SUB-MORAINE DEPOSITS IN NUMEDAL

I. Th. Rosenqvist
Institute of Geology, University of Oslo,
Blindern, Oslo 3, Norway

Abstract. The grain-size distribution and the content of light and heavy minerals have been determined in a sub-till sediment at Fønnebøfjord and in a sub-ablation moraine deposit at Lampeland. The over-consolidation due to drained ice load is calculated to have an approximate minimum value of 10 MN per m^2 for the Fønnebø deposit and a few hundred KN per m^2 for the Lampeland deposit. It is concluded that the Fønnebø material carried the weight of an inland glaciation, whereas the Lampeland material was sub-glacially deposited at a late stage. This work was a contribution to the Numedal Project.

Whereas it is well documented that loose deposits from before the last Ice Age have survived *in situ* in Sweden, Finland and Denmark, we have until recently found very few localities in Norway where it seems reasonable to assume that the sediments are older than the last Ice Age. Jan Mangerud (1965) has discussed this problem in Gudbrandsdalen. In this case, he definitely states that some of the deposits in the main valley and in some of the side valleys are older than the last glaciation and that they have been over-consolidated by the ice. The material he has dealt with is chiefly of glacio-fluvial origin from the first part of the last glaciation. This implies that it is reasonable to assume that also older deposits underlying these will be present. In part, extensive ground moraines overlie the glacio-fluvial sediments.

K.M. Strøm (1943) was of the opinion that the famous earth pyramids (Kvitskriuprestin) in Sel were eroded from moraines belonging to the Riss glaciation. However, Mangerud is of the opinion that these moraines belong to the last glaciation. The mineral grains in the Kvitskriuprestin are quite fresh, and no traces of chemical cementation or weathering processes are found which could be attributed to interglacial time.

Per Jørgensen has carried out X-ray investigations of the material below 2 μ belongong to these deposits. He found well-crystallized 2 M muscovite, together with quartz and feldspar, plagioclase as well as alkali feldspar, and in addition some chlorite. As no suitable oedometer was available in Bergen at the time when Mangerud carried out his investigations, he did not determine the preconsolidation stress, but he indicated the importance of Terzaghi's consolidation theory as a means of determining the effective stress system.

In a thesis (at the University of Bergen in 1967), S.A. Skreden dealt with the sub-moraine sediments from Voss. These clays were greatly over-consolidated, but no definite determination of the degree of over-consolidation was made in this case either.

During the construction of the Grieg Memorial Hall in Bergen, Mangerud carried out some tests with a small oedometer belonging to Bergen Materialprøveanstalt. This proved that the pre-consolidation was beyond the working range of the instrument. By determining the porosity of re-moulded and undisturbed material, it is seen that the effective pre-consolidation stress in any case was higher than 1.5 MN per m^2, corresponding to a drained load of more than 150 tons per m^2, probably about 200 tons per m^2.

In another thesis at the University of Bergen, Inge Aarseth (1971) dealt with large areas of pre-consolidated clays and silt from Ølve. He found in this case an effective pre-consolidation load corresponding to 200 tons per m^2.

In a letter of 2 February 1972, Jan Mangerud states that this is far too low for the reconstructed ice load, and he assumes that this is due to "imperfect drainage during loading". If so, we are dealing with a case in which the effective load is considerably reduced, due to high pore-water pressure or pressure in the water film below the ice. This again implies that we have had ice masses with a considerable pressure gradient in the pore water from the sediments below to the freely drained ground-water level. When Mrs. Roaldset and I (1971) found the important deposits of over-consolidated clay and sand below hard-packed ground

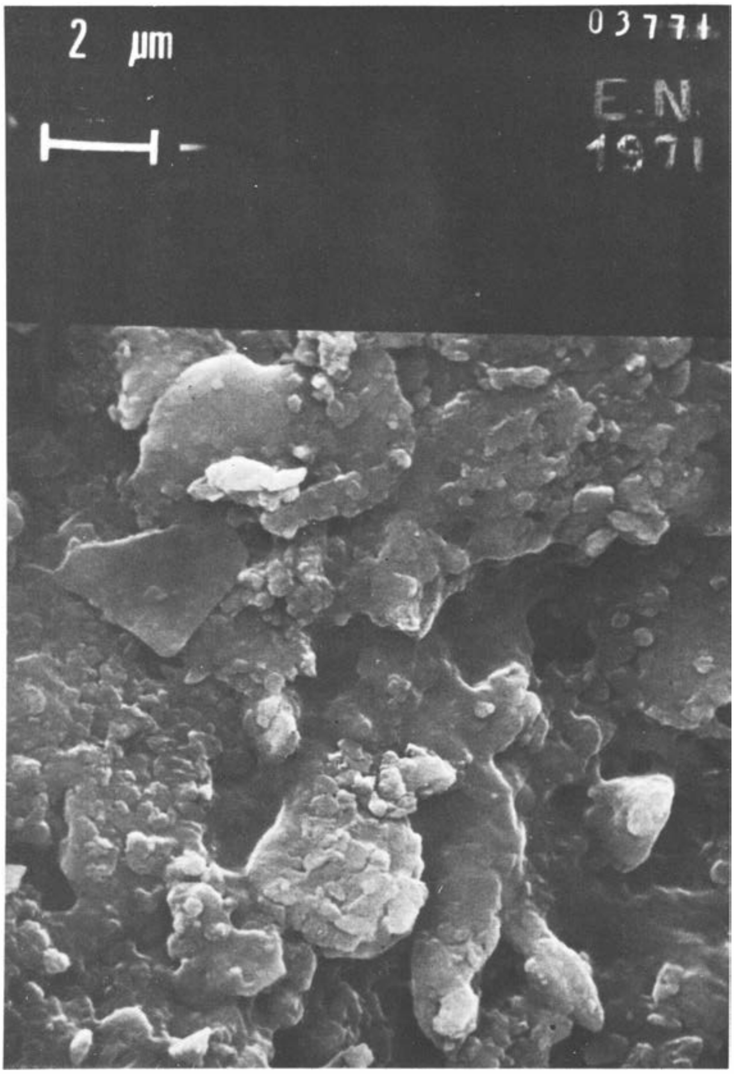

Fig. 1. Upper clay layer, Fønnebøfjord, horisontal section. 6300x.

moraine in the eastern part of Fønnebøfjorden in Uvdal, this was the first locality of sub-moraine clays in the Numedalen area. We have the large, filled, valley basins above Hvittingfoss in Flesberg and Rollag, in which cases we assume that we have similar sediments in the deeper strata, but no boring has proved this. Furthermore, we have some silt sediments at Lampeland which are overlain by ablation moraine. In contrast to the Fønnebøfjord sediments, the Lampeland sediments are, however, only slightly over-consolidated.

AN ATTEMPT TO DETERMINE THE CONSOLIDATION-STRESS PARAMETERS FOR THE SUB-MORAINE SEDIMENTS AT FØNNEBØFJORDEN

The most striking feature of the sub-moraine clays was the hardness and the fact that they did not crack during drying. It was obvious that the sediments represented greatly over-consolidated clays. For such material, it is difficult to carry out any oedometer test in order to

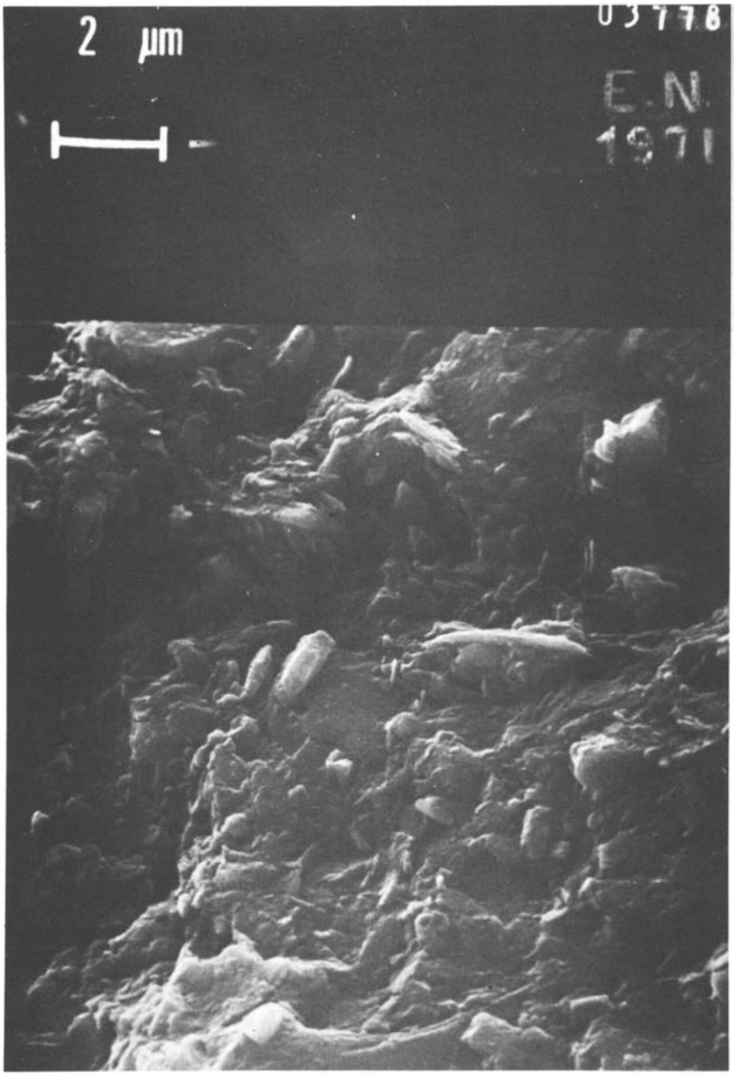

Fig. 2. Same clay, vertical section. 6300x.

determine the maximum consolidation stress. If this is to be done, we have to carry out very expensive borings and build suitable high-pressure oedometers. Indirectly, however, it is possible to approach the problem in theoretical and empirical ways. The fact that the clays did not shrink by furhter drying proves that they have been consolidated to beyond the shrinkage limit, which is normally 15–20 relative per cent below the plastic limit (Hogentogler, 1937). Furhtermore, we know that the water content of normally consolidated clay sediments follows an exponential function, so that the water content is infinitely high when the consolidation stress is zero, and zero when the consolidation stress is infinite.

If the water content of a given material can be determined as a function of the consolidation stress over a certain range of stresses, we may extrapolate from this range, using a formula of the type $W = A/\sigma n$. In this case, A and n are material constants, whereas W is the water content as a percentage of the dry weight. A formula of this type is in good agreement with the experimental and empirical data presented by Skemp-

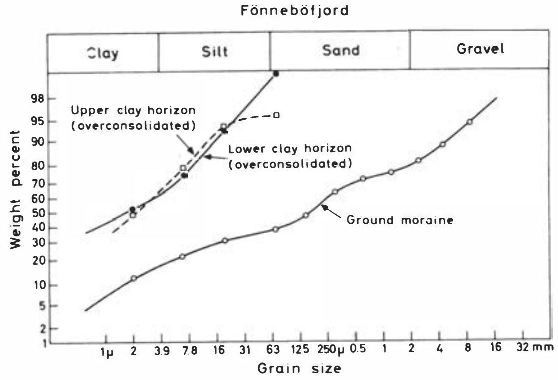

Fig. 3.

ton (1953). He examined a large series of clay deposits from Europe and North America, including silty glacial and postglacial clays from Horten in Norway and fat clays from Köping in Sweden. Skempton presents his data on a graph, giving an approximate relationship between the void ratio and the depth for normally consolidated sediments of various plasticities. These curves are based partly on natural profiles and partly on laboratory tests carried out in a high-pressure oedometer at Illinois University (up to 10 MN/m^2).

Bjerrum and Rosenqvist (1956) determined the relationship for the clay material from Åsrum in Lågendalen. This silty clay was of illitic-chloritic composition, corresponding to the clays of Uvdal, which is in the same valley. It was found that, independently of whether the clay was sedimented in fresh or salt water, it had a good correlation to the exponential formula and to Skempton's data. However, our tests were only carried out at low or moderate consolidation stresses, and we have to extrapolate far beyond our experimental range in order to reach the low content of the clays at Fønnebøfjord (the shrinkage limit).

The fundamental geotechnical data for the material at Fønnebø was determined at the Norwegian Geotechnical Institute on the following four samples$

(1) The bottom of overlying moraine.
(2) The slightly disturbed upper clay layer (Layer No. 8).
(3) Upper part of the lower clay layer (Layer No. 5).
(4) Lower part of Layer No. 5.

The plastic and liquid limits for the clays were as follows:

Table I

Sample no.	W_L	W_p
2	37.10	20.00
3	26.95	18.2
4	39.20	24.10

Using Hogentogler's relation between water content and pore ratio at the shrinkage limit, we calculate:

Table II

Sample no.	Water content, %	Void ratio
2	17	0.46
3	15	0.40
4	20	0.54

The grain size will be seen from the diagram. As will be seen, sample no. 3 is rich in the medium-grained silt fraction 2)6 µ. This is due to a thin silt layer in the middle of the sample, which was not separated. The difference between samples nos. 3 and 4 is not as large as we might assume from the geotechnical data, and outside the silt layer the shrinkage limit must be higher than the 15 % which we have calculated. As an average, we might assume the water content at the shrinkage limit to be 18 % for all three samples, and the pore ratio 0.47; we may use the consolidation data from Bjerrum and Rosenqvist (1956) for artificial sediments, in order to determine the material coefficients *A* and *n*. Using the "best fit" method, we then arrive at a value of $10^{1.04}$MN per m^2, or, in other words, an effective load of the order of 1000 tons per m^2.

If we use Skempton's empirical curves at liquid limit 50 and plasticity limit 25 and an average pore ratio for the clays of 0.47, this corresponds to an approximate depth of 2000 feet in normally consolidated sediments, which again is of the same order of magnitude as the calculated over-consolidation stress. As the data are approximate, it is not advisable to try to elaborate the material any further.

Under all circumstances, it is obvious that the consolidation stress was very much higher than the weight of the overlying moraine. It is not probable that this material alone consolidated the sediment.

Thus the moraine represents an *in situ* glacial deposit and not any hard-packed landslide material overlying the clays and sand. As the consolidation has been proved to be due to an overlying glacier, this must have had a thickness of at least 1000 m, provided it was fully drained at the bottom. (This means that there was no resistance for the meltwater below the ice between Uvdal and the ocean.) If this was not the case, the thickness of the ice may have been greater. There can be no possibility of a minor glacial advance; we have to do with a true inland ice.

THE LAMPELAND DEPOSITS

In contrast to the sub-moraine sediments in Fønnebø, we have another type of sub-glacial sedi-

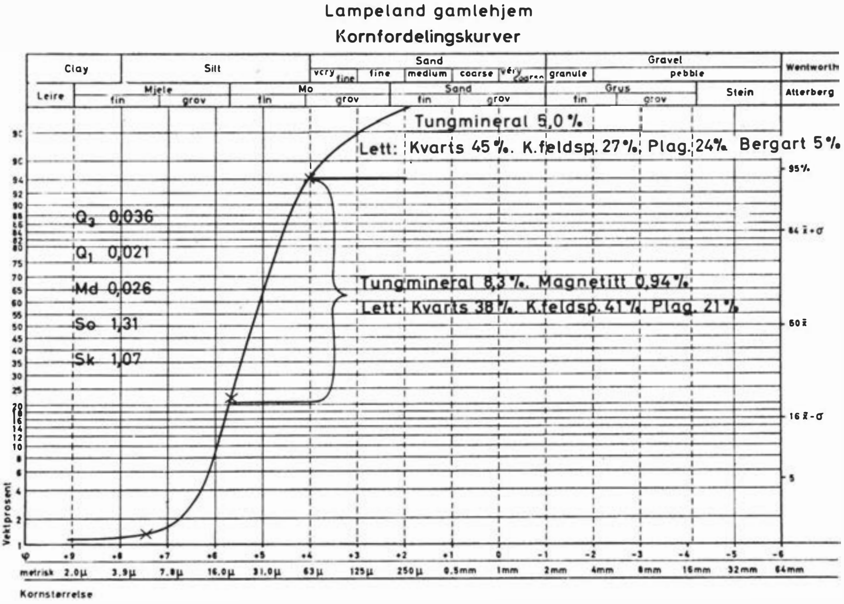

Fig. 4. Grain size distribution for the Lampeland silt in bulk.

ment in the same valley at Lampeland (220 m a.s.l., 80 km SE. of Fønnebø). Here we have a thin ablation moraine overlying layered silt, which is clearly tectonized but still rather loose and only slightly consolidated, corresponding maximally to a few hundred KN/m^2. This material is considered to be of a different age from the Fønnebø material and was probably deposited subglacially during the late stage of the melting-off of the inland ice.

A striking feature of the Lampeland sediment is that the coarse and fine layers are well sorted, that the fine layers contain more heavy minerals than the coarse layers, and furthermore that the maximal and minimal sizes of the heavy minerals are the same as those of the light minerals. It appears as if the layering has been produced by a sieving procedure, in which an unsorted material was first sived by a fine and then by a more open sieve. (Such sieveing procedures are sometimes seen by very inexperienced students but seem improbable in nature.)

One possibility is that the material was accurately sorted by being transported parts of its way in a thin water film below the glacier, and that the thickness of this water film varied from time to time, due to a rhythmic melting-off process at the bottom. Another explanation of the rhythmic sediment is that the mineral components were derived from two different sources – a more or less constant supply from a material rich in dark minerals and a rhythmic one from sources rich in light minerals. The origin of this material will be further discussed.

One point of importance about the Lampeland

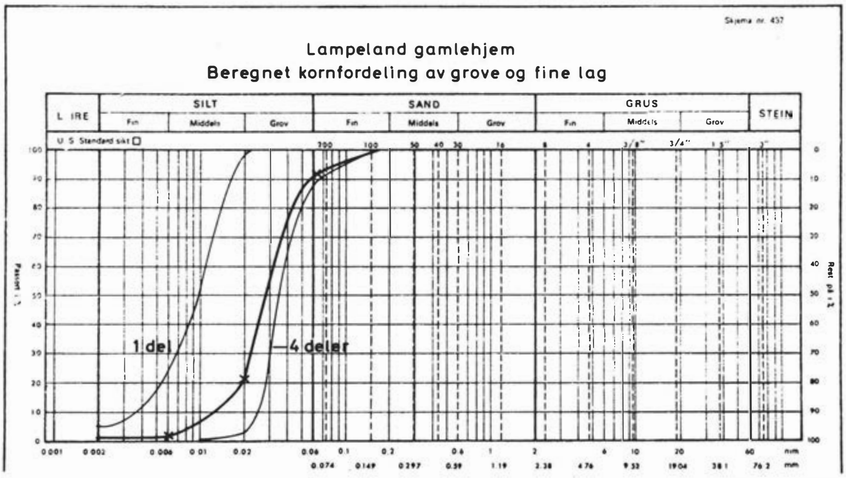

Fig. 5. Estimated grain size of the fine and coarse layers of Lampeland silt (from microscope counting).

sediment is, however, the clay content, which is very low but shows a very pronounced content of a 24–25 Å mixed layer mineral and a broad 10 Å illite. Thus it differs fundamentally from the clay content of the Kvitskriuprestin in Gudbrandsdalen. On the other hand, the clay of the Lampeland sediment corresponds to much of the material found along the Numedal valley, and supports the assumption that the source material has been exposed to an older weathering, whereas the Gudbrandsdalen material, which has about the same character, did not weather to this extent in postglacial time.

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