Climatic Influence on Morphology and Chemistry of Nine Loess-Profiles, Argentine

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Nine profiles developed in loess under a subtropical, continental climate with a pronounced climatic gradient (udic to aridic) were investigated morphologically and chemically in order to elucidate the influence of climate on soil genesis. Four morphological types developed: a) A1A2BtC-soils, b) ABC-soils, c) A(B)C-soils and d) AC-soils. Some variations could be related to the climatic variation, others were better related to texture or to palaeoclimatic (periglacial) conditions.

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INTRODUCTION

The soil landscape is generally regarded as the result of a continuous interaction between state factors of soil formation (climate, parent material, etc.), the soil forming processes (clay illuviation, podzolization, etc.) and the soil profile (Ultisol, Oxisol, etc.) in space-time. This is partly because the analytical method does not permit nature to be regarded as One, but separate it into interrelated elements, and this point of view is hence only an approximation although practical to the rational mind.

With this as a starting point the influence of one state factor on soil genesis can be indicated when it varies comparatively much more than other state factors. In this study the purpose is to elucidate the influence of climate (precipitation and potential evapotranspiration as expressed by the water balance) on soil morphology and chemistry in nine loess-profiles of NW-Argentine. The study was carried out during The Danish Scientific Expedition to Patagonia and Tierra del Fuego, 1978-79.

THE STUDY AREA

The nine profiles are situated on a line running from 26°51'S, 65°07'W to 27°02'S, 64°38'W in the San Miguel de Tucuman and Santiago del Estero provinces of northwestern Argentine. In the following the profiles will be numbered from 1 to 9, and will be shortened: p1 for profile 1, p2 for profile 2, etc. p1 lies furthest west and is the profile with the most humid climate, p9 furthest east and is the profile with the most arid climate (see Fig. 1).

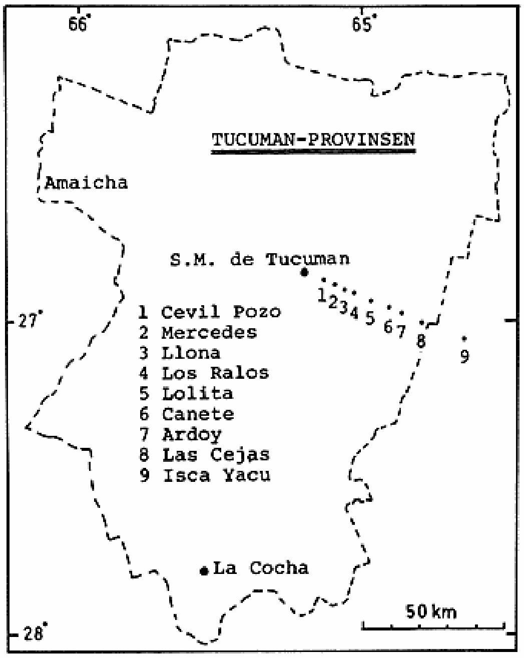

Fig. 1. Localization in NW-Argentina of the nine profiles.
Fig. 1. Placeringen af de 9 profiler.

STATE FACTORS OF SOIL FORMATION

Climate

Precipitation is high in summer related to advection of humid airmasses of tropical origin and low in winter due to the dominance of the subtropical high pressure cell which produces clear skies. Furthermore marked differences are noted from year to year. In the vicinity of p1 precipitation varied from 484-1255 mm/year in the period 1916-71 (Minetti, 1973a). Lastly, precipitation increases from east to west (from p9 to p1) as the major part of the humidity is shed in the form of orographic precipitation caused by the proximity of the Andes to which p1 is closest. p1-6 is situated in a Cwah climate, p7-9 in a BShwa climate (classification according to Köppen; Bruchmann, 1971b).

Table 1

	1		2	3		4		5	6
p 1	10		4	6		2		127	269
p 2	9		4	5		3		82	
p 3	7		3	4		5		67	211
p 4	7		3	4		5		66	213
p 5	3	3/4	2	1	3/4	8	1/4	30	
p 6	2		1	1		10		10	200
p 7	1	3/4	1	-	3/4	10	1/4	2	
p 8	0		0	0		12		0	179
p 9	0		0	0		12		0	

The length of the various periods of the water balance. 1: the moist period. 2: period of replenishment. 3: utilization period. 4: deficit period. 5: maximum amount of stored water (mm). 6: maximum amount of stored water before throughflushing (mm), calculated on the basis of an effective rooting depth of a 100 cm. Unit in 1 - 4 is months.

On the basis of Bruchmann (1976b, 1977) and Minetti (1975a) water balance diagrams for each profile are constructed. Minetti y Fogliata (1975) - using a »class A« pan - concluded that E_{pot} was underestimated by Thornthwaite's formula, but as no correction factor was worked out and Bruchmann used Thornthwaite for calculating E_{pot}, it is too low in the digrams. From table 1 appears the periods of replenishment ($P > E_{pot}$), utilization ($P < E_{pot}$, cumulative deficit less than maximum amount of stored water) and deficit ($P < E_{pot}$, cumulative deficit more than maximum amount of stored water). The length of replenishment and utilization periods clearly increase from p9 to p1. p8 and p9 have deficit in all months (monthly basis). Maximum stored water is 127 mm in p1, but from another part of the study it was shown that the soil was able to retain twice as much using an effective rooting depth of 100 cm. Therefore throughflushing does not occur theoretically, but as most of the rain falls as high intensity precipitation (up to 285 mm in 4 hours) throughflushing is most probable.

Temperature ranges from about 15°C in the coldest to 25°C in the warmest month.

Parent material

The parent material consists of loess mixed with volcanic ash in p1-8, in p9 of fluvially redeposited loess.

Physiography

All profiles lie on the flat to gently undulating Chacopampas plain, 400-450 metres above sealevel.

Vegetation

p1-5 is situated in the sugar cane area (formerly grassavanne), p6-7 in the soya area (formerly dry forest with a few cacti) and p8-9 in an area without agriculture (thorny forest with numerous thornbushes and many cacti) (Czajka und Vervoorst, 1956).

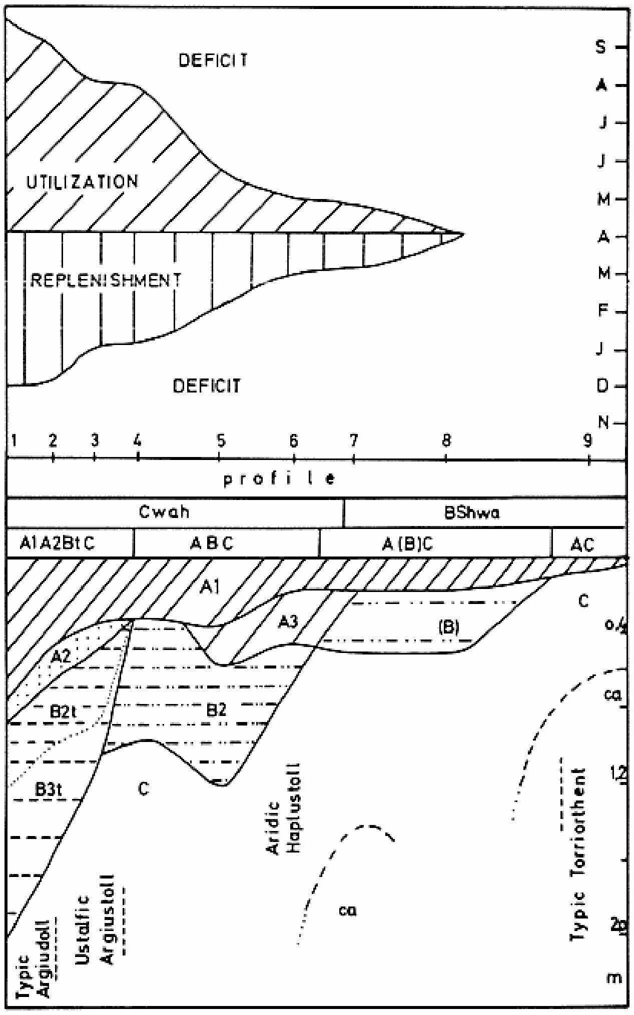

Fig. 2. Relationship between the waterbalance and pedological development. The upper half shows the variation of the waterbalance on a monthly basis for each profile – combined into a space-time diagram, the lower half the resulting solum. The central part shows the climatic classification (Köppen) and main morphological type. The lower, central and upper figure can be combined vertically.

Fig. 2. Forholdet mellem vandbalance og pedologisk udvikling. Øverst variationen af vandbalancen på månedsbasis for hvert profil kombineret i et rum/tidsdiagram. Nederst jordbundsdannelsen som resultat heraf. Den centrale del viser klimaklassifikationen (Köppen) og vigtigste morfologiske type. Den nedre, centrale og øverste del af figuren kan kombineres vertikalt.

Drainage

All profiles have a good inner and outer drainage, and no groundwater, concretions, mottles, etc. were observed.

METHODS

The profiles were described according to FAO's Guidelines for Soil Profile Descriptions (FAO, 1967).

Texture was determined by the hydrometermethod for fractions smaller than 40 μ and by dry or wet sieving for fractions larger than 40 μ.

Organic carbon was determined with a LECO-IR-12 apparatus, pH by the $CaCl_2$-method (soil-0,01 M $CaCl_2$ ratio of 1:2.5) and bases by the NH_4Ac-method.

DISCUSSION AND RESULTS

Morphological division

On the basis of morphology, the profiles can be divided into four groups (see figure 2):

1) *A1A2BtC-soils (p1-3)* with a mollic epipedon, an A2 horizon consisting of albic material and with an abrupt textural change between A2 and B2t.
2) *A1BC-soils (p4-6)* with a mollic epipedon and a well developed cambic B horizon.
3) *A1(B)C-soils (p7-8)* with a mollic epipedon and a structural B horizon (weak cambic).
4) *A1C-soils (p9)* with an ochric epipedon and without subsurface diagnostic horizons.

The A1A2BtC-soils (p1-3)

Clay illuviation is difficult to prove and as no micromorphological or fine clay (fraction less than 0,2 μ) investigations have been carried out, the identification as Bt is less conclusive. In the following various indications on clay illuviation will be given.

FIELDWORK

Clay skins were clearly observed being moderately thick and continuous in the B2t of p1 and thin and continuous in the B2t of p2 and p3, decreasing in thickness and amount downwards, the B3t being thickest in p1, the most humid profile. Clay skins were not observed in p4.

McKeague et al (1981) showed that of 54 field-identified argillic horizons, only 32 had more than 1% oriented, illuvial clay (Soil Taxonomy and FAO criteria for the argillic horizon), and as cutans produced by clay illuviation may be confused with stress cutans, the present field-identification of clay skins does not necessarily imply clay illuviation.

TEXTURE

The texture of the profiles is shown in table 2. The observed difference in clay content with a maximum in the B can be caused by 1) lithological discontinuities, 2) clay illuviation, 3) in-situ clay formation and/or, 4) in-situ clay destruction.

When calculating texture on a weight-% basis and a volumetric basis (provided no changes in volume takes place), the produced variation of the above-mentioned four processes is as follows: 1) *lithological discontinuity* - unpredictable, 2) *clay illuviation* - the clay fraction decrease in eluvial, increase in illuvial horizons by both methods, whereas other fractions increase in eluvial and decrease in illuvial by the weight-% method, but remain unchanged by the mg/cm³ method, 3) *in-situ clay formation* - the clay fraction generally reaches a maximum in the topsoil (except in desert soils) decreasing gradually downwards by both methods, whereas other fractions increase downwards because clay is partly formed by the diminuition of larger particles, and 4) *in-situ clay destruction* - in case of ferrolysis a decrease of the clay fraction by both methods take place, other fractions increase (weight-% method) or remain constant (mg/cm³ method).

Table 2

		<2 μ	2 – 20 μ	20 – 63 μ	63 – 125 μ	125 – 250 μ	250 – 500 μ	500 – 2000 μ
p1	Ap	23.7	46.5	13.3	6.0	5.2	1.2	0.4
	A11	17.1	36.0	24.6	7.8	9.2	2.0	0.4
	A12	15.7	25.4	10.2	11.6	13.4	2.4	0.2
	A2	7.5	28.6	33.8	8.6	15.0	5.0	1.2
	B2t	33.8	22.3	28.6	3.4	6.6	3.8	0.8
	B31t	31.4	34.8	23.1	2.8	3.6	3.2	0.8
	B32t	18.2	30.9	30.8	5.0	6.6	7.2	1.2
	C	17.1	31.0	29.6	5.8	6.8	8.0	1.6
p2	Ap	15.3	32.8	30.0	10.8	7.6	0.8	0.2
	A1	13.3	32.8	30.3	11.6	8.6	1.2	0.2
	A21	14.8	27.3	32.0	11.2	12.6	1.0	0.2
	A22	10.6	28.6	33.4	11.0	14.4	1.4	0.2
	B2t 70	27.8	26.3	32.9	5.0	5.8	1.2	0.2
	B2t 90	37.0	27.2	29.3	2.8	2.0	0.8	0.4
	B3t120	31.0	31.2	30.3	2.8	2.0	0.4	2.0
	B3t140	14.1	39.0	41.4	3.8	1.0	0.4	0.2
	C	10.8	36.3	44.2	5.0	2.2	1.0	0.4
p3	A1	17.0	33.1	28.9	9.6	7.6	1.0	0.4
	A2	7.6	29.5	31.6	11.8	17.0	2.0	0.2
	B2t	30.6	25.5	29.4	5.2	6.0	2.2	0.4
	B3t	36.0	22.2	32.8	3.4	3.2	1.6	0.4
	C	13.0	37.1	39.7	5.0	2.6	1.6	0.8
p4	Ap	18.2	33.9	28.6	8.0	7.4	1.2	0.2
	A1	18.1	32.1	29.6	8.2	8.4	0.6	1.0
	B	21.9	28.2	33.8	6.2	8.2	1.0	0.2
	C11	13.1	40.0	41.2	3.6	1.4	0.4	0.2
	C12	14.0	34.1	44.7	4.0	2.0	1.0	0.2

Texture (weight %).

The textural variation in the profiles must therefore be interpreted with care. Fadda (1968) applying micromorphology noted a decreased weathering downwards and observed clay-cutans (argillans) in Argiudolls and Argiustolls of the Chaco-pampas plain. As no hydromorphic features were observed in the present profiles, ferrolysis may be excluded.

Calculation of the texture on a clay, humus and $CaCO_3$-free basis by the formula $\frac{100 \times K}{100-(L+H+C)}$ where K = weight-% of a given fraction, L = weight-% clay, H = weight-% humus and C = weight-% $CaCO_3$ (see table 3) furthermore imply that lithological discontinuities are present, shown by the irregular variation of the various fractions down through the profile, a variation that cannot be explained by weathering alone.

Common to the 3 profiles is, that the B horizons contain more clay than the A and C horizons (weight-% basis), shown in fig. 3. As a comparison is also included the texture of p4. The A1, A2, Bt?, B and C horizons show distinct textural compositions although the material is too limited for any statistical analysis. In a textural homogenous parent material this implies clay transport from A2 to Bt, C being the parent material. From table 3 lithological discontinuities

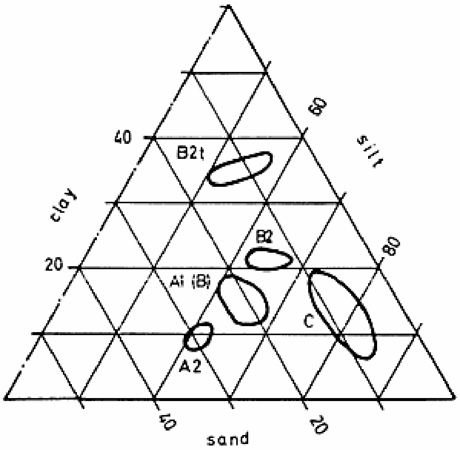

Fig. 3. The textural composition of the different horizons. Note: Only the lower right of the texture-triangle is shown.
Fig. 3. Teksturen i de forskellige horisonter. NB. Kun den nedre hojre del af teksturdiagrammet er vist.

were shown, however, but when comparing the clay content of the C-horizons (supplemented with investigations of Fadda (1968), Zuccardi et al (1968) and Zuccardi y Fadda (1971b, 1971c, 1972)), they all lie in the interval 9,46-21,50 % clay, that is, far below the clay content of the B2t horizons in p1-3 (33,78-37,04 %). This strongly indicate clay illuviation.

Table 3

		2 - 20 µ	20 - 63 µ	63 - 125 µ	125 - 250 µ	250 - 500 µ	500 - 2000 µ
p1	Ap	64.0	18.3	8.3	7.2	1.7	0.6
	A11	44.4	30.7	9.8	11.5	2.5	0.5
	A12	30.5	36.3	13.9	16.1	2.9	0.2
	A2	31.0	36.7	9.3	16.3	5.4	1.3
	B2t	35.2	45.0	5.4	10.4	6.0	1.3
	B31t	51.0	33.8	4.1	5.3	4.7	1.2
	B32t	37.9	37.7	6.1	8.1	8.8	1.5
	C	37.4	35.7	7.0	8.2	9.7	1.9
p2	Ap	41.9	34.0	11.6	11.3	1.0	0.3
	A21	32.4	38.0	13.3	14.9	1.2	0.2
	A22	32.1	37.5	12.4	16.2	1.6	0.2
	B2t 70	36.8	46.1	7.0	8.1	1.7	0.3
	B2t 90	43.5	46.9	4.5	3.2	1.3	0.6
	B3t120	45.6	44.3	4.1	2.9	0.6	2.9
	B3t140	45.5	48.2	4.4	1.2	0.5	0.2
	C	40.7	49.6	5.6	2.5	1.1	0.5
p3	A1	41.1	35.8	11.9	9.4	1.2	0.5
	A2	32.0	34.3	12.8	18.5	1.3	0.2
	B2t	44.6	37.1	7.6	8.7	3.2	0.6
	B3t	34.8	51.6	8.4	5.0	2.5	0.6
	C	42.8	45.7	5.8	3.0	1.8	0.9
p4	Ap	42.3	36.1	10.1	9.3	1.5	0.3
	A1	36.6	33.8	9.4	9.6	0.7	1.1
	B	36.1	43.2	7.9	10.5	1.3	0.3
	C11	34.0	48.5	4.2	1.7	1.2	0.2
	C12	39.7	51.9	4.7	2.3	1.2	0.2

Texture (weight %) calculated on a clay, humus and $CaCO_3$ free basis.

Table 4

		<2 µ	2 - 20 µ	20 - 63 µ	63 - 125 µ	125 - 250 µ	250 - 500 µ	500 - 2000 µ
p1	A1	219	460	314	100	117	26	5
	A2	114	423	501	127	222	74	18
	B2t	527	348	446	53	103	59	12
	C	257	464	443	87	102	120	24
p3	A2	93	360	385	144	207	24	2
	B2t	484	403	465	82	95	35	6
	C	193	553	592	75	39	24	12
p4	A1	280	497	459	127	130	9	16
	B	333	429	513	94	125	15	3
	C	197	604	622	54	21	6	3

Texture (volumetric basis, unit mg/cm^3).

Calculated on a mg/cm^3 basis (see table 4) clay increase from A to B and the following decrease to C is much more pronounced in p1 and p3 than in p4 and p6, and with only a minor difference between the clay content of the C-horizons. Loosening reduces clay content when measured on a mg/cm^3 basis, but as the A2 has a very low humus content and no crotovines, this factor is of little importance. Clay illuviation is therefore indicated by the volumetric method.

HUMUS

From table 11 appears the humus variation in p1-9. The humus content generally decreases downwards, except in p1-3, which have a secondary maximum in the B2 horizons. Dudas and Pawluk (1970) showed organo-clay complexes in Orthic Black Chernozems in the 0,2-0,08 µ fraction, and Gebhardt (1971) proved that organo-clay complexes were bound between silicate layers of montmorillonitic character in a Schwarzerde-Parabraunerde sequence. Illuvial clay is mainly fine clay (less than 0,2 µ) of montmorillonitic character, and the secondary humus-maximum may thus be explained by illuviation of clay-organic complexes. It may also be explained as an initial sombric horizon (illuvial humus subsurface horizon). A such was observed 50 km west of p1 in a cool, humid, subtropical climate developed in colluvium of loess with distinct illuvial humus on the ped surfaces. On the other hand, no illuvial humus was observed in p1-3.

Table 5

		clay content	porosity
p1	A2	114	44.0
	B2t	527	44.9
p3	A2	93	53.9
	B2t	484	40.2

Relationship between clay content (mg/cm^3) and porosity (%).

POROSITY

Porosity generally increase going from sandy to clayey soils, but as demonstrated in table 5, the tendency is the opposite when comparing the A2 and B2 horizons and this may be caused by clay illuviation.

Considering the above-mentioned evidence it is considered as most probable that p1-3 have an argillic horizon, and they are thus grouped together as A1A2BtC-soils, with precipitation higher than 830 mm/year and a moist profile in more than 7 months a year (udic or ustic moisture regime).

The ABC-soils (p4-6)

The ABC-soils differ morphologically from the A1A2BtC-soils by the absence of clay cutans and an A2 horizon, and by the presence of a coloured B, in places separated from the A1 by an A3. The B horizon meets the requirements of a cambic B, including a moderate angular to subangular blocky structure and a colour different from that of the A and C horizons (see table 6). Hue decrease and chroma and value increase downwards. The soils have between 680-830 mm/year of precipitation and a moist period of between 2-6 months (aridic moisture regime).

Table 6

	p4	p5	p6
A1/A3	10 YR 3/2	10 YR 4/3	10 YR 3/2
B2	7.5 YR 3/2	7.5 YR 4/4	7.5 YR 4.5/4
C	7.5 YR 5/4	7.5 YR 5/4	7.5 YR 5/6

Colours of the A, B, and C horizons in the ABC-soils. All colours on a moist basis.

The A(B)C-soils (p7-8)

The A(B)C-soils are the weakest developed of the soils with a B horizon, only separated from the AC-soils by having a structural B horizon developed. Furthermore they are distinguished from the ABC-soils as the (B) horizon has the same colour characteristica as the C-horizons, and is only classified as a cambic B because the profile is supposed to be decalcified (no $CaCO_3$ in any horizon of p8, only $CaCO_3$ in the IIC of p7). In p7 the C horizon qualifies structurally to be classified as cambic, but as it is cemented and contains $CaCO_3$ the lower boundary of solum is therefore easy to define. In p8 the position of the C is more problematic as it is decalcified and not cemented, but as the (B) has a moderate angular blocky and the C a weak to moderate subangular blocky structure, the depth of solum is based on strucural criteria. However, no plane can be inserted into the pedon saying that this separates the cambic from the noncambic horizon as there is a diffuse transition between the pedological and non-pedological part of the profile.

These soils are having a precipitation of 570-680 mm/year and a moist period of 0-2 months (aridic moisture regime).

The AC-soils (p9)

The AC-soils are distinguished from the other soils by the absence of clay skins and B horizons as the A horizon grades into the C horizon. The structure is weak to very weak subangular blocky if found at all. During the fieldwork it was not noted whether the pedon had structure in more than half the volume, but to the best of the authors memory this is not the case, and the horizon below A is consequently not classified as cambic, but as C. These soils have less than 570 mm/year of precitipation and no humid period (monthly basis).

THE THICKNESS OF SOLUM AND A1

Douglas et al (1967) conclude in a study of Mollisols that a combination of structural development, considerable clay accumulation, clay skins and the depth to completely unleached material gives the best approximation to the depth of solum. Considering the last factor, it is well known that salts of Ca, Mg, K and Na are leached to different depths due to differences in solubility, and considerable clay accumulation and structural development are very subjective terms, so although FAO defines the A and B horizons in terms of organic matter, quartz, clay, iron and/or aluminium and structure, the lower boundary of solum is ill-defined.

In the A1A2BtC-soils the lower boundary of field-observed clay skins were chosen as the lower boundary of solum, in the ABC-soils colour (related to iron) was the differentiating criteria, in the A(B)C soils structure and in the AC-soils colour (related to humus). Different criteria were therefore used for each group of soils.

The thickness of solum and A1 can therefore only be related to climate in the sense that the arbitrarily defined limit of solum generally increases with increasing length of the moist period (increasing precipitation, decreasing potential evapotranspiration, see fig. 2) but no linear relationship is present.

STRUCTURAL DEVELOPMENT

A moderate angular blocky structure dominates, strong structure is only found in the B2t of p1, weak structure in the C horizons of arid profiles, subangular blocky in A_p and C-horizons and prismatic structure as a transition phenomenon to blocky structure.

Texture is more important than climate in determining structural variation, which becomes evident from the following: In the A2 horizons af p1-3 clay content and Ca-saturation is higher than in the horizons of p9, but the former with lowest sand content shows a moderate angular blocky, the latter with a far higher sand content a weak subangular blocky structure, as sand has a more dispersive effect on structural development than silt. Comparing the B31t of p1 and the B2t of p3 (see table 7) the degree of structural development is also clearly related to texture.

On the other hand, the strong difference in the waterbalance between summer and winter have determined the range within which texture influences structure.

Table 7

	structure	clay	fine silt	coarse silt	sand	% humus	pH
B31t	strong	484	536	355	160	0.34	6.77
B2t	moderate	484	403	465	218	0.68	7.29

Structure, texture (mg/cm³), % humus, and pH of the B31t of p1 and B2t of p3.

CEMENTATION

A weak cementation was observed in the C-horizons of p4,6,7 and 8, which may be associated with 1) vertical or lateral transport of some substance followed by precipitation and cementation, or 2) fragipan genesis under a periglacial climate. The following discussion is based on the assumption that the cementation is caused by the same process.

p4 have a brittle structure in the C11, $CaCO_3$ is absent in the entire profile and the topographical gradient is close to 0°. Vertical transport of substances other than soluble products of $CaCO_3$ or fragipan are thus possible.

p6 have no $CaCO_3$ and lies ¾ way down on a 1 km long slope with a gradient of 2°. With a porosity of 45-55 % of which about half of the pores are larger than 3 μ (diameter), absent groundwater and the low gradient, lateral processes are improbable as it normally requires a high groundwater-table or an impermeable horizon for such movements to take place in the depth observed. Vertical processes and fragipan-genesis are thus probable explanations.

p7 contains $CaCO_3$ (1,5 %) in the cemented horizon, which is far too little to produce cementation, and lies in flat terrain.

p8 contains no $CaCO_3$ and lies in flat terrain.

As cementation is found both on flat and sloping terrain lateral transport processes are not probable. Vertical processes are not probable because the profiles lie in different climatic zones.

Common to the cemented horizons is that they are all found in the C horizon at approximately the same depth and having the same texture differing from abovelying horizons (see table 8).

Table 8

	% clay	silt (%) fine	silt (%) coarse	% sand	% humus	pH
p4	13.07	40.03	41.18	5.6	0.12	7.31
p6	10.84	36.26	45.31	7.2	0.41	7.14
p7	10.93	36.17	42.41	10.4	0.09	7.54
p8	11.95	38.15	41.60	8.2	0.10	7.51
p5	15.00	35.10	41.84	7.6	0.26	7.22
p9	6.74	13.31	27.51	52.1	0.34	7.70

Texture, pH, and humus for cemented and non-cemented C-horizons. Texture on a weight % basis.

Reaside (1964) analyzed the occurrence of loess fragipans with typical joint systems in New Zealand. These were formed under a dry and cold climate with low biological activity. During a later warmer and more humid climate the upper part of the pan loosened, producing a humus horizon. With increasing humidity the pan loosened to further depths. It is therefore most probable that the cementation is caused by fragipan genesis under the periglacial climate prevailing during the time of loess-deposition.

The absence of cementation in p1,2,3 and 5 can be explained by the extraordinary thickness of solum in these profiles (160-210 cm) and in p9 by the age as it consists of fluvial redeposited loess. The cementation is thus related to paleoclimatological and not to present climatological conditions.

BIOTURBATION

Crotovines were observed in p5 (very weak) and p8 and p9 (very clearly expressed, circular up to 10-15 cm in diameter). Their occurrence are indirectly related to climate as burrowers are found primarily in the arid zone because of the pronounced drying of the topsoil.

COLOUR DEVELOPMENT

Buntley and Westin (1965) proved a relationship between the product of the numerical notation of hue (1oYR = 3, 7.5YR = 4) and chroma and pedological development in a Chestnut-Chernozem-Brunizem climo-sequence, and this method is applied here in order to see if the colour profiles can separate the different morphological groups. From fig. 4 the following groups can be distinguished:

1) a clear minimum (A1) and maximum (C) plus secondary maximum (A2) and minimum (B2t) in p1 and p2, most clearly expressed in p1.

2) a clear minimum (A1) and maximum (C) with an intermediate step (A2 and B2t) (p3).

3) minimum in A1 increasing gradually downwards to maximum in C (p4-p8, less pronounced in p8).

4) a constant value throughout the profile (p9).

These curves are related to the spectral properties of the soil profiles, which are a function of humus, texture, moisture and free Fe-oxides.

A higher humus and water content give the soil a lower chroma as 1) A1 horizons with the same humus content have a lower chroma in the humid than in the semiarid zone, 2) the A3 horizons have less humus than A1, but a higher chroma in the rainy season.

In the A1A2BtC-soils with a secondary maximum in Bt, clay dominate the spectral properties of the Bt as clay gives a lower, Fe-oxides a higher chroma and clay-% is higher and Fe-% probably higher in B than C supported by data of Fadda (1968) who found a maximum of free iron-oxides in the Bt of a nearby Argiudoll.

The A2 have much less clay than Bt and probably less iron which explains the secondary maximum in A2.

The B horizon of ABC and A(B)C soils have a lower colour value than the C, explained by the 3-4 times higher humus content of the B and probably also by an initially higher Fe-content of the C.

In the semiarid zone the content of free Fe-oxides in comparable soils is constant (Fadda, 1968), and as the tex-

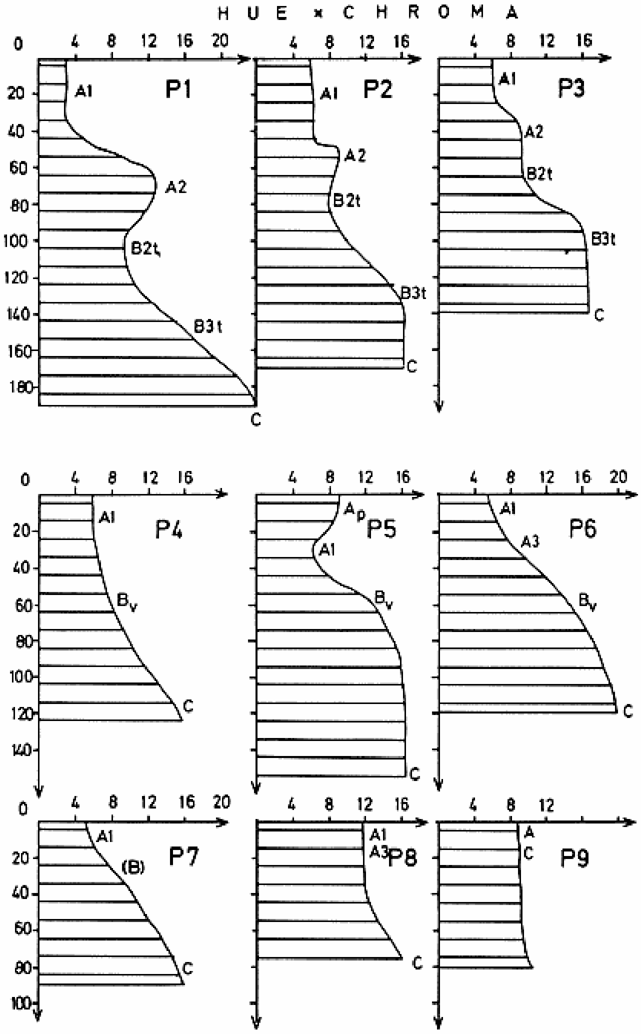

Fig. 4. The nine colour-profiles. The X-axis shows colourvalue, the y-axis depth in cm below surface.

Fig. 4. Farvebeskrivelsen af de 9 profiler. X-aksen viser farveværdien, y-aksen dybde i cm under overfladen.

ture and moisture profile was quite homogenous, the humus variation is therefore the major factor responsible for the observed variation in the colour profile.

The colour profile method is thus good to separate between A1A2BtC, (ABC + A(B)C) and AC soils, whereas the separation between ABC and A(B)C soils is less evident.

CHEMICAL PROPERTIES

Base saturation

Table 9

p1		p2		p4		p6		p8		p9	
A1	86.1%	A1	91.4%	A1	86.6%	Ap	78.2%	A1	86.6%	A	86.8%
A2	89.6	A2	90.2	B2	88.6	A3	81.8	(B)	90.4	C	96.5
B2t	89.2	B2t	90.8	C1	95.1	B2	88.0	C	93.0		
B3t	93.8	B3t	94.7	C2	95.8	C	92.3				
C	94.4	C	97.7								

Base saturation in % of p1, 2, 4, 6, 8, and 9.

The base saturation generally increases downwards (see table 9), and as the soils are only fertilized with nitrogen leaching is naturally most pronounced in the topsoil. The base saturation of the A1-horizon does not, however, decrease with increasing precipitation, and must thus be related to other factors. The depth at which the base saturation reaches a maximum does, however, increase with higher precipitation (see table 10).

pH

The pH value is more than 7 in C horizons, and between 5,83-7,05 in the A2 (normally too high a value for clay illuviation, but Fadda (1968) observed pronounced clay cutans (argillans) by micromorphological methods in nearby soils with a pH (KCl) higher than 7). There is no clear relationship between pH in the topsoil and precipitation, and only in the semiarid zone (p8-9) shows a gradual increase of pH with depth (see table 10). In p1,2,5,6 and 7 the variation is irregular which cannot be explained by bioturbation in p1 and p2 as the A1, A2, Bt and C horizons are clearly separated. Concluding, there is no clear relationship between pH and the elements of the water balance.

Table 10

BS_{max} (depth)			
p1	200 cm	p6	120 cm
p2	180 cm	p8	80 cm
p4	120 cm	p9	40 cm

Depth at which base saturation reaches a maximum.

Humus

The humuscontent decreases from the A1 (2-3%) to the C (0,1-0,3 %) except in p1-3 that have a secondary maximum in the Bt (see table 11). The sharpest decrease/cm takes place between the A1 and A2 (p1-3), A1 and B (ABC and A(B)C), except in p8 aml p9 which have a gradual decrease. In p1-7 it cannot be due to ploughing as this process only takes place in the upper A1 and it therefore indicates a natural and sharp decrease in biological activity, contrary to p8 and p9, where bioturbation was more pronounced throughout the profile and thus probably causing the gradual decrease in these profiles.

C/N

Nitrogen analyses were only carried out in the A1 and the C/N calculated (see table 12), mostly ranging from 10 to 13 indicating a mull humustype. With some discrepancies C/N decreases with maximum amount of stored water, indicating higher humus turnaround in the semiarid zone.

Table 11

		depth, cm	%humus	pH
p1	Ap	0- 20	3.68	6.7
	A11	20- 50	2.95	6.8
	A12	51- 75	1.09	6.6
	A2	75- 85	0.27	7.0
	B2t	85-122	0.72	6.8
	B31t	122-170	0.34	6.8
	B32t	170-210	0.14	6.7
	C	210-	0.14	7.0
p2	Ap	0- 21	2.52	7.3
	A11	21- 32	1.98	7.3
	A12	32- 46	1.74	7.1
	A21	46- 54	0.89	7.2
	A22	54- 64	0.53	7.1
	B2t	64-100	0.77	7.3
	B3t	100-160	0.31	7.3
	C	160-	0.10	7.1
p3	A1	0- 35	2.44	6.8
	A2	35- 47	0.32	5.8
	B2t	47- 85	0.68	7.3
	B3t	85-105	0.46	7.5
	C	105-185	0.17	7.6
p4	Ap	0- 22	2.49	7.0
	A1	22- 32	2.06	6.6
	B	32- 95	0.53	6.6
	C1m	95-155	0.12	7.3
	C12	155-	0.05	7.4
p5	Ap	0- 19	1.96	7.4
	A1	19- 40	2.08	7.2
	A3	40- 65	0.77	7.5
	B21	65-125	0.49	7.3
	B22	125-160	0.26	7.2
	C	160-	0.09	7.0
p6	A1p	0- 14	3.10	6.3
	A3	14- 43	1.65	6.8
	B	43- 95	0.60	7.1
	C1	95-140	0.41	7.1
	C2m	140-	0.19	7.5
p7	A1	0- 19	3.46	7.4
	A3	19- 47	1.87	7.0
	(B)	47-140	0.37	8.0
	Cm	140-	0.09	7.5
p8	A1	0- 19	2.10	6.8
	A3	19- 52	0.99	6.7
	(B)	52-122	0.36	7.0
	C	122-150	0.24	7.1
	Cm	150-	0.10	7.5
p9	A1	0- 25	2.28	6.6
	C1	25- 80	1.55	7.4
	C2	80-115	0.68	7.7
	C3	115-	0.34	7.7

Content of humus; pH in the nine profiles.

Tabel 12

p1	18.7	p4	13.0	p7	10.0
p2	11.5	p5	10.6	p8	10.7
p3	11.3	p6	12.1	p9	9.7

C/N.

CONCLUSIONS

The following processes were evident or probable:

1) translocation processes

a) clay, humus and perhaps Fe-illuviation as complexes.

b) leaching of bases.

c) bioturbation.

d) formation and destruction of a fragipan.

2) transformation processes

e) humus formation.

f) formation of structure.

These processes were related to the state factors as follows: The clay/humus/iron? - illuviation started with a precipitation higher than 830 mm/year and a moist period longer than 7 months. Leaching was strongest in the humid zone, decreasing towards semiarid areas, and bioturbation was indirectly related to climate as burrowers are most common in the semiarid zone. Cementation was related to palaeoclimatic conditions, its destruction to present climatic conditions. Humusformation and breakdown was poorly related to the climatic variation - least poor to maximum stored water, and structural development was related to the seasonal change in humidity, and to textural variation.

The processes had the following morphological and chemical consequences:

1) clay/humus/iron? - illuvation

a) development of an A2 and B2t horizon with clay maximum and secondary humus-maximum in B2t.

b) decreasing thickness of clayskins with depth and precipitation.

c) decreasing thickness of B3t with precipitation.

d) secondary colourmaximum in A2 and secondary colourminimum in B2t.

2) leaching

a) increasing base saturation downwards.

3) bioturbation

a) crotovines.

b) a regular decrease of humus content and pH.

4) cementation

a) harder consistence, sometimes genesis of brittle structure.

5) humusformation

a) genesis of A1/A3 horizons, decreasing thickness of A1 with drier climate.

b) colourminimum in A1.

The integrated effect of the above-mentioned processes resulted in the development of A1A2BtC, ABC, A(B)C and AC-soils, the A1A2BtC-soils found in the most humid, the AC-soils in the least humid area.

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