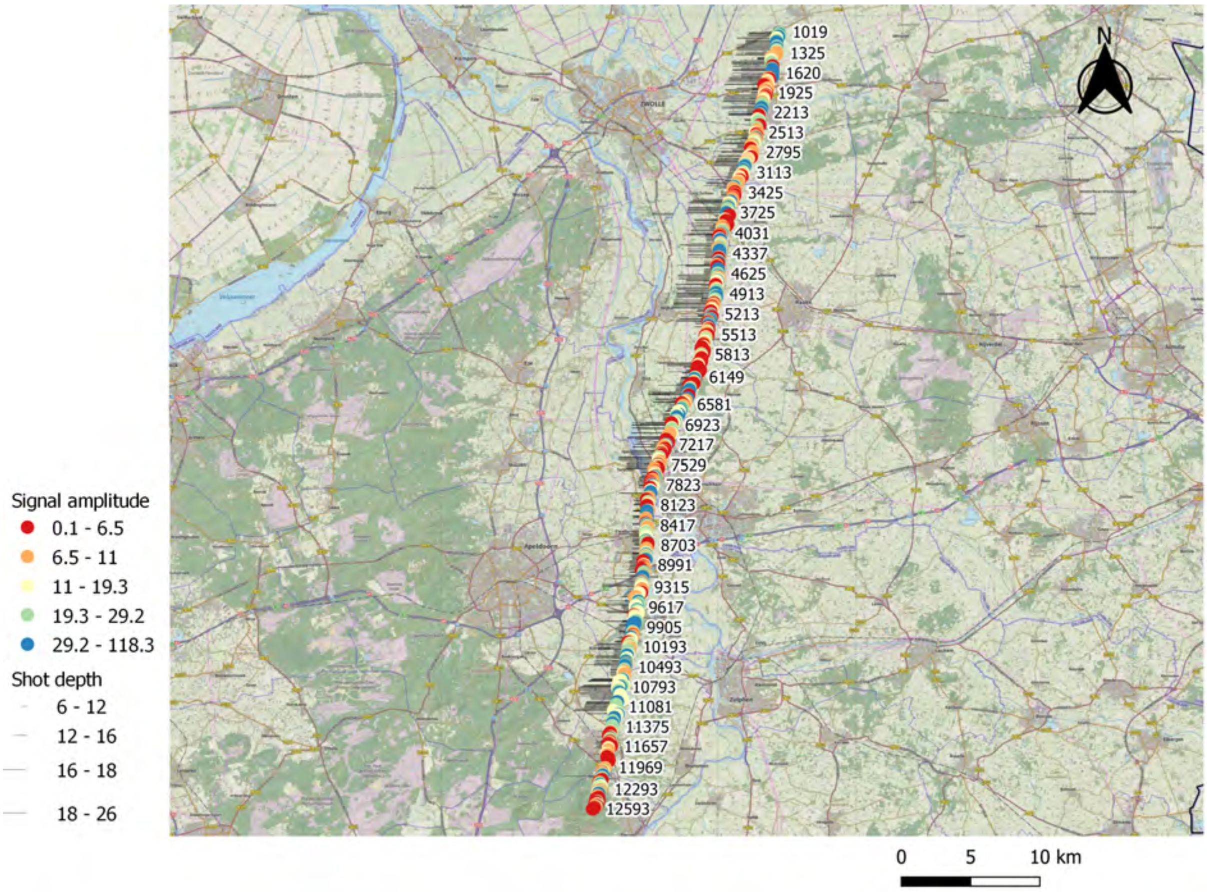


Figure 20: Regional map of line 12. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

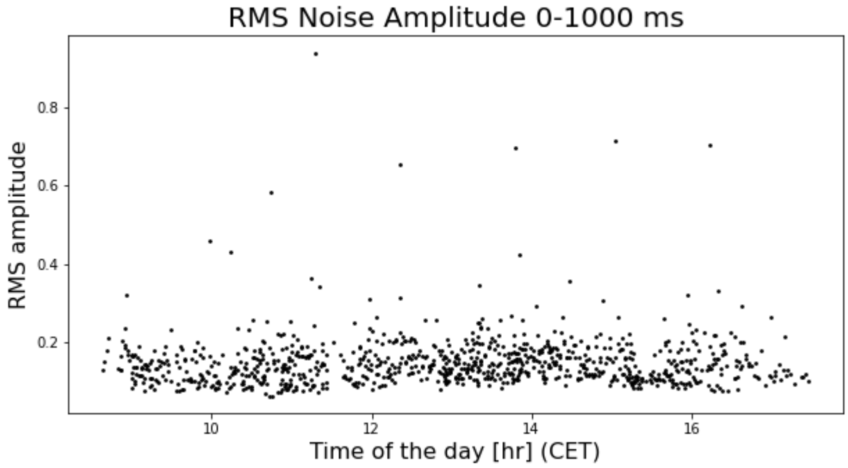


Figure 21: Noise amplitudes in the shot domain per time of the day

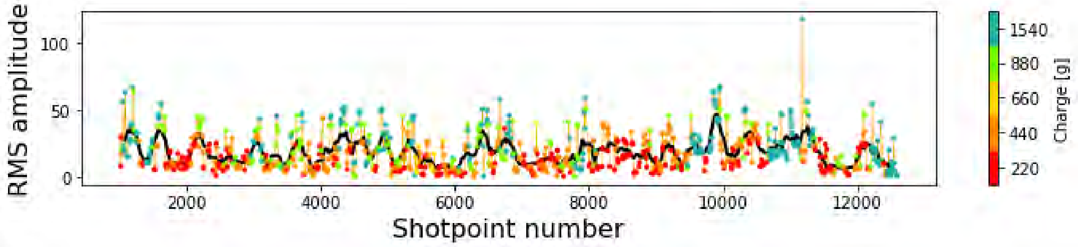


Figure 22: RMS Signal amplitudes in the 0-1s window

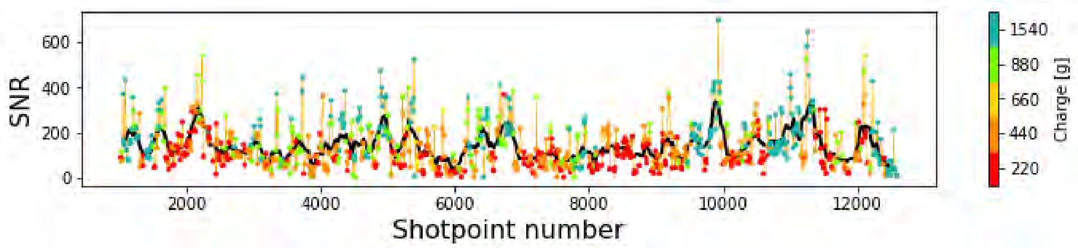


Figure 23: Signal to noise ratios in the 0-1s window with charge size indicator

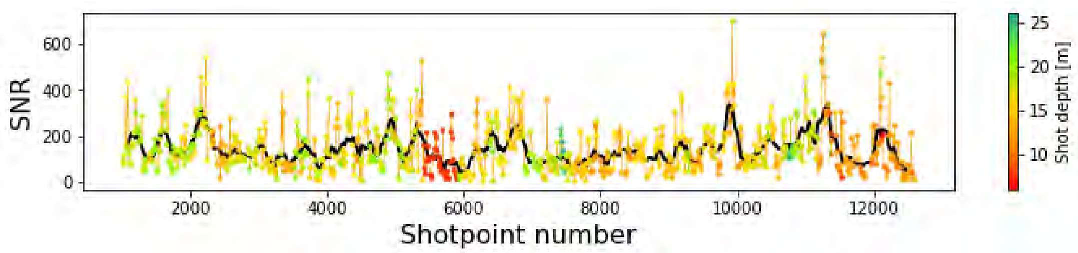


Figure 24: Signal to noise ratios in the 0-1s window with charge size indicator

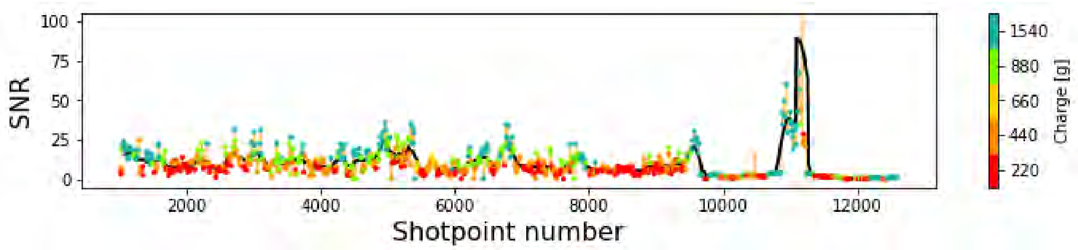
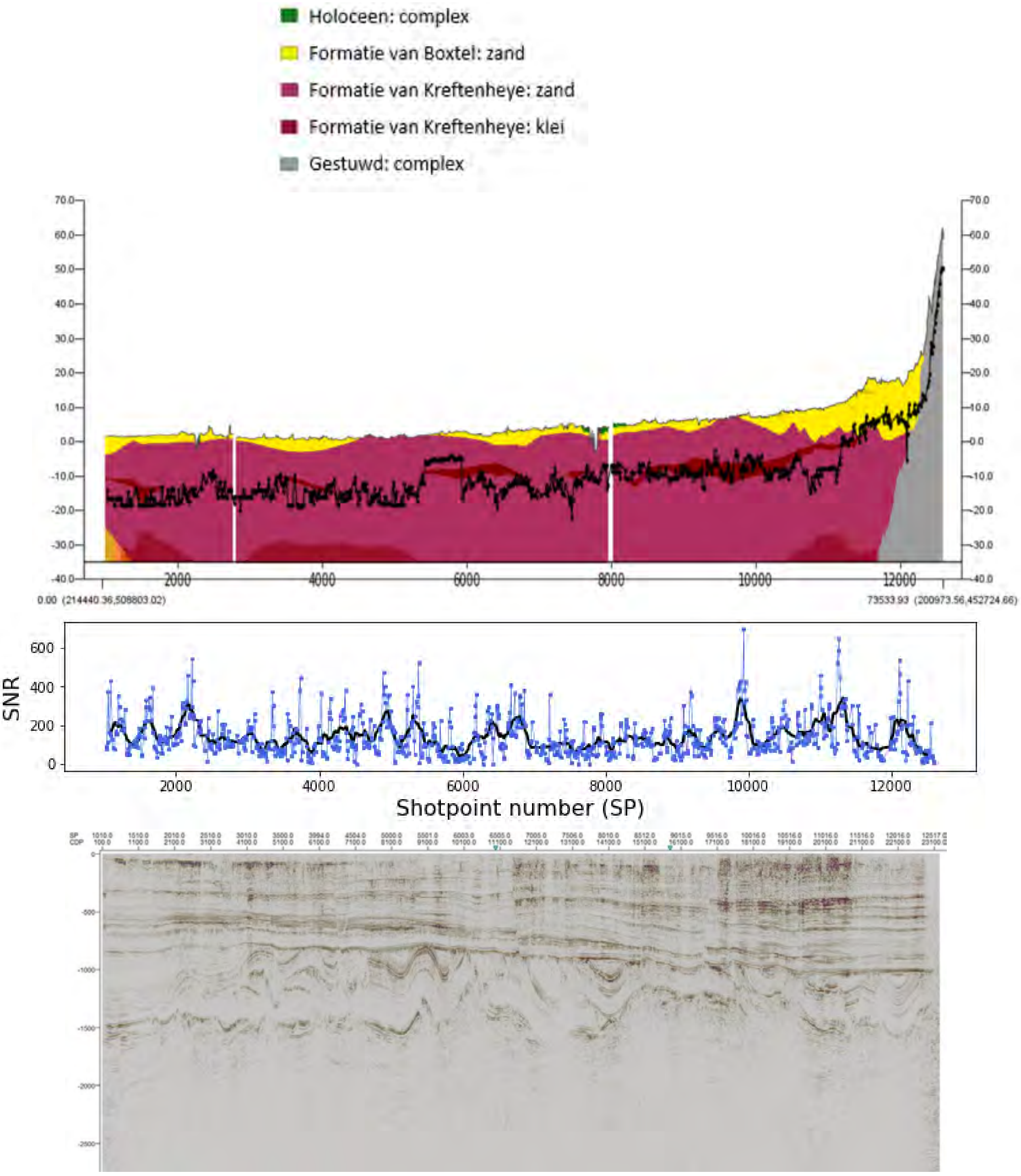


Figure 25: Signal to noise ratios in the 1-2s window with charge size indicator

a



b

c

Figure 26: SCAN012. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Final seismic section.

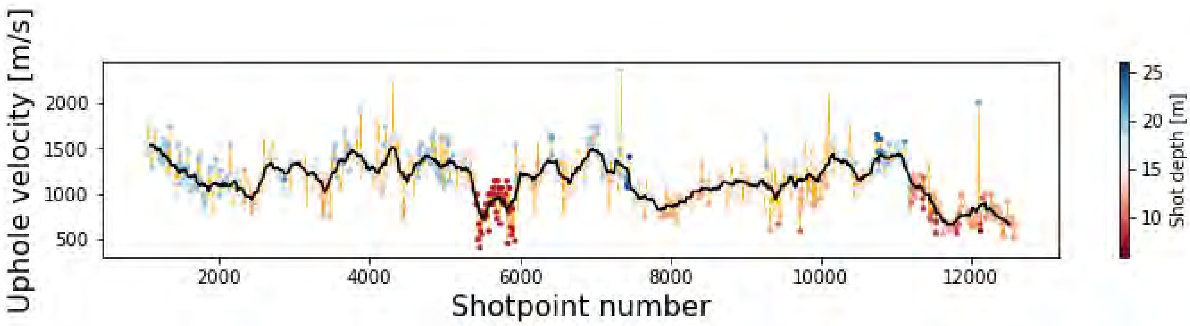


Figure 27: Uphole velocity with shot depth indicator, calculated from uphole times

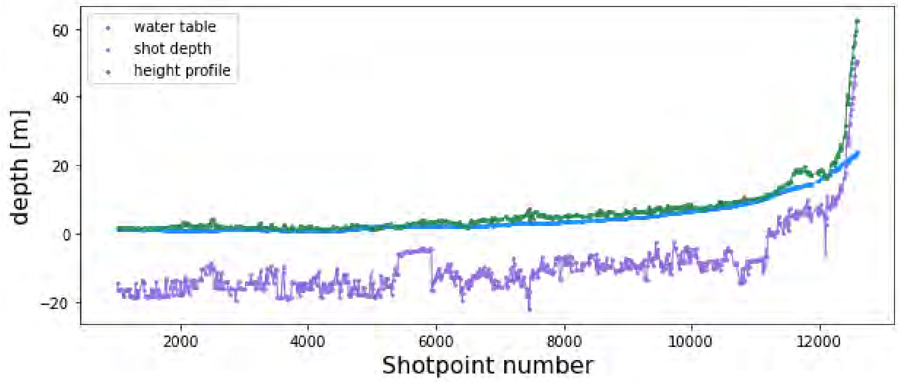


Figure 28: Ground water table along line 12

Receiver domain:

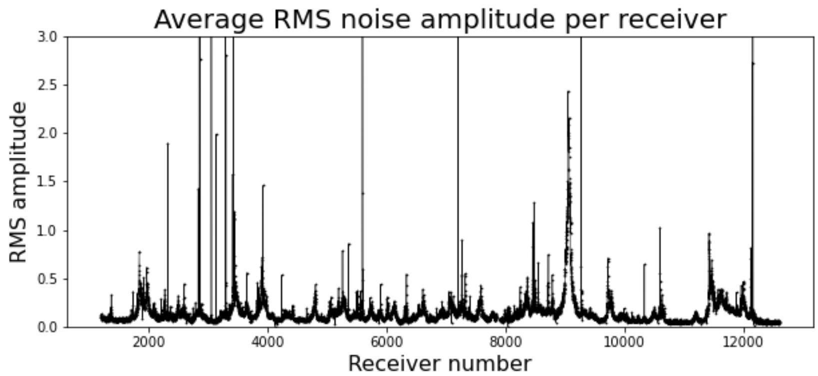


Figure 29: Noise amplitudes in the receiver domain

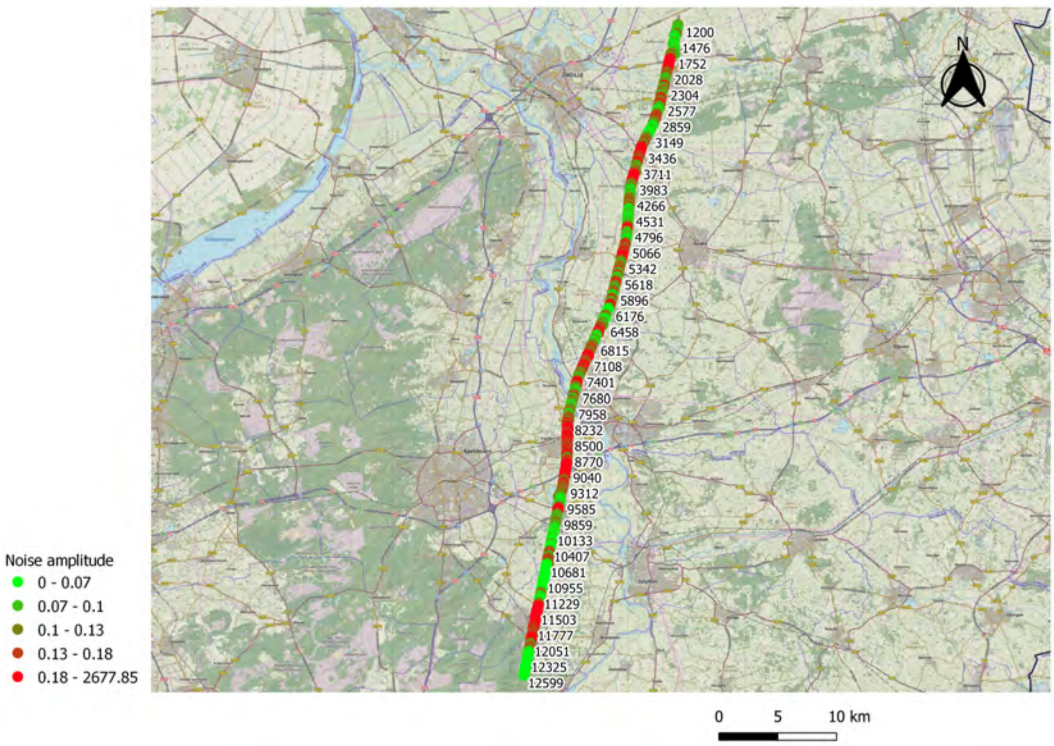


Figure 30: Regional map of line 12. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.3 SCAN013

Line 13 runs from south-west to north-east and runs east of Deventer. We see that the deeper shots between shotpoints 6000 and 7000 have relatively high velocities compared to the rest of the line. The noise per receiver map, figure 41, shows that relatively high noise levels are recorded near the A1.

Table 5: Acquisition parameters line 13

Number of shots	563
Range source station	1001.5-7901.5
Number of receivers	6947
Range receiver station	1001-7905
Total length	34.525 km

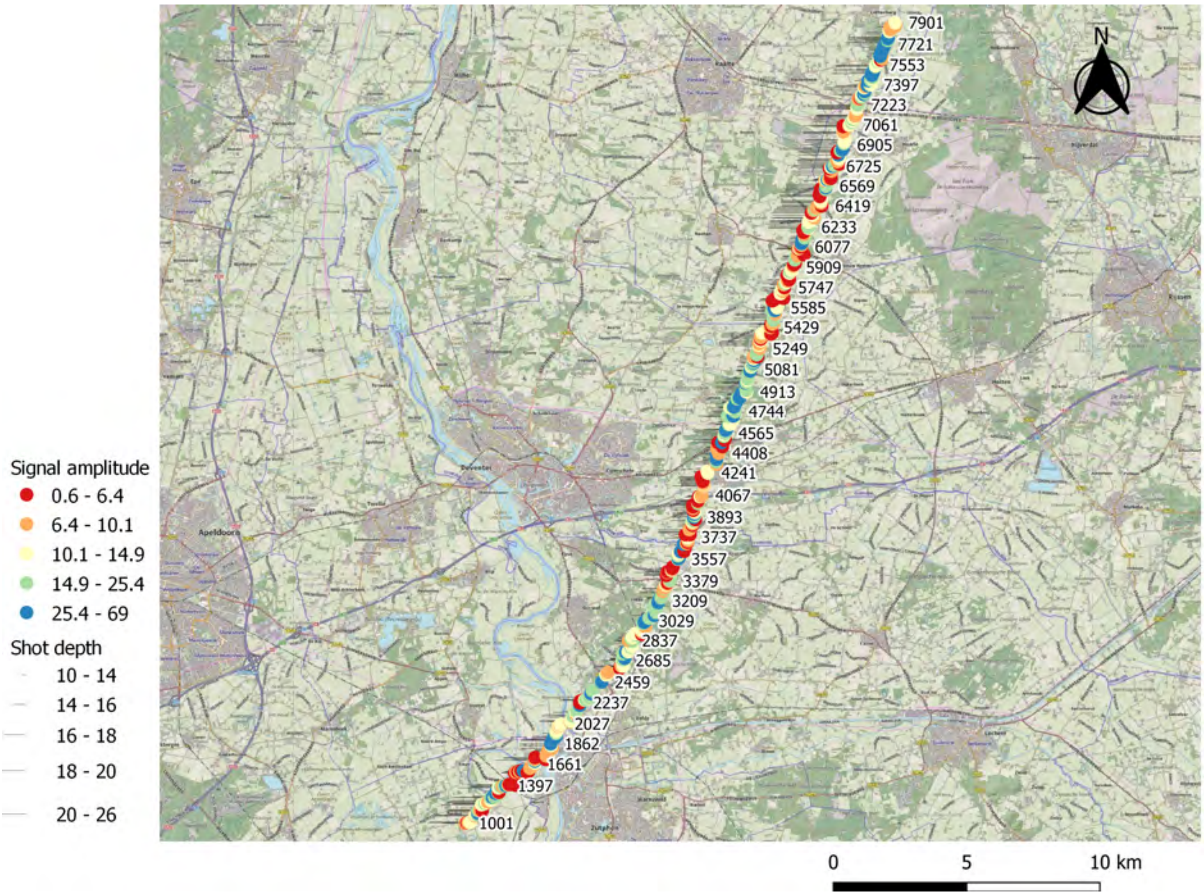


Figure 31: Regional map of line 13. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

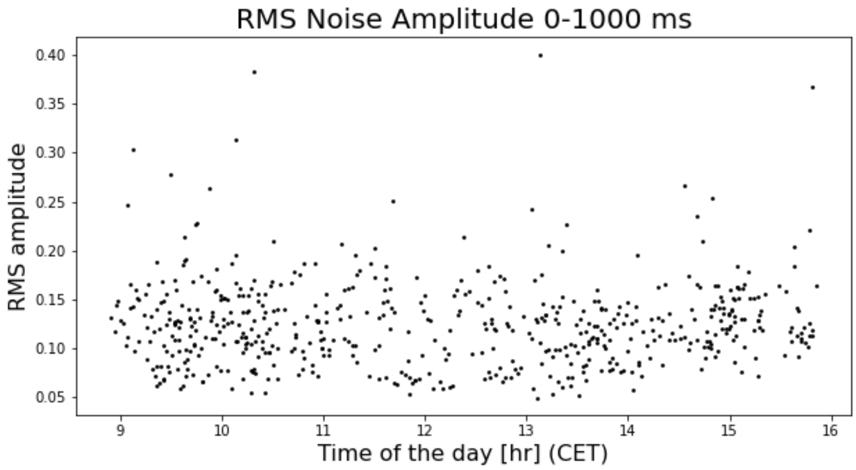


Figure 32: Noise amplitudes in the shot domain per time of the day

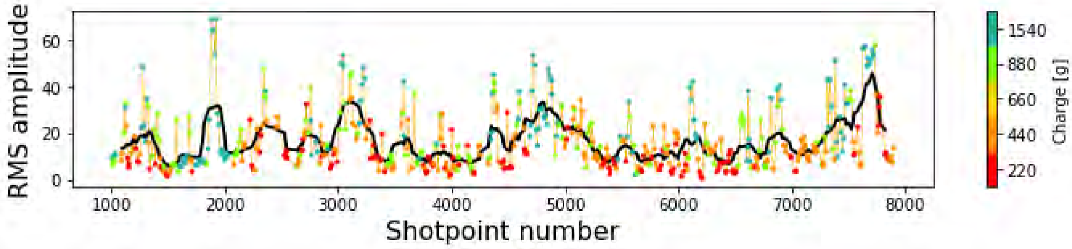


Figure 33: RMS Signal amplitudes in the 0-1s window

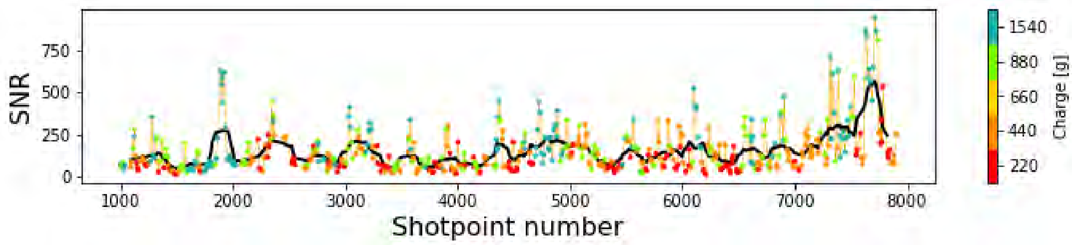


Figure 34: Signal to noise ratios in the 0-1s window with charge size indicator

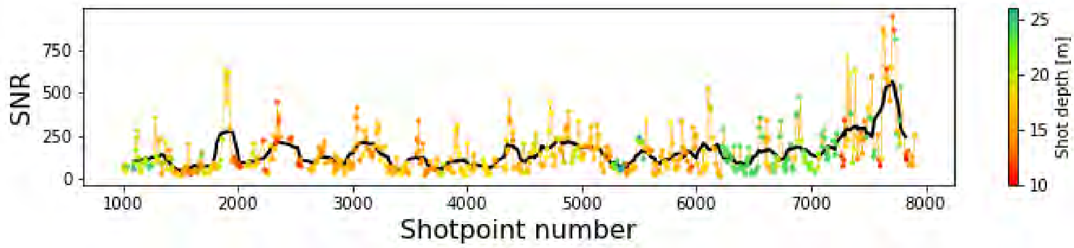


Figure 35: Signal to noise ratios in the 0-1s window with shot depth indicator

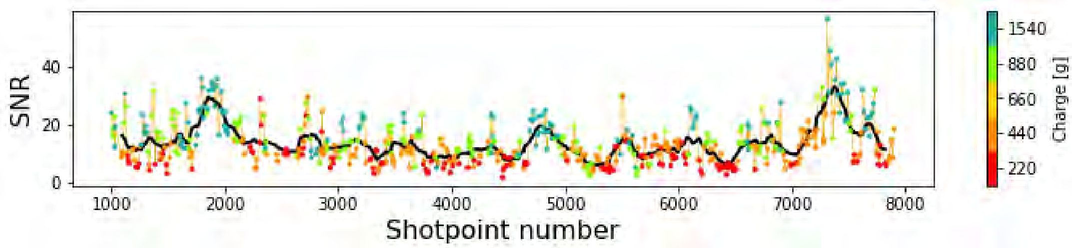


Figure 36: Signal to noise ratios in the 1-2s window with charge size indicator

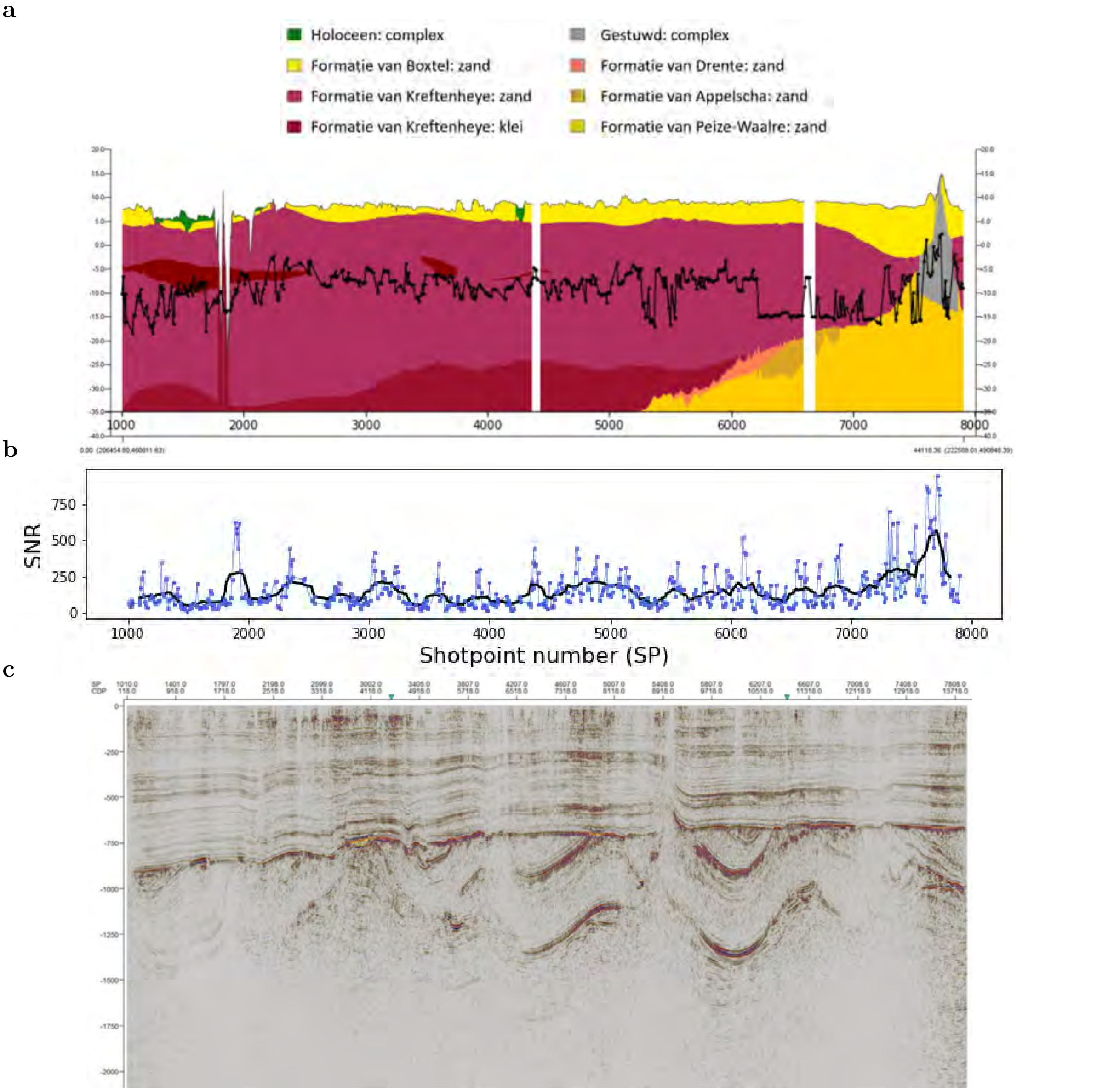


Figure 37: SCAN013. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Final seismic section.

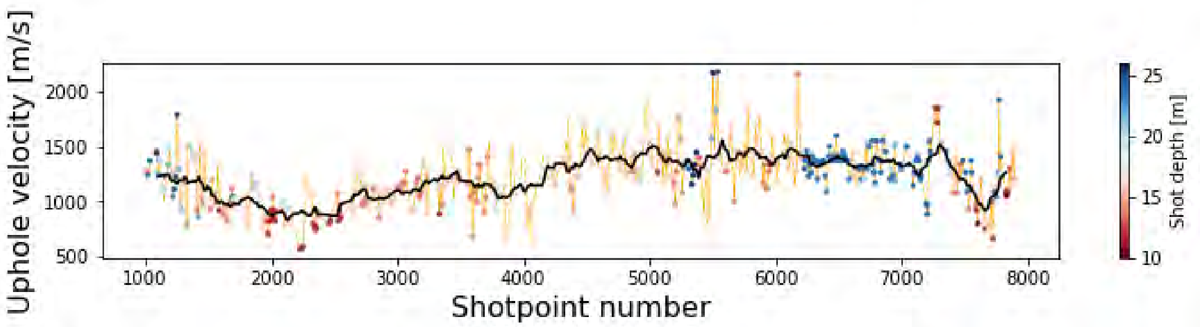


Figure 38: Uphole velocity with shot depth indicator, calculated from uphole times

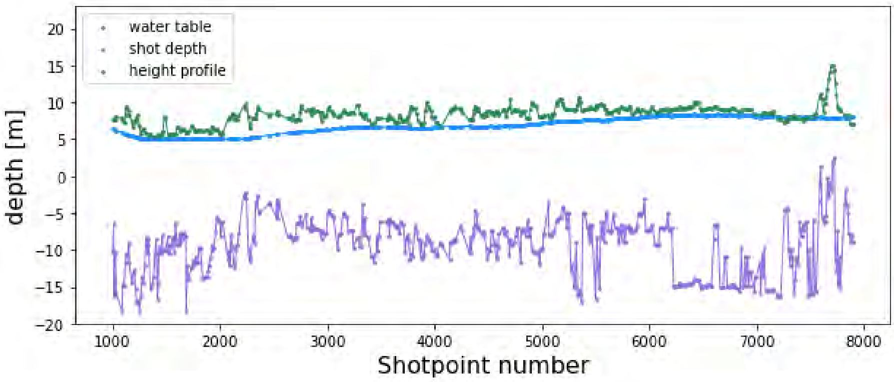


Figure 39: Ground water table along line 13

Receiver domain:

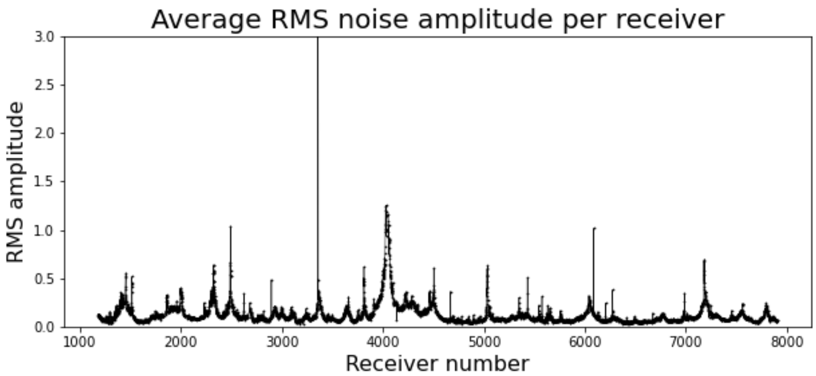


Figure 40: Noise amplitudes in the receiver domain

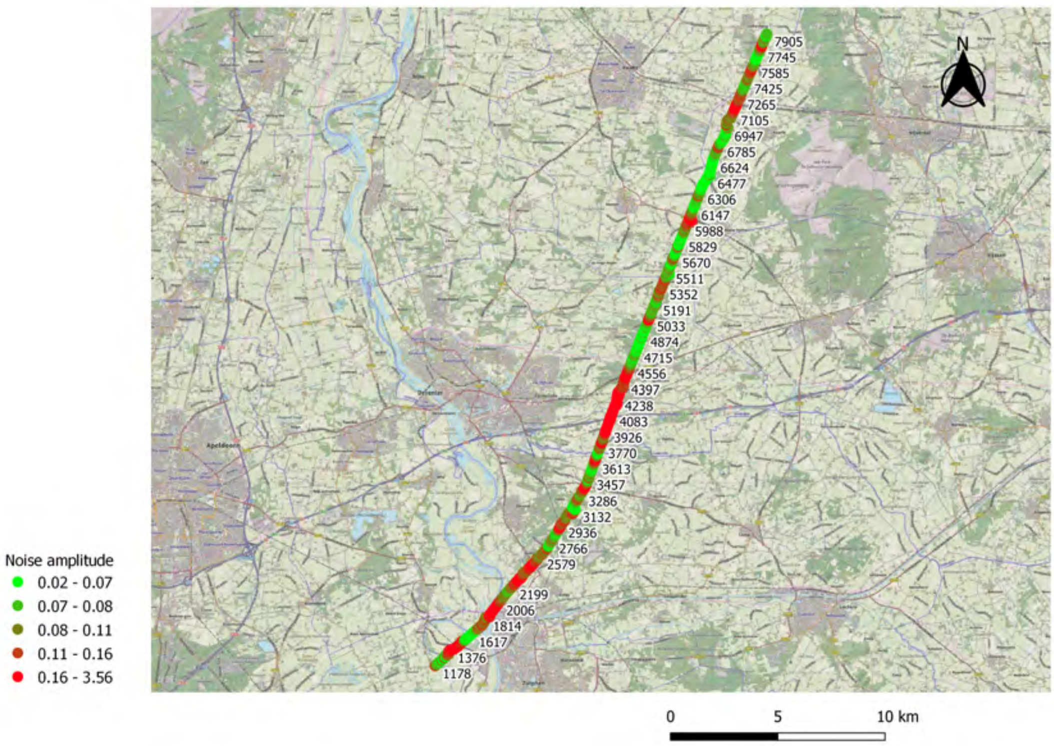


Figure 41: Regional map of line 13. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.4 SCAN014

Line 14 runs from west to east and runs north of Deventer. There is a shot gap of 450 meter because of the IJssel river crossing between shot location 3677.5 and 3773.5. East of the line shots are placed in the stowed glacial deposits, this time below the water table. All shots are placed below the water table (figure 50). The final seismic section clearly shows horizontal layers (the North Sea group) on top of some folded layers below (figure 48c). High noise amplitudes are found where the line crosses the A50 highway.

Table 6: Acquisition parameters line 14

Number of shots	563
Range source station	1001.5-7721.5
Number of receivers	6729
Range receiver station	1001-7729
Total length	33.605 km

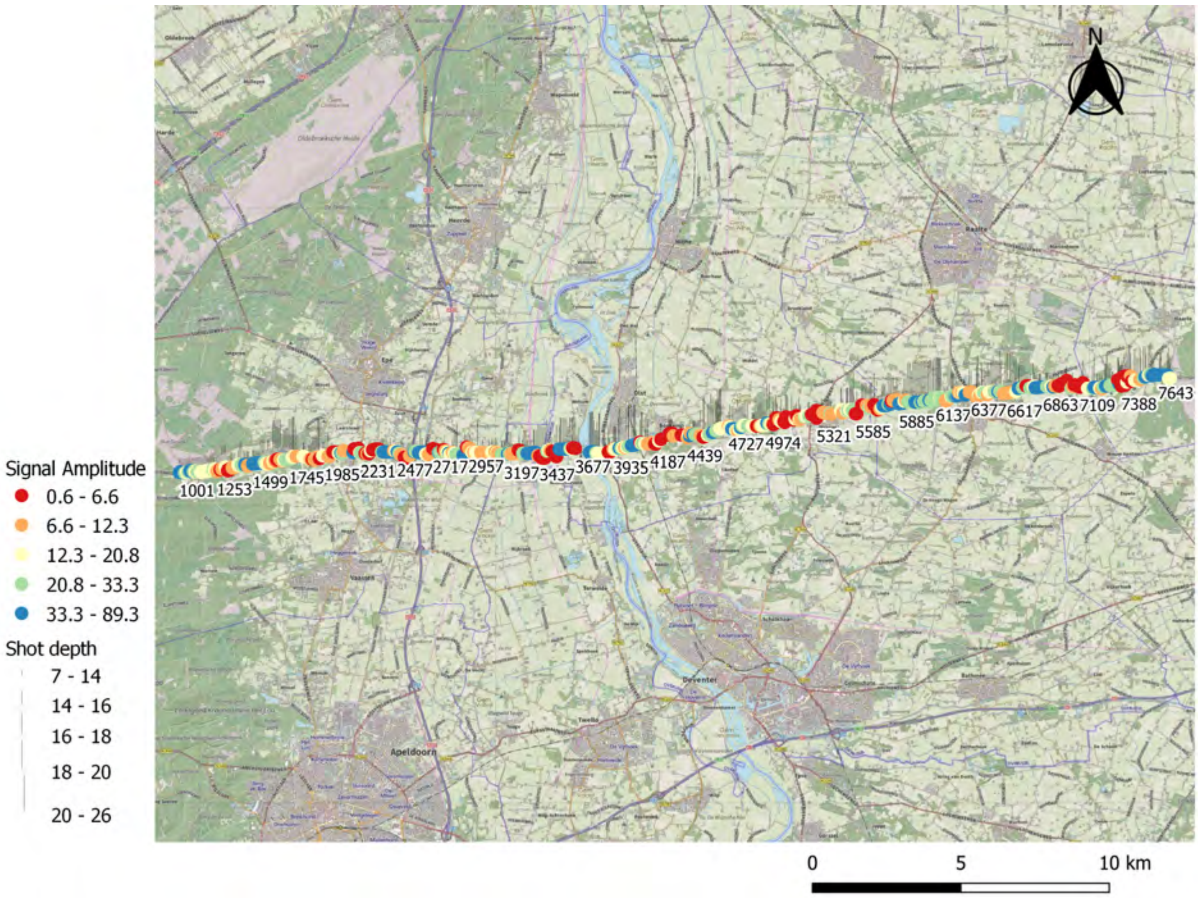


Figure 42: Regional map of line 14. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

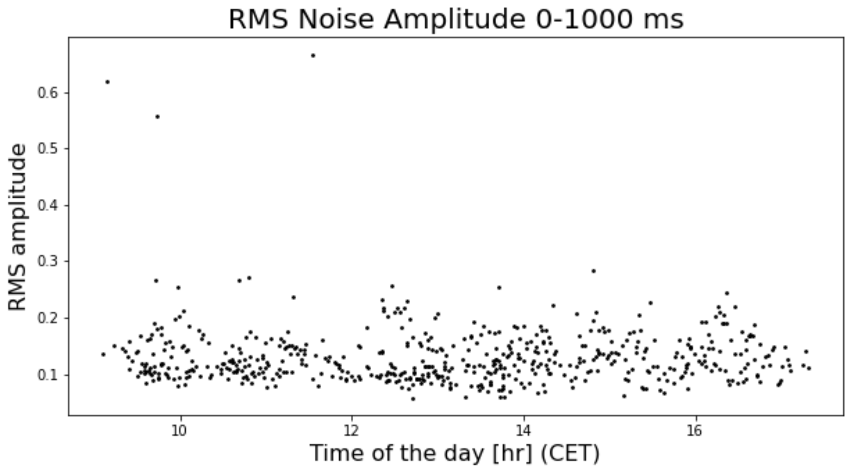


Figure 43: Noise amplitudes in the shot domain per time of the day

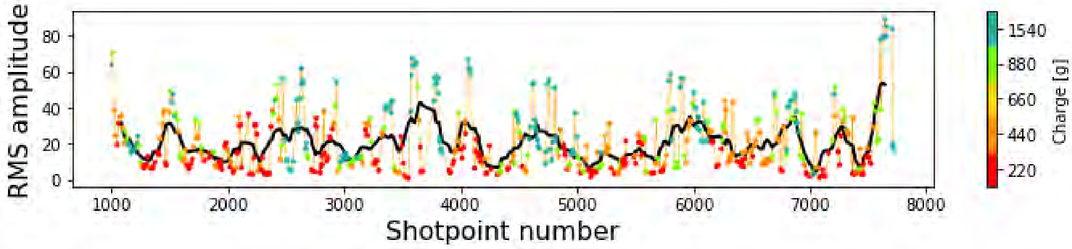


Figure 44: RMS Signal amplitudes in the 0-1s window

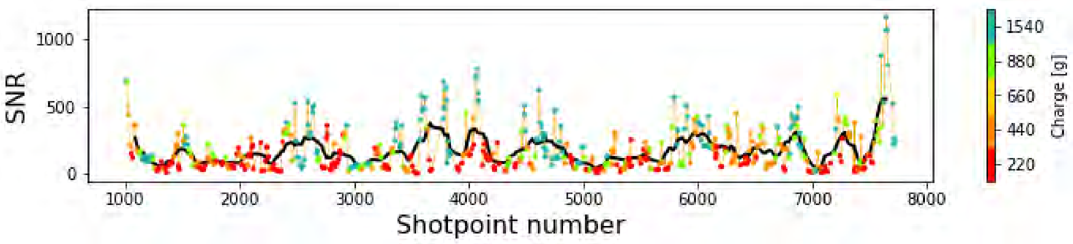


Figure 45: Signal to noise ratios in the 0-1s window with charge size indicator

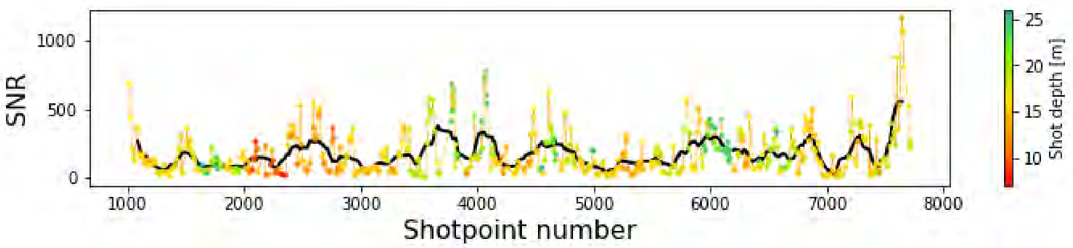


Figure 46: Signal to noise ratios in the 0-1s window with shot depth indicator

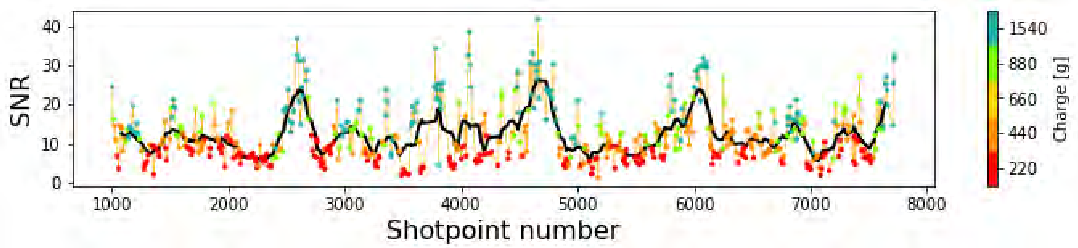


Figure 47: Signal to noise ratios in the 1-2s window with charge size indicator

a

b

c

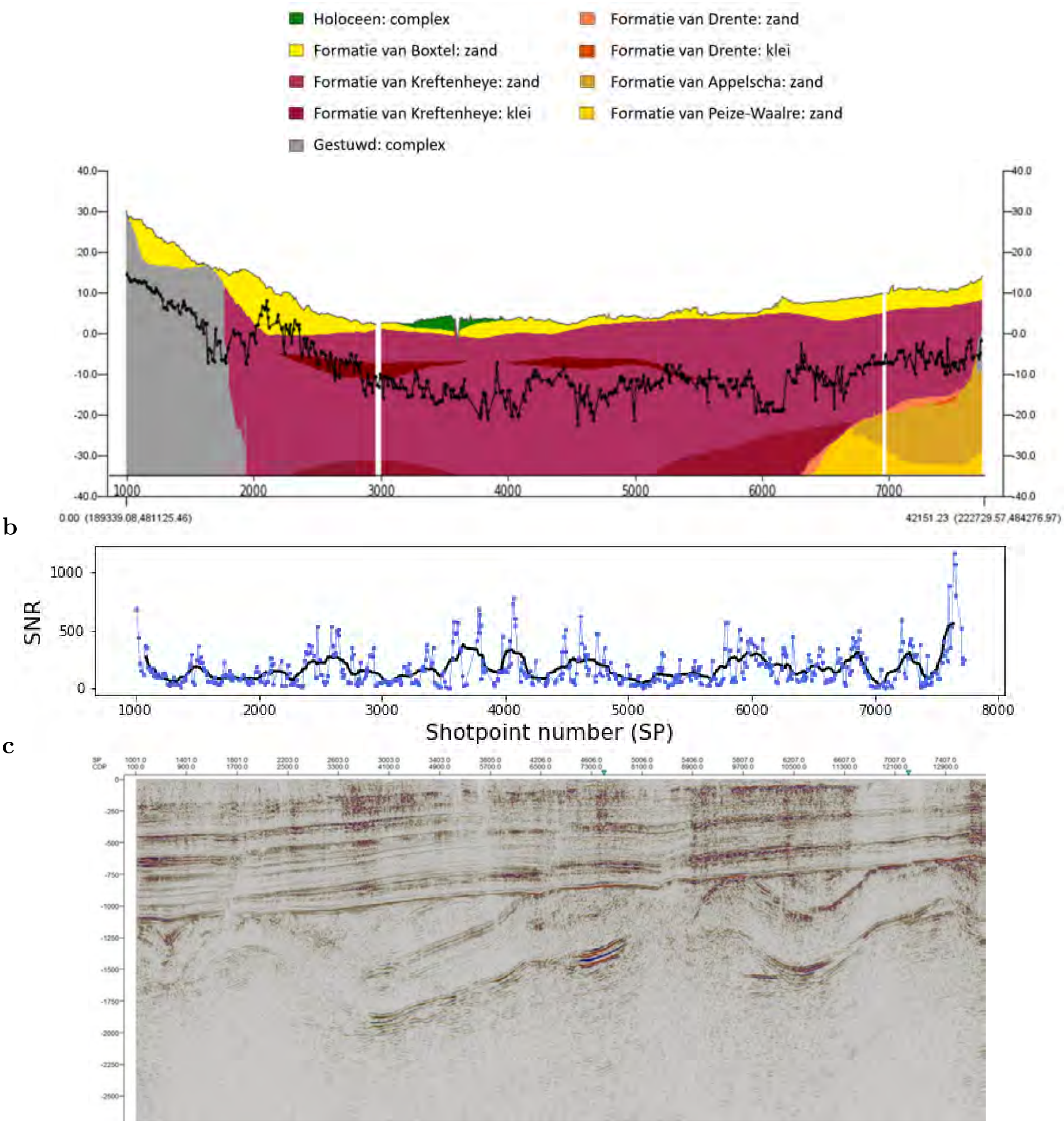


Figure 48: SCAN014. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Final seismic section.

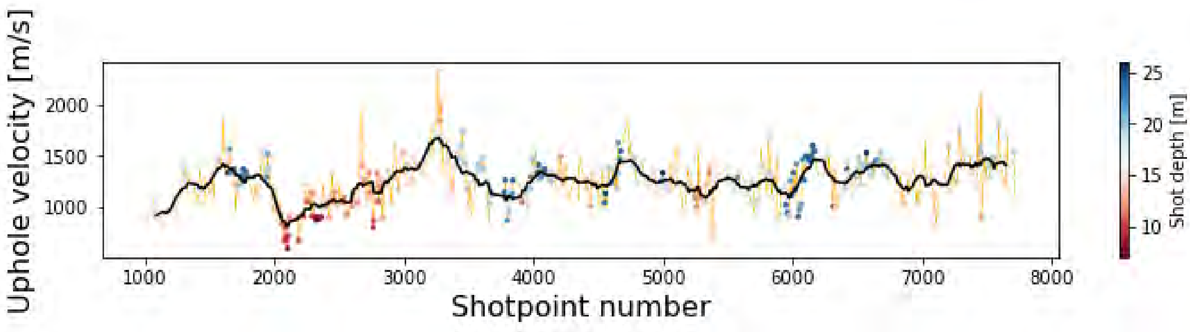


Figure 49: Uphole velocity with shot depth indicator, calculated from uphole times

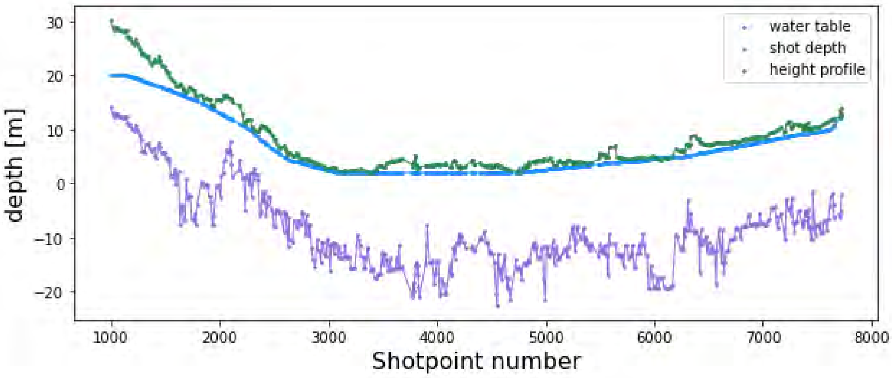


Figure 50: Ground water table along line 14

Receiver domain:

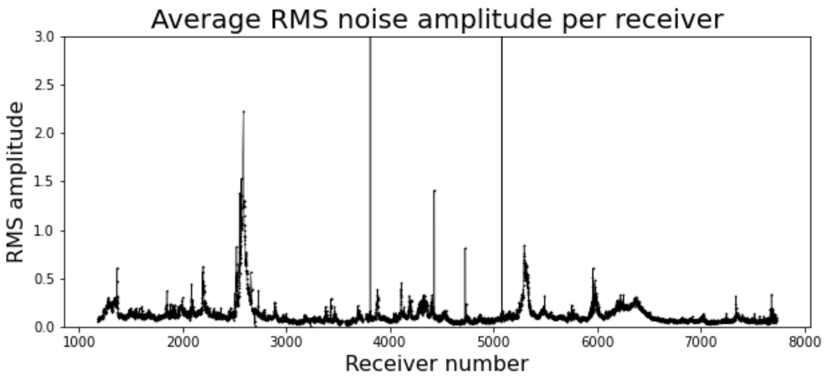


Figure 51: Noise amplitudes in the receiver domain

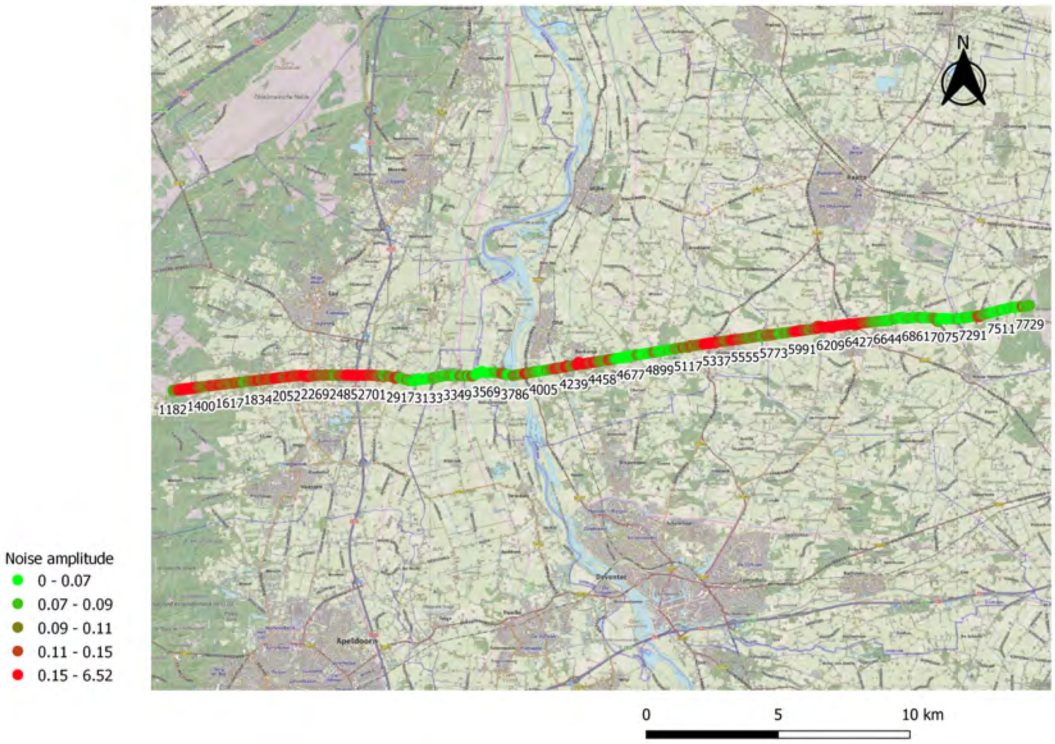


Figure 52: Regional map of line 14. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.5 SCAN015

Line 15 runs from west to east and runs north of Apeldoorn and south of Deventer. SNRs in the first half of the line are relatively low compared to the end of the line. In this final seismic image (figure 59b) we do not see folds in the bottom part as clearly as we see for line 14 (figure 48c). There are no shots above the ground water level. On the noise per receiver map 63, we see high noise amplitudes at the A50 and A1.

Table 7: Acquisition parameters line 15

Number of shots	503
Range source station	1001.5-7409.5
Number of receivers	6413
Range receiver station	1001-7413
Total length	32.045 km

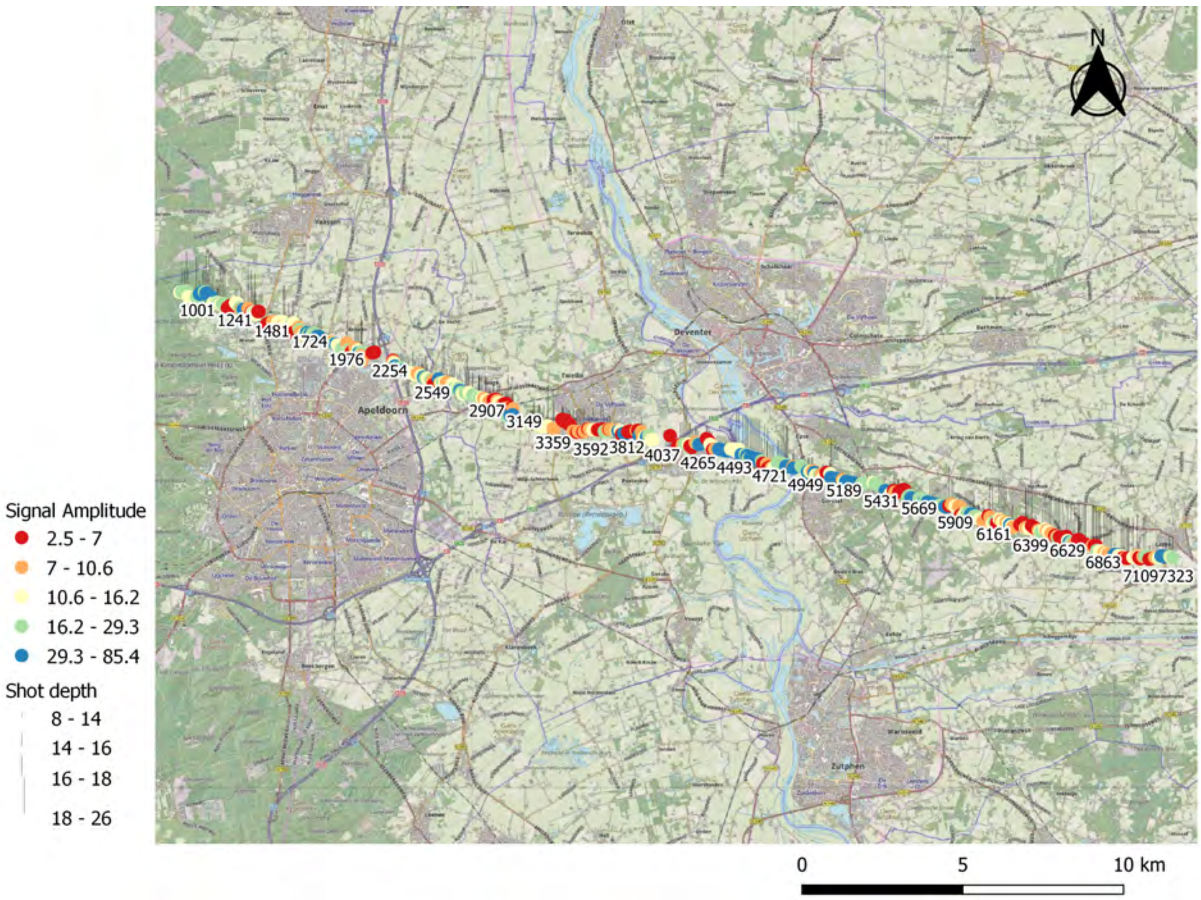


Figure 53: Regional map of line 15. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

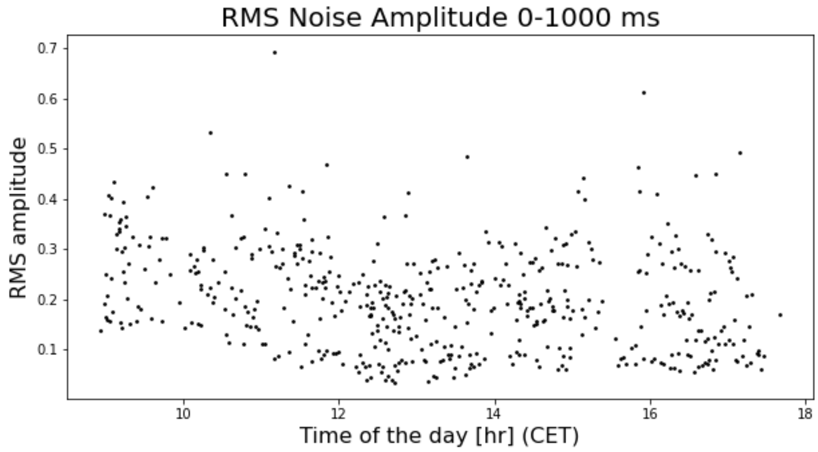


Figure 54: Noise amplitudes in the shot domain per time of the day

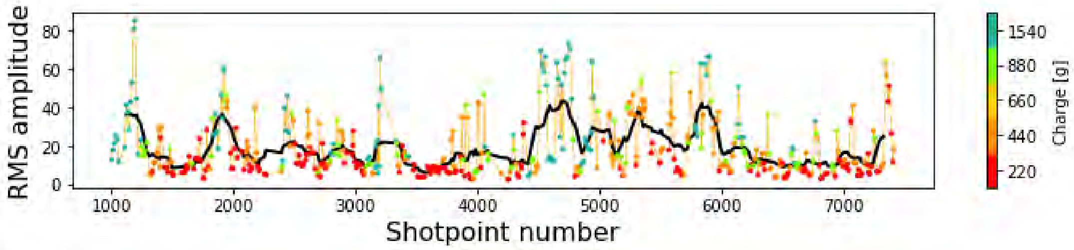


Figure 55: RMS Signal amplitudes in the 0-1s window

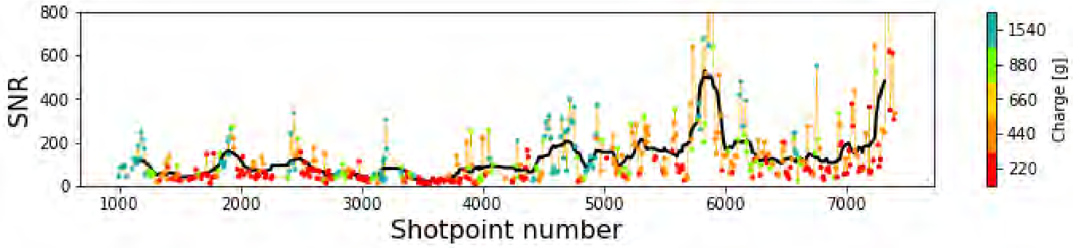


Figure 56: Signal to noise ratios in the 0-1s window with charge size indicator

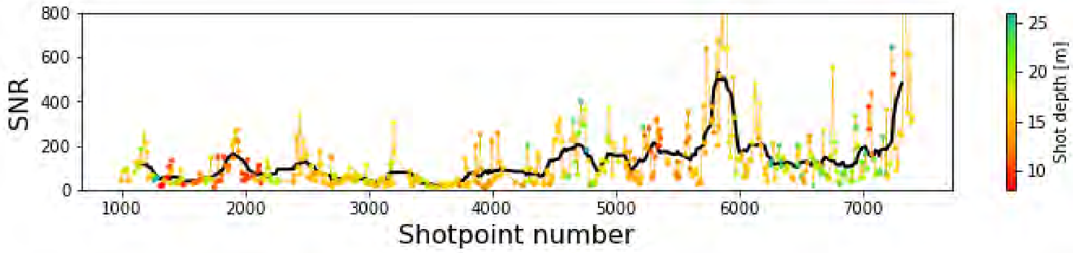


Figure 57: Signal to noise ratios in the 0-1s window with shot depth indicator

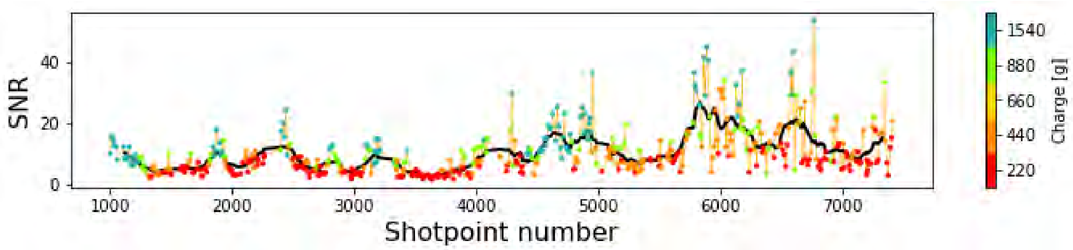


Figure 58: Signal to noise ratios in the 1-2s window with charge size indicator

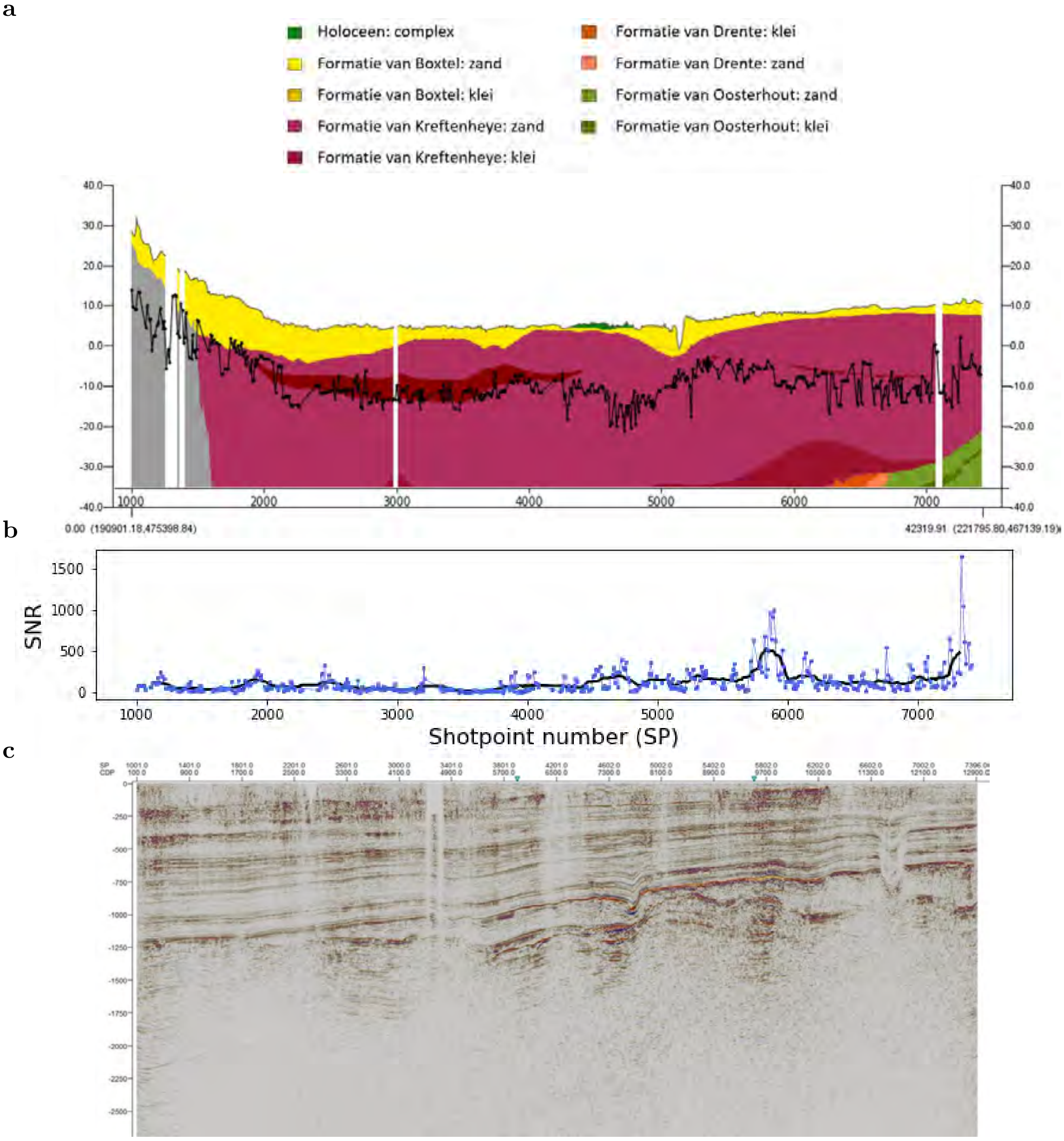


Figure 59: SCAN015. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Final seismic section.

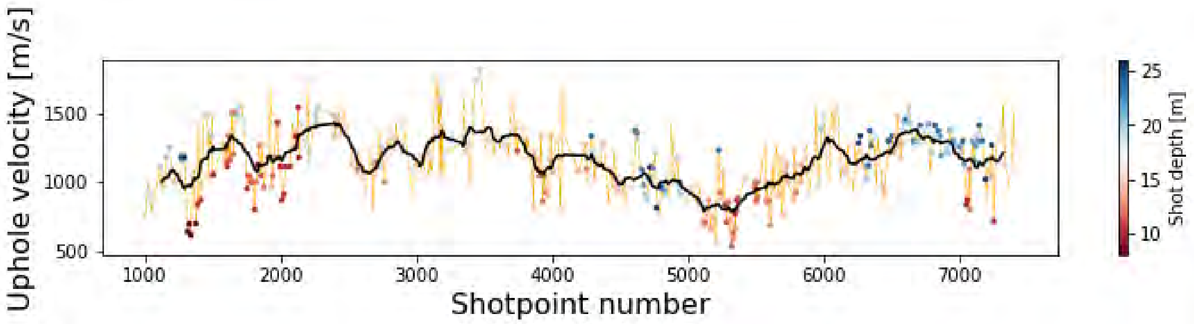


Figure 60: Uphole velocity with shot depth indicator, calculated from uphole times

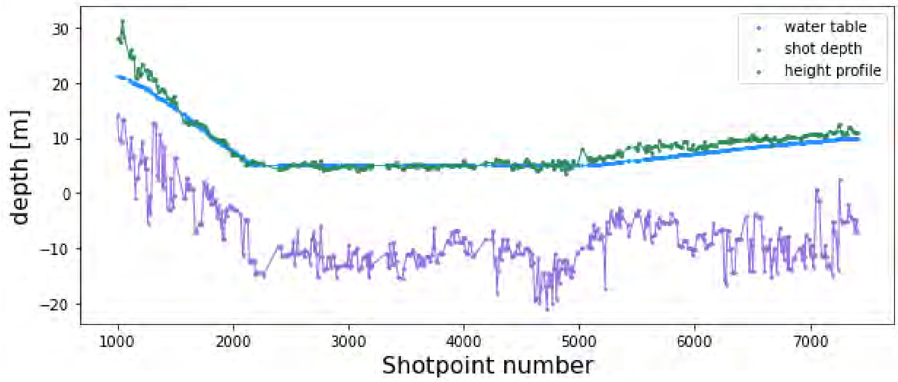


Figure 61: Ground water table along line 15

Receiver domain:

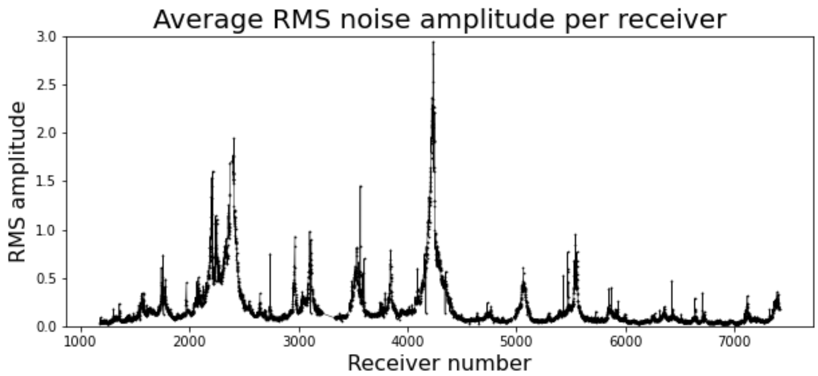


Figure 62: Noise amplitudes in the receiver domain

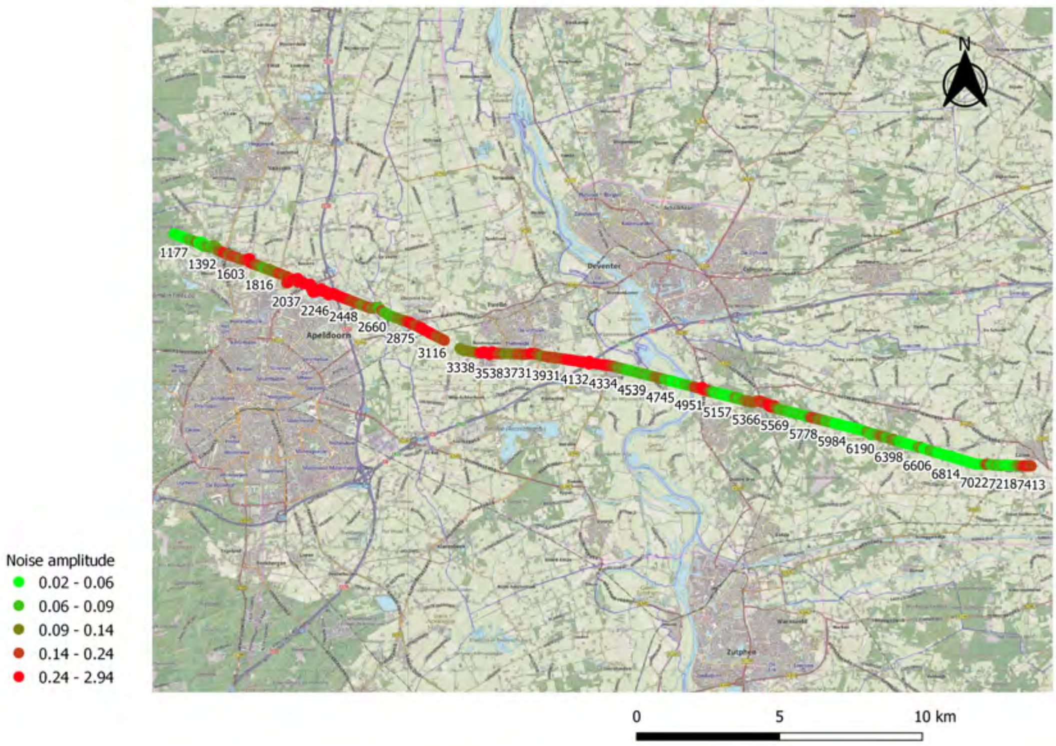


Figure 63: Regional map of line 15. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.6 SCAN016

Line 16 runs from south to north and runs west of Venlo. In the first half of the line shots are placed quite shallow, in the second half (from shotpoint number 8000 on) the shots are much deeper located. In the 1-2 seconds window (figure 69) we see very low SNRs in the far north of the line (11000 and further). This corresponds to shots in the stowed glacial deposits and also with shots that are taken above the water table. We see little signal in the final seismic section from 1500 ms two way travel time on (figure 70c). Noise amplitudes are high at the A73 and the A67 (figure 74).

Table 8: Acquisition parameters line 16

Number of shots	808
Range source station	1001.5-11406.5
Number of receivers	10415
Range receiver station	1001-11415
Total length	52.075 km

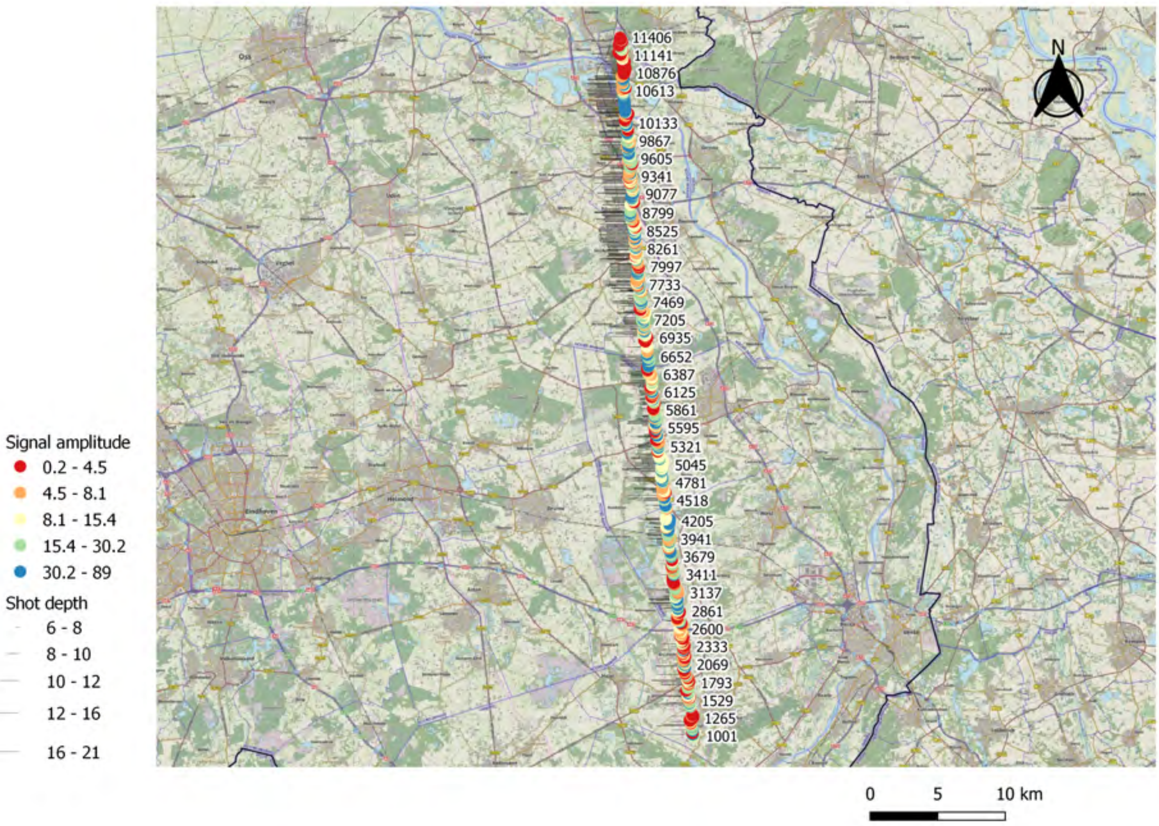


Figure 64: Regional map of line 16. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

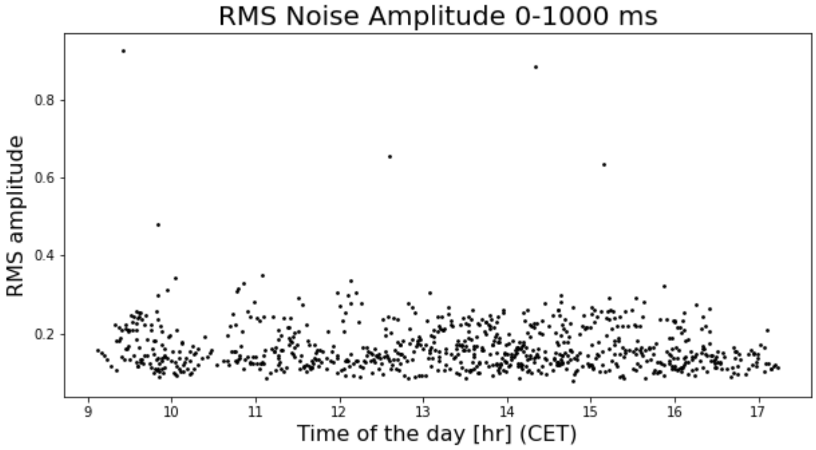


Figure 65: Noise amplitudes in the shot domain per time of the day

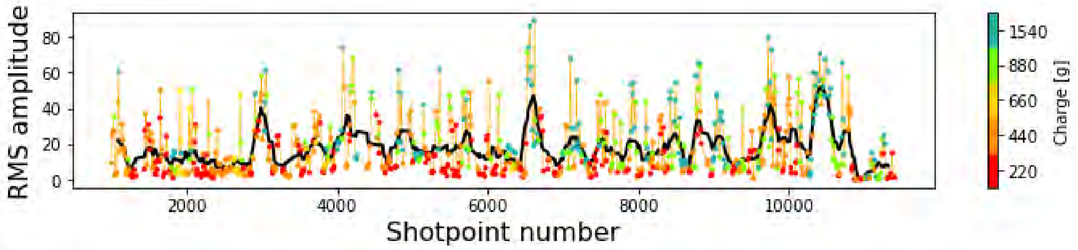


Figure 66: RMS Signal amplitudes in the 0-1s window

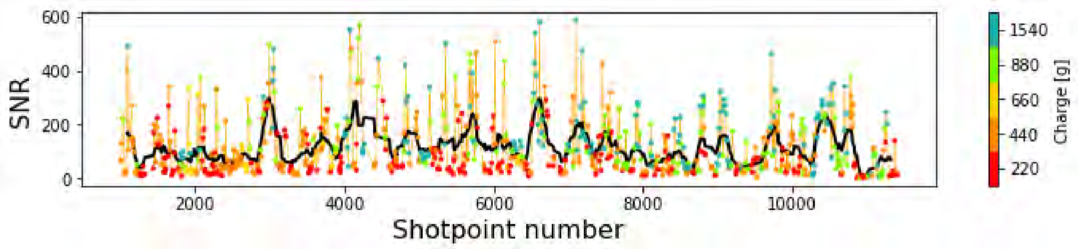


Figure 67: Signal to noise ratios in the 0-1s window with charge size indicator

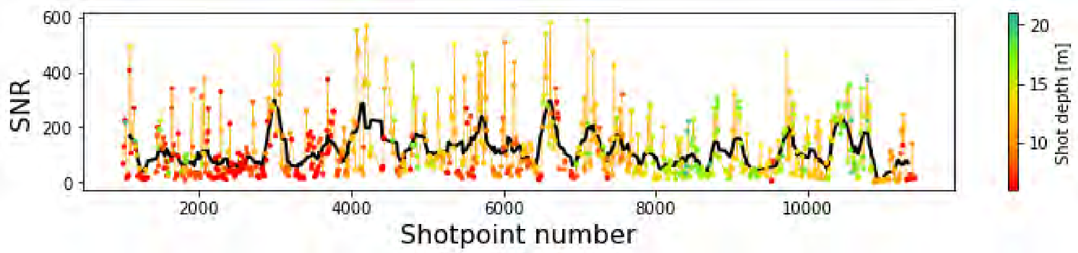


Figure 68: Signal to noise ratios in the 0-1s window with shot depth indicator

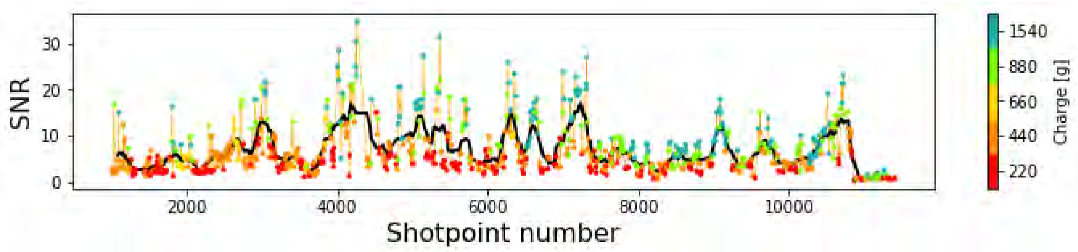


Figure 69: Signal to noise ratios in the 1-2s window with charge size indicator

a

b

c

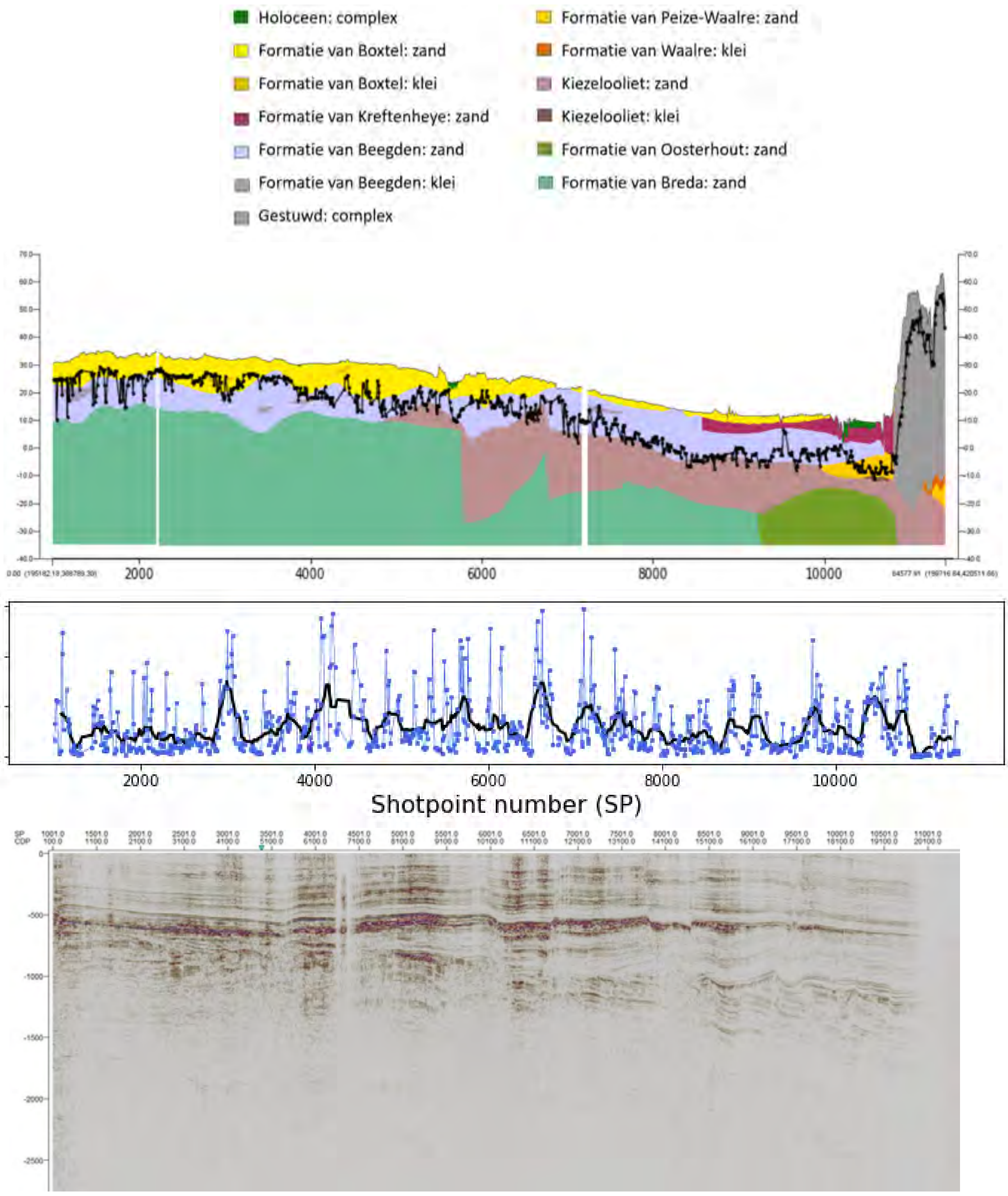


Figure 70: SCAN016. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Final seismic section.

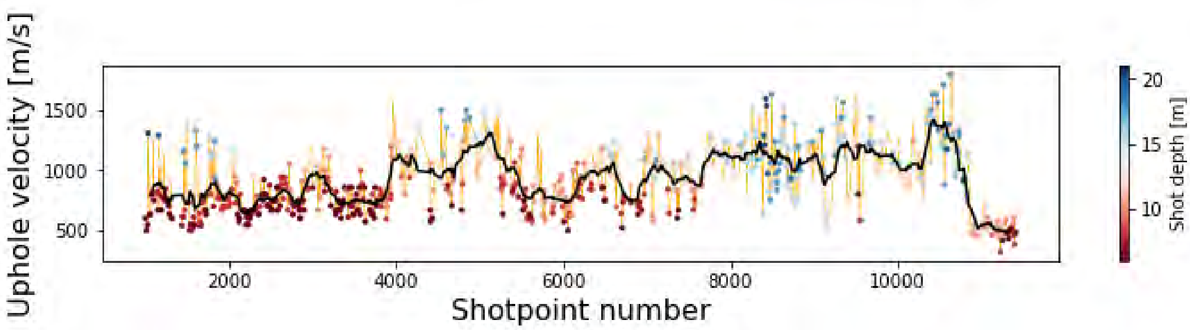


Figure 71: Uphole velocity with shot depth indicator, calculated from uphole times

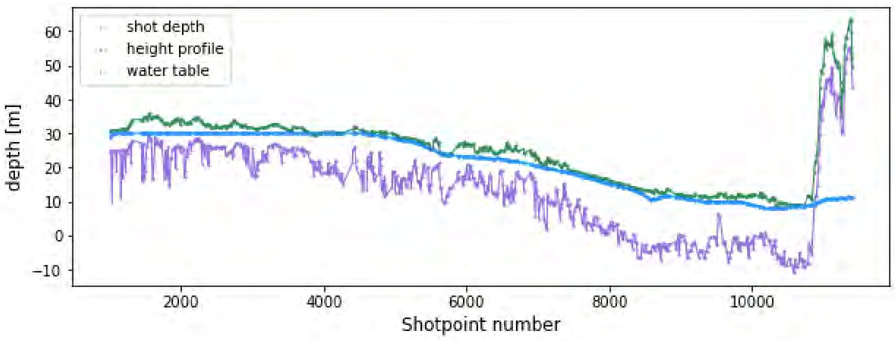


Figure 72: Ground water table along line 16

Receiver domain:

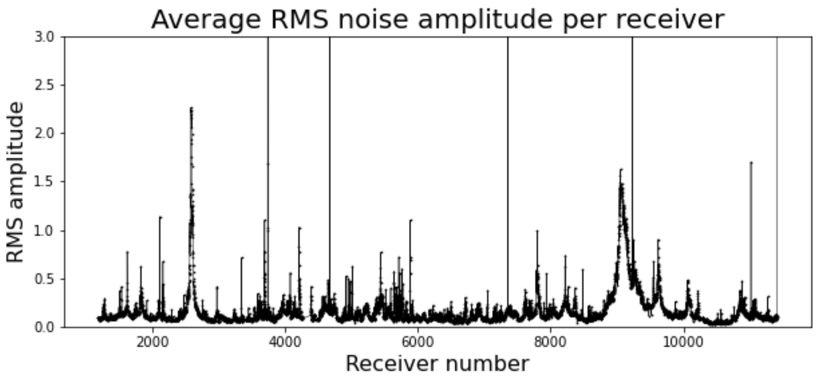


Figure 73: Noise amplitudes in the receiver domain

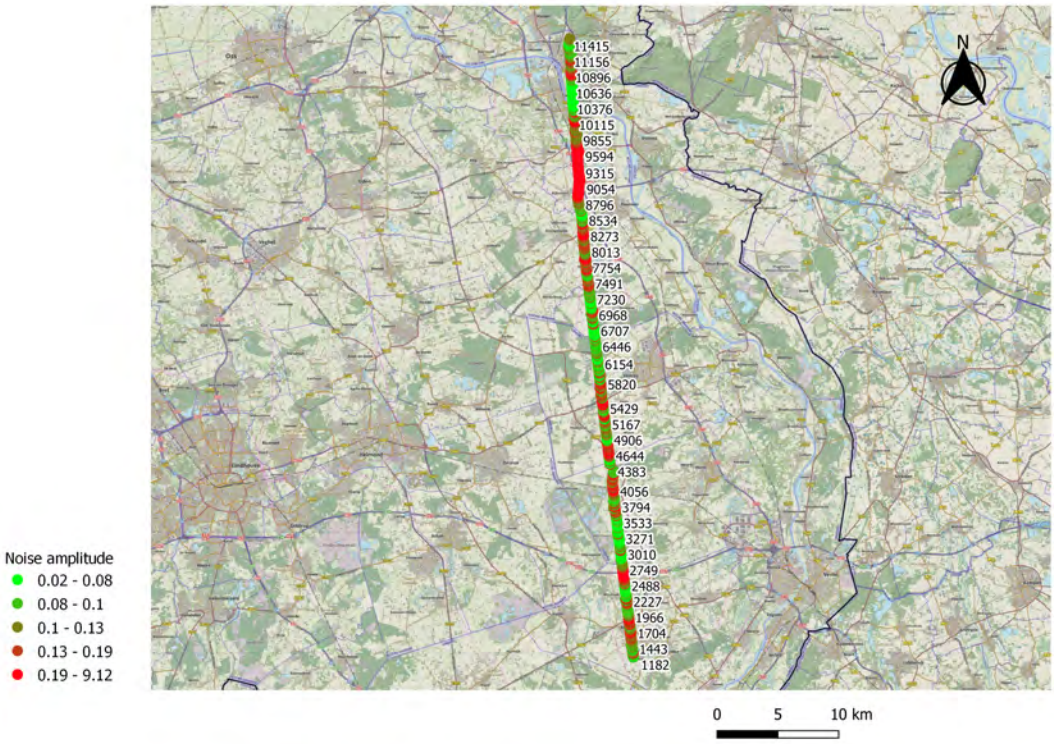


Figure 74: Regional map of line 16. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.7 UOBR017

Table 9: Acquisition parameters line 17

Number of shots	720
Range source station	6425.5-15353.5
Number of receivers	10014
Range receiver station	5026-15360
Total length	51.675 km

Line 17 runs from west to east and runs north of Eindhoven. This line is part of the Oost-Brabant consortium. Line 17 and further are processed by *DUG* at the moment of writing. We only have a fast track seismic section based on two weeks of processing available for lines 11 and 17-29 and not a final full seismic section. Line 17 is connected to line 18, which is located in line to the west. When *DUG* did the fast-track processing for line 17, they did not have the data for the line 18, hence the west end of the line shows this 'wedge' (figure 81c). Line 17 ended with a split-spread node layout, while normally the lines end with an end-off-spread layout. In the earlier case you have more long offset traces that contribute to the CDP, therefore this 'wedge' feature is created. Uphole velocities lie around 1000 m/s. All shots are located below the water table. The A2 and the A50 are crossing the line and around those crossings high noise amplitudes are found (figure 85).

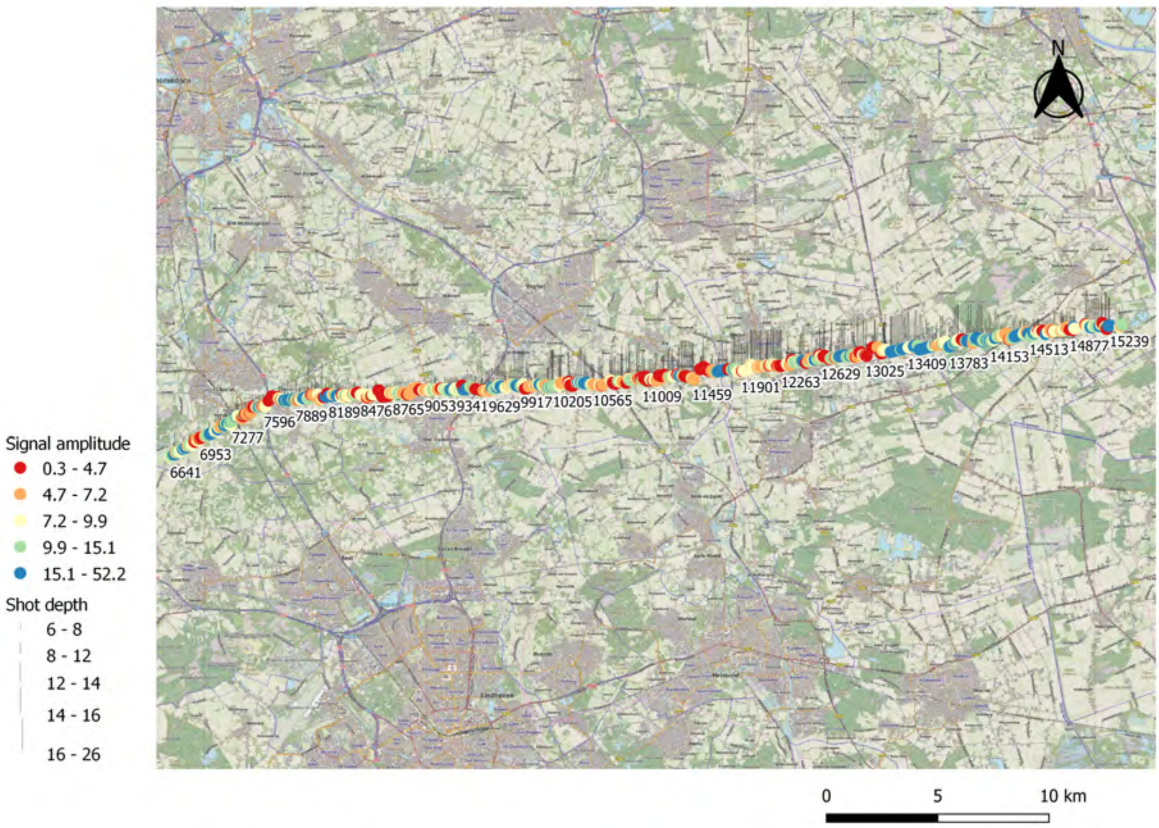


Figure 75: Regional map of line 17. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

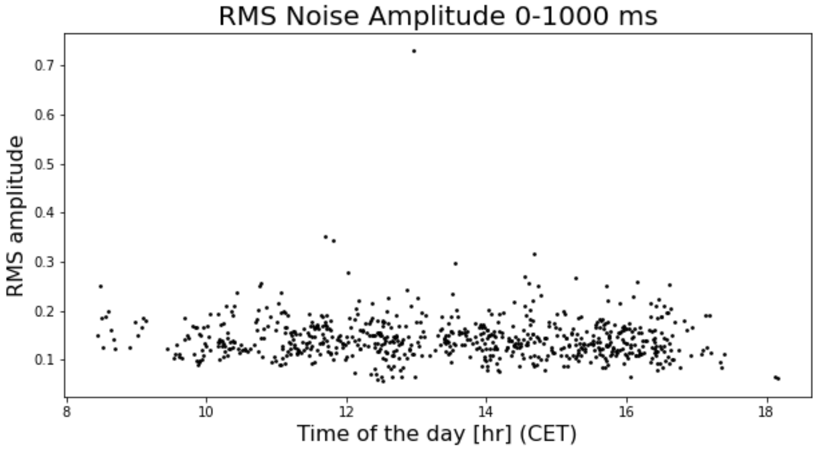


Figure 76: Noise amplitudes in the shot domain per time of the day

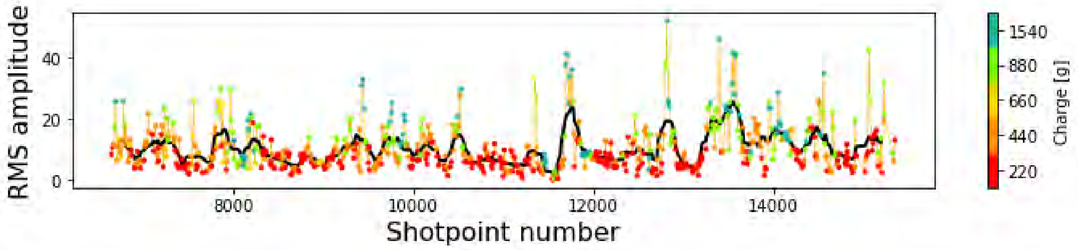


Figure 77: RMS Signal amplitudes in the 0-1s window

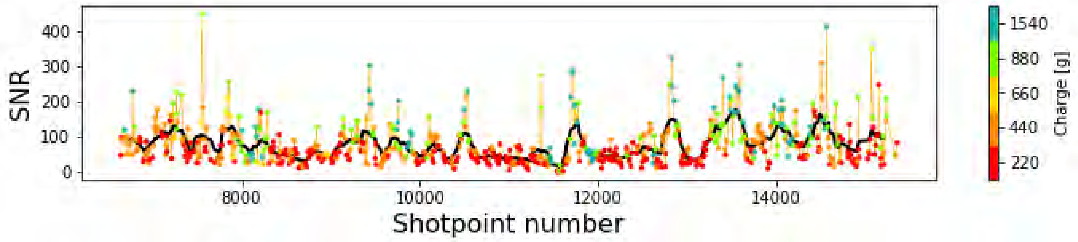


Figure 78: Signal to noise ratios in the 0-1s window with charge size indicator

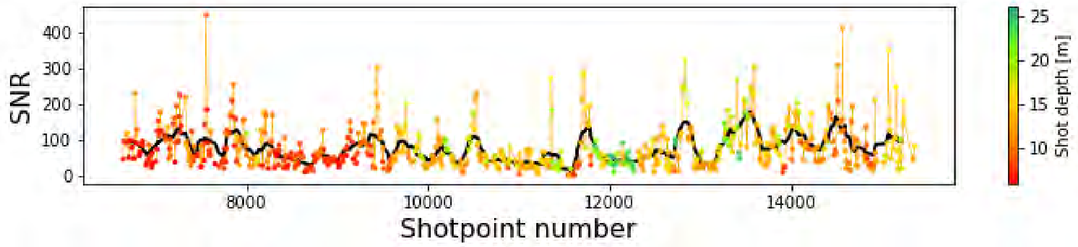


Figure 79: Signal to noise ratios in the 0-1s window with shot depth indicator

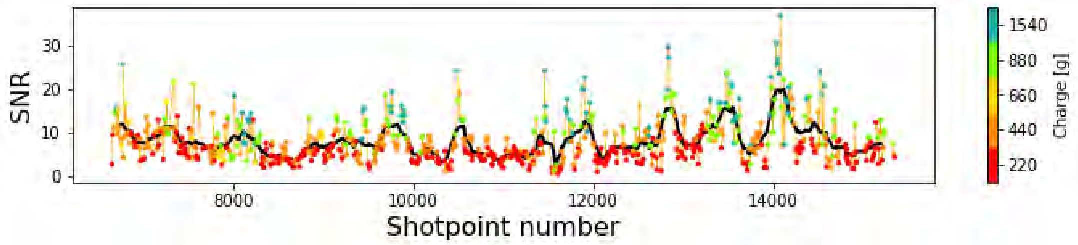


Figure 80: Signal to noise ratios in the 1-2s window with charge size indicator

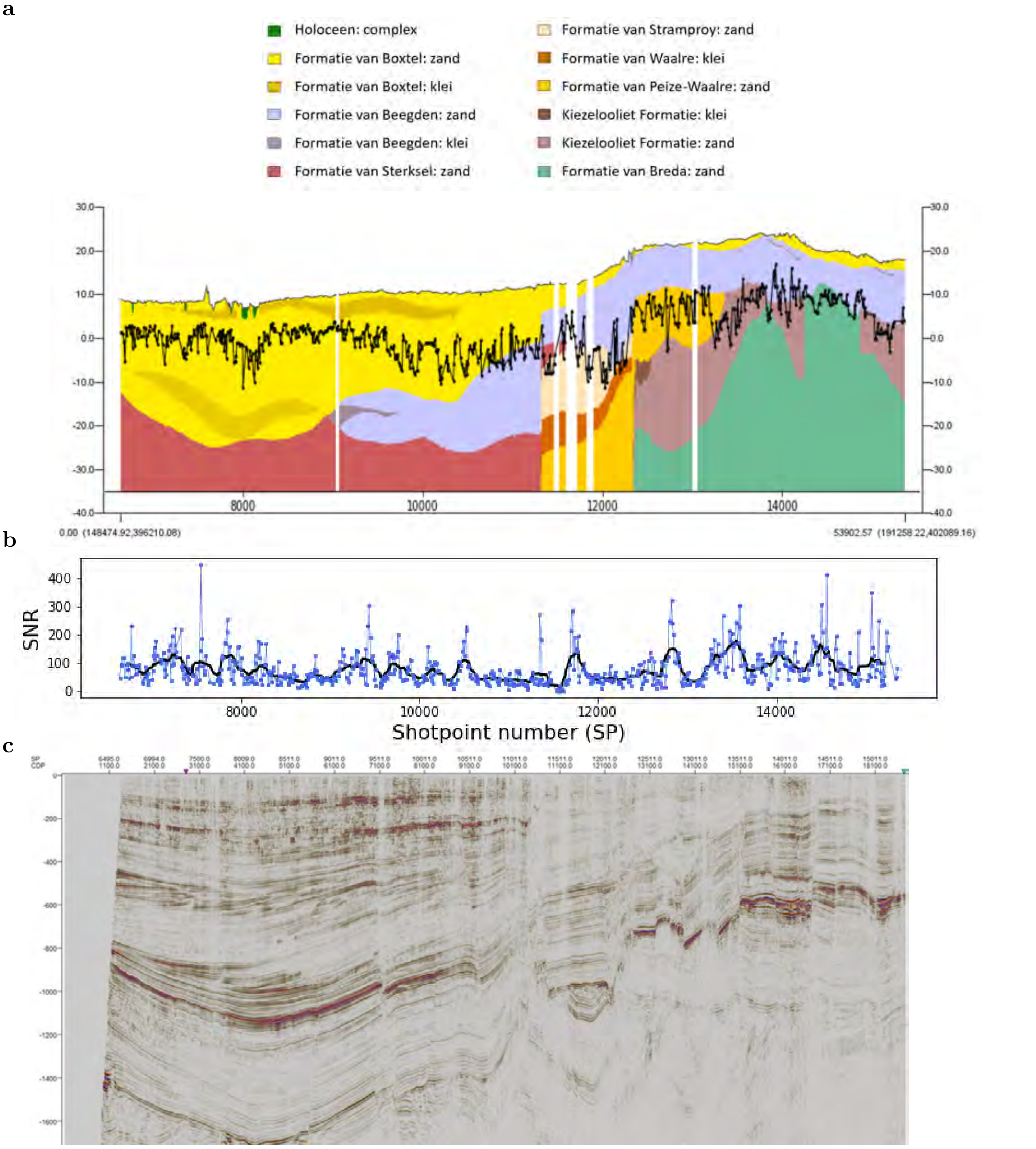


Figure 81: UOBR017. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

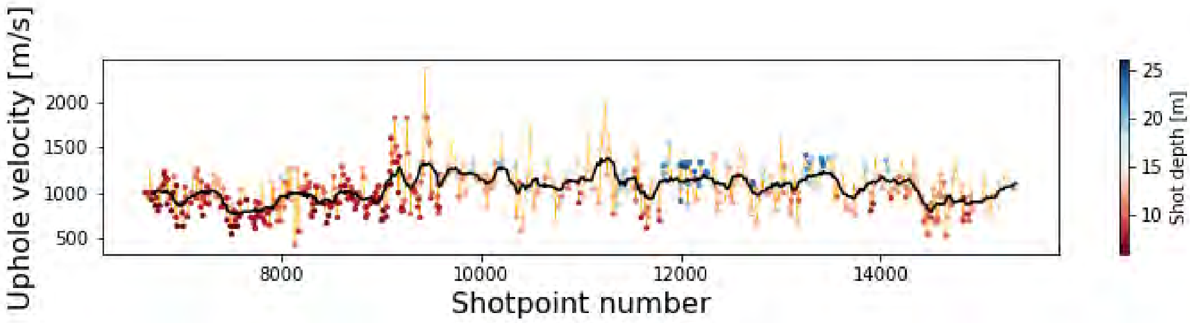


Figure 82: Uphole velocity with shot depth indicator, calculated from uphole times

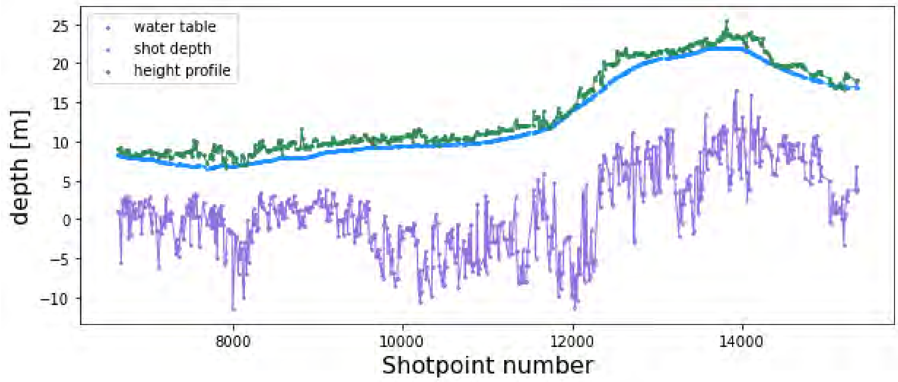


Figure 83: Ground water table along line 17

Receiver domain:

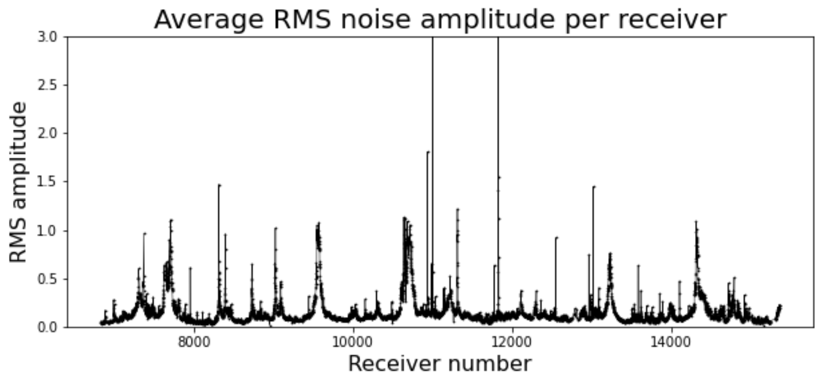


Figure 84: Noise amplitudes in the receiver domain

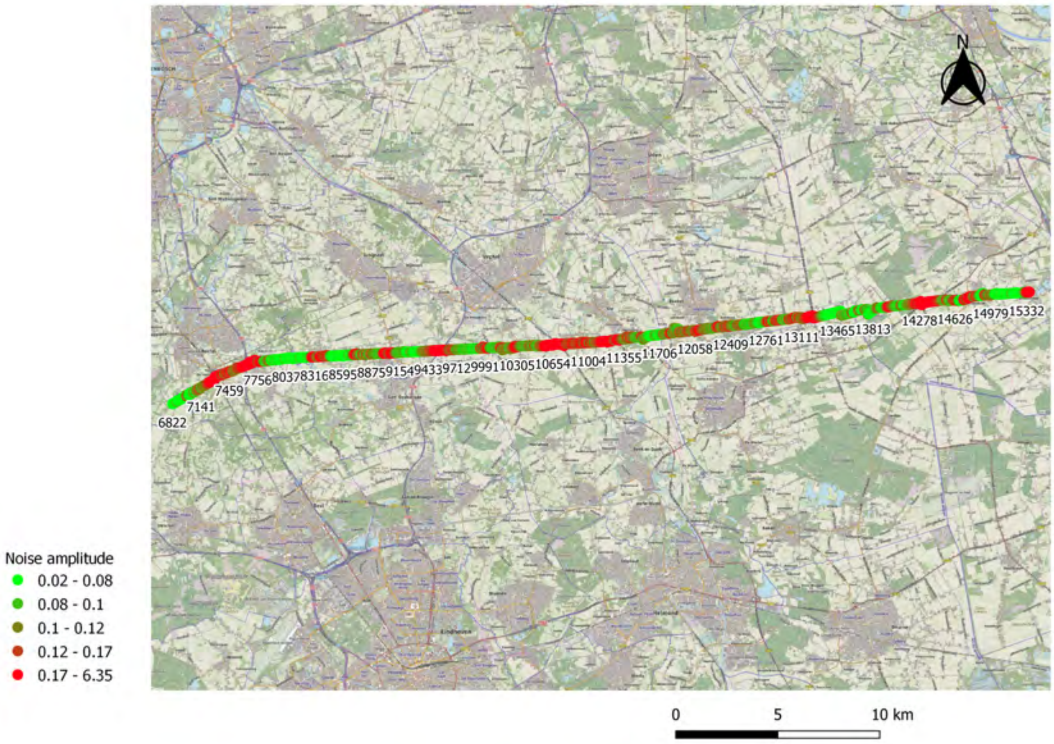


Figure 85: Regional map of line 17. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.8 SCAN018

Line 18 runs from south west to north east and runs south of Tilburg. This line is connected to line 17, which is located in line to the east. When *DUG* did the fast-track for line 18, they already had the shots for line 17, so at that stage they merged the 2 lines, and then delivered a merged fast track for lines 17 and 18 combined. We see only part of this merged line in the fast-track section below (figure92c). On the geological cross section of the subsurface (figure 92a) we see a large fault displacing the layers. This fault is also visible on the final seismic section. Uphole velocities lie around 1000 m/s and shots are placed relatively shallow. All shots are located below the water table. Where the A58 and the railways in the north cross the line, we find high noise amplitudes (figure 96).

Table 10: Acquisition parameters line 18

Number of shots	545
Range source station	1001.5-7829.5
Number of receivers	8229
Range receiver station	1001-9229
Total length	41.145 km

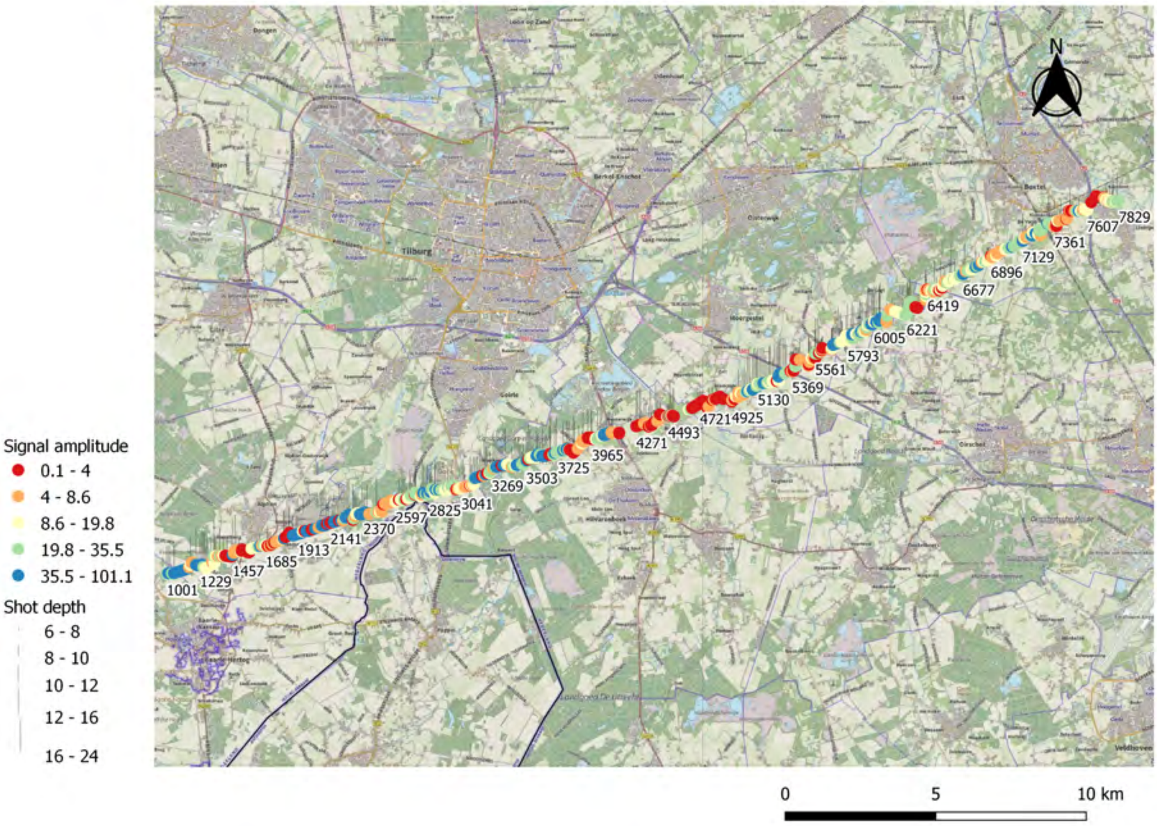


Figure 86: Regional map of line 18. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

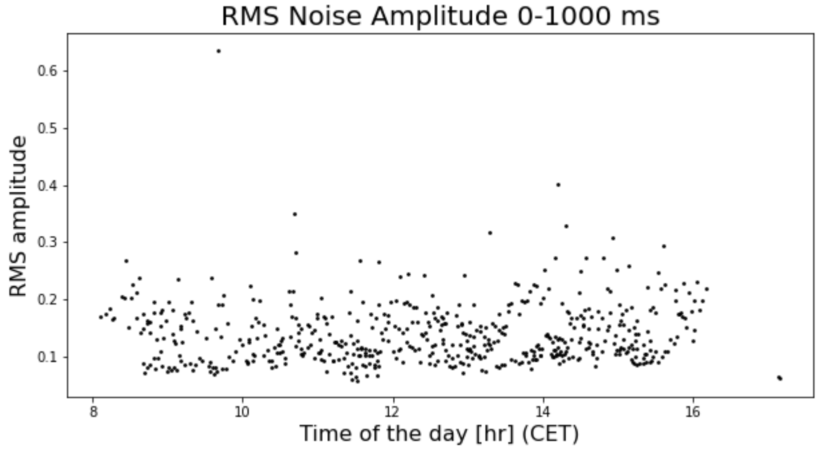


Figure 87: Noise amplitudes in the shot domain per time of the day

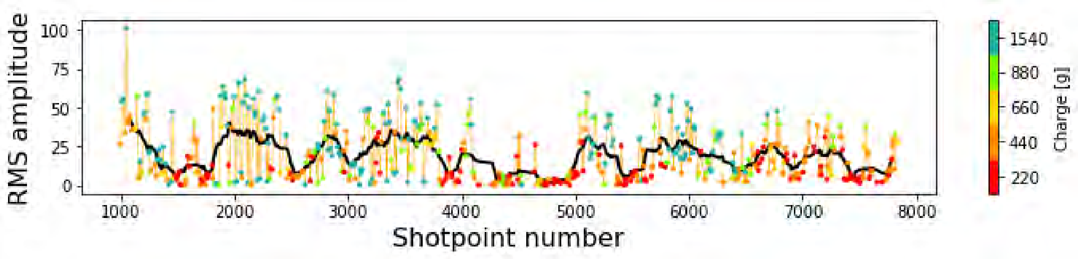


Figure 88: RMS Signal amplitudes in the 0-1s window

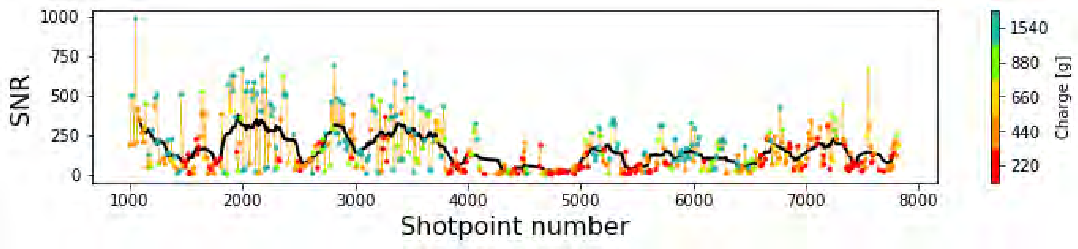


Figure 89: Signal to noise ratios in the 0-1s window with charge size indicator

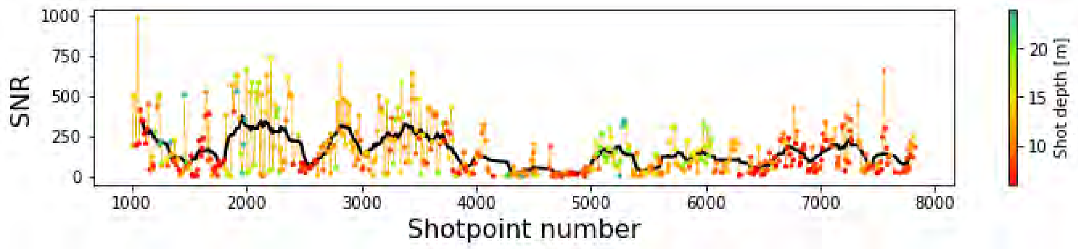


Figure 90: Signal to noise ratios in the 0-1s window with shot depth indicator

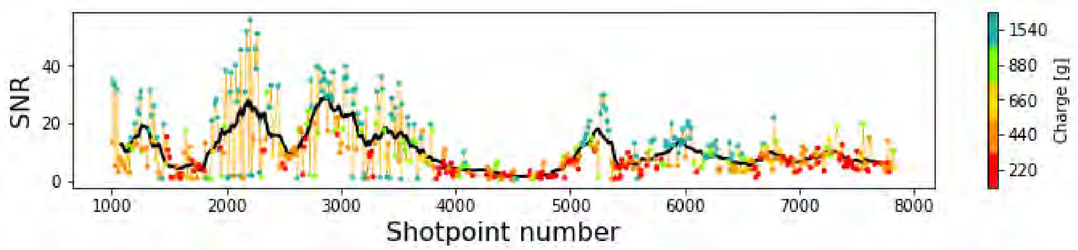


Figure 91: Signal to noise ratios in the 1-2s window with charge size indicator

a

b

c

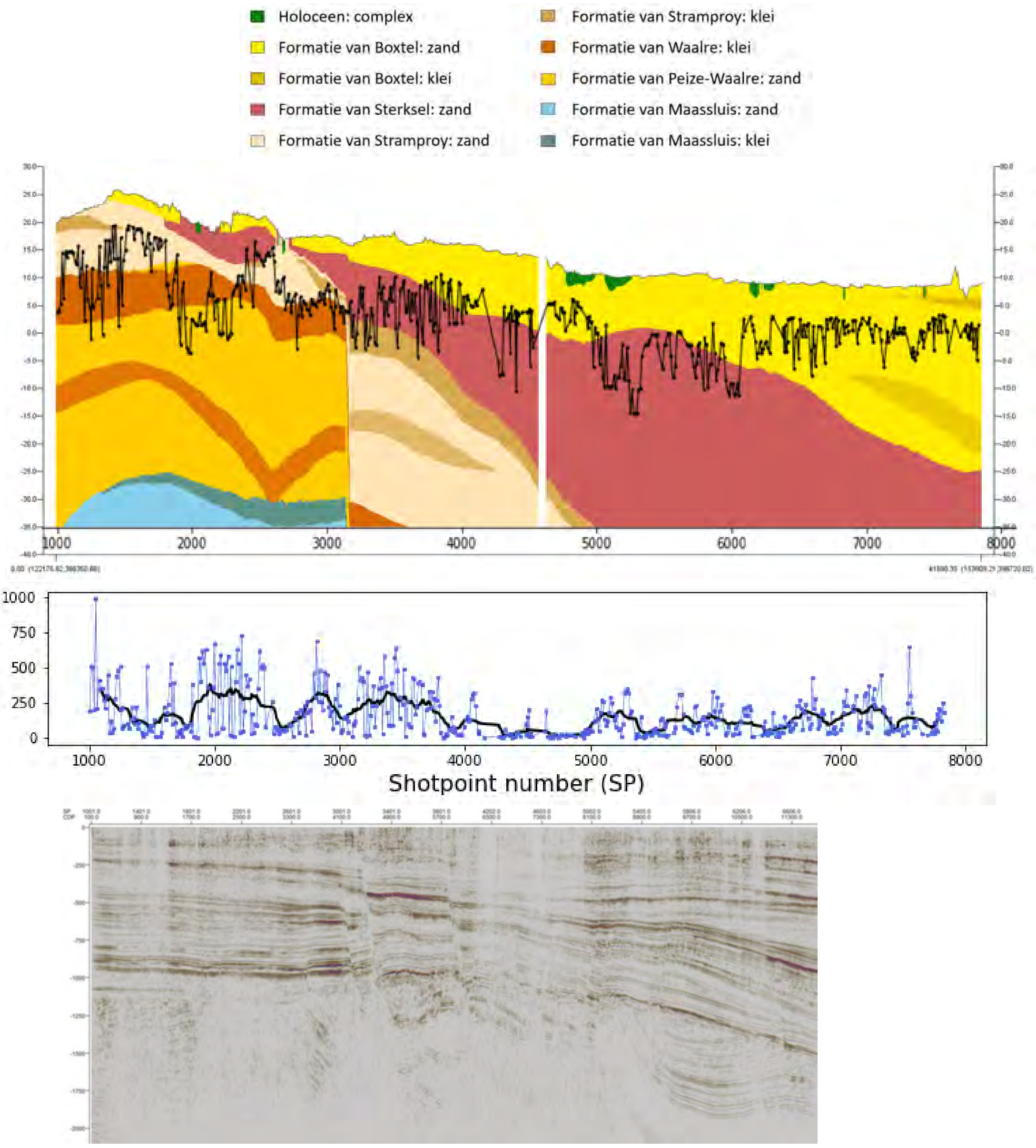


Figure 92: SCAN018. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

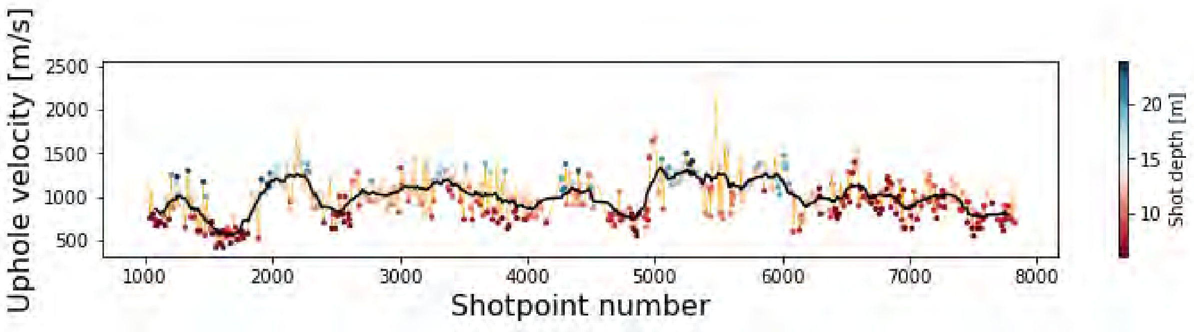


Figure 93: Uphole velocity with shot depth indicator, calculated from uphole times

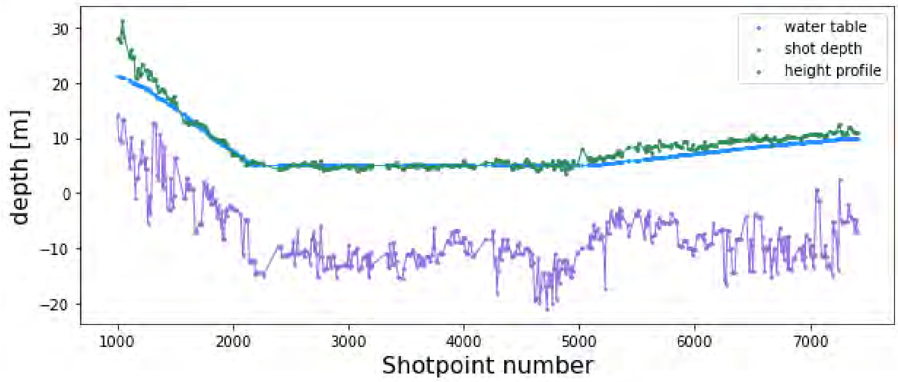


Figure 94: Ground water table along line 18

Receiver domain:

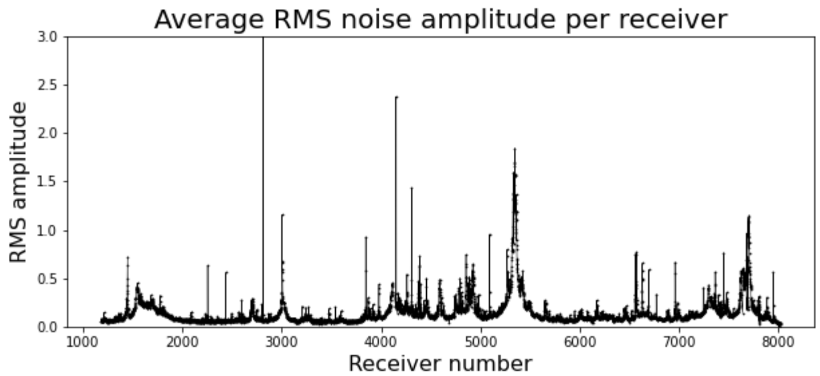


Figure 95: Noise amplitudes in the receiver domain

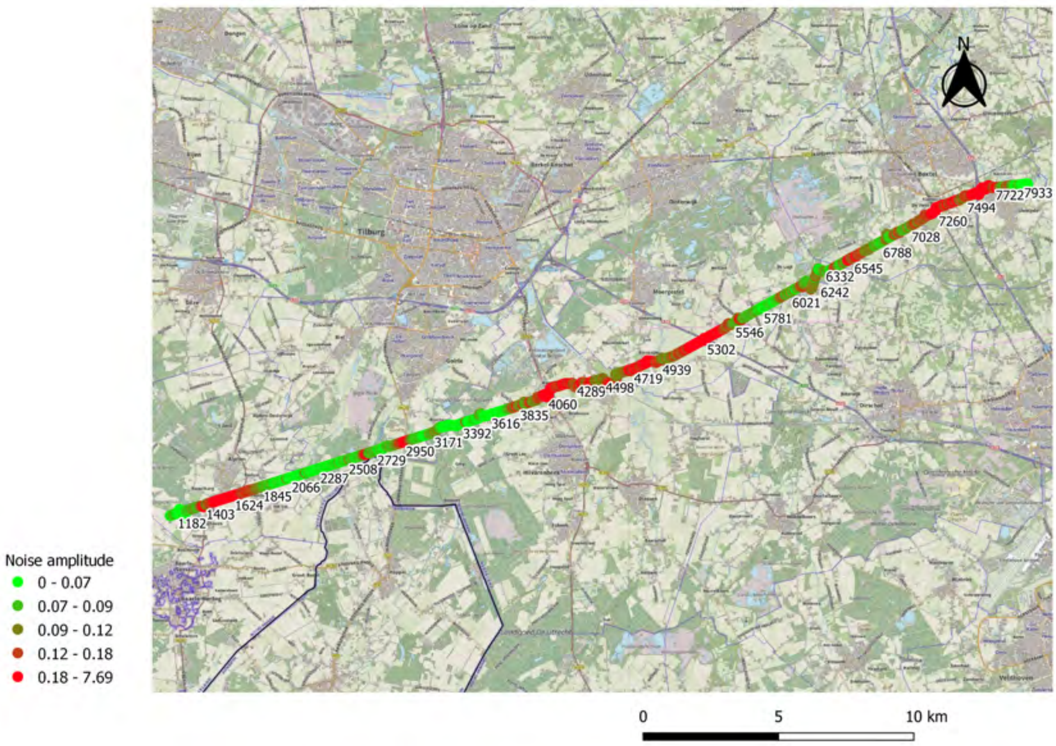


Figure 96: Regional map of line 18. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.9 UGOU021

Line 21 runs from north west to south east and runs from the north to the east of Utrecht. It is a relatively short line and it is part of the GOUD consortium. Near the city of Utrecht low charge sizes are used. Shots are placed relatively deep along this line. There is only little topography on this line as we see in figure 103a. Noise levels are high near the A27, A28, A12 and the railways that cross this line.

Table 11: Acquisition parameters line 21

Number of shots	326
Range source station	1085.5-4973.5
Number of receivers	4014
Range receiver station	1001-5014
Total length	20.070 km

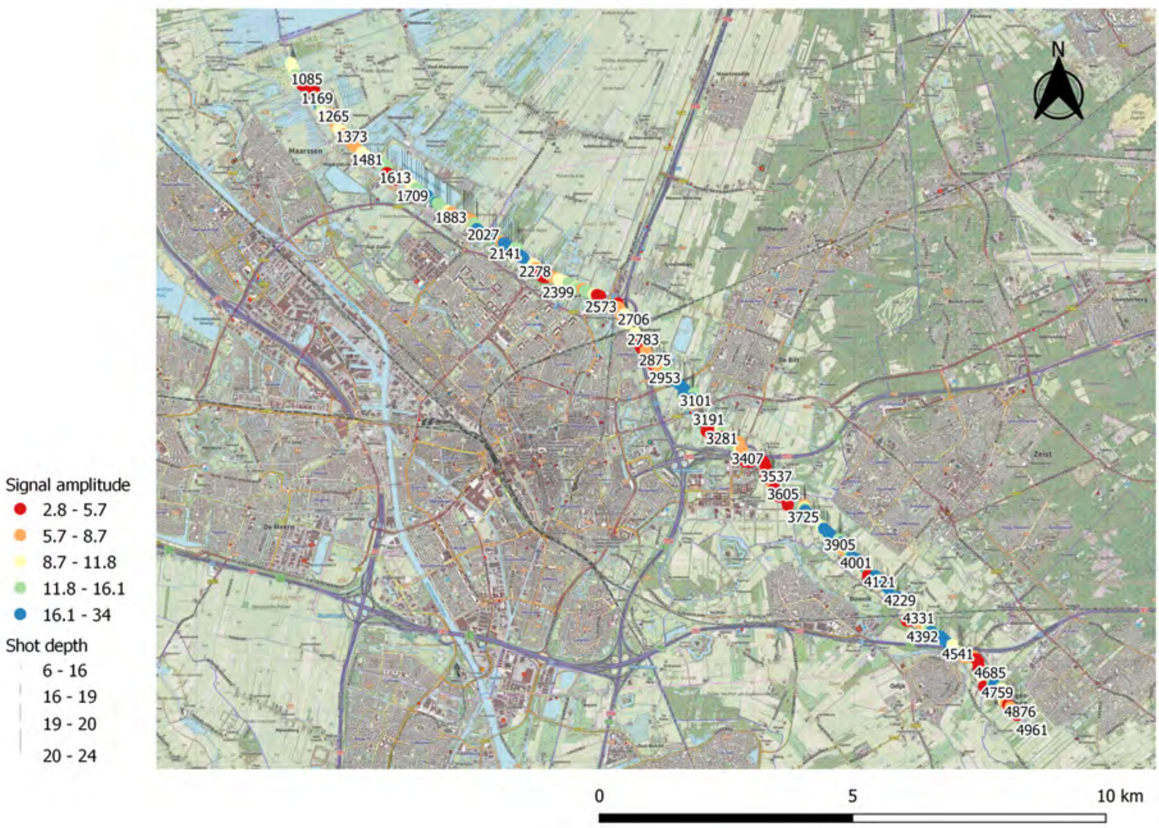


Figure 97: Regional map of line 21. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

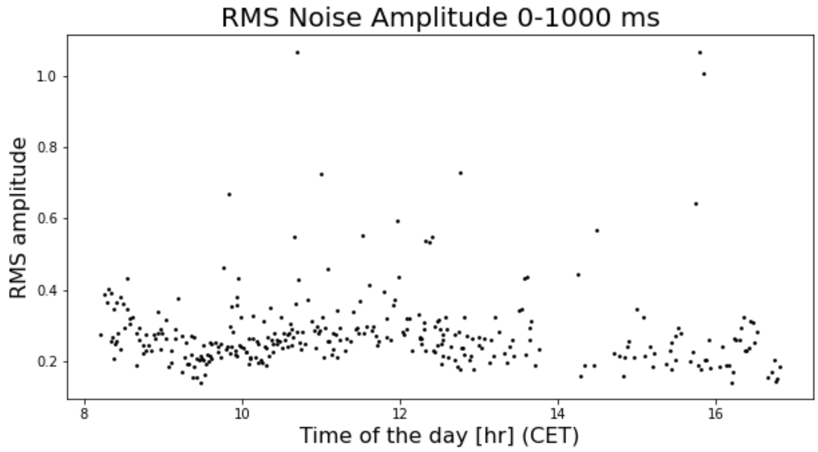


Figure 98: Noise amplitudes in the shot domain per time of the day

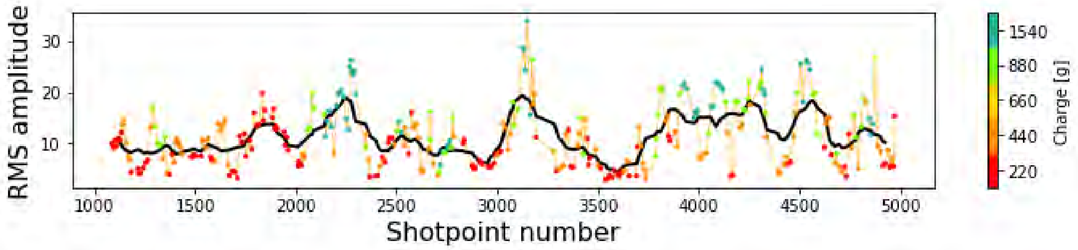


Figure 99: RMS Signal amplitudes in the 0-1s window

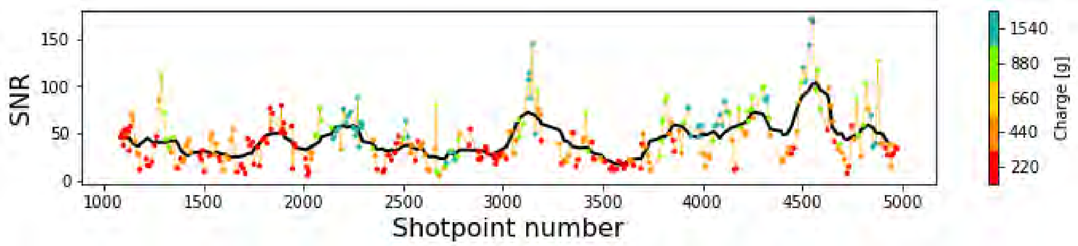


Figure 100: Signal to noise ratios in the 0-1s window with charge size indicator

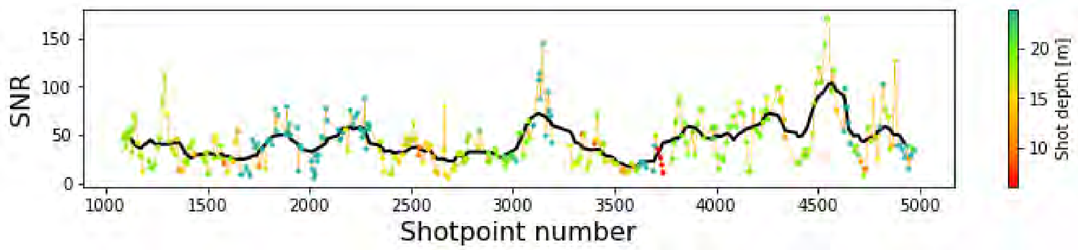


Figure 101: Signal to noise ratios in the 0-1s window with shot depth indicator

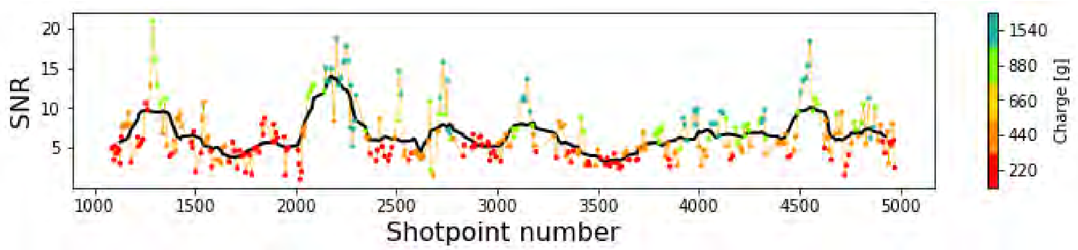


Figure 102: Signal to noise ratios in the 1-2s window with charge size indicator

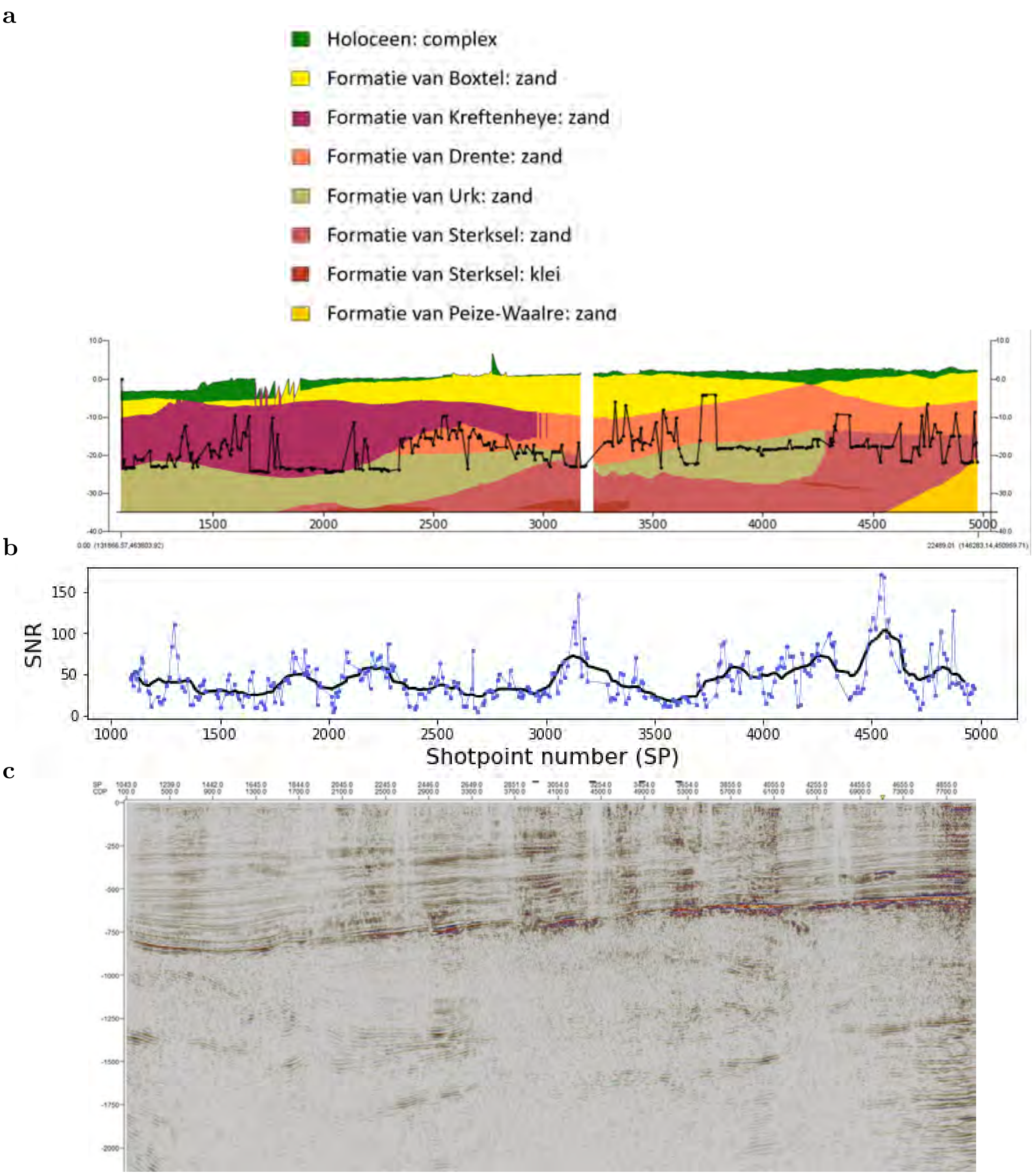


Figure 103: UGOU021. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

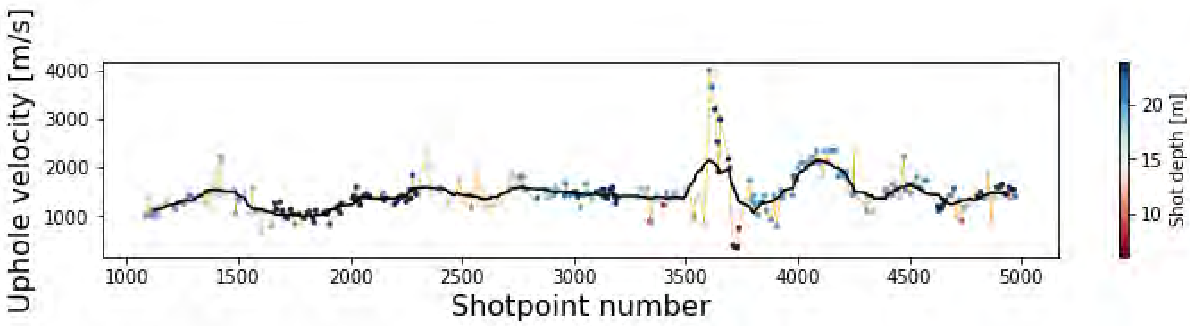


Figure 104: Uphole velocity with shot depth indicator, calculated from uphole times

Receiver domain:

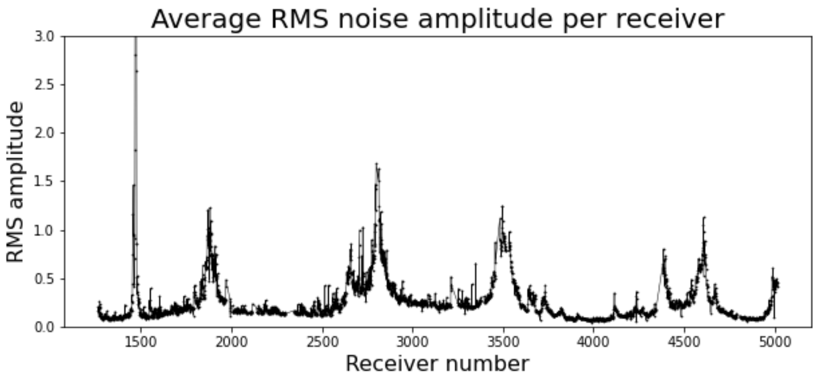


Figure 105: Noise amplitudes in the receiver domain

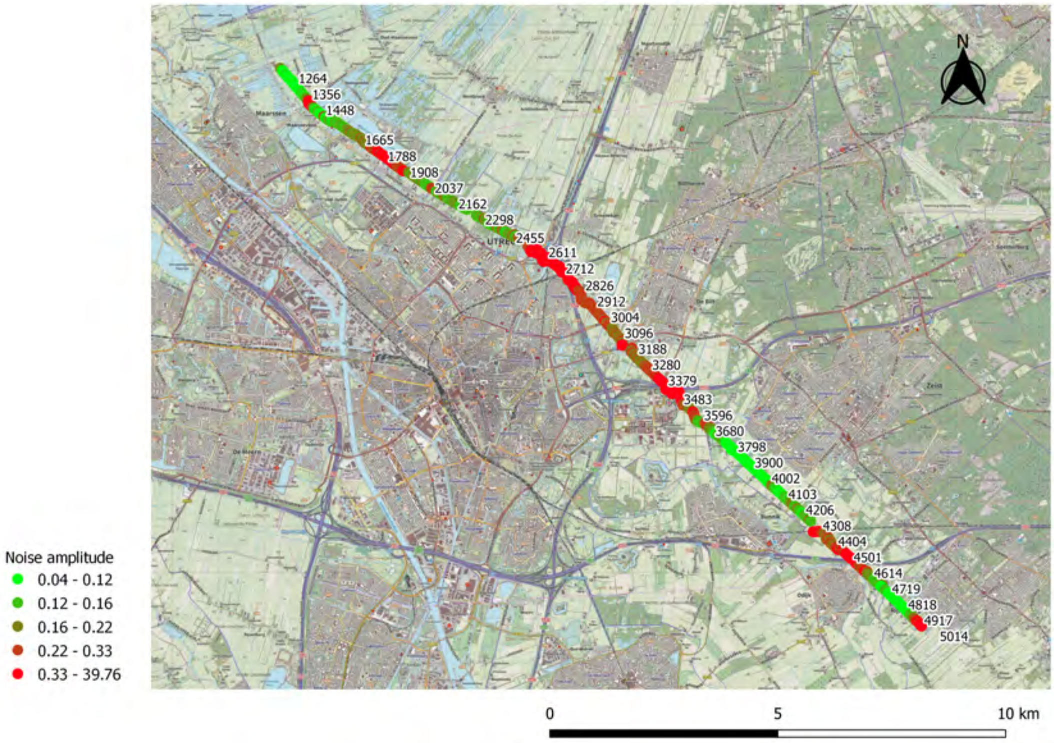


Figure 106: Regional map of line 21. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.10 UGOU022

Line 22 runs from west to east and runs south east of Utrecht and south of Amersfoort. This line is part of the GOUD consortium. A zone of low SNRs is found between shot point 7500 and 8200, corresponding to shallow shot depths as well as shots above the water table. In this region shots are placed in the stowed glacial deposits, grey in figure 113a. It corresponds to low data quality in the fast track (figure 113b). Near the A12 and the railway high noise amplitudes are observed.

Table 12: Acquisition parameters line 22

Number of shots	370
Range source station	4465.5-9065.5
Number of receivers	6048
Range receiver station	3023-9070
Total length	30.240 km

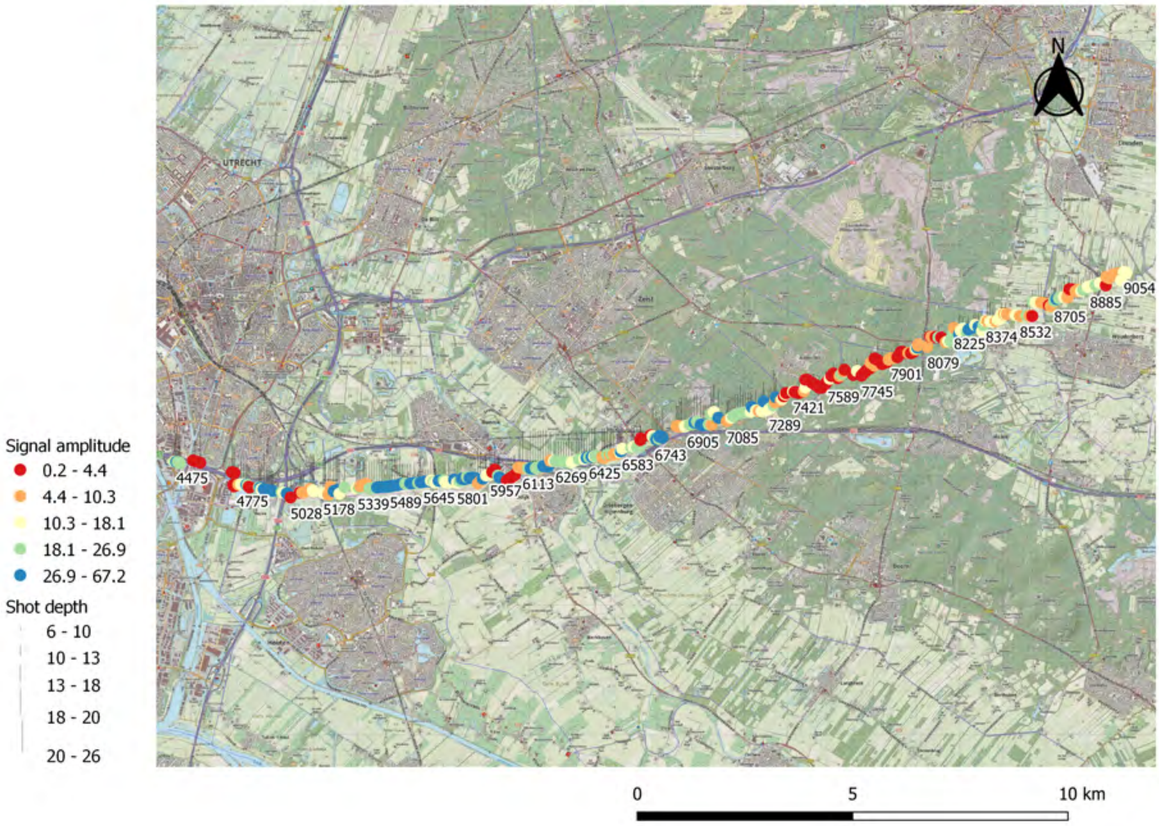


Figure 107: Regional map of line 22. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

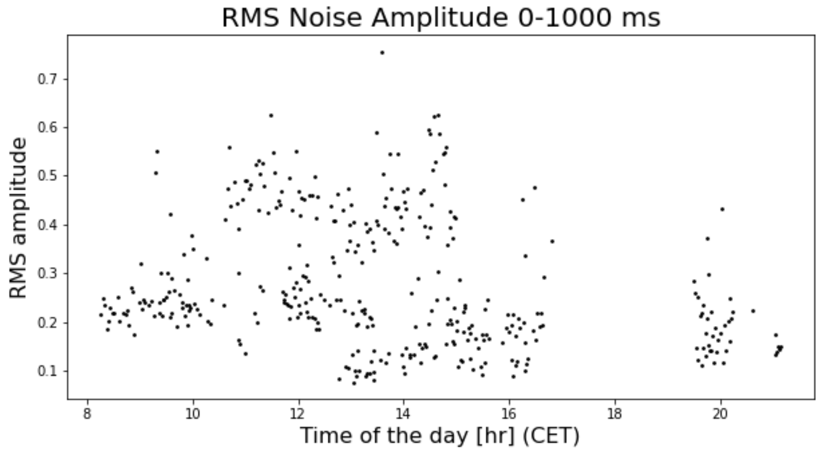


Figure 108: Noise amplitudes in the shot domain per time of the day

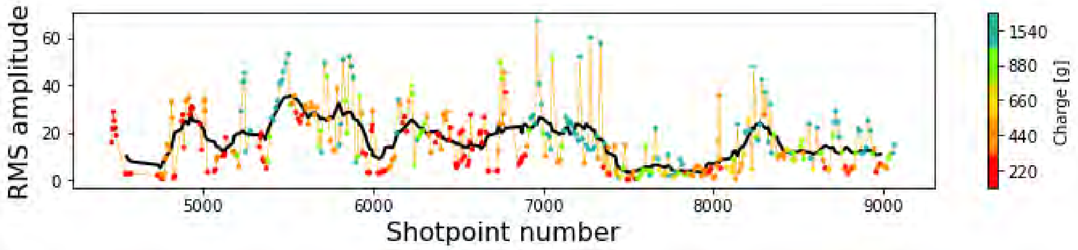


Figure 109: RMS Signal amplitudes in the 0-1s window

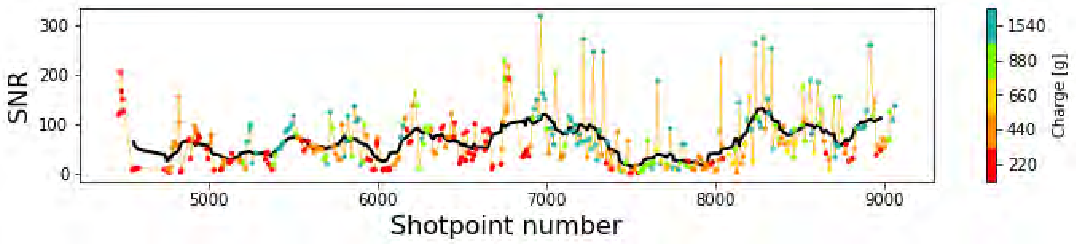


Figure 110: Signal to noise ratios in the 0-1s window with charge size indicator

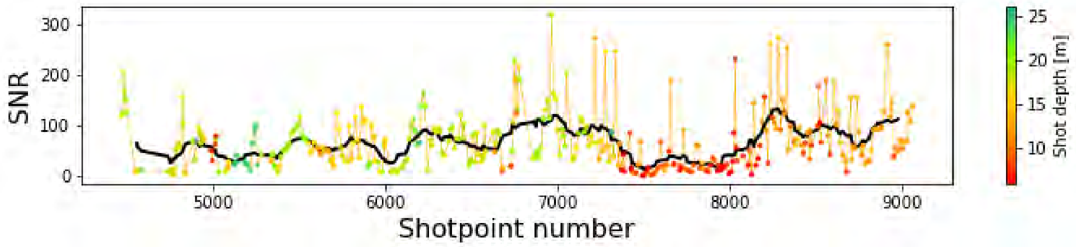


Figure 111: Signal to noise ratios in the 0-1s window with shot depth indicator

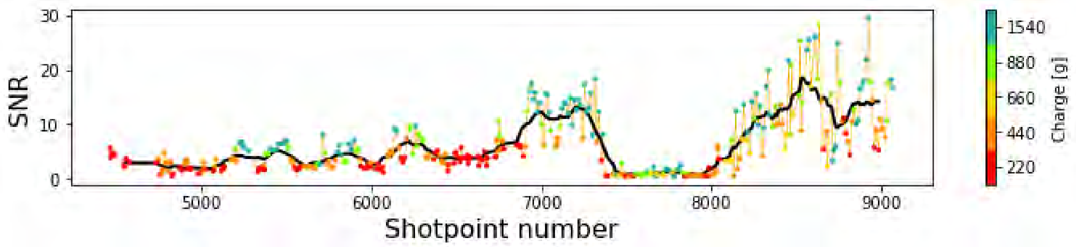


Figure 112: Signal to noise ratios in the 1-2s window with charge size indicator

a

b

c

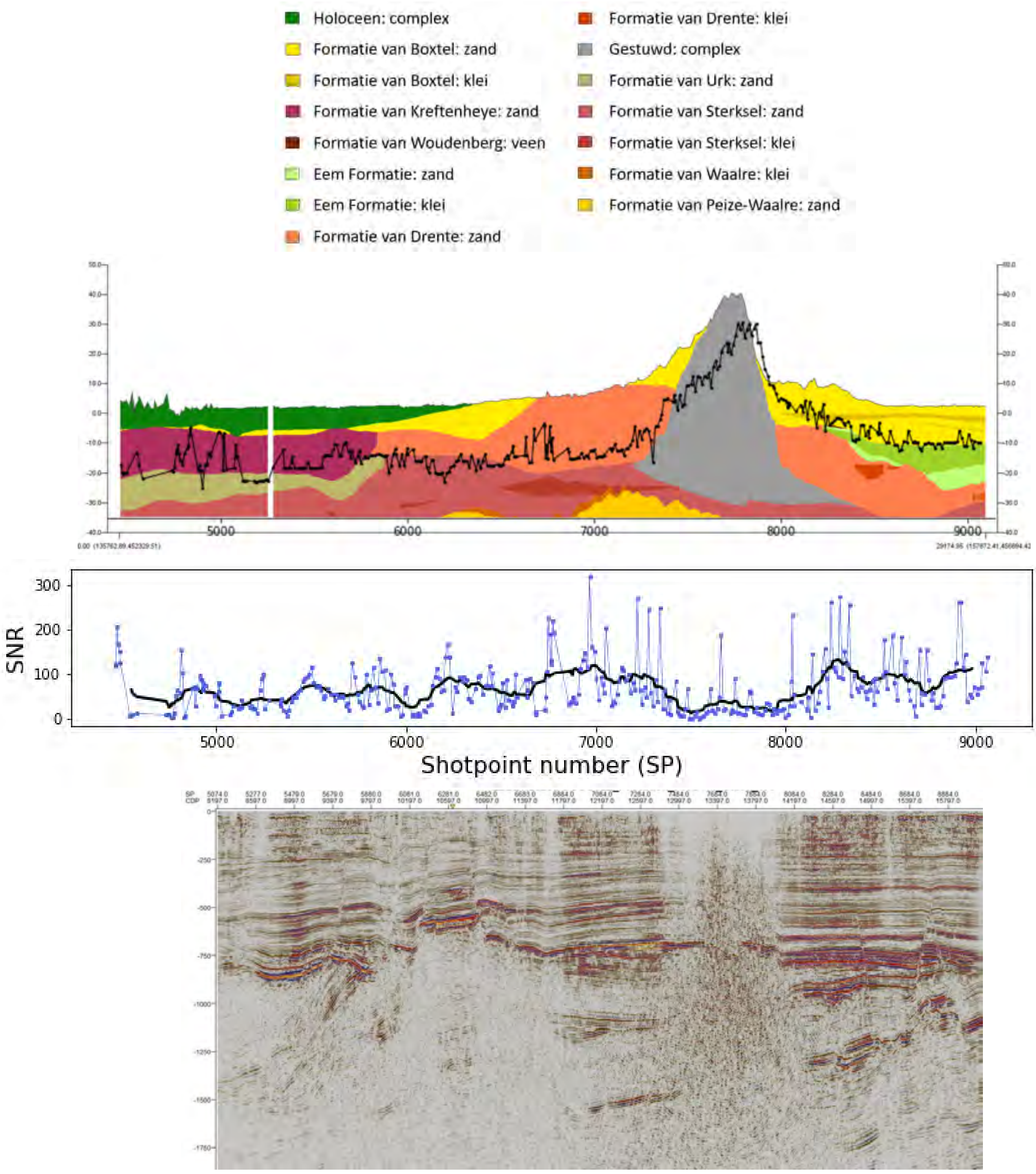


Figure 113: UGOU022. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

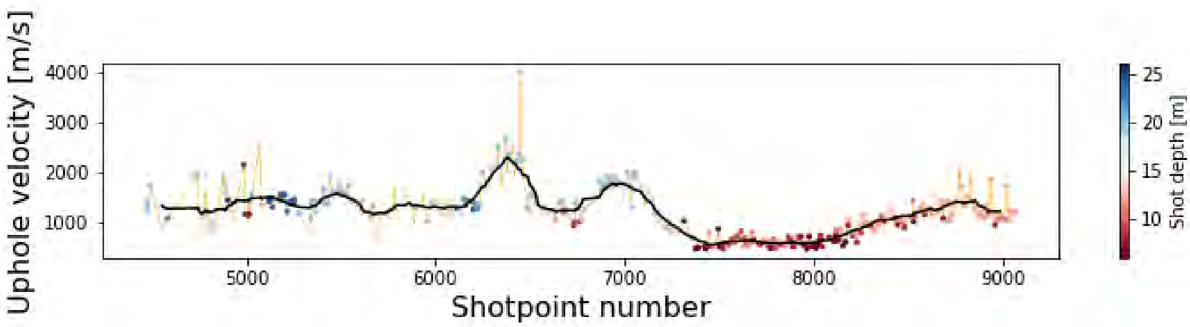


Figure 114: Uphole velocity with shot depth indicator, calculated from uphole times

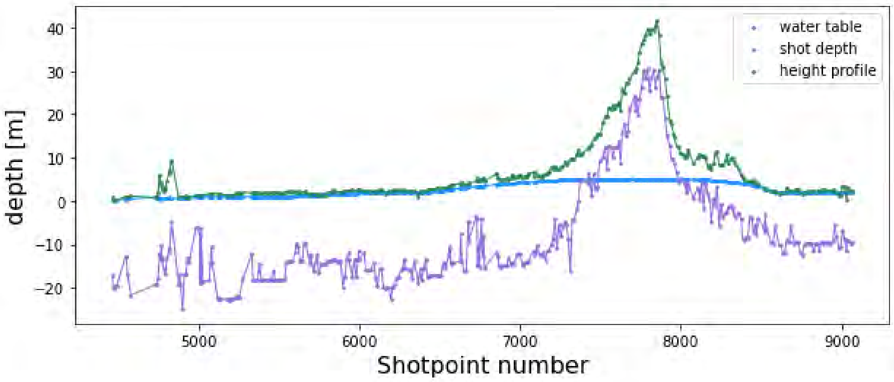


Figure 115: Ground water table along line 22

Receiver domain:

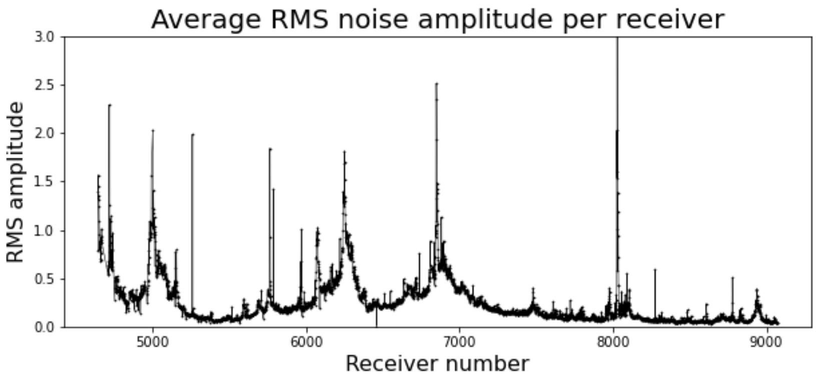


Figure 116: Noise amplitudes in the receiver domain

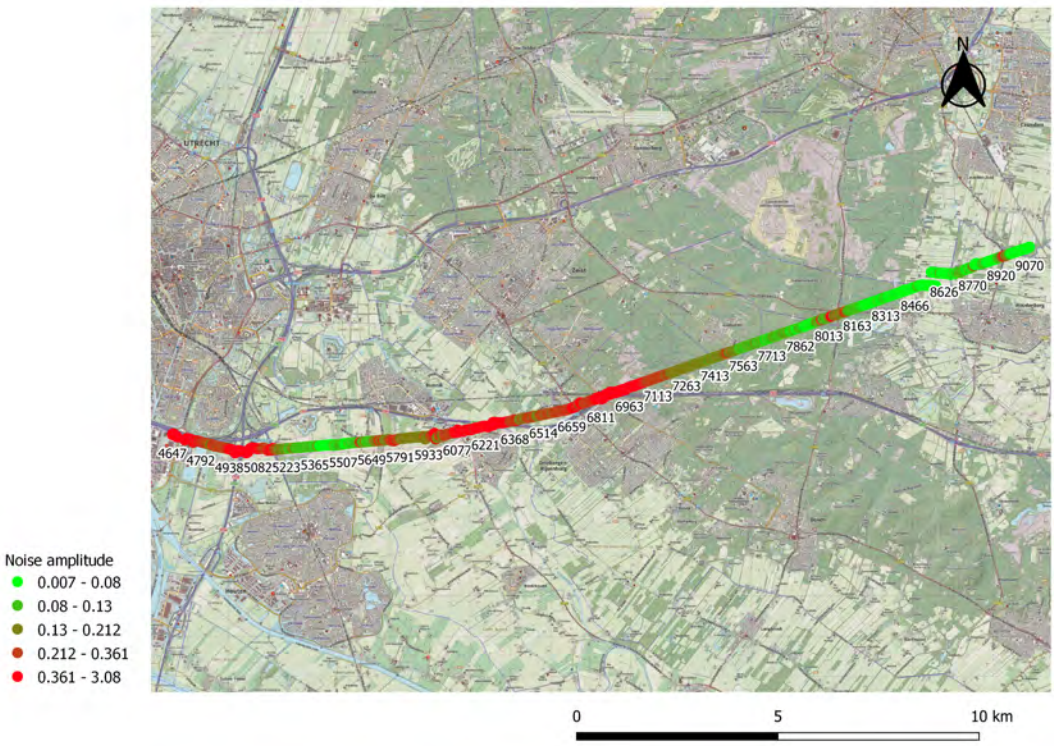


Figure 117: Regional map of line 22. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.11 SCAN023

Line 23 runs from east to west and runs south Utrecht. Between shotpoint 4000 and 5000 there are two shot gaps of 700m because of the crossing the Amsterdam Rijnkanaal and highway junction (figure 118). In figure 124 we see steeply dipping layers around ∼ shotpoint 3500 from 1000 ms on. There is a major source of noise in the middle of this line, close to the city (figure 126 and figure 127).

Table 13: Acquisition parameters line 23

Number of shots	374
Range source station	1012.5-5777.5
Number of receivers	6496
Range receiver station	1001-7267
Total length	31.335 km

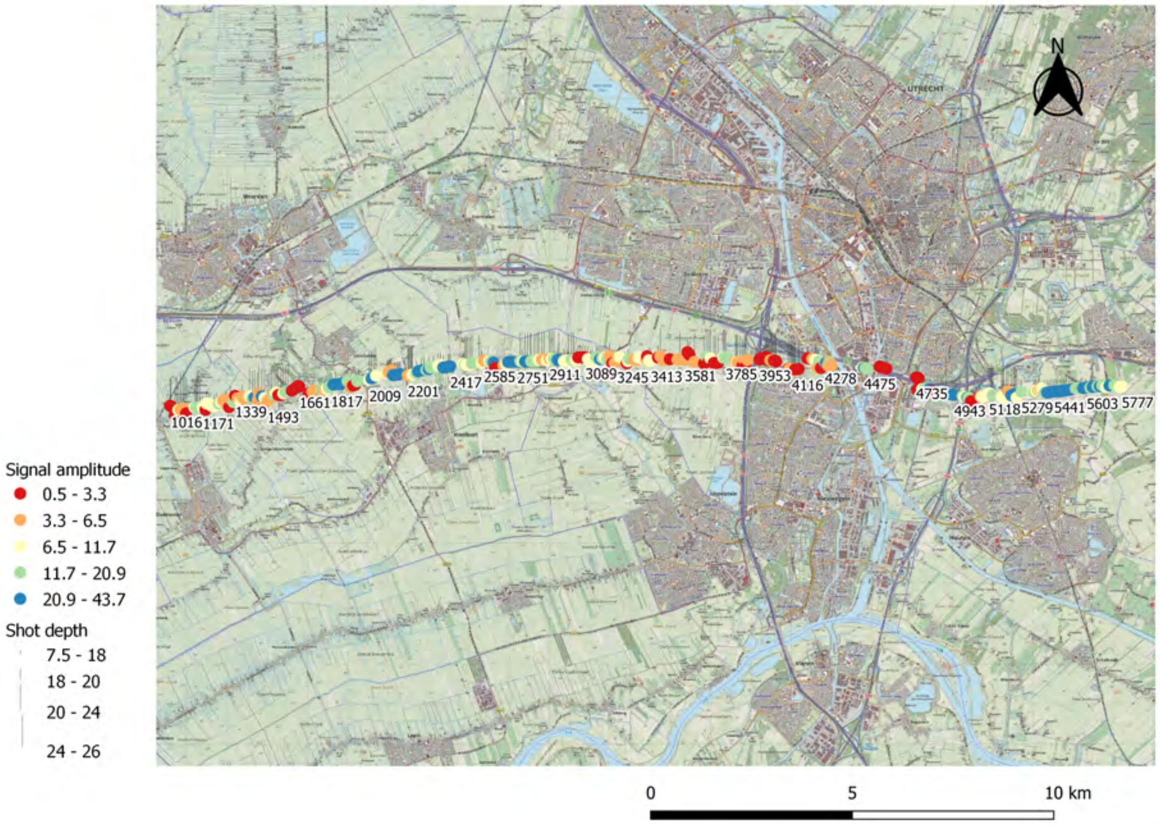


Figure 118: Regional map of line 23. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

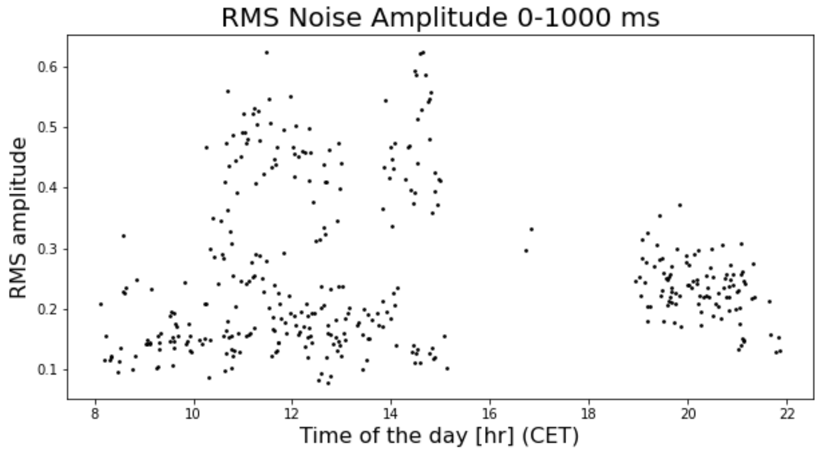


Figure 119: Noise amplitudes in the shot domain per time of the day

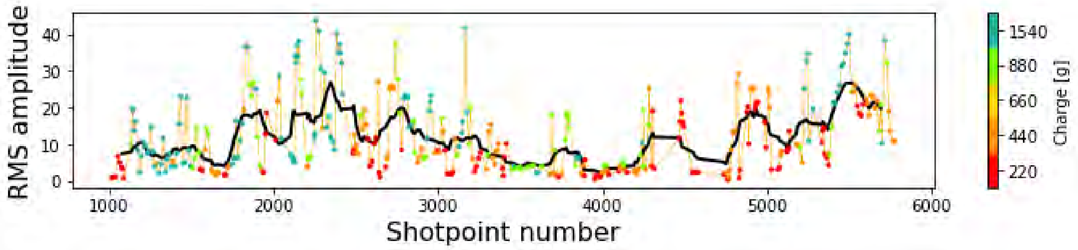


Figure 120: RMS Signal amplitudes in the 0-1s window

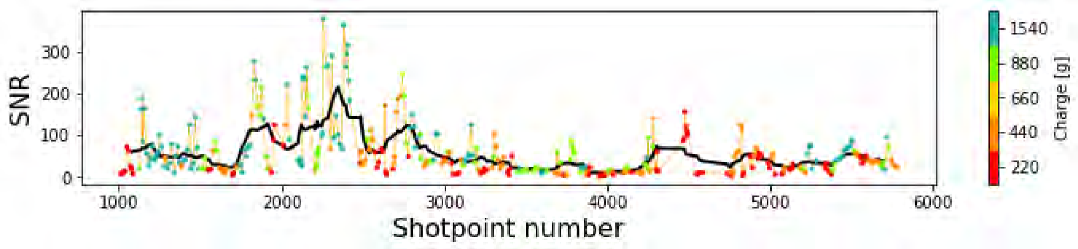


Figure 121: Signal to noise ratios in the 0-1s window with charge size indicator

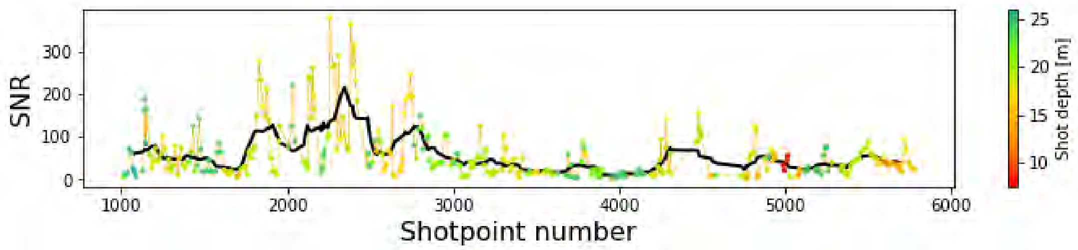


Figure 122: Signal to noise ratios in the 0-1s window with shot depth indicator

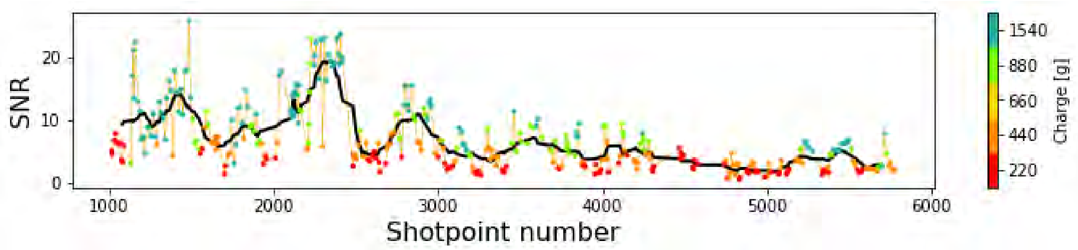
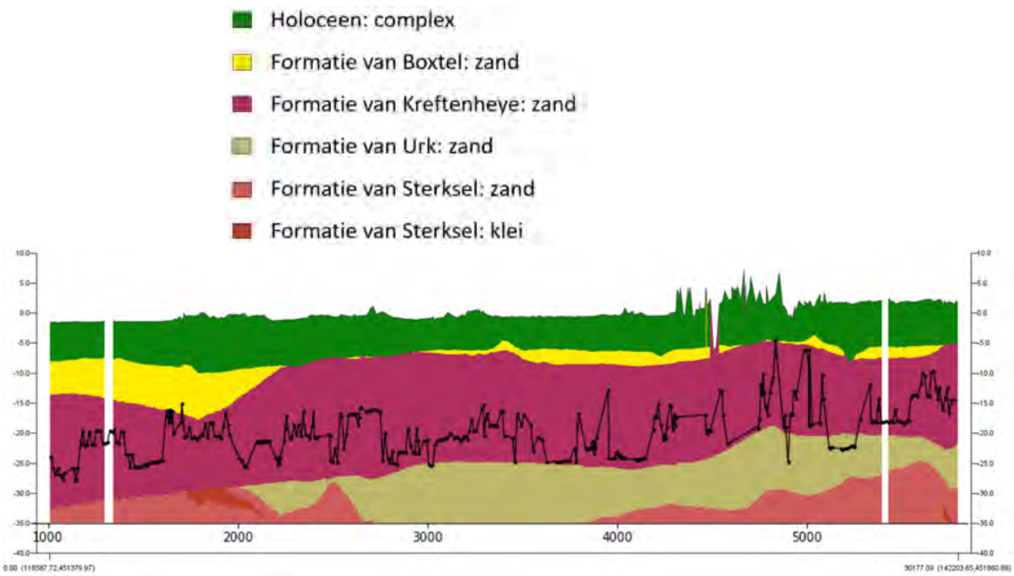
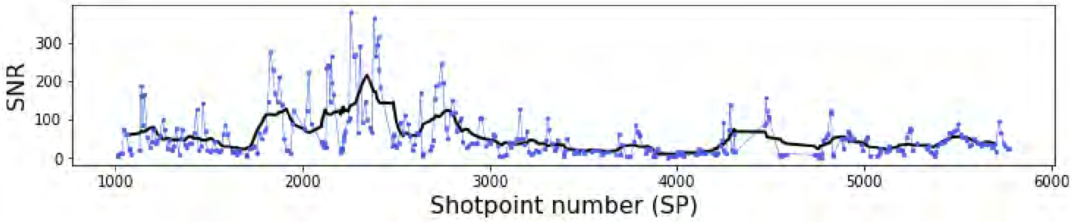


Figure 123: Signal to noise ratios in the 1-2s window with charge size indicator

a



b



c

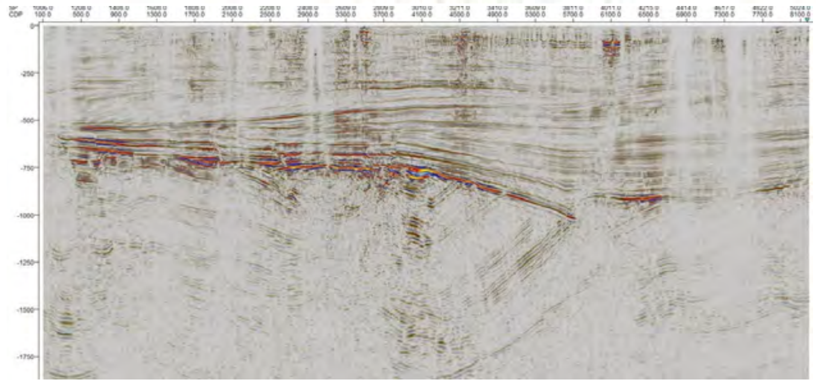


Figure 124: SCAN023. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

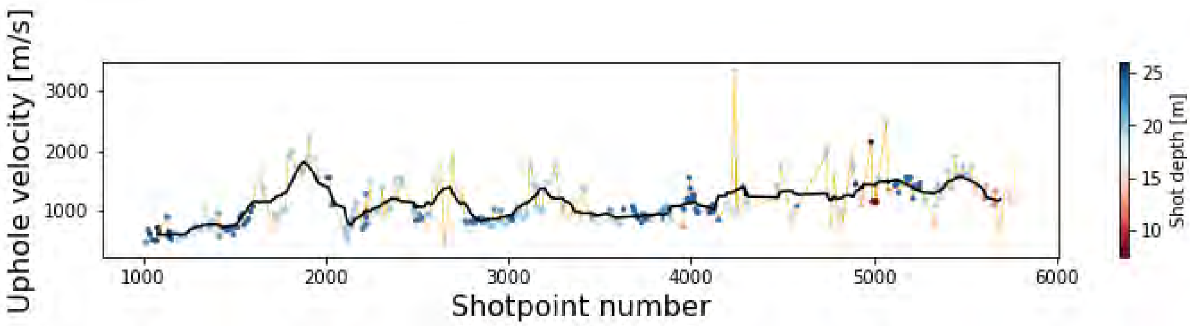


Figure 125: Uphole velocity with shot depth indicator, calculated from uphole times

Receiver domain:

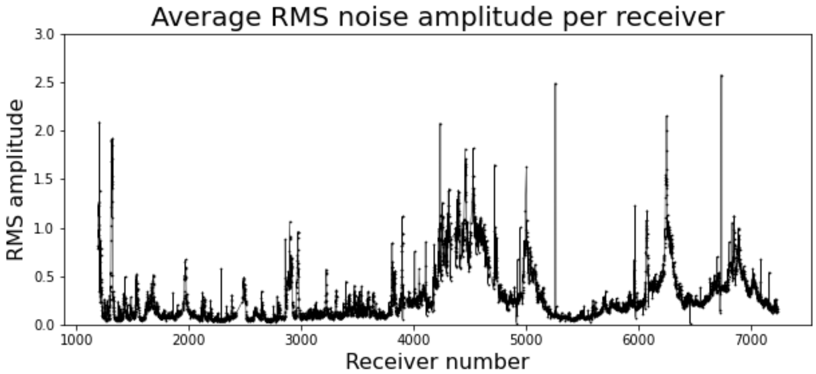


Figure 126: Noise amplitudes in the receiver domain

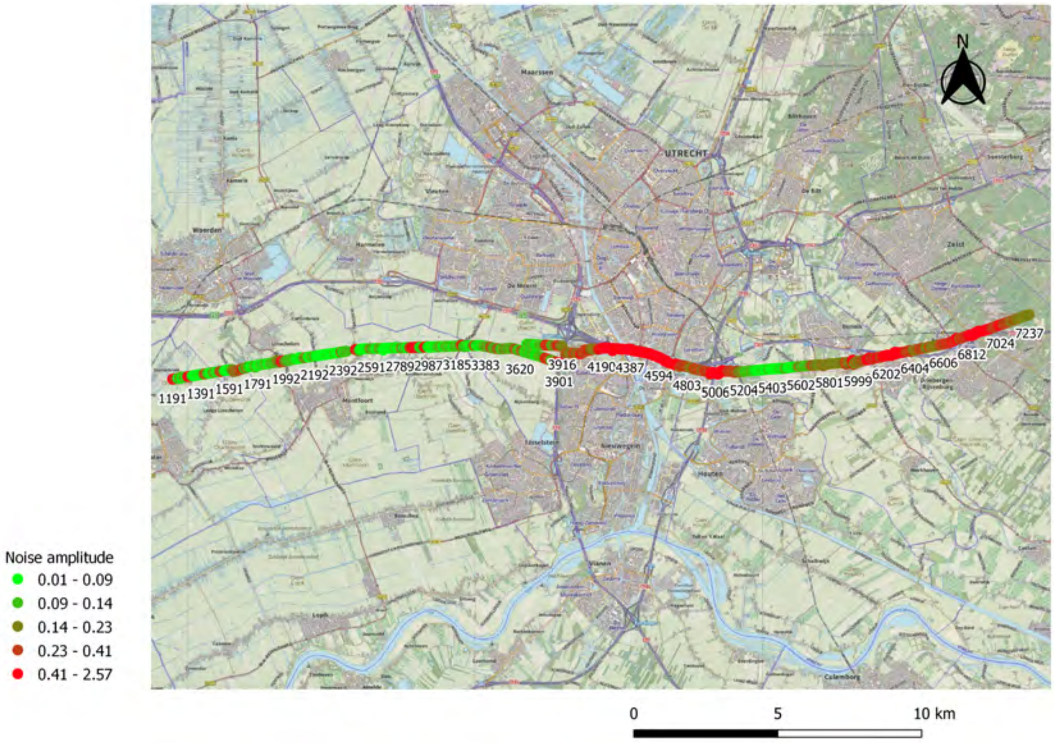


Figure 127: Regional map of line 23. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.12 SCAN024

Line 24 runs from south to north and runs south east of Amsterdam and west of Utrecht. Signal amplitudes are relatively high at the end on the line, but SNR is not that high because noise levels are high at this end of the line. Almost all shots are relatively deeply fired, > 16m. Receivers are continued a bit further north on the line, where no shots are fired. That is the reason the fast track is a bit extended. Around the A2 crossing noise amplitudes are high.

Table 14: Acquisition parameters line 24

Number of shots	478
Range source station	1001.5-6784.5
Number of receivers	7062
Range receiver station	1001-8062
Total length	35.310 km

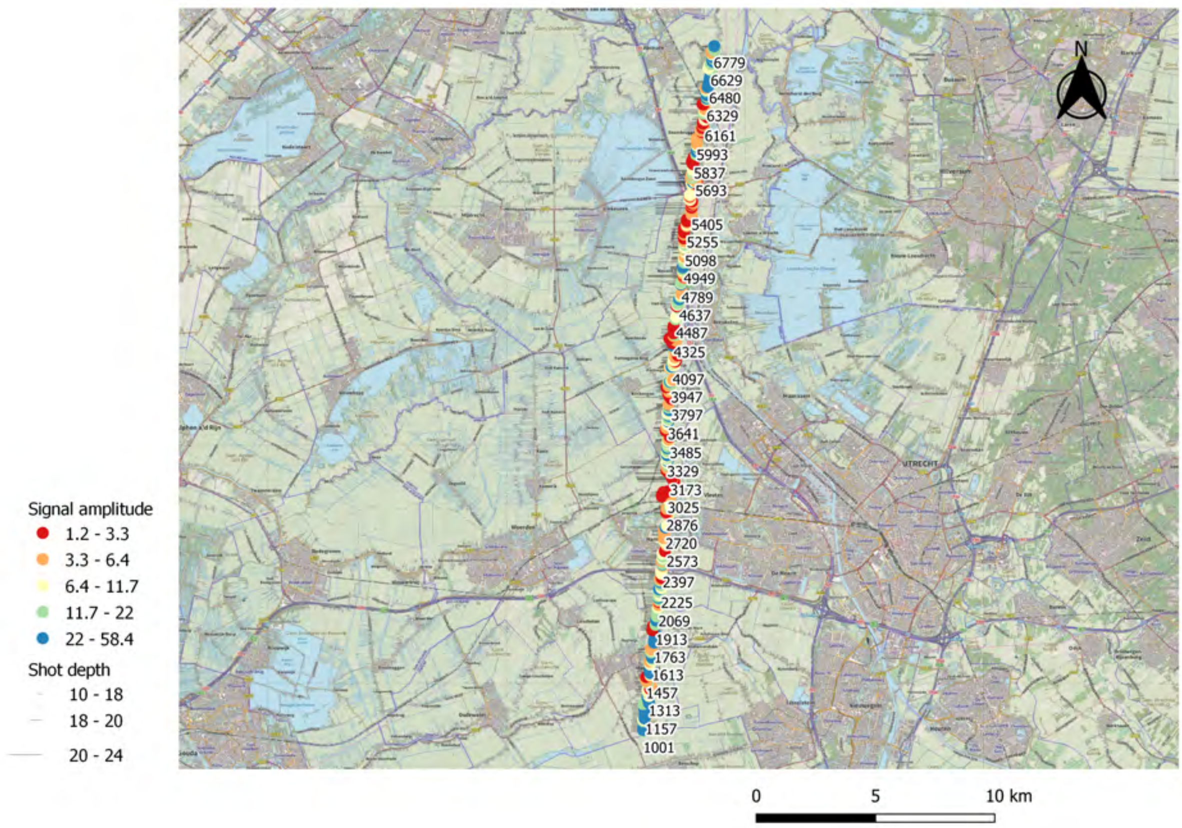


Figure 128: Regional map of line 24. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

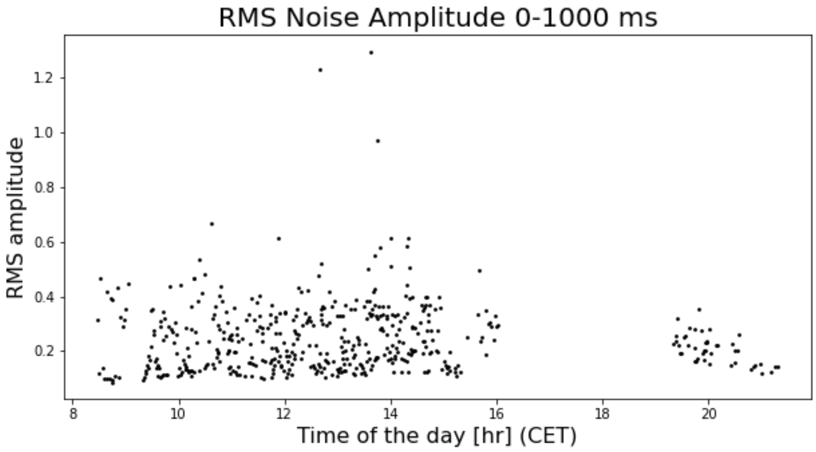


Figure 129: Noise amplitudes in the shot domain per time of the day

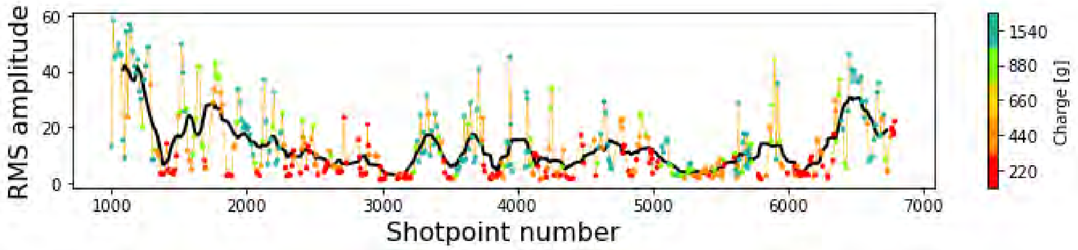


Figure 130: RMS Signal amplitudes in the 0-1s window

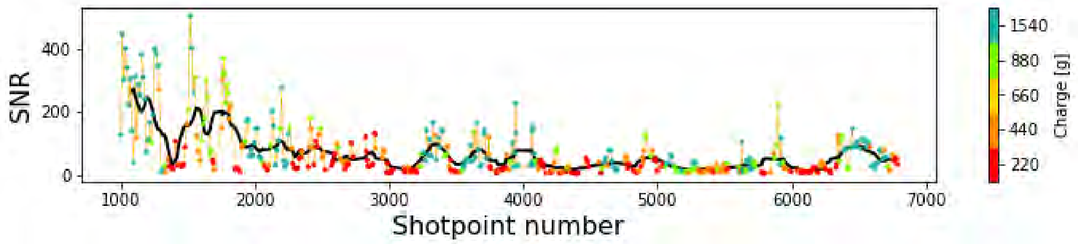


Figure 131: Signal to noise ratios in the 0-1s window with charge size indicator

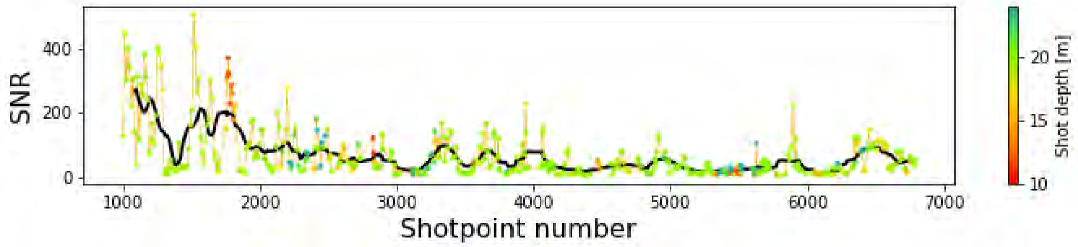


Figure 132: Signal to noise ratios in the 0-1s window with shot depth indicator

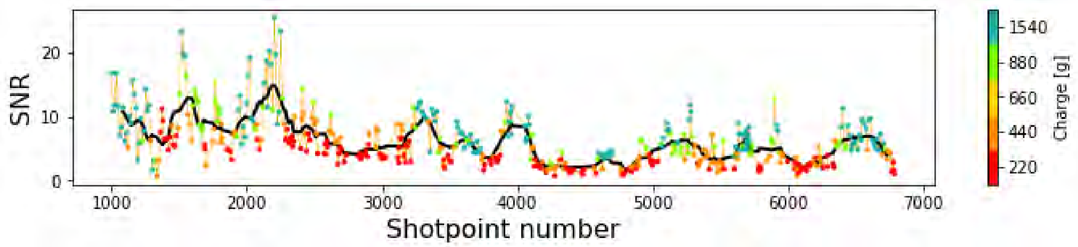
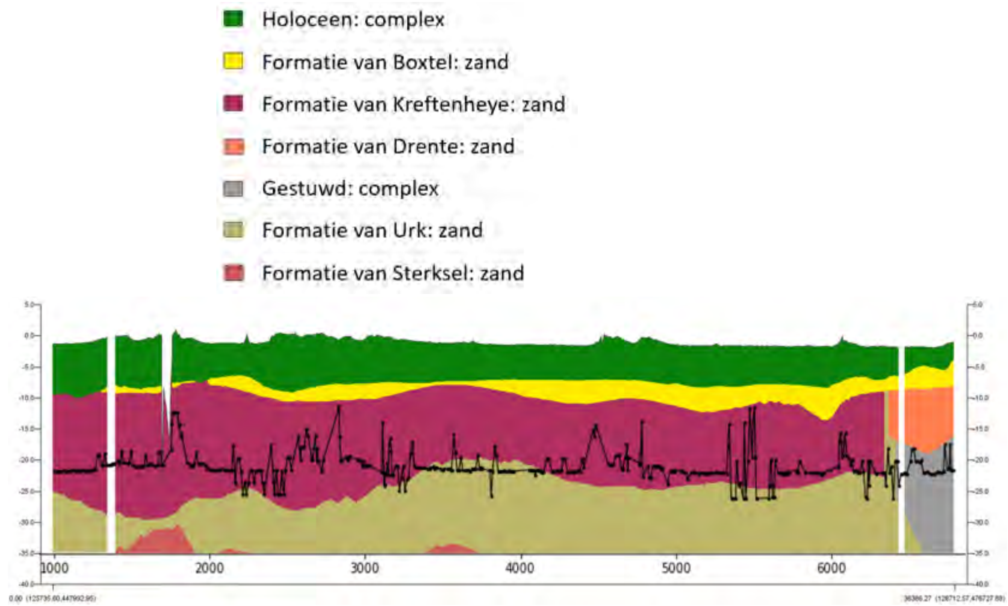
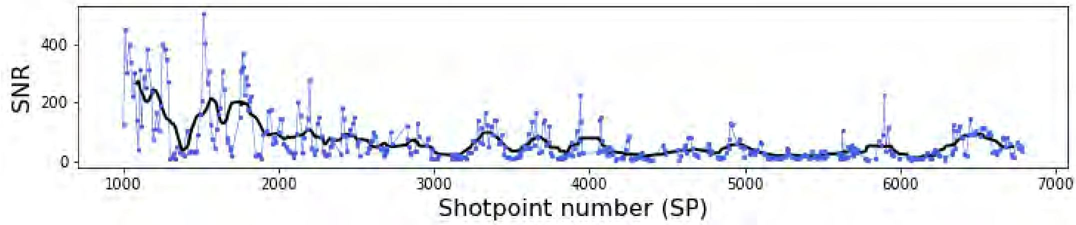


Figure 133: Signal to noise ratios in the 1-2s window with charge size indicator

a



b



c

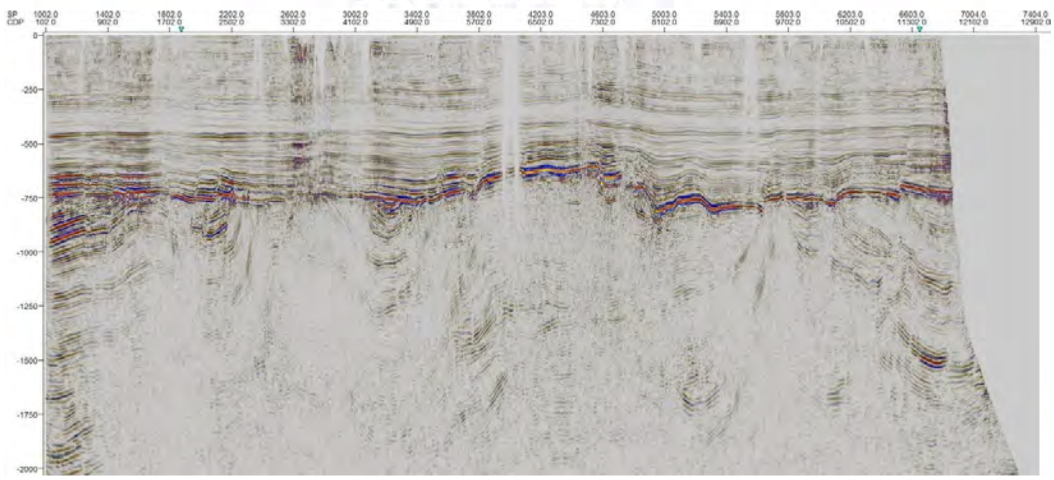


Figure 134: SCAN024. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

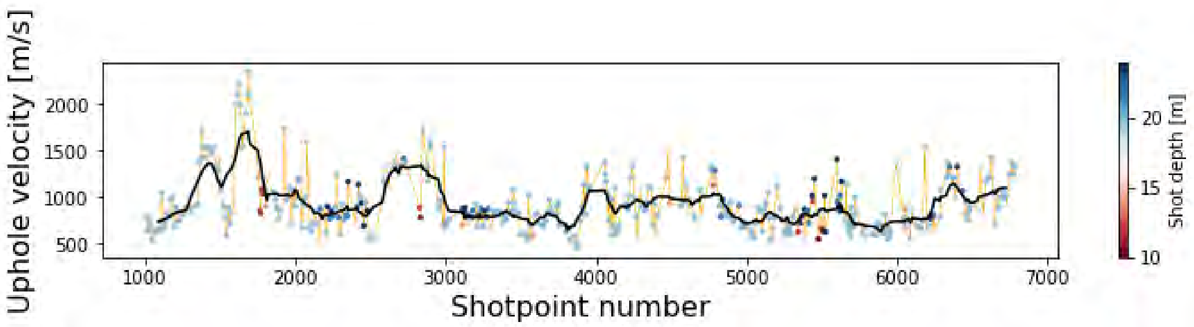


Figure 135: Uphole velocity with shot depth indicator, calculated from uphole times

Receiver domain:

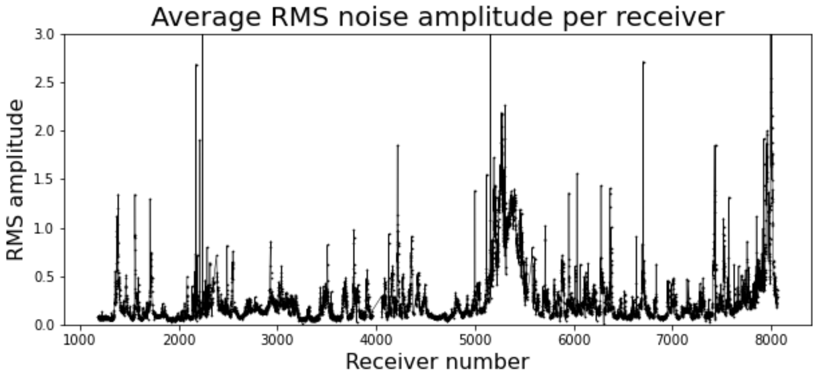


Figure 136: Noise amplitudes in the receiver domain

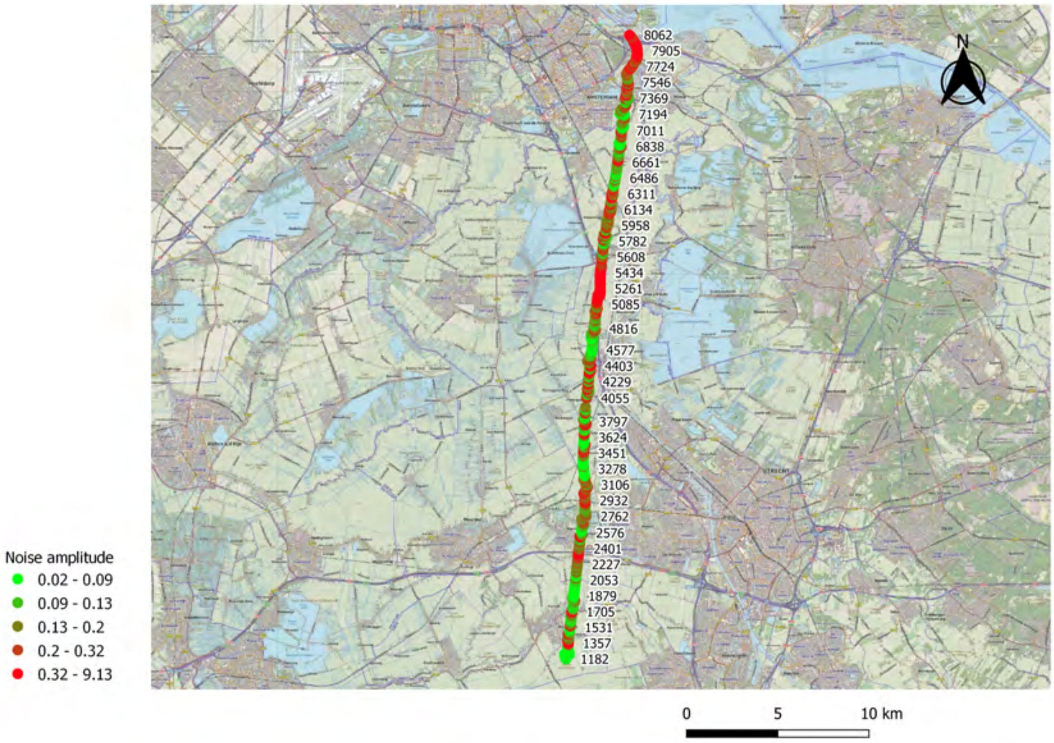


Figure 137: Regional map of line 24. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.13 SCAN025

Line 25 runs from south west to north east and runs south of Amsterdam and east of Alphen aan de Rijn. Signal amplitudes and therefore SNRs are low at the very beginning of the line. Those shots are taken in a wet area. The quality of the fast track at the beginning of the line is quite low. At the very end of the line there are receivers but no shots. Noise ampltitudes of the receivers up north are high, near Amsterdam.

Table 15: Acquisition parameters line 25

Number of shots	582
Range source station	1114.5-8537.5
Number of receivers	8925
Range receiver station	1001-9925
Total length	44.625 km

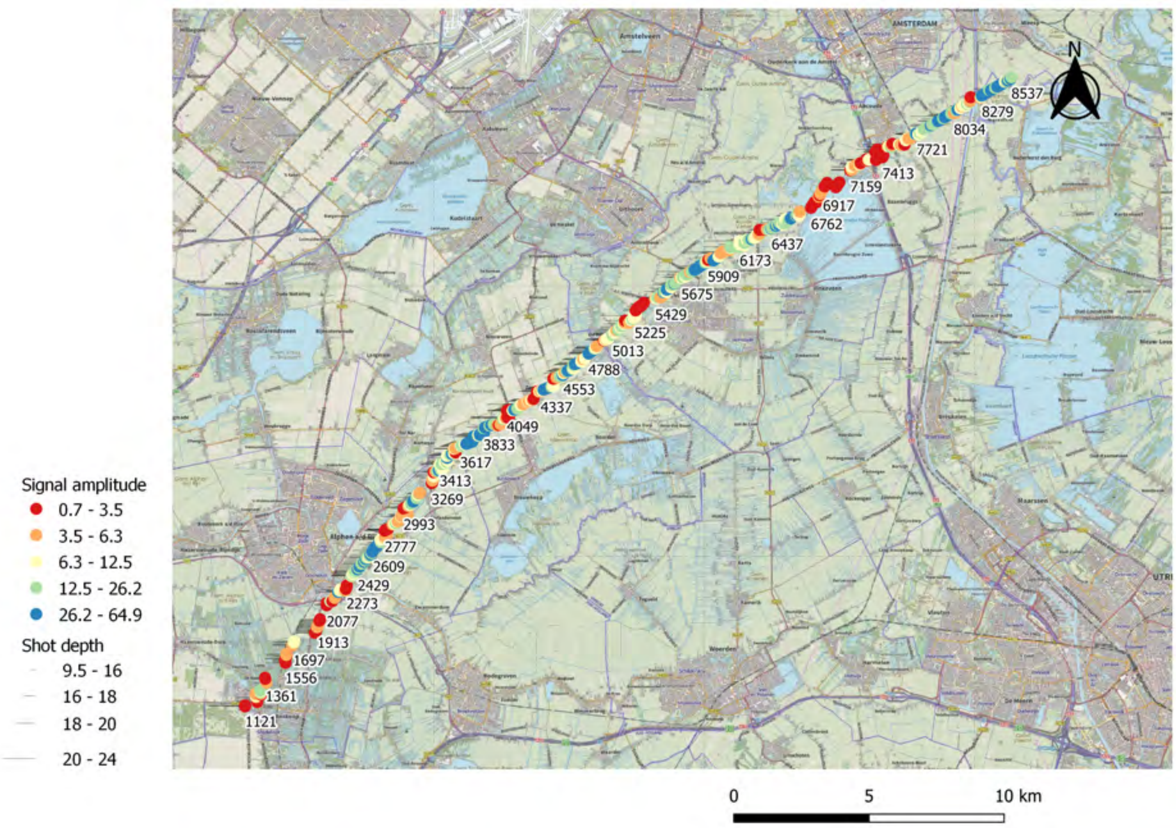


Figure 94: Regional map of line 25. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

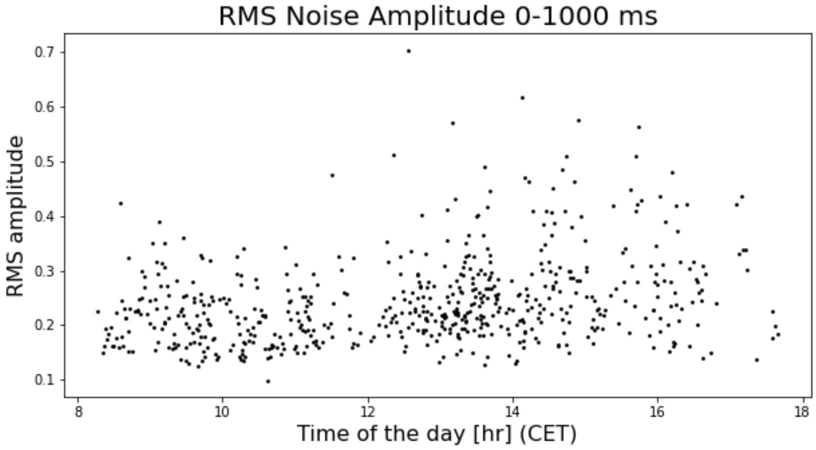


Figure 95: Noise amplitudes in the shot domain per time of the day

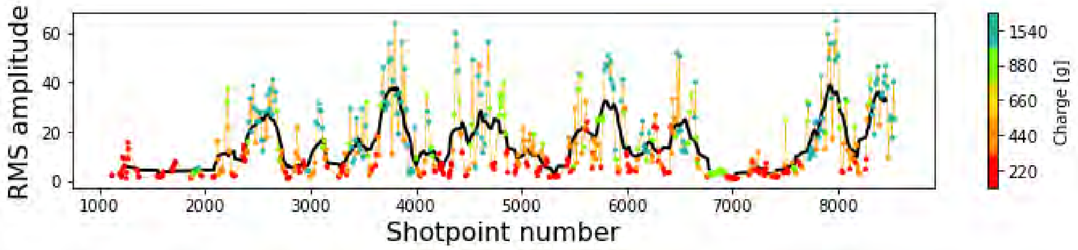


Figure 96: RMS Signal amplitudes in the 0-1s window

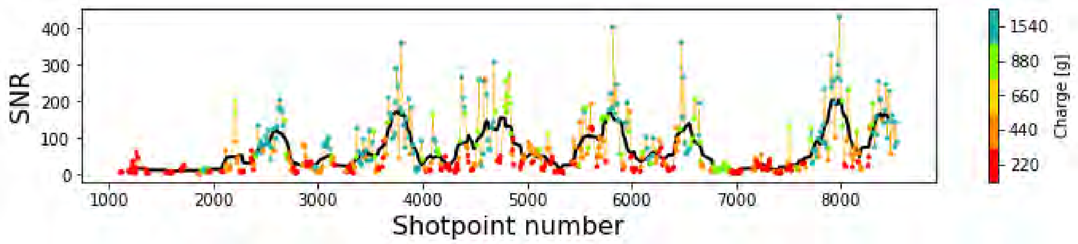


Figure 97: Signal to noise ratios in the 0-1s window with charge size indicator

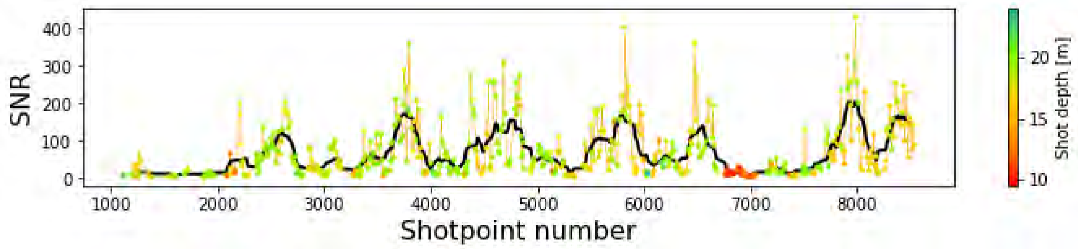


Figure 98: Signal to noise ratios in the 0-1s window with shot depth indicator

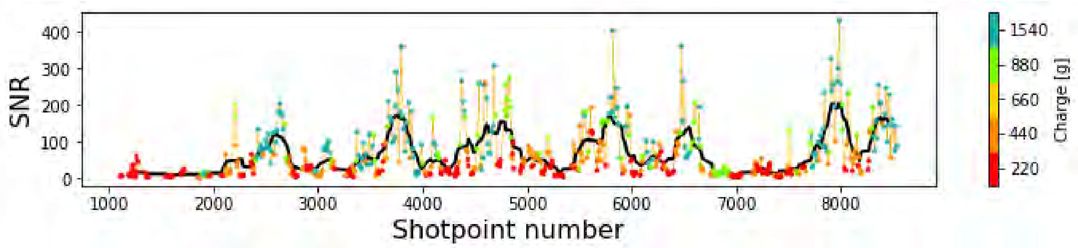


Figure 99: Signal to noise ratios in the 1-2s window with charge size indicator

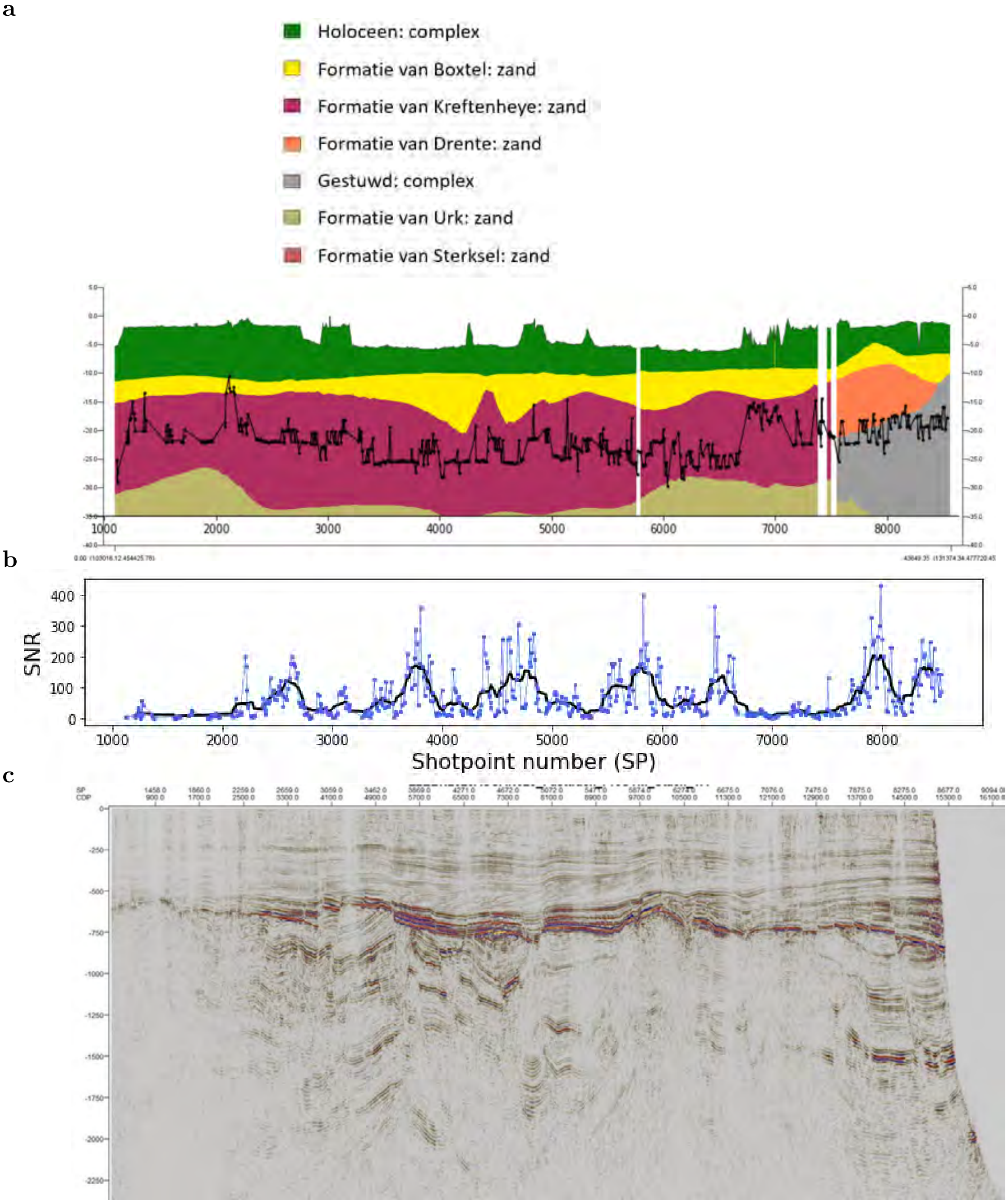


Figure 100: SCAN025. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

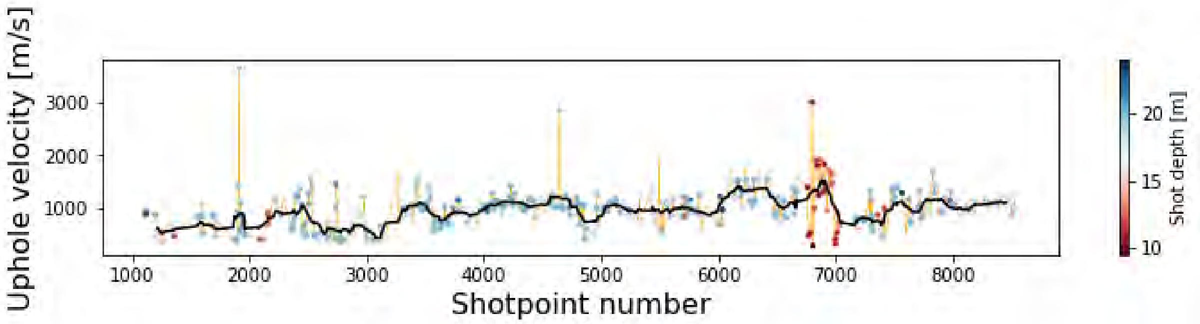


Figure 101: Uphole velocity with shot depth indicator, calculated from uphole times

Receiver domain:

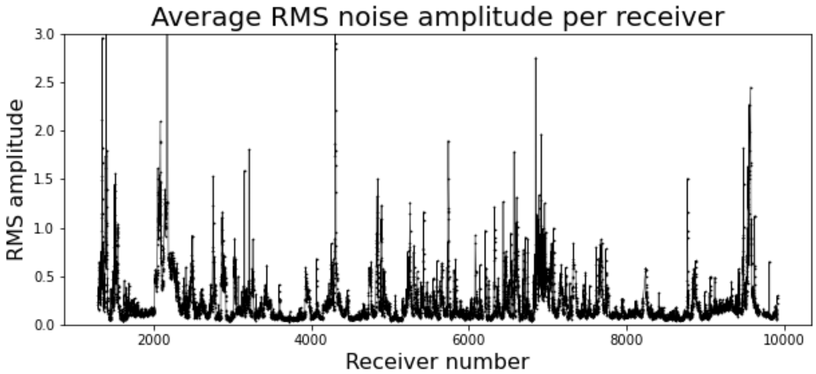


Figure 102: Noise amplitudes in the receiver domain

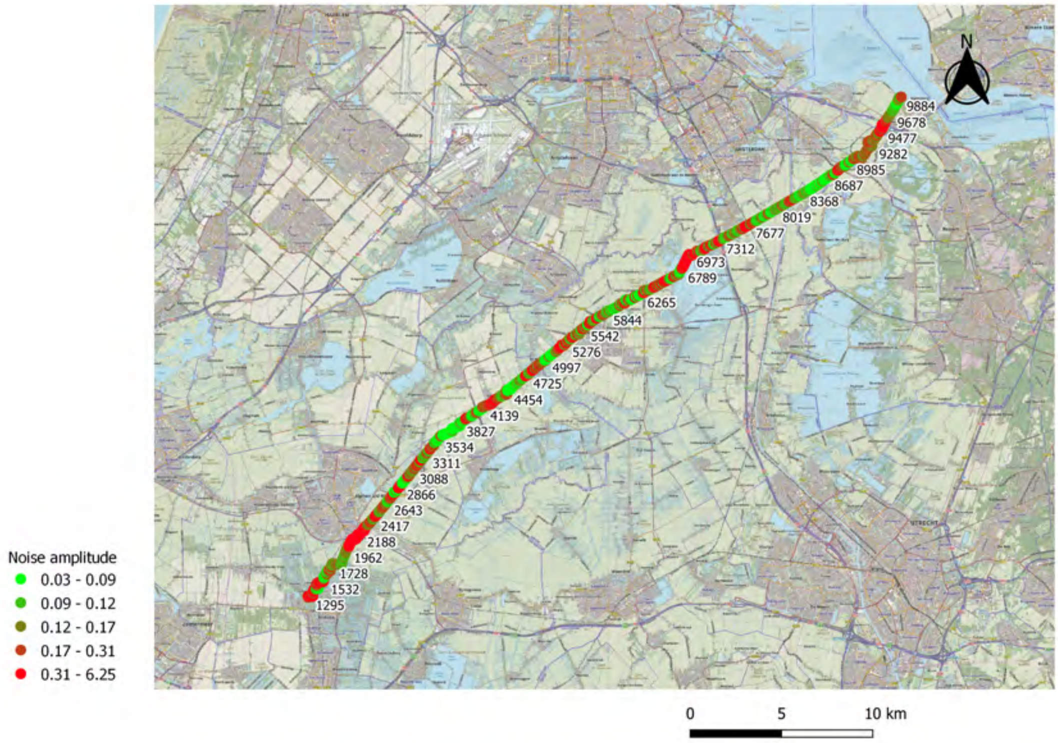


Figure 103: Regional map of line 25. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.14 SCAN026

Line 26 runs from south to north and runs west Amsterdam. There are two extremely large shot gaps with a width of 1.8 and 3.0 km respectively. Between receiver number 5000-6000 we see high noise amplitudes, this is also where the line crosses the A4 and a railway.

Table 16: Acquisition parameters line 26

Number of shots	567
Range source station	1001.5-9113.5
Number of receivers	8130
Range receiver station	1001-9130
Total length	40.650 km

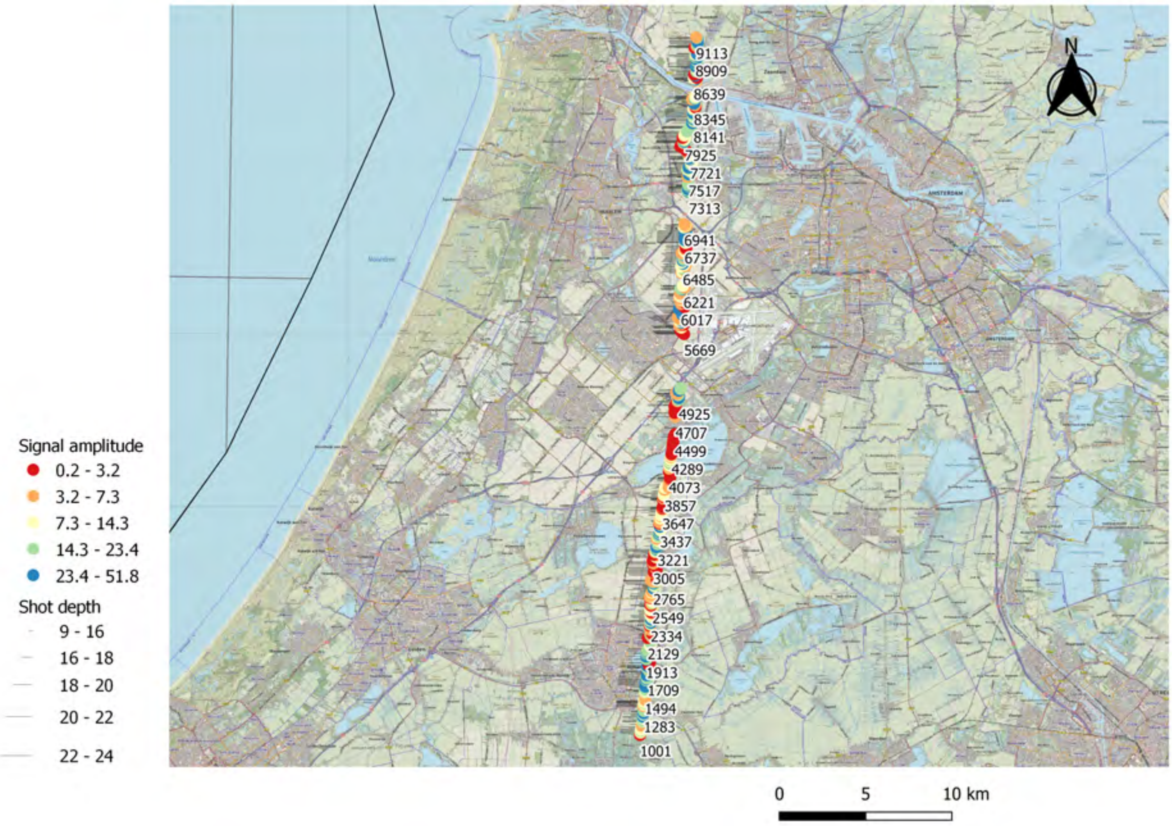


Figure 104: Regional map of line 26. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

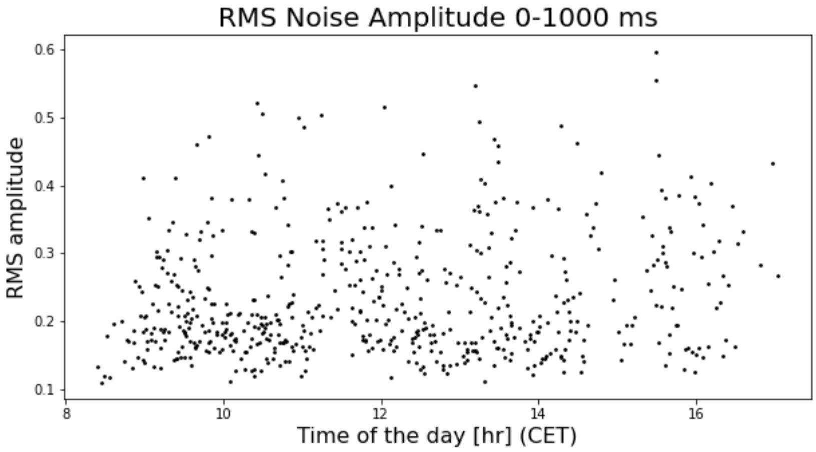


Figure 105: Noise amplitudes in the shot domain per time of the day

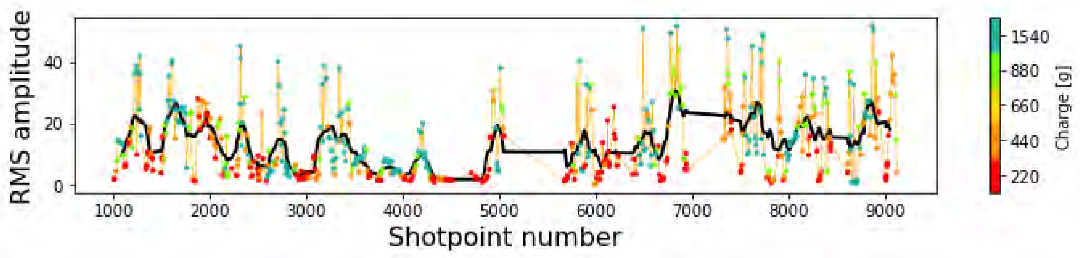


Figure 106: RMS Signal amplitudes in the 0-1s window

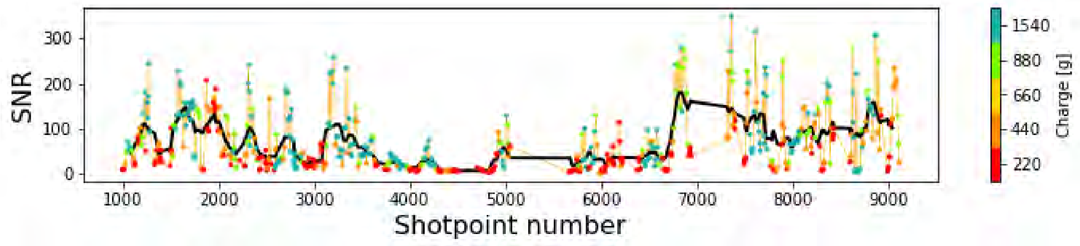


Figure 107: Signal to noise ratios in the 0-1s window with charge size indicator

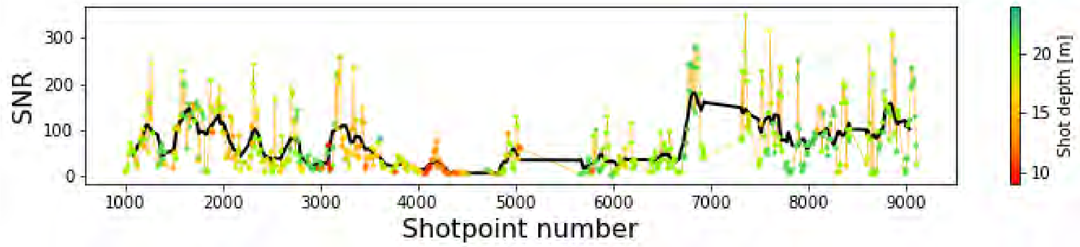


Figure 108: Signal to noise ratios in the 0-1s window with shot depth indicator

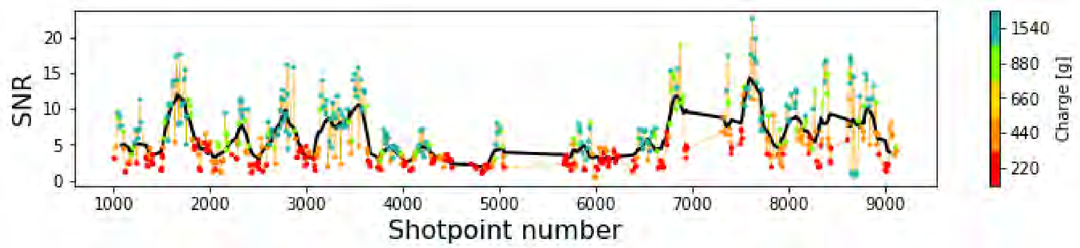
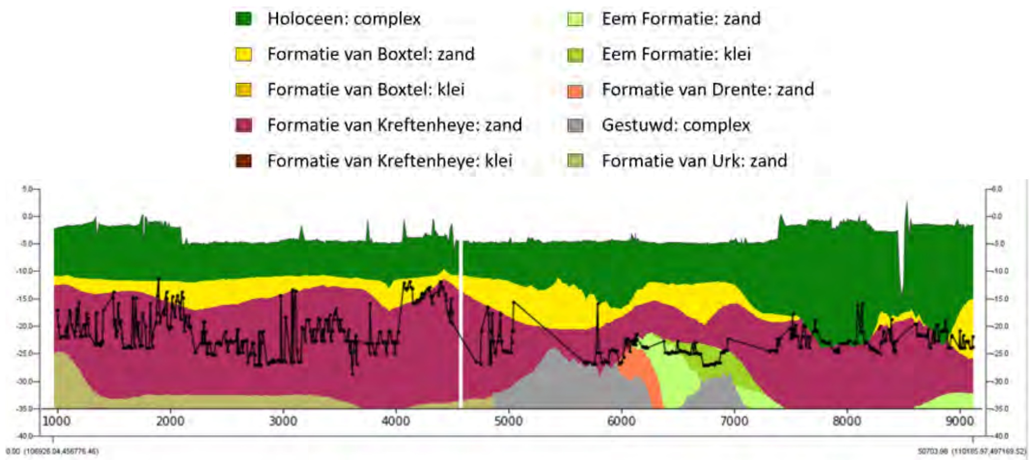
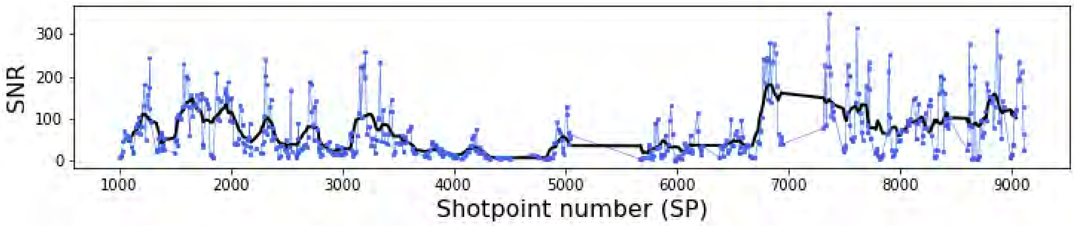


Figure 109: Signal to noise ratios in the 1-2s window with charge size indicator

a



b



c

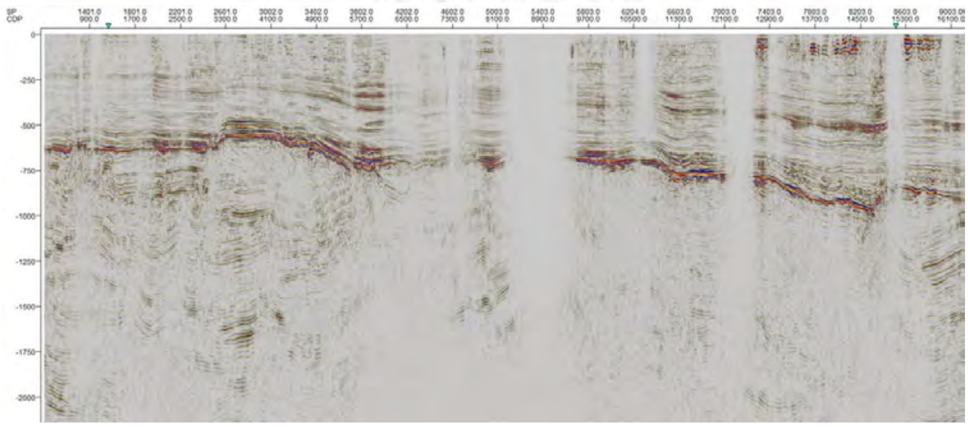


Figure 110: SCAN026. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

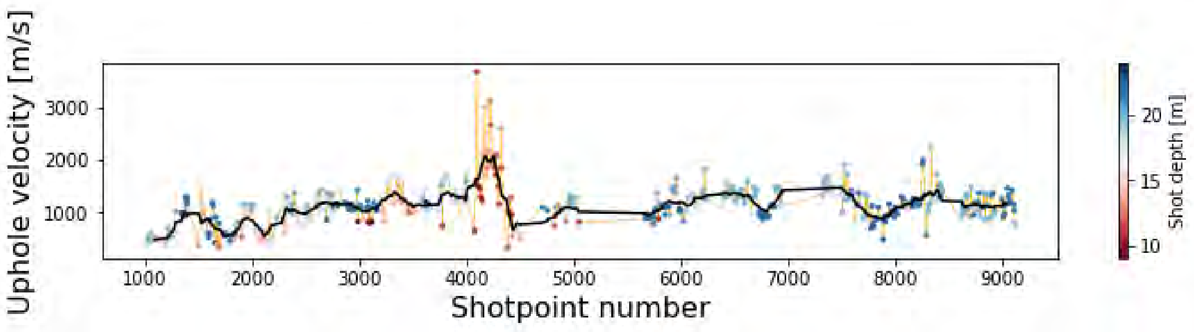


Figure 111: Uphole velocity with shot depth indicator, calculated from uphole times

Receiver domain:

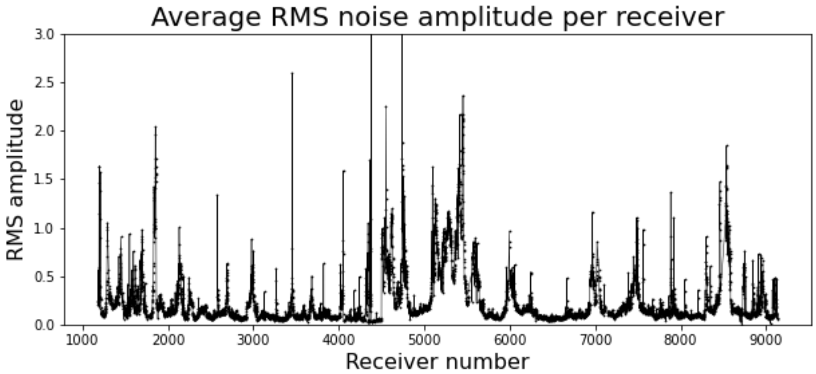


Figure 112: Noise amplitudes in the receiver domain

Figure 113: Regional map of line 26. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.15 SCAN027

Line 27 runs from north to south and runs east of Haarlem. There are some shot data gaps of ~500m on the line. In the first half of the line signal ampltides and SNRs are quite high. In the second half the signal amplitudes and SNRs are low except between shot point 3800-4400. High noise levels are found near the A9, the city Hoofddorp and the Noordzeekanaal.

Table 17: Acquisition parameters line 27

Number of shots	282
Range source station	1102.5-4877.5
Number of receivers	3885
Range receiver station	1001-4885
Total length	19.425 km

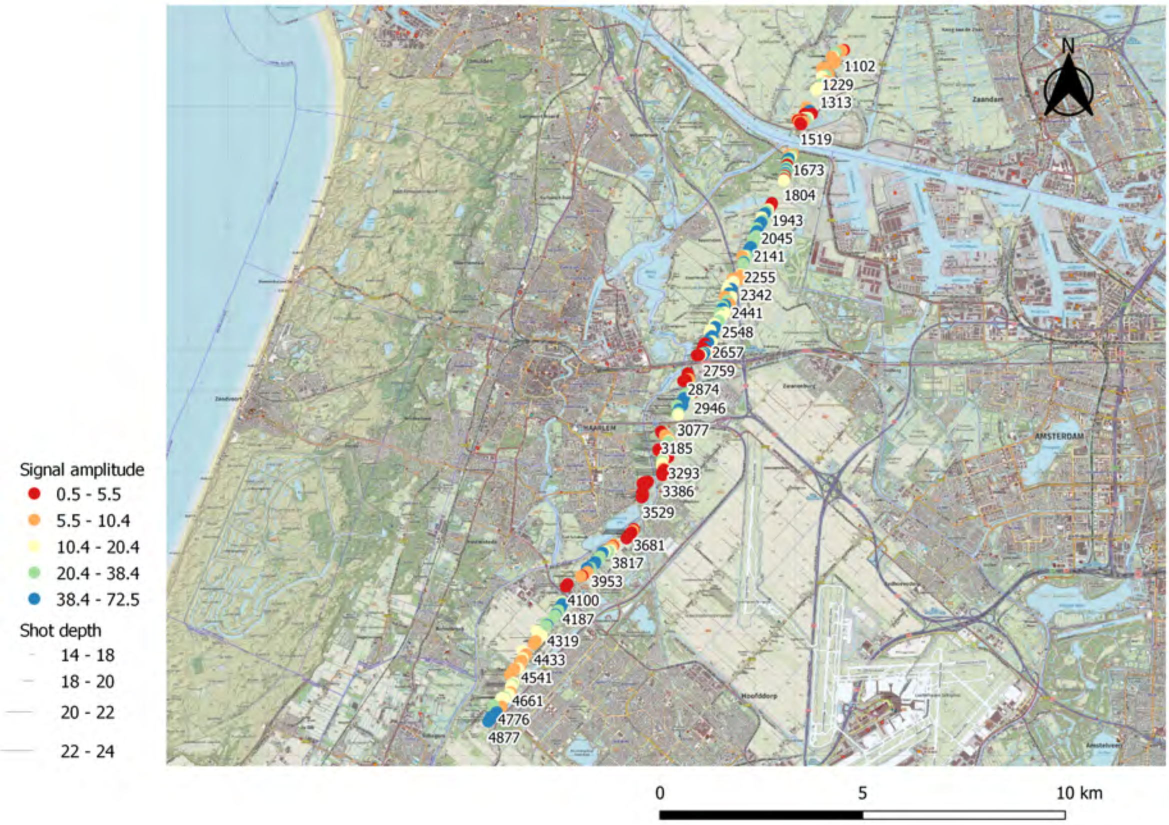


Figure 114: Regional map of line 27. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

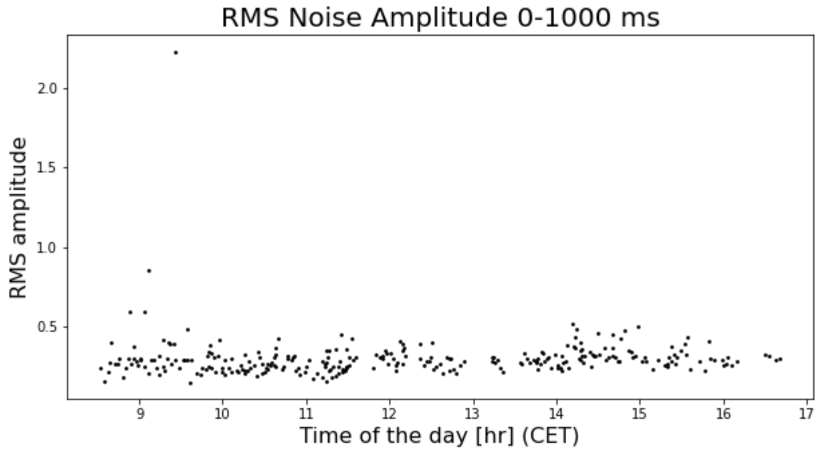


Figure 115: Noise amplitudes in the shot domain per time of the day

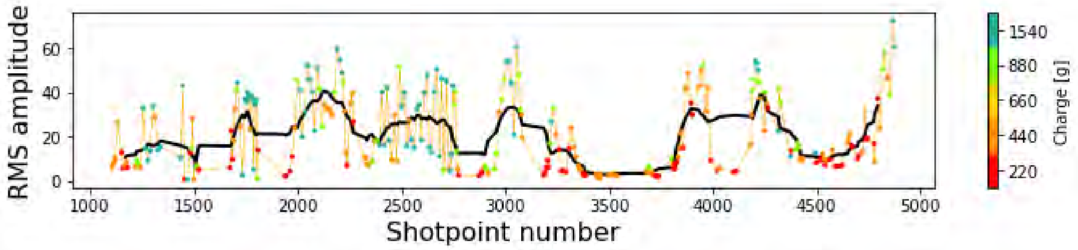


Figure 116: RMS Signal amplitudes in the 0-1s window

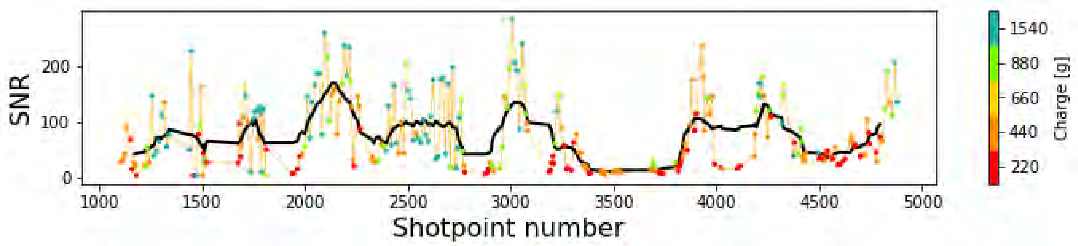


Figure 117: Signal to noise ratios in the 0-1s window with charge size indicator

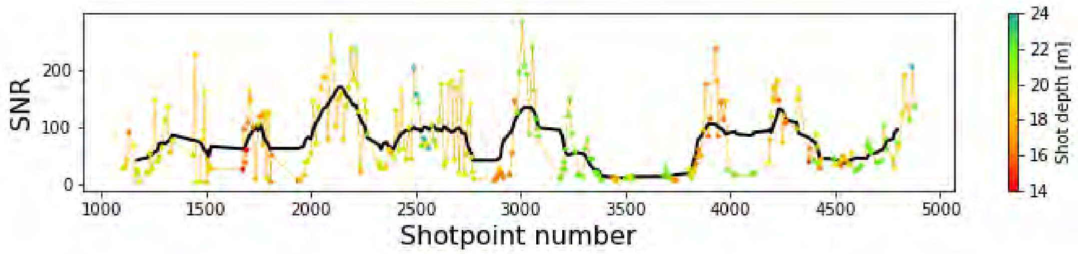


Figure 118: Signal to noise ratios in the 0-1s window with shot depth indicator

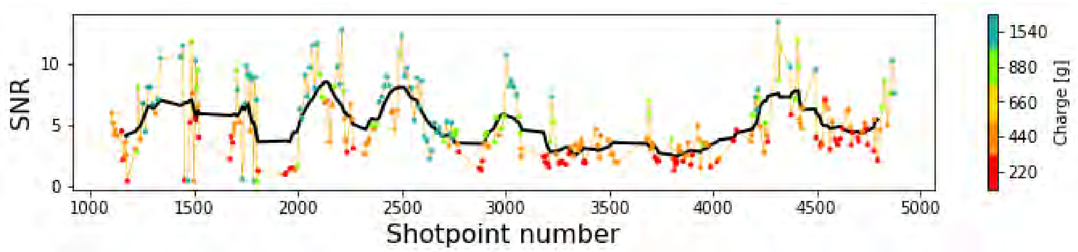


Figure 119: Signal to noise ratios in the 1-2s window with charge size indicator

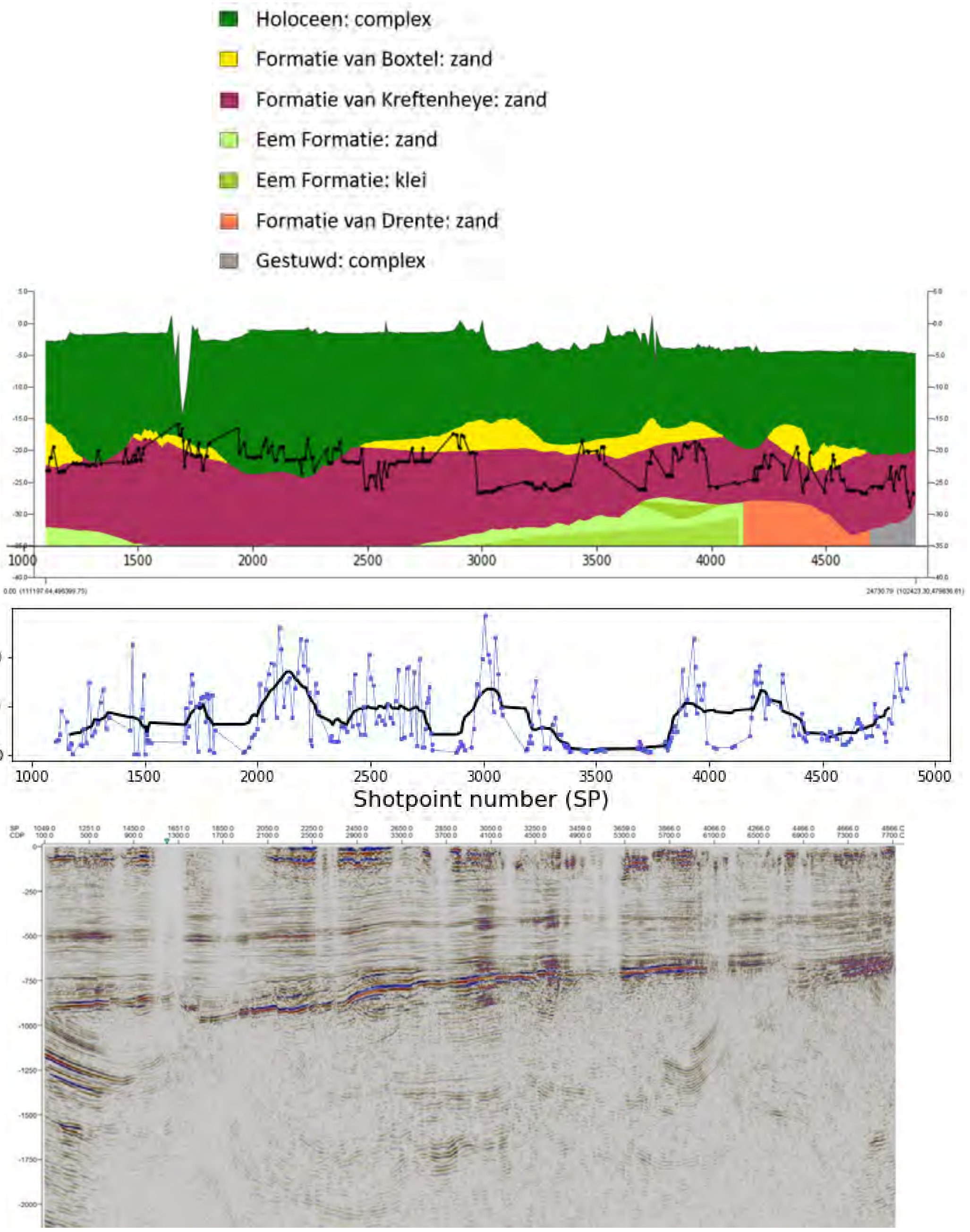


Figure 120: SCAN027. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

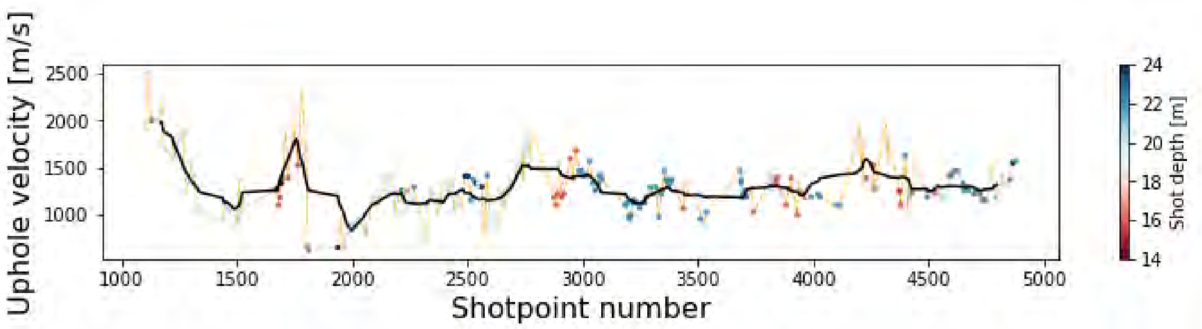


Figure 121: Uphole velocity with shot depth indicator, calculated from uphole times

Receiver domain:

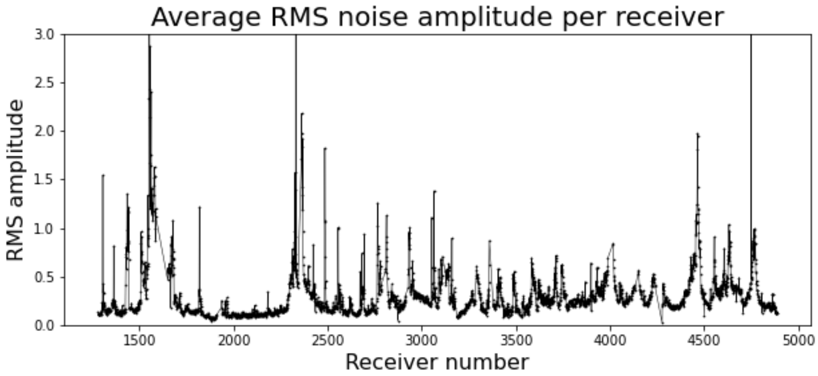


Figure 122: Noise amplitudes in the receiver domain

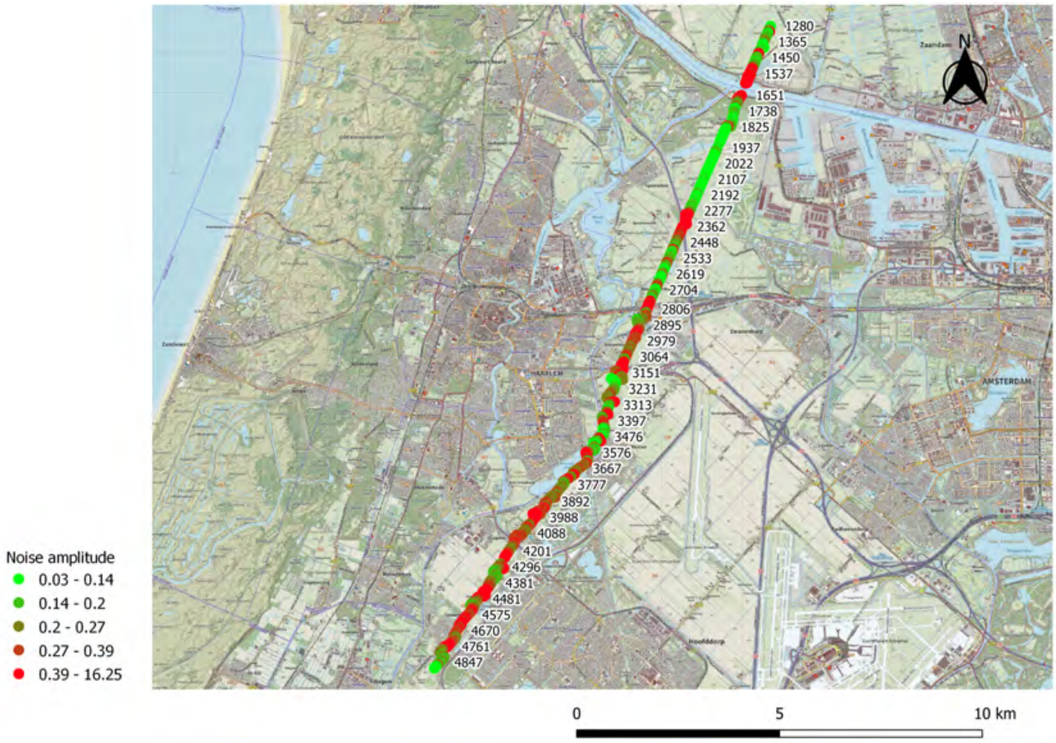


Figure 123: Regional map of line 27. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.16 SCAN028

Table 18: Acquisition parameters line 28

Number of shots	574
Range source station	1421.5-9289.5
Number of receivers	8283
Range receiver station	1001-9270
Total length	41.350 km

Line 28 runs from south west to north east and runs through Amersfoort. Because of permit restrictions at the military training base there is a shot gap between shotpoint number 3400 and 4300. Blessing in disguise this is also where a stowed glacial deposit layer is located and chances are that bad quality data was recorded otherwise. Receivers could still be placed and recorded the signal. Despite of a very little amount of shots, all shots are placed below the water table. In the first half of the line, where the line crosses the Veluwe noise amplitudes are quite high.

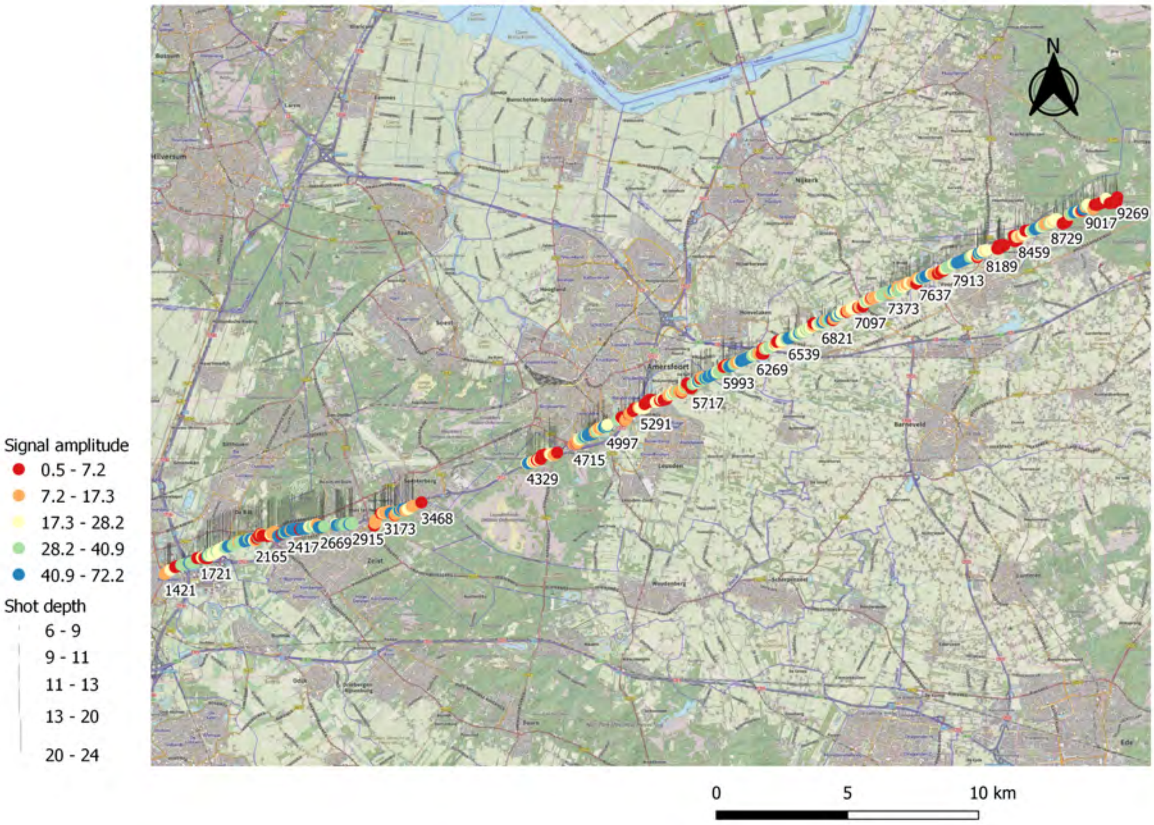


Figure 124: Regional map of line 28. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

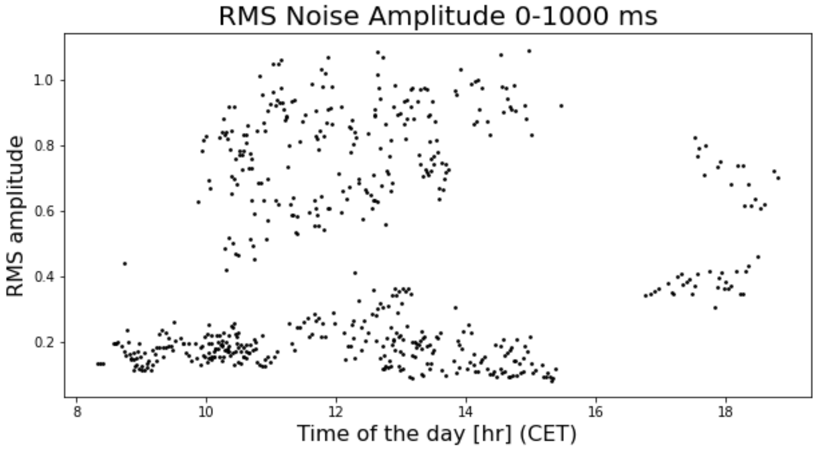


Figure 125: Noise amplitudes in the shot domain per time of the day

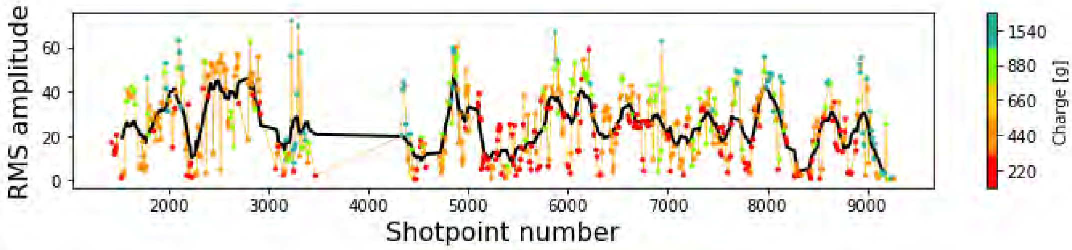


Figure 126: RMS Signal amplitudes in the 0-1s window

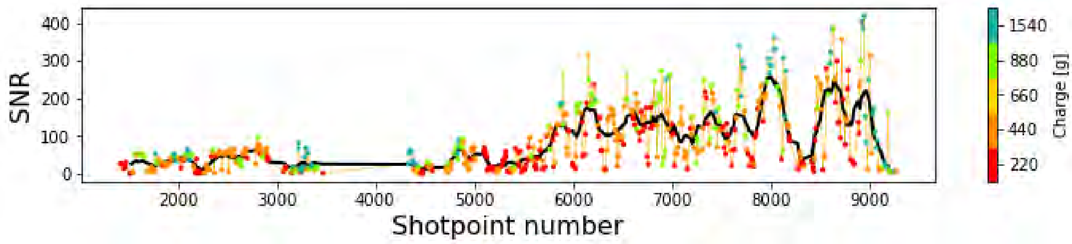


Figure 127: Signal to noise ratios in the 0-1s window with charge size indicator

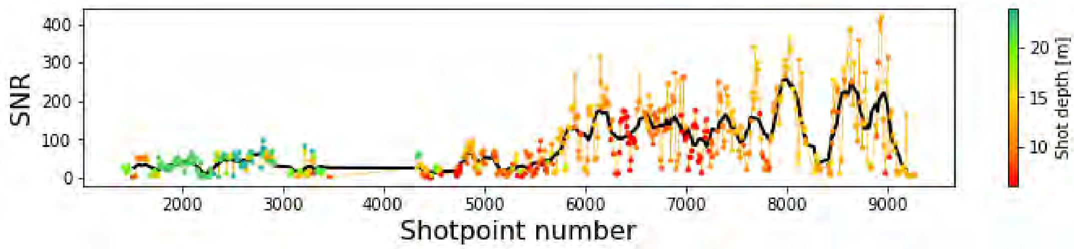


Figure 128: Signal to noise ratios in the 0-1s window with shot depth indicator

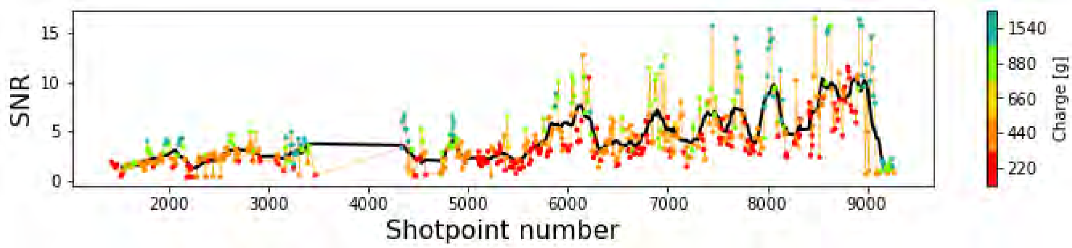


Figure 129: Signal to noise ratios in the 1-2s window with charge size indicator

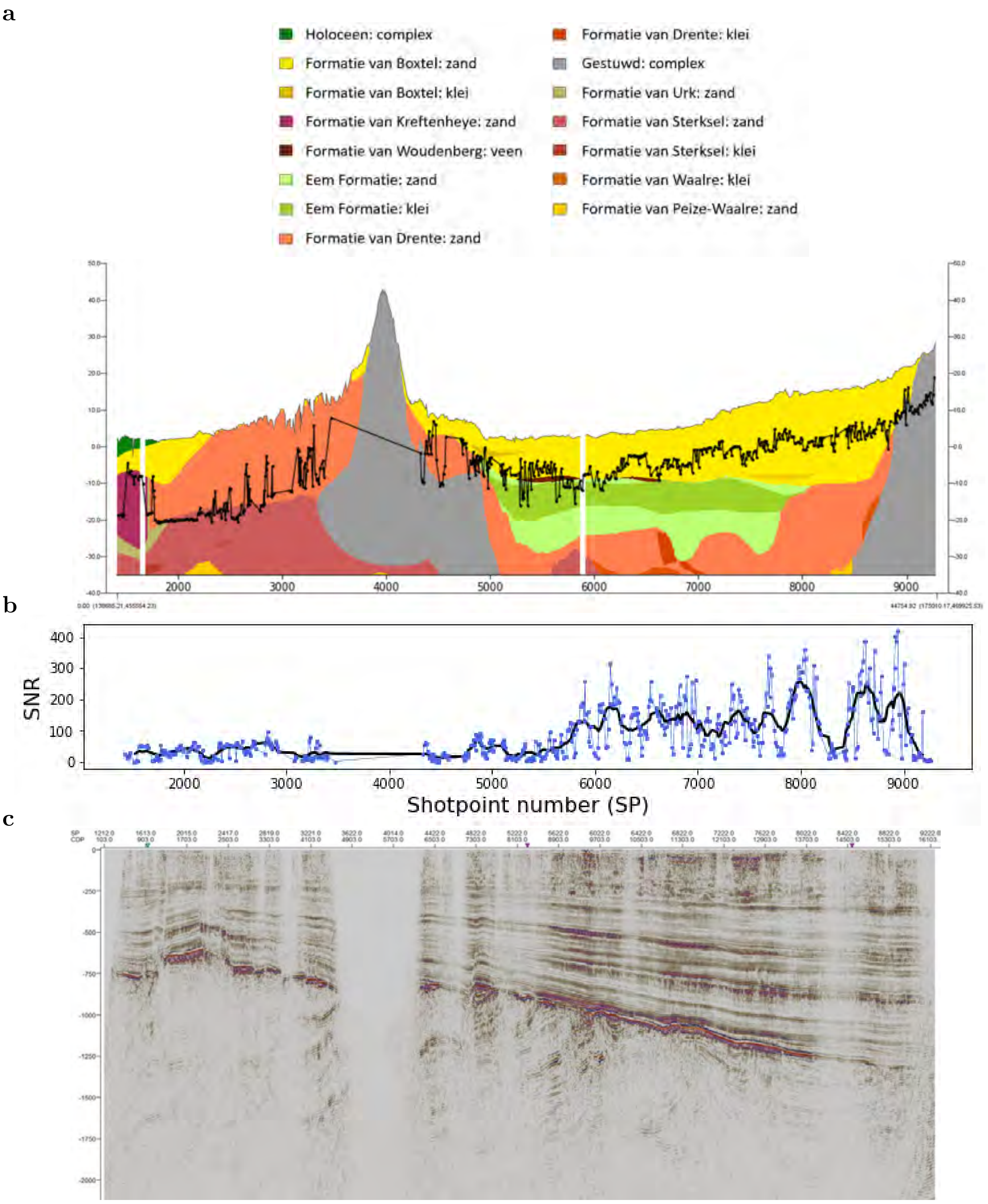


Figure 130: SCAN028. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

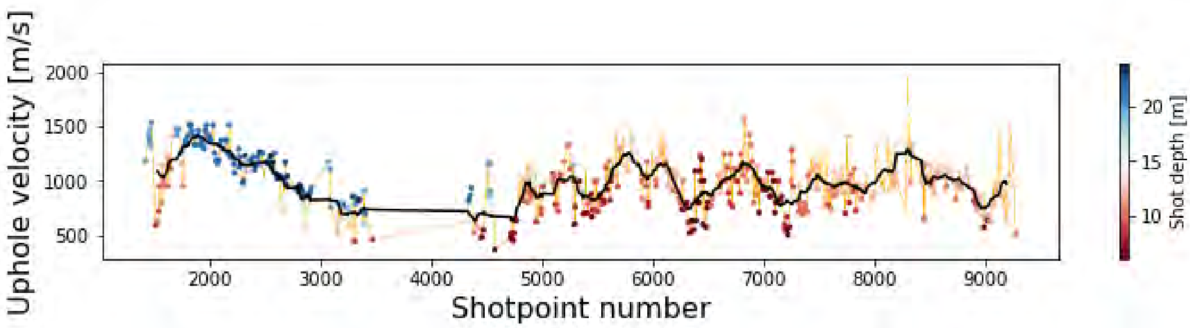


Figure 131: Uphole velocity with shot depth indicator, calculated from uphole times

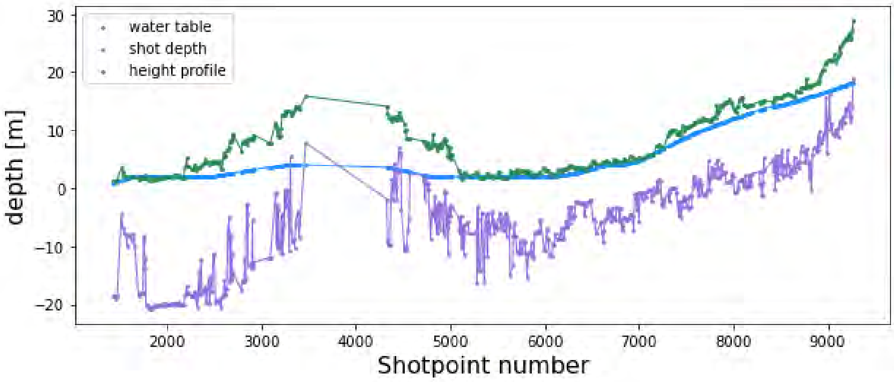


Figure 132: Ground water table along line 28

Receiver domain:

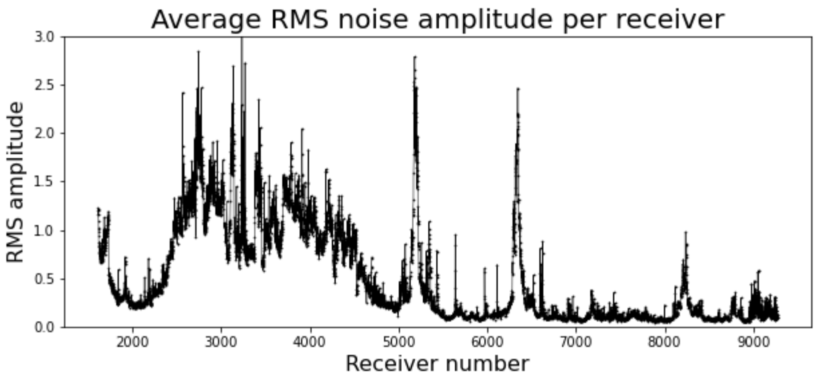


Figure 133: Noise amplitudes in the receiver domain

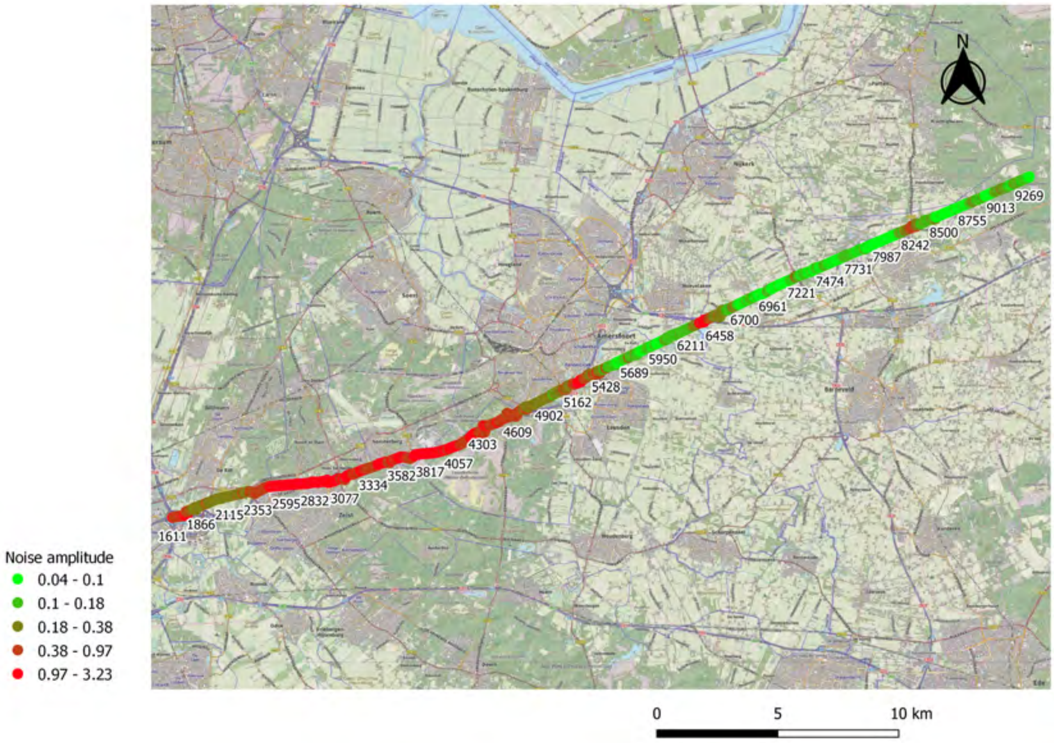


Figure 134: Regional map of line 28. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.1.17 SCAN029

Line 29 runs from west to east and runs south of Helmond and north of Venlo. The end of this line runs through Germany. Shots are placed relatively shallow (figure 139). On the geological cross section (figure 141) we see a fault around shotpoint 4500, this is also visible on the fast track (figure 141c). High noise amplitudes are observed near the A67, A73 and railways.

Table 19: Acquisition parameters line 29

Number of shots	817
Range source station	1016.5-10709.5
Number of receivers	9716
Range receiver station	1001-10716
Total length	48.580 km

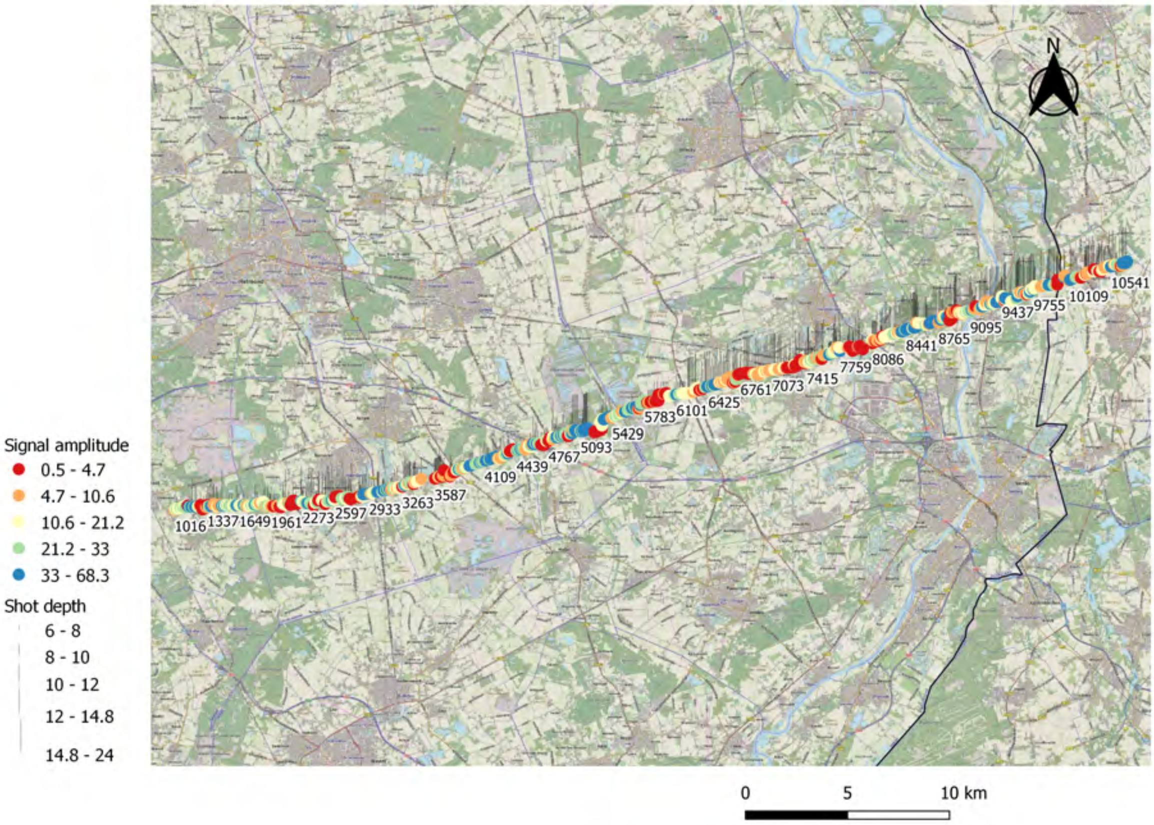


Figure 135: Regional map of line 29. The colours indicate the RMS signal amplitudes in shot domain and the bars indicate shot depth.

Shot domain:

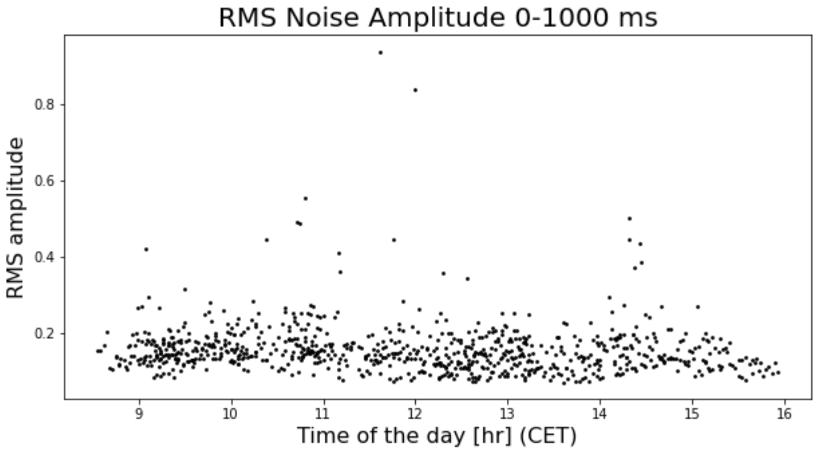


Figure 136: Noise amplitudes in the shot domain per time of the day

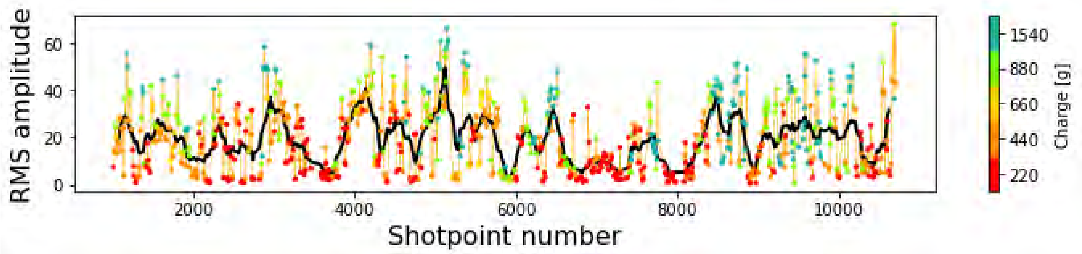


Figure 137: RMS Signal amplitudes in the 0-1s window

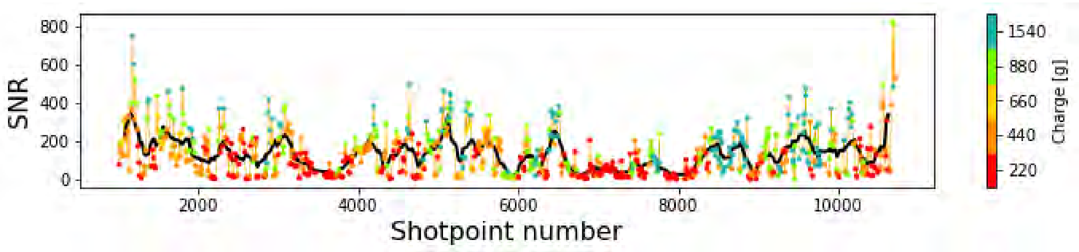


Figure 138: Signal to noise ratios in the 0-1s window with charge size indicator

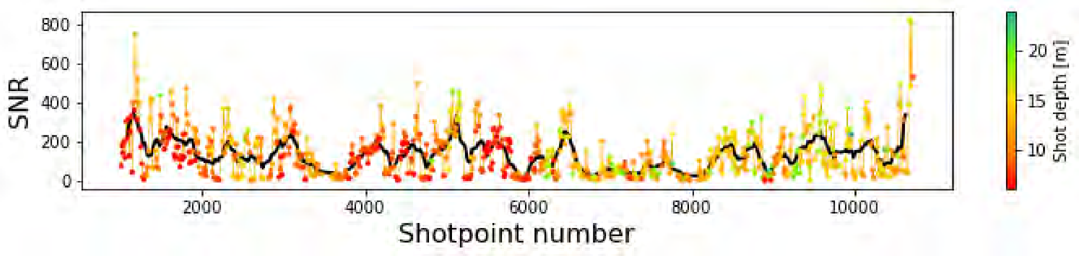


Figure 139: Signal to noise ratios in the 0-1s window with shot depth indicator

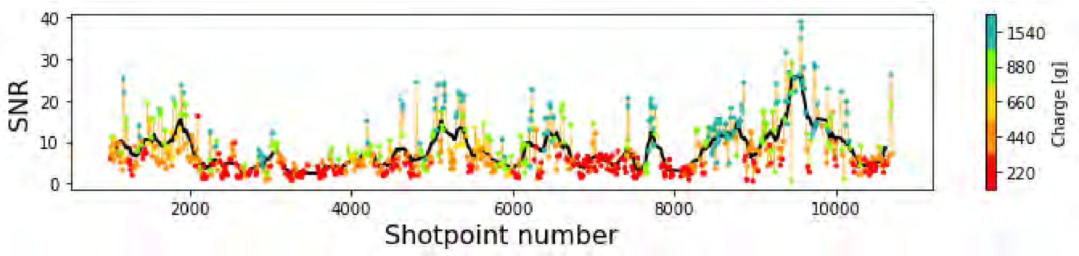


Figure 140: Signal to noise ratios in the 1-2s window with charge size indicator

a

b

c

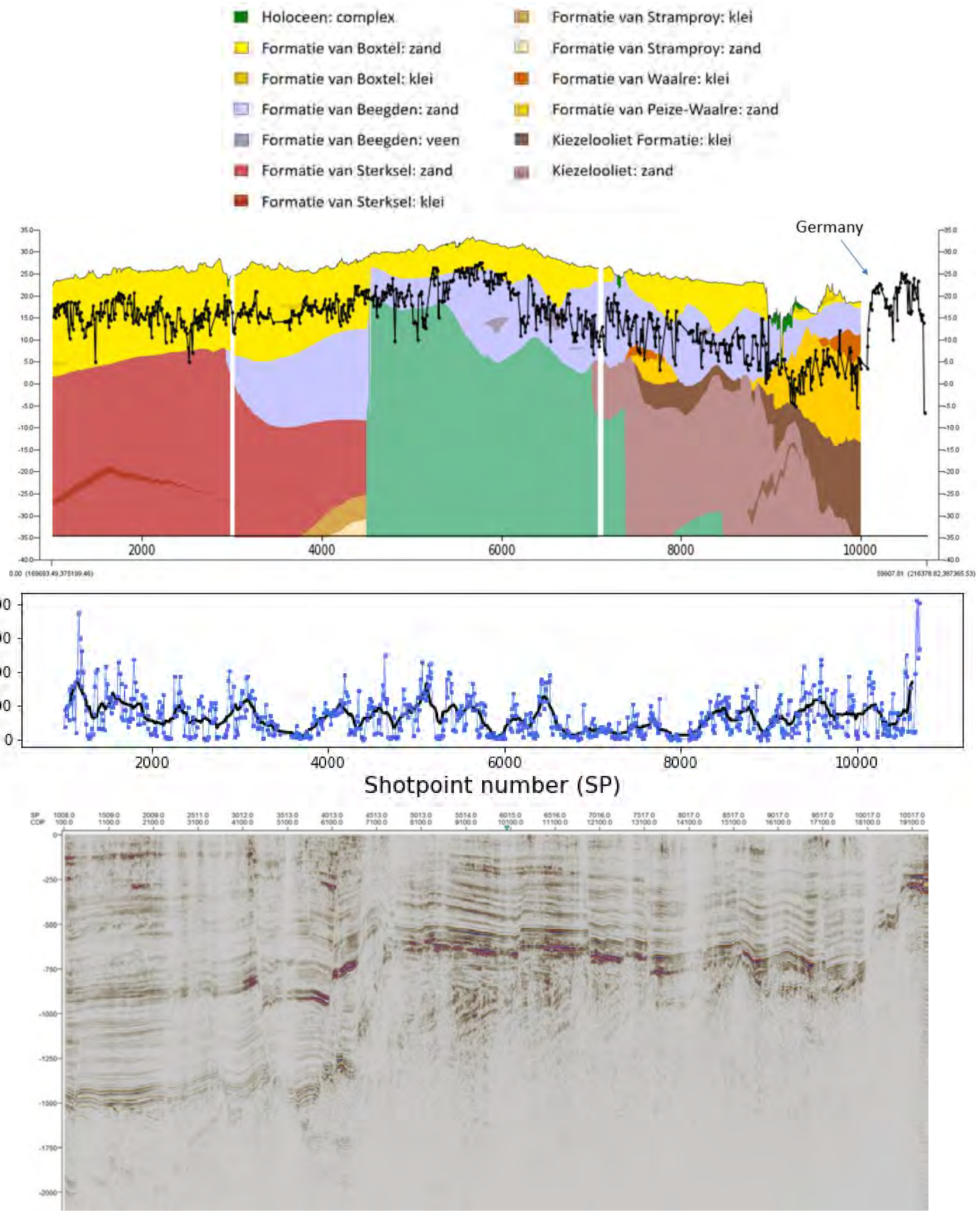


Figure 141: SCAN029. a) Near surface geology till 35 meters depth, the black line indicates the shot depth. b) Signal to noise ratio in the 0-1s window. c) Seismic section: fast-track.

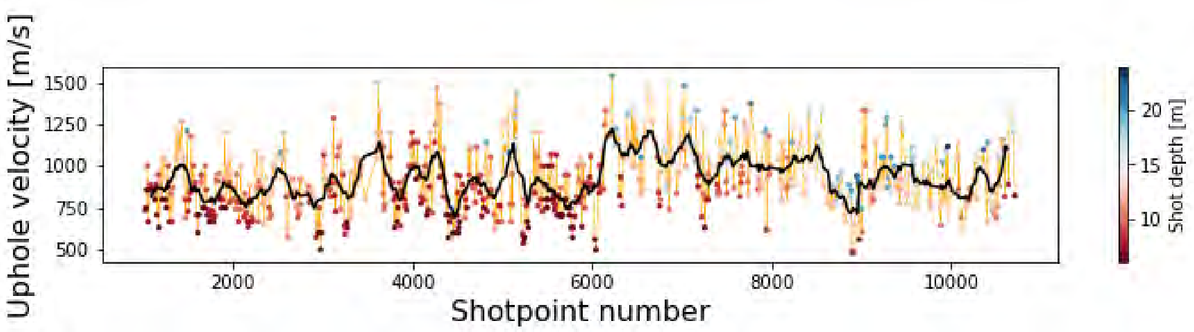


Figure 142: Uphole velocity with shot depth indicator, calculated from uphole times

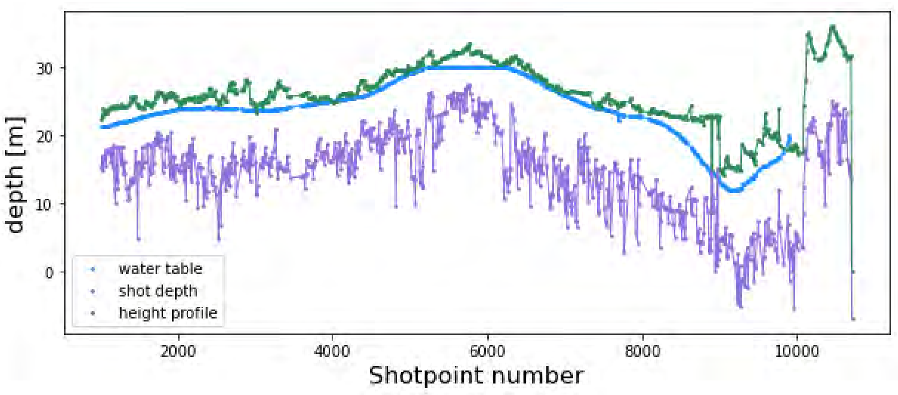


Figure 143: Ground water table along line 16

Receiver domain:

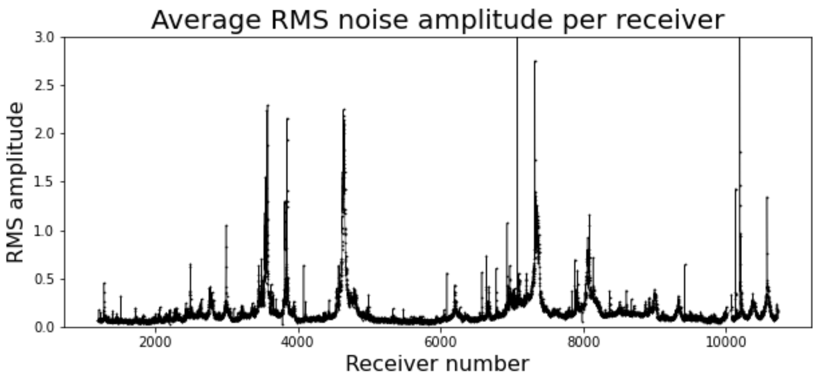


Figure 144: Noise amplitudes in the receiver domain

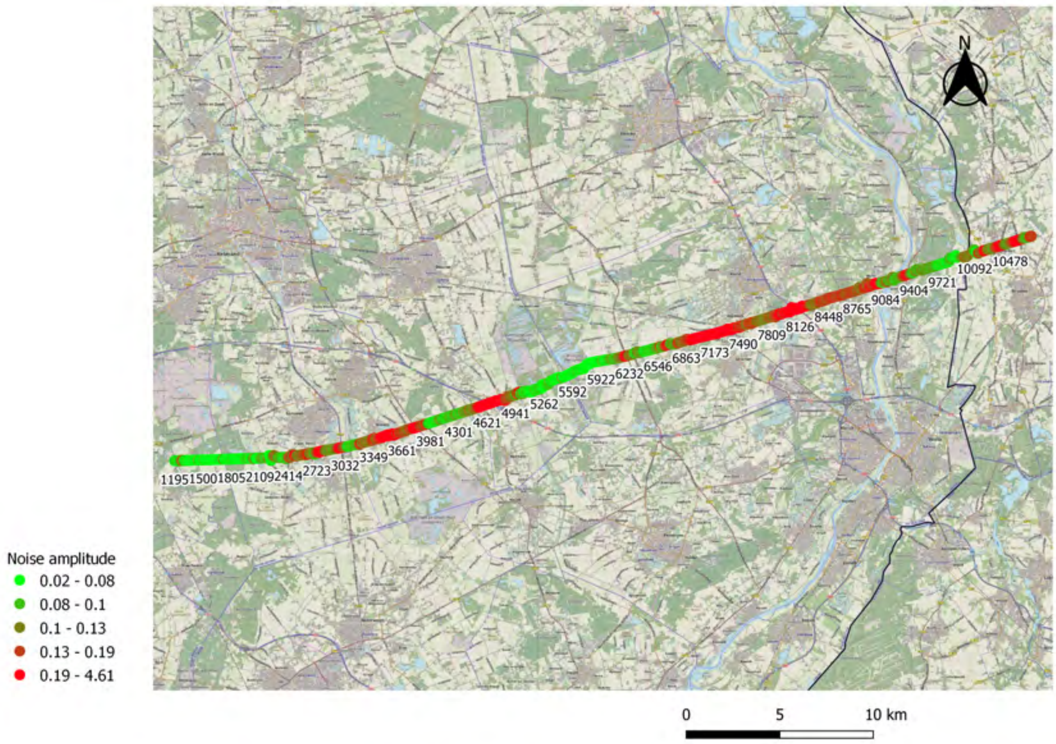


Figure 145: Regional map of line 29. The colours indicate the RMS noise amplitude per receiver, in the receiver domain.

3.2 Analysis between lines

Once we obtained all the data from all lines we were able to do analysis between the lines. For a total of 16203 shot points we know their charge sizes and shot depths. Initially both seem to have a big influence on the data quality i.e. SNR. From the conclusions of Van der Lucht [2020] and Janssen [2020] we know that surface geology, shot depth and charge size are the most important factors determining data quality.

Van der Lucht [2020] concluded:
"The most important driver of variation in the signal amplitudes over the course of a line is the near surface geology. Other important parameters are the shot depth and charge size. Deeper and higher charge size shot generally cause an increase in signal amplitudes and thus allow for a better imaging quality at larger depths. Glacial stowed deposits that are combined with an increase in elevation cause a very significant reduction of the data quality, these areas should be avoided for acquisition as much as possible. The most likely cause for this reduction in data quality is that the material is unconsolidated and absorbs/scatters shot energy and/or that shots in these areas are fired above the groundwater table."

We add the data points of the new lines to this analysis and look for the relations between lines. In this way we try to define the influence of the different parameters. In this section we also try to answer the uncertainty whether shots in glacial stowed deposits are of bad quality because of the material properties or because of the fact that they are shot above the water table.

3.2.1 Charge size

We start with looking at one line at a time. We define categories based on all possible charge sizes: 120g, 220g, 240g, 360g, 440g, 480g, 600g, 660g, 720g,840g, 880g, 960g, 1100g, 1320g, 1440g, 1540, 1560g. We sum all the SNRs within a charge size category and divide it by the total amount of shots in that category. Figure 146 *left* shows the result for all lines. We see that some lines have much higher SNRs than other lines. We also somehow see that overall SNR increases with increasing charge size, but because the absolute values vary between the lines that is hard to see. To be able to compare between lines, the SNRs are normalized between 0 and 1. From every line separately the maximum SNR value of that line gets a 1, the minimum SNR value gets a 0. Figure 146 *right* shows the normalized plot. We see a linear increasing trend: low charges give relatively low SNRs, high charges give relatively high SNRs. Since scatter points can appear on top on each other we cannot see all data points in this graph. Most lines have 1540g on 1 and most lines have 660g on 0. The latter is remarkable, for many lines the lowest charge 220g does not give the lowest SNR, but 660g does. There are only 202 out of 15031 datapoints in the 660g category.

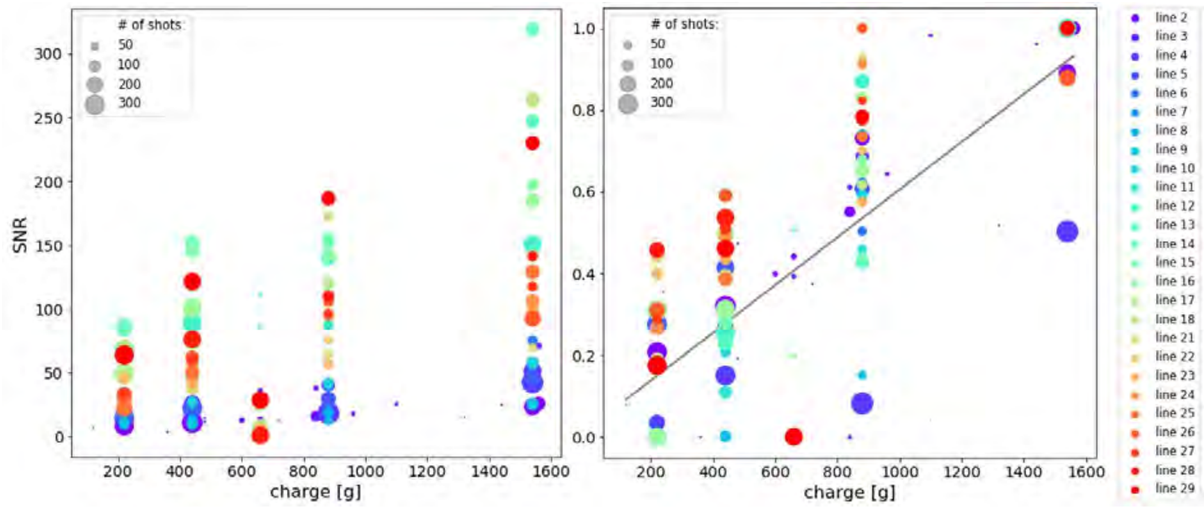


Figure 146: *Left*: SNR against charge size for all lines, *right*: normalized SNR against charge size for all lines. Colours indicate the different lines that are used in this analysis, the size of the circles indicated the amount of shots on that data point. The grey line is a weighed linear regression line.

Figure 146 *left* shows that some colours (lines) have higher SNRs than others. This might be linked to different regions where the data is acquired. To check that, four regions are distinguish: *mid, east, west, south*. In figure 147, we see that the lines within a region are very similar in SNR values and trends. This might have to do with different geological subsurface characteristics. Figure 148 shows which lines belong to what regions. Region *mid* shows the lowest SNRs, except for line 28 (highest orange data points). Regions *south* and *east* show the highest SNRs.

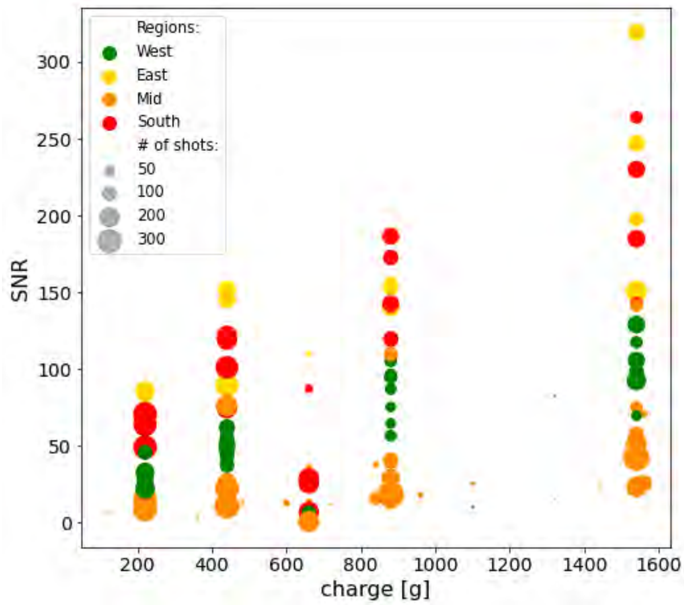


Figure 147: SNR against charge size for all lines per region. Colours indicate region and circle sizes indicate the amount of shots in a data point.

Figure 148: Lines divided by region. Regions mid, east, west and south are distinguished.

The fact that different regions give different absolute SNR values leads to the assumption that geology is of influence. In figure 149 we see a geological map of the near surface of the Netherlands (PDOK). In general the map can be split in two. In the east we have older deposits from the Pleistocene, the west is younger with deposits from the Holocene (TNO, dinoloket). We checked for every shot in which region it was taken. Figure 150 shows the result, for every shot the SNR value is shown, the colours indicate the geographical region. Since the points plot on top of each other it is hard to see if there are low SNR in for example the high sand grounds. To visualize this alternatively we made two graphs (figure 151). In figure 151 *left* we see the average value per physical region with its standard deviation. We see that for example the high sand grounds have a relatively high average SNR but also a very high standard deviation. Placing a shot in a sand ground does therefore not guarantee that SNR will be high as suggested by figure 147. The stuwwallen give low SNR in general. Figure 151 *right* shows the cumulative percentage. We see that the stuwwallen reach their maximum SNR earlier than the other regions. This makes it easier to see the distribution of SNR values.

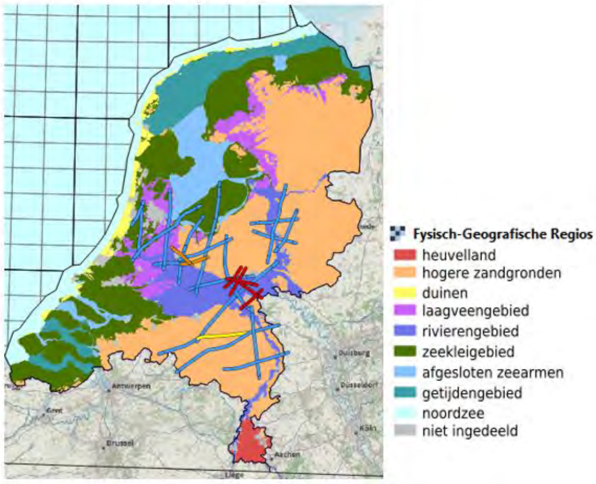


Figure 149: Physical geographical regions of the Netherlands.

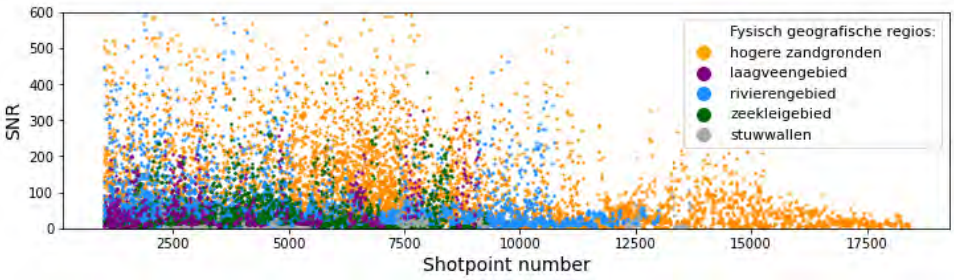


Figure 150: All shot points and their SNRs, the colours indicate the geographical region. Note that some lines are longer than others and that the points are plot on top of each other.

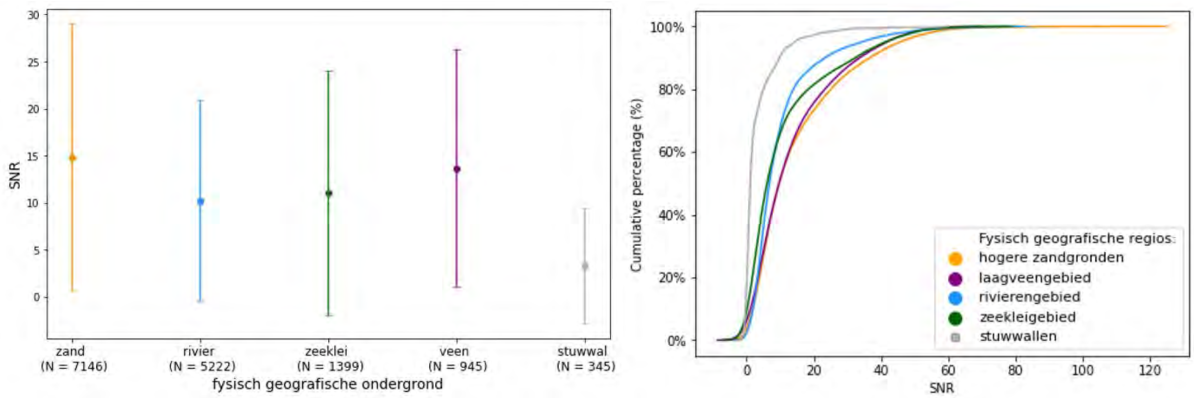


Figure 151: *Left*: average SNR per geographical region, *right*: distribution of SNRs for every geographical regions, plotted in cumulative percentage.

3.2.2 Shot depth

We also take a closer look at the shot depth parameter. Van der Lucht [2020] recommended an increased shot depth to increase the data quality and to image deeper targets successfully, based on analysis of lines 2-10. Figure 152 *top* shows again that for different lines the absolute SNR levels are different. To compare between lines the values are normalized (figure 152 *middle*). Most shots are taken at 16-20m depth as shown in the bar plot of figure 152 *bottom*. There are relatively little data points in a category below 12m. In general we see a trend from bottom left or upper right. The scatter seem larger than for the charge size parameter. However, the trend shows us that in general deeper shots give higher SNRs. It seems that 16-20m in general give relatively high SNRs.

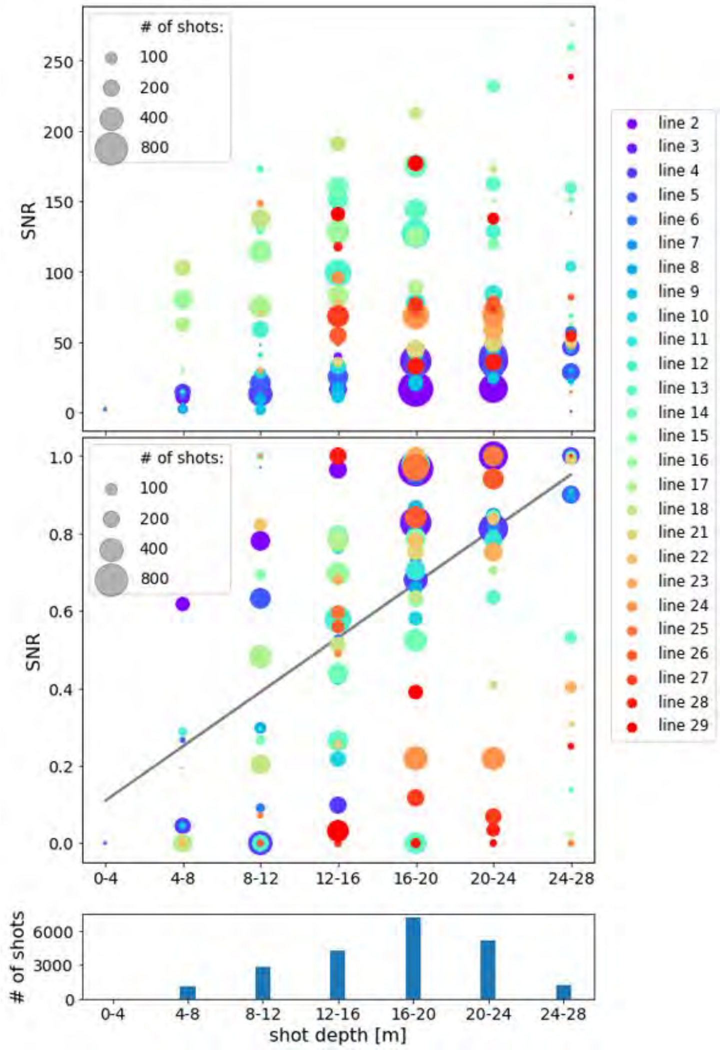


Figure 152: *Top*: SNR against shot depth for all lines, depth is divided in categories of 4 meters. *Middle*: normalized SNR against shot depth for all lines. Colours indicate the different lines that are used in this analysis, the size of the circles indicated the amount of shots on that data point. The grey line is a weighed linear regression line. *Bottom*: amount of shots per depth category.

A side note: drillers in the field place the explosive as deep as possible with a maximum of 24 meters (length ignition wire). When they enter a relatively hard layer they stop drilling and place the explosive on top of this layer. There are also governmental regulations on the minimum shot depth per charge size. Charges larger than 1000g need to be placed at least 10 meters deep (Wettenbank article 2.4.1). Similar regulations exist on shooting near houses, only low charges can be used in that case. Therefore a variety of different shot depths and charge sizes exists.

3.2.3 Ground water level

At the start of the internship one of EBN's main concerns was about acquisition in stowed glacial deposits. Very low signals were found on shots taken in this stowed glacial deposit layer (grey in the geological figures of section 2). Van der Lucht [2020] concluded that these areas should be avoid as much as possible. Henk van Lochem (collegue at EBN B.V.) suggested that ground water levels could also play a big role in obtaining good quality signals. So an effort was made to look for a correlation between ground water levels and SNRs, and we found that this is probably also related to the bad quality signals in the stowed deposits.

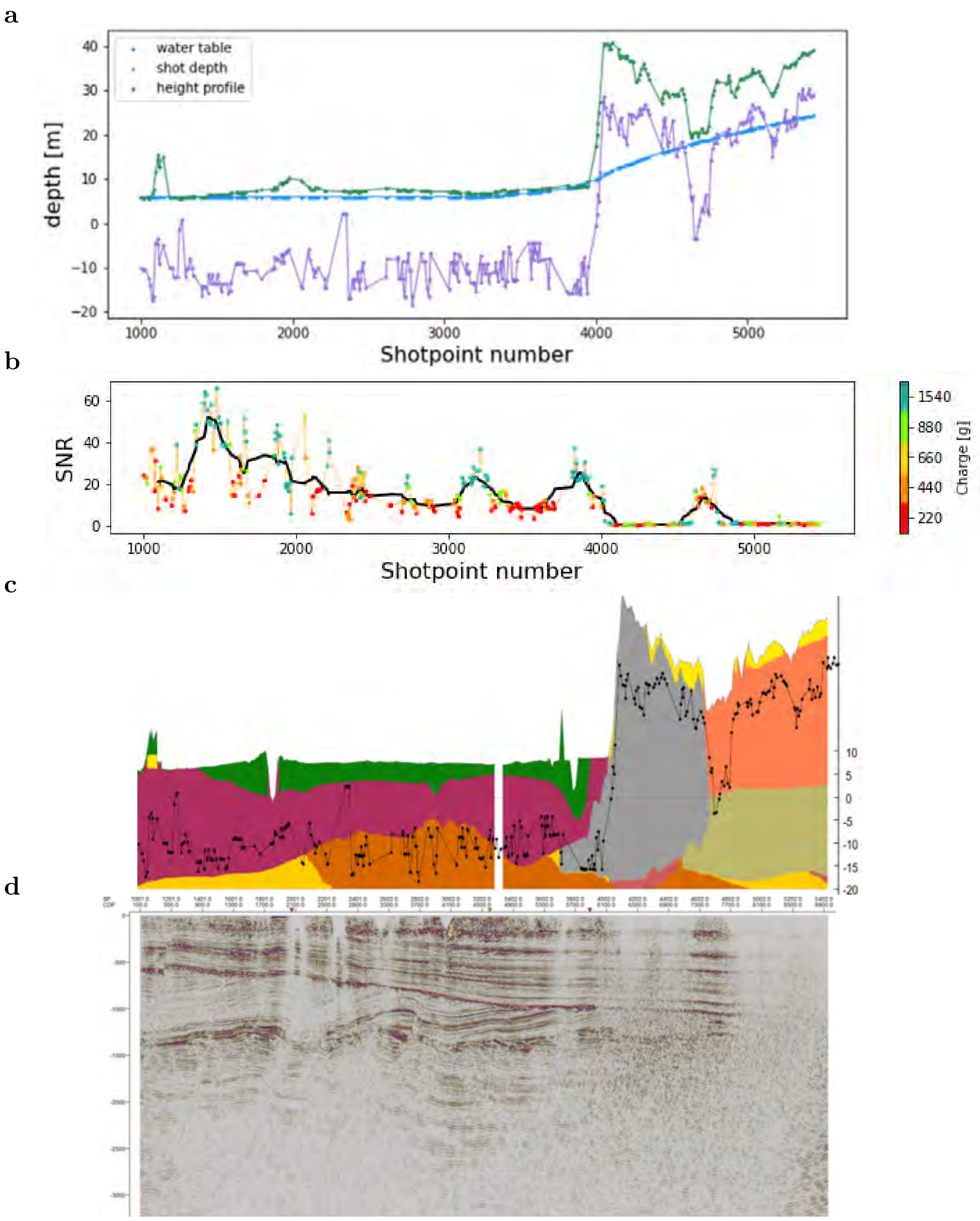


Figure 153: SCAN009 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

In the Netherlands most topography is created by these stowed glacial deposits, especially in the middle of the Netherlands. Several lines cross these elevated regions. For those lines the groundwater level is determined with use of the groundwater data base tool of grondwatertools.nl. In this analysis we look at lines that cross those elevated stowed glacial deposits and look at whether a shot is taken above or below the groundwater level.

All the lines that have elevated stowed glacial deposits are analysed and shown below. It seems that the reason the quality of the data is so bad in those regions is because the shots are fired above the water level. Figure 153 shows this most convincingly. In figure 153c we see a geological cross section of the subsurface. In grey we see the dipping stowed glacial deposits and in coral-orange we see horizontal layered glacial deposits. It is important to note that this material did not originate from the glacial itself, it is not an end moraine. The end of the glacial pushed the sand and clay deposits that were already located here, formed in the Pleistocene/before the last ice age. Therefore the material in the surrounding area is similar, the only difference is that it is stowed, forming dipping faults and folds. This is illustrated in figure 154. The grey colour indicates the stowed depositis, number 3 in figure 154. The coral-orange colour in the geological sections indicates a sandr (number 7 figure 154).

Figure 154: Formation of sandr and stowed glacial deposits [Naturalis]

Figure 153a shows that shots in the grey and coral orange area are shot above the water table, except for a small region. That is the valley of the Heelsumse Beek, where the water table is close to the surface. In this area we do see signal on the final seismic section (figure 153d). In the figures below the first page shows examples of shots taken in grey and coral-orange layers above the water level, the second page shows examples of shots taken below the water table.

Shots above the water table:

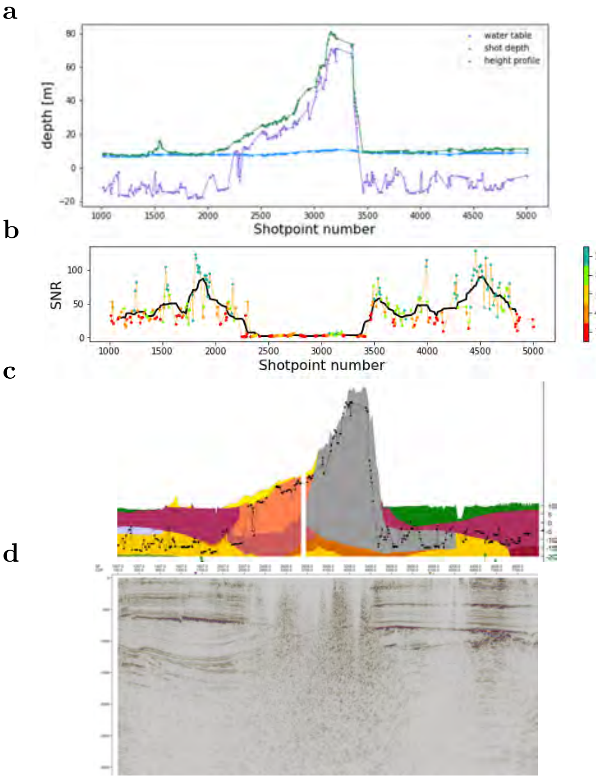


Figure 155: URKM006 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

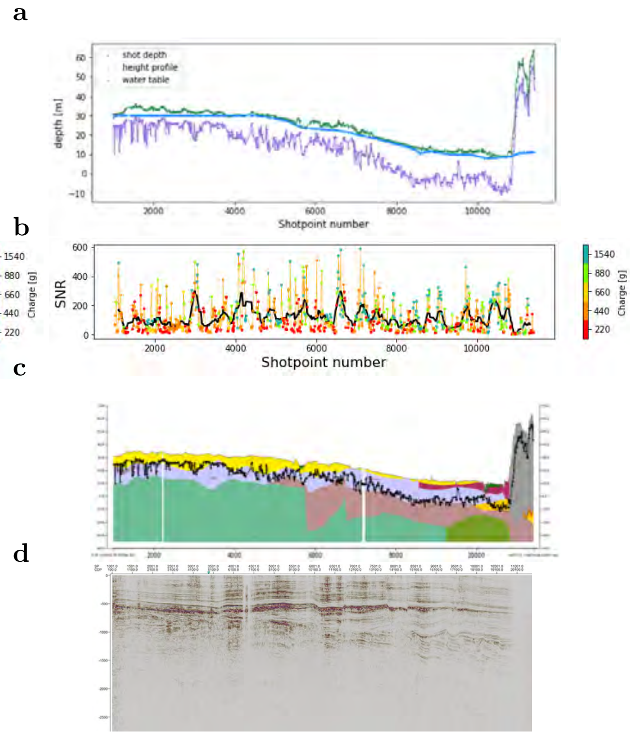


Figure 157: SCAN016 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

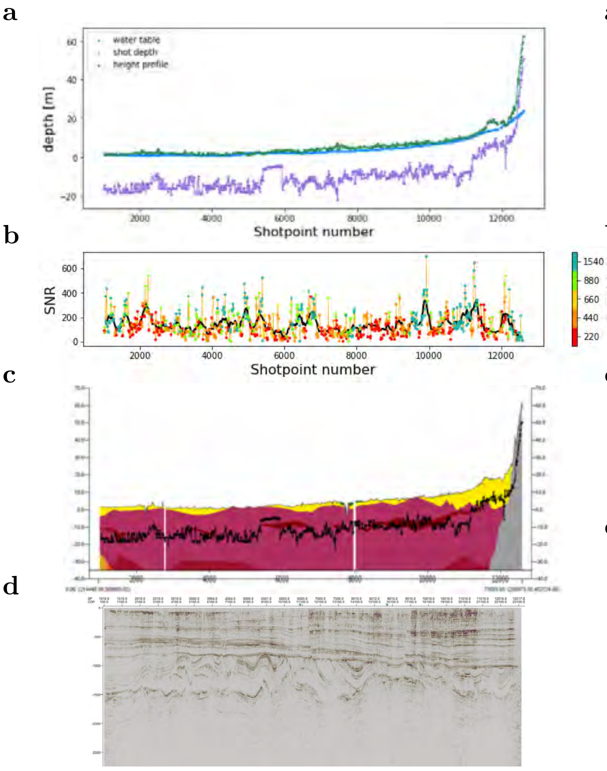


Figure 156: SCAN012 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

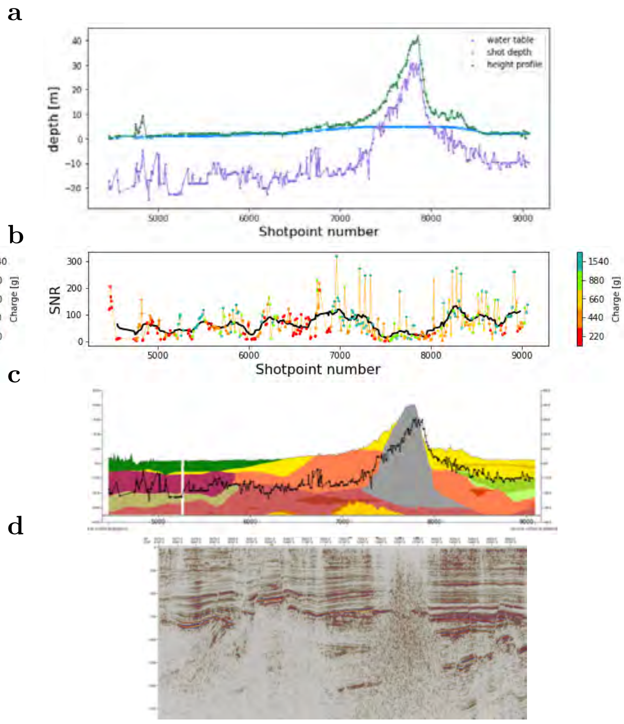


Figure 158: UGOU022 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

Shots below the water table:

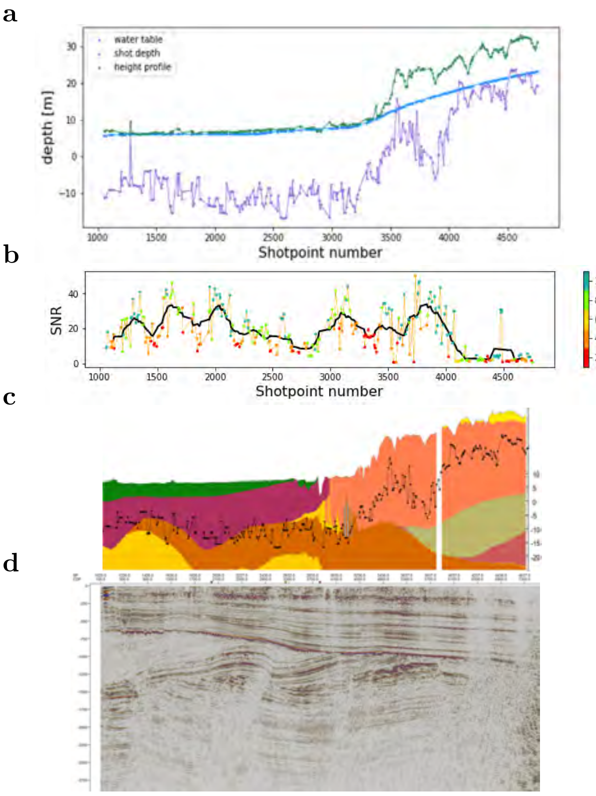


Figure 159: URKM008 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

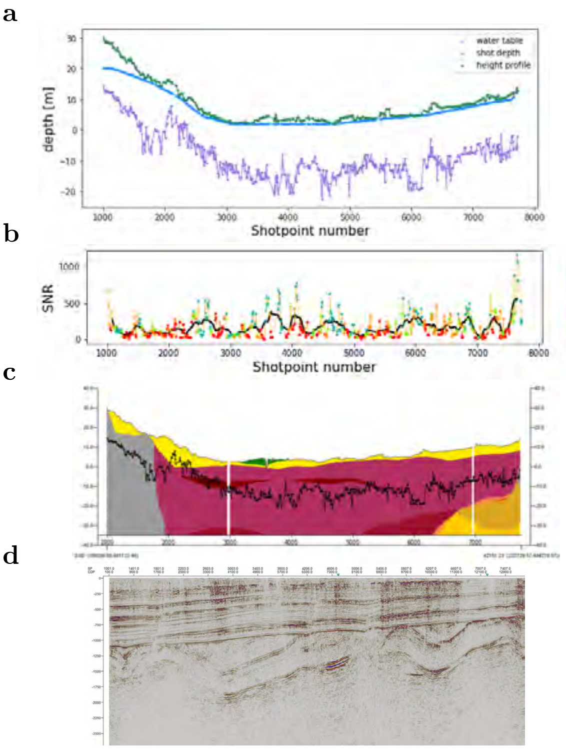


Figure 160: SCAN014 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

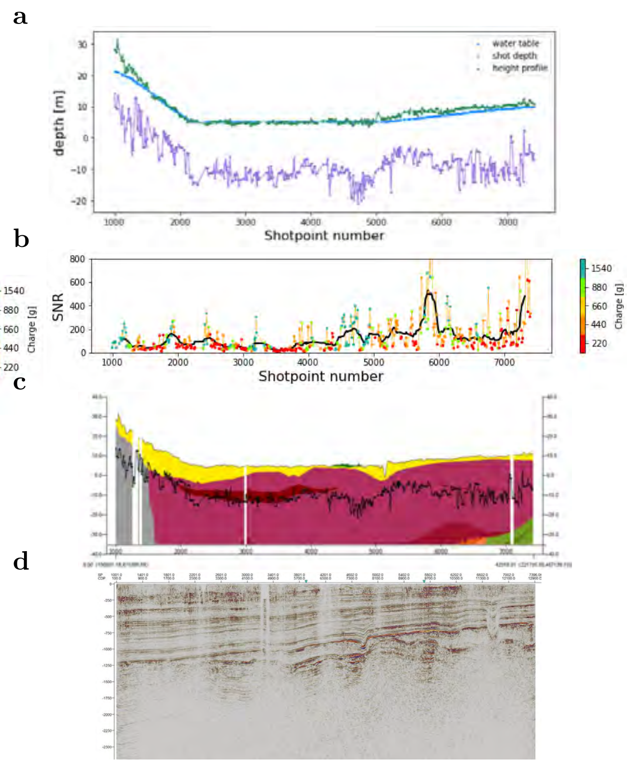


Figure 161: SCAN015 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

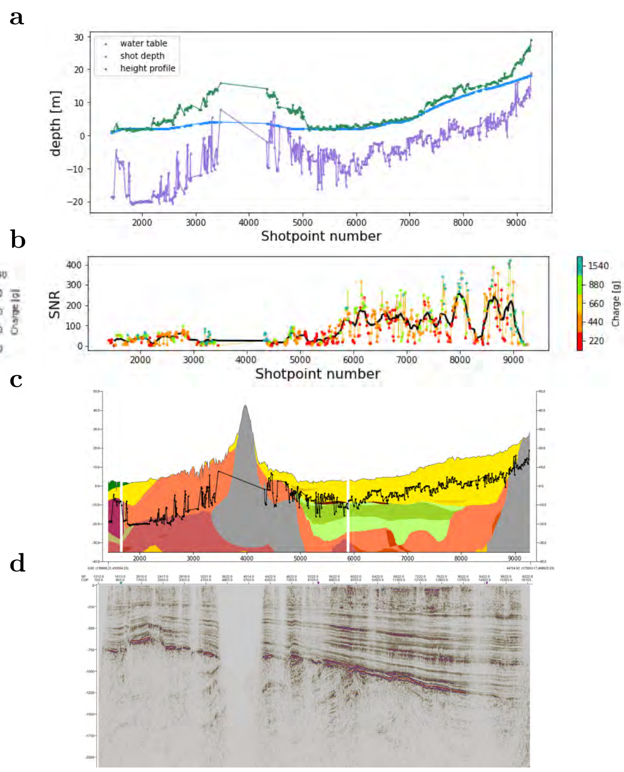


Figure 162: SCAN028 a) ground water table b) SNR along the line with charge size indicator c) near surface geological cross section till -35m d) final processed section.

3.3 Analysis of the final processed data of lines 2 - 16

The seismic processing company *DUG* finished the seismic processing for lines 2-10 and 12-16 during the course of this internship. In general most parts of the final cross sections are very clear and detailed, and many layers can be distinguished. Other parts are a bit blurry or vague, what we would call bad quality. A reason for this low quality could be for example data gaps, the lack of several shots in a row on the seismic line. For example on line 28 there is a large data gap because of permit restrictions on the military training base near the Veluwe, which will result in low quality on the final product. With your eye it is easy to distinguish bad and good quality data, even though it is also subjective. We would like to create a measure to quantify data quality. With this measure it will hopefully become possible to identify what parameters influence the final product. In this section we will first look for this measure and explain what works and what not, in the second part we will look at the effect of shot data gaps. In this analysis we only look at true amplitude plots with no automatic gain control.

3.3.1 Quality measure final product

RMS amplitude

In the first part of this report we looked at shots from the field data, without any processing. The quality was determined by signal to noise ratios for which RMS signal amplitudes and RMS noise amplitudes were determined. In this final product we cannot determine noise, since that is removed by processing as much as possible. A first attempt to measure quality was therefore to determine the RMS signal amplitude per CDP trace. Here we show an extreme case to see what happens. Figure 163 shows the cross section of the fast track *left*, after two weeks of processing and the final product *right*. In 5 different time windows the RMS amplitude is determined in *GLOBEClaritas*, shown in different colours. We know that the data is of low quality in the middle. Processing steps are designed to boost the signal, not the noise or other artefacts. In this example we see that in the middle amplitudes are boosted, the two peaks around CDP 3300 and 4300, even though that area is of low quality. Therefore RMS amplitude does not seem to be a good measure of quality by itself.

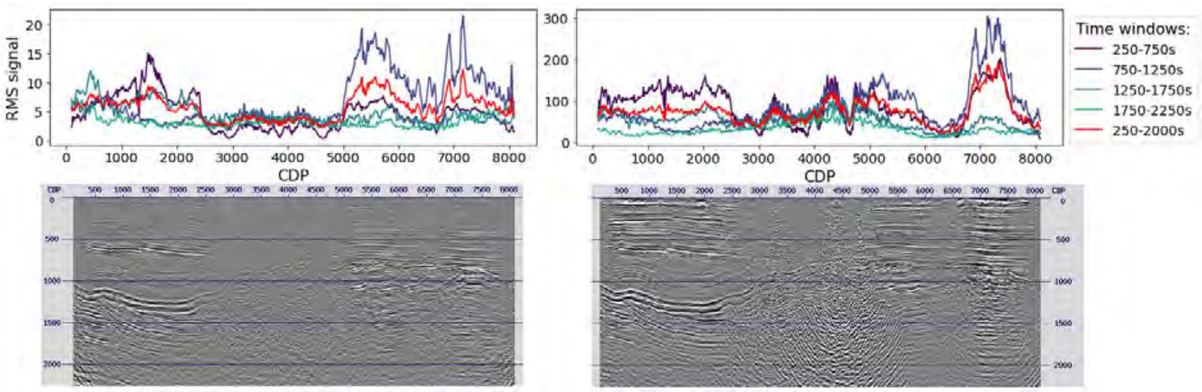


Figure 163: URKM006. *Left:* RMS signal amplitude of fast track calculated for 5 time windows on the section below. *Right:* RMS signal amplitude of final full calculated for 5 time windows on the section below.

Cross correlation time domain

When data is of good quality reflection lines are continuous within the section. Of course with the exception when a fault displaced the layers. Different layers can be distinguished and followed along the line on a good data plot. This is the reason to try cross correlation as a proxi for quality. Cross correlation assumes that all the coherent data on the seismic trace represents the seismic signal and all non-coherent data is representing noise. This assumption would break down when strong coherent multiples remain in the final processed data, as those multiples would be interpreted as signal, while in fact they are undesirably coherent noise. On very strongly dipping events this assumption is also compromised, as the reflection of the same geological interface would show a significant timeshift over a trace spacing of 25m (10 CDPs). Keeping that in mind we will see whether cross correlation can still be an adequate quality measure on our final seismic sections.

We take the cross correlation between every CDP trace and it's neighbour 10 traces to the right of the seismic cross section. The result of line 5 is shown in figure 164, as an example. This cross correlation coefficient (CC) should be high when the data quality is good and low when it is bad. In this example we see that the coefficients are very high to the right (CDP 20000-25000), where we have horizontal layers. Whereas on the left (CDP 0-10000), even though the response is much higher and more layers are distinguished, the CC is slightly lower. But we also see that in this region layers are dipping, resulting in different shapes of the CDP traces, therefore leading to less similarity. When we compare the region CDP 15000-20000 with CDP 20000-25000 we see similar data quality with the eye but the CC of the left bit is lower than on the right bit. Along CDP 15000-20000 there is a fold structure visible in the bottom layers, at 1-2s.

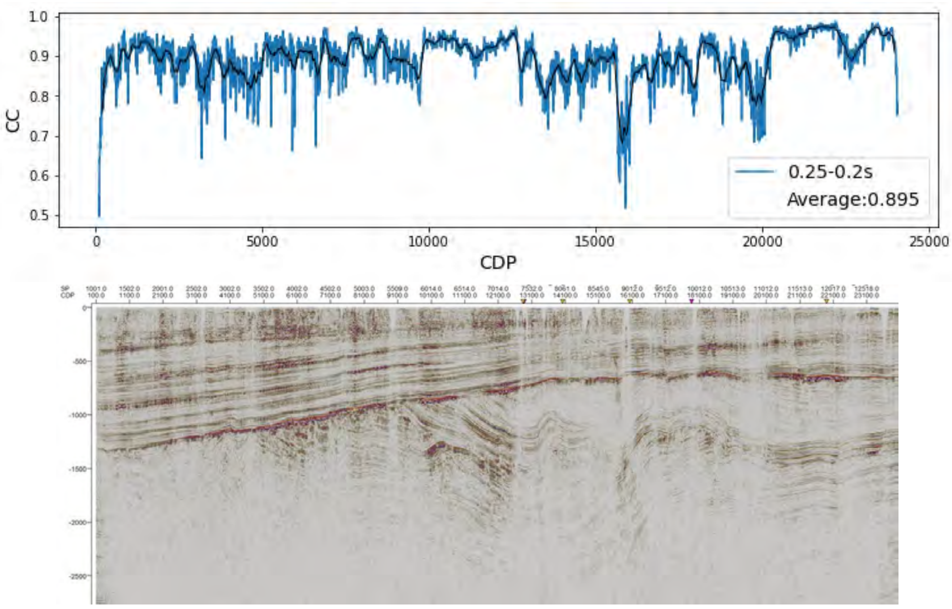


Figure 164: SCAN005. Cross correlation with neighbouring CDP traces. Trace step is 10 and the time window is 0.25-2s.

Cross correlation frequency domain

In order to capture the geological structures we will now look at the cross correlation in the frequency domain. For every trace the frequency spectrum is determined and those frequency spectra are compared, with it's neighbour frequency spectrum ten traces to the right. When we take the frequency content of a trace and compare it with another trace it does not matter when the layers are dipping, the frequency content will be the same. To show this we look at line 12. It has a horizontal layered top part, the North Sea group, and fold structures in the deeper part. We determine the cross correlation for the upper part and for the lower part to see the effect of analysing in both the time and the frequency domain.

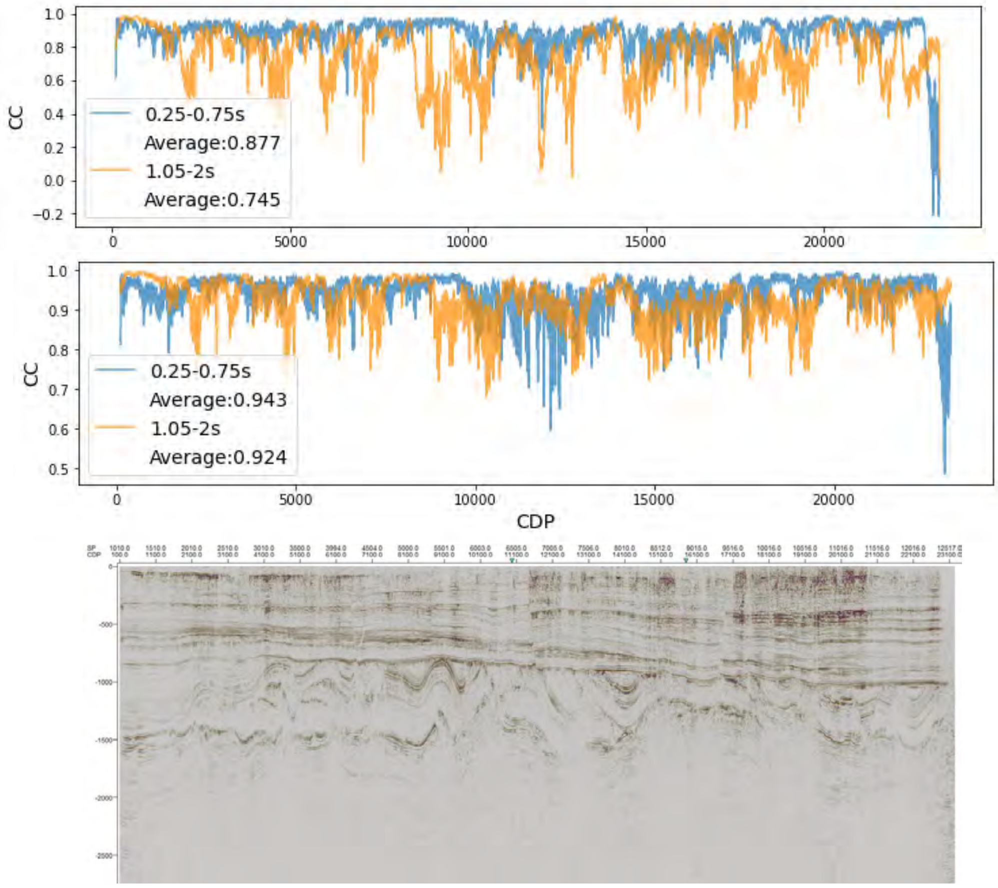


Figure 165: SCAN012. *Top:* Cross correlation in the time domain with neighbouring CDP traces. Trace step is 10, time windows are indicated with colours. *Middle:* Cross correlation in the frequency domain with neighbouring frequency spectra of the CDP traces. Trace step is 10, time windows are indicated with colours. *Bottom:* Final processed section.

What we can see in figure 165 is that cross correlations coefficients in the frequency domain are higher in absolute numbers than in the time domain, but also that the difference between the two time windows is relatively smaller. For the time domain (*top*) the lower window has much lower cross correlation coefficients than the upper window, while the difference in data quality is not that much.

Below all final processed sections are shown with corresponding cross correlations in both time (blue curve) and frequency (orange curve) domain as well as SNR plots in the shot domain. Note that the y-axis scaling is different for the time and frequency cross correlation coefficient (CC) curves.

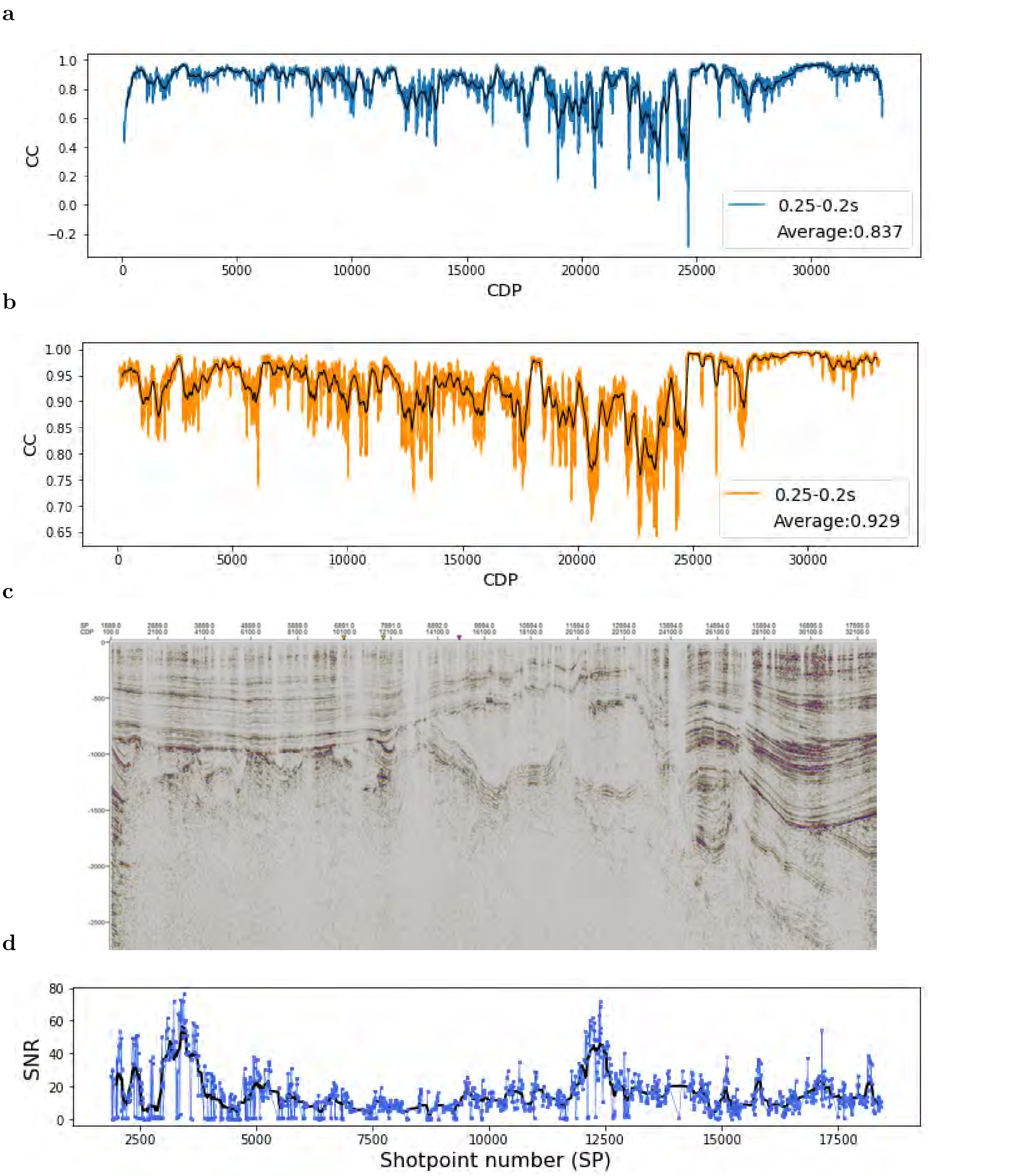


Figure 166: SCAN002. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

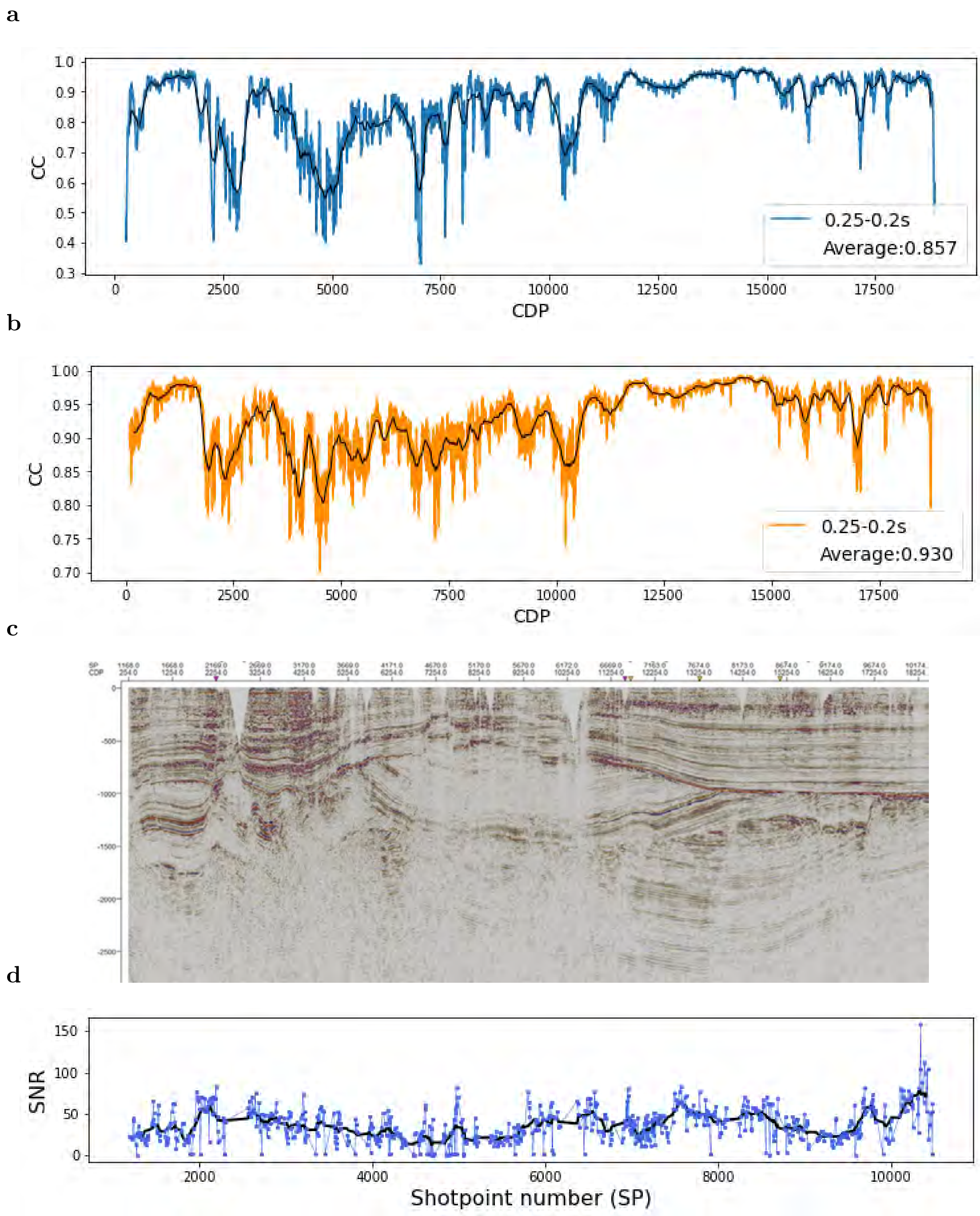
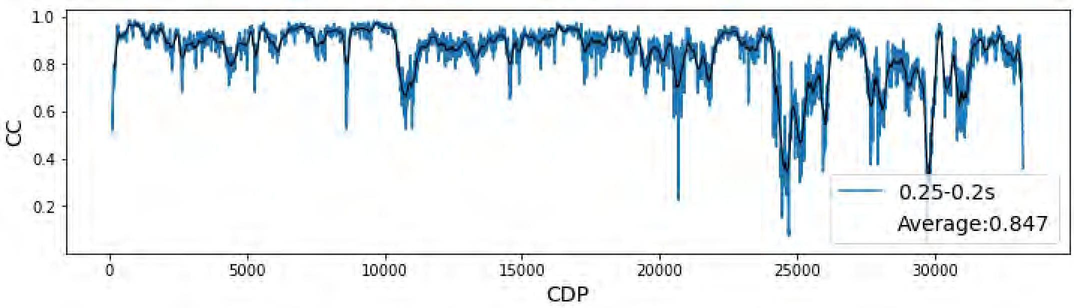
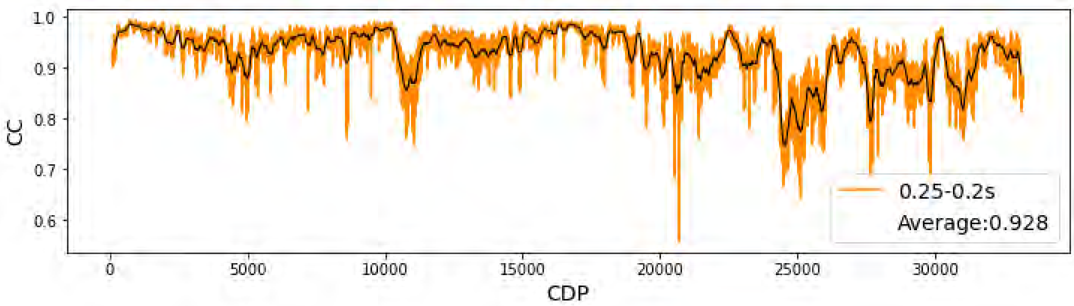


Figure 167: SCAN003. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

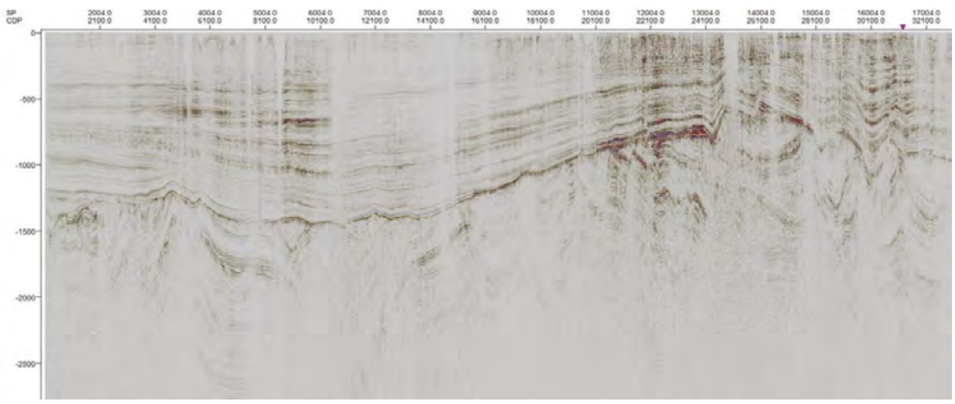
a



b



c



d

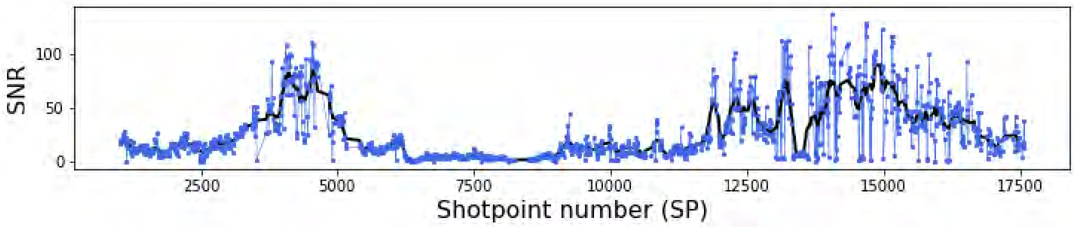
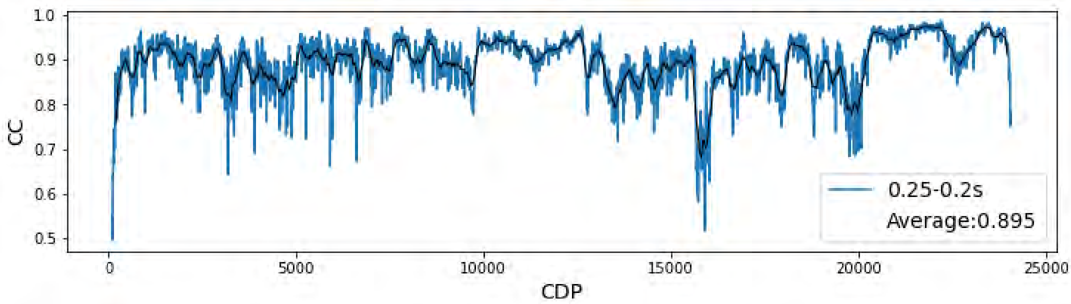
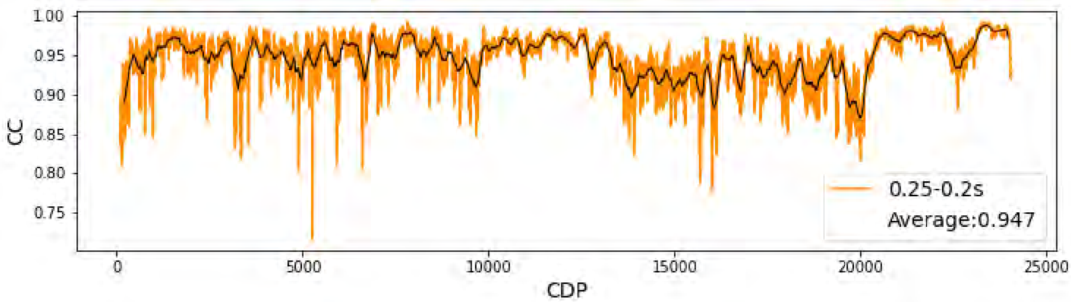


Figure 168: SCAN004. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

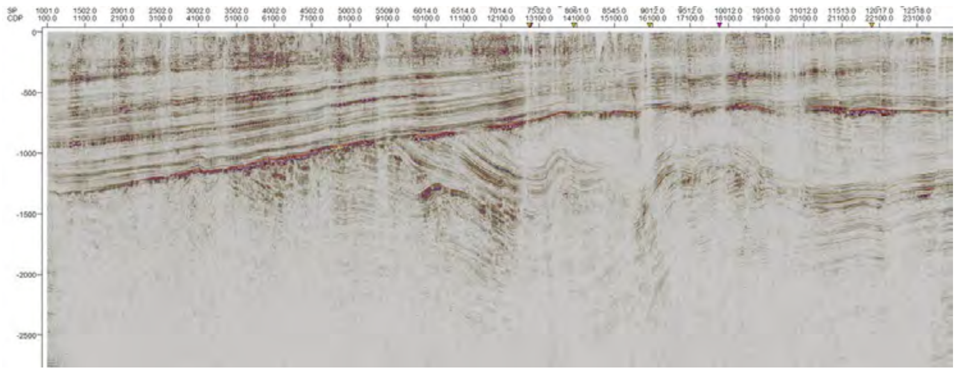
a



b



c



d

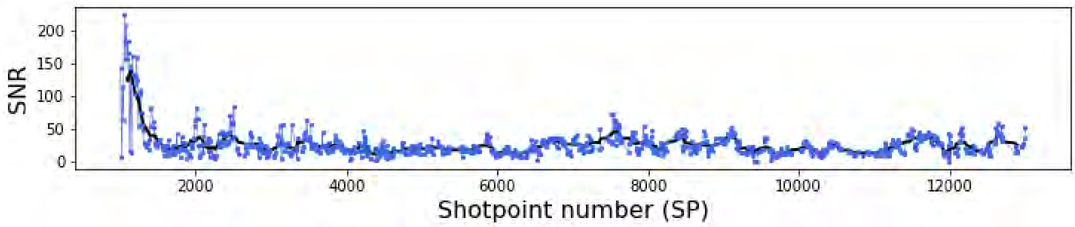


Figure 169: SCAN005. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

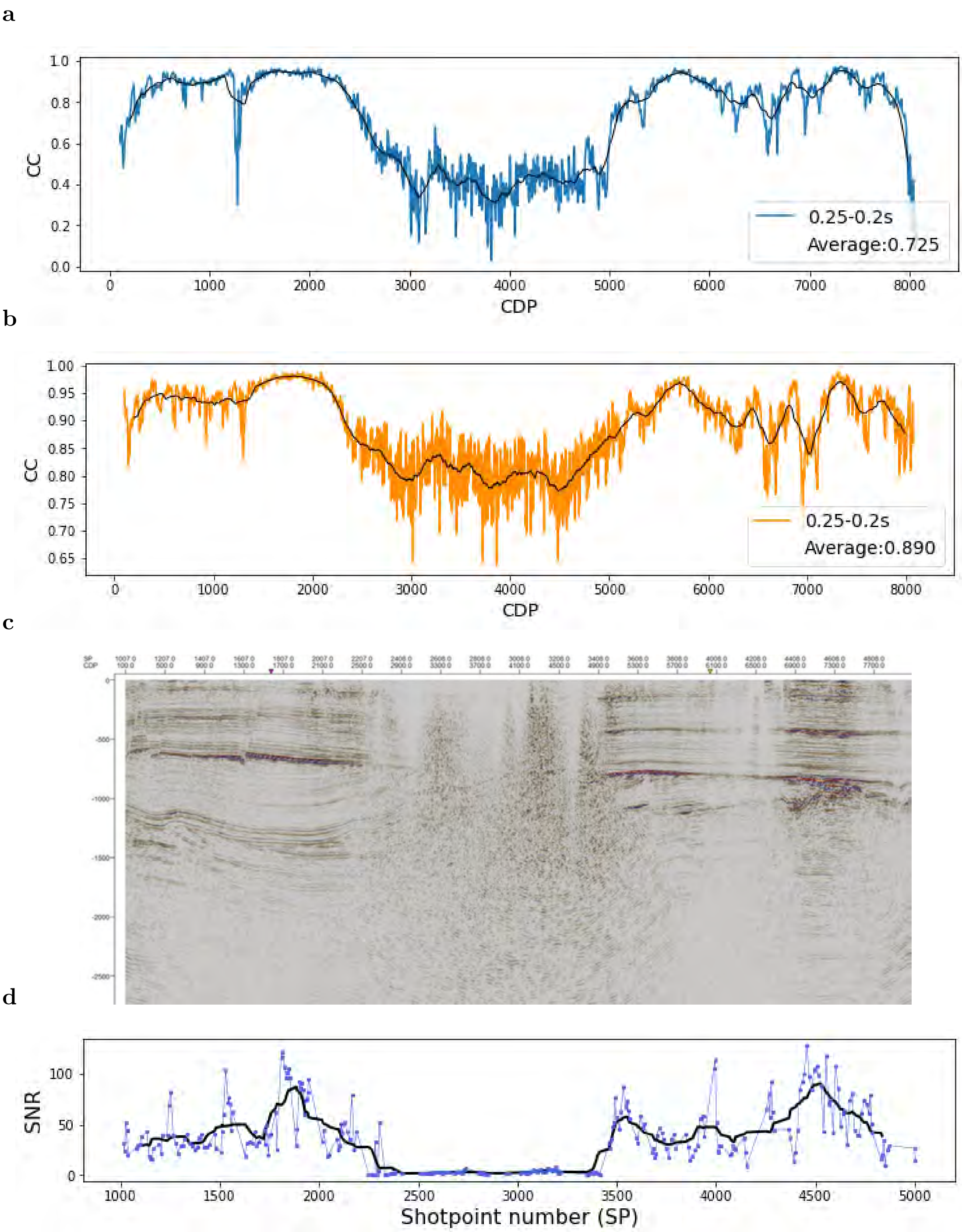
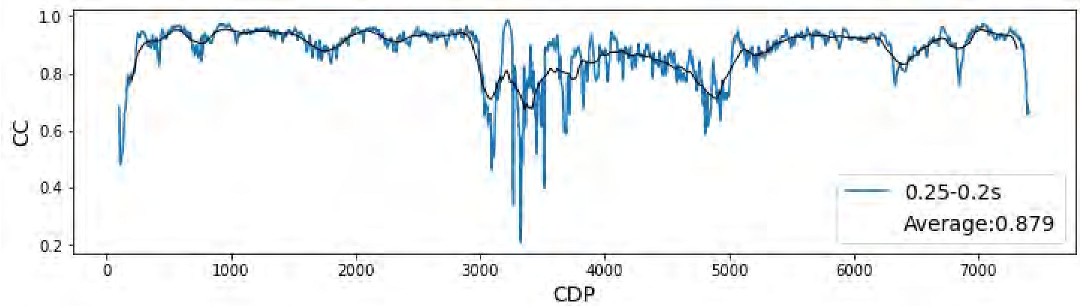
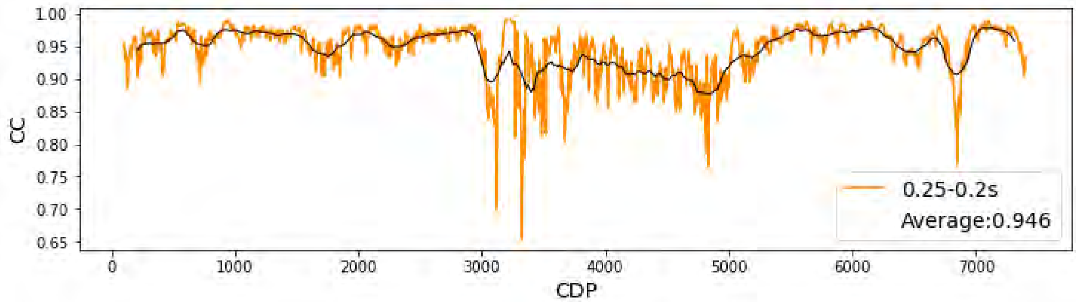


Figure 170: URKM006. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

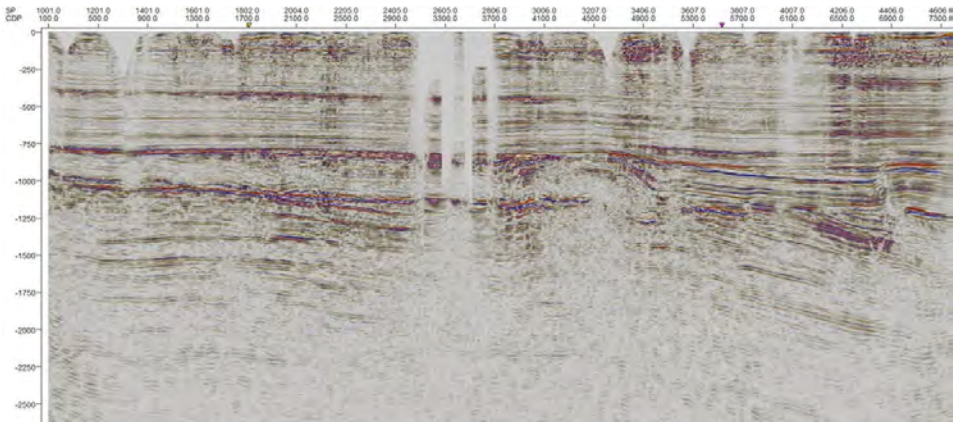
a



b



c



d

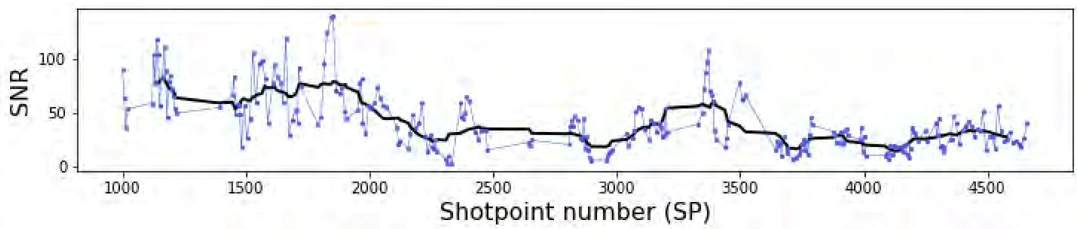


Figure 171: URKM007. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

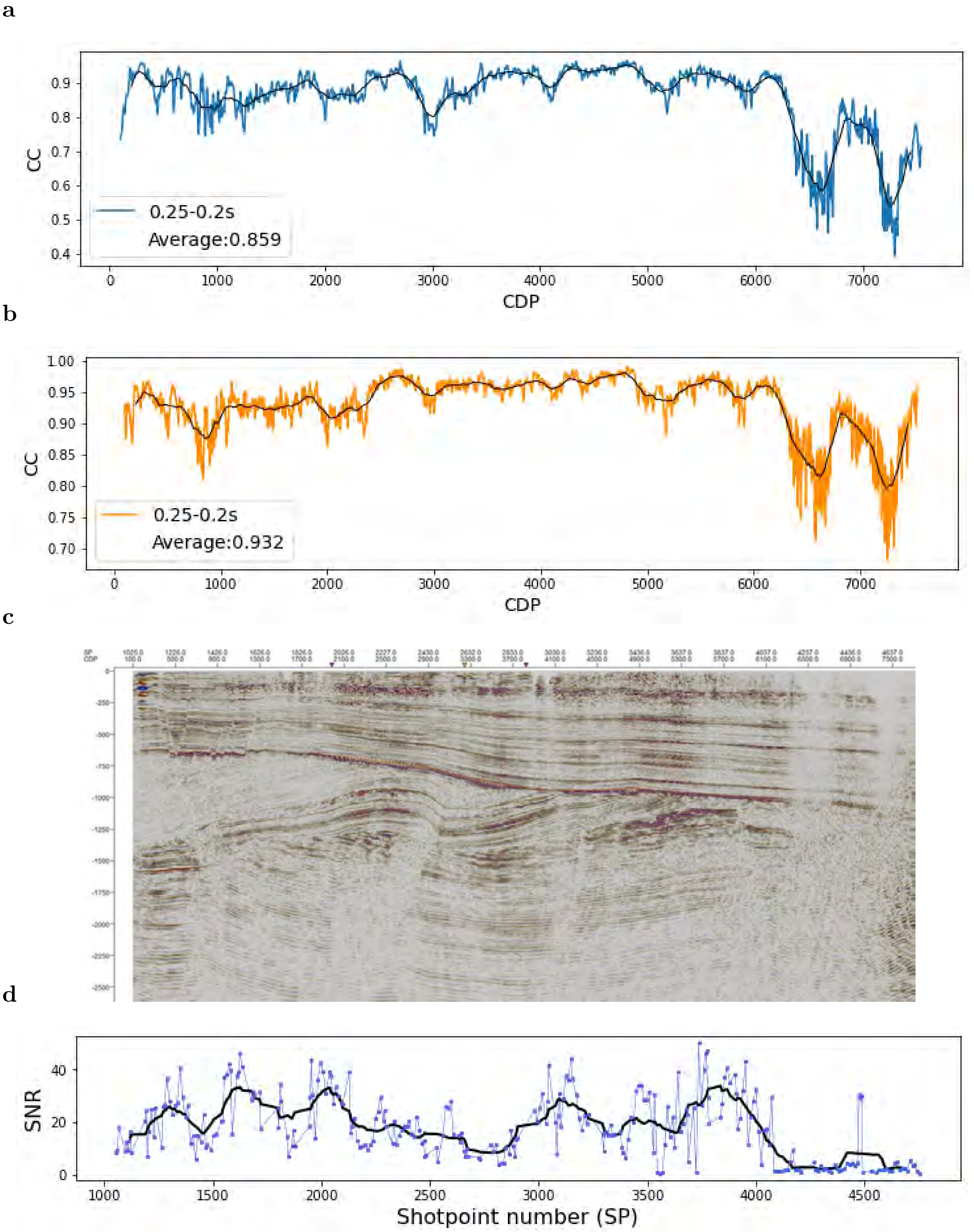
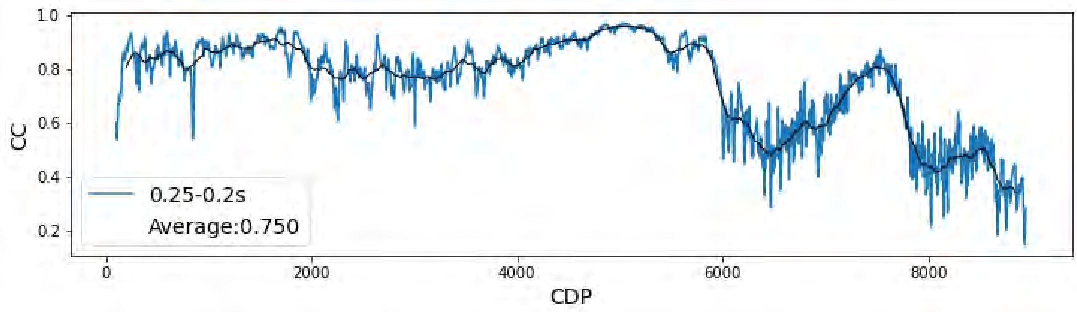
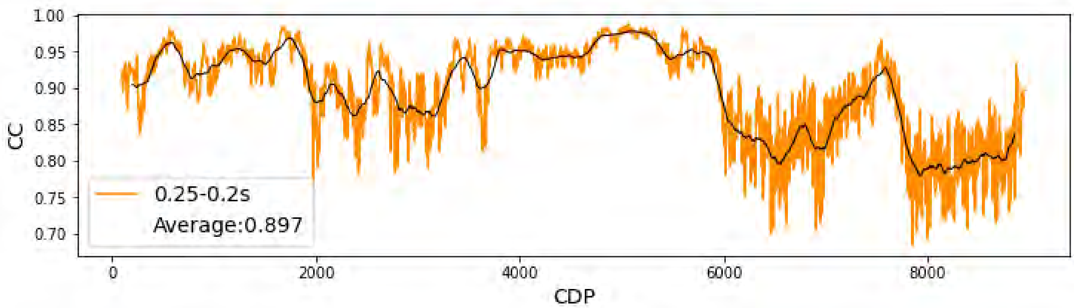


Figure 172: URKM008. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

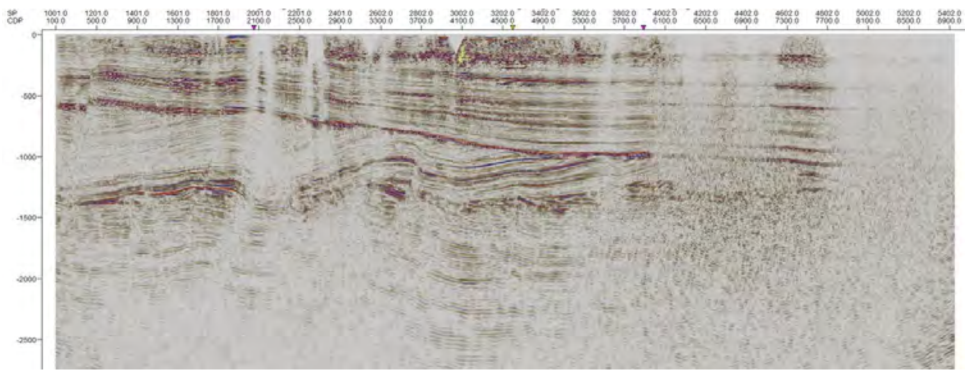
a



b



c



d

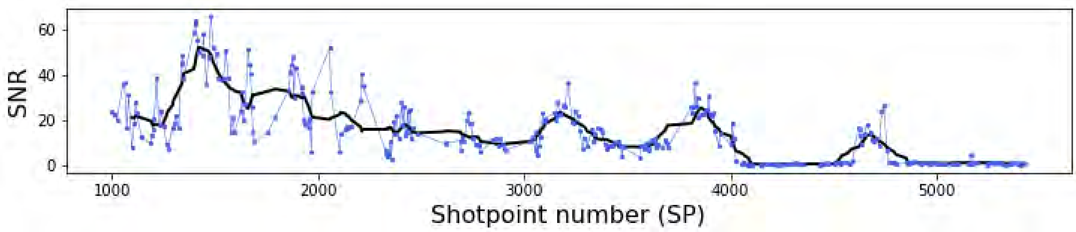
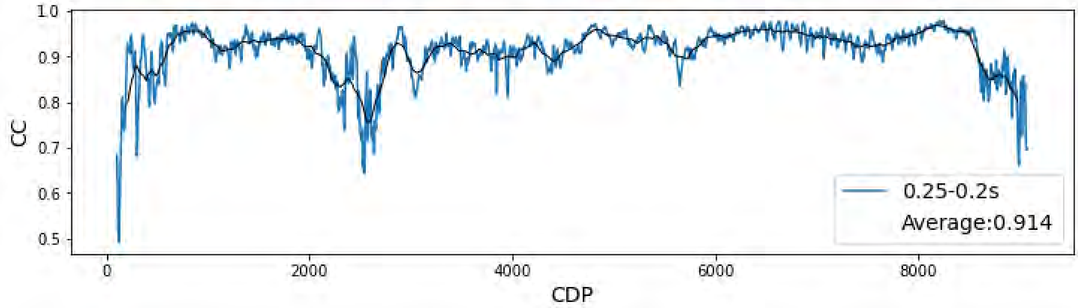
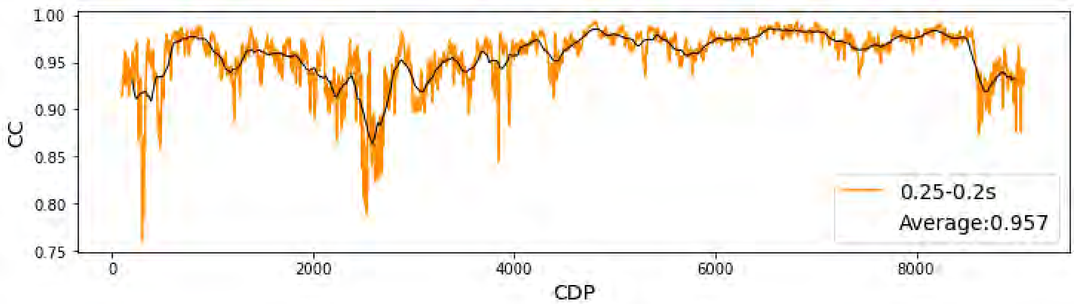


Figure 173: URKM009. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

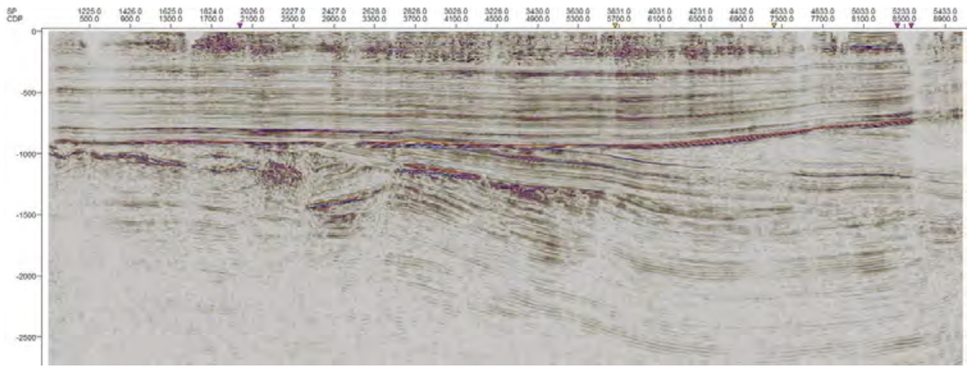
a



b



c



d

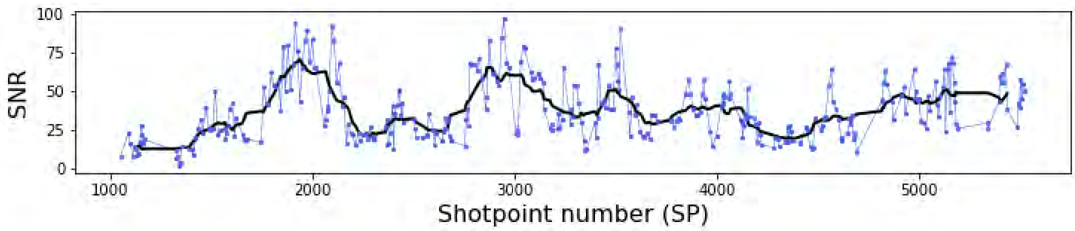


Figure 174: URKM010. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

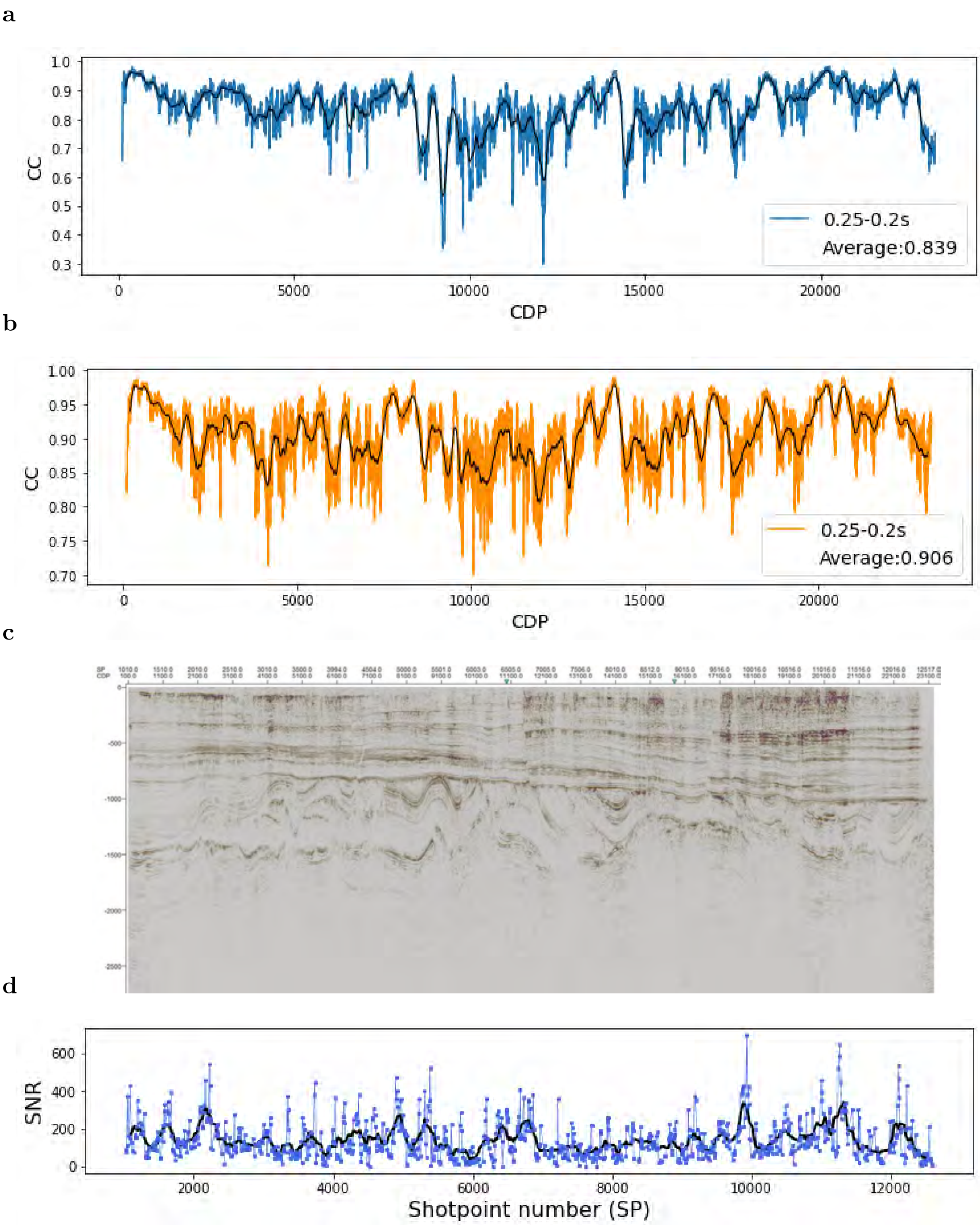
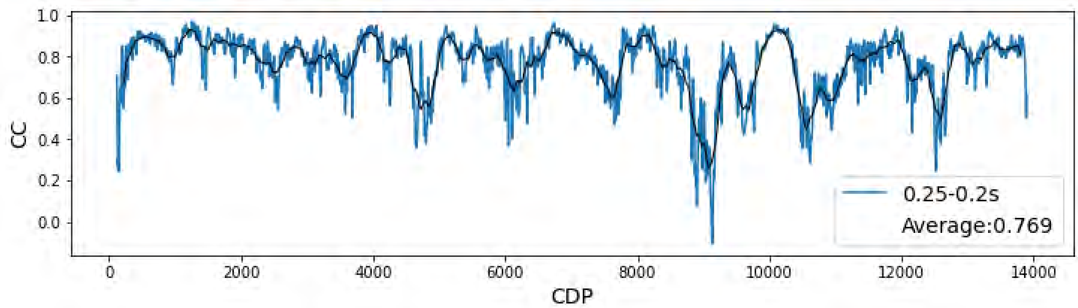
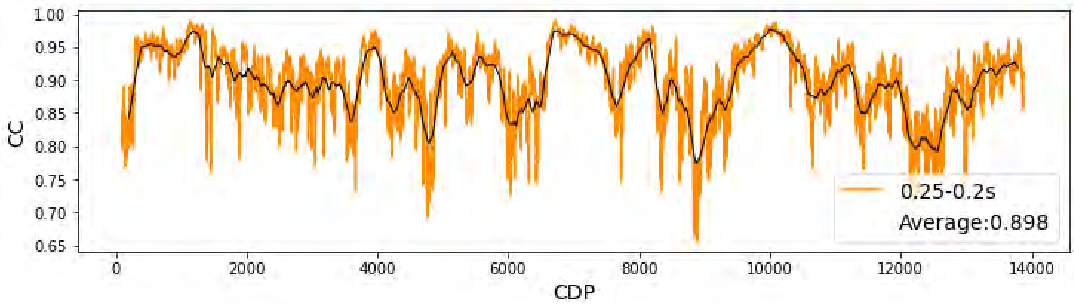


Figure 175: SCAN012. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

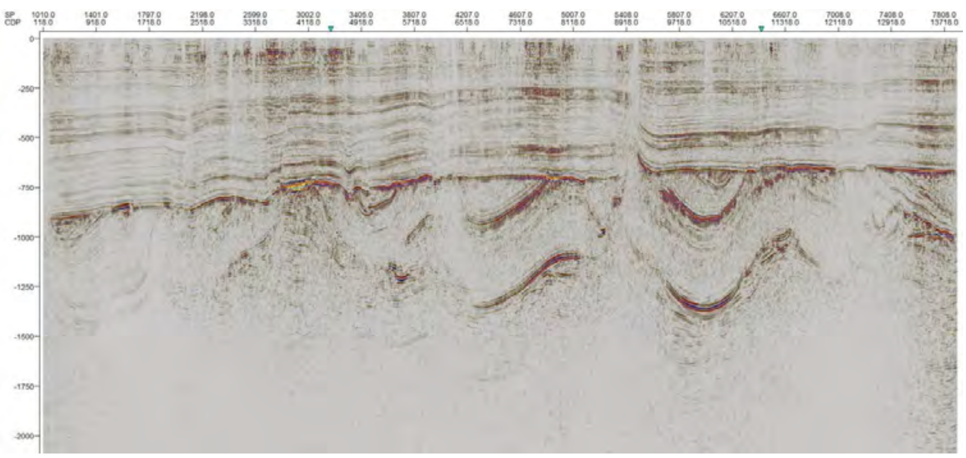
a



b



c



d

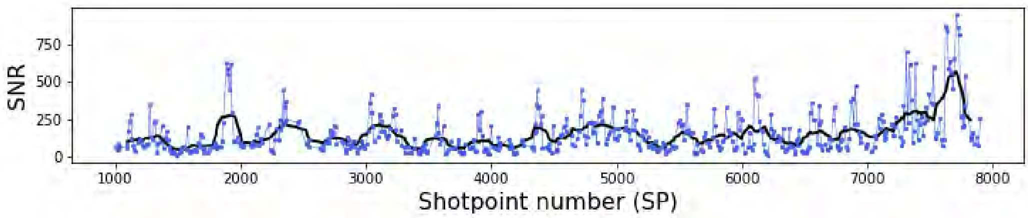


Figure 176: SCAN013. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

a

b

c

d

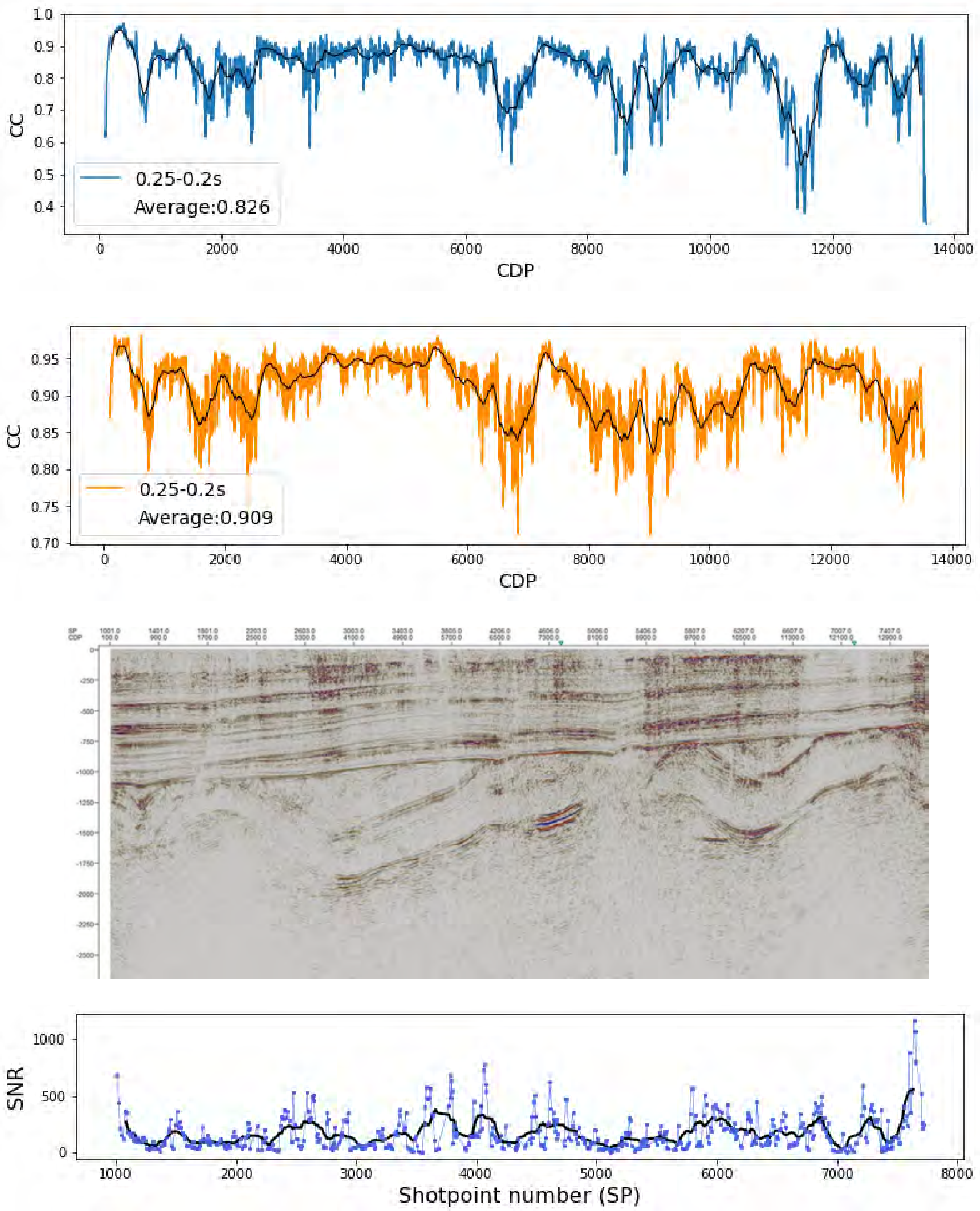


Figure 177: SCAN014. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

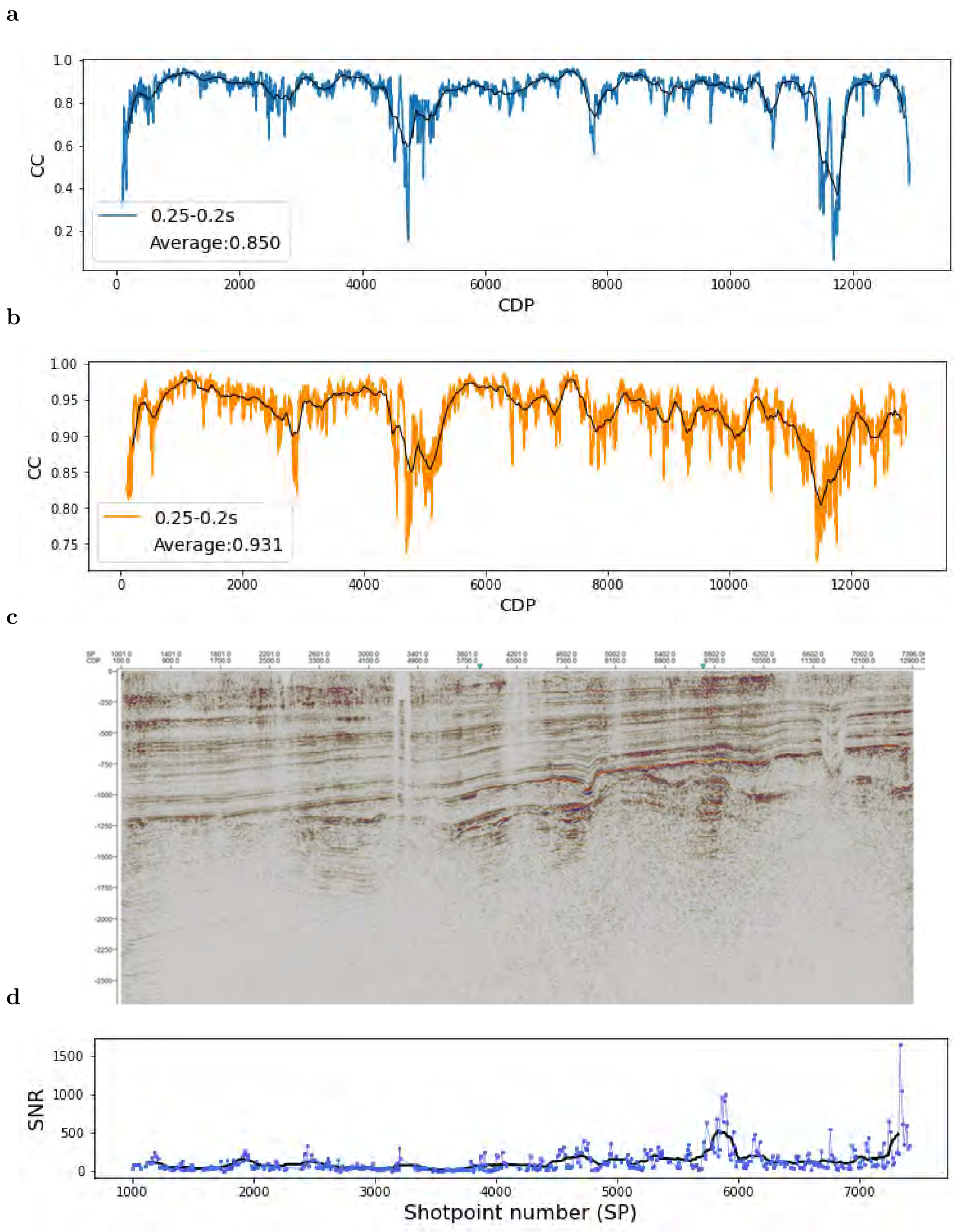


Figure 178: SCAN015. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

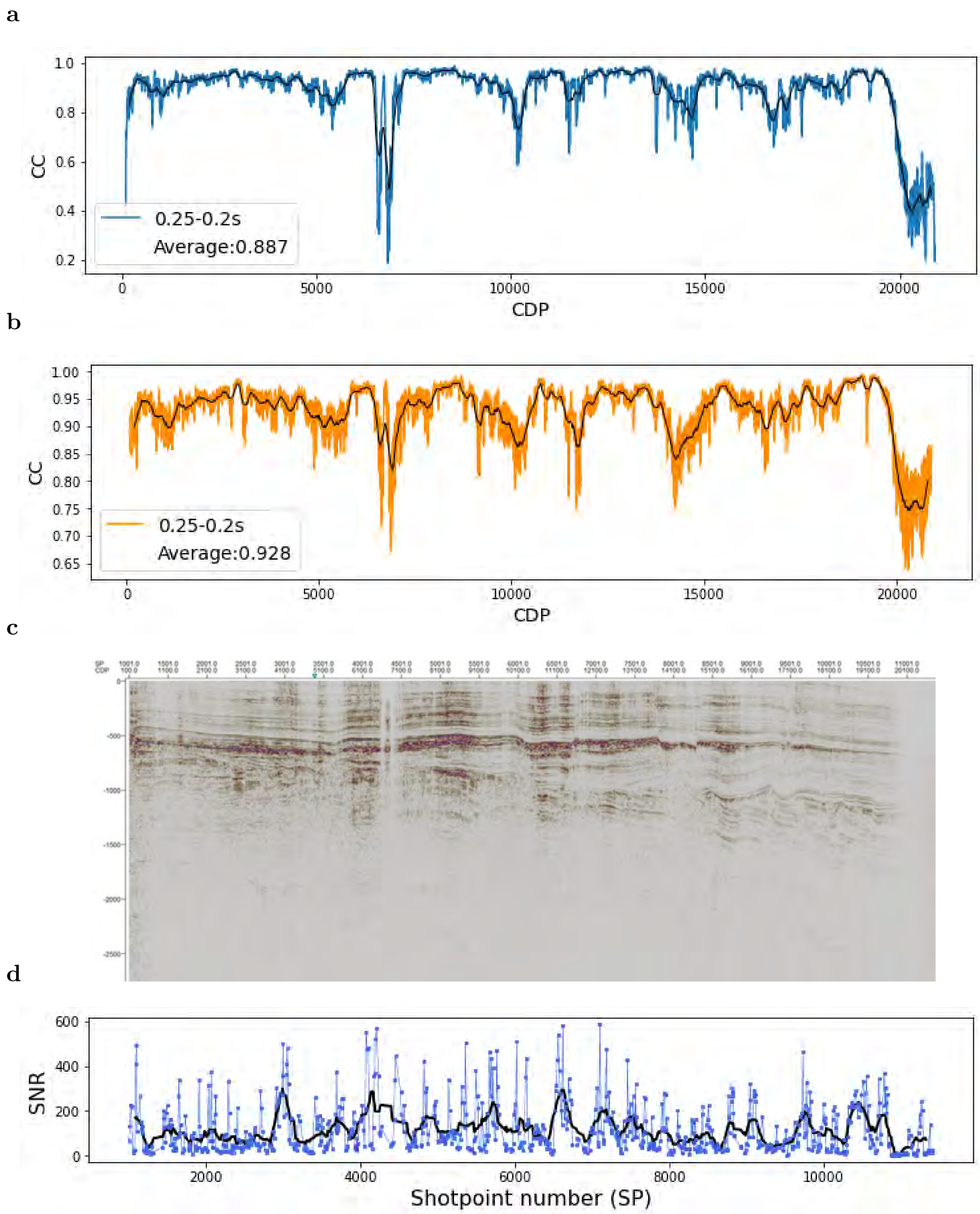


Figure 179: SCAN016. a) cross correlation in time domain b) cross correlation in frequency domain c) final processed seismic image d) SNR along the line.

Average frequency

Since we have not found the perfect quality measure yet we also tried something else: the average frequency. It's a geophysical component from every trace and might tell us something about quality. It turns out that this measure is worse, nevertheless it is good to show the results. Figure 180 shows the concept of average frequency. From the frequency spectrum of a trace, the average is taken so that left and right of the value, the same area under the curve is set. Figure 181 shows an example of the frequency spectrum of a randomly chosen trace, where the green area is the same size as the blue area. The average frequency for this spectrum is 54.87 Hz. The formula to calculate the average frequency is [Thongpanja et al., 2013]:

$$f_{mean} = \frac{\sum_{i=0}^{n} I_i \cdot f_i}{\sum_{i=0}^{n} I_i}$$

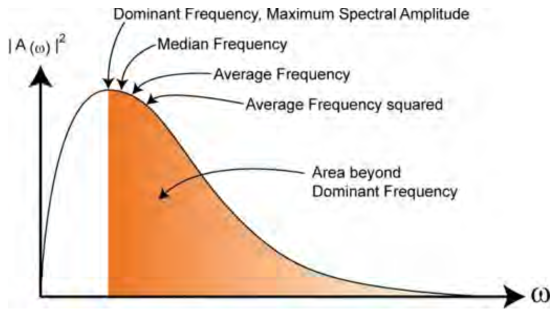


Figure 180: Possible frequency outputs [dGB Earth Sciences 2002 2015]

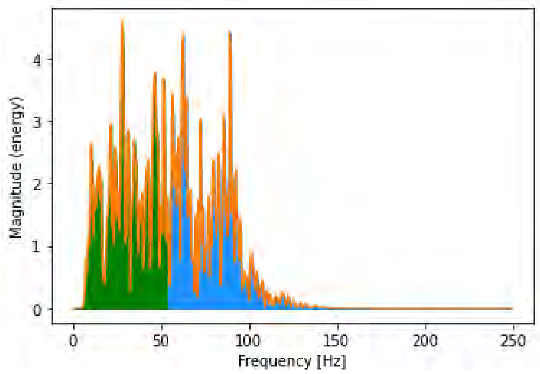


Figure 181: Frequency spectrum of CDP trace 10 of line SCAN015, green indicates the left area under the curve till the average frequency and the right is indicated in blue.

Where n is the number of frequency bins in the spectrum, f_i is the frequency of spectrum at bin i of n and I_i is the intensity of the spectrum at bin i of n.

Figure 182 shows the average frequency per CDP trace for two time windows. When we look at the end of this line there is almost no data so the quality measure needs to be very low there compared to other CDP traces. This is not the case, the average frequency even peaks at the end of the plot.

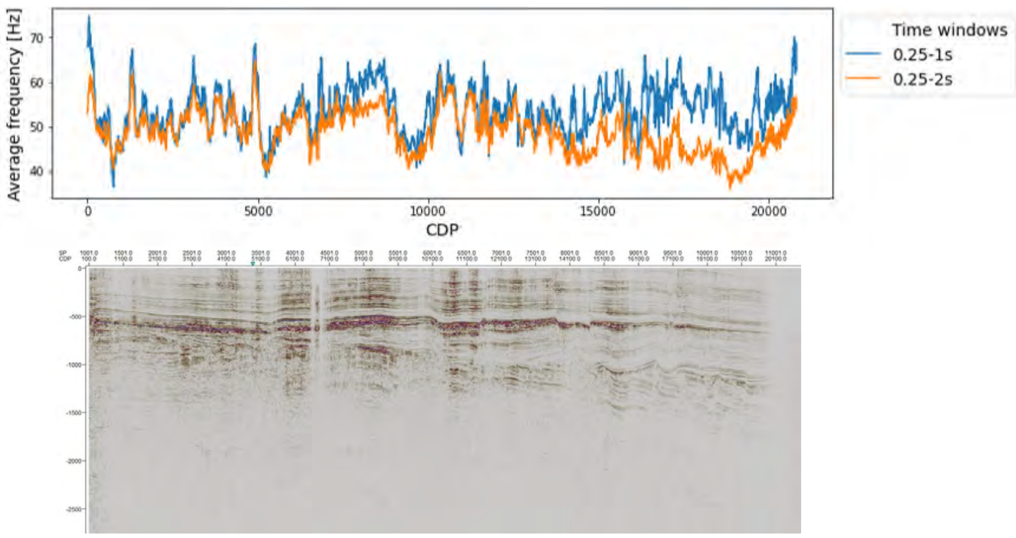


Figure 182: SCAN016. *Top:* Average frequency of the frequency spectrum per CDP trace, time windows are indicated with colours. *Bottom:* Final processed section.

3.3.2 Effect of shot data gaps

We will look at the effect of a shot data gap on the final seismic section. When for example a river or a city limits several shots in a row to be acquired, we would like to know what the effect is on the final result. We will use the cross correlation in both time and frequency domain as a measure for the quality but since we zoom in, it is also visible by eye. For this analysis we looked at very large shot gaps of 500m or larger, which happens about 60 times in the processed lines (2-10 and 12-16).

In this report we will look at examples of three shot data gaps along line 3. Figure 183 shows the final seismic section of this line and the fold along this line is shown. Fold is a measure of the redundancy of common depth point data (CDP), equal to the number of offset receivers that record a given data point or in a given bin and are added during stacking to produce a single trace [Schlumberger].

The maps of figures 184, 186 and 188 show where the shots gaps are located, green dots are shot points locations, brown dots are the geophone locations. The shots could not be placed because of the crossing of the rivers Lek and Rhine and because of the city Buren. Geophones could still be placed with a cross-line offset.

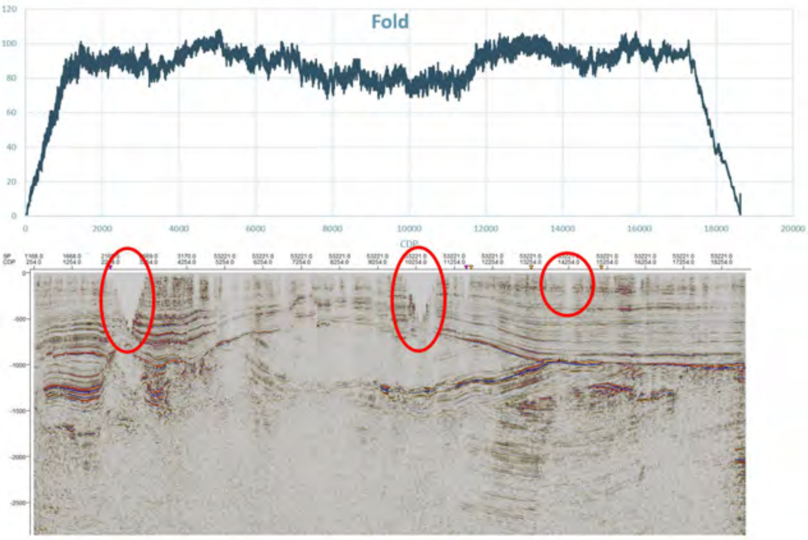


Figure 183: SCAN003. *Top:* Fold per CDP. *Bottom:* Final processed section. The red circles indicate the shot gap examples shown in this report.

In figure 185b we see a little dip in the cross correlation values in the shallow windows (mainly 0.25-0.5s) at the location of the shot gap. In this 0.25-0.5s window we also see some edge artefacts in the seismic section directly next to the shot gap. We don't see this dip in 185c. However, we see a remarkable dip in the purple window. We don't notice anything atypical on the final section (figure 185a). The scaling (y-axis) between the two CC's is also different, the dip in the frequency domain plot seems relatively less extreme than the dip in the time domain plot. In figure 187b and c we see in general lower coefficients for the shallow windows green and red than for the deeper windows yellow and purple. For the shot gap at CDP 2750 (figure 189) this trend is less clear.

Figure 184: SCAN003 map of shot gap CDP 14250. The green dots are shot point locations, the brown dots are receiver locations. The shot gap is 680 meters.

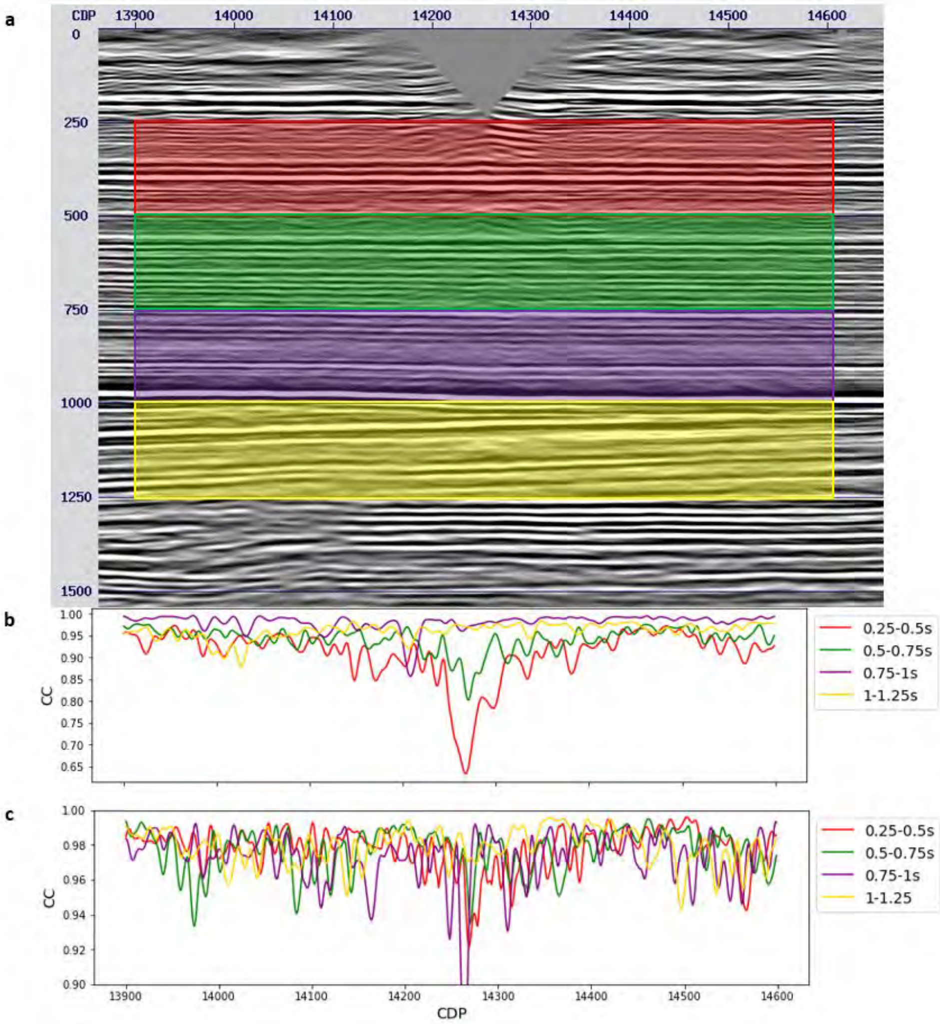


Figure 185: SCAN003 (a) Prestack migration final full seismic section around shot gap CDP 14250. The colours indicate four different time windows on which cross correlation coefficients are calculated, in both time domain (b) and frequency domain (c).

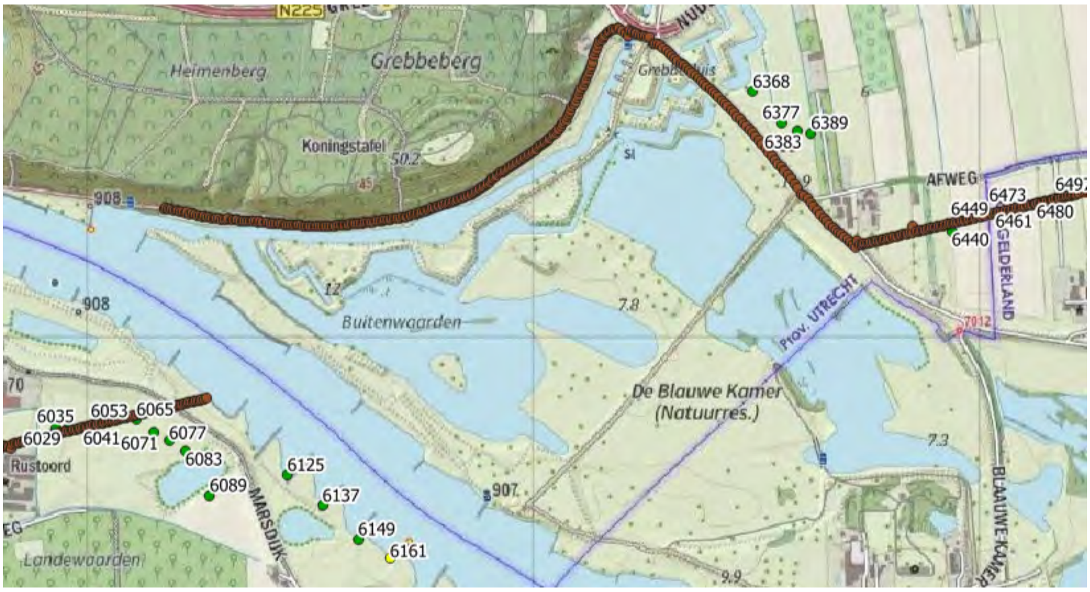


Figure 186: SCAN003 map of shot gap CDP 10400. The green dots are shot point locations, the brown dots are receiver locations. The shot gap is 1035 meter.

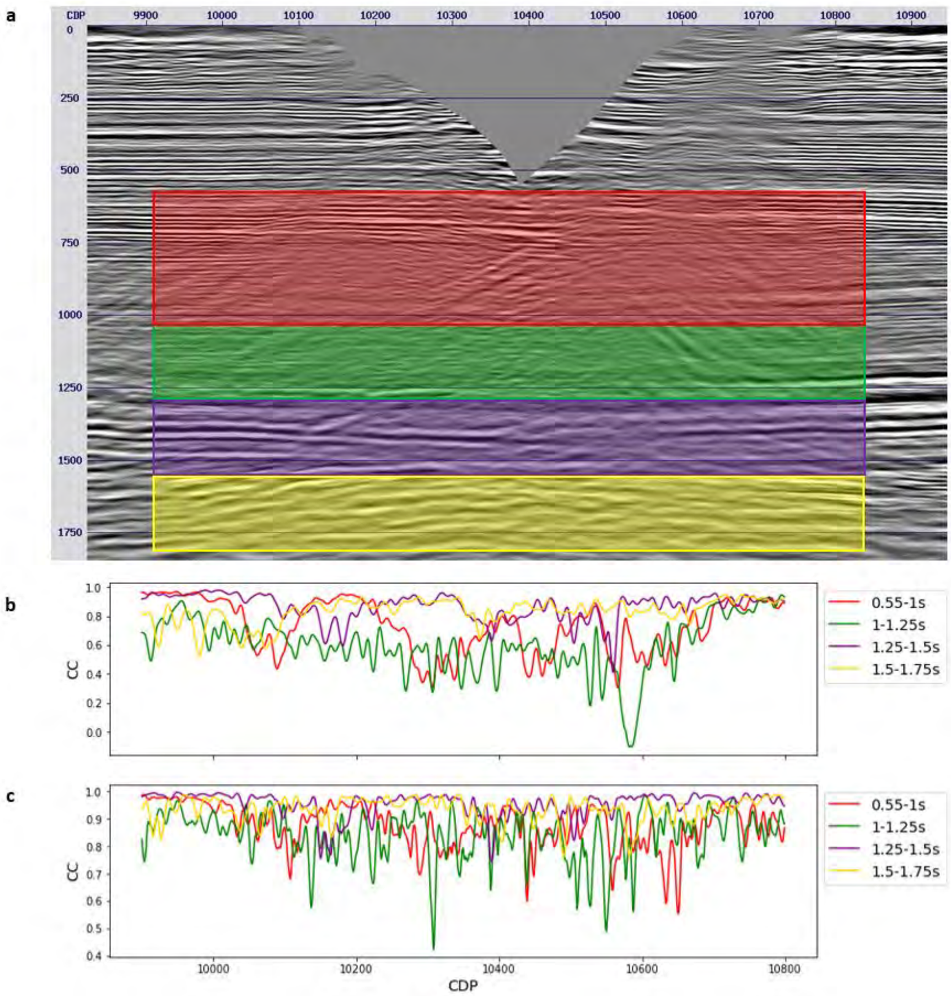


Figure 187: SCAN003 (a) Prestack migration final full seismic section around shot gap CDP 10400. The colours indicate four different time windows on which cross correlation coefficients are calculated, in both time domain (b) and frequency domain (c).

Figure 188: SCAN003 map of shot gap CDP 2750. The green dots are shot point locations, the brown dots are receiver locations. The shot gap is 1320 meter.

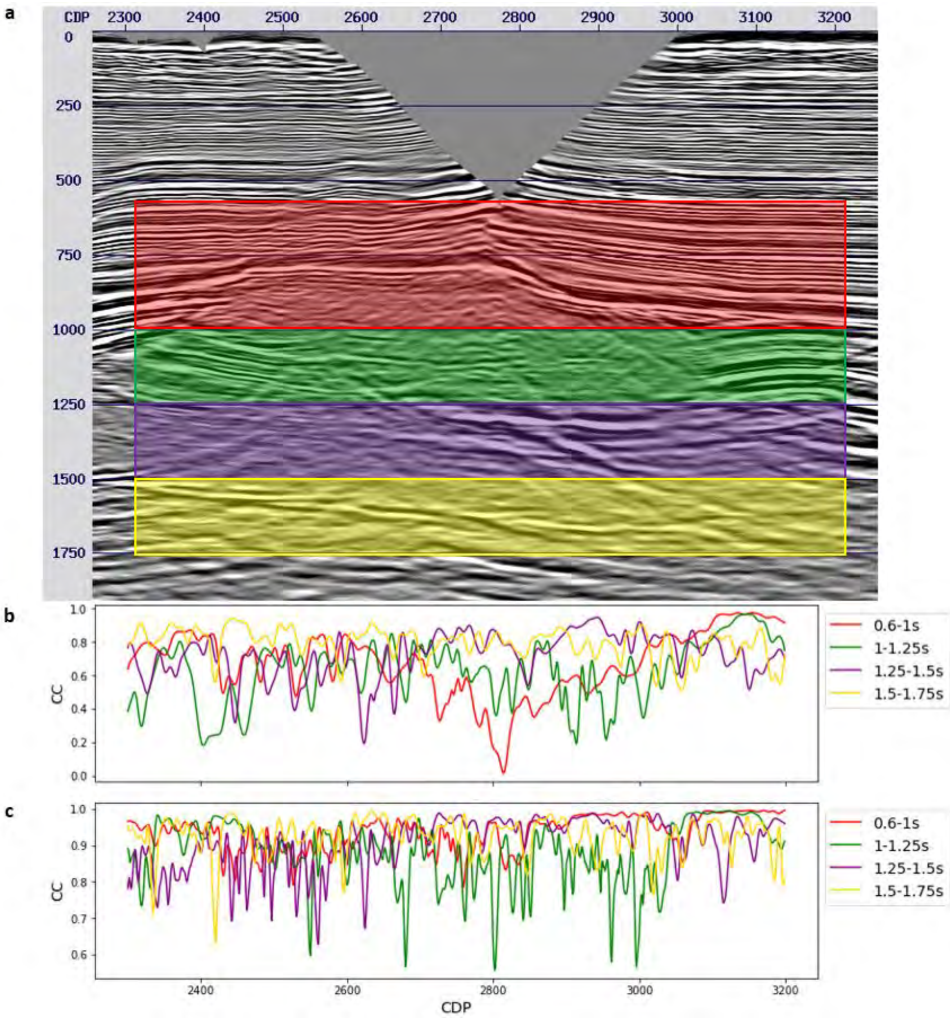


Figure 189: SCAN003 (a) Prestack migration final full seismic section around shot gap CDP 2750. The colours indicate four different time windows on which cross correlation coefficients are calculated, in both time domain (b) and frequency domain (c).

4 Discussion

In the results section (section 3) we already slightly interpreted the data, because every next analysis is based on what is found in the previous analysis. In this section we will elaborate on the findings.

4.1 Field data

A great variance exists between all shots because many different parameters are used. For every shot we see differences in signal amplitudes, noise amplitudes, signal to noise ratios, charge sizes, timing of the day, uphole velocities, shot depths, near surface geology and shot below or above the water table. This variety makes it hard to quantify the influence of different parameters on SNRs. In this chapter we describe what we think we can take from all the data we have analysed.

From the uphole velocity plots it seems that uphole velocity is dependent on shot depth. In general we see that deep shots correspond to a relatively high uphole velocity. This probably has to do with the wave speed which is faster for water than for air, and deeper shots usually have a relatively larger wave path below the water table. We also see on all noise receiver maps that where highways or railways cross the line, high noise levels are found for those receivers nearby. Also in urban areas noise levels are relatively high. In the time of the day plots we see that shots taken outside traffic rush hours usually generate lower noise amplitudes. Shots fired in glacial deposits (orange and grey in the geological cross section plots) are generally resulting in low SNRs, but when that is the case, shots are also fired above the water table as we see in the ground water table plots.

After analysing the charge size parameter for every line we can conclude that charge size has a very big influence on SNRs. For every line we see an linear increase, the higher the charge size the higher SNR (figure 146). This makes sense because higher charge sizes result in bigger explosions which will result in higher signal amplitudes. We also tried to correlate this to the near surface geology. When the lines are split in regions mid, west, east and south there seems to be quite a correlation. Region *mid* results in the lowest SNRs, and regions *south* and *east* in the highest SNRs. One reason for this could be the glacial deposits that are present in many lines in the *mid* region, where shots were fired above the ground water table. Besides, noise levels are generally higher in regio *mid* and *west* because it is denser populated. This division in regions is not based on near surface geology. When we labeled every shot with its corresponding physical geographical region according to the physical geographical map (figure 149) there was not a clear trend visible. Sand grounds on average give the highest SNRs, but the standard deviation is also very large (figure 150). Low SNRs are found in the stowed glacial deposits (stuwwallen).

On the normalized shot depth plot (figure 152) we also see a trend of deeper shots corresponding to higher SNRs, the scatter is a bit larger in this plot than the normalized plot for charge size. This could be because deep shots can also be taken with low charge sizes or they can be placed above the water table, which is not favorable as we saw in section 3.2.3. However, the trend shows us that in general deeper shots give higher SNRs. Deeper shots are assumed to have a better coupling with the subsurface and therefore the signal's energy will attenuates less. From this plot we can say that shot depth is one of the more important parameters in optimizing SNR values. It seems that 16-20m in general give relatively high SNRs.

When looking at lines that cross elevated stowed glacial deposits and looking at whether a shot is taken above or below the ground water table we found that shots taken above the ground water table generate bad quality data whereas shots taken below the water table in those deposits are not that bad. From this analysis we can conclude that the stowed glacial deposits are not the (primary) reason for bad quality data. There could of course be an influence of geology as well. This groundwater analysis indicates that firing shots below the water table is crucial in obtaining significant signal amplitudes and therefore a high signal to noise ratio.

All in all the data analysis taught us to shoot with a charge size as large as possible, to place the charge as deep as possible and also to always try to place the charge below the water table.

4.2 Final processed data

In this research we looked for a good quality measure for the final processed seismic section. RMS amplitude and average frequency did not fully meet our requirements, as each individual criteria can fail under certain circumstance. Cross correlation in both time and frequency domain seem to be good quality proxies, but both have their own pro's and con's.

Cross correlation in the time domain seems a good measure when layers are horizontal and continuous. However, this technique seems to lacks in capturing geological structures. Areas of good data quality in complex geological settings can easily get interpreted as poor data areas. It is a good quality proxi when all layers are horizontal but when dipping layers, fault systems or fold structures are present the shape of the trace changes too much so that the quality cannot be determined properly. Besides, since we compare the shape of the trace, a change in low frequency changes the shape less than a change in high frequency with the same amount. Therefore high frequency variations, which in general give more detail to your section, will come out as lower quality than low frequency variations.

Cross correlations in the frequency domain seem a better proxi for quality when you want to quantify dipping layers because the frequency content will be the same. However, it is important to mention that similar frequency spectra do not necessarily need to have a similar trace shape in the time domain. In other words, a noisy trace can have the same frequency content as a very high quality trace. Similarly, a reversed trace in the time domain will have the same frequency content but will not represent a continuation of layers in the seismic section.

None of the quality indicators work well under all circumstances, but with keeping that in mind, cross correlations are a good proxi for quality to work with. It is a multi-component problem that is not solved with neither of the cross correlation options. Nevertheless, cross correlation is a good first order approximation of quality of the seismic sections.

From the shot data gap analysis we can conclude that the effect of shot gaps is small on the final seismic sections. One of the main reasons for this is because compensation shots keep the fold high, meaning we have collected sufficient traces (albeit with a more limited offset distribution in the shot gap areas) and therefore we can suppress random noise to a similar degree as if the shots had been taken at the nominal locations. It will also help that even though shots could not be placed, receivers do still measure the incoming waves. When receivers are lacking as well the effect seems bigger. To conclude, it is always best to have as minimal shot gaps as possible, but skipping a shot once in a while does not seem to have a large influence on the final processed data quality. At most, a few hundred ms under the shot gap there is small influence, and of course, there is also no information in the muted wedge that arises because of the missing offsets that could not have been recorded due to the shot gap.

Now that we have a first order measure for data quality of the final processed seismic section, other analysis can be performed. For example on the effect of placing shots away from the center line, because the original line crosses buildings or rivers, on the final seismic image. How far perpendicular from the original line can you place a shot and what is the influence on the final product? There is also room for improvement on the quality measure by for example linking cross correlation in both time and frequency domain or by looking for other quality measures.

5 Conclusion

When analysing the field data we can define a SNR for every shot, a measure of quality. We see that the charge size is of great influence in determining quality. The higher the charge size, the more signal is generated, leading to higher SNRs. Shot depth seems also quite important, most shots are taken at a minimum of 16m and that generates average to high SNR values. An important finding in this research is the fact that shots taken above the water table generate low quality data. The primary problem of having bad shots in stowed glacial deposits seems to be caused by placing a shot above the water table. A relatively shallow shot below the water table will probably give better results than a relatively deep shot above the water table. Our recommendation is therefore to always shoot below the water table, to use a charge size as large as possible and place it as deep as possible.

When looking at the final processed images it is harder to determine quality. Different approaches are proposed. RMS signal and the average frequency of traces does not seems to be a good measure of quality by itself. The cross correlation in both time domain and frequency domain does a good job in determining quality. The limitation in the time domain is the disability of capturing folds, faults and strongly dipping layers. The limitation in the frequency domain is the insecurity whether certain frequencies belong to the true signal, to multiples or to random noise. When the layers are horizontal, both the time and frequency domain are a good first order proxi for quality, for other structures the cross correlation in the frequency domain is the best quality measure we have so far. When using cross correlation as a measure always keep in mind to check to quality for both domains since they both have their flaws.

The analysis on shot data gaps tells us that there is only a little effect on the final processed image, as long as sufficient replacement shots have been taken to reach a similar high CDP fold. Because when the fold is still high, enough information is generated about the structures below the shot gap and sufficient traces are collected to suppress random noise in a similar manner as without shot data gaps. In this way only the offset distribution of traces in the CDP gather is limited because near offsets are lacking. From our analysis it seems that the data at most a few hundred ms below the shot gaps are affected. Please do make as little shot gaps as possible to still obtain the best possible quality. But if there is no way around, it is not a big problem to skip a few shots as long as replacement shots are taken, according to our analysis. Also try to lay geophones over the shot gap area when that is possible. Even if a cross line offset is needed, it will help in obtaining a better image below the shot gap.

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