

SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 772 AVHANDLINGAR OCH UPPSATSER ARSBOK 73 NR 13

ÅKE HILLEFORS

THE LANDSLIDE AT GUNNILSE  
IN THE LÄRJE VALLEY  
WESTERN SWEDEN



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## ABSTRACT

On the 16th of September 1730 there was a great landslide in the Lärje valley, a tributary to the Göta River valley, Western Sweden. During Late-Glacial times clay had been deposited in the sea that at that time covered vast areas of Western Sweden including the Lärje valley, then a fiord flanked by rock plateaux. When the valley emerged above sea level, fluvial erosion and mass movements down the slopes began to form deep gullies in the clay deposits. The Gunnilse landslide was most probably released by fluvial undercutting when a high pore water pressure reduced the shear strength of the clay. By continuous leaching of salt from the pore water until the landslide happened, the clay had been sensitive. — The genesis, mineralogy and geotechnical properties of the marine clay are described together with the slope processes now taking place within the unstable gully area.

## INTRODUCTION

The marine clays of Western Sweden, and especially those in the Göta River valley, have long been known for their instability. There was a large landslide about AD 1150 (C14-dated on wood buried in the outfallen clay) at Jordfallet (= "The Soil Fall"; see Fig. 1). In 1648 huge masses of marine clay slid down into the Göta River at Intagan, 4 km south of Trollhättan, damming the river and killing 85 people (Järnefors 1957).

In modern times two large landslides have struck the Göta River valley, in 1950 at Surte (= "The Black Bank", alluding to the blue-black clay; see Fig. 1) and in 1957 at Göta, at a cost of 5 lives lost. Economic losses from property destruction and the blocking of land communications and canal traffic on the Göta River, including the hindrance to navigation on Lake Vänern, have been estimated at many tens of million Swedish Crowns.

On the 30th of November 1977 marine clay fell down from a slope at Tuve (Fig. 1), Hisingen, Gothenburg, where 9 people lost their lives and about 70 houses were destroyed (Hillefors 1978).

State Commissions have examined the causes of clay slide catastrophes in Western Sweden, with the aim of diminishing the risks (Frödin 1919, Jakobsson 1952, Caldenius and Lundström 1955, *Rasriskerna i Götaälv dalen* 1962, Sundborg and Norrman 1963). Areas of sensitive clay have been located and warning systems have been set up. Geological mapping has been performed (Järnefors 1959) as well as geotechnical investigations. Some protective measures have been recommended as e.g. protection against fluvial undercutting of river banks, removal of clay layers to reduce the shear strains in steep clay slopes.

The Gunnilse landslide is described on a land survey map from 1731 (Wilhelm Kruse, *Geometrisk Delineation af ett ansenligt Jordfall . . .*; Fig. 2). Today, this Jordfall area is a most interesting complex landform, surely worthy of protection from geomorphological, geotechnical, botanical and ornithological points of view. The slide scars and clay terraces on both sides of the channel upstream the slide area are typical features of a quick clay landslide and the clay itself is also worthy of a description.

## ROCK MORPHOLOGY

The rocks within the actual part of south-western Sweden consist of Precambrian gneisses and gneissgranites that originally formed sediments and intrusive granites. These sediments have been folded, which resulted in foliation structures striking about N—S and mainly dipping rather steeply to the west and tension cracks per-

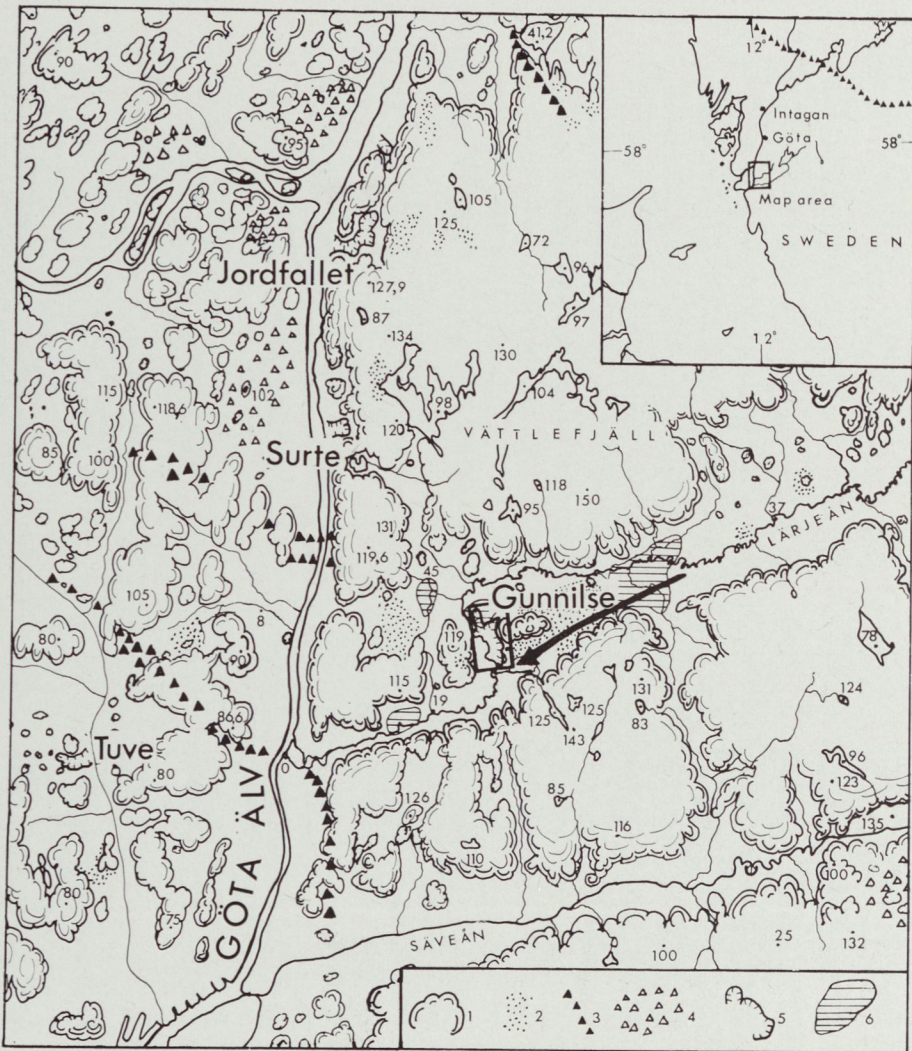


Fig. 1. Survey map of the investigated area. 1 = naked rock; 2 = glaciofluvial gravel and sand; 3 = end moraine (in the inset map the Middle Swedish End Moraines from the Younger Dryas); 4 = drumlin; 5 = landslide scar; 6 = clay deposit over 40 m thick (according to geotechnical investigations by Vattenbyggnadsbyrån, Göteborg). The arrow shows the probable course of the Lärje stream in Preglacial times or before the Last Glacial.

The landslide at Gunnilse happened in the Lärje valley in 1730. Other landslides occurred at Jordfallet and Surte in the Göta River valley about 1150 and 1950 respectively. In the northern parts of this valley two large landslides occurred at Intagan in 1648 and at Göta 1957. The landslide at Tuve happened on the 30th of November 1977.

The approximate N—S strike of the gneiss appears in the form of structure valleys (see the Vättelefjäll plateau). Perpendicular to the strike are broad zones, where joints and fractures, caused by tension and shearing, have concentrated. The Lärje valley, ending in the Göta River valley, has been eroded into such tension and shear zones. The relative height between the rock plateaux and the Lärje valley is about 70—100 m.

For the square — see Fig. 3.



pendicular to the strike. The granites have been strongly foliated by tectonization.

The area was then struck by a strong tangential compression from the west that resulted in overthrusting. The largest thrust zone appears in the Göta River valley. Minor overthrusts occurred along the foliation planes to the east of the Göta River valley (Wedel 1978, pp. 17, 40—52).

Later deformations from other directions than from the west could to a great extent use the preexisting joints, fractures and cracks. So the old open tension cracks could be closed and shearing and crushing could take place along them, i.a. areas close to the west of the Gunnilse area were strongly sheared with faults in NE—SW and NW—SE. Some other blocks have been reorientated and tilted (Lundegårdh 1958, Larsson 1967).

The shear zones and certain gneiss layers have been susceptible to weathering and fluvial erosion. A joint valley landscape thus originated during the Tertiary (perhaps already during the Cretaceous), when shore level displacement — lowering of the erosion basis — in Fennoscandia resulted in increased transport capacity of the streams and in fluvial incision.

The Quaternary ice sheets excavated several basins in the bedrock. On the relatively high plateaux these basins now are occupied by lakes and peat bogs. In the joint valleys the basins have been concealed by thick clay deposits. The glacial excavation was most effective where shear zones and "weak" gneissic structures intersect. Gunnilse is situated exactly in such an intersection. Infiltration and ground-water flow are and have obviously been concentrated to the structure planes and the joints, fractures, etc. (Wedel 1978, pp. 2—4). This fact has been of great importance to the local stability of the clay in i.a. the Göta and Lärje valleys.

## DEGLACIATION AND POST-GLACIAL DEVELOPMENT

The last ice sheet retreated from the WSW to the ENE in Western Sweden. On the rock plateaux the ice stagnated in contrast to the large joint valleys, including the Lärje valley, which drained large masses from the ice sheet. In these late-glacial fiords the ice margin terminated as steep cliffs. Within the deep rock

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Fig. 2. Part of the land survey map of 1731 by Kruse. The landslide area is marked by ponds and overturned trees — also within the bottleformed scar at "Slättmark, kallas Mässen", where bow-bent ridges of clay rise over the surrounding area. The old meandering course of the Lärje stream is stippled — observe the sharp bend in the lowermost part of the map. The new course of the stream runs fairly straight. The quick clay has moved upstream and filled the stream channel almost as far as the Äkrewall bridge (upper left part of the map) that was swept away. At this spot the dammed lake was 12 m deep. In fact the clay flowed several hundreds of metres further upstream from the bridge.

basins (Fig. 1, hatched area) the ice broke up into icebergs and a chaotic mass of calving ice (see Hillefors 1969, p. 264).

However, the ice margin stranded on bedrock thresholds and rock spurs in the valleys. Gravel, sand and varved clay were then heaped up, forming glaciofluvial accumulations that could divert the preglacial-interglacial drainage pattern in some places. This is just the case within the Gunnilse area, where only a narrow gap in the north has been left for the Lärje stream. This previously — perhaps in Preglacial times or anyway before the Last Glacial — flowed south of the rock hill Åsen, now dividing the Lärje valley into two arms (Fig. 1, arrow). The stream now flows due west, making a sharp bend to the south at Gunnilse, where it follows a N—S structure valley, whose steep slopes leave the clay in an unstable position. It was exactly here that the 1730 landslide happened.

At Gråbo (Grå = gravel; bo = dwelling-place), 12 km to the east of Gunnilse, a large glaciofluvial delta was also formed which, to some extent, now dams a large rock basin, where Lake Mjörn was formed by the isostatic uplift in Post-Glacial times. Because of this damming, the Lärje valley has formed a rather isolated marine basin, where clay and silt settled. Its dimensions are consequently out of proportion to those of the Lärje stream, which is now an "underfit stream".

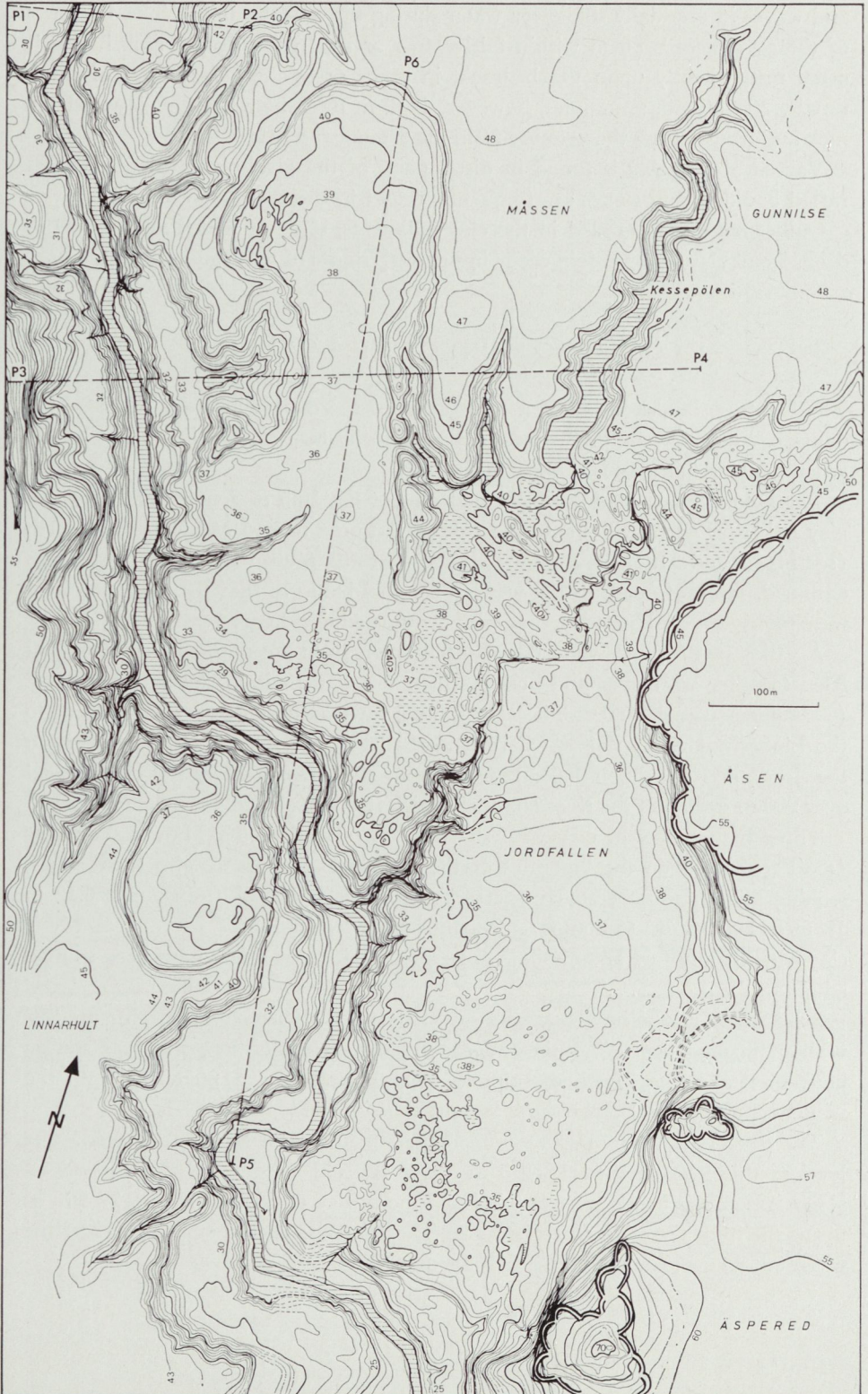
The ice left behind a very patchy and thin till cover on the rock plateaux. The mean precipitation during a year is about 800 mm and the evaporation is about 450 mm according to measurements performed by the Swedish Meteorological and Hydrological Institute. There is an extremely low overland flow within the rock plateaux with a thin till cover. The precipitation runs only short distances over rock surfaces and infiltrates then through structure planes, joints and especially shear zones. To some part, it is stored in the till accumulations (for a rather short time), peat bogs and lakes. Consequently, there is a strong groundwater flow from the rock plateaux downwards to the valleys where the clay deposits are exposed to a high pore water pressure directly or via a layer of friction material (silt, sand and gravel). (Cf. Wedel 1978, pp. 75—89, Lind 1979, in press.)

The coarse glaciofluvial deposits within the valleys also function as infiltration areas. This is considered to have been an important factor for causing the instability of the clay and also releasing the landslide at Gunnilse (Fig. 1).

Since Pre-Boreal time most of the clay sediments in the Lärje valley have been situated above sea level according to pollen analyses by Ann-Marie Robertsson, Stockholm (not published). The flat clay surfaces were formed by sea currents

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Fig. 3. Map of the landslide at Gunnilse showing its morphology. Equidistance 1 m. Profiles (see Fig. 4) have been marked. The even ground contrasts to the ground characterized by tilted blocks of the old dry crust with ponds and bogs in between (dashed area). (The dotted lines in the southeastern Jordfallen area — just around the foot of the slide scar — mark a dumping-ground.)



and waves in gradually shallower water during the isostatic uplift. The thickness of the clay exceeds 40 m within fairly large areas. In the deeper rock basins it often rests directly upon the bedrock, in other areas there is a layer of sand, usually 20—50 cm, sometimes, however, 1—2 m thick between the clay and the rock and transmitting the pressure from the groundwater flow.

Varved glacial clay is found in distal parts of the glaciofluvial deposits. Ice-raftered boulders and stones are frequently found in the marine and glacial clays.

Gullies have been eroded in the clay sediments, some of which are 20—30 m deep. Small clay slumps often occur in the steep slopes of these gullies.

### COEVAL ACCOUNT OF THE LANDSLIDE

The Gunnilse landslide led to a remapping of the estates in order to assess the damage. Fig. 2 is part of the land survey map by Kruse from 1731. The report accompanying this map is summarised below.

The landslide occurred during the evening of the 16th of September 1730. The clay fell from Åsen in the east and from a flat area named Måssen in the north (see Figs 2 and 3). It moved towards the west and south so that the stream was dammed. It also forced up the western channel banks so that the meadows here were mostly covered by it together with overturned deciduous trees.

A valley was formed when the clay fell down from the northeastern corner of Åsen together with trees and bushes. Then the water within the "grass valleys" (= gullies) was dammed. The clay flowed downwards and over the stream to the Linnerhult valley slopes, where it clashed towards the masses, coming from the Jordfallen (= "Soil Falls") area. From the Måssen area, the clay flowed over 900 m upstream the river channel, which it filled.

Three bent ridges of clay with sharp crests formed in the Måssen slide scar (see Fig. 2). Inside the "mouth" of the slide scar there were also such ridges, looking "like high-raftered church roofs with steep gables", from about 6.12 to 18 m in length and to about 7—9 m in height, consisting of a strong and blue clay without any turf or topsoil. ". . . people say that the ridges have been squeezed out of the ground . . ."

An oak was said to have "sailed away" from Åsen about 250 m towards the SW without turning over. "Within and around the clay fall there was reported to have been a strong stench of sulphur" from the 16th of September "until the winter tjäle (= frost) entered the ground".

The discharged clay masses dammed the stream and a lake was formed. The level of this lake reached 15—18 m above the old stream bed. The meadows along the stream bends were flooded and the bridge at Äkrewall (Fig. 2) 900 m upstream from the slide was destroyed. The lake was finally emptied. Then the water cut a new channel, marked on the map (Fig. 2).

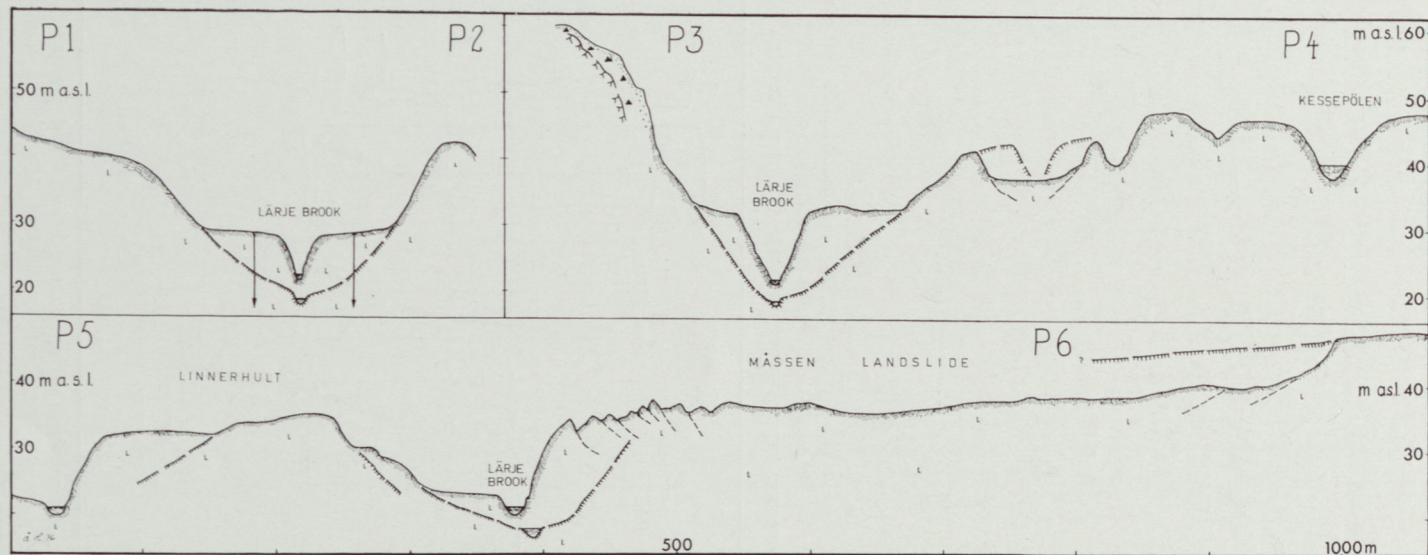


Fig. 4. Profiles. P1—P2 across the Lärje stream with two borings revealing the old land surface and the reconstructed stream position (L = clay). P3—P4 from the Linnarhult rock hill slope in the W (with an accumulation of till on its surface) to the clay terrace at about 32 m in the stream channel and to the E of the large, dammed gully with the pond named Kessepölen. Toothed lines show hypothetical old land surfaces. In the middle of the profile and to the right of it, the actual landslide area. To the right the bowl with the presumed old land surface (toothed lines) and slip surfaces (dashed lines); the out-slidened and upthrust clay nappes in the middle.

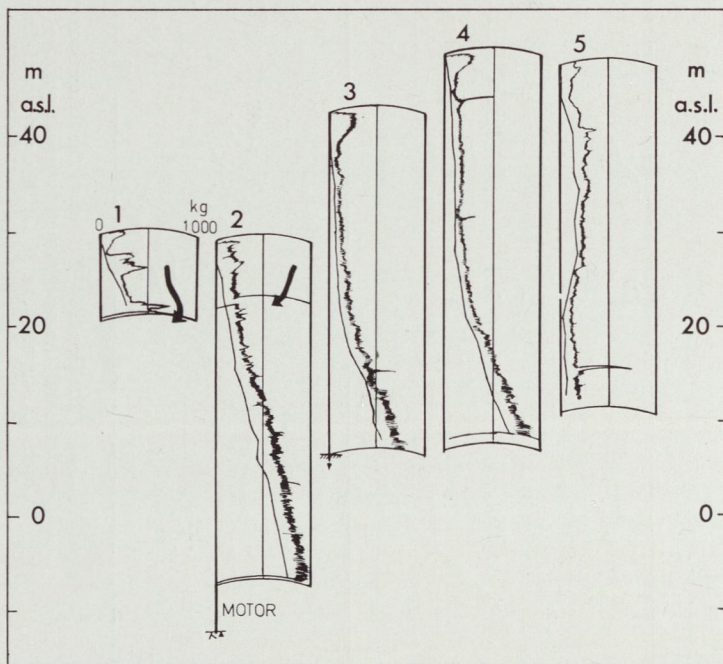
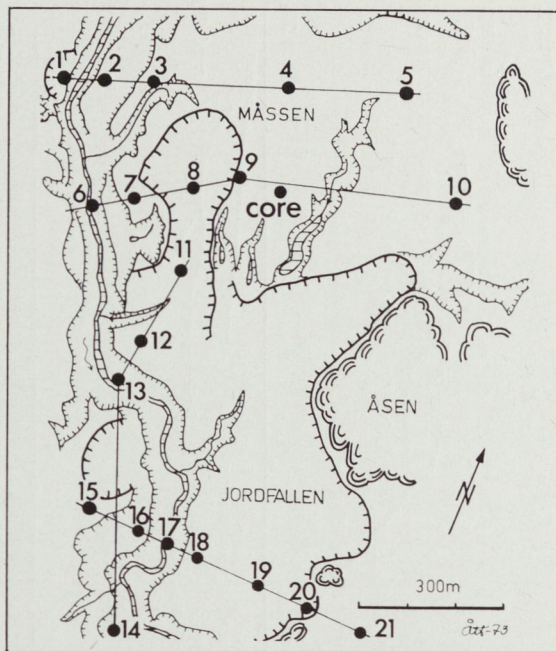


Fig. 5.a. Map of the geotechnical borings in the Måssen and Jordfallen areas. The diagrams shown in Figs. 5 b–e are marked by numbers, the Måssen diagram in Fig. 6 by "core".

Fig. 5.b. Diagrams of the borings along the northernmost profile in Fig. 5a. The jagged lines show the total force and the lines close to the left the friction to the mantle of the borer. The intervals between these curves mark the resistance to the point of the borer.

The high shear strength of the dry crust appears clearly. Below this crust there is a clay layer which is obviously very loose. Single laminae and layers of silt and sand appear as peaks. The arrows in diagrams 1 and 2 mark the probable old stream channel bottom and land surface, now covered by quick clay.

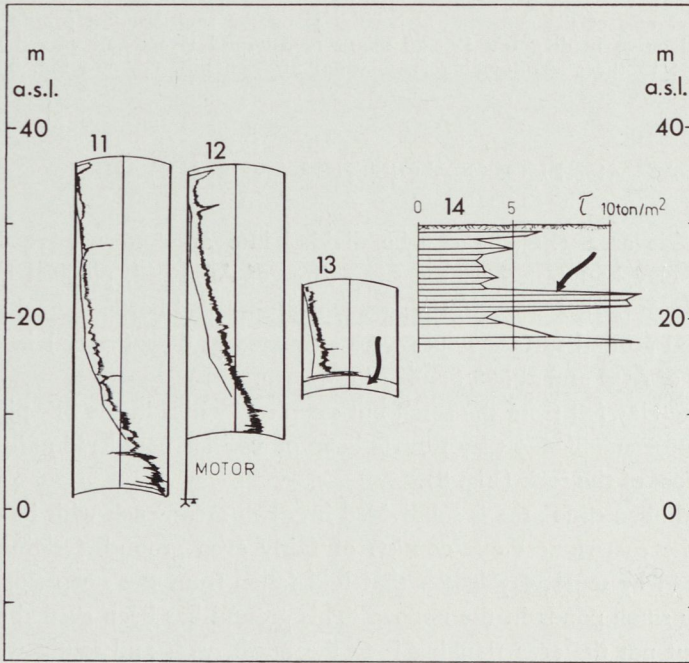
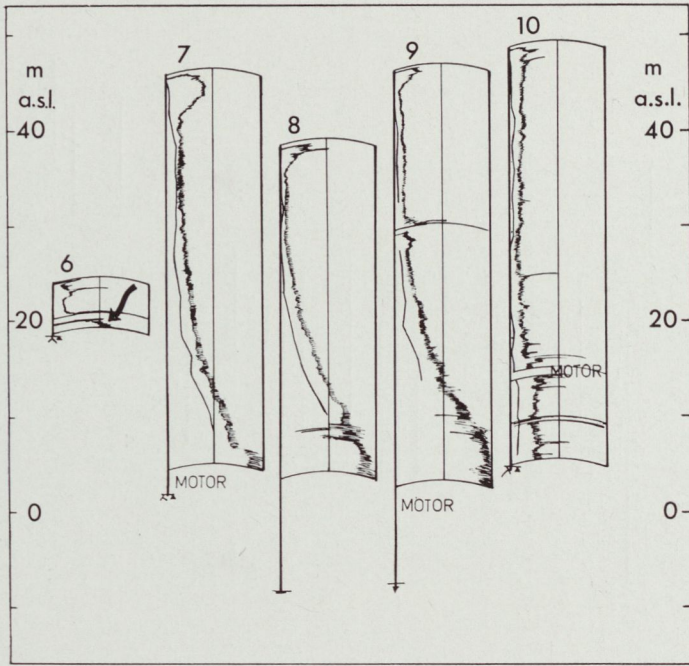


Fig. 5.c. Diagrams of the geotechnical borings along a northerly profile in Fig. 5a. The toothed curve in the deeper layers (diagram 10) might reveal sand layers and varved glacial clay situated close to the glaciofluvial accumulations at Asen hill. Cf. also Fig. 5 b: the explanations.

Fig. 5.d. Diagrams of the borings along the N—S profile in Fig. 5a. Diagram 14 is a vane test. Cf. also Fig. 5 b: the explanations.

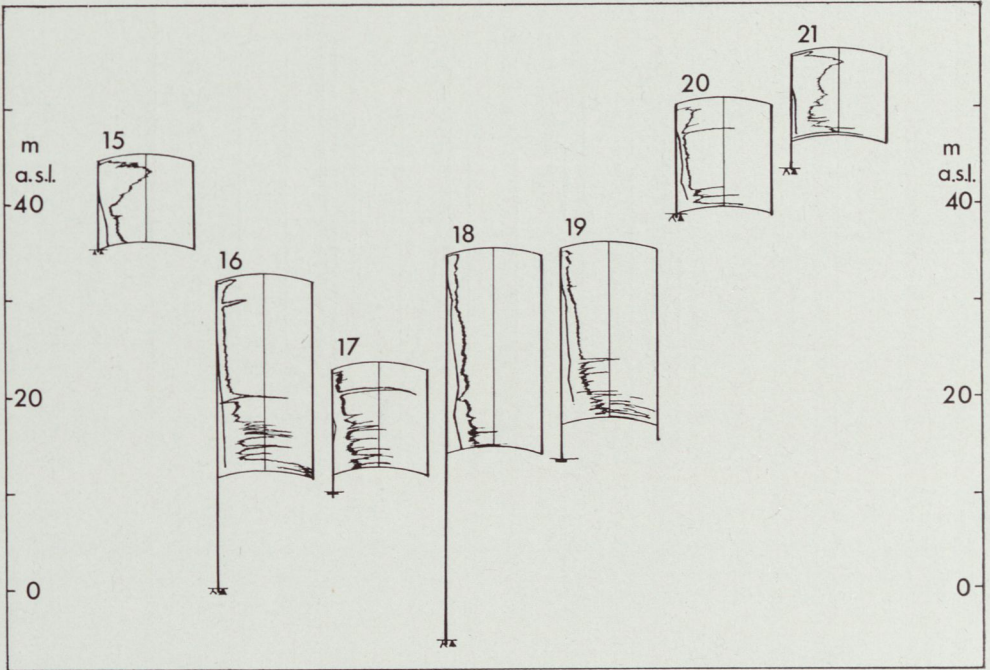


Fig. 5.e. Diagrams of the geotechnical borings along the southernmost profile in Fig. 5a. The toothed curve in diagrams 19—20 might reveal sand layers and varved glacial clay situated close to the glaciofluvial accumulations at Åsen hill. Cf. also Fig. 5 b: the explanations.

### MORPHOLOGY OF THE LANDSLIDE AREA

The landslide area (Fig. 3) can be divided into an eastern part, Jordfallen, where the clay had rested on the steep slope of Åsen hill, plucked by the ice, and a northern part, Måssen, forming a typical so-called bottle-shaped slide bowl. The original ground surface slopes were estimated at 8% ( $= 5^\circ$ ) in Jordfallen to the west of Åsen and at 5% ( $= 4^\circ$ ) in Måssen.

When the clay fell from the small but steep rocky hills in the SE, pieces of the rock also loosened. Today they form a heap of angular boulders in all about 200 m<sup>3</sup> at the foot of the rock (Fig. 8).

The Jordfallen slide area is subdivided into two areas, each with its own topography. The easternmost one consists of fairly even ground. Originally it was characterized by some clay ledges that had fallen from the steep slope of Åsen hill and by small ponds in the hollows. This ground has been evened out by the farmers, but not the area flanking it to the north, west and south, where tilted plinths and ledges of the original stiff crust formed the present rough topography (Fig. 9).

As the coeval report informs us the "grass valleys" between Jordfallen and Måssen were dammed by the landslide. The oblong pond Kessepölen (Fig. 3) seems to be fairly unique where its origin is concerned.

The Måssen slide area is characterized by a narrow debouchement or gate — "the bottle-neck" — and behind it the bowl which is semicircular and has a rear scarp sloping about 30°. Some well-preserved clay ledges can still be seen in their slumping position in the western part of the scar (Fig. 11). Besides the ground here is slightly undulating as it was evened out by the farmers for about 2 decades. The sharp-crested clay ridges — as high as "church roofs" — at the mouth of the scar have also been almost completely levelled.

As Kruse stated in his report, the clay first flowed to the south from the Måssen area and then to the west. It was forced to move upstream, guided by the channel, which was gradually filled by the liquefied clay. The new stream channel, formed when the lake emptied, is now flanked by clay terraces with their surfaces at 33 m a.s.l. close to Måssen and at 26 m a.s.l. about 1500 m upstream (Fig. 4). Boulders and stones now cover the bottom of the fairly straight stream channel. Borings have revealed the pre-slide ground surface beneath the clay terraces (Fig. 5).

On Kruse's land survey map of 1731 a slide scar was also drawn at Linnarhult on the western bank of the Lärje Brook (see Fig. 2). It must be older than the Gunnilse landslide as it was filled out by the clay that slid down from Åsen hill. Also in this area, i.e. downstream from the damming, there are terraces of clay on both sides of the channel, and an old dry crust with plant fragments has been found beneath 5 m of clay (Fig. 5 d, diagram 13).

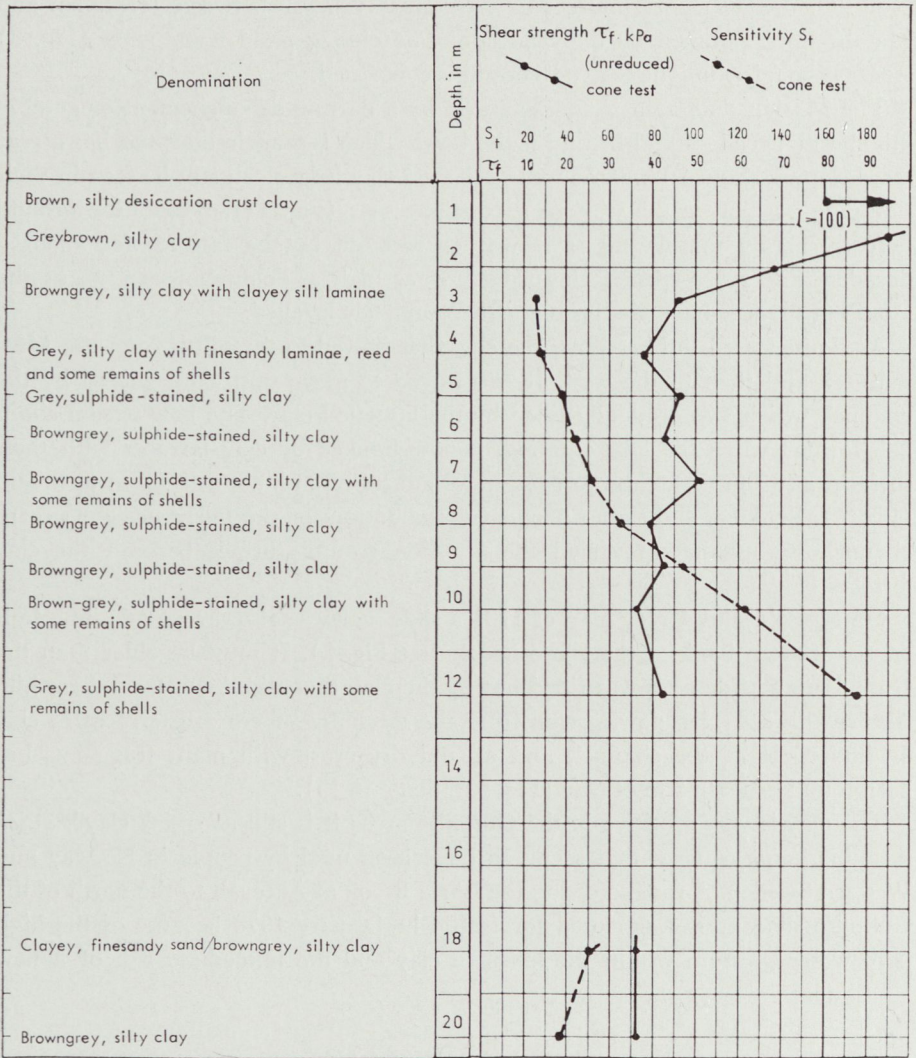
The clay is very sensitive in the Gunnilse area; it is still a "quick clay", *quick* meaning *living*, a term that seems to have been used by people in Norway and Western Sweden. A road, crossing the Lärje Brook at Äkrevall to the north of the Gunnilse slide area, was closed for traffic in January 1978 because of the high pore water pressure within the sensitive clay and the immediate risk of a new landslide.

## THE MARINE CLAY

### GENESIS

Isostatic depression from the ice sheet allowed the late-glacial sea to encroach across low-lying land. The Lärje valley was then a fiord bordered by rocky islands rising some tens of metres above sea level.

Clay settled in the late-glacial fiords. In shallow areas, such as along valley sides, sea currents and wave action resulted in sandy-silty clays being deposited. In deeper basins grey or brownish grey, sulphide-stained clays accumulated. Lenses and laminae of fine sand and silt are rather common.



The extensive and often thick clay deposits in Western Sweden — as in Southern Norway — seem to have a complex origin. Only a minor part of the clay particles may have been derived directly from the till being washed by melt-water streams from the ice sheet and by sea breakers along the valley shore slopes.

Remnants of deep-weathered Precambrian rocks, in lee- and stoss-side positions towards the glacial movement direction, show that weathering most probably took place in Preglacial times as an exogenic process (Hillefors 1969, pp. 16—25) regarding some localities, while others may indicate endogenic processes. It

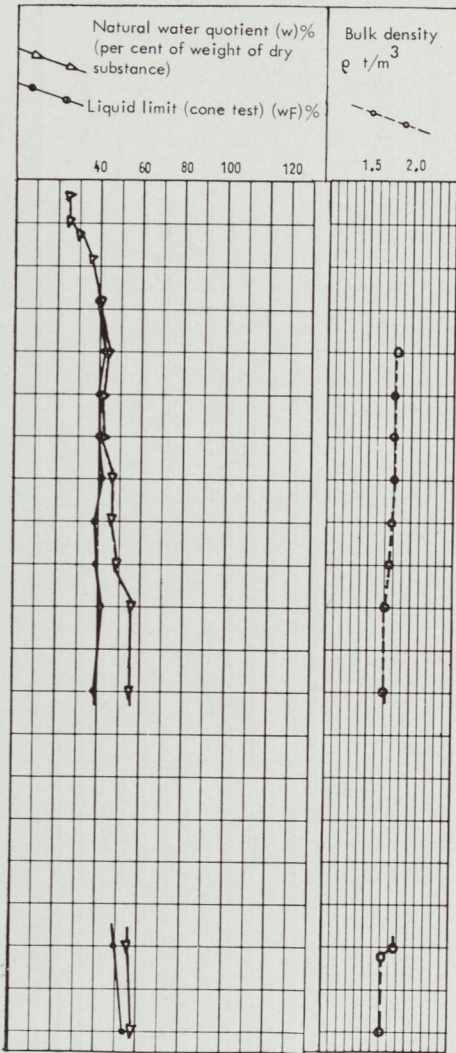
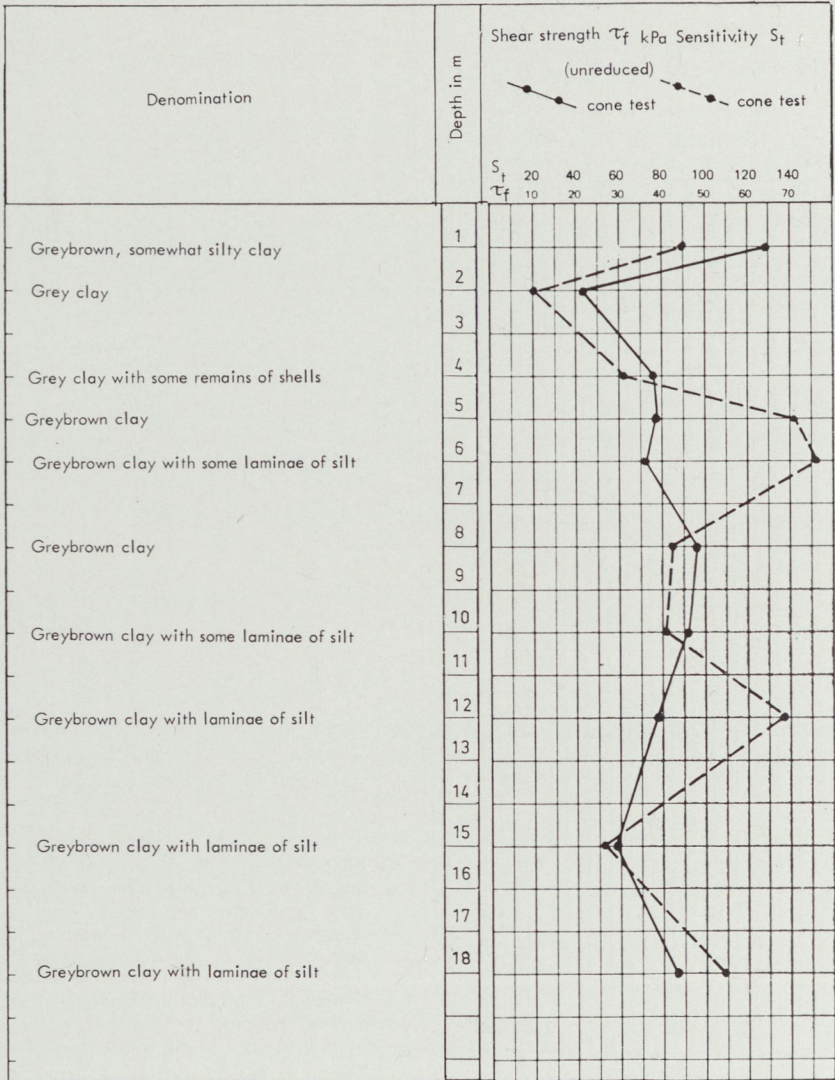


Fig. 6. Geotechnical diagram of the boring to the E of the Mässen landslide area (for the locality see Fig. 5 "core"). The samples from 14 and 16 metres fell out of the borer as the clay apparently was remoulded at the boring and thereby liquified. The "gap" between the two curves showing the natural water quotient and the liquid limit (cone test) is typical of quick clays.

is here of some importance to refer to the areas in northeastern Scania, southernmost Sweden, with deep kaolinization of Precambrian rocks, caused by exogenic weathering.

The disintegration of feldspars in gneisses and granites and of Cambro-Silurian shales in the province of Västergötland may have constituted a certain clay content in the preglacial and interglacial soils in Western Sweden. Today these soils appear to form an integral part of the late-glacial and post-glacial clays. This is directly indicated by the finds of Tertiary pollen and spores in the clays in the Göta River valley (Fries and Ross 1950). Tertiary pollen has also been re-



cognized in beds of till, sand and silt at Ellesbo and Dösebacka (unpublished analyses by Urve Miller and Ann-Marie Robertsson; cf. also Hillefors 1969, p. 78).

The marine clay in the joint valleys in Western Sweden seems to have been transported over great distances as clay suspensions, particularly during Younger Dryas, when the ice recession changed into a readvance and standstill in South Central Sweden, just in the province of Västergötland about 100 km NE of the Lärje valley (see inset map, Fig. 1). This stage lasted for about 800 years. Then the meltwaters with silt and clay flowed westward and i.a. through the Lärje

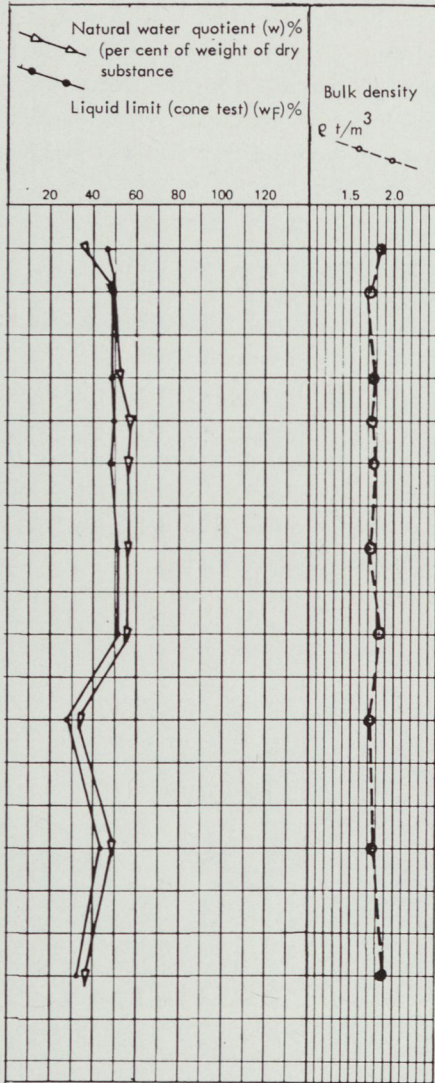


Fig. 7. Geotechnical diagram of the boring 18 (see the map Fig. 5). Below the dry crust there is a layer of highly sensitive clay. The "gap" between the two curves, showing the natural water quotient and the liquid limit (cone test), is widest where the clay layers with the highest sensitivity are found. — Characteristic of the clay in this boring are the silt laminae.

valley during continuous flocculation and settling.

The deposition was rapid during Late-Glacial times. Most of the Lärje valley clay accumulated after the area was released from the ice about 12 000 B.P. until shortly after the close of the Younger Dryas stadial at 10 000 B.P. Sea water with a salt content of about 30–35 ‰ remained as pore water.

In Western Sweden as in i.a. Southern Norway the sparse occurrence of till with a clay content of only 3–5 % contrasts with the thick deposits of clay in the joint valleys. Even if the marine clay has a considerable and also in some cases a predominant silt content, there remains a puzzling problem where the

genesis of the till and the clay is concerned. Rosenqvist (1975) believes that the bulk of the clay from the rocks weathered during Pre-Quaternary times was not incorporated in the ice but the quartz grains — remains from the weathering — were in great quantities. Later these sand masses were deposited as basal till, where they now make up a substantial part of the sand fraction. The sedimentary clays were formed chiefly during the Last Glacial.

#### MINERALOGY

The marine clay in Western Sweden has previously been analysed by X-ray but only in a few cases. Anyhow, very few diagrams have been published.

Four samples from different depths of a boring in the Måssen area have now been investigated by X-ray diffractometry — untreated, treated with ethylene and glycol and after heating to 450°C. All the diffractograms reveal a clay predominated by illite and with a small amount of chlorite. No swelling minerals or kaolinite were detected. Non-clay minerals were represented by feldspars, quartz and amphiboles. Only one diffractogram is published here (Fig. 12).

Torstensson (1973) mentions two marine clay samples from the Göta River valley, taken at depths of 4 m and 7 m respectively.



Fig. 8. Large boulders, which probably slid down when the clay fell out from the steep slope in the southernmost part of the Gunnilse landslide. The scar in this rock slope has not been completely covered by lichens, so it does not seem very likely that frost is responsible for recent shattering of the rock.



Fig. 9. Clay nappes of dry crust rise over elongated ponds and swampy grounds. A rich grove vegetation has developed. The southern part of the Gunnilse landslide.

Illite predominates, while the contents of chlorite, quartz and feldspar are low. The clay contains a small quantity of kaolinite and shows traces of expanding minerals such as montmorillonite. The content of carbonate is considerable, most probably deriving from decomposed shells and long-transported carbonate from the Cambro-Silurian beds in the province of Västergötland. Similarly, the content of chlorite and kaolinite could come from several, perhaps rather distant sources.

Obviously, there is a difference in mineral composition of the clay deposits in the Göta River valley and the Lärje valley. The explanation must be that the Göta River valley was both a late-glacial and post-glacial fiord which received clay suspensions from areas, much more extensive and varying and during much longer a time than the Lärje valley.

Varved glacial clay, deposited in the sea just outside the retreating ice has also been analysed by X-ray. The samples come from three localities — Gråbo, Grimbo and Fjärås Bräcka — situated at a distance of no more than 50 km from Gunnilse. Illite predominates in all three samples. The glacial clay at Gråbo and Grimbo, 14 km to the east and 8 km to the west respectively of Gunnilse, has a high chlorite content, at Grimbo there was also a minute kaolinite content. Feldspars and quartz are subordinate. The range of composition revealed is typical of glacial clays in Sweden according to Collini (1950, p. 195).

Marine clays in the Oslo region, Norway, are also predominated by illite (40%) and they have a fairly large chlorite content (20%) and some kaolinite, as well as quartz (25 %) and feldspar (15 %). In this area the Cambro-Silurian shales may be one of the sources of the clay material.

### STRUCTURE

The flaky clay minerals are arranged in different flocculated structures. The bonds between them are due to electrical charges, roughly positive at the edges and negative on the surfaces, and to ions in the pore water, when the clay was deposited in the sea. The consolidation processes have also played a role.

In this connection, marine clays are of the greatest interest. They are characterized by large, dense aggregates, separated by large voids. These aggregates are composed of some larger clay particles which have a definite arrangement and are strongly bound to each other. Between the aggregates there are connection links of small particles, haphazardly arranged in the natural state and much weaker united than the large ones (Pusch 1970, pp. 50—59).

When the clay is exposed to shearing, the movement is located to the weaker



Fig. 10. The dammed gully and the winding pond Kesepölen. To the left the clay-terrace surface. In the background the rocks with steep slopes down to the marine clay on the bottom of the joint valley.



Fig. 11. The western part of the bowl of the bottleformed Måssen landslide and the proximal part of it. Some back-tilted and slumped clay nappes are visible and small elongated ponds in between them. In the background the southern edge of the Vättlefjäll rock plateau, bordering the Lärje joint valley.

links, while the aggregates remain intact. The small particles in the links are simultaneously reorientated, as they turn their flat surfaces towards each other, forming so-called domains. If the clay is remoulded the "cardhouse structure" of the aggregates is also broken down (Pusch 1970, p. 69).

The pore water may be stored in the voids of the clay or it may diffuse through the aggregates and links. Closest to the clay minerals the pore water is influenced by the electrical charges of the crystals because of the dipolarity of the water molecules. With an increasing distance from the minerals a gradual transition to freely mobile water takes place.

In principle, cations are attracted to the negatively charged clay surfaces and anions to the positively charged edges of the particles. The interaction between the minerals and the pore water with ions is very complex and of importance to the arrangement of the particles of natural clays and thus also to the geotechnical properties of these clays (Forslind 1953, pp. 58—59).

Consequently the electrolyte cations may function in different ways. They may diffuse into the intercrystalline space, when attracted to the minerals. Here "they disturb the water lattice and partially compensate the repulsion between adjacent crystals, facilitating their approach" (Forslind 1953, p. 60). They may form

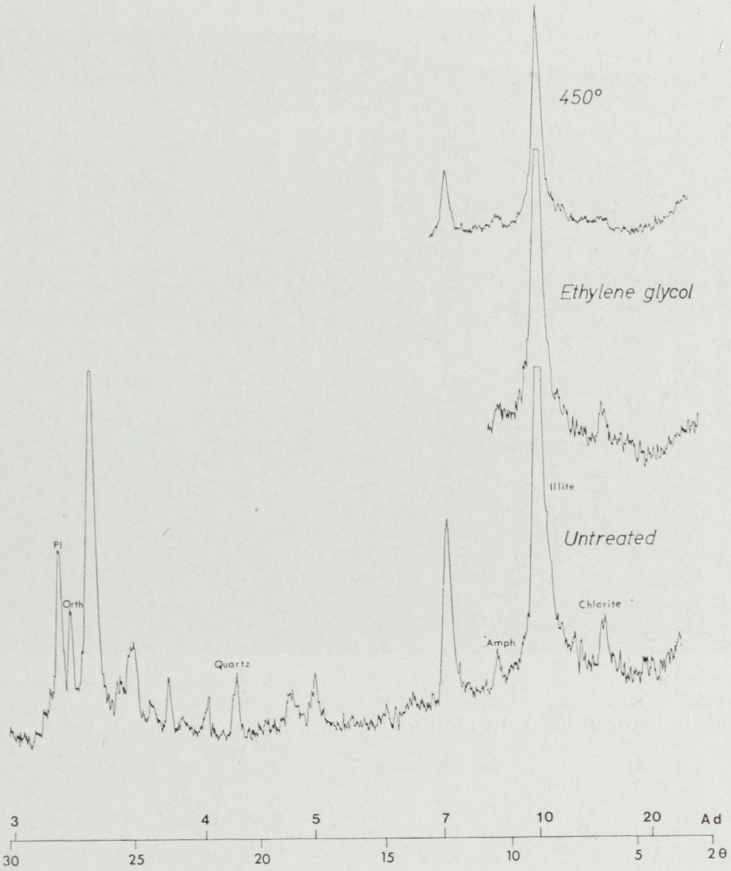


Fig. 12. X-ray diffractograms for oriented sample of marine clay from Gunnilse (12 m depth, the Mässen core). The clay minerals are illite (dominant) and chlorite. Non-clay minerals are quartz, feldspars and amphiboles. Other samples from 3, 6 and 9 m depth show the same composition.

bridges or may be polarized between two clay particles (Rosenqvist 1955, p. 51). In all these cases the cations unite the clay particles firmly, thereby contributing to the shear strength of the clay.

At shearing of marine clays, meaning that particle contacts are broken and domain structures are formed, the cations seem to take an active part in the process of establishing new contacts between the particles. However, if the clays are leached (see below), new interparticle contacts may not be established, as only a few ions are available for forming bridges or for polarizing, etc. between equally charged mineral surfaces as e.g. in the domains. Furthermore, when the concentration of ions in the pore water has decreased, a dissociation of adsorbed cations takes place from the minerals. Then their net negative charge increases (Pusch 1968, p. 3:21). Such a leached clay has a high sensitivity, i.e. a low shear strength

in the remoulded state. The concept of sensitivity has been discussed by i.a. Söderblom (1972, p. 1—2). He has divided the clays according to their proneness to deformation into so-called rapidity classes.

Organic matter of fibrous kind of chemical substances such as amino acids, phosphates or sulphides reduce the shear strength. They act as dispersing agents (Pusch 1970, p. 6, Söderblom 1966, p. 424, 1972, p. 5). The clay in the deep joint valleys in Western Sweden is often sulphide-stained or "sulphide-varved". The water exchange was obviously impeded by rock bars and thresholds in the late-glacial fiord-basins as can also be the case in fiords today. The bottom water in such basins could then be completely devoid of oxygen. Then hydrogen sulphide could be produced and manganese and iron sulphides could originate. The samples from the Måssen core (Fig. 6) show a sulphide-stained — and sensitive — clay. Because of the high late-glacial sedimentation rate the percental content of organic matter is low.

TABLE 1. Salt content of the clay in the Måssen core (for location see Fig. 5).

<i>Depth below ground surface in m</i>	<i>Salt content in the pore water in g/l</i>
3	4.5
8	6.4
12	2.3
18	2.5
20	4.8

Some samples from the Måssen core were also analysed for the salt content (Table 1). The analyses indicate that the clay had been strongly leached.

Since shear stresses are greatest in a thin cylindrical layer, it is the failure of that layer which actually starts the landslide. The clay is of course remoulded by the great friction. If it then is a highly sensitive clay, it will rapidly become liquified. Upon this slurry, moving downwards, ledges and blocks of the dry crust flow, clash together and are tilted. The landslide extends upslope until stable ground (bedrock or friction material) is reached or until the filling of the available hollow or valley downwards brings the slide into equilibrium. At Gunnilse the quick clay flowed upstream for a distance of about 1500 m.

#### STRATIGRAPHY, GRAIN SIZE DISTRIBUTION AND WATER QUOTIENT

There are some typical facies of the marine clay in Western Sweden. The deeper layers were deposited fairly close to the retreating ice margin. Then a sandy-silty clay was formed as meltwater streams transported sand and silt, which settled together with clay particles. As the ice front gradually disappeared towards the

NE, the silt and clay material became predominant. At the same time the land was isostatically lifted up, which meant that the archipelago became denser and the fiord valleys, including the Lärje valley, were increasingly protected from high waves, which consequently had a decreasing effect. The basins were then filled with a grey or brown-grey, silty clay.

According to 8 sedimentation analyses of clay samples from the Måssen core, the clay content is about 25—30 % in the lower layers (18—20 m depth from the ground surface) and 30—45 % in the upper ones, the remainder being almost exclusively silt, only 2—3 % coarser than 0.074 mm. Consequently the Måssen clay — and probably also the clay in the Lärje valley — is considerably coarser than the clay in the Göta River valley at e.g. Lilla Edet and Bäckebol, which has a clay content of 50—57 %, the remainder being silt (Pusch 1970, p. 26, Torstensson 1973, p. 51). This difference may reflect the changed sedimentation conditions during Late-Glacial and Post-Glacial times.

The borings in the Gunnilse area indicate that silty-sandy laminae occur in the clay sediments (Fig. 5, diagrams 4, 7, 8, 9, and 10). These laminae seem to have a rather large extension (cf. Wedel 1978, p. 53). When they appear in direct connection with the glaciofluvial accumulations, they are most probably interpreted as distal deposits of meltwater streams from the ice sheet. When they appear fairly high up in the clay sediment column, they may be the result of intensive washing of the valley sides by breakers and shore currents during violent storms. Such weather conditions must have been fairly frequent during Late-Glacial times, especially during the Younger Dryas stage (Hillefors 1969, p. 293, Liljequist 1974, p. 297).

The clay at Måssen has a water quotient in per cent of dry substance of 40—60 below the dry crust and 20—35 in the dry crust. The water quotient increases towards the depth and towards the eastern parts of the Gunnilse area near the glaciofluvial accumulations and Åsen hill.

#### PERMEABILITY

Three measurements have been made regarding the permeability in the vertical direction of the marine clay from the Måssen core (Table 2). The analyses show values which are consistent with investigations by e.g. Pusch (1970, p. 60), who reports a quick clay from Lilla Edet in the Göta River valley, made up of laminae with high clay and silt content and with a permeability coefficient of  $3.1 \times 10^{-7}$  cm/sec. Here horizontal flow was faster than the vertical flow. Pusch also stresses that the permeability diminishes in leached clays because of clogging of loose particles.

Even though it was not possible to measure the permeability parallel to the bedding in the Måssen core samples, it may still be possible to make deductions

TABLE 2. Permeability of marine clay from the Måssen core (for location see Fig. 5).

<i>Depth below surface in m</i>	<i>Permeability in cm/sec</i>
4	$1.5 \times 10^{-7}$
10	$1.8 \times 10^{-7}$
20	$5.8 \times 10^{-8}$

based on the penetration resistance to the borer (Fig. 5). According to this, the clay is evidently laminated (see above). A horizontal flow of ground-water from the glaciofluvial deposits to the east of the landslide area and from the Åsen and Linnarhult hills has obviously taken place, especially as a strong hydraulic gradient must be assumed here because of the topography, the relative relief being about 100 m (from rock crest to bottom of stream channel). The water quotient analyses support this conclusion.

#### LAND UPLIFT AND ITS EFFECTS ON THE MARINE CLAY

Perhaps even before isostatic recovery had progressed so far as to elevate the marine clays above sea level, their static and physico-chemical properties had been radically changed. The static safety factor of the clay masses on the sloping surfaces of the bedrock basement decreased as the counterpressure of the sea water gradually diminished and finally disappeared, and the undercutting of the clay slopes by running water increased the shear stress in these slopes.

Intensified leaching over thousands of years was caused by a ground-water flow, which increased as the hydraulic gradient from the surrounding rock plateaux towards the stream channel became steeper because of the land upheaval and the gradual fluvial incision. Consequently the clays became increasingly sensitive within large areas.

At the same time, however, draining of pore water from the clay in the layers above the ground-water table (about 5—6 m below the ground surface in the Gunnilse area according to the geotechnical borings) improved its shear strength. The top layer of the clay, about 1—2 m thick, has formed a dry crust due to desiccation and chemical weathering. This dry crust is characteristic of i.a. Fennoscandian Quaternary clays and proves that these clays are diagenetically developing. The crust has also shrunk by exchange of  $K^+$  for  $N^+$  (Rosenqvist 1955, p. 91, 1967, p. 15) so that fissures have formed in it. These may be failure indications and they allow fairly large amounts of rain and melt water to infiltrate. Consequently the underlying layers may be exposed to rather rapid stress changes.

Rosenqvist also points out the fact that recent sedimentary clays contain rock flour, representing minerals from magmatic and metamorphic rocks which have formed at elevated temperatures. Consequently, these minerals are not in chemi-

al equilibrium in the clays with low temperatures, meaning that they are continuously being broken down. Therefore, the weathering of feldspars will produce potash ions in the clay pore water, leading to a change in the K/Na relation, a process of importance in the stiff uppermost clay layer, as has already been pointed out.

According to Bjerrum (1967, 1971) quick clay may regain shear strength. When the pore water has been deprived of its ions, the chlorite minerals are not in equilibrium. The magnesium ions are then dissolved and form layers around the clay particles in the same way as the salt before the leaching, and they have the same effect as the "original" ions, which means that the liquid limit of the clay increases and the sensitivity decreases. Bjerrum also thought that cementation processes can take place by e.g. iron compounds being precipitated at the links between clay particles.

Rosenqvist furthermore thinks that compounds of organic matter, carbonates, gypsum, aluminium, iron, and silicon can precipitate under certain conditions and form stable cements at links between clay particles, resulting in a strengthening of the structures. Cementing of clays has been reported from Sweden (the Göta River valley) and eastern Canada (Rosenqvist 1967, p. 16).

Bjerrum's hypothesis, further elaborated by Rosenqvist, also implies that the leaching develops from below and upwards by the ground-water flow, guided by rock thresholds. This means that highly sensitive and leached clay lenses and layers may superimpose clay layers, which are also leached but not sensitive because they have regained their shear strength by chemical cementation of interparticle contacts. This situation could possibly be the case in the Måssen area according to the geotechnical borings (Figs 5 and 6), where a layer with a low salinity (Table 1), a sensitivity of at least 180 and a thickness of about 15 m superimposes a clay with an equally low salinity but with a sensitivity of about 70. Even in other areas of the Lärje valley such as Angered, 1 km to the west of Gunnilse, so-called overconsolidated clay has been found (Alte 1973) and in this case chemical cold welding might just be one of the causes of the increased shear strength.

Climatic changes during Post-Glacial times have surely also affected the shear strength of the marine clay. Periods of higher temperatures have been favourable for chemical weathering of the uppermost layer, the dry crust. Changes in precipitation have caused fluctuations in the ground-water table, which in its turn has caused changes in the pore water pressure. During wetter and colder climatic periods floods, fluvial undercutting, creep and slumpings have been more frequent and the shear stresses have increased.

In this connection it is of great interest that Grove (1972) provided information about the occurrence of landslides, rockfalls, floods, and avalanches during the so-called Little Ice Age in Norway. Studies of land survey maps from the

eighteenth century (Kruse 1731, Fineman 1759, etc.) of the Lärje valley indicate several minor slides and slumps along the stream channel. Therefore, the problem as to whether or not mass movements in Western Sweden were particularly frequent during the previously mentioned period is worthy of a special paper.

### CAUSES AND DEVELOPMENT OF THE GUNNILSE LANDSLIDE

The reconstruction of events leading up to this landslide in the 18th century must of necessity be tentative.

External and internal factors have been effective here as in other landslides.

Gullying, an external factor, obviously affected the clay deposits in the entire Lärje valley. At present the gullies are about 25 m deep. Hence the critical value for such steep clay slopes to fail had surely been exceeded according to Bjerrum (1971, p. 8), who in this case mentions the value 12—15 m with due regard to the properties of different clays.

Fluvial undercutting of the stream channel slopes released minor slides and slumps before the great landslide on September 16th 1730 as well as after it.

Wenner (1951) has shown that several landslides occurred in Western Sweden during the autumn months as did the great landslide at Gunnilse — and the catastrophe at Tuve (30th of November 1977). This is explained by the fact that the rivers in Western Sweden have an oceanic regime. Snow melt has, as to my knowledge, not caused any landslide here as in Norway. During autumns it is quite probable that the dry crust had become extremely heavy because of rain water. During such weather situations the clay also was exposed to a great pore water pressure at e.g. Gunnilse. This was one of the main causes of the Surte and Göta landslides in the Göta River valley (Jakobson 1952, pp. 39—42, Odenstad 1958, p. 84) and also at Tuve judging by preliminary investigations (personal communication from Civil Engineer Bengt Johansson, Gatukontoret, Göteborg). At Gunnilse the lenses of sand and silt in the clay in the eastern parts and close to Åsen hill and the glaciofluvial accumulations may consequently have had a direct effect on the instability of the clay and been the direct cause of the landslide, as has been stressed by Söderblom (1972, p. 2).

Obviously, the Gunnilse landslide area had long before the catastrophic failure on the 16th of September 1730 been exposed to high pore-water pressure, etc. But until then it had remained stable and resistant. To explain this problem we have to consider internal factors contributing to the reduced shear strength of the clay.

From Åsen hill, Linnarhult hill and the rock plateaux on both sides of the Lärje valley as well as from the glaciofluvial deposits — good infiltration formations — a ground-water flow has continuously moved downwards through the bedrock and through the clay towards the gullies and the stream channel for

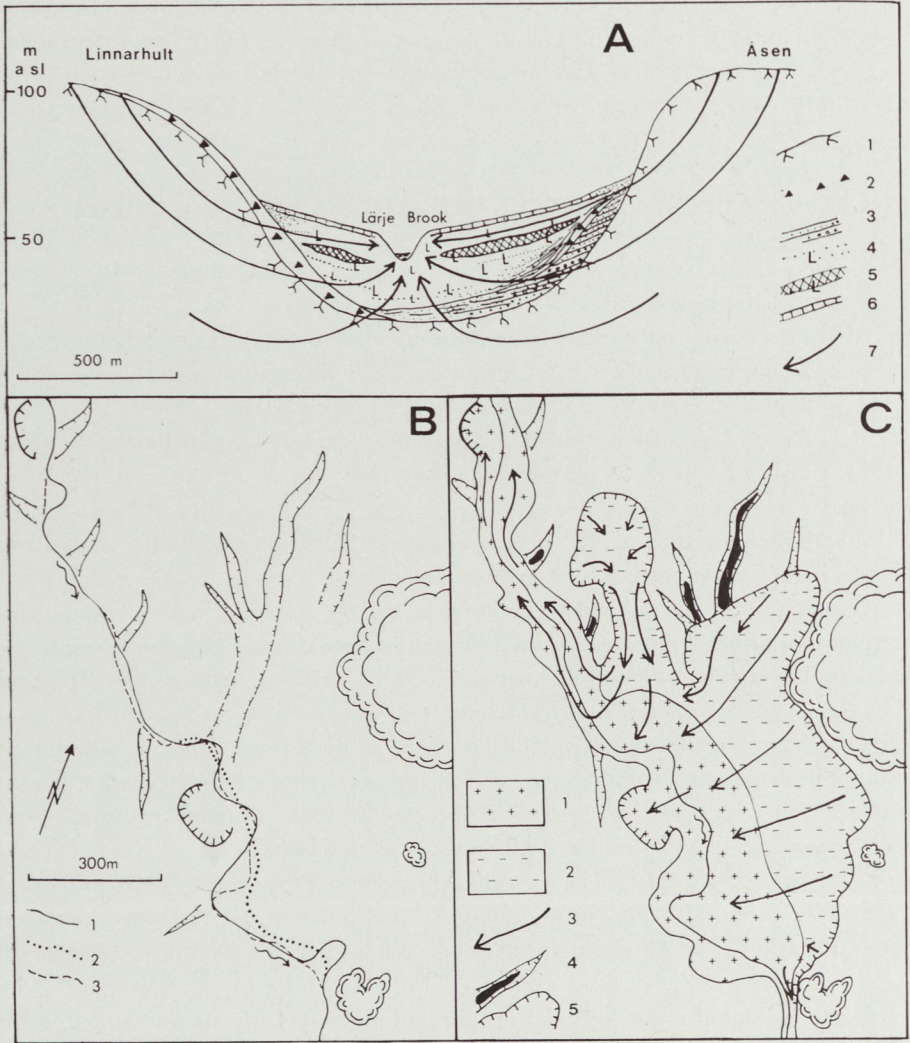


Fig. 13. A. Sketch of a cross-section of the Lärje valley between Åsen and Linnarhult. 1 = rock; 2 = till; 3 = sand and gravel (glacial lee-side deposit); 4 = marine clay with laminae of fine sand; 5 = layers of quick clay; 6 = dry crust; 7 = hypothetic ground-water flow trajectories.

B. The Gunnilse area before the slide — a reconstruction. 1 = the pre-landslide stream channel (according to Kruse's map, 1731); 2 = stream channel over the landslide area after the lake, dammed by downslidden clay, was emptied (also according to Kruse's map, 1731); 3 = the stream channel today; 4 = gullies, existing and — in the landslide area — hypothetic; it is very probable that there was at least one gully in the Jordfallen area before the slide.

C. Sketch map of the Gunnilse landslide area. 1 = area, elevated by the slide; 2 = area, lowered by the slide; 3 = hypothetic flow directions of the sliding clay; it is most probable that the slide began by an initial slumping in the eastern bank in one of the bends of the stream channel (see B); 4 = dammed gullies.

thousands of years (Fig. 13). This flow, facilitated by the sand and silt laminae in the clay, washed away the salt in the pore water of the marine clay. By leaching a highly sensitive clay, a quick clay, formed. This process seems to have started from the bottom and continued upwards. It has possibly been followed by a cold-welding, so that some clay layers have regained their shear strength to some extent.

The releasing cause of the landslide was most probably that a slump occurred in the eastern stream bank in one of the bends in the southern part of the Jordfallen area, where the Linnarhult landslide had happened previously. Then the stresses finally exceeded the shear strength of the clay. A cylindrical slide layer was then formed in the quick clay, probably about 7–10 m below the ground surface. This depth has been estimated from observations in other quick clay landslides in Norway in particular and from the geotechnical borings at Gunnilse.

So the clay began to slide and was then remoulded and became a slurry on which broken pieces of the dry crust flowed. The landslide retrograded until it reached firm ground on the steep westside of the Åsen rock hill. As it grew larger, deeper clay layers were involved. An extended slide scar was formed.

The clay within the Måssen area was directly set in motion when its southern support slumped away. Thus, the landslide continued by a retrogradation to the north and the bottleformed slide scar was formed. The quick clay moved to the south where it clashed against the masses that had fallen out from Åsen hill. Then it was forced to flow upstream the stream channel.

### THE LANDSLIDE AREA AFTER THE CATASTROPHE

The landslide area was used as pasture land by the farmers before the catastrophe. This use was of great economic importance at that time. The destruction was severe, so the ground had to be restored as soon and as much as possible. The farmers then had a great help of the winter frost and rains.

The central and eastern part of the Jordfallen area and some areas of the Måssen scar were probably fairly smooth immediately after the landslide. Outside them the ground, characterized by a rough topography consisting of plinths, heaps and ridges of clay with small bogs and ponds in between, was, however, some years after the landslide covered by bushes and a dense wood of alder, oak, birch, aspen, and lime (according to a land survey map by Fineman 1759), a vegetation that still covers the area.

Two gullies, 150 and 250 metres long and 10–12 metres deep, have been eroded into the clay, thrust up at the landslide. It is most probable that the farmers dug ditches to drain the areas, which they tried to reclaim. Then running water has cut itself gradually deeper. Now the gullies have bottom pavements of stones and boulders, washed out from the marine late-glacial clay.



Fig. 14. The gully slope close to the Lärje stream (left) and the terrace at 33 m level. This gully slope was very wet from ground-water seepage during the snowmelt season in 1973 and small slides of clay knolls were observed. View from the gully slope to the NW of the Måssen landslide and towards the NNE.



Fig. 15. A gully close to the western part of the Måssen landslide. It was dammed by the quick clay that flowed upstream the channel from the Måssen area and now forms a terrace bulge in front of the gully.



Fig. 16. A recent small landslide in a steep clay gully slope to the NW of the bottle-formed Måssen slide scar.

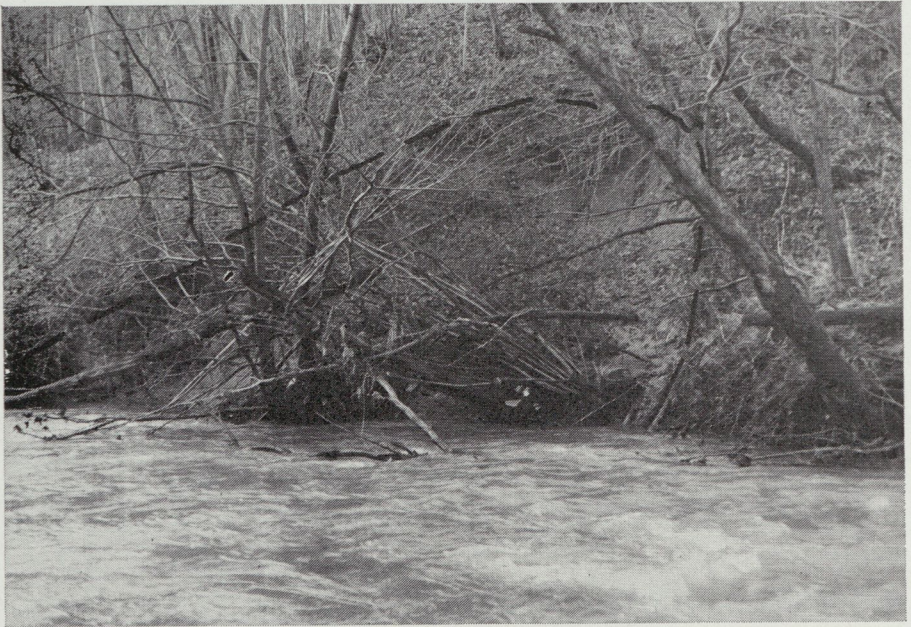


Fig. 17. The Lärje stream flows fairly swiftly through the clay masses that once dammed its channel. The standing waves reveal that boulders, washed out from the clay, have formed a pavement on the stream bottom. A fresh clay fall in the bank is visible. Several slumps of this kind appear along the channel banks.



Fig. 18. The gully slopes to the W of the Måssen landslide with many tussocks of *Deschampsia caespitosa* and *Juncus conglomeratus* (at the bottom). The gully bottom is filled with mould and clay which have been washed down. This material makes up a swamp (left) which drains into a sinkhole (the nearest arrow) in the clay. Then the water flows into a subterranean channel, the mouth of which is visible at the furthest arrow.

There is continuously a strong groundwater flow in the whole of the Gunnilse area. Some of the gully slopes to the west of the Måssen slide scar are very wet after heavy rains and snow melt as e.g. in 1973 (Fig. 13). The flow then follows the permeable fine sandy and silty laminae in the clay.

The branching system of the short gullies, which together forms a semicircular basin with a fringed back slope and is situated to the west of the Måssen scar, seems to have developed after the great landslide as Kruse has only drawn one small gully, aligned NE—SW, on his map from 1731. The same applies to Fineman's map from 1759.

Another gully system to the NW of the Måssen scar supports a large rill during rainy periods.

Both these gully systems had their exits blocked by the quick clay that flowed upstream. The water from the gullies percolates the blocking clay in front of their mouths (Fig. 14).

In recent years minor landslides and slumps have occurred on the steep slopes of the gullies and the stream channel (Figs 15 and 16). Solifluction and soil creep are active. During the winter, the frost reaches a depth of 1—1.5 metres. Due to the freeze-thaw process, blocks of the dry crust are dislodged and gra-

dually transported downwards along the gully slopes and further to the flat clay surfaces.

Some species of grass, i.a. *Deschampsia caespitosa* and sedges such as *Juncus conglomeratus* form tussocks in the gully area. These tussocks freeze more easily during the winter and dry up more easily than the surrounding ground. Consequently they become cracked and rifted and the soils are exposed to splash erosion. Naked soil stripes are therefore rather often seen from such grass tussocks in different stages of disintegration (Figs 18 and 19).

The gullies or "grass valleys" are used as pasture land. They are then exposed to erosion from cattle hooves, especially when the ground is wet. This trampling is one of the factors in the process of forming terracettes.

On a more restricted scale, water rats have been tunnelling in the gully slopes, particularly in the upper, drier parts as well as on the southerly and westerly



Fig. 19. A tussock of *Deschampsia caespitosa* (marked) is being destroyed by splash erosion. The soil is often carried up particularly by red ants of the genus *Myrmica* but also by the black ants *Lasius niger*. These tussocks are more exposed to the frost than the surrounding ground. When they freeze they are lifted up a little. This means that they later can be easily dried up. If then the vegetation cover is damaged, the soil is rapidly washed away.



Fig. 20. Water rats have tunnelled in the gully slopes and have thrown up heaps of mould at the mouths to these tunnels (arrows). The nearest heap has been washed and now forms a stripe because of the rain.

slopes. Naturally the tunnels have an undermining effect, as the heaps of excavated soil are washed downslope (Fig. 20).

The debris, accumulating on the gully bottoms, forms wet meadows as well as small swamps, which are too level for effective drainage or further transport. The grass binds the surface soil firmly. So, natural bridges have been formed on some of these gully floors. After heavy rains and during snow melt, artesian springs can be formed at the lower end of such soil bridges (Fig. 21). Around one of these springs, pieces of clay had been piled up by the upwelling water during a period of rapid snow melt in 1976.

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Professor I. Th. Rosenqvist, Institutt for Geologi, University of Oslo, stimulated my interest in marine clays during my visit to the Tönte Seminar in Norway, March 1973, and on an excursion to my investigation area in Western Sweden, September 1974. He has kindly tested clay samples for permeability. He has also reviewed this manuscript critically. Civil Engineer Sven Odenstedt, Vattenbyggnadsbyrån, Göteborg, has delivered copies of maps and profiles from the geotechnical investigations in the Gunnilse area. Civil Engineer Bengt Johansson, Gatukontoret, Göteborg, made it possible for me to obtain samples from the boring at Måssen and to have them geotechnically tested at the Gatukontoret Laboratory. Furthermore, he has kindly discussed geotechnical pro-



Fig. 21. Close-up of the mouth of the subterranean channel. The artesian water wells up to the left of the tussock. Straws and roots have been twisted together to form a roll in front of the bulge (arrow). The appearance of the bottom changes with the water discharge in the channel and lumps of clay as well as sand and silt can now and then be found on it.

blems, particularly those in the Gothenburg region. Doctors Urve Miller and Ann-Marie Robertsson, Geological Survey of Sweden, Uppsala, have kindly analysed samples of till and clays regarding their pollen content. Doctor Ernest Magnusson, Geological Survey of Sweden, Uppsala, has revised the manuscript critically and made valuable recommendations. The personnel of the Geographical and Geological Departments of the University of Lund have helped by typewriting, completing illustrations, correcting my English manuscript and performing the X-ray analyses of clay samples, respectively. Civil Engineer Åke Åkerström, Silikatforskningsinstitutet, Chalmers Institute of Technology, Göteborg, has also kindly assisted me in making X-ray analyses of clay samples.

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## REFERENCES

GFF = Geologiska Föreningens i Stockholm Förhandlingar  
 SGU = Sveriges geologiska undersökning

- ALTE, B., 1973: Kontrollerad grundvattensänkning för bestämning av förkonsolideringstrycket i djupa lerlager. — Väg- och Vattenbyggaren 6, 616—618.
- BJERRUM, L., 1967: Engineering Geology of Norwegian Normally Consolidated Marine Clays as related to Settlements of Buildings. Seventh Rankine Lecture. — Norges Geotek. Inst., Publ. 71, 1—38.
- 1971: Kvikkleireskred. Et studium av årsaksforhold og forbygningsmuligheter. — Norges Geotek. Inst., Publ. 89, 1—14.
- CALDENIUS, C., and LUNDSTRÖM, R., 1956: The Landslide at Surte on the River Göta Älv. A Geologico—Geotechnical Study. — SGU Ca 27.
- COLLINI, B., 1950: Om våra kvartära lerors mineralogiska sammansättning. — GFF 78, 528—536.
- FINEMAN, G., 1759: Geometrisk Charta öfwer Gunnilse By uti Elfsborgs Lähn. (Land Survey map). — Statens Lantmäteriverk, Gävle.
- FORSLIND, E., 1953: Water Association and Hydrogels. — Proc. of the Second Intern. Congr. on Rheology, 50—61, London 1954.
- FRIES, M., and ROSS, N-E., 1950: Pre-Quaternary pollen grains and spores found in Late-Glacial and Post-Glacial clays in Bohuslän, SW Sweden. — Stockh. Ark. f. Mineral. o. Geol., 1, 199—210.
- GROVE, J. M., 1972: The incidence of landslides, avalanches and floods in western Norway during the Little Ice Age. — Arct. and Alp. Res., 4, 131—138.
- HILLEFORS, Å., 1969: Västsveriges glaciala historia och morfologi. Naturgeografiska studier. Summary in English. — Medd. fr. Lunds Univ. Geogr. Inst., Avh. 60.
- 1978: Tuveskredet. — Svensk geogr. årsb. 54, 53—69.
- JAKOBSON, B., 1952: The Landslide at Surte of the Göta River, September 29, 1950. — R. Swedish Geotech. Inst., Proc. 5.
- JÄRNEFORS, B., 1957: Skredet vid Intagan år 1648. — SGU C 539.
- 1959: Jordartskarta över Götaälvdalen. — SGU Ba 20.
- KRUSE, W., 1731: Geometrisk Delineation af ett ansenligt Jordfall... Gunnared. Ange-rends socken, Älvsborgs län. — Statens Lantmäteriverk, Gävle.
- LARSSON, I., 1967: Anisotropy in Precambrian rocks and post-crystalline deformation models. — Geogr. Ann., 49A, 237—245.
- LIND, B., 1979: Lokalt omhändertagande av dagvatten—förutsättningar inom ett bergs-område. — Chalmers Tek. Högsk. Geohydrologiska forskningsgruppen, medd. (in press).
- LUNDEGÅRDH, P.-H., 1958: Göteborgstraktens berggrund. — SGU C 553.
- ODENSTAD, S., 1958: Jordskredet i Göta den 7 juni 1957. — GFF 80, 76—86.
- PUSCH, R., 1970: Clay microstructure. — National Build. Res., Doc. D8. Stockholm.
- ROALDSET, E., 1972: Mineralogy and geochemistry of Quaternary clays in the Numedal area, southern Norway. — Norsk geol. tidsskr., 52, 335—369.
- ROALDSET, E., and ROSENQVIST, I. TH., 1971: Adsorbed rare earth elements as a clue to the origin of some glacial clays. — Bull. Groupe franc. Argiles, 191—194.
- ROSENQVIST, I. TH., 1963: The influence of physico-chemical factors upon mechanical properties of clays. — Proc. 9 Nat. Conf. on Clays and Clay Miner. (Also in Norges Geotek. Inst., Publ. 54.)
- 1968: Mechanical Properties of Soils from a Mineralogical-Physical-Chemical View-point. — Commun. from Inst. f. Geol., Univ., Oslo.

- 1975: Origin and Mineralogy of Glacial and Interglacial Clays of Southern Norway. *Clays and Clay Miner.*, 23, 153—159.
- SAMUELSSON, L., 1978: Beskrivning till berggrundskartan Göteborg SO. — SGU Af 117.
- SÖDERBLOM, R., 1966: Chemical aspects of quick-clay formation. — *Eng. Geol.*, 1 (6), 414—431.
- 1972: Några synpunkter på begreppet kvicklera och kvicklerans betydelse för spridandet av skred. — Nordisk Geoteknikermöte i Trondheim 24—26 augusti 1972. Norges Geotek. Foren. 1973, 87—94.
- SUNDBORG, Å., and NORRMAN, J., 1963: Göta älv. Hydrologi och morfologi. Med särskild hänsyn till erosionsprocesserna. — SGU Ca 43.
- TORSTENSSON, B.-A., 1973: Kohesionspålar i lös lera. En fältstudie i modellskala. — Doktorsavh. vid Chalmers Tek. Högsk., N 5, 79.
- WEDEL, P., 1978: Grundvattenbildning, samspelet jordlager och berggrund. Exemplifierat med ett försöksområde i Angered. — Chalmers Tek. Högsk. Geohydrologiska forskningsgruppen, medd. nr 22.
- WENNER, C.-G., 1951: Data on Swedish landslides. — *GFF* 73, 300—308.

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