Soils from Warthe till at the Emmerlev Klev in southern Denmark Stratigraphy and paleopedology

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Stratigrafical investigations of the Emmerlev till are carried out. The two-deck lessivée-surface water gley soils in the boulder clay with coversand on top and marked podzolization are investigated by physical, pedochemical and mineralogical methods. Recent and relic soil characteristics are further distinguished by means of micromorphological analyses.

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INTRODUCTION

At the south-western Danish coast line the 2 km long Emmerlev Klev is stretching from the township Emmerlev (about 14 km NW of Tønder) in nothern direction. Geologically speaking it is a section in the relatively level groundmoraine deposits of the »Saalian glaciation sensu latu« (*Andersen* 1965). Because of two peat layers of the Eemian interglacial, which came into existance in depressions of the Saalian till, the cliff raised the interest of geologists. Since the soils on Saalian tills frequently display the characteristics of interglacial and interstadial weathering *Felix-Henningsen* (1979) carried out pedostratigraphical investigations of the locality. Apart from the precise stratigraphical definition of the basal moraine these studies aimed at defining the influence of Eemian pedogenesis on morphological and pedochemical qualities of the recent soils. The results are summarized in the following.

THE STRATIGRAPHIC POSITION OF THE TILL

The Emmerlev Klev is essentially formed by till which is relatively rich in limestone and clay and whose uppermost 2-3 m are weathered into boulder clay. In the southern and northern part of the cliff the moraine descends below sea level, and here it is overlain by sands devoid of stones and gravels which are in turn capped by a thin stony soliflual mantle. At some places the sands have preserved remnants of interstadial podzols. These sediments also overly the Eemian peat in the depressions (fig. 1). *Andersen* (1965) considers them as Early Weichselian niveo-fluvial and eolian deposits typically filling in depressions of this time (conv. *Menke* 1974; *Felix-Henningsen* 1979). In the south of soil profile 1 (fig. 1) greenish-grey clay beds of the Upper Eocene (oral communication by *W. Hinsch*, Geological Survey Kiel) underlie the till.

In the immediate neighbourhood of soil profile 3 the base of the 6 m thick moraine was exposed. Thereunder is an older sandy loam with feeble carbonate content (< 5 %) which contains floes of humic micaceous clay of Tertiary age (oral communication by *B. Menke*, Geological Survey Kiel).

As early as 1910 *Gagel* hinted at the modest weathering intensity of the Emmerlev till and compared it to the 10 meters' weathering of the Drenthe ground moraine on the Isle of Sylt which is exposed in about 20 km western distance at the Rote Kliff. He consequently attributed the two moraines to different glaciations, namely the »upper and lower ice age«. In view the differences in weathering intensity and petrographic composition (fig. 2) as compared to the tills of lower Saalian age (Saalian s.s. or Drenthe) also *Becksmann* (1931), *Gripp* (1964), *Andersen* (1965) and *Liedtke* (1975) are inclined to consider the Emmerlev till as a Warthe deposit.

In order to corroborate the stratigraphy of the above authors, *G. Schlüter* from the Geological Survey Kiel applied his boulder statistics procedure *(Schlüter* 1978). The counting results proved the petrographic composition of the ground moraine to be heterogenious. While as a rule Warthe ground moraines are characterized by a high amount of east-fennoskandian index boulders (*Woldstedt/Duphorn* 1974, s. 66) their number is quite variable in the Emmerlev till. Their percentage, and in particular the amount of Åland boulders, Red and Brown Quartz-Porphyrs and singular Finnish Rapakiwi Granites, varies between 20 and 25 % at the nothern and southern ends of the cliff line, while it decreases to 6,5 % in the central parts. According to *Schlüter* (1978) a Warthe age of the till appears likely. In contrast the amount of eastfennoskandian index boulders never exceeds 10 % in the Drenthe till at the Rote Kliff on the Isle of Sylt.

The distinctly lower values obtained from material from the central part of the Emmerlev Klev are very likely to be due to the incorporation of allochthonous material into the ground moraine as can be also deduced from dispersed major inclusions of sandy boulder clay of Drenthe age.

In order to further corroborate these results *J. Ehlers*,

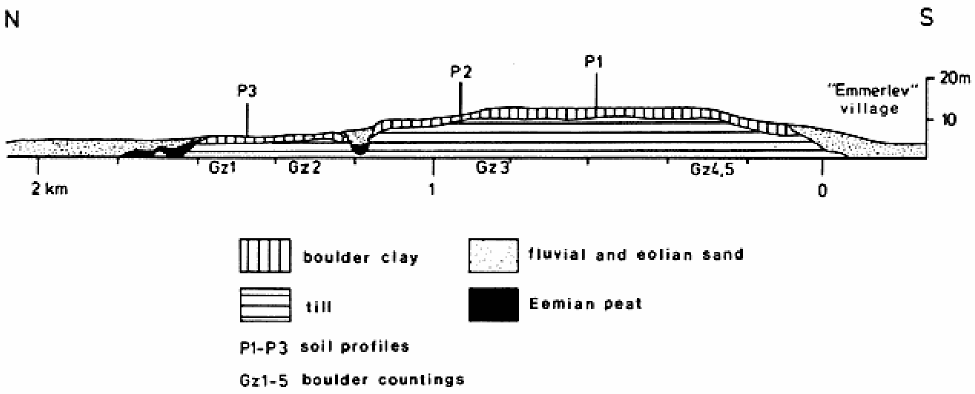

Fig. 1. Longitudinal profile of the Emmerlev Klev.

Geological Survey Hamburg, carried out fine gravel analysis of the 3-5 mm.s. fraction. The fine-gravel composition with its very low quartz (5,9 %) and high flintstone (32 %) and chalk contents corresponds to those of the »Niendorfer moraine« of the middle Saalian in Hamburg. The latter is correlated with the Drenthe II stage in Lower Saxony by *Meyer* (1973), which the term »Warthe« is also used for in Schleswig-Holstein.

Summarizing it may be stated that the boulder and fine-gravel composition of the Emmerlev till is very different from that of the first Saalian moraine of the Rote Kliff on the Isle of Sylt (*Felix-Henningsen* 1979).

Therefore the Emmerlev till may be correlated with a younger stage of the Saalian complex.

MORPHOLOGICAL, PHYSICAL AND CHEMICAL PROPERTIES OF THE SOILS

The chalk-rich moraine of Emmerlev Klev mostly has a depth of decalcification between 2 and 3 meters. In the northern part of the cliff the depth of weathering is decreasing down to 1,5 m while the chalk content of the parent material is increasing definitely. From this till a lessivé-pseudogley (surface water gley) soil association with differences in depth of weathering and intensity of podzolization of the sandy topsoil has developed.

The horizon sequence of the soils investigated shows fig. 3. They are all two-deck soils, since the boulder clay is buried by 60-80 cm of coversand, which mostly orginated in this place under periglacial conditions of the Weichselian from the cryoturbate and soliflually reworked topsoil horizons of the Eemian soil impoverished in clay. This sandy-stony layer on the top of the boulder clay is a typical characteristic of soils from Saalian till (*Dücker* 1954; *Heinemann* 1964; *Roeschmann* 1967, 1971; *Kopp* 1968). The soil horizons in this sandy topsoil show differences in their development. In most areas, as shown in profile 2 (fig. 3) a rusty coloured, podzolic B_{fc} horizon with mottling by logged surface water follows below the humic A horizon. In the deeper part of the cover sand a pale yellowish-brown eluvial (E) horizon, characterized by wet bleaching, lessivation and very marked rusty mottling by logged surface water occurs. In smaller areas the podzolic B_{fc} horizon is lacking (profile 1, fig. 3), while the intensity of logged surface water seems to increase. In some areas in the northern part of Emmerlev Klev a typical iron-humic-podzol has dveloped, while due to a higher sand content in the boulder clay and therefore decreasing density the influence of logging surface water here is decreasing too.

The border from the sandy topsoil to the boulder clay mostly shows characteristics of periglacial destruction like frost wedges and sand involutions. The dark brown boulder clay is a sandy to strong sandy loam with a very marked polyhedral to prismatic structure. Well developed clay coatings, very often bleached by logged water and intensive

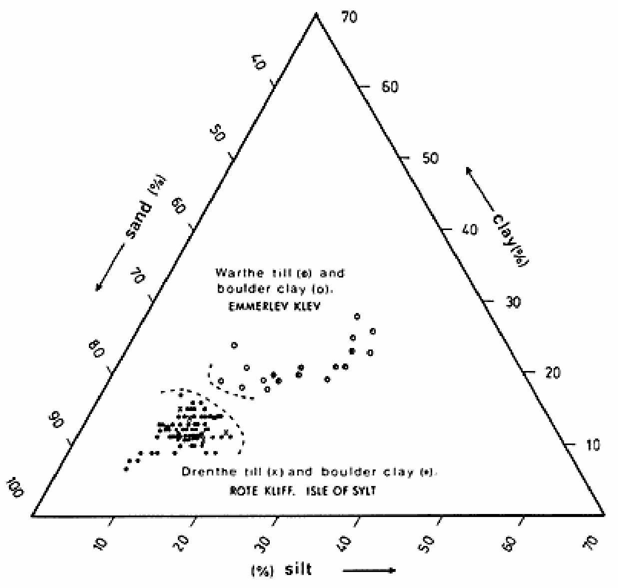

Fig. 2. Differences in granulometry of Drenthe and Warthe moraines.

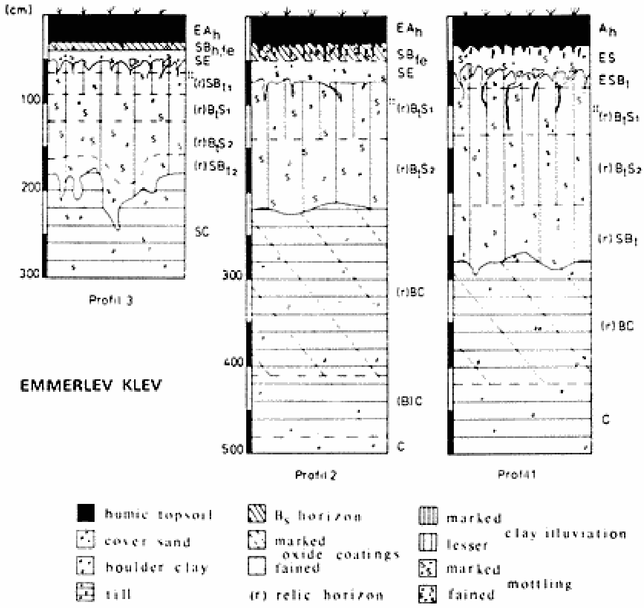

Fig. 3. Morphology of the soils at Emmerlev Klev.

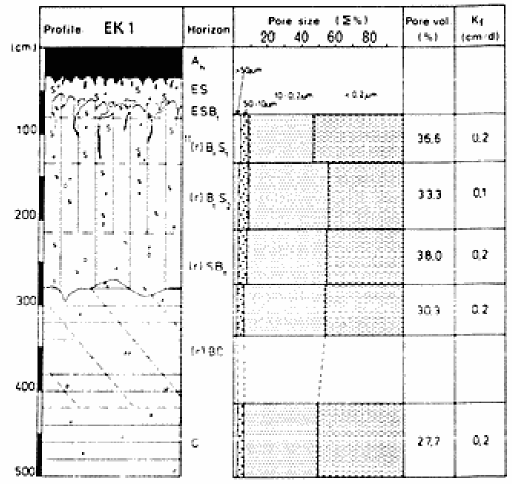

Fig. 4. Poresize distribution, total porevolume and water permeability (K_f) of a lessivé-surface water gley from Emmerlev till.

mottling by secondary surface water gleyification, which both decrease with increasing depth, are indicative for B_tS or SB_t horizons.

The till only and predominantly shows a horizonation corresponding to that of profiles 1 and 2 (fig. 3). The grey-brown colour, due to brunification in the upper part, is connected with prismatic structure and clay-iron coatings on the ped surfaces. With increasing depth it changes to coherent structure and dark-grey colour, which is due to incorporation and equal distribution of organic substances in the till. Mineralogical analysis of the clay fraction also shows an amount of chlorite in this horizon. In the upper grey-brown till horizon both organic substances and chlorite was subject to destruction by oxidation and brunification.

The carbonate content (fig 5) of the till is increasing at Emmerlev Klev from south to north (P 1: 13 %; P 2: 22 %; P 3: 32 % $CaCO_3$) while the depth of weathering is decreasing in the same direction.

The finer soil material (<2 mm) of the till has 19-23 % clay, 20-27 % silt and 49-60 % sand (fig. 2 and 5). In the boulder clay horizons the content of clay is increasing towards the surface due to neoformation and illuvation. With increasing depth of weathering from profile 1 to profile 3 both intensity and depth of clay illuviation are decreasing too.

The cover sand contains a distinctly smaller amount of clay (7-12 %) and silt (fig. 5), while the amount of sand, especially in the middle and coarse fractions is higher, due to relic lessivation processes, solifluction and deflation of fine material under periglacial conditions. The present day soil in the cover sand predominately shows a clay maximum in the humic A horizon, but features of recent clay migration and illuviation into the deeper part of the cover sand are micromorphologically visible.

While the coversand has a good percolation capacity the density of the boulder clay and till, especially the very low contents of large pores (> 50 μm - 10 μm, fig. 4) causes impeded drainage and surface gleyification.

The maximum of fine pores (< 0,2 μm) in the upper horizon of the boulder clay corresponds with the maximum of clay enrichment by illuviation. Marked differences in the total pore volumes (fig. 4) between boulder clay and till indicate the influences of decalcification, formation of polyhedral and prismatic structures, as well as the penetration by finer roots, which cause the lower density of the boulder clay.

Fig. 5 and 6 represent some of the pedochemical properties. The gradients of base saturation and pH value, as well as the distribution of exchangeable cations with the relative high amount of exchangeable Ca^{++} demonstrate the relatively inferior influence of leaching processes on the sorptive phase as compared with soils from Drenthe tills (*Felix-Henningsen* 1979, 1980). The increasing values of the sandy topsoil are indicative for the influence of agricultural chalking.

The amounts of free iron and manganese oxides are increasing from the parent material to the top of the boulder clay, which corresponds to the influence of weathering processes. While the Fe maximum correlates with that of clay content, manganese oxides attain their maximum in the deeper part of the boulder clay, which is due to hydromorphic translocation. In the horizons of the sandy topsoil their gradients are modified by processes of hydromorphic leaching and podzolization.

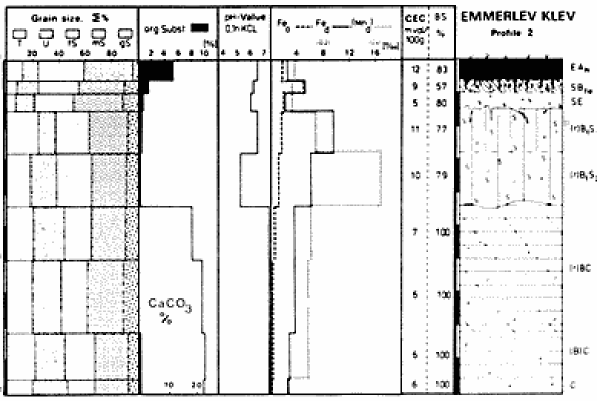

Fig. 5. Podzolized lessivé-surface water gley from Emmerlev till – granulometry, contents of organic matter and carbonates, pH values, contents of oxalate (Fe_o) and dithionite (Fe_d, Mn_d) soluble oxides, cation exchange capacity (CEC) and base saturation (BS).

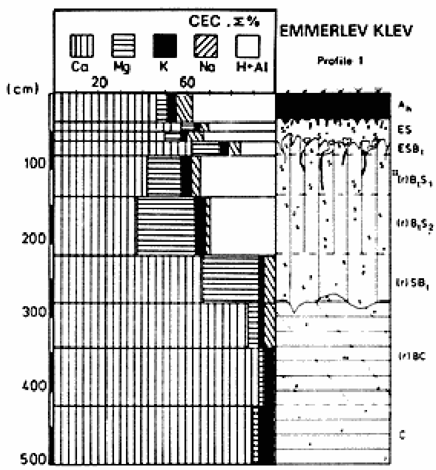

Fig. 6. Distribution of exchangable cations in a lessivé-surface water gley from Emmerlev till.

Mineralogical analyses of the silt and fine sand fractions (tab. 1) reflect the weathering gradient of the soil, as expressed in the pedochemical results. The content of quartz with its high stability to weathering is increasing from till to topsoil due to continuous delivery from coarser fractions. The amounts of feldspars and phyllosilicates in absolute and in relative proportions to quartz are decreasing in the same way by weathering.

In the clay mineral fraction illite is predominant while in the upper horizons of the boulder clay and especially in the coversand 14 Å minerals (vermiculites and secondary chlorites) appear.

Summarizing it may be said that the soils from Warthe till at the Emmerlev Klev reflect greater depth and intensity of weathering than surface water gleyed lessivé soils from Weichselian till as described by *Stremme* (1958, 1979), *Blume* (1961, 1968) or *Glückert* (1974).

These differences in weathering status affecting the same soil type are an expression of the longer period of weathering and the summary influence of pedogenic processes during the Eemian interglacial, Weichselian interstadials and the Holocene, which formed the soils on Warthe moraines. Also the relatively strong podzolization of the sandy topsoil, which is much lesser in soils on Weichselian tills, indicate the interglacial, interstadial and periglacial preweathering of the coversand.

PALEOPEDOLOGICAL RESULTS

The properties of the Emmerlev Klev soils described above and their differences to soils from Weichselian tills infer that they could be relic soils which began to form at the beginning of the Eemian interglacial. Their properties had been changed during the Weichselian by interstadial and later on by Holocene soil forming processes. The results of physical, pedochemical and mineralogical investigations described in this paper display the polygenetic character of the soil as derived from mixed samples of the various soil horizons.

Relic and recent soil characteristics cannot be distinguished by these summary unspecific methods; by far better are the macro and especially the micromorphological procedures discussed below.

The coversand, which is derived predominantly from material of the underlying boulder clay, impoverished in clay during the Eemian and periglacially reworked during the Weichselian, in fact constitutes a new sediment, from which the Holocene soil horizons developed.

Macromophologically they indicate surface gleyification (mottles, concretions) and podzolization ($B_s$horizon). Also micromorphologically speaking these processes predominate; thus changing the characteristics of the prior (holocene) clay migration. Thin, highly birefringent, undisturbed coatings around coarser grains or in form of hanging meniscs between them, have in the $B_s$horizons covers by layered iron-humic compounds, which are due to the podzolization. In soil profiles, where the permeability of the boulder clay below is better which leads to decrease of water logging in the cover sand, a weak clay enrichment horizon is developed at its base. Many rounded aggregates with a higher clay content and displaying a dense microstructure similar to that of the B_t horizons in the boulder clay, are dispersed within the sandy matrix of the coversand horizons. In these aggregates oxide concretions and coatings of illuviated clay, the latter mostly broken and reworked in the matrix, are encountered. They can be interpreted as soil relics from the Eemian B_t horizon incorporated into the coversand by soliflual processes.

The SB_t and B_tS horizons in the boulder clay display characteristics of clay illuviation and surface gleyification. The matrix of these horizons shows a clay-rich, dense micro-

Table 1

horizon		quartz	Q : F	Q : Ph	
I	A_h	34.3	4.7	7.0	cover-sand
	A_hE	34.7	4.6	6.5	
	ES	32.5	3.7	4.4	
II	rB_tS_1	30.7	3.8	3.0	boulder clay
	rB_tS_2	27.0	3.7	2.9	
	rSB_t	28.2	3.7	2.4	
	BC_1	25.7	3.6	2.0	till
	BC_2	25.7	3.8	2.1	
	C	24.4	3.2	2.3	

Content of quartz (weight %) and relations of quartz to feldspar (Q : F) and quartz to phyllosilicates (Q : Ph) of the fraction 2 - 200 µm of a lessivé-surface water gley from Emmerlev till.

structure with pores and root channels the number of which decreases with depth. Only near the upper limit of the boulder clay some of them show thin illuvial, undisturbed clay coatings with well birefringence, due to recent clay illuviation from the coversand, while these features lack in the deeper parts. In their place remains of thick clay coatings are quite numerous. They are disturbed by secondary cracks, covered by coarser silty and sandy material and often reworked into the matrix. They characteristically display a distinctly weaker birefringence than recent coatings and can be interpreted as relic features of the Eemian pedogenesis. Because the relic clay coatings represent a feature of relatively high stability, they have not been remodelled by recent pedogenesis but were strongly disturbed and reworked by periglacial processes. The characteristics of surface gleyification, such as zones of bleaching beneath oxide accumulations and concretions, overlying the illuvial clay coatings indicate that they are due to a secondary process subsequent to the increase in density of the B_t horizons due to clay illuviation and possibly also caused by increasing humidity of climate.

Contrary to the clay coatings the features of surface gleyification are of distinctly lesser stability, hence they cannot be distinguished with respect to relic or recent character. But concretionary oxide acculumation inside the soil relics and covered by recent clay coatings allochthonous, well-rounded oxide concretions in the coversand definitely indicate that surface gleyification was already a dominant soil forming process during the Eemian.

SOIL EVOLUTION

The results of micromorphological investigations show that the soils from Warthe till at the Emmerlev Klev display characteristic relic features of Eemian pedogenesis. As such they correspond to those of a buried Eemian soil from Warthe till of the locality Schalkholz (Schleswig-Holstein), where *Menke* (1974, 1976) and *Felix-Henningsen* (1979) elucidated the history of Eemian pedogenesis by palynological and paleopedological investigations.

Following the initial decalcification of the till and brunification of the boulder clay, the climatic optimum of the Eemian interglacial (Corylus and Tilia zones) was the time of clay illuviation giving rise to a marked B_t horizon below a topsoil impoverished in clay.

Menke (1976) qualifies the sites of this time as eu to mesotrophic with warm summers and mild winters. From the Tilia zone upwards the influence of surface gleying increased and was intensified by pedogenic clay illuviation. In the subsequent Carpinus zone in all sites mineral depletion and acidification increased hence the intensity of clay translocation lessened and podzolization commenced in the now sandy topsoils. It dominated from the end of the Carpinus zone when Coniferes and Calluna species began to spread while summer temperatures diminished. The continuous increase of macroclimatic humidity coupled with decreasing summer temperatures and still relatively mild winters intensified the features of surface gleyification.

The podzolized surface horizons of the Warthe moraines were remodelled during weaker phases of podzolization in Early Weichselian interstadials. Later on it was transformed into a homogenous coversand by cryogenic and soliflual processes during the Weichselian periglacial.

With the beginning Holocene the surface gleyification continued, because the physical conditions of the deeper, clay-enriched horizons of the boulder clay had not changed essentially. Weak processes of clay migration in the coversand may have been of relative short duration and the weathering processes changed to podzolization coupled by low clay content, base saturation and high acidity due to preweathering of the substrate. In the latest phase of evolution the soils at Emmerlev Klev became changed in their soluble and sorptive phases by anthropogenic fertilization.

In summary it can be stated that the Eemian relic soil on Warthe moraines, a podzolic lessivé-surface water gley, after periglacial reworking continued to develop along the same pedogenetic lines during the Holocene.

SUMMARY

Stratigraphical investigations of the Emmerlev till by boulder statistics and fine-gravel analysis led to an interpretation as Warthe moraine of middle Saalian age. The two-deck lessivé-surface water gley soils in the boulder clay and coversand on top, with a depth of decalcification varying between 1,5 and 3 m and marked podzolization of the sandy topsoil, were investigated by physical, pedochemical and mineralogical methods to precisely determine their characteristics, properties and status of weathering. They reflect a deeper and more intensive development, than soils of the same type from Weichselian till, which infers the summation of weathering processes of the Eemian interglacial, Weichselian interstadials and periglacial times, as well as the Holocene. Recent and relic soil characteristics could be distinguished

by means of micromorphological analyses. Their results display that clay enrichment in the B_t horizons followed by surface gleyification had been the dominating processes during the Eemian interglacial. After periglacial reworking and formation of the coversand this relic soil continued to develop during the Holocene in the same pedogenic direction to a podzolized lessivé-surface water gley.

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