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Micromorphological characteristics reflecting soil-forming processes during Albeluvisol development in S Norway

Características micromorfológicas de los procesos de edafogénesis durante el desarrollo de Albeluvisoles en el S de Noruega

Caraterísticas micromorfológicas refletindo os processos de formação do solo durante o desenvolvimento de Albeluvisols na Noruega S

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ABSTRACT

This paper presents micromorphological observations of the only two Albeluvisol chronosequences to have been reported in the international literature so far. These observations are combined with existing profile morphological and soil chemical data in order to identify the major processes involved in the development of Albeluvisols. The study area is located in the counties Vestfold and Østfold on the western and eastern sides of the Oslofjord, S Norway. The region is characterized by continuous glacio-isostatic uplift over the Holocene, and hence the age of the land surface increases continuously from the beach towards the higher elevations. Twelve soil pits in loamy marine sediments were investigated, six each in Vestfold and Østfold; in addition, three samples of fresh sediments were taken from the shoreline.
Results of this study suggest that as soon as the land surface is raised above sea level, drainage of the coarse pores and aeration of the upper part of the young soils leads to five major processes:

i) development of deep desiccation cracks, forming a polygonal pattern;
ii) compaction, taking place as soon as the land surface reaches an elevation above sea level that leads to drainage of the coarse pores;
iii) pyrite oxidation, releasing sulfuric acid;
iv) rapid decarbonatization of the originally calcareous sediments through carbonate dissolution by acids from pyrite and iron oxidation;
v) precipitation of iron hypocoatings and coatings in the capillary fringe

The next morphological change, also taking place within less than 2.1 ka, is horizon differentiation into Ah, Eg and Btg horizons due to the limited water permeability of the fine-textured sediments. Eg horizons, for example, become lighter in colour with time.
The process leading to the next morphological change in the soil profiles is clay illuviation, which is also already present in the 2.1 ka-old soil. Soil pH in the upper part of the E horizon of this soil is already too low for significant clay mobilization. Clay illuviation is still active in all soils studied, but the upper boundary of the clay mobilization zone is at 20-50 cm depth. Progressive clay illuviation is recorded by the increasing thickness of clay coatings and proportion of voids having clay coatings. Clay mobilization and iron co-eluviation in the upper parts of the Eg horizons cease within less than 2.1 ka, whereas weathering and formation of clay minerals and iron oxides continue, leading to formation of a BE horizon in the upper part of the Eg horizon.
Albeluvic tongues start to form after 4.6-6.2 ka. They develop preferably along the desiccation cracks. Albeluvic material is washed into the cracks, and enhanced leaching of bases and clay eluviation takes place in the cracks. As both processes proceed, the albeluvic tongues get longer and wider.

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Clayey intercalations occur in the Stagnic Albeluvisols of the sequence, and the following concept is suggested to explain their genesis: after snow melt or a rainy period infiltrating water arrives at the lower end of an albeluvic tongue, the tongue fills up with water, and perched water also accumulates on top of the dense Btg horizon. Water, carrying suspended clay, penetrates under pressure from the tongue into the Btg horizon, where additional clay is mobilized. The clay settles when the velocity of the water decreases, forming clayey intercalations in the dense matrix of the Btg horizon.

RESUMEN

Este trabajo presenta las observaciones micromorfológicas de las dos únicas cronosecuencias de Albeluvisoles recogidas en la bibliografía internacional hasta el momento. Estas observaciones se combinan con datos previos de morfología y propiedades químicas de los perfiles con el fin de identificar los procesos más importantes que han tenido lugar durante su desarrollo. La zona de estudio está localizada en los condados de Vestfold y Østfold, al oeste y este del Oslofjord (S Noruega), y ha estado sujeta a un levantamiento glacio-isostático continuo a lo largo del Holoceno. En consecuencia, la superficie del terreno es cada vez más antigua desde las zonas de playa hacia las áreas más elevadas. Se investigaron doce suelos sobre sedimentos marinos de textura franca, seis de ellos en Vestfold y otros seis en Østfold. Además se tomaron tres muestras de sedimentos frescos en la línea de costa.

Los resultados de este estudio sugieren que, en cuanto la superficie del terreno se eleva por encima del nivel del mar, el drenaje de los poros más gruesos y la aireación de la parte superior de los suelos jóvenes da lugar a cinco procesos principales:

i) el desarrollo de grietas poligonales con fuerte desecación;
ii) una compactación, producida cuando la superficie del terreno alcanza una determinada elevación por encima del nivel del mar que causa el drenaje de los poros más gruesos;
iii) la oxidación de pirita, que produce ácido sulfúrico;
iv) una rápida decarbonatación de los sedimentos carbonatados originales a través de la disolución de carbonato por los ácidos producidos a partir de la oxidación de pirita y hierro;
v) la precipitación de revestimientos e hiporrevestimientos de hierro en la franja capilar.

El siguiente cambio morfológico, que se produce también en menos de 2,1 ka, es la diferenciación de horizontes de tipo Ah, Eg y Btg debido a la limitada permeabilidad hidráulica de los sedimentos de textura fina. Los horizontes Eg adquieren un color más claro con el tiempo.

El proceso que da lugar al siguiente cambio morfológico en los perfiles de suelo es la iluviación de arcilla, también observada en el suelo que tiene 2,1 ka. En este suelo, el pH en la parte más superficial del horizonte E es todavía demasiado bajo para que se produzca una significativa movilización de arcilla. La iluviación de arcilla todavía se produce en todos los suelos estudiados pero el límite superior de la zona de movilización de arcilla se encuentra a una profundidad entre 20 y 50 cm. La progresiva iluviación de arcilla se refleja en un aumento del espesor de los revestimientos de arcilla y de la proporción de poros con revestimientos de arcilla.

La movilización de arcilla y la co-eluviación de hierro en las partes más superficiales de los horizontes Eg cesa en suelos con menos de 2,1 ka, mientras que la meteorización y formación de minerales de la arcilla y óxidos de hierro continúa, dando lugar a la formación de un horizonte BE en la parte más superficial del horizonte Eg.

Las lenguas albelúvicas aparecen tras 4,6-6,2 ka y se desarrollan preferentemente a lo largo de las grietas de desecación. El material albelúvico se lava hacia las grietas y en ellas se produce un aumento de lavado de bases y la eluviación de la arcilla. A medida que ambos procesos progresan, las lenguas albelúvicas se hacen más largas y anchas.

Las intercalaciones arcillosas se producen en el Albeluvisol Estágnico de la secuencia. La génesis propuesta es la siguiente: cuando tras el deshielo o algún periodo húmedo, el agua que se va infiltrando alcanza la parte inferior de una lengua albelúvica, la lengua se llena de agua y el agua colgada se acumula también sobre la parte superior del horizonte Btg denso. El agua, cargada de arcilla en suspensión, penetra bajo presión desde la lengua en el horizonte Btg, donde se produce una movilización adicional de arcilla. La arcilla se va acumulando cuando la velocidad del agua disminuye, formando intercalaciones arcillosas en la matriz densa del horizonte Btg.

KEY WORDS
Micromorphology, polygonal cracks, iron coatings, illuvial clay, intercalations

PALABRAS CLAVE
Micromorfología, grietas poligonales, revestimientos de hierro, arcilla iluvial, intercalaciones

PALAVRAS-CHAVE
Micromorfologia do solo, gretas poligonais, camadas de ferro, argila iluvial, incrustações

RESUMO

Este trabalho descreve observações micromorfológicas relativas às duas únicas cronosequências de Albeluvisols até agora referidas na literatura internacional. Estas observações foram combinadas com os dados existentes sobre o perfil micromorfológico e caraterísticas químicas do solo de forma a identificar os principais processos envolvidos na formação dos Albeluvisols.
A área de estudo situa-se nos condados Vestfold e Østfold no lado ocidental e oriental do Fiorde de Oslo, Noruega S, e caracteriza-se por uma contínua elevação glacio-isostática durante o Holoceno. Desta forma, a superfície terrestre vai ficando continuamente mais velha a partir da costa em direção às maiores elevações. Investigaram-se sedimentos marinhos de doze poços argilosos seis em Vestfold e seis em Østfold; Para além disso, recolheram-se três amostras de sedimentos frescos da linha costeira.
Os resultados deste estudo sugerem que, assim que a superfície terrestre se eleva acima do nível do mar, a drenagem dos poros grosseiros e o arejamento da parte superior dos solos jovens conduz a cinco processos principais:

i. desenvolvimento de profundas gretas obedecendo a um padrão poligonal;
ii. compactação assim que a superfície terrestre se eleva acima do nível do mar que conduz à drenagem dos poros mais grosseiros;
iii. oxidação da pirite com libertação de ácido sulfúrico;
iv. descarbonatação rápida de sedimentos originalmente calcários através da dissolução dos carbonatos pelos ácidos libertados pela pirite e oxidação do ferro;
v. precipitação de hipocamadas de ferro e de camadas da franja capilar.

A alteração morfológica seguinte que ocorre também a menos de 2,1 ka, é a diferenciação de horizontes em horizontes Ah, Eg, e Btg devido à limitada permeabilidade de água dos sedimentos de textura fina. Os horizontes Eg vão-se tornando mais claros com o tempo.
O processo que conduz à seguinte alteração morfológica nos perfis do solo é a iluviação de argila, que já é também observada nos solos com 2,1 ka de idade. O pH na parte superior do horizonte E nestes solos é já demasiado baixo para provocar a mobilização de argila. A iluviação de argila está ainda ativa em todos os solos estudados, encontrando-se o limite superior da zona de mobilização de argila em 20-50 cm de profundidade. A iluviação progressiva de argila regista-se através do aumento da espessura dos revestimentos de argila e proporção de orifícios com revestimentos de argila. A mobilização de argila e a co-eluviação de ferro na parte superior dos horizontes Eg cessam a menos de 2,1 ka, enquanto as intempéries e formação de minerais de argila e de óxidos de ferro continuam, levando à formação de um horizonte BE na parte superior do horizonte Eg.
A formação de línguas de Albeluvic começam a observar-se após 4,6-6,2 ka. Desenvolvem-se preferencialmente ao longo das gretas. O material Albelúvico é lavado nas gretas conduzindo a uma maior lixiviação de bases e a eluviação de argila tem igualmente lugar nas gretas. À medida que ambos os processos prosseguem as línguas albelúvicas tornam-se mais longas e mais largas.
Ocorrem incrustações argilosas nos Stagnic Albeluvisols da sequência sugerindo-se o seguinte conceito para explicar sua génese: quando após o derretimento da neve, ou um período chuvoso, a água de infiltração atinge a extremidade inferior de uma língua albelúvica a língua preenche-se com água e a água superficial acumula-se também no topo do denso horizonte Btg. A água, que transporta a argila suspensa, penetra sob pressão da língua no horizonte Btg, onde se verifica uma mobilização adicional de argila. A argila pára quando diminui a velocidade da água, formando incrustações argilosas na densa matriz do horizonte Btg.

1. Introduction

Soil chronosequence studies are a key to understanding the progressive changes of soil properties over time as a result of ongoing soil-forming processes, and hence for assessing the rates at which different soil-forming processes proceed. In the last decades, numerous soil chronosequence studies have been reported from various climatic regions around the world. These include studies of sequences of Podzol formation in temperate to cool, humid climates (e. g. Birkeland 1984; Barrett and Schaetzl 1992, 1993; Egli et al. 2001; Sauer et al. 2008); soils characterized by clay illuviation that were extensively studied in Mediterranean climates (e. g. Torrent et al. 1980; Harden 1982, 1988; Merritts et al. 1991; Alonso et al. 1994; Dorronsoro 1994; Eppes et al. 2008; Sauer et al. 2010); and a number of soil chronosequence studies carried out on soils with clay illuviation in humid-temperate climate (e.g. Howard et al. 1993; Leigh 1996; Jongmans et al. 1991; McIntosh and Whitton 1996; Vidic and Lobnik 1997).

Albeluvisols are widespread in the northern part of the humid-temperate climate zone of Eurasia (ISSS Working Group RB 1998). Micromorphological characteristics of Albeluvisols in Russia were described by e.g. Targulian et al. (1974), Gerasimova (2003) and Bronnikova and Targulian (2005); Kühn et al. (2006) carried out micromorphological analyses on Albeluvisols in northern Germany. However, the only Albeluvisol chronosequences that have been reported in the international literature so far are two chronosequences from South Norway (Sauer et al. 2009, 2012), comprising six pedons each, and these are also subject of this paper. Two previous papers presented standard analytical data and soil chemical changes with time (Sauer et al. 2009), and compared the changes observed in reality to changes suggested by the model SoilGen (Sauer et al. 2012) developed by Finke (Finke and Hutson 2008; Finke 2012). This third paper on these soils focuses on the results of micromorphological analyses of the twelve soil profiles, which are combined with the existing soil macromorphological and chemical data in order to identify the major processes involved in the development of Albeluvisols.

2. Study Area

The study area is located in the counties Vestfold and Østfold on the western and eastern sides of the Oslofjord, S Norway, between 59° and 59°40' North and 10° to 11°30' East. Average monthly temperatures vary from -2.8 °C to -5.3 °C in February and 15.8 °C to 16.8 °C in July. The vegetation consists predominantly of mixed forest. The final retreat of the ice at the termination of the last glacial took place in this area between 13,900 and 11,500 years BP. Since then, the area has been characterized by continuous glacio-isostatic uplift. Hence, in most of the area no distinct marine terraces were formed, but the land surface continuously ages from the beach towards the higher elevations. Marine sediments with silty clay loam or similar texture are widespread in Vestfold and Østfold. They tend to have a coarser texture in the upper 20-40 cm, since each location was at the beach position during the transition from marine to terrestrial conditions. The rock underneath the sediments in Østfold consists predominantly of Iddefjordsgranite. In Vestfold, Permian lavas, mainly rhomb porphyries, form the bedrock underlying the marine sediments in the northern part of the study area. South of these lavas, the geological basement consists mainly of larvikite, a variety of monzonite. Larvikite is a coarse-grained plutonic rock with high plagioclase and apatite contents (Sørensen et al. 2007).

3. Material and Methods

Twelve soil pits in loamy marine sediments were investigated, six each in Vestfold (VF) and Østfold (ØF), all of them under forest, with maximum slopes of 12%. Land surface ages at the sites range from 2,100 to 11,050 years (Table 1); in addition, three samples of fresh sediments were taken from the shoreline. The ages of the land surfaces were deduced from local sea level curves (Henningsmoen 1979; Sørensen et al. 2007, 2012). The soil profiles were described according to FAO (1990) and classified according to WRB (IUSS Working Group WRB 2006). Samples were taken by horizon; horizons > 40 cm were subdivided for sampling. Soil pH (H_2O), soil organic carbon (SOC), particle size distribution, pedogenic iron (Fe_d) and total element composition of the samples were determined as described in Sauer et al. (2009), where also the results of these analyses were reported in more detail. Undisturbed samples for thin section preparation were taken from the Btg, Bg and Eg/Btg horizons using Kubiëna boxes of 8 cm height, 6 cm width, and 4 cm thickness. The undisturbed samples were subjected to acetone exchange, impregnation with resin (Palatal P80-02), and hardening for ca. six weeks. Then, they were cut into 5 mm thick, slide-sized blocks, which were polished by abrasive paper and diamond paste from one side. The polished side was fixed to slides (format: 28 x 48 mm) using the same resin. The blocks on the slides were then ground to a thickness of ca. 30 μm, polished and covered with a cover glass.

Table 1. Location, elevation, age, exposition, slope and classification of the soil profiles forming the two soil chronosequences in Vestfold (VF) and Østfold (ØF)

Soil profile (location)	Coordinates	Age (years)*	Soil horizons (FAO 2006) and WRB classification (IUSS Working Group WRB 2006)
VF2.4 (Sem)	59°17.047'N 10°20.036'E	2,100 ± 100	Ah – BEg – Eg1 – Eg2 – Btg1 – Btg2 – Ctr – Cr Luvic Endogleyic Cutanic Stagnosol (Endoeutric, Siltic)
VF4.5 (Ramnes)	59°20.043'N 10°16.029'E	4,200 ± 150	Ah – Ap (relict) – Eg – BEg – Btg1 – Btg2 – Btg3 – Cg – C Luvic Cutanic Stagnosol (Endoeutric, Siltic)
VF8.8 (Holmen)	59°11.026'N 10°05.001'E	6,000 ± 150	Ah – Ap (relict) – BEg – Eg – Eg/Btgx1 – Eg/Btgx2 – Btgx1 – 2Btgx2 – 3Cg Stagnic Cutanic Fragic Albeluvisol (Dystric, Siltic)
VF6.6 (Fossan)	59°23.042'N 10°15.015'E	6,900 ± 150	Ah – Ap (relict) – BEg – Eg – Eg/Btgx – Btgx1 – Btgx2 – C Stagnic Cutanic Fragic Albeluvisol (Endoeutric, Siltic)
VF7.3 (Gjein)	59°14.023'N 10°09.049'E	8,000 ± 150	Ah – BEg – Eg – Eg/Btgx – Btgx1 – Btgx2 – Cg Stagnic Cutanic Fragic Albeluvisol (Endoeutric, Siltic)
VF9 (Torp)	59°12.024'N 10°15.032'E	9,400 ± 200	AE – Bs – BEg – Eg – Eg/Btgx – Btgx – Bg – Cg Stagnic Cutanic Fragic Albeluvisol (Endosiltic, Protospodic)
ØF3 (Løkkevika)	59°08.039'N 11°14.004'E	3,000 ± 250	Ah – BE – Eg – Btg – Bg – Blg – Cr Alic Endogleyic Stagnosol (Albic, Hyperdystric, Siltic)
ØF4 (Tomb)	59°18.849'N 10°49.103'E	3,500 ± 200	Ah – Ap (relict) – Eg – Btg – Btrg – Cr Luvic Endogleyic Stagnosol (Endoeutric, Endosiltic)
ØF7.5 (Husevja)	59°19.017'N 11°02.032'E	6,550 ± 150	Ah – AE – Bs – BEg – Eg/Btgx – Btgx – Cg – R Stagnic Cutanic Fragic Albeluvisol (Episiltic, Protospodic)
ØF5 (Navestad)	59°14.053'N 11°07.053'E	6,650 ± 150	Ah – Ap (relict) – Eg – Eg/Bg – Btgx1 – Btgx2 – Cr1 – Cr2 Stagnic Endogleyic Cutanic Fragic Albeluvisol (Endoeutric)
ØF8 (Os Kirke)	59°27.574'N 11°27.574'E	9,750 ± 150	Ah – EB – Eg1 – Eg2 – Eg/Btgx – Btgx – BCg – Cg Endostagnic Cutanic Fragic Albeluvisol (Endoeutric, Siltic)
ØF11 (Båstad)	59°40.037'N 11°18.014'E	11,050 ± 150	Ah – AE – Bs – Eg – Eg/Btgx – Btgx – BCg1 – BCg2 – BCg3 – C Stagnic Cutanic Fragic Albeluvisol (Dystric, Siltic, Endofluvic, Protospodic)

*ages derived from calibrated ^{14}C dates in calendar years before sampling; uncertainty includes uncertainty of dating, uncertainty due to distance of the particular site from locations of dated sea level curves and uncertainty of elevation as derived from 1:5000 maps.

4. Results

4.1. Soil texture and profile morphology

Since the profile morphology has already been described in detail by Sauer et al. (2009), only the main characteristics and changes over time are summarized here; this paper will then focus on soil micromorphology. The fresh marine sediments contain varying amounts of shell fragments and have pH (H_2O) 7.5-7.7. Texture of the soils is silt loam or similar; they have typically 40-70% silt, 20-40% clay and 1-20% sand. The upper ca. 40 cm are usually somewhat coarser textured, which reflects sedimentation under littoral conditions during the last phase before the land surface rose above sea level. The subsoils are usually very dense and correspond to fragipans; their structure is characterized by large prisms. Main changes in profile morphology over time include progressive paling of the Eg horizons (Figure 1a). Remarkably, the E horizon thickness does not increase with increasing soil age. Instead, the lower boundary of the Eg horizon is at 40 cm depth in the youngest soils of both sequences, and stays at this depth in all soils except for two pedons (VF7.3, VF9), where it is shallower, most likely due to erosion. Thin clay films are already present in the youngest soil investigated (VF2.4, 2.1 ka); they become thicker and more abundant with soil age. A common feature of all soils investigated is the presence of deep vertical cracks, forming polygons in horizontal sections. Albeluvic tongues start to penetrate from the Eg horizon down into the Btg horizon after ca. 5-6 ka (Figure 1b). They develop preferably along the cracks, especially along intersections of cracks. The general sequence of soil development hence leads from Endogleyic Stagnosols to Stagnic Albeluvisols.

The upper part of the E horizon turns progressively brownish, and finally initial podzolization occurs (Figure 1c). The initiation of podzolization depends on vegetation; the 9.75 ka-old soil under mixed forest (ØF8) shows no signs of podzolization yet, whereas the 6.55 ka-old soil under spruce (ØF 7.5) already shows signs of initial podsolization.

Bleaching in the upper part of the soils and mottling below indicate temporary water stagnation (Figure 2a). The mottling occurs inside the prisms of the Bg or Btg horizons, whereas the surfaces of the prisms are iron-depleted (Figures 2b, 2c). The three youngest soils, 2.1, 3.0 and 3.5 ka in age and located 7, 10 and 12 m a.s.l., are moreover influenced by groundwater (Figure 4a).

1 a) 1 b) 1 c)

Figure 1. Main changes in profile morphology over time. **a)** The E horizon becomes paler. As an example, the photograph shows profile ØF5, representing a 6.65 ka-old soil with a well-developed albic E horizon. **b)** Albeluvic tongues start to develop after ca. 5-6 ka. The photograph shows profile ØF8 (9.75 ka old) to 60 cm depth, where a horizontal section was cleaned before digging deeper. The horizontal section at 60 cm depth exhibits the polygonal pattern of the albeluvic tongues penetrating down in the cracks between the large prisms of the Btg horizon. **c)** The upper part of the E horizon turns brownish as clay mobilization at this depth comes to an end but weathering and formation of pedogenic iron oxides continue. Finally initial podzolization occurs. The photograph shows profile ØF11 representing the oldest soil of the two chronosequences (11.05 ka old).

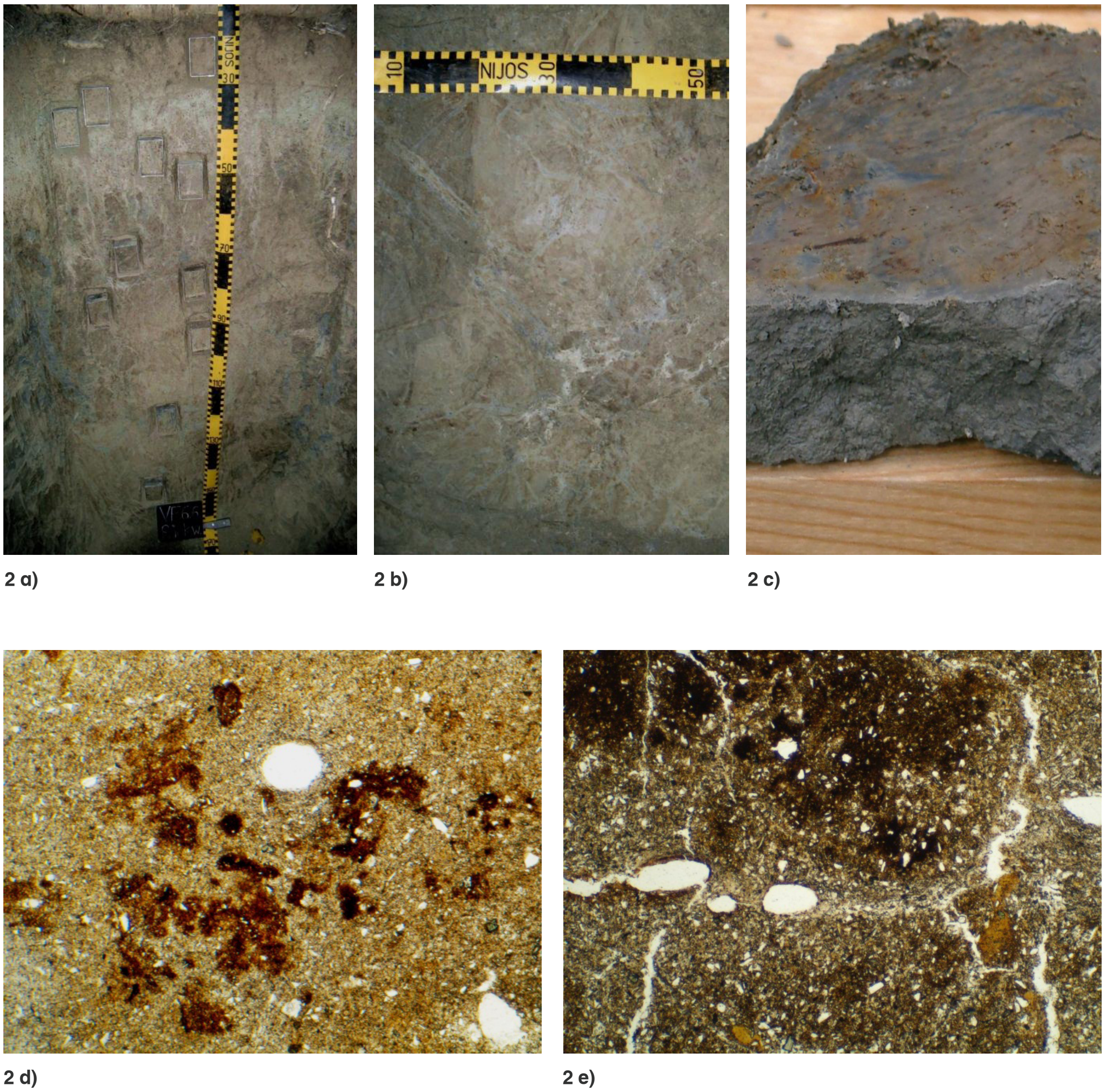


Figure 2. Impeded drainage is characteristic for all soils of the two chronosequences. Both macro- and micromorphological indicators of stagnic conditions are well-expressed. **a)** Profile VF6.6 (Stagnic Cutanic Fragic Albeluvisol, 6.9 ka old); **b)** horizontal section of profile VF6.6 at 134 cm depth exhibiting polygonal pattern of iron-depleted ped surfaces; **c)** slice of typical large prism from profile ØF8 (Endostagnic Cutanic Fragic Albeluvisol, 9.75 ka old) showing gray, iron-depleted surface and mottled inner part; **d)** Btg1 horizon of profile VF7.3 (8 ka old, sample from 45-53 cm depth) having channel structure, mottled matrix and iron nodules (PPL, width of photo: 2.2 mm); **e)** Btg2 horizon of profile VF6.6 (6.9 ka old, sample from 92-100 cm depth) having angular or subangular blocky microstructure; iron impregnations and nodules occur inside the micro-aggregates, whereas their surface is iron-depleted (PPL, width of photo: 2.2 mm).

4.2. Soil classification according to WRB

The youngest soils studied are a 2.1 ka-old soil in Vestfold (pedon VF2.4) and a 3 ka-old soil in Østfold (pedon ØF3). Both are Stagnosols influenced by clay illuviation and by groundwater between 50 and 100 cm depth. Moreover, the 2.1 ka-old soil shows clay coatings in the voids of its Btg horizons and is hence classified as Luvic Endogleyic Stagnosol (Endoeutric, Siltic). The 3 ka-old soil shows no clay coatings but a distinct increase in clay content between 40-80 cm depth; it is classified as Alic Endogleyic Stagnosol (Albic, Hyperdystric, Siltic).

The two next older soils, a 3.5 ka-old soil in Østfold (ØF4) and a 4.2 ka-old soil in Vestfold (VF4.5) show progressive clay illuviation, but no additional features compared to the younger soils; they are classified as Luvic Endogleyic Stagnosol (Endoeutric, Endosiltic) and Luvic Stagnosol (Endoeutric, Siltic), respectively.

The next older soils are two soils in Vestfold, 6 ka and 6.9 ka in age (VF8.8 and VF6.6), and two soils in Østfold, 6.55 and 6.65 ka in age (ØF7.5 and ØF5). These soils already exhibit distinct albeluvic tonguing. The colour of the tongues and the lower parts of the E horizons are very light (often Munsell value 5-6, chroma 2), while the upper parts of the E horizons are brownish (e.g. Munsell colour 10YR4/3). The 6.55 ka-old soil (ØF7.5), located under spruce, in addition shows initial podzolization in the upper part of the former E horizon, whereas still no podzolization is recognized in the 6.9 ka-old soil (VF6.6) under mixed forest. These four soils of intermediate age (6.0-6.9 ka) are classified as Stagnic Cutanic Albeluvisol (Dystric, Siltic) (VF8.8), Stagnic Cutanic Fragic Albeluvisol (Episiltic, Protospodic) (ØF7.5), Stagnic Endogleyic Cutanic Fragic Albeluvisol (Endoeutric) (ØF5), and Stagnic Cutanic Fragic Albeluvisol (Endoeutric, Siltic) (VF6.6), respectively. The qualifier "Protospodic" is not listed in the qualifiers for Albeluvisols. It has been built from the qualifier "Spodic" in the WRB general qualifier list and the specifier "Proto", defined in WRB as "indicating a precondition or an early stage of development of certain features" (IUSS Working Group WRB 2006). The concept of "Protospodic" was introduced by the authors during the WRB field trip 2010 to Norway, and there was agreement among the group that the use of this qualifier adds important information to the classification of a soil.

The oldest soils of the two chronosequences are marked by increasing length of the albeluvic tongues and by more frequent occurrence of initial podzolization in the upper part of the E horizon. An 8 ka-old soil (VF7.3) is classified as Stagnic Cutanic Fragic Albeluvisol (Endoeutric, Siltic); the two next older soils, a 9.4 ka-old soil (VF9) and a 9.75 ka-old soil (ØF8), are classified as Stagnic Cutanic Fragic Albeluvisol (Endosiltic, Protospodic) and Endostagnic Cutanic Fragic Albeluvisol (Endoeutric, Siltic), respectively. The oldest soil, 11.05 ka in age (ØF11), is classified as Endostagnic Cutanic Fragic Albeluvisol (Dystric, Siltic, Endofluvic, Protospodic).

4.3. Chemical alteration during soil development

Soil pH (H_2O) in the upper part of the E horizon drops below the pH range most suitable for clay mobilization within less than 2.1 ka (**Figure 3**). The A horizons of soils exhibiting initial podzolization (VF9, ØF7.5, ØF11) have pH 3.6-3.9, those of all other soils have pH 3.7-4.7. Soil pH increases with depth to pH 4.4-6.3 in the Eg horizons and pH 5.3-7.1 in the Btg and Bg horizons.

Fe_d/Fe_t ratios are 0.21-0.35 in the A horizons and generally decrease with depth. Only soils showing initial podzolization (VF9, ØF7.5, ØF11) exhibit Fe_d/Fe_t maxima below the A horizon. Additional Fe_d/Fe_t ratio maxima occur in the oxidized horizons of the two youngest, groundwater-influenced, pedons (VF2.4, ØF3). Several pedons exhibit also slightly increased Fe_d/Fe_t ratios in the Btg horizons. Mean profile Fe_d/Fe_t ratios (weighted means of the horizon data of the upper meter) show a linear increase with soil age (Østfold: $y = 1.30 \cdot 10^{-5}x + 0.16$; $R^2 = 0.88$, and Vestfold: $y = 1.25 \cdot 10^{-5}x + 0.13$; $R^2 = 0.76$).

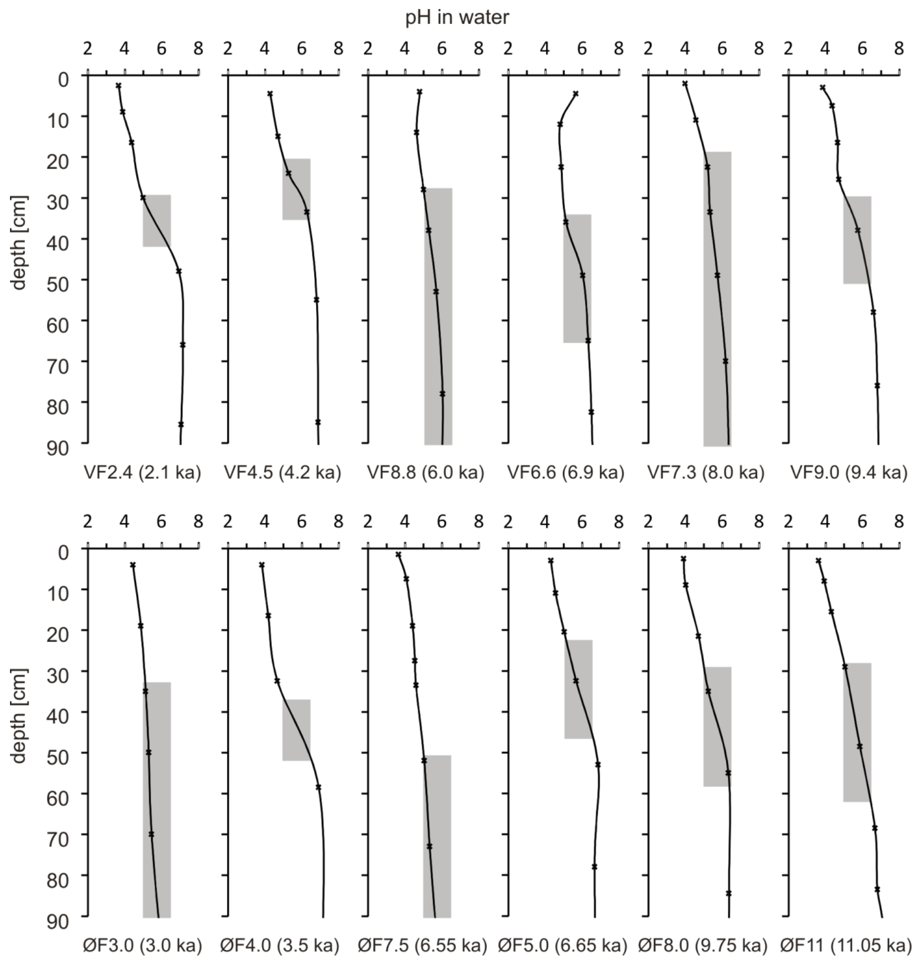


Figure 3. Soil pH (water) of the twelve pedons. The gray boxes indicate the soil depth at which pH is most suitable for clay mobilization.

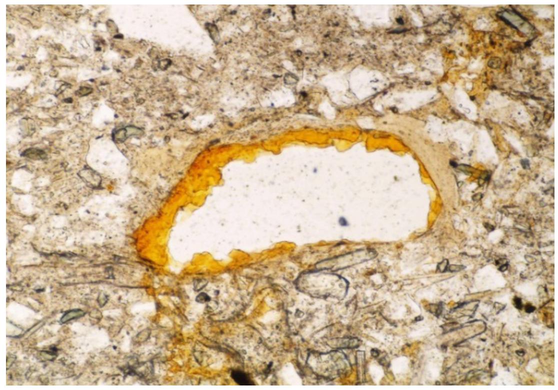
4.4. Soil micromorphology

4.4.1. *Microstructure and hydromorphic features*

Btg horizons of the younger soils (up to 3.5 ka) have channel structure; Btg horizons of older soils with very silty texture and low clay content have a massive or channel microstructure as well (**Figure 2d**). The matrix of such Btg horizons without micro-pedality is mottled, and iron nodules are common. Channels are usually surrounded by depletion hypocoatings. Btg horizons of more loamy intermediate and older soils have angular or subangular blocky microstructure; in these cases, iron impregnations and nodules occur inside the micro-aggregates, whereas their surface is iron-depleted (**Figure 2e**).

In addition, many channels and vughs in the subsoils of the three youngest soils, VF2.4, ØF3.0, ØF4 (2.1, 3.0 and 3.5 ka), have iron oxide hypocoatings and coatings, reflecting groundwater influence (**Figure 4c**). The iron oxide coatings (ferrans) can be subdivided into ferrans without birefringence and internal structure (**Figure 4b**) and ferrans composed of goethite fibers, which are often arranged in concentric bundles and show several growth zones (**Figures 4d, 4e**). Voids with very thick ferrans may in addition have amorphous iron oxide infillings. Weak birefringence of the goethite fibers indicates their crystallinity in contrast to the amorphous character of the iron oxide infillings (**Figure 4f**).

4 a)



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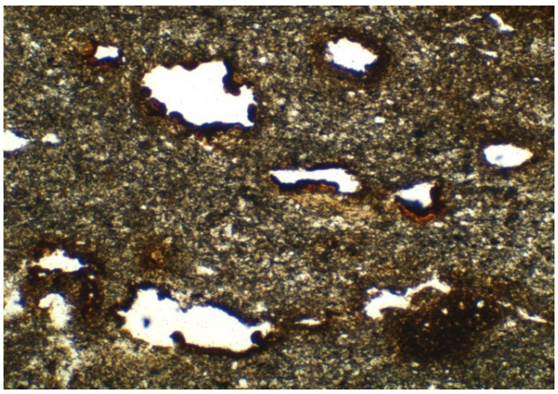
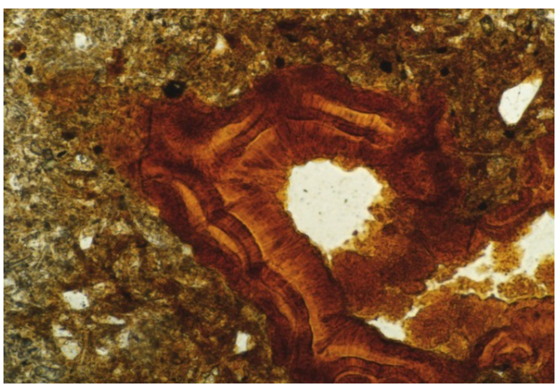
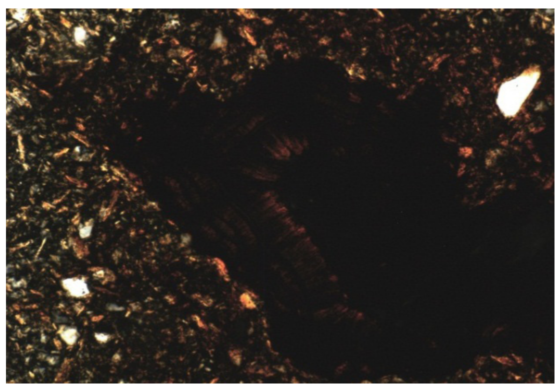


4 c)

4 d)



4 e)



4 f)

Figure 4. The youngest soils of the chronosequence are influenced by groundwater. **a)** Profile ØF3 (3 ka old); **b)** Blg horizon of profile ØF3 at 93-101 cm depth: channel with older clay coating and younger iron oxide coating (ferran) due to gleying (PPL, width of photo: 0.53 mm). **c)** Blg horizon of profile VF2.4 (2.1 ka old, sample from 40-48 cm depth), typical part of the thin section: channels and vughs are abundant, most of them having iron hypocoatings, many also iron coatings (ferrans) (PPL, width of photo: 2.2 mm); **d)** Close-up of previous photo: ferran composed of goethite fibres, arranged in concentric bundles and showing several growth zones (PPL, width of photo: 0.33 mm); **e)** Blg horizon of profile VF2.4 (sample from 40-48 cm depth): thick ferran composed of goethite fibres; in addition partial infillings of amorphous iron oxides occur (PPL, width of photo: 0.53 mm); **f)** Same as previous photo, XPL: the goethite fibers show weak birefringence, indicating their crystallinity in contrast to the amorphous character of the iron oxide infillings.

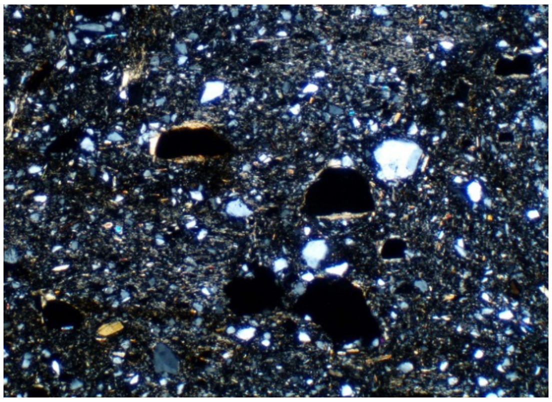
4.4.2. *Clay coatings and albeluvic tongues*

Clay illuviation starts in these soils within less than 2.1 ka. In the 3 ka-old soil (ØF3) some channels have older clay coatings covered by younger ferrans, which indicates that clay illuviation and gleying dynamics interfere in the youngest soils (**Figure 4b**). Thicknesses of clay coatings and the proportion of voids having clay coatings both increase with soil age (**Figures 5a, 5b**). The illuvial clay is partly pressed into the surrounding matrix by swell/shrink processes (**Figure 5b**).

Thin section analysis also reveals the composition of the Albeluvic tongues. Thus, it may also support classification because the tongues of an Albeluvisol are defined as having "a particle-size distribution matching that of the coarser textured horizon overlying the *argic* horizon" (IUSS Working Group WRB 2006). Moreover, analysis of the shape and the components of albeluvic tongues as well as the distribution and orientation of the components with regard to the tongue boundaries and possibly remaining void in the centre of the tongue enables conclusions to be drawn on the involved processes. Examples are shown in **Figure 5c** and **d**. The albeluvic tongues clearly consist of silty Eg material that has fallen or been washed into cracks in finer-textured Btg material. Illuvial clay is found on the original surface of the former crack as well as along the present wall of the remaining void formed by the silty Eg material (**Figure 5c**). Furthermore, fragments of illuvial clay occur in the silty Eg material in the cracks (**Figure 5d**). These observations lead to the conclusion that accumulation of Eg material in the cracks and clay illuviation are contemporaneous processes. Clay coatings form prior to and during accumulation of Eg material. When Eg material, on which clay coatings have settled, moves further down, the clay coatings are disrupted.

4.4.3. *Clayey intercalations*

Clayey intercalations are a common feature in the intermediate and older soils, *i.e.* in the Albeluvisols. No intercalations occur in the 3.5 ka-old and younger soils (Stagnosols). The Btg1 horizon of the 4.2 ka-old soil (VF4.5) still shows no clayey intercalations, but some areas with strial b-fabric occur (**Figure 6a**). In soils older than 6 ka clayey intercalations are very typical; they usually have strial b-fabric (**Figure 6b**). The appearance of some clayey intercalations suggests that they have been washed in by percolating water (**Figure 6c**). The same material that occurs as clayey intercalations in the matrix may also form hypocoatings (**Figure 6d**). In most cases, clayey intercalations can easily be distinguished from normal coatings of illuvial clay, because normal clay coatings are layered, have higher birefringence, and sharp extinction bands, which is not the case for clayey intercalations (**Figure 6e**). However, in places strongly oriented clay occurs as thick hypocoatings, appearing as an intermediate feature between normal illuvial clay and clayey intercalations (**Figure 6f**). The Btg1 horizon of the 6 ka-old soil, which is very dense, has the same clayey material that forms intercalations in other thin sections, but in this case it occurs only as coatings (**Figure 6g**); also transitions between this material and normal clay coatings are observed in this horizon (**Figure 6h**).



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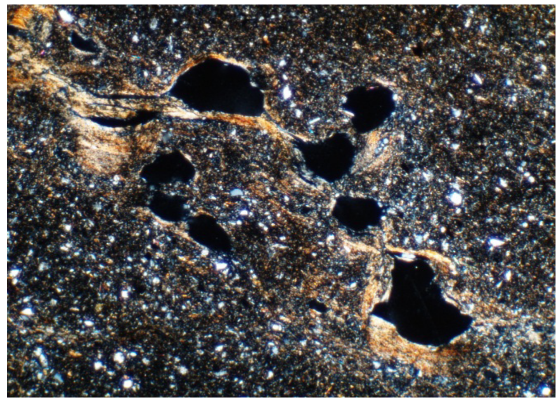
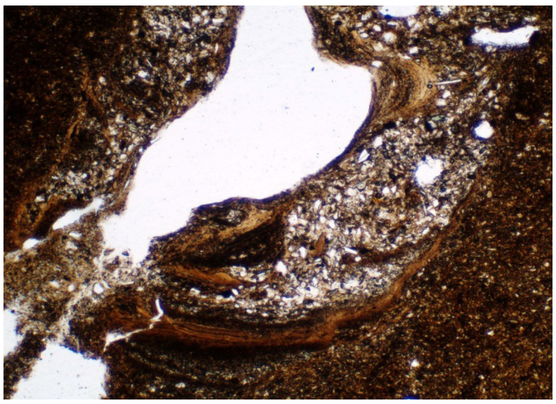


5 b)



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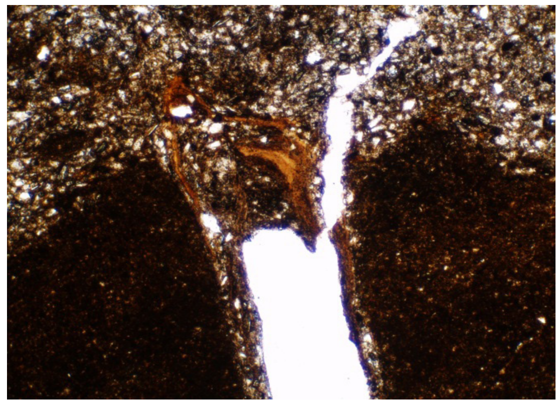
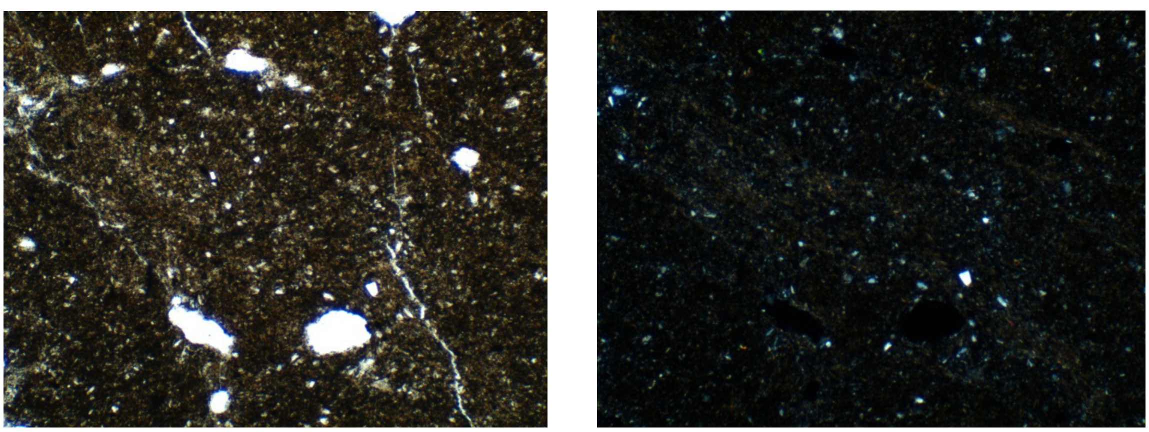
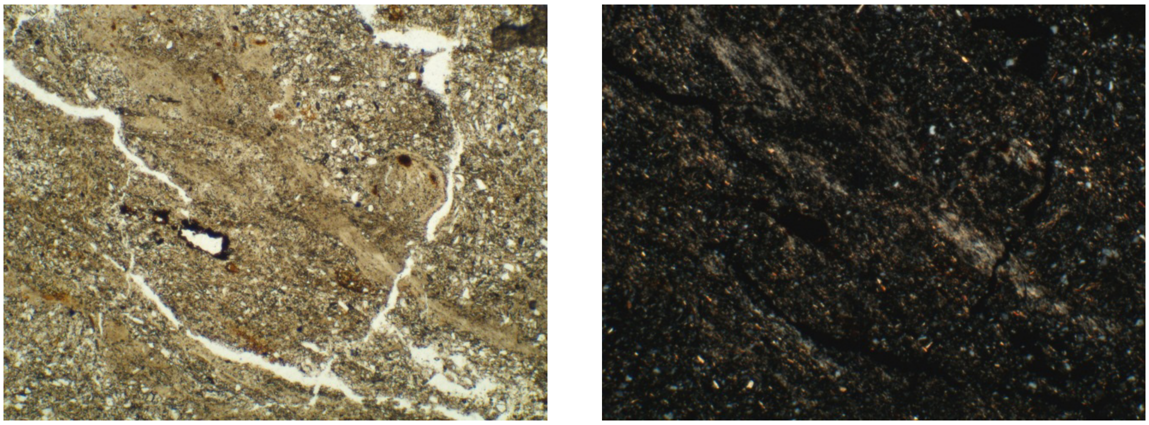


5 d)

Figure 5. Clay and silt translocation (width of photos: 2.2 mm). **a)** 3,000 year-old soil (profile ØF3), Bg: A minor proportion of the channels have thin clay coatings (XPL = with crossed nicols). **b)** 9.75 ka-old soil (profile ØF8), E/Btg: Many channels, even in the silty albeluvic tongues, have prominent clay coatings (XPL). **c)** 9.75 ka-old soil (profile ØF8), E/Btg: Silt and illuvial clay (partly still related to the remaining channel and partly fragmented) in a crack surrounded by Btg material (PPL = with plane polarized light). **d)** 9.75 ka-old soil (profile ØF8), E/Btg: Silt and fragments of illuvial clay entering a crack in Btg material (PPL).



6 a)



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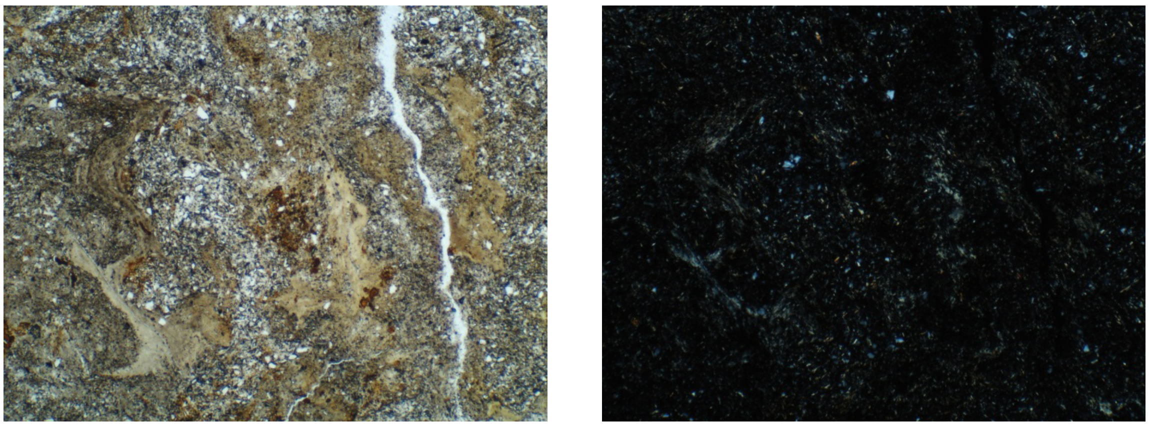

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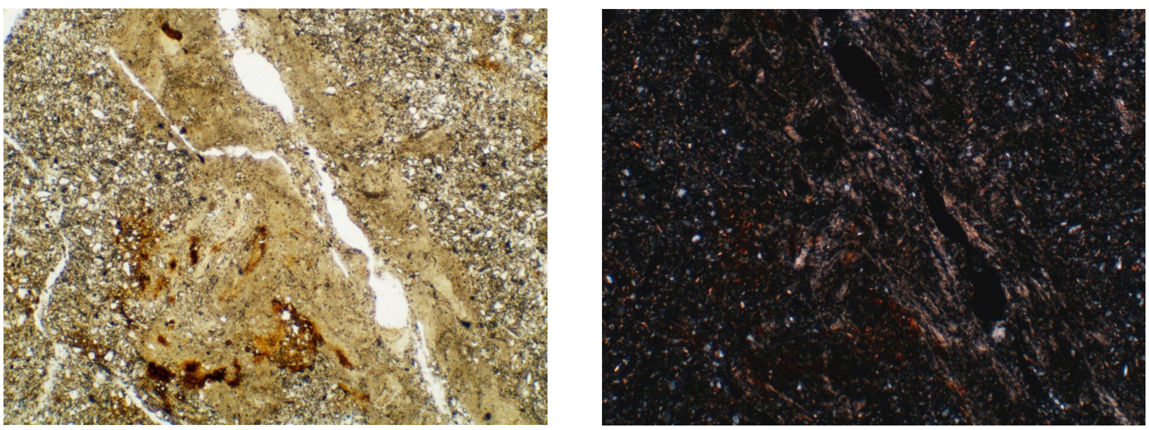

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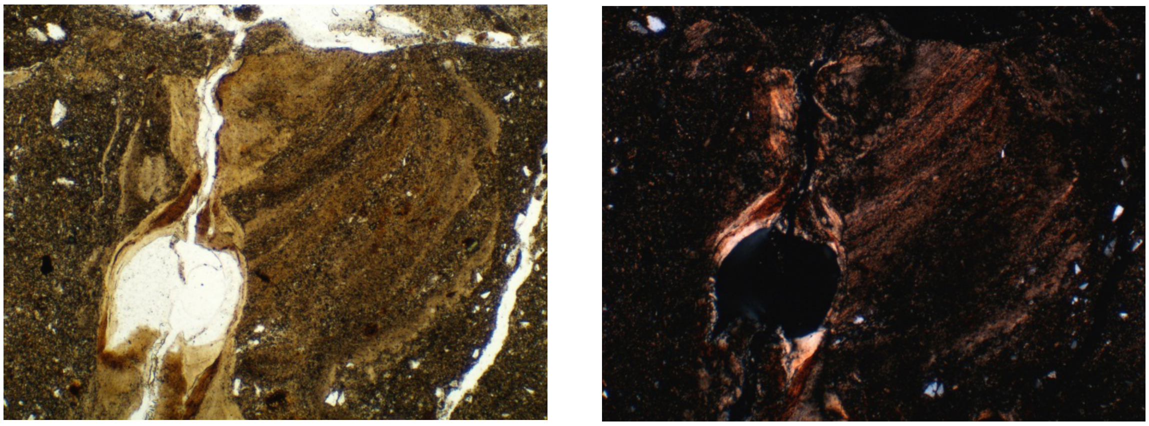

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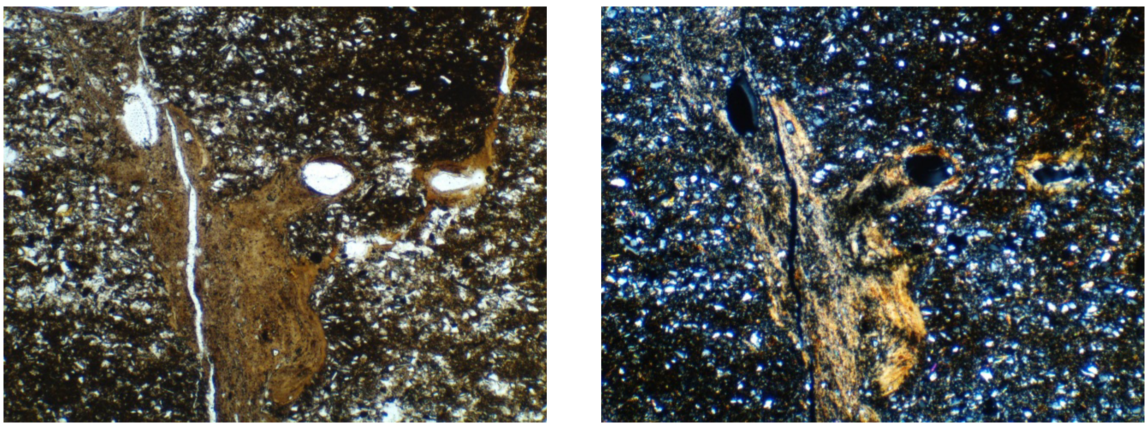

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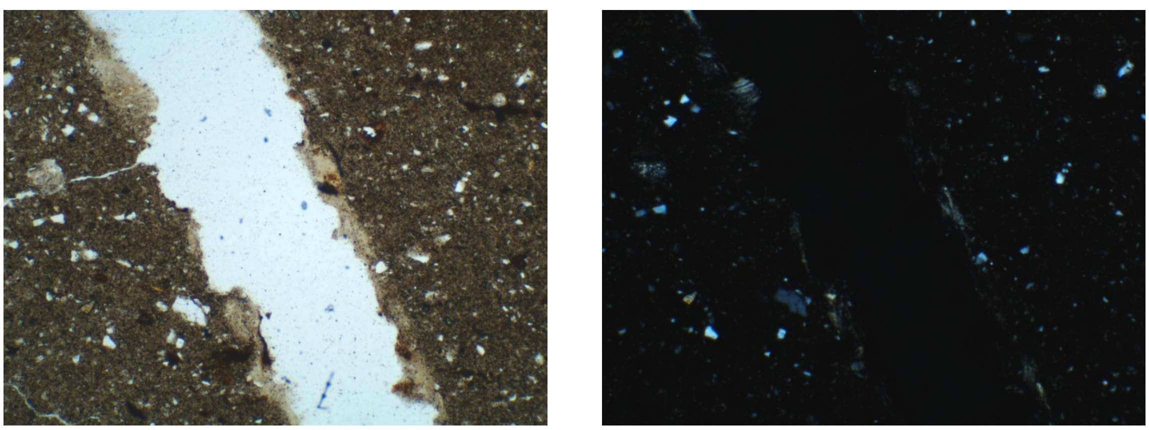
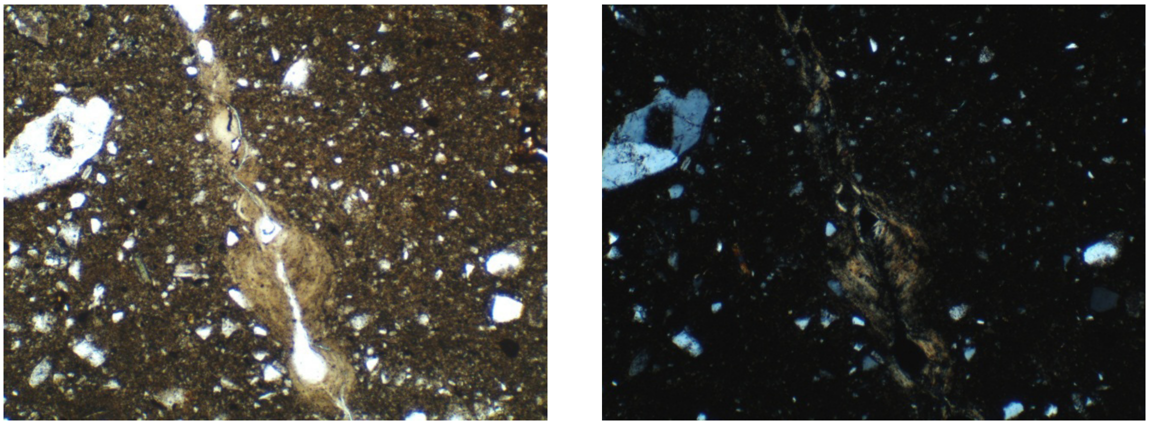


6 g)



6 h)

Figure 6. Intercalations, illuvial clay and transitions (widths of all photographs correspond to 2.2 mm; left PPL; right XPL). **a)** Btg1 horizon of profile VF4.5 (4.2 ka-old, sample from 47-55 cm depth): No clayey intercalations are visible in the loamy matrix; crystallitic b-fabric still predominates, but areas with strial b-fabric occur; **b)** Btg2 horizon of profile VF6.6 (6.9 ka-old, sample from 92-100 cm depth): Clayey intercalations are very typical; most of them have strial b-fabric; **c)** Same thin section as in b: Clayey intercalations, their appearance suggesting that they have been washed in; **d)** Same thin section as in b and c: Hypocoating composed of the clayey material that otherwise occurs as intercalations in the matrix; **e)** Btg horizon of ØF11 (11.05 ka-old, sample from 66-74 cm depth): Normal coating of illuvial clay and clayey intercalation; in contrast to the intercalation, the clay coating is layered, has higher birefringence, and sharp extinction bands; **f)** Same thin section as previous photo: Thick hypocoating of oriented clay, appearing as in-between illuvial clay and clayey intercalations; **g)** Btg1 horizon of VF8.8 (6 ka-old, sample from 92-100 cm depth): The same clayey material that forms intercalations in other thin sections, only occurs as coatings in this very dense horizon; **h)** Same thin section as in g: Transition between the material shown in g) and normal clay coating.

5. Discussion: soil-forming processes in marine sediments in S Norway

5.1. Early soil-forming processes: shrinkage, compaction, decarbonatization, iron dynamics controlled by groundwater influence

The marine sediments contain varying amounts of (sedimentary) organic matter. Microbial decomposition of the organic matter involves reduction of sulfur and formation of pyrite as long as the sediment is still below sea level. As glacio-isostatic uplift raises it above sea level, aeration of the upper part of the young soils leads to five major processes: i) formation of desiccation cracks, starting at the soil surface and penetrating down as the groundwater table (relatively) drops; ii) compaction; iii) pyrite oxidation with release of sulfuric acid; iv) rapid decarbonatization due to reaction of carbonates with acids from pyrite oxidation; v) precipitation of iron oxides as hypocoatings and coatings, including thick ferrans of fibrous goethite (Figure 4). The latter process takes place in the capillary fringe (Cl horizon) and hence moves down the profile as the groundwater table drops with time; in the 3000 year-old soil (ØF3; 10 m a.s.l.) the Cl horizon is at 80-110 cm depth. In the older soils, groundwater becomes less important for the further soil development.

The youngest soil studied (besides three samples taken from the shore) is 2,100 years old, and so the progression of processes within the first 2,100 years was not directly observed. However, several characteristics that are present in the younger soils in S Norway were also reported by Kooistra (1978) from the intertidal zone and salt marsh of the Oosterschelde area (The Netherlands), and reclaimed soils on 116 to 260 year-old polders in the same area. Therefore, it is very likely that some of the early processes in the Norwegian soils proceed similarly to those described for the Oosterschelde area and earlier summarized by Pons and Zonneveld (1965) as “soil ripening” processes. A major difference is that the Dutch coast has an extended intertidal flat, due to a tidal range of several meters, whereas the intertidal zone in the study area in S Norway is very narrow because the tidal range is only about 35 cm (tide chart of Nevlunghavn). Nevertheless, most soil-forming processes taking place in S Norway shortly after the land has fallen dry must be similar to those observed by Kooistra (1978) in the Dutch polder soils. For instance, horizontal sections of the Norwegian soils always show polygonal cracks. They are interpreted as desiccation cracks, forming as soon as the coarse pores in the formerly completely water-saturated upper part of the soil are drained. This assumption is based on the observation of Kooistra (1978), who reported that desiccation cracks formed polygons 20-40 cm in diameter in the intertidal flats; they were still present in the reclaimed soils of the polders.

Btg horizons of all soils investigated in this study were very dense. It is assumed that compaction takes place as the land surface gets high enough above sea level that the water drains from the coarse pores, analogous to compaction in Dutch polder soils compared to loose packing in soils of the intertidal flat observed by Kooistra (1978).

Pyrite and iron dynamics were more complex in the study area of Kooistra (1978) than in S Norway, due to the wide tidal range in the Netherlands, causing repeated oxidation/reduction cycles with release of considerable amounts of acids that rapidly dissolved carbonates. Despite the difference in tidal dynamics, it is assumed that pyrite and iron oxidation lead to rapid decarbonatization in S Norway as well. This assumption is supported by the fact that the Ah horizon of the 2.1 ka-old soil in Norway has pH 3.7, whereas water-saturated soils along the shore are slightly alkaline (three analyzed samples had pH 7.5-7.7).

Many channels in the subsoils of the three youngest Norwegian soils, VF2.4, ØF3.0, ØF4 (2.1, 3.0 and 3.5 ka) have iron hypocoatings and coatings, including thick ferrans composed of radial goethite fibres. These groundwater-related features are supposed to start forming in the capillary fringe as soon as the land surface reaches a height above sea level at which the coarse pores are drained. This assumption is also in agreement with the observation of Kooistra (1978), who reported that iron hypocoatings (neoferrans) along cracks and channels were very common in soils of the intertidal flats and salt marshes; iron coatings occurred as thin, amorphous ferrans in soils of the intertidal flats and as thick fibrous goethite coatings in soils of the salt marshes. It is likely that pyrite oxidation provided a relevant additional source of iron in the formation of the thick ferrans.

5.2. Horizon differentiation due to perched water, clay illuviation, and brunification

The next morphological change, taking place also within less than 2.1 ka, is horizon differentiation into Ah, Eg and Btg horizons. This horizon sequence indicates limited water permeability of the fine-textured sediments. The lower boundary of the Eg horizon is at 40 cm depth from the beginning of Eg horizon formation. Eg horizons become lighter in colour with time, but their lower boundary stays strikingly constant at about 40 cm. Müller (1965) already reported a constant E/B boundary at 30-40 cm depth in clay-illuviated soils of Germany. His explanation for this phenomenon was that 30-40 cm is the depth down to which the diurnal warming and cooling penetrates in summer, and he interpreted the boundary as an analogy to the thermocline in lakes. It has to be added that it is also the depth of the greatest and most frequent changes of soil moisture, freeze-thaw cycles, and the zone of the most intensive bioturbation, root respiration and exudation. These processes may change the physical properties of the upper 40 cm, creating a boundary at 40 cm depth. Since a boundary of physical material properties would influence water infiltration, it is likely that the lower boundary of the Eg horizon follows this physical boundary. This seems plausible because it is well known that soil horizon boundaries tend to follow sedimentary boundaries, where physical properties of parent materials change abruptly.

The process leading to the next morphological change in the soil profiles is clay illuviation. Even the youngest, 2.1 ka-old soil (VF2.4), has clay coatings although the difference in the clay content between the Eg and Btg horizon does not allow for the classification of the soil as a Luvisol. It is assumed that clay illuviation starts very early in these soils. First, clay mobilization is facilitated by high sodium saturation and collapse of marine mudflakes in the course of desalinization (Kooistra 1978). After completion of desalinization, clay illuviation is controlled by Ca and Mg saturation, and mainly takes place at pH 6.5-5.0. Soil pH in the upper part of the 2.1 ka-old soil (VF2.4) is already too low for significant clay mobilization; the main zone of clay mobilization is at ca. 30-40 cm depth (**Figure 3**). Clay illuviation has proceeded until present in all soils studied, but the upper boundary of the clay mobilization zone has moved to 20-50 cm depth in the twelve pedons. Progressive clay illuviation is recorded in increasing thickness of clay coatings and proportion of voids having clay coatings (**Figures 5a, 5b**). Clay illuviation is, however, not well reflected in the particle size distribution. In most profiles the clay content clearly increases from the Eg to the Btg horizon, but does not or only slightly decreases below. The reason for this textural depth pattern is that the deeper sediment layers in the profiles were deposited under deep-water conditions, so that finer-textured sediments were deposited, whereas the uppermost sediment layers were deposited in a littoral environment.

As mentioned above, clay mobilization and iron co-eluviation in the upper parts of the Eg horizons cease within less than 2.1 ka. However, weathering and formation of clay minerals and iron oxides continue. Since clay minerals flocculate in the presence of Al^{3+} cations under the prevailing acid conditions, clay minerals and iron oxides stay at the depth where they have been formed and lead to brunification and thus the formation of a BE horizon in the upper part of the Eg horizon. The lower part of the Eg horizon gets progressively lighter in colour due to ongoing clay mobilization, iron co-eluviation and iron depletion caused by water stagnation above the Btg horizon.

5.3. Formation and development of albeluvic tongues

Formation of albeluvic tongues starts after 4.6-6.2 ka of pedogenesis. The tongues develop preferably along the polygonal desiccation cracks, especially along intersections of cracks. The cracks are preserved over the 11.05 ka period of soil development investigated in this study. As mentioned above, they form as soon as the land surface gets high enough above sea level to allow for drainage of the coarse pores. The cracks become more prominent with soil age due to repeated wet/dry and freeze/thaw cycles. Albeluvic material is washed into the cracks, leading to an absolute accumulation of albeluvic material there, which is a major process of albeluvic tongue development. Clay coatings may form in the cracks, but subsequently be disrupted when the material on which they settled is washed deeper down inside the crack. Moreover, the cracks act as pathways of strong preferential flow. Hence, leaching of bases and clay eluviation is considerably enhanced along the cracks compared to the surrounding soil matrix. Consequently, the material in the cracks becomes more clay-depleted with time. This process, which is the second process that contributes to the development of albeluvic tongues, could be regarded as residual accumulation of albeluvic material. As both processes -absolute and residual accumulation of albeluvic material- proceed, the albeluvic tongues get longer and wider. Horizontal sections demonstrate that in this way the tongues develop at the expense of the prisms, the latter being subsequently consumed by the growing albeluvic tongues that surround them.

5.4. Formation of clayey intercalations

Within the soil chronosequences studied, clayey intercalations are found only in the Stagnic Albeluvisols, not in the Stagnosols. The following concept is suggested to explain this observation. After a rainy period and especially after snow melt, water percolates down the albeluvic tongues by preferential flow. The velocity of the preferential flow allows for remobilization of clay coatings and fragments of clay coatings that are embedded in the tongue. When the water arrives at the lower end of an albeluvic tongue, the tongue rapidly fills up with water, and perched water accumulates also on top of the dense Btg horizon. The longer the albeluvic tongue the higher the water column and hence the pressure with which the water is pressed from the tongue into the surrounding Btg horizon. Water, carrying suspended clay, penetrates from the tongue into the Btg horizon, where additional clay is mobilized. This process is assumed to be still active in all Stagnic Albeluvisols of the two chronosequences, because pH at this depth is still suitable for clay mobilization (**Figure 3**). The clay settles when the velocity of the water decreases, forming clayey intercalations in the dense matrix of the Btg horizon.

The concept on the genesis of clayey intercalations obtained from this study is based on the concept of Fedoroff and Courty (2012), which has been modified according to the observation made in this study that clayey intercalations were common in Stagnic Albeluvisols but not in Stagnosols. Fedoroff and Courty (2012) interpreted intercalations as "the water-saturated counterpart" of coatings of illuvial clay in non-waterlogged soils. Our concept differs in that we suggest that vertical clay remobilization and translocation, following gravitation, mainly takes place in the albeluvic tongues of Albeluvisols, but the final step of intercalation formation involves water that is pressed from the tongues into the surrounding matrix, which means that clay translocation in this case has also a lateral component and that much of the clay is redistributed within the same horizon. In the case of the Norwegian soil chronosequences, albeluvic tongues seem to be required to produce clayey intercalations. However, the Btg horizon samples of the Stagnosols were taken from the central parts of the Btg horizons so that clayey intercalations that might be present in the upper centimeters of Stagnosol Btg horizons would not have been found. It seems possible that clayey intercalations are formed in the upper centimeters of Stagnosol Btg horizons by vertical water movement as well.

6. Conclusions

Soil formation in marine sediments of S Norway starts as soon as the land surface is raised above sea level. Drainage of the coarse pores and aeration of the upper part of the young soils lead to five major processes:

- i) development of deep desiccation cracks, forming a polygonal pattern;
- ii) compaction, taking place as soon as the land surface reaches an elevation above sea level that leads to drainage of the coarse pores;
- iii) pyrite oxidation, releasing sulfuric acid;
- iv) rapid decarbonatization through carbonate dissolution by acids from pyrite oxidation;
- v) precipitation of iron hypocoatings and coatings in the capillary fringe

The next morphological change, taking place also within less than 2.1 ka, is horizon differentiation into Ah, Eg and Btg horizons due to limited water permeability of the fine-textured sediments. Eg horizons become lighter in colour with time, but their lower boundary stays at about 40 cm, probably because this is the zone of most intensive bioturbation, root respiration and exudation, greatest and most frequent changes of temperature, soil moisture, and freeze-thaw cycles. It is assumed that these processes may create a boundary of physical material properties at 40 cm depth which predefine the lower boundary of the Eg horizon.

The process leading to the next morphological change in the soil profiles is clay illuviation, which is already observed in the 2.1 ka-old soil. It is assumed that clay illuviation starts in these soils when still high sodium saturation facilitates clay mobilization. This very early phase of clay illuviation is not strong enough, however, to produce argic horizons. After completion of desalinization, clay illuviation is controlled by Ca and Mg saturation, and mainly takes place at pH 6.5-5.0. Soil pH in the upper part of the 2.1 ka-old soil is already too low for significant clay mobilization. Clay illuviation is still active in all soils studied, but the upper boundary of the clay mobilization zone is at 20-50 cm depth. Progressive clay illuviation is recorded in increasing thickness of clay coatings and proportion of voids having clay coatings.

Clay mobilization and iron co-eluviation in the upper parts of the Eg horizons cease within less than 2.1 ka, whereas weathering and formation of clay minerals and iron oxides continue, leading to formation of a BE horizon in the upper part of the Eg horizon.

Albeluvic tongues start to form after 4.6-6.2 ka. They develop preferably along the polygonal desiccation cracks. Albeluvic material is washed into the cracks, and enhanced leaching of bases and clay eluviation takes place in the cracks. As both processes proceed, the albeluvic tongues get longer and wider.

Clayey intercalations are found only in the Stagnic Albeluvisols, not in the Stagnosols. The following explanation is suggested: When after snow melt or a rainy period infiltrating water arrives at the lower end of an albeluvic tongue, the tongue rapidly fills up with water, and perched water accumulates also on top of the dense Btg horizon. Water, carrying suspended clay, penetrates under pressure from the tongue into the Btg horizon, where additional clay is mobilized. The clay settles when the velocity of the water decreases, forming clayey intercalations in the dense matrix of the Btg horizon.

7. Acknowledgments

We thank Dr. Maja Kooistra for very constructive discussion on early soil-forming processes in marine sediments and for sending her PhD thesis and a number of papers on the topic, which helped us to better understand the earliest processes taking place in these soils. We also thank Professor Nicolas Fedoroff for his inspiring presentation and discussion at the 14th IWMSM in Lleida 2012, which stimulated us to examine clayey intercalations in the Norwegian thin sections more carefully. We will keep his memory in great honor.

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