



Landslide and ravine distributions related to ground conditions in elevated marine deposit in Mid-Norway

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Abstract

The Trondheim and Gauldal areas in Mid-Norway are characterized by thick marine deposits from the ice age and deglaciation period. The following glacio-isostatic rebound has led to river incisions in the valleys and extensive landsliding and ravine erosion. This study is based on data from an upgraded Quaternary geological map of this region for the areas below the highest sea level after the last ice age, with a focus on landslide scars and ravines. The study has a multidisciplinary approach, which is important in order to get a good regional geological understanding of the ground conditions and the landscape development. This means that geological, geomorphological, geotechnical, geophysical and hydrogeological data are used. The study area is divided into six parts, based on natural topographical divisions and the distribution of landslide scars and ravines. Factors influencing the development of sensitive clay and the triggering of landslides are described for each area; these include sediment distribution, thicknesses and stratigraphy, bedrock topography, the degree of leaching of clay, groundwater conditions, the number, size and shape of landslides, and the distribution of rivers, streams and ravines. The study shows that the size, behaviour and erosional potential of the main river or stream influence the landscape development to a high degree. The erosional basis, stratigraphy and presence of bedrock are essential for leaching and the development of quick clay.

Keywords Landslide · Ravine · Gully · Quick clay · Landscape development

1 Introduction

During and after the last ice age, several hundred metres of glaciomarine and marine deposits accumulated in Norwegian fjords. These sediments were subsequently exposed due to glacio-isostatic rebound and can be detected up to the marine limit (ML), i.e. the highest level that the sea reached in an area following the ice age. Leaching of the marine clay by fresh groundwater alters the chemical composition of the pore water in the marine clay, and “quick clay” may develop (in Norway defined as clay with a remoulded shear strength of ≤ 0.5 kPa) (Rosenqvist 1953; Torrance 1983; and others). In general, quick clay

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can develop downwards, upwards and laterally. Groundwater flow and gradient are important, and are influenced by, for e.g. the presence of coarse-grained material, sediment layering and bedrock topography. The stratigraphy influences the leaching processes of marine clay, as shown by Solberg et al. (2007); Hansen et al. (2007a); Eilertsen et al. (2008). With further leaching of the quick clay, more stabilizing ions from the groundwater will dominate the pore water, and strengthens the bonds between the clay particles (Hilmo 1989; Helle et al. 2016).

When quick clay is remoulded, it completely liquefies. Landslides involving quick clay can change the landscape radically within a few hours, and are one of the most severe geological hazards below the marine limit in Norway.

Terrain changes that lead to a disturbance of the stability equilibrium of a slope are an important contributor to quick-clay landslides. This occurs naturally due to river and stream erosion, but also due to human activity. High pore-water pressure, groundwater erosion and vibrations are other important factors. Often, there is a combination of geological, morphological and physical prerequisites for a landslide, with a single cause that eventually triggers the landslide (e.g. Cruden and Varnes 1996, Ryan et al. 2022).

Systematic mapping of landslides and ravines in marine deposits is, together with information about the ground conditions, important in order to understand the landscape development. The number and ages of landslide scars and ravines give an understanding of the earlier and present erosional situation. Resulting landslide inventory maps and analyses of areas are important for hazard zonation and safety measures.

One purpose of this paper is to present data from an updated Quaternary geological map for the study area below the marine limit. This data include traces of erosional landforms such as ravines (also known as gullies) and landslides scars. Analyses and statistics of these occurrences, such as number, sizes and shapes, are carried out and presented. Another purpose is to present the geological characteristics of the different parts of the study area, and how these are linked to the occurrences and sizes of landslides and ravines. Important factors for the degree of leaching, quick-clay development in marine clay, and triggering of landslides will also be discussed.

The present study is based on data and research from several projects in the study area during the last 15–20 years, and is a combination of geological, geomorphological, geo-technical, geophysical and hydrogeological data. A multidisciplinary approach such as this is important in order to better understand the landscape development in marine clay areas, and may be a useful input to hazard and stability evaluations.

2 Earlier mapping of landslide scars and ravines in marine deposits

There have been large variations in the amount of focus invested in systematic, detailed mapping of landslide scars and ravines in elevated marine sediments in the parts of the world where this is relevant. The following section outlines some examples of such mapping in Norway, Sweden and Canada. Only a few of these studies had the opportunity to use high-resolution LiDAR data (Light Detection and Ranging) for the mapping of landslides, and many scars are therefore not mapped. In addition, the geological understanding in connection to the landslide distribution was not considered in all the studies.

In Norway, landslide scars and ravines are mapped as part of the Quaternary geological mapping programme at the Geological Survey of Norway (NGU). The Quaternary geological maps provide a general overview of the surface sediment distribution and landforms

(NGU 2024). The amount of detail depends on the scale, focus, base data and the age of the mapping. The Quaternary geological map and the information on the marine limit are used as susceptibility information for marine clay presence (Hansen et al. 2017). This, together with information about topography and erosion, and data from ground investigations, are the basis for the quick-clay hazard mapping in Norway—a national programme that has been, and still is, running since the early 1980s (NVE 2021). The mapping identifies zones where large, quick-clay landslides potentially can occur. These zones, in turn, are subjected to a risk classification as a basis for planning and mitigation work (Havnen et al. 2017). However, quick clay is also present outside the identified quick-clay hazard zones, and even small landslides can be fatal—especially in urban areas. Quaternary geological maps may be used as an awareness tool for the areas below the marine limit that has no mapped hazard zones.

Relatively few studies have been carried out on detailed mapped landslide occurrences and their connection to ground conditions for large areas in marine clay deposits in Norway. Foster and Heiberg (1971), Jørstad and Hutchinson (1961), Karlsrud et al. (1985), and Solberg et al. (2007) discuss which parts of a valley / river system have highest landslide activity. Hansen et al. (2007b) and Eilertsen et al. (2008) focus on stratigraphic variability of the erosional pattern and how geology influences this development, with regard to river incision, groundwater erosion and landslide activity. L’Heureux (2012) documented the retrogressive behaviour and the mobility of 37 quick-clay landslides in Norway. One of his discussions were how the terrain influences how large a landslide may be, and how the landslide debris are evacuated (open or channelled terrain).

Norway has a National landslide event database, mainly for historical landslides (NSDB 2024). The information mainly consists of landslide type, time of the event and a short description, but have limited geological information.

Additionally, in 2019, the Geological Survey of Norway (NGU) and the Norwegian Environment Agency started a nationwide mapping programme of “red-listed landforms” such as ravines and landslide scars in marine deposits (van-Boeckel et al. 2023). This gives large data sets of detailed mapped landslide scars and ravines from different parts of Norway. Statistical analyses of the landslide morphology, partly with data from the study area of the present paper, have been carried out (Penna and Solberg 2022).

Rankka et al. (2004) reported on geological prerequisites, chemical and mineralogical compositions, and processes leading to the formation of quick clay in Sweden. The study concluded that quick clay is mostly detected in the following areas: close to bedrock valley sides; above and below thick and continuous deposits of coarse sediments, sometimes only where the clay is located close to the coarser layer; and close to outcropping and buried hillocks. Based on these and other criteria, Persson et al. (2014) statistically predicted quick-clay formation in south-west Sweden by making a spatial model that considered paleogeographic, hydrogeological and stratigraphic variations. The Geological Survey of Sweden (SGU) has analysed the morphology of landslides in fine-grained sediments and made a database for Sweden (Melchiorre et al. 2014). SGU also carries out mapping of landslide scars and ravines which are presented in a web map service (SGU 2024).

Some of the early mapping of landslides in marine clay for use in hazard analyses in Canada were made by Mitchell and Markell (1974), Lebuis et al. (1983), Geertsema and Schwab (1997) and others. A PhD work by Quinn (2009) dealt with the spatial relationship between specific physiographical and geological features, and the occurrence or absence of large landslides, in sensitive clay, in eastern Canada. Some of the conclusions from this work were that all large landslides tend to occur along the banks of existing or abandoned watercourses; additionally, the maximum size of large landslides appears to be positively

correlated with the size of the drainage feature; and finally, landslides appear to be more common where soils are thicker. In addition, large clusters of retrogressive landslides are associated with the presence of emerging bedrock hills, and new retrogressive flow slides tend to occur close to old slides. Quinn et al. (2011a) concluded that landslides will terminate before reaching a reverse break in the slope, such as a ravine or an adjacent, older landslide crater. However, Geertsema et al. (2006) showed that new landslides can capture older, shallower landslides.

Quinn et al. (2011b) presented basic geometric data for 32 large landslides in sensitive clay in Canada and Norway from the literature, ranging in size from 8000 to 2.9 million m². In addition, statistical analyses were made for 1259 retrogression landslides in eastern Canada. Also Demers et al. (2017) presented the mapping of 3500 retrogressive landslides in sensitive clay in Quebec based on LiDAR data. They also emphasized the importance of detailed and reliable landslide inventories in hazard mapping.

3 Marine clay landslide types

Definitions of landslides are often based on parameters such as material type, material properties and failure mechanisms. These general classifications often need local adaptations for different parts of the world. Landslides in marine clay may involve remoulding of quick clay, but not always, and for old landslide scars it is not always easy to conclude if this was the case. Detailed LiDAR data collected shortly after a landslide event may indicate material properties, i.e. sensitivity and shear strength. If most of the clay involved in the landslide was quick and remoulded during the event, the scar will most likely be emptied. If just a thin layer of quick clay was present, larger blocks may be left behind in the scar.

In some landslide events, more than one landslide type or mechanism may be involved. In the present paper, landslides in marine clay are classified based on the updated Varnes classification system by Hungr et al. (2014), Quinn (2011b) and the Norwegian Water Resources and Energy Directorate (NVE hereafter) guidelines for safety against landslides in quick clay (NVE 2020). The following classifications are used:

Surficial slides or *Soil creep* occur when the soil is saturated, for e.g. after heavy rainfall or during snow melt. The sliding plane is shallow, and often parallel to the terrain surface.

Rotational slides or *Soil slumps* occur when homogenous and cohesive soil moves in one piece and shows a clear rotation. There is little internal deformation. It involves the riverbank, and the backscarp is normally just behind the top of the slope. The sliding plane for rotational landslides goes significantly deeper than the sliding plane for surficial slides.

Retrogressive slides or *Flows* occur when the soil partly or completely liquefies. The landslide crater is often “empty”, with a fully or partially exposed sliding plane. Some debris can also be left behind in the scar, e.g. as deformed blocks. This landslide type may have a “bottle-neck” shape, where the gate of the slide scar is narrower than the largest width of the slide scar. The slide scar is often relatively deep with steep back-slopes, but this depends on the level of the sliding plane. A retrogressive slide generally involves transport of debris some considerable distance downstream, and may also involve significant upstream transport in adjacent streams.

Flake slides or *Translational slides* occur when blocks of cohesive soil slide on an inclined planar sliding plane, formed by a weak layer. The remoulding process is often driven by progressive failure (forward directed or backward directed). The monolithic slide material remains more or less intact during movement. Flake slides generally occur in

relatively flat terrain, where quick clay or other weak layers often are thin surface-parallel layers in the ground.

Lateral spreads occur when a series of coherent clay blocks float on a layer of remoulded clay. It leaves a distinct horst and graben morphology. The landslide debris is most often transported a short distance from the landslide scar.

4 Setting and general geology in the area

The study area comprises ground areas below the marine limit (ML) in the municipalities of Trondheim and Melhus in Mid-Norway. The total area is almost 400 km². The study area is divided into six parts (Fig. 1): Trondheim North (TN), Nidelv Valley (NV), Tiller Klæbu (TK), Byneset (B), Gauldal North (GN) and Gauldal South (GS). The extension of the areas is based on natural topographical divisions and the distribution of landslide scars and ravines in the study area.

4.1 Bedrock geology

Bedrock maps for the area are at a scale of 1:50,000 and 1:250,000 (Wolff 1976; Chaloup-sky 1977; Solli et al. 2003; Gasser et al. 2018). The study area mainly consists of metamorphic rocks, such as schists, greenstone, phyllite and greywacke. South in the study area, Gauldal is crossed by some bands of rhyolite (volcanic rock) and conglomerate (sedimentary rock).

4.2 Deglaciation and following landscape development

The onset of glacier retreat from the study area happened prior to the Younger Dryas cold period, and the sea followed the retreating glacier margin. The sea level was relatively high due to a strong glacio-isostatic depression of the crust. The Gauldal valley specifically was one of the main glacier pathways in the Trondheim region and the valley is very deep due to glacial erosion. Seismic investigations show that the sediment is 500 m thick in Gaulosen (Rise et al. 2006), and at least 300 m in other places in the Gauldal valley (Sindre 1980). Depth to bedrock is less in Klæbu and Trondheim, but data from drilling and geophysical investigations show large variations, often over short distances. The glacial and postglacial history of the Trondheim and Gauldal regions have been mapped and described by Reite (1983, 1985, 1994, 1995), Olsen et al. (2015), Rise et al. (2006) and others. The earlier Quaternary mapping scale in the area was 1:50,000, and not very detailed with regard to, for e.g. landforms such as landslide scars and ravines.

The highest sea level after the last glaciation (ML) was about 160 m above present sea level in the north-western part of the study area, and about 175–180 m a.s.l. in the southern part (Reite 1983, 1985). An enormous amount of sediment was transported by glacial meltwater from the east and south and settled in the fjord in front of the glacier. This resulted in the accumulation of extensive and thick, fine-grained glaciomarine and marine deposits. Nevertheless, several massive coarse-grained glaciofluvial deposits are also present (Fig. 1). These deposits accumulated in the fjord during temporal stops or short glacier readvances. The highest sedimentation rates took place on the slopes of the glaciofluvial deposits, but clay and silt were continuously deposited in the basin in front of the retreating glacier. Gauldal was a relatively narrow fjord with several straits through the glaciofluvial

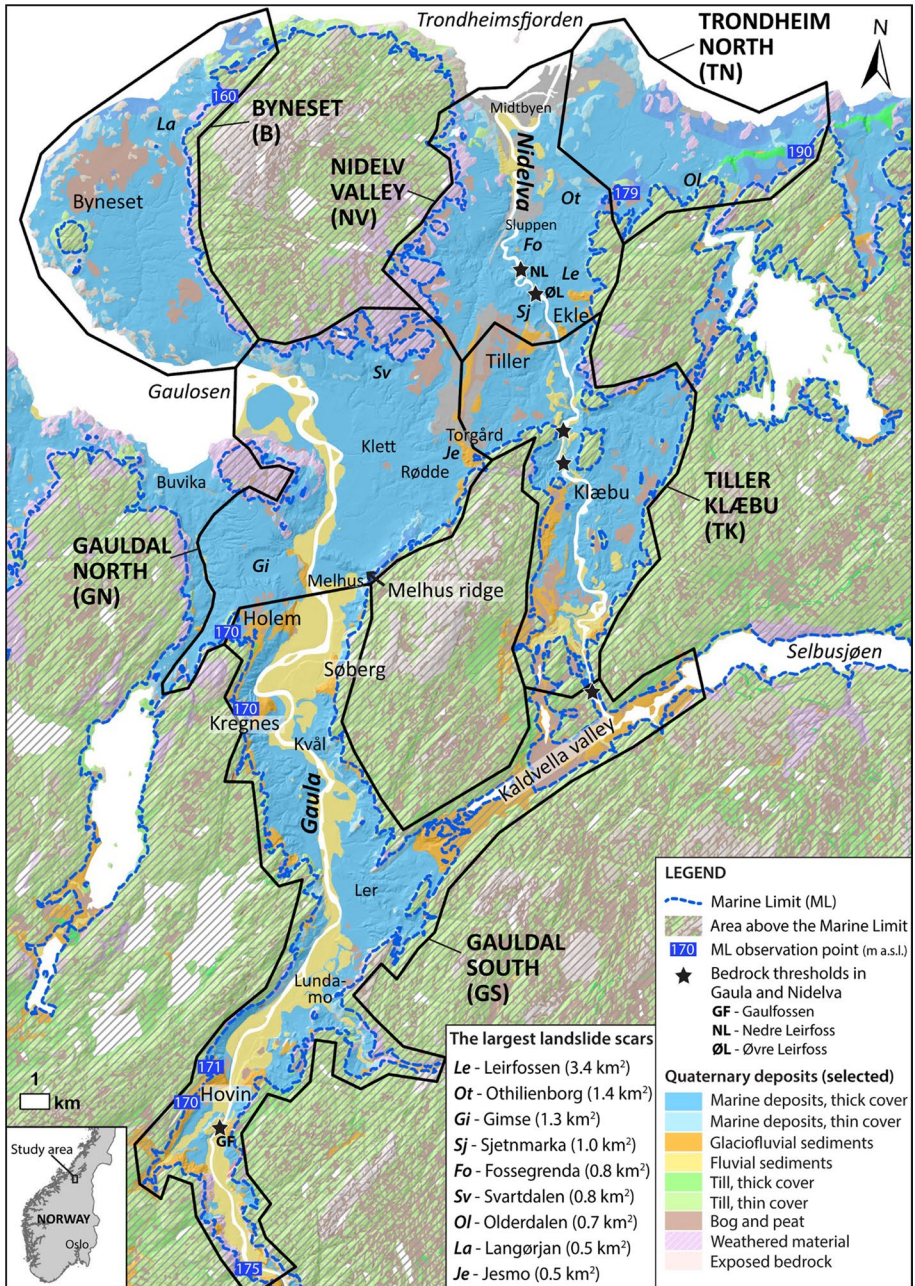


Fig. 1 Quaternary geological map from the study area. The new map parts are the areas below the marine limit. See NGU (2024) for more details on the map

deposits, and here, strong tidal currents probably held fine-grained material in suspension and transported it northwards. Due to this, sedimentation was hindered within the uppermost 20–30 m of the water column and clay deposits are thus only found below this level (Reite 1994).

The glacio-isostatic rebound of the crust following glacier melt caused a fall of relative sea level that was rapid in the beginning of the Holocene and then slowed. The present day rebound of the region is ca 3 mm per year (Reite 1994). A constructed shoreline displacement curve for Trondheim reflects the overall sea-level trend (Fig. 2). This curve can be used for Trondheim and as a guideline for the northernmost part of Gauldal valley, but diversions from the trend are expected to increase southwards.

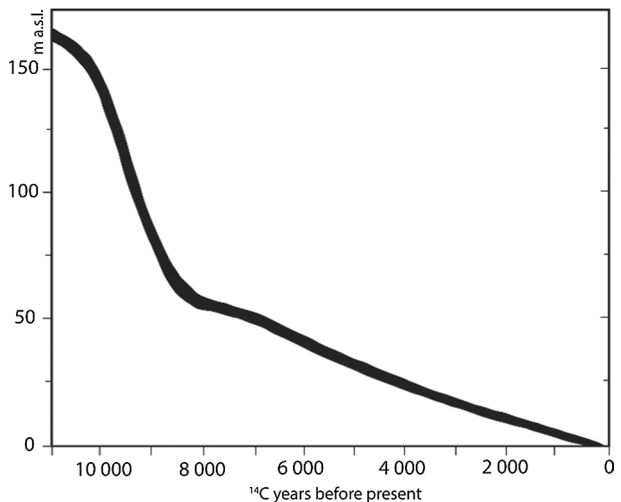
The relative sea level fall caused the emergence of the previously deposited glacial and fjord-marine deposits. The base level lowering led to fluvial erosion of the older deposits, and landslide activity. River plains and fans were constructed at still lower levels while delta progradation shifted gradually northwards. For this reason, several, distinct fluvial and deltaic terraces are preserved along the Gaula and the Nidelva.

4.3 The rivers Nidelva and Gaula

There are two large rivers in the study area: the Nidelva and the Gaula (Fig. 1). The Nidelva comes from Selbusjøen (157 m a.s.l.) and runs through Klæbu and Trondheim into Trondheimsfjorden. The Nidelva has a relatively uniform water discharge, due to the large Selbusjøen reservoir. There are five bedrock thresholds with waterfalls north of Selbusjøen that influence the river course and the base level of erosion (Fig. 1). The mean water discharge is 3193 million m³/year (NVE 2024a). From the outlet of Selbusjøen to the outlet in Trondheimsfjorden there is a height drop of 7–8 m per km.

The Gaula runs through Gauldal into Gaulosen and comes from the mountains south of the study area. The Gaula has large variations in water discharge, but the mean water discharge is 2592 million m³/year (NVE 2024a). The Gaula is regarded as one of Norway's most dangerous flood rivers. A lack of lakes/reservoirs allows the river to respond quickly to heavy rainfall and flooding. During the catastrophic flood in AD 1940, the

Fig. 2 Shoreline displacement curve for Trondheim Centre for the last 11,000 years, mostly based on data from Frosta (Kjemperud 1986) and Verdalsøra (Sveian and Olsen 1984), and dating of shorelines in Trondheim. Modified from Reite et al. (1999)



water level was 14.5 m higher than the low-water level at Gaulfossen, with a discharge of 3060 m³/s (SNL 2024). Gaulfossen is the only bedrock threshold for the Gaula in lower Gauldal (Fig. 1). In the south in the Melhus municipality, the Gaula lies 56 m a.s.l. From this location to the outlet in Gaulosen, there is a height drop of about 2 m per km.

5 Data sets and methods

5.1 LiDAR data, aerial photos, GIS tools

The Quaternary geology and landforms were mapped in ArcGIS (ESRI) from hillshade images based on high-resolution digital elevation models (DEMs) (with point densities 2 and 5) from LiDAR data, provided by the Norwegian Mapping Authority (Kartverket 2024). In addition, topographical maps and aerial vertical photos (orthophotos) were used. Old aerial photos were highly valued, in order to understand the development in areas of urbanization and farming.

For the landslide scars, the edges were drawn as line symbols in ArcGIS, with the landslide outlet gate open. The ravines were drawn as line symbols downstream. Also, ravines without a very sharp v-shaped cross section were drawn—in order to indicate the drainage pattern in the area. Some of the ravines had previously sharper v shapes (seen on old aerial photos), but are today only faintly visible due to agricultural levelling. A few landslides in the study area were known from before, but have during this work been more precisely mapped. The mapping scale for the project was in general 1:20,000, but some of the landforms have a mapping scale of 1:10,000 or better.

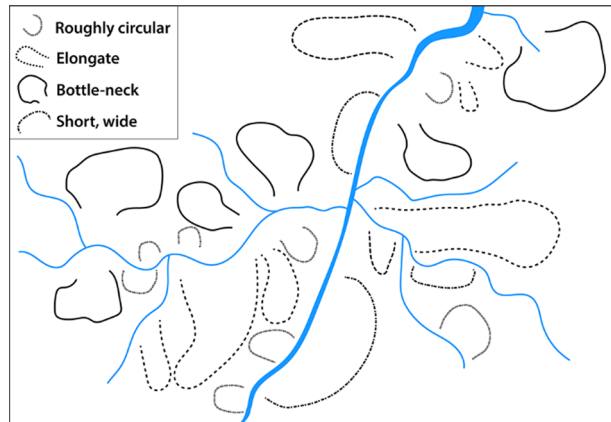
NGU's mapping routine for landslide scars is to draw the backscarps of the landslides, and not necessarily the whole detachment area. Only parts of a scar may be recognized in the terrain. Therefore, the size of the scar may be underestimated. For the analyses, some of these were “repaired” or removed. Most of the scars are very old, and their shapes may have been changed due to erosion, new landslides that interfere with older scars, agricultural levelling and infrastructure construction work. This also means that the landslide mechanism can be difficult to determine.

The mapped landslides in this study were divided into the different shapes presented in Quinn et al. (2011b): “short and wide”, “roughly circular or equidimensional”, “elongate” and “bottle-neck”. “Short and wide” sometimes includes just remains of a scar, not the whole original detachment area that potentially had another shape. Some of the “roughly circular or equidimensional” scars may originally have been “bottle-neck” craters that were later altered. Some “elongate” scars can be difficult to differentiate from ravines with flat and wide bottom. Figure 3 shows examples of these shapes.

Tools in ArcGIS were used to convert landslide line symbols into polygons for area calculation. The detachment areas of the mapped landslides were grouped into the following classes:

- Large landslides: larger than 500,000 m²
- 100,000–499,999 m²
- 30,000–99,999 m²
- Small landslides: less than 30,000 m²

Fig. 3 Examples of the landslide scar shapes



5.2 Field inspection

Field inspections were done in large parts of the study area, in order to map and understand the landscape. The distribution of sediments was studied in sections/cuts in infrastructure construction sites. Samples from about 1 m depth were collected with the use of a hand-held soil probe. Bedrock outcrops were also mapped.

Guzetti et al. (2012) discuss the difficulty of detecting landslides in the field, in particular old landslides. This may be due to the size of the landslide that often is too large to be seen completely in the field. This difficulty is also in part due to the fact that old landslides are often partially or totally covered by forest, and may be partly dismantled by other landslides and erosion processes, and human activity, including agricultural and forest practices. Therefore, the combining of fieldwork with LiDAR data and aerial photos from different years is necessary.

5.3 Data from ground investigations and maps

There is plenty of geotechnical data available in the study area, especially in the urban areas (NADAG 2024). This data have been used to get an overview of sediment types and depth to bedrock. Close to some of the landslides and ravines, soil properties from geotechnical drilling data have been studied in detail. Data from groundwater wells are used for depth to bedrock (GRANADA 2024).

There are over 130 hazard zones for potential landslides in sensitive clay in the study area. The location of the zones, their properties and documentation are provided by the Norwegian Water Resources and Energy Directorate (NVE 2024a, b).

The upgraded Quaternary geological data are included in NGU's superficial deposits database. Geophysical data from seismic, resistivity and ground penetrating radar measurements have been used for subsurface information. Bedrock maps have also been used. All these map views and databases are available from the Geological Survey of Norway (NGU 2024).

Rankka et al. (2004) and Quinn (2009) presented the following factors that influence the development of sensitive clay and triggering of landslides: deposition in a marine environment; leaching of salt; artesian groundwater; high permeability layers within the clay deposit; thickness of clay sediment; presence of limestone bedrock; underlying

coarse-grained material; bedrock topology; catchment areas; three-dimensional effects; stage of river development; height above present sea level; organic soils; temporal factors such as groundwater levels; and mineralogy. The present study outlines and discusses most of these factors.

5.4 Dating of landslide events

The relative age for some of the landslide scars are derived from the shoreline displacement curve, with the assumption that the river size, discharge and average gradient of the main rivers have been approximately the same during the last part of the Holocene. This may of course have changed due to climatic variations.

The most reliable age of a prehistoric landslide event is obtained by dating in situ plant material covered by landslide deposits. Organic material dispersed in landslide deposits will give a maximum age for the event. Radiocarbon ages in the paper are referred to with “years BP”, while calibrated ages are presented as “years BC/AD”, or “calendar years BP”.

6 Results

6.1 Ground conditions and terrain characteristics

The updated Quaternary geological map for the study area below the marine limit (ML) is shown in Fig. 1 (Riiber et al. 2015, Solberg and Riiber 2019, Solberg et al. 2019). Tables 1 and 2 give an overview of some characteristics of the different parts of the study area, with focus on factors important for the development of sensitive clay and the triggering of landslides. Figure 4 gives an impression of the morphology, and Fig. 5 shows the mapped landslide scars and ravines.

The overall gradient of the terrain below ML is less than 5° (Kartverket 2024). A few areas are between 5° and 15°. This is of course apart from the ravine slopes and landslide backscarps that locally are 45° or more. Areas with preserved old seabed are relatively flat.

Based on data from ground investigations (NADAG 2024), quick clay is in general located relatively deep underneath plateaus, and closer to the surface in lower parts of a slope and below ravine bottoms. In ridges, the pore-water pressure measurements often indicate that the ground water level is several metres below the surface, and that there are hydrostatic conditions further down. This is probably a reason why some steep clay slopes do not fail (NGI 2008). At greater depths, and often in the lower parts of the slopes, the pore pressure may be higher than hydrostatic due to large height differences (e.g. NGI 2008).

A general summary of the landscape and ground conditions in the six parts of the study area is presented in the following, see also Figs. 1, 4 and 5, and Tables 1 and 2.

In *Trondheim North (TN)*, the western part of the terrain is gently sloping towards the sea and has very few ravines and landslide scars. However, the submarine areas north of TN show traces of many slides (Lyså et al. 2008). The eastern part has a large moraine ridge and more relief made by ravines and landslides. The area lacks a large and dominating river or stream system, and was less exposed to high sedimentation rates such as in the Nidelv valley. The clay in TN is generally leached, probably downwards from the surface, but also upwards from below due to the relatively shallow bedrock (depth often less than 10 m). However, most quick clay is detected in the eastern part, where

Table 1 Factors influencing the development of quick clay (QC) and triggering of landslides. Based on data from field work and mapping, and from NGU (2024), NADAG (2024), GRANADA (2024), NVE (2024a)

	Trondheim North (TN)	Nidelv Valley (NV)	Tiller Klæbu (TK)	Byneset (B)	Gauldal North (GN)	Gauldal South (GS)
Marine limit (m a.s.l.)	175	175	175–180	160	175	175–180
Area height above present sea level (m)	0–140	0–175	70–180	0–130	0–160	3–180
Number of QC hazard zones	4	37	24	26	17	24
Presence of rivers/ streams/ ravines and the state of the system	<ul style="list-style-type: none"> • No large river. • Few ravines and streams. • Many ravines are partly piped. 	<ul style="list-style-type: none"> • Mature river system (Nidelva). • Erosion protection measures. • Several ravines, the two largest are 4 and 5 km long. 	<ul style="list-style-type: none"> • Mature river system (Nidelva). • Erosion protection measures. • Several ravines, the two largest are both 4.5 km long. 	<ul style="list-style-type: none"> • A young to mature stream system with a lot of branches (Ristbekken). • Erosion protection measures in parts of the system after a landslide in 2012. 	<ul style="list-style-type: none"> • Mature river system (Gaula), probably more mature than the Nidelva. • Erosion protection measures. • Several ravines, the largest is 6.5 km long. 	<ul style="list-style-type: none"> • Mature river system (Gaula), probably more mature than the Nidelva. • Erosion protection measures. • Three small tributary rivers, and several small ravines.
Bedrock types and Main fracturing directions (MFD)	<ul style="list-style-type: none"> • Greenstone and green schist. • MFD: NE-SW. 	<ul style="list-style-type: none"> • Greenstone and green schist; gabbro, locally with diabase intrusions. • MFD: E-W. 	<ul style="list-style-type: none"> • Greenstone and green schist; gabbro, locally with diabase intrusions; conglomerate; greywacke; basalt; sandstone; quartz schist. • MFD: NE-SW. 	<ul style="list-style-type: none"> • Quartz mica schist; chlorite schist; sericite muscovite phyllite with quartz and calcite intrusions. • MFD: E-W. 	<ul style="list-style-type: none"> • Greenstone and green schist; gabbro, locally with diabase intrusions. • MFD: NNE-SSW. 	<ul style="list-style-type: none"> • Greenstone and amphibolite; clay slate, sandstone and limestone; conglomerate, sedimentary breccia; rhyolite, rhyodacite, dacite and keratophyre. • MFD: NE-SW.

Table 1 (continued)

	Trondheim North (TN)	Nidelv Valley (NV)	Tiller Klæbu (TK)	Byneset (B)	Gauldal North (GN)	Gauldal South (GS)
Bedrock topography and depth to bedrock	<ul style="list-style-type: none"> • Bedrock outcrops or thin sediment cover several places, especially along the coast. • Mainly less than 10 m to bedrock, but locally up to 70 m. 	<ul style="list-style-type: none"> • Two bedrock thresholds in the main river. • Bedrock outcrops in the western valley side. • In general great sediment thicknesses: Locally over 100 m down to bedrock, but locally over 100 m down to bedrock, mainly in the middle of the valley. • Undulating, 15–30 m deep buried bedrock threshold below Sluppen and Othilienborg. 	<ul style="list-style-type: none"> • Three bedrock thresholds in the main river. • In general great sediment thicknesses: Locally over 100 m down to bedrock. • Some bedrock outcrops in the central parts of Klæbu. 	<ul style="list-style-type: none"> • Bedrock threshold in the stream's outlet. • Bedrock along the coast. • The central part is a “trough” with up to 120 m depth to bedrock. 	<ul style="list-style-type: none"> • Bedrock lies deep, locally at least 300 m down to bedrock. • Locally bedrock outcrops in valley sides. 	<ul style="list-style-type: none"> • One bedrock threshold in the main river. • Locally buried thresholds. • Up to 300 m depth to bedrock in the valley bottom. • Locally bedrock outcrops in the valley sides.

Table 2 Factors influencing the development of quick clay and triggering of landslides. Based on data from field work and mapping, and from NGU (2024), NADAG (2024), GRANADA (2024)

	Trondheim North (TN)	Nidelv Valley (NV)	Tiller Klæbu (TK)	Byneset (B)	Gauldal North (GN)	Gauldal South (GS)
Layering/permeability	<ul style="list-style-type: none"> Mainly low-sensitive, silty clay in central parts of the area. A moraine ridge in the eastern part. The eastern part also has small glaciofluvial deposits. Locally coarse deposits (till) between clay and bedrock. 	<ul style="list-style-type: none"> Coarse layers in the clay close to glaciofluvial deltas, and close to fluvial deltas on different levels. In the south, probably coarse deposits between clay and bedrock due to large glaciofluvial deltas. 	<ul style="list-style-type: none"> Coarse layers in the clay close to two glaciofluvial and fluvial deltas, and to small coarse deposits from side valleys. Probably coarse deposits between clay and bedrock in several places due to large glaciofluvial deltas and/or till. 	<ul style="list-style-type: none"> Mainly clay, very little coarse layers. Locally coarse deposits (till) between clay and bedrock. 	<ul style="list-style-type: none"> Coarse layers in the clay close to glaciofluvial deltas. Probably coarse deposits between clay and bedrock in several places due to large glaciofluvial deltas and/or till. 	
Artesian groundwater	<ul style="list-style-type: none"> Often hydrostatic conditions. 	<ul style="list-style-type: none"> In general excess pore pressure or artesian conditions in the bottom of the ravines, and negative pore pressure below the top of slopes or the plateaus. 	<ul style="list-style-type: none"> Locally artesian conditions. 	<ul style="list-style-type: none"> Locally artesian conditions. 	<ul style="list-style-type: none"> Often hydrostatic conditions or negative pore pressure due to draining layers in the clay. There may be excess pore pressure or artesian conditions in the slope bottoms. 	
Topography	<ul style="list-style-type: none"> Gently sloping terrain towards the sea. Most of the area is probably old seabed. More relief in the eastern part. 	<ul style="list-style-type: none"> Dominated by many landslide scars and some ravines in the southern part. Some old seabed in the west and the south. 	<ul style="list-style-type: none"> Dominated by many landslide scars and ravines in the central and southern part. Some small areas of old seabed. 	<ul style="list-style-type: none"> Dominated by landslide scars and ravines in the central and southern part. Some areas of old seabed. 	<ul style="list-style-type: none"> The main river has eroded the valley to a high degree, and the valley floor is quite flat. Locally, terraces and old delta plains. Many landslide scars and ravines in the valley sides. Some old seabed in SW and NE. 	<ul style="list-style-type: none"> The main river has eroded the valley to a high degree, and the valley floor is quite flat. Locally, terraces and old delta plains. Very little old seabed left. Some undulating clay areas with numerous landslide scars and ravines.

Table 2 (continued)

	Trondheim North (TN)	Nidelv Valley (NV)	Tiller Klæbu (TK)	Byneset (B)	Gauldal North (GN)	Gauldal South (GS)
Degree of leaching of salt / Presence of quick clay (QC) Data from drilling and resistivity	<ul style="list-style-type: none"> • Most QC in the NE part, but also present elsewhere. 	<ul style="list-style-type: none"> • Much QC in the whole area, but most on the eastern side of the Nidelva. • Often 5–15 m thick QC layer deeper than 5–10 m below the surface. • Sometimes QC in two separate layers. • Locally, 20–30 m thick QC. • QC lies deeper under the plateaus than under the ravine bottoms. 	<ul style="list-style-type: none"> • Much QC in the whole area, and few areas are unaffected by ravines/land-slides. • Often 15–20 m thick QC layer deeper than 15–25 m below the surface. • Sometimes QC in two or three separate layers. • Locally, 30 m thick QC. 	<ul style="list-style-type: none"> • The clay is leached down to or just below the ravine bottoms, with salty clay below. • Often QC from +–10 m depth. 	<ul style="list-style-type: none"> • QC is located at varying depth, and there is a lot of QC in the area (10–30 m thick layers). • In the eastern part, the clay is leached down to or just below the ravine bottoms if the depth to bedrock is large (> 60 m) and the clay more homogeneous. • Where bedrock is shallower, all the clay is in general leached and locally quick. 	<ul style="list-style-type: none"> • In the northern part, the clay is leached to a high degree. • Often 10–30 m thick QC layer deeper than 15–25 m below the surface. • Sometimes QC in two separate layers. • Locally, 50 m thick QC. • In the southern part, 10–20 m thick QC layer deeper than 10–20 m below the surface.

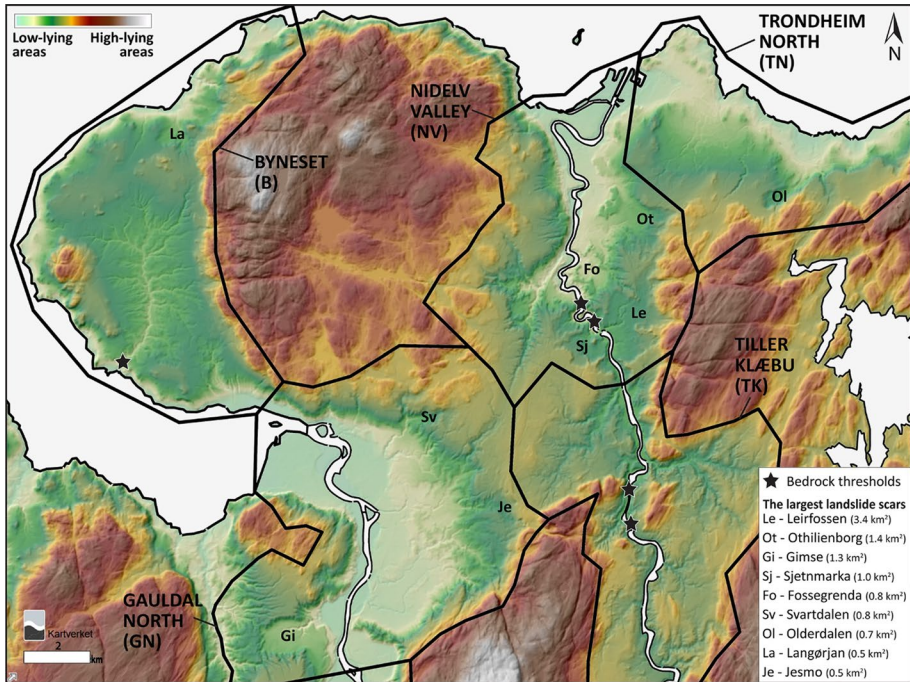


Fig. 4 DEM height plot showing the morphology/terrain of parts of the study area. Laser data from Kartverket (2024)

the gradients are somewhat steeper. Here also, more coarse material is present, in connection to the moraine ridge and in some small glaciofluvial deposits. There is one large landslide in the area: Olderdalen (0.7 km²).

In *Nidelv Valley (NV)*, very little of the old seabed is preserved. The Nidelv river has, together with some large ravine systems, eroded the valley and probably triggered most of the 140 mapped landslides. This area has four of the largest landslides in the entire study area. Most of the clay is probably leached, due to the presence of large glaciofluvial deposits in the southern part. The large landslides are all distal to these deposits, and bedrock is also close in nearby hills or as buried, but relatively shallow, thresholds. In Trondheimsfjorden, in the present day Nidelv delta, distinct, clay-rich beds are common in the fjord-marine deposits (Hansen et al. 2011). These beds are interpreted as originating from at least eight large quick-clay landslides along the Nidelva.

Tiller Klæbu (TK) is the area with the highest number of landslides and ravines, but most of the landslides are less than 30,000 m². Almost all terrain below ML is influenced by erosion and landsliding. The Tiller part is proximal to a large glaciofluvial deposit and is called “the Tiller bay” in Sveian et al. (2007). Here, a delta was deposited early in the Holocene, with sand and gravel layers in the clay. The area is today thoroughly leached and has a large amount of quick clay. Also the Klæbu part has sources of coarse material interfingering the clay, and is surrounded by high bedrock hills.

In *Byneset (B)*, there is a glacially eroded trough in the bedrock up to 120 m deep, probably due to soft slates in central parts of the area, and hard, quartz-rich bedrock along the shore (Solberg et al. 2016). In some parts the old seabed is preserved, but

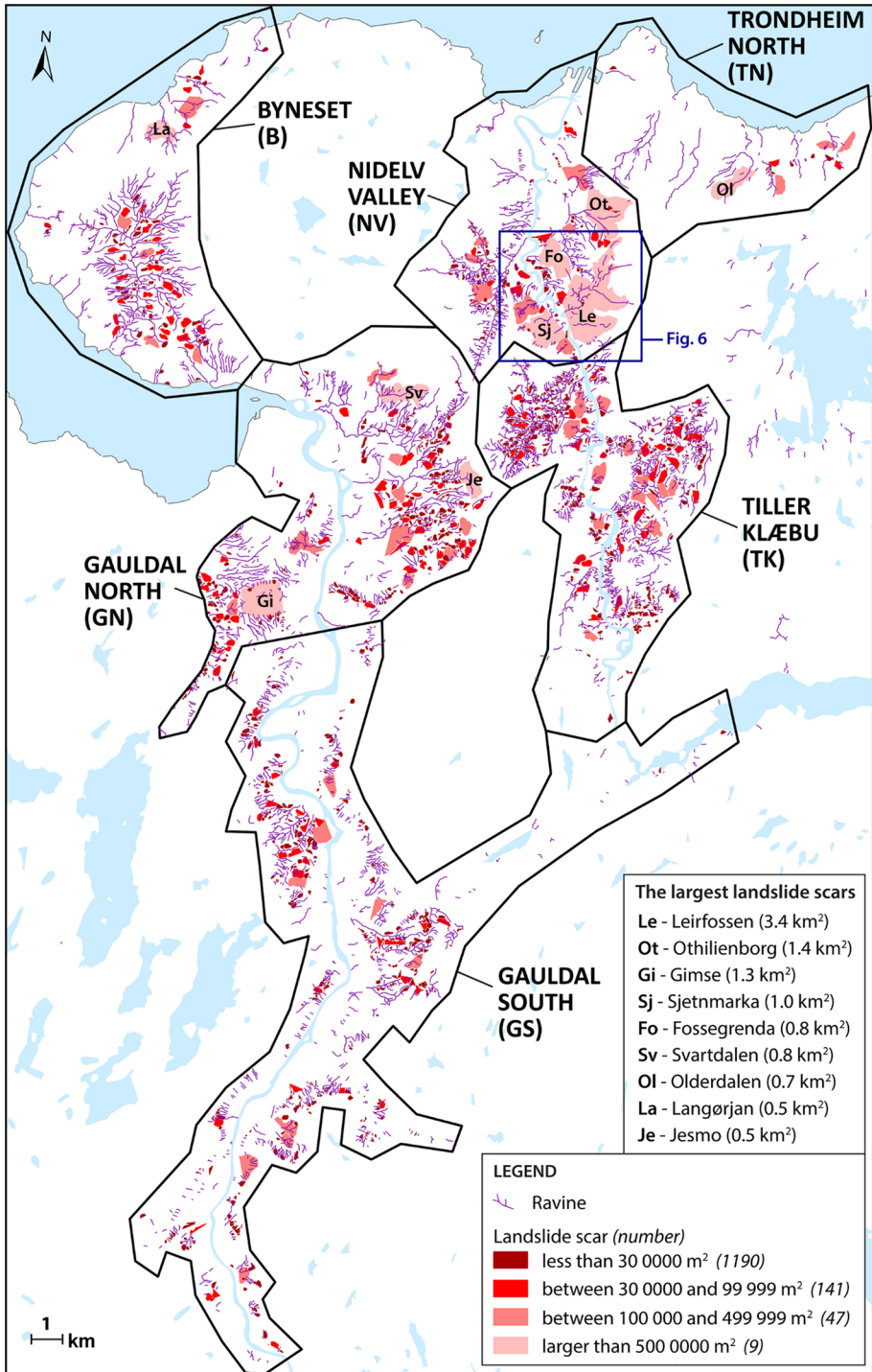


Fig. 5 Distribution of landslide scars and ravines below the marine limit in the study area

Table 3 Number of landslide scars and ravines in the different parts of the study area (total number in italics). The highest number of landslide scars (of different sizes) and ravines in bold

	Trondheim North	Nidelv Valley	Tiller Klæbu	Byneset	Gauldal North	Gauldal South
Number of landslide scars						
Larger than 500,000 m ²	1	4	0	1	3	0
100,000–499,999 m ²	3	7	13	5	10	9
30,000–99,999 m ²	2	11	33	27	40	28
Less than 30,000 m ²	10	118	420	70	263	309
Total number of landslide scars	<i>16</i>	<i>140</i>	<i>466</i>	<i>103</i>	<i>316</i>	<i>346</i>
Total number of ravines/ravine parts	78	571	1198	414	611	854

Table 4 Number of landslides per km² in the different parts of the study area. Note that the extension of the areas includes some sea and/or some areas above ML (see Fig. 1)

	Trondheim North	Nidelv Valley	Tiller Klæbu	Byneset	Gauldal North	Gauldal South
Area (km ²)	39	51	57	56	72	124
Number of landslides	16	140	466	103	316	346
Number of landslides / km ²	0.4	2.7	8.2	1.8	4.4	2.8

centrally the area is dominated by ravines and landslide scars, revealed as a dendritic pattern (Figs. 4 and 5). The outlet of the main stream is on bedrock, which acts as the erosional basis. This controls the depth of the ravines and the landslides, which are relatively shallow. The sediments are mainly marine clay deposits, with very few coarse layers.

In *Gauldal* (*GS*, *GN*), the river Gaula has eroded more or less the whole valley floor. Large parts of the valley bottom are flat with old river terraces. However, some localities are left with undulating clay terrain. A large number of ravines and landslide scars are mapped in these areas and in the valley sides. Coarse layers in the clay are located close to glaciofluvial deltas. In general, the bedrock lies deep in the middle of the valley, and is very steep in the valley sides. The northern part has three of the largest landslides in the entire study area.

6.2 Landslide scars and ravines

Almost 1400 landslide scars and 800 km of ravines are mapped in the study area. 86% of the landslides have an area of less than 30,000 m², and nine landslides are larger than 500,000 m² (Fig. 5, Table 3). Table 4 shows the number of landslides per km² in the different parts of the study area.

Table 5 gives the number of general landslide shapes in the different parts of the study area, and Fig. 3 shows examples of the shapes in the study area. The group “roughly

Table 5 Number of landslide shapes in the different parts of the study area, based on classification in Quinn et al. (2011b). The highest number of landslide scars of different shapes in bold

Shape of crater	Trondheim North	Nidelv Valley	Tiller Klæbu	Byneset	Gauldal North	Gauldal South	Sum
Short, wide	7	33	87	18	57	45	247
Roughly circular or equidimensional	4	67	206	43	146	159	625
Elongate	4	17	76	22	46	71	236
Bottle-neck	1	23	97	20	67	71	279

circular or equidimensional” dominates, and about half of the landslides less than 30,000 m² have this shape. These are likely formed by rotational slides, but may also be retrogressive slides. The latter is the main landslide mechanism for the bottle-neck-shaped scars, and possibly also for the elongate craters. For the landslides larger than 100,000 m², a combination of retrogressive and flake sliding is likely. Flake sliding may have formed the short and wide scars. This also applies to lateral spreads, but there are few, if any, traces of this landslide mechanism in the area. However, traces of lateral spreads may have been partly erased due to area development or agricultural levelling.

The age of most scars are unknown. In the study area about 60 clay landslides are included in NSDB (NSDB 2024). In addition, about 70 landslides below ML are classified as “unspecified landslides in soil”. A tentative age estimate may be based on the scars position in the terrain, comparing with the shoreline displacement and the level of close-lying river/stream. This was done for some of the largest landslides, see below and Table 6.

6.3 The largest landslides

The largest landslides, larger than 500,000 m², are located in four of the study area parts. The landslide mechanism was retrogression, most likely in combination with translational sliding. It is possible that some of the landslides, such as Othilienborg, Sjetnmarka and Leirfossen, occurred in more than one step, based on different levels in, and the shape of, the scars. The large landslides are all prehistoric, except for Jesmo that potentially is from around 1650 (Table 6).

Sjetnmarka (NV) has two distinct levels in the scar bottom (ca 93 m a.s.l. and ca 106 m a.s.l.). The back-slopes are up to 40 m high. In the outlet gate of the landslides there is a hill, Storhaugen (Figs. 6 and 7). The top is relatively flat with a weak gradient towards the north, and is 10–11 m lower than the Tiller area to the south and west. Based on drillings, most of this hill consists of sediments, i.e. layered clay and sand/gravel (Rambøll 2012). Bedrock in the river just north of Storhaugen continues with a peak underneath the hill (Hillestad 1974). There is also shallow bedrock (0–6 m depth) in parts of the landslide scar, and the bedrock reaches gradually higher elevation towards the south (NADAG 2024). The deposits of Storhaugen were probably part of the Tiller-Ekle glaciofluvial delta before the landsliding. Field inspection shows that there are groundwater springs in the slope foot of the scar, and one of them has acted as a well for several households. In a drilling Sand (1999) discovered peat at ca 3 m depth, just above bedrock. This was in the foot slope of the upper western part of the scar (Fig. 6). ¹⁴C-dating of the humus gave the age 3640 ± 85

Table 6 The nine largest landslides in the study area

Name	Study area	Area (km ²)	Potential ages	Close-lying glaciofluvial delta	Close-lying bedrock hills	Potential main triggering factor(s)
Leirfossen	NV	3.4	Early Holocene (Sand 1999). Probably more than one step	x	x	River erosion
Othilienborg	NV	1.4	Several stages, the latest maybe 655 years BP (Sand 1999)		x	River or stream erosion
Gimse	GN	1.3	Younger than ca 6500 years BP (landslide gate at 55–56 m a.s.l.)	x		River erosion
Sjetmarka	NV	1.0	First stage in early Holocene, second stage ca 3600 years BP (Sand 1999)	x		First stage: river erosion, second stage: high pore-water pressure
Fossegrenda	NV	0.8	Younger than ca 4000 years BP (landslide gate at 30 m a.s.l.)	x		River erosion
Svardalen	GN	0.8	Prehistoric		x	Stream erosion
Olderdalen	TN	0.7	Younger than 7000 years BP (landslide gate at ca 50 m a.s.l.)		x	Coastal erosion
Langørjan	B	0.5	Younger than 8500 years BP (landslide gate at ca 60 m a.s.l.)		x	Coastal erosion
Jesmo	GN	0.5	AD 1650 (Grønlie 1953)	x		High pore-water pressure, stream erosion

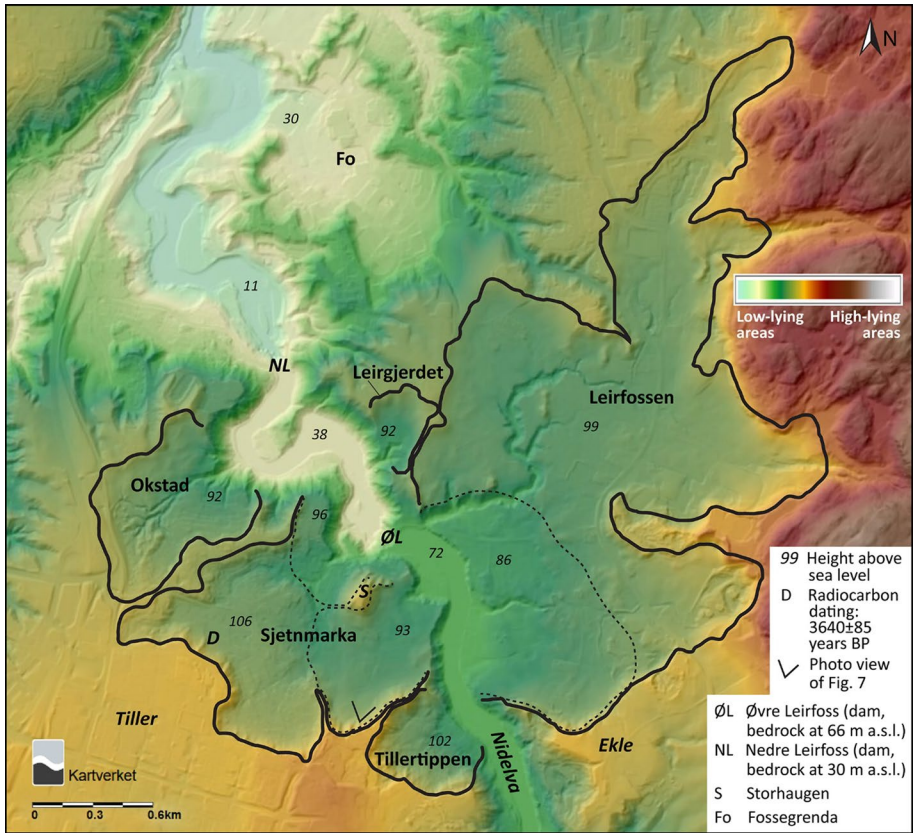


Fig. 6 DEM height plot showing the morphology/terrain of the landslide scars around Øvre Leirfoss (ØL) and Nedre Leirfoss (NL) in Nidelv Valley. The edges of the scars are drawn, with open landslide outlet gates. Dashed lines indicate landslide parts that may have occurred separately. Laser data from Kartverket (2024)



Fig. 7 View northwards from the southern backscarp of Sjetnmarka landslide (see Fig. 6 for photo view). The Leirfossen landslide scar is on the other side of the Nidelva. Øvre Leirfoss (bedrock threshold) is on the other side of Storhaugen. Note the sandy sediments in the foreground, which is part of the Tiller-Ekle glaciofluvial deposit (Fig. 1). Photo: IL Solberg

years BP (cal. 2130–1895 BC). Above the peat there was silty clay, probably deposits from surficial slides in the slope and/or a filling.

The *Leirfossen (NV)* landslide is the largest preserved scar in the Nidelv river system, and it is over twice as big as the second largest (Othilienborg) (Figs. 5, 6 and 7). It has up to 40 m high back-slopes. The lowest and central parts of the scar bottom are, respectively, ca 86 m and ca 99 m a.s.l. The volume of the scar is about 75 million m³ (L'Heureux 2012). The scar lies opposite the Sjetnmarka landslide, and both landslides lie close to the Tiller-Ekle glaciofluvial deposit (Fig. 1) and have outlets towards the Nidelva.

The *Gimse (GN)* landslide is the largest preserved scar in Gauldal (Fig. 5). It has quite a flat bottom with up to 50–60 m high back-slopes. The volume of the scar is about 55 million m³. The outlet gate of the scar is located about 55–56 m above the present level of the Gaula. If the Gaula triggered the landslide, it may be younger than 6500 years BP, taking into account some landslide deposits in the scar, the river gradient today, and the shoreline displacement curve (Fig. 2).

The *Jesmo (GN)* landslide is located close to and west of the Tiller-Ekle glaciofluvial deposit. Below the coarse sediments there is clay, and in this sediment boundary in the eastern slope of the scar there is a groundwater spring with relatively high discharge (Grønlie 1953). An excavation in deposits close to the Gaula showed landslide deposits from at least two events that are younger than 1000 years, and the one from AD 1650 may be the Jesmo landslide (Reite et al. 1999; Grønlie 1953).

The *Langørjan (B)* and *Olderdalen (TN)* landslides have outlet gates towards the sea. The height of the landslide gates may be used to estimate a maximum age for the landslides. They were likely terrestrial, since they do not seem to have been reworked by wave processes during the postglacial regression (Lyså et al. 2008). The Langørjan gate is ca 60 m a.s.l. and the Olderdalen gate is ca 50 m a.s.l. This gives the maximum ages of 8500 years BP and 7000 years BP, respectively.

For Svartdalen, Langørjan, Olderdalen and Leirfossen, bedrock hills nearby may have been important to increase the leaching and quick-clay development. Underneath the Sluppen and Othilienborg areas there is a buried bedrock threshold (Tønnesen 1996) that may have increased the leaching of the clay above. In the Gimse, Leirfossen, Sjetnmarka and Jesmo scars, with their locations distal to ice-marginal deltas at Hølem (Gi) and Tiller-Ekle (Le, Sj, Je), marine clay can be found interfingering with coarse layers facilitating quick-clay development (Fig. 1, Table 6).

For four of the large landslides, erosion in the main river was the likely trigger (Table 6). However, high pore-water pressure may have influenced the stability for most of the large landslides. In addition, some events may have been triggered by earthquakes (Hansen et al. 2011).

7 Discussion

7.1 Importance of stratigraphy and bedrock topography for quick-clay development

There are large variations in the stratigraphy of the study area. One important factor is a location's proximity to past sources of coarse material, such as glaciofluvial or fluvial deltas. Such areas have several coarse layers that interfinger clay, often below a top layer of more homogeneous clay. Distal to a delta, the coarse layers get thinner and less frequent.

The amount of and/or the thicknesses of silt/sand/gravel layers within the clay will influence the local groundwater movement. Coarse layers pinching out in the clay often lead to an increased pore-water pressure and enhanced leaching of the clay. On the other hand, thick and frequent layers of sand and gravel drain the slope effectively if the layers reach surface contact in both ends (i.e. upslope and downslope, see Fig. 8). A number of the landslides in the NV, TK, GN and GS areas are located close or very close to glaciofluvial or fluvial deltas.

In clay deposits with very thin and few silt or sand layers, the quick-clay development can be slow. For such deposits, quick clay may constitute thin layers. In Buvika, such thin quick-clay layers were the failure planes of large flake-type landslides, dated to be maximum 1.5–2.5 thousand calendar years BP (west of GN, Fig. 1) (Solberg et al. 2008a, b). Here, continued leaching resulted in a thicker quick-clay layer, and scars from younger events are present in the flake-slide deposits. A similar situation was revealed in large road cuttings in the Klett area (GN, Fig. 1) (Solberg and Hansen 2017). Here, thick, not completely remoulded deposits from several landslide events were detected, and newer landslides have occurred in these deposits.

Figure 8 summarizes potential preconditions for quick-clay development with regard to coarse layers interbedded with clay. The figure is only a guideline, and there are exceptions and transitional forms.

Areas without coarse deposits nearby have very few sand/gravel layers in the clay, as shown in Byneset. Here, studies showed an increase in salt content with depth, potentially caused by enrichment of ions due to leaching downwards (Solberg et al. 2016). There is much less leaching below the ravine bottom, probably due to the relatively impermeable sediments and large depths to bedrock in central Byneset. According to Carson and Geertsema (2002), a thick clay deposit will take some time to leach, even when buried aquifers exist. Also, the massive clay deposit should be more prone to flow-sliding where the underlying bedrock or aquifer is not too far below the valley floor level. However, the landslides

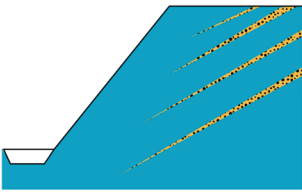
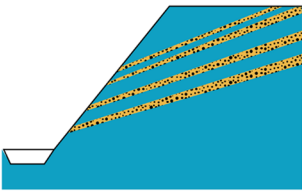
Stratigraphy and geometry	Dominating groundwater process	Relative rate of quick-clay development	Possible landslide type or development of other landscape elements
Thin/thick coarse layers that pinch out in clay, fed by surface water (surface contact layers)	 <p>Pore pressure build-up. Leaching of clay.</p>	Slowly with thin/few coarse layers, faster with thick/many coarse layers	<p>Flake landslide if thin layer of quick clay is remoulded.</p> <p>Retrogressive landslide if thick layer of quick clay is remoulded.</p>
Thin/thick coarse layers with surface contact in both ends	 <p>Draining of slope. Degree of leaching depending on number of layers and their thicknesses.</p>	Moderate to fast	<p>Faster ravine development.</p> <p>Moderate sized landslides occur between ravines.</p> <p>Often large landslides close to deltaic deposits.</p>

Fig. 8 Conceptual diagram of a slope profile showing possible preconditions for development of quick clay in areas with coarse-grained layers and resulting landscape elements. There will be transitional forms and exceptions. Figure modified from Solberg (2007)

in the study areas occur both in areas of thick overburden, and where bedrock is shallow. The leaching, therefore, seems to be linked to both geological prerequisites, such as depth to bedrock and stratigraphy, and the landscape development, governed by base level of erosion and river migration. In the study area, the quick clay is generally located somewhat closer to the surface in Trondheim (5–10 m) (TN, NV, B, Tiller) than in Gauldal (GN, GS) and Klæbu (15–20 m). This is probably connected to the sediment thicknesses and erosion depth of ravines and rivers.

The topography of the bedrock, both covered and uncovered by sediments, will influence the quick-clay development. A steep, high hill of fractured bedrock will supply the clay deposits in lower terrain with water and give high artesian pressure. The present study is in accordance with a study in Quebec, Canada that shows that strong hydraulic gradients associated with high pore pressure accelerate the leaching of salt, and also directly trigger mass movement (Carson 1981).

Several localities in the study area have during the last 20 years been investigated using resistivity measurements (e.g. Solberg et al. (2008a, b, Buvika), (2012, Rødde), (2014, Melhus), (2016, Byneset); Sandven and Solberg (2014, Kaldvella valley)). The resistivity data indicate the distribution of leached and unleached clay, coarse sediments and bedrock. The clay properties are verified by borehole data. A general result from these investigations is that in clay terrain with multiple landslide scars and ravines, almost all the clay above the river level is leached, and that intact, salt marine clay often occurs as pockets or layers below the stream/ravine level. The distribution of quick clay is linked to the groundwater drainage patterns and gradients. Shallow depths to bedrock may lead to upward groundwater flow and significant leaching, which locally can explain the presence of quick clay below stream/ravine levels. This is also documented in other studies (e.g. Lebus et al. 1983; Janbu et al. 1993; Rankka et al. 2004). In areas where the bedrock is at greater depths and/or the clay is relatively homogenous, leaching and quick-clay development mainly take place downwards and laterally, e.g. in and between river/ravine slopes (Fig. 9).

7.2 Landslides in marine clay deposits

The maximum size of large landslides in the study area is not uniquely positively correlated with the size of the drainage feature, as was the case in the study by Quinn (2009). Five of the largest landslides probably had outlets in the main rivers, two in small streams and two in the sea. The topography in the study area, with the narrow bedrock-confined valleys, is quite different from the large and in general gentle clay plains of the Champlain sea area in Canada. Quinn et al. (2011a) stated that landslides terminate before reaching

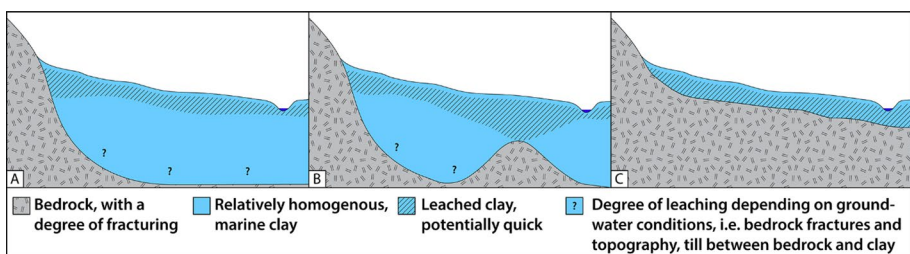


Fig. 9 Principle drawing of leaching of relatively homogenous marine clay, with regard to bedrock's depth, fracturing and topography

a reverse break in slope, such as a ravine or an adjacent, older landslide scar. This seems to be the case in the study area. However, some landslides had sliding plane below older scars, as also shown in Canada by Geertsema et al. (2006). There is a tendency for scars to occur in clusters, as also documented in Penna and Solberg (2022).

The length of the retrogression, or the size of the detachment area, is, in addition to restrictive topographical conditions, limited by the presence of thick deposits of sand/gravel or non-sensitive clay that act as local subsurface barriers. A barrier must however be large enough to remain stable, even if the support disappears during a landslide. Mapping of thick coarse-grained deposits or bedrock will help to classify areas as relatively stable. Geophysical and geotechnical investigations are tools for evaluation of such barriers (e.g. Solberg et al. 2008a, b; Solberg et al. 2016). In the study area, six of the largest landslides and at least half of the second largest landslides occurred close to bedrock or coarse sediments that limited retrogression.

In the Nidelv Valley study area, some of the levels of the landslide scars are clearly connected to the erosional bases. For instance, the Leirfossen and Sjetnmarka landslides are located upstream of a bedrock threshold (Fig. 6). According to the location and height in the terrain, the first step(s) of the landslides probably occurred very early in the Holocene (Fig. 6, Table 6). The main river eroded through the Tiller-Ekle glaciofluvial deposit, which led to high and steep slopes with a lowered groundwater level. These were probably favourable preconditions for the landslides. Sand (1999) discusses these conditions, and if it is possible that the clay became quick so early after the rebound of the sediments. Despite the consolidating load of glaciofluvial deposits, the underlying clay may have been soft and with little shear strength. This made it vulnerable to sliding when the river cut the deposit and steepened the slopes. Some of the other scars in the vicinity have landslide gates at similar heights as Sjetnmarka and Leirfossen, and may have been triggered in the same period of time (Fig. 6).

Large parts of the valley fill deposits in the Gauldal valley have been removed since deglaciation and the river has meandered and/or changed its course many times. Together with landslide activity, the river has deposited and eroded sediments more or less over the whole valley width. Numerous landslides and flood events have added to the complexity. It is probable that traces of landslides have been removed by erosion and landsliding to a large degree.

Most of the landslides in the study area have an outlet towards existing or abandoned watercourses. Some of the landslides have one or more ravines in the scar bottom, a few of these continue behind the backscarp. Usually, landslides occur between ravines and do not remove them (e.g. Lebus et al. 1983; Geertsema and L'Heureux 2014). However, this depends on the depth of the sliding plane compared to the depth of the ravine. In the 2020 Gjerdrum landslide event, five small ravines were part of the detachment area (Ryan et al. 2021). Ravines often form during the draining of scars after an event, but may also be an indicator of the groundwater and draining conditions in the surrounding sediments.

7.3 Triggering of landslides

The rapid glacio-isostatic rebound, especially during the first part of the Holocene, can be seen as an important underlying cause of landslides, as also emphasized in Lyså et al. (2008). As the sea level fell, excess pore pressure, in combination with gravitational processes and groundwater flow, led to river and ravine downcutting of the terrain.

River and stream erosion that leads to undercutting and slope failure is the most common natural landslide trigger in marine clays in Norway. Erosion in the slope foot in ravines, streams and rivers is the likely trigger of most of the landslides in the study area. E.g. almost all the mapped landslide scars in Byneset have outlets towards a ravine. These landslides are not very deep and are controlled by the ravine/stream level, i.e. the erosion base level. This may be a reason for the few landslides in TN, since there are few streams in this area.

The landslides Sjetnmarka and Jesmo have strong groundwater springs in their backscarps, indicating high pore-water pressures in the deposits. This probably intensified the quick-clay development, but may also have been a triggering factor in combination with erosion.

Potential triggering factors for landslides close to the shore are wave erosion and/or submarine landslides that propagate landwards. This may have been the case for the Langørjan and Olderdalen landslides.

Landslide records from several localities in Trondheimsfjorden indicate that landslide events at ca 8000, 3500, 1700 and 400 calendar years BP could have been triggered by earthquake activity (Bøe et al. 2003; Hansen et al. 2011). In Canada, Demers et al. (2017) document that the largest landslides in the Quebec area are associated with historical and prehistorical earthquakes.

7.4 Landslide deposits and mobility

Landslide debris is not always easily recognized in the terrain. As shown above, quick-clay landslides do not just occur in “untouched” sediments from the ice age or deglaciation, but may also occur in redeposited landslide debris that was not completely quick or remoulded in the first event. This makes it more difficult to outline the landslide history and the landscape development. Large, well-exposed sections revealing structures and layers in the deposits help the interpretation. In addition, geotechnical and geophysical data, LiDAR data and aerial photos may be useful for the interpretation of landslide deposits.

The mobility, i.e. the escape of debris during a landslide, is partly dependent on the surrounding terrain, as also discussed by Carson and Lajoie (1981) and Geertsema and L’Heureux (2014). In narrow ravine valleys, and especially if the landslide occurred perpendicular to the ravine, the debris often decelerates quickly. The speed of the deceleration is influenced by the debris’ viscosity or degree of remoulding, and the amount of quick clay present in the deposit. If a large amount of debris remains in the scar and is hindered from escaping, this may prevent further retrogression.

Remoulded landslide debris that escapes into a narrow ravine valley may also flow upstream in tributary ravines, as was the case for a landslide in Byneset in 2012 (Solberg et al. 2016). Here, the run-out distance reached 1 km downstream of the landslide gate and dammed the nearby tributary ravines. Damming can lead to changed watercourses and erosion in new parts of the slopes.

Debris from a small landslide or rotational slide may be deposited just outside the landslide outlet gate. In some cases, the river or stream erodes these deposits and make the area vulnerable to new landslides. This was the case in Målselv, Troms, when a 3500 m² landslide in 2001 removed a ca 600 m² scar from 2000 (Eilertsen et al. 2008). This shows that the debris from a landslide in clay can be eroded relatively quickly, as also shown from other events in Norway (L’Heureux 2012).

A large outlet area, for example, a river, the sea, or a wide valley such as Gauldal, allows the debris to escape more easily from the scar. This also facilitates further landslide propagation if other necessary conditions are present. In such cases, the run-out distances may be large, as in the Rissa landslide in 1978 (L'Heureux et al. 2012). However, remoulded quick clay may follow the river and be deposited many kilometres from the detachment area, as shown in the Nidelv valley by Hansen et al. (2011).

7.5 Ravine development

In general, ravine development follows the incision of the main rivers in the study areas. Almost all the main ravines terminate in river valleys, which also control the level of incision. Groundwater and surface erosion often play an important role in the formation of ravines. Thick and frequent layers of sand and gravel drain a slope, leading to seepage erosion, especially if many of the layers reach surface contact in both ends (Fig. 8). Seepage erosion in thick coarse layers also leads to vertical settlements in the ravine head, which occasionally can be difficult to separate from landslide scars (Solberg et al. 2007). In addition to landslide scars and slope failures, surficial slides or soil creep in different levels of the slopes are common in the ravine slopes, due to groundwater, surface and stream erosion. The surface erosion results in overturned trees, and the lack of vegetation cover may accelerate the erosion.

In Gauldal North, in the slope from Hølem towards Buvika, there is extensive ravine formation in the distal western part of the glaciofluvial deposit (Figs. 1 and 5). The coarse material interfingering the clay constitutes a stratigraphy that facilitated ravine erosion during the glacio-isostatic rebound (Solberg et al. 2007). Most of the landslide scars in this area seem to be connected to the ravine development, and there are few large landslides with outlets towards Buvika. The distance between the ravines is small, which reduces the probability for large slides since landslides often are restricted laterally by deep ravines. This is in accordance with Geertsema and L'Heureux (2014), who present three ways ravines act as barriers for extensive retrogression. The first way is the reduced lateral earth pressure due to the negative shape of the terrain; the second is the thick dry crust clay that develops between the ravines from several sides; and the third way is the lowering of the groundwater table.

The Tiller Klæbu area has the highest number of ravines and of landslide scars less than 30,000 m², and also the highest number of landslides per km². Both areas are confined, Klæbu by bedrock and Tiller by the “Tiller bay”. There are a large amount of coarse layers in the clay. The course of the Nidelva has, in this area, not varied much in the Holocene (Sveian et al. 2007), which has preserved the ravines and scars. This is in contrast to Gauldal where the river has migrated much, and where large amounts of sediments and traces of landslides and ravines are removed by the meandering and course-changing Gaula river (Solberg and Hansen *subm*).

7.6 Landslide hazard assessment

For the development of landslide hazard assessment, it is important to use all available data on ground conditions combined with detailed geological knowledge of a region. This will give a better overview of the landscape and help the interpretation of its further development. In addition, landslide inventory maps with statistical analyses of the occurrences of landslide scars and morphological parameters may help quantify landslide activity and

spread potential. This is important information with regard to hazard mapping, as also emphasized by e.g. Quinn et al. (2011a), Demers et al. (2017), Ryan et al. (2022) and Penna and Solberg (2022).

8 Conclusions

The possibility for detailed Quaternary geological mapping has increased considerably after high-resolution terrain models became available. Large data sets of landslide scars and ravines can be used together with other data sets for better understanding of geology, ground conditions and landscape development. Also, statistical analyses and interpretation of large data sets can be used as part of the work to further develop the methodology for susceptibility and hazard mapping.

The landscape of the study area has experienced dramatic changes since the last deglaciation due to the glacio-isostatic rebound and the following quick-clay development, rivers and streams downcutting, ravine development and landsliding. The size, behaviour and erosional potential of the main river and smaller streams influence the landscape development to a high degree.

Quick clay is located in all parts of the study area. The leaching of clay seems to be linked to geological prerequisites, such as depth to bedrock and stratigraphy, and to the landscape development, governed by base level of erosion and river migration.

In homogenous clay where the bedrock is at great depths, leaching and quick-clay development mainly take place downwards and laterally, down to or just below the ravine/stream level.

Shallow depths to bedrock may lead to upward groundwater flow. This, together with downwards and laterally leaching of the clay deposit, can result in large amounts quick clay.

Clay deposits close to glaciofluvial or fluvial deltas often have layers of silt, sand and gravel. This has intensified the leaching process in the clay, and is sometimes connected with high pore-water pressures.

All the largest landslides in the study area are located close to bedrock and/or to coarse deposits.

It is important to outline the local conditions of areas prone to quick-clay landslides in order to understand further landscape development. For this purpose, geological, geomorphological, geotechnical, geophysical and hydrogeological data should be combined. For the study area, some general characteristics are outlined below, which may be transferable to other areas of similar geological conditions:

8.1 Narrow river valley (Nidelv valley (NV and TK))

- Relatively high sedimentation rates during the deglaciation.
- Large glaciofluvial deposits.
- Thick marine clay deposits, and large amounts of quick clay.
- Relatively high relief in the marine deposits.
- Relatively stable river course, partly due to several bedrock thresholds.
- Landslides: ca 600, almost 90% are less than 30,000 m². Four large landslides.

8.2 Wide river valley (Gauldal valley (GS, GN))

- High sedimentation rates during the deglaciation.
- Large glaciofluvial deposits.
- Thick marine clay deposits, and a lot of quick clay.
- Low relief in the central part, somewhat higher in the marine deposits in the valley sides.
- Meandering river.
- Few bedrock thresholds.
- Landslides: ca 660, ca 86% are less than 30,000 m². Three large landslides.

8.3 “Trough-shaped” area (Byneset (B))

- Moderate sedimentation rates during the deglaciation.
- Thick marine deposits surrounded by bedrock outcrops.
- Quick clay in the upper parts of the clay deposits.
- Some old seabed preserved.
- Relatively low relief in the marine deposits.
- Dendritic ravine pattern.
- Landslides: ca 100, ca 68% are less than 30,000 m². One large landslide.

8.4 Coastal area (Trondheim North (TN))

- Relatively low sedimentation rates during the deglaciation.
- Mainly thin marine deposits over bedrock. Some quick-clay deposits.
- Large areas of old seabed preserved.
- Low relief in the marine deposits.
- Few streams and ravines.
- Landslides: 16, ca 63% are less than 30,000 m². One large landslide.

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References

- Bøe R, Rise L, Blikra LH, Longva O, Eide A (2003) Holocene mass movements in Trondheimsfjorden, Central Norway. *Norw J Geol* 83:3–22
- Carson MA (1981) Influence of porefluid salinity on instability of sensitive marine clays: a new approach to an old problem. *Earth Surf Process Landf* 6:499–515
- Carson MA, Geertsema M (2002) Mapping in the interpretation and risk assessment of flowslides. In: Bobrowsky PT (ed) *Geoenvironmental mapping; methods, theory and practice*. AA Balkema, Lisse, Netherlands, pp 667–696
- Carson MA, Lajoie G (1981) Some constraints on the severity of landslide penetration in sensitive deposits. *Geogr Phys Quat* XXXV:301–316
- Chaloupsky J (1977) Bedrock map Hølanda 1521-2, M 1:50 000. Geological Survey of Norway
- Cruden DM, Varnes DJ (1996) *Landslide types and processes*. Transportation Research Board, U.S. Natl Acad Sci 247:36–75
- Demers D, Robitaille D, Lavoie A, Paradis S, Fortin A, Ouellet D (2017) The use of LiDAR airborne data for retrogressive landslides inventory in sensitive clays, Québec, Canada. In: Thakur V, L'Heureux JS, Locat A (eds) *Landslides in sensitive clays: from research to implementation*. Advances in natural and technological hazards research 46. Springer. <https://doi.org/10.1007/978-3-319-56487-6>
- Eilertsen RS, Hansen L, Bargel TH, Solberg IL (2008) Clay slides in the Målselv valley, northern Norway: characteristics, occurrence, and triggering mechanisms. *Geomorphology* 93(3–4):548–562
- Foster RH, Heiberg S (1971) Erosion studies in a marine clay deposit at Romerike, Norway. *Geotech Inst, Norway*, p 88
- Gasser D, Svendby K, Solli A, Slagstad T (2018) Bedrock map Orkanger 1521-1, M 1:50 000. Geological Survey of Norway
- Geertsema M, L'Heureux JS (2014) Controls on the dimensions of landslides in sensitive clays. In: L'Heureux JS, Locat A, Leroueil S, Demers D, Locat J (eds) *Landslides in sensitive clays: from geosciences to risk management*. Advances in natural and technological hazards research 36. Springer. <https://doi.org/10.1007/978-94-007-7079-9>
- Geertsema M, Schwab JW (1997) Retrogressive flowslides in the Terrace–Kitimat, British Columbia area: from early post-deglaciation to present - and implications for future slides. In: *Proceedings of the 11th Vancouver geotechnical society symposium*. pp 115–133
- Geertsema M, Cruden, DM, Schwab JW (2006) A large rapid landslide in sensitive glaciomarine sediments at Mink Creek, northwestern British Columbia, Canada. *Eng Geol* 83(1–3):36–63
- GRANADA (2024) National groundwater database. Available from https://geo.ngu.no/kart/granada_mobil/. Accessed Feb 2024
- Grønlie A (1953) *Leinstrand i den aller eldste tida*. Johan Christiansens boktrykkeri, Trondheim (**in Norwegian**)
- Guzzetti F, Mondini AC, Cardinali M, Fiorucci F, Santangelo M, Chang KT (2012) Landslide inventory maps: new tools for an old problem. *Earth Sci Rev* 112:42–66
- Hansen L, Eilertsen RS, Solberg IL, Rokoengen K (2007a) Stratigraphic evaluation of a Holocene clay-slide in northern Norway. *Landslides* 4(3):233–244
- Hansen L, Eilertsen RS, Solberg IL, Sveian H, Rokoengen K (2007b) Facies characteristics, morphology and depositional models of clay-slide deposits in terraced fjord valleys, Norway. *Sediment Geol* 202:710–729
- Hansen L, L'Heureux JS, Longva O (2011) Turbiditic, clay-rich event beds in fjord-marine deposits caused by clay slides on land – paleoenvironmental interpretation and role for submarine mass-wasting. *Sedimentology* 58:890–915. <https://doi.org/10.1111/j.1365-3091.2010.01188.x>
- Hansen L, Solberg IL, Jarna A, Nordahl B (2017) Developments in mapping and web presentation of fjord-marine deposit distributions for quick-clay related work in Norway. In: Thakur V, L'Heureux JS, Locat

- A (eds) Landslides in sensitive clays: from research to implementation. *Advances in natural and technological hazards research* 46. Springer. <https://doi.org/10.1007/978-3-319-56487-6>
- Havnen I, Ottesen HB, Haugen ED, Frekhaug MH (2017) Quick-Clay Hazard Mapping in Norway. In: Thakur V, L'Heureux JS, Locat A (eds) *Landslides in sensitive clays: From research to implementation. Advances in natural and technological hazards research* 46. Springer. <https://doi.org/10.1007/978-3-319-56487-6>
- Helle TE, Nordal S, Aagaard P, Lied OK (2016) Long-term-effect of potassium chloride treatment on improving the soil behavior of highly sensitive clay – Ulvensplitten, Norway. *Can Geotech J* 53:410–422. <https://doi.org/10.1139/cgj-2015-0077>
- Hillestad G (1974) Seismisk undersøkelse, Hallsteingård, Trondheim, Sør-Trøndelag. Geol Surv Norw Report 1214 (in Norwegian)
- Hilmo BO (1989) Marine sensitive leirers mineralsammensetning, kolloidkjemi og mekaniske egenskaper. PhD thesis, Dep Geol and Miner Resour Eng, NTNU, Trondheim, Norway (in Norwegian)
- Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide type, an update. *Landslides* 11(2):167–194. <https://doi.org/10.1007/s10346-013-0436-y>
- Janbu N, Nestvold J, Røe Ø, Sveian H (1993) Leirras - årsaksforhold og rasutvikling. In: Walberg Ø (ed) *Verdalsboka. Ras i Verdalen*, vol B. Verdalen kommune, pp 739–784 (in Norwegian)
- Jørstad F and Hutchinson JN (1961) Orienterende undersøkelser av skredfaren in Namdalen. Norw Geotech Inst Report 0.910 (in Norwegian)
- Karlsrud K, Aas G, Gregersen O (1985) Can We Predict Landslide Hazards in Soft Sensitive Clays? Summary of Norwegian Practice and Experiences. Norw Geotech Inst 158
- Kartverket (2024) LiDAR data from the Norwegian Mapping Authority. Available from <https://hoydedata.no>. Accessed Feb 2024
- Kjemperud A (1986) Late Weichselian and Holocene shoreline displacement in the Trondheimsfjord area, central Norway. *Boreas* 15:61–82
- L'Heureux JS (2012) A study of the retrogressive behaviour and mobility of Norwegian quick clay landslides. In: Eberhardt E, Froese C, Turner KA, Leroueil S (eds) *Proceedings of the 11th International and 2nd North American Symposium on Landslides and Engineered Slopes*, Banff, Canada, June 3–8 2012. Vol. 1, pp 981–988
- L'Heureux JS, Eilertsen RS, Glimsdal S, Issler D, Solberg IL, Harbitz CB (2012) The 1978 quick clay landslide at Rissa, mid-Norway: subaqueous morphology and tsunami simulations. In: Yamada Y et al. (eds) *Submarine mass movements and their consequences. Advances in natural and technological hazards research* 31. Springer
- Lebuis J, Robert JM, Rissmann P (1983) Regional mapping of landslide hazard in Quebec. In: *Proceedings of the symposium on slopes on soft clays*. Swed Geotech Inst Report No. 17. Linköping, Sweden, pp 205–262
- Lyså A, Hansen L, Christensen O, L'Heureux JS, Longva O, Olsen H, Sveian H (2008) Landscape evolution and slide processes in a glacioisostatic rebound area; a combined marine and terrestrial approach. *Mar Geol* 248:53–73
- Melchiorre C, Smith CA, Rodhe K (2014) Analysis of landslide scarp data, Sweden. Geol Surv Swed Report Dnr: 315-1895/2014
- Mitchell RJ, Markell AR (1974) Flowsliding in sensitive soils. *Can Geotech J* 11:11–31
- NADAG (2024) National database of ground investigations. Available from <https://geo.ngu.no/kart/nadag>. Accessed Feb 2024
- NGI (2008) E6 Jaktøyen-Tonstad. Områdestabilitet i kvikkleiresoner. Områdestabilitet - vurdering. Norw Geotech Inst Report 20071661-2, Rev. April 1 25 2008 (in Norwegian)
- NGU (2024) Quaternary geological map, Bedrock map, and Geophysical data from Geological Survey of Norway are available from <https://www.ngu.no/geologiske-kart>. Accessed Feb 2024
- NSDB (Nasjonal skredhendelsesdatabase) (2024) Norwegian landslide database. Available from <https://gis3.nve.no/link/?link=SkredHendelser>. Accessed Feb 2024
- NVE (2020) Sikkerhet mot kvikkleireskred. NVE Report 1/2019 (in Norwegian)
- NVE (2021) Kvikkleirekartlegging – metoder, status og videre arbeid. NVE Report 12/2021 (in Norwegian)
- NVE (2024a) NVE Atlas. Available from <https://atlas.nve.no>. Accessed Feb 2024
- NVE (2024b) Reports from mapping of quick-clay hazards zones in Trøndelag. Available from <https://www.nve.no/flaum-og-skred/kartlegging/faresonekart-kommuner/trondelag/> and <https://atlas.nve.no>. Accessed Feb 2024
- Olsen L, Høgaas F, Sveian H (2015) Age of the Younger Dryas ice-marginal substages in Mid-Norway – Tautra and Hoklingen, based on a compilation of ¹⁴C-dates. *Geol Surv Norw Bull* 454:1–13
- Penna I, Solberg IL (2022) Statistiske analyser av morfologiske parametre for leirskred i Trøndelag og Viken. Geol Surv Norw Report 2022:029 (in Norwegian)

- Persson MA, Stevens RL, Lemoine Å (2014) Spatial quick-clay predictions using multi-criteria evaluation in SW Sweden. *Landslides* 11:263–279
- Quinn PE, Diederichs MS, Rowe RK, Hutchinson DJ (2011a) A new model for large landslides in sensitive clay using a fracture mechanics approach. *Can Geotech J* 48:1151–1162. <https://doi.org/10.1139/T11-025>
- Quinn PE, Hutchinson DJ, DiederichsRowe MS (2011b) Characteristics of large landslides in sensitive clay in relation to susceptibility, hazard, and risk. *Can Geotech J* 48(8):1212–1232
- Quinn PE (2009) Large landslides in sensitive clay in Eastern Canada and the associated hazard and risk to linear infrastructure. PhD Thesis, Dep of Geol Sci and Geol Eng, Queen's University
- Rambøll (2012) Hallstein gård. Datarapport fra grunnundersøkelse. Rambøll Report 6120535-1, November 5 2012 (in Norwegian)
- Rankka K, Anderssen-Sköld Y, Hultén C, Larsson R, Leroux V, Dahlin T (2004) Quick clay in Sweden. *Swed Geotech Inst Report* 65
- Reite AJ (1994) Weichselian and Holocene geology of Sør-Trøndelag and adjacent parts of Nord-Trøndelag county, Central Norway. *Geol Surv Norw Bull* 425:1–30
- Reite AJ (1995) Deglaciation of the Trondheimsfjord area, Central Norway. *Geol Surv Norw Bull* 427:19–21
- Reite AJ, Sveian H, Erichsen E (1999) Trondheim fra istid til nåtid – landskapshistorie og løsmasser. *Geol Surv Norw Gråsteinen* 5 (in Norwegian)
- Reite AJ (1983) Trondheim. Description of the Quaternary geological map 1621-4, M 1:50 000. *Geol Surv Norw No* 391 (in Norwegian)
- Reite AJ (1985) Støren. Description of the Quaternary geological map 1621-3, M 1:50 000. *Geol Surv Norw Skrifter* 65 (in Norwegian)
- Riiber K, Høgaas F, Solberg IL (2015) Updating of Trondheim municipality Quaternary geological map, interpreted by LiDAR and field inspections. Available from www.geo.ngu.no/kart/losmasse_mobil/
- Rise L, Bøe R, Sveian H, Lyså A, Olsen HA (2006) The deglaciation history of Trondheimsfjorden and Trondheimsleia, Central Norway. *Norw J Geol* 86:419–438
- Rosenqvist IT (1953) Considerations on the sensitivity of Norwegian clays. *Géotechnique* 3:195–200
- Ryan J, Bruvoll A, Foldal KM, Hæreid GO, Muthanna TM, Nordal S, Ottesen HB, Solberg IL (2021) Årsakene til kvikkleireskredet i Gjerdrum 2020. The Gjerdrum expert team Report dated September 29 2021. <https://www.regjeringen.no/contentassets/3dadce8f7fad94608861163fa524023c0/no/pdfs/arsakene-til-kvikkleireskredet-i-gjerdrum-2020.pdf> (in Norwegian)
- Ryan J, Bruvoll A, Foldal KM, Hæreid GO, Muthanna TM, Nordal S, Ottesen HB, Solberg IL (2022) På trygg grunn. Bedre håndtering av kvikkleirerisiko. Norges offentlige utredninger, NOU 2022:3. The Gjerdrum expert team Report delivered March 28 2022. <https://www.regjeringen.no/contentassets/a65c53c3028443fea787bf0c331035c8/no/pdfs/nou202220220003000dddpdfs.pdf> (in Norwegian)
- Sand K (1999) Fra istid til Nidarens. Report, NGF-stipend 1998, Norsk geoteknisk forening (in Norwegian)
- Sandven R, Solberg IL (2014) Geophysical and geotechnical site investigations for a major highway in a quick-clay area. In: L'Heureux JS, Locat A, Leroueil S, Demers D, Locat J (eds) *Landslides in sensitive clays: from geosciences to risk management. Advances in natural and technological hazards research* 36. Springer. <https://doi.org/10.1007/978-94-007-7079-9>
- SGU (2024) Map viewer Landslides and gullies. <https://www.sgu.se/en/products/maps/map-viewer/jordk-artvisare/landslides-and-gullies/>. Accessed Feb 2024
- Sindre A (1980) Seismiske målinger i Gauldalen 1972–1979. *Geol Surv Norw Report* 1641(in Norwegian)
- SNL (2024) Gaula. Store norske leksikon. <https://snl.no/Gaula>. Accessed Feb 2024
- Solberg IL, Hansen L (2017) Befaring av skjæring for ny E6 ved Klett. Trondheim NGU Report 2017:001 (in Norwegian)
- Solberg IL, Rønning JS, Dalsegg E, Hansen L, Rokoengen K, Sandven R (2008a) Resistivity measurements as a tool for outlining quick-clay extent and valley-fill stratigraphy: a feasibility study from Buvika, central Norway. *Can Geotech J* 45:210–225. <https://doi.org/10.1139/T07-089>
- Solberg IL, Hansen L, Rokoengen K (2008b) Large, prehistoric clay slides revealed in road excavations in Buvika, mid-Norway. *Landslides* 5:291–304. <https://doi.org/10.1007/s10346-008-0122-7>
- Solberg IL, Hansen L, Rønning JS, Haugen ED, Dalsegg E, Tønnesen JF (2012) Combined geophysical and geotechnical approach for ground investigations and hazard zonation of a quick-clay area. *Mid Norway Bull Eng Geol Environ* 71(1):119–133
- Solberg IL, Dagestad A, Dalsegg E (2014) 2D resistivitetmålinger ved Brubakken, Melhus sentrum og Skjerdingstad i Melhus kommune. Sør-Trøndelag Data Og Tolkninger NGU Report 2014:022 (in Norwegian)
- Solberg IL, Long M, Baranwal V, Gylland A, Rønning JS (2016) Geophysical and geotechnical studies of geology and sediment properties at a quick-clay landslide site at Esp, Trondheim, Norway. *Eng Geol* 208:214–230

- Solberg IL, Riiber K (2019) Updating of Klæbu municipality Quaternary geological map, interpreted by LiDAR and field inspections. Geological Survey of Norway. Available from https://geo.ngu.no/kart/losmasse_mobil/. Accessed Feb 2024
- Solberg IL, Hansen L, Rokoengen K (2007) Distribution of clay slides in fjord-valley deposits and their role in valley development, example from Mid Norway. In: Schaefer VR et al (eds) Proceedings of 1st North American Landslide Conference, Vail, Colorado, June 3–8 2007. The Association of Environmental & Engineering Geologists, Denver, Colorado. Special Publication vol 23, pp 472–487. ISBN 978-0-975-42953-2
- Solberg IL, Riiber K, Gislefoss L (2019) Updating of Melhus municipality Quaternary geological map, interpreted by LiDAR and field inspections. Geological Survey of Norway. Available from https://geo.ngu.no/kart/losmasse_mobil/. Accessed Feb 2024
- Solberg IL (2007) Geological, geomorphological and geophysical investigations of areas prone to clay slides: Examples from Buvika, Mid Norway. PhD Thesis, Dep Geol and Miner Resour Eng, NTNU, Trondheim, p 213
- Solli A, Grenne T, Slagstad T, Roberts D (2003) Bedrock map Trondheim 1621-4, M 1:50 000, Preliminary version. Geological Survey of Norway
- Sveian H, Dahl R, Løvø G (2007) Nidelva fra istid til Brattøra. In: Fremstad E, Thingstad PG (eds) Nidelva, Trondheims hjerte. Bli med ut vol 7, pp 14–31
- Sveian H, Olsen L (1984) En strandforykvningskurve fra Verdalsøra, Nord-Trøndelag. *Nor Geol Tidsskr* 64:27–38 (in Norwegian)
- Tønnesen JF (1996) Gravimetri for kartlegging av løsmassemektigheter i Trondheim. *Geol Surv Norw Report* 95:078 (in Norwegian)
- Torrance JK (1983) Towards a general model of quick clay development. *Sedimentology* 30:547–555
- van-Boeckel M, Christoffersen M, Solberg IL, Nordahl B, Liinamaa-Dehls A (2023) Mapping of red-listed landforms in Norway. NGF Vinterkonferansen January 4–6 2023, Trondheim, Norway
- Wolff FC (1976) Bedrock map Trondheim M 1:250 000. Geological Survey of Norway

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