Soil Formation on the Peninsula Tugtuligssuaq, Melville Bay, North West Greenland

Bjarne Holm Jakobsen

Jakobsen, Bjarne Holm: Soil Formation on the Peninsula Tugtuligssuaq, Melville Bay, North West Greenland. Geografisk Tidsskrift 88:86-93 Copenhagen, 1988

The geography of soils has been studied on the peninsula Tugtuligssuaq, Melville Bay, N.W. Greenland. Soil formation and pedogenesis in relation to soil age and paleoclimate are discussed.

Keywords: *Subpolar desert soil zone, soil formation, soil age, paleoclimate.*

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The centenary of the birth of Knud Rasmussen in 1879 was celebrated by a cooperative Danish-Greenlandic multidisciplinary expedition to Melville Bay, North West Greenland. As a part of the investigations during the summer of 1979 a study of soil geography was carried out on the peninsula Tugtuligssuaq, the largest ice free land area in Melville Bay.

The aim was to study soil formation in the subpolar desert zone, the pedological zone between the polar desert and the tundra, and to investigate whether soil-geographic studies may throw light on the relative age of different land surfaces and provide information about paleoclimatology.

AREA OF STUDY

In the Melville Bay (fig. 1) the Greenland Ice Cap reaches the sea only interrupted by some rocky headlands of which the peninsula Tugtuligssuaq is the largest, running 20 km NE-SW with an area of roughly 68 km^2. The peninsula consists of mountain massifs which have their steepest slopes on the NW coast. To the south more gentle mountain slopes and river valleys open to the coast (figures 2 and 3). A mapping of the geomorphology (Jacobsen et al., 1980) shows northerly directed cliffs with occurrences of scree and less steep, southerly directed block slopes. The valleys, depressions between elevated areas, and places along the south coast, show gently sloping and horizontal ground. In parts of these areas with a higher proportion of finer material various forms of frost sorting and solifluction processes are observed.

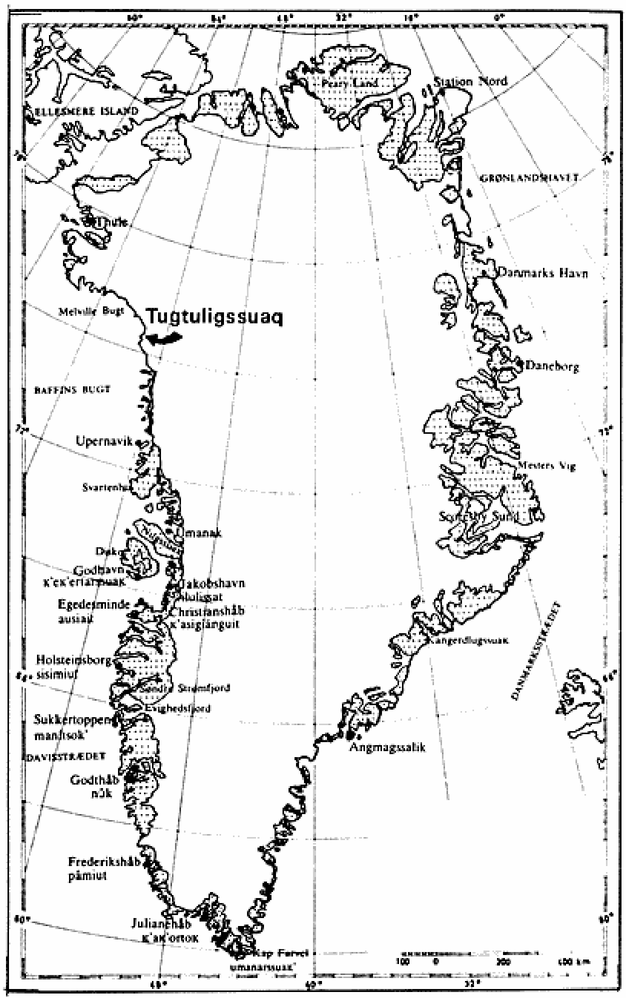

Fig. 1. Map of Greenland and location of Tugtuligssuaq.

The climate is high arctic, maritime. Meterological stations (period 1961-1982) c. 350 km to the north and to the south have recorded mean annual temperatures of c. -10°C and c. -7°C respectively, winter month mean temperatures of c. -23°C and c. -19°C, whereas mean temperatures in July and August reach c. +4°C and c. +6°C. From measurements in 1978-1979 (Thingvad, 1981) the precipitation at Tugtuligssuaq is reckoned to be somewhat higher compared to the mean precipitation values (1961-1982) of c. 110 mm and c. 250 mm for the respective stations north and south of the area. In the period mentioned (1978-1979) c. 500 mm were recorded at Tugtuligssuaq as compared to 167 mm and 288 mm for the respective stations, with maximum precipitation in the period July-September.

The vegetation is usually very sparse mostly due to a long-lasting snow cover and unstable soils and block fields. In early snow-free areas with fine textured materials the vegetation can generally be termed poor dwarf shrub heath (Fredskild et al., 1980).

Fig. 2. Aerial photograph of Tugtuligssuaq. Geodetic Institute, copyright A173/80.

METHODS

The soils of the area were identified during a survey carried out in July 1979. About 35 profile pits were dug to describe pedogenetic phenomena. The soils were described according to FAO (1975), Guidelines for Soil Profile Description, and samples were collected from the major horizons. In the field pH was measured in a 1:1 w/w soil:water suspension. The air dried samples were passed through a 2 mm sieve and analyzed using the following methods. Particle sizes were analyzed by sieve and hydrometer methods (Madsen, 1983). Organic carbon was determined by combustion in a LECO induction furnace. CEC was calculated as the total amount of exchangeable cations. Exchangeable bases (Ca, Mg, Na and K) were determined after extraction with a NH_4Ac-solution. Total exchangeable Fe, Al and H were determined by Piper's method (Borggaard et al., 1979). Dithionite-extractable Fe and Al were analyzed by a dithionite-citrate-bicarbonate method (Mehra and Jackson, 1958), pyrophosphate-extractable Fe and Al by a method described by McKeague (1967). Extracted Fe and Al were determined by atomic absorption spectrophotometry (AAS).

THE SOILS OF TUGTULIGSSUAQ

Variations in the intensity of the main soil-forming processes are reflected in the soil geography of Tugtuligssuaq. These processes are controlled by a complex interaction

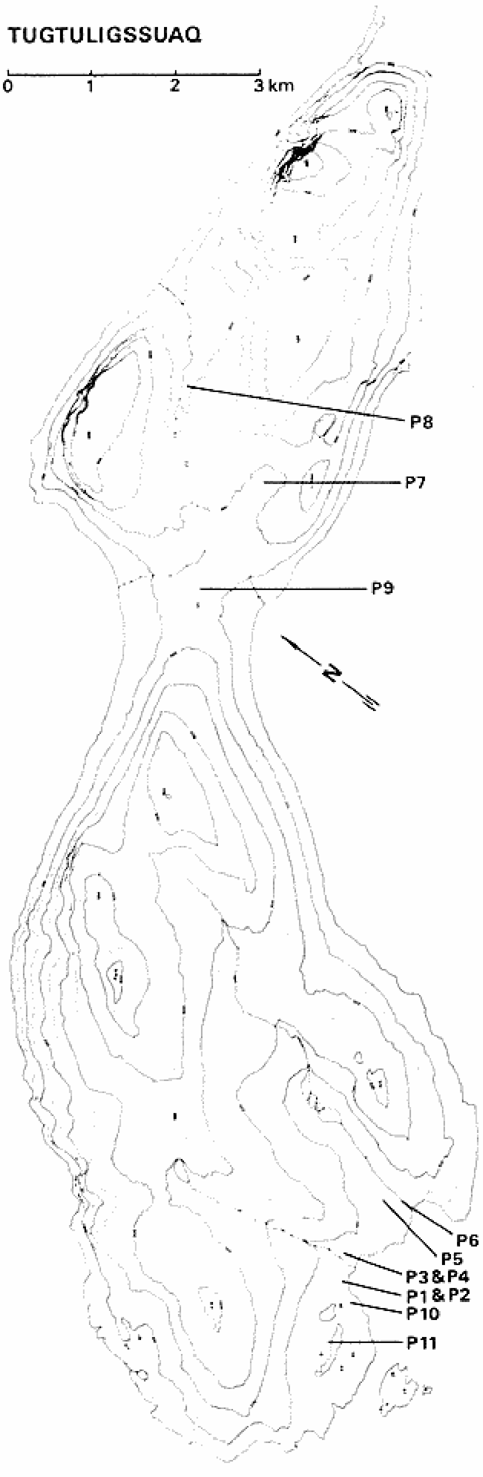

Fig. 3. Topographical map of Tugtuligssuaq with indication of study sites. The map is compiled photogrammetrically by N. G. Mortensen, University of Copenhagen, on the basis of vertical aerial photographs (U.S. Air Force 1953). Contour intervals are 25 m.

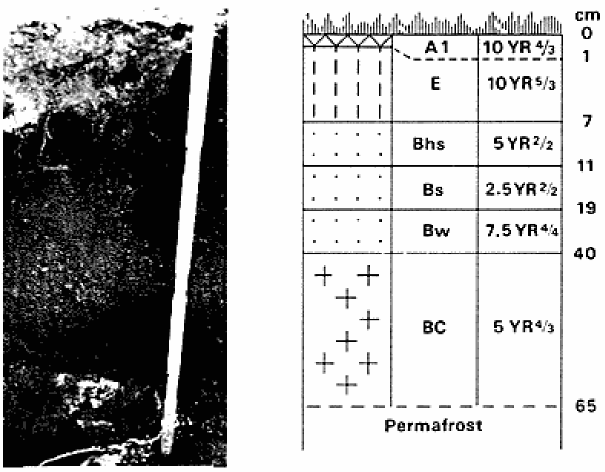

Fig. 4. The studied soil profile P1, a podzolized arctic brown soil.

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Hor.	% C	pH	CEC	V %	Fe-D	Fe-P	Al-D	Al-P
Ah	3.99	5.1	-	-	1.88	0.42	0.80	0.66
E	1.39	5.4	12.5	3.3	2.26	0.53	1.00	0.82
Bhs	1.60	5.6	10.7	1.9	2.07	0.81	1.60	1.50
Bs	0.81	5.6	9.1	3.7	1.62	0.52	1.40	1.22
Bw	0.23	5.7	3.5	6.7	0.88	0.24	0.52	0.52
BC	0.44	5.7	5.8	2.8	1.24	0.38	0.94	0.92

Table 1. Chemical properties of soil profile P1. Horizon(Hor.), organic carbon(%C), pH, cation exchange capacity in meq/100g(CEC), base saturation(V%), Fe-D and Al-D(dithionite-citrate extractable Fe and Al) and Fe-P and Al-P(pyrophosphate extractable Fe and Al).

of the soil-forming factors: climate, organisms, relief, parent material and time.

As the peninsula is built up of easily weathered gneisic bedrock, all high-lying and steeply sloping areas are dominated by a debris cover of cobble- and boulder-size rock fragments with protruding bedrock. On gently sloping to horizontal ground in the valleys and along the coast soil formation takes place in tills, glaciofluvial and delta deposits and in material from mass-wasting processes. Mainly arctic brown soils, polar desert soils and tundra soils (Tedrow, 1977) are found in these areas. In some

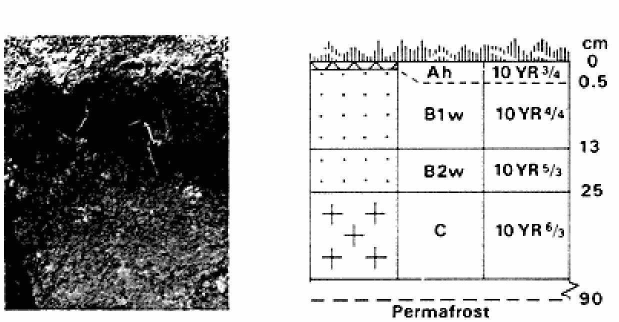

Fig. 5. The studied soil profile P3, a transition between polar desert and arctic brown soil.

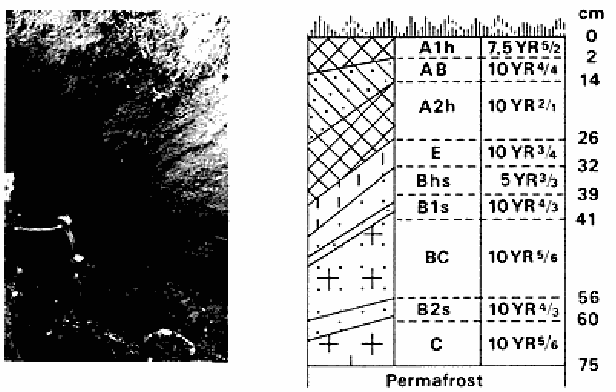

Fig. 6. The studied soil profile P2, a podzolized arctic brown soil.

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Hor.	% C	pH	CEC	V %	Fe-D	Fe-P	Al-D	Al-P
A1h	1.84	5.3	20.8	6.7	2.03	0.59	0.74	0.72
AB	0.71	5.5	10.4	5.1	1.87	0.48	0.64	0.54
A2h	13.10	5.4	42.9	2.8	7.37	5.07	6.40	5.44
E	0.42	5.5	6.5	4.3	1.18	0.40	0.60	0.50
Bhs	0.57	5.5	6.6	4.5	1.36	0.46	0.82	0.66
B1s	0.48	5.4	5.1	4.5	0.79	0.49	0.94	0.92
BC	0.20	5.6	4.0	3.5	0.79	0.16	0.38	0.36
B2s	0.50	5.5	4.4	4.7	1.39	0.39	1.20	1.06
C	0.16	5.6	2.8	4.0	0.83	0.17	0.46	0.46

Table 2. Chemical properties of soil profile P2.

arctic brown soils evidence of podzolization and lessivation can be observed.

In the western part of the peninsula in well drained positions on gravelly coarse sand podzolized arctic brown soils are found. (P1 and P2 in fig. 3). A poor shrub/lichen heath covers the area, root development reaches 20-35 cm into the soil, and the permafrost table is situated at a depth of 65-75 cm. Morphological and chemical data (figures 4 and 5, tables 1 and 2) show that the soils are strongly acid in the upper horizons and become a little less acid with depth. The base saturation is very low in all horizons which indicates intensive leaching. Extraction analyses of Fe and Al show an accumulation of especially aluminium in B_{hs}- and B_s-horizons. In P1 nearly no iron seems to have been translocated from A- to B-horizons,

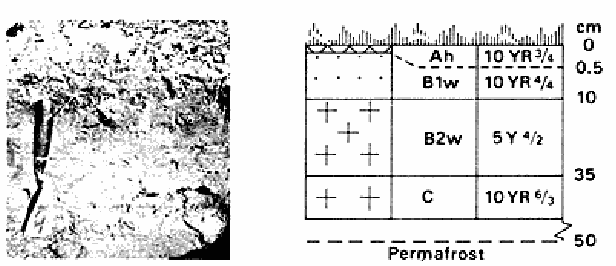

Fig. 7. The studied soil profile P4, a transition between polar desert and arctic brown soil.

Fig. 8. The slope containing profiles P3 and P4.

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Hor.	% C	pH	CEC	V %	Fe-D	Al-D
Ah	1.71	5.2	11.3	13.6	2.06	1.00
B1w	0.59	5.6	9.8	3.3	1.94	0.94
B2w	0.21	6.3	5.4	15.2	2.70	1.50
C	0.23	6.2	3.2	23.4	2.57	1.06

Table 3. Chemical properties of soil profile P4.

whereas the translocation of aluminium is significant. In P2, in which the translocation of iron is somewhat clearer, the illuvial B-horizon has a banded appearance. Besides in the B_{hs}-horizon, the illuvial Fe, Al and C are found in two layers of loamy fine sand in the gravelly coarse sandy delta deposit (B_{1s} and B_{2s}). No cementation of the B-horizon is observed. The soils P1 and P2 are developed on the same delta deposit. P2 is situated nearest the higher-lying landscape, and the podzolized arctic brown soil profile has been deformed and covered by solifluction material, horizons A_{1h} and AB. The chemical and morphological evidences of podzolization are not quite sufficient to allow the soils to be classified as cryorthods. The soils are belonging to the Great Group cryopsamment (Soil Survey Staff, 1975).

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Hor.	% C	pH	CEC	V %	Fe-D	Al-D
Ah	2.52	5.2	-	-	3.25	0.76
Bw	0.23	6.5	3.1	43.1	2.05	0.44
Bwg	0.07	6.3	5.6	9.5	1.73	0.34
Bt	0.32	6.1	5.8	16.9	2.62	1.00
C	0.23	6.1	4.0	15.7	1.86	0.68

Table 4. Chemical properties of soil profile P5.

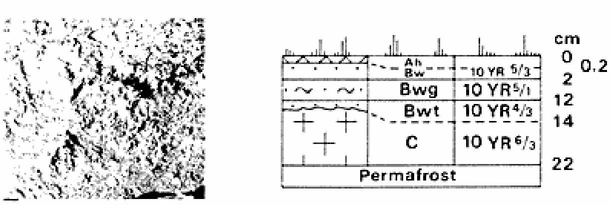

Fig. 9. The studied soil profile P5, a transition between polar desert and arctic brown soil, showing clay eluviation.

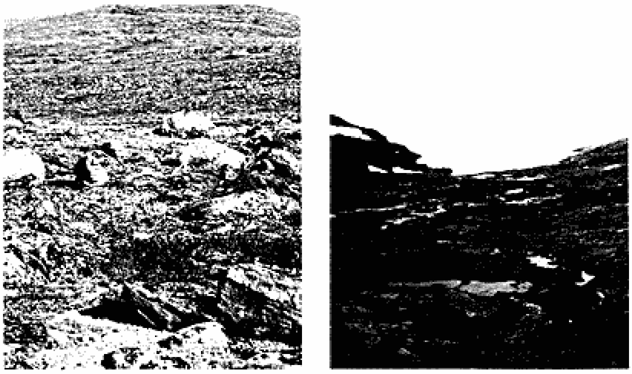

Fig. 10. Sites for soil profiles P5 (to the left) and P6 (to the right).

Not far from profiles P1 and P2 in well drained positions on gravelly coarse sandy and gravelly, sandy, loamy till material, A-B_w-C profiles are found (P3 and P4 in fig. 3). A very poor dwarf shrub heath covers the ground (fig. 8) causing only weak soil development with very thin A-horizons. On gravelly coarse sandy sites roots reach a depth of about 25 cm, and the permafrost table is situated at a depth of about 90 cm. On gravelly, sandy, loamy sites the permafrost table is reached at a depth of about 50 cm and roots only reach about 15 cm into the ground. From figures 5 and 6 and table 3 is seen that a thin, strongly acid A-horizon covers only moderately acid subsoil horizons. The base saturation (V) is somewhat higher compared to the podzolized arctic brown soils P1 and P2, thus indicating less intensive leaching relative to the input of bases in the topsoil. V generally increases with depth, but shows a pronounced local maximum in the A-horizon. There is no morphological evidence of significant translocation of Fe, Al and C in the profile. Variations in Fe-D and Al-D are followed by small variations in the textural composition of till material. The soils P3 and P4 are referred to as a transition between polar desert and arctic brown soils

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Hor.	% C	pH	CEC	V %	Fe-D	Al-D
O	-	-	-	-	-	-
Ah	8.76	5.8	-	-	7.00	2.68
ACg	6.01	5.6	44.0	15.4	0.90	3.36

Table 5. Chemical properties of soil profile P6.

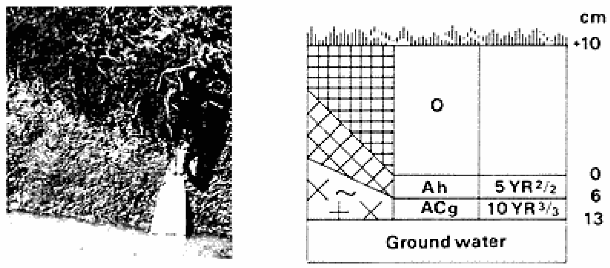

Fig. 11. The studied soil profile P6, a meadow tundra soil.

Fig. 12. Site for soil profile P8.

Fig. 14. Site for soil profile P9.

(Tedrow, 1977). According to Soil Survey Staff (1975), the soils are belonging to the Great Groups cryochrept, cryorthent or cryopsamment.

In the next valley going eastward, meadow tundra soils (fig. 11 and table 5) are found in the bottom of the valley (P6 in fig. 3), whereas a transition between polar desert and arctic brown soils (fig. 9 and table 4), with clear evidence of lessivation is found in gently sloping areas (P5 in fig. 3). A poor dwarf shrub heath covers the slopes, where soils are developed on gravelly, sandy, loamy till material. Mostly due to the permafrost table, already met at a depth of about 20 cm, the soils are imperfectly drained, and roots only reach about 10 cm into the ground. In the bottom of the valley, soils are poorly drained and the ground water is reached at a depth of about 25 cm. Roots from the fen vegetation reach about 20 cm into the soil. Lessivation in the soils on the slopes (fig. 10) is indicated by small clay skins on ped surfaces

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Hor.	% C	pH	CEC	V %	Fe-D	Al-D
Ah	-	-	-	-	-	-
B1w	0.17	6.1	2.1	27.5	0.98	0.26
B2w	0.08	6.5	1.9	38.3	1.15	0.26
C	0.04	6.7	1.1	60.4	1.08	0.18

Table 6. Chemical properties of soil profile P7.

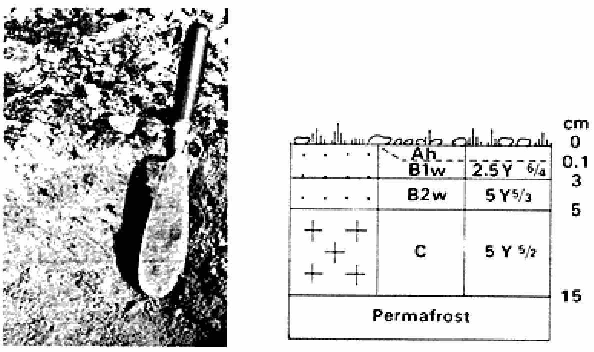

Fig. 13. The studied soil profile P7, a polar desert soil.

and by textural analysis. The clay content in the C-horizon is 7.6 %, in A_h-, B_w- and B_{wg}-horizons from 3.4 to 5.8 % and in the B_t-horizon 12.3 %. Only the very thin A-horizon shows to be strongly acid, whereas B- and C-horizons show weak to moderately acid reaction (table 4). Maximum base saturation is observed in the surface horizon probably due to a pronounced upwards directed transport of bases primarily induced by plant growth during the short summer period. Variations in Fe-D and Al-D are probably reflecting horizont textural composition resulting from lessivation processes. The meadow tundra soils are moderately acid, and the gyttja-like appearance of soil material in A_h- and AC_g-horizons indicates that organic-rich sandy loam is carried to the area by sheet and rill erosion processes such as can be observed on valley slopes. According to Soil Survey Staff (1975) the thickness of the B_t-horizons in P5 is not sufficient to qualify for an argillic horizon, for which reason the soil is included in the Great Group cryochrept. Soils in the valley depression are classified as cryaquepts.

In the eastern part of the peninsula three polar desert soils have been investigated (P7-P9 in fig. 3). To judge

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Hor.	% C	pH	CEC	V %	Fe-D	Al-D
Ah	-	-	-	-	-	-
C1	0.26	6.3	4.4	50.0	2.38	0.40
C2	0.21	7.2	4.7	65.4	2.39	0.46

Table 7. Chemical properties of soil profile P8.

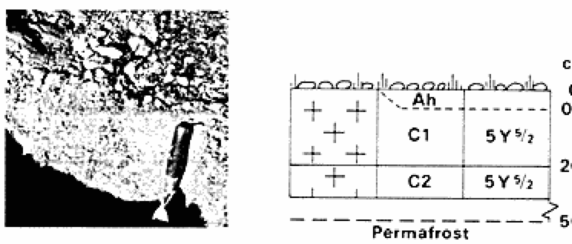

Fig. 15. The studied soil profile P8, a polar desert soil.

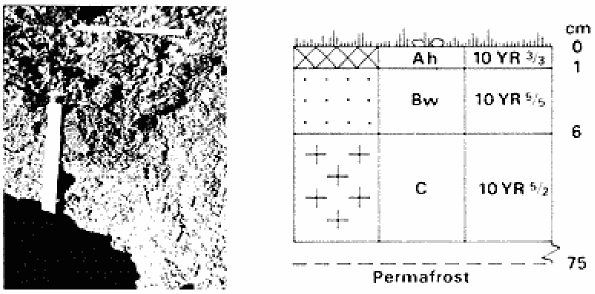

Fig. 16. The studied soil profile P9, a polar desert soil.

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Hor.	% C	pH	CEC	V %	Fe-D	Al-D
Ah	3.32	5.0	11.2	36.1	1.82	0.70
Bw	0.35	5.9	3.0	13.8	1.27	0.58
C	0.19	6.0	2.8	13.7	1.79	0.56

Table 8. Chemical properties of soil profile P9.

from the position in the landscape the soils must be expected to represent a chronosequence, the relative age increasing from P8 to P7 to P9. On gravelly, loamy, coarse sandy till material covered by a very poor dwarf shrub heath (fig.12) only weak soil development is observed in P8 (fig. 15 and table 7). The moderately well-drained, nearly neutral (A)-C soil profile shows no signs of intensive weathering and leaching. The base saturation is relatively high (50 %) and no coloured B-horizon is observed below the very thin A-horizon (roughly 1 mm). The permafrost table is met at a depth of about 50 cm and roots reach about 20 cm into the soil.

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Hor.	% C	pH	CEC	V %	Fe-D	Fe-P	Al-D	Al-P
A1h	4.76	5.6	30.9	19.7	5.56	2.29	2.20	1.70
B1w	1.13	5.9	9.4	16.2	2.01	0.90	1.02	0.86
C1	0.50	5.9	6.1	15.4	2.03	0.48	1.16	0.96
A2h	9.69	5.9	54.1	17.1	5.64	2.71	3.78	3.60
E	1.29	6.0	9.7	24.1	2.46	0.69	1.08	0.80
B2w	0.32	6.0	3.5	13.6	1.14	0.22	0.78	0.64
C2	0.28	5.9	4.7	13.7	1.78	0.21	0.84	0.72

Table 9. Chemical properties of soil profile P10.

In P7 (fig. 13) the permafrost table is situated at a depth of only 15 cm and roots only reach about 5-10 cm into the soil. This very shallow active zone, as compared to P8, is probably caused by the finer textural composition in P7. A very poor dwarf shrub heath covers only slightly gravelly, loamy, sandy till material. In the moderately well-drained, weakly acid soil a coloured B-horizon of 5 cm is observed with a base saturation of about 25-40 % (table 6). A somewhat more advanced stage in soil development is hereby seen in P7 as compared to P8.

In P9, which is developed on gravelly, coarse sandy till material covered by a poor dwarf shrub heath (fig. 14), an approx. 1 cm A-horizon is observed (fig. 16). Roots reach about 30 cm into the soil, and the permafrost table is situated at a depth of about 50-70 cm. A strongly acid A-horizon covers a moderately acid subsoil (Table 8). Humus accumulation in the topsoil, the formation of a coloured B-horizon and a relatively low base saturation indicate more extensive weathering and leaching in the soil profile. All three profiles are classified as belonging to the Great Group cryochrept (Soil Survey Staff, 1975).

Two polysequence soil profiles covered by dwarf shrub heath in the western part of the peninsula (P10 and P11 in fig. 3) are shown in fig. 17 and fig. 18. In P10 a leached arctic brown soil on slightly gravelly, stratified, loamy, sandy till material has been covered by about 20 cm solifluction material of gravelly sandy loam. An arctic brown soil is seen in this top layer. Cryoturbation processes have dislocated the horizontation in the fossil arctic brown soil. The moderately well-drained soil is moderately acid, and extractable Fe and Al reflect the varying weathering intensity with maximum values in the two A-horizons (table 9).

In P11 an arctic brown soil profile on stratified fluvial sand has been covered by gravelly, sandy, loamy solifluction material also showing an arctic brown soil profile.

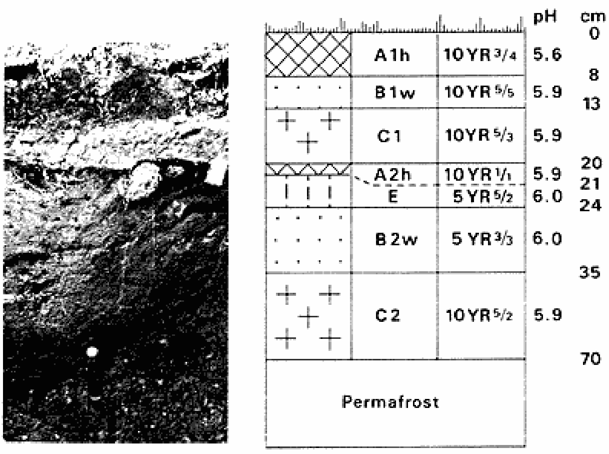

Fig. 17. The studied polysequence soil profile P10.

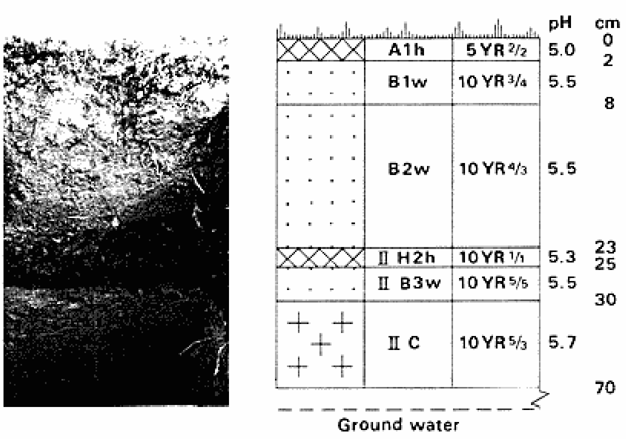

Fig. 18. The studied polysequence soil profile P11.

Both soils have strongly acid A-horizons and moderately acid subsoils. No deformation by cryoturbation of the fossil soil is observed, only a weak deformation of the A-horizon when solifluction material covered the site. The groundwater table is reached at a depth of 70 cm, no permafrost table is observed.

Soil Formation

The subpolar desert soil zone (Tedrow, 1977) has no unique genetic soils of its own, but shows a characteristic pattern of soils in the landscape. As a transition zone between the polar desert and the tundra the intensity of major soil-forming processes also takes an intermediate position. Terrestrial soil-forming processes, with low organic matter accumulation, without intensive leaching and with alkalization of soil profiles dominate in the polar desert, whereas hydromorphic processes, more extensive organic matter accumulation, leaching and some podzolization are characteristic of the tundra zone.

Organic Matter Accumulation

The amount of organic matter on and in soils of Tugtuligssuaq varies within a wide range. The polar desert-like soils in the eastern part of the peninsula show low organic matter contents due to a very sparse vegetation cover, primarily determined by long periods of snow cover which result in cold soils and a short growing season. The difference in relative age of soil surfaces is clear when comparing P8 and P9 (fig. 12 and fig. 14). On neighbouring and also otherwise similar land surfaces the vegetation cover at P9 is 75-100 %, whereas an only 10-20 % vegetation cover is seen at P8. Especially in environments that have short growing seasons, long periods are needed for the vegetation to occupy the soils. Even longer periods are needed in freely drained soils before a steady state is reached in soil organic matter. Therefore the amount and distribution of organic matter in relatively young soils with otherwise similar soil-forming factors is a useful measure for evaluating relative age.

In the western part of the peninsula in moderately well-drained soils (P1-P5), a somewhat higher content of organic matter is observed in the subsoil, probably due to leaching of humus substances at a more advanced stage in soil development. Meadow tundra soils (P6) show the highest organic matter contents, due to both an impeeded organic matter decomposition and an input of soil organic matter from soil erosion.

Leaching, Podzolization and Gleying Processes

When examining the major terrestrial soil types in freely drained positions a zonation can be observed regarding the intensity of weathering and leaching. In the western part of the peninsula acid soils with low base saturation and beginning podzolization are observed (P1-P4). The intensity of weathering and leaching decreases eastward, indicated by the horizontation and a less pronounced lowering of pH and base saturation (P5-P9). Birkeland (1978) points at the formation of coloured (cambic) B-horizons as the most useful measure of soil age differentiation, whereas Wright et al. (1959) used both morphological, chemical and mineralogical characteristics in order to indicate a chronosequence in soil formation. Percolating precipitation, net primary production and organic matter decomposition control the intensity of leaching. On Tugtuligssuaq some of the observed differences in leaching intensity can probably be explained by a somewhat more cold and dry climate in the eastern part of the peninsula especially during the summer period. Indications of a weak climatic gradient were observed during the two-month visit in the summer of 1979. When comparing soil profiles P8 and P9 in the eastern part of Tugtuligssuaq the found differences in weathering and leaching intensity can probably be explained by variations in the time factor. Therefore also the observed most advanced stages in soil weathering and leaching in soils in the western part of the peninsula are probably influenced by a general westward increase in time for soil formation. When using the weathering and leaching intensity as an indicator of soil age it seems to be important, especially in arctic areas with low soil-forming potential, that no clear differences in climate are present (Bockheim, 1979). Therefore only relative young soils with similar exposure within relative small areas are expected to give useful information about the relative age of soils when comparing the weathering and leaching intensity in cold climates.

Weakly expressed podzolization morphology is only observed in the coarse textured soils in the western part of Tugtuligssuaq. A dense vegetation cover without any accumulation of organic matter on the soil surface indicates high organic matter decomposition which increases the amount of organic compounds able to mobilize iron and aluminium. In all the studied podzolized arctic brown soils the B-horizon has a banded appearance (table 2). Comparing the amounts of Fe-D, Fe-P, Al-D and Al-P, aluminium seems to be closely related to organic compounds, Al-P/Al-D close to one, whereas iron in B-horizons seems to be mainly present in inorganic compounds. The translocation of aluminium possibly takes place as soluble metal-organic compounds, whereas some iron is possibly translocated by microbially induced redox processes.

In soil profiles P4 and P5 (tables 3 and 4) the lower B-horizon shows high values of Fe-D and Al-D, which coincide with an accumulation of clay in these horizons. In these gravelly, sandy, loamy soils clay and some amorphous minerals accumulated in the lower B-horizon probably originating from clay minerals and weathering products in the topsoil, translocated by percolating precipitation. The distribution of organic carbon in P5 (table 4) indicates that some mobilized organic compounds are probably trapped in the lower B-horizon.

Morphological and chemical evidences of gleying processes are very weak, and no mottling is observed in soils on Tugtuligssuaq. This is caused by a weak development of microbially induced redox processes due to cold temperatures, low organic matter content and a short frost-free season. On sandy, loamy soil material (P4 and P5) in areas with a relatively dense vegetation cover, some bleaching due to pseudogleying is observed (figures 7 and 9). Restricted percolation, that periodically produces a perched water table due to a frozen and/or clay illuviated subsurface horizon, causes reduction and loss of iron from soil horizons.

The polysequence soil profiles P2, P10 and P11 show high contents of organic C and extractable Fe and Al in the fossil A-horizons (tables 2 and 9). Compared with the present surface horizons this probably indicates that a period with more stable soil surfaces and a more luxuriant vegetation cover has preceded periods with a sparser vegetation cover and more intensive solifluction. Probably the higher weathering intensity and the increased soil humus formation are caused by warmer conditions with a longer snow-free period. Holocene pollen and macro fossil diagrams from lakes on Tugtuligssuaq, indicating that deglaciation of the area occurred c. 9000-8500 B.P., also reveal a period with warmer conditions than today, which was followed by a cooling, probably increasing frost boil and solifluction activity (Fredskild, 1985). When comparing the deformation of polysequence soil profiles (P2, P10 and P11) it is clear that freely drained coarse-textured soil materials resulting in deep-lying permafrost tables have impeded cryoturbation processes, whereas more intensive cryoturbation is observed in more fine-textured soils.

CONCLUSION

Tugtuligssuaq is situated in the subpolar desert soil zone with podzolized and clay eluviated arctic brown soils, typical arctic brown soils, polar desert soils and tundra soils. The geography of soils shows gradually more advanced stages in soil formation westward which indicates differences in the relative age of the soils and possibly a weak climatic gradient, with more maritime conditions in the western part of the peninsula. Features of polysequence soil profiles give some information about the paleoclimate, i.e. warmer conditions than today in a period following the deglaciation c. 9000-8500 B.P.

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