NGU REPORT 2020.038

GPR survey at Arildsløkka, Trondheim for the detection of historical reinforcement structures along the Nidelva riverbank

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REPORT

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Title:
GPR survey at Arildsløkka, Trondheim for the detection of historical reinforcement structures along the Nidelva riverbank

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Summary:
The Norwegian Water Resources and Energy Directorate (NVE) is investigating measures to prevent landslides at Arildsløkka, Trondheim city center. Historical evidence shows that the area was secured by timber boxes in the year 1730 however, it is unknown whether these structures are still intact or if they have been reduced to single rows of pillars which are visible today. According to technical reports, the river flow has deepened the riverbed outside of these pillars up to a depth of 10 meters, creating a risk for the historic reinforcement system. For NVE to be able to assess the possibilities for carrying out modern reinforcement construction operations in the area, information is needed about the status of the old safety system.

To indirectly detect the support structure in the vicinity of the timber boxes, NGU has performed two GPR surveys in the area, one in November 2019 and a more detailed second one in May 2020. The goal of these surveys was to resolve the status of these historical reinforcement structures either directly e.g. by detecting wooden pillars or timber boxes or indirectly e.g. by investigating the sedimentary geological layers of the study area. The first survey was conducted as close to the timber boxes as possible with one GPR-line running along the northern Nidelva riverbank and the second at the only open space available south of Ila church, on a small green area in steep terrain.

Data processing has revealed two distinct dielectric regimes west and east of the Nidareid bridge, where the overall penetration in the former is larger than the latter. Plotting the results against a historical map from 1772, we were able to identify a clear coherence between higher penetration and brackets of anchoring on the riverbank but also areas of reduced penetration depths that could indicate weakening in the reinforcement structures. We were also able to follow a gravel/sand trough that possibly frames the old Skansen fortress that used to exist in the area and a high density of buried objects that if correlated linearly, they could indicate buried timber but also modern pipes.

Overall, we were able to detect possible horizontal pillars of the historical anchoring system in the study area and to infer possible geological changes that could be linked to manmade structures by using GPR penetration depth as an evaluation criterion.

Keywords:	Geophysics	Georadar
Sediments	Archaeology	Stability
Reinforcement Structures	Trondheim	

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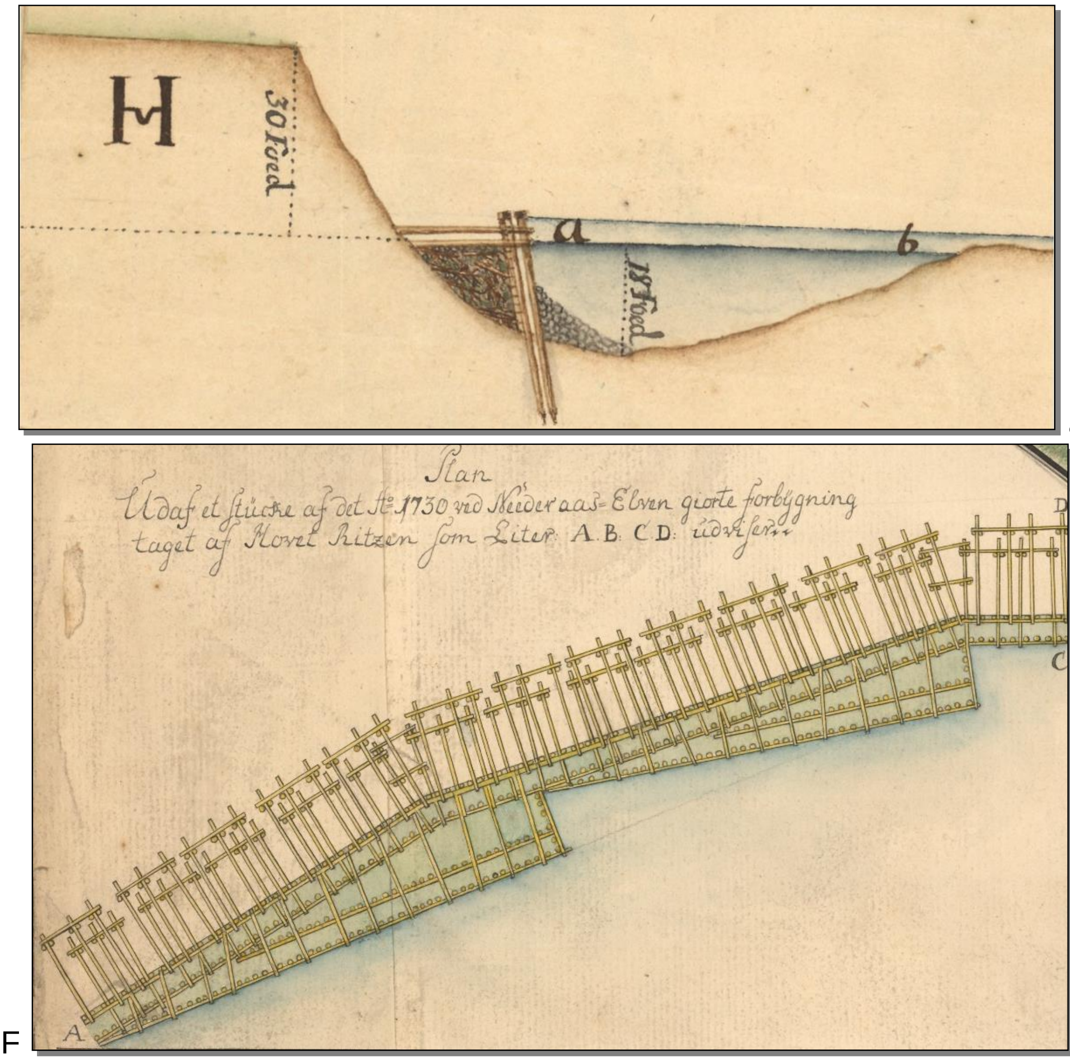
1. INTRODUCTION

The Norwegian Water Resources and Energy Directorate (NVE) is investigating measures to prevent landslides at Arildsløkka, Trondheim, the area south of Ila church by the Nidelva river. Historical evidence shows that the area was secured by timber boxes in the year 1730 (perhaps the oldest type of security measures known in Norway) however, it is unknown whether these structures are still intact or if they have been reduced to rows of pillars visible today. According to a technical report by Sweco Grøner (Trondheim Byteknikk, 2007), the river flow has deepened the riverbed outside of these pillars up to a depth of 10 meters, creating a risk for the historic reinforcement system. For NVE to be able to assess the possibilities for carrying out modern reinforcement construction operations in the area, information is needed about the status of the old safety system. **Figure 1.1** shows the old timber box structure: vertical piles were embedded in the riverbed and supported by boulders while horizontal pillars were anchored in the slope, creating boxes which were filled with varied materials. However, with modern reinforcement construction work, it is not known what load is tolerated with respect to the weight of machinery, whether it is possible to dig behind the boxes during the construction operation, etc.



a)

F b)

Figure 1.1*: Cross section (a) and plan view (b) of the reinforcement timber boxes at Arildsløkka from 1730 (details from historical map - Kartverket, 1772).*

To indirectly detect the support structure in the vicinity of the timber boxes, NGU has performed two GPR surveys in the area, one in November 2019 and a more detailed second one in May 2020. The goal of these surveys was to investigate the geological layers and thus extract possible information on the status of the historical reinforcement structures. The survey area is located at Arildsløkka in the heart of the city of Trondheim, an area of high ambient noise in relation with infrastructure (power cables in the ground, train tunnel running close by, etc.) and limited access due to buildings and fences. Therefore, the first survey was conducted as close to the boxes as possible with one GPR-line running along the northern Nidelva riverbank and the second at the only open space available south of Ila church, on a small green area in steep terrain.

2. METHOD

Ground Penetrating Radar (GPR) or Georadar, as it is also commonly named, is an electromagnetic geophysical technique which can be used to investigate stratification in the underground. It uses electromagnetic fields to probe lossy dielectric materials to detect structures and changes in material properties within the materials (Davis & Annan, 1989). With GPR, the electromagnetic fields propagate as essentially nondispersive waves. The signal emitted travels through the material, is scattered and/or reflected by changes in impedance, giving rise to events which appear similar to the emitted signal (Butler, 2005). These reflected signals are registered at the surface and utilized to reconstruct interfaces in the ground. This is achieved by the compilation images where 1D electromagnetic "soundings" are positioned consecutively to create a uniform 2D image (radargram).

In lossy dielectric materials, electromagnetic fields can only penetrate to a limited depth before being absorbed. Hence, exploration depth is always a variable. However, the frequency range where GPR functions is between 1 and 1000 MHz, and the choice of frequency also controls the projected depth of an investigation. In lower frequencies, the pulses are easily dispersed while at higher frequencies the signal absorption becomes too strong and the penetration depth extremely limited. GPR studies are therefore planned with a frequency choice that compromises penetration depth (lower frequencies) with desired signal resolution (higher frequencies) in relation to the survey goals.

3. DATA COLLECTION

The first stage of the survey consisted of a 427-meter-long GPR profile along the northern Nidelva riverbank shared in two parts: one west (profile AR100-00W) and one east (profile AR100-00E) of Nidareid bridge. The purpose of these profiles was to investigate the geology as close to the timber boxes supporting the slope as possible, essentially a very narrow corridor on the Nidelva riverbank. Positioning for the locations of these boxes and other pillars in the study area is provided by a historical map (Kartverket, 1772). **Figure 3.1** presents the location of the profiles measured in the first survey, plotted on the historical map from 1772 (top) and on a recent orthophoto of the study area. In order to highlight the historic reinforcement structures (timber boxes, anchoring areas, pillar rows) in relation with the GPR survey, their positions were digitized and plotted as rectangles on both maps in **figure 3.1**.

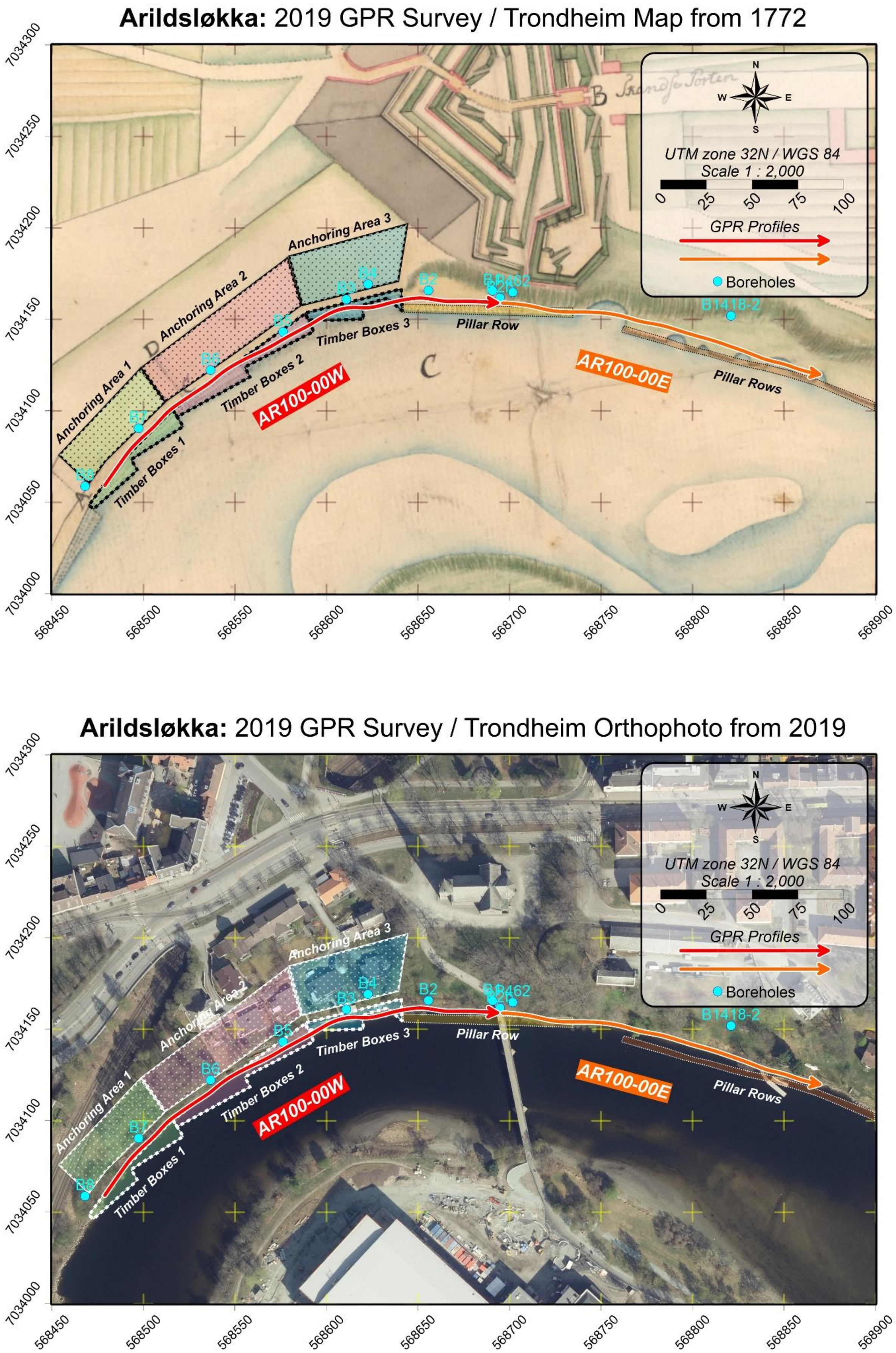


Figure 3.1: Positioning for GPR profiles collected at Arildsløkka in November 2019 plotted on historical map (Kartverket, 1772) and contemporary orthophoto of Trondheim (Norge i bilder, 2019) with available boreholes (NADAG, 2020).

The survey was conducted on highly unstable boulders and/or dense vegetation (**figure 3.2)**. Fieldwork was carried out on the 21st and 22nd November 2019 in cold and arid conditions which are ideal for GPR investigations. The 100 MHz antenna frequency was selected according to the dimensions of the assumed structures (5 meters). Due to the difficult terrain conditions the *step-mode* measuring mode was applied where the antennas were mounted on a specially designed frame (**figures 3.3** and **3.4**). Traces were gathered every 0.5 m on a measuring tape spread along the route of the profile while positioning was logged independently with a Garmin GPSMAX 60Cx handheld GPS. Positioning was also aided by landmarks in the area such as housing, fences, cables, etc. The system employed was PulseEKKO PRO and since measurements were logged manually, a special feature of the Sensors & Software Ultra Receiver™ was used which allowed the sampling 8,192 stacks in about three seconds per trace for the 100 MHz antenna and a time window of 1000 ns. Thus, we collected very robust data with higher penetration than standard GPR surveys.

Figure 3.2: *Photos from the first GPR survey at Arildsløkka in November 2019.*

The second stage of the survey was decided to be carried out with higher resolution and possible 3D coverage at a selected site in the survey area. This site was a small green area just below Ila church next to Nidareid bridge (**figure 3.3**) where time availability limited us to a 2.5D GPR. The slope was therefore scanned with several parallel profiles using primarily 200 MHz and filling the gaps in between with 100 MHz antenna measurements. 200 MHz allows for very detailed surveying that does not reach as deep as 100 MHz but produces data of superior detail. In total, nine profiles of various lengths were collected with the 200 MHz system (AR200-01 to AR200-09, **figure 3.4**), covering a total of 213 meters with trace interval equal to 0.10 m (2139 traces). Each trace was measured using 16,384 stacks (repetitions) to achieve the best data quality and depth penetration, and the measuring time for the utilized antenna frequency and the 400 ns time window was two seconds.

Figure 3.3: *Photos from the second GPR survey at Arildsløkka in May 2020.*

After the completion of this set of measurements, the gaps between the 200 MHz profiles were filled with 100 MHz lines which sampled traces every 0.25 m and thus required less time to conclude. Again, nine profiles were measured, eight in the gaps between the 200 MHz lines (AR100-01 to AR100-08) and a 9th along the same line as profile AR200-01, called profile AR100-01a. A total of 224 meters were measured (2249 traces) using again 16,384 stacks but this time with a lower time window than in the first survey stage (700 ns) in order to keep the measuring time per trace near three seconds. Fieldwork was concluded in four days i.e. the 25th, 26th, 28th and 29th of May 2020 and an area of about 620 square meters was covered. In total, the GPR survey at Arildsløkka consists of 864 meters of manually measured linear profiles. The GPR data was compared with data from geotechnical boreholes, available from the National Database of Ground Investigations (NADAG, 2020).

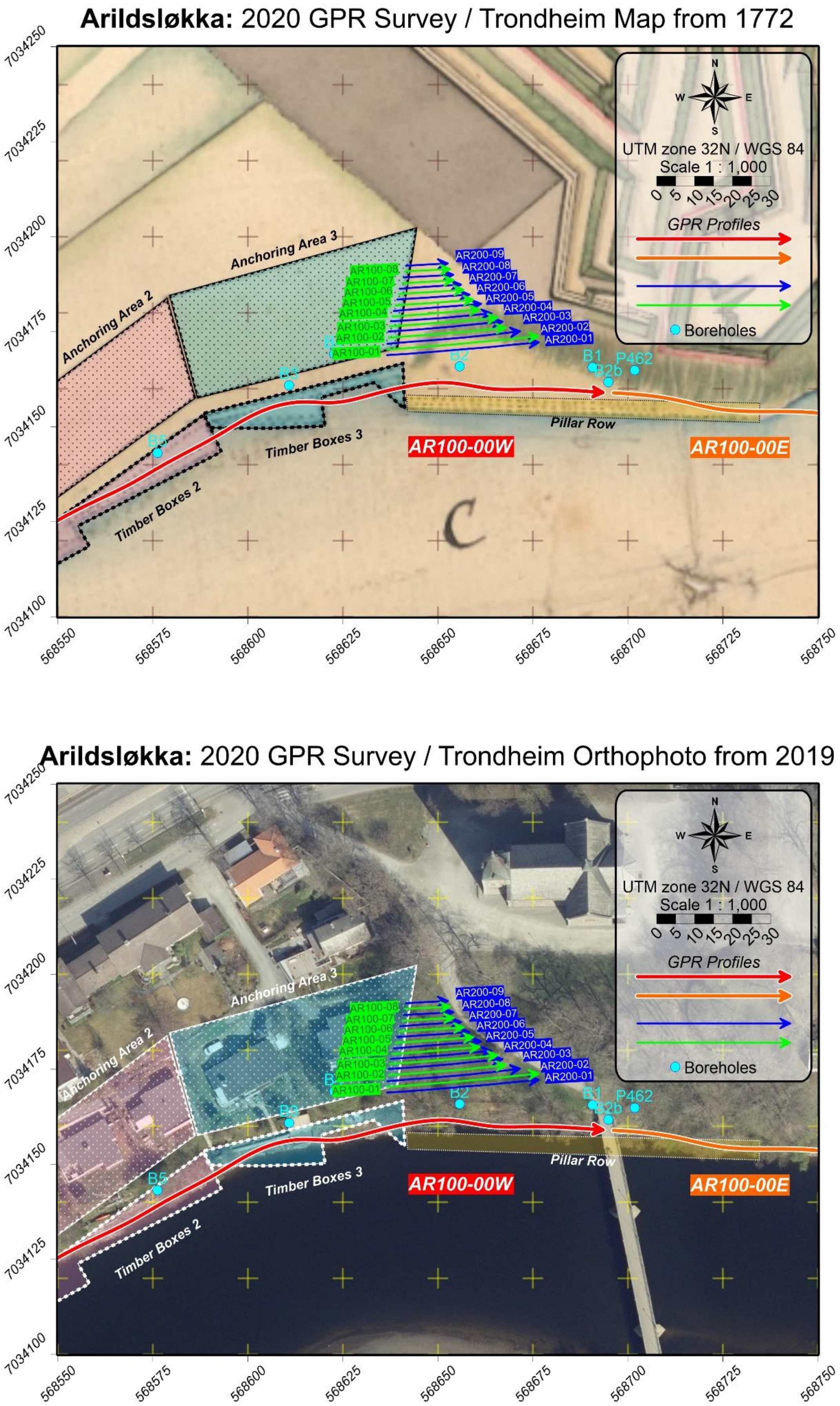


__Figure 3.4:__ Positioning for GPR profiles collected at Arildsløkka in May 2020 plotted on historical map (Kartverket, 1772) and contemporary orthophoto of Trondheim (Norge i bilder, 2019) with available boreholes (NADAG, 2020).

4. DATA HANDLING / PROCESSING

Preprocessing of GPR data requires refining of positioning and sampling elevation from available Digital Terrain Models (DTM). In the case of Arildsløkka, positioning was logged with a handheld GPS which has a 3-meter error margin. However, the variety of landmarks in the survey area and the availability of high resolution orthophotos allowed us to position the profiles using indirect ways e.g. distance from roads or buildings, crossing points at fences, etc. After optimal positioning was assigned to every trace, elevation values were sampled from the Mapping Authority's 5pkt 2017 DTM (0.25 m resolution) in Trondheim for the profiles to be processed and plotted with true distance and topography. Positioning for each profile is shown in **tables I** (first survey – 100 MHz), **II** (second survey – 200 MHz) and **III** (second survey – 100 MHz).

Profile Name	X (in meters)	Y (in meters)	Length (in meters)
AR100-00W	568693,4	7034159,0	0
”	568595,4	7034149,7	49,3
”	568510,8	7034096,9	149,0
”	568478,9	7034059,3	247,5
AR100-00E	568696,2	7034158,9	0
”	568770,4	7034149,1	74,8
”	568842,0	7034127,5	149,7
”	568869,5	7034120,0	178,1

Table I: *X and Y coordinates for profiles measured along Nidelva with the 100 MHz antenna (in UTM zone 32N / WGS 84).*

Profile Name	X (in meters)	Y (in meters)	Length (in meters)
AR200-01	568636,6	7034168,9	0
”	568676,5	7034172,2	40
AR200-02	568636,7	7034171,8	0
”	568671,6	7034175,1	35
AR200-03	568637,1	7034175,1	0
”	568667	7034177,6	30
AR200-04	568637,6	7034177,7	0
”	568664,1	7034179,8	26,5
AR200-05	568638,4	7034180,5	0
”	568661,4	7034182,4	23
AR200-06	568639,3	7034183,5	0
”	568658,3	7034184,8	19
AR200-07	568640,1	7034186,3	0
”	568656,1	7034187,4	16
AR200-08	568641	7034189,3	0
”	568654	7034190	13
AR-200-09	568641,6	7034192,4	0
”	568652,6	7034193	11

Table II: *X and Y coordinates for profiles measured next to Nidareid bridge with the 200 MHz antenna (in UTM zone 32N / WGS 84).*

Profile Name	X (in meters)	Y (in meters)	Length (in meters)
AR100-01a	568636,6	7034168,9	0
”	568676,5	7034172,2	40
AR100-01	568636,6	7034170,3	0
”	568676,5	7034173,8	40
AR100-02	568637	7034173,4	0
”	568667,9	7034176,1	31
AR100-03	568637,3	7034176,4	0
”	568665,7	7034178,7	28
AR100-04	568638	7034179	0
”	568660,9	7034180,8	23
AR100-05	568638,9	7034181,9	0
”	568659,3	7034183,4	20,5
AR100-06	568639,8	7034184,9	0
”	568656,8	7034186	17
AR100-07	568640,7	7034187,7	0
”	568654,2	7034188,6	13,5
AR100-08	568641,3	7034190,9	0
”	568653,2	7034191,5	12

Table III: *X and Y coordinates for profiles measured next to Nidareid bridge with the 100 MHz antenna (in UTM zone 32N / WGS 84).*

All collected data were processed with the use of the software package EKKO_Project v.5. The data collected on the first survey (profiles AR100-00W and AR100-00E) required tailoring due to problems related to the unfriendly terrain such as bad signal due to poor ground coupling, damaged cables due to vegetation, shifted polarity between fragments of the profile, lost signal due external noise such as buried power cables, gaps in the data due to manmade structures such as piers or walls. The processing routine utilized a straightforward approach, and all steps are presented in **table IV**. It should be noted that the employed velocity (0.083 m/ns) was not calculated by performing CMP (Common Mid Point) method but from hyperbolas formed in the second survey by sewage and piping in the ground.

Processing module	***Value / Description***
Bandpass Filter 100 MHz	*Fc1 30 % / Fp1 60 % / Fp2 130 % / Fc2 170 %*
FK Migration / Depth Conversion	*Velocity 0.083 m/ns*
Dewow	*Window Width (Pulse Widths): 1.33*
Background Subtraction	*Filter Width: 20 m (rectangular)*
1st Survey SEC2 Gain (100 MHz)	*Attenuation 1.1 dB/m, Start Gain 0.4, Maximum Gain 800*
2nd Survey SEC2 Gain (200 MHz)	*Attenuation 1.7 – 2.1 dB/m, Start Gain 0.6 – 0.7, Maximum Gain 1600*
2nd Survey SEC2 Gain (100 MHz)	*Attenuation 1.3 – 1.35 dB/m, Start Gain 0.5 – 0.65, Maximum Gain 1600*

Table IV: *Processing modules employed in EKKO_Project v5.*

5. FIRST SURVEY RESULTS

5.1 Radargrams for AR100-00 West and East (100 MHz)

In this section, the processing results for profiles AR100-00W and AR100-00E are presented. **Figure 5.1** displays the resulting radargrams for both profiles along with borehole data close to the profiles and anchoring areas as delineated in the map from 1772 shown in **figure 3.1**. It also shows interpretations concerning prominent reflectors in the ground and overall penetration depth and shaded areas of increased ambient noise. The borehole data incorporated in these radargrams have been fitted to the elevation of the profiles, even though all of them are drilled north of the survey lines. However, most of these boreholes are within five meters of the actual GPR profiles – with only a few exceptions – and therefore can be used as ground truth to help interpreting our results. Accurate distancing and direction of the position for each borehole is given in **figure 5.1**.

The borehole data indicate that the dominant sediments in the survey area are gravel/sand of various grain size and this is very well reflected in our results by the high penetration depth achieved locally. The occasional presence of silt/clay in the area does not hinder the signal from penetrating deep in the ground west of Nidareid bridge (profile AR100-00W – **top figure 5.1**), but it does so east of the bridge where the penetration depth is substantially decreased (profile AR100-00E – **bottom figure 5.1**). Our results validate that the study area offers different penetration depths locally, according to the composition of the ground and marks two distinct dielectric regimes west and east of the Nidareid bridge.

The gravel/sand layers which are dominant west of our study area together with the high number of stacks we were able to utilize by collecting our data in step mode, enable the electromagnetic signal to penetrate as deep as 20 meters locally, which well exceeds the assumed dimensions of the timber boxes. We may distinguish three areas of increased penetration, namely from 0 to 30, 70 to 110 and 200 to 240 meters distance. The reflectors revealed in profile AR100-00W are sub-horizontal in their majority which indicates naturally deposited sediments but also locally arcing downwards, portraying possible depressions in these layers. The most prominent of them represent changes in grain size in the ground and are shown in black dotted lines in **figure 5.1**. Penetration depth in this profile is almost continually high except for an area between 130 and 190 meters. According to the borehole data, there is no drastic geological change there, however, the GPR penetration depth shown in red dotted line in **figure 5.1** is drastically decreased (from 20 to 10 meters). Reflectors can still be seen in depth, but they are very weak compared to their neighboring ones and this can be linked to water saturation.

The eastern side of our study area surveyed by profile AR100-00E shows the opposite dielectric regime than the western one i.e. presents limited penetration depth (red dotted line) as easily seen in **figure 5.1**. Generally, it remains below 10 meters with this value only achieved locally at 0 to 10 and 60 to 70 meters distance. Typically, depth coverage is closer to 5 meters which is indicative of higher clay/silt content, also verified by the limited borehole data. Respectively, less prominent reflectors are marked in this profile with black dotted lines.

Despite the very good data quality and sufficient penetration depth for the predominant parts of the profiles, the data shows no direct indication for the existence of any wooden construction even though GPR data of such resolution should have responded to such infrastructure. However, assuming the ancient reinforcement were equal or similar to what is presented in figure 1.1a and b, one must assume that the timber boxes are not in existence any longer but the second or even third row of pillars is what is exposed today along the riverbank.

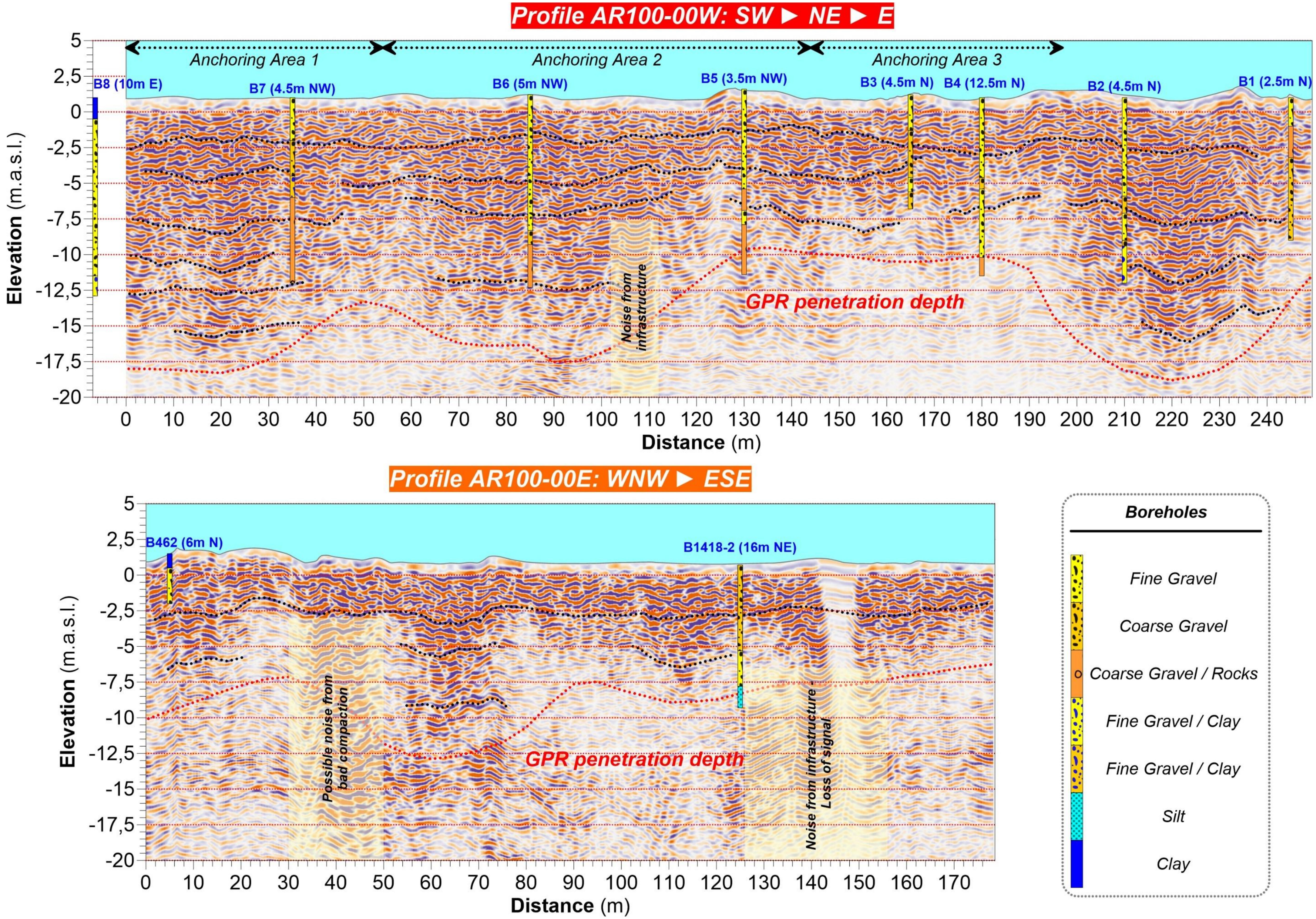


Figure 5.1: *Processed radargram for profiles AR100-00W & AR100-00E with interpretations (red dotted line: GPR penetration depth, black dotted lines: prominent reflectors). Boreholes B1-B8 are from TK (1898), B462 is from TK (1986) and B1418-2 is from TK (2008). Borehole reports are available from NADAG (2020). Anchoring areas in AR100-00W are referring to the inferred construction, shown in figures 1.1b and 3.1.*

5.2 Interpretation for AR100-00 West and East (100 MHz)

To better understand the proposed interpretation in 5.1, the results of the survey were plotted on a historical map of Trondheim city center from 1772 i.e. about 40 years after the construction of these reinforcement structures. **Figure 5.2** displays a simplified point cloud of the achieved GPR penetration depth plotted on top of the georeferenced historical map of Arildsløkka from 1772 (top) and a recent orthophoto of Trondheim city center (bottom). A standard rainbow color scale was employed to display the change in penetration depth with cold colors indicating lower and warm colors higher penetration depth.

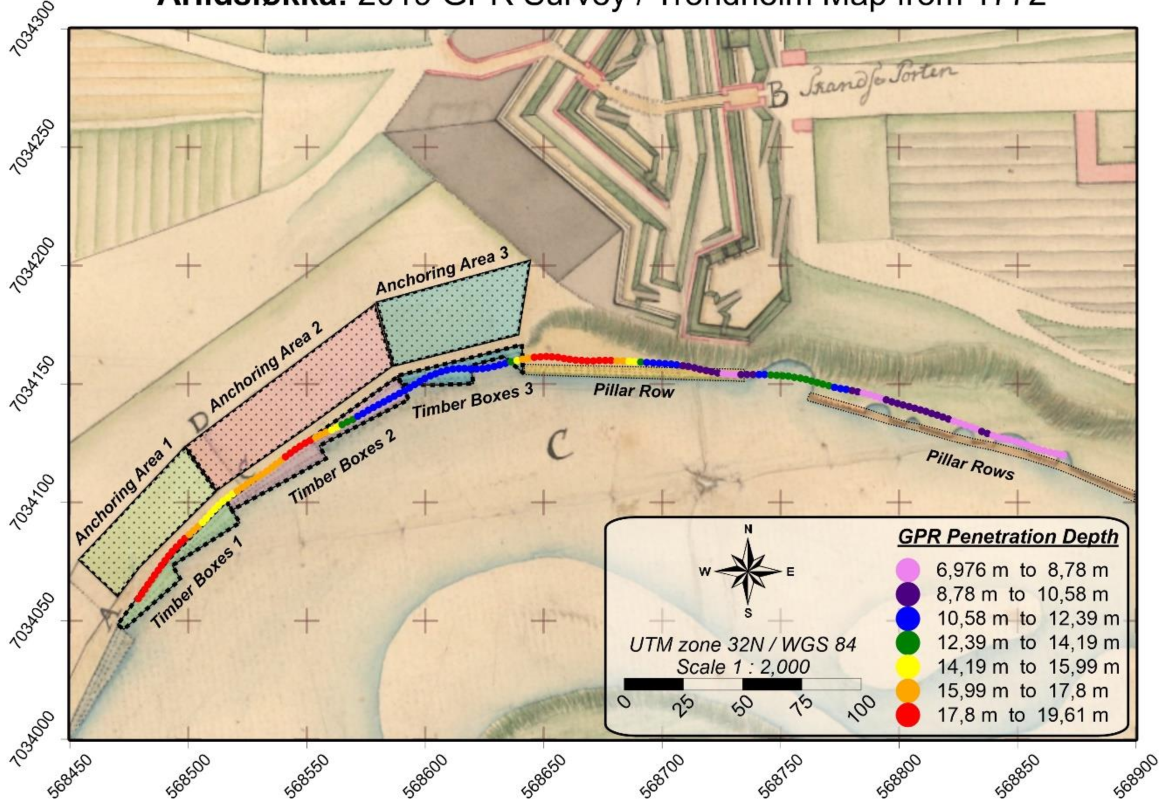
The historical map displays the Skansen fortress that used to control the western entrance to the city, now replaced by Ila church, while the timber boxes are depicted by jagged rectangles covering the western part of the Nidelva riverbank. The rectangles above them indicate the extent of timber anchoring in the slope while more pillar rows are depicted east of Nidareid bridge, without being accompanied by timber boxes.

Using this plan view, it is easy to discern the different penetration depth west and east of Nidareid bridge but also note the correlation between the rectangles in the map showing the timber boxes and anchoring areas, and deeper depth penetration. Thus, timber boxes areas 1 and 2 are described by a higher depth penetration at their center which is decreasing towards its edges (more prominent in timber boxes area 2). The same pattern is also observed just south of old Skansen fortress i.e. nowadays Ila church which could be linked to underground remains of the fortress. By revisiting **figure 5.1** we can observe that downward arcing reflectors indicating depressions in the gravel/sand layering are matching the center of the anchored areas in all cases.

However, even though timber boxes area 3 follows the above described pattern, it is not characterized by deep signal penetration but by a uniform lower coverage which is roughly half compared to the one observed at the other boxes (between 10,5 and 12,5 meters). This is indicative of a possible weakening in the structure due to pressure added from the housing just above this area (**bottom figure 5.2**). The same applies for the eastern edge of timber boxes area 2, with penetration depth regaining its maximum values again as soon as the housing stops.

As mentioned in the previous section, penetration depth throughout the area east of Nidareid bridge is steadily low, apart from a patch where penetration depth is roughly between 12,5 and 14,5 meters and is shown in green color at the bottom map in **figure 5.2**. Whether this is an indication of a timber box similar to the ones in the west or not remains unclear. In any case, if timber boxes are present in this side of the riverbank, they do not offer the same depth penetration either due to clay/silt or due to weakening resembling timber boxes area 3. An interesting area of low penetration/ steep topography may be seen exactly right of the Nidareid bridge, below the remains of an old bastion which is still visible in the modern orthophoto southeast of Ila church. This could also indicate another weakened system due to high load.

Arildsløkka: 2019 GPR Survey / Trondheim Map from 1772



Arildsløkka: 2019 GPR Survey / Trondheim Orthophoto from 2019

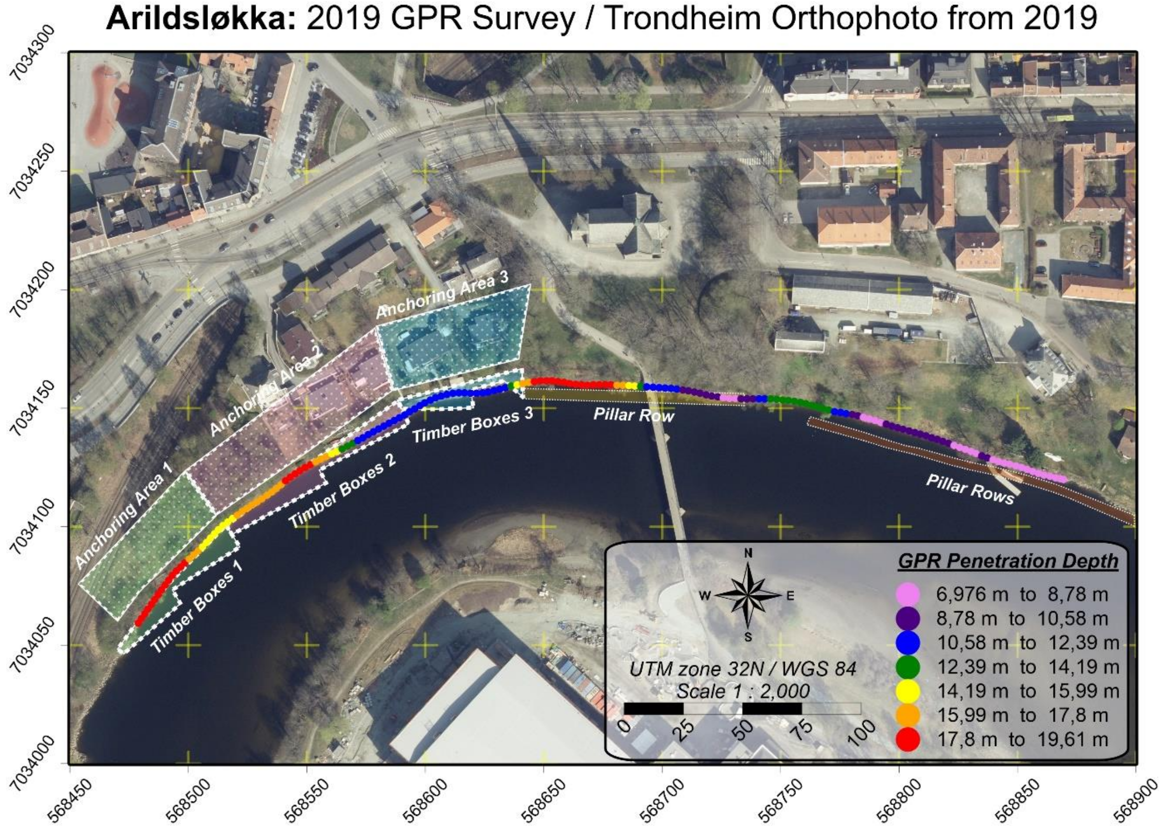


Figure 5.2: *GPR Depth penetration point cloud for profiles AR100-00W & E plotted on a historical map (top - Kartverket, 1772) and a recent orthophoto of Trondheim (bottom – Norge i Bilder, 2019). Gridded rectangles refer to digitized positions for timber boxes, anchoring areas, and pillar rows.*

6. SECOND SURVEY RESULTS

6.1 Radargrams for AR100-01 to AR100-08 (100 MHz)

The processing results for profiles AR100-01 to AR100-08 are presented in this section. **Figure 6.1** displays the resulting radargrams for all profiles scanning from south to north (profiles positioned about 3 meters apart), along with borehole data close to the profiles as well as interpretations concerning prominent reflectors in the ground and the overall penetration depth. The borehole data incorporated in these radargrams have been fitted to the elevation of the profiles, while accurate distancing and direction of the position for each borehole is given in **figure 6.1**. As seen in **figure 2.3**, all profiles are limited to the west by a house fence, while their eastern end roughly matches the pedestrian path leading down to Nidareid bridge from Ila church. Therefore, profile lengths are decreasing as we move uphill.

There are few boreholes in this area, but the borehole profiles available also indicate gravel/sand of various grain size, which again allows us to achieve high penetration depth for utilizing 100 MHz antennas. The southernmost profiles measured are the longest (AR100-01 and AR100-01a) and they yield results which are comparable to what is seen in the area between 190 and 240 meters of profile AR100-00W, which is located about 8.5 meters south of the profile AR100-01. Specifically, we attain maximum penetration depth of about 18 meters in the middle of these profiles while coverage decreases towards the profiles' edges. Unfortunately, the house fence here did not allow the extension of the profiles to the west in order to uncover the entire deep penetration basin morphology. In addition to that, the shortening profiles towards the north, cover less and less of the aforementioned formation, with the last profile AR100-08 only covering the eastern half of it.

Black dotted lines in **figure 6.1** show again prominent reflectors which appear to be sub horizontal where the penetration is deeper and can be linked to grain size changes within the naturally deposited gravel/sand sediments. However, on the eastern edge of the study area, these reflectors are tilted upwards before the GPR signal penetration is lost. This possibly frames an outlet channel of the river towards the fjord which was infilled with sand and gravel and appears to be naturally formed or a small marine underwater backsliding that was subsequently refilled. We may assume that the same pattern is repeated on the western side of this gravel/sand patch, but its true shape and form could not be investigated due to dense housing in the area. The red dotted lines in **figure 6.1** display the penetration depth achieved in approximation and since this is a 2.5D study, it can be used to identify the orientation of this dielectrically permeable channel.

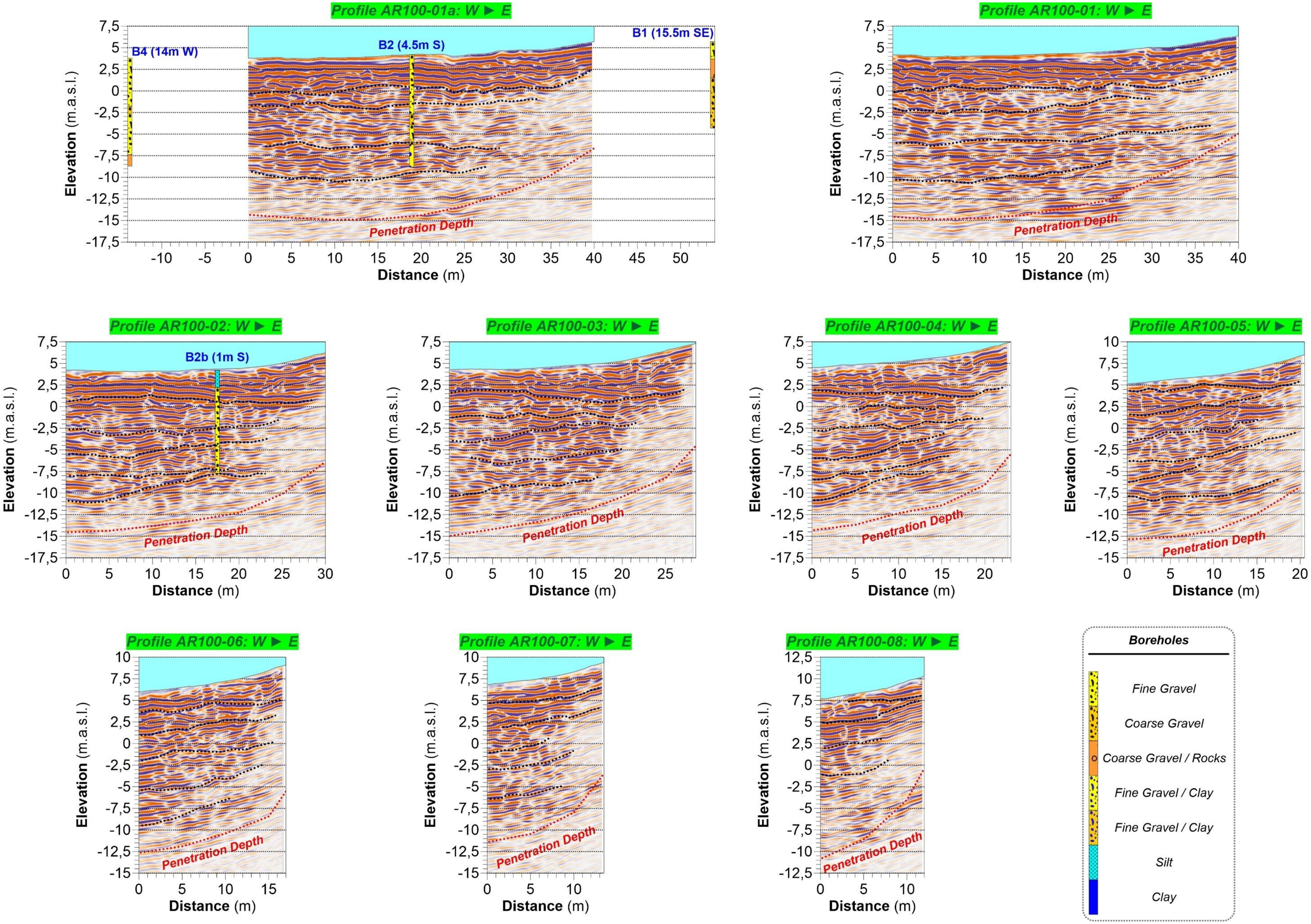


Figure 6.1: *Processed radargram for profiles AR100-01 until AR100-08 presented from south to north with interpretations (red dotted line: GPR Depth Penetration, black dotted lines: prominent reflectors). Boreholes B1, B2 and B4 are from TK (1898) and B2b is from TK (2001). Borehole reports are available from NADAG (2020).*

6.2 Radargrams for AR200-01 to AR200-09 (200 MHz)

Figure 6.2 presents the processing and interpretation results for profiles AR200-01 to 09 in the same mode as in **figure 6.1**. Radargrams are arrayed as they were measured from south to north, neighboring boreholes are fitted/plotted to the elevation of the GPR profiles while interpretations include prominent reflectors since the use of 200 MHz frequency antennas cannot reach the same depth penetration as 100 MHz antennas and therefore it is not comparable to our previous results. As seen in **figure 3.4**, all AR200 profiles are parallel at a median distance of roughly 3 meters, filling the space between the AR100 profiles at an average distance of 1.5 meters. As in the case of the AR100 profiles, the AR200 profiles are limited by the house fence to the west and the pedestrian path to the east, resulting in a decreasing line length towards the north.

Hyperbolas shown in dotted blue lines in **figure 6.2** indicate objects in the ground shown in light green circles. Their presence helped us define the propagation velocity for the electromagnetic signal in the ground by fitting to theoretical curves and led to the 0.083 m/ns value used in our processing. Additionally, such hyperbolas are artificial effects originating from buried objects that are intersected perpendicularly by our profiles. And it is possible that they are caused by elongated bodies such as pipes or even tree logs in this context (minimum detectable object dimensions by 200 MHz antennas is 17 cm). It must be noted that radargrams displayed in **figure 6.2** show the migrated signal e.g. *all hyperbolas are collapsed to points shown in light green circles* and blue dotted lines originate from unmigrated data. Finally, hyperbolas are preferably presented only for this frequency due to its higher resolution.

The use of a 200 MHz frequency which is twice as high as the one utilized in the rest of the survey, results to a limited penetration depth compared to the ~20 meters achieved there. However, the level of details in the reflectors detected is twice as high and that can be seen in **figure 6.2**. Maximum penetration depth here is somewhere between 10 and 11 meters which is unexpectedly high for 200 MHz antennas and is due to the 16,000 stacks used per trace collected and the gravel/sand environment which is characterized by low dielectric values.

Moreover, higher resolution offered using 200 MHz antennas enables the picking of more detailed prominent reflectors which are shown in black dotted lines in **figure 6.2**. Their majority is still sub-horizontal, but some additional morphological features can be extracted, based on the higher level of detail. Profiles AR200-01 to 04 present a series of strong reflectors above sea level which appear to be arcing upwards, especially in profiles AR200-02 to 04. Then, reflectors are flattened in depth until about 4 to 5 meters below sea level where they obtain a downward arcing form. However, after profile AR200-05 and until profile AR200-09, layering appears less disturbed before we mark the upward tilting towards the pedestrian path also seen in 100 MHz profiling, which again frames a gravel/sand trough of high penetration.

The 200 MHz antenna measurements validate that the formations surveyed are naturally deposited sediments, due to the detectable layering. Human intervention is therefore probably limited for this specific area, but there are several hyperbolas that indicate buried objects. Their spatial correlation is therefore examined in one of the following sections. The reason for loss of signal towards the pedestrian path cannot be discerned with certainty.

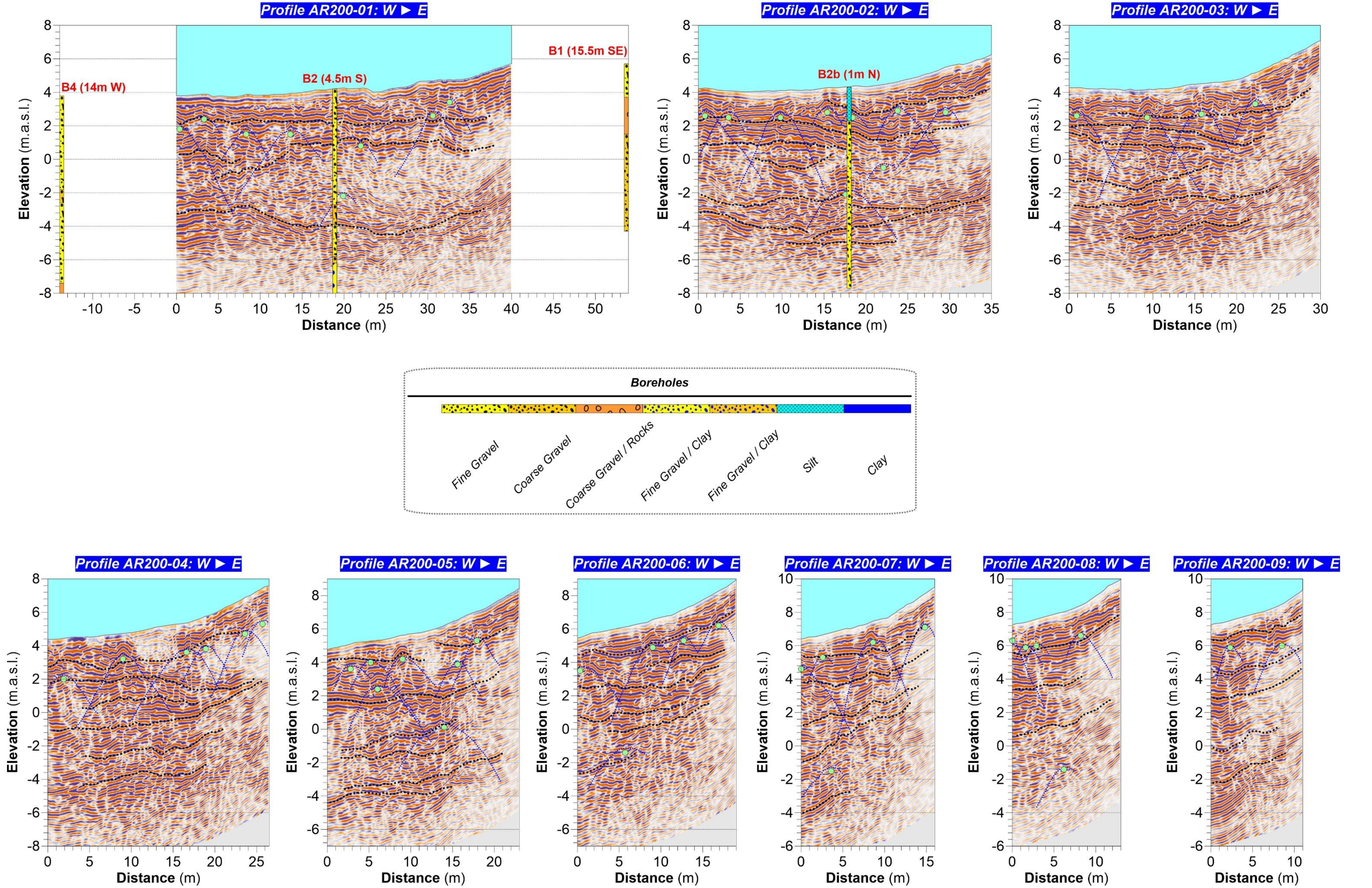


Figure 6.2: *Processed radargram for profiles AR200-01 until AR200-09 presented from south to north with interpretations (black dotted lines: prominent reflectors, blue dotted lines: hyperbolas, light green circles: buried objects). Boreholes B1, B2 and B4 are from TK (1898) and B2b is from TK (2001). Borehole reports are available from NADAG (2020).*

6.3 Interpretation for all AR100 and AR200 profiles (100 & 200 MHz)

The results obtained during the second survey with the use of 100 MHz are of course compatible with those from the first and therefore they were plotted against the same historical map of Trondheim city center from 1772. **Figure 6.3** displays the same point cloud shown in **figure 5.2** enriched with the penetration depths from the second survey, plotted on top of the georeferenced historical map of Arildsløkka from 1772 (top) and a recent orthophoto of Trondheim city center (bottom). The color scale employed is identical as before, describing low penetration with cold and high penetration with warm colors.

The plan view shown in **figure 6.3** reveals the north-westward continuation of the deep penetration trough detected next to the river. This trough is framed by black (top) and white (bottom) dotted lines and is unfortunately disrupted by the housing seen in the current orthophoto of Trondheim. However, plotting these results on top of the 1772 map of the city, shows that the limit of this high penetration gravel/sand patch matches the limit of the shaded perimeter of the old Skansen fortress which could have operated as a moat. According to archaeological records, the moat was backfilled with sand and debris from the earthworks at Skansen (Bratberg, 1996), which could in part explain the loss of GPR signal to the east of the study area if clay materials were also utilized.

When it comes to the western end, we were not in position to investigate the continuation of the lowered penetration depth seen along the river or how the high penetration channel is directed towards the north. Regardless, it is logical to assume that the area framed by a rectangle in the historical map lying north of timber boxes area 3, would possibly allow limited depth penetration at least close to the riverbank. Whether this low penetration section would have a similar northwest orientation or not is unknown.

Figure 6.4 presents the spatial distribution of all detected objects in the ground, as they were interpreted and extracted from the higher resolution 200 MHz results. Again, a point cloud presentation is utilized where these objects are divided in three groups according to the depth that they appear to be buried at: deeper objects are shown in black, shallower in orange and everything in between in white. Most of these objects appear to be within the first 2 meters of soil and there is a linear correlation between them that could indicate buried pillars or large pipes. Cabling in the ground provided by Trondheim municipality does not appear to interfere with our interpretations and hyperbolas matching its course are probably not caused by it. However, no information on large pipes is available to us therefore it is possible that some of these hyperbolas could be linked to sewer outlets seen on the surface of the survey area.

Figure 6.4 also presents an attempt to link points that could possibly form straight lines and thus indicate buried logs from the old reinforcement structures. These interpretations are shown in dark (top) and pale (bottom) brown dotted lines and are preferentially chosen parallel to either anchoring area 3 or Skansen's old moat. The density of hyperbolas seen in our 200 MHz results indicates that if they can be assigned to timber logs, these can be found on the first 2-4 meters of soil while the sediment layers beneath that point are undisturbed. The fact also that such hyperbolas are consistently apparent in all measured profiles, could indicate that the timber logs are in relatively good condition and not worn away.

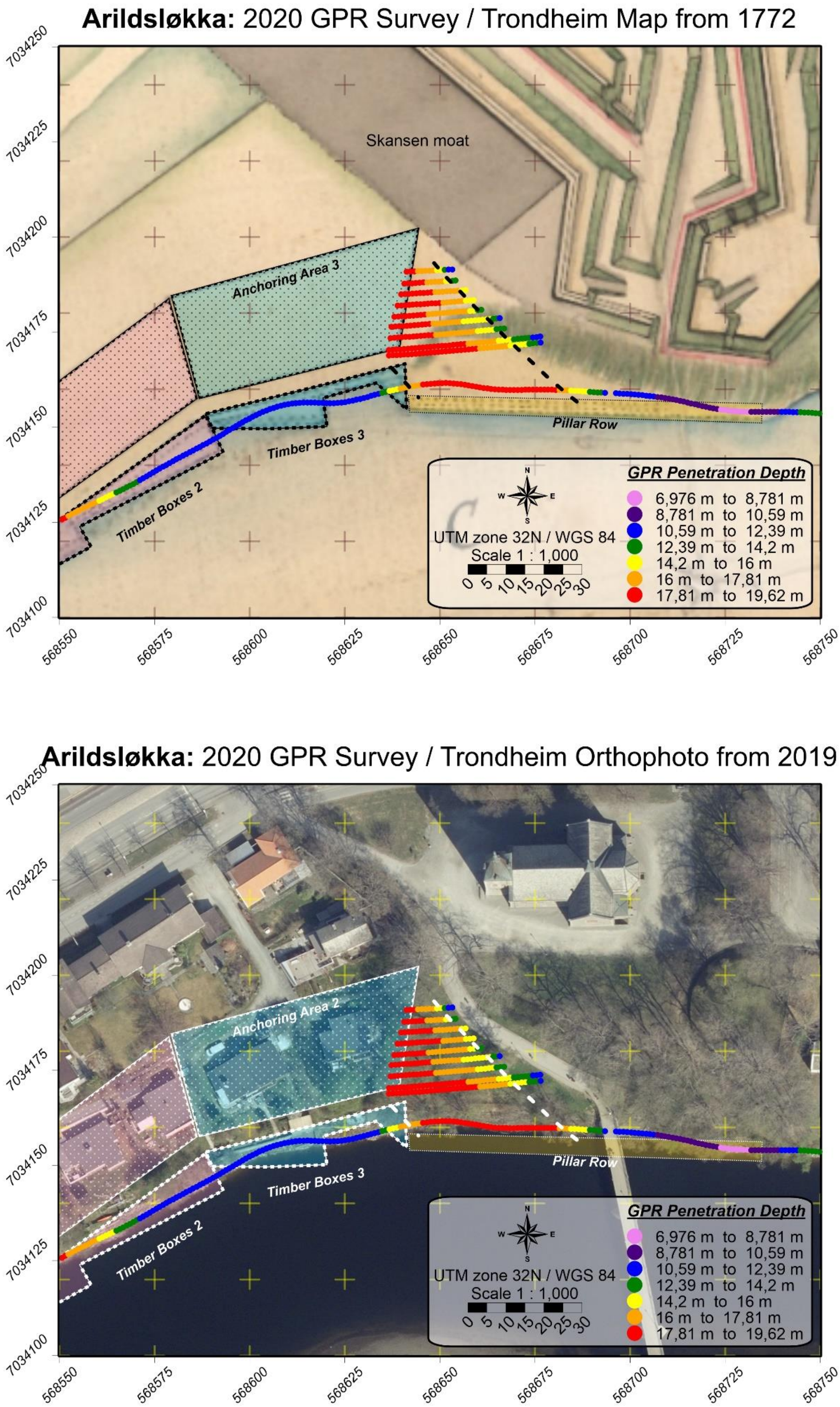


Figure 6.3: *GPR Depth penetration point cloud for all AR100 profiles plotted on a historical map (top - Kartverket, 1772) and a recent orthophoto of Trondheim (bottom – Norge i Bilder, 2019). Gridded rectangles refer to digitized positions for timber boxes, anchoring areas, and pillar rows.*

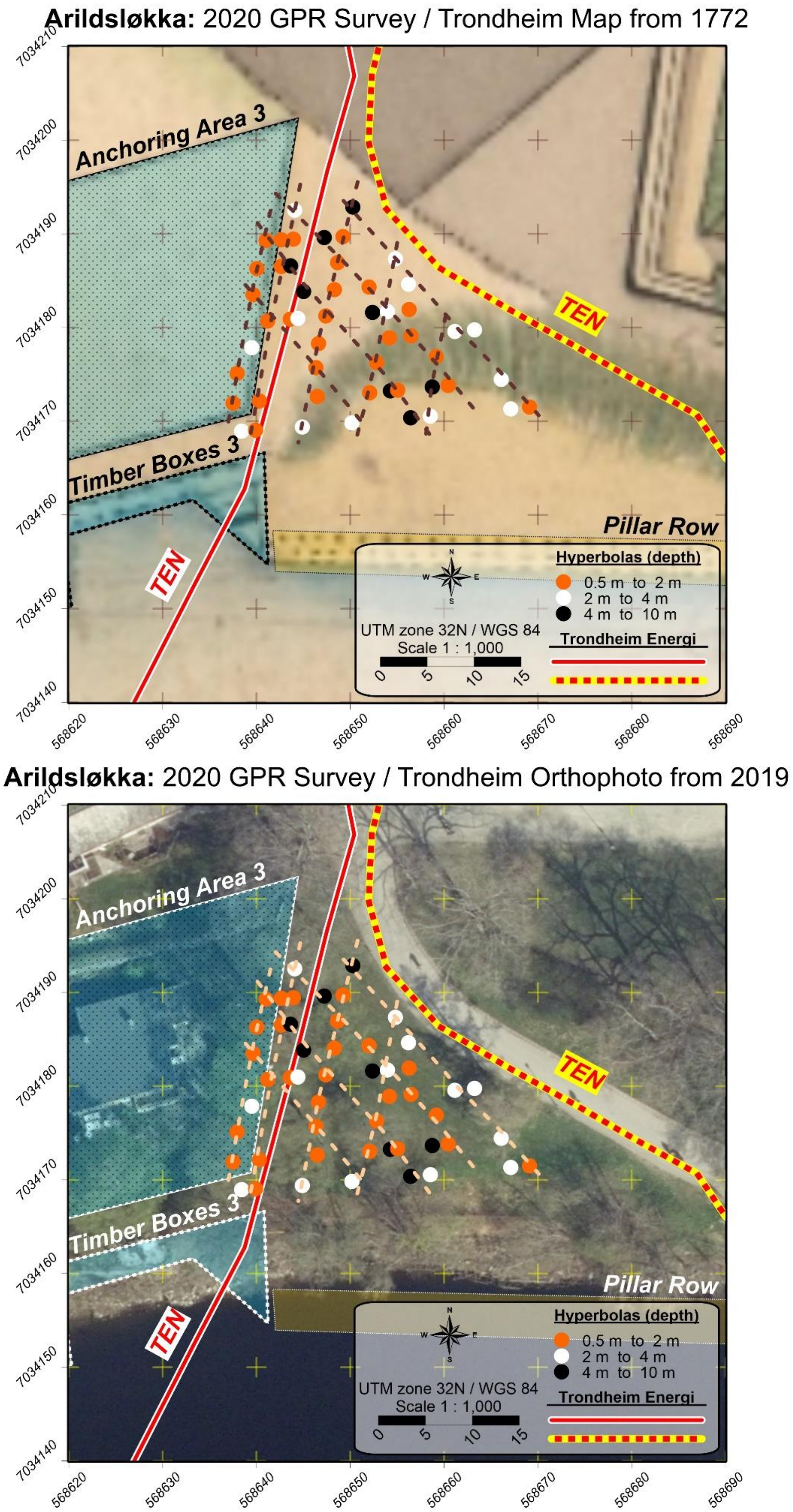


Figure 6.4: *GPR hyperbola positioning point cloud for all AR200 profiles plotted on a historical map (top - Kartverket, 1772) and a recent orthophoto of Trondheim (bottom – Norge i Bilder, 2019). Gridded rectangles refer to digitized positions for timber boxes, anchoring areas, and pillar rows.*

7. CONCLUSIONS

In conclusion, GPR application in this project has again proved the method to be low-cost, fast, and efficient. It has also been shown that it can yield useful information even in densely built urban environment, regardless of the various sources of noise at the Arildsløkka locality. The use of step mode for conducting the GPR measurements has allowed the usage of high stacking numbers for both frequencies, which combined with the favorable environment which according to boreholes is dominated by gravel/sand, led to generally very high penetration depths. By using 8,192 stacks for 100 MHz and 16,384 stacks for 200 MHz antennas, we were able to permeate 20 and 10 meters respectively into the ground and thus exceed the assumed dimensions of the timber boxes at Arildsløkka.

Processing of the data from the first survey has revealed areas of increased penetration within which reflectors appear to be sub-horizontal and probably represent changes in grain size of the gravel/sand sediments. Two distinct dielectric regimes west and east of the Nidareid bridge were unveiled, where the overall penetration in the former is larger than the latter. Focusing on the western part and plotting the results against a historical map from 1772, we were able to identify a clear coherence between higher penetration and brackets of anchoring on the riverbank just above the timber boxes. However, there is an area just west of Nidareid bridge were penetration is halved and this could possibly indicate weakened support in this locality which matches the modern housing in the area. Respectively, reflectors marked in the processed data continuously appear in depth. In the middle of anchoring areas as depicted in the historical map, some reflectors attain a down-arcing form, which is more prominent in depth, whereas penetration is decreased near their edges.

East of the Nidareid bridge, on the other hand, GPR surveying has in general shown limited penetration with only a few exceptions. Here borehole data indicate higher presence of clay/silt, which can partly justify this shift in penetration. Wooden pillars are still visible in the river nowadays, but according to the historical maps, no timber box support structures were made there. An area that requires attention, is found exactly east of the bridge, where penetration is diminished exactly below a bastion of the old Skansen fortress whose remains are still visible in the terrain today.

The second survey focused on an area just north of a high penetration basin right next to the Nidareid bridge. The high penetration pattern was validated by a 2.5D survey on both 100 and 200 MHz frequencies. Reflectors are again found to be sub-horizonal with more details to be observed in the 200 MHz profiles as expected. Plotting the penetration depth achieved in the second survey together with the results of the first, we were able to identify a northwest trending channel/trough. The penetration is lost next to the pedestrian path leading to the bridge from Ila church. Again, this result matches the structures shown in the historical map from 1772 well.

Altogether, we may deduce that all areas surveyed with GPR reveal reflectors that indicate naturally deposited sediments, especially on larger depths. An area just west of the Nidareid bridge with limited depth penetration may indicate a stability threat for the old reinforcement structure while the density of hyperbolas and subsequently of buried objects on both 100 and 200 MHz results of the second survey can be directly linked to the old anchoring system. Spatial correlation is obviously linear but an outlook of the sewer system in the area is a necessary action for modern structures to be excluded. Moreover, we were able to infer possible geological changes that could be linked to manmade structures by using GPR penetration depth as an evaluation criterion.

8. ACKNOWLEDGEMENTS

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