Clay Migration and Podzolization in a Danish Soil

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In clayey soils in Denmark the pedological development normally leads to the formation of argillic horizons. In few places the argillic horizon is degradated and a podzol develops in the clay-poor eluvial horizon. This paper describes a profile of this type, situated in Northern Jutland.

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This paper deals with a profile, a polysequum, in which the result of podzolization and clay migration is clearly demonstrated. The profile is situated in Rold Skov in Northern Jutland, fig. 1. This area was covered by ice during the Würm glaciation which ended approximately 12000 years ago. After the glaciation period parts of the glacial landscape were transgraded by the sea, and parts lay exposed as islands with shallow waters in between. Due to the general upheaval of land during the last 10000 years, these islands are today linked together by marine forelands.

The presented profile has developed in glacial deposits in which the soil forming processes have not been active for more than 12000 years. During the main part of this period the dominant soil moisture regime has probably been udic and the temperature regime probably mesic (Soil Survey Staff 1975). Today the mean annual values for Rold Skov are: temperature between 7-8°C, precipitation approximately 700 mm, and potential evapotranspiration approximately 500 mm. During the summer, the soil will often dry out, in wintertime heavy leaching will occur.

Soil profile description

The profile is situated in a beach forest on a high-lying morainic plateau in Rold Skov. The area has been covered by forest at least during the last 300 years, probably much longer. The profile was described according to a Danish system (Madsen 1983) which in many ways is similar to FAO Guidelines for Soil Profile Description.

Fig. 1. Map of Denmark and the location of Rold Skov.
Fig. 1. Kort over Danmark med angivelse af Rold Skov.

Profile description

O1f (3-0):	dark brown mor-layer.
A'1 (0-8):	dark gray (10YR 4/1 dry) loamy sand having many white sand grains, weak subangular blocky, soft, very few stones, many roots, clear and irregular.
A'2 (8-20):	light gray (10YR 7/2 dry) loamy sand, weak subangular blocky, soft, few stones, few roots, clear and irregular.
B'2s (20-33):	dark brown (7,5YR 4/4 moist) sandy loam, weak subangular blocky, firm, discontinued weakly cemented, very few stones, many roots, gradual and smooth.
B'3s (33-50):	strong brown (7,5YR 5/6 moist) loamy sand, weak subangular blocky, friable, discontinued weakly cemented, very few stones, few roots, clear and smooth.
A2x (50-82):	light yellowish brown (2,5Y 6/4 moist) loamy sand, very firm, few stones, very few roots, gradual and smooth.
B2tgx (82-120):	strong brown (7,5YR 5/6 moist) sandy loam, silty light coloured ped surfaces, extremely firm, very few stones, no roots.
B3tg (120-):	strong brown (7,5YR 5/6 moist) sandy loam.

	texture u							OM	pH		$CaCO_3$	Dith. citr.		exch. bases m. eq.				CEC	V
	<2	2-20	20-63	63-125	125-200	200-500	500-2000	0/0	H_2O	$CaCl_2$	0/0	Fe 0/00	Al 0/00	Ca	Mg	K	Na	m. eq.	0/0
A'1 (0- 8)	2	8	13	12	29	25	8	3.1	4.5	3.6	0	0.4	0.1	0.37	0.15	0.07	0.03	5.3	12
A'2 (8- 20)	2	9	14	13	28	25	8	0.5	4.6	3.7	0	0.6	0.1	0.12	0.03	0.03	0.01	1.2	17
B'2s (20- 33)	9	10	12	12	26	21	8	2.5	4.2	3.7	0	9.5	1.6	0.25	0.12	0.06	0.04	20.5	2
B'3s (33- 50)	5	9	8	10	27	29	11	0.7	4.7	4.3	0	2.7	1.7	-	-	-	-	-	-
A2x (50- 82)	5	9	10	12	28	26	9	0.7	4.8	4.4	0	2.0	1.4	0.12	0.02	0.03	0.02	7.8	2
B2tgx (105-110)	13	9	9	10	25	26	8	-	4.7	3.9	0	-	-	0.10	0.09	0.10	0.05	8.2	4
B3tg (150-160)	14	8	11	11	23	24	9	-	4.7	4.0	0	-	-	-	-	-	-	-	-

Table 1. Analytical results of the investigated profile in Rold Skov.
Tabel 1. Analyseresultater fra det undersogte profil i Rold Skov.

Soil sampling and analyses

Soil samples were taken from all horizons and the following analyses were carried out.

Texture analyses were carried out using the hydrometer method (Hansen 1961, Mathiesen et al. 1976). The content of organic matter was determined by using an IR-Leco apparatus (Tabatabei et al. 1970, Mathiesen et al. 1976). On samples suspended in H_2O and 0.01M $CaCl_2$ pH was measured potentiometrically. For both liquids a soil-liquid ratio of 1:2.5 was used. Dithionite-citrate soluble iron and aluminum were determined as described in Soil Conservation Service (1972) and the cation exchange capacity and exchangeable bases were determined as described in Borggård et al (1979).

Results and discussions

The analytical data are shown in table 1. The grain size distribution indicates that the profile is developed in sandy glacial till with nearly the same distribution of material within the silt- and sand fraction. The profile is strongly leached, pH (H_2O) is around 4.5 and the base saturation is very low especially in the subsoil. The decrease in base saturation with depth is not due to liming but, rather to the liberation of bases when organic matter decomposes. Among the exchangeable bases calcium dominates, which is normal for Danish soils except for young marine soils where sodium dominates.

		Fe 0/00	Al 0/00
SRo2	B2s	4.1	1.1
	B3s	2.8	1.5
SRo3	B2s	4.9	3.6
	B3s	1.5	6.0
SRo4	B2s	3.3	1.2
	B3s	1.3	1.9

Table 2. The distribution of dithionitecitrate-soluble iron and aluminum in the B-horizons for different soils in Rold Skov.
Tabel 2. Fordelingen af dithionitcitratopløseligt jern og aluminium i B-horisonterne fra podzoler i Rold Skov.

The distribution of dithionite-citrate soluble iron and aluminum (Fe_d, Al_d) and organic matter down through the profile shows clearly a podzolization in the uppermost half metre. The upper 20 cm of the profile is the eluvial horizon, below this the illuvial horizon is situated from 20 to 50 cm depth. The eluvial horizon is divided into an 8 cm thick dark gray A1-horizon containing white sand grains superimposing a light gray A2-horizon poor in organic matter, Fe_d and Al_d.

The yellowish brown illuvial horizon is most clearly expressed in the amount and distribution of Fe_d and organic matter. The maximum value of Fe_d and organic matter is found in the upper part of the illuvial horizon while the maximum value of Al_d is found in the lower part of the illuvial horizon. This dissimilarity in the location of the maximum value for Fe_d and Al_d in the illuvial horizon is frequently found in podzols developed beneath deciduous forest in Himmerland as shown in table 2. Table 2 shows the amount of Fe_d and Al_d in the B2 and B3-horizon in three other podzols situated in Rold Skov beneath beech forest. In podzols developed beneath coniferous trees and heather vegetation the maximum value for Fe_d and Al_d is normally found in the upper part of the illuvial horizon.

The profile is developed in a parent material homogeneous in texture. This is demonstrated in table 3, where the percentage distribution of silt and sand is outlined. Table 3 shows an equal distribution of the grain size fraction greater the 2μ down through the profile.

Because of the great uniformity in the distribution of sand and silt in the profile the most reasonable explanation of the great diversities in clay content must be migration of clay. The variation in clay content indicates two separated clay illuviated horizons, one beginning at 82 cm depth and another between 20 and 33 cm depth. There were no clearly expressed clay cutans in these two horizons. For the Bt-horizon between the depth of 20 cm and 33 cm this is probably due to bioturbations and the podzolization of the horizon, while the lowest of the two horizons was slightly degradated. In the lower Bt-horizon silt cutans were present at the ped surfaces, forming tongues

	2-20μ	20-63μ	63-125μ	125-200μ	200-500μ	>500μ
A'1	8	14	13	31	26	8
A'2	9	15	13	29	26	8
B'2s	11	14	13	29	24	9
B'3s	9	8	11	29	31	12
A2x	9	11	13	30	28	9
B2tgx	10	10	12	29	30	9
B3tg	9	13	13	27	27	11

Table 3. The percentage distribution of silt and sand in the different horizons.
Tabel 3. Den procentvise fordeling af silt og sand i de forskellige horisonter.

or interfingerings in the illuvial horizon. In the lower Bt-horizon the formation of pseudogley was prominent, the horizon was consolidated and it appeared as a fragipan. The bulk density in the fragipan was approximately 1.80 g/cm³, much higher than in the superimposing podzol, where the bulk density in the eluvial horizon was around 1.4 g/cm³ and in the illuvial horizon around 1.5 g/cm³.

The pedological development of the profile over time

An explanation of the pedological development in the investigated profile, comprising the formation of a Bs-horizon, two different Bt-horizons one slightly degradated, and the formation of a fragipan is shown in fig. 2.

After the deposit of the parent material an A1-horizon will soon be developed because of the establishment of a vegetation cover. Below the A1-horizon a structural B-horizon will be developed due to bioturbation or a coloured B-horizon may be developed due to weathering of iron rich silicates. The profile will probably only be slightly leached and the soil is classified as an Eutric Cambisol according to FAO-Unesco (1974).

The annual surplus of precipitation causes a leaching of calcium carbonate, if present, and a leaching of exchangeable bases in the profile. The pH-value drops to around 5, a clay migration occurs, and the lower Bt-horizon will develop and affect the profile's hydraulic conductivity. In the eluvial horizon the hydraulic conductivity will be higher than in the illuvial horizon and in the parent material below. This is not only due to differences in clay content, but also to the decrease in the amount of coarse pores with increasing depth. This gives rise to the formation of surface-water gley in the B and C-horizon.

The development of a fragipan in the Bt-horizon might be due to the clay migration, where the illuvial clay makes the Bt-horizon dense (Knox 1957, Iha et al. 1963, Vanderford et al 1966) or the fragipan is developed due to compaction caused by permafrost just after the Würm glaciation (FitzPatrick 1956, Lozet et al. 1971, Van Vliet et al. 1981). On the basis of the analytical data it is not possible to conclude which of the two processes has formed the fragipan, but the presence of a compact A2-horizon above the Bt-horizon might indicate that the fragipan is developed due to periglacial processes. The soil is now an Orthic Luvisol or an Orthic Acrisol depending on the base saturation (FAO-Unesco 1974).

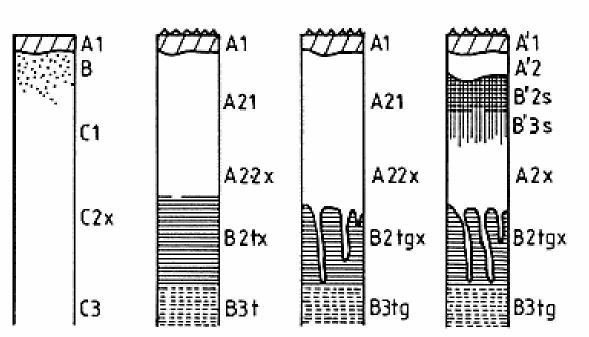

Fig. 2. The assumed pedological development for the profile in Rold Skov.
Fig. 2. Det formodede pedologiske udviklingsforløb for den undersøgte profil i Rold Skov.

The annual leaching of the profile makes the soil very acid, and pH (H_2O) drops to around 4 in the uppermost metre. The development of a moderate to strong structure in the Bt-horizon, in combination with the formation of very dense peds (fragipan), forces the penetrating water to follow the cracks between the aggregates. This leads to a removal or destruction of the clay minerals on the ped surfaces, and bleached tongues of silty material develop. This formation of degradated Bt-horizons is preveously described e.g. by Bouma et al (1966), Ranney et al (1969). Bullock et al. (1974) and in Denmark by Madsen et al. (1980). The soil is now according to FAO-Unesco (1974) a Dystric Podzoluvisol.

In the acid eluvial horizon above the Bt-horizon a podzolization has taken place. The podzolization of the eluvial horizon might run simultaneously with the degradation of the lower Bt-horizon. The podzolization is not only due to the acidification of the soil but e.g. also to the low clay content, the type of vegetation and the decomposition state of the organnic compound. The podzol has clearly expressed well-defined horizons, A'1-A'2-B'2s-B'3s. The texture is nearly the same within the silt and sand fractions in all horizons, while great differences are present in the clay content, table 3. The A'-horizons contain 2% of clay, the B'2s-horizon contains 9% of clay, and the B'3s-horizon and A2-horizon contain 5% of clay. This indicates a clay migration from A' to B'2s. A podzolization and clay migration giving rise to the same eluvial and illuvial horizon is previously described by Guillet et al (1975). They investigated two podzols, one below deciduous forest and one below heather vegetation. The profile below forest shows clearly clay illuviation into the spodic horizon while this was not the case in the profile below the heather vegetation, where clay destruction was profound.

It is, based on the analytical data, not possible to prove whether the clay migration and the podzolization are running simultaneously or not. Guillet et al. (1975) proposed the two processes to run more or less simultaneously, but the clay migration is dominating in the beginning while podzolization dominates later on.

According to Guillet, the clay migration must occur at very low pH-values, which is in contrast to the more common belief that the free aluminum ions present in the soil water will flocculate the clay particles and prevent their migration. A possible explanation of the clay migration in the podzol might be that organic compounds make complexes with the aluminum ions (Guillet et al. 1975) and therefore decreases the possibility of flocculation of the clay minerals. The profile is now, according to FAO-Unesco (1974), an Orthic Podzol.

Summary
The pedological development in a sandy loamy soil in Northern Jutland, Denmark, has been described. The profile was strongly leached, a clay migration has taken place, and a marked Bt-horizon was developed. The Bt-horizon was later slightly degradated. In the eluvial horizon to this Bt-horizon a podzol has been formed, in which a new clay migration has taken place.

Resumé
Den pedologiske udvikling i en lerblandet sandjord i Rold Skov er blevet beskrevet. Jorden var stærkt udvasket, og en tydelig lerakkumulationshorisont var udviklet fra 82 cms dybde. I lerudvaskningshorisonten var der udviklet en podzol, og en ny lernedslemning havde fundet sted.

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