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THE INFLUENCE OF TOPOGRAPHY ON THE DEVELOPMENT OF ALFISOLS ON CALCAREOUS CLAYEY TILL IN DENMARK

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SUMMARY

A detailed macro- and micro-morphological study of seven closely-adjacent soil profiles on calcareous clay tills in a long-established beech wood in central Denmark, shows that depth of decalcification, thickness of textural B horizon, development of umbric epipedons and development of albic sub-horizons are all related to slope inclination, slope form and to relative situation in the slope complex.

The soils may be classified within four subgroups of Alfisols, while one is a Mollisol. The MAST of 8°C poses problems of typification at suborder level between frigid and mesic classes.

Development of clay skins and of glaebules and concretions as indicators of the redeposition of mobilised components, are present to greater extent in stable slope situations, with least lateral subsoil water movement. Development of albic horizons is related to greater lateral water movement.

Development of cutanic features by argilluviation – argillans – do not exclude features formed by redeposition of carbonates – calcitans. Soil plasmic fabrics with both features are termed calcisepic fabrics and prove deposition of clay and carbonates in the same soil horizons, usually the lower B and C(g) horizons.

Morphologically the dark epipedons show intense humification and many fecal pellets because of the undisturbed and high plant productivity and intense biotic activity. The micromorphology is one of isotic argillasepic plasmic fabrics. The argillic horizons are dominantly insepic or vosepic, while the calcareous C horizons are either argillasepic, or calci-vosepic or calcisepic. It is possible that some of the carbonate reprecipitation post-dates the argilluviation, the carbonates derived during secondary dissolution in the suprajacent horizons.

1. INTRODUCTION

The paper presents the results of an investigation of the morphology of a soils sequence developed on a 13000 year old calcareous Weichselian till under beech vegetation in eastern Jutland, Denmark 56°17'N 10°28'E (fig. 1). The investigation forms a part of the Danish beech forest project, a subsection of the International Biological Programme (IBP), the location of the study site being called Hestehaven.

Generally studied the soils are Alfisols (SOIL SURVEY STAFF 1975) and are very similar to the Gray-Brown Podzolic soils, as described by THORP, CADY & GAMBLE (1959) in North America. Similar soils in north-central Europe have been investigated by SCHLICHTING & BLUME (1961). They studied 20 profiles developed on similar late

Pleistocene calcareous parent materials around the western part of the Baltic Sea. Apart from one Pararendzina, the soils described by these authors are Parabraunerde some of which are modified by pseudogley features and/or by podzolisation. Three of the profiles were from Denmark, a Parabraunerde, a Pseudogley Parabraunerde and a Podzol-Parabraunerde, all with beech vegetation. There are very few Danish studies of similar soils, although FOBIAN (1966), BUNTING (1970), HOLSTENER-JØRGENSEN (1973) and FAIZY (1973) have demonstrated horizons of clay accumulation. FOBIAN describes his profiles as Parabraunerde while the other authors do not classify the soils.

The present paper contains an interpretation of seven soil profiles inside an area of 6 hectares on a south-facing slope. With an elevation varying from 11 to 33 metres, development of these soils is related to topographical situation and texture of the parent materials. The soils are classified according to the American Classification System (SOIL SURVEY STAFF 1975), though this has raised problems with regard to the temperature boundaries between suborders of Alfisols in Denmark, which do not accord with their usage in the United States.

2. RESEARCH AREA

2.1. GEOLOGY AND TOPOGRAPHY

The field area (fig. 1 inset) is situated within the large terminal moraine of the Kalø Vig Glacier lobe (HARDER 1908) and is 1 km from the sea (Aarhus Bay). This lobe was part of the last great advance during the Weichsel Glaciation to the D-line, or East Jutland line, dated by MÖRNER (1969) to about 13.000 B.P.

The field area (fig 1 and photo 1) lies on the south-facing slope of a ridge, 1 km long and 0.4 – 0.5 km wide, running parallel to the terminal moraine. The highest elevation of the hill is 34 m OD. The terminal moraine rises to 100 m OD, 1.5 km north of the investigated area. The average gradient of the south-facing slope is 8% with 10-12% at the centre. A more gentle slope (3%) is found in the south east. The geology of the area has not been surveyed in detail, but the present investigation indicates that it is composed of clayey till, which, as normal for Danish tills, is of very complex composition. The most important constituents are metamorphic and igneous rock fragments from the Scandinavia Shield with a matrix of Cretaceous and Tertiary limestones, and clays of more local origin. The till parent material has a calcium carbonate content of about 20 per cent (15 to 21%). The topography of the area is shown in Figure 1.

2.2. CLIMATE AND SOIL TEMPERATURE REGIME

The range of mean annual temperature for Denmark (DET DANSKE METEOROLOGISKE INSTITUT 1975) is from 7.1°C to 9.4°C, with the highest values generally close to the coast because of the marine effect. The values are very close to the boundary between the fridig and the mesic temperature regimes defined by a 8°C mean annual soil temperature (SOIL SURVEY STAFF 1975).

The forest microclimate in the studied IBP area was investigated by NIELSEN (1976) and HANSEN (1976). In the present paper the climate is only considered with reference to the classification of the soil. The soil temperature at 50 cm depth was measured with a ther-

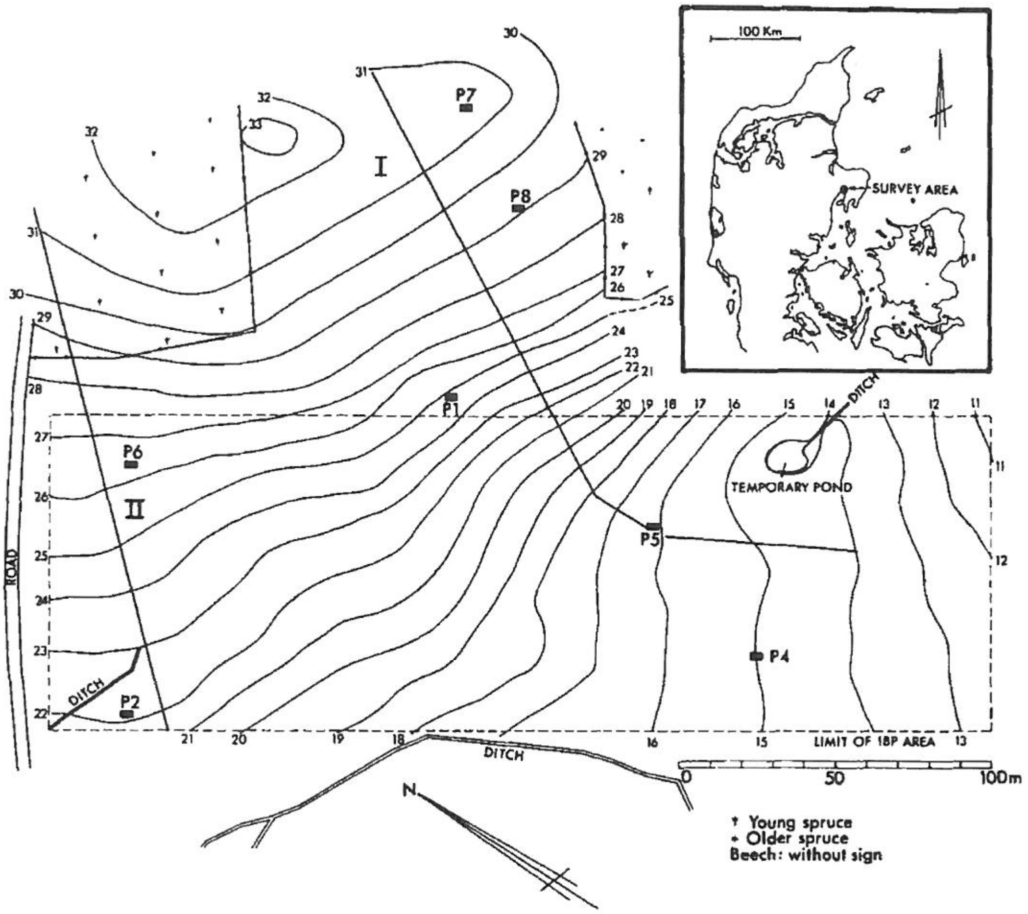

Fig. 1: Topographic map of the field area at Hestehaven, showing the profile sites and the lines of the cross sections. The map is an extension of a map of the IBP area made by Hedeselskabet. All unshaded areas occupied by beech wood. Contour heights in metres above O.D.

Photo 1: General vue of the slope from profile 4 in NW direction, approximately the same as cross section I (fig. 1). May 1979 at the end of the *Anemone nemorosa* flowering.

mograph fitted with mercury-in-steel probes and having one revolution per week. Soil temperature measurements (Table 1) are compared both to air temperature measured in a Stevenson screen, and to data from the meteorological station at Ødum, 21 km west of the IBP area. In Ødum the period under consideration was 0.3°C warmer than the 30-year mean. Further, the temperature in Hestehaven was higher than in Ødum during the whole period, leading to a long-term mean air temperature in Hestehaven close to 8.5°C. As the mean soil temperature for the measuring period was 1.3°C lower than the air temperature, mean annual soil temperature is close to 7.0°C.

It is surprising that mean annual soil temperature is lower than mean annual air temperature in the wood. This is opposite to the normal findings under grass. KRISTENSEN (1959) for example, found that the temperature at a depth of 50 cm under grass was 2.0°C higher than at a height of 2 m. Moreover, SOIL SURVEY STAFF (1975) claims (probably relying on SMITH et al. 1964) that "We can estimate the mean annual soil temperature for much of the United States by adding 1°C to the mean annual air temperature". SMITH et al. also measured differences in summer soil temperature between forest and arable land. They found deciduous forest soil to be 1.5-2.5°C colder than the cultivated soil. If these results are valid for Hestehaven, as indicated by our measurements, the soil temperature regime would change from frigid to mesic, if the wood were cleared. This problem is being investigated further by our institute by comparing forest and grass areas. The evidence is of interest in that it shows that the site is at the transition from mesic (temperate) to frigid (boreal) climates.

2.3. SOIL MOISTURE REGIME

According to DET DANSKE METEOROLOGISKE INSTITUT (1975) the mean annual precipitation for the area is about 600 mm and the potential evapotranspiration about 500 mm (JOHANNESSEN 1970). The moisture regime is characterised as udic. The mean annual moisture surplus (precipitation-actual ET) is 250 mm (BUNTING 1970).

Soil moisture was investigated by HANSEN (1976) by means of weekly measurements with a neutron probe. Water levels in the profile pits were also registered during 1974-75. The intallation of tubes for the neutron probe was complicated by the presence of stones in the till. As a result only poor contact was achived between the upper part of the tube and the soil. Consequently, the results can only be judged semi-quantitatively (Table 2). The zone of saturation rises from December-January when the soil water level is at depths of 2.3 m or more, to March-April, when it reaches a maximum height close to the surface. Minimum level of water table is assumed to be found where the change in soil water content, measured by the neutron probe is small, i.e. where the coefficient of variation is less than 10%. However the greater thickness of soil above the level to low soil chroma colours (Table 2) suggests that the zone of saturation in most years is found at a greater depth than measured in the period 1974-75. Profile 2 has the highest maximum water level, only 16 cm from the surface as well as the longest period with water levels above a depth of 50 cm (Table 2). Nevertheless, the greatest depth of the saturation zone in 1974, 2.6 m, was not greater than in the other profiles. This seems to indicate that the profile has poor internal drainage rather than a higher permanent water table. According to the data in table 2, the saturation zone oscillates through 2-3 metres depth. As the water flow lines on the slope are probably affected by the profile pits it is admitted that the pit water level may be higher than the real level of the soil water (Table 2) (WHIPKEY & KIRKBY 1978).

Tab. 1: MONTHLY MEAN VALUES OF SELECTED CLIMATIC DATA

	Meteorogical Station Ødum				Hestehaven Forest (IBP site)		
	Air temperature mean 1931-1960 °C	Air temperature 2,0 m 1974-75 °C	Precipitation mean 1952-1973 mm	Precipitation 1974-75 mm	Air temperature 2,0 m 1974-75 °C	Soil temperature 50 cm depth 1974-75 °C	Precipitation 1974-75 mm
March	1,3	3,3	32,5	25	3,5	3,4	22
April	5,8	7,6	37,9	11	8,5	5,8	17
May	11,0	9,7	44,4	27	10,7	7,0	29
June	14,4	13,2	51,6	15	14,8	9,5	28
July	16,4	14,0	77,2	86	15,4	11,0	87
August	15,9	15,1	74,2	45	16,2	12,3	29
September	12,5	12,6	54,9	91	13,9	11,9	63
October	8,3	5,9	64,2	84	7,4	8,5	107
November	4,5	4,9	69,6	72	5,1	6,5	85
December	1,9	3,7	53,9	95	4,2	4,8	77
January	-0,5	4,0	42,5	98	4,6	4,9	98
February	-0,8	1,1	33,1	(11)	1,6	4,1	(13)
Year	7,6	7,9	636,0	660	8,8	7,5	655

Tab. 2: VARIATION IN THE WATER-TABLE LEVEL IN FIVE PROFILES AT HESTEHAVEN

	Depths to highest water level in profile pits 1)		Periods with water level above 50 cm depth 1)		Depth to change of chroma (Munsell) 1) 4-5/4 to 4-5/1	Depth to lowest level of saturated zone
	cm 1974	cm 1975	days 1974	days 1975	cm	cm 1974
Profile 1	> 120	102	none	none	> 400	> 330
2	41	16	4/4-18/4 (14)	9/4-7/5 (28)	> 400	260
4	88	44	none	9/4-16/4 (7)	390	280
5	61	35	none	9/4-16/4 (7)	350	230
6	58	42	none	9/4-16/4 (7)	390	260

1) Data from HANSEN (1976)

2.4. VEGETATION

The Hestehaven wood is a part of the old natural beech-oak forest around the Kalø Estate. Hestehaven, first mentioned in 1685, was then composed of beech and oak. It was intensively used for grazing, which had a restrictive influence on rejuvenation. About 1825 the wood was fenced in, but apparently grazing went on to a minor extent until 1886 (NIELSEN 1972). Nothing suggests that the area has ever been ploughed.

The present vegetation (photo 1) is composed of a homogeneous stand of 90 year old beech (*Fagus sylvatica L.*) and some saplings of beech and ash (*Fraxinus excelsior L.*). Measurements by HENRIKSEN (1972) showed that the overstorey in autumn 1971 had a mean height of 29.0 m, and a density of 191 trees/ha. The mean stem diameter, 1.3 m above ground, was 43.1 cm. The total standing crop was 498.4 m^3/ha, and the annual increment was 12-16 m^3/ha (1967-71).

The annual litter fall was investigated by NIELSEN (1977) in the period 1967-75. The total annual fall of litter components was 435-535 g dry matter/m^2 yr., of which leaves constituted 240-300 g dry matter/m^2 yr. The productivity of the ground flora was investigated by HUGHES (1975). The net production above and below ground in the year 1969 was 160 g dry matter/m^2 yr., which was about one third of the tree litter fall. *Anemone Asperula odorata L., Melica uniflora Retz.*, and *Carex sylvatica Huds.* accounted for 80% of this production.

3. METHODS

3.1. PROFILE LOCATIONS

The sites of soil profiles 1 to 6 (fig. 1) were chosen according to discernment of significant slope changes and to an unpublished map showing clay content of the topsoil in the IBP area (PETERSEN 1969). Profile 1 would have the lowest and profile 2 the highest clay content in the topsoil, confirmed by our analyses. Profiles 4 to 6 were placed in an area with clay contents intermediate between those of profiles 1 and 2 and located to show the influence of the topography and slope position (Fig. 1). Profile 4 was placed on the footslope in the area of least slope. Profile 5 was sited just beneath the steepest slope on which profiles 1 and 8 were placed, while profile 6 was located on the less steep part of the slope above profile 2. Later profile 7 was examined on the slope crest, and profile 8 below it, and above profiles 1 and 5 on the slope, this in order to get more information about the probable influence of sediment and of solute transport from the upslope area lying outside the IBP study boundary (fig. 1).

3.2. FIELD METHODS

The soil descriptions follow the American System (SOIL SURVEY STAFF 1975) using a Munsell Soil Color Chart. The standard terminology has been supplemented by the use of the symbol (g) for pseudogley features as defined by SCHEFFER & SCHACHTSCHABEL (1976), and BC for horizons in which some calcium carbonate is left undissolved. The profiles were measured and generalised sketches are shown in figure 2. The profile pits, which were left open, were inspected several times each year in different moisture conditions to check the field descriptions and to measure the seasonal variation of soil water level in the pits during winter and spring and to observe lateral seepage and variation of internal soil properties on drying and wetting.

3.3. LABORATORY METHODS

In the laboratory the following measurements were carried out:

Total carbon by dry combustion in a Leca instrument, pH in 1:1 soil-water mix, and 1:1 soil-lN KCl. Exchangeable bases by leaching the soil with ammonium acetate at pH 7 (CHAPMAN 1965); bases by atomic absorption; exchange acidity in profiles 1-6 by the meta-nitrophenol method at pH 8.1 (PIPER 1944); in profiles 7 and 8 by the barium chloridetriethanolamine method (PEECH 1965). In some samples from profiles 7 and 8, CEC was also determined at pH 7 by the above ammonium acetate method modified by use of ethanol and centrifugation instead of isopropanol and suction filtration (DE CONINCK 1973). Carbonates by the gas-volumetric method (ALLISON & MOODIE 1965) using pure $CaCO_3$ as standard. For particle size distribution, 50 g samples were oxidized with 6% H_2O_2, and $Na_4P_2O_7$ was used as dispersing agent. In profiles 7 and 8 calcium carbonate was removed from the samples before dispersion by acetic acid-ammonium acetate buffer at pH 5.5 (MØBERG 1976). Parallel, untreated samples from these profiles were also included in the textural analyses. After removal of the fine fractions ($< 44\ \mu$) by wet sieving, the coarse fraction was dry-sieved for 20 minutes using ASTM standard 20 cm sieves on a $\sqrt{2}$ scale. Sedimentation analysis was carried out with Andreasen pipettes in a water bath at 20°C. All data are given in percent of the soil fraction less than 2 mm in size.

Micromorphological descriptions were made of samples from profiles 1, 2, 5, 7 and 8. The description follows the system of BREWER (1976). Thin sections (approx. 2 × 3 cm) were produced after impregnation with polyester resin under vacuum, the resin diluted with methacrylic acid methyl ester; a peroxide hardener and cobalt accelerator were also added in proportions 100:100:1:0.54.

4. RESULTS

4.1. PROFILE DESCRIPTIONS

The 0 horizons of the profiles are described in very general terms, because decomposition of the organic matter in the area has been described by others, e.g. YEATES (1972). The 01 horizon is only 3-5 cm thick and composed of leaves, cupules of beech and remains from the ground flora. The degree of fermentation increases down through the horizon and according to HENNING PETERSEN (personal communication, 1978) the decomposition period for the beech leaves to the unrecognizable stage is between 2 and 3 years.

Profile 1 is situated in the centre of the IBP research area on the steepest slope.

Profile 1 Mollic Paleboralf, fine-loamy, mixed parent material; maximum slope segment, 12% inclination to south, cross section 1, figs. 1 and 5. In the A2, B2t, B3t(g) and C horizons cobbles and stones constitute between 10% and 25% of the total volume, many of the cobbles and stones are weathered and soft.

A11 0 to 7 cm, very dark grayish brown (10YR 3/2 moist, 5/3 dry) very fine sandy loam; weak medium granular structure held together by plant roots; very friable, non sticky, non plastic; clear wavy boundary.

A12/13 7 to 54 cm, very dark grayish brown (10YR 3/2 m, 6/3 d) fine to very fine sandy loam; massive to weak medium subangular blocky; very friable, slightly sticky below 31 cm; gradual wavy boundary.

A2 54 to 67 cm, brown (10YR 4-5/3 m, 7/3 d) in the central thicker part and yellowish brown (10YR 5/4) in the thinner part; fine sandy loam; massive to weak medium subangular blocky; non sticky, non plastic, non coherent; clear wavy boundary.

B & A 67 to 80 cm, a horizon composed of A2 and B2t material arranged with 5-10 cm wide pockets of A2 material penetrating into the Bt to a depth of 95 cm. Boundary between A2 and B2t material is abrupt and wavy.

B2t 80 to 123 cm, brown to dark brown (7.5YR 4/4 m, 5/4 d) sandy clay loam; moderately strong coarse to very coarse blocky structure with thin brown clay skins; sticky and plastic; gradual wavy boundary.

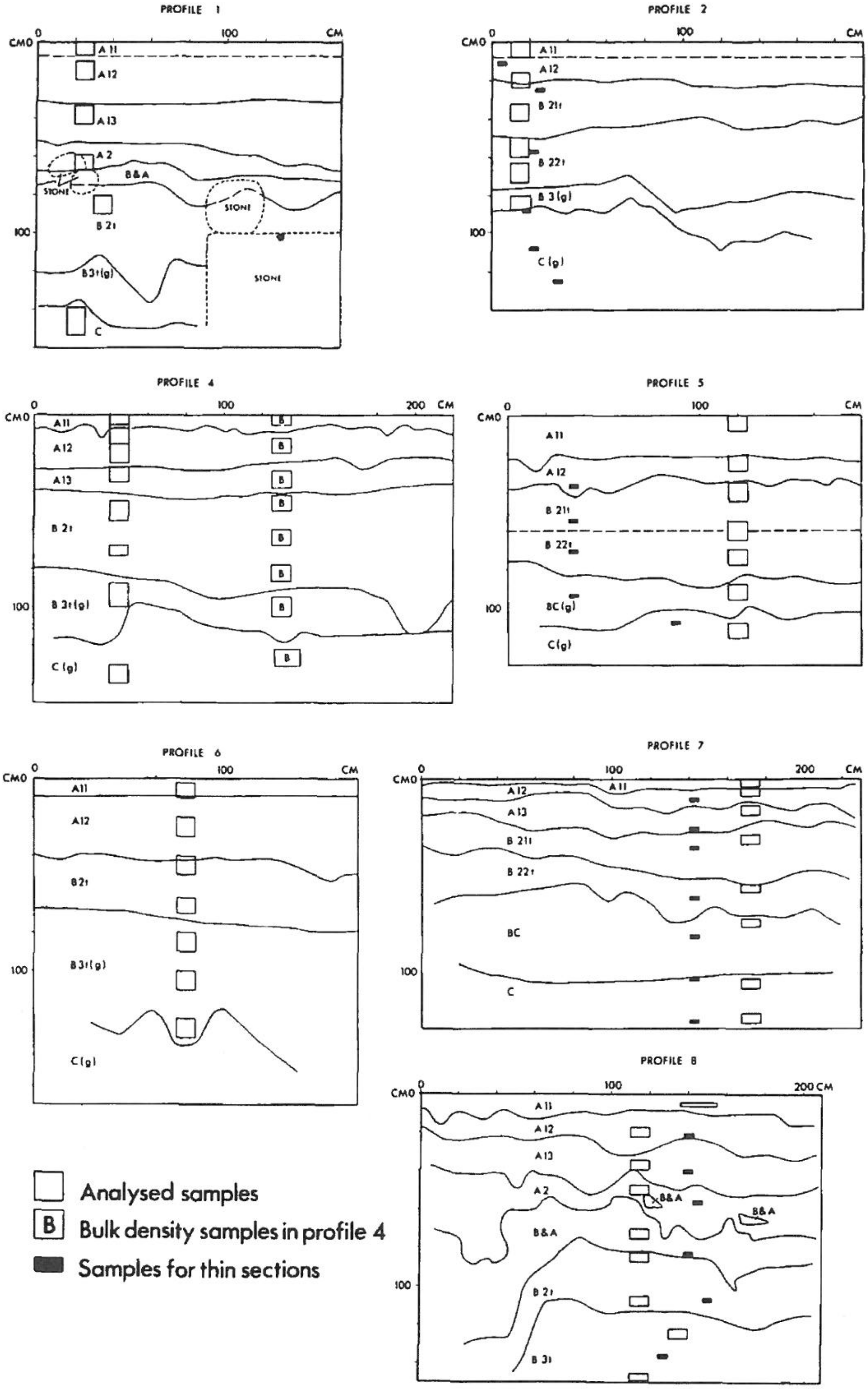

Fig. 2: Horizonation of the profiles and sampling depths for analysis and thin section description.

B3t(g) 123 to 142 cm, brown (7.5YR 5/4 m); loam arranged in a polygon-like pattern divided by 2-3 cm thick zones of light olive gray (5Y 6/2 m) loam between the polygons, otherwise similar to that of the B2t.

C 142 to > 160 cm, light yellowish brown (10YR 6/4 m, 7/3-4 d) loam; violent effervescence with HCl.

Micromorphology 8-10 cm. Voids are mostly channels and compound packing voids, some orthovughs, a few metavughs. The plasma is composed of unrelated humus with scattered clay flakes. Frequent pellets of many types and a few plant remains. Agglomeroplasmic to intertextic related distribution pattern. Argillasepic to isotic plasmic fabric.

Micromorphology 46-48 cm. Voids as in 8-10 cm. Mostly unrelated organic plasma, but some thin (10μm) argillans. Some fecal pellets and plant remains. Intertextic related distribution pattern. Argillasepic to isotic plasmic fabric.

Micromorphology 82-84 cm. Many ovoid metavughs in rows with or without inter-connection, a few metaskew-planes. Clayey plasma arranged as thick (200 μm) voidcutans, some voids completely filled with weakly-oriented clay. Some iron nodules with rather sharp boundaries, often in voids covered with argillans. Few fecal pellets, little or no organic plasma. Agglomeroplasmic to porphyroskelic related distribution pattern. Skel-in-vosepic plasmic fabric.

Micromorphology 97-99 cm. Thinner void argillans, some diffuse iron nodules and fecal pellets. Agglomeroplasmic to porphyroskelic pattern. Vo-insepic plasmic fabric.

Micromorphology 135-137 cm. Most voids are vughs which, in the limefilled channels, lie in rows. Some of the vughs seem to have developed through carbonate solution. Two types of plasma occur, clay and calcite, both often occurring as cutans. Calcite dominates as coatings (calcitans) along the larger voids. Clay forms cutans around many of the vughs and along planes. Argillans are often seen on the inside of voids in and on the calcite linings (see fig. 4). The gray brown unrelated plasma dominating the thin section is a combination of clay and calcite. Some diffuse iron nodules and a few fecal pellets are present. The related distribution pattern is porphyroskelic with a vo-calci-asepic plasmic fabric. There are many lime fragments and fossils.

Interpretation

This profile, sited on the steepest slope, has a deep, strongly-eluviated A horizon, with very low base saturation, relatively low bulk density, the highest silt/clay ratio of all profiles (2.6), and the clay content of the eluvial horizon is less than half of that in the illuvial horizon. It has abundant channels and tongues of albic material into the B-horizon reaching down to 95 cm depth, all of which can conduct water rapidly in a lateral direction. The profile is decalcified as deep as 1.35 m and the C horizon shows redeposition of calcite together with argillans (fig. 4 and section 4.2). Features of pseudogley are seen from 1.1 m depth and deeply-interred animal debris occurs down to 1.35 m, attesting the marked change of seasonal moisture condition in the solum on this relatively steep (12%) slope.

Profile 2 Mollic Eutroboralf, fine-loamy, mixed; 3% inclination to south-west; lower part of cross section II (figs. 1 and 5).

A11 0 to 7 cm, very dark grayish brown (10YR 3/2 m, 5/3 d); very fine to fine sandy loam; moderate, weak, medium granular; very friable; wavy clear boundary.

A12 7 to 21 cm, dark brown to brown (10YR 4/3 m, 6/4 d); very fine to fine sandy loam or loam, with few coarse distinct reddish mottles; massive to weak medium, sub-angular blocky aggregates; friable, slightly hard; clear wavy boundary.

B21t 21 to 45 cm, strong brown (7.5YR 4/6 m, 6/4 d); sandy clay loam with dark grayish brown (10YR 4/2) coated ped surfaces; few fine to medium distinct dark mottles containing manganese; moderate medium blocky; very firm, hard; gradual wavy boundary.

B22t 45 to 79 cm, yellowish brown (10YR 5/6 m, 6/4 d); sandy clay loam; brown to dark brown (10YR 4/3) clay skins on peds, changing gradually to light gray or olive gray (5Y 6-7/2) downwards; coarse prismatic breaking into coarse blocky; firm and hard; gradual wavy boundary.

B3(g) 79 to 95 cm, yellowish brown (10YR 5/8 m, 6/4 d), and strong brown (7.5YR 5/8 m); loam arranged in 5-10 cm aggregates surrounded by 2-3 cm thick light gray (5Y 6/1) zones; sticky, plastic; gradual wavy boundary.

C(g) 95 to > 140 cm, yellowish brown (10YR 5/8 m) and pale brown (10YR 6/3 m); fine blocky peds with light gray (10YR 7/1 m) surfaces; non sticky, slightly plastic; violent effervescence with HCl.

Micromorphology 10-12 cm. Macro-channels separate the peds. A few vughs and compound packing voids within the S-matrix. Mostly humus plasma, with some unrelated clay plasma. Some diffuse iron and manganese nodules. Frequent pedotubules, many fecal pellets and plant remains. Agglomeroplasmic pattern. Argillasepic to isotic plasmic fabric.

Micromorphology 24-26 cm. Straight smooth broad planes without cutans. Otherwise very few voids, except some mammilated vughs, in the S-matrix. Much clay plasma arranged, partly randomly, partly banded. A few thin argillans. Some diffuse iron and manganese nodules, a few distinct iron nodules and some fecal pellets. The peds are very well developed, well-accomodated and packed normally as multiangular blocky peds. Agglomeroplasmic to porphyroskelic pattern. In-vosepic plasmic fabric.

Micromorphology 56-58 cm. Irregular macrovoids, ortho-skew planes and vesicles, sometimes arranged in a linear way. The clay plasma is arranged both as cutans and void infillings. Argillans are thin and not well-oriented. A few ferrans, some diffuse iron nodules and sharp manganese nodules. Some fecal pellets. The matrix of the thin section is quite inhomogeneous; in some areas, some fillings of silt material (> 1 mm. wide) are seen in the vicinity of the macrovoids. Agglomeroplasmic pattern. In-vosepic plasmic fabric.

Micromorphology 87-89 cm. The plasma is an unrelated, homogeneous mixture of clay and calcite. No cutans, but some diffuse iron and manganese nodules. Porphyroskelic pattern, calci-asepic plasmic fabric. Many lime fragments and fossils.

Micromorphology 107-109 cm. Few weak metavughs, vesicles, a few channels (250 μm Ø) and some skew planes. In areas with dissolution of the lime plasma, the vughs are extremely irregular. The plasma is an unrelated nonhomogeneous mixture of clay and lime which is weakly cutanic with very few and thin argillans inside the lime cementations. Several calcitans are seen. Many diffuse iron and manganese nodules. In some parts the lime cementation fills all voids, so that plasma is distributed quite unequally. Between these zones are plasma-poor areas. The related ditribution pattern is variable from granular to porphyroskelic. Vo-calci-asepic plasmic fabric. Many lime fragments and fossils are present.

Micromorphology 124-126 cm. Very clear sorting is seen. In plasma-poor areas, simple packing-voids and an homogeneous mixture of clay and lime plasma are present with a few argillans, ferrans and calcitans, a few diffuse iron and manganese nodules and some fecal pellets. The voids are very irregular vughs, especially in the areas of limey plasma, with some skew planes. Porphyroskelic related distribution pattern, in plasma-poor parts, intertextic to granular. (vo)-calci-asepic plasmic fabric.

Interpretation

Profile 2 in the mid-slope position, but on a gentle slope, has a very thin A horizon, with a relative shallow solum (95 cm). The macro- and micro-structure of the A and upper B horizons is relatively massive, with a tendency to banding, a relict of former deposited material and of a drying influence. The lower B and C horizons are irregularly developed with some parts recalcified and argilluviated; in others there is no differential movement of lime from the clayey matrix, though there is generally much lime dissolution and vugh development. The linearity of this dissolution would indicate preferential solution within a limited depth (c20 cm) and very localised adjacent redeposition of lime. The irregular pseudogley pattern, compared with the more regular prism-like pattern in the other profiles together with the textural stratification, indicates an inhomogeneous parent material.

Profile 4 Mollic Eutroboralf, coarse-loamy, mixed; nearly level area at foot of the slope, 2% inclination (figs. 1 and 5).

The profile is characterized by weathered gravel and stones, which can be crushed in the hand. The weathered material is estimated at 25-50% of the gravel content, which in turn is about 25% of the whole volume.

A11 0 to 8 cm, very dark grayish brown (10YR 3/2 m, 4/3 d); fine sandy loam; weak medium granular structure held together by plant roots; slightly sticky, slightly plastic, friable; clear wavy boundary.

A12 8 to 25 cm, very dark grayish brown (10YR 3/2 m, 4/3 d); fine sandy loam; massive to weak medium subangular blocky; slightly sticky, slightly plastic, very friable; clear smooth boundary.

A13 25 to 40 cm, very dark grayish brown (10YR 3/2 m, 5/3 d); gravelly sandy loam with pale mineral grains; structure and consistence as in A12; gradual smooth boundary.
B2t 40 to 98 cm, varying between dark grayish brown (10YR 4/2 m, 5/4 d) and brown (10YR 5/3 m, 6/6 d), in the upper part to yellowish brown (10YR 5-6/4 m) in the lower, with dark yellowish brown (10YR 4/4 m) ped surfaces; gravelly sandy loam; very coarse blocky; slightly sticky to sticky, plastic; gradual wavy boundary.
B3t(g) 98 to 109 cm, yellowish brown (10YR 5/8 m) arranged in 5-10 cm wide vertical polygons, separated in prisms by 2-3 cm wide grayish brown (10YR 5/2 m) stripes; gravelly sandy loam; sticky, plastic, firm; wavy clear boundary. (Horizon not present in east side of profile).
C(g) 109 to >150 cm, brownish yellow (10YR 6/8 m) arranged in 5-10 cm wide vertical polygons separated by 2-3 cm wide light gray (5Y 7/2 m) and pale brown (10YR 6/3 m) stripes; loam; breaking into medium platy structure; sticky slightly plastic; violent effervescence with HCl, fine roots are seen, even at 135 cm.

Interpretation

Profile 4 in the footslope area, has a remarkably gravelly solum with up to 60 per cent gravel (pct. of fine earth) in the lower A horizon. The vertical range of porosity in the upper metre is greatest of the soils (67% to 40%), and the C horizon is very compact with a bulk density of 2.0 g/cm^3.

Contrary to the usual view of footslope soils, this soil is base-desaturated in the A horizon ($<$ 40%, to 35 cm depth) and the surface horizons acidified (pH $<$ 5.0) and degraded, with the lower horizons split into prism-like structures separated by light gray iron-depleted streaks showing the pseudogley features caused by the fluctuating water level.

Profile 5 Typic Argiboroll, fine-loamy, mixed; concave segment, 5% inclination to south, cross section I.
A11 0 to 25 cm, very dark grayish brown (10YR 3/2 m, 4/3 d), fine sandy loam; moderate medium granular; very friable, slightly stickly, slightly plastic; clear smooth boundary.
A12 25 to 37 cm, dark brown (10YR 3/3 m, 5/3 d); fine sandy loam; massive to weak medium subangular blocky; very friable, slightly sticky, slightly plastic; clear wavy boundary.
B21t 37 to 60 cm, dark yellowish brown (10YR 4/4 m, 6/4 d); sandy clay loam to loam; weak fine and medium blocky; sticky, plastic, firm; tongues of A12-material, 5-10 cm wide reach into the B21t, thinning downwards; gradual boundary.
B22t 60 to 83 cm, dark yellowish brown (10YR 4/6 m, 6/4 d); fine sandy loam; coarse prismatic breaking into coarse blocky peds with thin clay skins; sticky, plastic, very firm; gradual wavy boundary.
BC(g) 83 to 105 cm, mixture of light gray (5Y 6/2 m) and yellowish brown (10YR 5/6 m); fine sandy loam, with a few light brownish gray (10YR 6/2 m) clay skins; moderate coarse blocky; sticky, plastic; clear wavy boundary.
C(g) 105 to > 140 cm, mixture of light gray (5Y 7/2 m) and strong brown-yellowish brown (8.75YR 5/6); fine sandy loam to loam; structureless, massive, sometimes breaking into moderate medium blocky peds with pale brown surfaces; sticky, plastic; violent effervescence with HCl.
Micromorphology 36-38 cm. The thin section is crossed by transverse 0.5 mm wide weak metaplanes, some vughs, a few chambers and areas of compound packing voids are present. The plasma is of humus and some unrelated clay plasma, also a few weak argillans. Few diffuse sesquioxidic nodules. Some fecal pellets and pedotubules. Agglomeroplasmic to intertextic pattern. Vo-argillasepic to isotic plasmic fabric.
Micromorphology 54-56 cm. The voids are divided into weak metaplanes and channels: many ovoid, irregular metavughs and some vesicles. Clay plasma dominates, arranged partly as argillans though partly unrelated. Few diffuse and some sharp iron nodules. Few pedotubules and fecal pellets. Porphyroskelic pattern. Skel-in-vosepic plasmic fabric.
Micromorphology 70-72 cm. The voids are all lined as meta channels, vesicles, chambers and ovoid vughs. Some voids are filled with clay and sesquioxides, though mainly clay plasma arranged as thick (105-200 μm) strongly-oriented cutans, but some are unrelated. Some cutanic sesquioxidic plasma (ferrans) is seen. Fairly frequent iron nodules. Porphyroskelic pattern. In-vosepic plasmic fabric.

Micromorphology 93-95 cm. The voids are wide though weak metaplanes, vughs and vesicles. Mostly unrelated clay plasma or arranged as a few thin void cutans. Some fecal pellets, a few lime fragments. Porphyroskelic pattern. Vo-insepic plasmic fabric.

Micromorphology 107-109 cm. Mostly unrelated clay plasma or arranged as thin argillans. No sign of calcite crystals or cementation. Some traces of iron-stained plasma. Vo-insepic plasmic fabric.

Interpretation

Profile 5, situated just below the steep slope, is a relatively compact clay enriched profile, with marked huminification and nitrofication and conforms more closely to a base-enriched lower slope profile with so high a base saturation (Table 4) that the epipedon becomes mollic and the profile meets the criteria of a Boroll. It i also alkaline below 30 cm depth and hence shows no diagnostic pattern of carbonate-clay interactions.

Profile 6 Mollic Eutrobalf, fine-loamy, mixed; in the middle of the rectilinear cross section II, 7% inclination to the south west (figs. 1 and 5).

A11 0 to 9 cm, very dark grayish brown (10YR 3/2 m, 4/3 d); fine sandy loam; moderate medium granular structure held together by plant roots; very friable; clear wavy boundary.

A12 9 to 48 cm, dark brown (10YR 3/3 m, 5/3 d); fine sandy loam; massive to structureless, breaking into very weak medium subangular blocky; very friable, slightly hard; clear wavy boundary.

B2t 48 to 74 cm, yellowish brown (10YR 5/6 m, 6/4 d); very fine to fine sandy loam, (loam in the lower part); coarse prismatic structure breaking into coarse blocky with continuous brown (10YR 5/3 m) clay skins, 0.5 mm thick; gradual wavy boundary.

B3t(g) 74 to 135 cm, yellowish brown (10YR 5/6) loam with light olive gray (5Y 6/2) 2-5 cm wide stripes arranged in a 20-30 cm wide polygon-like pattern; few to common fine distinct dark Mn mottles; coarse prismatic, breaking into coarse blocky; sticky, plastic; gradual wavy boundary.

C(g) 135 to 25o cm, like B3t(g) but with violent effervescence with HCl; the polygon-like pattern becomes gradually weaker downwards and stops at 250 cm; thin roots being concentrated in the cracks reaching to 250 cm.

Interpretation

Prolife 6 has the deepest epipedon of the soils, despite its position in an upslope area. Structurely poorly-developed with high bulk density, the vertical cracks and channels in the B-horizon have markedly thick, though widely-separated clay skins. The increase in clay content from A to B horizon (4.2 %) is the least in all the soils studied. The pale cracks in the pseudogley polygons show the depth (2.5 m) to which soil dehydration causes shrinking of the soil mass and corresponds to the lowest level of the saturated zone as determined in 1974 (2.6 m, table 2).

Profile 7 Eutric Glossoboralt, fine-loamy, mixed; crest of slope in cross section I (figs. 1 and 5).

A11/12 0 to 13 cm, dark brown (10YR 3/3 m, 3-5/2 d); very fine to fine sandy loam, few coarse fragments; moderate fine to medium granular; very friable; many roots of all sizes; several wormholes lined with beech leaves; clear smooth to wavy boundary.

A13 13 to 24 cm, brown to dark brown (10YR 4/3 m, 6/4 d), fine sandy loam; some coarse fragments and some roots; moderate strong, very fine to fine angular blocky; firm; clear wavy boundary.

B21t 24 to 45 cm, brown to dark brown (10YR 4/3 m, 5/6 d); sandy clay loam; with dark yellowish brown (10YR 4/4 m) clay skins, few coarse fragments, few fine roots; moderate to strong coarse prismatic breaking into moderate medium angular blocky. Clay skins are seen on almost every ped face, but especially on prism faces; where the root concentration is also highest; firm to riable, clear to gradual wavy boundary.

B22t 45 to 64 cm, yellowish brown (10YR 5/6 m, 6/4 d) sandy clay loam with dark brown (10YR 3/3) clay skins; few fine roots and some coarse mineral fragments; strong very coarse prismatic breaking into moderate fine to medium weak angular blocky structure; firm to friable; clear to gradual wavy boundary.

BC 64 to 104 cm, yellowish brown (10YR 5/7 m, 6/4 d); sandy clay loam with dark yellowish brown

(10YR 3/4 m) clay skins, few fine roots; moderate, medium to coarse prismatic structure breaking into moderate medium angular blocky- firm to friable- effervescence with HCl; gradual wavy boundary.
C 104 to 140 cm, light yellowish brown (10YR 6/4 m, 7/3 d); fine sandy loam (including lime); massive, structureless; effervescence with HCl.
Micromorphology 10-12 cm. The voids are mostly orthochannels, irregular orthovughs and compound packing voids. Both humus and clay plasma present. Several fecal pellets and an aggrotubule (3 mm Ø). Agglomeroplasmic pattern. Isotic to argillasepic plasmic fabric.
Micromorphology 25-27 cm. Very similar to 10-12 cm. Several aggrotubules and many fecal pellets. Some sesquioxide glaebules, some with sharp, some with diffuse boundaries.
Micromorphology 35-37 cm. The void system consists of skew planes and of channels connected by planes, with linearly-arranged meta-vughs, also orthovughs and vesicles. Th largest planes and channels are coated with 25-100 μm thick argillans: the thin planes are orthovoids. Plasma is clay, arranged as argillans, especially as void argillans or as randomly-arranged flakes. A few fecal pellets and diffuse organic or sesquioxidic nodules. Porphyroskelic pattern. Vo-insepic plasmic fabric.
Micromorphology 61-63 cm. Clay plasma with strong birefringence, mostly as thick void argillans, otherwise as unrelated flakes. Several large voids are filld with clay. Some fecal pellts and many diffuse, mostly Mn glaebules. Porphyroskelic pattern. Vo-insepic plasmic fabric.
Micromorphology 81-83 cm. Many irregular metavughs and vesicles. Channels are more irregular than in B22t. The clay plasma is arranged partly as flakes and partly as cutans. The thickest argillans are situated around vesicles. Many diffuse, irregular sesquioxidic nodules and a few fecal pellets. A few lime fragments. Porphyroskelic pattern with tendency to intertextic. Vo-insepic plasmic fabric.
Micromorphology 103-105 cm. Vughs and vesicles appear mostly in those parts with a limey plasma. Two sorts of plasma, clay and lime, both occur, often as cutans. A mixture of the two forms a'dense matrix. Many argillans, a few calcitans and sesquans occur. A glaebular halo of iron and some diffuse iron and manganese nodules are present. A few fecal pellets. Agglomeroplasmic to porphyroskelic pattern. Calci-a-vosepic plasmic fabric. Many lime fragments (fossils) are present, several showing dissolution.
Micromorphology 125-127 cm. Fewer argillans. Channels filled with lime. Large lime fragments.

Interpretation

This soil in the crestal position (figs. 1 and 5), does not exhibit an albic horizon, it has a very well-developed though thin Bt horizon with very thick clay skins. The carbonatic material is closest to the surface (65 cm) of all the soils studied, despite having the lowest pH of all the A1 horizons analysed. The epipedon is relatively thin and less isotic in thin section. The argillic horizon has the most marked illuviation of clay and, because of more intense root penetration, the organic content of the Bt horizon is significantly greater and its bulk density less than the other argillic horizons studied. The clay plasma is strongly birefringent and the lower BC and C horizons show undifferentiated clayey and limey plasma, the differential leaching of clay and lime being more marked in most of the other soil profiles on the slope sites.

Profile 8 Mollic Paleboralf, fine-loamy, mixed; 8% inclination; convex segment of cross section I (figs. 1 and 5 and photo 2).
A11 0 to 12 cm, very dark grayish brown (10YR 3/2 m, 4/2 d); fine sandy loam; many roots; moderate granular, soft; abrupt wavy boundary.
A12 12 to 26 cm, dark brown (10YR 3/3 m, 4/3 d); fine sandy loam; frequent roots; moderate very fine to fine granular; friable; clear wavy boundary.
A13 26 to 45 cm, dark brown (10YR 3/3 m, 4/4 d); fine sandy loam with many fine roots, few stones; massive, to very weak fine subangular blocky; friable; clear to abrupt wavy boundary.
A2 45 to 71 cm, yellowish brown (10YR 5/4 m, 7/3 d); fine sand with few fine roots; massive, structureless; friable; clear to abrupt, irregular boundary.
B & A 71 to 102 cm, horizon composed of A2 and B2t material, with 5-10 cm wide pockets of A2 material penetrating the B2t horizon. Depth of the pockets is up to 5 cm. Boundary between A2 and B2t material is abrupt.
B2t 102 to 128 cm, yellowish brown (10YR 5/5 m, 6/5 d); sandy clay loam with yellowish brown

(10YR 5/6) clay skins; moderate strong to very strong, fine to medium angular blocky; firm; clear to gradual wavy boundary.

B3t 128 to 160 cm, yellowish brown (10YR 5/5 m, 6/4 d); sandy clay loam changing to loam in the lower part of the horizon; moderate medium angular blocky; friable; coarse distinct mottles, brown (10YR 5/3) surrounded by yellowish brown (10YR 5/6).

C > 160 cm, effervescence with HCl, auger sample.

Micromorphology 20-22 cm. Orthochannels, orthovughs and compound packing voids. Several aggrotubules, many fecal pellets and some plant remains. Agglomeroplasmic pattern. Argillasepic to isotic plasmic fabric.

Micromorphology 39-41 cm. Humus plasma and some unrelated clay plasma. A few diffuse sesquioxidic nodules. Some aggrotubules, plant remains and many fecal pellets. Agglomeroplasmic to inter-textic pattern. Plasmic fabric as in A12, but with less plasma.

Micromorphology 55-57 cm. The plasma distribution is very inhomogeneous with areas almost devoid of plasma and other areas containing large clayfilled voids. The plasma-poor part of the plasmic fabric looks like the fabric in A13; in the other part it is in-vosepic. Related distribution patterns are agglomeroplasmic to intertextic and porphyroskelic, respectively. Void argillans are common in the plasma-rich part. Many diffuse sesquioxidic nodules.

Photo 2: Profile 8 on the upper slope section. Scale divisions are 20 cm.

Micromorphology 82-84 cm. Chiefly clay plasma, some without birefringence, though most of the clay is present as thick (200 μm) voidcutans. Some fecal pellets and many diffuse, irregular sesquioxidic nodules. Some Mn nodules also. Agglomeroplasmic to porphyroskelic pattern. Vo-insepic plasmic fabric.

Micromorphology 106-108 cm. The metavoids are vesicles, channels and vughs. Clay plasma is dominating and appars mostly as void cutans and weak grain cutans. Some iron stained plasma is observed. The argillans are thin and weakly-oriented. Glaebules as in B1, but fewer. Some pedotubules and fecal pellets. Agglomeroplasmic to porphyroskelic pattern. Skel-in-vosepic plasmic fabric.

Micromorphology 135-137 cm. Many vughs, several rows of vesicles, but no planes and only a few channels. Plasma as in B2t, but here arranged in thick, strongly-oriented, voidcutans. Some iron-stained plasma in nodules or as cutans inside argillans. Some fecal pellets and many glaebules as in B1. Agglomeroplasmic to porphyroskelic pattern. In-vosepic plasmic fabric.

Interpretation

This profile (8) situated in the upper slope position is the deepest and most strongly-developed of the soils investigated. The lime is leached to a depth of 1.6 m and the clay content of the illuvial horizon is more than twice of that in the eluvial horizon. The deep development is reflected in all the horizons. The profile has the thickest of both eluvial and illuvial horizons, a clear B and A transition horizon and a pronounced albic horizon. The differential precipitation of clay and lime is not observed in the horizons studied, but presumably occurs below 1.7 m. Glaebules are present at 1.3 m depth, but there is no sign of pseudogley polygons, indicating the better drainage condition in this upper slope position.

4.2. MAIN MICROMORPHOLOGICAL FEATURES OF THE SOILS

Because of the limited size of the thin sections, micromorphological description is mainly concerned with the nature of the S-matrix. Pedotubules, fecal pellets and worm holes are found mainly dominating all the A horizons, but frequently occur in the B horizon, indicating intense and deep-reaching biological activity. Moreover, existing plant remains all appear fresh, suggesting that decomposition must be rapid and that earthworms incorporate organic material relatively deeply in the soils in response to the rapid drying of the profiles. Determination of the plasmic fabric was quite difficult because of the complex nature of the relationships of humus/clay in the upper horizons and of clay/calcite plasma in the lower horizons. The A horizons generally have isotic plasmic fabrics, because of the intense biological activity acting on the humus, with scattered clay flakes. The resulting fabrics are called argillasepic to isotic.

All Bt horizons show argillan development, which features also occur in the C horizons. The lower slope soils show sesquans in the B22t horizons at depths less than 75 cm from the surface. Often ped faces in B horizons are covered with argillans, but also a few sesquans are observed in the lower part of the B horizons or in the C horizons of all the profiles. When calcite precipitates in C horizons, a special fabric, not mentioned by BREWER (1976), occurs. It is here called either calciasepic, or calcisepic fabric, and is particularly present in profiles 1, 2 and 7, and possibly in profile 8 beyond the soil depth studied. Discrete calcitans and C horizons are discussed later.

Important features are the many voids filled with partly-orientated clay. These are most frequently found in the B2t and B22t horizons, also in the A2 horizon in profile 8. Such vughs and vesicles are often arranged linearly, probably the majority of them are vesicular cavities left by calcium carbonate dissolution. A few examples of ferrans and ferriargillans inside voids covered with argillans are found, in the B2t horizon in profile 1 at 80 cm depth; in the B22t in profile 5 at 70 cm and in the B3t in profile 8 at 130 cm depth.

Tab. 3: SUMMARY OF MAIN MICROMORPHOLOGICAL FEATURES IN THE STUDIED SOILS

Profile	Horizon	Depth cm	Cutans			Sesquioxidic	Related	Plasmic fabric
			arg.	sesq.	calci	nodules	distribution pattern	
1	A11	8-10					aggl-inter	argil-isot
Mollic	A2	46-48	/				inter	argil-isot
Paleboralf	B2t	82-84	xx			x	aggl-porph	skel-in-vo
	B2t	97-99	x			xx	aggl-porph	vo-insepic
	C	135-137	x	/	x	x	porph	vo-calci-a
2	A12	10-12					aggl-inter	argil-isot
Mollic	B21t	24-26	x			x	aggl-porph	in-vosepic
Eutroboralf	B22t	56-58	xx	x		xx	aggl-porph	in-vosepic
	C(g)	107-109	x		x	xx	porph-gran	vo-calci-a
	C(g)	124-126	x	x	x	x	porph-gran	(vo)-calci-a
5	A12	36-38	/			x	aggl-inter	vo-argil-isot
Typic	Bt	54-56	x			x	porph	skel-in-vo
Argiboroll	B22t	70-72	xxx	x		xx	porph	in-vosepic
	BC(g)	93-95	x			x	porph	vo-insepic
	C(g)	107-109	x			xx	porph	vo-insepic
7	A12	10-12				x	aggl	isot-argil
Eutric	A13	25-27				x	aggl	isot-argil
Glossoboralf	B21t	35-37	xx			xx	porph	vo-insepic
	B22t	61-63	xxx			xx	porph	vo-insepic
	BC	81-83	xx			xxx	porph-inter	vo-insepic
	C	103-105	xx	x	x	xx	aggl-porph	calci-a-vo
	C	125-127	x		xx	x		
8	A12	20-22					aggl	argil-isot
Mollic	A12	39-41				x	aggl-inter	argil-isot
Paleboralf	A2	55-57	x			xx	aggl-inter/porph	argil-isot/in-vo
	B&A	82-84	xx			xxx	aggl-porph	vo-insepic
	B21t	106-108	x			xx	aggl-porph	skel-in-vo
	B3t	135-137	xx	x		xx	aggl-porph	in-vosepic

Abbreviations

Cutans

arg.: argillans
sesq: sesquans
calci: calcitans

Patterns

aggl.: agglomeroplasmic
inter: intertextic
porph: porphyroskelic
gran: granular

Fabrics

argil: argillasepic
isot: isotic
skel: skelsepic
in: insepic
vo: vosepic
a: asepic
calci: calcisepic

/ : trace
x : few
xx : common
xxx : very common

Even more interesting is the presence of argillans and calcitans not only in the same horizons, but also in the same voids. In the C horizons in profiles 1, 2 and 7 argillans are seen upon calcitans, i.e. the argillans are deposited after the calcite deposition (fig. 4), the calcite deposition filling a void, itself the result of either drying or the solution of primary carbonate. This is seen rather deep down (to 62 cm), within the calcium carbonate-containing horizons. In other micro-sites calcitans and argillans are intercalated, with minor redeposition of lime upon argillans which enclose minor inner calcitans.

Features like glaebules are difficult to semiquantify, because a thin section only covers a small part of a horizon. This might explain the lack of pattern in their distribution. However, it should be noted that profiles 2, 5 and 7 have nodules even in the uppermost parts. Almost all glaebules are diffuse nodules, indicating, according to BREWER (1976), either the absence of rying, or uniform conditions of iron-manganese precipitation over large areas in the soil. A few distinct nodules are seen, mostly of manganese, in profile 2 at 30-45 cm depth in the B21t horizon, and at 75-120 cm in the B3t horizon of profile 6, both on the gentler western slope.

5. DISCUSSION

5.1. PARENT MATERIAL

The parent material shows some variation, as might be expected for tills. KUNDLER (1961) measured clay formation in similar soils in Germany and found that it was of minor importance in comparison with clay illuviation. Assuming the rate of clay formation to be insignificant, the calculated mean clay content thus gives a reasonably good estimate of the original content in the parent material. Table 5 shows the mean clay percentage weighted for horizon depth, in both the A and B horizons.

The parent material of the solum ranges from sandy clay loam in profile 7 with an average clay content of 22.5%, to sandy loam in profile 4 with 13.3% clay. The latter profile has a relatively higher proportion of gravel and stones.

The content of calcium carbonate in parent materials ranges from 15 to 24 %. Measurements were made on auger samples, taken at 25 cm depth intervals from 1.25 metres down to 4 metres at profiles 2 and 6 give the following results: in profile 2 the $CaCO_3$ content varies from 15.o to 21.5%, with a mean value of 17.6%; in profile 6 the range is 18.0 to 23.6%, mean 21.5%. The calcium carbonate appears primarily as fossils (mainly bryozoa) and secondly as microcrystalline calcite precipitation (discussed later).

As the average lime content in Danish clayey tills was found to be about 20% by AHRENTZEN (1975), our profiles seem to be representative for Danish tills in this respect.

The clay minerals in the C horizons of four of the profiles were identified by X-ray diffraction. Mica, smectite, vermiculite and some interstratified minerals were found. The B horizons have, as is to be expected, an accumulation of smectite, especially in the fine clay fraction. There were also minor amounts of clay-size quartz and feldspars.

5.2. MORPHOLOGY OF THE EPIPEDONS

All the profiles are characterized by thick dark epipedons (table 5), and with the exception of that of profile 2 all satisfy the criteria for either umbric or mollic epipedons. The development of these thick epipedons may be explained in terms of the high and uninterrupted organic production of both the beech trees and the ground vegetation (section 2.4.). High biological activity causes rapid decomposition of the plant material, as expressed in low C/N ratios (table 4) and a good mixing of the organic and mineral constituents in the upper parts of the soil profiles to form isotic plasmic microfabrics and crumb microstructures. In none of the profiles do the epipedons reach down into the illuvial horizon. They always fill the eluvial horizon, except in profiles 1 and 8, where eluviation is intense and the A horizon very thick, its lower part being an albic subhorizon. The apparent correlation between the thicknesses of epipedons and of eluvial horizons is due to the changes in consistency and in structure which results from clay eluviation from the A horizons. This permits more efficient

Tab. 4: PHYSICAL AND CHEMICAL DATA OF THE PROFILES

Profile	Horizon	Sample depth	Particle size distribution Pct. < 2 mm				Bulk density	Porosity	Org. C	N
		(cm)	> 2 mm	2000-50 µm	50-2 µm	< 2 µm	(g/cm^3)	Pct.	Pct.	Pct.
1	A11	0-10	10	61,3	28,4	10,3	0,99		2,14	0,199
	A12	10-20	4	60,8	28,3	10,9	1,32		0,85	0,073
	A13	33-43	11	61,2	28,3	10,5	1,48		0,54	0,056
	A2	59-67	8	72,8	20,5	6,7	1,66		0,12	
	B2t	80-90	35	66,7	12,1	21,2	1,72		0,21	
	C	135-145	3	47,6	33,8	18,6				
2	A11	0-8	1	52,4	34,7	12,9			3,33	0,204
	A12	16-24	1	51,4	32,3	16,3			0,58	0,051
	B21t	32-41	2	47,6	27,4	25,0			0,33	0,032
	B22t	50-60	2	56,1	21,4	22,5			0,23	
		63-73	2	61,6	22,7	15,7			0,15	
	B3(g)	80-88	1	47,3	30,9	21,8			0,17	
4	A11	0-5	15$^{2)}$	63,4	26,4	10,2	0,80$^{2)}$	69$^{2)}$	3,00	0,228
	A12	5-15	8	63,1	25,6	11,3	1,38	48	1,64	0,136
		15-25	61	63,4	25,4	11,2	1,35	49	1,23	0,113
	A13	28-35	56	62,7	27,1	10,2	1,50	44	0,68	0,063
	B2t	45-55	50	58,1	26,8	15,1	1,46	46	0,36	
		68-73	31	64,0	21,7	14,3	1,73	36	0,26	
	B3t(g)	88-100	43	56,5	28,4	15,1	1,62	40	0,20	
	C(g)	130-140	5	50,3	33,9	15,8	2,02	25		
5	A11	0-10	5	57,8	27,9	14,3	1,01	61	2,38	0,207
	A12	20-30	4	60,1	26,1	13,8	1,50	44	0,76	0,073
	B21t	35-45	2	50,2	28,1	21,7	1,65	39	0,34	0,039
		55-65	4	50,2	29,7	20,1	1,73	36	0,20	
	B22t	70-85	10	53,8	28,1	18,1	1,66	39	0,17	
	BC(g)	88-96	5	55,0	26,8	18,2	1,66	39		
	C(g)	108-116	12	52,0	34,3	13,7	1,75	36		
6	A11	2-10	3	57,5	28,2	14,3	1,31	50	2,10	0,191
	A12	20-30	4	56,2	29,0	14,8	1,50	43	1,04	0,108
	B2t	40-50	6	51,6	29,4	19,0	1,60	41	0,40	0,047
		62-70	2	48,1	30,2	21,7	1,70	38	0,23	
	B3t(g)	80-90	4	46,8	33,1	20,1	1,76	35	0,20	
		100-110	3	47,8	32,9	19,3	1,75	35	0,18	
		125-135	7	45,5	33,1	21,4	1,82	33	0,16	
7	A11	0-5	2	56,2	28,1	15,7	1,27	49	2,91	0,222
	A12	5-9	4	57,8	25,7	16,5	1,11	56	1,70	0,158
	A13	14-19	9	58,4	25,2	16,4	1,49	43	0,94	0,087
	B21t	29-34	10	48,4	27,0	24,6	1,46	42	0,43	
	B22t	55-59	2	48,5	23,7	27,8	1,55	42	0,33	
	BC	73-77	5	53,2	25,9	20,9	1,44	46		
	C	104-109	6	48,0	31,2	20,8	1,69	36		
		122-127	5	49,4	33,3	17,3	1,64	38		
				(55,3)$^{3)}$	(30,8)$^{3)}$	(13,9)$^{3)}$				
8	A11	4-6	22	62,8	26,8	10,4			3,21	0,247
	A12	17-21	9	64,1	25,6	10,3	1,12		1,85	0,168
	A13	34-39	11	63,9	26,5	9,6	1,34	48	0,92	0,090
	A2	47-52	22	66,7	27,1	6,2	1,42	46	0,29	
	B&A	70-74	9	53,3	25,9	20,8	1,53	42	0,31	
	B2t	82-87	11	57,7	22,0	20,3	1,62	40	0,24	
		105-110	5	50,9	26,0	23,1	1,52	44	0,21	
	B3t	122-127	6	47,7	27,0	25,3	1,60	40	0,30	
		145-150	4	49,4	28,4	22,2	1,65	38		
	C	163-178								
		193-208	5	46,6	32,6	20,8	1,64	38	0,23	
		213-228		(53,0)$^{3)}$	(27,7)$^{3)}$	(19,3)$^{3)}$				

1) exchange acidity
2) samples from slightly different depths, see fig. 2
3) calciumcarbonate removed

C/N	pH_{H_2O}	pH_{NKCl}	CEC $\sum$cat.	CEC NH_4OAc	Extractable cations meq/100g					Base sat.	$CaCO_3$ eqv.
					Ca^{2+}	Mg^{2+}	K^+	Na^+	$H^{+1)}$	Pct.	Pct.
11	4,62	3,89	17,7		3,1	0,6	0,3	0,2	13,5	24	
12	4,48	3,84	13,1		0,8	0,2	0,1	0,1	11,9	9	
10	5,31	4,35	8,9		2,6	0,5	0,1	0,2	5,6	36	
	6,71	5,72	7,1		4,0	0,4	0,1	0,2	2,4	66	
	7,09	5,66	13,9		10,5	0,9	0,2	0,4	2,0	86	
						0,9	0,2	0,5	0,5		19,4
16	5,31	4,62	22,7		6,1	1,1	0,2	0,2	15,2	33	
11	5,31	4,08	10,0		3,7	0,8	0,1	0,2	5,0	49	
10	5,72	4,37	17,8		10,2	2,0	0,2	0,3	5,1	71	
	6,03	4,69	13,8		7,7	1,5	0,2	0,3	4,1	70	
	6,30	5,01	13,3		8,4	1,3	0,2	0,3	3,0	78	
	6,55	5,21	13,7		9,0	1,2	0,2	1,0	2,3	83	
13	4,80	3,81									
12	4,67	3,53	15,2		1,6	0,5	0,1	0,2	12,8	16	
11	5,02	3,62	13,5		1,7	0,7	0,1	0,2	10,9	20	
11	5,41	3,89	13,2		3,9	1,0	0,1	0,2	7,9	40	
	6,08	4,41	13,4		7,8	1,4	0,1	0,3	3,7	72	
	6,58	4,77	17,1		11,8	1,6	0,2	0,4	3,1	82	
	7,08	5,63	12,2		9,4	0,8	0,1	0,4	1,6	87	
	8,20	7,20				8,9	0,2	0,4	0,5		14,7
11	6,11	4,37	20,6		10,7	1,2	0,1	0,5	8,1	60	
10	6,78	5,78	14,2		10,0	0,9	0,1	0,6	2,7	81	
9	7,52	5,80	15,1		11,7	1,3	0,2	0,3	1,6	90	
	7,72	5,99	14,1		10,9	1,2	0,2	0,3	1,5	89	
	7,86	6,07	13,7		11,0	0,9	0,2	0,4	1,3	91	
	7,82	7,02				1,1	0,2	0,4	1,1		3,4
	8,36	7,11				1,0	0,2	0,4	0,9		19,7
11	4,66	3,77	20,6		4,5	1,0	0,2	0,2	14,7	29	
10	5,55	4,53	14,2		6,5	1,0	0,1	0,2	6,4	55	
9	6,66	5,53	14,3		9,9	1,1	0,1	0,3	2,8	80	
	7,07	6,54	16,9		13,0	1,4	0,2	0,3	2,0	88	
	7,27	5,95	15,0		11,2	1,2	0,2	0,3	2,1	86	
	7,37	6,09	14,0		10,7	1,2	0,2	0,3	1,5	89	
	7,42	6,23	14,1		11,0	1,2	0,2	0,3	1,5	90	
13	3,98	3,28				1,2	0,3	0,3	12,8		
11	4,07	3,42	11,5	8,9	1,7	0,5	0,2	0,3	8,8	23	
10	4,43	3,53	12,7	8,0	2,1	0,6	0,2	0,3	9,5	25	
	5,07	3,59	12,7		5,3	1,6	0,2	0,4	5,2	59	
	5,59	3,70	14,0	7,6	7,3	2,1	0,2	0,3	4,1	71	
	8,21	7,09		12,7		1,7	0,2	0,2			12,0
	8,22	7,20									20,1
	8,33	7,33		7,0		1,2	0,2	0,2			18,6
13	4,27	3,58	18,2	10,4	2,3	0,9	0,2	0,4	14,4	21	
11	4,21	3,40	14,2	6,9	0,9	0,4	0,2	0,3	12,4	13	
10	4,49	3,69	10,2	5,6	1,1	0,3	0,2	0,2	8,4	18	
	5,21	3,92	6,3	3,6	1,2	0,4	0,1	0,1	4,5	29	
	5,30	3,63	14,6	12,2	3,7	2,5	0,2	0,2	8,0	45	
	5,35	3,63	17,2	10,7	7,4	3,0	0,3	0,2	6,3	63	
	5,59	3,72	13,3	10,6	4,8	2,6	0,3	0,3	5,3	60	
	6,00	4,19	15,2	11,7	6,5	2,6	0,5	0,3	5,3	65	
	6,68	4,92	13,3	10,6	7,9	1,4	0,4	0,2	3,4	74	
	8,51	7,43									18,3
	8,61	7,52		6,1		0,9	0,3	0,2			19,8
	8,75	7,53									20,6

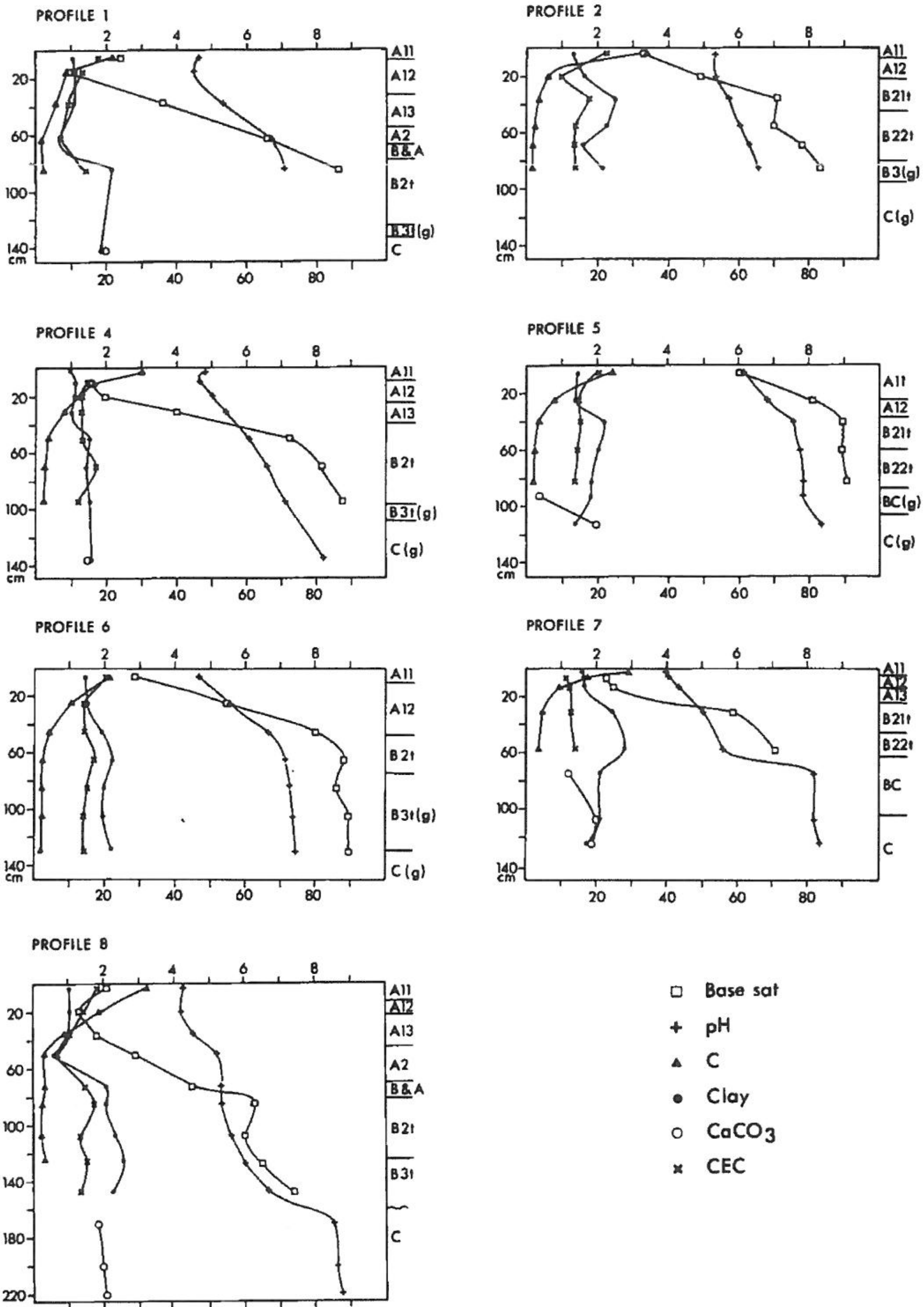

Fig. 3: Important properties of the profiles as a function of the soil depth. Upper lateral scale shows organic carbon (% C), and pH in water. Lower scale shows clay content, base saturation, and calcium carbonate content, ($CaCO_3$) in percent, and cation exchange capacity, (CEC), in meq. per 100 g soil. Thickness of horizons marked as found at sample sites.

biological mixing of the whole horizon in horizons of lighter texture.

The soils typically have an umbric epipedon and the two exceptions can be explained in terms of variations in the hydrological conditions. The epipedon in profile 5 below the steep

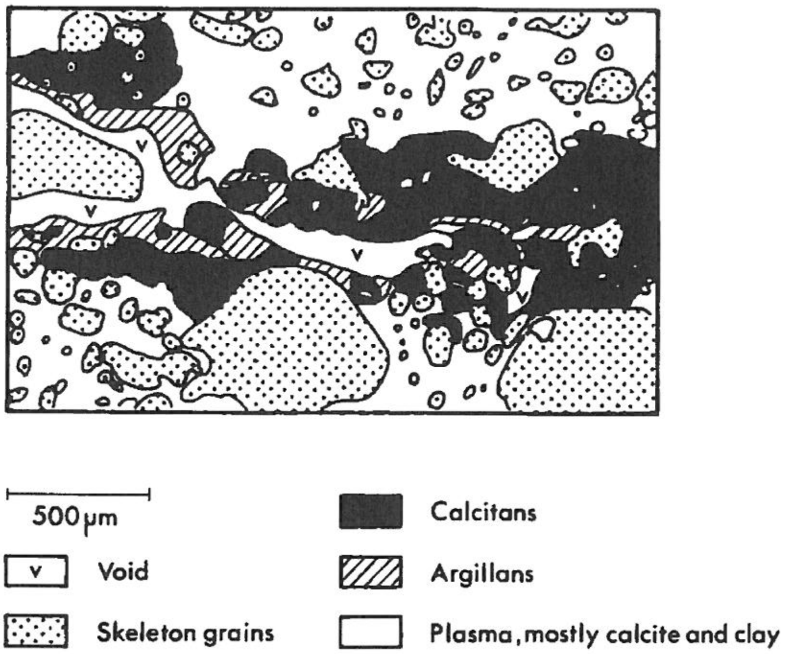

Fig. 4: Sketch of a thin section from the C horizon (103-105 cm) in profile 7 showing complex deposition of argillans and calcitans.

slope is mollic, since we can assume that there is a laterally-moving water supply, rich in bases, from the up-slope area. The ochric epipedon in profile 2 can be explained by the lower organic production and slower decomposition with a C/N ratio of 16, the highest found in this study. According to the measurements of rowth made by HENRIKSEN (1972), the beech trees around profile 2 grow more slowly than the other trees in the area. This diminished productivity is probably related to frequent anaerobic conditions caused by poor drainage, shown by the high water level (table 2), the presence of mottles in the uppermost part (table 3) and by the placing of an old ditch near profile 2, which represents the only visible historical attempt at land improvement in the research area.

5.3. DECALCIFICATION - CALCIFICATION

The boundary between the B and C horizons is put at the depth where the content of calcium carbonate is the same as in the parent material. The designation BC is used, when some small amount of calcium carbonate has been removed. This depth is very different for each of the profiles (table 5). It is most shallow (65 cm), in profile 7 on the crest and deepest in profile 8 (160 cm) and in profiles 1 and 6 (135 cm) on the steepest slopes. As the original CaCO content is about 20% (weight percent) (table 5), almost one-fifth of the original volume of parent material must have been removed from the solum.

In several thin sections from C horizons deposits of microcrystalline $CaCO_3$ were found as thick coatings along channels and as void infillings or wall coatings in large voids (fig. 4). This is interpreted as a secondary precipitation of carbonate, mobilized from the solum during periods of leaching and reprecipitated when the soil dries out periodically. Hence its interdigitation with clay coatings.

5.4. CLAY MIGRATION

All the profiles have features of clay migration, although the development of the eluvial and illuvial horizons varies as does the intensity of clay eluviation and argilluviation.

The clay migration is indicated both by the particle size distributions (table 4) and by the observation of numerous clay skins in the B horizons visible both in the field and in the thin sections. Table 3 shows the relative amount and development of argillans. However the void fillings, as mentioned in the profile descriptions, are not included. Only profiles 5 and 7 have a significant maximum of the clay content in the B2t horizon, followed by a decrease towards the C horizon. The other profiles have still high clay contents in the C horizons (the C horizon in profile 2 is not included). The samples from the C horizons in profiles 7 and 8, analysed after removal of $CaCO_3$, seem to indicate that the calcium carbonate has a higher proportion of silt and clay size than the noncarbonate fraction. This might conceal the lower limit of the illuviation of clay.

Profile 8 shows an extremely deep development of the Bt horizon with the maximum clay content occurring as deep as 125 cm, which is 55 cm below the top of the B horizon. Further, the boundary between A2 and B material is irregular with tongues of A2 in the B horizon and some pockets of B material included in the A2 horizon. This is also found in profile 1. It seems reasonable to explain this as a weak degradation of the upper part of the illuvial horizon, where the clay is remobilized and the fabric of the upper B horizon is degraded.

5.5. INTERPRETATION OF THE SLOPE INFLUENCE

As summarized in table 5 and figure 5 the seven profiles are very differently developed in spite of their very close spatial relationship. Some of the differences may be explained by the variance of the particle size distribution of the parent material, though the major differences between pofiles seem to be related to topography, such as position on the slope and steepness of the slope.

The distribution of the soils on the slope, not least those with albic horizons, leads to the suggestion that lateral subsurface water movement is an important factor in the hydrology of the slope and the development of the soils. Strong lateral flow is possible for at least two reasons. First, because of the sloping water table, there is a downslope vector component in the saturated and capillary-rise zones. Second, the decrease in permeability with soil depth can induce similar movement even though saturation is not reached. The slope soils all have a rather abrupt break in clay content from A to the B horizons, in all but one case more than 50 percent relative clay increase (table 4 and figure 3), and all have a high content of swelling clay minerals (see 5.1.). In wet conditions there is higher permeability in the A than in the B horizon. The occurrence of lateral water flow above saturated soil is possible in late winter and spring, when and where the saturation level is high.

To check if it was possible to observe lateral water movement in the albic horizon, small pits (60 × 100 cm) were dug down to the upper part of the B horizon during the winter 1977-78. It had earlier been observed that the walls of the older pits were frequently frozen at times when the top soil elsewhere was not frozen (due to protection by the organic horizon and/or snow cover). The pits were therefore covered with water resistant lids to prevent freezing of the walls.

Lateral flow was actually observed in March, when snow, equivalent to approximately 65 mm water, melted in a few days. It was seen as small mudflows from the lower parts of the

Tab. 5: SELECTED PROPERTIES OF THE PROFILES

Profile	1	2	4	5	6	7	8
Thickness of epipedon, cm	32	20	35	37	47	24	42
Thickness of eluvial horizon (A), cm	67	21	40	37	47	24	71
Thickness of illuvial horizon (B= B&A+ B2+ B3),cm	75	73	69	68	88	40	89
Mean clay content of eluvial horizon, %	9,6	14,6	10,7	14,1	14,6	16,2	9,1
Mean clay content of illuvial horizon, %	19,9	21,3	14,8	20,0	20,0	26,2	22,3
Mean clay content of A+ B horizon, % (i.e. estimated original clay content)	15	20	13,3	18	18	22,5	16,5
Mean depth to pseudogley, cm	111	79	89	83	74	-	-
Mean depth to $CaCO_3$, cm	135	95	109	95	135	65	160
Content of $CaCO_3$ in C horizon	19,4	(17,6)	14,7	19,7	(21,5)	18,6	20,6
Epipedon	umbric	ochric	umbric	mollic	umbric	umbric	umbric
Boralf, great group	pale	eutro	eutro	argi 1)	eutro	gloss	pale
subgroup	mollic	mollic	mollic	typic	mollic	eutric	mollic
Udalf, great group	gloss	hapl	hapl	argi 2)	hapl	hapl	gloss 3)
subgroup	haplic	mollic	mollic	typic	mollic	mollic	haplic

1) Typic Argiboroll
2) Typic Argiudoll
3) see text (6)

albic horizon. After scraping the walls clean they again became wet a few minutes later. The B horizon was not completely saturated at the time and the nearest deeper pits contained only water from the collected snow.

This observation seems to confirm the occurrence of the lateral subsurface water movement. However, more intensive studies are needed to discover how frequently it occurs and how much water drains laterally as compared to the vertical flow component.

The effects of this lateral subsurface flow are to produce a pale albic horizon, of low chroma and high value, the result of depletion of clay, fine silt and dithionite extractable iron. Macrostructures are very weak because of the loss of colloidal binding materials, weak subangular granular or incoherent structures, non-sticky and friable, non-hardening.

It should be noted that there is no sign of surface erosion in the slope system. The reason for this must be a high infiltration capacity due to the granular structure of the A1 horizons, reinforced by the protective effect of the round flora and the leaf litter layer.

Cross section I (fig. 5) represents the steepest part of the slope. Profile 7 on the crest with the most clay-rich parent material has the shallowest solum (64 cm). The only water input is precipitation, which drains both vertically and laterally. The profiles on the convex segment (8) and the maximum segment (1), have very deep sola (142-160 cm) with thick umbric epipedons, and are the only ones with albic horizons. The lower clay contents of the parent materials here is a contributing factor to the deeper development of the solum; yet the main reason must be the lateral subsurface water movement from upslope, in addition to the vertical leaching. Hence the deep development of the solum can be explained in terms of greater through-flow of water with a pH at the same level as is found in the upper part of the soil. The occurrence of the mollic epipedon in profile 5, on the concave slope segment, can then be ex-

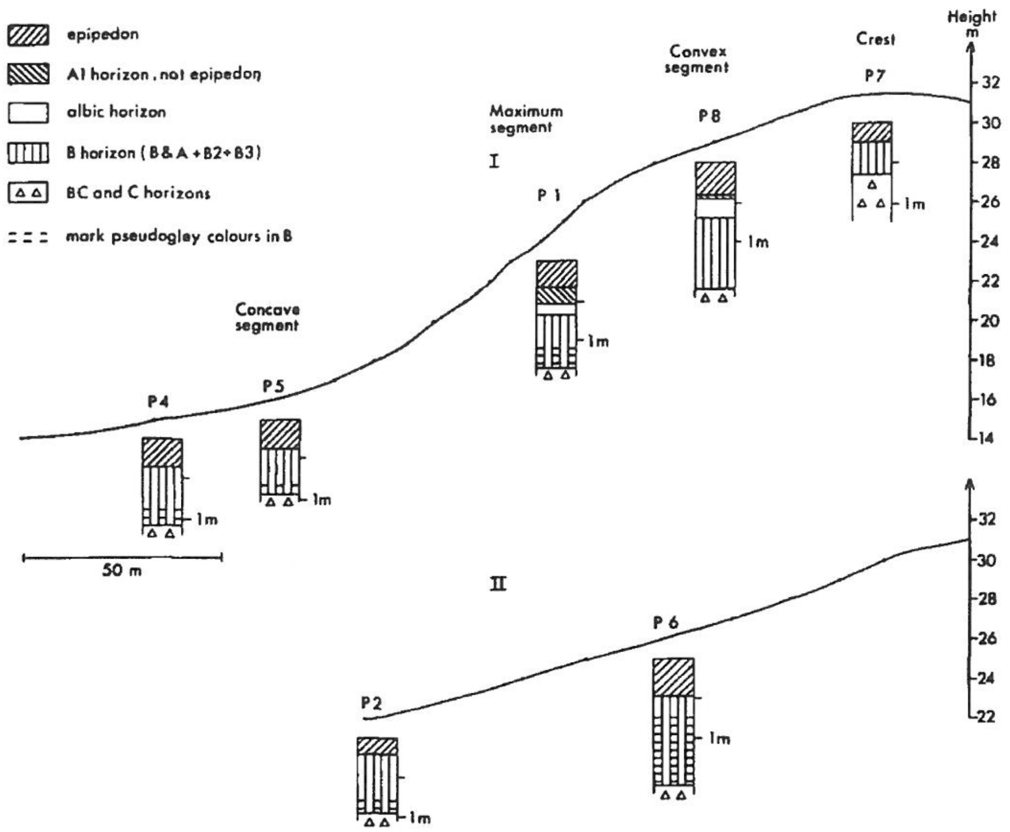

Fig. 5: Slope profiles showing the topographical position of the soil profiles. Vertical exaggeration X5. Note that some of the soil profiles are projected on the line. This means that the distance between profiles 4 and 5 is greater than shown, (see fig. 1), where the slope profiles are marked.

plained as a result of a lateral supply of water, rich in bases accumulated on its way down the slope. Profile 4 is too far removed from the slope to be influenced by this lateral water movement. It represents the development on the more level area, with coarser parent material and lower clay content. The lack of an albic horizon, as is found in profiles 1 and 8, supports the view that lateral water movement is the main factor in creating the albic horizons on the steeper slope.

Cross section II (fig. 5), represented by profiles 2 and 6, is characterized by a less steep inclination and less variation in clay content of the parent material (c 21%) than is the case in cross section I. Profile 6, in the middle of the slope, has some of the features seen in profiles 1 and 8, i.e. the deep solum and thick epipedon. Still, there is less vertical transport of clay and the albic horizon is absent. The fact that pseudogleying occurs nearer the surface, together with the higher water level in spring, indicates slower drainage. Profile 2 is situated on the lower part of the slope. As mentioned in section 2.3., there are indications of poor internal drainage in the soil around profile 2, e.g., the presence of manganese nodules in the B21 at 25 cm and mottles as high as in the A12 horizons at 10 cm depth.

6. CLASSIFICATION

The profiles are classified according to the American system (SOIL SURVEY STAFF

1975). With one exception all the profiles are Alfisols. Profile 5, on the concave segment, however, has so high a base saturation that the epipedon becomes Mollic and therefore the profile belongs to the Mollisol order. For both orders the subdivision is problematic because of the temperature criterion. The measured soil temperature (table 1 and section 2.3.), indicates a frigid regime, but removal of the forest would almost certainly cause a temperature increase of 1-2° (see section 2.2.). This would provide a mesic soil temperature regime (SOIL SURVEY STAFF 1975). Consequently the profiles are here classified in both the Boralf (Boroll) and Udalf (Udoll) suborders and the soils of this part of Denmark relate to both latitudinal and longitudinal boundaries. The identification of the soils in the Soil Taxonomy is complicated because the soils relate to the division between two orders and two suborders.

The Mollisol, profile 5, may be allotted to the Typic Argiborolls (Typic Argiudoll). Profile 4 on the level part and profiles 2 and 6 on the gentle slope in cross section II are Mollic Eutroboalfs (Mollic Hapludalfs) because the Bt horizon is within 60 cm of the surface and has a high base saturation. Profile 7 on the crest is very similar to these three profiles, but it is shallower and has a base saturation of less than 60% in the upper part of the argillic horizon. Thus the profile is a Eutric Glossoboralf. If allotted to the Udalf suborder, it is a Mollic Hapludalf. Profile 1 on the maximum segment and profile 8 on the convex segment, both have deep argillic horizons and weak tongueing, so they are Mollic Paleboralfs (Haplic Glossudalfs).

The classification of the soils in Hestehaven nonetheless expresses quite well the differences in profile development. The dominating form is Mollic Eutroboralf (Mollic Hapludalf). It has developed into a Typic Argiboroll in the concave slope segment and into Mollic Paleoboralfs on the maximum and convex segments, because of the effect of the lateral water movement. An Eutric Glossoboralf is formed on the crest of the slope.

It is commonly considered that soil temperature, rather than air temperature, is most relevant to soil processes. In the absence of adequate soil temperature measurements it has been customary to use modified standard air temperatures (SMITH et al., 1964). Yet the local ecosystem and climatic conditions have a major influence on soil temperature. Our experience has shown that this local influence departs radically from the expected, and that such "anomalies" can change the suborder to which a given soil can be assigned. It is therefore misleading to derive "soil temperature" by modifying air temperature as long as the local climatic influence is not fully understood. Rather than implying a greater degree of accuracy than can, in fact, be achieved, it is preferable to use standard air temperature as a dividing criterion at the suborder level.

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