Coastal landslides associated with confined aquifers and land uplift in Sweden

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Omslagsbild: A geologist with SGU's drilling equipment at the southern Ulvsvik landslide.
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INNEHÅLL

SAMMANFATTNING

Vid ett antal platser som utgjorde kust under tidig holocen, för 9 700–9 400 kol-14 år sedan, har jordskred påträffats. I *Early Holocene coastal landslides linked to land uplift* (Smith m.fl. 2017) redogörs för tänkbara orsaker och samband mellan dessa. Utifrån dessa slutsatser; främst att det verkar ha funnits underliggande slutna akviferer vilka genom landhöjning och kustförskjutning har hamnat över havsnivån, har yngre kuststräckor med liknande geologiska förutsättningar identifierats och undersökts. Endast tre yngre skredplatser kunde identifieras, men det är fullt möjligt att dessa skred har samma orsaker som de äldre. Det är dock tydligt att denna typ av skred har blivit ovanligare. I denna rapport föreslår vi två möjliga förklaringar till den minskade förekomsten:

- Under tidig holocen var klimatet fuktigare, vilket bidrog till högre grundvattennivåer och därmed högre portryck.
- Stora områden höjdes ur havet under tidig holocen, vilket innebar ökad sannolikhet att områden med dessa förutsättningar skulle bildas, jämfört med senare tid.

Syftet med denna rapport är att sammanställa slutsaser och resultat från nämnda undersökningar för att ge geologer ett underlag vid bedömning av förutsättningarna för denna typ av skred I modern tid.

PURPOSE

Recent investigations in western Sweden have demonstrated a link between confined aquifers, land uplift, and coastal landslides during the early Holocene (Smith et al. 2017). The purpose of this report is to summarize these results for geologists and assess if areas with similar geologic conditions along the present coast of Sweden are susceptible to similar landslides.

EARLY HOLOCENE LANDSLIDES

Five large (more than 1 km in length or width) relic landslides located near Råda, Mariedal, Lerdala, Sörmon, and Sunne in western Sweden were investigated to determine the timing and cause of landsliding (Fig. 1). The investigation involved both detailed LiDAR-based analysis of the geomorphology and a field campaign of drilling and geotechnical probing to determine the stratigraphy associated with each landslide (Smith et al. 2014, Smith et al. 2017).

Four different geomorphic relationships can link the landslides to the paleo-coastlines (Smith et al. 2017). First, in ideal cases, the scarp cuts raised shorelines and younger raised shorelines overlie the deposit. Second, a distinct change in surface roughness distinguishes wave-washed parts of the deposits from those that are not wave-washed. Third, the complete lack of a visible deposit suggests that the lower reaches of the landslide extended below sea level, while the scarp remains abrupt and unaffected by wave action. Fourth, the very low travel angles of the studied landslides indicate a submarine origin. The coastal geomorphology can be used in conjunction with shore displacement curves from south (Björck & Digerfeldt 1986) and north (Risberg et al. 1996) of Lake Vänern to constrain the timing to the early Holocene, about 9 500 ^{14}C years ago (Smith et al. 2017).

The results of the drilling and geotechnical investigations show that all five landslides share the same general stratigraphy. Ice-proximal glaciomarine sand is overlain by glaciomarine clay, and the clay is overlain by a regressive sequence of littoral silt and/or sand (Smith et al. 2017). This stratigraphy creates confined aquifers in the lower sand units. A comparison of scarp relief to drillings located just above the scarps reveals that the landslides occurred across the tops of these confined aquifers (Smith et al. 2017).

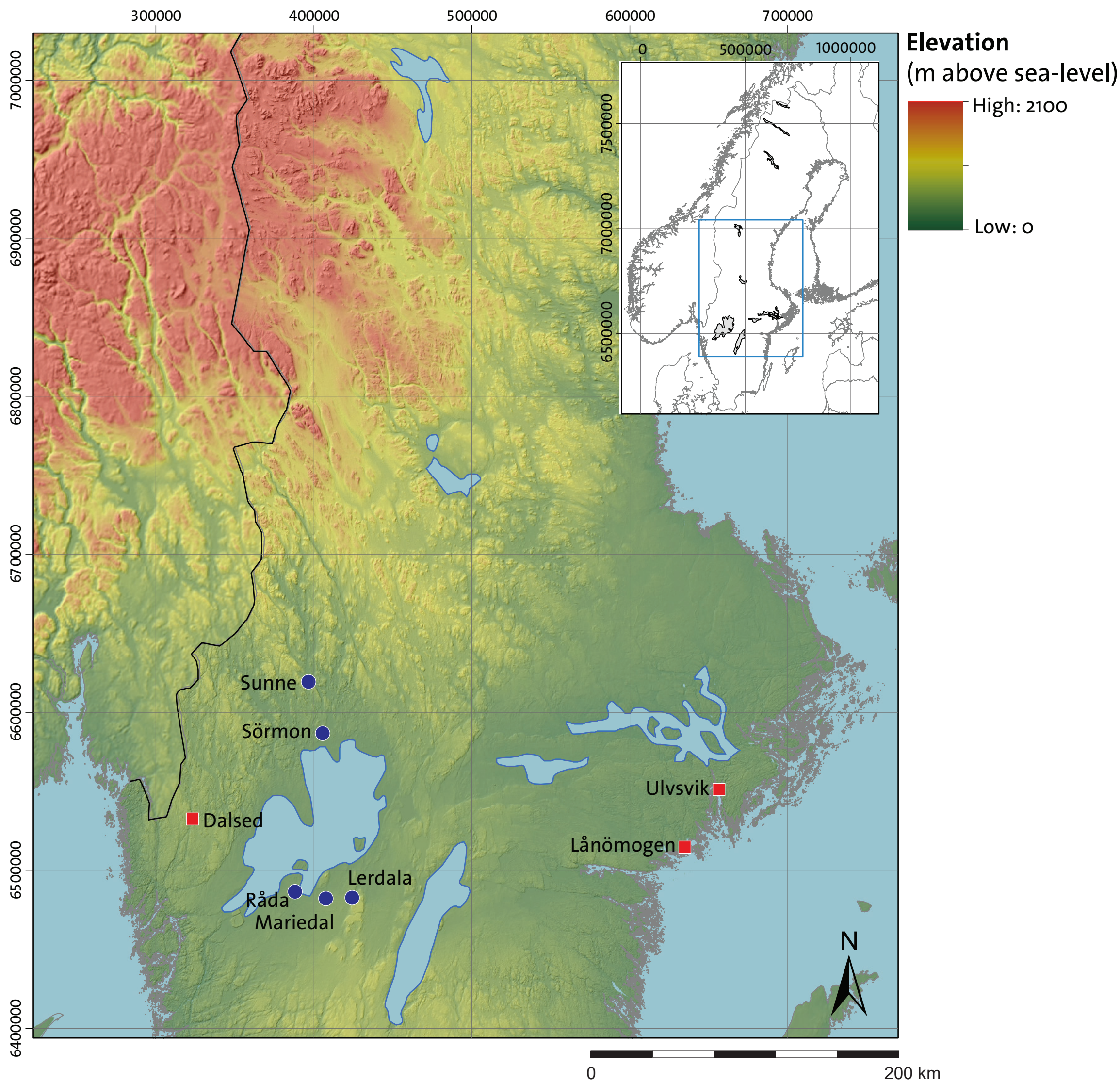

Figure 1. Fennoscandia and the locations of the landslides discussed in the text. The blue circles are from Smith et al. (2017), and the red squares are from this study.

Figur 1. Fennoskanderna och de områden som diskuteras i texten. Blå cirklar markerar observationspunkter från Smith m.fl. (2017), och röda rutor markerar observationspunkter från denna studie.

The geomorphic link between the landslides and the coastlines coupled with the stratigraphic link between the landslides and the confined aquifers suggests that both coastal processes and hydrogeology are important underlying causes of the large landslides in western Sweden. More specifically, the emergence above sea level of the recharge zones of the confined aquifers has been proposed as the cause of the instabilities (Smith et al. 2017). As the recharge zones first rose above sea level, the aquifers were able to accumulate pore pressures. In places where the confined aquifers were nearthe surface, the pressures in the aquifers approached the lithostatic pressure and caused slope failures on low-angle slopes (Table 1). These failures then retrogressed from a marine setting across what were then the coastlines and onto land.

Table 1. Morphometric data of landslides described in the text. Blank fields indicate that the value cannot be caluclated with available data.

Name	Scarp Length	Scarp relief (m)	Length (m)	Width (m)	Crown (masl)	Toe (masl)	Relief (m)	Travel (degrees)	Floor slope (degrees)	Adjacent slope (degrees)
Dalsed east	840	13	400	730	154	123	31	4,36	9	1
Dalsed west	1440	13		320	157	157			4	2
Lerdala *	3830	12	1910	1 280	96	65	31	0,93	3	2
Lånömogen	1320	4		360	19				2	2
Mariedal *	4340	13	4220	2 830	112	69	42	0,58	4	1
Råda **	3940	9	2050	1 570	87	63	25	0,69	2	2
Sunne *	6120	7		1 630	120				3	1
Sörman north *	780	3	480	460	88	83	5	0,60	2	2
Sörman south *	1280	11	740	1 030	103	83	20	1,49	4	2
Ulvsvik south	660	9		160	32				4	5
Ulvsvik north	750	2		330	41				3	3

* Smith et al., 2017

** Smith et al., 2017, Smith et al., 2014

Dalsed landslides

The western Dalsed landslide (Fig. 1 & 2) exhibits many of the characteristics of the landslides described by Smith et al. (2017). Thus, it can be used as an example to explain better the geology associated with these large early Holocene landslides.

The geomorphology of the western Dalsed landslide indicates that failure occurred at the coastline. The lack of a visible deposit in high-resolution LiDAR imagery (Fig. 2) suggests either a long runout or extensive reworking by waves; both indicate that the lower parts of the slide occurred below sea level. The scarp reaches its highest elevation along the eastern side. Here, it is sharp and clearly has not been affected by wave action. Thus, the western Dalsed landslide occurred at what was then the coastline. In addition to the coastal occurrence of the landslide, the geology also suggests the presence of a confined aquifer. Although the area is a glaciofluvial delta composed of highly-permeable sand and gravel (Fig. 3), the water levels in the lakes Lilla le and Stora le differ by 34 vertical meters, which indicates the presence of a confining layer, perhaps silty forest beds. Without drill data, it is not possible to determine with certainty whether the landslide was related to pressure within the confined aquifer or not because it is not known where the sliding surface is located relative to the stratigraphy.

The eastern Dalsed landslide (Fig. 2) occurred later than the western landslide and was not associated with emergence of groundwater recharge zones. The sharp crested deposit of the eastern slide indicates that it has not been wave washed and that the slide occurred after the area rose above sea level. Additionally, organic material collected from near the base of the peat bog that is dammed behind the deposit (Fig. 3) yielded radiocarbon dates as old as 3 905 +/- 50 years before present (Table 2). This provides a minimum limiting age for the eastern landslide. The eastern Dalsed landslide is of interest because it occurred along the continuation of the scarp of the western landslide and points to the obvious susceptibility of over-steepened slopes to landsliding. Overall, this appears to be relatively rare with these landslides as no evidence of secondary landsliding was reported in the previous research (Smith et al. 2017). The secondary sliding at Dalsed is likely linked to the hydrogeology of the slope, but no drilling has been conducted to confirm this.

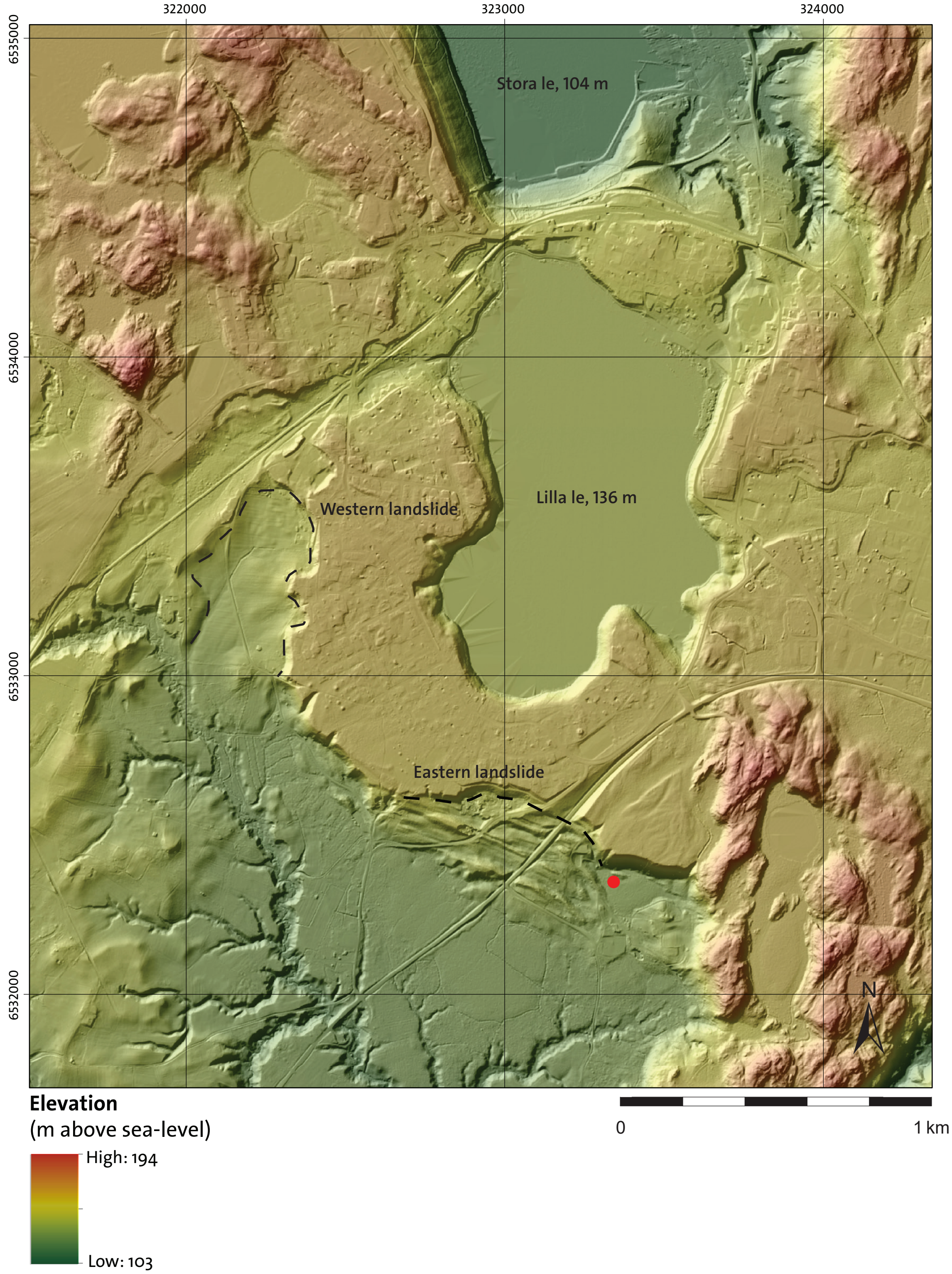

Figure 2. LiDAR-derived shade-relief image of the Dalsed landslides (Landmäteriet 2015). The dashed lines mark the landslide scarps, and the red circle marks the location of the peat core.

Figur 2. LiDAR bild av jordskredet vid Dalsed (Lantmäteriet 2015). De streckade linjerna markerar jordskredskanten och den röda punkten markerar platsen där torvkärnan togs.

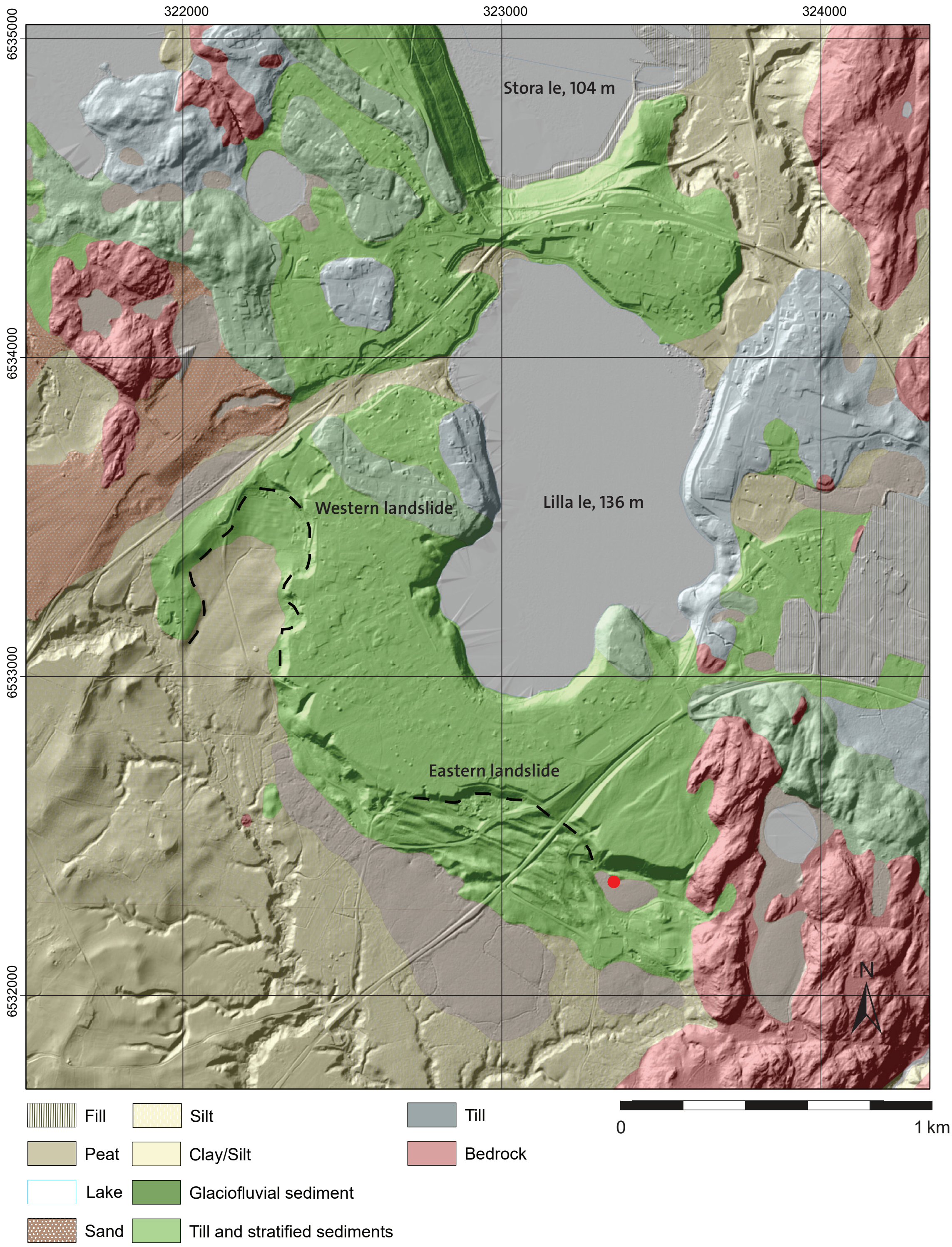

Figure 3. Surficial deposits map (SGU jordartsdatabas) shown over the LiDAR-derived shade-relief image (Lantmäteriet 2015) of the Dalsed landslides. The dashed lines mark the landslide scarps, and the red circle marks the location of the peat core.

Figur 3. Jordartskarta (från SGUs jordartsdatabas) kombinerad med LiDAR-höjddata (Lantmäteriet 2015) över jordskredet vid Dalsed. De streckade linjerna markerar jordskredskanten och den röda cirkeln markerar provpunkten där torvkärnan togs.

Table 2. Information pertaining to the radiocarbon dating of organic material on the eastern Dalsed landslide.
Tabell 2. Informaton från kol-14-mätningarna av organiskt material från det östra Dalsedskredet.

Core	Lab no	Material	Depth (cm)	Latitude	Longitude	^{14}C years	1 sigma
Dalsed R1A	LuS 11665	wood	265–270	58.89457	11.93368	3905	50
Dalsed R2A	LuS 11666	wood	185–190	58.89472	11.93355	3390	50

Late Holocene landslides

Given the prevalence of coastal landslides during the early Holocene, a search was undertaken to locate more recent coastal landslides in similar geologic settings.

Finding modern analogs

The search for confined aquifers along the present-day coast of Sweden was conducted using high-resolution, LiDAR-derived elevation data (Lantmäteriet, 2015) and information from the Geological Survey of Sweden's (SGU) databases in a geographic information system. Location data on glaciofluvial sediments of all grain-sizes, were extracted from the 1:25 000–1:100 000 surficial deposits database (SGU jordartsdatabas) and buffered by 100 m. The coastline from Lantmäteriet's 1:1 million scale map of Sweden was also extracted and buffered by 100 m. The areas where these two sets of buffered polygons intersect has been mapped as coastal glaciofluvial sediments (Fig. 4). This is a minimum estimate of such deposits because glaciofluvial sediments are often overlain by postglacial sand in areas below the highest coastline, and postglacial sand was not included in the analysis. Once the areas of coastal glaciofluvial sediments were delimited, each area was examined using LiDAR-derived imagery for geomorphic evidence of landsliding.

In all of Sweden, only three landslides were found in association with glaciofluvial sediments along the present-day coast, and one of the slides was already included in the SGU landslide and ravine database (SGU, jordskred och ravin databas). All three of the landslides are located where the mid-Sweden end moraine zone intersects the east coast. Two are located at Ulvsvik and the third is located at Långömogen (Fig. 1). These moraines are continuations of the moraines associated with the Råda, Lerdala, and Mariedal landslides in western Sweden (Smith et al. 2017) and represent the grounding line of the Fennoscandian Icesheet during Younger Dryas times (Johnson and Ståhl 2010). Thus, the glaciofluvial sediments were deposited in deepwater and are in places overlain by a confining layer of clay.

Southern Ulvsvik landslide

The southern Ulvsvik landslide underwent geomorphic and stratigraphic investigations similar to those described by Smith et al. (2017) for the landslides in western Sweden. The geomorphology indicates that the slide occurred at the coastline (Fig. 5). The sharp scarp has not been affected by wave action, and the lack of a visible deposit indicates that it slid into the water. Additionally, the scarp cuts a raised shoreline at 26 m above sea level. Based on the shoreline displacement curve of Miller (1982), this provides a minimum age for the landslide of ~3 300 ^{14}C years.

SGU drilled three holes above the scarp of the southern Ulvsvik landslide (Fig. 6). Hole U1 is located north of the scarp near an area of thin sediments overlying bedrock (Fig. 5 & 6). From the bottom up the stratigraphy includes 1.2 m of gravelly, silty sand (likely till), overlain by 1.9 m of glaciolacustrine clay, overlain by 4.3 m of postglacial sand with some interbedded silt (Fig. 7).

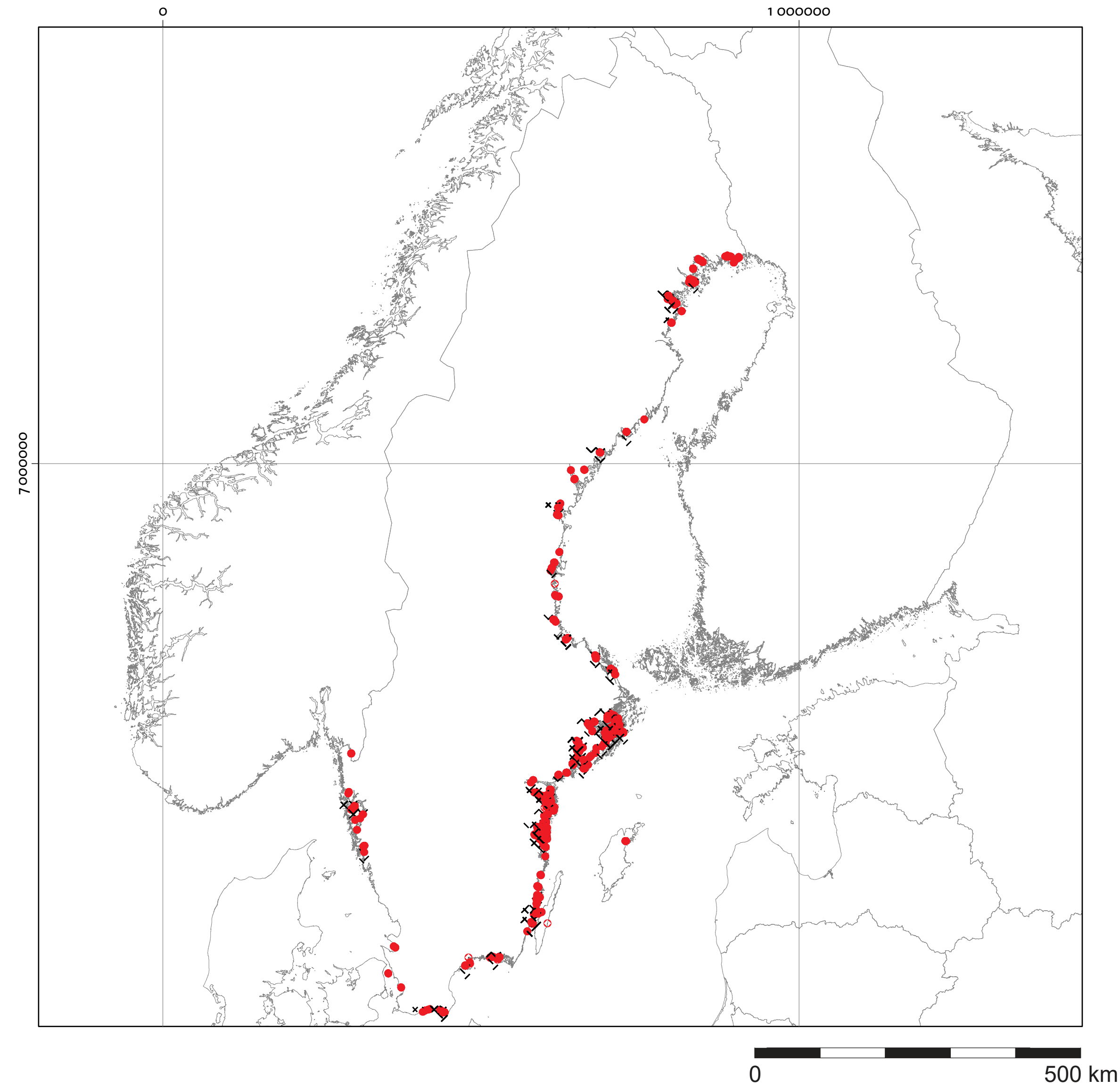

Figure 4. Fennoscandia with areas of coastal glaciofluvial sediments mapped in red.

Figur 4. Fennoskanderna samt områden med i Sverige kartlagda kustnära isälvsediment markerade.

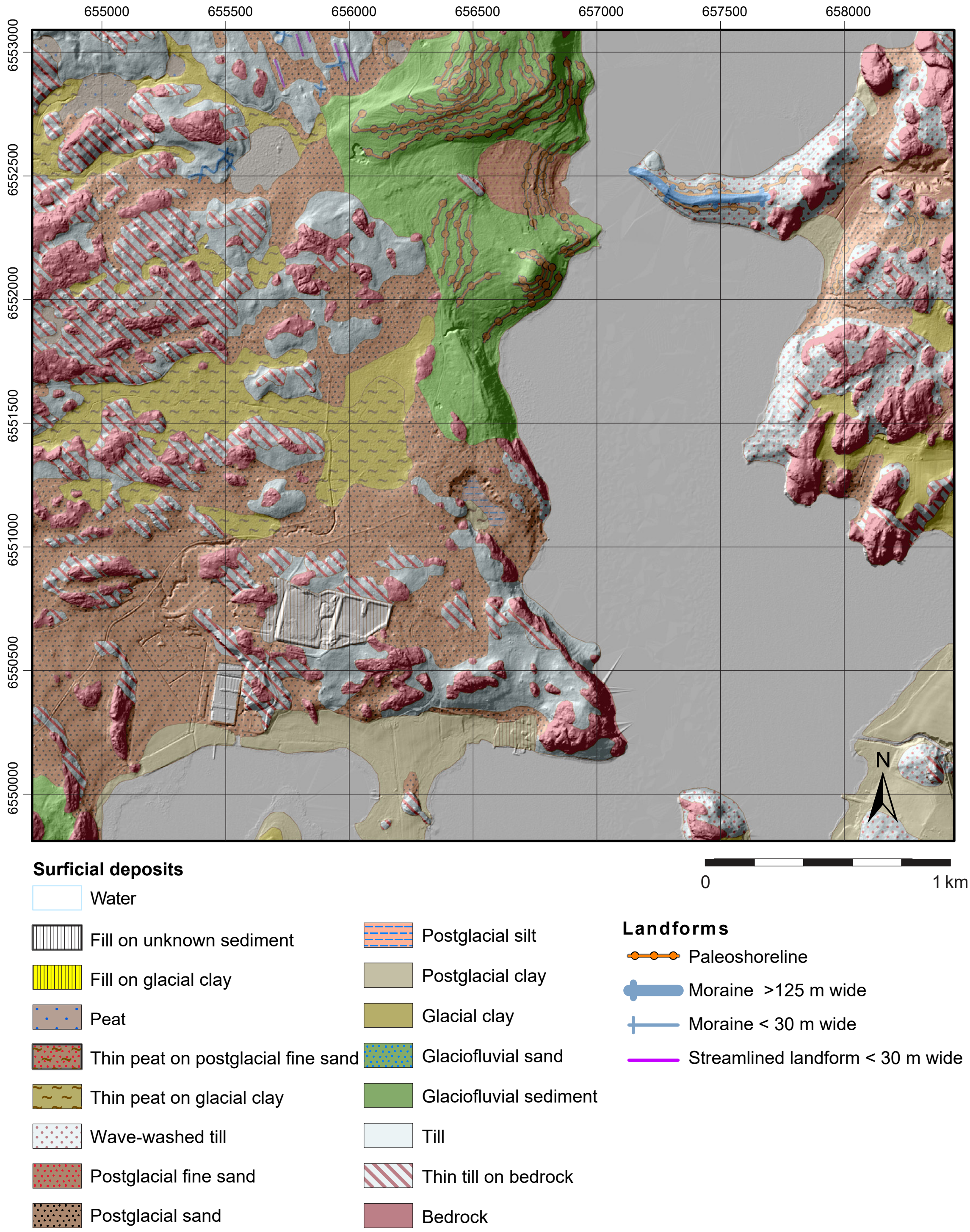

Figure 5. Surficial deposits map (SGU jordartsdatabas) shown over the LiDAR-derived shade-relief image of the Ulvsvik landslides (Lantmäteriet 2015). The dashed lines mark the landslide scarps.

Figur 5. Jordartskarta (SGUs jordartsdatabas) kombinerad med LiDAR-höjddata (Lantmäteriet 2015) av jordskredet vid Ulvsvik. De streckade linjerna markerar jordskredskanten.

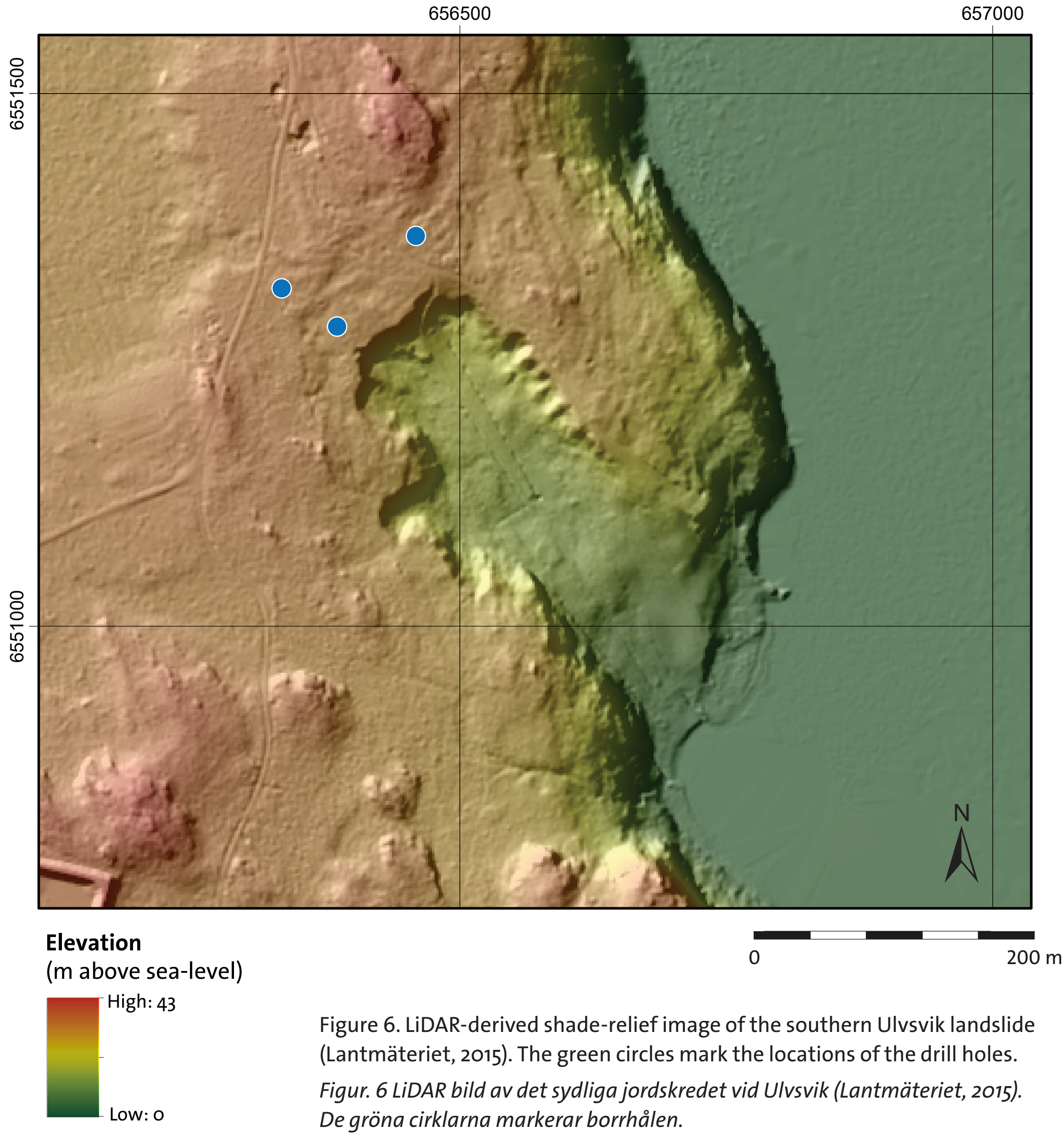

Figure 6. LiDAR-derived shade-relief image of the southern Ulvsvik landslide (Lantmäteriet, 2015). The green circles mark the locations of the drill holes.

Figur. 6 LiDAR bild av det sydliga jordskredet vid Ulvsvik (Lantmäteriet, 2015). De gröna cirklarna markerar borrhålen.

The lowermost unit was wet but could not conduct much water due to the high silt content.

Hole U2 is the western-most and is located about 100 m from the scarp (Fig. 6). From the bottom up, the stratigraphy includes 2.0 m of hard, dry silt (poor sediment recovery from the drill) overlain by 9.0 m of postglacial sand with one thin silt bed (Fig. 8). No confining layer and no water were encountered in hole U2.

Hole U3 is located about 30 m northwest of the scarp (Fig. 6). From the bottom up the stratigraphy includes 4.0 m of glaciolacustrine sand, overlain by 1.0 m varved glaciolacustrine clay, overlain by 4.0 m postglacial sand with some silt at the base. Additionally, a probe was thrust beyond the extent of the boring to a total depth of 27 m without encountering bedrock. When the probe was recovered, the rods below 14.9 m depth were wet indicating the location of the water table.

The stratigraphy varied significantly between the holes (Fig. 7–9), but this is not unusual for ice-proximal deposits. Hole U3 is closest to the centre of the landslide and is likely to be most

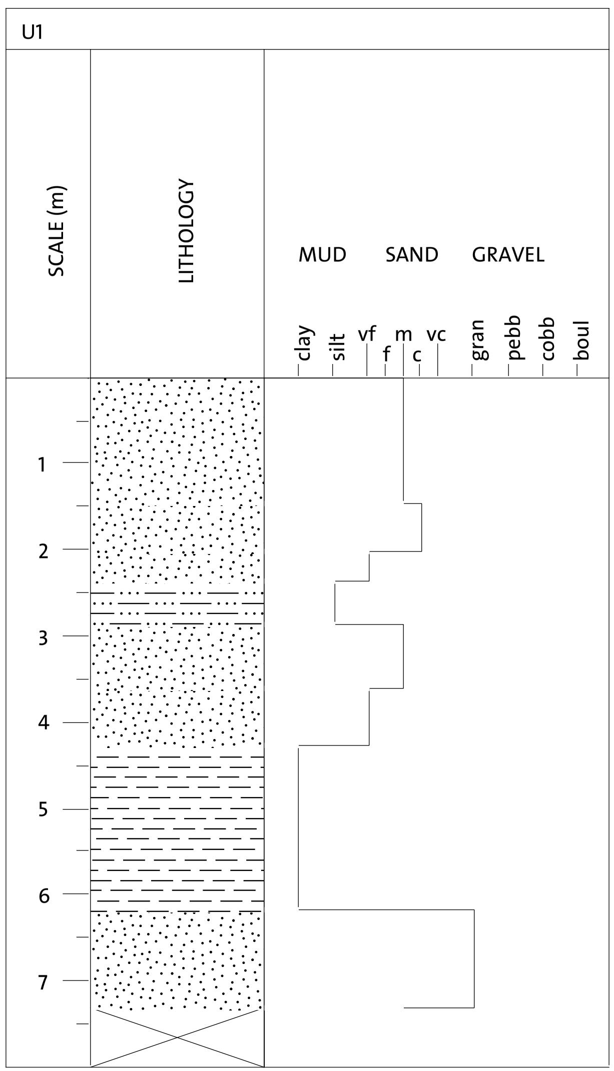

Figure 7. Stratigraphic column for hole U1 (Zervas et al. 2009).

Figur 7. Stratigrafisk information från borrning U1 (Zervas et al. 2009).

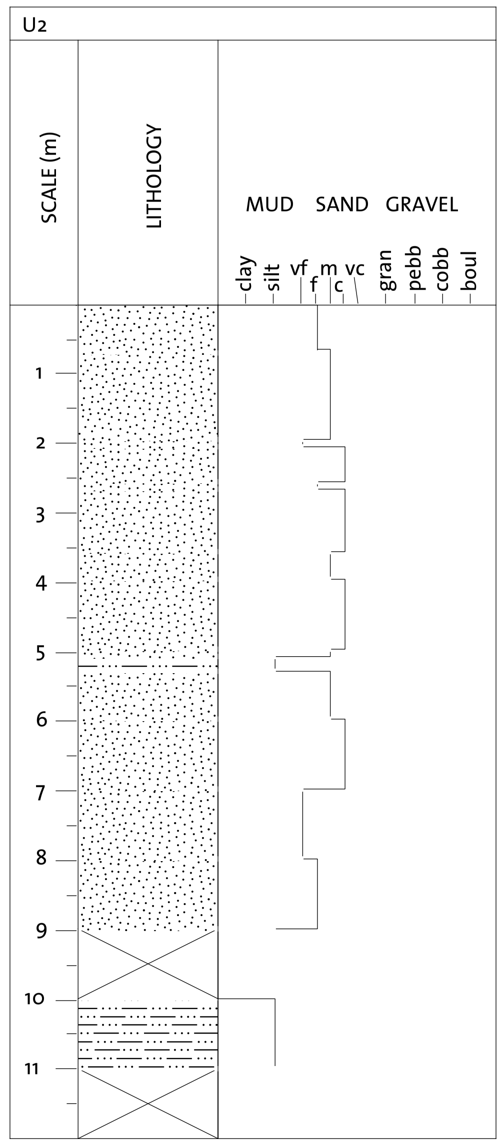

Figure 8. Stratigraphic column for hole U2 (Zervas et al. 2009).

Figur 8. Stratigrafisk information från borrning U2 (Zervas et al. 2009).

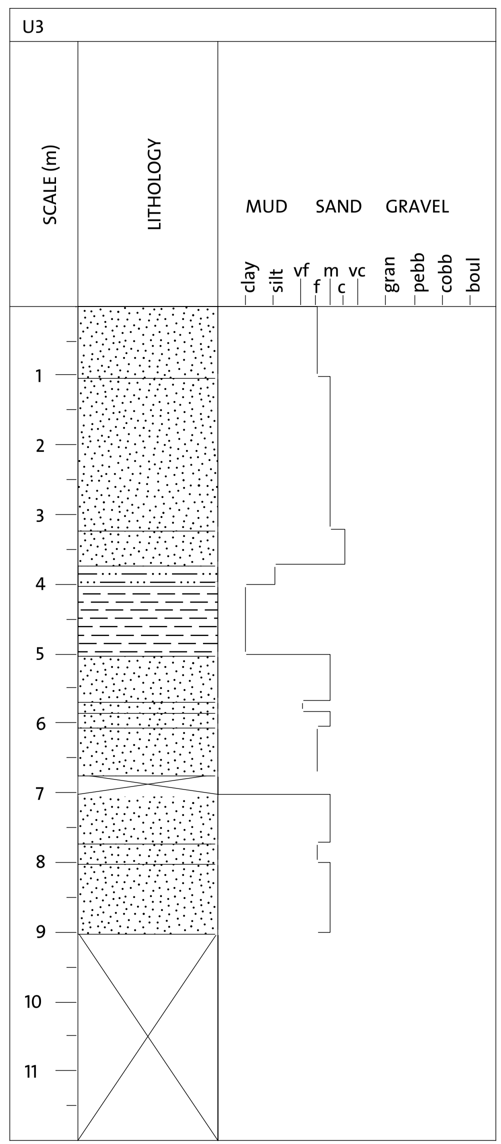

Figure 9. Stratigraphic column for hole U3 (Zervas et al. 2009).

Figur 9. Stratigrafisk information från borrning U3 (Zervas et al. 2009).

representative of the pre-landslide stratigraphy. The geology at this location, with the glaciolacustrine clay overlying a thick sequence of glaciolacustrine sand, is conducive to formation of a confined aquifer. The relief of the scarp is 9 m, and the sliding surface is within the upper parts of the lower sand unit. Although both the geomorphology and stratigraphy at the southern Ulvsvik landslide are similar to the older landslides in western Sweden (Smith et al. 2017), the hydrogeology is different.

Measurements within the confined aquifers at both Sunne and Sörmon revealed nearly artesian water pressures that reached 3–4 m above the tops of the aquifers. At Ulvsvik, the water table is about 6 m below the top of the aquifer, and the lower sand unit is not pressurized. This current lack of pore pressure may suggest that the southern Ulvsvik landslide is unrelated to water pressure, but two other explanations remain. First, the year 2016 was exceptionally dry and water levels are well below normal in the aquifers of southern Sweden. Second, the occurrence of the landslide may have allowed the aquifer to drain. The landslide scar extends from bedrock on the southwest side to within 40 m of bedrock on the northeast side (Fig. 5). Since this bedrock bounds the lower aquifer, the landslide covers nearly the same area as the aquifer. It does not seem farfetched that an aquifer-scale landslide could disrupt the stratigraphy to the extent that a confined and pressurized aquifer drained and became an unconfined aquifer.

Northern Ulvsvik landslide

The northern Ulvsvik landslide lies about 1 km north of the southern one (Fig. 5). It is adjacent to a grounding-line moraine that is mapped as glaciofluvial sediment (Fig. 10). The geomorphology indicates that the landslide occurred entirely below sea level. The entire scarp is subtle and has been affected by wave action. Additionally, the entire landslide is overlain by distinct raised shorelines. Based on the elevation of the top of the scarp at 41 m above sea level (Table 1) and the shore displacement curve of Miller (1982), the landslide occurred prior to ~4400 ^{14}C years ago.

Although drilling has not been conducted to determine if a confined aquifer exists, the facts that the northern Ulvsvik landslide occurred below sea level and in glaciolacustrine sand suggests a possible link to the other landslides. The important difference is that the northern Ulvsvik landslide did not retrogress onshore. It is difficult to assess how common such landslides are from the terrestrial record because they have a low preservation potential during regression.

Lånömogen landslide

The third landslide located within coastal glaciofluvial sediments is at Lånömogen about 40 km southwest of Ulvsvik (Fig. 11). The deposits are associated with a Younger Dryas (12 900–11 700 BP) age grounding-line moraine. The geomorphology of the Lånömogen landslide indicates that it occurred at the coast line. The upper-most portion of the scarp is sharp and has not been affected by wave action, but the lack of a visible deposit indicates that the lower reaches of the landslide occurred below sea level. The scarp cuts a raised shoreline at 17 m above sea level, and the landslide is therefore younger than ~2 700 ^{14}C years old (Miller, 1982). Although no stratigraphic data exist that definitively link the Lånömogen landslide to the presence of a confined aquifer, the coastal occurrence in glaciolacustrine sediments is consistent with the settings of the large early Holocene landslides in western Sweden (Smith et al. 2017).

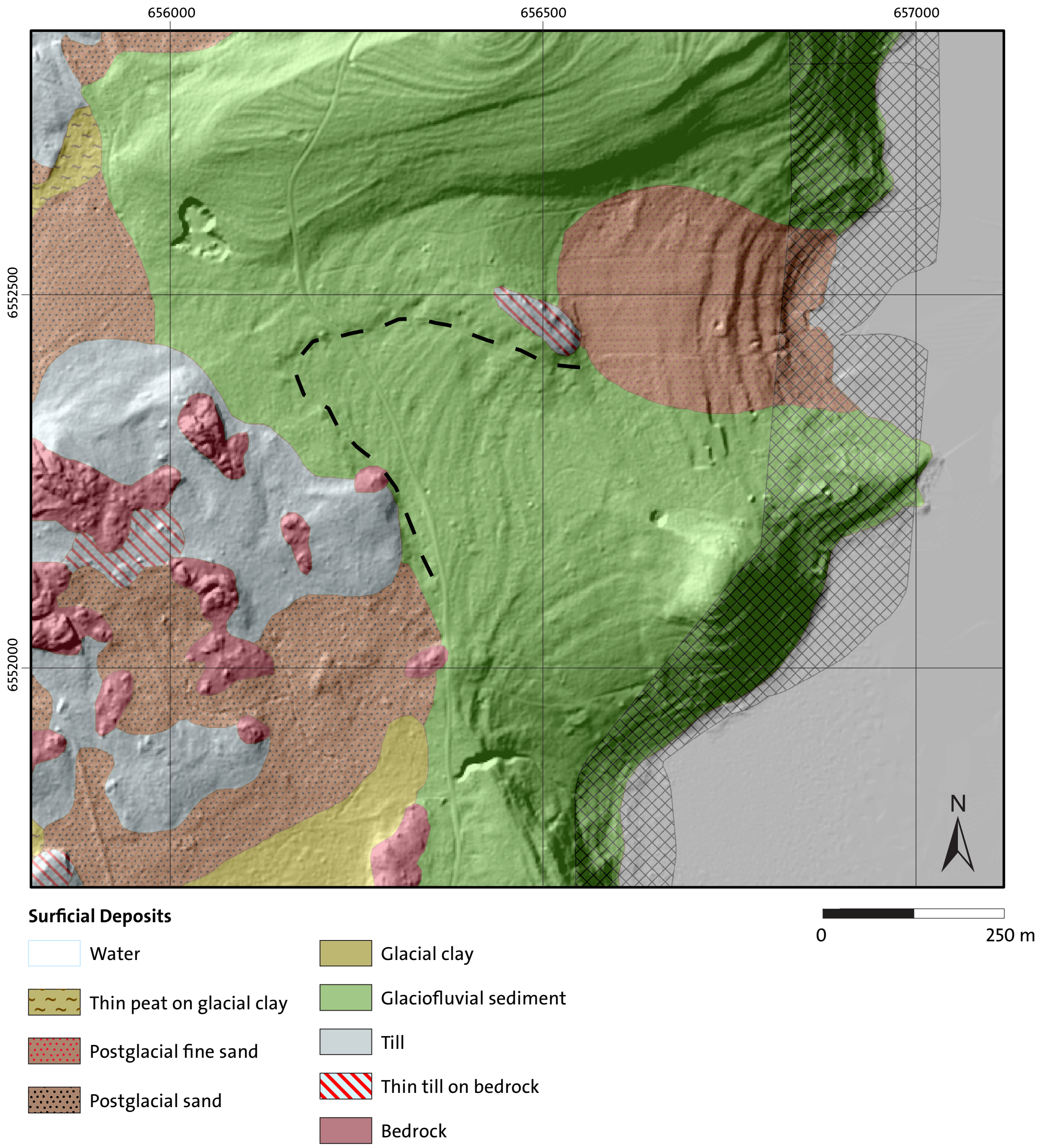

Figure 10. Surficial deposits map (SGU jordartsdatabas) shown over the LiDAR-derived shade-relief image (Lantmäteriet 2015) of the northern Ulvsvik landslide. The dashed lines mark the landslide scarp, and the cross-hatching marks areas mapped as coastal glaciofluvial sediments.

Figur 10. Jordartskarta (från SGUs jordartsdatabas) kombinerad med LiDAR-höjddata (Lantmäteriet, 2015) över det nordliga jordskredet vid Ulvsvik. De streckade linjerna markerar jordskredskanten och de streckade områdena markerar kustnära isälvsediment.

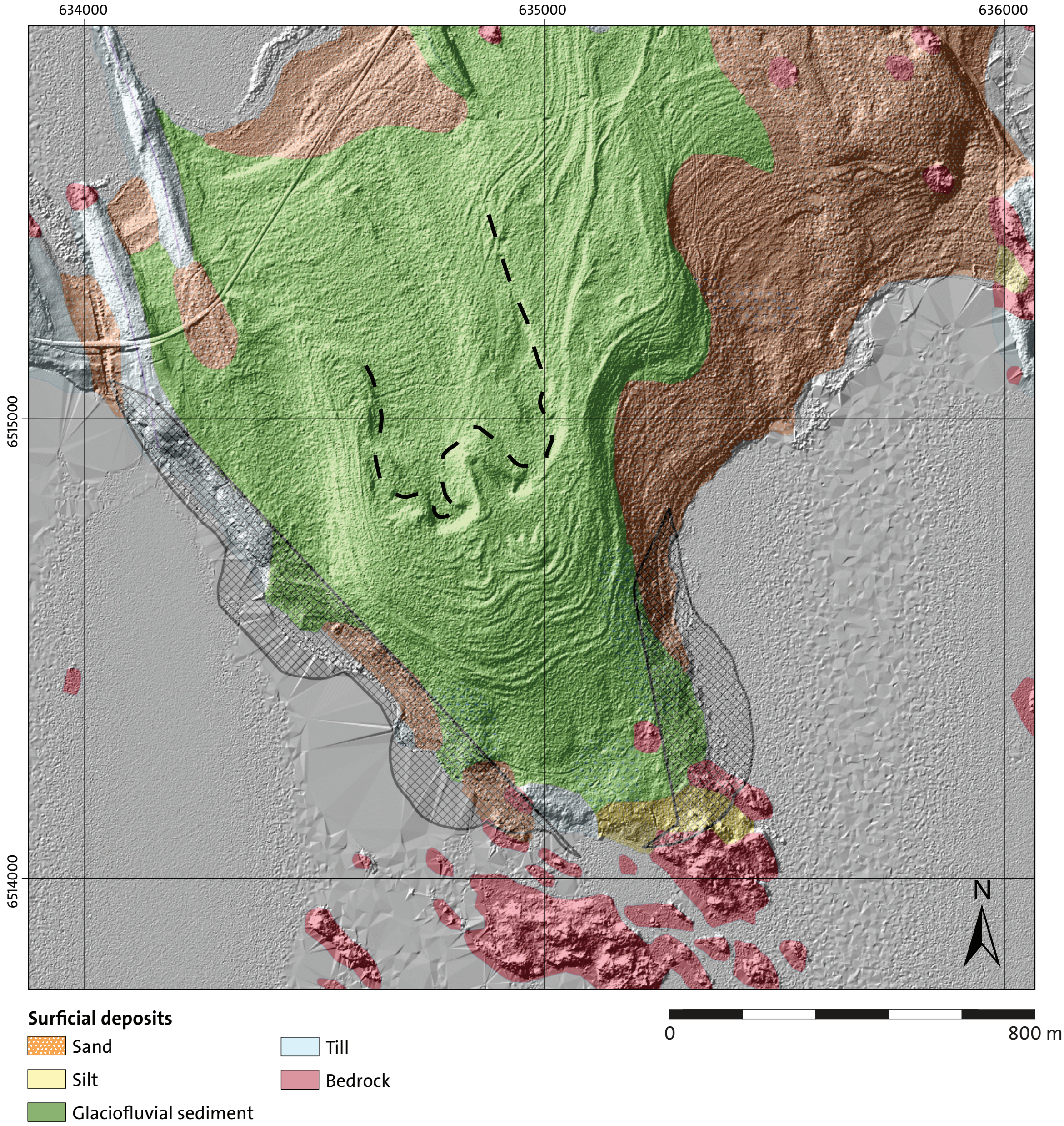

Figure 11. Surficial deposits map (SGU jordartsdatabas) shown over the LiDAR-derived shade-relief image of the Lånömogen landslide. The dashed lines mark the landslide scarp, and the crosshatching marks areas mapped as coastal glaciofluvial sediments.

Figur 11. Jordartskarta (SGU jordartsdatabas) kombinerad med LiDAR-höjddata (Lantmäteriet 2015) över Lånömogen-jordskredet. De streckade linjerna markerar jordskredskanten och de streckade ytorna markerar kustnära isälvsediment.

DISCUSSION

Large coastal landslides in confined glacial sand aquifers were rather common early Holocene events in Sweden (Smith et al. 2017). However, similar geologic settings do not seem to generate as many or as large landslides along the late Holocene coastline. There are multiple mechanisms that may explain this change in landslide frequency. Here we discuss two possibilities that may have worked in conjunction with each other.

First, the early Holocene climate in Sweden was generally wetter than the late Holocene climate (Seppä et al. 2005). If wetter conditions led to higher groundwater tables and pore pressures in confined aquifers, then climate may have played a role in the more frequent occurrence of landslides.

Second, the higher occurrence of landslides in the early Holocene relative to the late Holocene may relate to the decreasing land uplift and regression rates. Due to the more rapid uplift and despite the globally rising sea level (Waelbroeck et al. 2002), regression rates were higher during the early Holocene than the late Holocene. Thus for a given period of time, more land rose above sea level during the early Holocene than the late Holocene. It stands to reason that with greater land surface emergence comes greater aquifer recharge zone emergence and a greater occurrence of landslides.

To demonstrate this, we use the shore-level displacement model of Påsse and Daniels (2015) to compare areas that emerged between 11 000 and 10 000 years ago to areas that emerged between 4 000 and 3 000 years ago. These time periods, expressed in calendar years in the model, correspond approximately to the occurrence of early and late Holocene landslides which were described in ^{14}C years. According to the model, 12 621 km^2 of Swedish land emerged between 11 000 and 10 000 years ago (Fig. 12) and 5 999 k of Swedish land emerged between 4 000 and 3 000 years ago (Påsse & Daniels 2015). These findings indicate that 2.1 times more emerged during a 1000-year period in the early Holocene than in the late Holocene. All else being equal, an accompanying ~2-fold increase in the emergence of aquifer recharge zones could also be expected during the early Holocene, which could have contributed to the higher occurrence of landslides.

CONCLUSIONS

Relative sea-level lowering and the emergence of aquifer recharge zones has been suggested as a cause for the occurrence of numerous coastal landslides above confined aquifers during the early Holocene in Sweden (Smith et al. 2017). These relationships are explained, and areas with similar geologic conditions are mapped along the present-day coast of Sweden. A search of these geologically similar areas yielded only three landslide scars that date from aprox. 4 400 to aprox. 3 300 ^{14}C years ago. Although data are limited, it is possible that the late Holocene landslides share the same underlying causes of failure as the early Holocene landslides. Nevertheless, such slides are much less common during the late Holocene.

Two possible mechanisms, perhaps working together, are put forth to explain the higher prevalence of landslides during the early Holocene. These mechanisms include:

- A wetter early Holocene climate may have contributed to higher water tables and pore pressures.
- Larger areas of land emerged during the early Holocene, which increased the likelihood of recharge zone emergence.

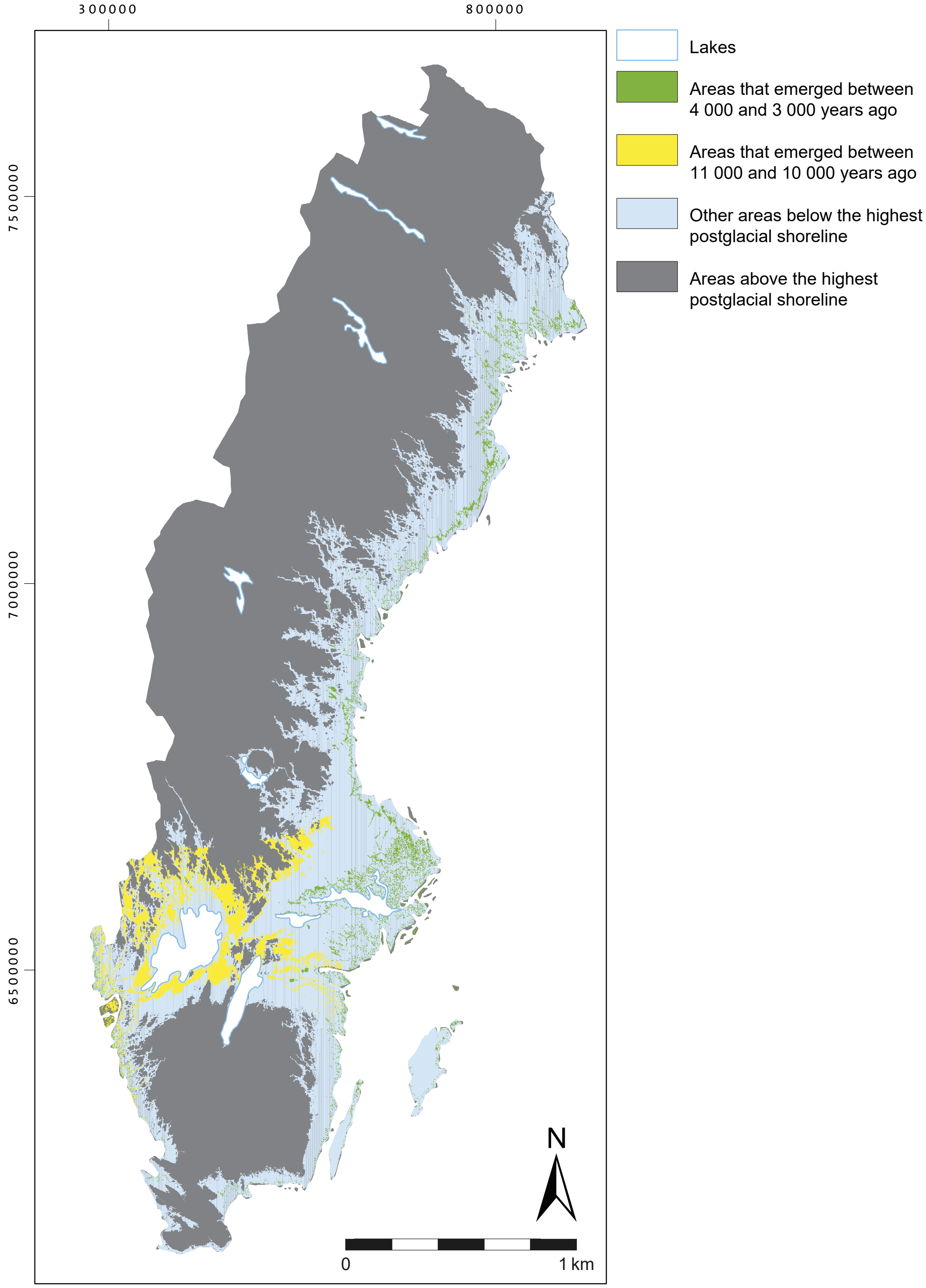

Figure 12. Map of Sweden showing areas modeled (Påsse & Daniels 2015) to have emerged above water level 11 000–10 000 years ago and 4 000–3 000 years ago. The dark gray areas within the colors mark areas of mapped glaciofluvial deposits (SGU jordarts database).

Figur 12. Karta av Sverige som visar områden som uppkom over havsnivån 11 000–10 000 och 4 000–3 000 år sedan (Påsse and Daniels, 2015) . De mörkgrå områden inom färgat områden markerar isälvsediment (SGU jordarts database).

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