Runar Lillebo Jakobsen

Parameter Study for Mobility of Rock Avalanches and Rock Collapses in Western Norway.

Master's thesis in Engineering Geology
Supervisor: Reginald Hermanns
Co-supervisor: Vanja Skålnes Haugsnes and Francois Noel
July 2023

Master's thesis

NTNU
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Abstract

The extent of how single parameters such as lithology, substrate and topography affect the mobility of large volume rock slope failures (RSFs) is not well known. Two recent large RSFs of similar volume in the European Alps, the Flücthorn rock avalanche (Petley, 2023) and the Brienz RSF (Loew et al., 2023), highlight the importance of understanding how other factors than volume affect the mobility of such events.

In this thesis 28 historic RSFs in western Norway were analyzed to test a potential methodology of parameter study of historical RSFs. Five parameters effect on mobility was tested; landslide classification, lithology, substrate, topographic constraints on the run-out and the run-out profile form.

Given the amount of used data in the parameter study the results need to be verified by implementation of the methodology on a larger data set. However, the main goal of the thesis was to test the methodology and the results are secondary. From the testing of the methodology in this thesis the recommendation for future studies is to find an alternative to the run-out profile form as this parameter was deemed unreliable. The run-out profile form is closely related to the achieved mobility and therefore other topographic parameters such as release area dip angle might prove to be of more interest for further study.

The parameter study was done based on the methodology by Scheidegger (1973) with the relation between volume and mobility being central. With this relation as the foundation the trends of different categorizations of each parameter was analyzed and compared. The analyses show that landslide classification is the parameter with greatest effect on mobility of the ones in the analysis, with rock collapses attaining a much lower mobility than rock avalanches. The second most influential parameter according to the analysis was the substrate. There was little variation in lithology so no viable results were produced. For the topographic constraints there are possibly to few data points to produce meaningful results. Overall in the analysis certain possible trends have been identified but due to the low data amount further work is required to prove the validity of these results.

Sammendrag

I hvilken grad enkelte parametere som bergart, substrat og topografi påvirker mobiliteten til fjellskred ("Rock collapse" og "Rock avalanche") er ikke velstudert. To nylige skredhendelser i de europeiske alpene, Flücthorn rock avalanche (Petley, 2023) og Brienz rock slope failure (Loew et al., 2023), fremhever viktigheten av å forstå hvordan disse andre faktorene enn volum påvirker mobiliteten til slike skredhendelser.

I denne masteroppgaven er 28 historiske fjellskred fra Nord-Vestlandet analysert for å teste en metodologi for undersøkelse av historiske fjellskred. Fem parametere har blitt testet for deres effekt på mobilitet: Skredklassifiseringen, bergarter, substrat, topografiske begrensninger langs utløpet og utløpsprofilformen.

Gitt mengden data brukt i parameterstudien bør resultatene fra denne oppgaven verifiseres ved implementasjon av metodologien i større datasett. Hovedmålet i masteroppgaven har vært å teste metodologien og resultatene er sekundære. Resultatet av testingen av metodologien er å anbefale at utløpsprofilformen som parameter bør erstattes av en mer egnet topografisk parameter. Utløpsprofilformen ble ansett som upålitelig da den ser ut til å være sterkt knyttet til mobiliteten fjellskredet oppnår. Anbefalingen er derfor å heller benytte andre topografiske parametere som for eksempel fallet i løsneområdet i fremtidige studier.

Denne parameterstudien ble gjennomført basert på metodologien introdusert av Scheidegger (1973), der relasjonen mellom volum og mobilitet er meget sentral. Med denne relasjonen som fundament ble trendene til de forskjellige parameterne analysert og sammenlignet. Analysen viser at skredklassifiseringen er parameteren med størst påvirkning på mobiliteten av de som ble undersøkt. Skred klassifisert som "Rock collapse" oppnådde mye lavere mobilitet enn skred klassifisert som "Rock avalanche". Den nest mest innflytelsesrike parameteren var substrat. Det var liten variasjon i bergartene i datasettet så ingen meningsfylte funn ble gjort for denne parameteren. Det ser også ut til at det var for få datapunkter til å få gjennomført en god analyse på de topografiske begrensningenes påvirkning på mobiliteten. Helhetlig har flere mulige trender blitt funnet blant parameterne, men metodologien bør gjennomføres på et større datasett for å verifisere at disse funnene ikke er påvirket av den lave datamengden.

Acknowledgments

This thesis is the culmination of my five year M.Sc in Engineering Geology at the Norwegian University of Science and Technology (NTNU). The thesis is written in cooperation with the Geological Survey of Norway (NGU). My main supervisor have been Reginald Hermanns (NTNU and NGU) and co-supervisors Vanja Skålnes Haugsnes (NGU) and Francois Noel (NGU). The thesis work was completed during the spring term of 2023.

I would like to thank my supervisors Reginald, Vanja and Francois for great help, discussions and guidance during the thesis work. Without you this would have been impossible.

Further i want to thank my friends and classmates from "Tekniske Geofag" at NTNU for five wonderful years and great memories, even through a pandemic. Without you this journey would not be the same!

Lastly i want to thank my family and my girlfriend for their endless support.

Trondheim, July 2023

Runar Lillebo Jakobsen

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1 Introduction

1.1 Background

Since the start of mapping unstable rock slopes in Norway, more than 670 sites with the potential to develop rock slope failures (RSFs) have been identified by The Geological Survey of Norway (NGU) (Penna et al., 2023b). In the 20th century 175 lives were lost due to rock avalanches in Norway (Furseth, 2006). To reduce the consequences of future rock slope failures it is of great interest to improve our estimation of how far these landslides will travel, in other words their mobility. One way to study the mobility of large volume rock slope failures is to investigate previous landslides. NGU has created an inventory of historical large volume RSFs consisting of at least 248 events (Penna et al., 2023b). The highest concentration of RSF events are in western and northern Norway (Blikra et al., 2006; Hermanns et al., 2012; Penna et al., 2023a; Penna et al., 2023b).

In June of 2023 the European Alps had two large RSFs of similar volume, the Flücthorn rock avalanche on 11th of June and the Brienz RSF on 15th of June. Both events are of volumes estimated in the range around 1-2 million cubic meters for the initial landslide mass but produced vastly different mobility (Loew et al., 2023; Petley, 2023). The Flücthorn rock avalanche, based on initial estimations, reached a mobility within expectations of a rock avalanche of this volume, whereas the Brienz RSF reached a mobility more in line with what is expected of a rock collapse. The Brienz RSFs run-out reached extremely close to the northern boundary of the town Brienz. If the RSF had attained the mobility expected of a rock avalanche of similar volume the damages to the town had been much more severe. Further study of the events could be of great value, especially given that prefailure terrain models are available contrary to the historical events used in this thesis.

Figure 1: Recent RSF in Brienz, Switzerland. Picture of the frontal landslide deposit and the town of Brienz (Loew et al., 2023).

1.2 Aim of the study

The aim of the thesis is to study several geological and topographical factors effect on the mobility of large volume rock slope failures in western Norway. The thesis is a preliminary test of the methodology, to lay the foundation for further implementation on the national RSF inventory on a larger scale. The thesis work is based on the suggestions of previous works such as Nicolet et al. (2022) and Penna et al. (2023b). A decrease in uncertainties for run-out estimations of large volume RSFs could have a large value to society both monetarily and for risk mitigation. An example of how the current methods for estimating the mobility of large volume RSFs would be incorrect is the RSF in Brienz in June of 2023. With the methodology used in Norway today we would estimate that the town of Brienz would be hit directly by the landslide masses, whereas in reality the masses stopped short of the village. With more than 670 unstable rock slopes mapped in Norway a higher certainty in our run-out estimations could be of great value to society.

The goals of the thesis are:

- Establish a methodology for further study of factors effect on large volume RSF mobility.
- Test the methodology on a preliminary study with a selection of events from the NGU RSF inventory.
- Present the results of the study, and suggest improvements to the methodology based on a comparison of the results to previous studies.

As part of the thesis work all the RSF events studied have been reevaluated using remote sensing including a reevaluation of landslide classification, new volume estimations using slope local base level technique (SLBL) and new mobility measurements. This data is available in the appendix.

1.3 Approach and limitations

As part of the thesis work data from 28 large volume RSF events in western Norway have been compiled. This data was then used in a empirical comparative study to look for potential effects five different factors, both geological and topographic, have on the mobility of RSFs. The amount of RSFs included in the thesis was limited due to time constraints, and the priority is testing the methodology rather than producing highly accurate estimates of how the different factors affect the mobility of RSFs.

As part of limiting the number of RSFs a geographic constraint was included, all the RSFs in the thesis are located in north-western Norway. More specifically the county of Møre og Romsdal and the northern part of the county Vestland from the Sognefjord area and north. This area is part of the western gneiss region, a large geological unit in Norway. The lithology of the area is mainly gneisses formed as part of the Caledonian orogreny (Ganzhorn et al., 2014). The landscape is dominated by deep fjords with steep valley sides, and a high concentration of the RSFs in Norway have occured here (Penna et al., 2023b). During the last ice age most of the soil was eroded into the sea with the ice flows, due to the relatively short time since deglaciation large parts of the region have little to no soil cover, the biggest exception being the valley floors of the larger valleys (Ramberg, 2008).

2 Theory

2.1 Rock slope failures

Rock slope failures (RSF) develop on slopes steeper than 25°, but are most commonly seen in slopes with a steepness greater than 34° (Penna et al., 2023b). Large unstable rock slopes development is associated with geologic and landscape conditions, in southern Norway they are mostly formed in over-deepened valleys and fjords (Penna et al., 2023a). Unstable rock slopes can develop for millennia before a landslide is triggered when the stability is overcome by deformation or external forces (Hilger et al., 2021). In this thesis RSF will be used as a general term including both rock avalanches and rock collapses, while rock avalanche and rock collapse will be used per the definitions of Hermanns et al. (2022).

2.1.1 Rock avalanche

The most commonly documented landslide types developed from large volume RSF is rock avalanches. Rock avalanches typically develop from failures with a volume greater than $0.1 \cdot 10^6 m^3$ but Velardi et al. (2020) and Kolstad (2021) found that $0.25 \cdot 10^6 m^3$ might be more correct based on data from Norway. In the preliminary project assignment (Jakobsen, 2023) several high volume rock avalanche events across the globe with a mobility lower than (AoR higher than) 30° AoR (> 0.6 H/L) were documented. This suggests that other factors besides volume and landslide movement mechanics can affect the mobility of rock avalanches in a large degree.

Heim (1932) describes the flow like movement mechanism that is characteristic for rock avalanches. This flow like movement is thought to be the main factor in the high mobility of rock avalanches compared to other landslides from rock. Nicoletti and Sorriso-Valvo (1991) have described the three run-out patterns formed by rock avalanches (fig. 2). These patterns are a result of the flow like movement of rock avalanches and its relation to the slope form/obstructions along the run-out path. Rock avalanches have a characteristic deposit morphology that makes mapping of historic events possible (Hermanns et al., 2022). Rock avalanche deposits often form a carapace consisting of large blocks above a matrix supported inverse sorted soil with internal features such jigsaw facies and fragmented facies (Strom, 2006; Dufresne et al., 2016).

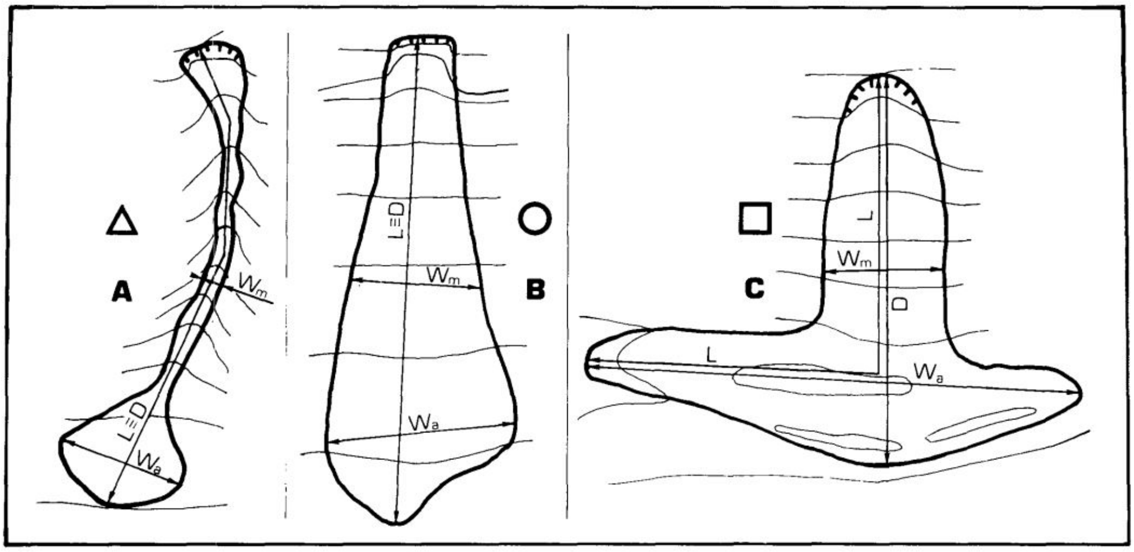

Figure 2: Three depictions of possible run-out patterns formed by rock avalanches due to different topographic constraints. A) Lateral constraint leading to channalization. B) Unconstrained rock avalanche. C) Rock avalanche run-up on opposite valley side leading to a latteral spread. (Nicoletti & Sorriso-Valvo, 1991)

2.1.2 Rock collapse

The term rock collapse was defined by Hungr et al. (2014) as *"rock mass on an irregular rupture surface consisting of a number of randomly oriented joints, separated by segments of intact rock (...) that is often very sudden and extremely rapid."* This terminology was introduced to fill the gap between rock fall and rock avalanche, but included a narrow structural condition. Hermanns et al. (2022) suggests a more broad definition to better fill the gap regardless of structure conditions: Rock collapses are rapid rock slope failures with limited interaction of fragments. They can entrain substrate along the travel path and deposit with a mobility $H/L > 0.625$ (Angle of reach > 32°), inline with Coulomb's law of sliding friction (Shreve, 1968). Commonly observed volumes of rock collapses range from 10,000 to millions of cubic meters, however the amount of rock mass simultaneously in movement is likely not greater than 100,000 cubic meters (Hermanns et al., 2022). The geological and topographical conditions that produce a rock collapse as opposed to a rock avalanche in large volume rapid RSFs are not fully understood.

2.2 Large volume RSF Mobility

The mobility of RSFs is usually described with the angle of reach (AoR) or height/length (H/L). The angle of reach (fahrböschung) is the angle from the top of the crown down to the toe of the deposit, it is directly correlated to H/L as it can be calculated by $tan^{-}1(H/L)$ (Heim, 1932; Hsu, 1975; Shreve, 1968;). Where the H is the vertical height difference from the toe of the deposit to the crown of the back scarp and the L is the horizontal length between the same points along the central run-out path (Hermanns et al., 2022). Higher AoR is a lower mobility as the angle is measured from horizontal at the crown and down toward the toe, H/L is similar as a higher H/L value points to a shorter run-out compared to the vertical distance traveled (fig. 3).

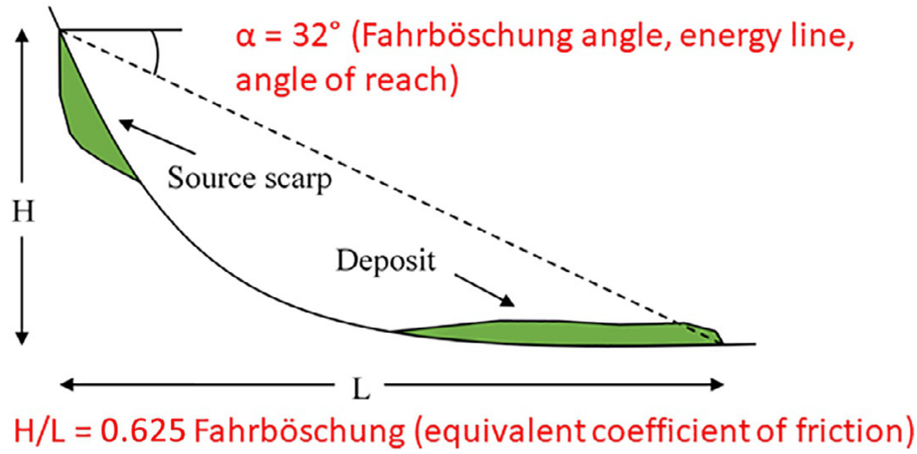

Figure 3: Schematic of a RSF defining height (H), run-out length (L) and angle of reach (AoR) (Fahrböschung) after Scheidegger (1973). Run-out length is measured as a horisontal line along the flow path, not a direct line from crown to toe (Hermanns et al., 2022).

When the volume of rapid RSFs is greater than $0.1 \cdot 10^6 m^3$ we see an increase in probable mobility based on empirical data from other RSF events (Scheidegger, 1973; Corominas, 1996; Velardi, 2019)(fig. 4). However this relation defined by Scheidegger (1973) is always given, Penna et al. (2023b) presents data that suggests that the relation by Scheidegger may not be the only major influence on rock avalanche mobility. Penna et al. (2023b) found larger correlation between the mobility and the slope angle of the source area than the more commonly presented relation between mobility and volume.

This increase in mobility as a relation to volume is only documented for rock avalanches, where as in rock collapses we expect a mobility lower than $AoR \approx 31°$ similar to RSFs smaller than $100{,}000 m^3$.

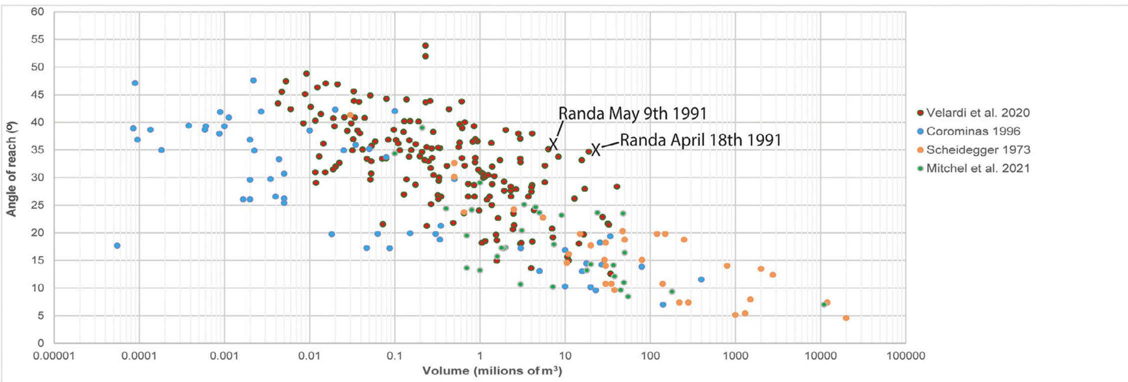

Figure 4: Plot of AoR versus volume relation for the four datasets by Velardi (2019), Corominas (1996), Scheidegger (1973) and Mitchell et al. (2020) with the addition of the two events from Randa in 1991. From Hermanns et al. (2022).

Nicoletti and Sorriso-Valvo (1991) found that rock avalanches with lateral constraints produced higher mobility than unobstructed rock avalanches. Rock avalanches with frontal constraints produced the lowest mobility in general. Multiple studies have found a relation between substrate along the travel path and mobility for rock avalanches. Hungr and Evans (2004) found that entrainment of liquefiable material from the run-out path increased the mobility in rock avalanches. Aaron and McDougall (2019) documented a decrease of mobility on unsaturated substrates, and a increase of mobility on saturated substrates.

2.3 Remote sensing tools

Per 2022 a digital terrain model (DTM) covering the whole of mainland Norway was available through The Norwegian Mapping Authority (Kartverket). The DTM is a three dimensional scan of the terrain, removing all vegetation opposed to a digital surface model (DSM) that includes all objects and vegetation (Hattestad, 2020). The models are produced by aerial LiDAR scans with a 1x1 meter resolution. A result of the DTM being produced by vertical LiDAR scans is that the resolution on steep slopes is reduced, as the 1x1 meter resolution is in the horizontal plane. In certain slopes this can give vertical distances of tens of meters between two data points. The DTM can be used to produce hillshade maps with programs such as ArcGIS Pro (Redlands, CA: Environmental Systems Research Institute, 2023) or 3D point cloud models with programs such as CloudCompare (GPL Software, 2023). Hillshade maps and 3D point cloud models are both great tools for remote mapping of RSFs as they provide a much better visualization of the terrain than traditional maps (Francioni et al., 2019).

2.4 Norwegian run-out estimation of potential rock avalanches

The current methodology for run-out estimations of large volume RSFs in Norway heavily depends on the relation between volume and mobility presented by Scheidegger (1973) (Oppikofer et al., 2018). Blikra et al. (2001) found the relation to be conservative compared to the mobility seen in 25 RSFs, with 90% of events not reaching the mobility suggested by the “Scheidegger curve”. Therefore this relation is still the most used for initial assessment of potential run-out of large volume RSFs. Further analysis of the run-out is done in scenarios where there are potential damages due to the run-out or secondary effects based on the initial estimation by the empirical relation. In these cases run-out modeling with the software Flow-R (www.flow-r.org) have been adopted as the primary method. Further modeling of the run-out and secondary effects such as damming, dam breaching and displacement waves may be used if deemed necessary from the Flow-R model and potential for failure in the unstable slope.

The Norwegian building code, as of 2017, demands that landslide risks are taken into consideration for all new building projects (Direktoratet for byggkvalitet, 2017).

There are three safety classes defined for different building types based on the consequence if such building is hit by a landslide. Class S1 is used for buildings with infrequent human activity such as garages, sheds and piers. Class S2 is used for buildings that rarely gathers more than 25 people such as houses and cabins. Class S3 is used for buildings with large gatherings of people or people who are less able to evacuate such as malls, apartment buildings, hospitals, kindergartens, schools and emergency services. Each of these classes have their own limit to maximum nominal yearly probability of landslides as seen in Table 1. It is however important to note that a lot of older buildings in Norway are in areas of higher nominal yearly probability than the limits set by the newer building regulations, and in some towns it is a large problem to find areas available to build according to the new building code.

Table 1: Safety classes and their maximum yearly probability (Direktoratet for byggkvalitet, 2017).

Safety class for landslide	Consequence	Maximum nominal yearly probability
S1	Small	1/100
S2	Medium	1/1000
S3	Large	1/5000

3 Method

3.1 NGU rock slope failure database

The foundation of the data used in this master thesis is from NGUs inventory of rock slope failures in Norway. The inventory includes information about location, volume, mobility, deposit area, release area and the age of the event where available. Some data, such as volume and mobility (H/L) have been recalculated for all events as part of the thesis work. A reevaluation of the deposit and release areas as well as landslide classification have also been done. Both the original and the reevaluated deposit and release areas are shown in the data sheets of Appendix A where applicable. All data used in the thesis (ex. volume (and deposit area for volume calc.), run-out profiles, H/L (AoR) etc.) have been produced specifically for this thesis but using the national RSF inventory as reference.

3.2 Choosing events for the thesis

Due to the limited time and resources available for the master thesis a limitation on the amount of RSF events had to incorporated. For the thesis a selection of 28 large volume RSF events was chosen for further study. An initial aim of 30 RSF events from 3 different categories was set. We chose to include events of both *rock collapse* and *rock avalanche*, and from the rock avalanches we decided to include both low mobility (H/L > 0.5) and "normal" mobility events. Note that the actual normal mobility for a rock avalanche is dependent on the volume following the current norms in the scientific community, and that these names therefore might be misrepresenting the mobility of a given event compared to its volume. This gave us three major categories to search for in the NGU RSF inventory. Based on this initial selection from all available data it emerged that the geographic area with the highest concentration of events fitting our three categories was the north-western region of Norway. Here we had at least 10 sites for each of the three categories before reevaluation and removal of the ones not fit for thesis work. The specific geographic area chosen can be seen in Figure 5. From the initial selection we narrowed it down to 28 events based on the chosen geographic area and data availability. This was done by excluding all sites with the run-out into large bodies of water as there are limitations on access to high detail bathymetry in Norway.

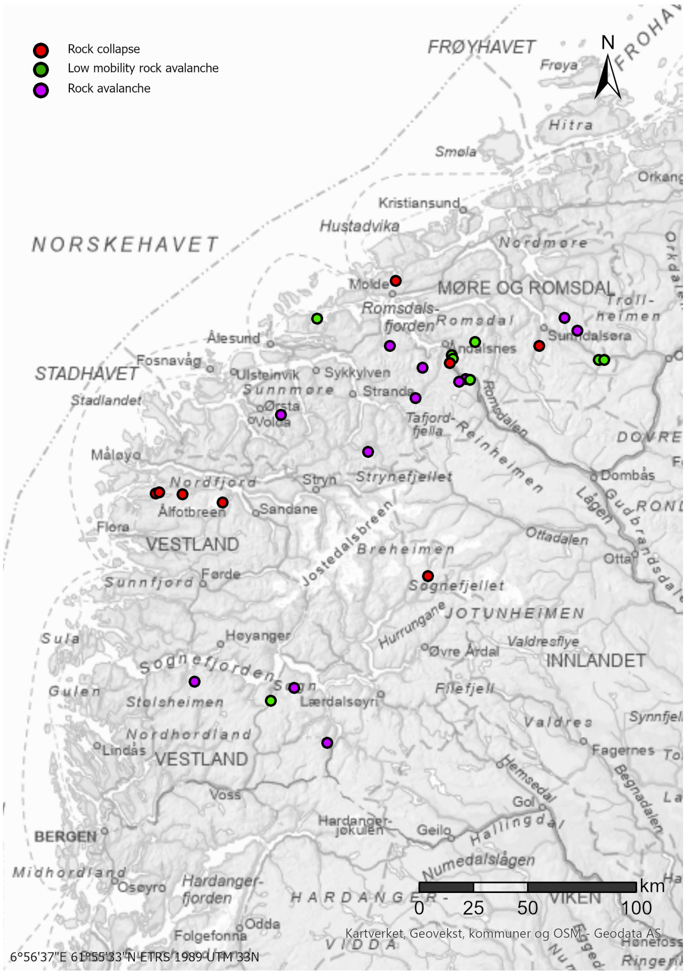

Figure 5: Geographical distribution of events studied in the thesis. Events are grouped after landslide classification with the subdivide of rock avalanches based on mobility. Low mobility here is defined as H/L ≥ 0.5 regardless of volume.

3.3 Remote sensing

The Norwegian Mapping Authority provides a national Digital Terrain Model (DTM) (Kartverket, 2023) in a 1x1 meter resolution. The DTM can with software such as CloudCompare (GPL Software, 2023) be used to produce 3D point cloud models, see Figure 6. The DTM is made by Aerial LiDAR scans, with the points in the models being evenly spaced in the horizontal plane. Due to the scanning method the distance between points in vertical surfaces can be many times greater than in less steep surfaces (Figure 6).

As part of the thesis work the DTM have been used in several applications including; remote sensing (3D point cloud), reclassification of certain events, mapping the deposit and release area of events and making elevation profiles of the run-out path.

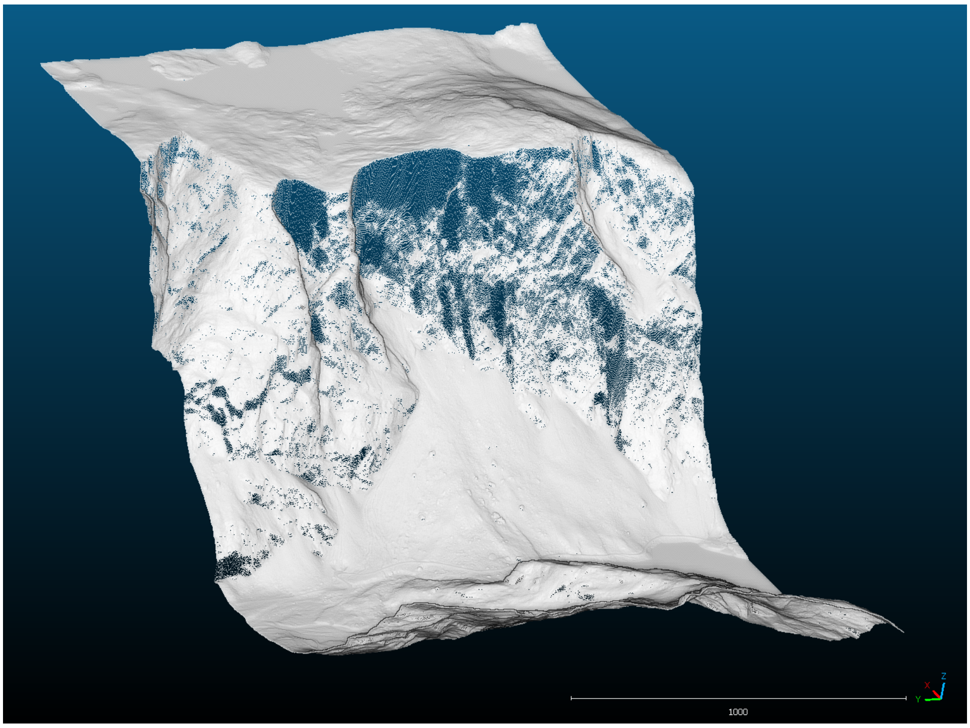

Figure 6: Example of a 3D point cloud model in CloudCompare, specifically of the event "Dalaosen" (ID:934).

3.3.1 Volume estimation (SLBL)

The volumes of the landslide events in the thesis was estimated using slope local base layer (SLBL) on the landslide deposit. This method draws a surface through the deposit from the lateral edges with certain parameters that can be chosen. The volume above this surface is then calculated and given as an estimate for the landslide volume. In this thesis we assumed a straight surface through the deposit with no deepening. This is to ensure that we do not overestimate the volume of the landslide, but can lead to underestimation. The calculation process is automated through a ArcGIS Pro tool, the input being a polygon of the deposit area, a digital terrain model and parameters for deepening. A digital terrain model with 10x10 meter resolution was chosen for this due to the calculation time, Velardi (2019) found the result difference between 1x1 meter and 10x10 meter resolution to be insignificant for RSFs of a volume greater than 0.1 million m^3.

3.4 Parameters

To compare and group the events a slight simplification of the geology and topography was deemed necessary. The chosen parameters for each category is given in Table 2.

Table 2: Parameters and their sub-groupings

Run-out topography	Run-out profile	Landslide classification	Lithology	Substrate
Unobstructed	> 50% steep decent	Rock collapse	Granitic gneiss	Moraine
Channelized	< 50% steep decent	Rock avalanche	Other gneiss	Colluvium/Moraine
Channelized, thereafter unobstructed	Stepped decent	Low mobility rock avalanche	Sandstone	Colluvium/Alluvium
Against opposite valley side			Gabbro	
Ag.Opp.Valley side, thereafter channelized			Phylite	

3.4.1 Topography

For topography we have defined two factors for comparison, Topographical constraints along the run-out path and the run-out profile form. For the topographical constraints we have chosen three main parameters following Nicoletti and Sorriso-Valvo (1991) (fig. 2), but also included combinations of these. The parameters used are:

- Unobstructed
- Channelized
- Channelized, thereafter unobstructed
- Against the opposite valley side
- Against the opposite valley side, thereafter channelized

The inspiration for looking at the profile form comes from a french method for rockfall mapping BRGM (2021). Their categories were established for rock falls and had limitations on length as well as profile form. This methodology was attempted to be structured so it could be used for large volume RSFs but in the end a totally new categorization was established with inspirations from their categories. The profiles for every event is available as figures in appendix A (ex. fig. 7, 8 and 9), or in appendix B as a spread sheet with location and elevation data. To better fit with large volume RSFs the three new categories were defined as:

- Profile form where >50% is steep decent.
- Profile form where <50% is steep decent.
- Profile form with “stepped” decent, one or more relatively flat sections interrupting the descent.

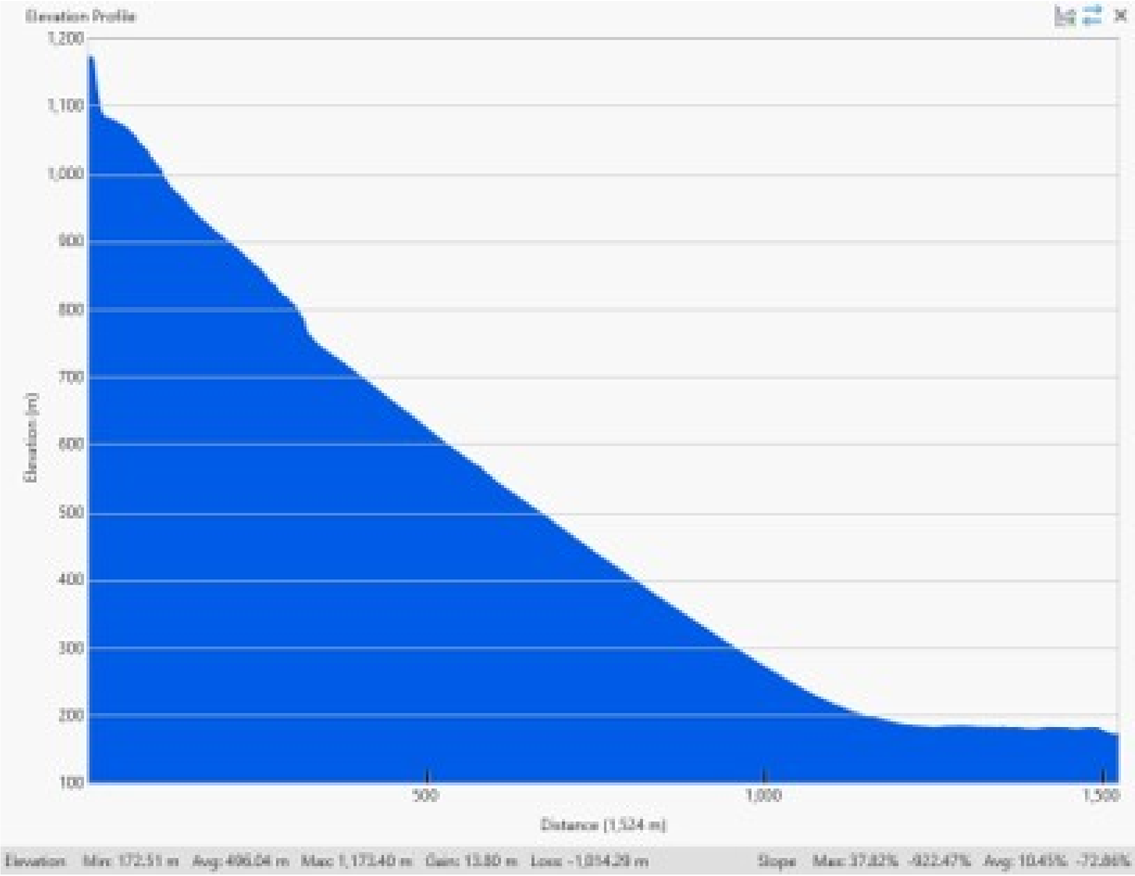

Figure 7: Example of run-out profile, > 50% decent (ID:1025).

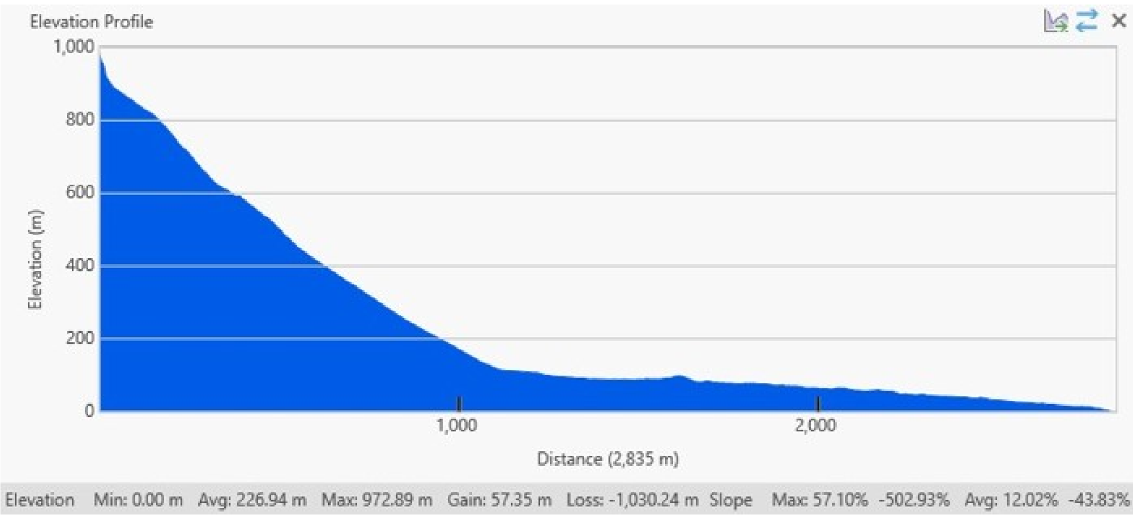

Figure 8: Example of run-out profile, < 50% decent (ID:949).

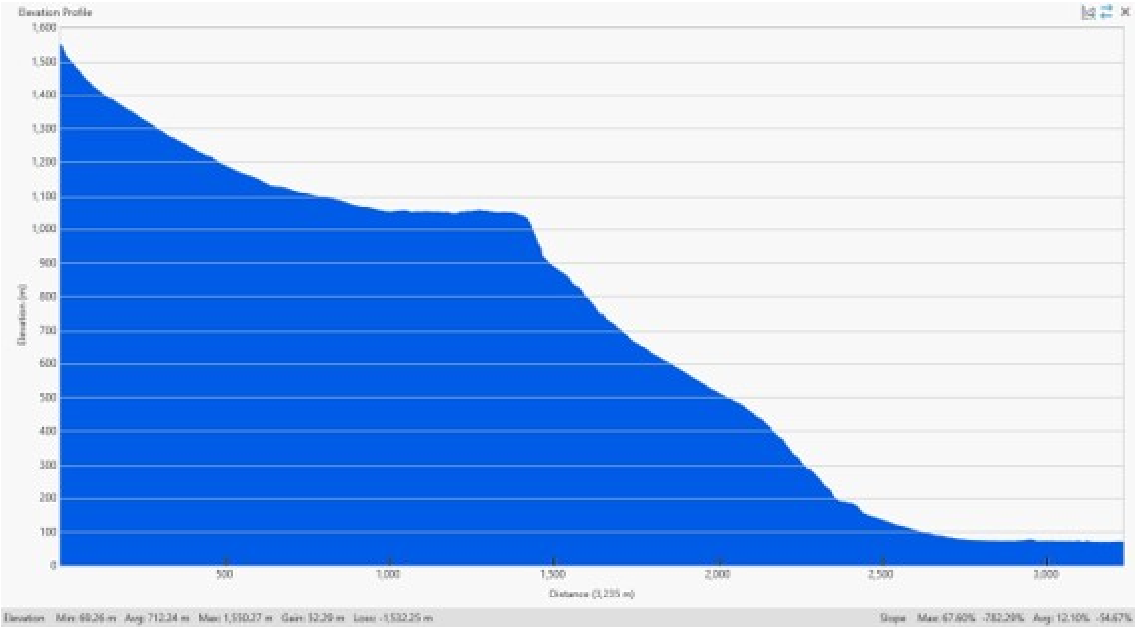

Figure 9: Example of run-out profile, stepped profile (ID:1020).

3.4.2 Geological factors

The geological factors we have chosen to investigate are:

- Landslide classification
- Lithology
- Substrate

The landslide classification is based on the existing classifications done in NGUs RSF inventory, with reclassification of some events. Three classifications are used, Rock Collapse, low mobility Rock avalanche and Rock avalanche. The only difference between "low mobility rock avalanche" and "rock avalanche" is that "low mobility rock avalanche" have a $H/L \geq 0.5$, a limit chosen when we did our initial selection of events. This classification of "low mobility" Rock Avalanches should therefore not be considered closely as it is only a result of the initial selection and does not add any depth to our data other than ensure that events of lower mobility are included in the data set.

The Lithology is categorized based on the mapped lithology in the release area. The source for this information is the NGU bedrock map, using the best available map (lowest map scale).

The substrate is the material the landslide is moving on, and partially eroding. Hungr et al. (2014) and Mitchell et al. (2020) both indicate that substrate is of importance to the mobility of RSFs. The parameters chosen for the study are generalized similar to the categories in geological maps, eg. "Moraine" and "Alluvial deposits" . The data is from NGUs national maps of superficial deposits. As large

Volume RSFs have run-out of up to several kilometers a maximum of two types of deposits are used in our data set. This simplification is done to group the data and make it more applicable for the comparative empirical study.

3.5 Compiling data

The data compiled in this thesis is presented in two ways, as data sheets for each individual RSF event in Appendix A and in a spreadsheet in Appendix B. Both ways of presenting the data have their advantages. The individual data sheets are a great resource to quickly get an understanding of the individual event, and the spreadsheet is ideal for studying the whole data set comparatively. The data sheets in Appendix A are especially great at visualizing the topography and scale of the events, which is not easily done in the number focused spreadsheets.

3.5.1 Data sheets for individual RSF events (Appendix A)

The data sheets consist of 3 main parts; a hill shade map, a profile of the approximate central run out path and a data section with the main geological and topography data (fig 10). The hillshade map includes a scale bar, both the deposit and release area and a approximate central run out path. Where applicable new iterations of features are included in addition to the ones from the NGU RSF inventory (Appendix A). For some sites the release area is uncertain and the general area is then marked instead. The deposit area, release area and run out path from the NGU inventory are included in all events where they were available. New iterations are only included in the events where there were changes, the exception being the new iteration of the run out path lineament always being drawn as this is the lineament for the run-out profiles.

3.5.2 Excel database (Appendix B)

Appendix B is a excel worksheet including the comparative analysis based on the parameters, and individual sheets for each RSF. The individual sheets include the run-out profiles given with numerical values as well as calculations of H/L etc.

4 Results

In total 28 rock slope failures have been analyzed and mapped, 8 rock collapses and 20 rock avalanches. The rock avalanches are further categorized into low mobility or normal mobility with an arbitrarily chosen limit on mobility to $H/L \geq 0.5$ or angle of reach $\geq 26.5°$. There is no physical difference between "low mobility rock avalanche" and "rock avalanche" this is just a sub-division included to cover the spread of mobility when selecting sites from the RSF inventory. The split categorization was implemented to ascertain the inclusion of a number of low mobility rock avalanches and not just ones with excessive mobility.

4.1 Data sheets

Data sheets are made for each individual RSF event, including a map and a profile of each event (fig. 10). They can be found for all events in appendix A. Further description is available in Section 3.5.1. The data sheets presents the RSF events location, certain parameters related to the mobility and the geometry of the landslide with both a hillshade map and a profile along the central run-out path. The data sheets present the geographical extent of the RSFs in a way the empirical graphs cannot.

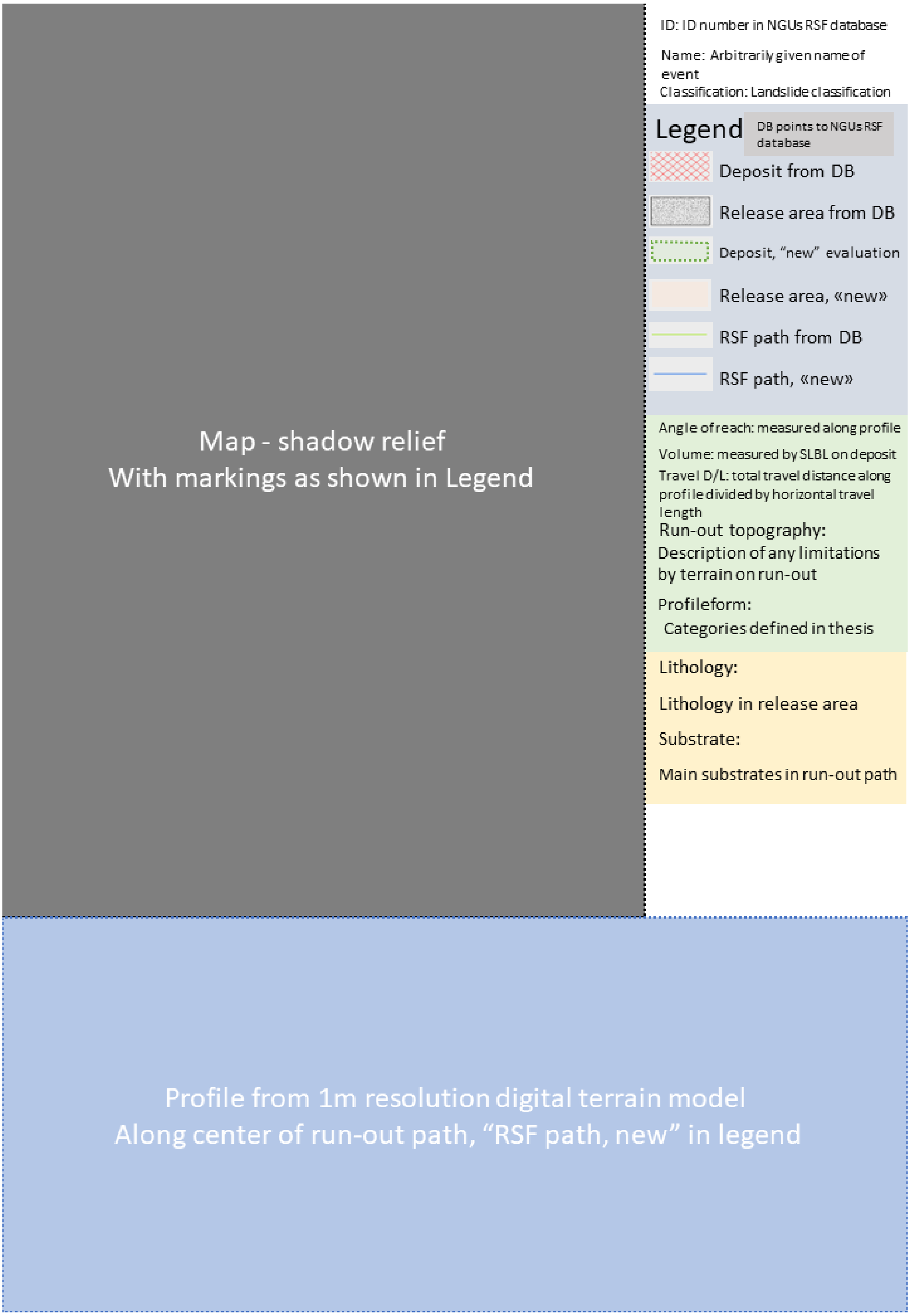

Figure 10: Descriptive depiction of the data sheets available in Appendix A. Presents the general layout of the data sheets in appendix A, and description of data presented on the right hand side of the data sheets.

Four data sheets, Figure 12, 13, 14 and 15, have been included to further present the data available in Appendix A. Figure 12 is the data sheet for *Navardalsnebba* (ID: 933), the second largest (volume) and second highest mobility rock avalanche in the data set. Navardalsnebba is a site where the rock avalanche have crossed two valleys, reaching the opposite valley side before spreading laterally at both occasions. This is something that is not possible to present well with our chosen parameters. This is a consequence of the simplification of our parameters, and would not be clear if one only referenced the spreadsheet.

Figure 13 is also a slightly special case, *Dalaosen* (ID: 934). We have classified Dalaosen as a rock collapse, but the site may at first glance look like a rock avalanche deposit due to the seemingly lateral spread down valley, which is a feature that is not part of a rock collapse. However the current theory based on studying the hillshade and 3D point cloud model (fig. 11) is that this is a result of a dam breach. This event highlights the importance of the DTM and especially the 3D point cloud model, as it allows for a more detailed look at the topography of the deposit in remote sensing work. The area of the possible dam breach deposit was included in the rock collapse deposit as no field study have verified the possibility of a dam breach, this way we are certain the mobility is not higher than presented in the data.

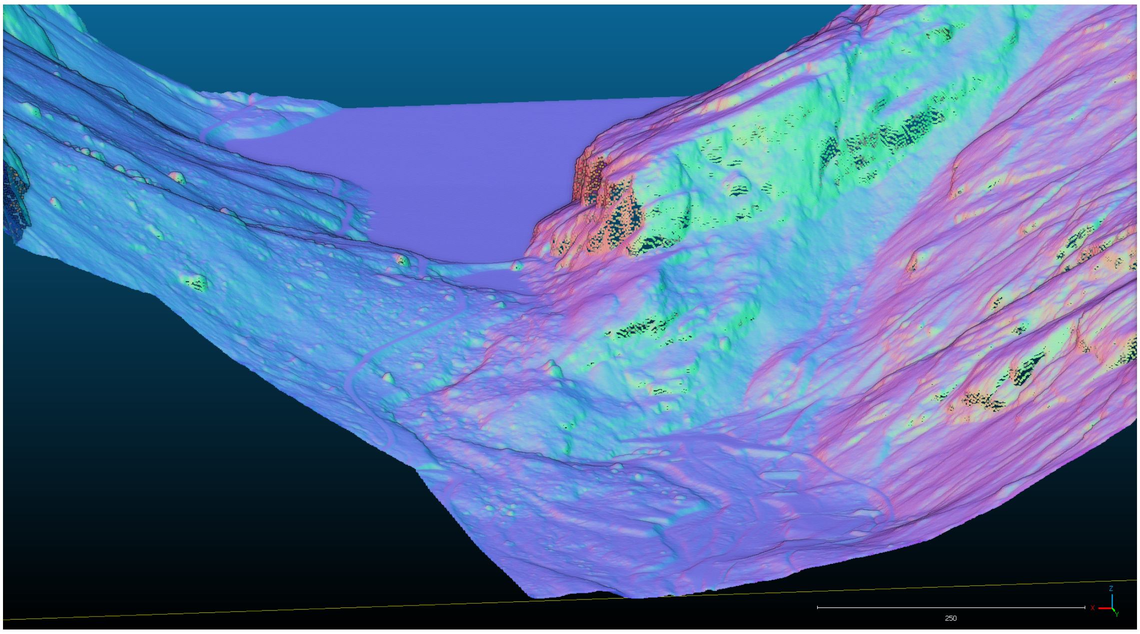

Figure 11: Point cloud model of the dam breach at Dalaosen (ID:934) rock collapse deposit.

Månyta (ID:1042) is a rock collapse deposit. But as we see in the hillshade on the data sheet, Figure 14, there are multiple other smaller RSFs from the same area. Some of these deposits where included in the mapped deposit from the NGU inventory. The very steep valley sides in this area are not easily seen on the hillshade in Figure 14, however in the 3D point cloud model they are clearly visible (Figure 16). This lead to a reevaluation and redrawing of the deposit area.

Ivasnasen (ID:1068) is classified as a low mobility rock avalanche with AoR = 29.7°

(H/L= 0.57) (fig. 15). The site is relatively uneventful with the exception of the run-out into the river. There might have been some degree of erosion on the deposit along the river. There are some lateral constraints on the run-out but the path is so wide that it has been classified as unobstructed.

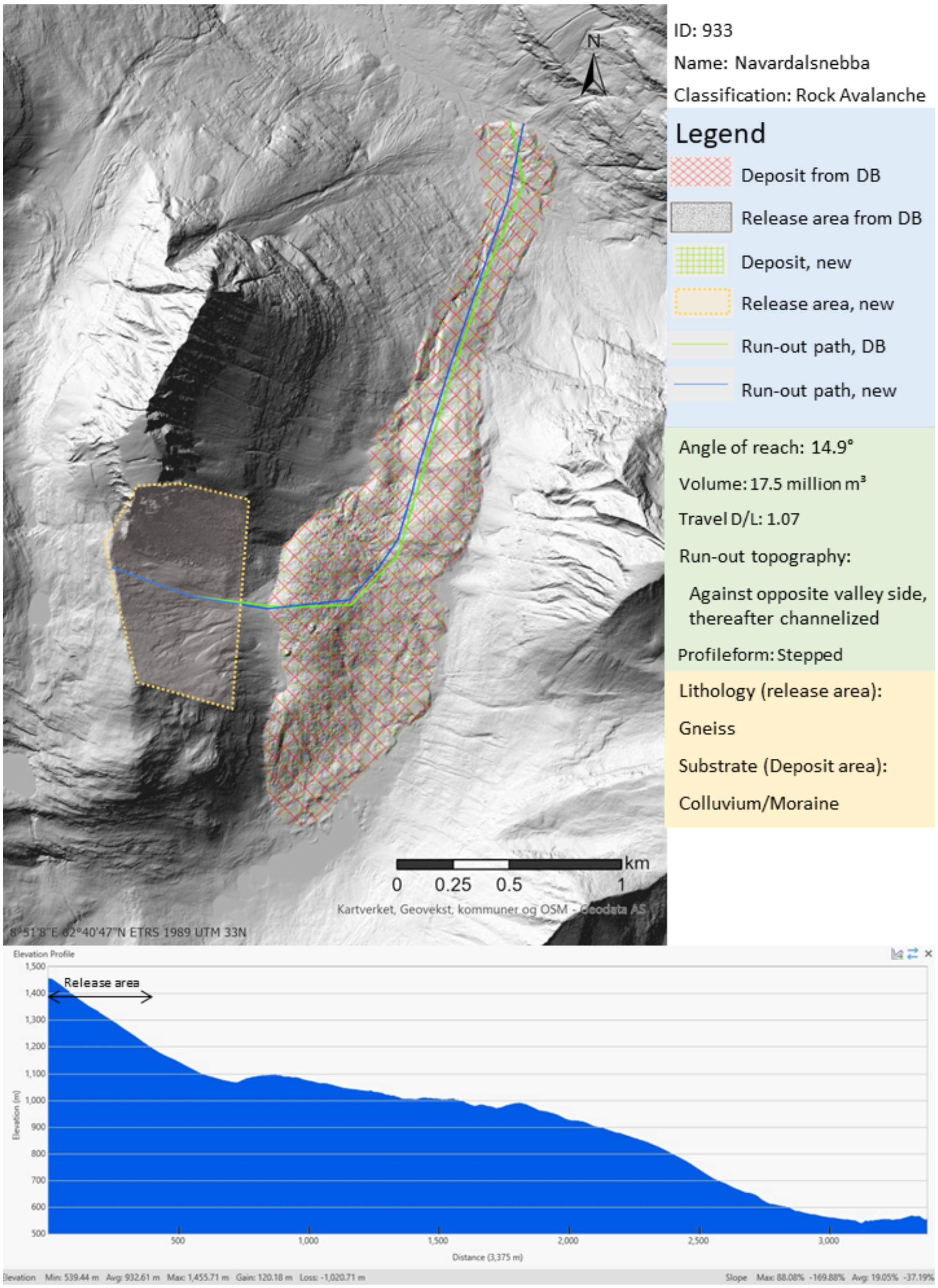

Figure 12: Extract from Appendix A, data sheet for Navardalsnebba (ID:933).

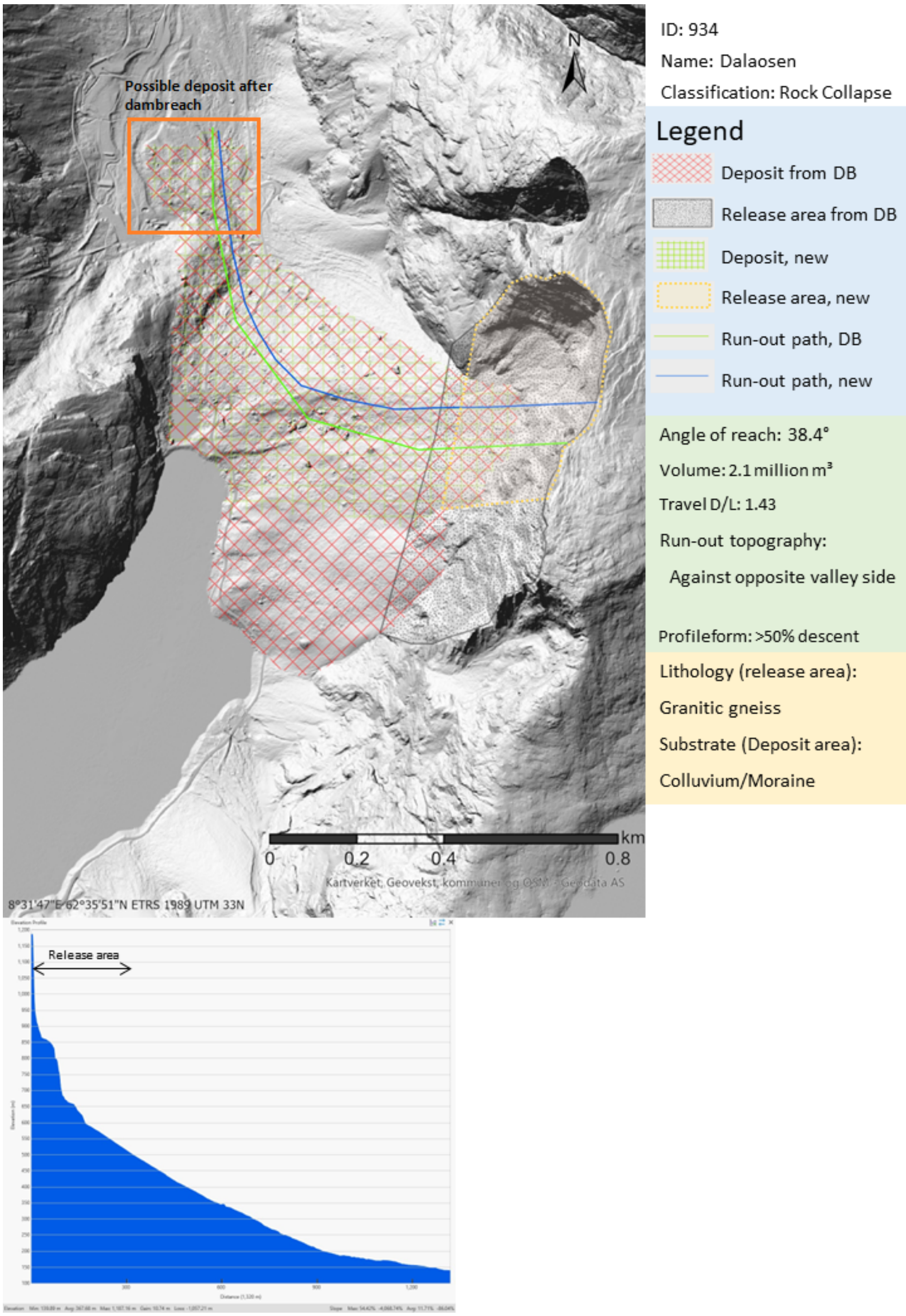

Figure 13: Extract from Appendix A, data sheet for Dalaosen (ID:934).

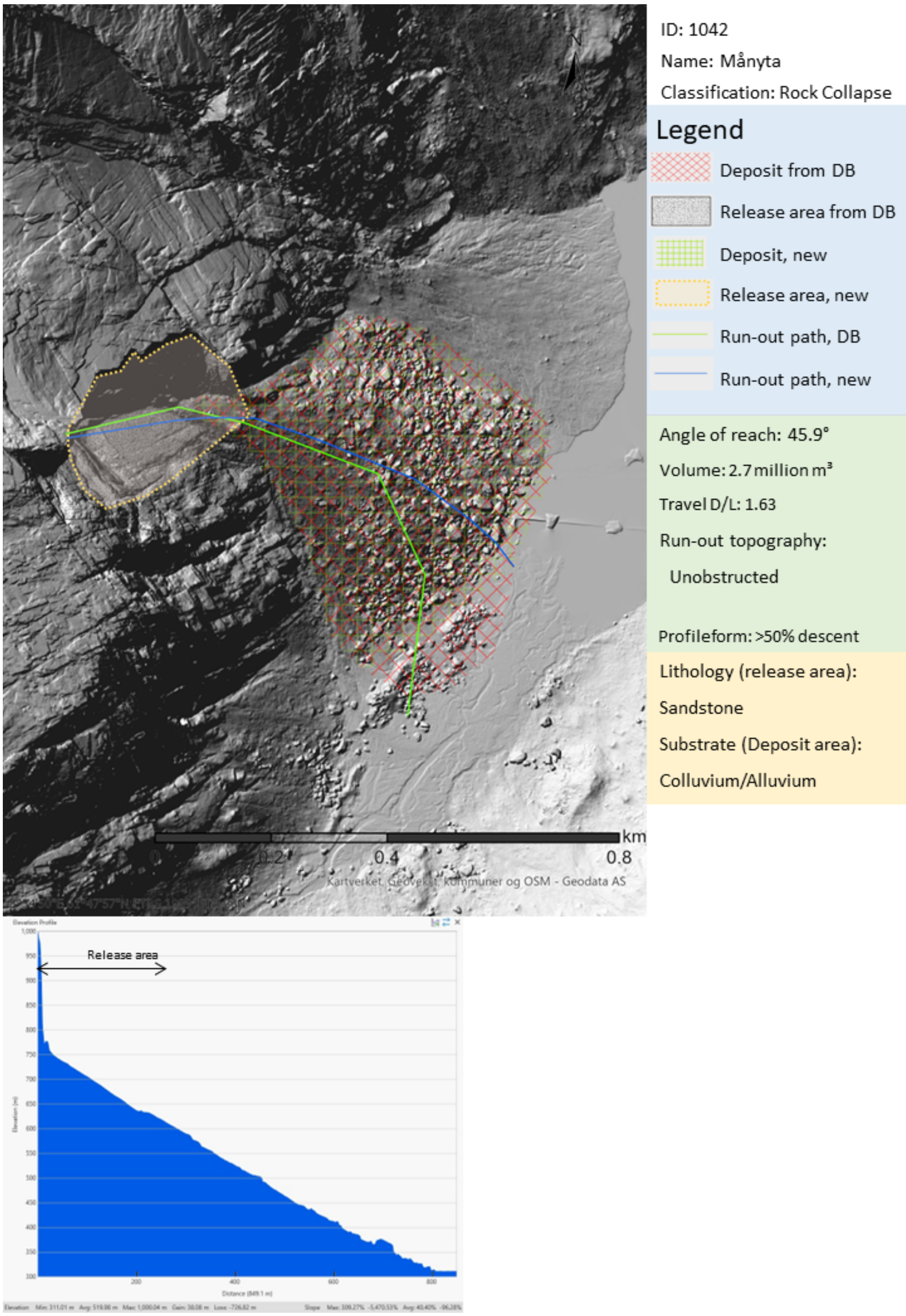

Figure 14: Extract from Appendix A, data sheet for Månyta (ID:1042).

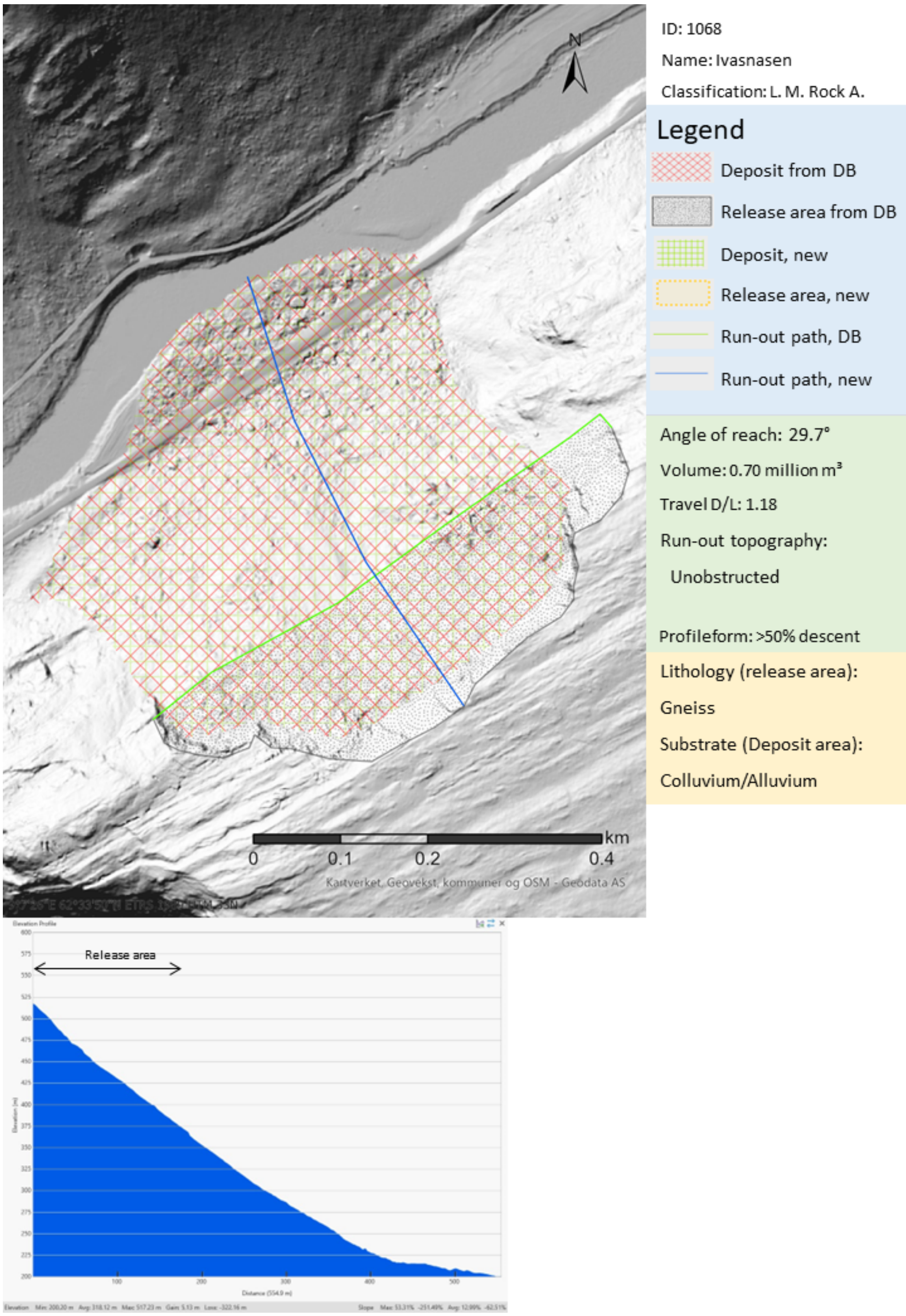

Figure 15: Extract from Appendix A, data sheet for Ivasnasen (ID:1068).

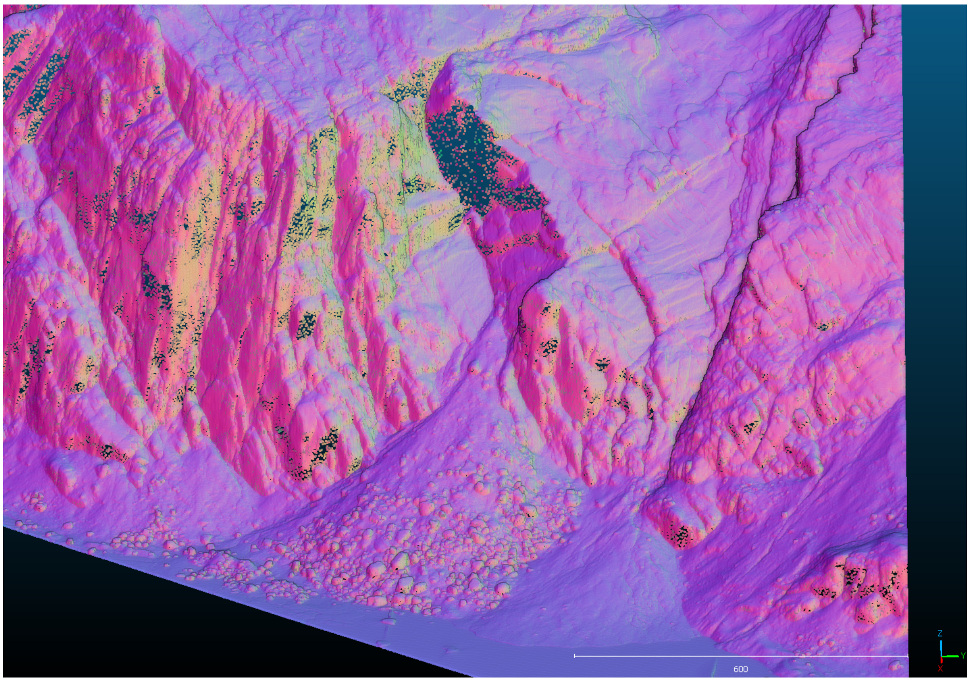

Figure 16: 3D point cloud model of Månyta (ID:1042), with HSV colors to represent surface orientation.

4.2 Statistical analysis of mobility

Data from the 28 large volume RSFs in western Norway were compiled and a statistical analysis of how 5 different factors affect mobility in rock avalanches have been applied. The individual events were plotted with angle of reach/volume ratio and compared with the parameters we investigated. The graphs also include a secondary graph showing the variation of AoR in the individual groups without a second axis. The Scheidegger curve (Scheidegger, 1973) and the truncated Scheidegger curve (Corominas, 1996) are included in the figures for reference to the current empirical estimation in use for hazard mapping RSFs in Norway. We have not done any multivariate analysis including more than one of these 5 factors at the same time.

4.2.1 Landslide classification

Our findings support the observation that the landslide mechanics are a major factor in large volume RSF mobility, where one would expect a much higher mobility in rock avalanches than rock collapses (Hermanns et al., 2022). The angle of reach measured for the rock collapses in the data set is between 31° and 54°, where as the mobility of the rock avalanches were measured to between 15° and 33° (fig. 17). Its clear from the data that rock collapses tend toward a lower mobility compared to rock avalanches, even at volumes exceeding 1 million cubic meters. Due to the major impact on mobility by the landslide type our investigation of other factors will only present data for rock avalanches, but the complete data is available in appendix B.

The calculated trend lines show a increase in mobility with an increase in volume for both rock collapses and rock avalanches (tab. 3). The individual trend lines for low mobility rock avalanches and rock avalanches can be disregarded as this is a product of the chosen classification and has no real value. The trend line for both rock collapse and rock avalanches are shallower than the proposed Scheidegger line, but show a distinct trend of increased mobility with volume.

Table 3: Calculated logarithmic trend lines of mobility per landslide classification.

Landslide classification	Trend line
Rock collapse	$y = -1.711log(x) + 39.54$
Rock avalanche	$y = 0.053log(x) + 19.85$
Low mobility rock avalanche	$y = 0.749log(x) + 30.20$
Combination of all rock avalanches	$y = -1.842log(x) + 25.14$

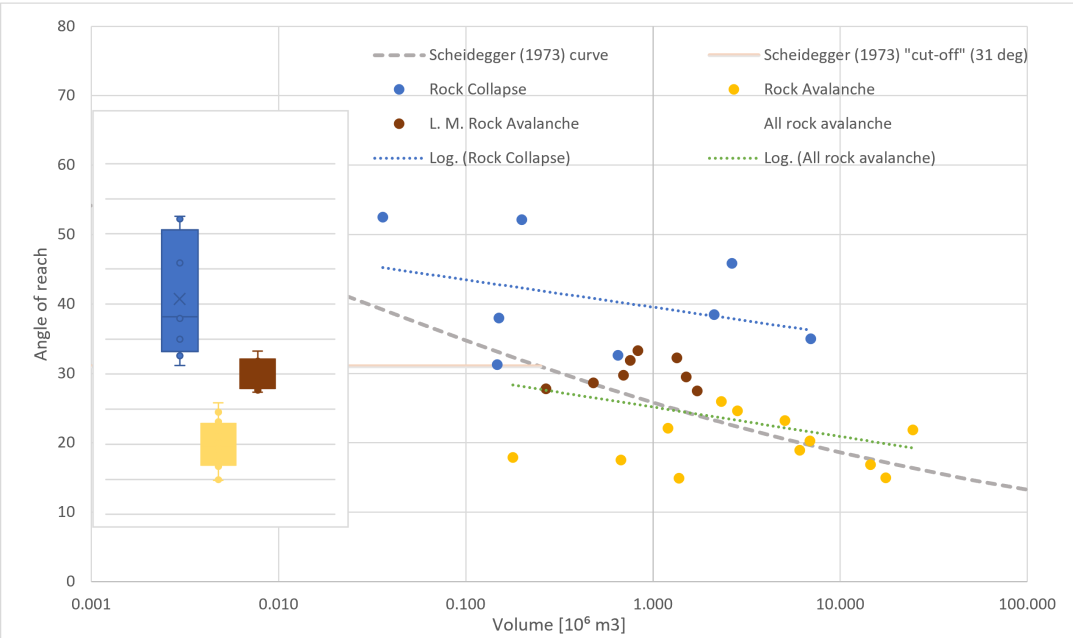

Figure 17: Graph of the angle of reach to volume ratio for the events investigated in the thesis, grouped by the landslide classification with the sub-division of the rock avalanches by mobility as mentioned earlier (3.4). Trend lines for rock collapse and the all rock avalanches combined are drawn as dotted lines.

4.2.2 Lithology

The geographic region the data is from is dominated by gneiss, therefor only three of twenty rock avalanche events did not consist of gneiss. These three events are of different lithology and therefor provide little statistical insight into how these lithology affect mobility. Both categories of gneiss show a similar trend in mobility with very limited variation between the two (fig. 18). The gneisses have a large variance in mobility at any given volume. The trend lines of both categories of gneiss are almost identical (tab. 4).

Table 4: Calculated logarithmic trend lines of mobility per lithology for rock avalanches studied in the thesis.

Lithology	Trend line
Granitic gneiss	$y = -1.383 log(x) + 23.78$
Gneiss (other)	$y = -1.652 log(x) + 24.77$

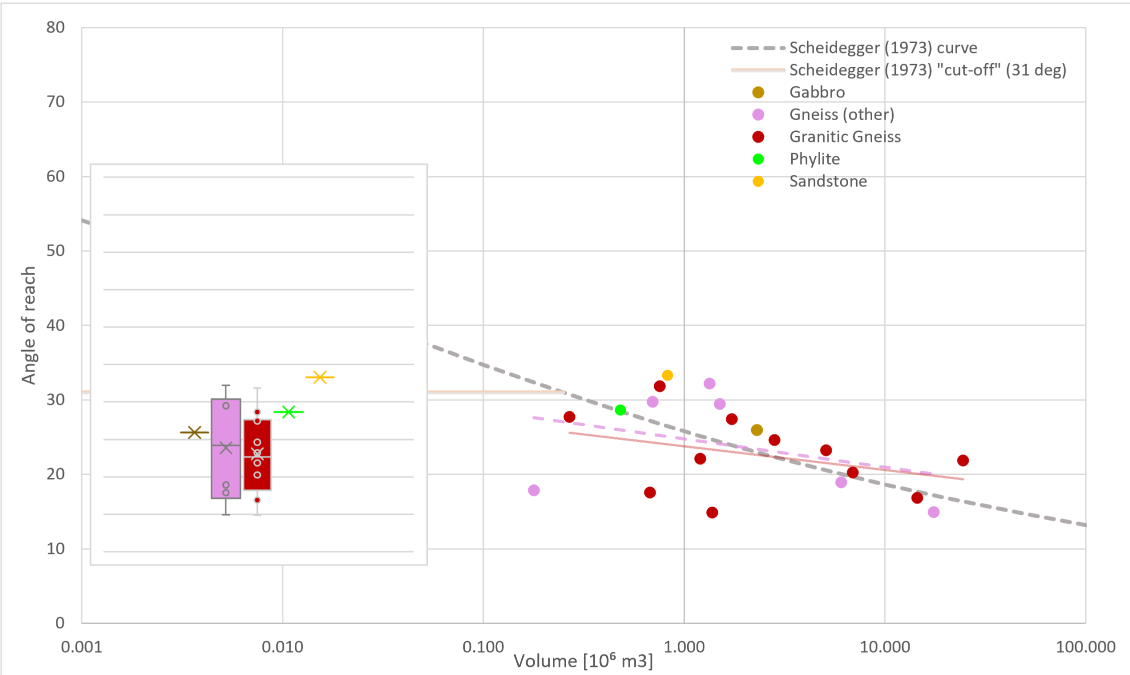

Figure 18: Graph of the angle of reach to volume ratio for the rock avalanche events investigated in the thesis, grouped by lithology. Trend lines are drawn for "Gneiss (other)" and "Granitic gneiss".

4.2.3 Substrate

The substrate for each given deposit has been compiled from NGUs geological maps. To simplify only the two substrates with longest extension along the travel path was used. This led to three categories where one only has a single data point. The gathered data shows a clear trend that rock avalanches on colluvium/Moraine have a higher mobility than events on colluvium/alluvium deposits (fig. 19). It should be noted that the event where only moraine was mapped along the travel path a lower mobility than all events in the category "colluvium/moraine" was calculated.

The trend line for the events categorized as Colluvium/Moraine is relatively flat, but with a overall high mobility (tab. 5). The events categorized as Colluvium/Alluvium produced a steeper trend line, with a low mobility at volumes around 1 million m^3 but a large increase of mobility with volume increase.

Table 5: Calculated logarithmic trend lines of mobility per substrate mapped along travel path for rock avalanches studied in the thesis.

Subtrate	Trend line
Colluvium/Alluvium	$y = -5.506log(x) + 30.85$
Colluvium/Moraine	$y = -0.659log(x) + 20.56$

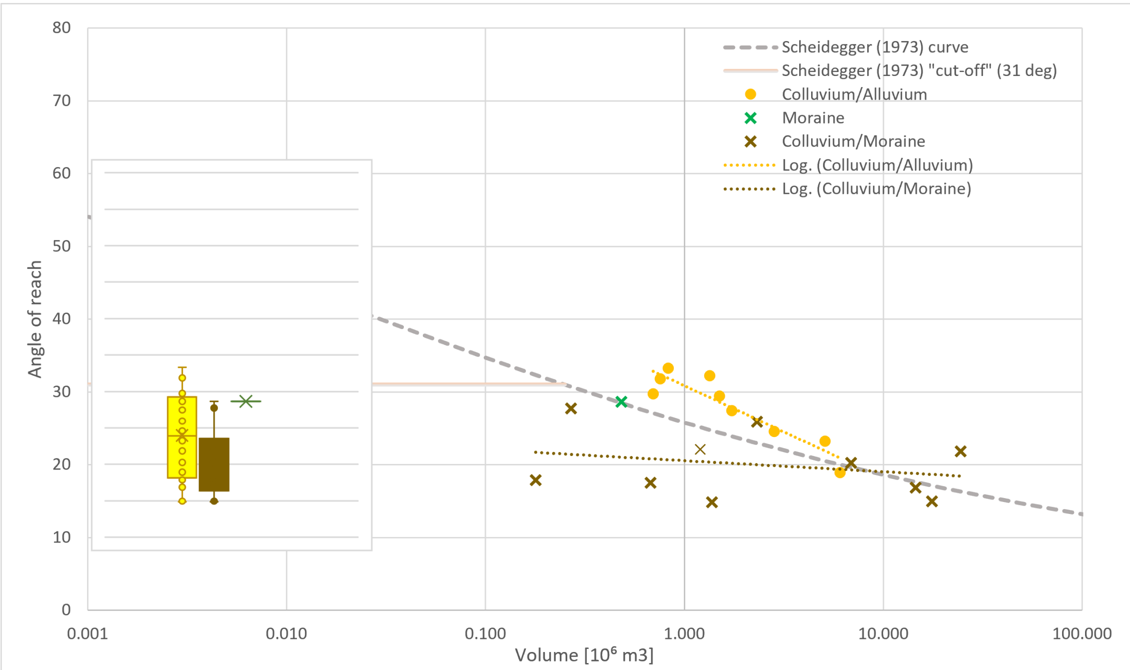

Figure 19: Graph of the angle of reach to volume ratio for the events investigated in the thesis, grouped by substrate.

4.2.4 Run-out topography

The run-out topography is here a description of obstructions to the rock avalanche mass during run-out, for example reaching the opposite valley side or canalization due to lateral obstruction along the path. The rock avalanches that were canalized early in the run-out, then later where without obstruction produced the lowest mobility with both events AoR being measured to > 31° (fig. 20). The unobstructed rock avalanches produced relatively low mobility, every event except one plotting above the Scheidegger curve. The unobstructed event with relatively high mobility far exceeded the estimation from the Scheidegger curve. The events that reached the opposite valley side without any additional movement plot close to the Scheidegger curve. The category with highest mobility is by far the events that reached the opposite valley side and continued to flow channelized down valley. Five out of eighth events in this category exceeds the mobility estimated by the Scheidegger curve, especially the small volume events in this category have excessive mobility compared to the estimation. All these categories produced relatively flat trend lines with the exception of the events that reached the opposite valley side without channelizing that almost matched the Scheidegger curve (tab. 6).

Table 6: Calculated logarithmic trend lines of mobility per run-out topographic constraint for rock avalanches studied in the thesis.

Topographic constraint	Trend line
Channelized, therafter unobstructed	$y = -2.25log(x) + 32.88$
Unobstructed	$y = 0.202log(x) + 26.74$
Against opposite valley side	$y = -2.625log(x) + 25.69$
Ag. Opp. Valley side, therafter channelized	$y = 0.333log(x) + 17.85$

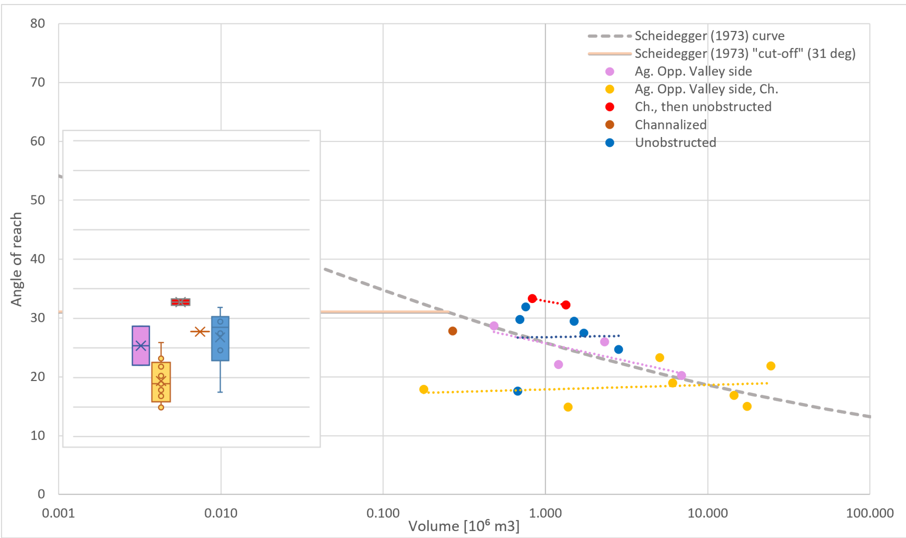

Figure 20: Graph of the angle of reach to volume ratio for the events investigated in the thesis, grouped by run-out topographic constraints as described in Section 3.5.1.

4.2.5 Profile form

Three categories where defined based on the rock avalanche run-out profiles; $> 50\%$ descent, $< 50\%$ descent and stepped profiles (7, 8 and 9). The events with stepped profiles plot closely to the estimation by the Scheidegger curve, with the exception of one event with excessive run-out. The group with $< 50\%$ descent mostly plot above the curve, with one exception slightly below the Scheidegger curve. The final group with $> 50\%$ decent all plot around the 15-25°mark, even at the lower volumes where this is quite excessive compared to the empirical estimates by Scheidegger (1973).

The trend lines of $< 50\%$ descent and stepped run-out profiles are almost exactly the same but with a difference of $\approx 6.7°$ AoR more mobility for the events with a stepped profile (tab. 7). The trend line for events with a run-out profile where $> 50\%$ is descent is positive with a increase of volume.

Table 7: Calculated logarithmic trend lines of mobility per run-out profile form for rock avalanches studied in the thesis.

Run-out profile form	Trend line
$> 50\%$ descent	$y = -2.568log(x) + 29.17$
$< 50\%$ descent	$y = 0.574log(x) + 18.756$
Stepped descent	$y = -2.567log(x) + 22.41$

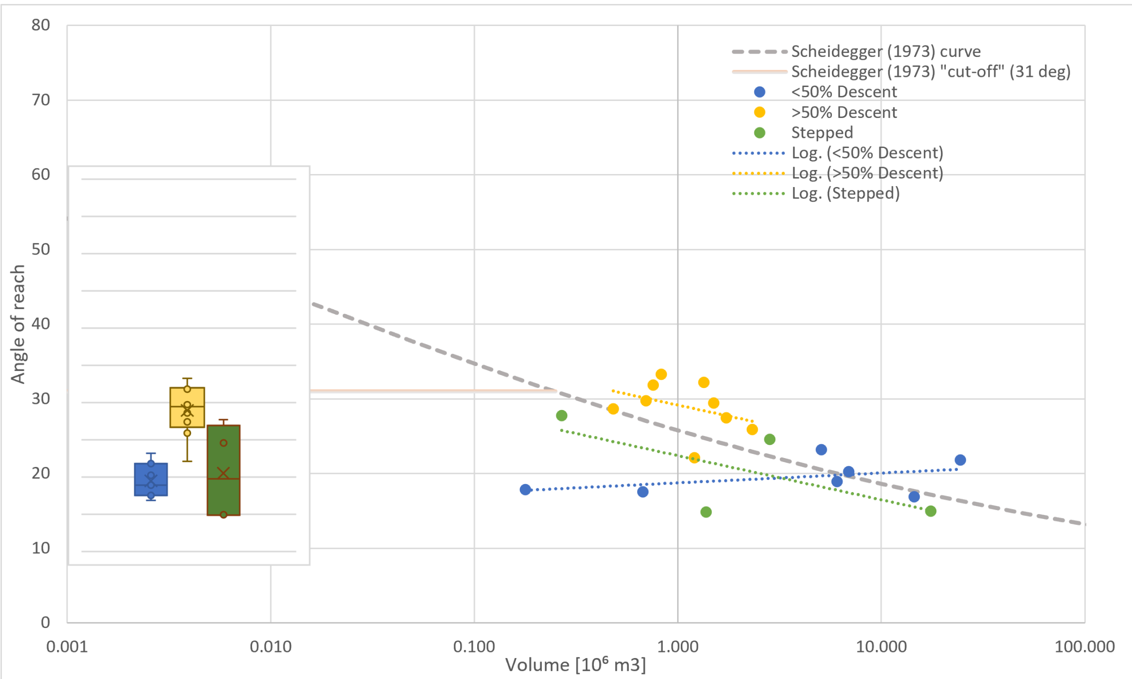

Figure 21: Graph of the angle of reach to volume ratio for the events investigated in the thesis, grouped by profile form. Three groups; stepped profiles, $> 50\%$ and $< 50\%$ of the run-out profile being descent.

5 Discussion

5.1 Data quality

When studying historical RSFs there are a lot of uncertainties and the place this is most noticeable is the volume estimation. The method chosen for volume estimation was SLBL on the deposit of the RSF, but some of these were formed thousands of years ago. This opens the possibility that the current deposit might be eroded or that other slope processes such as rock falls have built the deposit up. This uncertainty in volume leads to an uncertainty in the mobility analysis as these are based on the ratio of mobility against volume. Penna et al. (2023b) estimated the volume of a number of Norwegian RSFs using both the deposit and the release area. They found that the volume estimated by SLBL on the deposit were smaller than those estimated using the release area, this is opposite of what is expected due to bulking and entrainment of material during the run-out (Hungr & Evans, 2004). Since conservative parameters were chosen when applying the SLBL method the volume estimates in the thesis are likely to be conservative, and a more detailed estimation might lead to volumes up to ten times larger in the most extraordinary cases.

The thesis have analyzed a total of 28 RSFs with 20 of these being classified as rock avalanches. This amount is quite limited to draw conclusions on the effect of the studied parameters on RSF mobility. Previous works such as Corominas (1996) studied over 200 events to produce their result, though more landslide classifications were investigated. The trends observed in this thesis should be evaluated using larger data sets before they are accepted as fact. NGU plans to further incorporate and expand the current use of certain parameters in their inventory to ease further studies, and possibly apply some of the methodologies tested in this thesis to the national RSF inventory as a whole.

The generalization of data could also plays a large role in the results. Rock avalanches are major landslide events with run-outs up to several kilometers. For example to only assign a combination of two substrates for a rock avalanche could be lacking. Also the distance of the run-out path on each substrate is not part of the analysis. A event with run-out path mostly on colluvial material and a small fraction on alluvial material will be represented the same way as a event with a more equal or opposite substrate distribution. There is a large variation between the rock avalanche events, though similarities might be presented through the generalization it might also obscure the actual impact of the parameters studied.

5.2 Results

The landslide classification is the biggest factor on large volume RSF mobility observed in this thesis. There is a major difference between the mobility of rock avalanches and rock collapses which is supported by the findings from international events studied in Jakobsen (2023). All the rock collapses analyzed have a lower mobility than $AoR = 31°$ close to the definition given by Hermanns et al. (2022) though there is an apparent trend toward higher mobility with volume increase. This could be because of the lack of data, in general there is a large variance in the mobility of the rock collapses of the thesis, especially in the lower volumes where both the highest and lowest mobility events are plotted. This could also point toward other factors than volume being dominant in the mobility of rock collapses. The rock avalanches also trend toward a higher mobility with volume at almost the same apparent trend line as the rock collapses. Compared to Scheidegger (1973) we see a higher mobility at lower volumes, but a lower mobility at volumes exceeding 1 million m^3. Because of the large impact landslide classification had on mobility rock collapses were removed from the other four analyses.

The lithology of the rock avalanches studied was not very diverse, three events that where not from a type of gneiss, a majority of events released from granitic gneiss and the rest from other various classifications of gneiss. The lack of diversity in the data leads to no real results, it is not possible to determine or even point towards how lithology might affect mobility in rock avalanches from the data.

As early as Heim (1882) it was recognized that the substrate along the run-out path could affect the mobility of rock avalanches. This increase in mobility due to entrainment of liquefiable material from the run-out path was also found in other studies such as Hungr and Evans (2004). The data from this thesis points towards a higher mobility when the landslide masses travel on moraine compared to alluvial soils. Aaron and McDougall (2019) documented an increase in mobility on saturated substrates. This could be the effect giving rock avalanches on moraine a higher mobility than those on alluvial deposits as moraines often have a lower permeability than alluvial deposits. Since these rock avalanches are historic there is no data available on the saturation of the soil at the time of the events. There might also be a topographical difference between these categories. Most of the events categorized as moraine are from relatively smaller valleys while those categorized as alluvial are from larger valleys. It should also be noted that 70% of the rock avalanches categorized as Colluvium/Moraine have a mobility exceeding the Scheidegger curve, in contrast to Blikra et al. (2006) who found that 90% of Norwegian rock avalanches did not exceed the Scheidegger curve. Therefore one might suspect that this trend might be changed if the data set was expanded in size. Further study is required to find the actual cause of this apparent difference in mobility.

Topographic constraints along the run-out path is well documented to affect the mobility of rock avalanches (eg. Nicoletti and Sorriso-Valvo, 1991). Contrary to Nicoletti and Sorriso-Valvo (1991) the data from this thesis suggests that frontal constraints such as reaching the opposite valley side does not lower the mobility of rock avalanches, in most cases the landslide mass will continue flowing along the valley after reaching the opposite side. Events categorized as “unobstructed” and “against opposite valley side, thereafter channelized” trend toward a lower mobility with higher volume, this goes against the commonly agreed concept and may indicate a lack of data to properly study these parameters with accuracy.

Analyzing the run-out profile against mobility is a new and previously untested methodology. After analyzing the data there seems to be a greater relation between the achieved mobility and the run-out profile than the profile form and probable mobility. Every "low mobility rock avalanche" except one was categorized as $> 50\%$ descent while every other rock avalanche was categorized as either stepped or $< 50\%$ descent. Therefore it is suggested to not use this methodology in further study of rock avalanche mobility.

5.3 Methodology

In general the data set analyzed in this thesis seems to be to small to accurately predict the individual factors effect on large volume rapid RSFs mobility. The thesis work lays the foundation for improving the methodologies and expanding the data set to the whole national RSF inventory, and possibly take it even further and incorporate other national inventories. As the amount of data available continuously increases and the methods are improved the understanding of RSF mobility is likely to improve.

The empirical approach to study single parameters and their effect on RSF mobility is definitively viable, and have been developed and expanded upon since Scheidegger (1973) popularized the method. There is a need for large data sets when applying the method to ensure the validity of the results, especially when the degree of generalization increases. There are definitively arguments for and against the generalization of data but it is required when using the empirical approach. Large volume RSFs are extremely complex landslides and to study them, especially comparatively, is difficult. As seen by the two large volume RSF events in the European Alps in June of 2023 volume is not enough to accurately predict the mobility of such events. A better understanding of how kinematics, topography, lithology, substrate etc. effect the mobility is required to improve the accuracy of the mobility estimations for such events.

In depth studies of singular events or few similar events can prove useful, especially when studying the effect of topography. High detail DTMs are becoming more available, and the coverage is constantly expanding. This will in the future be a great source of data to study recent and future RSFs, but these events are not very common with a limited number each year. Therefore it is important to also use the expanding inventories of historical events in combination with the more modern approaches.

In Norway the empirical approach using the estimation by Scheidegger (1973) is still in use for initial mobility assessment. Further work to improve the mobility estimation is mostly done on sites where the initial estimate point towards potential risk to infrastructure or human lives. A new empirical relation calculated by applying the same principles as Scheidegger (1973) and Corominas (1996) on the Norwegian national RSF inventory should a more accurate representation for Norwegian RSFs.

The biggest effect on mobility found in this thesis work was landslide classification. Therefore it would be of great importance to be able to determine if a unstable rock slope would develop into a rock collapse or rock avalanche. However the geological and topographic factors that determine this is not fully understood. Future studies into how rock collapses develop should be prioritized, even though it is a relatively rare landslide type which is not well documented both in Norway or internationally (Jakobsen, 2023).

6 Conclusion

28 RSFs from western Norway have been studied and analyzed to test the proposed methodology for empirical assessment of geological and topographical parameters effect on large volume RSF mobility. The thesis aimed to test this methodology on a small scale before possible implementation of the whole Norwegian national RSF inventory. In the analysis certain possible trends have been identified but due to the low data amount further work is required to prove the validity of these results.

Two of the five parameters analyzed have clear apparent effect on the mobility of RSFs. The parameter with clearest effect on mobility was the landslide classification, with a $\approx 14°$ higher AoR for a given volume (tab. 3) compared to the rock avalanches. The variation in mobility between rock collapses were however relatively high (fig. 17). Due to the large effect landslide classification had on mobility rock collapses were excluded from the other analyses. The other parameter with an apparent clear effect on mobility was substrate. However there are uncertainties in the validity of these results and further study is deemed necessary before any conclusion is drawn. Lithology produced no clear results as there was only to categories with more than 2 points of data, and these were "granitic gneiss" and "gneiss (other)" (fig. 18). They have close to no difference in mobility compared to each other and a more complete data set is required for further study. For the topographic constraints two of four categories had positive trend lines (tab. 6) which is against the commonly accepted norm of a increase in mobility with volume, therefore the results are deemed unlikely to represent reality unless proven on a larger data set.

The last parameter analysis, run-out profile form, was deemed unreliable as there seemingly is a large relation between the achieved mobility of the RSF and the profile form, rather than the profile form leading to the mobility seen in the events. For future studies I recommend to find alternative topographical parameters such as release area slope angle as studied in Penna et al. (2023b) to replace the run-out profile form.

Future studies

Recommendations for further work to improve the understanding of large volume RSF mobility:

- Perform an empirical study of the volume/mobility relation on the whole of the national RSF inventory and improve the current methodology for initial run-out estimations of unstable slopes in Norway.
- Apply the methodology tested in this thesis to the whole of the national RSF inventory to improve the understanding of geological and topographic factors effect on RSF mobility.
- Study the geological and topographic conditions that form rock collapses, including the kinematics. Evaluate the possibility of predetermining if a unstable slope will develop into a rock collapse or a rock avalanche.

- Further study the correlation between the dip angle of the source area and the mobility of RSFs as described by Penna et al. (2023b).
- Study the effect of topography on RSF mobility in events where pre-failure DTMs and post-failure DTMs are available, such as the Flücthorn and Brienz RSF events of June 2023.

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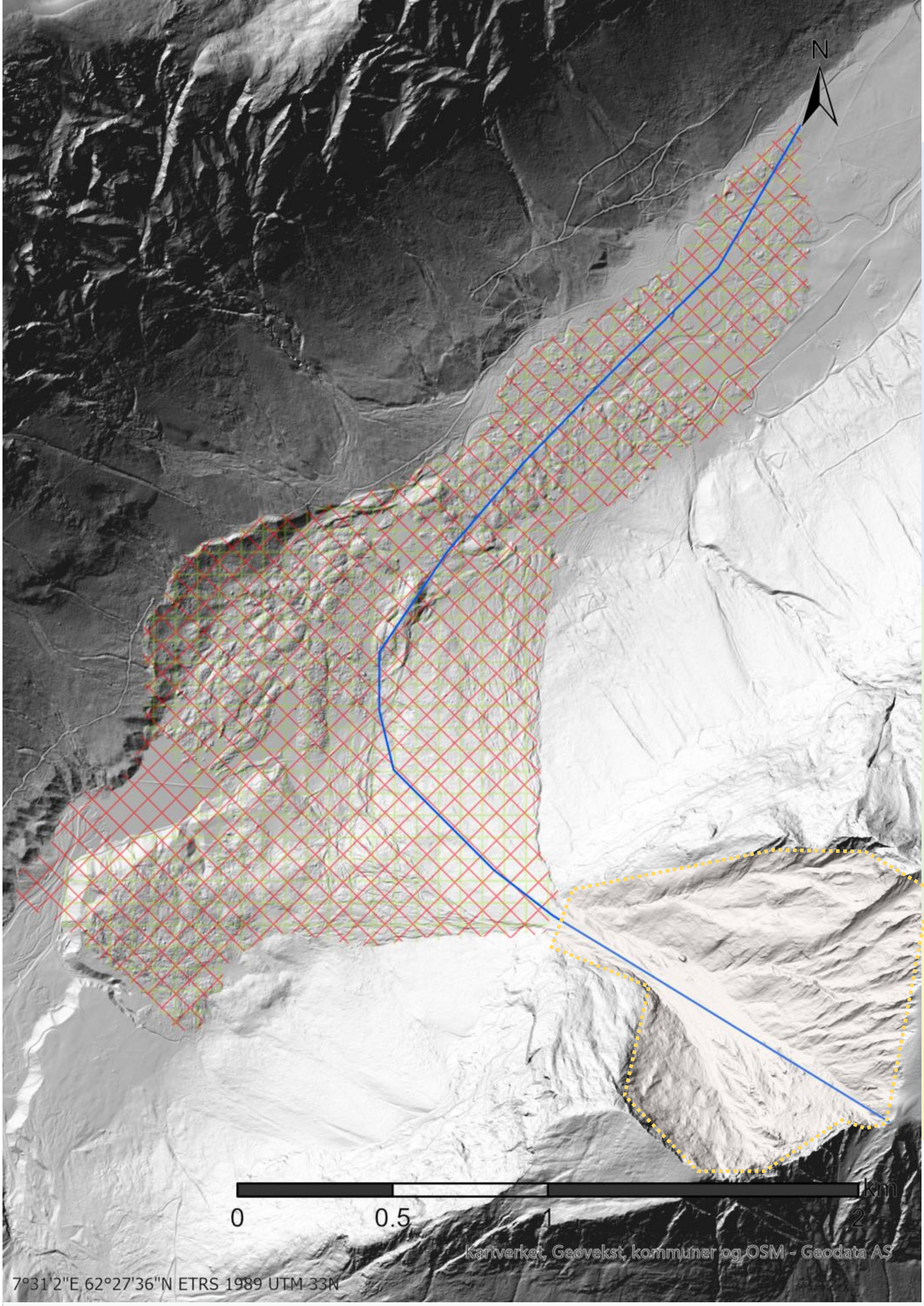
Appendix summary

Appendix A includes data sheets for each individual event with maps, profiles and general data, see section Section 3.5.1 for details.

Appendix B includes the excel work sheet, only the main table is included in this text document, the whole excel file with data from each individual analysis and RSF event is available in the ZIP file at NTNU Open.

A Appendix A



ID: 929

Name: Gråfonnfjellet

Classification: Rock Avalanche

Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 16.9°

Volume: 14.5 million m³

Travel D/L: 1.09

Run-out topography:

Against opposite valley side, thereafter channelized

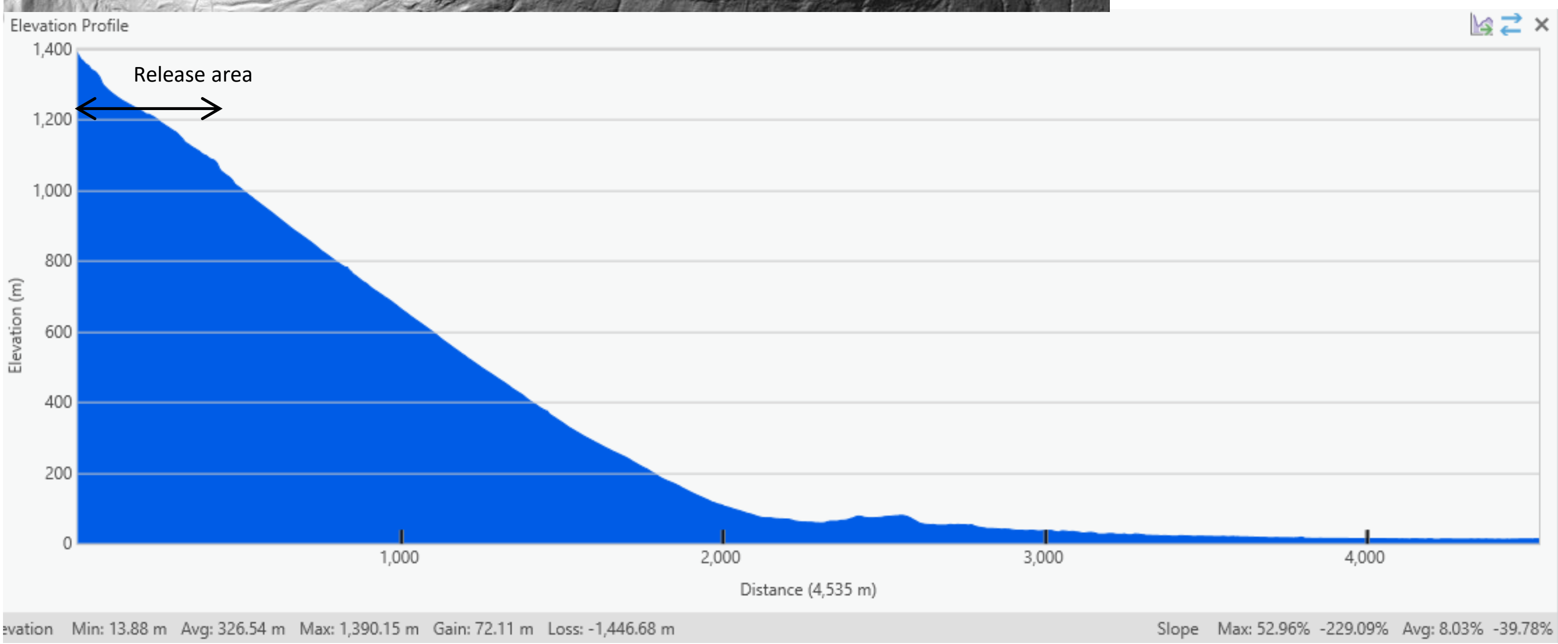
Profileform: <50% descent

Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

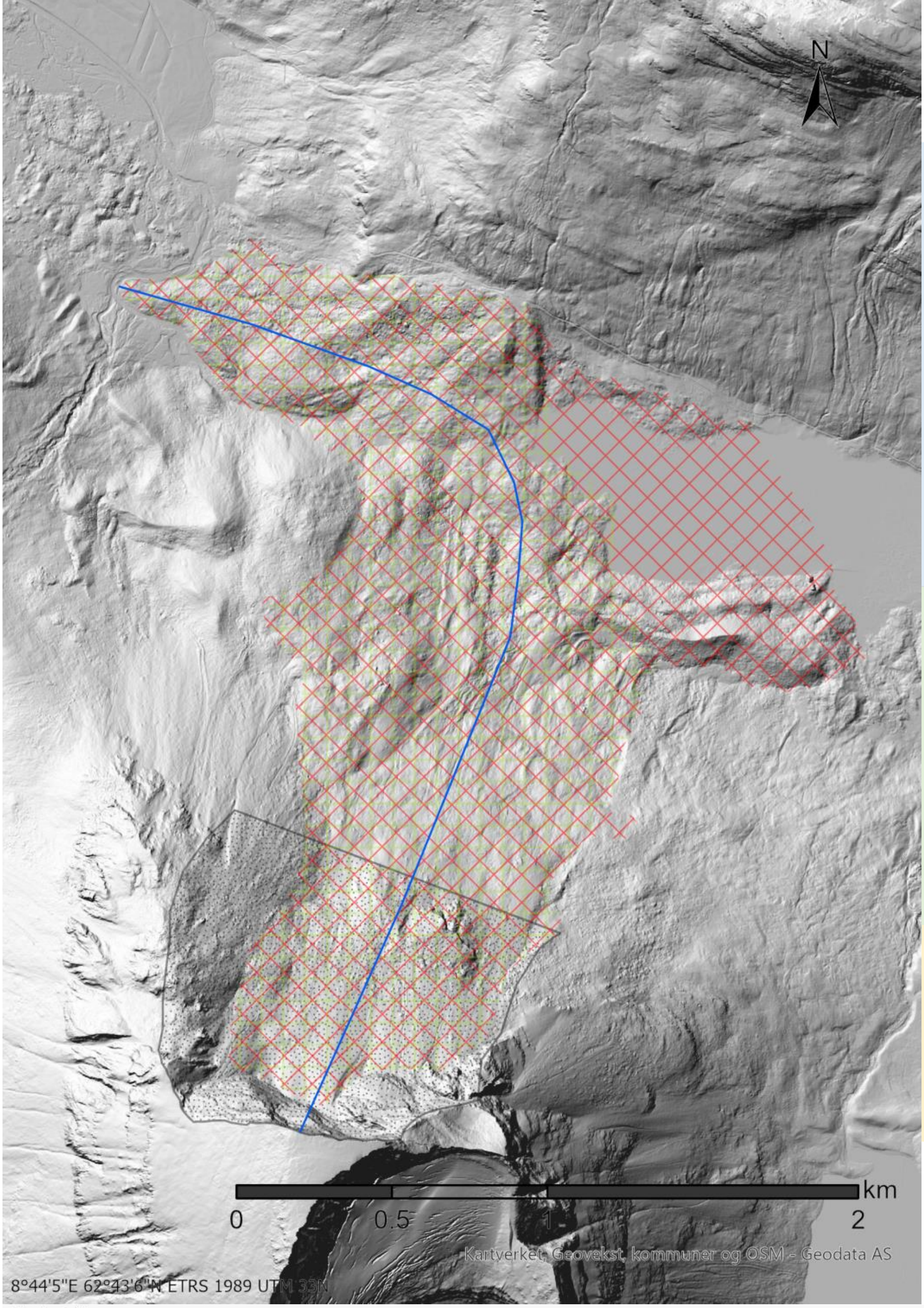
Colluvium/Moraine



ID: 930

Name: Innerdalen

Classification: Rock Avalanche



Legend

Deposit from DB

Release area from DB

Deposit, new

Release area, new

Run-out path, DB

Run-out path, new

Angle of reach: 21.8°

Volume: 24.5 million m³

Travel D/L: 1.16

Run-out topography:

Against opposite valley side, thereafter channelized

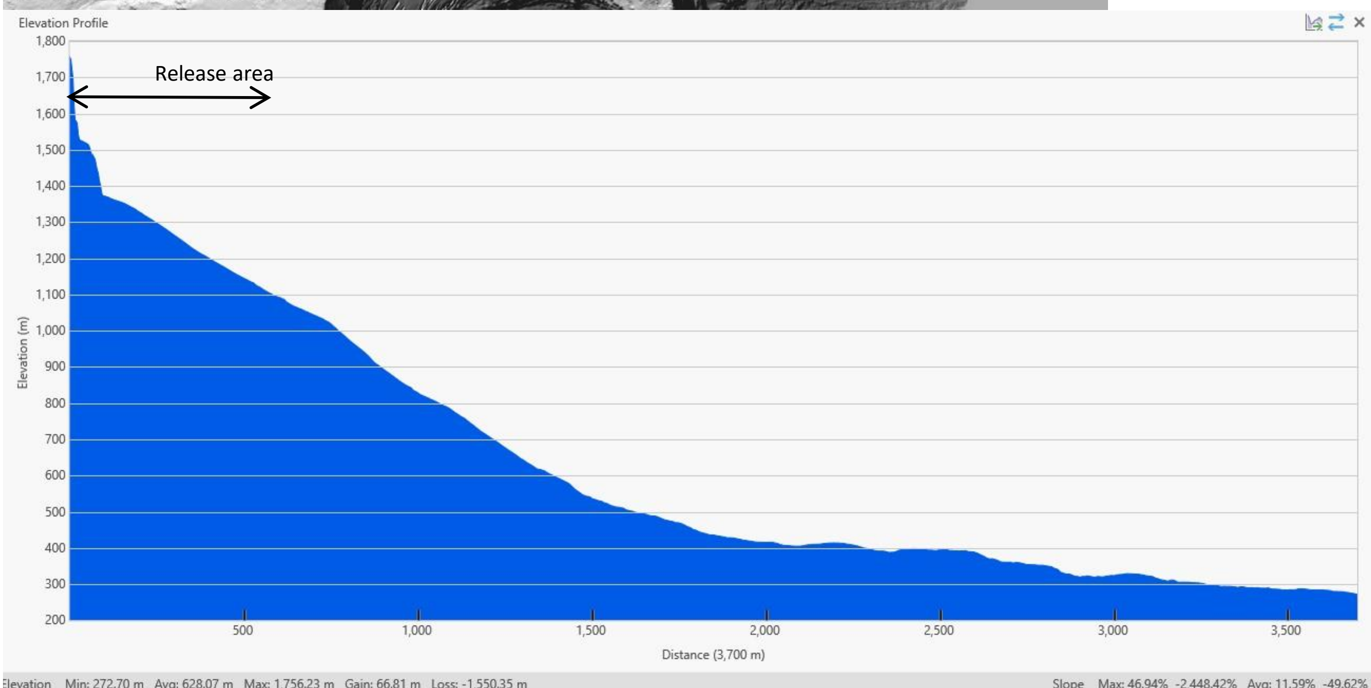
Profileform: <50% descent

Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

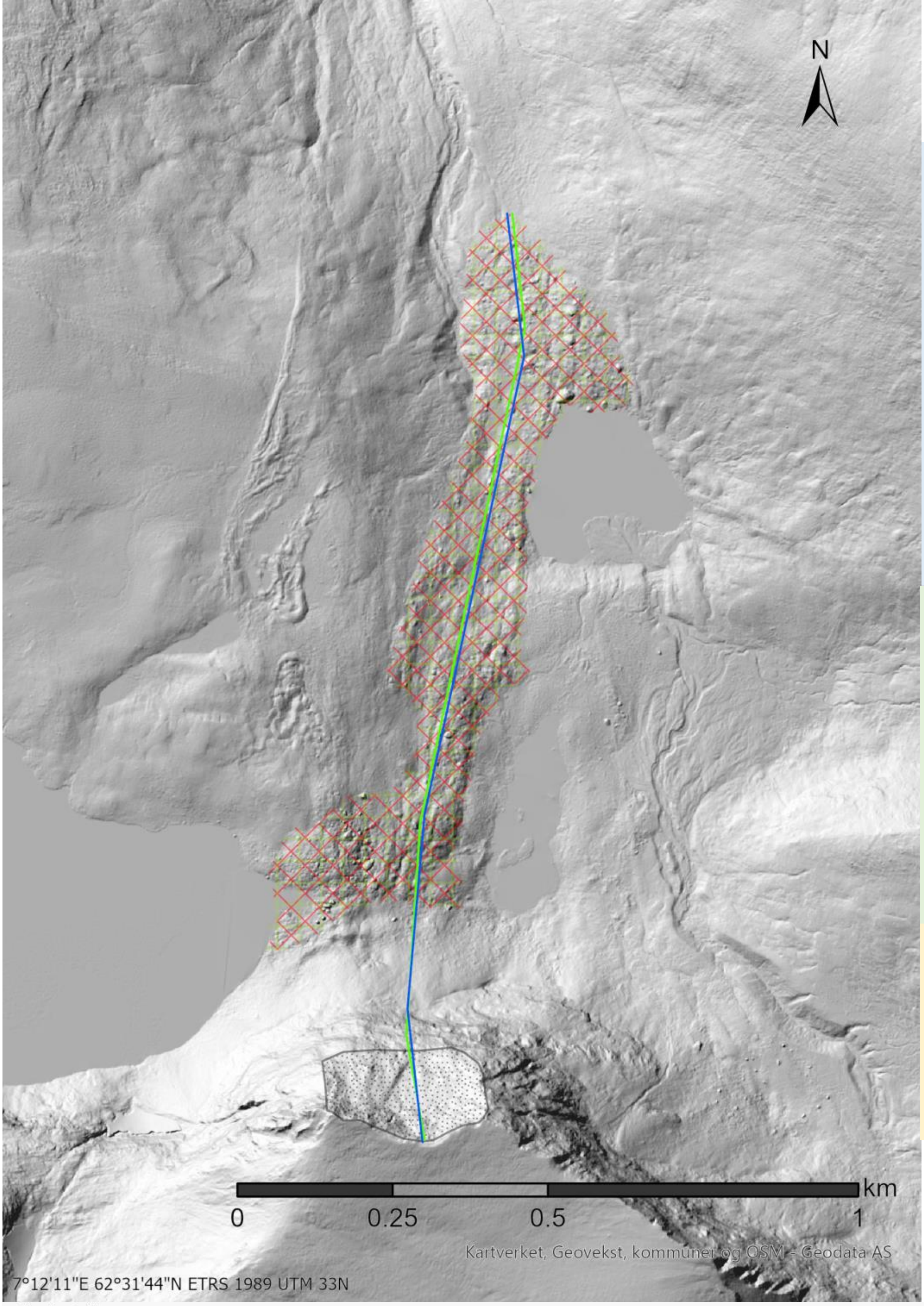
Colluvium/Moraine



ID: 931

Name: Blåfjellet (2)

Classification: Rock Avalanche



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 17.5°

Volume: 0.675 million m³

Travel D/L: 1.13

Run-out topography:

Unobstructed

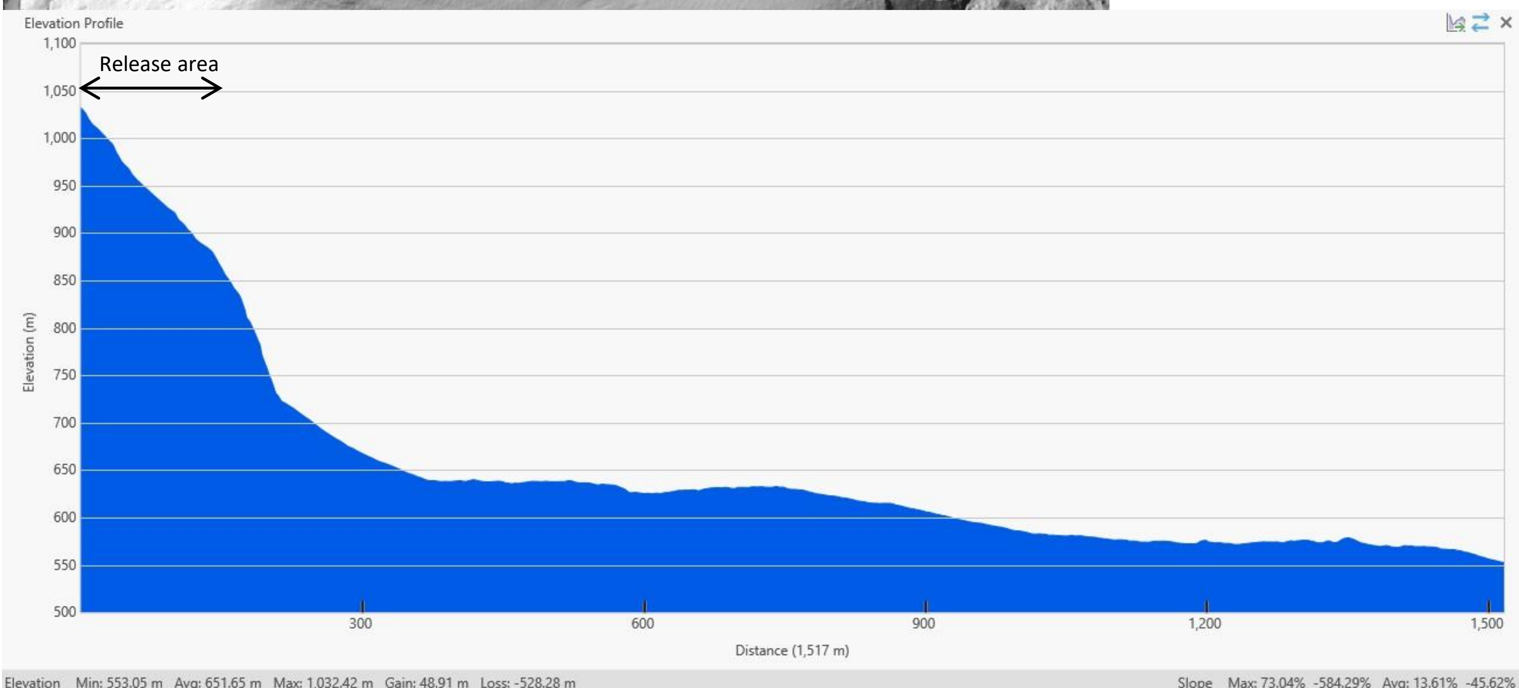
Profileform: <50% descent

Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

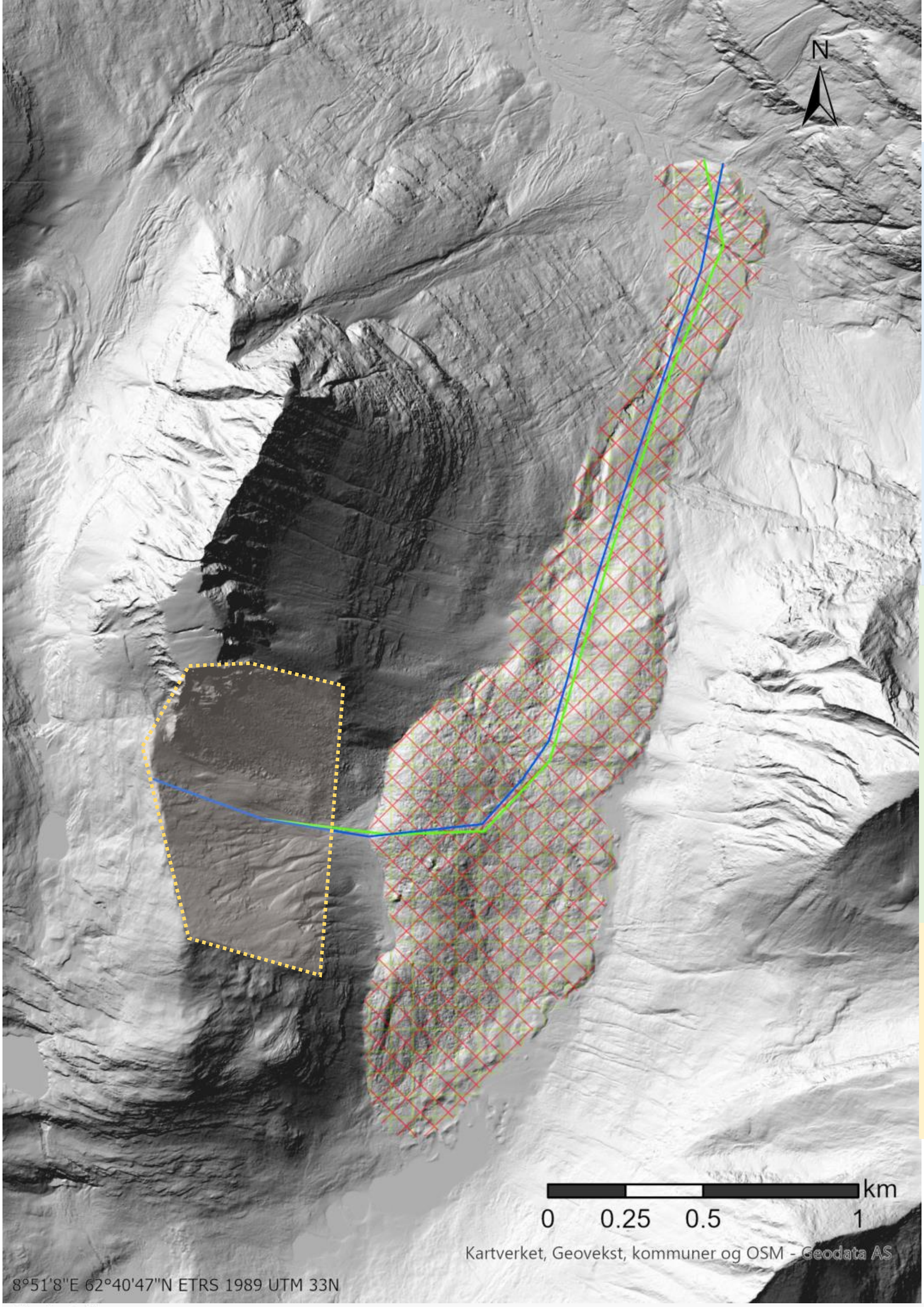
Colluvium/Moraine



ID: 933

Name: Navardalsnebba

Classification: Rock Avalanche



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 14.9°

Volume: 17.5 million m³

Travel D/L: 1.07

Run-out topography:

Against opposite valley side, thereafter channelized

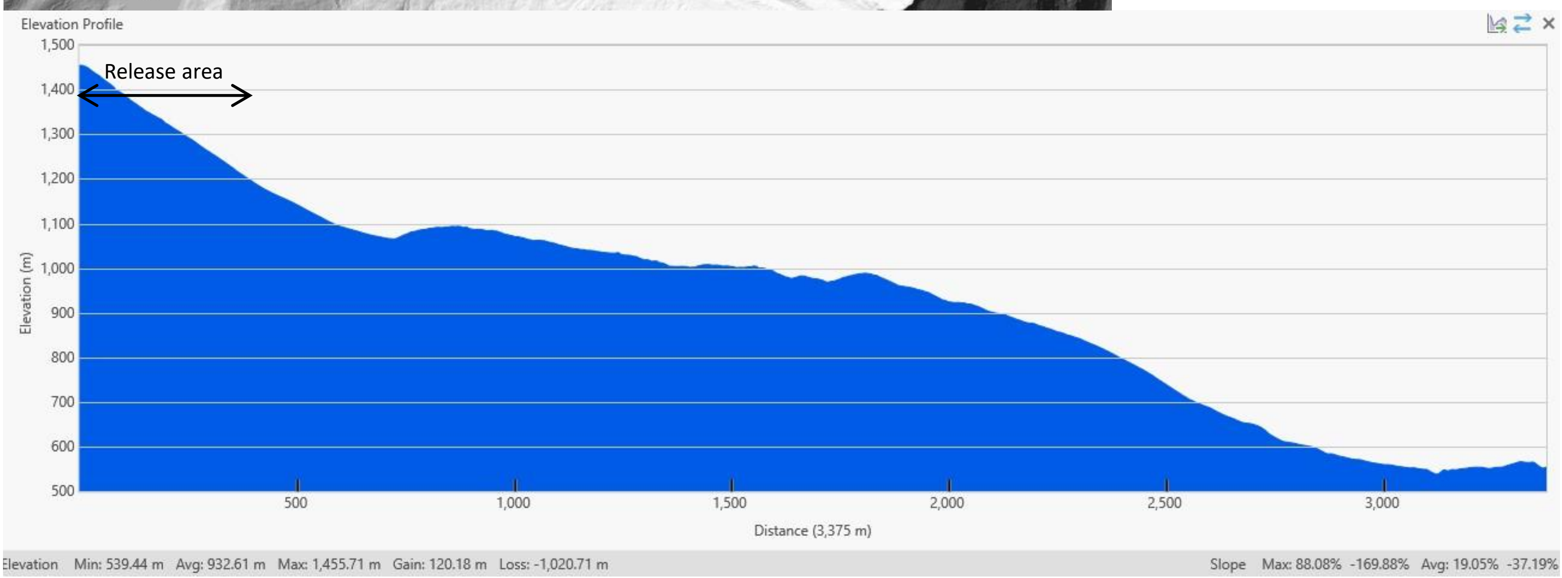
Profileform: Stepped

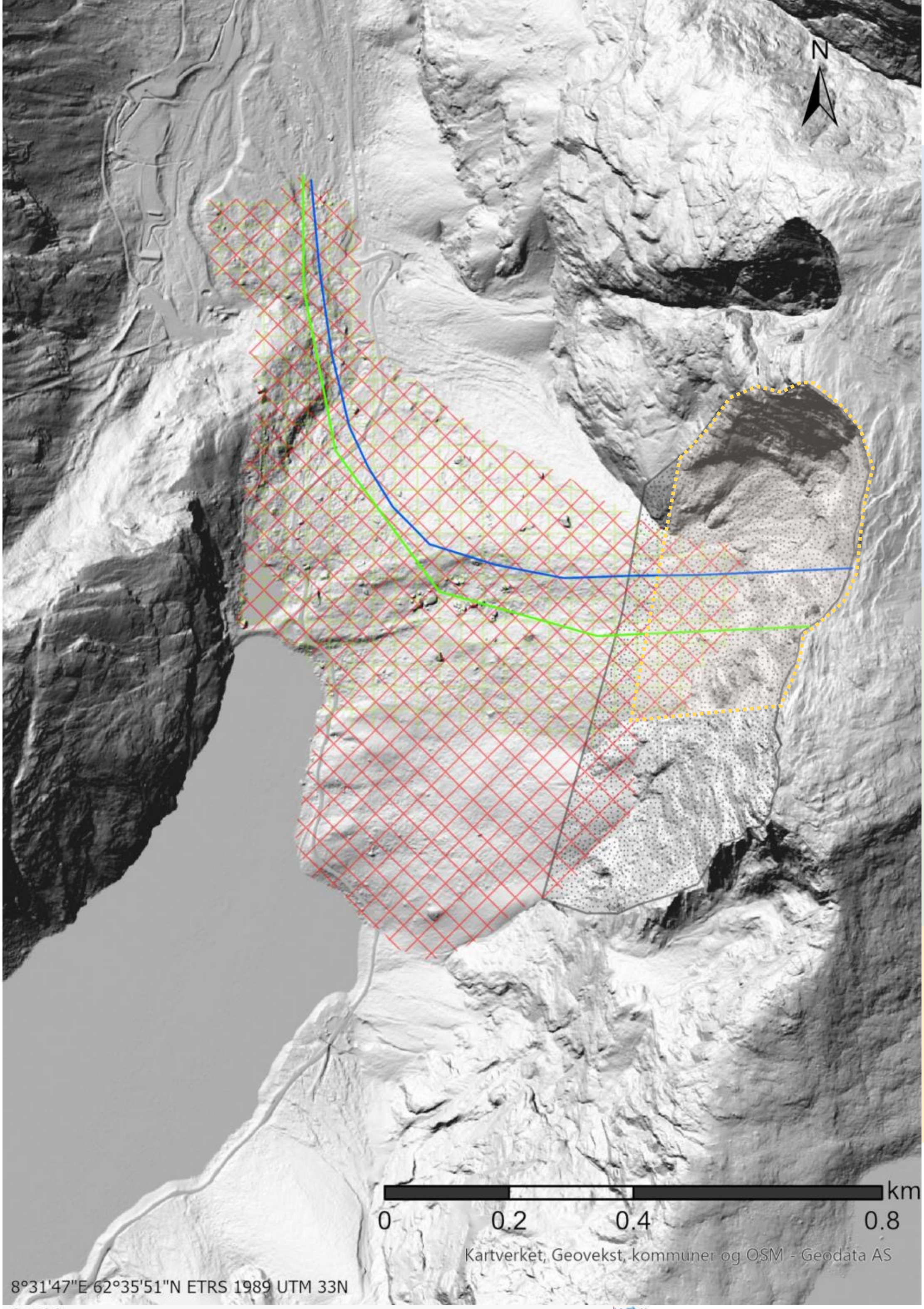
Lithology (release area):

Gneiss

Substrate (Deposit area):

Colluvium/Moraine





ID: 934

Name: Dalaosen

Classification: Rock Collapse

Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 38.4°

Volume: 2.1 million m^3

Travel D/L: 1.43

Run-out topography:

Against opposite valley side

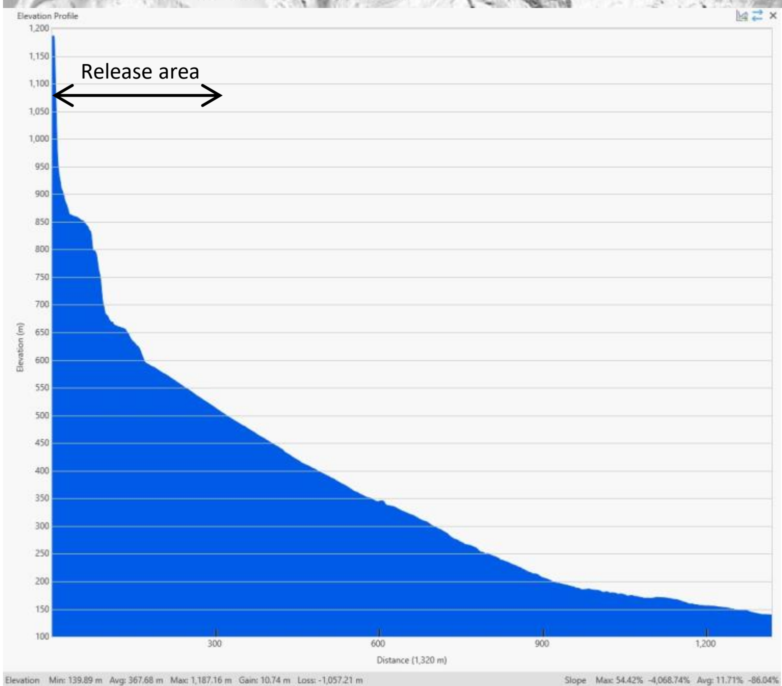
Profileform: >50% descent

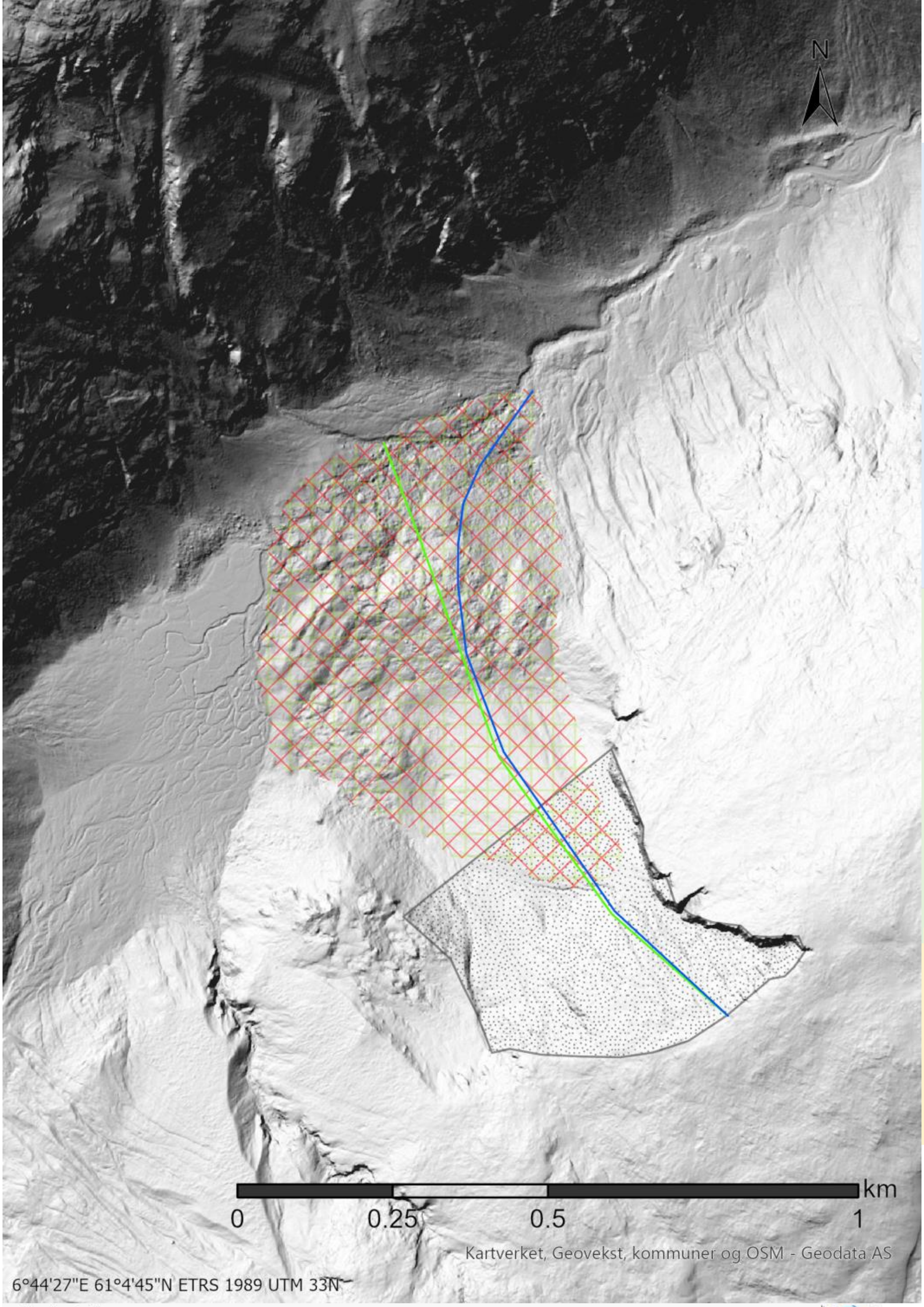
Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

Colluvium/Moraine





ID: 936

Name: Gullsete

Classification: L. M. Rock A.

Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 25.9°

Volume: 2.3 million m³

Travel D/L: 1.14

Run-out topography:

Against opposite valley side

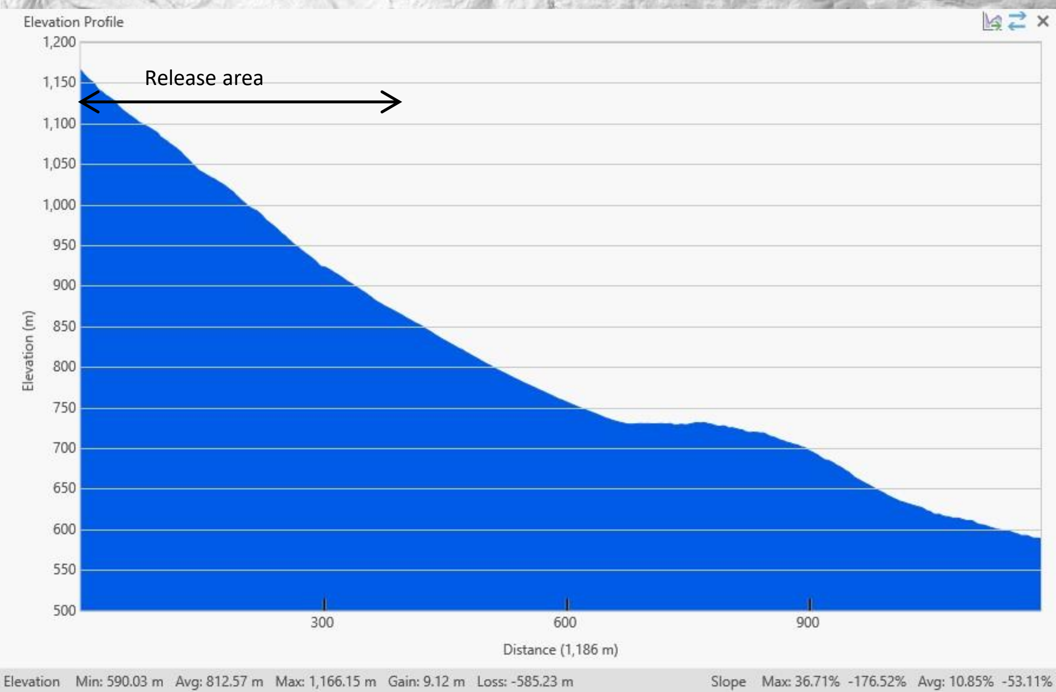
Profileform: >50% descent

Lithology (release area):

Gabbro

Substrate (Deposit area):

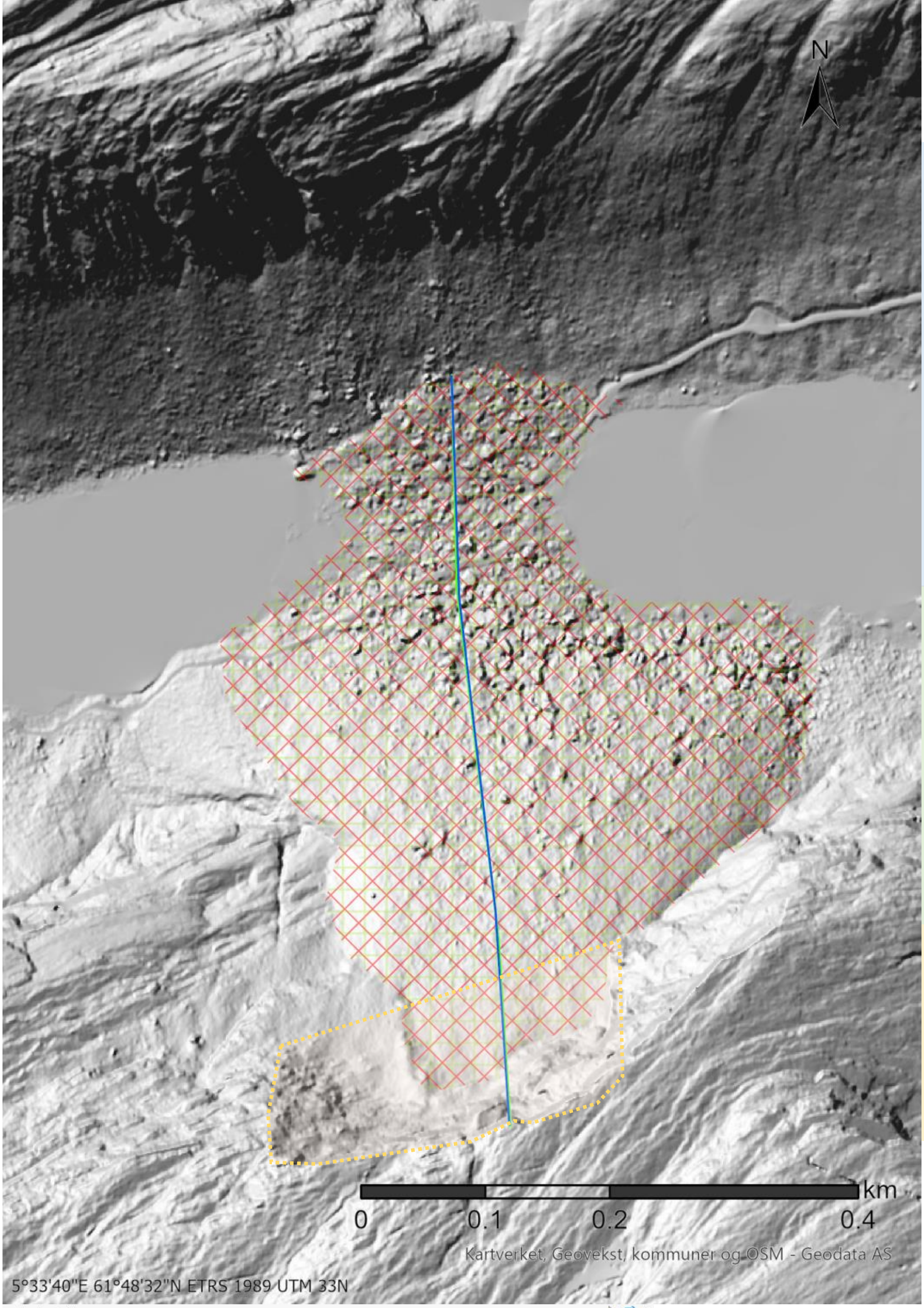
Colluvium/Moraine



ID: 941

Name: Snønyken

Classification: Rock collapse



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 32.6°

Volume: 0.65 million m³

Travel D/L: 1.32

Run-out topography:

Against opposite valley side

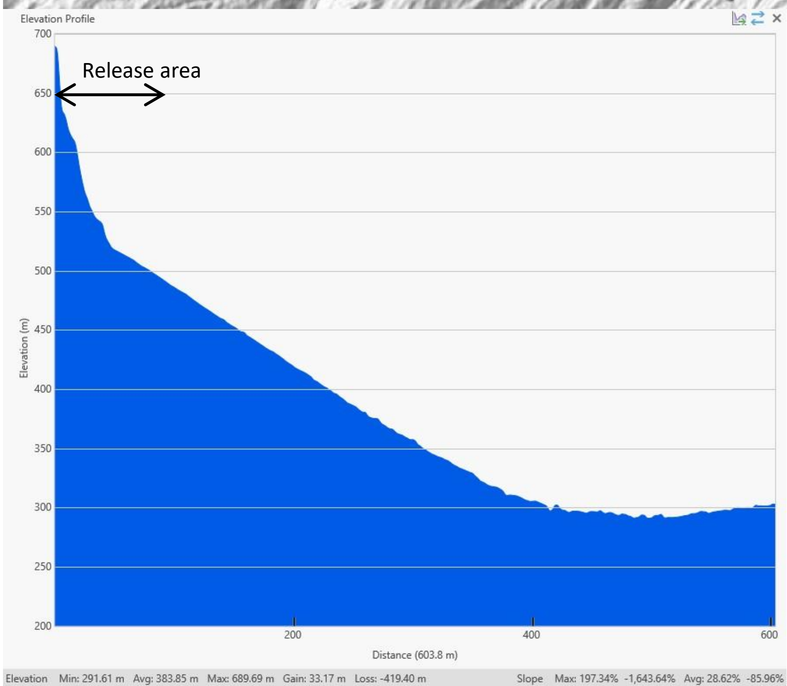
Profileform: >50% descent

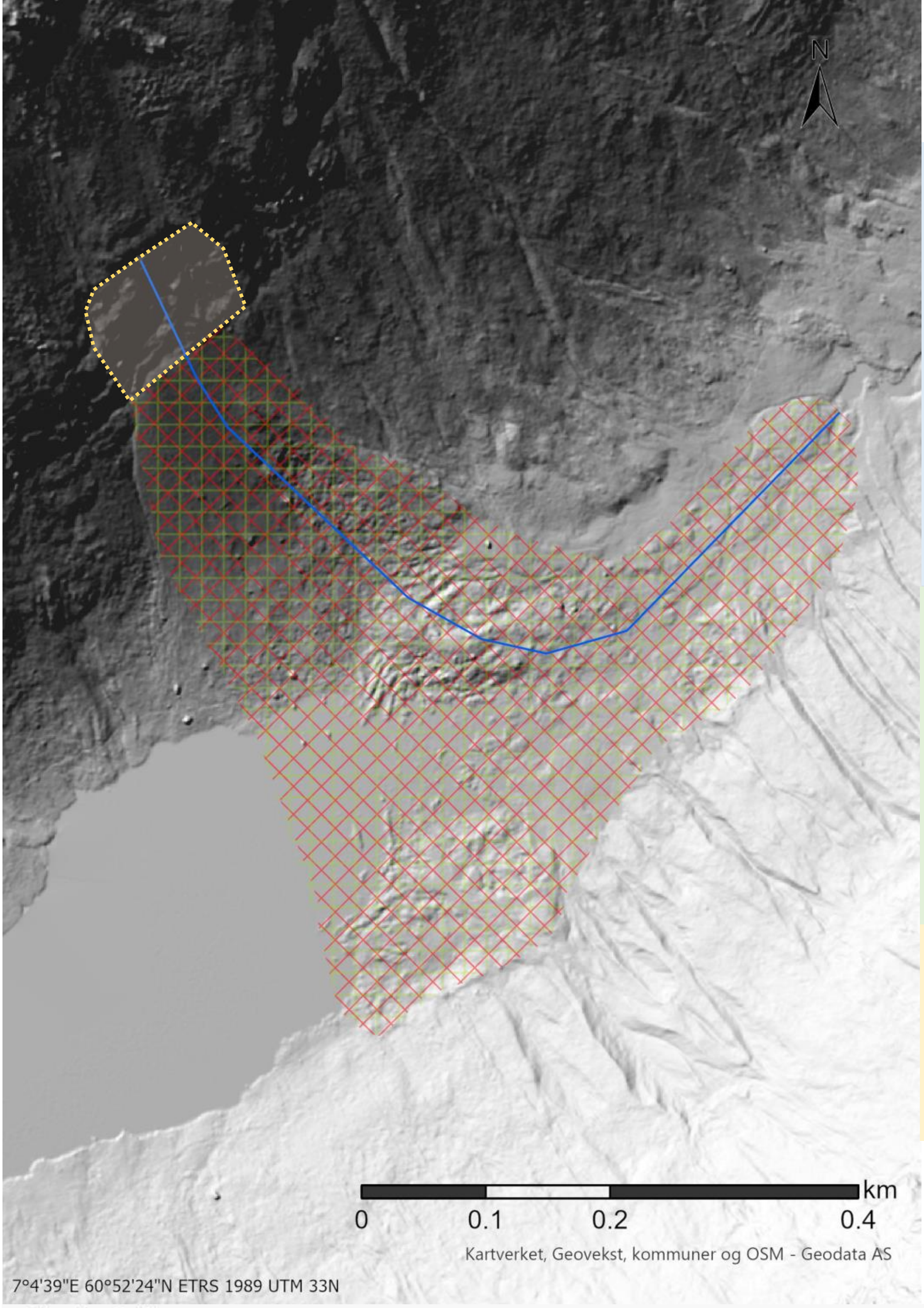
Lithology (release area):

Sandstone

Substrate (Deposit area):

Moraine





ID: 942

Name: Øyestølen

Classification: Rock Avalanche

Legend

Deposit from DB

Release area from DB

Deposit, new

Release area, new

Run-out path, DB

Run-out path, new

Angle of reach: 17.9°

Volume: 0.18 million m³

Travel D/L: 1.10

Run-out topography:

Against opposite valley side, thereafter channelized

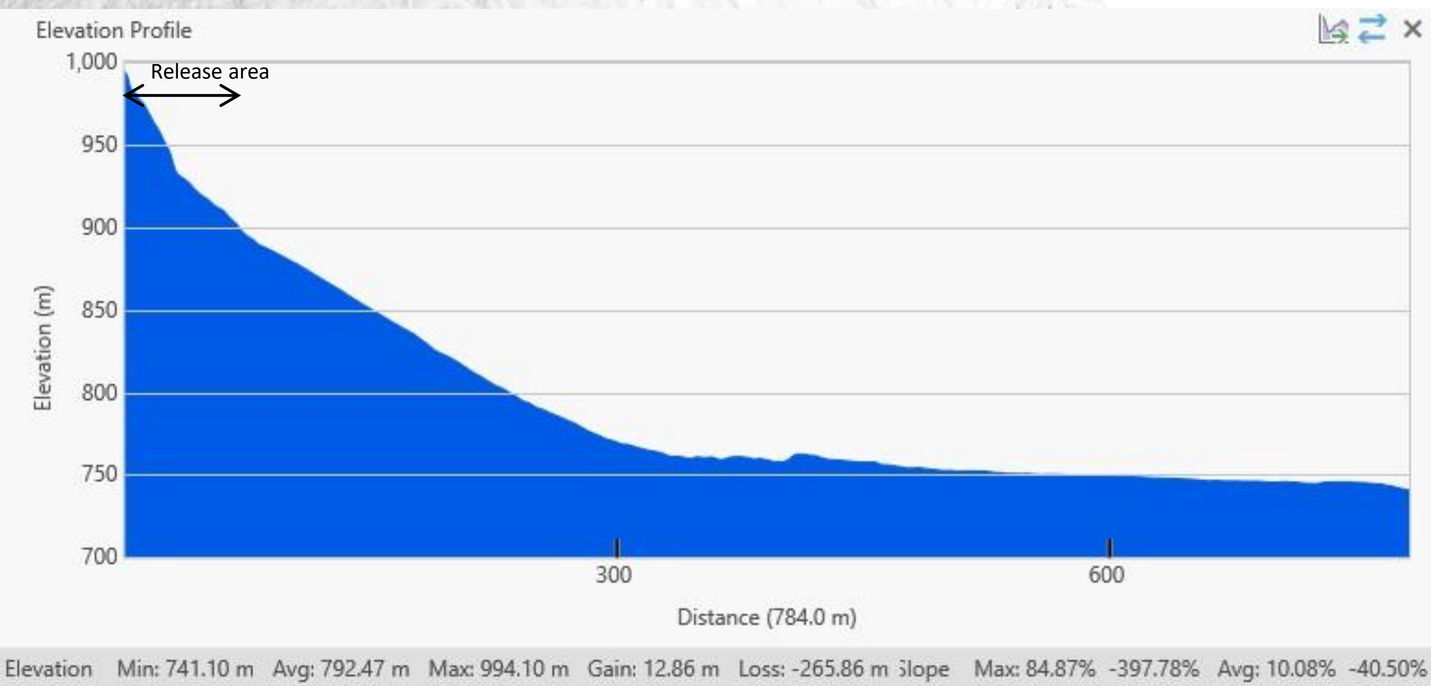
Profileform: <50% descent

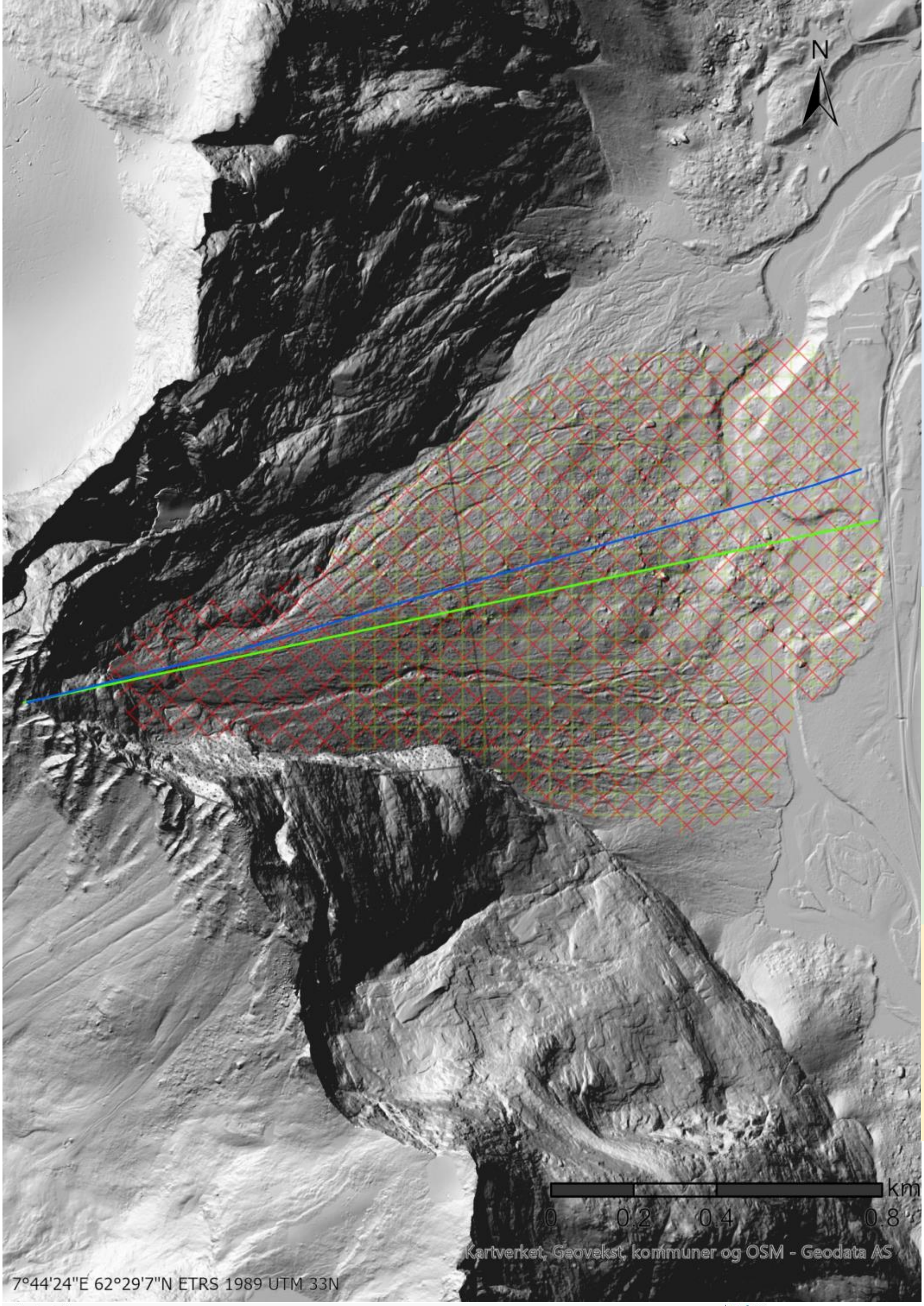
Lithology (release area):

Gneiss

Substrate (Deposit area):

Colluvium/Moraine





ID: 948

Name: Trollveggen

Classification: Rock Collapse

Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 35.0°

Volume: 7.0 million m³

Travel D/L: 1.34

Run-out topography:

Unobstructed

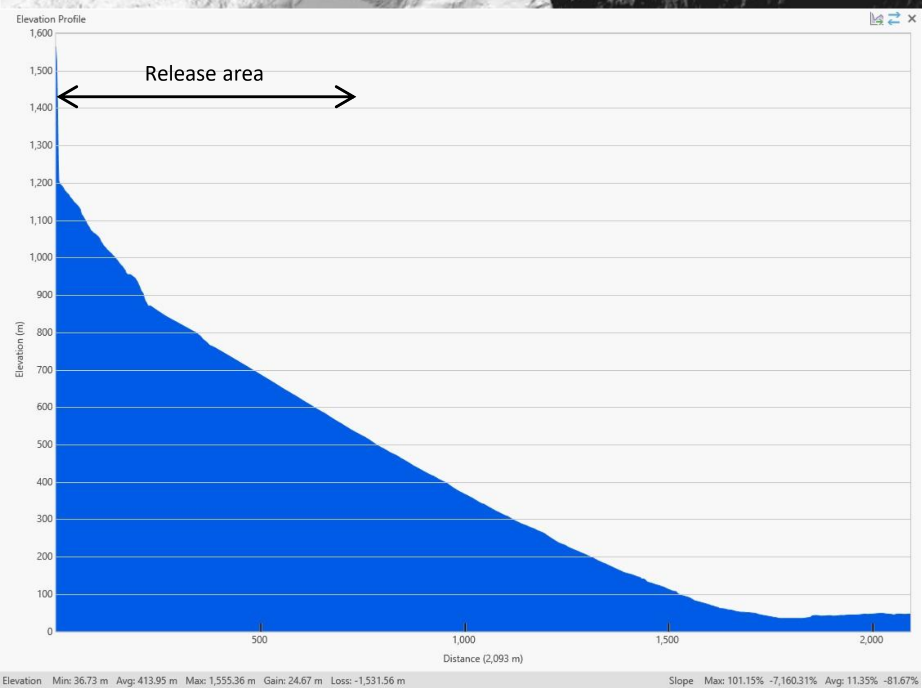
Profileform: >50% descent

Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

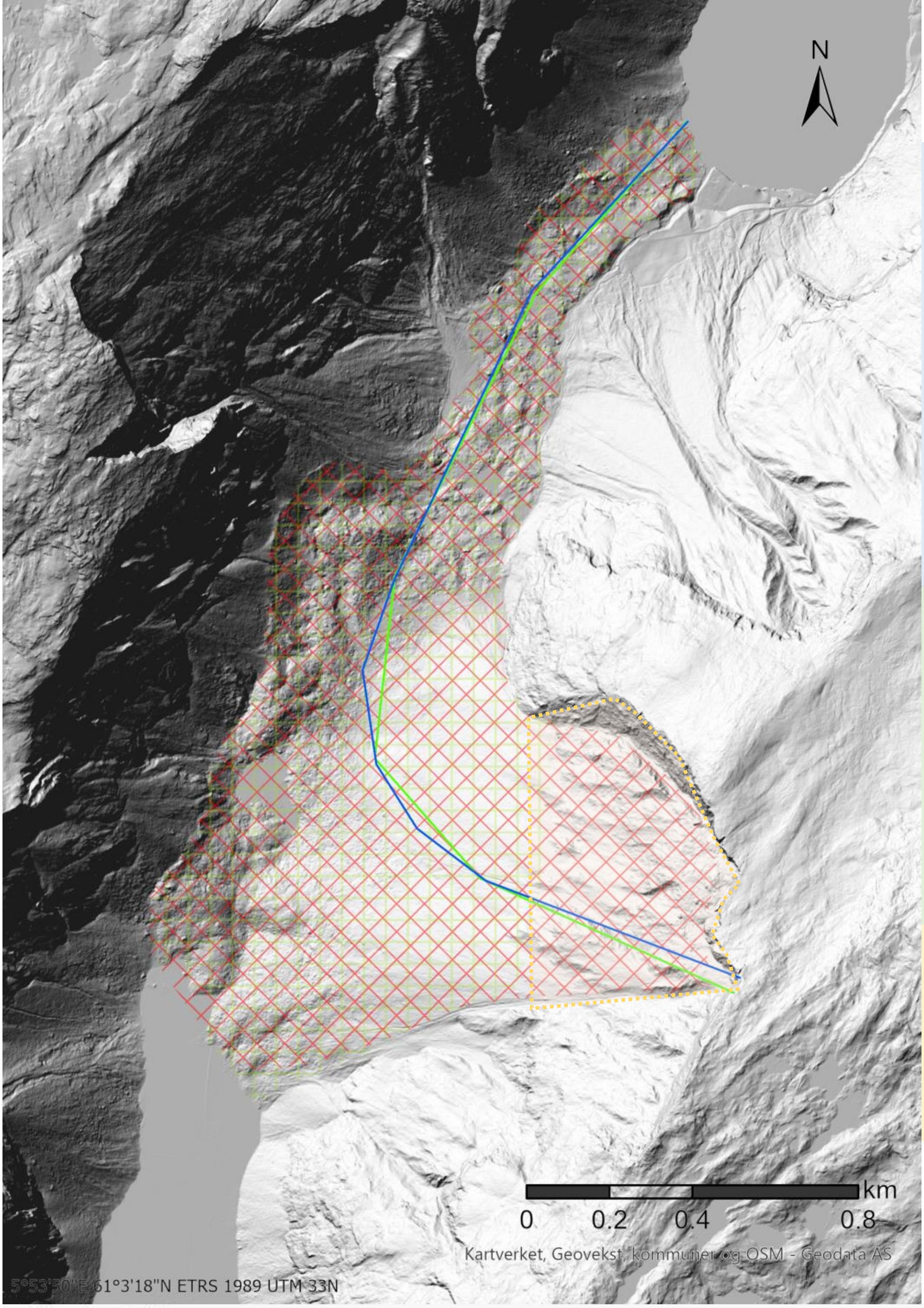
Colluvium/Alluvium



ID: 949

Name: Blåfjellet (1)

Classification: Rock Avalanche



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 18.9°

Volume: 6.1 million m³

Travel D/L: 1.13

Run-out topography:

Against opposite valley side, thereafter channelized

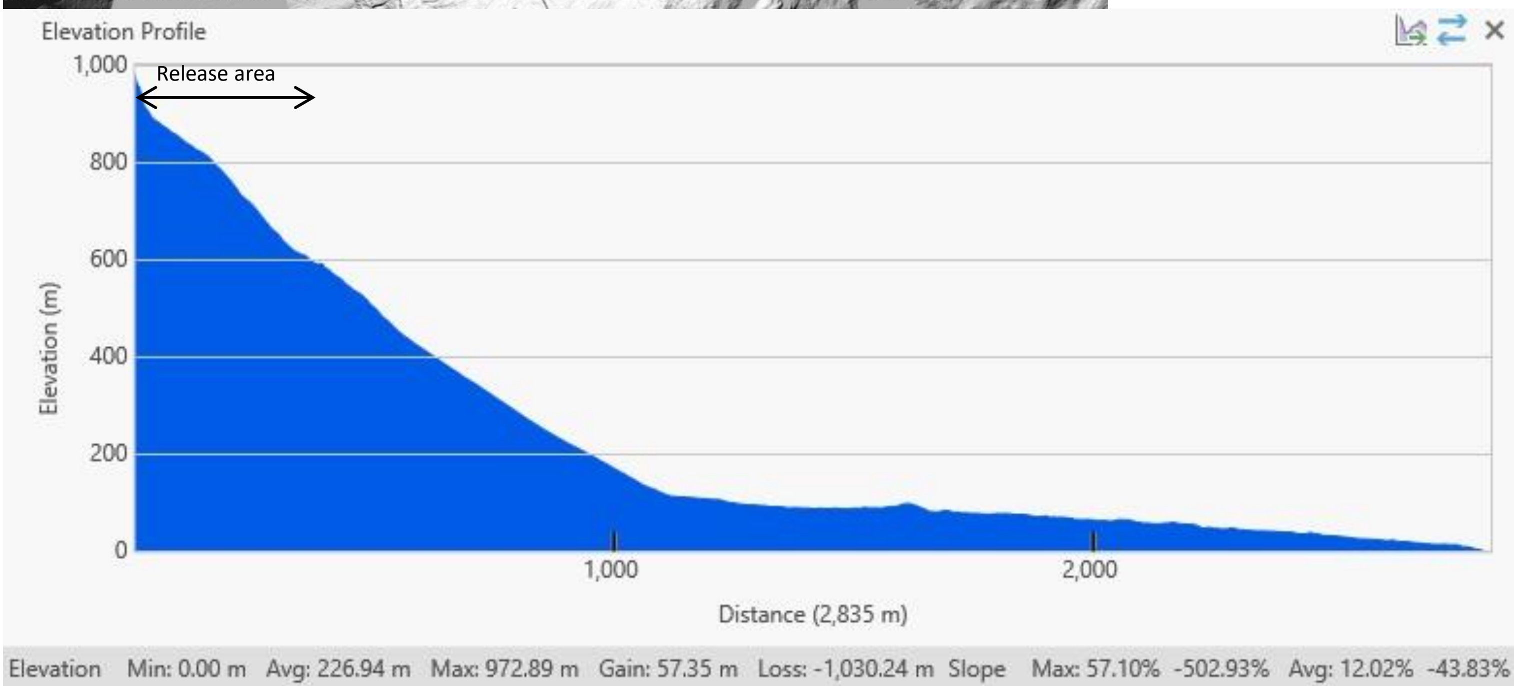
Profileform: <50% descent

Lithology (release area):

Gneiss

Substrate (Deposit area):

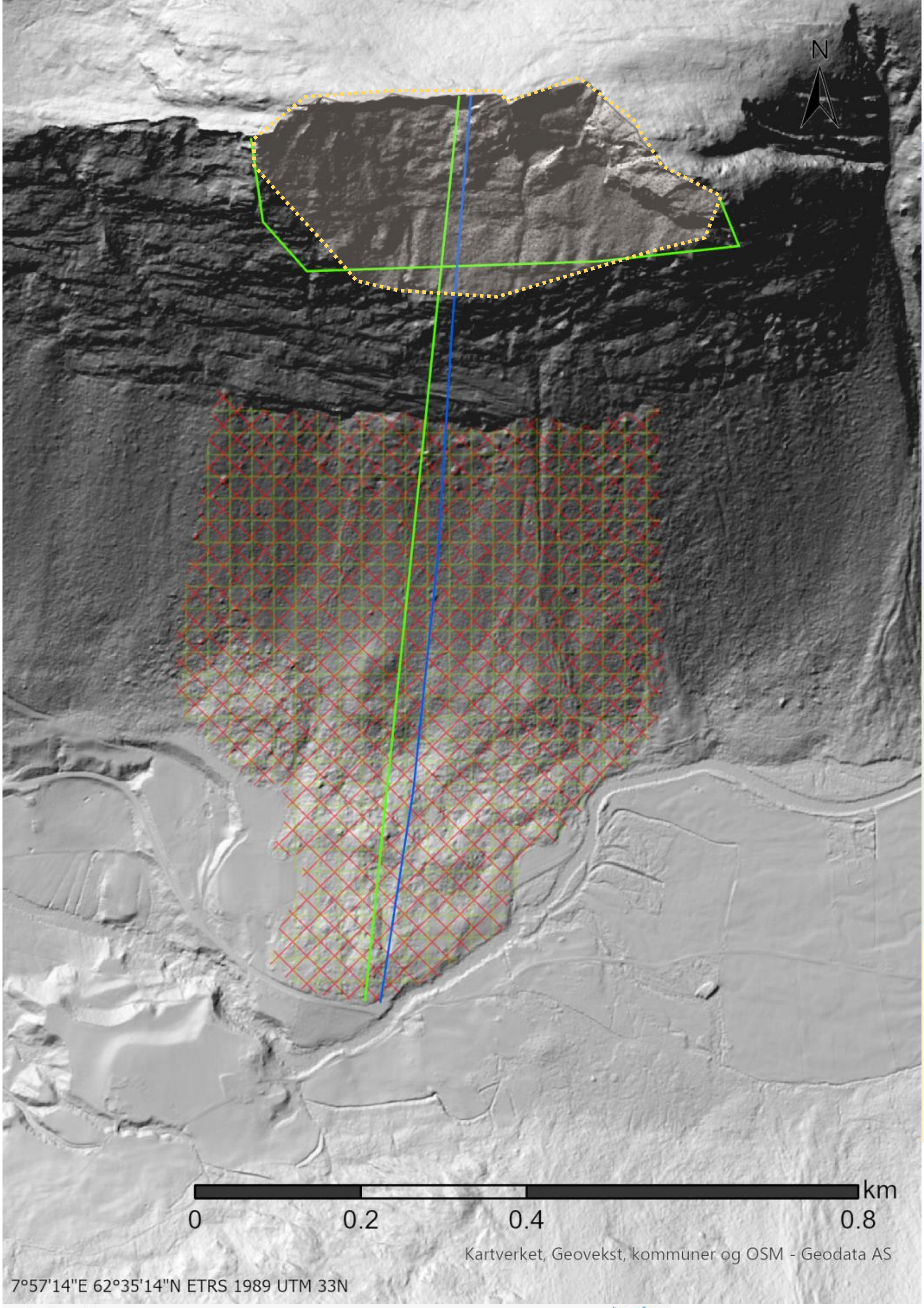
Colluvium/Alluvium



ID: 950

Name: Husenebba

Classification: L. M. Rock A.



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 31.8°

Volume: 0.76 million m^3

Travel D/L: 1.25

Run-out topography:

Unobstructed

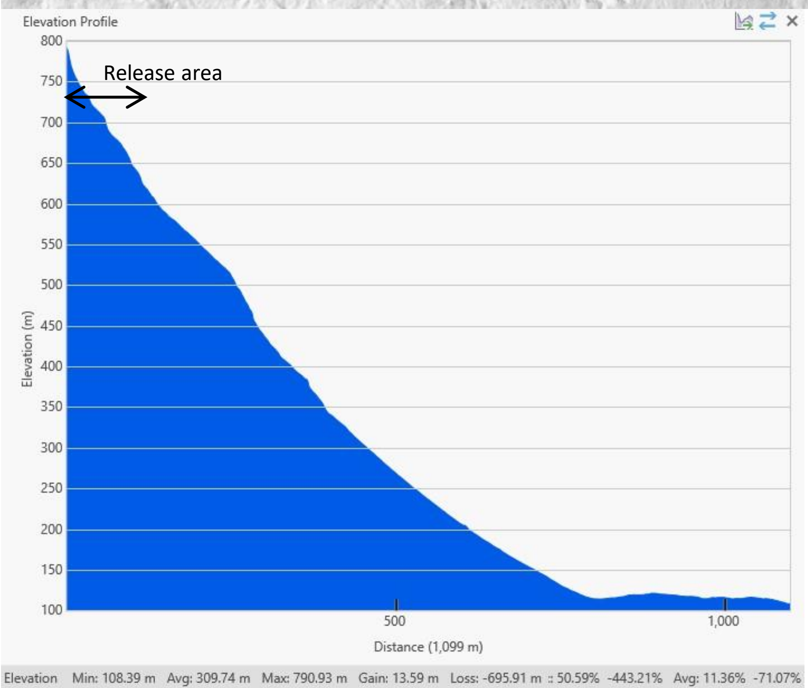
Profileform: >50% descent

Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

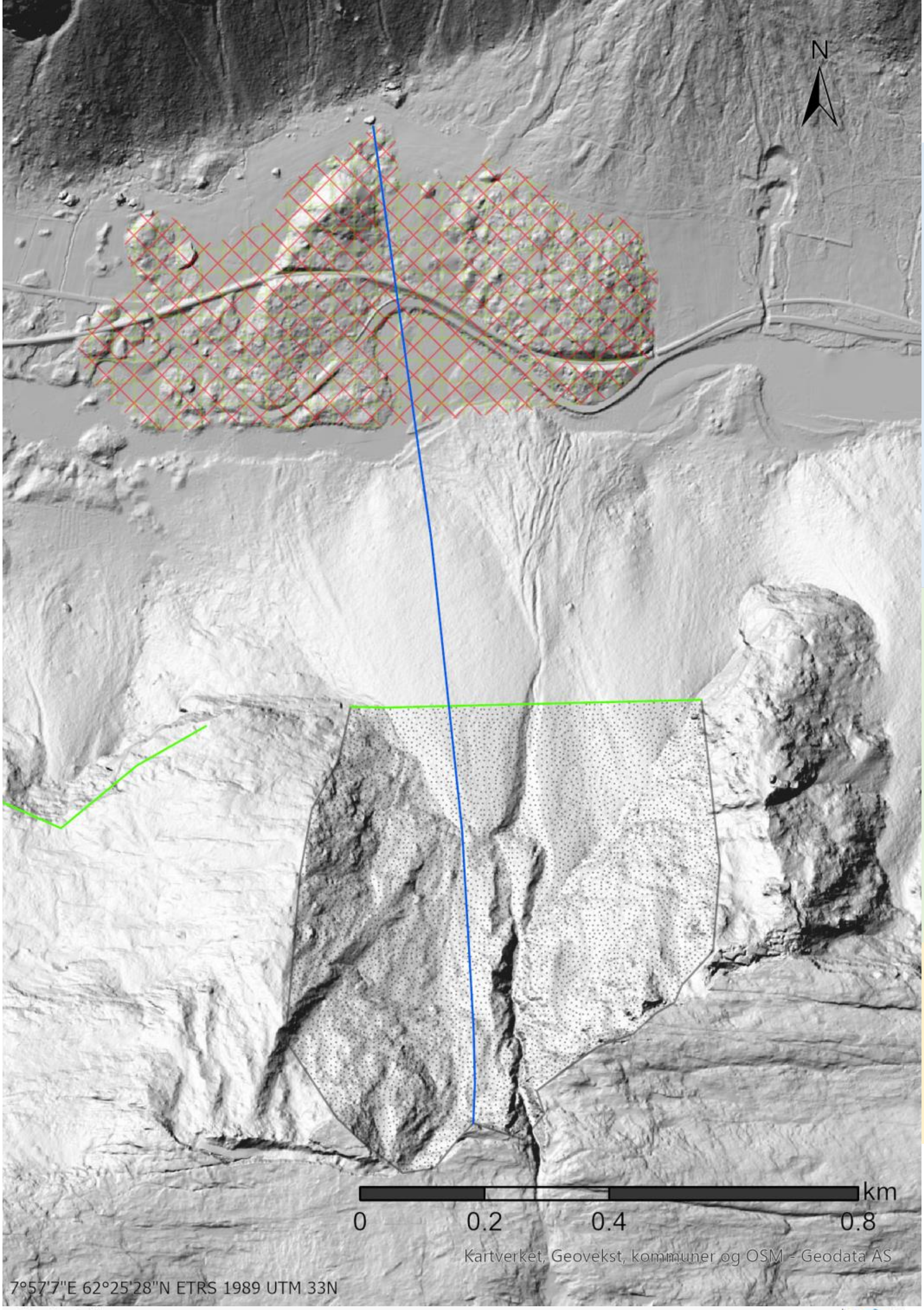
Colluvium/Alluvium



ID: 953

Name: Skiriaksla

Classification: L. M. Rock A.



Legend

Deposit from DB

Release area from DB

Deposit, new

Release area, new

Run-out path, DB

Run-out path, new

Angle of reach: 27.5°

Volume: 1.7 million m^3

Travel D/L: 1.20

Run-out topography:

Unobstructed

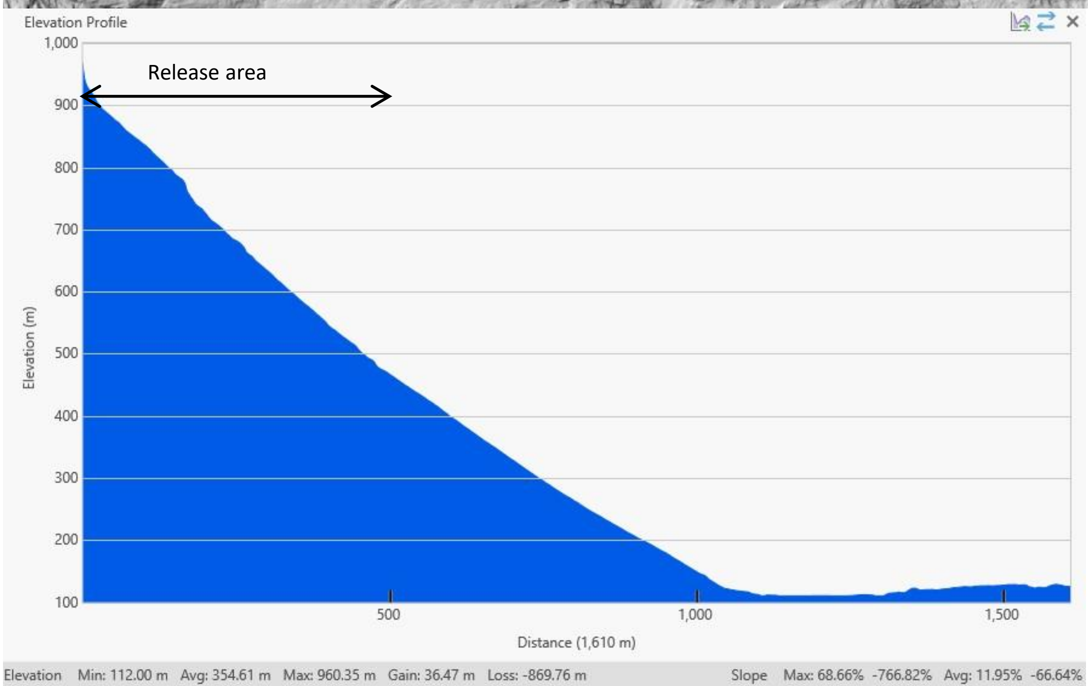
Profileform: >50% descent

Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

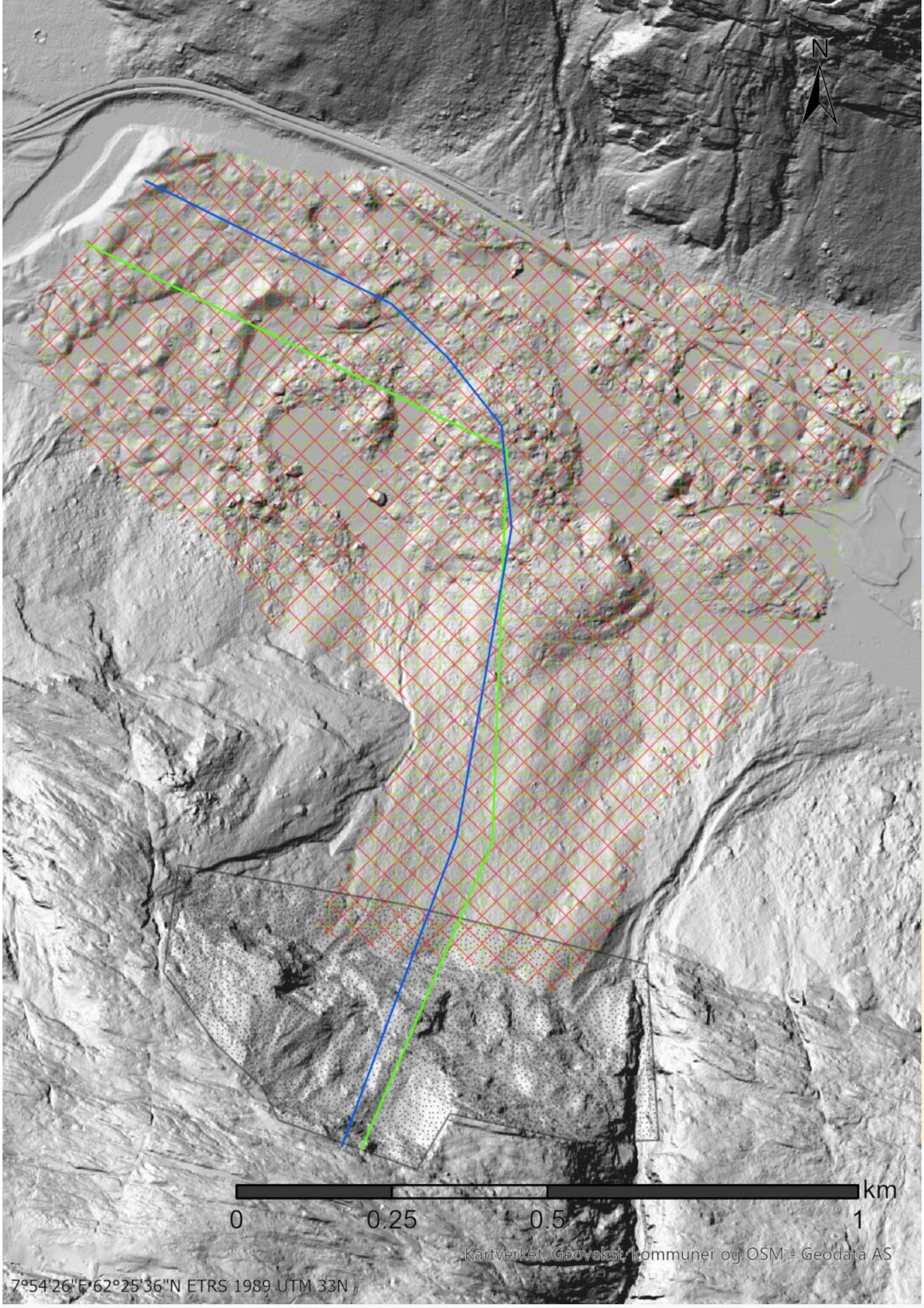
Colluvium/Alluvium



ID: 954

Name: Skulnebba

Classification: Rock Avalanche



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 23.2°

Volume: 5.1 million m^3

Travel D/L: 1.18

Run-out topography:

Against opposite valley side, thereafter channelized

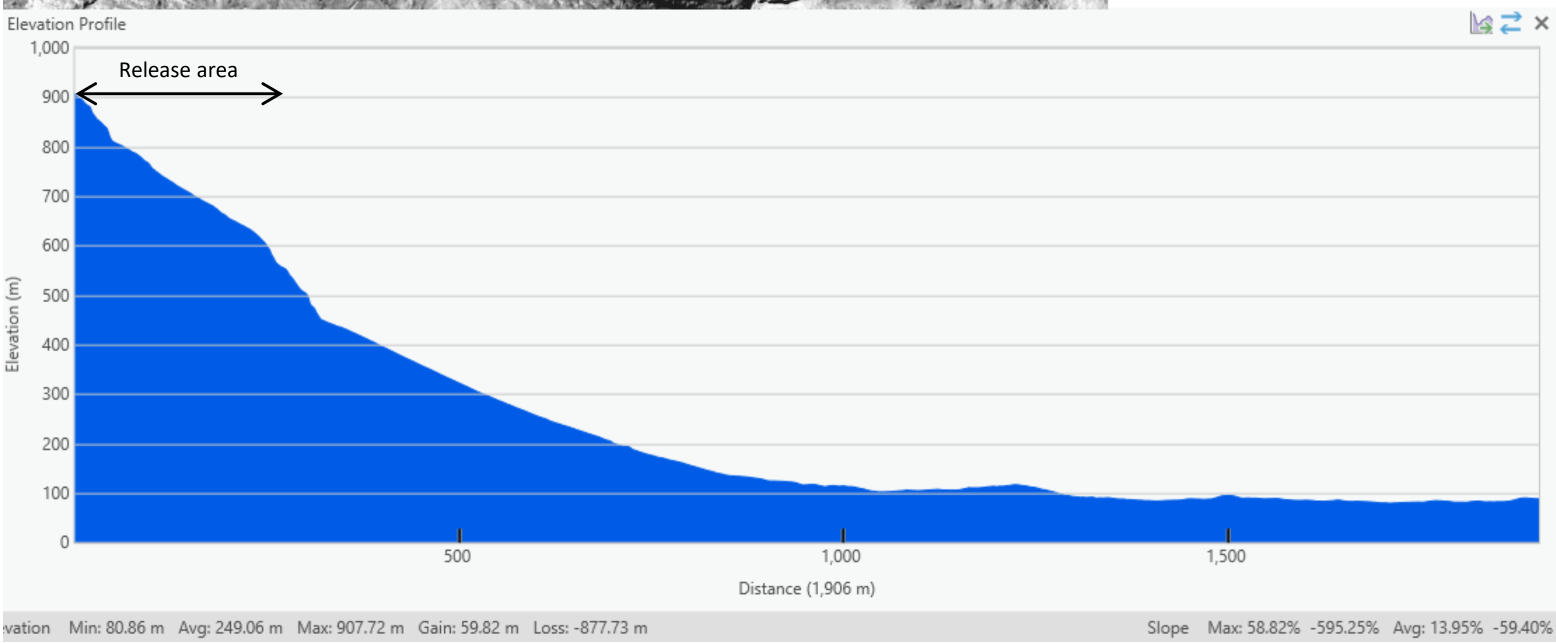
Profileform: <50% descent

Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

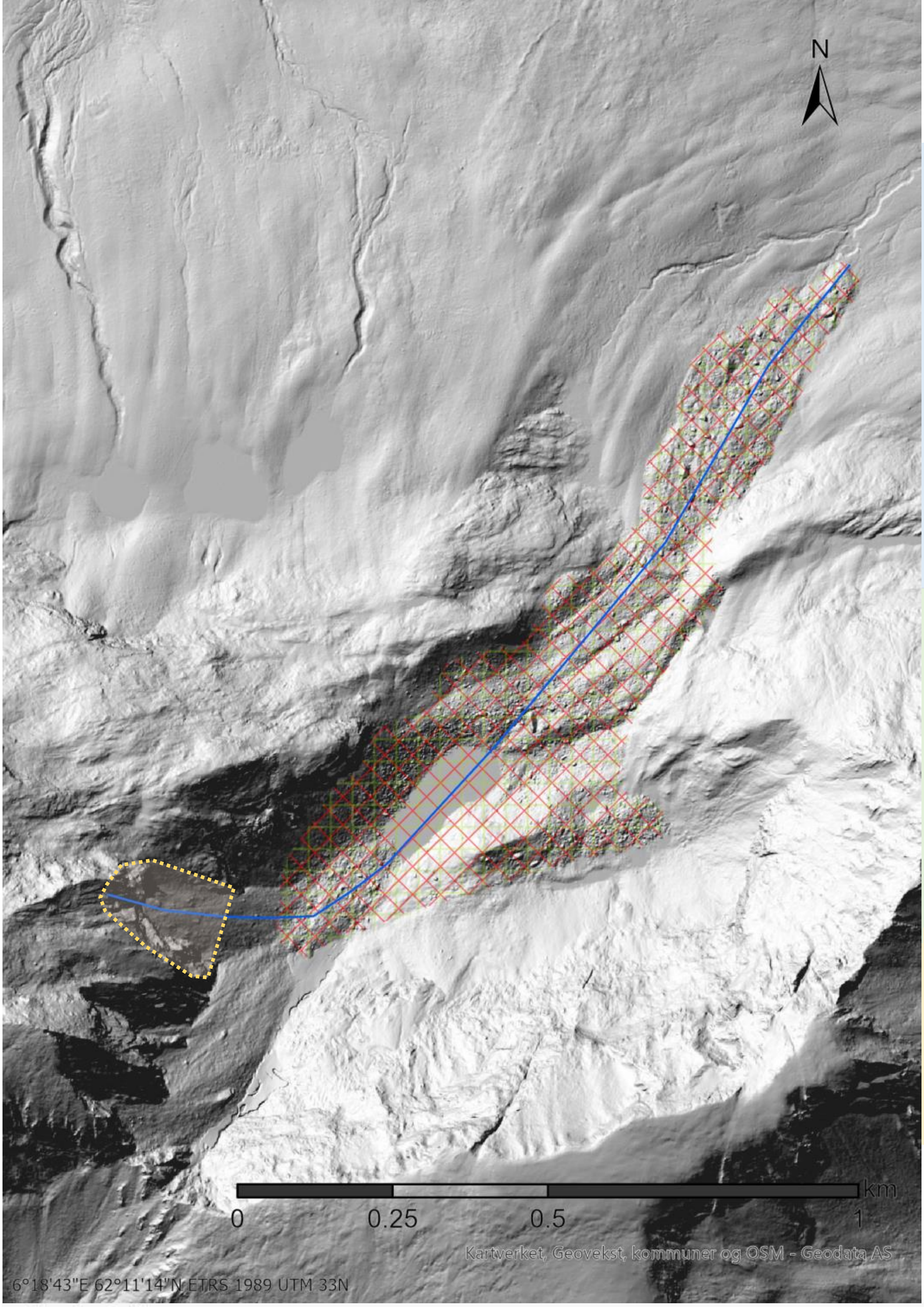
Colluvium/Alluvium



ID: 1014

Name: Blåtinden

Classification: Rock Avalanche



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 14.9°

Volume: 1.4 million m^3

Travel D/L: 1.09

Run-out topography:

Against opposite valley side, thereafter channelized

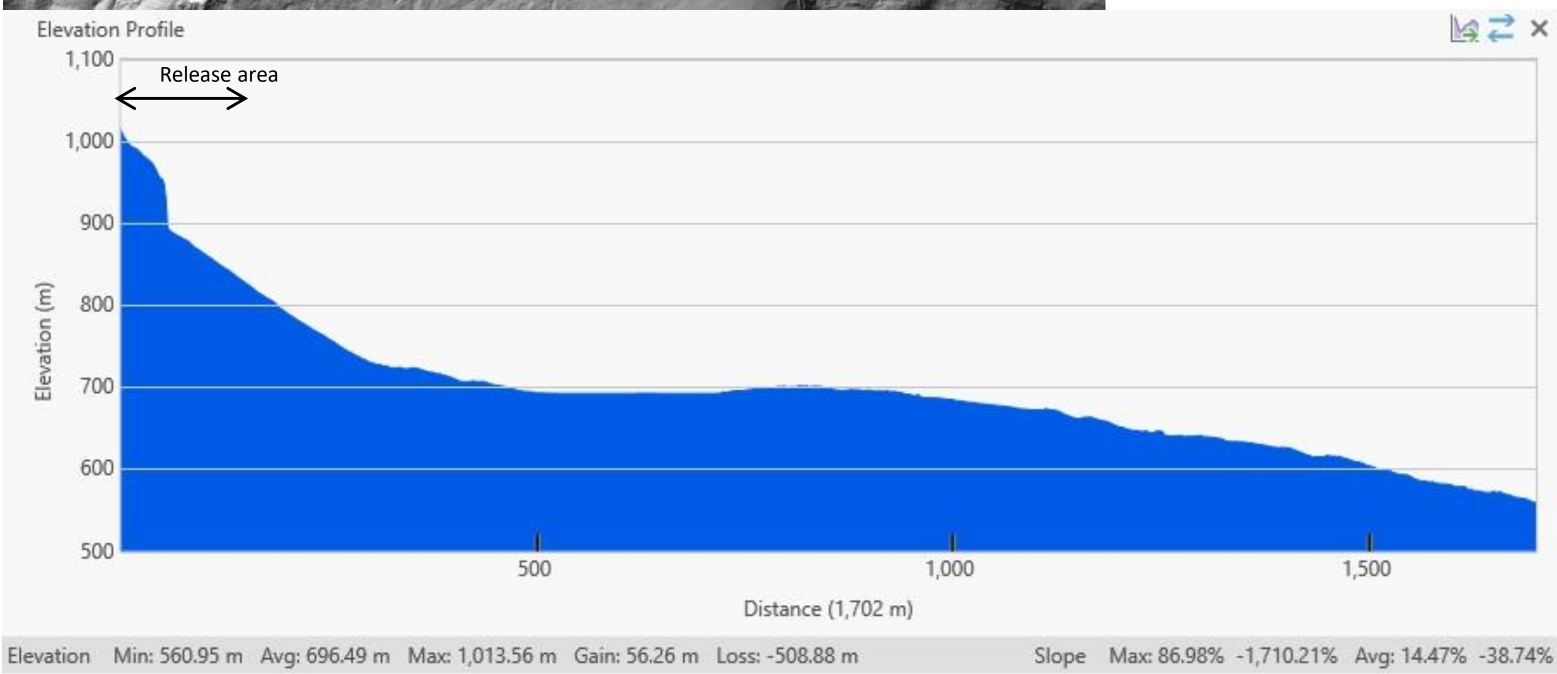
Profileform: Stepped

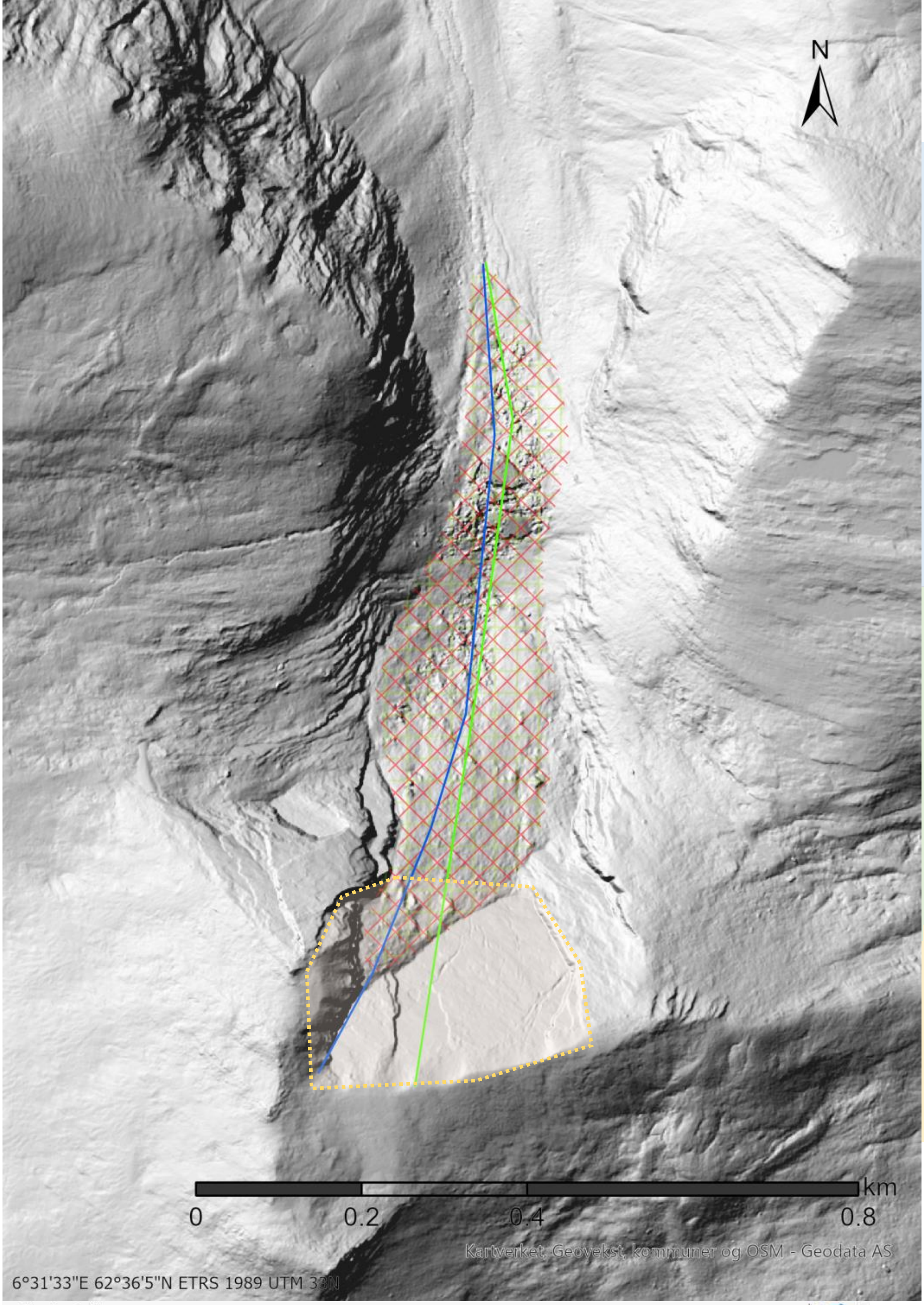
Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

Colluvium/Moraine





ID: 1017

Name: Blåfjellet (2)

Classification: L. M. Rock A.

Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 27.7°

Volume: 0.27 million m³

Travel D/L: 1.16

Run-out topography:

Channelized

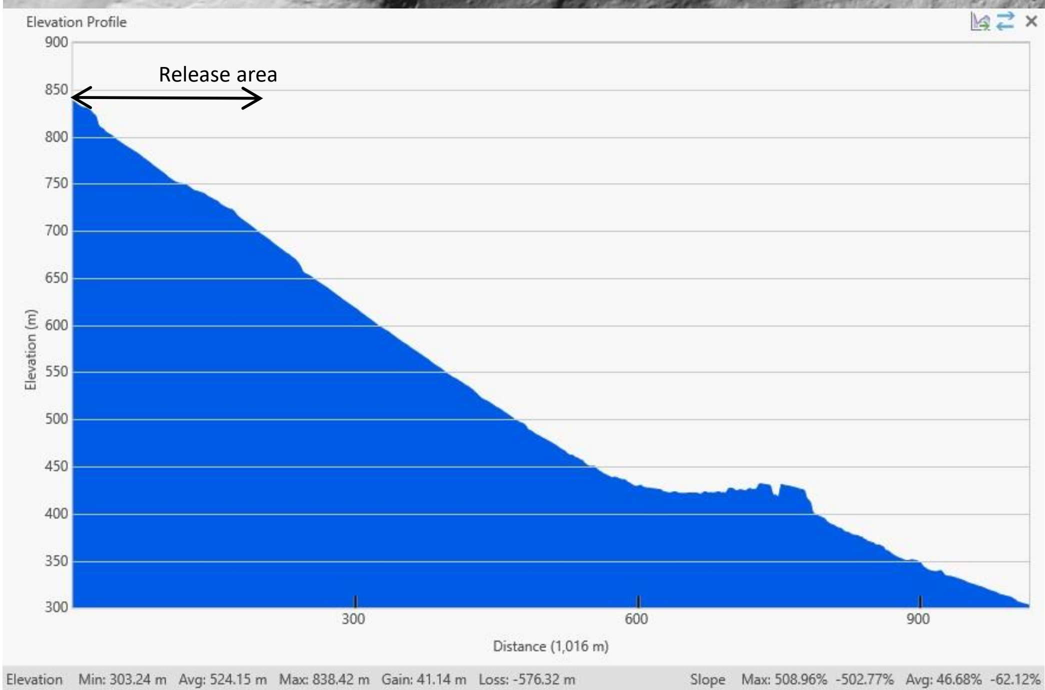
Profileform: Stepped

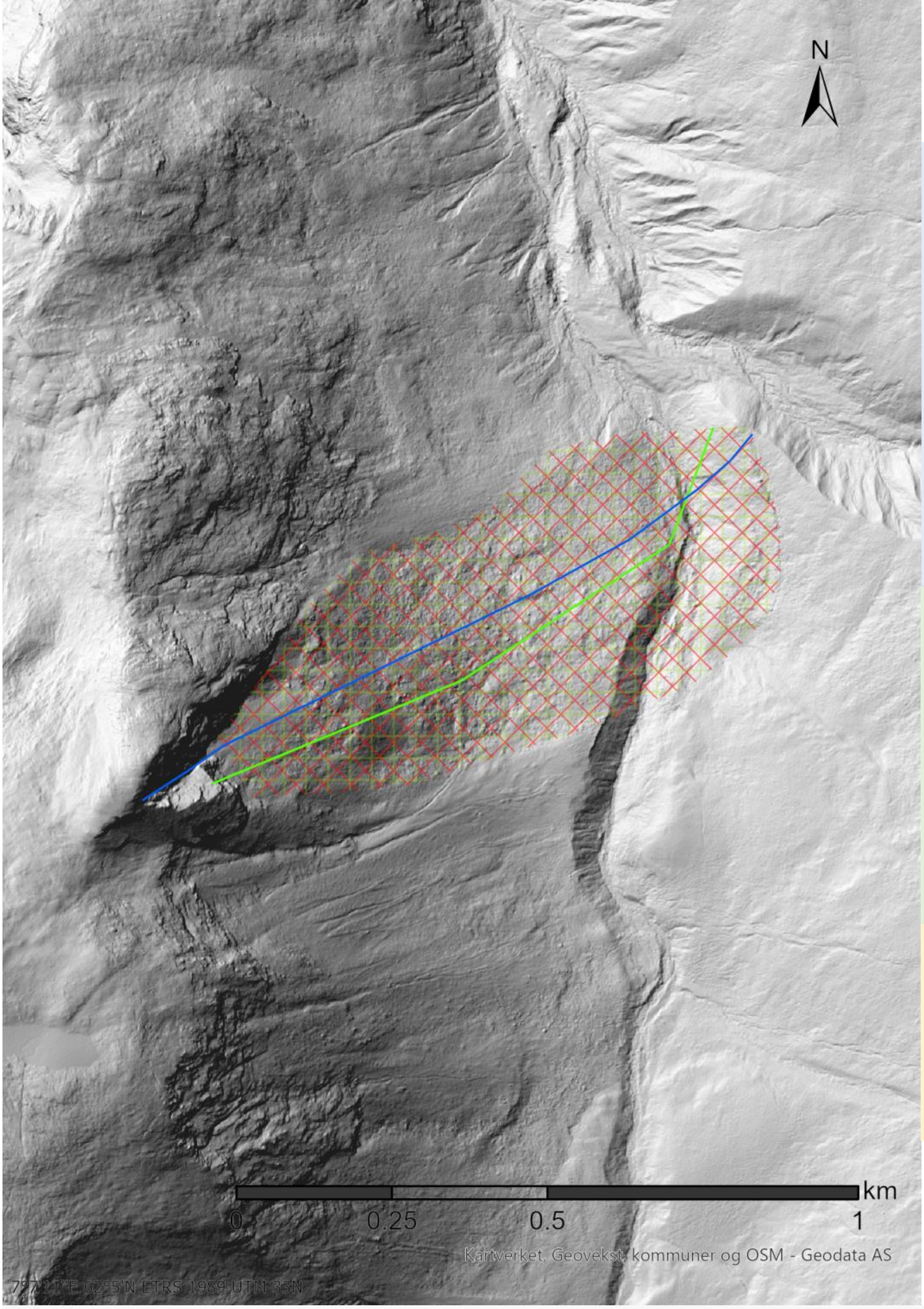
Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

Colluvium/Moraine





ID: 1018

Name: Gjerklandsegga

Classification: Rock Avalanche

Legend

Deposit from DB

Release area from DB

Deposit, new

Release area, new

Run-out path, DB

Run-out path, new

Angle of reach: 22.1°

Volume: 1.2 million m³

Travel D/L: 1-14

Run-out topography:

Against opposite valley side

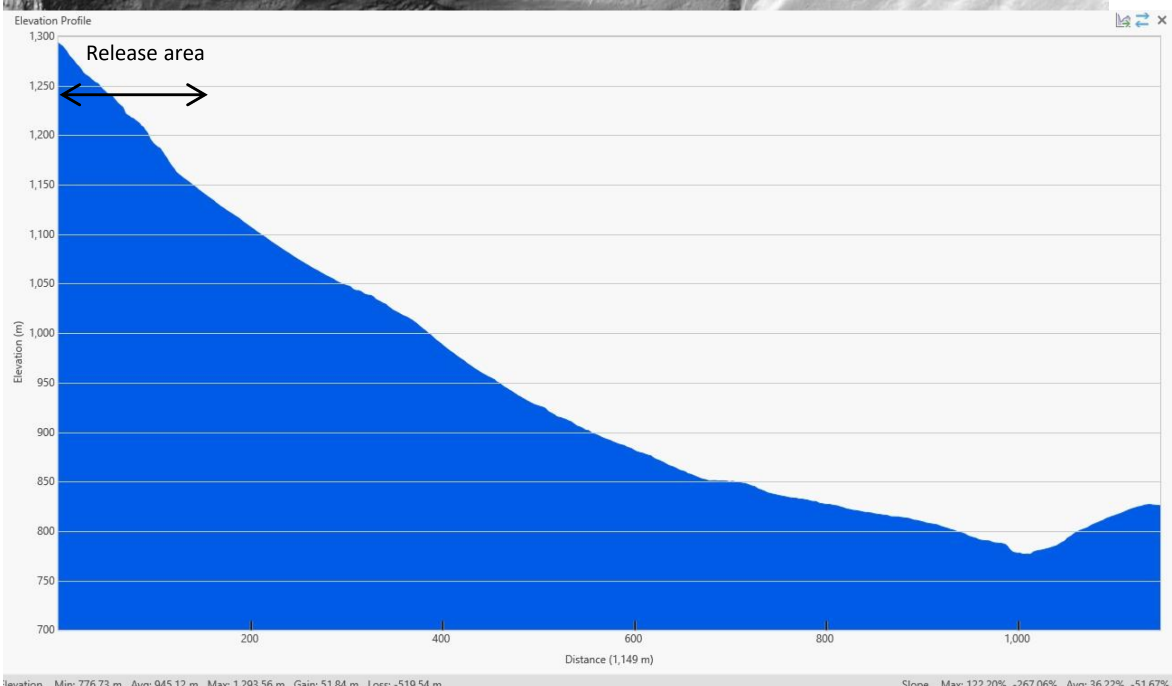
Profileform: >50% descent

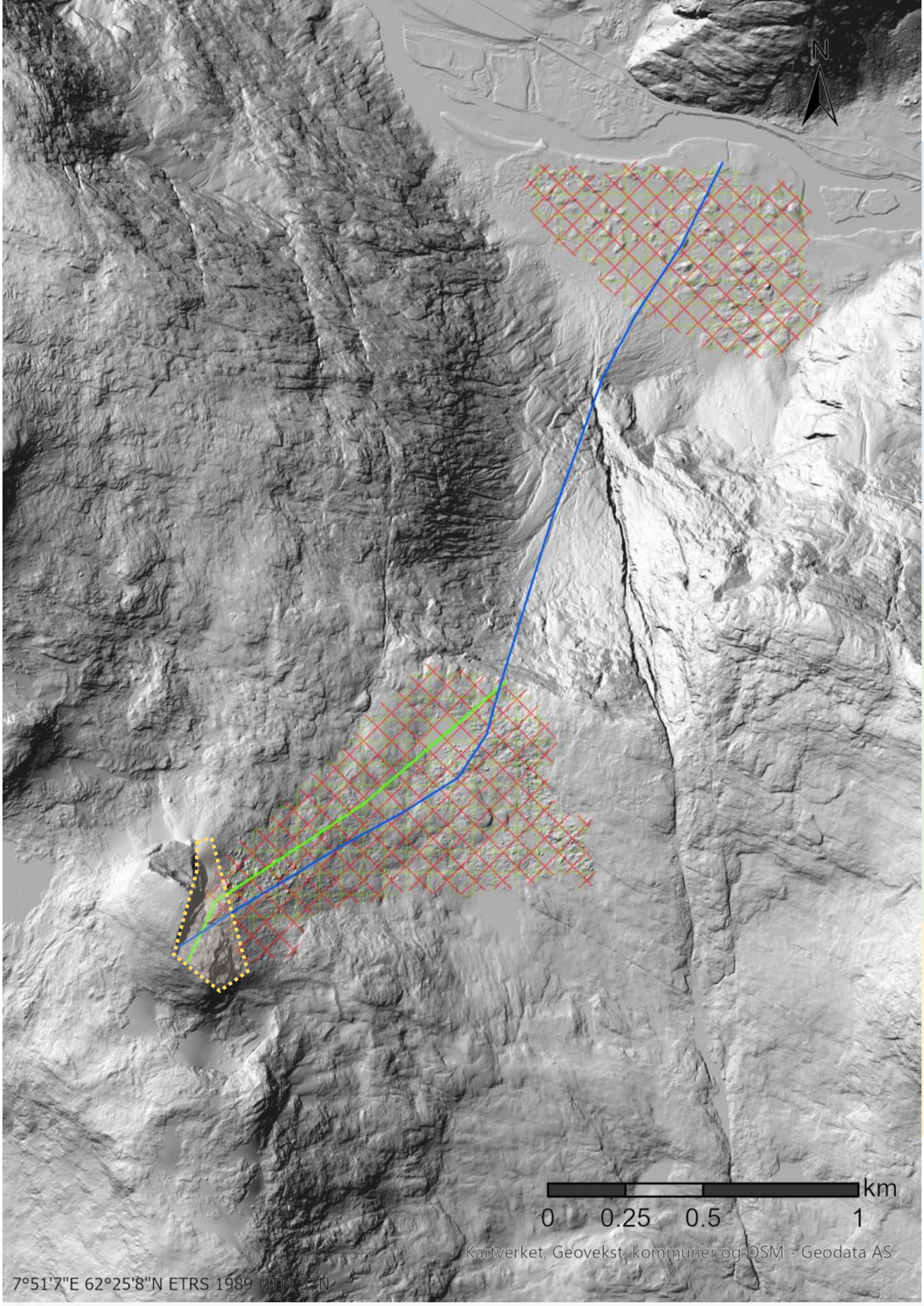
Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

Colluvium/Moraine





ID: 1020

Name: Svarttinden

Classification: Rock Avalanche

Legend

Deposit from DB

Release area from DB

Deposit, new

Release area, new

Run-out path, DB

Run-out path, new

Angle of reach: 24.6°

Volume: 2.8 million m³

Travel D/L: 1.16

Run-out topography:

Unobstructed

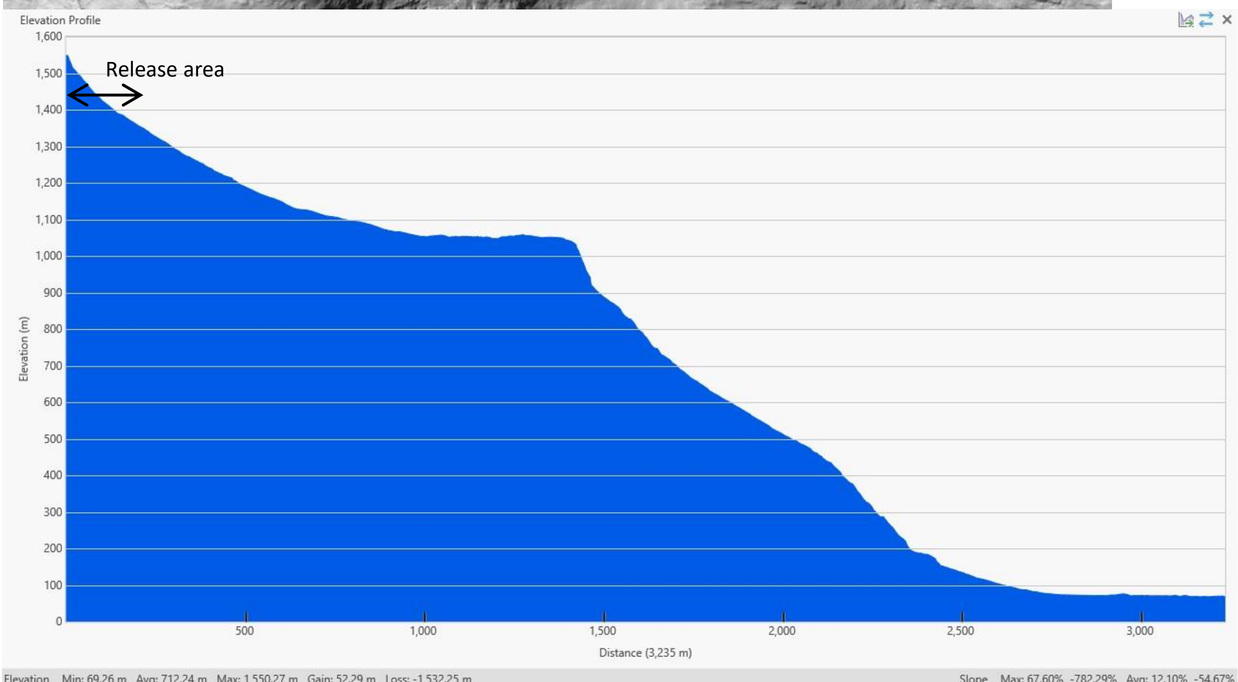
Profileform: Stepped

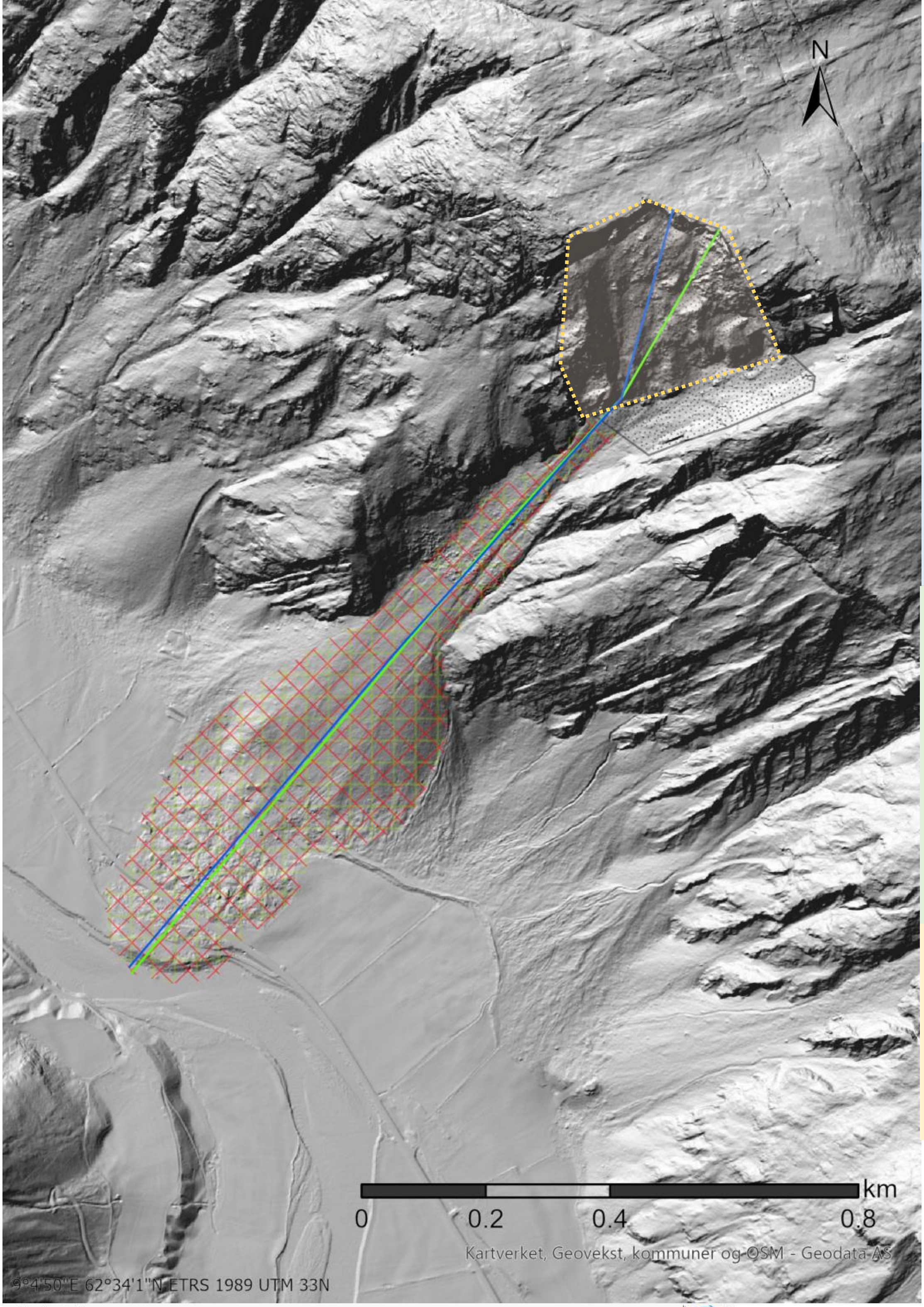
Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

Colluvium/Alluvium





ID: 1025

Name: Ekkertinden

Classification: L. M. Rock A.

Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 33.3°

Volume: 0.83 million m³

Travel D/L: 1.26

Run-out topography:

Channelized, thereafter unobstructed

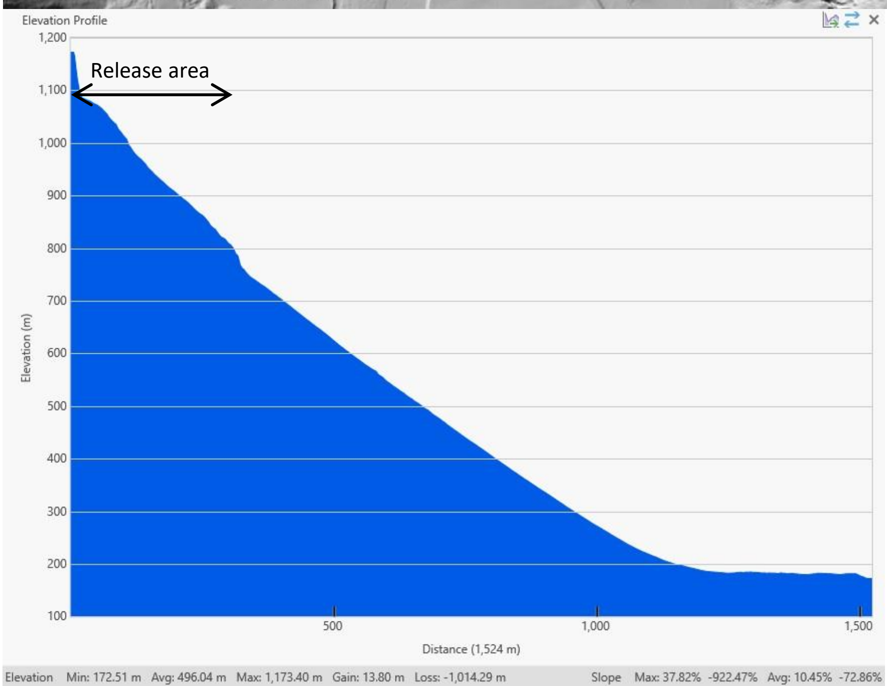
Profileform: >50% descent

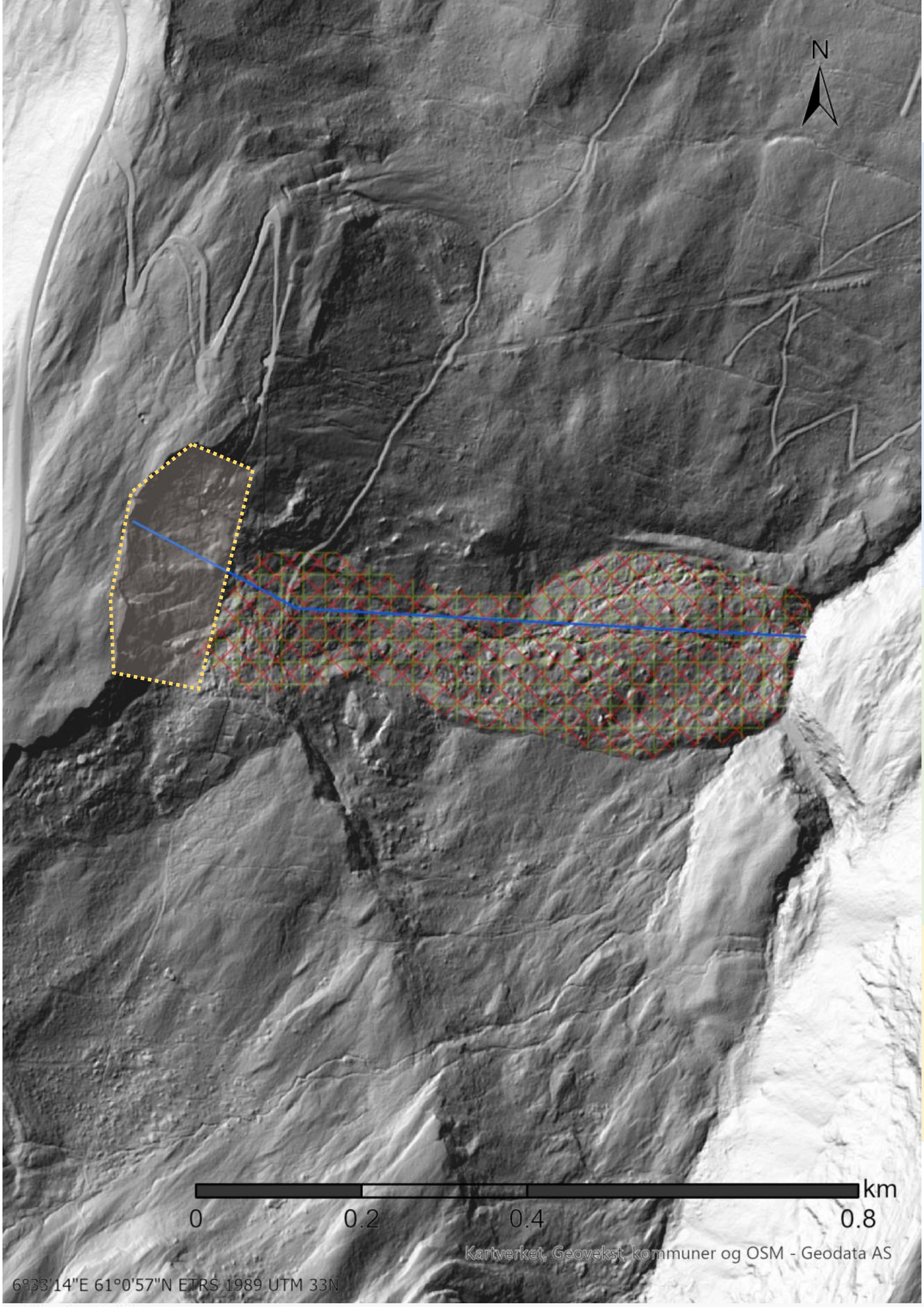
Lithology (release area):

Sandstone

Substrate (Deposit area):

Colluvium/Alluvium





ID: 1032

Name: Øvrisdalen

Classification: L. M. Rock A.

Legend

Deposit from DB

Release area from DB

Deposit, new

Release area, new

Run-out path, DB

Run-out path, new

Angle of reach: 28.6°

Volume: 0.48 million m³

Travel D/L: 1.15

Run-out topography:

Against opposite valley side

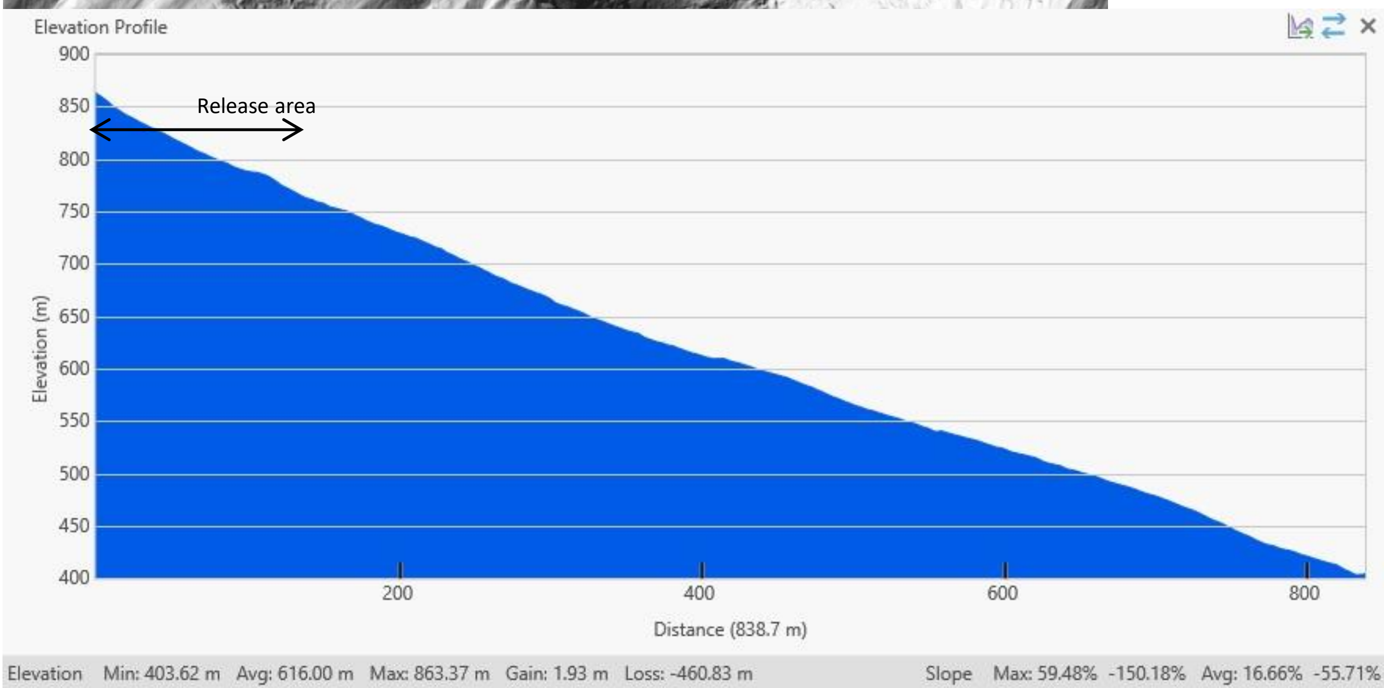
Profileform: >50% descent

Lithology (release area):

Phylite

Substrate (Deposit area):

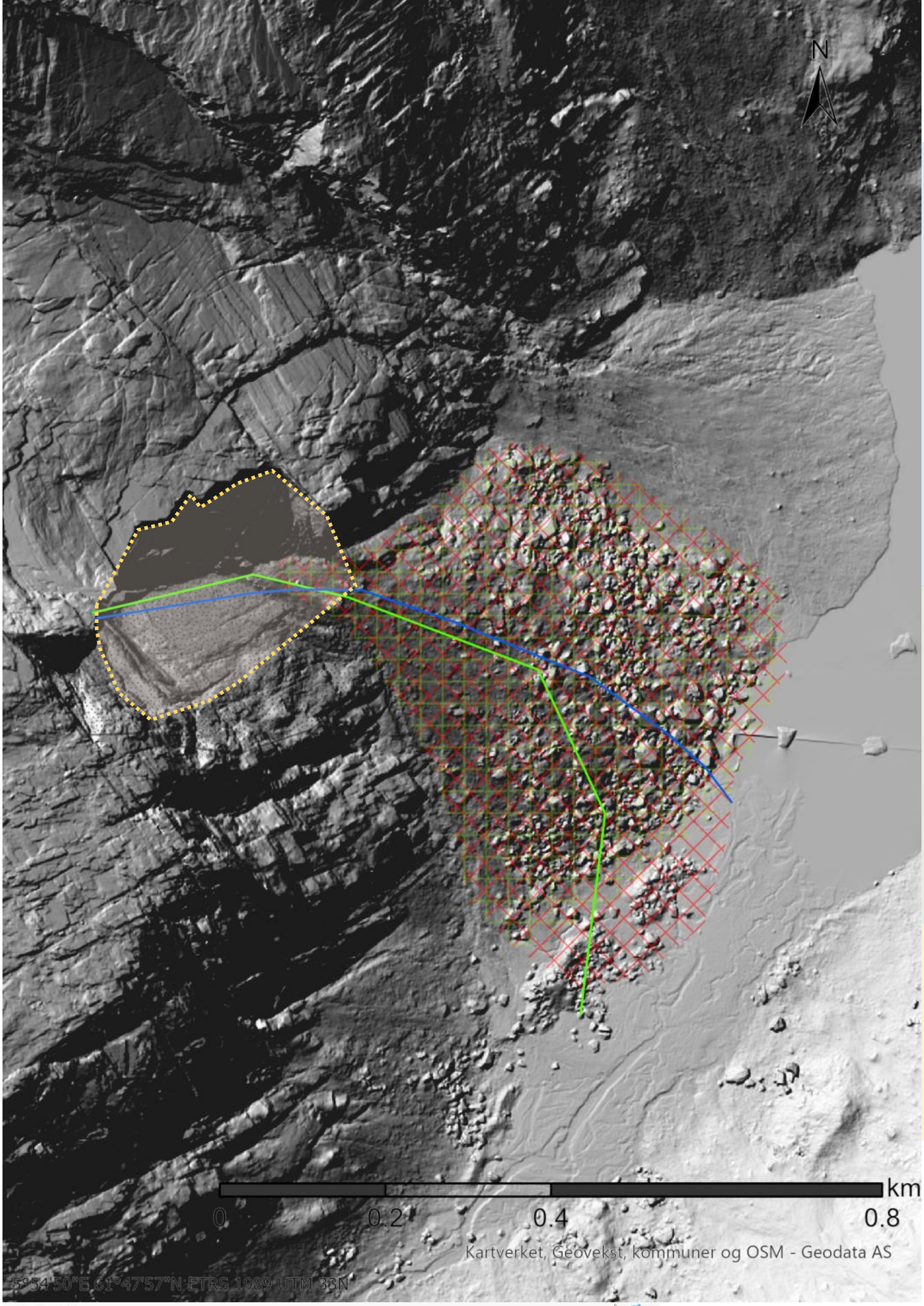
Moraine



ID: 1042

Name: Månyta

Classification: Rock Collapse



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 45.9°

Volume: 2.7 million m³

Travel D/L: 1.63

Run-out topography:

Unobstructed

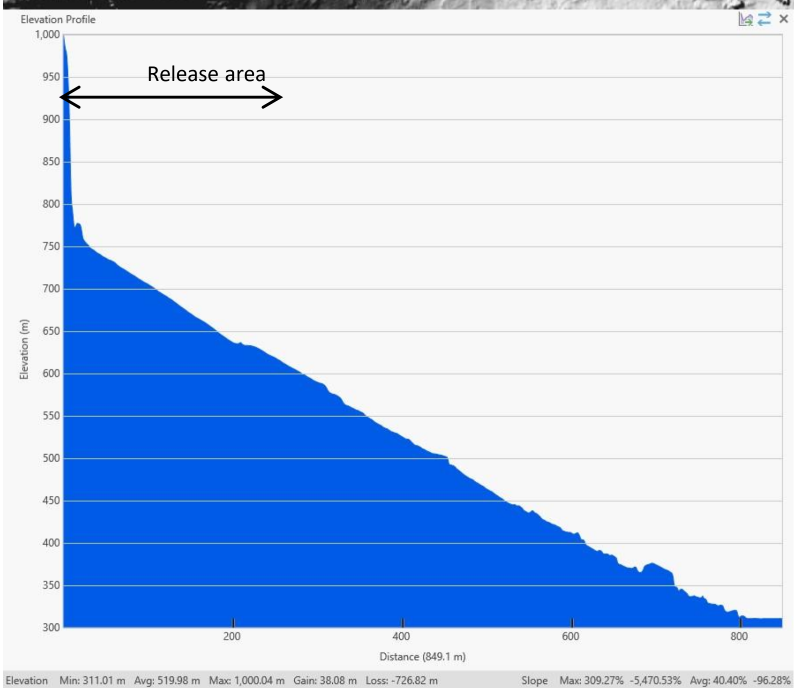
Profileform: >50% descent

Lithology (release area):

Sandstone

Substrate (Deposit area):

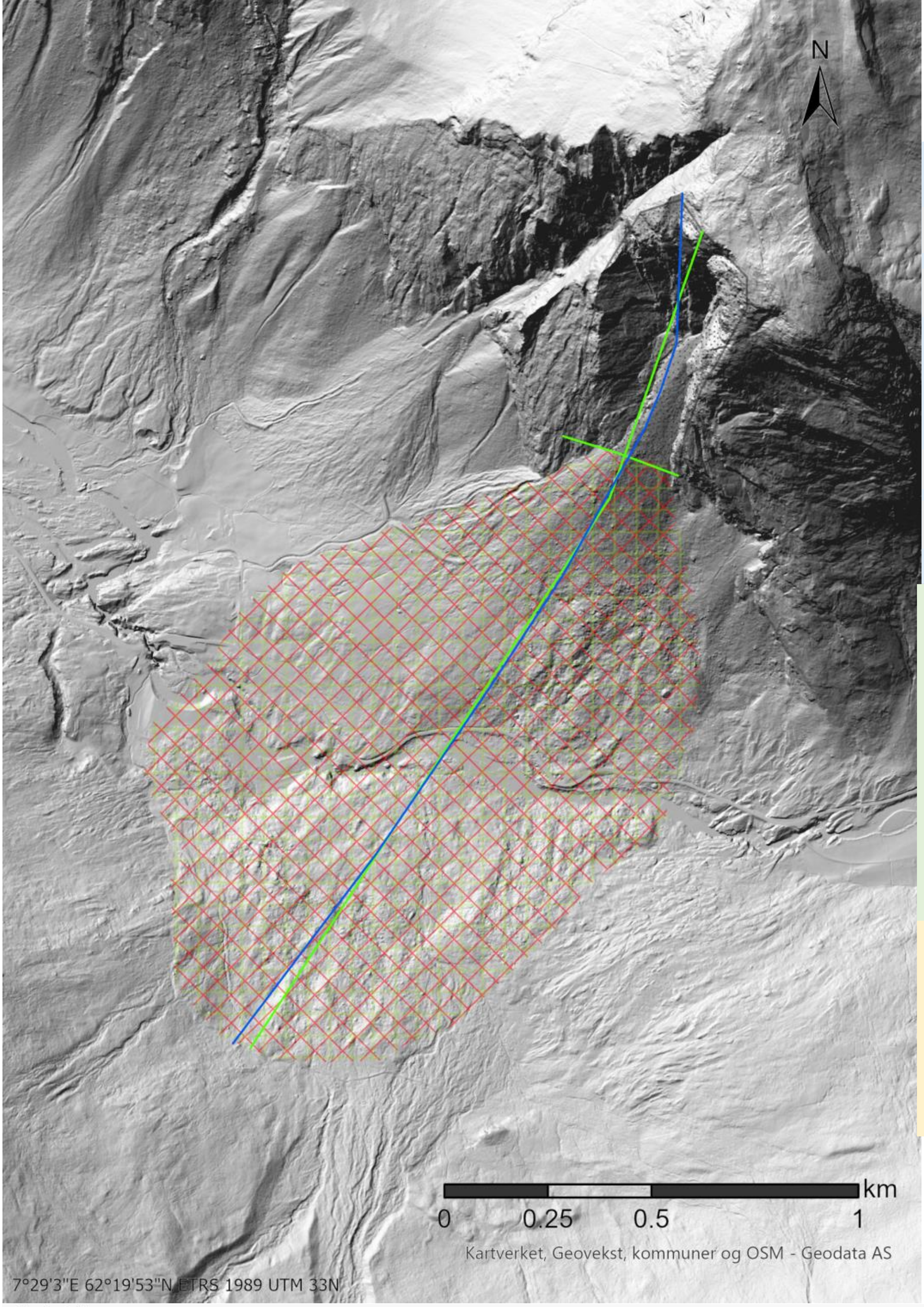
Colluvium/Alluvium



ID: 1067

Name: Alstadfjellet

Classification: Rock Avalanche



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 20.2°

Volume: 6.9 million m³

Travel D/L: 1.16

Run-out topography:

Against opposite valley side

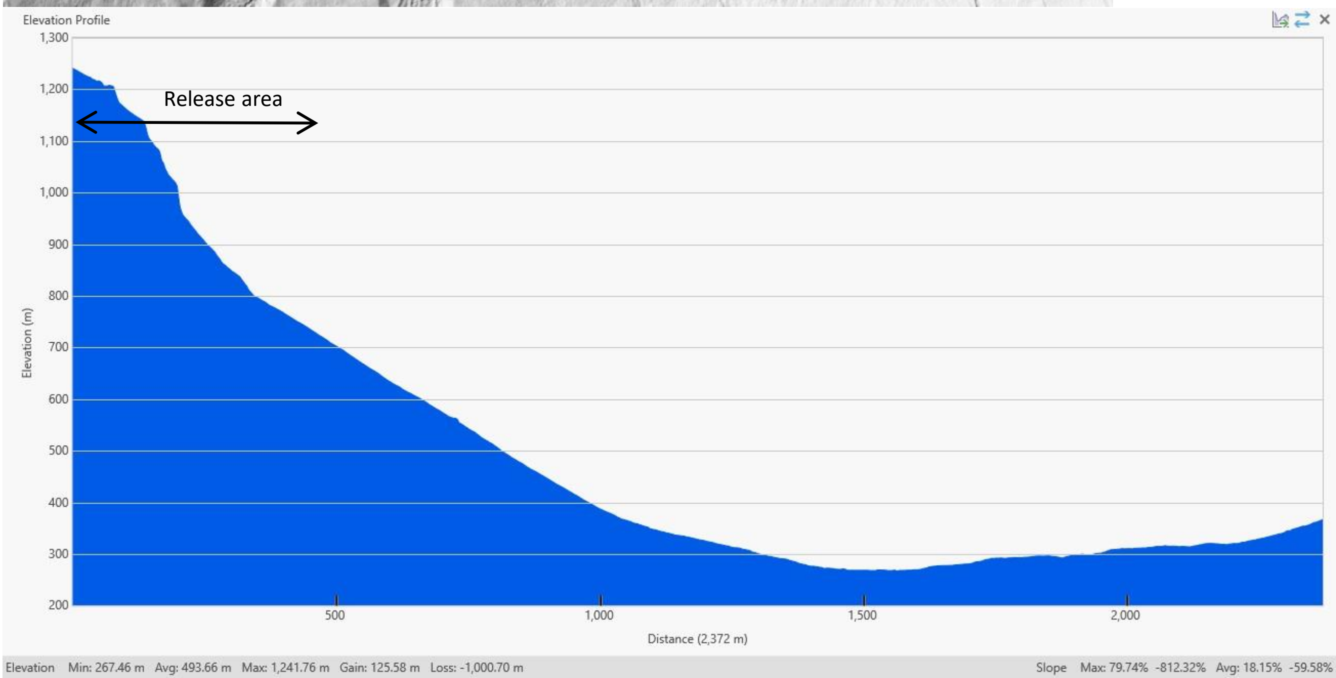
Profileform: <50% descent

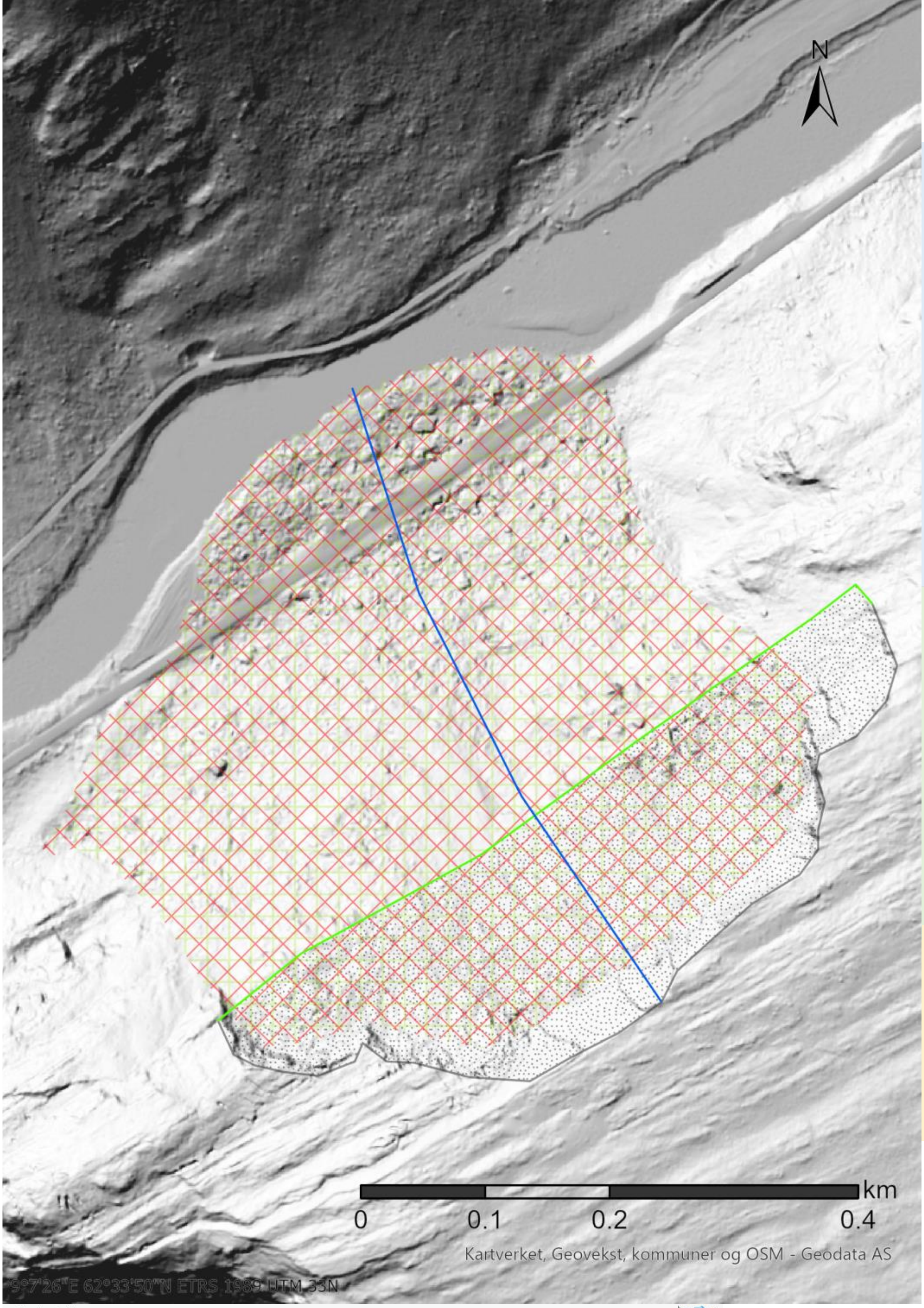
Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

Colluvium/Moraine





ID: 1068

Name: Ivasnasen

Classification: L. M. Rock A.

Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 29.7°

Volume: 0.70 million m³

Travel D/L: 1.18

Run-out topography:

Unobstructed

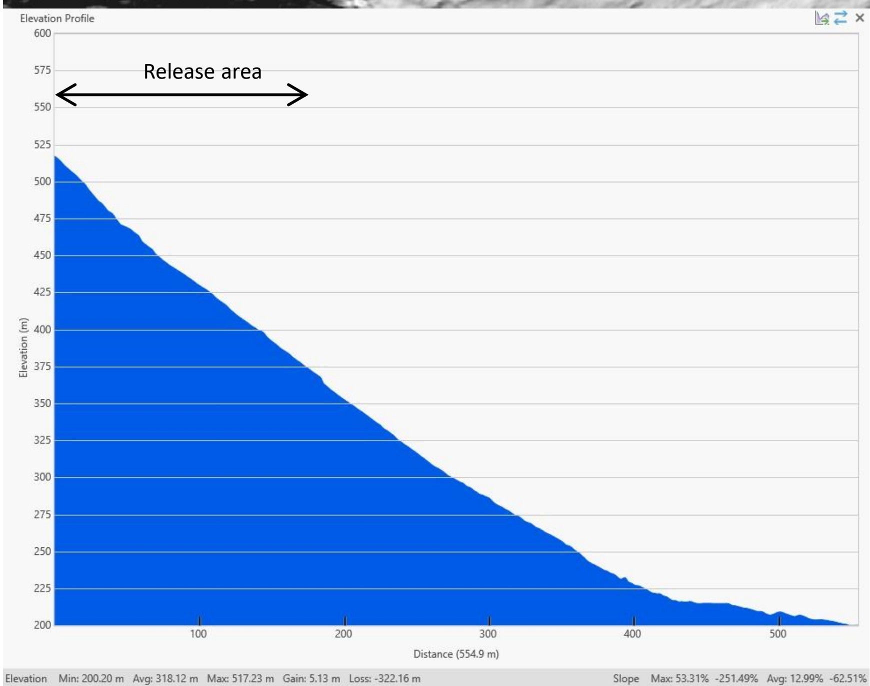
Profileform: >50% descent

Lithology (release area):

Gneiss

Substrate (Deposit area):

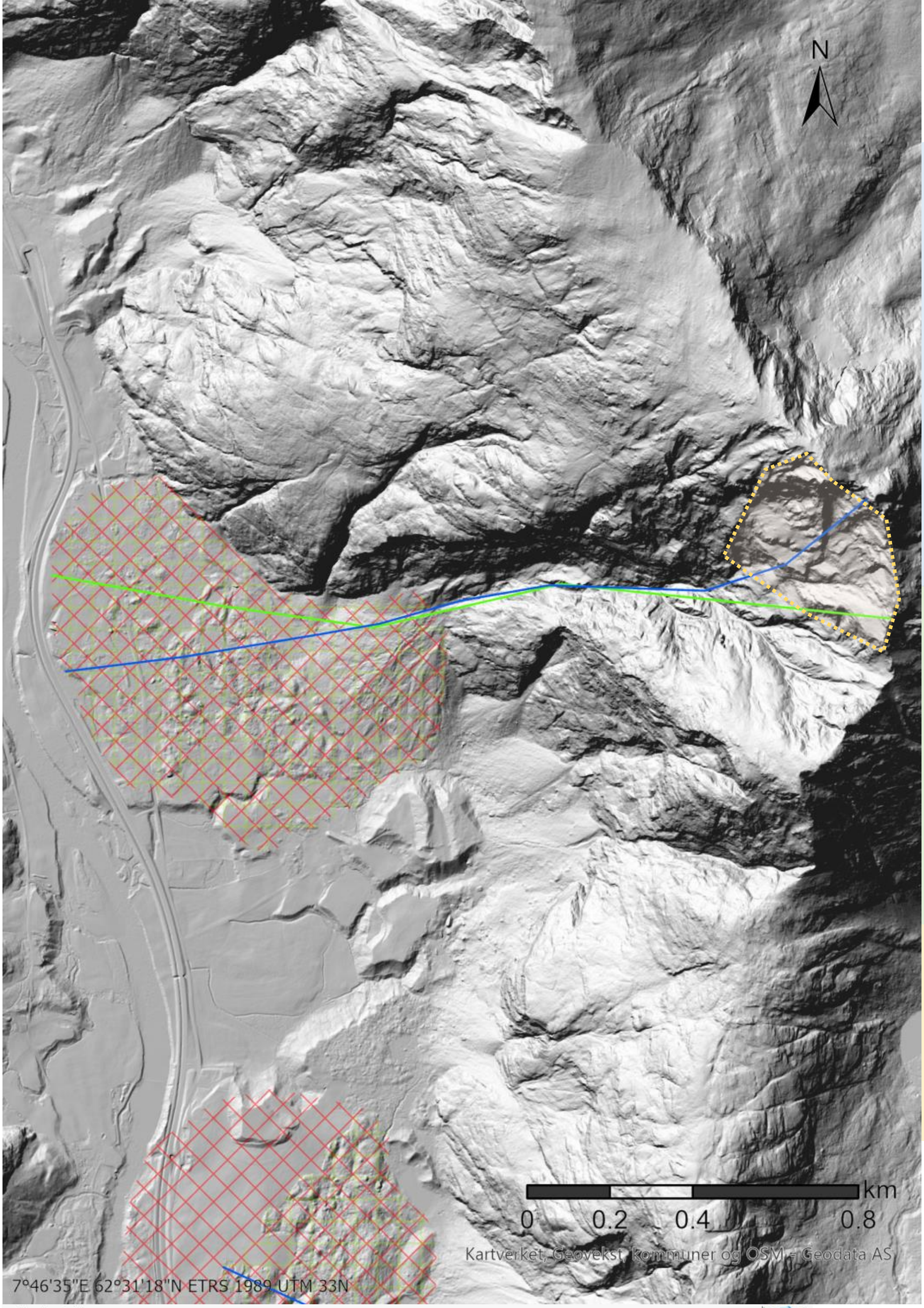
Colluvium/Alluvium



ID: 1069

Name: Tomberg

Classification: L. M. Rock A.



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 32.2°

Volume: 1.3 million m³

Travel D/L: 1.27

Run-out topography:

Channelized, thereafter unobstructed

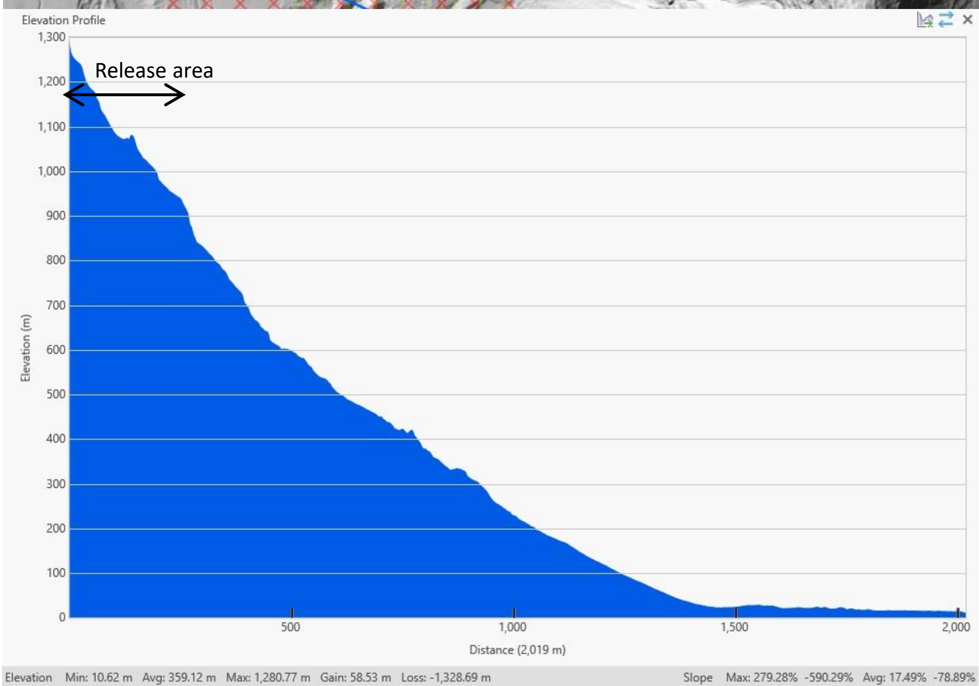
Profileform: >50% descent

Lithology (release area):

Gneiss

Substrate (Deposit area):

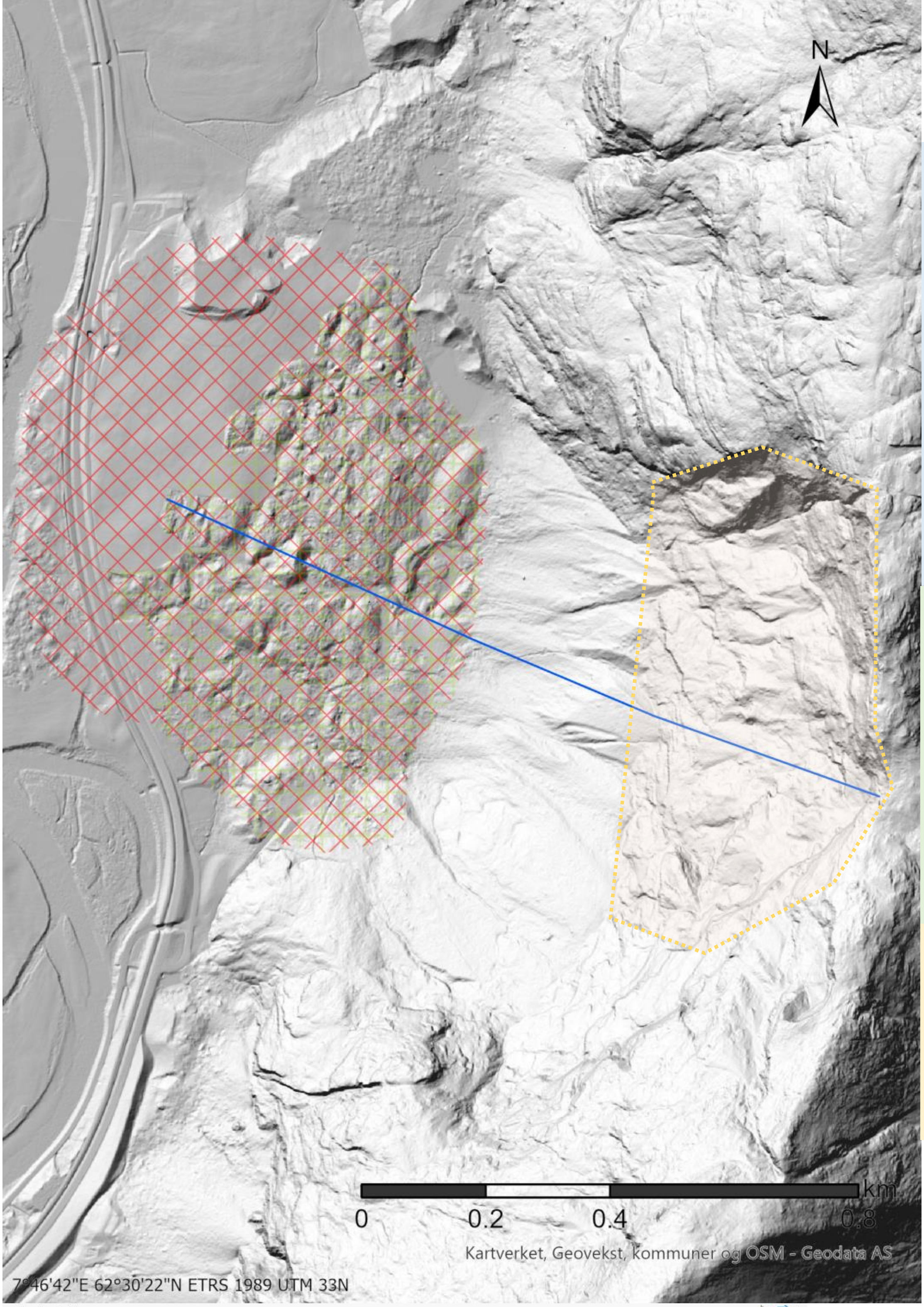
Colluvium/Alluvium



ID: 1074

Name: Litlefjellet

Classification: L. M. Rock A.



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 29.5°

Volume: 1.5 million m^3

Travel D/L: 1.26

Run-out topography:

Unobstructed

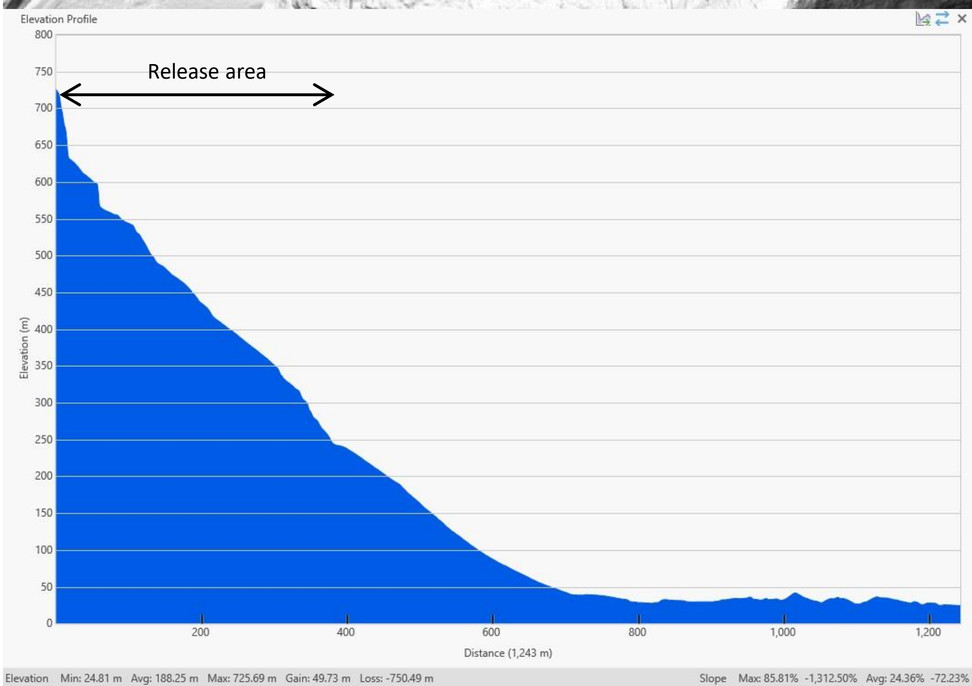
Profileform: >50% descent

Lithology (release area):

Gneiss

Substrate (Deposit area):

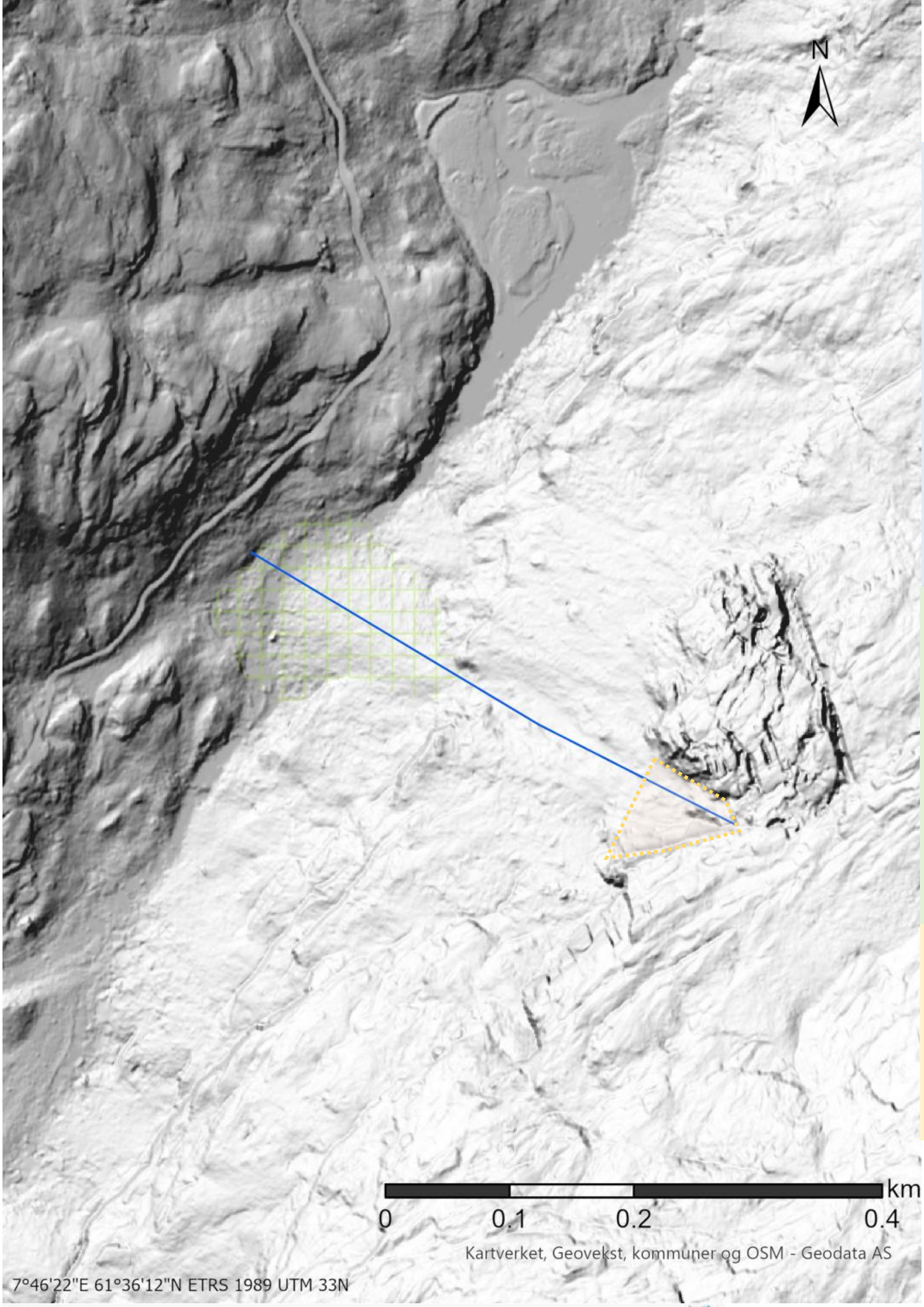
Colluvium/Alluvium



ID: 3161

Name: Tverrdalen

Classification: Rock Collapse



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 52.5°

Volume: 0.036 million m³

Travel D/L: 1.86

Run-out topography:

Against opposite valley side

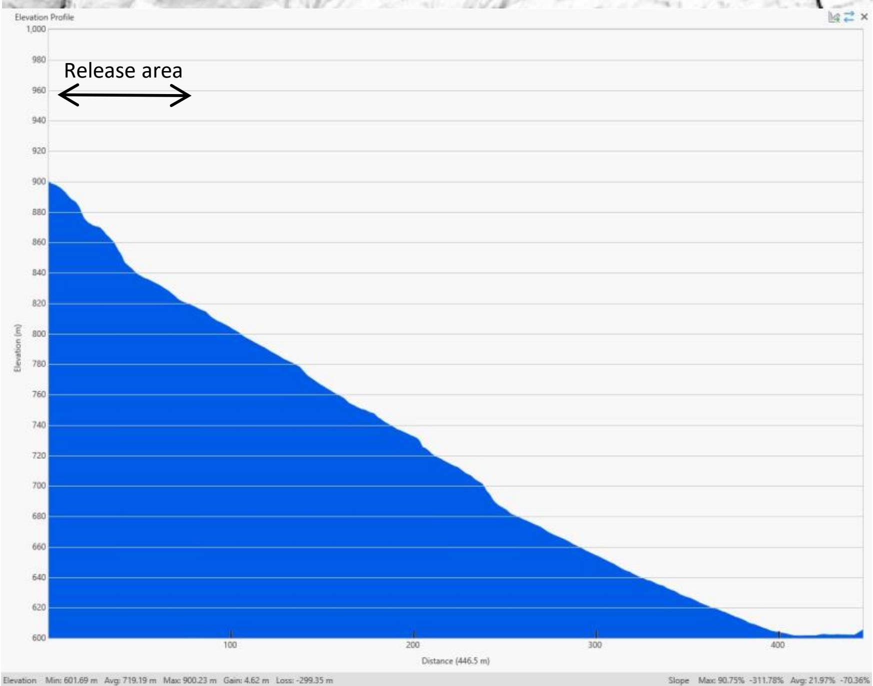
Profileform: >50% descent

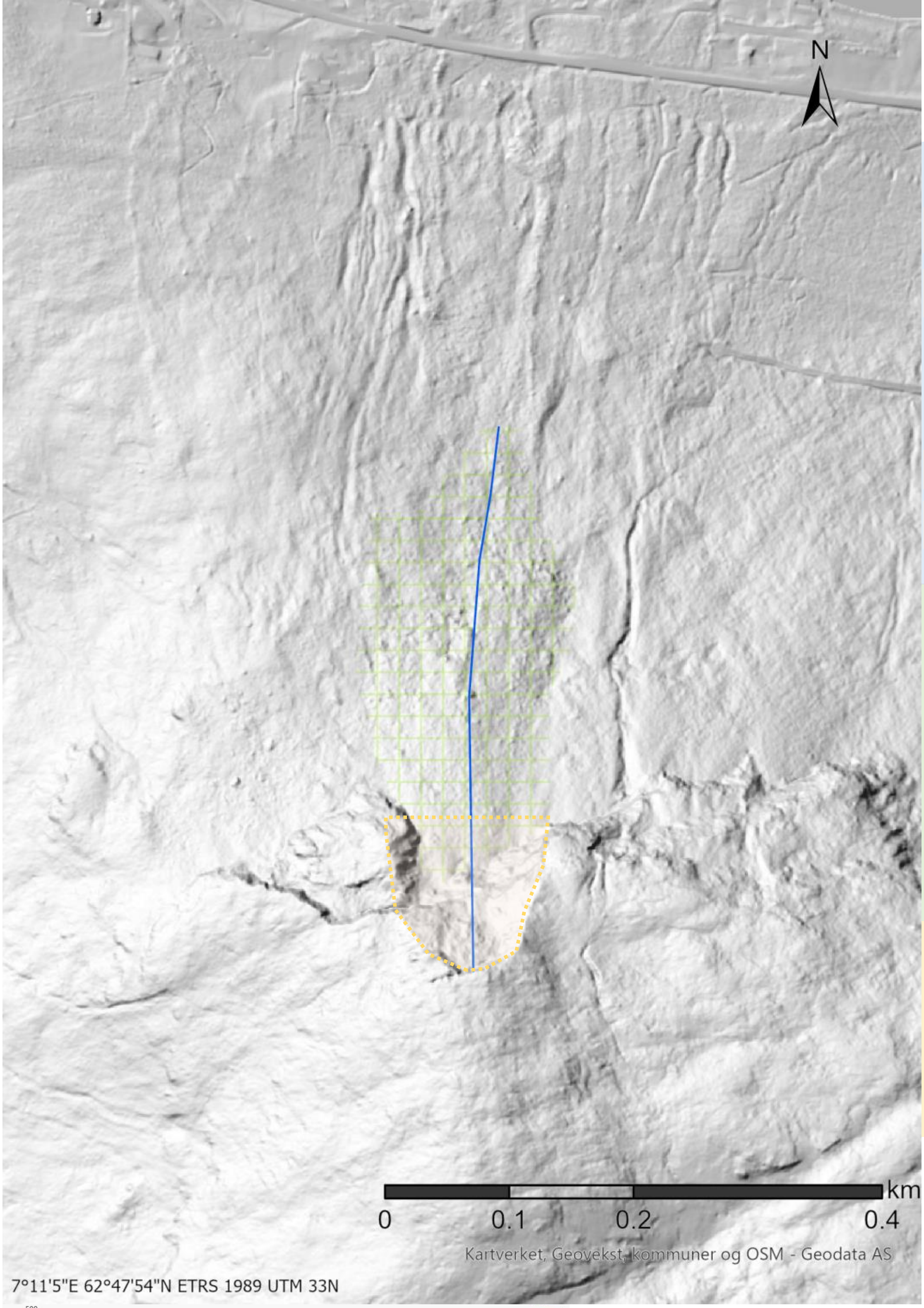
Lithology (release area):

Gneiss

Substrate (Deposit area):

Bedrock/Colluvium





ID: 3170

Name: Røssfjellet

Classification: Rock Collapse

Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 38.0°

Volume: 0.15 million m³

Travel D/L: 1.29

Run-out topography:

Unobstructed

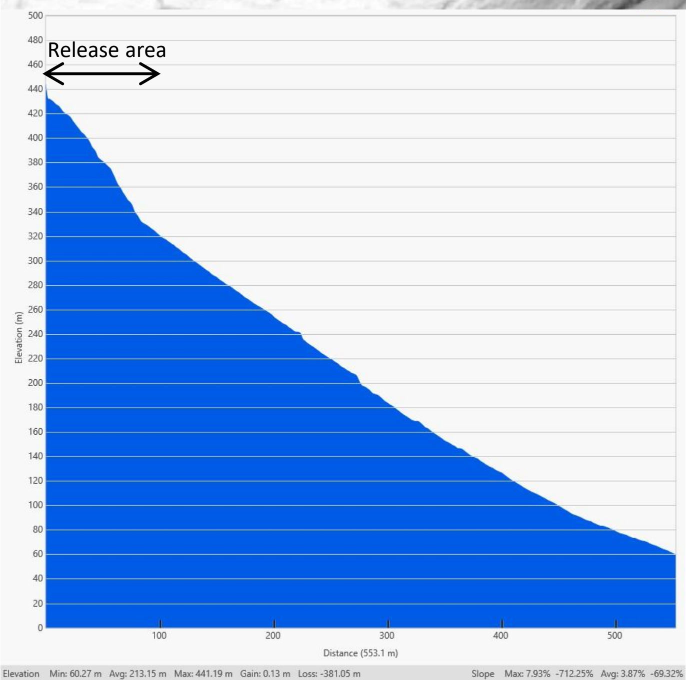
Profileform: >50% descent

Lithology (release area):

Granitic gneiss

Substrate (Deposit area):

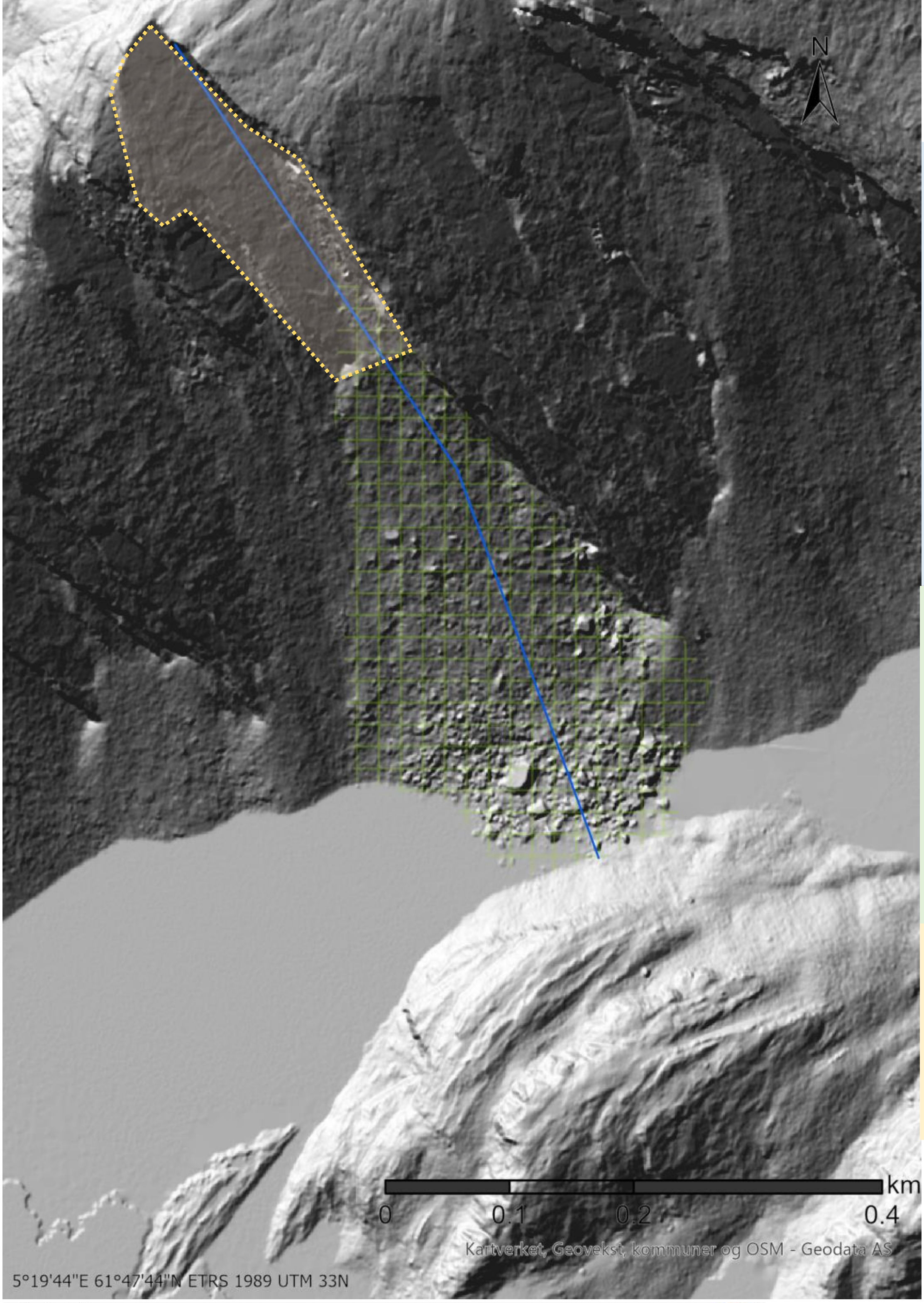
Moraine



ID: 7520

Name: Svelgsvatnet

Classification: Rock Collapse



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 52.1°

Volume: 0.20 million m³

Travel D/L: 1.87

Run-out topography:

Against opposite valley side

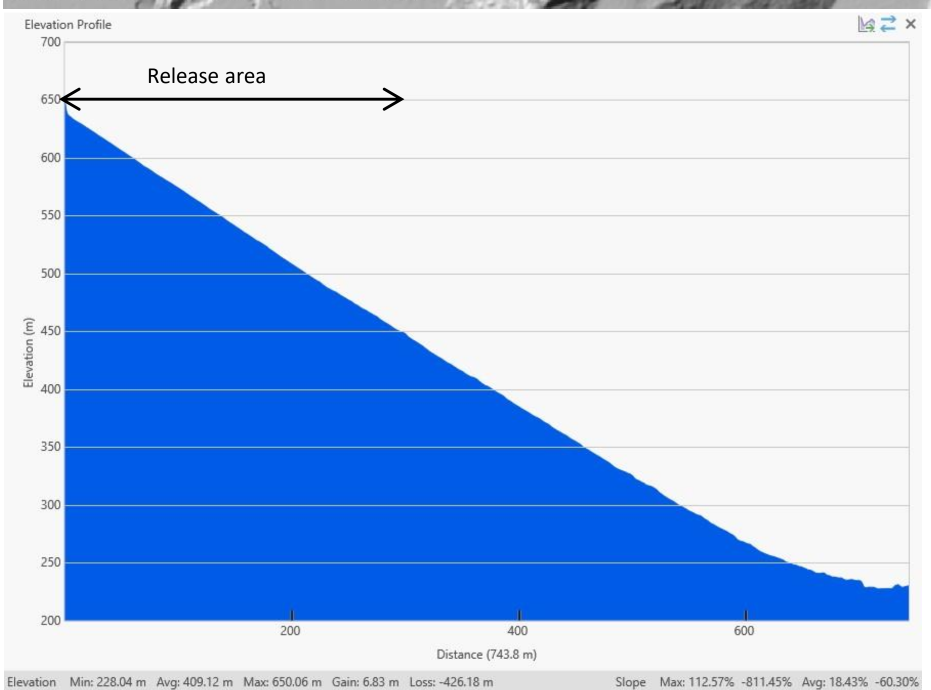
Profileform: >50% descent

Lithology (release area):

Sandstone

Substrate (Deposit area):

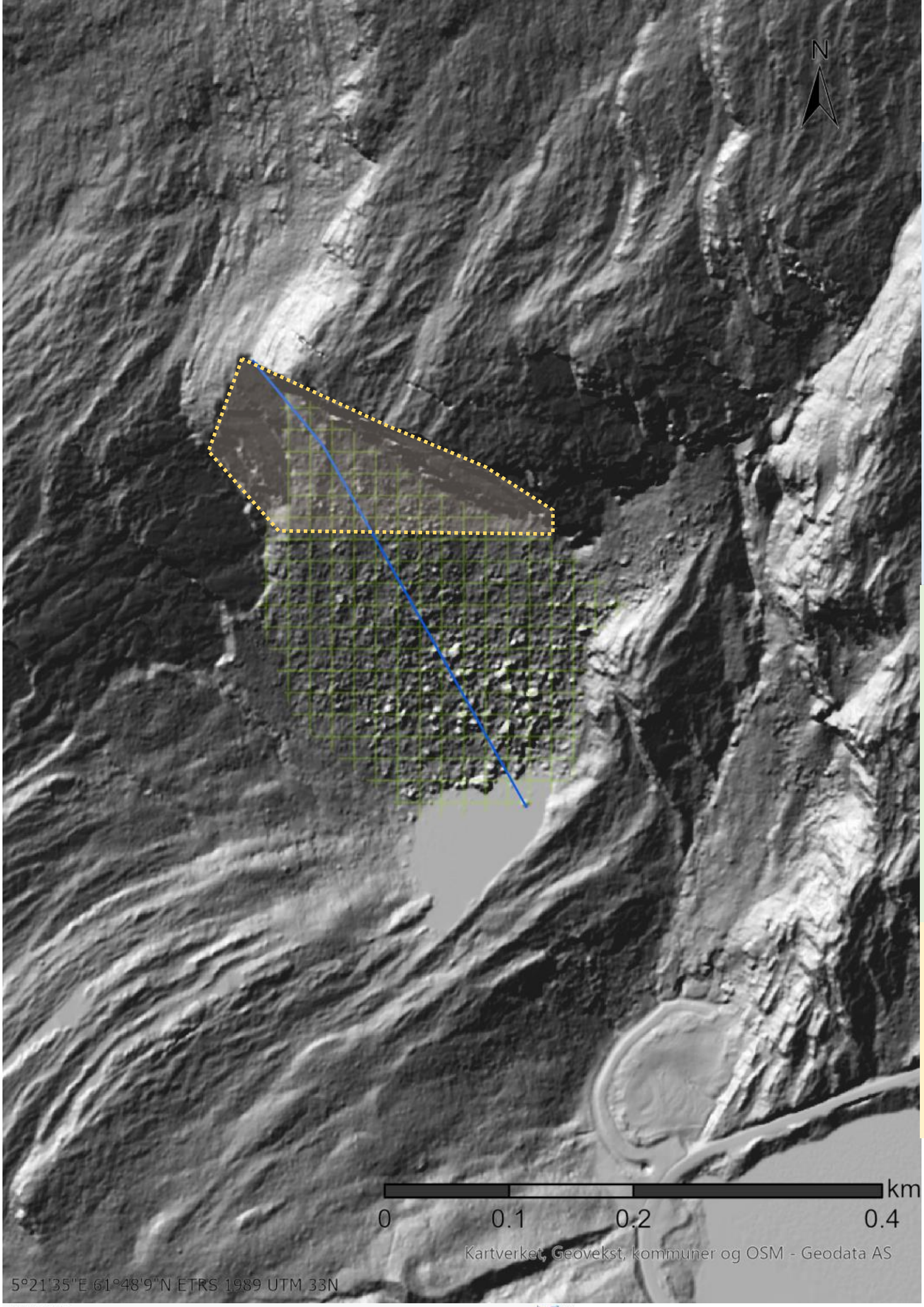
Bedrock/Colluvium



ID: 7522

Name: Øvre Botnen

Classification: Rock Collapse



Legend

- Deposit from DB
- Release area from DB
- Deposit, new
- Release area, new
- Run-out path, DB
- Run-out path, new

Angle of reach: 31.3°

Volume: 0.15 million m³

Travel D/L: 1.18

Run-out topography:

Unobstructed

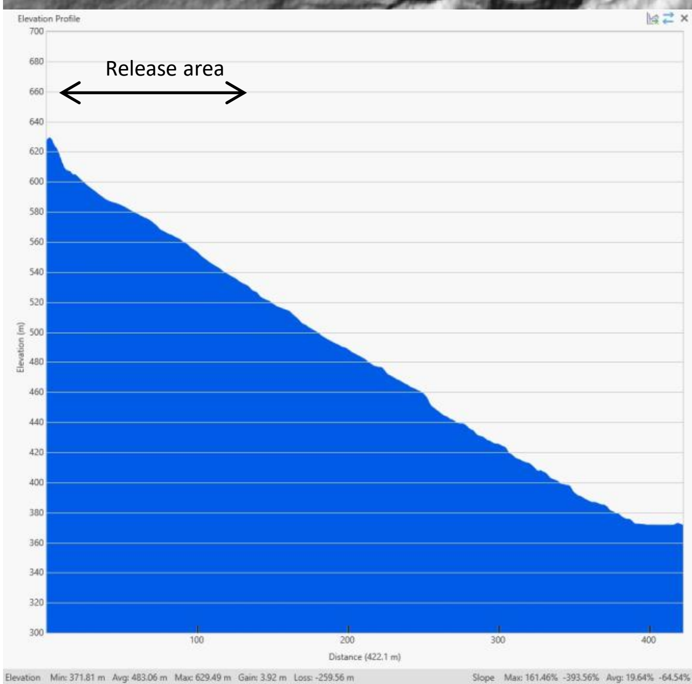
Profileform: >50% descent

Lithology (release area):

Sandstone

Substrate (Deposit area):

Colluvium/Moraine



B Appendix B

ID	Name	Volume 10^6 m^3	(m^3)	H/L	Angle of Reach	Classification	Lithology	Substrate	Run-out topography	Profileform	Travel_D/L
929	Gråfonnfjellet	14.514	14514300	0.303	16.8697918	Rock Avalanche	Granitic Gneiss	Colluvium/Moraine	Ag. Opp. Valley side, Ch.	<50% Descent	1.09
930	Innerdalen	24.507	24507200	0.401	21.84780112	Rock Avalanche	Granitic Gneiss	Colluvium/Moraine	Ag. Opp. Valley side, Ch.	<50% Descent	1.16
931	Blåfjellet (3)	0.675	674679	0.316	17.54021573	Rock Avalanche	Granitic Gneiss	Colluvium/Moraine	Unobstructed	<50% Descent	1.13
933	Navardalsnebba	17.527	17526899	0.267	14.94904391	Rock Avalanche	Gneiss (other)	Colluvium/Moraine	Ag. Opp. Valley side, Ch.	Stepped	1.07
934	Dalaosen	2.120	2119680	0.793	38.43085425	Rock Collapse	Granitic Gneiss	Colluvium/Moraine	Ag. Opp. Valley side, Ch.	>50% Descent	1.43
936	Gullsete	2.317	2316830	0.486	25.93029074	Rock Avalanche	Gabbro	Colluvium/Moraine	Ag. Opp. Valley side	>50% Descent	1.14
941	Snønyken	0.652	651628	0.640	32.61429962	Rock Collapse	Sandstone	Moraine	Ag. Opp. Valley side	>50% Descent	1.32
942	Øyestølen	0.178	178325	0.322	17.86906886	Rock Avalanche	Gneiss (other)	Colluvium/Moraine	Ag. Opp. Valley side, Ch.	<50% Descent	1.10
948	Trollveggen	6.968	6968280	0.700	34.97454126	Rock Collapse	Granitic Gneiss	Colluvium/Alluvium	Unobstructed	>50% Descent	1.34
949	Blåfjellet	6.074	6073680	0.3430	18.92965111	Rock Avalanche	Gneiss (other)	Colluvium/Alluvium	Ag. Opp. Valley side, Ch.	<50% Descent	1.13
950	Husenebba	0.756	756030	0.6210	31.8385217	L. M. Rock Avalanche	Granitic Gneiss	Colluvium/Alluvium	Unobstructed	>50% Descent	1.25
953	Skiriaksla	1.728	1727580	0.519	27.450525	L. M. Rock Avalanche	Granitic Gneiss	Colluvium/Alluvium	Unobstructed	>50% Descent	1.20
954	Skulnebba	5.084	5083820	0.429	23.21902143	Rock Avalanche	Granitic Gneiss	Colluvium/Alluvium	Ag. Opp. Valley side, Ch.	<50% Descent	1.18
1014	Blåtinden	1.379	1378550	0.266	14.87719007	Rock Avalanche	Granitic Gneiss	Colluvium/Moraine	Ag. Opp. Valley side, Ch.	Stepped	1.09
1017	Blåfjellet (2)	0.269	268543	0.5260	27.74538838	L. M. Rock Avalanche	Granitic Gneiss	Colluvium/Moraine	Channalized	Stepped	1.16
1018	Gjerklandsegga	1.206	1206040	0.406	22.10115631	Rock Avalanche	Granitic Gneiss	Colluvium/Moraine	Ag. Opp. Valley side	>50% Descent	1.14
1020	Svarttinden	2.825	2824510	0.458	24.60166365	Rock Avalanche	Granitic Gneiss	Colluvium/Alluvium	Unobstructed/Channelized	Stepped	1.16
1025	Ekkertinden	0.831	830550	0.657	33.29392259	L. M. Rock Avalanche	Sandstone	Colluvium/Alluvium	Ch., then unobstructed	>50% Descent	1.26
1032	Øvrisdalen	0.482	481726	0.546	28.64082129	L. M. Rock Avalanche	Phylite	Moraine	Ag. Opp. Valley side	>50% Descent	1.15
1042	Månyta	2.650	2650210	1.031	45.86852586	Rock Collapse	Sandstone	Colluvium/Alluvium	Unobstructed	>50% Descent	1.63
1067	Alstadfjellet	6.901	6901120	0.369	20.25184833	Rock Avalanche	Granitic Gneiss	Colluvium/Moraine	Ag. Opp. Valley side	<50% Descent	1.16
1068	Ivasnasen	0.697	697129	0.572	29.75229053	L. M. Rock Avalanche	Gneiss (other)	Colluvium/Alluvium	Unobstructed	>50% Descent	1.18
1069	Tomberg	1.339	1339430	0.630	32.22005487	L. M. Rock Avalanche	Gneiss (other)	Colluvium/Alluvium	Ch., then unobstructed	>50% Descent	1.27
1074	Litlefjellet	1.504	1503540	0.565	29.46741709	L. M. Rock Avalanche	Gneiss (other)	Colluvium/Alluvium	Unobstructed	>50% Descent	1.26
3161	Tverrdalen	0.036	35980	1.3033	52.50101165	Rock Collapse	Gneiss (other)	Bedrock/Colluvium	Ag. Opp. Valley side	>50% Descent	1.86
3170	Røssfjellet	0.150	150355	0.780	37.96380587	Rock Collapse	Granitic Gneiss	Moraine	Unobstructed	Stopped on slope	1.29
7520	Svelgsvatnet	0.199	198803	1.285	52.11347433	Rock Collapse	Sandstone	Bedrock/Colluvium	Ag. Opp. Valley side	>50% Descent	1.87
7522	Øvre Botnen	0.147	147499	0.607	31.25487386	Rock Collapse	Sandstone	Colluvium/Moraine	Unobstructed	>50% Descent	1.18

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