Soil formation as an indication of relative age of glacial deposits in Eastern Greenland

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A chrono-sequence of soils has been studied in a proglacial valley extending from the Midtluagkat Glacier on the island Angmagssalik Ø in Eastern Greenland. The relative age of soils and a probable sequence of especially translocation processes are discussed in relation to soil characteristics.

Keywords: *Eastern Greenland, soil formation, soil chrono-sequence.*

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From the Sermilik Research Station on the island Angmagssalik Ø in Eastern Greenland the Institute of Geography, University of Copenhagen, carries out investigations of the impact of climatic change in an arctic environment. Mass balance studies of a glacier – Mitdluagkat Glacier – and studies of dynamic processes in both the terrestrial and the marine system are undertaken. As a part of this research a study of the geography of soils was initiated in 1989 with the aim to use pedological information to determine the relative age of landscapes and to investigate the succession of fossile and recent soil-forming processes in the area. In this paper the first results are presented from a study of a chrono-sequence of five soils.

STUDY AREA

On the island Angmagssalik Ø, situated at the coast of south east Greenland (fig. 1), the geology is dominated by gneisic and granitic bedrock, which also includes sequences of metamorphic sediments. The geomorphology is characterized by erosion features and deposits from local glaciers. The Mitdluagkat Glacier (30 km^2 is the largest glacier on the island, and in a proglacial valley from this glacier, with the orientation E(NE) – W(SW), a sequence of soils was studied (fig. 2). All soils are developed in relatively coarse- textured till material. One soil profile was studied in the dwarf shrub heath covered landscape outside the valley. This soil profile 0 (P0) is representative for well drained south- facing areas which were not glaciated during the Holocene. The other 4 soils studied are situated in the bottom of the valley. P1 is situated on a moraine ridge near the present coastline. This ridge (fig. 2) represent the outermost position of the Mitdluagkat Glacier during the Holocene, and are probably from the late 1700. P2-4, which are from the landscape between this moraine ridge and the present position of the glacier, are situated on ridges at sites chosen from photographic data that show the position of the glacier front in 1933, 1958 and 1970. From this material it is concluded that soil formation at site 2 started in early 1900, at site 3 in

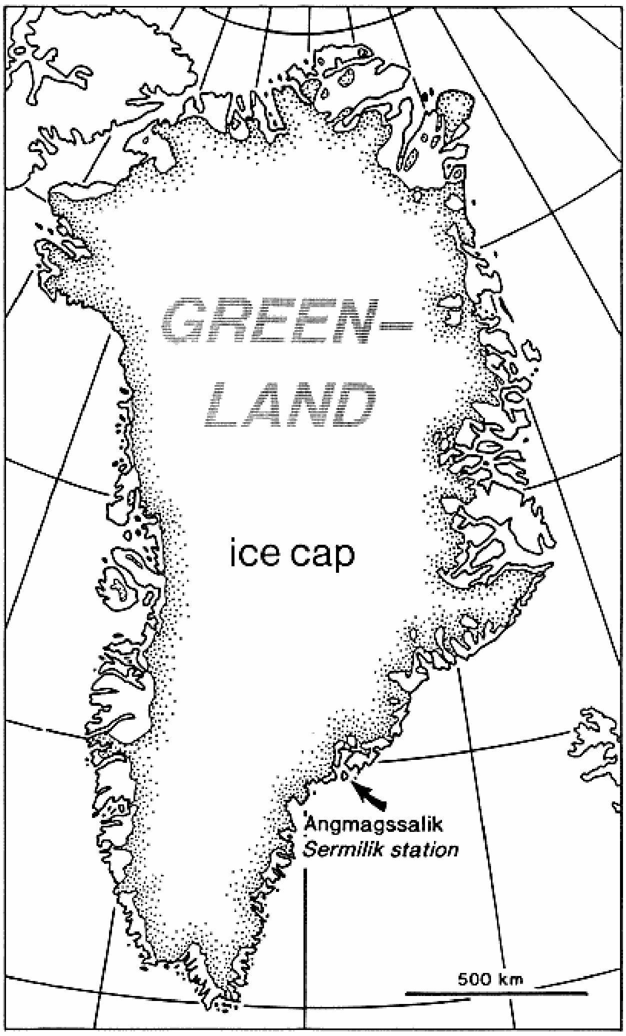

Fig. 1. The location of the island Angmagssalik Ø in Greenland.

Fig. 1. Angmagssalik Ø i Grønland.

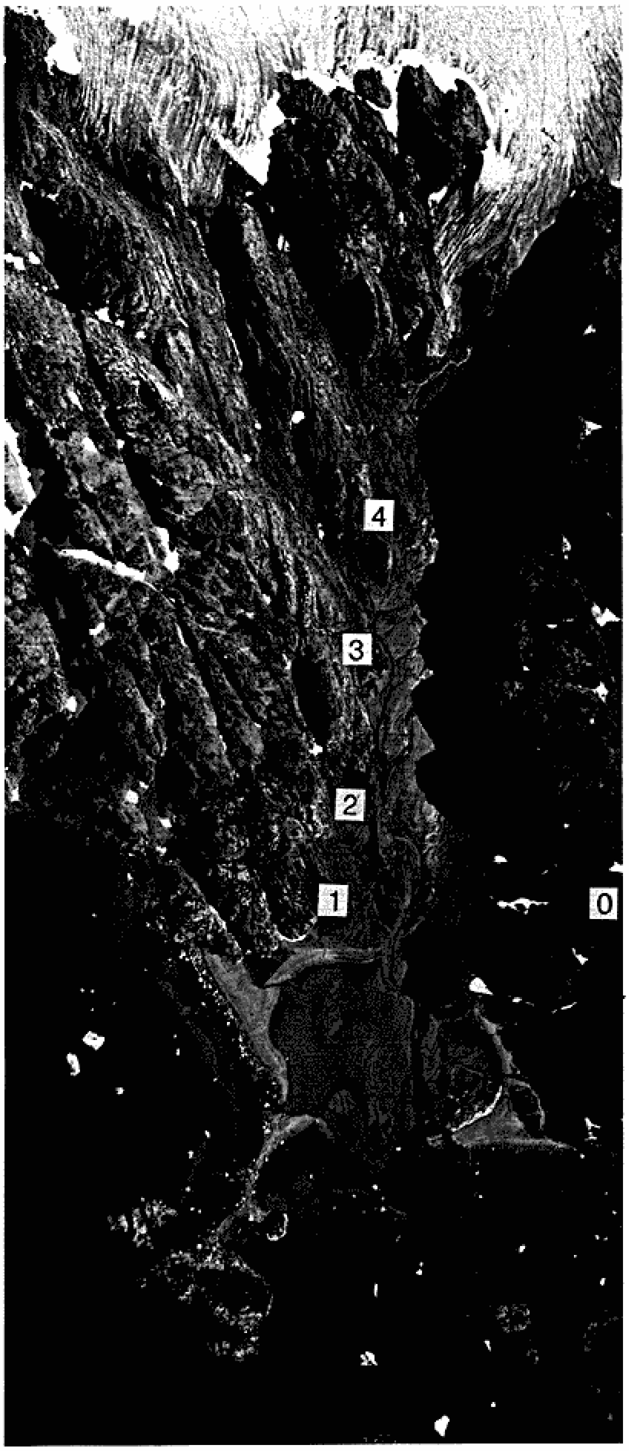

Fig. 2. Aerial photograph of the study area. Study sites are marked by numbers (0-4). Scale about 1:14000.

Fig. 2. Flyfoto af undersøgelsesområdet. Jordprofilernes placering er angivet ved numrene 0-4. Kort & Matrikelstyrelsen, copyright A 220/90. Målestoksforholdet er ca 1:14.000.

mid-1900 and that the till material at site 4 was deposited 20-25 years ago. All soils are situated on low-angle, convex slopes facing southerly directions. The vegetation – dwarf shrub heath – on these young landscapes is scattered, and the vegetation cover decreases from site 1 toward site 4. Soil profiles were studied on vegetated slope segments.

The climate in this part of Eastern Greenland is low arctic. From meterological observations in Angmagssalik (1895- 1970) the mean annual temperature is -1.2°C. The mean temperature of the varmest and coldest month – July and February – is 6.9°C and -14.9°C, respectively. Mean annual precipitation (1921-1950) is 749 mm with somewhat lower precipitation during the summer period. The soil temperature regime is assumed to be cryic, and the area has a udic soil moisture regime.

METHODS

The soils were described according to F.A.O. (1977). Samples were collected from the major horizons and from a series of fixed depths in BC and C horizons. The following methods were used for analysing the fine earth ((2 mm); pH was measured in 1:2.5 w/w soil:0.01 M $CaCl_2$ suspension. Organic carbon was determined by combustion in a LECO induction furnace, and total N was analysed by Kjeldahl digestion. Phosphorus was determined spectrophotometrically after extraction with 12 N sulphuric acid. Total P was determined after extraction of soil heated to 550°C, and inorganic P without heating of the soil. Silicon was determined spectrophotometrically (Morrison and Wilson, 1963) after acid oxalate extraction (McKeague and Day, 1966). Iron and aluminium were determined by atomic absorption spectrophotometry (AAS) after being extracted by the dithionite-citrate method of Mehra and Jackson (1958), by the pyrophosphat method of McKeague (1967) and by the acid oxalate method of McKeague and Day (1966). Exchangeable bases were also analysed by AAS after extraction by $NaOOCCH_3$ and NH_4OOCCH_3. Exchangeable H and Al were determined by titration after extraction with KCl, with and without addition af NaF. The cation exchange capacity at the actual pH of the soil (CECe) was calculated as the total of exchangeable cations determined by the above mentioned methods. The CEC at a pH 8.2 was determined by analysing the extractable Na in the soil extracted with $NaOOCCH_3$ (Borggaard et al., 1987).

RESULTS

All five soil profiles are situated on slightly convex slopes of about 10° facing southwesterly directions. They are formed in coarse-textured till material, and the relatively young soils in the bottom of the valley (P 1-4) only show weak horizon differentiation (table 1). In P0, which has been formed during the Holocene, the morphological dif-

Profile/ Horizon	Depth(cm)	Colour(moist)	Morphological features.
Profile 0			
A	0 - 7	7.5YR 2/3	Stony, gravelly sand; weak, medium crumb structure.
Bv	7 -16	5YR 3/4	Stony, gravelly sand; weak very fine subangular blocky structure.
BC1	16-30	7.5YR 4/6	Stony, gravelly sand; structureless.
BC2	30-(50)	7.5YR 4/4	Stony, gravelly sand; structureless.
Profile 1			
A	0 - 0.5	10YR 4/2	Stony, gravelly loamy sand; weak medium crumb structure.
Bv	0.5-3.5	10YR 4/4	Stony, gravelly loamy sand; weak very fine subangular blocky structure.
BC	3.5-6	2.5Y 4/3	Stony, gravelly loamy sand; structureless.
C	6 -(45)	2.5Y 6/4	Stony, gravelly loamy sand; structureless.
Profile 2			
A	0 - 0.3	10YR 3/4	Stony, gravelly loamy sand; weak very fine crumb structure.
BC	0.3-3	2.5Y 3/3	Stony, gravelly loamy sand; structureless.
C	3 -(45)	5Y 5/2	Stony, gravelly loamy sand; structureless.
Profile 3			
A	0 - 0.3	10YR 4/3	Stony, gravelly sandy loam; weak fine crumb structure.
BC	0.3-3	2.5Y 5/3	Stony, gravelly sandy loam; structureless.
C	3 -(45)	5Y 4/2	Stony, gravelly sandy loam; structureless.
Profile 4			
A	0 - 0.2	-	Stony, gravelly sand; weak very fine crumb structure.
BC	0.2-3	2.5Y 5/3	Stony, gravelly sand; structureless.
C	3 - (45)	5Y 5/2	Stony, gravelly sand; structureless.

Table 1. Major morphological features of the five studied soil profiles.

Tabel 1. De fem undersøgte jordes morfologiske hovedtræk.

Profile/ Horizon		Sample depth	pH	%C	%N	C/N	C/P	o.P ppm	io.P ppm
0	A	0- 7	5.16	9.58	0.015	639	228	421	155
	Bv	8-12	5.37	1.57				152	174
	BC1	20-25	5.49	0.53				69	67
	BC2	30-35	5.67	0.44				42	94
	BC2	40-45	5.77	0.40				57	60
1	A	0-0.5	4.49	4.53	0.263	17	190	239	654
	Bv	1- 3	5.48	0.90				163	675
	BC	4- 5	5.76	0.23				61	747
	C	8-12	6.01	0.12				40	665
	C	20-25	6.42	0.07				75	553
	C	30-35	6.65	0.09				52	663
	C	40-45	6.72	0.04				0	621
2	A	0-0.3	5.38	1.96	0.127	15	142	138	894
	BC	1- 3	5.63	0.35				110	770
	C	4- 5	5.91	0.10				65	646
	C	8-12	6.17	0.06				73	737
	C	20-25	6.34	0.03				121	721
	C	30-35	6.55	0.03				123	670
	C	40-45	6.65	0.03				32	638
3	A	0-0.3	5.34	1.76	0.132	13	75	235	840
	BC	1- 3	5.52	0.35				63	827
	C	4- 5	6.27	0.13				14	685
	C	8-12	6.55	0.12				0	752
	C	20-25	6.68	0.12				25	715
	C	30-35	6.70	0.12				5	651
	C	40-45	6.66	0.12				28	678
4	A	0-0.2	5.80	0.63	0.049	13	38	168	850
	BC	1- 3	6.61	0.09				71	790
	C	4- 5	6.65	0.09				27	646
	C	8-12	6.67	0.09				95	745
	C	20-25	6.79	0.04				131	734
	C	30-35	6.70	0.05				73	854
	C	40-45	6.55	0.03				103	1383

Table 2. Chemical properties of P0-P4. Organic P (o.P) and inorganic P (io.P) are given as ppm.

Tabel 2. Kemiske egenskaber for profilerne P0-P4. Organisk P (o.P) og uorganisk P (io.P) er angivet i ppm.

ferentiation is more conspicuous and reaching deeper into the soil. In P0 and also weakly developed in P1, there is observed a thin (1-2 mm) bleached soil layer (grayish colour) just below the A horizon. No bleaches soil material is observed in P2-P4.

The thickness of A horizons and their content of organic C decrease markedly from profile 0 toward profile 4 (table 2). The decrease in organic C with depth is generally also more rapid, going from P0 to P4. The rooting depth decreases from about 40 cm in profiles 0, 1 and 2, to about 30 cm in P3, whereas roots only reach a depth of about 10 cm in P4. Simple field observations show that at comparable depth the root intensity increases from P4 to P0. In P3 the root intensity is relatively high, especially in deeper horizons. In P3 the content of clay-size material from field tests is found to be about 10-15 %, whereas the clay content in the other soils varies between 2-10 %.

The pH profiles of the soils are shown in figure 3. At a depth of about 40-45 cm the pH of the parent material is relatively stable in the young soils in the bottom of the valley, and ranges from 6.55 to 6.72. The lowering of pH in the A horizons, and also in deeper-lying horizons, decreases from P1 to P4. In P4 there is only observed a lowering of pH in the very thin A horizon (2 mm). In the zonal soil P0, pH values increase with depth but do not exceed 5.77 within the studied profile depth.

The amount of exchangeable bases (table 4) is generally increasing with depth in all five soils. In A horizons there is observed a secondary maximum of basic ions. Compared with the basic ion content of lower C horizons, the maximum in A horizons is more clear, going from P4 to P1. The base saturation (table 4), especially %V2 calculated from CECe, generally follows the same pattern as the total of basic ions; %V1, calculated from $CEC_{8.2}$ is relatively low, due to the high potential acidity of the soils. The exchangeable bases are dominated by Ca. In the younger soils in the bottom of the valley K is the next dominating basic ion followed by Mg and Na, whereas the saturation sequence in the zonal soil is Ca, Mg, K and Na. CECe is much lower than $CEC_{8.2}$. In P4 $CEC_{8.2}$ exceeds CECe by a factor 1.2-4. This factor is generally increasing with soil age, from P4 to P0, and reaches values of 11-14 in P0.

The content of organic phosphorus generally decreases with depth. C/P values (table 2) calculated for the organic

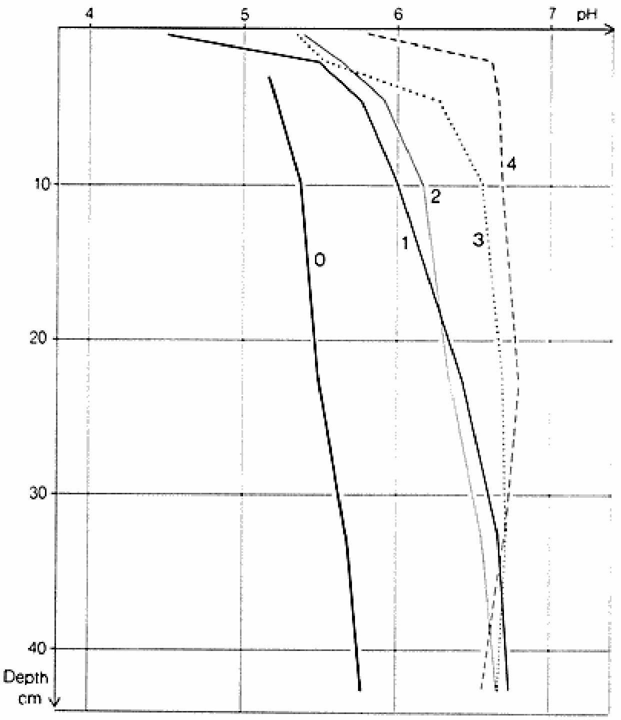

Fig. 3. pH-profiles of the five studied soils.

Fig. 3. De fem undersøgte jordes pH-profiler.

matter of A horizons show a decrease from 228 in the zonal soil to 38 in the soil closest to the present position of the glacier. The inorganic phosphorus content is much lower in the zonal soil than in the younger soils in the bottom of the valley. The average content of inorganic phosphorus in P0 is about 110 ppm, whereas a general increase is observed from values about 650 ppm to 850 ppm going from P1 to P4. Calculations of the C/N values for the organic matter of A horizons show relatively low values in the young soils in the bottom of the valley. The C/N ratio show a slight increase from 13 to 17 going from P4 to P1. In the organic rich A horizon of P0 the C/N value is extremely high, reaching a value of 639.

Results from the extraction of Al, Fe and Si are shown in table 3. A local maximum of acid oxalate extractable Al (Alo) and Si (Sio) is observed in the C horizons. This maximum is generally found at a still shallower depth going from P0 to P4. In the zonal soil P0 – and only in this soil – a clear second maximum of Alo and Sio is observed just below the A horizon, in the Bv and BC1 horizons. This maximum of inorganic Al and Si is followed by a maximum in pyrophosphate extractable Al (Alp). Slightly higher values of Alp just below the A horizons are also observed in P1 and P2, but not in P3 and P4. In P1 and P2, the increase in Alp is not followed by significant increases in Alo and Sio.

Profile/	Horizon	Sample depth	Fe-d	Fe-o	Fe-p	Al-d	Al-o	Al-p	Si-o ppm
0	A	0- 7	8.98	1.26	2.07	2.27	3.25	1.94	103
	Bv	8-12	23.37	3.01	1.83	7.86	10.30	5.27	1133
	BC1	20-25	22.83	4.76	1.04	6.47	11.11	4.27	1178
	BC2	30-35	25.24	2.62	1.05	5.83	8.78	3.85	940
	BC2	40-45	25.93	2.53	0.98	5.16	9.26	3.09	1319
1	A	0-0.5	4.25	0.40	0.25	0.74	0.84	0.10	42
	Bv	1- 3	2.95	0.58	0.41	0.48	0.77	0.27	97
	BC	4- 5	3.47	0.65	0.29	0.58	0.77	0.30	170
	C	8-12	3.86	0.57	0.21	0.45	0.83	0.15	148
	C	20-25	3.19	0.30	0.22	0.41	0.54	0.21	169
	C	30-35	3.44	0.58	0.30	0.50	0.87	0.18	188
	C	40-45	3.74	0.39	0.25	0.31	0.72	0.16	250
2	A	0-0.3	3.78	0.37	0.57	0.34	0.65	0.05	71
	BC	1- 3	3.93	0.73	0.43	0.42	0.57	0.47	137
	C	4- 5	4.13	0.59	0.28	0.26	0.58	0.21	210
	C	8-12	3.60	0.54	0.31	0.17	0.65	0.15	218
	C	20-25	3.91	0.63	0.24	0.21	0.67	0.09	320
	C	30-35	4.32	0.69	0.29	0.58	0.95	0.14	413
	C	40-45	4.11	0.65	0.72	0.80	0.98	0.33	336
3	A	0-0.3	3.54	0.48	0.70	0.36	1.11	0.19	108
	BC	1- 3	4.23	0.52	0.46	0.49	1.35	0.12	206
	C	4- 5	4.00	0.45	0.33	0.29	2.12	0.06	372
	C	8-12	4.91	0.48	0.33	0.31	2.28	0.04	513
	C	20-25	5.63	0.49	0.41	0.60	2.04	0.01	426
	C	30-35	5.39	0.45	0.39	0.57	1.88	0	432
	C	40-45	4.76	0.51	0.42	0.50	1.67	0	428
4	A	0-0.2	3.14	0.26	0.38	0.15	1.68	0.32	139
	BC	1- 3	3.57	0.30	0.28	0.21	1.16	0.06	181
	C	4- 5	3.36	0.36	0.24	0.18	1.02	0.11	177
	C	8-12	3.73	0.33	0.23	0.26	1.32	0.10	233
	C	20-25	3.40	0.34	0.25	0.34	1.29	0.10	229
	C	30-35	3.30	0.37	0.24	0.35	1.22	0.07	217
	C	40-45	3.07	0.50	0.25	0.24	1.14	0.06	217

Table 3. Chemical properties of P0-P4. Dithionite-citrate extractable (d), acid oxalate extractable (o) and pyrophosphate extractable (p). Fe and Al are given as per thousand.

Tabel 3. Kemiske egenskaber for profilerne P0-P4. Dithionit-citrat ekstraherbart (d), oxalat ekstraherbart (o) og pyrophosphat ekstraherbart (p). Fe og Al er angivet i promille.

The content of extractable Fe is generally higher in the zonal soil P0 than in the soils in the bottom of the valley. In P0, maximum values for Fed and Feo – but not for Fep – are observed in Bv and BC horizons. In the young soils P1 to P4, variations in iron content between horizons and profiles are small.

DISCUSSION

Both morphological and chemical properties of the five soils clearly show that the stage of soil formation primarily is determined by the time factor. Differences in soil properties are distinctive, both between P0 and profiles 1-4, where the probable difference in age is about 7-9000 years, but also between P1-P4, which have developed in parent material deposited with intervals during the the last about 200 years. As the soil-forming potential is low in arctic regions, it is important – when studying soil chrono-sequences – that differences within other soil forming factors, such as climate, relief and parent material, are of minor importance (Bockheim, 1979). The present study, which is restricted to a small area, primarily analyses a sequence of young soils, apart from P0. The

Profile	Horizon	Ca	Mg	K	Na	H	Al	CECe	$CEC_{8.2}$	%V1	%V2
0	A	2.19	0.53	0.31	0.17	0.11	2.13	5.44	73.47	4.4	58.8
	Bv	0.32	0.16	0.10	0.20	0.04	2.55	3.37	42.54	1.8	20.7
	BC1	0.47	0.22	0.09	0.05	0.06	3.11	4.00	54.32	1.5	20.8
	BC2	0.85	0.30	0.08	0.05	0.20	1.82	3.30	47.20	2.7	38.8
	BC2	2.18	0.49	0.10	0.09	0.12	1.81	4.79	52.57	5.4	59.7
1	A	2.87	0.48	0.46	0.13	0.12	0.44	4.50	52.43	7.5	87.6
	Bv	0.43	0.11	0.16	0.03	0.05	0.27	1.05	9.39	7.8	69.5
	BC	0.36	0.08	0.14	0.02	0.02	0.13	0.73	7.35	8.2	82.2
	C	0.51	0.10	0.15	0.02	0.02	0.13	0.91	6.17	12.6	85.7
	C	0.71	0.12	0.15	0.01	0.02	0.06	1.07	6.94	14.3	92.5
	C	0.82	0.13	0.17	0.01	0.02	0	1.15	10.46	10.8	98.3
	C	0.90	0.15	0.19	0	0.02	0	1.26	11.79	11.4	98.4
2	A	1.03	0.19	0.23	0.08	0.07	0.39	1.99	10.44	14.7	76.9
	BC	0.19	0.04	0.09	0.02	0.03	0.30	0.67	4.88	7.0	50.7
	C	0.44	0.06	0.11	0.06	0.04	0.06	0.77	4.09	16.4	87.0
	C	0.49	0.10	0.11	0	0.03	0.04	0.77	3.86	18.1	90.9
	C	0.74	0.13	0.18	0.01	0.02	0	1.08	6.91	15.3	98.1
	C	0.89	0.14	0.21	0.06	0.02	0	1.32	7.04	18.5	98.5
	C	0.95	0.15	0.24	0.01	0.02	0	1.37	6.54	20.6	98.5
3	A	1.04	0.24	0.27	0.11	0.16	0.68	2.50	12.30	13.5	66.4
	BC	0.45	0.08	0.12	0.03	0.05	0.56	1.29	3.86	17.6	52.7
	C	0.79	0.12	0.17	0.03	0.05	0.10	1.26	6.11	18.2	88.1
	C	1.34	0.18	0.23	0.04	0.04	0.02	1.85	4.75	37.7	96.8
	C	1.18	0.15	0.22	0.03	0.02	0.02	1.62	3.42	46.2	97.5
	C	1.10	0.13	0.24	0.03	0.04	0	1.54	4.96	30.2	97.4
	C	1.09	0.13	0.22	0.02	0.04	0	1.50	4.39	33.3	97.3
4	A	0.86	0.19	0.15	0.07	0.10	0.19	1.58	4.85	26.6	81.6
	BC	0.68	0.09	0.03	0	0.04	0.07	0.91	1.27	63.0	87.9
	C	0.74	0.10	0.13	0	0.04	0.03	1.04	4.75	18.3	93.3
	C	0.85	0.12	0.15	0	0.06	0	1.18	2.38	47.1	94.9
	C	1.12	0.13	0.15	0	0.03	0	1.43	4.88	29.3	97.9
	C	1.12	0.13	0.15	0	0.03	0	1.43	1.74	80.9	97.9
	C	0.90	0.11	0.19	0	0.02	0	1.22	3.37	35.6	98.4

Table 4. Chemical properties of P0-P4. Exchangeable cations, cation exchange capacity at the actual pH of the soil (CECe) and at pH 8.2 ($CEC_{8.2}$). Values are in meq/100g. Base saturation %V1 is calculated using $CEC_{8.2}$, %V2 using CECe. Sample depths are the same as in tables 2 and 3.

Tabel 4. Kemiske egenskaber for profilerne P0-P4. Ombyttelige kationer, kationombytningskapacitet ved jordens aktuelle pH (CECe) og ved pH 8.2 ($CEC_{8.2}$). Værdierne er i mækv/100g. Basemætningen %V1 er beregnet ud fra $CEC_{8.2}$, %V2 ud fra CECe. Prøveudtagningsdybderne er de samme som i tabel 2 og 3.

soils have very similar parent material, exposure and drainage, and should therefore be able to give useful information about the relative age of soils, when comparing organic matter accumulation and evidence of weathering and leaching. Furthermore, it seems possible to demonstrate a sequence of soil-forming processes, characteristic for a subarctic environment. The five stages of soil formation will first be discussed in order of increasing age.

Stage 1 (P4, soil age approx. 20-25 years): The accumulation of organic matter is restricted to the very thin (2 mm) A horizon (0.63 % C). The mull-like humus has low C/N and C/P ratios, indicating rapid decomposition of plant material in a nutrient-rich soil. The very shallow biological activity, which limits the nutrient uptake by plants (e.g. bases for hydrogen) and the production of organic acids by humification to the uppermost soil layer, is reflected in soil pH and base saturation. A relatively small lowering of pH and base saturation is only seen in the upper few centimetres of the soil. At this very early stage of soil formation a translocation is recognized of Si and Al in inorganic forms, from the upper 10 cm of the soil into deeper horizons. An early inorganic translocation of Si followed by Al into the subsoil has also been reported from subarctic Podzols in south west Greenland (Jakobsen, 1989), and from soil chrono-sequence studies in Canada (Wright wt al., 1959).

Stage 2 (P3, soil age approx. 40-50 years): The accumulation of inorganic compounds of Si and Al translocated from the upper 10 cm of the soil is, compared to stage 1, somewhat more distinct. The accumulation of organic matter has continued (1.76 % C in the A horizon) and reaches deeper into the soil. The increasing biological activity is also reflected in pH and base saturation values. Respiration of soil organisms and plant roots, nutrient uptake, humification and leaching with high rainfall have lowered pH and base saturation to a greater depth. From the depth distribution of basic ions and of %V2, a local minimum in bases and base saturation is seen in the soil layer just below the A horizon. This negative gradient in %V2 from the A horizon to the next deeper lying horizon increases with soil age from P4 to P0, and is probably caused by an accelerated recycling of nutrients to the soil surface by plants. In spite of this recycling of bases the base saturation level generally decreases with soil age, and a marked acidification of the soils to a still greater depth is observed.

Stage 3 (P2, soil age approx. 80-90 years): The C/N and C/P ratios of the accumulated organic matter have increased slightly – compared to stage 2 and 1 – which has also the acidification of soil horizons. The accumulation of inorganic compounds of Al and Si is observed at a greater depth (>30 cm). In the upper soil horizons values of pyrophosphate extractable Al indicate that organic complexants probably have initiated the translocation of organo-metallic complexes from the A horizon. This process – the most important podzolization process – represents a more advanced stage of soil formation compared to stage 1 and 2, as it implies higher soil acidity, and higher concentrations of organic complexants formed in a less biologically active and nutrient-deficient soil environment.

Stage 4 (P1, soil age approx. 200 years): In this oldest soil in the bottom of the valley, the acidification has advanced further, and the pH in the A horizon has lowered to 4.49. The organic matter content of the soil has increased markedly (4.53 % C in the A horizon), and the form of humus has changed to a more moder like form (C/N = 17). The evidence for an early inorganic translocation of Al and Si into the subsoil can still be observed in the deeper part of the C horizon, simultaneously with the occurrence of a very thin bleached E horizon just below the A horizon. This bleached soil layer probably represents an intensification of the activity of organic complexants. The general increase in the content of organic matter, and probably also in the content of amorphous metal-oxyd-hydroxydes, has increased the amount of variable charges in the soil. This is seen as still higher potential acidity of soils – higher $CEC_{8.2}$ compared to CECe – as soil age increases. The higher CEC values of P3 – relative to values in the somewhat younger soil P2 – are explained by differences in clay content. This demonstrates the importance – when analysing soil sequences - to combine the comparison of quantitative results from the analyses of soil horizons, with the comparison of the characteristic, complex patterns caused by the sequence of still more advanced soil-forming processes.

Stage 5 (P0, soil age approx. 7-9000 years): There is a major difference in age from stage 4 to stage 5. The accumulation of organic matter in the soil has increased markedly as has also the C/P, and especially the C/N ratio. The formation of a thicker mor A horizon (9.58 % C) has promoted an extensive translocation of Al and also of Fe from the A horizon. Apparently Fe is included in translocation processes probably only after the establishment of pronounced periods with a reducing environment in the A horizon. This presumably implies the formation of a thick organic-rich horizon, in spite of the udic soil moisture regime in the area. From the extraction values of Fe (no maximum in Fep in Bv and BC1) it is seen that iron probably is mobilized in the A horizon and leached to deeper horizons by organically induced redox processes. Organic complexants not necessarily participate in the translocation of iron, as is also demonstrated in subarctic Podzols in southwest Greenland, where iron-rich Bs horizons, with very low Fep and % C values, are observed below horizons very rich in Al and reactive organic compounds (Jakobsen, in prep.). The accumulation of inorganic forms of Al and Si is still evident in the deeper part of the C horizon. But also in the Bv and BC1 horizons, with maximum values of organically complexed Al, a marked accumulation of inorganic forms of Al, Si and some Fe is observed. This probably indicates that periodically – when the concentration of organic complexants is low – processes of inorganic translocation of Al, Si and Fe take place. These inorganic podzol forming processes in cold climates are also reported from Canada (Wang et al. 1986). At this advanced stage of soil formation the soil is very low in bases and show a high variable charge and potential acidity. The distribution of bases and base saturation follows the same pattern as in P1-P3, but the low values reflect the advanced stage of leaching.

Summarizing the change in horizon characteristics from P0- P4, it is evident that in this area soils are formed as a result of multiple processes (Simonson, 1978). The following sequence of dominating processes can be recognized.

The invasion of plants and the leaching of rainfall immediately initiate an accumulation of organic matter and a decrease of pH and base saturation in the uppermost soil layer. Concurrently, a leaching starts – in inorganic forms - of Al, Si and probably also P. The chemical elements are probably translocated in the form of mixed inorganic sols as demonstrated for Si, Al and Fe by Taylor (1988). With increasing age these chemical characteristics of the soil profile generated by the mentioned processes gradually become more distinct. During early stages of soil formation there is also observed a gradual increase in C/N and C/P ratios and a gradual decrease in the total content of inorganic P in the soil profile. As also discussed by e.g. Walker and Syers (1976), changes in forms and amounts of soil P seem to be a useful measure for determining the relative age of soils. In the early period of soil formation (about 100 years) the accelerated recycling af nutrients by plants presumably intensifies the accumulation of basic ions – especially Ca - in the A horizon. This results in an increasing negative gradient of bases and base saturation (%V2) from the A horizon to the next underlying horizon.

Within 100 years from the beginning of soil formation, the leaching of the A horizon has reached a level, where the impeded biological activity in the nutrient-deficient A horizon allows organic complexants to eluviate metalllic ions from the A horizon. Soon after, the first morphological evidences are observed in soil profiles, the appearance of thin, bleached E horizons and stronger coloured Bv (Bvs) horizons.

The continued leaching and gradual decrease in pH, base saturation and in availability of nutrients (increasing C/P and C/N) promote the intensity of translocation processes. Gradually the translocation of Al, Si and Fe into the B horizon becomes more distinct.

Comparing the complex, total signature of soil-forming processes, it seems possible to make a rather detailed relative dating of soils within the studied area. The comparison of single or few soil characteristics can easily lead to misinterpretation of soil age. In the present study e.g., organic matter accumulation in P3 – compared to the older soil P2 – is influenced by an only slightly higher clay content. This has promoted the rooting of plants and intensified soil-forming processes, especially in the uppermost soil layers. The implication of various soil characteristics and a multiple-process model will optimize the value of soil sequence studies in relation to the chronology of landscapes and the influence of climatic changes on soil formation.

CONCLUSION

The study of a chrono-sequence of five soils in a proglacial valley in low-arctic, Eastern Greenland indicates that stages of soil development have to be analysed as a complex result of multiple-process activity, and that a joint comparison of several soil profile characteristics is necessary to give detailed information about soil age.

In the present study a combination of the following characteristics has shown useful: Profile morphology, organic matter accumulatiom, pH profiles, C/N and C/P ratios of the organic matter of A horizons, content of inorganic P in soils, depth and distinctness of horizons with both inorganically and/or organically translocated Al, Fe and Si, the saturation of soils with different basic ions, the level and variation with depth of base saturation, the increasing potential soil acidity and the amount of variable charges in soils.

It has been shown that the comparison of stages of soil formation, by interpreting the complex picture of many different soil characteristics, makes it possible to determine the relative age of soils rather detailed. Also in very young landscapes (0-200 years old) it seems possible – from a study of the sequence of early soil forming processes – to distinguish between soils only differing a few decades in age.

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Sammendrag

I en proglacial dal syd for Mitdluagkat Gletscheren på Angmagssalik Ø i Østgrønland er der foretaget en undersøgelse af en kronosekvens af jorde. Ud fra jordbundsegenskaberne var det hensigten at bestemme jordenes relative alder samt at kortlægge en eventuel generel sekvens af karakteristiske translokationsprocesser.

Jordbundsundersøgelserne viste, at de forskellige stader, jordbundsudviklingen gennemløber, bør analyseres som et resultat af multibel-proces aktivitet. Dette betyder, at en samtidig vurdering af en lang række jordprofilegenskaber er nødvendig for at opnå detaljerert information om jordenes alder. I den aktuelle undersøgelse har følgende jordbundsegenskaber været inddraget i den samlede vurdering: profilmorfologi, akkumulation af organisk materiale, pH- profiler, det organiske materiales C/N og C/P forhold, indholdet af uorganisk fosfor, dybden og tydeligheden af horisonter med organisk og uorganisk omlejret Al, Fe og Si, basebelægningen, jordens potentielle surhed og mængden af variabel ladning.

Den samlede tolkning af alle de nævnte jordbundsegenskaber afslører en tydelig sekvens af tidlige jordbundsdannende processer, og gjorde det muligt at skelne detaljeret mellem stadier i jordbundsudviklingen og dermed jordenes relative alder. I den proglaciale dals unge landskab ((200 år) var det således muligt at skelne mellem jorde hvis alder kun afveg med få tiår.

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