Soil formation in marine sediments and beach deposits of southern Norway: investigations of soil chronosequences in the Oslofjord region

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ABSTRACT

We investigated the development of Albeluvisols and Podzols with time in southern Norway. The Vestfold region at the western shore of the Oslofjord was chosen because it is characterized by continuous glacio-isostatic uplift for the last 12,000 years. Due to the permanent elevation process, no distinct marine terraces have been built, and the age of the sediments continuously increases with distance from the modern coastline. Albeluvisol development was assessed in a soil chronosequence on loamy marine sediments with ages ranging from approximately 1,800 to 10,200 years. The most obvious change during soil development was that after 4,500 – 5,000 years light tongues intruded from the E horizon into the B horizon, and became more pronounced with time. The combined thickness of the A and E-horizons was constant at 40 ± 3 cm in 9 of the 12 profiles and did not change with age. The organic matter content of the A-horizons, the fine silt to coarse silt ratio of the Btg horizons and the Fe_o/Fe_d ratio all decreased with soil age, whereas the thickness of the organic surface horizon and B horizon, as well as the Fe_d/Fe_t ratio all increased.

Podzol development was investigated in a chronosequence on sandy beach sediments, the ages of the soils ranging from 2,400 to 8,500 years. All soil properties investigated –the organic matter content of the B horizons, clay content, Fe_o, Al_o, Si_o, Fe_o/Fe_d and Fe_d/Fe_t – tend to increase with advancing podzolization, and are strongly correlated with soil age. Topsoil pH values decrease with age. The characteristic Bh and Bs horizons had developed after approximately 4,000 years.

Key words: soil chronosequences, marine sediments, beach deposits, Albeluvisols, Podzols, Oslofjord, Norway

RESUMEN

En este estudio investigamos el desarrollo en el tiempo de Albeluvisoles y Podzoles en el sur de Noruega. Se consideró a la región de Vestfold, en la costa occidental del fiordo de Oslo, dado que esta zona ha estado sujeta a un continuo levantamiento isoestático glacial durante los últimos 12,000 años. Este proceso de levantamiento permanente no ha permitido la formación notable de terrazas marinas y la edad de los sedimentos depositados se incrementa en forma continua en función de la distancia a la línea de costa actual. El desarrollo de Albeluvisoles se evaluó en una cronosecuencia de suelos formados a partir de sedimentos marinos limosos de edades que varían en un intervalo de aproximadamente 1,800 a 10,200 años. El cambio más prominente a lo largo de la evolución de estos suelos ocurrió después de 4,500 a 5,000 años, cuando intrusionan lenguas de coloración clara desde el horizonte E hacia el *horizonte B, las cuales se van haciendo más pronunciadas con el tiempo. El espesor combinado de los horizontes A y E se mantuvo constante en 40 ± 3 cm en 9 de los 12 perfiles estudiados y no cambió con el tiempo. Tanto el contenido de materia orgánica de los horizontes A, como la razón entre limos finos y limos gruesos en los horizontes Btg y la razón Fe_o/Fe_d disminuyeron con la edad del suelo, mientras que el espesor del horizonte orgánico superfcial, el espesor del horizonte B y la razón Fe_d/Fe_t se incrementaron con el tiempo.*

El desarrollo de los suelos de tipo Podzol se estudió en una cronosecuencia de suelos desarrollados a partir de depósitos de playa arenosos, cuyas edades varian entre 2,400 y 8,500 años. Todas las propiedades de los suelos –el contenido de materia orgánica en los horizontes B, el contenido de arcilla, Fe_o, Al_o, Si_o, Fe_o/Fe_d y Fe_d/Fe_t – tienden a incrementarse al avanzar la podzolización y están fuertemente correlacionadas con la edad del suelo. El pH del suelo superficial disminuye con el tiempo. Los horizontes característicos Bh y Bs se desarrollaron después de aproximadamente 4,000 años.

Palabras clave: cronosecuencias de suelos, sedimentos marinos, depósitos de playa, Albeluvisoles, Podzoles, fiordo de Oslo, Noruega.

INTRODUCTION

A soil chronosequence consists of soils of different age that have developed on similar parent material and under comparable climatic conditions and vegetation cover (Jenny, 1980; Vreeken, 1975).

Vreeken (1975) distinguished pre-incisive, post-incisive and time-transgressive sequences. The soil development of pre-incisive chronosequences starts isochronously and ends at different times. On the contrary, the soil development of post-incisive sequences begins at different times and ceases isochronously. The beginning and ending of time-transgressive sequences are both at different times. These chronosequences can be divided into time transgressive with or without historical overlap. The studied sequences are post-incisive chronosequences.

Vidic and Lobnik (1996) investigated a chronosequence (5,000 years – 1.8 million years) in the Ljubljana basin in Slovenia showing the development of Luvisols. They observed steady conditions in soil development after 980,000 years, when progressive and regressive processes reached an equilibrium.

Several investigations on chronosequences have been carried out in North America on soils formed in sandy parent materials which are subjected to podzolization. Singleton and Lavkulich (1987) investigated a chronosequence of very young soils (127–550 years) on beach sands of Vancouver Island. They described chronofunctions of organic matter, oxalate- and dithionite-extractable Fe and Al and of available Ca, Mg and K. A mature Podzol with an E and Bs horizon developed after less than 371 years. Barrett and Schaetzl (1992) examined the podzolization process on sandy terraces of Lake Michigan. The development of a spodic horizon took about 4,000 to 10,000 years. In a further study Barrett (2001) described Podzol development in aeolian sediments at Lake Michigan. In this case, the formation of the spodic Bs-horizon needed more than 5,000 years. In Scandinavia, chronosequences on sandy beach deposits and glacial outwash were established by Mokma *et al.* (2004). The age of the investigated soils ranged from 230 to 1,800 and 8,300 to 11,300 years. All soils showed E and Bs horizons, and the development of a Podzol took less than 8,300 years. The thickness of the total solum and of the characteristic Podzol horizons increased with time. The comparison of these studies shows that the temporal dynamics of podzolization processes may vary considerably. Most of the differences in the velocity of soil development can be explained by different climate and parent material.

Studies of chronosequences in southern Norway are rare. Semmel (1969) investigated Podzol development on three sandy fluvial terraces in northern Scandinavia at heights of 6 m, 16 m and 25–30 m above sea level. The thickness of the E horizon increased from 3 cm in the 6 m terrace to 8 cm in the 25–30 m terrace, and the Bs horizon increased from 8 cm to 48 cm. Mellor (1985, 1987) examined a chronosequence on neoglacial moraine ridges <100–230 years old. All soils showed signs of podzolization. Properties like organic carbon content, cation exchange capacity, exchangeable cations and dithionite and pyrophosphate soluble Fe and Al increased, pH decreased with time.

Thus far, no studies have been carried out on the development of Albeluvisols with time. In this work, we present a study of soil chronosequences on marine sediments and beach sands of the Oslofjord region, with special focus on the development of Podzols and Albeluvisols.

MATERIALS AND METHODS

Study Area

The study area is located in Vestfold, on the western coast of the Oslofjord (Figure 1), which is part of the temperate zone. The mean annual temperature of the southern Vestfold region is 6 °C (January: -4 °C; July: 16 °C), and the mean precipitation is 1,000 $mm \cdot a^{-1}$ (Johansen, 1980).

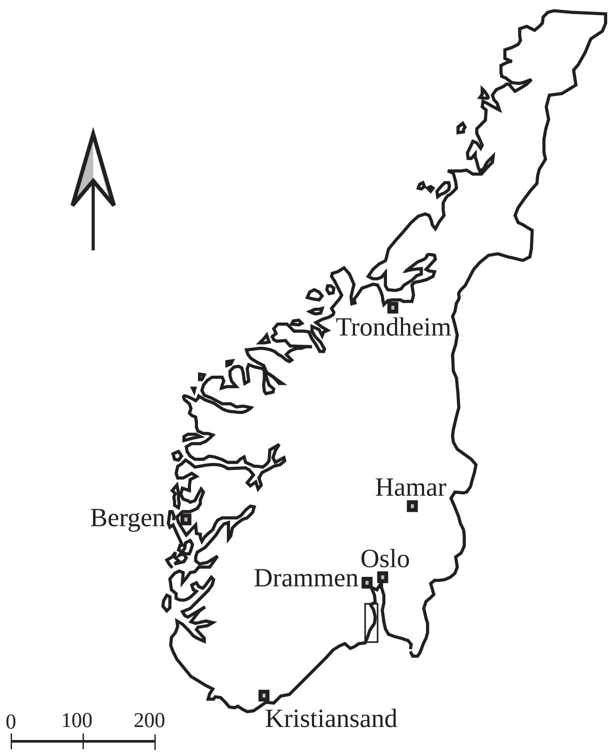

Figure 1. Location of the study area in southern Norway. Frame shows location of chronosequences in Vestfold.

Climate data of Denmark show that the Holocene temperature increased during Preboreal and Boreal and had its maximum in the Atlanticum with a mean July temperature of around 18.5 °C. During Subboreal and Subatlanticum it decreased again (Donner, 1995). Boreal and Subboreal were characterized by dryer conditions, whereas in the Atlanticum and early Subatlanticum the climate was more humid than today.

The region has been characterized by continuous glacio-isostatic uplift for the last 12,000 years. Consequently, no distinct marine terraces have been built, and the age of the land surface increases continuously with elevation. Several sea level curves for different locations within the Oslofjord, based on a large number of radiocarbon dates (Henningsmoen, 1979; Sørensen, 1999) allowed us to infer the soil age at each location from its elevation above sea level (Figure 2).

The soil parent materials are non-calcareous loamy marine sediments in which Albeluvisols develop and beach sands with podzol formation. The ages of the investigated soils range from 1,800 to 10,200 years BP (loamy marine sediments) and 2,300 to 10,000 years BP (beach sands) (Table 1). The bedrock of the Vestfold region consists predominantly of Permian monzonite and latite (Lutro and Nordgulen, 2004). Most of the soils are situated under natural mixed forests. The profiles VF 2.4 and SVF 4.0 are under natural deciduous woodland, whereas VF 7.3 and VF 9.0 are under *ca.* 20 and 40 years old planted spruce forests.

Field methods

The sites were chosen on the basis of calibrated ^{14}C-dated sea level curves for southern Vestfold. Soil pits were dug in nearly flat positions under forest showing no evidence of significant anthropogenic influence. Eleven profiles were described according to FAO (1998) and sampled, six on loamy marine sediments (Albeluvisol sequence) and five on beach sands (Podzol sequence). At least one sample was taken from each horizon, and several samples were taken if the thickness was more than 40 cm. We tried to dig the soil pits deep enough to sample the C horizons, but most of the soils on loamy marine sediments did not show unaltered material within 2 m depth, so that only a few C horizon samples were obtained. The depth of the soil pits ranged from 90 to 230 cm. Structure, texture, presence of coarse fragments, rooting depth, moisture and hydromorphic features were determined in the field, and the bulk density class according to Harrach and Vorderbrügge (1991), based on aggregate size, accomodation, degree of compaction, penetration resistance and the amount of macropores, was estimated. The complete soil descriptions will be published elsewhere.

Laboratory methods

The moist colour of the samples was determined by comparison with the Munsell soil colour chart. The aggregates in the air dried samples were carefully smashed and the samples passed through a 2 mm sieve. All analyses were performed on the <2 mm fraction. pH was determined in deionised water using a soil:water ratio of 1:2.5 (Schlichting *et al.*, 1995). Organic matter content was calculated from carbon contents measured with a C/N-element analyzer by multiplying with 1.724.

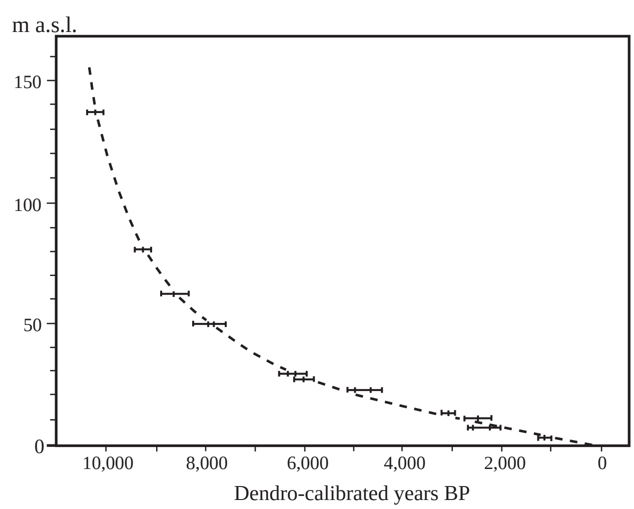

Figure 2. Dendro-calibrated sea level curve for southern Vestfold (changed after Henningsmoen, 1979).

The sand fractions were separated by sieving, and the silt and clay fractions determined by the pipette method (Schlichting *et al.*, 1995). Dithionite-soluble Fe (Fe_d) was measured by atomic absorption spectrometry (AAS) (Schlichting *et al.*, 1995). Oxalate-extractable Fe (Fe_o), Al (Al_o) and Si (Si_o) were measured by inductive coupled plasma-optical emission spectrometry (ICP-OES). Total amounts of Fe (Fe_t), Al (Al_t), Si (Si_t), Ti (Ti_t) and Zr (Zr_t) were analyzed in fused discs by X-ray fluorescence.

Chronofunctions for all soil properties and the Ti_t/Zr_t ratio were based on mean values for the different horizons, which were weighted according to bulk density and horizon thickness. They were calculated for each profile to the depth of the shallowest profile, 155 cm for the chronosequence on loamy marine sediments, and 90 cm for the chronosequence on beach deposits.

The analytical results were used to calculate depth functions and chronofunctions of the soil properties investigated. For the chronofunctions, linear ($y = a \cdot x + b$) or exponential ($y = e^{ax}$; $y = ae^{bx}$) equations were applied, depending on which model gave the greatest coefficient of determination (R^2).

Table 1. Elevation, age, distance from the sea and soil classification of the two chronosequences in Vestfold.

	Elevation (m a.s.l.)	Age in years BP*	Dist. from the sea (m)	Soil classification (FAO, 1998)
Chronosequence on loamy marine sediments				
VF 2.4	7	1,800 ± 50	960	Stagni-Gleyic Luvisol
VF 4.5	23.5 ± 5	4,600 ± 100	5,500	Stagnic Luvisol
VF 6.6	37 ± 1	7,000 ± 100	8,070	Stagnic Albelu-visol
VF 8.8	32	7,000 ± 100	5,300	Stagnic Albelu-visol
VF 7.3	49	8,700 ± 100	5,440	Stagnic Albeluvisol
VF 9.0	73	10,200 ± 150	4,170	Stagnic Albeluvisol with weak podzolization
Chronosequence on beach deposits				
SVF 2.4	10	2,300 ± 10	120	Endostagnic Arenosol
SVF 3.0	22 ± 6	3,850 ± 100	190	Dystric Arenosol
SVF 4.0	26 ± 6	4,600 ± 100	1,940	Endostagnic Cambisol
SVF 7.2	40 ± 7	7,800 ± 100	4,300	Endostagnic Podzol
SVF 8.5	58 ± 7	10,000 ± 150	4,600	Endostagnic Podzol

*calibrated ^{14}C-years BP (Sørensen unpublished).

RESULTS

Chronosequence on loamy marine sediments

All soils of the sequence show light coloured E horizons not only caused by clay depletion but mainly by waterlogging as indicated by hydromorphic features (mottles, manganese coatings) in the horizons below. The colour becomes progressively lighter with increasing age of the soils. Between the Ah and E horizons, a Bw horizon develops, which may partly or completely replace the E horizon. With the exception of the two oldest soils, the lower boundary of the E horizon (or Bw horizon developed in former E horizon) is remarkably constant at 40 ± 3 cm depth. This could be related to the fact that the most extreme and the most frequent temperature changes occur at this depth, leading to differences in physical weathering above and below a 40 cm depth.Such differences may determine the depth of the horizon boundaries, since pedogenic processes tend to follow physical boundaries, if present. The most obvious change during soil development is that light coloured tongues, immerging from the E horizon downwards into the B horizon, developed between 4,500 and 5,000 years and became more strongly pronounced with time.

Since perfect homogeneity of sediments is impossible, the degree of heterogeneity has to be determined. For this purpose we used the ratios of Ti_t/Zr_t of the weighted means of all horizons. Excluding the oldest soil, Ti/Zr ratios ranging from 20 to 25 give a measure of the degree of chemical heterogeneity of the sediments (Table 2).

The pH values increase with soil depth, in the youngest soil from 3.7 to 5.4, and in the oldest soil from 3.9 to 6.9 (Figure 3). The type of organic surface layer in the younger soils (up to 7,000 years) ranges from mull to moder, and in the older soils between moder and raw humus. There is a slight decrease in the ratio of fine silt to total silt in the Btg-horizons from 0.53 to 0.29 (Figure 4).

The amounts of Fe_d, Fe_o, Alo and Si_o are generally smaller in the A and E horizons than in the Btg, Bg and C horizons. The greatest Al_o amounts usually occur in the lowest horizons (Bg and C horizons, Table 3). In addition, Fe_o, Fe_d and Al_o contents are increased in almost all Bw horizons, compared to the adjacent horizons. The Si_o contents also show a weak trend to follow this pattern, but only in the older soils.

Usually, the Fe_d/Fe_t ratio increases from the A to the Bw horizon and then decreases downwards (Figure 5). However, the youngest soil shows a Fe_d/Fe_t maximum in the A horizon, and in the 7,000 years old soil VF 8.8 there are maxima in the E and 2Btg2 horizons. The Fe_o/Fe_d ratio tends to decrease with profile depth (Figure 6), though the Fe_o/Fe_d ratio is very large in the Btg2 horizon of the youngest profile. The ratio of Fe_d/Fe_t increases with soil age from 0.14 to 0.26, showing a very strong correlation (Figure 7).

Table 2. Ti_t/Zr_t ratio of the soils (mean values of all horizons).

Soils on loamy marine sediments						
Soil age (a)	1,800	4,600	7,000	7,000	8,700	10,200
Ti_t/Zr_t	22.4	23.7	24.6	19.7	22.0	16.2
Soils on beach deposits						
Soil age (a)	2,300	3,800	4,600	7,800	10,000	
Ti_t/Zr_t	11.7	10.2	13.1	9.5	11.5	

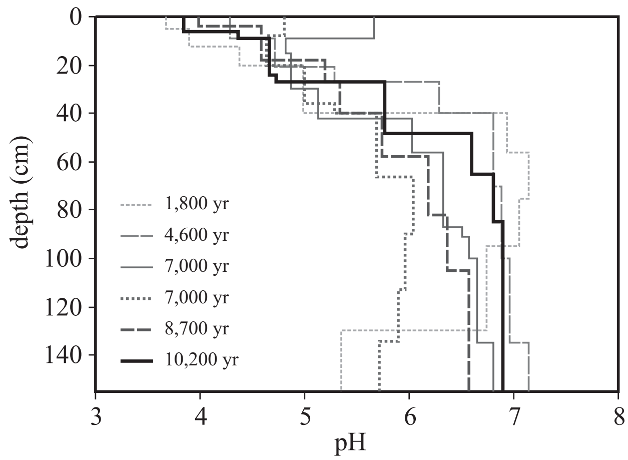

Figure 3. Depth function of the pH values of the soils on loamy marine sediments.

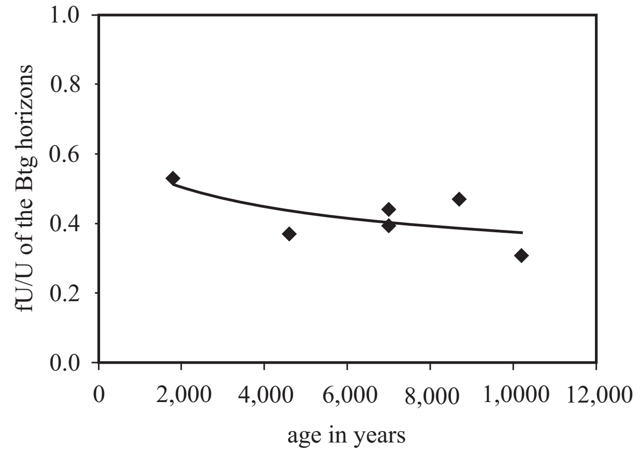

Figure 4. Chronofunction of fine silt/total silt (fU/U) for the soils on loamy marine sediments.

The Fe_o/Fe_d ratios do not show any clear trend with time (Figure 7).

The Btg horizons increase in thickness from 16 cm in the youngest soil to 30 cm and 35 cm in the 4,600 and 7,000 years old soil VF 6.6, and 36 cm in the oldest soil, but decrease to 23 cm in the other 7,000 years old soil VF 8.8, and to 18 cm in the 8,700 years old soil. The depth of the lower boundary of the Btg horizons increases from 56 cm in the youngest to 113 cm in the 7,000 years old soil VF 8.8.

Chronosequence on beach deposits

Evidence for podzolisation first appears in the development of an E horizon between 2,300 and 3,850 years. In soils older than 4,600 years, the Bw horizons have turned into Bhs and Bsw horizons. The 7,800 and 10,000 years old soils show the diagnostic Bs horizon of a mature Podzol.

In the case of the soils on beach sands, the Ti_t/Zr_t ratios of 9.5 to 13.1 (Table 2) can again be used as a measure of the degree of homogeneity of the sediments.

The pH-values increase downwards (Figure 8). For the pH chronofunction, the weighted mean values of 20–90 cm depth were used, because the pH of the A horizon of the 4,600 years old soil shows some influence from the surface. The mean values decrease with soil age from 4.5 in the youngest soil to 3.8 in the oldest (Figure 9).

The thickness of the organic surface layer increases with age from 5 cm after 2,300 years to 10 cm after 10,000 years. An exception is the 3,850 years old soil with an organic layer of 9 cm. The amount of humus in the B-horizons increases with time from 2.99 $kg \cdot m^{-2}$ to 13.32 $kg \cdot m^{-2}$ (Figure 10). The type of organic layer changes from mull in the youngest soil to typical moder, and finally to raw humus-like moder in the oldest.

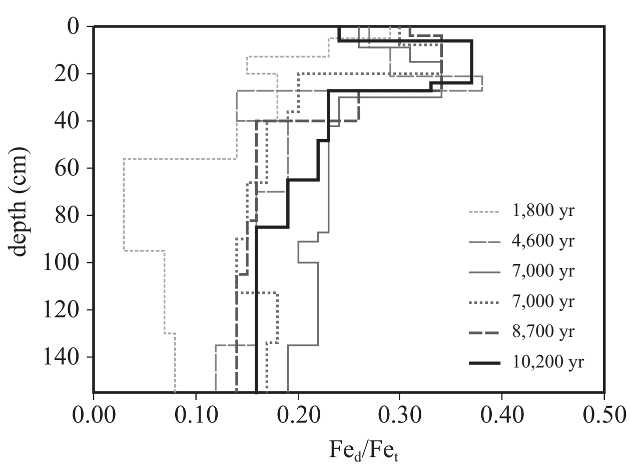

Figure 5. Depth functions of Fe_d/Fe_t for the soils on loamy marine sediments.

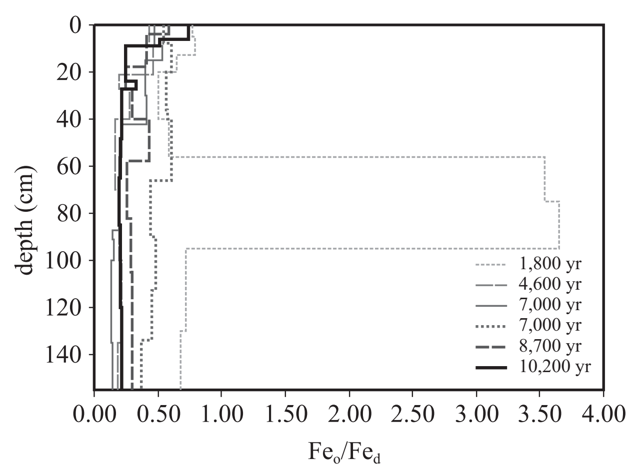

Figure 6. Depth functions of Fe_o/Fe_d for the soils on loamy marine sediments.

Table 3. Amounts of Fe_d, Fe_o, Al_o and Si_o in the soils on loamy marine sediments. *relictic; **sampled with auger.

		Depth (cm)	Fe_d ($kg \cdot m^{-2}$)	Fe_o ($kg \cdot m^{-2}$)	Al_o ($kg \cdot m^{-2}$)	Si_o ($kg \cdot m^{-2}$)
VF 2.4	Ah	5	0.31	0.23	0.16	0.002
	Bw	12.5	0.48	0.37	0.24	0.007
	E1	20	0.46	0.29	0.11	0.008
	E2	40	0.19	0.10	0.02	0.005
	Btg1	56	1.41	0.83	0.17	0.082
	Btg2 upper	75	0.41	1.44	0.17	0.107
	Btg2 lower	95	0.52	1.89	0.16	0.096
	Btg3	130	1.77	1.27	0.30	0.119
	Bg	>155	1.43	0.97	0.22	0.093
	Σ		6.98	7.39	1.55	0.519
VF 4.5	Ah	9	0.61	0.26	0.18	0.006
	Bw	21	1.41	0.64	0.39	0.018
	Bwg	27	1.69	0.34	0.09	0.018
	Btg1	40	1.22	0.34	0.16	0.049
	Btg2	70	4.78	0.77	0.43	0.194
	Btg3	100	4.16	0.83	0.41	0.215
	Btg4	135	4.64	1.02	0.54	0.295
	Bg	170	3.70	0.67	0.47	0.265
	C	>230	6.85	1.62	0.71	0.476
	Σ		29.06	6.49	3.38	1.536
VF 6.6	Ah	9	0.62	0.29	0.15	0.010
	r*Ap	15	0.58	0.31	0.13	0.006
	Bw	30	2.68	1.08	0.53	0.038
	E	42	1.79	0.73	0.29	0.034
	E+Btg1	56	4.88	1.06	0.36	0.150
	Btg1 upper	87	5.90	1.16	0.38	0.190
	Btg1 lower	91	0.76	0.11	0.05	0.025
	Btg2 upper	100	1.48	0.22	0.11	0.054
	Btg2 middle	135	6.29	0.83	0.40	0.220
	Btg2 lower	170	5.29	0.76	0.38	0.208
	Btg2 auger**	195	3.45	0.83	0.33	0.201
	C	230	4.63	1.17	0.51	0.309
	Σ		38.35	8.55	3.62	1.445
VF 8.8	Ah	8	0.78	0.42	0.22	0.014
	rAp	20	1.38	0.83	0.40	0.025
	Bw	36	1.66	0.93	0.80	0.090
	E	40	0.47	0.27	0.13	0.017
	E+Btg1	66	3.03	1.83	0.53	0.124
	E+Btg2	90	3.27	1.44	0.47	0.163
	Btg	113	2.62	1.24	0.46	0.144
	2 Btg upper	134	1.71	0.75	0.22	0.064
	2 Btg lower	155	1.72	0.63	0.21	0.057
	3 Bg	>175	2.41	1.11	0.39	0.116
	Σ		19.05	9.45	3.83	0.814
VF 7.3	Ah	4	0.48	0.27	0.19	0.008
	Bw	18	2.87	1.15	0.57	0.024
	E	27	1.94	0.48	0.22	0.020
	E+Btg1	40	2.04	0.61	0.25	0.040
	Btg1	58	2.35	0.99	0.34	0.112
	Btg2 upper	82	3.29	0.86	0.34	0.173
	Btg2 lower	105	2.98	0.85	0.36	0.206
	Bg	>190	9.66	2.87	1.30	0.713
	Σ		25.61	8.08	3.57	1.296
VF 9.0	Ah	6	0.23	0.17	0.13	0.004
	Bsw	9	0.32	0.17	0.08	0.003
	Bw	24	1.86	0.47	0.28	0.013
	E	27	0.44	0.14	0.06	0.004
	E+Btg	48.5	1.50	0.33	0.15	0.050
	Btg upper	65	2.37	0.49	0.23	0.093
	Btg lower	85	2.36	0.48	0.23	0.123
	Bg1 upper	120	3.74	0.80	0.42	0.222
	Bg1 lower	156	3.64	0.80	0.41	0.222
	Bg2	>214	6.85	1.91	0.68	0.433
	Σ		23.31	5.76	2.67	1.167

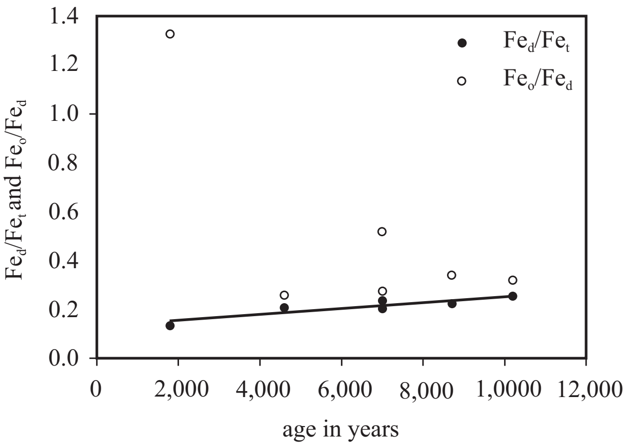

Figure 7. Chronofunctions of Fe_d/Fe_t and Fe_o/Fe_d for the soils on loamy marine sediments ($Fe_d/Fe_t = 1.23^{-5}\cdot time + 0.129$; $r^2 = 0.83$).

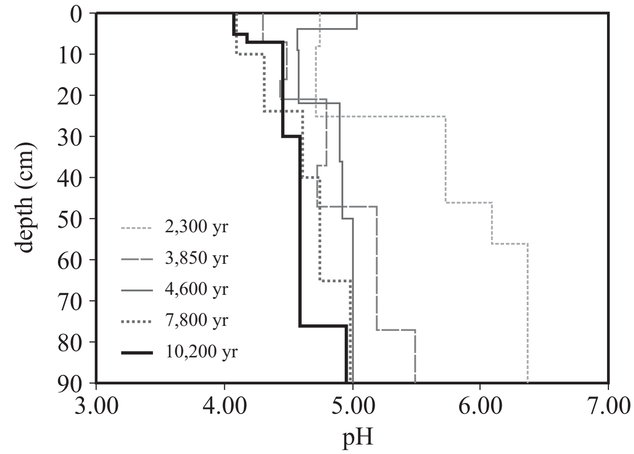

Figure 8. Depth function of the pH value of the soils on beach deposits.

The amounts of Fe_d, Fe_o, Al_o and Si_o are greater in the Bh and Bs horizons than in the respective A horizons, but their maxima occur below the Bh/Bs horizons, in the Bg, BC and C horizons (Table 4). The weighted mean concentrations of Fe_o, Al_o and Si_o all increase with profile age (Figure 11). The amounts of Fe_o and Al_o doubled between 3,850 and 4,600 years old soils from 0.89 $kg\cdot m^{-2}$ to 2.15 $kg\cdot m^{-2}$ (Fe_o) and from 0.87 $kg\cdot m^{-2}$ to 1.72 $kg\cdot m^{-2}$ (Al_o). Strong increases also occur in 7,800 and 10,000 years old soils.

The Fe_d/Fe_t and Fe_o/Fe_d ratios are both larger for B horizons and smaller for A and C horizons (Figures 12 and 13). The Fe_d/Fe_t ratios (weighted means) increase with soil age from 0.15 to 0.22 (Figure 14). The Fe_o/Fe_d ratios also increase with age from 0.46 to 0.53 (Figure 14).

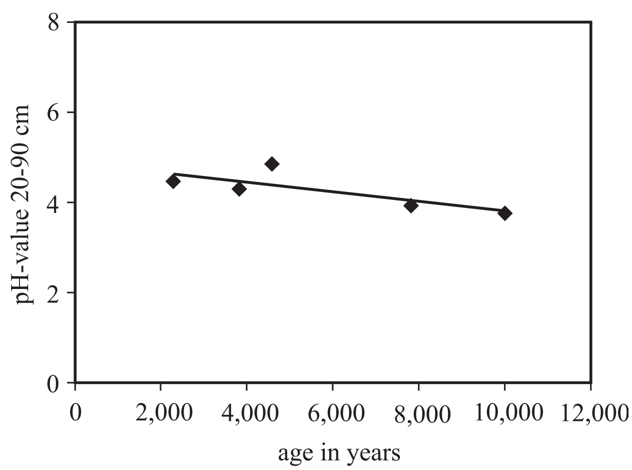

Figure 9. Chronofunction of the pH value in 20–90 cm depth of the soils on beach deposits (weighted mean values; pH = -0.0001·time + 4.875; $r^2 = 0.62$).

DISCUSSION

Chronosequence on loamy marine sediments

The change in the organic surface layer from mull to moder in soils up to 7,000 years, and to moder and raw humus in the older soils is in accordance with the lower pH values in the topsoil. A slight decrease in the ratio of fine silt to total silt in the Btg horizons indicates *in situ* weathering of fine silt to clay (Langley-Turnbaugh and Bockheim, 1997).

The increased amounts of Fe_d in the lower horizons are caused by the formation of iron concretions and mottles in the Btg- and Bg-horizons. The great amounts of Fe_o, Al_o and Si_o are attributed to an inhibition of the crystallization process by waterlogging and influence of groundwater in the lower parts of the soils. Formation of organic complexes may prevent crystallization in the Bw horizons, which can explain the higher values of Fe_o and Al_o in the Bw horizons of almost all soils.

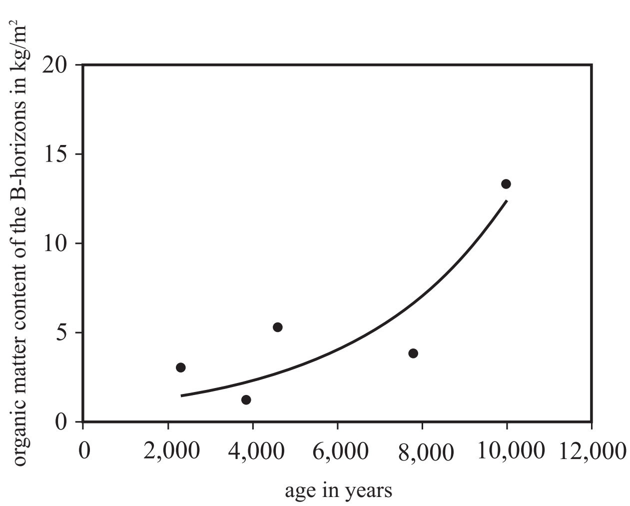

Figure 10. Chronofunction of the organic matter (OM) content of the B horizons of the soils on beach deposits ($OM = e^{0.0003\cdot time}$; $r^2 = 0.78$).

The higher Fe_d/Fe_t ratios in the Bw horizons are the

Table 4. Amounts of Fe_d, Fe_o, Al_o and Si_o of the soils on beach deposits.

	Depth (cm)	**Fe_d ($kg \cdot m^{-2}$)**	**Fe_o ($kg \cdot m^{-2}$)**	**Al_o ($kg \cdot m^{-2}$)**	**Si_o ($kg \cdot m^{-2}$)**
SVF 2.4					
Ah1	8	0.35	0.18	0.11	0.006
Ah2	25	1.14	0.61	0.38	0.019
Bw	46	0.71	0.39	0.25	0.018
BC	56	0.26	0.12	0.07	0.010
Cg1	115	1.56	0.63	0.26	0.044
2 Cg2	>135	1.35	0.28	0.11	0.042
Σ		5.37	2.21	1.18	0.139
SVF 3.0					
AE	7	0.15	0.07	0.06	0.005
Bw1	16	0.25	0.09	0.08	0.010
Bw2	21	0.10	0.04	0.09	0.010
BC	37	0.28	0.11	0.07	0.006
Ahb	47	0.24	0.06	0.11	0.004
BC	77	0.53	0.22	0.26	0.020
BCg	124	2.10	1.09	0.72	0.126
2 Cg	138	1.21	0.30	0.09	0.032
Cr	>180	2.53	1.13	0.62	0.394
Σ		7.39	3.11	2.10	0.607
SVF 4.0					
Ah	4	0.25	0.11	0.07	0.002
AE	9	0.32	0.14	0.09	0.003
Bh	22	0.82	0.36	0.21	0.008
Bs	36	0.71	0.36	0.37	0.024
Bw	50	0.62	0.27	0.47	0.065
BCg	90	2.72	0.91	0.50	0.102
Σ		5.44	2.15	1.71	0.204
SVF 7.2					
AE	10	0.49	0.28	0.15	0.005
Bsh	24	1.06	0.67	0.37	0.012
Bs1	40	0.65	0.44	0.46	0.029
Bs2	65	0.88	0.50	0.49	0.06
BCg	105	1.62	0.84	1.19	0.284
2 Cg	>140	3.75	2.22	0.65	0.120
Σ		8.45	4.95	3.31	0.51
SVF 8.5					
AE	5	0.12	0.06	0.08	0.001
E	7	0.05	0.02	0.02	0
Bs	30	1.74	1.31	1.02	0.026
2 Bs2	76	4.02	2.75	3.55	0.154
3 Cg	>105	2.79	1.45	3.17	0.753
Σ		8.72	5.59	7.84	0.934

result of the formation of iron oxides in these horizons (brunification). The increasing Fe_d/Fe_t ratio with soil age shows a strong correlation (R^2=0.83). This reflects the progressive weathering of Fe-bearing minerals with time. The absence of a clear time trend of Fe_o/Fe_d ratios can be explained by other factors (in this case redox processes and organic matter content) having greater impact on the Fe_o/Fe_d ratio than the time factor.

The thinner Btg horizon in the 7,000 years old soil VF 8.8 and in the 8,700 years old soil is the result of the progressive growth of tongues downwards from the E into the Btg horizons that results in the replacement of the upper part of the Btg horizons by E/Btg horizons.

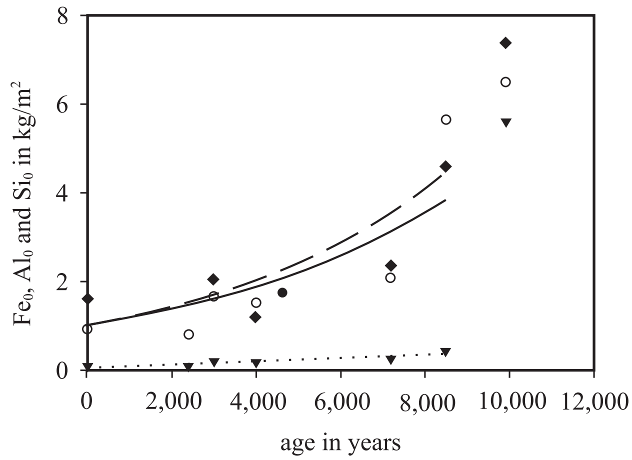

Figure 11. Chronofunctions of Fe_o (solid), Al_o (dashed) and Si_o (dotted) for the soils on beach deposits ($Fe_o = 0.714e^{0.0002 \cdot time}$; $r^2 = 0.85$; $Al_o = 0.266e^{0.0003 \cdot time}$; $r^2 = 0.94$; $Si_o = 3.68^{-5} \cdot time + 0.044$; $r^2 = 0.84$).

Steady state of soil development (when the sum of progressive and regressive processes equals zero; Johnson and Watson-Stegnar, 1987), as found in the older soils of the Ljubljana Basin (Vidic and Lobnik, 1996), could not be observed. Most of the chronofunctions, like organic matter content of the A horizons and the fine silt/total silt ratio of the Btg horizons, decrease with increasing soil age, whereas the Fe_d/Fe_t ratios increase with time.

Chronosequence on beach deposits

The weighted mean values of the pH decrease with soil age. This process is followed by proceeding podzolization. The thickness of the organic surface layer increases with age in the same way as acidification proceeds. The change of the organic layer type from mull in the youngest to raw humus-like moder in the oldest soil reflects the ongoing

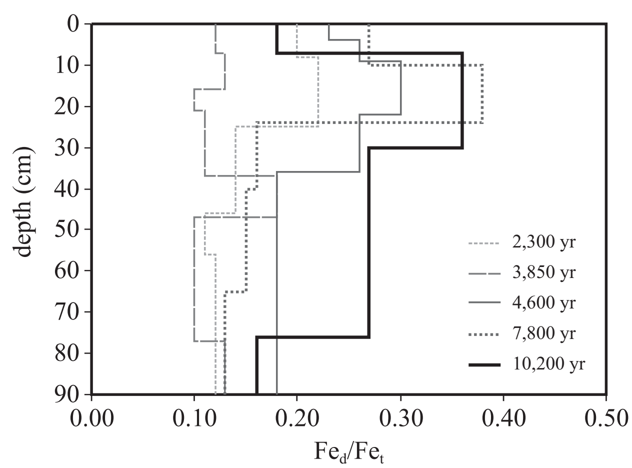

Figure 12. Depth functions of Fe_d/Fe_t for the soils on beach deposits.

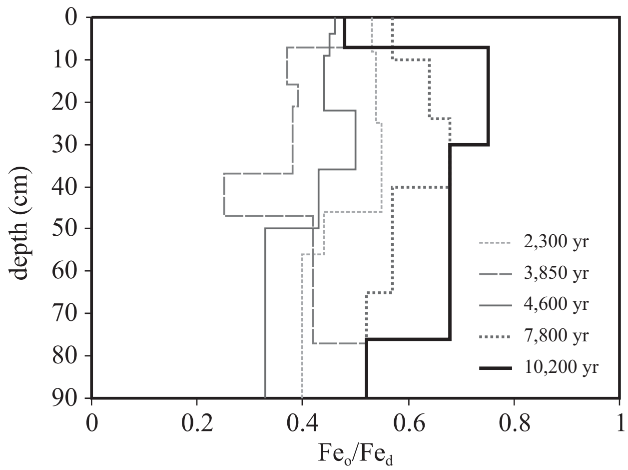

Figure 13. Depth functions of Fe_o/Fe_d for the soils on beach deposits.

podzolization and hence reduced biological activity.

The maxima of Fe_d, Fe_o and Al_o in the Bg, BC and C-horizons and minima of Fe_d, Fe_o and Al_o in the E horizon of the 10,000 years old soil are attributed to translocation and precipitation of iron and aluminium oxides. The increase of Fe_o, Al_o and Si_o (weighted mean values) with profile age indicates progressive podzolization. The same trend was observed in soils on beach sands in Canada (Singleton and Lavkulich, 1987). With the appearence of Bhs and Bsw horizons between 3,850 and 4,600 years, the amounts of Fe_o and Al_o reached more than double the values in younger soils. There is an increase in thickness of the Bs horizons as well as a strong increase of Fe_o, Al_o and Si_o between 7,800 and 10,000 years. These results agree well with the increase of horizon thickness observed by Semmel (1969) on fluvial terraces in northern Scandinavia.

The maxima of Fe_d/Fe_t and Fe_o/Fe_d in the B horizons indicate translocation of iron from the A into the B horizons and formation of pedogenic iron oxides. The Fe_d/Fe_t ratios increase with soil age because of progressive weathering and formation of pedogenic iron oxides, whereas the increase in the Fe_o/Fe_d ratios with age is probably related to the formation of organic complexes, which inhibit the crystallization process.

In summary, the contents of organic matter, clay, Fe_o and Al_o and the Fe_o/Fe_d and Fe_d/Fe_t ratios increase with soil age, whereas pH decreases. Tamm (1920) estimated that Podzols in Scandinavia developed within 1,000 to 1,500 years. However, in this study, distinct podzolization was first observed in the 3,850 years old soil, and the diagnostic Bs horizon of a mature Podzol did not develop until 7,800 years.

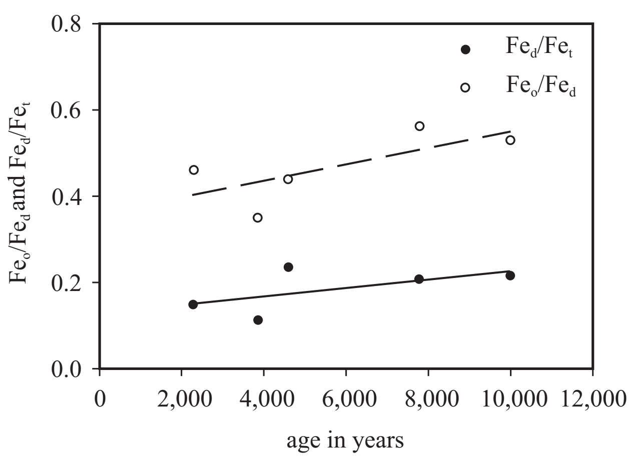

Figure 14: Chronofunctions of Fe_d/Fe_t (solid) and Fe_o/Fe_d (dashed) for the soils on beach deposits ($Fe_d/Fe_t = 9.91^{-6}$*time + 0.126; $r^2 = 0.36$; Fe_o/Fe_d $=1.88^{-5}$*time + 0.359; $r^2 = 0.51$).

CONCLUSIONS

The chronosequence on marine sediments in southern Norway shows that, in a temperate climate, E and a Bt horizons developed in loamy sediments after approximately 2,000 years. Topsoil acidification intensified with time. Al_o, Fe_d and Fe_t increased until an age of about 7,000 years but decreased with further development. The development from Luvisol to Albeluvisol has taken place after about 4,500 years with the formation of characteristic tongues, which became broader, deeper and more distinct with time.

On sandy deposits, which favour podzolization, most of the soil properties investigated (organic matter content of the B-horizons; amounts of Fe_o, Al_o and Si_o; ratios of Fe_o/Fe_d and Fe_d/Fe_t) increase with time, except for pH, which shows a linear decrease. A Bw horizon has formed after 2,300 years. The process of podzolisation first resulted in the development of an E horizon that appears in profiles between 2,300 and 3,850 years. A mature Podzol developed between 4,600 and 7,800 years. Podzolization in beach sands in the Oslofjord region takes more time than in other parts of Scandinavia or northern America probably because of the milder climate in this area.

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