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Depth to bedrock and bedrock morphology from gravity measurements at Melhus, Melhus Municipality, Sør-Trøndelag

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Title:
Depth to bedrock and bedrock morphology from gravity measurements at Melhus, Melhus Municipality, Sør-Trøndelag

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Summary:

This report presents geophysical interpretation results of gravity data as part of a project entitled ORMEL. The main objective of the project is to discern the amount of groundwater, and hence energy, that can be withdrawn from the major sand and gravel sediments in Melhus. The object for this study was depth to bedrock and bedrock morphology. The gravity method is one of the best techniques when sediment thickness estimation is required due to its low cost compared to other methods and the fact that it can be easily implemented in urban areas. This is exactly the case with our study area which is surrounding Melhus city center along the river Gaula.

The gravity survey contains 175 gravity stations with 133 of them positioned along 5 profiles with normally 100 m spacing between each station. The other 42 gravity stations are regional measurements mainly located on bedrock exposures found outside the sediment region. After the acquisition phase, the data has been transformed into Bouguer anomalies and the regional trend which is characterized by an increase in the field towards the southeast has been removed. The sediments in the valley are causing local anomaly lows along the measured profiles with a maximum of 8 mGal.

Gravity modeling was performed with the use of GM-SYS module of the Geosoft Oasis Montaj software. Our models were constrained by data coming from several NGU databases such as drillhole depths, density sampling, geological data and other geophysical interpretation results. During modeling, we have kept originally a constant sediment density of 2.0 g/cm^3 while the bedrock was given a value of 2.85 g/cm^3 (greenstone). The sediment density was decided after comparing results with a seismic survey which coincided one of our gravity profiles.

Gravimetric interpretation indicates that sediments in the region may acquire a maximum thickness of ~300 meters (~250 meters below sea level). These interpretations were then enriched with additional sediment thickness data originating from various NGU related sources and a total depth to bedrock map has been constructed. The final map presented in this report portrays a good approximation of the qualitative but also quantitative distribution of sediments in the study area. In brief, sediments appear to be deeper and more voluminous north of Melhus city center than south of it. Uncertainty of depth to bedrock is estimated to ± 10% of calculated depth.

Keywords:	Geophysics (Geofysikk)	Gravimetry (Gravimetri)
Modeling (Modellering)	Bedrock (Berggrunn)	Soil Thickness (Løsmassemektighet)
		Scientific Report (Fagrapport)

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1. INTRODUCTION

The ORMEL project (Optimal resource utilization of groundwater for heating and cooling in Melhus and Elverum) started in 2015 and will be the driving force for several field activities in Melhus and Elverum city centres in the period 2015-2017. The main objective of the project is to provide a scientifically solid and sustainable foundation for optimal utilization and management of groundwater resources in the two municipalities. Essentially, the amount of groundwater, and hence energy, that can be withdrawn from the major sand and gravel sediments must be mapped. A means of accomplishing this is by delineating the bedrock morphology and thus calculating the dimensions of the sediments overlaying it. The project is a collaboration between Melhus (project owner) and Elverum municipalities, NTNU Institute of Geology and Rock mechanics (project management), Energy and Process Engineering, the Geological Survey of Norway (NGU) and consulting company Asplan Viak AS. The project is funded by the Regional Research Fund - Central Norway (RFFMN), where the participants have self cost at approximately 30% each.

The survey area is part of the valley surrounding Melhus city center in Sør-Trøndelag county and covers about 12 square kilometers in total. This region underwent glacial erosion in previous geological times which formed deep fjord basins at the lower parts of such valleys. These valleys have been later filled with late to post-glacial deposits which we intend to map. The survey area is populated, therefore, the gravity method was the best suited for use in an urban environment such as this. The NGU has performed gravity measurements along profiles in the area which have been processed and interpreted in this report with the use of suitable software. Through this process we have acquired reliable regional information on sediment thickness and morphology of the basin, a task performed at lower costs and to greater depths than other available geophysical methods such as refraction seismic or electrical resistivity tomography. It should also be noted that similar gravity mapping of sediment thickness and bedrock morphology has been conducted in several valleys in Trøndelag municipalities in the past (Tønnesen, 1987; Tønnesen, 1991a; Tønnesen, 1991b; Tønnesen, 1993; Tønnesen, 1996; Tassis et al., 2014) and in some other areas in Norway (Tønnesen, 1978; Gellein et al., 2005).

2. DATA ACQUISITION & PROCESSING

2.1 Data acquisition

Collection of gravity data has been done with a Scintrex CG5 gravimeter. In total the survey consists of 175 gravity stations with 133 of them positioned along 5 profiles with normally 100 m spacing between the stations (**figure 1**). The other 42 gravity stations are regional measurements mainly located on bedrock exposures found outside the sediment region. All profiles begin and end with measurements on exposed bedrock localities and are used as anchor points when modelling. In order to control diurnal drift, designated measurements have been taken at a base station next to Melhus Church. All of these data were tied to the Norwegian Mapping Authority's base gravity station at the NGU for the correction to the absolute value of the gravity field. The distance between the gravity stations along profiles was normally measured by counting steps, while positioning and topography elevations were determined with the use of a differential GPS (Topcon Legacy) giving normally a height and position accuracy better than 10 cm.

The gravity survey was planned by Jomar Gellein and Jan Steinar Rønning. Jomar Gellein did all the gravity measurements (7 days between September 23rd and October 14th 2015) and taken care of all the levelling work of the gravity stations. Additionally, he has performed all pre-processing of the gravity data after the fieldwork period was finished.

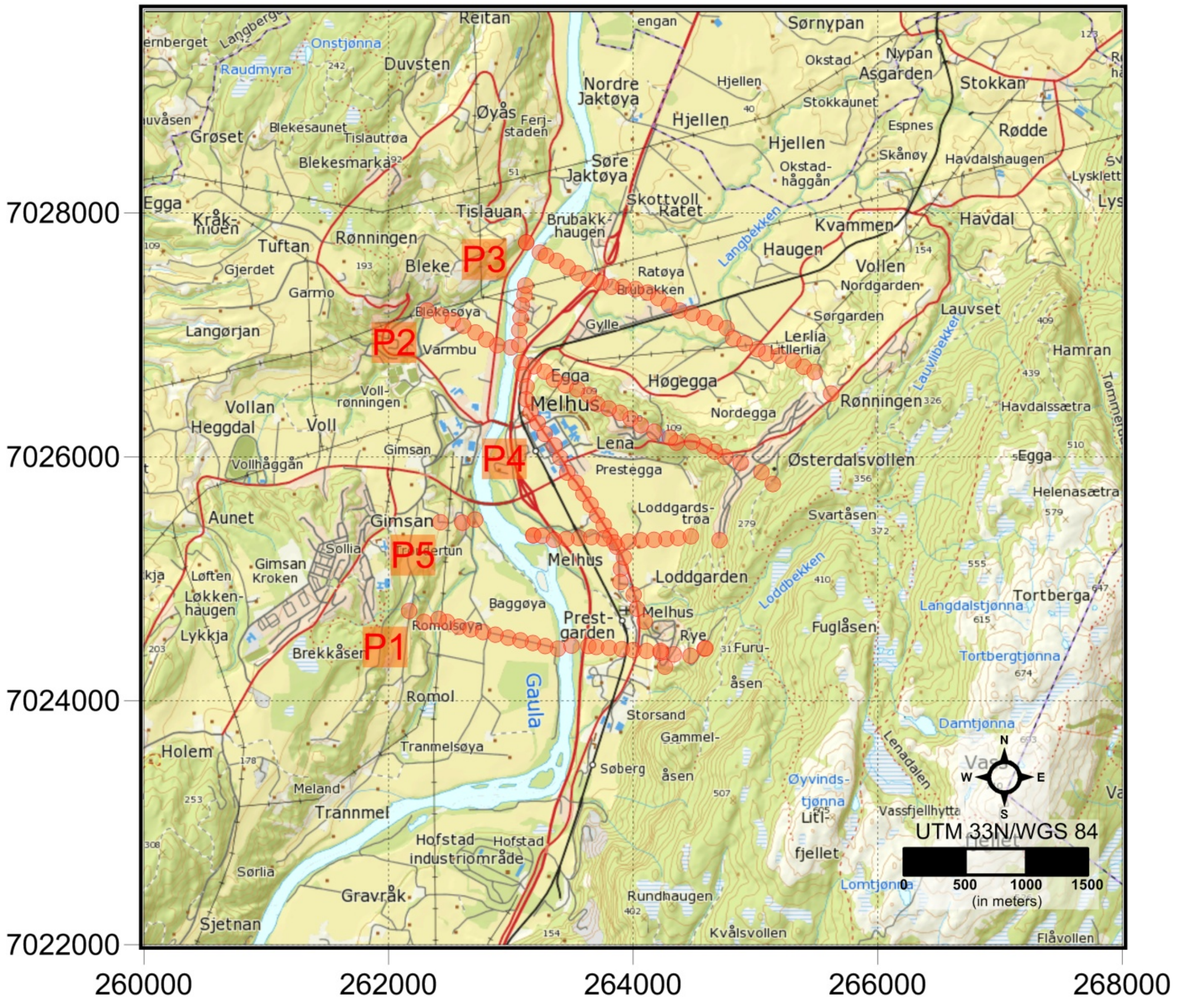

Figure 1: Distribution of gravity measurements along profiles in the Melhus area.

Four out of five gravity profiles are sub-parallel to each other covering the area of the Melhus city center. One profile (profile number 4 - **figure 1**) runs diagonally from the NW corner to the SE one and will be used as a means of control for the area between the sub-parallel profiles. The dimensions of the study region are roughly 3.5 km for both axes resulting in a total area of about 12 km^2.

2.2 Data pre-processing

The measured gravity data was first corrected for the diurnal drift and then for the free-air effect wherever this was needed. Conversion to Bouguer anomalies was conducted by the standard NGU procedure (Mathisen, 1976). Both Bouguer and terrain corrections have utilized the standard density of 2,67 g/cm^3. For the immediate neighboring area around the measuring points, the terrain correction was determined from point elevation data selected with the use of 5 circles with radii of 50, 100, 200, 400 and 800 m respectively and 8 points per circle.

3. BACKGROUND DATA

In order to be able to successfully process and interpret the Bouguer anomalies present in our profiles, it is important to have sufficient knowledge of the geology of the region and realistic density values for both bedrock and quaternary sediments. Therefore, it is essential to establish which formations will be included in our models as dictated by the geology of the region and subsequently, what dimensions should they have (depth and superficial spread) and what density. This kind of additional data may come from geological maps of the Melhus area (bedrock and quaternary), as well as density of rock samples in the region and drillings that have reached as deep as bedrock. The NGU is in possession of such data which have been selected, evaluated and employed in our modeling procedure. Furthermore, the Melhus city center area has been subjected to other geophysical and modeling methods whose results aid us in further constraining the final product of this report.

3.1 Bedrock geology and petrophysical properties

The wider area can be divided in three main lithological groups. These are the Gula Group (Cambrian mica schist), the Støren Group (Ordovician greenstones) and the Hovin Groups (Ordovician sandstones and shales). No petrophysical sampling has been done by the NGU in the area during recent years.

According to Åm et al. (1973), the greenstones in the area have an average density of 2.84 g/cm^3. Skilbrei (1990) has collected a large amount of samples in several areas in Sør- and Nord-Trøndelag counties albeit not within our area of interest. The greenstone samples belonging to the Støren Group present a density which varies from 2.72 to 3.40 g/cm^3 (94 samples gathered in areas neighboring our study area) with the areas nearest to Melhus being between 2.80 and 2.90 g/cm^3. Taking all available data into account, a value of 2.85 g/cm^3 was chosen as a fairly good approximation for the density of the bedrock formation used in the modeling procedure.

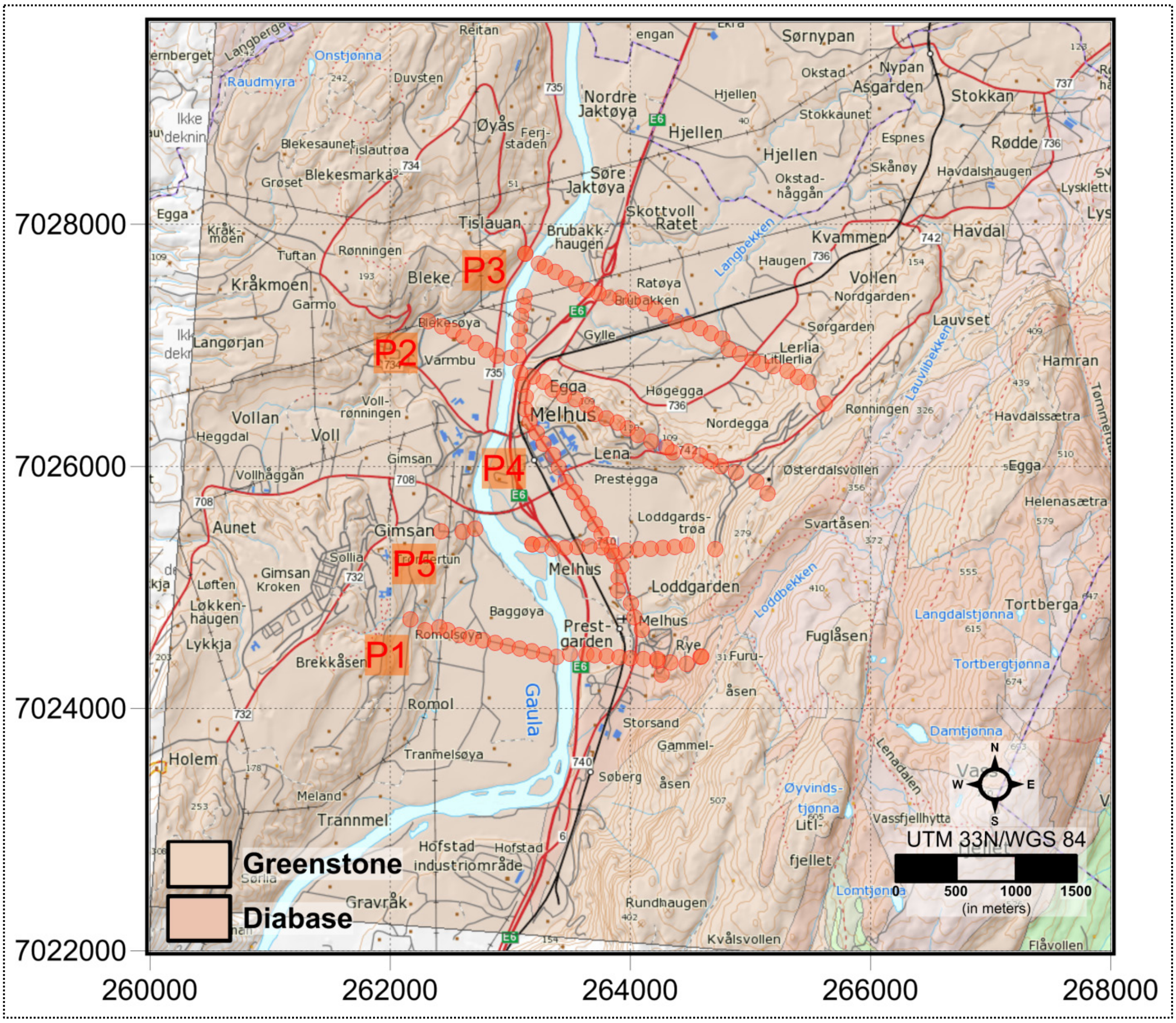

Figure 2: Positioning of gravity measurement profiles in relation with major bedrock formations of the Melhus area (http://geo.ngu.no/kart/berggrunn/, Bedrock map 1:50000).

3.2 Drilling information and depth to bedrock

The Melhus area contains a number of boreholes drilled mainly at Melhus city center and some other localities which can be used as a direct regulating factor in gravity modeling. From a total record of almost 28 drillings that coincide with our study area, only 6 managed to reach bedrock. The ones that haven't managed to reach bedrock are mainly clustered around the Melhus city center and the deepest of them drilled 87 meters of sediments without meeting any bedrock. Some of them offer information on the layering within the sediments but this issue will be addressed in the following section. Drillings that have indeed reached bedrock will be used as point values to constrain gridding at the end of the interpretation process.

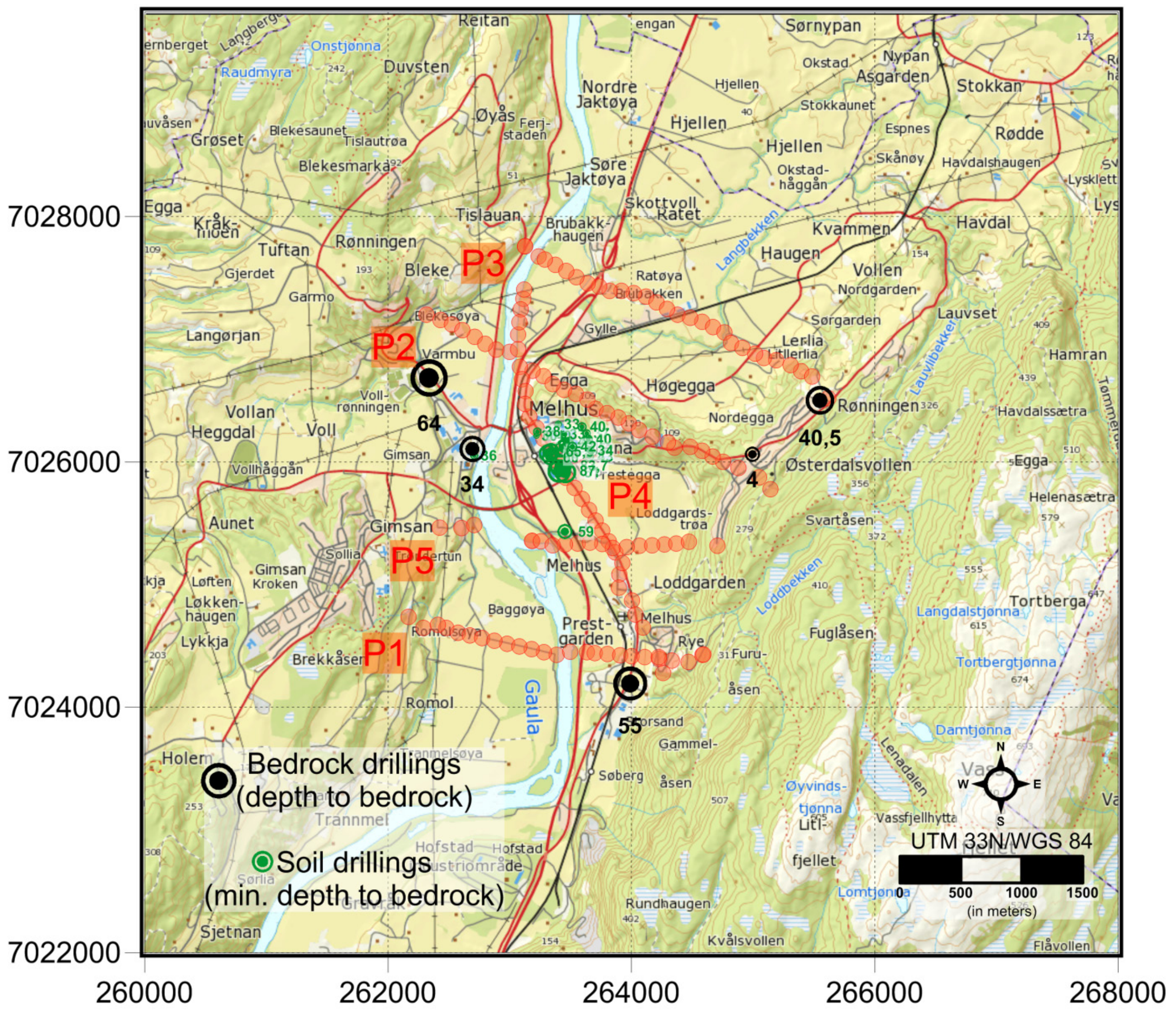

Figure 3: Positioning of NGU monitored boreholes in the Melhus area. Symbols sized in respect with the depth they represent, both for bedrock (black) and soil depth (green). Orange dots depict gravity profiles. Data from NGU database GRANADA.

Table I shows the particular boreholes that have been drilled to bedrock (fjellbrønn) while **table II** shows those that have not. These drillings indicate the minimum depth at which bedrock may be found. Unfortunately, only a handful of drillholes had indeed reached bedrock within the survey area. On the other hand, the dense drilling performed at Melhus city center failed to pierce through the whole thickness of the sediments which appears to be significant. However, we may at least consider that sediment layers in this subarea are more than 87 meters thick and apply this information as a constraint in the modeling.

Drill number	Easting UTM 33N	Northing UTM 33N	Depth to bedrock
38831	264993	7026062	4
37194	265550	7026501	40.5
52096	263924	7024193	55
52095	263989	7024193	55
54454	262692	7026106	34
Idrettsvegen 1	262338	7026684	64

Table I: Bedrock drillings (Data from NGU database GRANADA).

Drill number	Easting UTM 33N	Northing UTM 33N	Total borehole depth
359	263771	7026399	14
6813	263314	7026212	40
51517	263438	7026112	65.5
51516	263463	7026136	60
80480	263650	7026042	43
82705	263313	7026069	69
72453	263456	7025914	81
72455	263417	7025968	83.7
74261	263405	7025927	87
74251	263481	7026161	45
74250	263442	7026226	33
74249	263397	7026307	33
64110	263218	7026213	30
64111	263227	7026247	38
87139	263327	7026035	60
87103	263631	7026232	37
86942	263338	7026083	65.5
8341	263642	7026185	40
8340	263594	7026286	40
6809	263670	7026092	34
54248	262708	7026050	36
49436	263454	7025431	59
77648	263513	7026125	42

Table II: *Drillings that haven't reached bedrock. Data from: NGU database GRANADA.*

3.3 Deposits/Sediments

The surface in Melhus is dominated by thick marine deposits, which in some places are overlain by fluvial sediments (**figure 4**). Observing topography one can easily identify a rise in the terrain at Melhus city center (Egga) which can be interpreted to be the remains of a glaciofluvial marginal deposition accumulated at the front of a glacier during the last ice age, about 10,000 years ago. Sediments consist of a 5 to 30 m thick layer of clay overlaying sand and gravel (Hugdahl 1979; Multiconsult 2006). Such an interpretation is also supported by drillings carried out in connection with geothermal energy projects in Melhus center. Samples that have been collected and then tested in the laboratory show that the clay cover is partly quick clay (Multiconsult 2006). It is believed that the Melhus uplift was extending throughout the valley's width toward Gimsan, but probably not as high as in Melhus city center. Later isostatic uplift and erosion of the river Gaula interrupted marginal deposition. As in Brubakkhaugen, mudslide masses of alluvial deposits are also found at Melhus city center. These sediments are described in detail in Hansen et al. (2007).

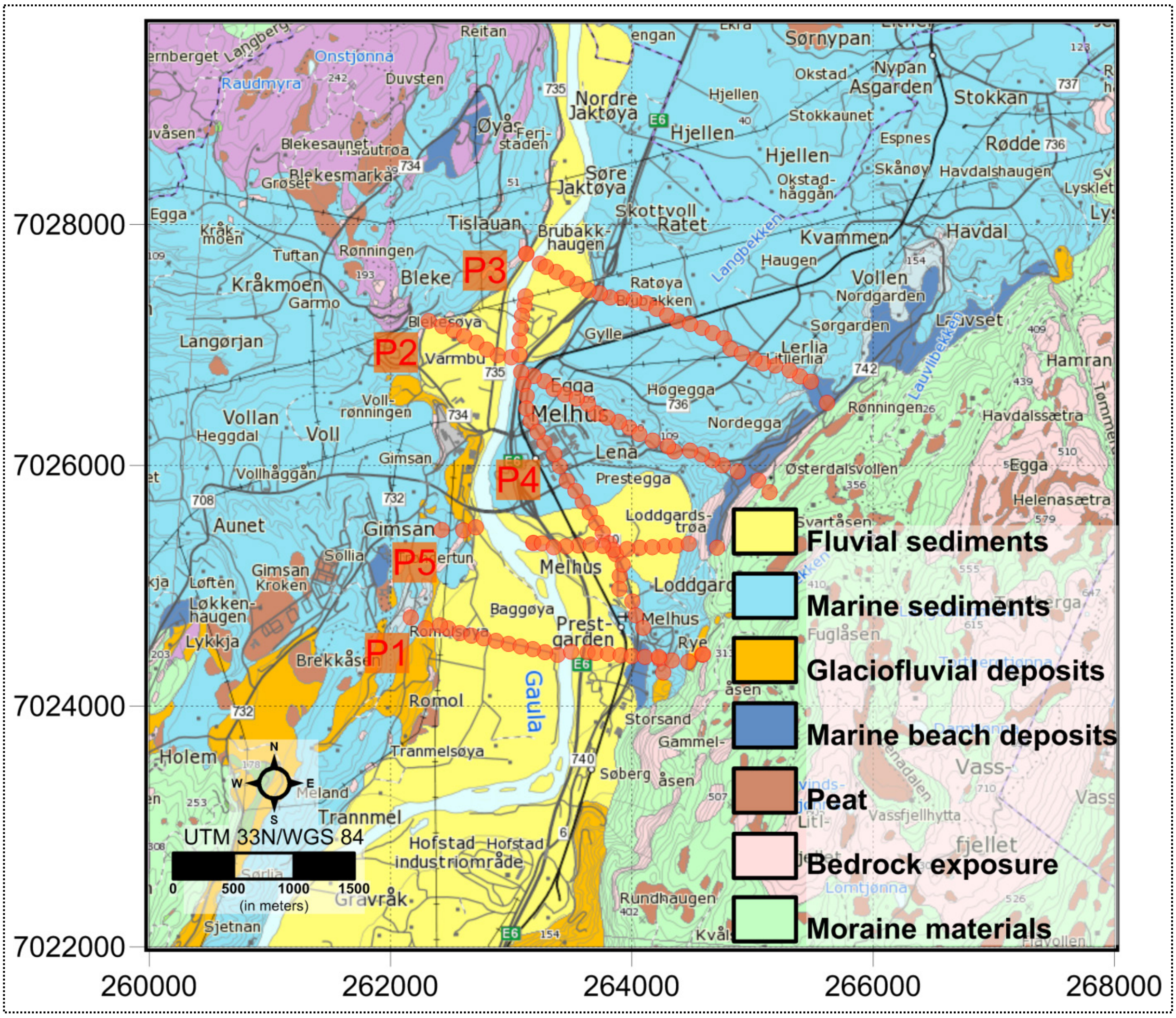

Figure 4: Map of quaternary deposits/sediments in the Melhus area in relation with the gravity measurement profiles (http://geo.ngu.no/kart/losmasse/).

As can be seen in **figure 4** our profiles are first and foremost crossing fluvial (sand and gravel) and marine (clay) sediments. Several of the aforementioned drillings, regardless of not reaching bedrock, have revealed that these sediments if combined can have distinctive thicknesses (30 meters or more) and can possibly be underlain by moraine. In gravity, formations of slight density contrast (~0.20 g/cm^3) do not have a visible effect in the modeling procedure unless bearing a thickness which is at a scale of tens of meters. In this sense, our modeling has been focused on marine sediments (clay/silt), sand/gravel (fluvial and glacifluvial) and moraine. The densities of the Quaternary deposits in our region are believed to range from 1.8 to 2.2 g/cm^3 for both fluvial and marine sediments, depending mainly upon the porosity. For moraine, the densities range from 2.2 to 2.5 g/cm^3 according to the degree of compaction and the clay content (Grønlie & Jørgensen, 1974). For our models we have used an equal density value of 1.9 g/cm^3 for both clay/silt and sand/gravel and 2.2 g/cm^3 for moraine. The choice of density values was determined in accordance to long time experience within the NGU but also in order to yield a mean density of 2.0 g/cm^3 for the entire sediment layer in Melhus. The reasoning for this will be described in following sections.

3.4 Additional geophysical/geological studies in Melhus

Sediment thickness has been already surveyed with the use of gravity in neighboring areas during previous years by Tønnesen in Gaulosen (1991) and Trondheim (1995) and Tassis et al. in Orkdalen (2014). These studies offer a good basis for gravity modeling. **Figure 5** shows that the Melhus area has also been subjected to other geophysical profiling in the past. This additional information can be used as a further constraining tool but also as knowledge pool for reaching a satisfactory result.

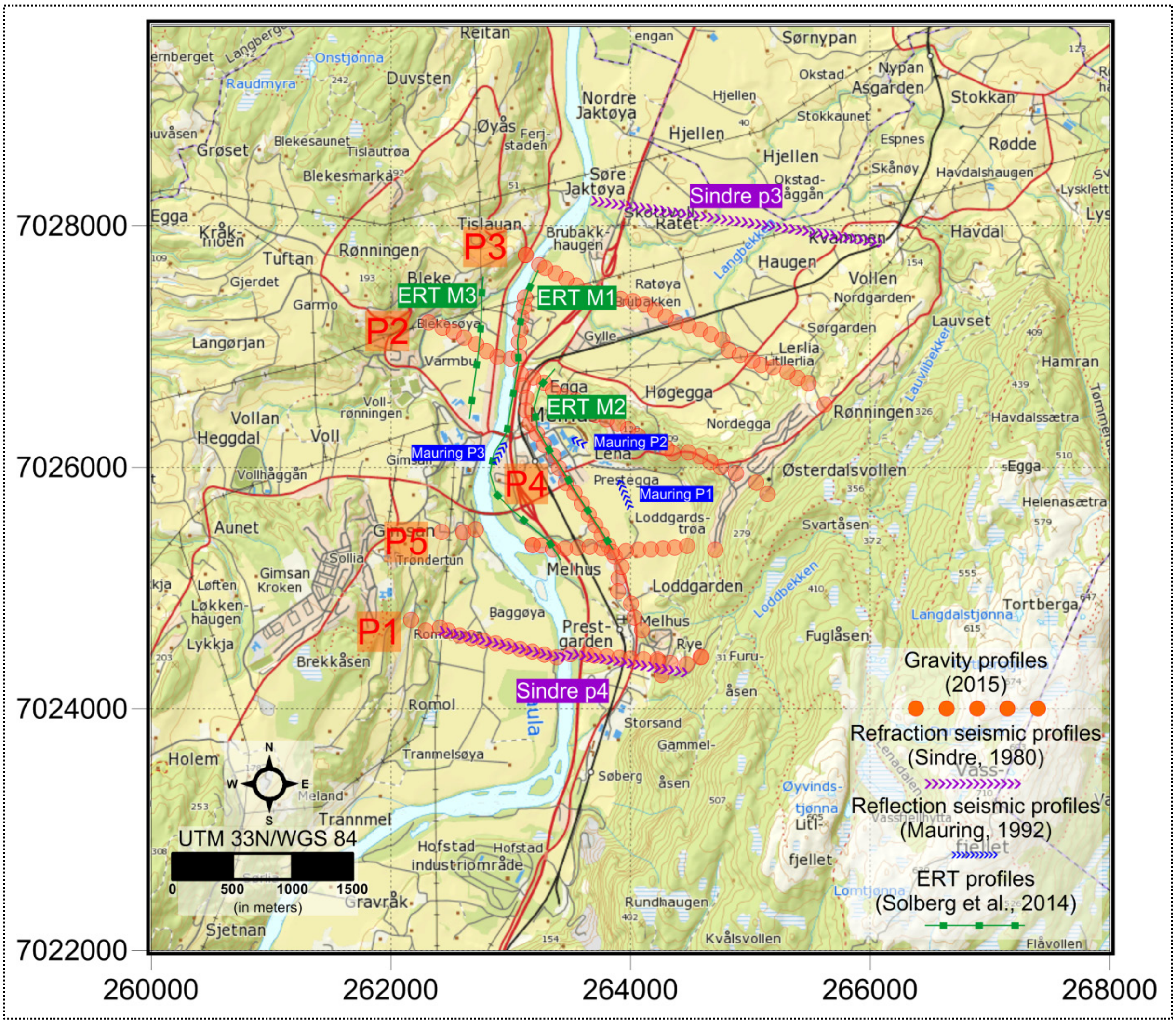

Figure 5: Older geophysical profiling in Melhus in relation to the gravity profiling (ERT: Electric Resistivity Traversing, Sindre lines are refraction while Mauring lines are reflection seismic)).

Two sets of seismic profiling have been done in the area and their results published in NGU reports. First by Atle Sindre (1980) with a series of refraction seismic lines enveloping the Gaula river from Gaulosen to the north until Hovin to the south. As can be seen in **figure 5**, refraction seismic profile 4 (numbering as in original report) coincides almost entirely with gravity profile 1. Seismic profile 3 on the other hand lies north of gravity profile 3 at a distance varying from 700 meters to 1.4 kilometers. Both of these profiles may be used as constraining factors with emphasis given on seismic profile 4 which can help us calibrate the densities used in gravity profile 1 in a more accurate manner.

Eirik Mauring (1992) has also performed a number of small reflection seismic lines in areas close to Melhus city center in order to map depth to bedrock which is indicated to be deeper than 200 meters. His profiles do not coincide with any of our gravity lines but his results are covering areas where no information on depth to bedrock can be obtained by gravity. Therefore, his interpretations can help construct a better depth to bedrock grid at the end of the modeling and interpretation procedure for the gravity data.

Same applies for the ERT measurements performed by Einar Dalsegg as part of a project aimed at mapping sedimentary formations in Melhus by Solberg et al. (2014). As can be seen in **figure 5**, parts of the ERT profiles match parts of the gravity profiles (beginning of M1 with beginning of gravity profile 4, mid to end M2 with mid to end gravity profile 4) which can be potentially useful in the modeling procedure wherever this is rendered possible due to the limited survey depth compared to gravity modeling. However, in central parts of the valley, the ERT do not reach down to bedrock.

The master's thesis by Førde (2015) is dealing with numerical modeling of Quaternary geology in Melhus city center area. In her dissertation, one may also find the results of applying drilling information to produce geological cross sections displaying the structure of different sediment formations. Although the deeper layers of these profiles are based on intuition and not on actual data, the superficial layering between clay/silt and sand/gravel could be used in our gravity models. However, considering the fact both these layers have almost identical densities, it is not possible to be distinguished during gravimetric modeling. These two layers will be considered as one in the following sections.

4. DATA MODELLING AND DENSITY CALIBRATION

Additionally to the conversion of raw gravity into Bouguer anomalies which has been performed by Jomar Gellein, the regional field must be removed from all profiles in order to isolate the anomaly caused by the sediment layers in the survey area. Local and regional trends often mask the target gravity effects considerably. Sometimes regional gravity trend effects may exceed local desired anomalies by some tenfold although not in a study area of this size. Therefore, this field which is due to geological sources of a much larger scale must be removed before proceeding to the modeling procedure.

Furthermore, having decided that a representative density for greenstones at Melhus is 2.85 g/cm^3, an equally educated assessment must be made for the density of the sediment formations thought as a whole. In order to calibrate the soil density, seismic profile 4 interpretation (Sindre, 1980) will be utilized as a constraint. We will try to match the bedrock interpretation in that profile by maintaining a constant bedrock density and modifying the sediments in profile 1 (**figure 5**) until the bedrock interpretation resulting from gravity modeling is as close as possible to the seismic profile.

4.1 Removal of regional trend

The regional gravity field in the wider Melhus area can be seen in **figure 6**. The contour grid has been compiled with Kriging method using the Bouguer gravity values produced for this present survey as well as measurements resumed in the previous years (red stars). A general regional trend that can be identified presents an increasing in the field towards the southeast.

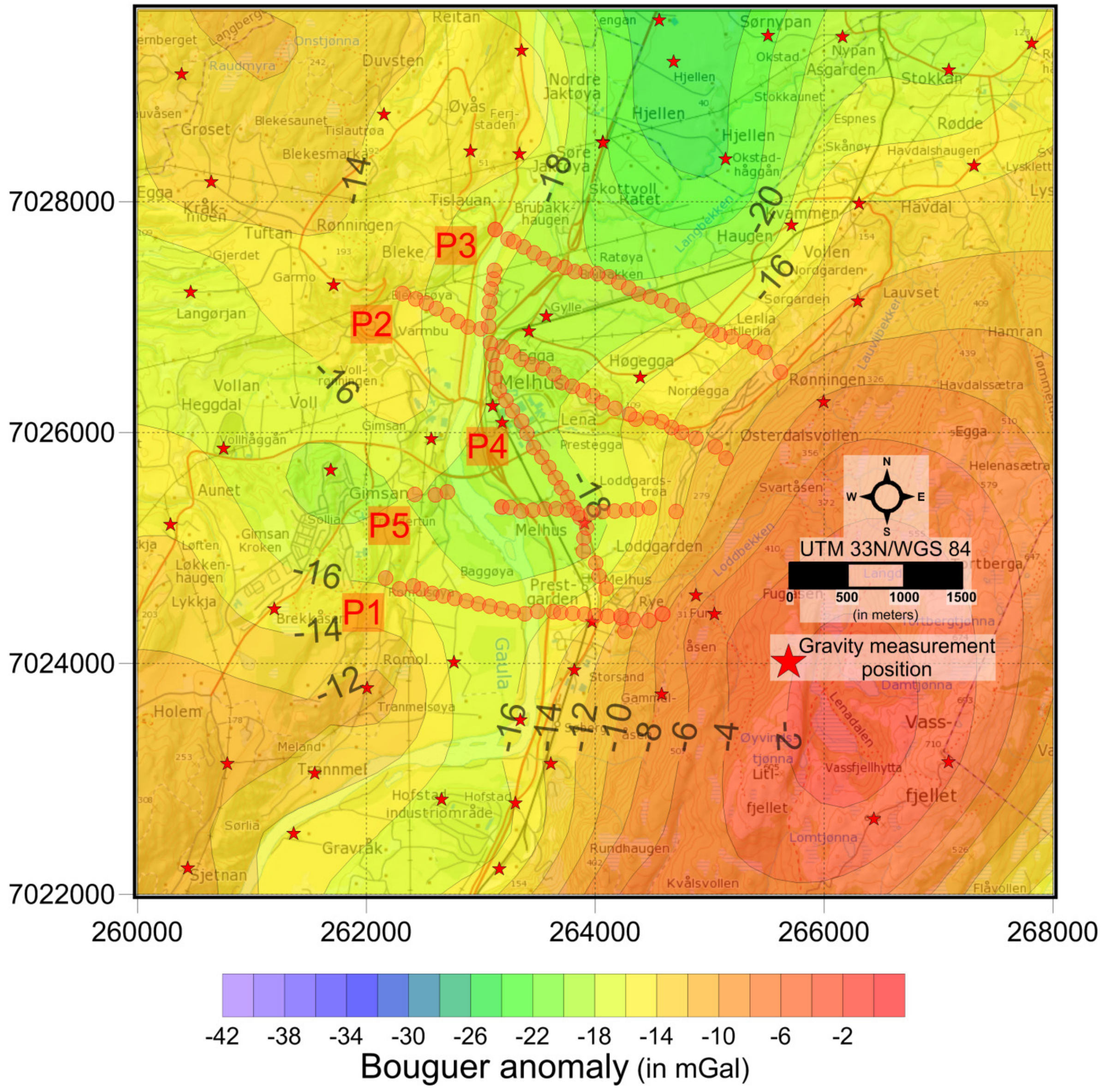

Figure 6: Bouguer anomaly distribution in the wider Melhus area. Data from measurements performed in this project (orange dots) and NGU database DRAGON (red stars).

For the removal of the regional trend the following method was applied: all profile edge points have been fitted with a first order polynomial (linear). Each profile was then subtracted from its respective linear field and the resulting profile represents the residual field. The whole procedure is shown in **figure 7** where results are presented. Linear fitting was preferred due to the relatively small size of the survey area and the limited length of the gravity profiles. All mathematical operations performed during the regional field removal process have been compiled in a MATLAB code which yields the residual profiles automatically. **Figure 7** presents the regional removal results for gravity profile 1 only. Results for the rest of the profiles are in accordance to the scheme in **figure 7** and present a similar form in respect with the gravity increase trend towards the southeast.

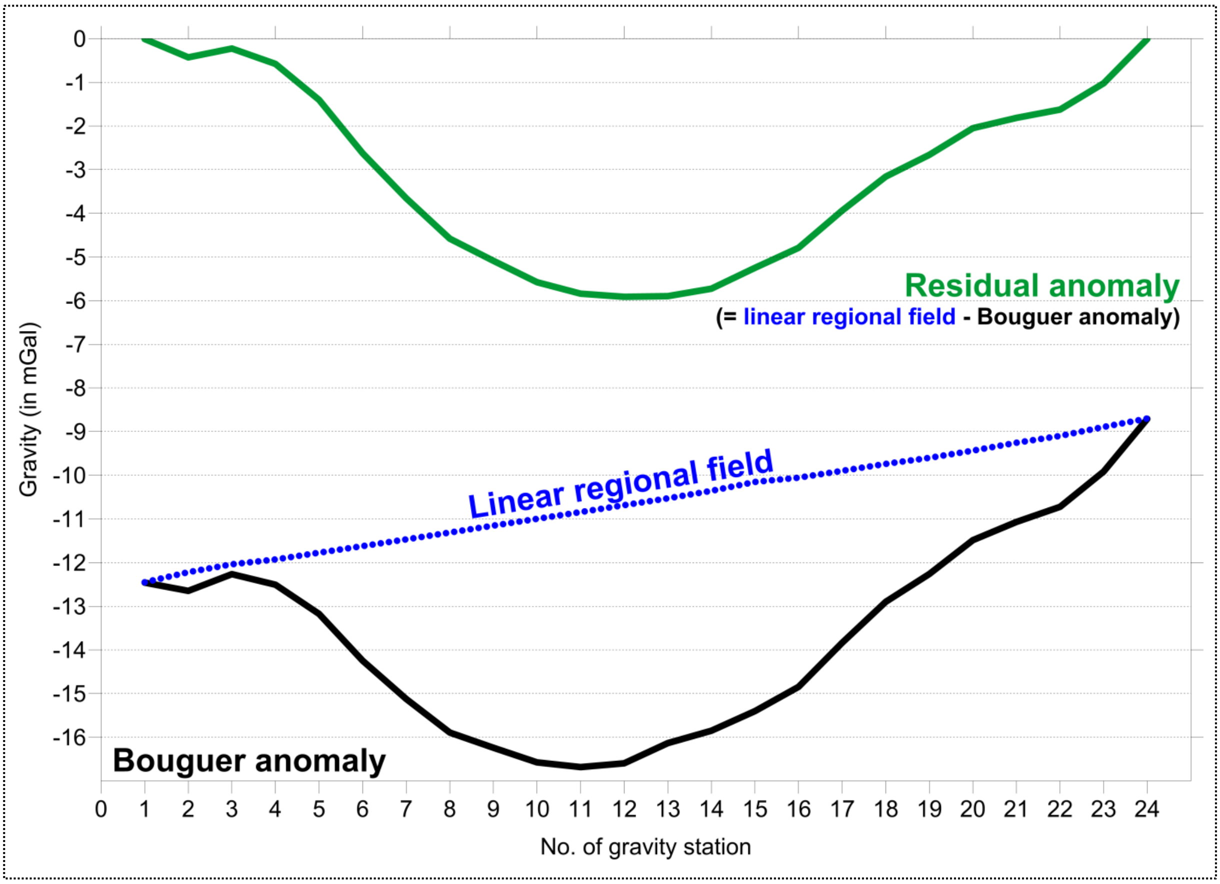

Figure 7: *Fitting of a polynomial regional trend on the extended P1 profile (top) Results of removing the regional trend from the original Bouguer anomaly (bottom)*

The residual field for each profile is the isolated anomaly caused by low density formations in the Melhus area, stripped of the broader regional field. The resulting gravity varies between -10.85 to -0.21 mGal with the highest residual anomaly variation found in the northernmost profile (10.1 mGal - P3) and the lowest in the southernmost (5.44 mGal - P1). This is a first indication that there is an increase in sediment thickness and volume from south to north which causes a respective increase in the observed Bouguer anomaly.

4.2 Density calibration

After producing the residual gravity field, the next step is to proceed to the actual modeling. However, constraining the procedure beforehand is essential to diminish the non-uniqueness problem plaguing gravity modeling. In this sense, all additional information connected to the formations appearing in the models and their respective densities and dimensions (thicknesses) will be used to narrow down the possible outcomes and force our models to be precise.

Modeling has been performed with the use of GM-SYS GX menu of the Geosoft Oasis Montaj software Version 8.1. In all cases we have used a reduction density equal to 2,67 g/cm^3 while each gravity station has been placed on the measured topographic height. The maximum half space depth for all our models was set equal to 1 km while in the horizontal sense, the model block rectangle was extended 30 km more than its normal length towards both directions (2.5 D modeling).

Every gravity model contains at least two geological formations. Two formations in a model equal to four unknowns i.e. their geometrical shape (thickness vs. horizontal expansion) and densities. Three formations equal to six unknowns and so forth. Essentially this means that the more formations we add to our models, the more complex the problem becomes. Therefore, it is always advisable to begin with a simplified model containing two formations i.e. bedrock and soil. As already mentioned, the greenstone density in the area is 2.85 g/cm^3 and its morphology has been already outlined by seismic line 4 (Sindre, 1980). In this way, using gravity modeling trying to match the morphology of bedrock by locking its density to 2.85 g/cm^3 and indirectly constraining the geometrical shape of the soil formation between bedrock and topography, leaves us with an equation with one unknown. In other words, by "knowing" the dimensions of bedrock and soil and the density of bedrock we can deduce the density of soil. This procedure is shown in **figure 8** for profile 1 versus seismic line 4 by Sindre (1980).

As can be seen in **figure 8**, we have shaped our model's bedrock formation in such a way that the modeled gravity (continuous black line - top graph) matches the observed gravity (dots - top graph). However, this can happen if only the soil acquires a density equal to 2.0 g/cm^3. This density represents a mean density for all the different sediment formations contained within the geometric shape we have given to soil. This value is in good agreement with the value Tønnesen (1991) has used in his modeling of Gaulosen, just north of the current survey area. It should be noted that the area to the east of the profile were discrepancies between interpretations is larger, may be due to the fact that the terrain is rather steep in the area and steep terrains induce errors and uncertainties in the seismic results. However, a pretty good match has been achieved in terms of overall shape and maximum depth to bedrock, therefore further modeling will be performed using this 2.0 g/cm^3 as a sediment density for all other profiles.

Figure 9 presents the results of the same procedure in the north. In this case, the seismic line number 3 does not coincide with our northernmost profile number 3. However, it is useful to see how the application of the calculated soil density from the profile in the south will delineate bedrock in the north following the same procedure. Sindre's report (1980) indicates that sediment thickness is increasing towards the north, reaching a value of 450 meters at the Gaula river delta region. This means that seismic line 3 should illustrate deeper sediments than the projected result from gravity profile 3.

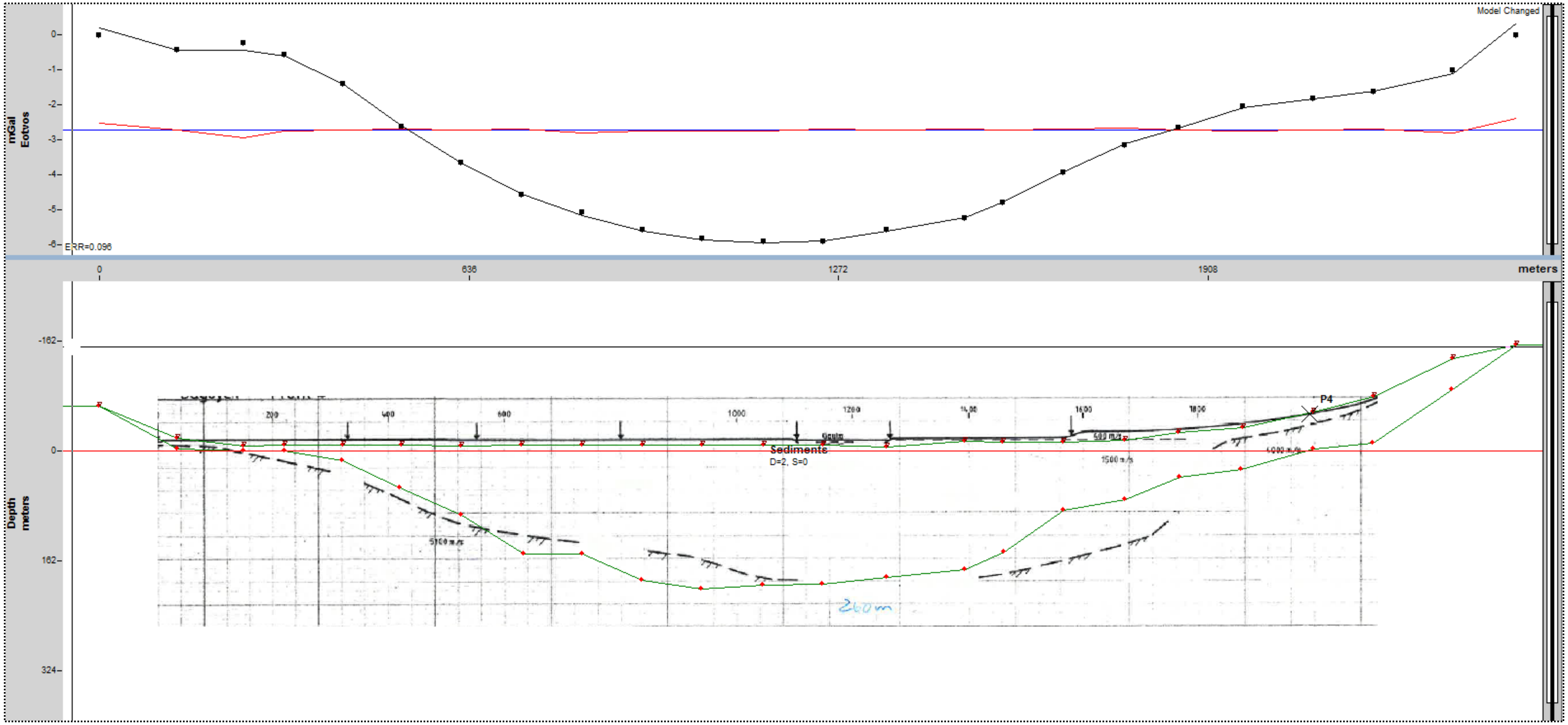

__Figure 8:__ Depth to bedrock interpretation using seismic profile 4 (Sindre, 1980) to constrain gravity modeling along gravity line 1. Bottom: cross sections superimposed - gravity interpretation (green line with red dots) versus seismic depth to bedrock delineation (black line) Model soil density is 2.0 g/cm^3. Top: Residual anomaly (black dots) versus calculated gravity based on the model below (continuous black line). Red line represents error (standard deviation - does not follow the axis units).

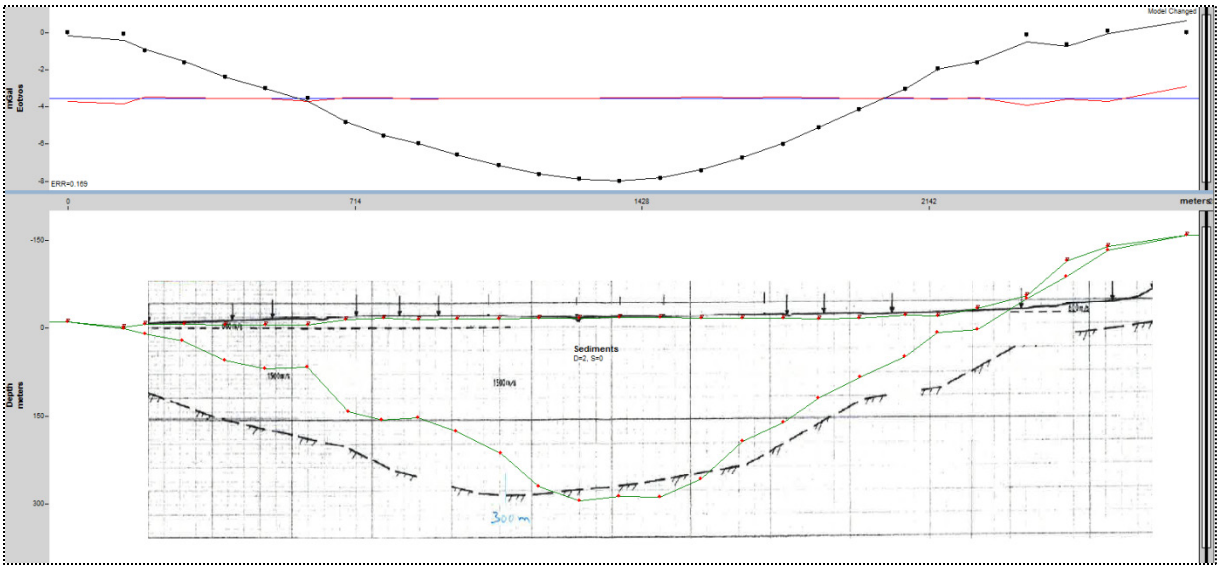

Figure 9: *Depth to bedrock interpretation using seismic profile 3 (Sindre, 1980) to constrain gravity modeling along gravity line 3 and soil density equal 2.0 g/cm^3. Bottom: Cross sections superimposed - gravity interpretation (green line with red dots) versus seismic depth to bedrock delineation (black line). Top: Residual Bouguer anomaly (black dots) versus calculated gravity based on the model below (continuous black line).*

As can be seen in the bottom part of **figure 9** our expectations are met. The bedrock morphology shown with a green line (gravity interpretation) lies shallower than the black line which illustrates bedrock as derived from seismic interpretation. This means that a soil value of 2.0 g/cm^3 (density contrast 0.85 g/cm^3) is a good estimation for the entire survey area and no severe variations in soil density are expected.

Having determined a satisfactory mean density for sediments and considering the fact that this formation consists mainly of clay/silt, sand/gravel and possibly moraine as indicated by adjacent drilling, the sediment formations can be further split into these bodies. However, no information are available regarding densities in these materials, therefore this approach is done for academic purposes only. Clay/silt and sand/gravel were assigned densities of 1.90 g/cm^3 and moraine one of 2.20 g/cm^3. The fact that clay and sand/gravel have approximately the same density robs us of any chance of differentiating these two formations with the use of gravity. As already mentioned, these two formations will be considered as one, knowing that sand & gravel dominate over clay in all cases. The clay/silt/sand/gravel and moraine limit on the other hand can be thought of as a problem of two equations with two unknowns. Using the same notion as before, the shape of the whole soil formation is kept constant and by assigning the aforementioned densities to these sub-formations, we let gravity decide the thickness of moraine and at the same time the one of sand & gravel/clay i.e. their thicknesses were modified accordingly for the calculated gravity to match the observed one. More information about this will be given in the following section.

5. MODELING RESULTS AND DESCRIPTION

Each interpreted profile is illustrated in two parts. Bottom part contains the resulting cross section which shows the formations included in the models, the densities attributed to them during processing and their eventual calculated dimensions. Clay/silt/sand/gravel is shown in orange/blue and moraine in green color while bedrock is shown in brown. Doing so, we have tried to present results which are coherent with the already existing maps. All models have been plotted down to 300 meters of depth. Both axes are in meters and the X and Y axis ratio is 1:1. In this way, the depth of sediments illustrated can be seen in its true extent compared to its lateral dimensions. A general direction of each cross section is given at the beginning and end of the X axis with geographical coordinates in the WGS 1984 system. Beginning and ending of each profile as well as general direction are given in **table III** in WGS84, UTM zone 33N.

Top part shows the values of the residual anomalies at the observed measuring points (black dots), the calculated values from the model (blue line) and a graph of the mathematical error of the model (red line). All graphs contain a legend which is showing the color correspondence, as well as the arithmetical value of the calculated error. The calculated error is equal to the standard deviation of the differences between observed and calculated residual values in each point in model. We should also note that the error curve does not correspond to the Y axis scale. The error value in each figure represents the standard deviation of the differences between measured and calculated gravity for the entire profile. The red line on the other hand represents the plot of these differences in each station. Y axis represents the gravity value range which is not the same for the differences. The plotting takes place after adding to these differences a mean value corresponding to the minimum and maximum value of the Y axis of each profile in order to plot them along with the measured and calculated gravity. This was done in order to highlight areas where the model is less reliable i.e. areas where the red line is deflecting from its horizontal mean value. A straight line means good model fitting.

Profile no.	Beginning		Ending		Direction	Total length (in meters)
	Easting	Northing	Easting	Northing		
1	262167	7024739	264585	7024426	WNW-ESE	2502
2	262317	7027202	265141	7025778	NW-SE	3216
3	263124	7027758	265617	7026521	NW-SE	2854
4	263124	7027758	264259	7024279	NNW-SSE	3829
5	262425	7025464	264706	7025316	W-E	2322

Table III: *Coordinates of beginning and ending of each gravity profile in UTM 33N/WGS84 as well as their general direction.*

All resulting models have been exported from GM-SYS and illustrated in Golden Software's Surfer 12 program, version 12.8.1009 (64-bit). This was done in order to create a more presentable illustration of our results.

5.1 Profile 1

Profile number 1 is the southernmost profile in the study area. It is situated at the south end of the survey region with Melhus city center lying about 1.7 km to the north. It is 2502 meters long and contains 24 gravity measuring points. Both starting and ending points are measured on exposed bedrock while the general direction of the line is WNW to ESE. The profile is crossing Gaula halfway with measurements performed on both river banks. The Bouguer anomaly variation is equal to 6 mGal and the maximum anomaly effect of the sediments is about 5.5 to 6.0 mGal in the area between 990-1250 meters.

As we can see in **figure 10**, sediments in the area reach a maximum depth of ~195 m below sea level central in the profile (~205 m total thickness) at about 1100 meters of horizontal distance. The sediment formation is then gradually reduced in thickness towards both ends, but with a higher rate towards the west-northwestern side. Bedrock is set equal to a density of 2.85 g/cm^3 as described in the previous sections while the block representing sediments was divided into two separate formations: (i) Sand & gravel/clay with a density of 1.9 g/cm^3 and (ii) Moraine with a density of 2.2 g/cm^3. The only drilling to bedrock information available for this profile is a depth of 55 m at the eastern part of the profile and 200 m to the south (**figure 10**) which provides us with the information that sand & gravel/clay are expected at least down to 55 meters. The calculated error for this modeling result is 0.101 which means that our model is pretty accurate in a mathematical sense.

As described above, we have assumed that moraine is overlaying bedrock at the bottom of the sediment block. Thereby, model for profile 1 has been constructed with moraine underlying gravel and overlying greenstones. The differentiation of sediment layers is based on the geometrical shape of the sediment valley which has been determined beforehand with the use of a mean density of 2.0 g/cm^3. Using the densities for gravel and moraine specified in the previous paragraph**, one possible solution** is a valley filling of clay/silt and sand/gravel down to 135 m and 70 m of moraine below that. In this way, we match the gravitational effect of a single density sediment block by adjusting the surface between sand/gravel and moraine. It should be noted that these thicknesses are as accurate as the assumptions made about the densities of the gravel and moraine and refer to this density setting alone.

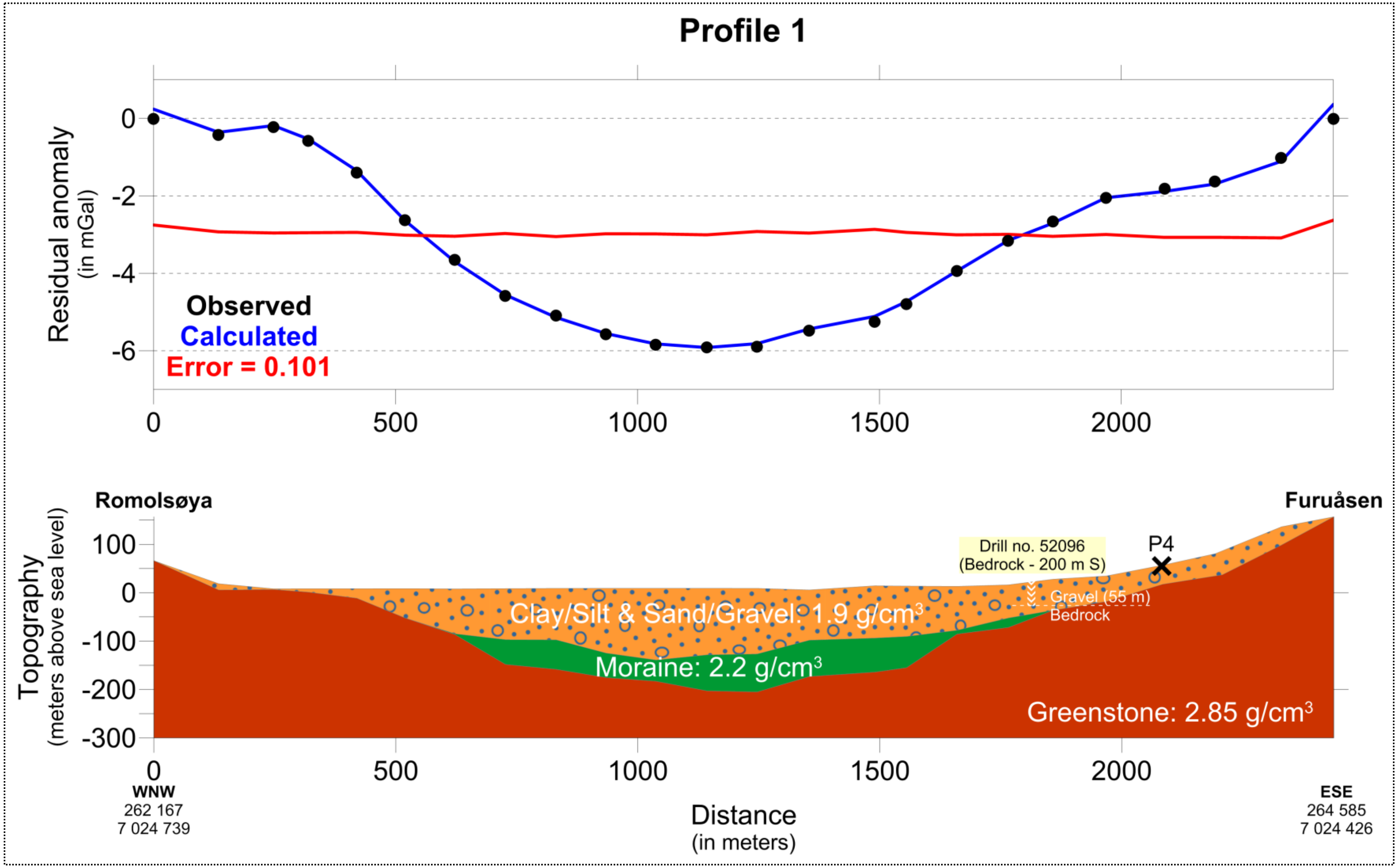

Figure 10: *Modeled depth to bedrock - Profile 1. Bottom side: cross section showing the sediment formation dimensions (in meters) and distribution as well as utilized densities for both sediments and bedrock (in g/cm^3). Top side: Observed and calculated gravity data graph with error estimation (red curve).*

5.2 Profile 2

Profile number 2 is situated about 2 km north of profile 1 in a sub parallel position. The distance from profile 1 is about 2500 m in the NW and 1500 in the SE end. It crosses the valley on top of "Egga", a topographical uplift filled with glaciofluvial sand/gravel with marine sediments on top (Clay/silt, Hugdahl 1979). Profile 2 has a total length of just over 3200 meters. It consists of 29 gravity measurements roughly taken every 100.

The general direction of the profile is NW to SE. Once again both end points have been measured on exposed bedrock in order to facilitate the modeling process. The Bouguer variation along the profile is about 8 mGal, and the maximum anomaly effect of the sediments is found in the area between 1650-1850 meters. The modeling procedure has attributed this anomaly to a sediment layer which is ~315 m thick after 1750 meters of horizontal distance. Not that this increased depth to bedrock is partly explained by a topographical high.

Figure 11 illustrates the shape of this low density body which is similar to the one in profile 1. Sediment depth is again diminishing towards the profile's ends, giving its place to exposed bedrock. This time bedrock rises more abruptly to the east instead of the west. Unfortunately, the drillings matching profile 2 have not reached bedrock but they have provided us with three clay thickness point measurements (max. 14 meters). The error for this modeling setup is 0.356 which is relatively high due to the fact that the observed gravity values follow a rather ragged path.

It is not possible to distinguish clay/silt from sand/gravel with the use of gravity since they share densities and therefore both these formations are displayed together. A possible model is clay/silt and sand/gravel with a thickness of ~205 meters on top of 85 m of moraine.

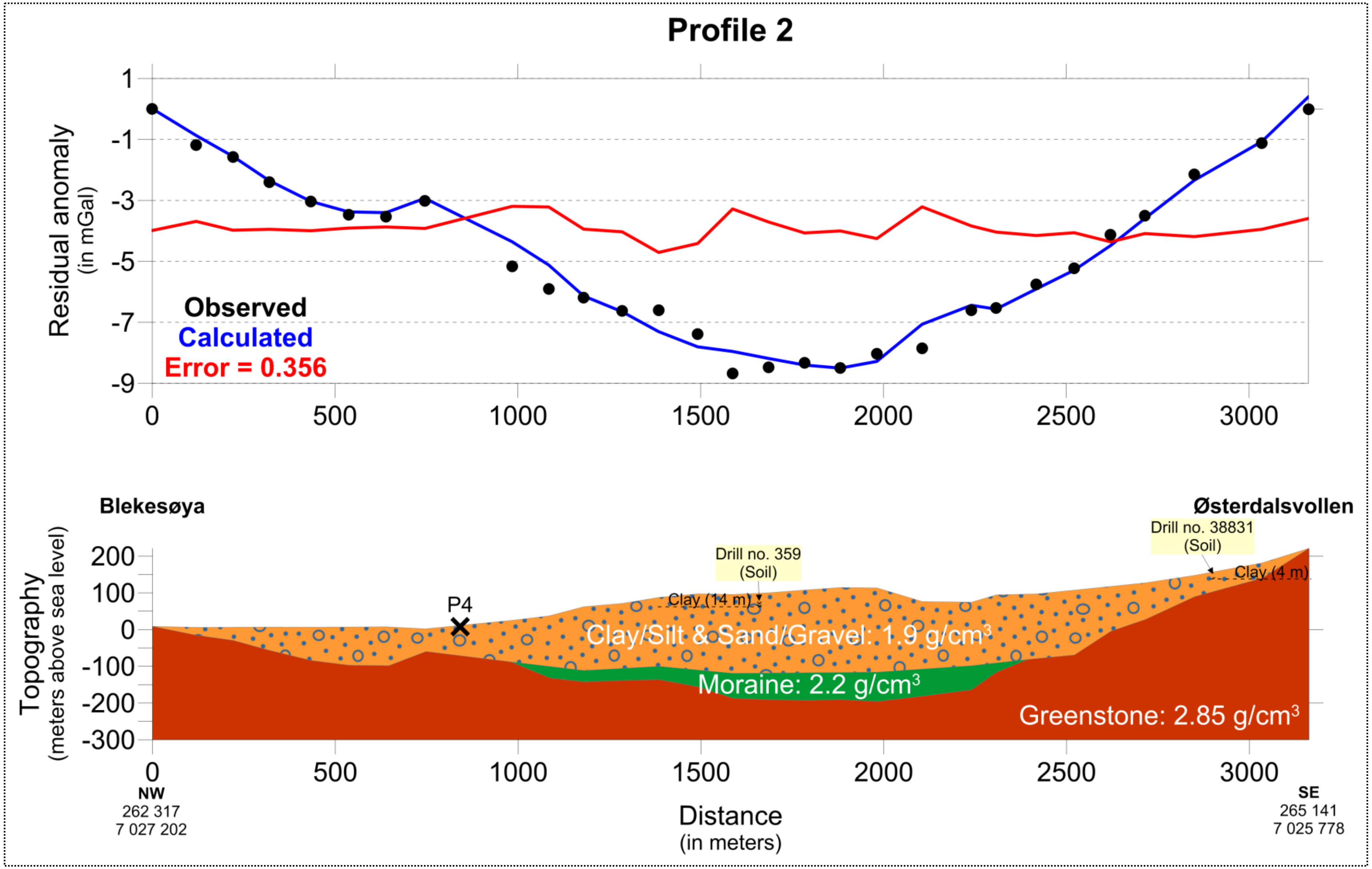

Figure 11: Modeled depth to bedrock - Profile 2. Bottom side: cross section showing the sediment formation dimensions (in meters) and distribution as well as utilized densities for both sediments and bedrock (in g/cm^3). Top side: Observed and calculated gravity data graph with error estimation (red curve).

5.3 Profile 3

Profile number 3 can be found about 900 meters north of profile 2, stretching along an almost parallel NW-SE direction. Its total length is ~2850 meters and measurements have been performed in 28 stations. The residual anomaly variation is about 8 mGal while the maximum effect of the sediments can be seen in the area between 1150-1400 meters.

Modeling results can be seen in **figure 12**.The setting utilized is the same as in profile 2, consisting of greenstones as bedrock and a sediment valley which can be broken down to clay/silt, sand/gravel and moraine. Since no drilling coincides with the profile, the sketching of clay was done based on geological intuition and Førde's master thesis (2015). As in all other cases, beginning point at Tislauan and ending point at Rønningen were measured on bedrock exposure and the sediment valley is limited between these points. In this particular case, the calculated gravity matches the observed field quite successfully as can be deduced by the small error value of 0.159.

After fitting the rest of the observed gravity using the mean sediment density of 2.0 g/cm^3, a soil body resulted with a maximum thickness of ~310 m. In this possible model, the sand & gravel/clay layer has been found with a total thickness of ~200 m and inductively moraine ended up being no more than 110 m thick. Overall, profiles 2 and 3 demonstrate deeper bedrock conditions which are partly caused by the general topographical height above sea level in the area.

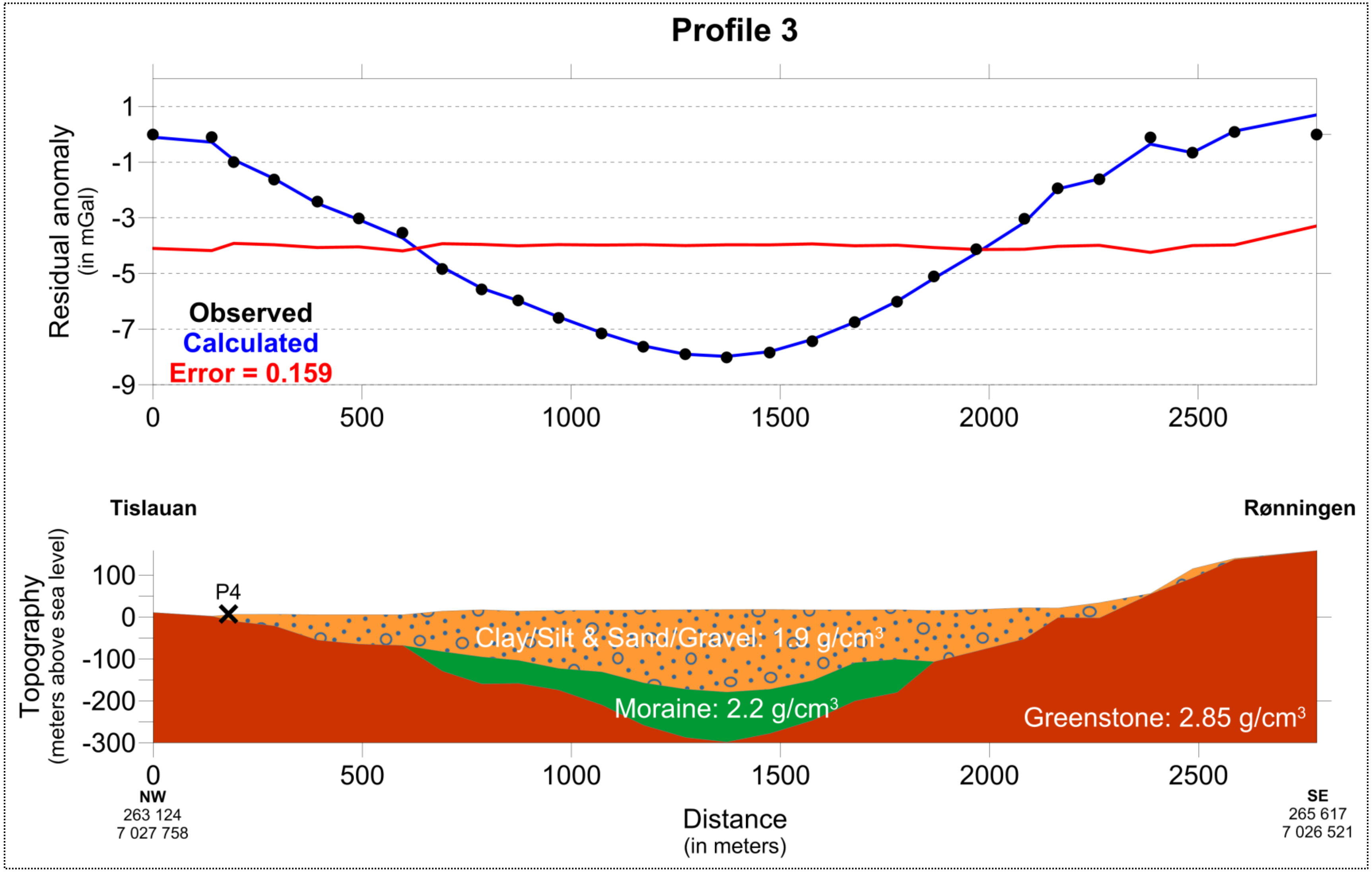

Figure 12: *Modeled depth to bedrock - Profile 3. Bottom side: cross section showing the sediment formation dimensions (in meters) and distribution as well as utilized densities for both sediments and bedrock (in g/cm^3). Top side: Observed and calculated gravity data graph with error estimation (red curve).*

5.4 Profile 4

Profile number 4 has been measured differently than the other profiles. Its starting point is identical to the starting point of profile 3 (Tislauan) while the profile finishes at Søberg, an area really close to end of profile 1. In this way, the profile crosses the valley diagonally and its purpose is to connect the areas between the sub-parallel profiles and aid the gridding process following modeling.

Its total length is just above 3800 meters, which makes profile 4 the longest profile measured in this project. It contains 32 point gravity measurements and the maximum anomaly effect of the sediments is about 5 mGal in the area between 2100-2350 meters. The resulting error is 0.29 which is a shows a good mathematical fit between the observed and the calculated field.

Once again, drillings in the proximity of profile 4 only indicate minimum bedrock depth since they have not reached bedrock. Nonetheless, the drillings give a rather good outline of the clay layer sitting on top of all other sediments with a thickness of ~55 m. The total sediment package extends down to a maximum depth of ~200 m as a whole, meaning that sand/gravel and moraine can amount a thickness of ~145 m. Indeed, using the already established densities of 1.9 and 2.2 g/cm^3, sand & gravel/clay appears to be ~95 m thick at most while moraine extends for another 50 m before bedrock is met. Where profile 2 and 4 meet, sand & gravel/clay dominates down to ~90 m of depth.

As seen in **figure 13**, sediments obtain their maximum thickness just after the middle of the profile, filling a rather narrow valley. However, no assessment as to the morphology of bedrock along the S-N direction can be made due to the fact that profile 4 does not follow the deepest parts of the sediment valley, but rather connects the northwest corner of the survey area to the southeast. Finally, there has been an effort to incorporate those parts of the ERT profiles (Solberg et al., 2014) which coincide with profile 4 in the modeling procedure. Unfortunately, the electrical resistivity distribution is not as simple as the density distribution that we have chosen.

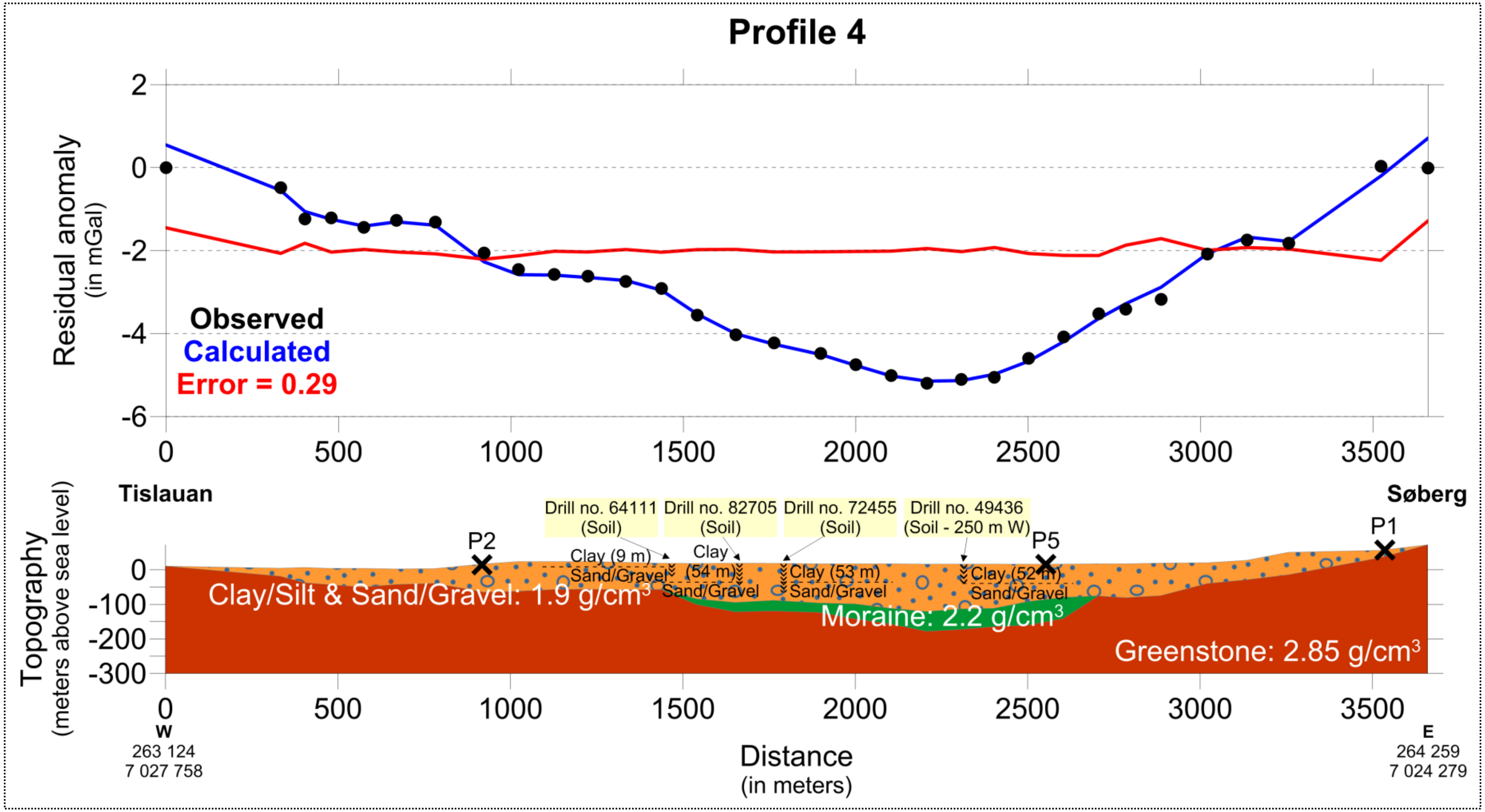

Figure 13: *Modeled depth to bedrock - Profile 4. Bottom side: cross section showing the sediment formation dimensions (in meters) and distribution as well as utilized densities for both sediments and bedrock (in g/cm*^{3}*). Top side: Observed and calculated gravity data graph with error estimation (red curve).*

5.5 Profile 5

Profile number 5 is the last profile for this survey and is located about 800 m south of Melhus city center and 800 m north of profile 1. It is stretching for 2320 meters from Gimsan until Loddgardstrøa in an almost W to E direction and consists of 19 measurements. Profile 5 is the shortest profile in this survey and crosses the Gaula river at a point where the bank is rather broad. This results in an almost 300 meter gap in the beginning of the line where measurements were impossible to obtain. Regardless of this, the maximum effect of the sediments comes up later in the profile at 1050-1250 meters and is equal to 7.0 mGal.

Only one drilling coincides with profile 5 and is a soil drill i.e. a drilling that has not reached bedrock. The same drilling also appears in profile 4 and as in that case, it helps as sketch the clay layer overlaying the rest of the sediments in the area.

The total thickness of sediments extracted from gravity in this profile using average soil density of 2.0 g/m^3 is ~280 m with the error for this estimation being 0.169. In case of moraine in the valley bottom this can be about 110 m thick, which means clay/silt and sand/gravel might be about 170 m thick.

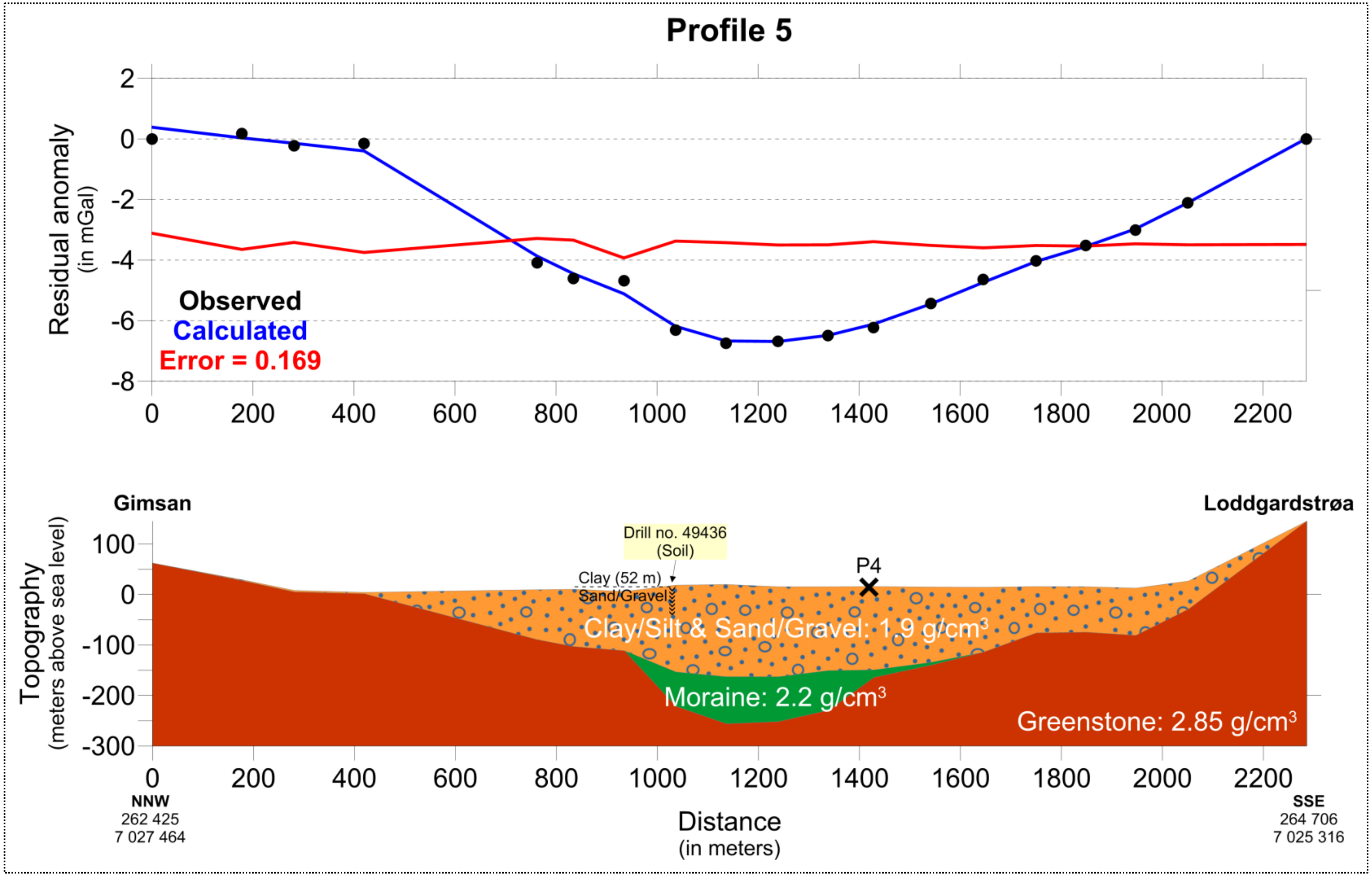

Figure 14: *Modeled depth to bedrock - Profile 5. Bottom side: cross section showing the sediment formation dimensions (in meters) and distribution as well as utilized densities for both sediments and bedrock (in g/cm^3). Top side: Observed and calculated gravity data graph with error estimation (red curve).*

6. DEPTH TO BEDROCK

As seen in **figure 1** the profiles measured in Melhus are not parallel to each other and their point measurements were not placed on the nodes of a normal grid. Instead they are distanced hundreds of meters apart, normally varying around a kilometer of projected distance. It is easily understood that trying to create a depth to bedrock grid will result in large areas of speculated values which only depend on the interpolation method used. To overcome this problem we had to enrich our depth to bedrock file with several additional data. The final depth to bedrock database consists of:

a) gravity modeling interpreted depths
b) drillings that reached bedrock (table I),
c) bedrock exposure positions at the beginning and end of each profile and
d) seismic interpretations by both Sindre (1980) and Mauring (1992) which have been digitized for this purpose.

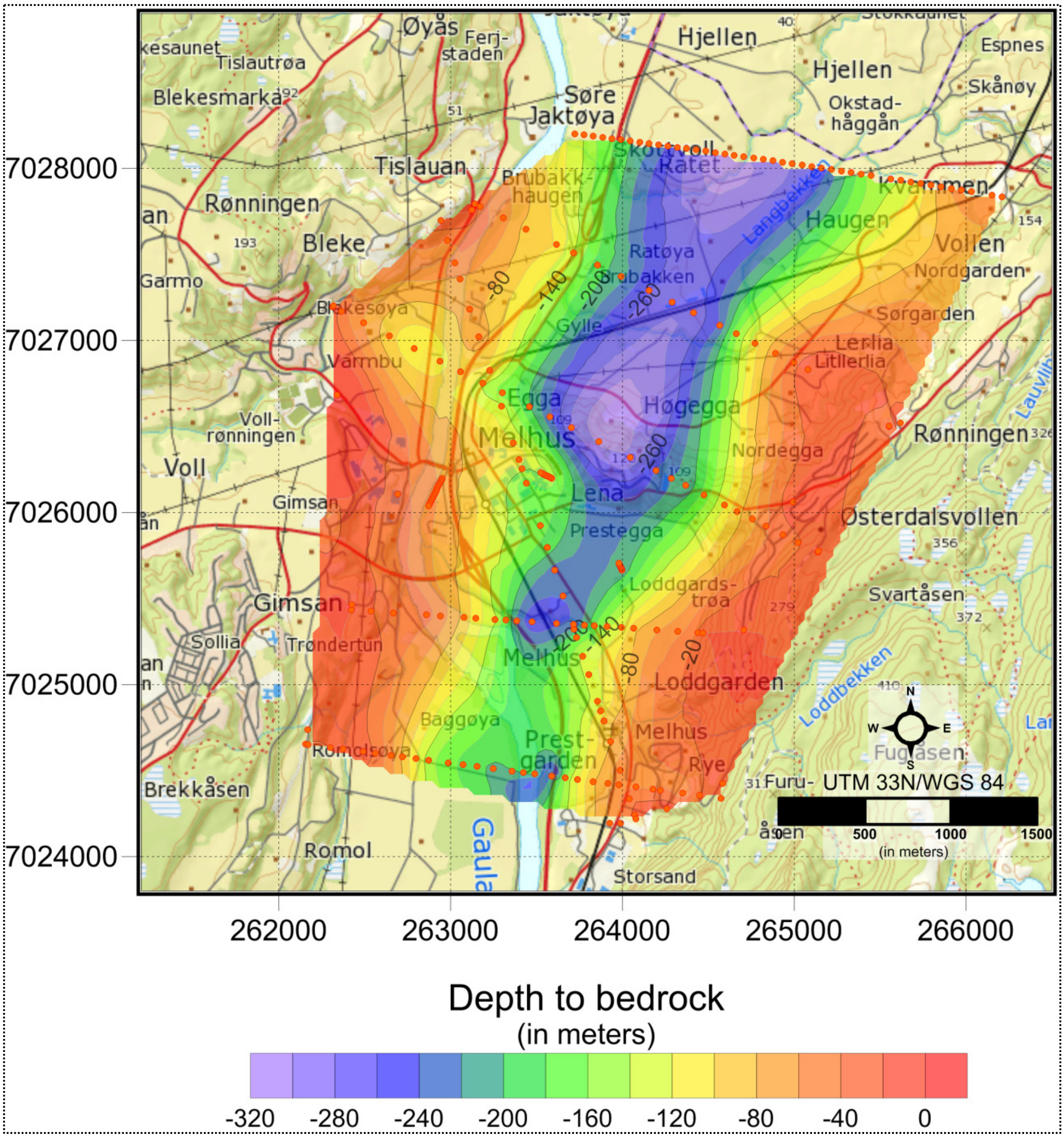

Figure 15: Depth to bedrock distribution in meters as measured from topography. Orange dots represent all depth to bedrock point estimations used in the calculation of the grid.

Although the effect of uneven spacing throughout the gridded area is not possible to overcome 100%, the available data included in the depth to bedrock database give us an acceptable coverage of the study area.

The resulting grid has been compiled using Kriging method and the theoretical model obtained from the respective variograms. The grid spacing designated was 50 m per axis and the areas not containing data were blanked. **Figure 15** shows the final depth to bedrock contour map which displays depth from topography and not depth from sea level as originally exported from GM-SYS. Some gridding discrepancies may be observed at the bottom part of the survey area where gravity line 1 and seismic line 4 coincide but the respective bedrock interpretations differ. Despite the divergence in this small area, **figure 15** presents a map of sediment thickness along the Gaula river whose accuracy is strongly dependent of the density values picked for modeling. **Figure 16** shows the same grid plotted in Google Earth giving a pseudo-3D impression of the Melhus area sediment distribution.

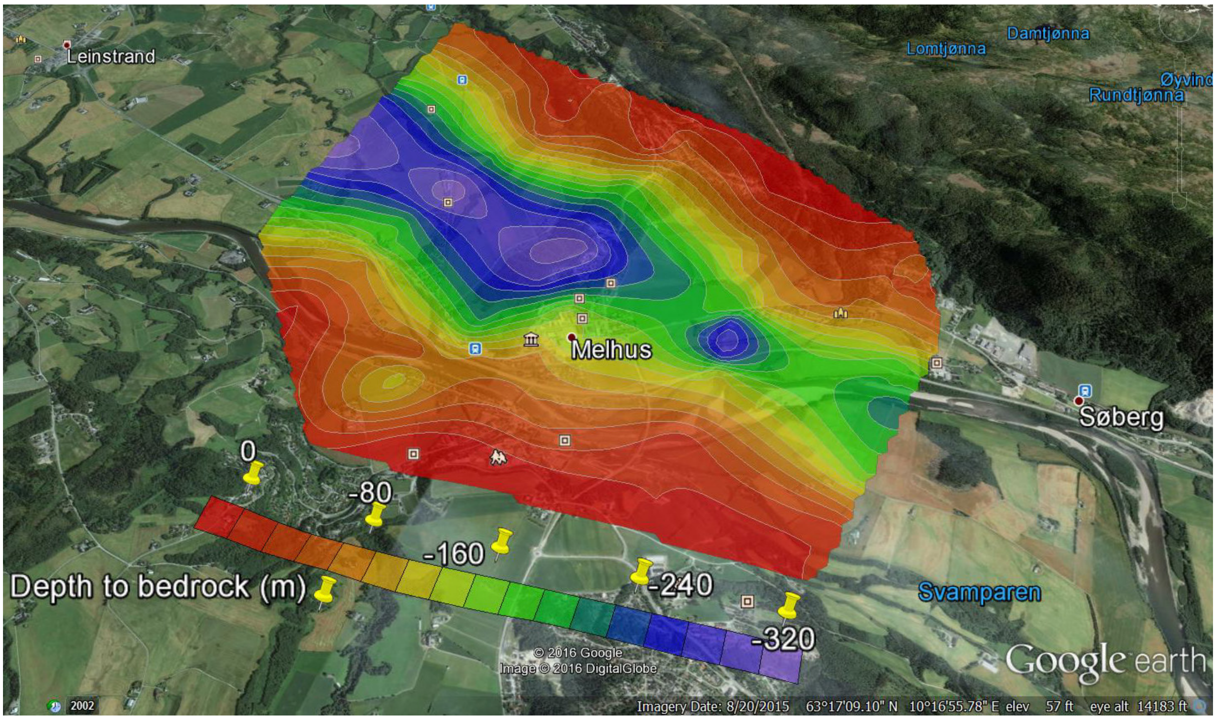

Figure 16: *Google Earth image of the Melhus area with gridded depth to bedrock plotted.*

Figure 17 exhibits a 3D representation of the sediment body enclosed in the sediment hosting valley. The 3D body was constructed in Geosoft Oasis Montaj by initially forming a geostring containing 2D slices of all the sediment valleys modeled and then wireframing them together by connecting their edges. In all sub-figures we have used a vertical exaggeration of 2 in order to highlight the vertical characteristics, i.e. the thickness of sediments. This was done due to the fact that the 3D body is 10 times longer than it is deep (~3.5 km vs. 320 meters respectively).

The depiction in **figure 17a** (view from above and south by southwest) illustrates the positioning of each individual sediment valley floating in 3D space before any wireframing took place. **Figure 17b** (view from east) shows how profile 4 interconnects all profiles and the agreement in depth estimation at the points where the other profiles intersect with it. Wireframing (i.e. interconnecting) these profiles, we obtain a 3D sediment body which is also available on 3D pdf format where users can rotate it freely to an angle of their choosing according to their desired perspective.

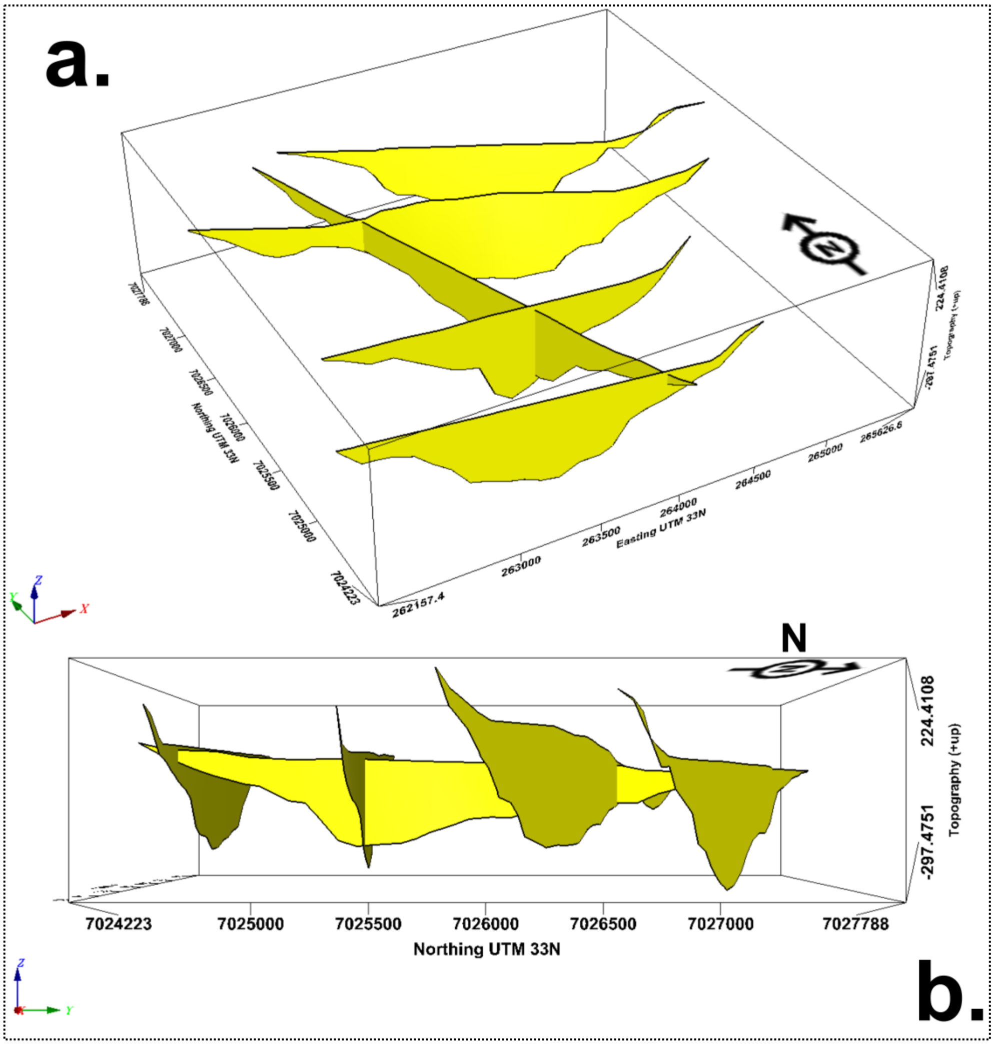

Figure 17: *3D representation of the calculated sediment body at Melhus: a. 3D plotting of the interpreted profiles (view from SSE). b. Profile 4 connecting/intersecting all other profiles (view from southeast). All distances and depths in meters, all coordinates in WGS84/UTM 33N and all profiles vertically exaggerated by 2.*

Figure 18 shows the morphology of the bedrock surface in 3D space compiled in Surfer 12. The top part of the figure displays depth from topography and assumes that the surface at 0 meters is flat. This type of plotting accentuates the morphological characteristics of the bedrock valley as opposed to the bottom part of the figure which shows its true morphology. This is done by using depth from sea level (meters above sea level) as shown in all the 2D profiles.

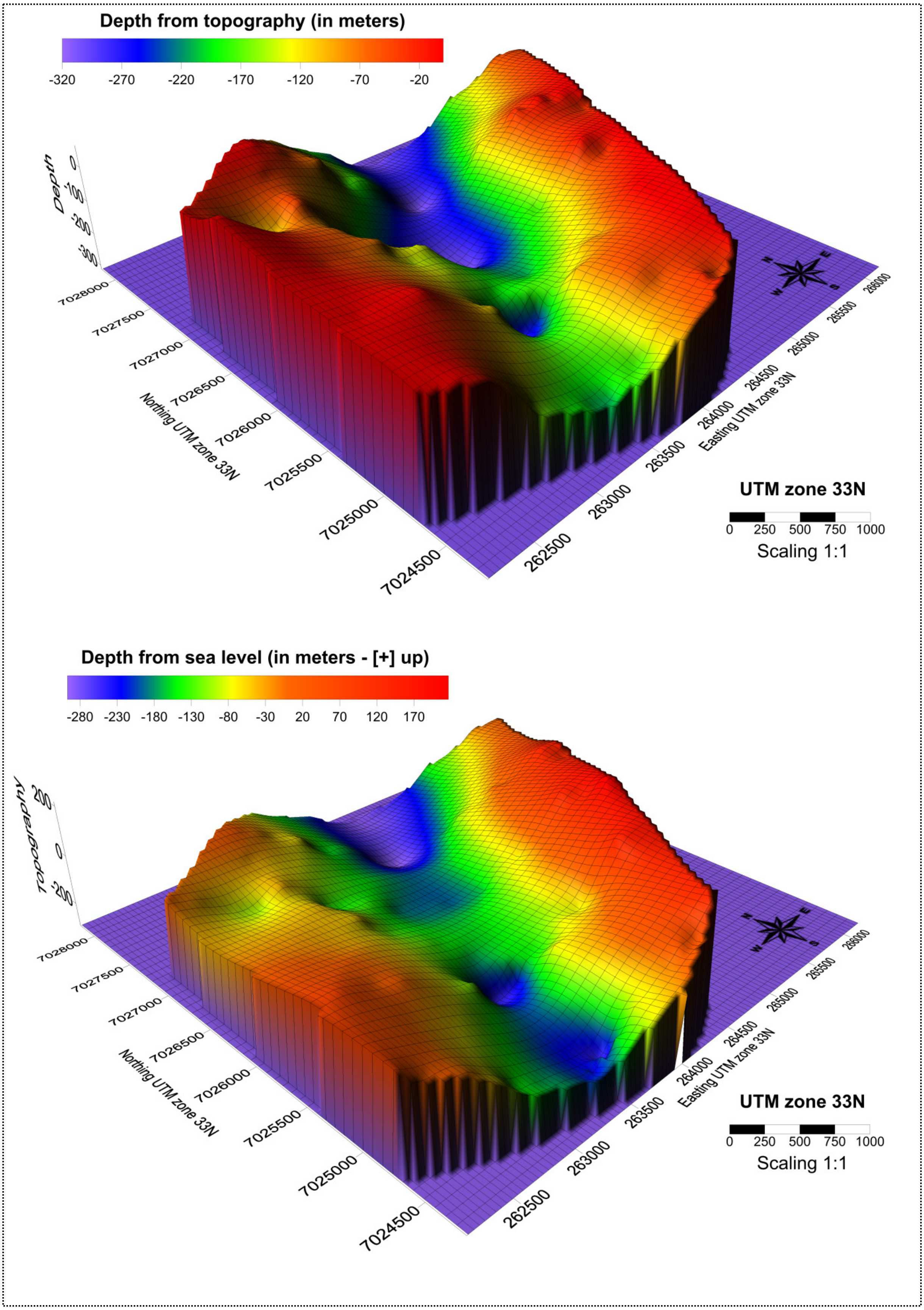

Figure 18: *Bedrock morphology as calculated from gravity modeling using depth from topography (top) and depth from sea level (bottom).*

7. DENSITY VARIATION EFFECT

It has already been stated that the depth to bedrock estimations presented in this report are as accurate as the assumptions made about the densities of the participating formations. Exactly how accurate, is a reasonable question to ask. In order to answer this question we have to test the effect of variable densities in gravity modeling. Testing variable densities though must be limited to the most doubtful formation in a sense that if all formation densities are treated as variables, the possible models become too many to present.

We assume that the density we have assigned to bedrock is most likely close to the real one and small variations do not affect the modeling results noticeably. This is due to the fact that greenstone density was chosen based on studies which performed sampling and density measuring. However, the number of density observation in the measured area is low, and should be supplemented. When testing the effect of density variation, we will keep the greenstone density constant at 2.85 g/cm^3. Now, the sediment density calculated by fitting bedrock interpretation between seismic line 4 and gravity profile 1 is an educated guess since the fitting achieved was not perfect. In this context, the sediment formation density is indeed the most doubtful assumption made before modeling.

We have tested the effect of two sediment density variations in connection to the utilized average value of 2.0 g/cm^3. Modeling was then repeated with the use of densities equal to 1.9 and 2.1 g/cm^3 and the resulting soil thicknesses (depth to bedrock) where again gridded and mapped. These results are shown in **figure 18**. The top side of this figure displays the depth to bedrock grids obtained with the new density values together with the selected final result. The bottom part shows the resulting 2D bedrock delineation for profile 1 after using all three sediment densities described above.

Primarily, we may deduce that a change in sediment density does not affect the shape of the resulting valley much and the depth contours retain the same pattern for the most part. Secondly, increase in sediment density (less density contrast) means increase in calculated depth to bedrock. If we narrow it down to profile 1 shown at the bottom of **figure 18**, we can see that a 0.1 g/cm^3 increase in sediment density equals to a ~25 meter increase in depth at the deepest part of the resulting basin. This difference in thickness becomes smaller and smaller along the slopes of the bedrock valley until the interpretations almost match each other at shallower depths. Once again we can observe that besides the quantitative difference between interpretations, the shape of the valley follows the same pattern regardless of sediment density.

Considering the geological composition of the sediment formation we may assume that the densities chosen for the above described test also represent the minimum and maximum values that they can obtain i.e. the margin of error. Essentially, this means that a projected error for the map presented in **figure 16** would be maximum ±25-30 m for the deepest parts of the sediment valley and reducing towards the fringes. In short, variation in sediment density may give an uncertainty of ± 10% of calculated depth.

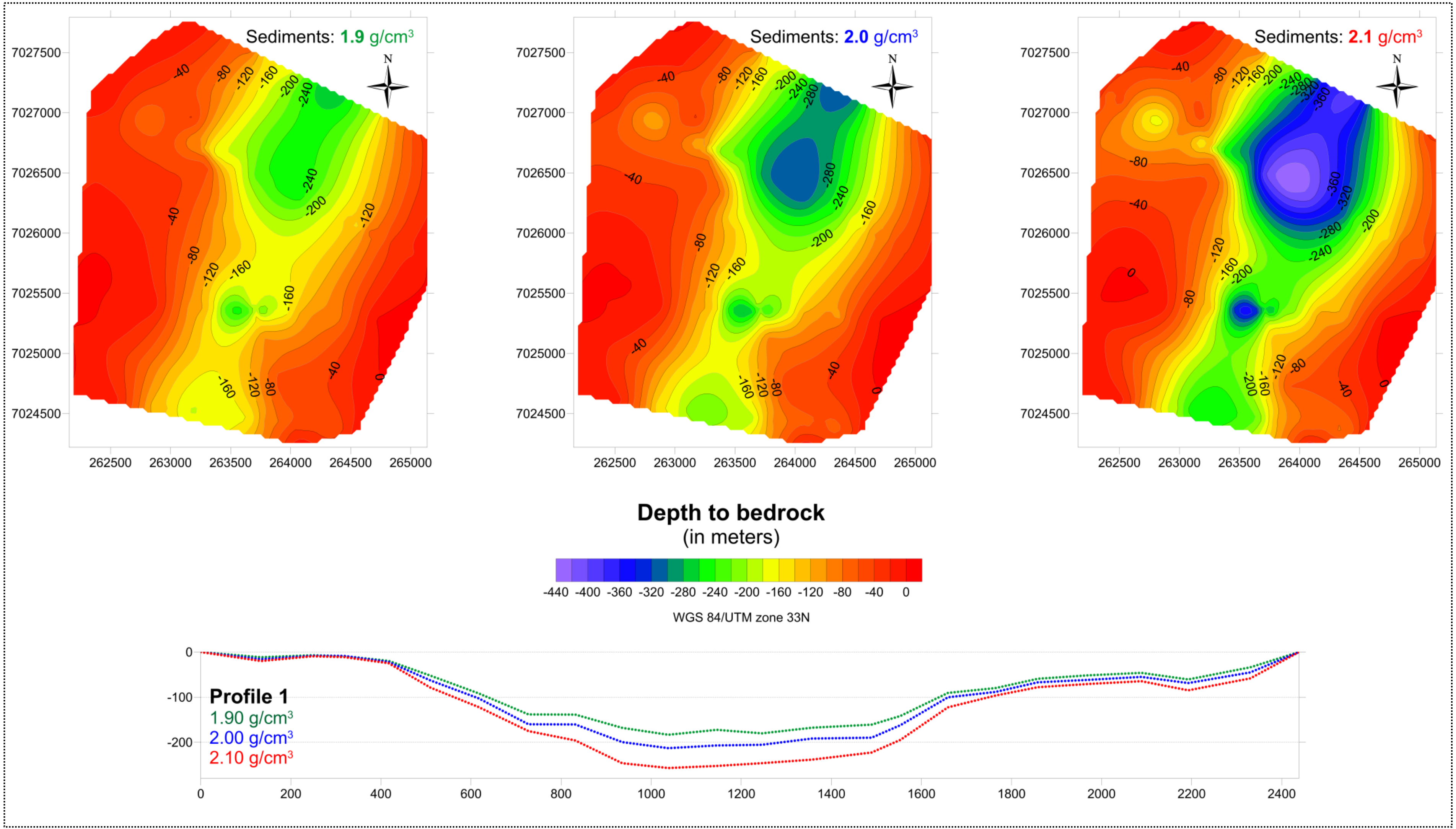

Figure 19: *Top: effect of three variations of sediment density on the resulting depth to bedrock grid (1.9, 2.0 and 2.1 g/cm³). Bottom: same effect on the 2D interpretation of profile 1.*

8. DISCUSSION AND CONCLUSIONS

In this study, we have attempted to map the thickness of sediments around the area of Melhus city center in Melhus municipality by using gravity in combination with data available in NGU managed databases. More specifically and in addition to gravity data, we have also incorporated borehole depth and density measurements, bedrock delineations originating from other geophysical studies in the region (mainly seismic) as well as bedrock and quaternary geological data. By doing so, we have ensured that our models share properties (at least to the knowledge database extent) with the actual formations in the area. **Figures 15**, **16**, **17** and **18** present the undulations of a soil layer overlaying a greenstone basement whose densities have been set equal to 2.0 and 2.85 g/cm^3 respectively and kept constant throughout the whole process. At a second stage, we have attempted to divide the single sediment formation into sub-layers based on the geology revealed by drilling data available to us.

In the interpretation of refraction seismic done by Sindre (1980), the soil velocities are in the order of 1500 – 1600 m/s while moraine velocities might be as high as 2000 – 2200 m/s. Based on this, there is no indication of moraine material at depth from the seismic work. However, a layer with higher velocities can be in a blind zone (Reynolds 2011), which means it is impossible to discover in refraction seismic. A moraine layer at depth is therefore possible, but it will have a limited thickness controlled by the velocity contrast and at which depth it appears. We cannot exclude a moraine layer at depth from the seismic work, but in case we have so, the depth to bedrock will be even bigger, and a lesser density contrast is needed to model the gravity anomalies. In our gravity modeling, we calibrated the overall average soil density without any moraine at depth. In the final model presentation, we have included a possible moraine layer, but kept the depth to bedrock fixed as indicated with the average soil density.

Our results indicate that the sediment thickness is greater at the northern part of the study area (a bit over 300 meters) than at its southern counterpart (~250 meters or less). Moreover, the sediment holding valley appears to be narrower in the south while opening up in the north. If this is combined with the larger bedrock depths calculated there, they result in a larger sediment volume north of Melhus city center than south of it. Quantitatively, the width of the valley containing sediments of 100 m thickness or more is about 1.5 km while in the south it is below 900 meters. This pattern appears to be followed when examining the results of splitting the sediment formation into clay/silt/sand/gravel and moraine.

Gravity measurements along profiles around Melhus city center revealed that sediments cause negative anomalies with amplitudes up to 8 mGal. Thereby, density models have been compiled and after fitting the observed gravity with the theoretical response of these models, sediment thicknesses have been calculated over an area of about 12 km^2. Gravimetric interpretation indicates that sediments in the region may acquire a maximum thickness of ~315 meters (~265 meters below sea level). These interpretations were then enriched with additional sediment thickness data originating from various NGU related sources and a total depth to bedrock map has been constructed. The additional information has helped the gridding process by constraining it in areas where no gravity interpretation was available (space between profiles). The final map portrays a good approximation of the qualitative but also quantitative distribution of sediments in the study area. In brief, sediments appear to be deeper and more voluminous north of Melhus city center than south of it. The resulting sediment body formation is also available in 3D format (3D pdf file).

Uncertainty in the soil density estimation may give a variation of +/- 25-30 m in depth to bedrock in the deepest parts of the valley or in average of ± 10 % of estimated depth.

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