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Georadar measurements for Statens Vegvesen at Kistefoss - Kleggerud and Roa, Jevnaker and Lunner kommuner

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Title:
Georadar measurements for Statens Vegvesen at Kistefoss – Kleggerud and Roa, Jevnaker and Lunner kommuner.

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Summary:
In October 2015, the NGU conducted Georadar measurements in two locations: at Kistefoss – Kleggerud just south of Jevnaker in Jevnaker municipality and north of Roa in Lunner municipality, Oppland county. The survey is funded by the Norwegian Public Roads Administration (Statens vegvesen) and its purpose is to test the method's efficiency in supplementing the construction of new roads. More specifically, our main goal is to discover the maximum thickness of sediments and delineate the depth at which bedrock lies.

All measurements have been handled by Georgios Tassis from NGU and Tore Thomassen from Statens vegvesen. Two Georadar systems have been employed for this purpose: Pulse EKKO PRO by Sensors & Software and RTA by Malå. All measurements were resumed in three days during the 10th and 12th of October 2015.
This report presents the measurement scheme (method, execution and processing) along with all the processed radargrams which resulted from the measured profiles. Each profile is accompanied by commenting on the results while the profiles themselves are presented in 1:1 scale (depth scale equal to distance scale) in three Appendices.

The results of this survey portray the benefit of Georadar application in surveying sediment thickness or depth to bedrock in connection to road construction. The use of unshielded antennas where maximum depth penetration is required was not optimal for this survey due to the fact that cultural noise levels were high. Effects coming mainly from power lines have been identified and after discarding them, the GPR implementation has detected layers which are in their majority in good agreement with the existing drilling information in the region. The penetration depth is small especially in Roa regardless of the low frequency antenna used. Our results indicate a maximum depth to bedrock of over 15 m for the area south of Jevnaker and around 6 m (3 m mean value) for the Roa area.

The depth to bedrock maps presented in this report should be thought of as trends of bedrock undulations and not accurate depths since accurate velocity values do not exist and the wavelength of the GPR signal for the 50 MHz antenna is quite broad (more than 1 m locally) and therefore respective errors are expected when picking surfaces on such radargrams. Some positioning problems due to the fact that the Malå RTA system had to be used to survey difficult terrain, should also be taken into consideration when these bedrock trend maps are examined.

Keywords:	Geophysics	Georadar
Bedrock	Sediment thickness	Road construction
		Scientific report

CONTENTS

FIGURES

TABLES

APPENDIX

1. INTRODUCTION

In October 2015, the Geological Survey of Norway (NGU) conducted Georadar measurements in two locations in Oppland County. The first area was at Kistefoss – Kleggerud south of Jevnaker in Jevnaker municipality and the second north of Roa in Lunner municipality. The survey is funded by the Norwegian Public Roads Administration (Statens vegvesen) and its purpose is to test the method's efficiency in supplementing the construction of new roads. More specifically, our main goal is to discover the maximum thickness of sediments and delineate the depth at which bedrock lies.

All measurements have been handled by Georgios Tassis from NGU and Tore Thomassen from Statens vegvesen. Two Georadar systems have been employed for this purpose: Pulse EKKO PRO by Sensors & Software for a number of profiles running through smooth fields in Roa and RTA by Malå for profiles done both in Jevnaker and Roa. All measurements were resumed in three days during the 10th and 12th of October 2015.

The first area of interest is south of the town of Jevnaker, next to Kistefoss and Kleggerud, where a new road is going to be constructed in an area which consists of farmland and a patch of forest. In this area one profile has been conducted with a total length of ~1.55 km (**figure 1**). The second area is located north of Roa where several profiles covering 2.4 km of surveying have been conducted using both aforementioned GPR systems (**figure 2**). The total distance covered with Georadar measurements for this study is ~3.95 km distributed in 15 profiles of various lengths.

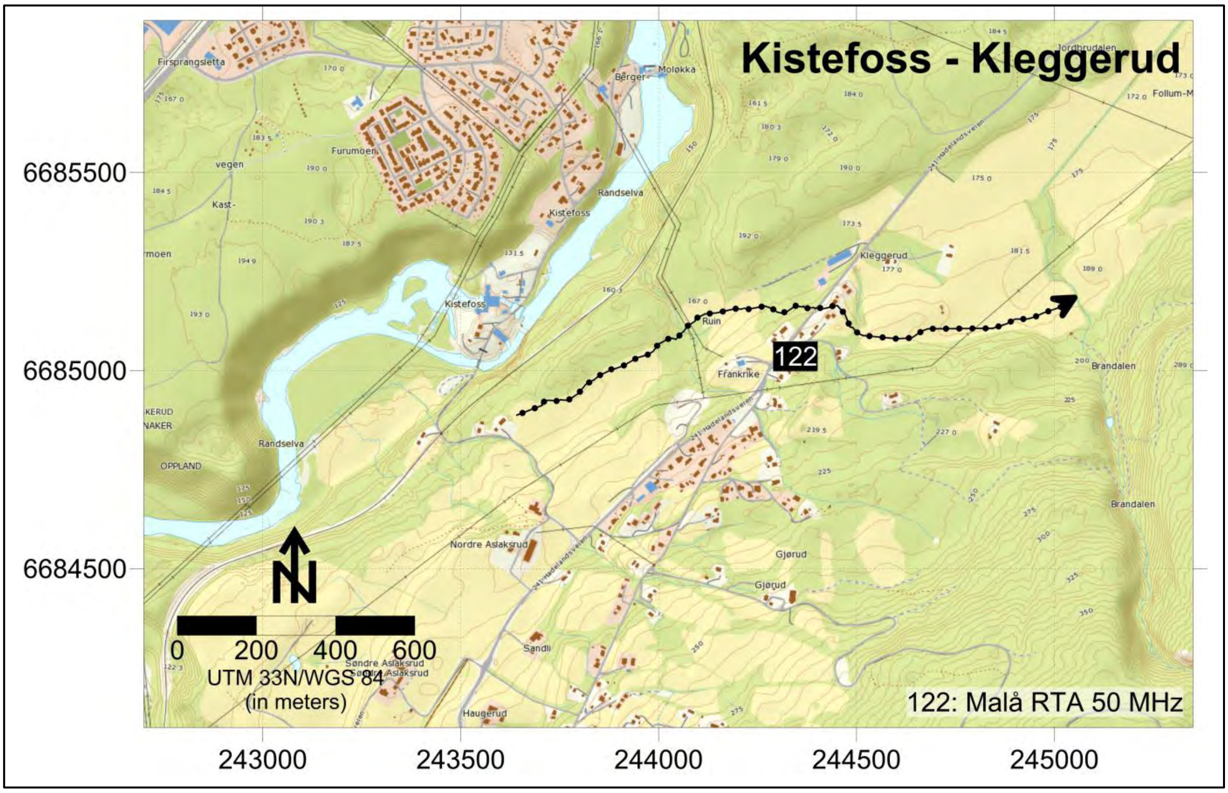

Figure 1: Geographical distribution of the Georadar profile conducted south of Jevnaker.

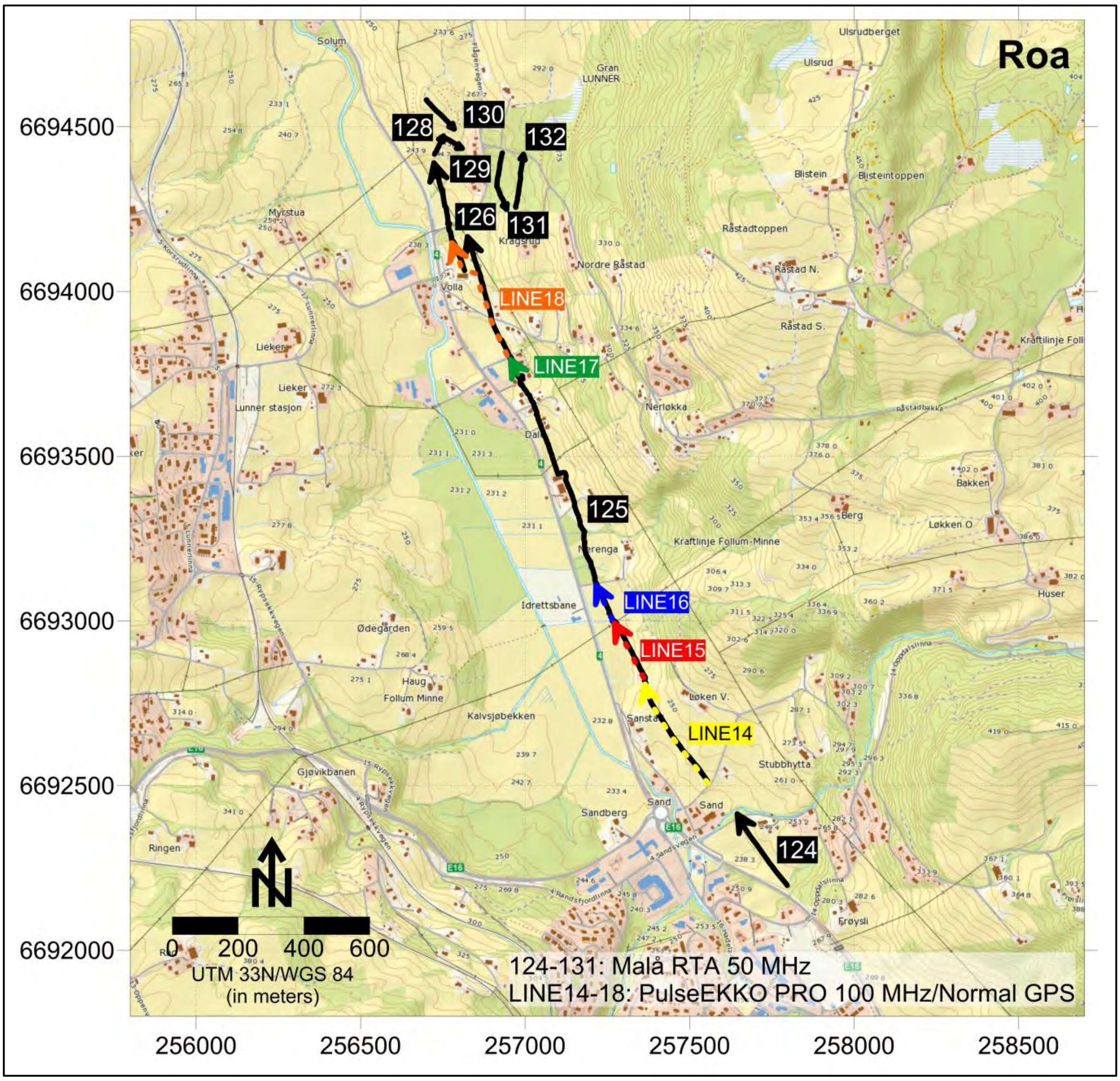

Figure 2: Geographical distribution of the Georadar profiles conducted north of Roa. S&S profiles (colored lines) begin where the previous lines stop.

This report will focus on presenting the results obtained via processing of the GPR profiling. Additional information such as compatible drilling depth to bedrock measurements provided to us by Statens vegvesen has also been employed to facilitate the extraction of conclusions.

2. METHOD DESCRIPTION, MEASUREMENTS AND PROCESSING

2.1 Method description

The Ground Penetrating Radar (GPR) or Georadar is an electromagnetic method which can be used to survey the layering and structure of the subsurface. The method is based on the recording of reflected electromagnetic pulse waves from interfaces in the ground. The electromagnetic wave is inserted into the ground with the use of a specially designed antenna which functions as a transmitter. Part of its energy is reflected on boundaries which represent a change in the ground's dielectric properties and returns to the surface. The rest of the energy continues downwards and can be reflected on other subsurfaces it comes across. On the surface, the reflected signal can be registered with the use of a receiver antenna and subsequently sent to a control unit for enhancement and digitization. In this recording with proper processing we may define the two-way travel time until each detected reflector and with the knowledge of the wave's velocity in the ground, we can convert these travel times into accurate depths.

2.2 Data acquisition

Acquisition parameters are shown in **table 1**.

Profile #	GPR System	Frequency (MHz)	Time window (ns)	Sampling frequency (MHz)	No. of stacks
122	Malå RTA	50	2101.84	506.22	1
124	Malå RTA	50	2101.84	506.22	1
125	Malå RTA	50	2101.84	506.22	1
126	Malå RTA	50	2101.84	506.22	1
128	Malå RTA	50	2101.84	506.22	1
129	Malå RTA	50	2101.84	506.22	1
130	Malå RTA	50	2101.84	506.22	1
131	Malå RTA	50	2101.84	506.22	1
132	Malå RTA	50	2101.84	506.22	1
LINE14	S&S	100	1000	1250	4
LINE15	S&S	100	1000	1250	4
LINE16	S&S	100	1000	1250	4
LINE17	S&S	100	1000	1250	4
LINE18	S&S	100	1000	1250	4

Table 1: Sampling characteristics of each profile.

As already mentioned, two GPR systems have been employed in this survey whose performance has already been found to be quite similar (Tassis et al., 2015; Tassis & Rønning, 2015). Most profiles have been carried out with Malå's RTA (Rough Terrain Antenna) system using a 50 MHz antenna. This system offers the possibility of performing Georadar measurements in rough terrains and forested areas due to its flexible antenna setting which resembles a snake. However, when utilizing this Georadar we are presented with positioning problems since the instrument's GPS is not mounted where the actual measurements take place namely between the transmitter and receiver antennas but on the surveyor who carries the storing and display unit. When 50 MHz is the antenna frequency employed, this discrepancy is ~7 m i.e. each trace is being registered 7 meters behind its assigned GPS reading (**figure 3**). This error is corrected for in the processing. However, this can lead to errors when profiles change direction and it is expected that the RTA measurement positioning will be suffering in accuracy. The problem will be addressed again later in this study with notes which will be added to each interpreted image originating from the Malå GPR.

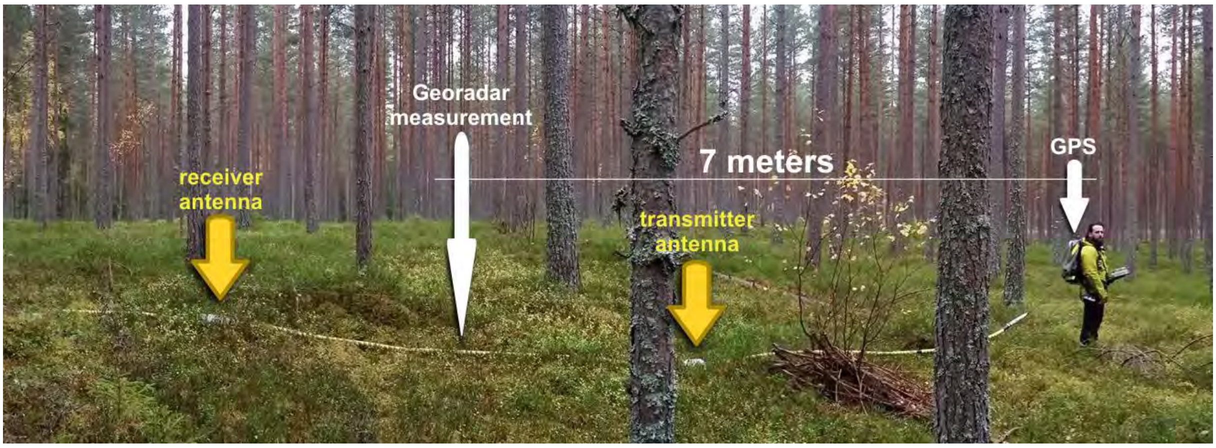

Figure 3: Explanation scheme for the 7 meter discrepancy in measurement positioning for Malå RTA Georadar (50 MHz antenna frequency).

As can be seen in **figure 2**, the survey area north of Roa is done mainly in farmland, in a sparsely populated area. This allowed us to perform measurements using the wheeled cart system called PulseEKKO PRO by Sensors & Software using a 100 MHz antenna sacrificing penetration depth to achieve higher resolution. This particular system using this particular frequency is bulky and cumbersome and cannot be used in dense forested and rough terrains but it is reliable and produces high quality data. In our case, this system has been employed in smooth farmland where wheat has been already harvested. Furthermore, our technicians at the NGU have upgraded the instrument by adding an external GPS on the cart between transmitter and receiver. This allows us to register traces with their true GPS positioning as opposed to the RTA instrument. Unfortunately, it was not possible to use the Sensors & Software system at Jevnaker.

The measurements acquired with the PulseEKKO PRO mounted GPS are accurate and also include topography. Unfortunately, the other GPS unit employed by the Malå RTA system is not accurate neither in positioning nor in topography. For this purpose, all recordings had to go through refining and in some case repositioning according to already marked points by Statens vegvesen. Points representing wrong readings (singular or sets of points) have been removed from our profiles and replaced by interpolation values along the assumed course of the profile. After refining the X and Y coordinates for each profile, topography was obtained by sampling the Norwegian Digital Terrain Model (DTM, 10 m resolution) for the aforementioned coordinates. Topography was then smoothed with a low pass filter to avoid abrupt changes due to limited resolution. Our profiles contain traces which are recorded every 0.5 m and therefore the point resolution in every radargram is higher than the available DTM. All the extra blank GPS positioning has been filled with minimum curvature interpolation. Topography is shown together with each radargram in a separate plot at the respective Appendices. Applying topography on the radargrams would result in distorting the shape of artificial effects and making them look like underground surfaces to the untrained eye.

The profile at Jevnaker and the majority of profiles performed in Roa have been measured with the use of the Malå 50 MHz Rough Terrain Antenna (RTA). This antenna frequency has been employed in order to reach the maximum depth penetration as wanted by Statens vegvesen. Additionally, parts of the longest profile done in Roa have been re-surveyed using the PulseEKKO PRO system and employing the 100 MHz antenna. This was done in order to produce more detailed radargrams for these sub areas since the overall penetration depth is small and due to the fact that higher frequency antennas sacrifice larger penetration depths (unneeded in Roa) in favor of higher resolution.

A very important parameter when performing GPR measurements is the Time Window i.e. the total registration time. A higher Time Window allows the Georadar to record data from deeper reflectors therefore, we have set a values of 1000 and 2000 ns (nanoseconds) for 100 and 50 MHz antenna usage respectively. However, the actual survey depth is controlled by the electric conductivity of the ground and in our case does not allow the signal to penetrate deeper than 600 ns in Jevnaker as can be seen in the Average Trace Amplitude (ATA) plot in **figure 4**. As for the survey area in Roa, **figure 5** indicates that the penetration depth achieved for 50 MHz Malå is ~ 300 ns while for 100 MHz S&S it is ~150 ns. The ATA plot is a useful pre-processing tool which allows us to discern the time that the signal decays back to noise levels. Essentially, this indicates the maximum penetration depth for any given area.

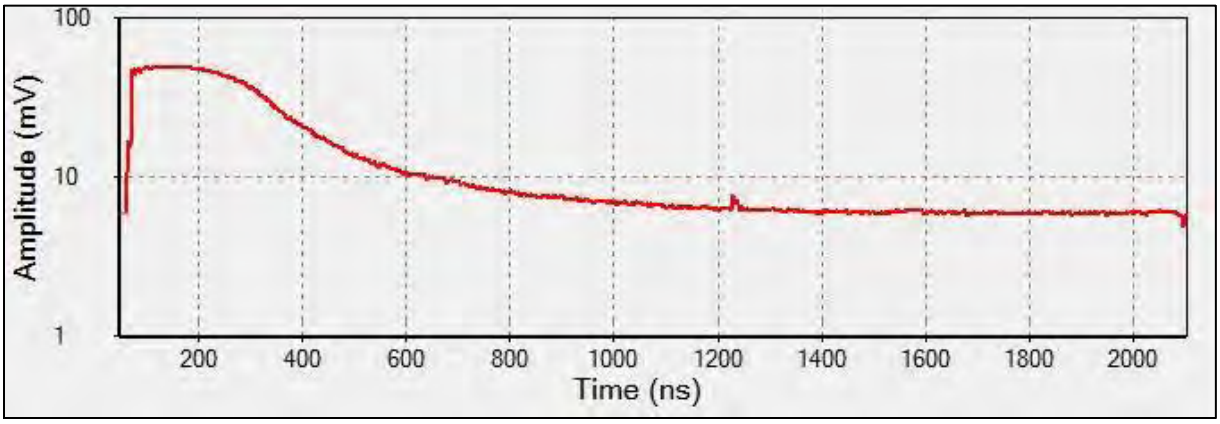

Figure 4: Average Trace Amplitude plot for Malå RTA Georadar profile at Jevnaker.

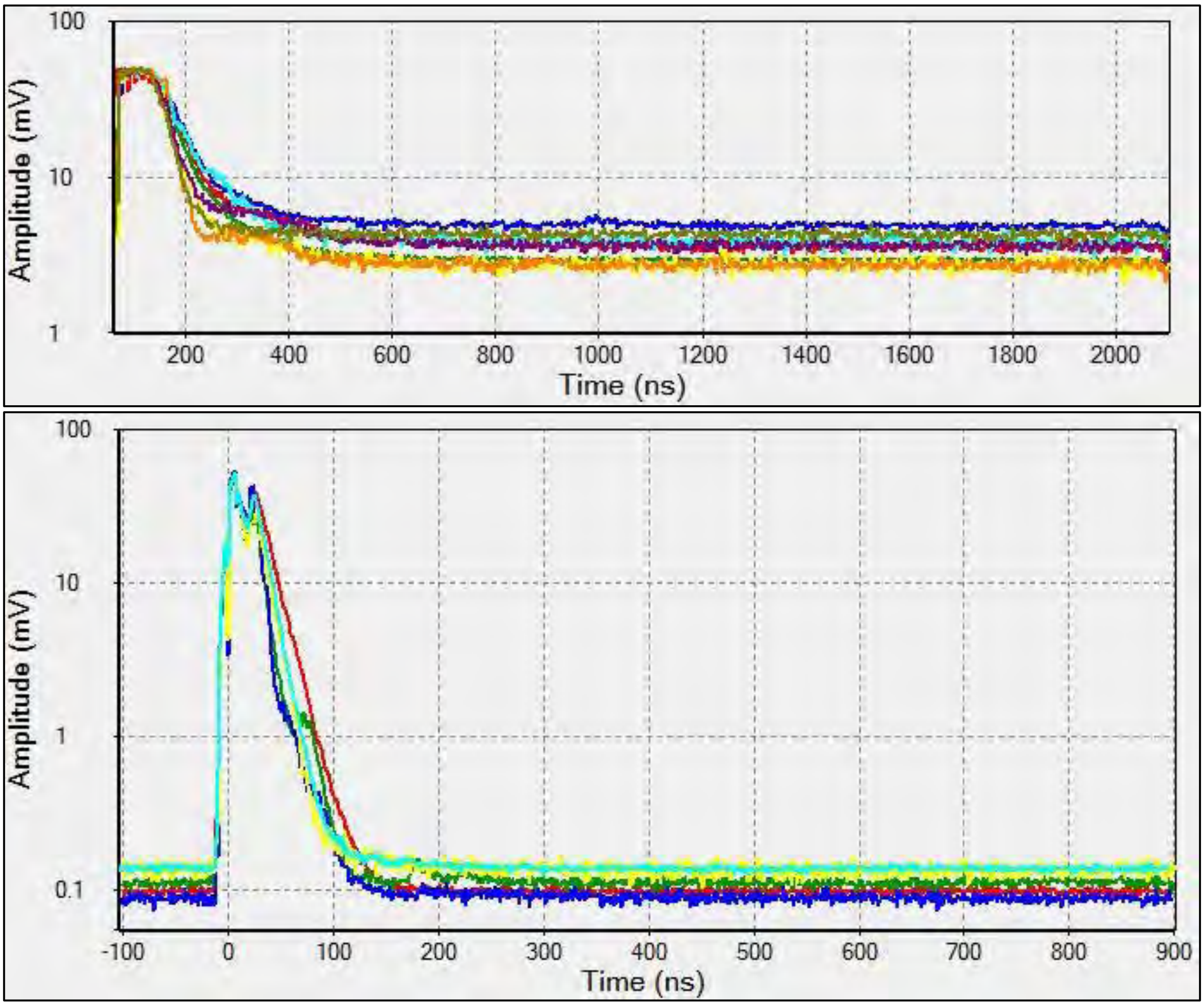

Figure 5: Average Trace Amplitude plot for 50 MHz Malå RTA (top) and 100 MHz PulseEKKO PRO (bottom) Georadars (different colors represent different profiles).

No Common Mid Point (CMP) measurement has been performed in order to calculate the ground velocity. Therefore, the velocity had to be selected according to the formations present in the survey areas. In Jevnaker the profile is crossing glaciofluvial sediments while in Roa the profiles also come across glaciofluvial sediments as well as moraine formations. The velocity chosen is equal to 0.1 m/ns which is assumed as a good approximation for both areas. Essentially, the penetration depth for Malå is 20 meters in Jevnaker and 15 meters in Roa while for Sensors & Software (100 MHz) it is around 7.5 meters (Roa).

2.3 Data processing

All profiles were processed with the use of RadExplorer 1.42 (DECO Geophysical 2005, Bouriak, S. et al 2008) from Malå Geoscience. The routines used in processing are the following: DC removal, time-zero adjustment, background removal, AGC amplitude correction, bandpass filtering (12-25-75-150 MHz), and finally conversion to depth. **Table 2** explains the effect of implementing these routines.

Background removal is the most sensitive processing tool used in GPR data processing and its purpose is to remove the strong flat signal present in the first nanoseconds of each radargram. Strong surface waves are an issue that has already been tackled by Tassis et al. (2015) and Tassis & Rønning (2015) when Malå RTA is being utilized. However, bedrock could also be locally flat in each profile meaning that the aforementioned wave is not the only flat reflector that will be appearing in the data. A strong background removal filter (short length) would of course remove the surface wave but it would also scramble all other flat reflectors detected throughout the profile. Essentially the application of such a filter would result in the distortion of flat reflectors or even the complete removal of such horizontal layers. In this sense, only weak background removal has been employed (long length i.e. equal to the entire length of each profile) in order to isolate the surface wave and leave all other horizontal reflectors uninfluenced.

Routine	Effect on data
DC Removal	Removes the constant component of the signal
Time zero adjustment	Sets the time where first break occurs
Background removal	Subtracts a mean trace
Automatic Gain Control (AGC)	Equalizes amplitude along the traces
Bandpass filtering	Increases signal/noise ratio
Conversion to depth	Converts nanoseconds to meters on the Z axis

Table I: Processing routines employed in RadExplorer.

2.4 Data presentation

All profiles are presented without the incorporation of topography due to the fact that artificial effects cannot be identified in the ground when profiles are displayed along with topography. In this sense, we have not exaggerated our profiles in depth vs. horizontal position. This analogy has been kept constant and equal to 1:1 i.e. depth scale is equal to distance scale. Drillings which coincide or lie relatively close to the survey lines are marked in each profile to help interpretation and their positioning is shown in white pins on the maps attached to each Appendix. Again, it should be noted that matching drillings and trace positions within Malå profiles is dubious due to the inaccuracy of the GPS system attached to the Georadar. This is not the case with the Sensors & Software georadar but still not all boreholes coincide with the path of the profiles. On the other hand, all drillings presented in the results have reached bedrock.

Distance is shown in every profile on the top (every 20 meters) and in more detail at the surface of each profile (every 5 meters). Interpreted reflectors are shown in yellow lines within the profiles. These interpretations are not continuous throughout the length of the radargrams due to the fact that in some areas it is neither possible nor safe to pick any surface.

3. RESULTS

3.1 Malå RTA profile in Jevnaker: line 122

The processed image for line 122 is shown in **Appendix -01**.
Since the profile is over 1500 m long and the displayed depth is just 25 m, **line 122** is presented in four parts to keep the 1:1 analogy scale in both axes.
The profile is crossing farmland at the edge of forested areas with the whole area being sparsely inhabited and containing only a small number of farmhouses. However, the area is also traversed by power lines which run sub parallel and diagonally to the profile and even cross it at several locations (see ticked straight lines in **figure 1** and attached map in **Appendix-01**). The presence of these power lines causes a number of artificial effects i.e. false anomalies which although being prominent do not disturb the data and appear only on the lower levels of the radargrams which only contain noise. We will try to pinpoint these false anomalies in the result description but generally, inclining straight lines in depth are not natural features and may represent not fully developed hyperbolas from targets above the ground. Examples of such features can be seen throughout the profile but should not be taken under account. The only artificial effect present in **line 122** which is strong enough to surface over the signal can be seen at 720 meters of horizontal distance caused by the junction of two power lines with the profile.

The profile is surveying glaciofluvial (first half) and fluvial sediments (second half) therefore an average velocity of 0.1 m/ns is a good estimation for the region. Drillings are available only for the last 600 meters of the profile while no such information has been made available for the rest of its length. Therefore, the assessment made for the first 900 meters of the profile will be solely based on the radargram shown in **Appendix-01**. A clear dipping reflector in the beginning of the profile reveals a probable increase in sediment thickness of over 10 m. This thickness is maintained for only a few tens of meters before the reflectors start inclining upwards and reduce in depth, reaching their shallowest point around 100 meters of distance (around 5 m). Subsequently bedrock seems to be deepening again at 160 meters until ~8 m and encloses a series of horizontal reflectors which are interrupted by a mishmash of reflectors at 180 and 230 meters that could be attributed to bedrock exposure. These flat reflectors extend for another 200 meters maintaining a somewhat constant depth of about 5 to 6 m.

After 400 meters of horizontal distance reflectors become discontinuous and fragmented but their total depth doesn't appear to be larger than 6-7 m. The same pattern with horizontal reflectors disturbed by possible bedrock uplift seems to be the case in this part of the radargram also. Positions of bedrock upheaval interrupting shallow horizontal reflectors (less than 5 m) could be pinpointed at 520, 560 and 630 meters. At 720 meters a strong artificial effect marks the beginning of an area which contains lots of unclear reflectors which mingling with one another and making any assessment risky.

The presence of reflectors seems to be clearing at about 860 meters where a shallow flat reflector is found at 5 m depth. Then, after 880 meters there is a large increase in depth which according to a drilling at 955 meters that didn't reach bedrock, should be more than 10 m. The reflectors present in that position extend even below 15 m but the most continuous ones indicate that bedrock shouldn't be deeper than 12 or 13 m.

At 990 meters a strong reflector appears which is smoothly deepening towards the east from about 8 m until over 10 at 1120 meters. Two neighboring drillings present in the area indicate that depth to bedrock is close to 8 m (7.8 at 1155 meters and 7.7 at 1195 meters). However, the detected reflectors appear at a somewhat larger depth which could be due to bad positioning or difference in velocity locally.

The drillings found at 1235 (10.3 m), 1245 (11.6 m), 1255 (10.7 m) and 1275 meters (13 m) on the other hand appear to be matching the previously mentioned strong reflector almost perfectly. This layer is becoming shallower after 1290 meters, a pattern not validated by a drilling at 1295 meters which reveals an even higher depth to bedrock. Once again, bad positioning could be a reason for this. The drilling done at 1335 meters again is matching nicely with a set of relatively flat reflectors at 8.8 m and same goes for the next one which indicates that sediments are thicker than 7.5 m at 1355 meters of distance. This is actually a point where sediments begin to increase in depth quite significantly as a series of boreholes that didn't reach bedrock indicate that sediments throughout the remaining length of the profile are thicker than 15.8 m. This poses a problem since reflectors are detectable for this particular frequency down to 15 m with small exceptions of deeper levels therefore, the penetration depth is not sufficient. It should be reminded again that the penetration depth achieved is always dependent on both antenna frequency and soil electric conductivity. Considering the fact that the lowest frequency antenna available has been employed, this limitation is induced to the data by the ground itself.

Indeed, after 1380 meters along the radargram these thick sediment layers appear undulating until the end of the profile but the GPR results fail to delineate their true depth. Another aspect is that there is a possibility that for this particular area of dry fluvial sediments the velocity might as well be 0.12 m/ns instead of 0.1 m/ns. That would increase the penetration depth to 18 m instead of 15, but still all layers below that level would not be detected. A lower frequency antenna (25 MHz) could reveal layers from deeper levels but unfortunately it is not available to the NGU. Even in that scenario, the depth penetration limitation could be due to fine grained material found at this depth which would prevent the signal from penetrating farther regardless of antenna frequency. Conclusively, this last part of the profile is lacking the required penetration to map the sediment layers in the region.

3.2 Line 125 and LINES14 to 18

A almost 1850 meter long profile at Roa (Line 125) is measured by the Malå RTA 50 MHz. Partly this line is remeasured with Sensors & Software EKKO Pro with 100 MHz antennas (Lines 14 – 18).

The processed images for line 125 and LINE14 to 18 are shown in **Appendix-02**.

The Malå profile is over 1800 m long and the displayed depth is 20 m, therefore **line 125** is again split into four sub-profiles to maintain the 1:1 analogy scale in both axes. **LINE14** to **18** are shown exactly over **line 122** to match the positions where the profiles coincide and easily compare results. The displayed depth for the profiles performed with PulseEKKO PRO is 10 meters due to the fact that higher frequency limits depth penetration in favor of resolution. Drilling positions and depth to bedrock measurements are shown as before in red color for both profiles (where applicable) while interpreted reflectors are shown in colored lines within the radargrams. These positions are more accurate for PulseEKKO PRO than for Malå but not all of them coincide 100% with the positions in which their shown within the radargrams. Nonetheless, they are marked to facilitate any assessment.

All profiles are performed from south to north and sub parallel to the main road (route 4) at a distance varying from 30 to 120 meters. The area is moderately inhabited with several housing which is expected to cause some artificial effects but the biggest problem in our data is caused by the many power lines which run parallel and perpendicular to all the profiles conducted in the area. In any case, most of the profiles present good signal conditions especially when they cross harvested farmland. The most prominent artificial effects plaguing the data can be found at 380, 570, 730, 830, 880, 970, 1000 1040, 1200, 1250, 1320, 1390, 1450, 1580 and 1850 meters distance. The PulseEKKO PRO profiles on the other hand are "cleaner" and present an increased resolution which is of course expected. It should be noted that **line 125** was not possible to be covered with S&S profiles in its entirety due to difficult terrain conditions which didn't allow a cart to be utilized.

Line 125 and **LINE14** begin with a series of reflectors which extend to 10 and 5 meters depth respectively. However, not all of them represent bedrock which is a fact supported by a borehole at 80 meters which indicates that sediments in this part of both profiles are no more than 3 m thick. No continuous reflectors can be followed until this point in both profiles but at around 120 meters, a deepening reflector formulates which locally reaches almost 5 meters of depth. This reflector remains solid and undulates throughout the length of **LINE14** with a higher resolution than **line 125** and a mean depth that does not deviate much from the 3 m measurement that another drilling at 280 meters has given.

An obstacle on the surface led us to terminate **LINE14** and begin a new profile called **LINE15** just a few meters farther to the north. However, this profile has also been juxtaposed with **line 125** with correct positioning in order to align the equal survey area between the two radargrams. Both profiles portray a very smoothly deepening reflector starting at 450 meters (70 meters in **LINE15**) and becoming 5 m deep at 570 meters (190 meters in **LINE15**). It should be noted that **line125** is plagued by a strong artificial effect at 570 meters which masks the aforementioned reflector. This false anomaly is caused by a target above ground which also prevented **LINE15** to continue any farther.

The new profile named **LINE16** picks up just a few meters away from where **LINE15** was terminated. It distinctively displays the same reflector undulating smoothly at ~6 m of depth and then becoming shallower around 65 meters of distance and reaching a depth of ~3 m which is maintained until the end of the profile. The same pattern is repeated in **line 125** although with a lower resolution which results in overall larger depths. The aforementioned layer emerges from the artificial effect which masked its presence at 580 meters and also undulates at ~7 m depth before ascending to ~4 m or less at 650 meters of distance. Nonetheless, the most detailed image obtained with the S&S system and the 100 MHz antenna is more trustworthy in quantitative terms. Without any additional data, it is not possible from the GPR data to say what is causing this reflection.

After 700 meters of distance in **line 125** and for the following 650 meters only Malå data are available since the terrain was not suitable for the PulseEKKO PRO cart to be utilized. This part of the profile is characterized by a higher number of apparently linear artificial effects which interfere with the detected reflections and in some cases mask them. Examples of such cases can be seen at 740, 870, 1040 and1250 meters where the centre of large artificial effects can be seen blurring the reflectors and making their distinction problematic. However, it is safe to trust a rather strong reflector extending throughout this part of the profile with a mean depth of ~3 m as dictated by a number of drillings available in the area (2.9 m at 855 meters, 3 m at 905 meters, 3 m at 930 meters, 2.8 m at 1090 meters, 4 m at 1140 meters, 3 m 1170 meters, 3.6 m at 1220 meters, 3.1 m at 1290 meters and 2.9 m at 1335 meters).

LINE17 starts 1360 meters within **line 125** at an area where strong artificial effects still plague the Malå data. At 1370 meters (20 for **LINE17**) a strong false anomaly makes it impossible to discern whether a 3 m drilling at the area is verified by any reflector in **line 125**. However, the **LINE17** is clear enough to display a smoothly ascending reflector which is in quite good agreement with the aforementioned drilling. The area between 1400 and 1440 meters in **line 125** is free of artificial effects, unveiling a number of horizontal reflectors which seem to go deeper than the 2 m depth to bedrock measurement at 1425 meters.

This discrepancy is verified in **LINE18** which starts at 1430 meters within **line 125**. Although the S&S 100 MHz antenna profile does not contain the 2 m drilling, reflectors within the first 15 meters of the profile appear to be at least 4 m deep before rising to shallower depths. At 1445 meters in **line 125** another strong false anomaly masks the continuation of reflectors but the layers detected in **LINE17** demonstrate that the sediments in this area are around 3 m thick as a drilling at 1465 meters indicates. For the remaining 350 meters both profiles display relatively flat reflectors which fit the 3 m depth dictated by two drillings 1510 and 1690 meters (80 and 260 meters for **LINE17**). Some local deepening may be found between 1500 and 1700 meters (80 and 280 meters for **LINE17**) however, these reflectors should not exceed a depth of 5 m.

A linear feature going from 20 meters depth at position 1620 almost to the surface at position 1840 is probably a side reflection from a powerline. This is not seen at all at the Sensors & Software 100 MHz data. This can be dependent on frequency but also on antenna performance.

3.3 Shorter profiles in Roa: lines 124, 126, 128-132

The processed images for lines 124, 126 and 128-132 are shown in **Appendix-03**.

Line 124 lies at the southern extension of **line 125** covering a farmland area east of the Roa city center and was planned to be connected with **line 125** forming a 2 km long profile. However, a horse ranch which was not possible to be entered has interrupted the surveying course and the result was this 260 meter-long profile. **Line 124** presents reflectors which gain in depth towards the north and reach a maximum of ~7 m after 130 meters of distance. Nevertheless, drillings at 130 and 400 meters have found bedrock at 3 and 2.9 m respectively but their placing along the profile indicates that some sediment deepening could exist between those points. Unfortunately, a strong artificial effect at the end of the profile masks whatever layers could be detected in the area after 220 meters.

On the other hand, **line 126** lies at the north extension of **line 125** and covers an area a bit closer to the main road. This profile is also plagued by several artificial effects especially at the beginning of the line, but low sediment thicknesses are to be expected (less than 3 m). There are lots of either coinciding or neighboring drillings throughout the 350 meters of the profile and when the levels of noise are low, they match quite well with the shallow reflectors that have been detected by the Malå RTA GPR. One exception is a drilling at 180 meters which has yielded a depth to bedrock of 1.5 m while the Georadar has detected obviously deeper layers in that particular position. However, this drilling is about 30 meters away from the profile downhill towards the road therefore it is safe to trust that depth to bedrock at this particular position is around 3 m, as in the majority of the area.

Lines 128, **129** and **130** are covering a small area north of **line 125** and none of them exceeds 120 meters in length (**lines 128** and **129** are just above 60 meters long). No drilling information is available for this region therefore, no depth to bedrock correlation can be made with the resulting radargrams. All profiles display almost horizontal layering with reflectors down to 5 m depth. However, as already seen in previous cases, the lack of resolution may result in an overestimation of depths. Therefore, it is expected that sediments in this area have a thickness of ~3 m also.

Lines 131 and **132** lie to the northeast of the survey area and represents a deforested area with lots of tree trunks and other obstacles on the surface. **Line 131** displays relatively deeper reflectors than **line 132** but both of these layers appear to be relatively flat and undisturbed. A depth of around 3 m should also be the rule for the sediments in this area also.

3.4 Summary of results

Interpretation results are shown in **figures 6**, **7** and **8** which display how the bedrock trends rather than its quantitative characteristics. The picked depth to bedrock estimations have been gridded and plotted against the area map. It should be noted that results for Malå RTA in Roa have been gridded separately from the results from PulseEKKO PRO for the same area for two reasons. First is the difference in resolution which makes the 50 MHz RTA results more inaccurate and second due to the fact that PulseEKKO PRO data do not suffer from positioning problems and their coordinates are accurate as opposed to the Malå RTA data. The profile at Jevnaker is shown in **figure 6** while the profiles for Roa are shown in **figure 7** (Malå RTA lines) and **figure 8** (PulseEKKO PRO lines). In Jevnaker bedrock appears to be deepening towards the east but we should keep in mind that the drillings supporting this claim lie on the easternmost part of the profile while some of them have not reached bedrock. Regardless of this, the deepest reflectors detected have been interpreted and mapped in **figure 7** although the drilling information in the region indicates that sediments in the area are thicker than picked (see **section 3.1**). In Roa the results for both systems are coherent presenting a depth to bedrock which does not vary much from a mean value of 3 m. **Figure 8** contains data from more profiles therefore covers a larger area while **figure 9** covers a smaller area but with higher resolution. It should be noted that the resulting grids are more trustworthy in the vicinity of picks (black dots in **figures 7, 8** and **9**) than farther away from them.

4. DISCUSSION.

4.1 Technical discussion

As already explained Malå RTA data suffer in positioning accuracy for two reasons: a) low quality of compatible GPS system and b) due to the 7 meter offset between measurement and GPS point registration (see **figure 3**). In order to compensate for these problems, positioning has been manually refined by getting rid of all the obviously wrong points and all picks where moved 7 meters back against the direction of the profile to match their true position. Still, inaccuracy is at least as high as the GPS specified one (3-4 meters).

In addition, drilling has taken place before the GPR profiling and that is not recommended. In fact, NGU proposes that in the future, such surveys should be done the other way around: GPR profiling should lead investigations and then drilling should occur in positions picked by the presence and/or depth of reflectors. Otherwise, accurate matching of drilling positions within GPR profiles can prove a very difficult task impaired by further inaccuracy.

In this study, two frequencies have been employed with the use of two GPR systems. Due to unavailability of time, profiles were produced without any prior frequency testing. The use of a 50 MHz antenna (Malå RTA) proved to be problematic in two ways. First, the resolution of the produced reflections was lower than required for such shallow sediment layers. Reflectors identified in the respective radargrams presented a high wavelength which in cases exceeded 1 m of width. This subsequently reduced the efficiency but most importantly the accuracy of the interpretation procedure. Re-measuring parts of the aforementioned profiles with the use of a 100 MHz antenna (PulseEKKO PRO), resulted in a big improvement in resolution and produced reflectors of significantly lower wavelength.

The 50 MHz antenna proved to be extremely sensitive to the effect of power lines in the vicinity of the profiles. The power lines generated prominent artificial effects which haven't been observed when the 100 MHz antenna was employed. These false anomalies appeared like wide hyperbolas and linear features at a depth proportionate to the profile distance from the power lines. Such strong noise is impossible to remove and could cause misinterpretations especially when non experts are viewing such results. Overall, if prior testing had been done, the 100 MHz antenna would have been chosen over the 50 MHz, sacrificing unneeded depth penetration for resolution since sediment thickness in the region is small.

4.2 Geological discussion

Interpretation was connected to the available drilling data with drillings down to bedrock being used except the case of Jevnaker where some boreholes that didn't reach bedrock were employed for auxiliary reasons. Wherever a measured bedrock depth matched a reflector, this reflector was picked throughout its length and thus an estimation of the sediment thickness was extracted. Other strong reflectors have also been picked in the absence of borehole measurements to supplement the final sediment depth estimation grid but in the lack of such additional drilling information, any assessment is risky due to the fact that said reflectors may not necessarily represent bedrock.

The results are as accurate as the velocity calculation in the region. In our processing we have used a velocity equal to 0.1 m/ns which was chosen accordingly to the geological formations present in the region. Essentially this velocity transforms 100 ns of signal penetration into 5 meters of depth. However, velocity can change within the area and cause uncertainty problems. Detailed velocity mapping for each profile would be time consuming and would eradicate the method's advantage of fast implementation. Therefore, in order to maintain this high production rate in GPR profiling, we have assumed that the velocity of 0.1 m/ns is constant for all the profiles throughout their length and depth. This assumption inserts an uncertainty factor to the interpretation since GPR wave velocity is not constant in any given area, even if a single sediment formation is dominant in every profile. For example, the same 100 ns of penetration could correspond to 5.5 meters of depth for a velocity of 0.11 m/ns but also 4.75 meters of depth for a velocity of 0.095 m/ns. Such changes in velocity within the same formation can be induced by the presence of water i.e. drier areas will allow waves to travel faster than wet ones. Conclusively, the interpretation results are prone to velocity variations due to the presence of water in the same formation or the variety of different formations encased in each profile.

The survey area has proven to be quite challenging for the use of GPR. Penetration depths were small especially in Roa although low frequency antennas were also employed (50 MHz), reflectors were not continuous and therefore not easy to follow in radargrams, various surface targets created a big number of artificial effects which masked possible reflectors obstructing interpretation and the errors in GPS positioning for the Malå RTA system and the mismatch between drillings and profile routes rendered the whole interpretation procedure problematic. However, useful information was extracted from the all the profiles and sediment thickness estimation maps were created.

In the present survey, it is impossible to identify the bedrock reflection without any information from drillings or bedrock exposures. On the other hand, georadar can give a continuous image of interfaces mapped in drillholes and in this way these two methods supplement each other.

5. CONCLUSIONS

The results of this survey portray the benefit of Georadar application in surveying sediment thickness or depth to bedrock in connection to road construction.

The use of unshielded antennas where maximum depth penetration is required was not optimal for this survey due to the fact that cultural noise levels were high. Power lines which were present in the area have induced false anomalies in the data rendering interpretation a challenging task. The final processed images have helped us detect layers which are in their majority in good agreement with the existing drilling information in the region but these results are not as accurate quantitatively.

Generally, the estimated penetration depth is moderate in Jevnaker and rather small in Roa due to the respective electrical conductivities of the deeper layers in both regions. The profile conducted in the area south of Jevnaker (Kistefoss - Kleggerud) failed to detect bedrock on its easternmost end while the lack of any drilling information in its western half only allowed us to portray a general morphological trend in the area by picking reflectors with no indication whether they represent bedrock or not. On the other hand, sediments in Roa are not expected to be more than 6 meters deep with a mean sediment thickness of around 3 meters. Be that as it may, the sediment-bedrock limit was not clearly detected with the application of GPR for reasons varying from large signal wavelengths that increase uncertainty to geological restrictions that didn't offer enough penetration. All depth to bedrock maps presented in this report are consistent with the GPR methodology and theory however, degrading factors present in this study should always be taken under consideration when utilizing these results. We suggest that these maps should be treated as trend maps indicating the overall bedrock morphology than quantitative depth to bedrock measurements.

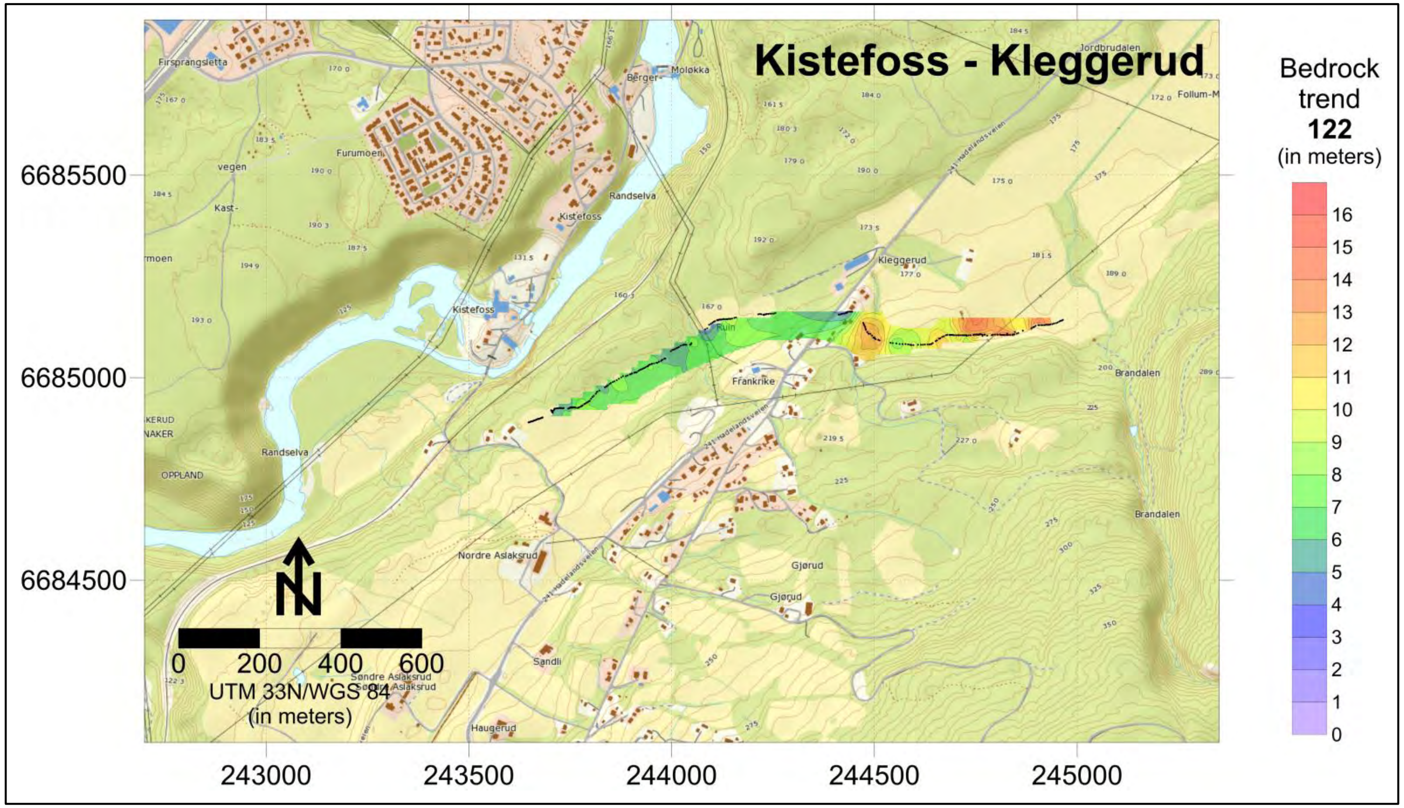

Figure 6: Trend map of bedrock morphology in Kistefoss - Kleggerud (Malå RTA 50MHz profile).

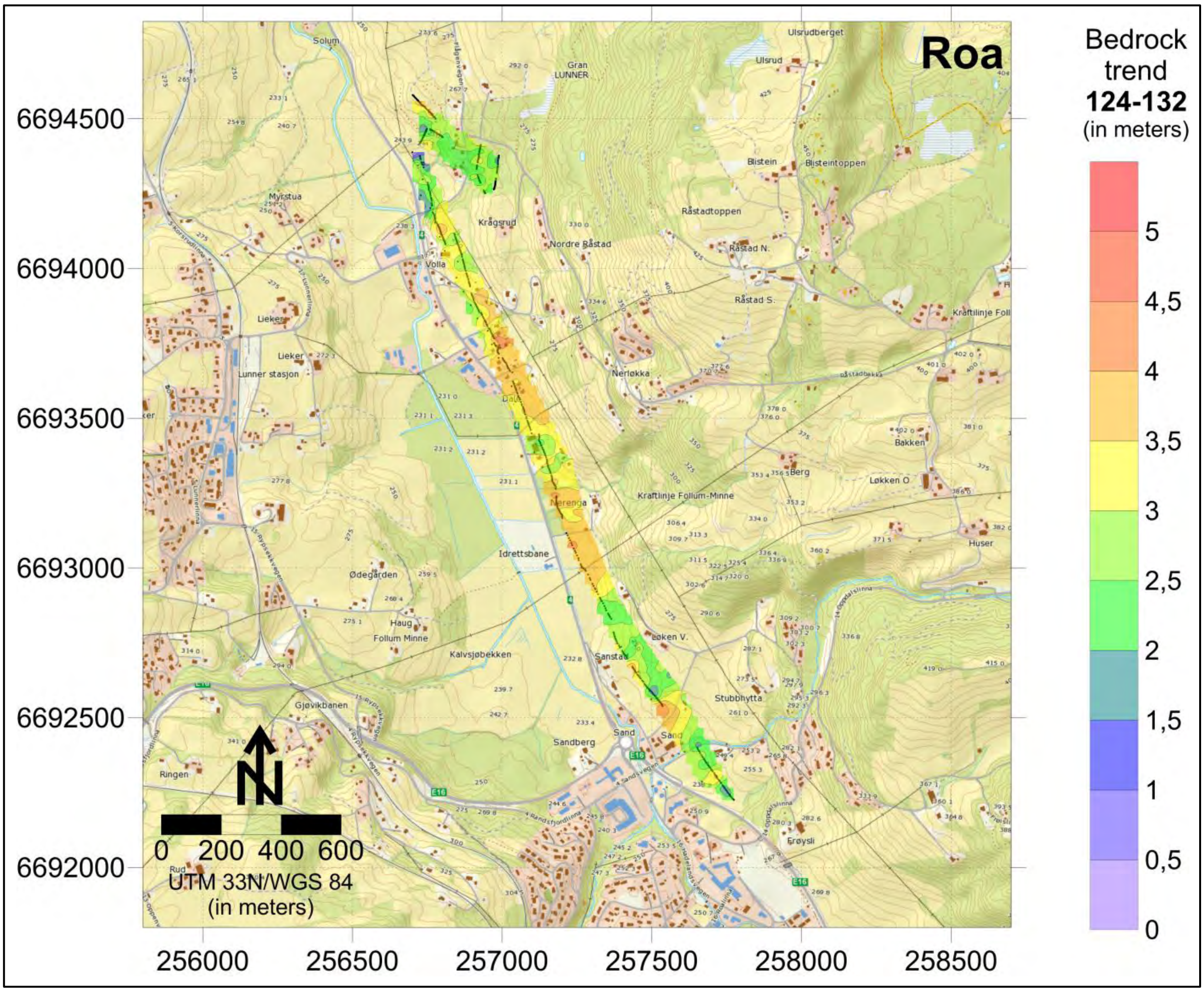

Figure 7: Trend map of bedrock morphology in Roa (Malå RTA 50 MHz profiles).

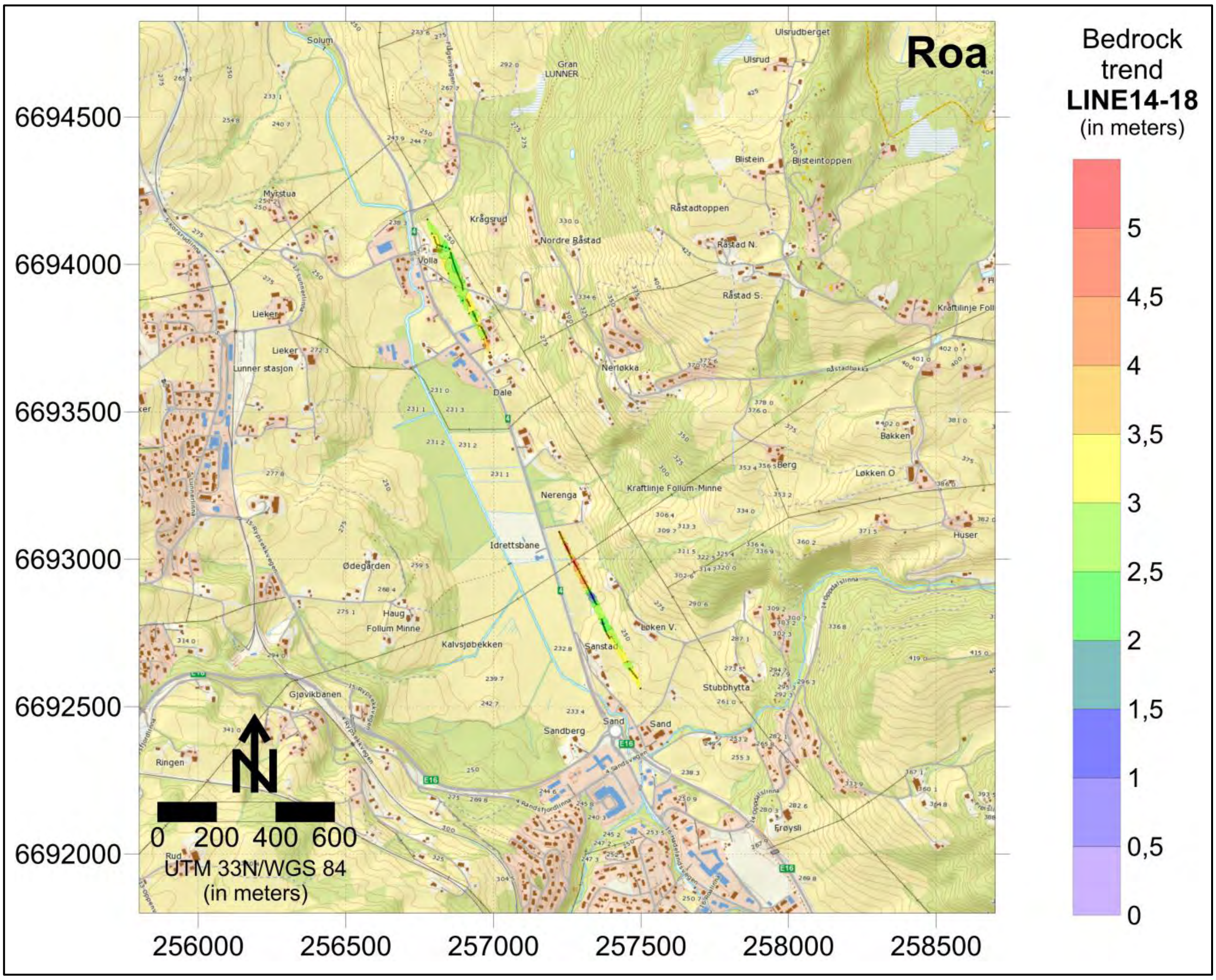

Figure 8: Trend map of bedrock morphology in Roa (PulseEKKO PRO 100 MHz profiles).

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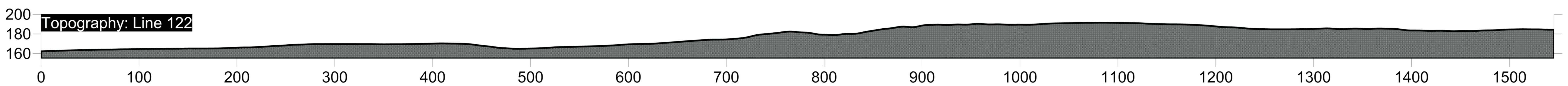
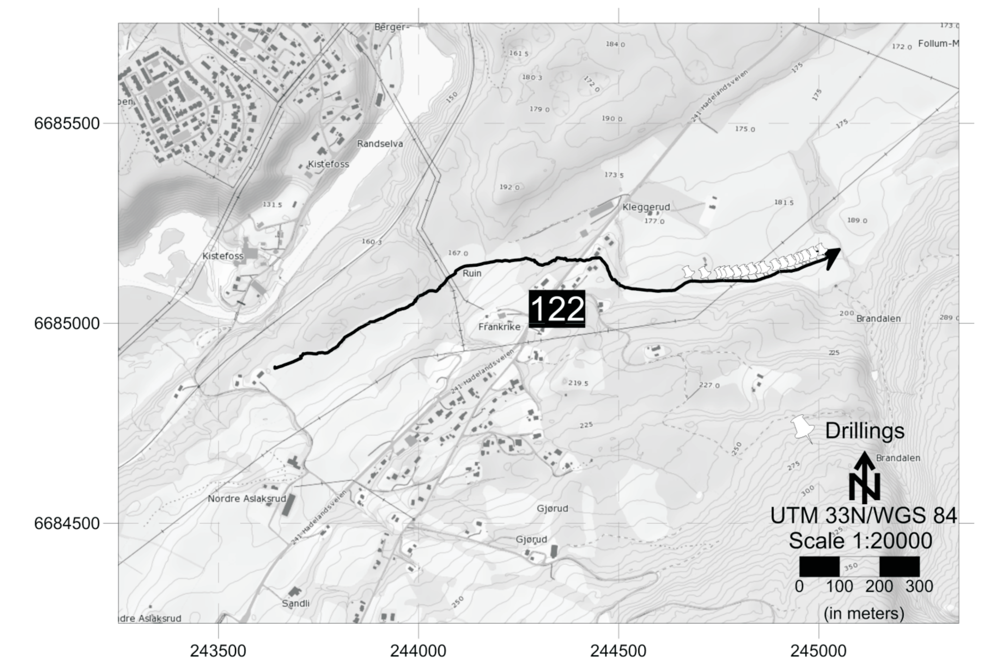
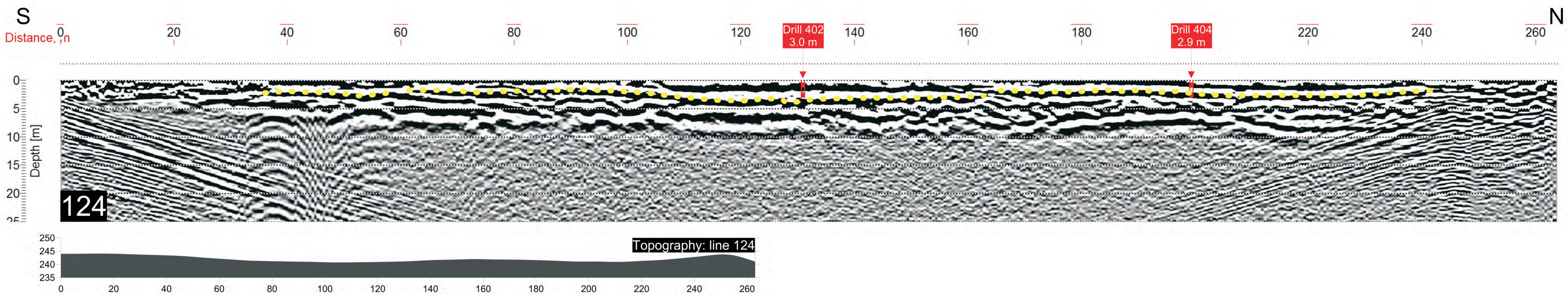
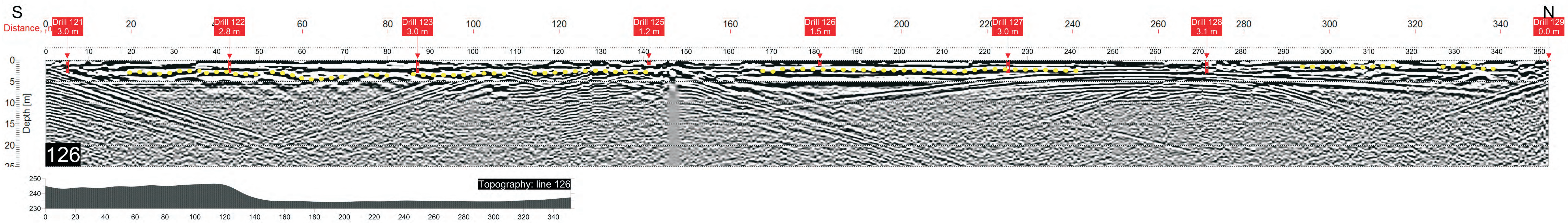


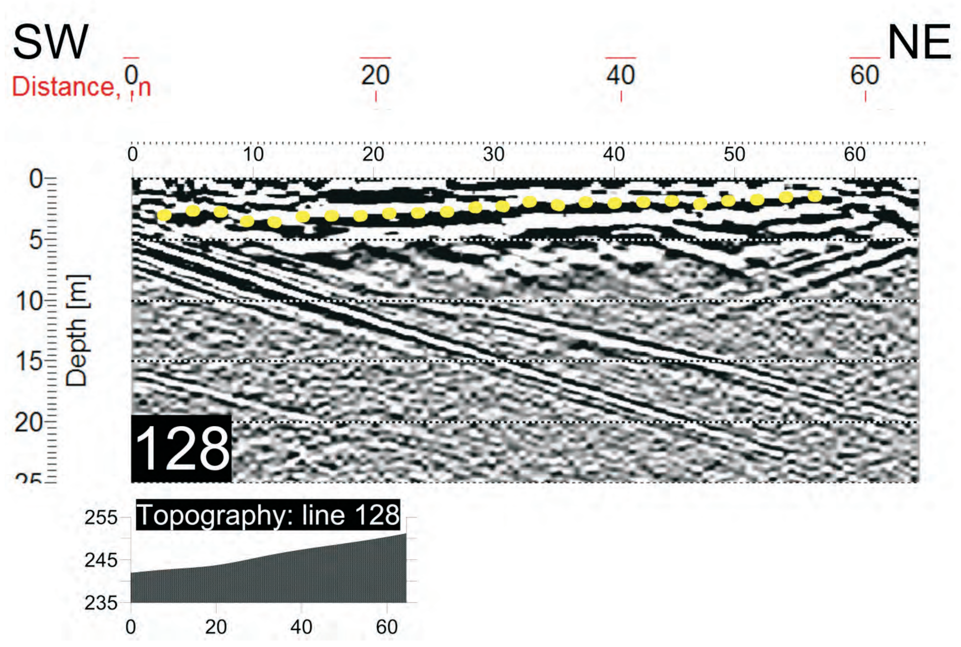


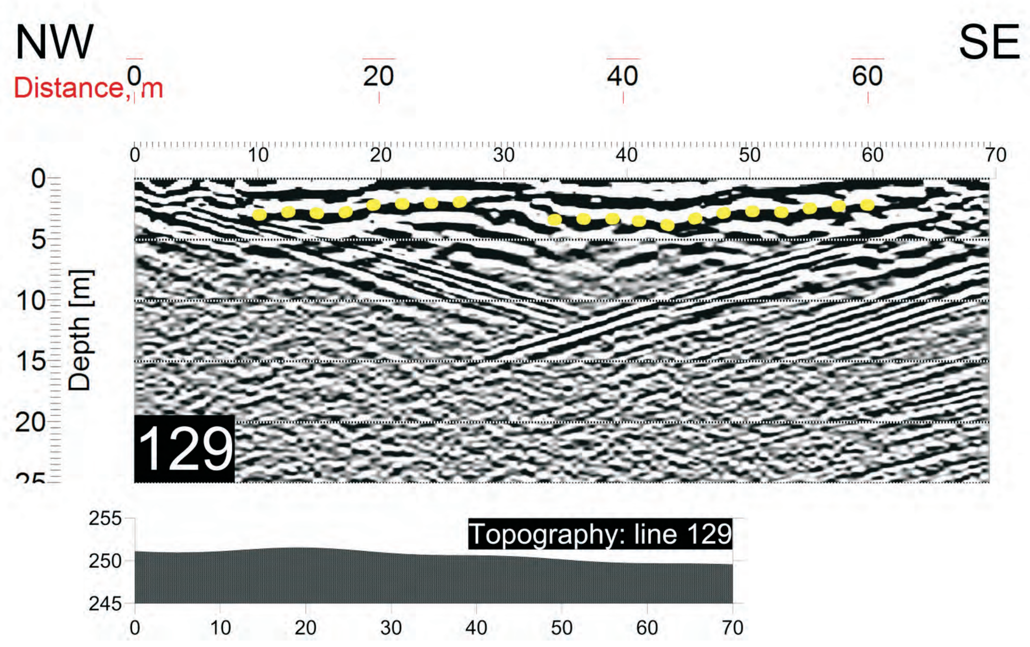
STATENS VEGVESEN GEORADAR LINE 122 (MALÅ RTA - 50 MHz) KISTEFOSS - KLEGGERUD JEVNAKER KOMMUNE, OPPLAND	MÅLESTOKK 1:20000 (MAP)	MÅLT GT TEGN GT TRAC KFR KONF	OCT 2015 DEC 2015
NORGES GEOLOGISKE UNDERSØKELSE TRONDHEIM	TEGNING NR 2015.062-01	KARTBLAD NR 1815 II	

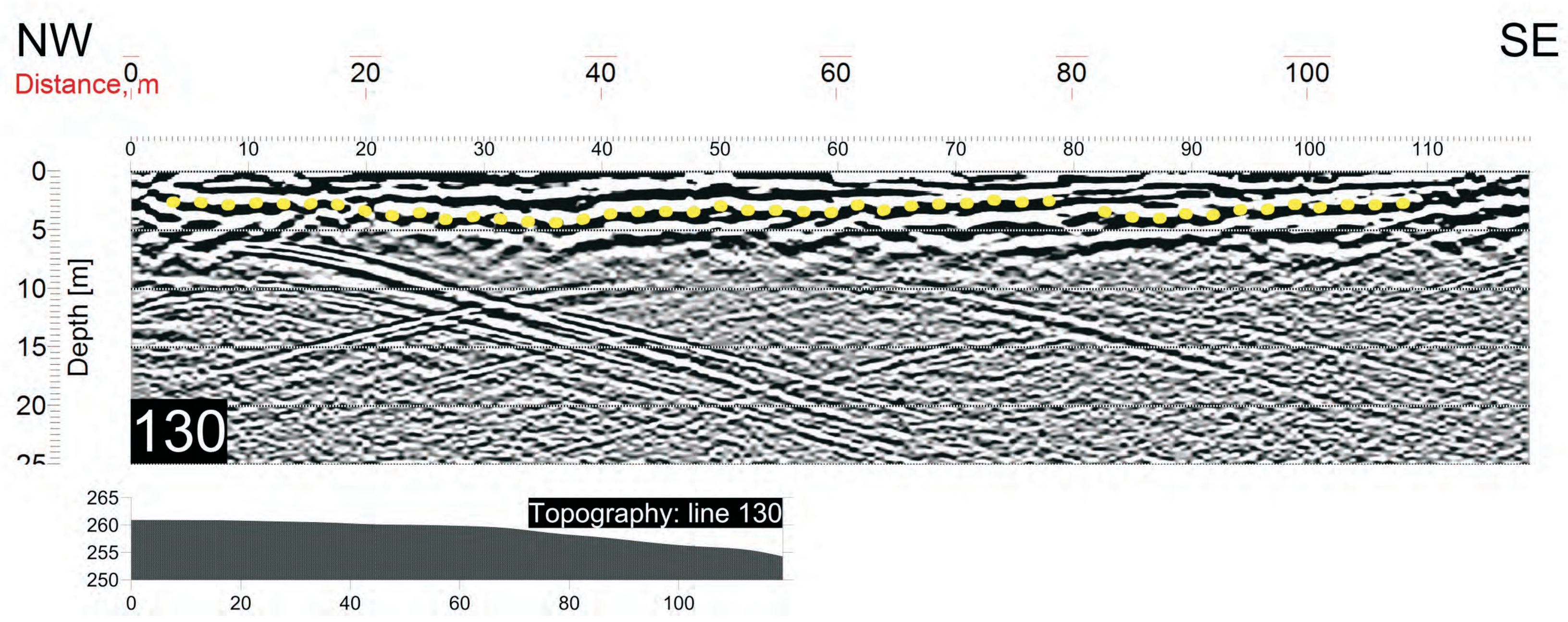
STATENS VEGVESEN GEORADAR LINE 125 (MALÅ RTA - 50 MHz) & 14 TO 18 (PULSE_EKKO PRO - 100 MHz) ROA LUNNER KOMMUNE, OPPLAND	MÅLESTOKK 1:25000 (MAP)	MÅLT GT	OCT 2015
		TEGN GT	DEC 2015
		TRAC	
		KFR KONF	
NORGES GEOLOGISKE UNDERSØKELSE TRONDHEIM	TEGNING NR 2015.062-02	KARTBLAD NR 1815 I	

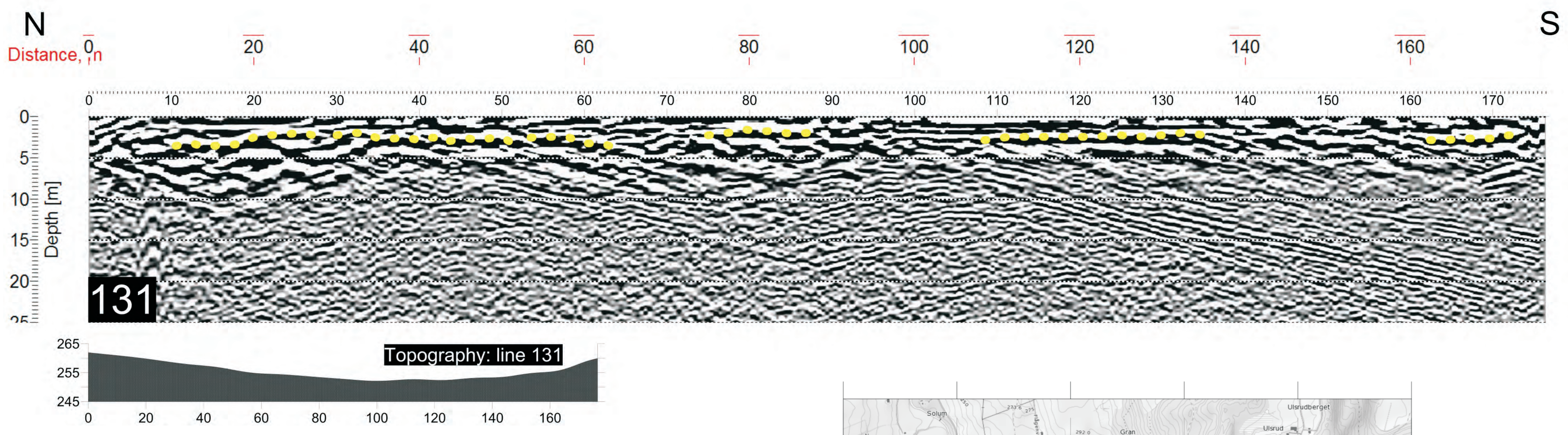


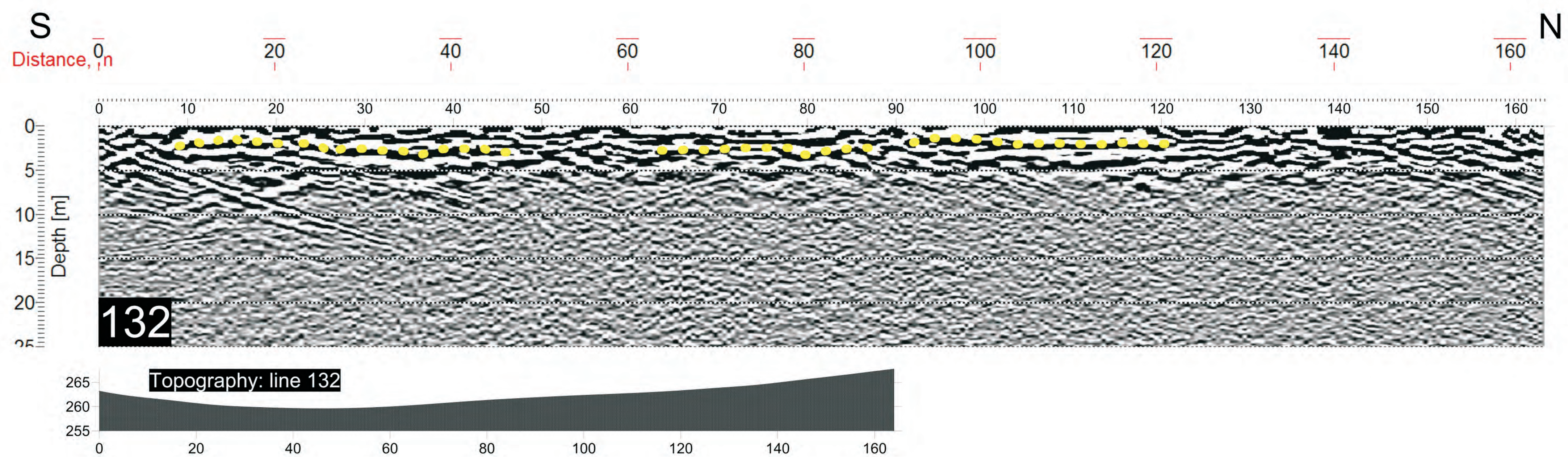


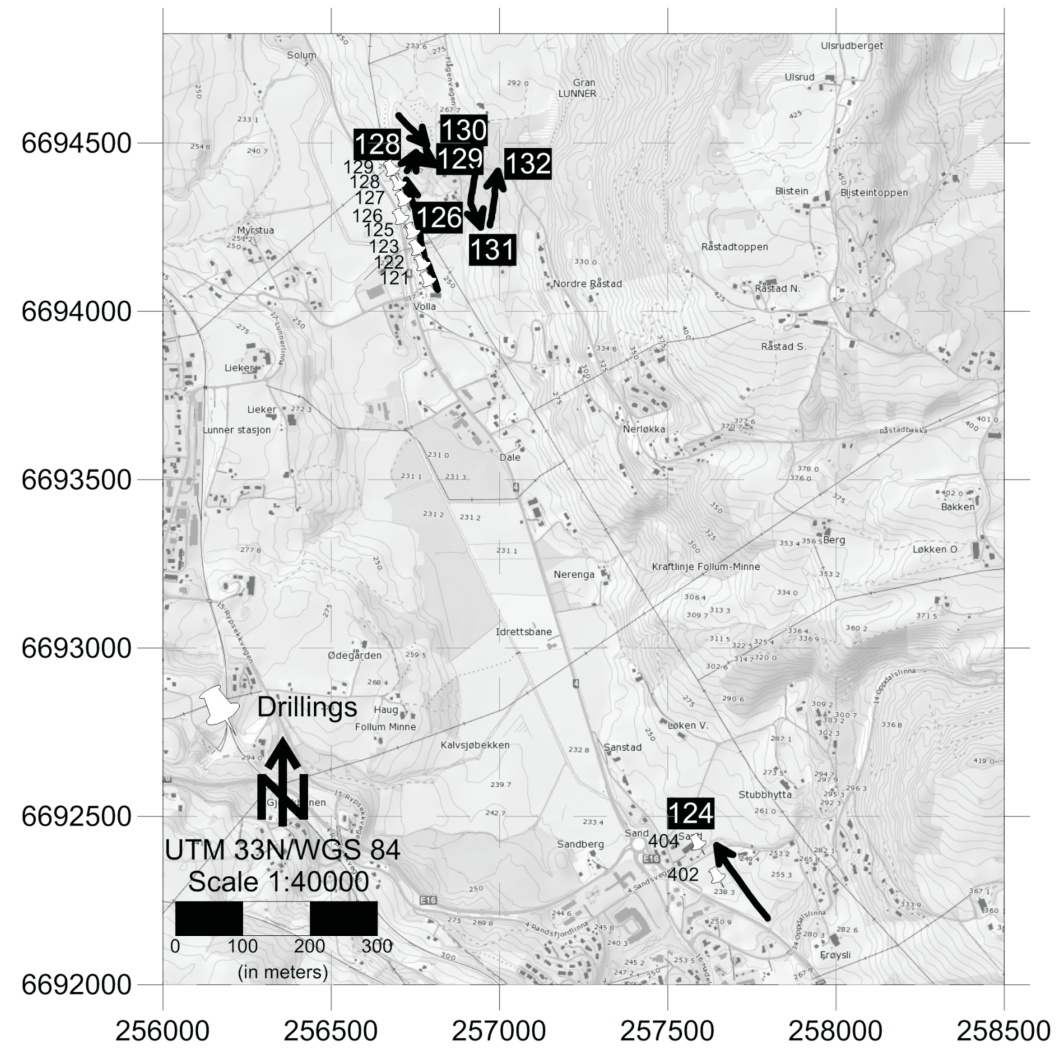












STATENS VEGVESEN

GEORADAR LINES 124, 126, 128-132 (MALÅ RTA - 50 MHz)

ROA

LUNNER KOMMUNE, OPPLAND

MÅLESTOKK		
1:40000 (MAP)	MÅLT GT	OCT 2015
	TEGN GT	DEC 2015
	TRAC	
	KFR KONF	

NORGES GEOLOGISKE UNDERSØKELSE

TRONDHEIM

TEGNING NR 2015.062-03

KARTBLAD NR 1815 II

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