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ORIGIN AND MINERALOGY GLACIAL AND INTERGLACIAL CLAYS OF SOUTHERN NORWAY

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Abstract—The Numedal River basin (6000 km^2) in central and east Norway contains 3×10^9 m^3 of clayey material, corresponding to a clay loam sediment, which contains 2 million tons of absorbed rare earth elements.

The clay mineralogy varies systematically from the till clays to a marine facies. It is concluded that the phyllosilicates of the clay fraction and tills originated from phyllosilicate minerals of the crystalline bedrock through a degradation partly due to preQuaternary weathering which dissolved a great part of the rock-forming minerals.

INTRODUCTION

Ever since Geikie (1877), it has been known that the marine finegrained sediments on the Scandinavian peninsula and consequently in Norway differed from deposits normally called clays outside of glaciated areas. The same conditions are valid for similar sediments in other parts of the world such as the northern part of North America, New Zealand and northern Soviet Union, etc. The characteristic grain size ranges from fine sand to grains finer than 2 μm. In the field it is often impossible to distinguish clays from sediments which actually should be called silt. Clays containing more than 80 per cent particles finer than 2 μm with more than 80 per cent of this fraction consisting of phyllosilicates are very rare. All silt deposits contain considerable amounts of phyllosilicate minerals of the same type as in the clays.

The most common clay minerals are illites and chlorites with some vermiculites. Kaolinites and montmorillonites are subordinate. Before this examination started most Norwegian pedologists and geologists believed that these finegrained sediments were developed during and after the last glaciation by a fluvial separation from the till material according to grain size and effective diameter without any marked chemical change in the individual minerals. Further, it was assumed that the till material from the last ice age was developed by mechanical crushing and abrasion of the underlying bedrock essentially uninfluenced by preglacial weathering processes.

Due to the isostatic uplift of the peninsula after the ice age in Scandinavia there are large areas of clay sediments which were deposited in salt water. There are also corresponding clays deposited in brackish water and under limnic conditions. Altogether, these clay sediments have one feature in common, that their activity—in Skempton's (1953) sense of the word—is low. The grain size distribution is assumed to be a result of mechanical abrasion and mechanical hydraulic separation and sedimentation. Only the uppermost layers of the sediments show marked traces of surface weathering in postglacial time.

When Goldschmidt (1954) published his *Geochemistry of the Earth* he advocated the old view that the fine-sediments in Scandinavia represent unweathered mechanically crushed-up bedrock. He analyzed samples of these sediments in order to obtain an average analysis of the underlying bedrock. The general trend of his analysis was that the chemical composition of the silt and clay sediments did not deviate very much from the average of the earth's crust. (He did not investigate the trace and minor elements of the loose deposits.) There were two marked discrepancies, i.e. for sodium and for calcium. These elements were obviously depleted 20–40 per cent relative to the other ions. Professor Goldschmidt believed that this was due to postglacial leaching.

Because there are very few places where solid bedrock in outcrop shows signs of active chemical weathering the concept that the loose deposits—especially the clay sediments—developed from crushed-up unweathered bedrock, has been especially strong in Norway.

Large engineering projects in recent years have uncovered weathered rocks in increasing number. Several localities with Quaternary sedimentary deposits older than the last glaciation have been found in Norway and such deposits are well-known in Denmark and Sweden. Some typical examples are described by Mangerud (1965), Roaldset (1973), Rosenqvist (1975), Skreden (1967), Vorren (1972) and Aarseth (1971).

Authigenic clay minerals transformed from the underlying solid rock have been described by Reusch (1901, 1903), Goldschmidt (1928), Barth (1939) and Rosenqvist (1951). These are quite exceptional and are thought to be without any significance for the mineralogy and formation of the normal Quaternary and postglacial clay sediments.

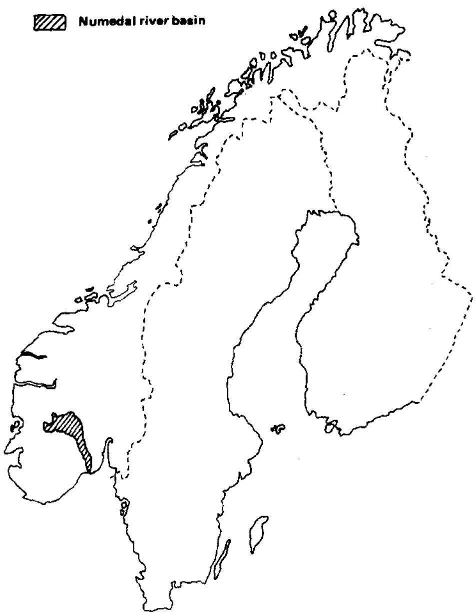

Fig. 1.

The Scandinavian peninsula was uplifted probably in early Tertiary time by a series of extensive flexures along the west coast. The combined action of 50 million years of weathering and erosion in a mild climate probably left a late Pliocene surface with deep chemical weathering profiles but none of these profiles are evident today.

In 1967 the Institute for Geology at the University of Oslo started "The Numedal Project". The purpose of this project is to investigate the validity of the older hypothesis concerning the genesis of the clay deposits. Since its beginning field work has involved 12–14 participants each summer and at least 3–4 graduate students and senior scientists have taken part in the laboratory work each year. From the work of all of these co-workers, who will each publish their results in individual papers, today it is possible to draw broad conclusions from their geological, geochemical, geophysical, mineralogical, petrographical, micropaleontological, colloidal-chemical and paleontological investigations.

BEDROCK GEOLOGY

The Numedal river basin (Fig. 1) was selected as a field of research for various reasons. First of all the direction of the valley corresponds very closely to the direction of the last ice movement during the last glaciation. Furthermore, the basement consists mostly of magmatic and metamorphic rocks with some low metamorphic Paleozoic sediments. The upper 4000 km^2, i.e. $\frac{2}{3}$ of the total area, is very sparsely inhabited; 6435 people lived there in 1969. The area is 0·8 per cent farm land, 14 per cent forest, 2·3 per cent moor and the rest barren mountains and there is no polluting industry.

The valley system is in three geological provinces (Fig. 2). These are:

The Telemark suite

The bedrock consists of metamorphic rocks and granites. The metamorphic rocks are mostly Precambrian sediments consisting of quartzites, greywackes and metavolcanics. Phyllosilicates in the metamorphites are biotite, muscovite and chlorite. The metavolcanics contain well crystallized chlorites. The intensity of metamorphism varies but most frequently it is the quartz–albite–epidote–almandine subfacies, i.e. the upper part of greenschist facies.

The Kongsberg Bamble formation

The middle part of the river valley lies in this formation. It consists of gneisses, biotite–diorites, amphibolites, diabases and some granites. The degree of metamorphism varies but corresponds mainly to the amphibolite facies and upper part of the greenschist facies.

The Oslo region

The lower part of the river valley lies in the Oslo region. Here rocks are monzonitic syenites with some alkali granites and the phyllosilicate content is very low. Low metamorphic and non-metamorphosed Cambro–silurian rocks with poorly crystalline phyllosilicates are sparsely represented.

The geomorphology of the region is divided into three parts (Fig. 3).

Region I is the high mountain plateaux and the deep-cut valleys of the tributary rivers in the upper part of the catchment area. All bedrock belongs to the Telemark suite. The total area is 2800 km^2.

Region II makes up the main valley area including the surrounding heights down to the glacial marine upper limit at the city of Kongsberg. The bedrock here is Kongsberg Bamble formation with some rocks from the Telemark suite. This area is 1370 km^2.

Region III below the marine limit coincides almost perfectly with the Oslo region.

One hundred and forty-nine bedrock samples from regions I and II have been analyzed because these regions have contributed considerably to the loose deposits in region III. The average analysis calculated from samples taken according to a grid from the various rock units multiplied by their area and the product divided by the total area, 4176 km^2, is shown in Table 1.

The average mineralogical composition of the different types of bedrock in the Numedal river basin area is given in Table 2 which was compiled by Korböl (1972) from point counting carried out by Mrs. Brit Löberg.

THE QUATERNARY DEPOSITS

The Numedal river (Lågen) is the second longest river in Norway (300 km). The total catchment area is roughly 6000 km^2. In late glacial time the lower

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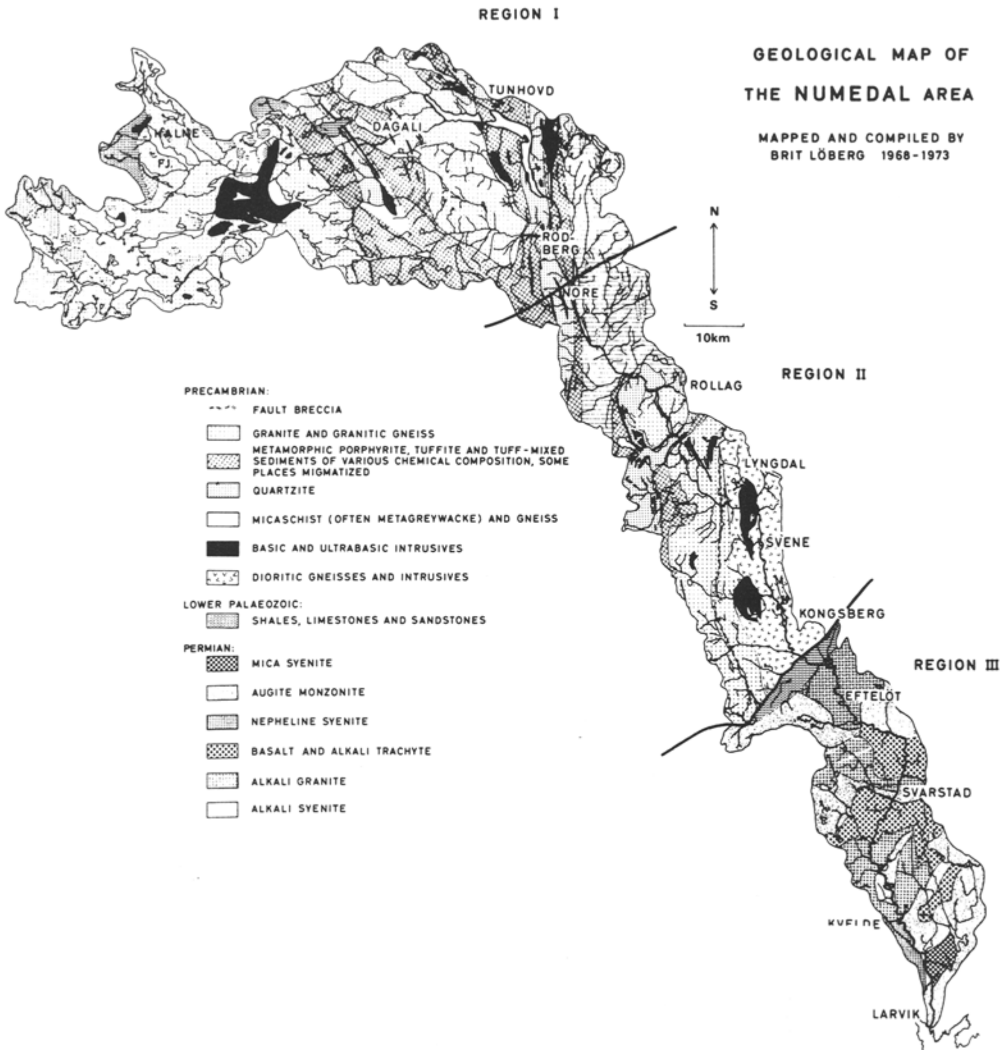

Fig. 2.

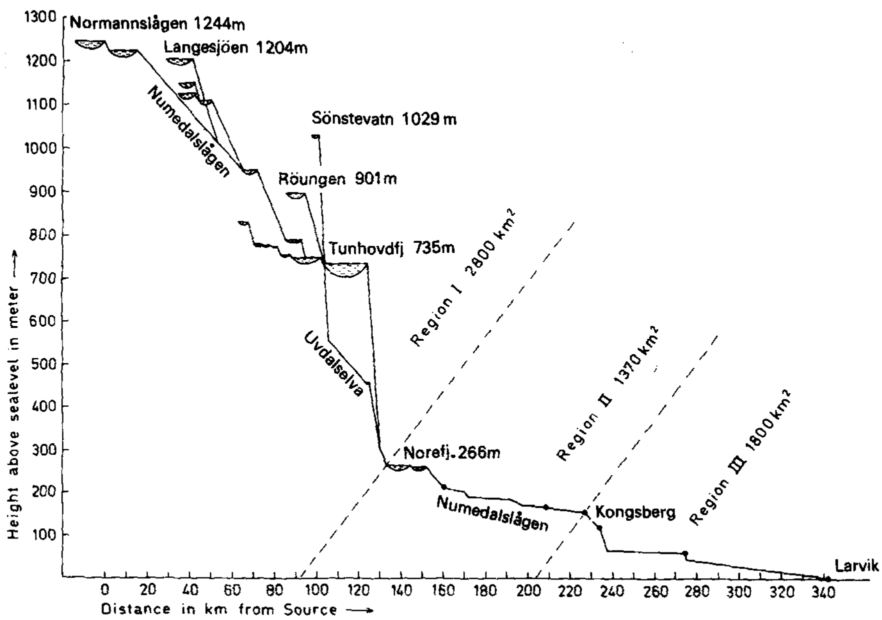

Fig. 3.

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Table 1. Average chemical composition of bedrock Regions I + II

Sample	Average (%)	Standard deviation
SiO_2	70·42	5·39
TiO_2	0·61	0·27
Al_2O_3	12·98	2·79
Fe_2O_3	4·57	1·41
MnO	0·08	0·03
MgO	1·43	0·59
CaO	2·25	1·43
Na_2O	2·88	0·66
K_2O	3·36	1·13
P_2O_5	0·20	0·08
Loss ignition	1·01	0·44
Sum	99·79	
No. of samples	149	
Area	4176 km^2	

100 km of the valley was below sea level and formed the Kongsberg fjord. These marine and estuarian deposits cover the bedrock. Based on detailed mapping on the scale 1:5000 and 1:10000, seismic profiles, borings and laboratory investigations, the calculated volume of the loose deposits is $11 \cdot 10^9$ m^3 (Table 3). Of this sum about 4×10^9 tons of particles is $<2\,\mu$. This corresponds to 3×10^9 m^3 of the average sedimentary clay.

In addition there are extensive Pleistocene sediments from this rock system in the fjord and ocean outside the valley. Not much is known about these sediments although two summer expeditions making seismic and acoustic measurements have taken 28 short core samples from the sea bottom down to a depth of 400 m. This material is being studied by Mr. T. M. Rønningsland in a thesis not yet finished.

Table 3. Quaternary deposits in the Numedal river basin ($\times 10^9$ m^3)

Tills (below pebble size)	6·0*
Marine silty clay	1·7†
Lacustrine clay silt and sands	1·0*
Estuarian sands and silts	0·8*
Filled river valley basins	1·5‡
Sum	11

Degree of certainty:
* Fair. † Good. ‡ Low.

Trygve Dekko (1973) examined the mineralogy of the sand fraction in the tills from the regions I, II and III (Table 4). From chemical analyses and X-ray powder diffraction evaluations, the mineral composition of fractions finer than 64 μm of the tills has been determined by Klaus Lien (1973) (Table 5). It is quite obvious that the sand and silt fractions of the tills are considerably richer in quartz than the bedrock (Table 2).

Dekko (1972) found that the average sand in the various loose deposits corresponds to a mixture of approximately half unweathered ground-up bedrock and half pure quartz. If the quartz is residual from earlier weathering, then a minimal amount of bedrock equal to or greater than the volume of the present loose deposits has been fully weathered and the residual material mixed with fresh rock during the last of the Quaternary glaciations.

THE CLAY

The relatively low content of clay minerals in the tills indicate a considerable mineralogical separation during the formation of the till. Apparently the mineral material included in the ice during the last

Table 2. Average mineralogical composition for some rock types in Numedal and Lågendal basins

Area	Type of mineral	Quartz (%)	K-feldspar (%)	Albite and plagioclase (%)	Phyllosilicates and dark minerals (%)
Telemark suite	Metamorphic porphyries, tuffs, etc.	31	18	16	35
	Micaschists and metagreywacke	60	19*	—	21
	Quartzite	93	2	—	5
	Rollag granite	38	26	26	10
	Telemark granite	33	32	31	4
Kongsberg Bamble	Kongsberg granite	29	31	37	3
	Granite south of Kongsberg	36	38	15	11
	Amphibolite	5	—	31	64
	Dioritic gneisses	32	2	38	28
Oslo region	Ekerite (alkali granite)	25	62†	5	8
	Larvikite	3	35	48	14
	Nordmarkite	2	87†		11
	Lardalite	—	62†	13‡	25

* Sum feldspar.
† Perthitic feldspar.
‡ Nepheline.

Table 4. The average composition of sand in tills—Regions I, II and III

Region	No. of samples	Grain fraction (μ)	Quartz (%)	K-feldspar (%)	Plagioclase (%)	Dark minerals (%)	K-feldspar/ Plagioclase (%)
I	24	125–63	53·9	19·8	20·7	5·6	0·96
	26	250–125	50·5	20·0	24·9	4·6	0·80
	24	500–250	46·9	21·6	27·9	3·6	0·78
II	32	125–63	58·2	12·6	19·7	9·5	0·64
	37	250–125	61·3	10·9	19·9	7·9	0·55
	29	500–250	60·0	13·9	20·2	5·9	0·69
III	20	125–63	53·6	19·7	18·4	8·3	1·07
	22	250–125	50·6	24·0	20·0	5·4	1·20
	20	500–250	45·6	27·9	20·9	5·6	1·33

Table 5. The average composition of silt samples from Regions I and II

	Quartz (%)	K-feldspar (%)	Plagioclase (%)	Clay minerals (%)	Mafic minerals (%)
Region I					
64-32 μm	42·0	21·1	30·0	—	6·9
32-16 μm	38·8	22·6	32·6	3·0	3·0
16-8 μm	32·8	22·0	32·2	10·0	3·0
8-4 μm	26·5	20·8	30·9	17·8	4·0
4-2 μm	19·1	21·4	32·4	23·1	4·0
Region II					
64-32 μm	42·0	16·2	30·5	—	11·3
32-16 μm	42·1	18·3	30·6	3·0	6·0
16-8 μm	38·0	18·4	27·6	10·0	6·0
8-4 μm	33·2	17·9	24·2	16·7	8·0
4-2 μm	27·1	17·3	25·9	21·7	8·0

Table 6. Average chemical composition of Numedal river basin clays

	Weight (%)	Standard deviation (%)
SiO_2	51·8	3·92
TiO_2	0·89	0·12
Al_2O_3	16·5	1·94
Fe_2O_3	11·3	2·08
MnO	0·16	0·05
MgO	3·98	1·07
CaO	2·36	1·04
Na_2O	2·10	0·41
K_2O	5·00	0·75
Loss ignition	5·92	3·52

glaciation did not enter the tills in equal proportions. The finer fraction separated from the ice to a great extent before the tills formed. Only part of the clay minerals were removed from the tills by later erosion and separation processes. On the basis of 83 chemical analyses of the fraction finer than 2 μ from the till and marine clays, Roaldset (1972) gives the average chemical composition for the Numedal area (Table 6). These analyses are presented for till, marine and limnic clays in Table 7.

X-ray powder diffraction investigations of the mineral composition are in process. Preliminary data, published by Roaldset (1970), gave the following results:

(1) All samples contained illite.

(2) The illite content is very variable. In the till clays 10–40 per cent of the fraction finer than 2 μ is illite. In the marine deposit 40–60 per cent is illite.

(3) The illites are both dioctahedral and trioctahedral. The ratio between trioctahedral and dioctahedral illite is somewhat higher for the sediments in the outer part of the valley system than in the clay fraction from in the moraines in the upper part.

(4) In addition to illite all samples contain chlorite (3–40 per cent), vermiculites (trace–40 per cent), mixed layered minerals in variable amounts, quartz (2–20 per cent), microcline (2–20 per cent), and acid plagioclase (1–20 per cent).

(5) Most samples from tills and moraines and all marine clays in the Numedal river basin area contain some amphibole, sometimes up to 20 per cent.

Table 7. Chemical compositions of clays < 2 μ from Numedal area

	Till clays		Marine clays		Limnic clays	
	Average (%)	Standard deviation	Average (%)	Standard deviation	Average (%)	Standard deviation
SiO_2	50·90	±3·87	52·82	±3·33	51·15	±0·49
TiO_2	0·86	±0·14	0·89	±0·07	0·88	±0·04
Al_2O_3	17·39	±1·99	15·69	±1·42	18·60	±1·41
Fe_2O_3	10·58	±2·18	11·76	±1·69	11·00	±1·69
MnO	0·17	±0·07	0·15	±0·03	0·20	±0·08
MgO	3·39	±1·44	4·36	±0·64	3·73	±0·72
CaO	2·97	±1·10	2·11	±0·86	1·79	±0·06
Na_2O	2·11	±0·46	2·16	±0·33	1·94	±0·40
K_2O	4·61	±0·91	5·28	±0·45	4·61	±0·77

(6) None of the analyzed samples, except in podsol profiles, contain appreciable amount of montmorillonites. However, mixed layer minerals between illite–montmorillonite and chlorite–montmorillonite are rather common.

The content of expanding minerals is low or absent in most clays. (This is also the case for all other Pleistocene–Holocene clays in Norway.) Different types of deposits have some special characteristics. Boulder clays are characterized by a high content of illite and chlorite together with illite–chlorite mixed layer minerals. The clay material in the marine sediments of the lower part of the valley frequently contains vermiculite and mixed layer minerals with vermiculitic layers.

In the marine profiles the amount of different minerals varies at different levels. Clay mineral content differs reciprocally between trioctahedral illite and vermiculite versus chlorite–vermiculitic mixed layer minerals.

In summary: (1) The mineralogy of the fraction $<2\,\mu$ shows a great variance among the sediments and they all differ from the crystalline bedrock. (2) This fraction cannot be derived from the bedrock by only mechanical grinding processes. (3) The rate of weathering and neoformation of clay minerals clearly shows that these minerals cannot have crystallized by an authigenic growth from solutions during or after the last glaciation. It is hardly possible that they arose by authigenic processes during the interglacial Quaternary periods. (4) The silts and clays have a very high content of phyllosilicates compared to the average bedrock. This suggests that feldspar and amphibole minerals may have hydrolyzed or have been removed from the area. (5) The phyllosilicates show no sign of being authigenic; they are considered to represent degraded, primary phyllosilicates of the old metamorphic rocks.

RARE EARTH ELEMENTS IN THE CLAY MINERALS

Elen Roaldset (*op. cit.* 1970) has studied the clay minerals and their content of rare earth elements (REE) (yttrium and lanthanides). Because REE are specifically and strongly adsorbed by clay minerals this seems to be an indicator of the minimum amount of weathering solution which has percolated through the clay fractions. The average of 17 moraine clays in the Numedalen river basin gave 491 ppm total REE. The maximum value was 1290 ppm. Most of the REE was in the exchange position.

The glacial and postglacial marine clays in the lower part of the valley had an average of 335 ppm Σ REE (56 samples). The maximum value was 625 ppm. Apparently when clays with high concentrations of rare earth elements come into marine water an ion exchange process and an adjustment towards the normal pattern of marine sediments takes place.

Earlier (Roaldset and Rosenqvist, 1971) reported that the minimum amount of absorbed REE in the whole Holocene sediments of the Numedal area is at least 6×10^5 tons and probably considerably more. More recent calculations based on the additional mapping in 1971–1973 show a value nearer to 2×10^6 tons. This corresponds to an entire REE content of 1×10^{10} tons of average bedrock, which is thus the minimum amount of rock which has been chemically weathered in order to supply the REE found adsorbed on the sediments inside the present shore line.

The present rate of weathering (which is probably higher than in earlier times due to the industrial acid atmosphere of Europe) has been investigated by Ingebrigt Jenssen (1972) through two years of continuous sampling (2 days per week) of the river waters and rain water in the main valley and three side valleys above the inhabited area. From these samples the amount of average rock that had to be dissolved in order to deliver the amount of sodium, calcium and magnesium in the river water in excess of the rain water was calculated. The best figure amounts to 6×10^4 tons of average rock or 10 tons/km^2 per year. Although a complete break-down is unnecessary in order to liberate the quartz and degrade the micas, it is obvious that an average of several hundred thousand years would be needed in order to produce the excess quartz and REE found in the sediments inside the present shore line.

The idea that preglacial Tertiary weathered rock material has influenced the glacial sediment finds support south of the mapped area. In Denmark Anderson and Jensen (1961) have shown that the sand fractions in the Quaternary deposits derived from glacial drift material have a very high quartz content (up to 97 per cent). This is very much higher than the bedrock of the Scandinavian peninsula, from which the sand and loams originated, and indicates an old weathering surface. There are also indications that the feldspar content, although low, increases with decreasing age, so that the sands from the last glaciation have more crushed-up unweathered bedrock than the sands from the older Quaternary ice ages.

CONCLUSION

In the Numedal river basin in SE Norway sand, silt and clay minerals originated by mixing nearly unweathered, abraded rock material with a fair amount of preglacial (Tertiary), weathered material. Quartz and phyllosilicates are enriched relative to the other bedrock minerals. The sedimentary clays developed mostly during the last ice age. The separation of clay material from the sand occurred before the tills formed.

Tills and moraines have been further eroded and mechanically separated, forming parts of the postglacial clays. The phyllosilicates of the tills originated from the phyllosilicate minerals of the crystalline bedrock through chemical degradation. Some of this degradation occurred in the preQuaternary weathering profiles where most of the feldspar minerals, pyroxenes, amphiboles and micas were broken down.

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More than 30 participants have taken part in the project. Each has contributed to the picture which is presented here. Without their intensive work it would not have been possible to carry out the project.

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