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Mobility of iron-oxide associated elements in pseudogley soils; influence of parent material age and land use

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**A B S T R A C T**

Pseudogleys, a colloquial term for some Retisol-classified soils, are subjected to periodic water stagnation beneath their surface resulting in a spatially and temporally heterogeneous redox environment, which produces patterns from the dissolution and precipitation of Fe (oxy)hydroxide minerals. This study investigates the mobility and redistribution of other soil elements, namely metals, associated with reducible Fe (oxy)hydroxide minerals (extracted by citrate-bicarbonate-dithionite) in four Danish pseudogley profiles under forest or agricultural land use and with Saalian-age or Weichselian-age parent material. Of the analyzed elements, a depletion of Fe and Mn was observed in the upper horizons, while Co, Cr, Cu, Ni, and V showed mobility in the matrix of pseudogley profiles, influenced by redox activity, podsolization, and clay illuviation soil forming processes. Further, Cr and V showed horizontal redistribution in the argic horizon, likely due to an Fe (oxy)hydroxide-influenced precipitation gradient along the macropore structures. The influence of agricultural land use suggests reduced mobility of Fe, Cr, and V but not Mn, Co, Cu, or Ni compared to forested land use, which supports greater acidification and podsolization processes. Older, Saalian-age parent material led to more mottled retic properties while younger, Weichselian-age parent material produced glossoic and retic properties. The findings of this study conclude that not only Fe and Mn are influenced and mobilized by the redox conditions of pseudogley soils, but that some elemental redistribution may also be influenced directly by an Fe-controlled gradient along the macropore structures.

**1. Introduction**

Pseudogley soils are characterized by periodic water stagnation above a denser clayey subsurface horizon. This dense material stops waters from passing through, creating a chemically reducing environment that facilitates the redistribution of iron oxide minerals and other susceptible elements (Borch et al., 2010; Driessen and Deckers, 2001; Westergaard and Hansen, 1997; Vpraskas and Wilding, 1983). While pseudogleys are not a specified WRB Reference Soil Group, they classify as Retisols, Podzols, or Luvisols (IUSS Working Group WRB, 2015; Dondeyne and Deckers, 2019).

When the parent material of pseudogleys originates from clay-rich glacial deposits, known as moraine till, networks of fractures offer preferential flow pathways for percolating soil water (Beven and Germann, 1982). These fractures, referred to as macropores, developed because of freeze–thaw cycles from permafrost conditions and from the shrinking and swelling of clay minerals during pedogenesis in a periglacial, or near-glacial margin environment. Through this preferential transport, macropores allow for clay and iron illuviation to occur. This can generate an albic material, much paler and lower in color chroma compared to the clay-rich argic horizon to which it infiltrates. The border between the two materials is thus defined by a strong reddish-ochre face concentrated in redistributed iron. This redistribution occurs through the reduction of iron that is chemically and biologically controlled by the degradation of soils organic matter (SOM), followed by the dissolution of iron that is initially facilitated by periodic water stagnation above the argic horizon (Lindbo et al., 2010).

Pseudogley features are typically observed at the boundary between the eluvial E and illuvial B horizons of a soil profile (IUSS Working Group WRB, 2015, Vpraskas and Wilding, 1983). The resulting pseudogley features are described as glossoic properties, where albic material from the E horizon descends as deep tongue patterns into the underlying B horizon, or as retic properties, where there is an interfingerling of albic material into the B horizon (IUSS Working Group WRB, 2015). It is important to note that other soil forming processes, such as clay illuviation, podsolization, weathering, and geological shifts in parent

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material, may enhance or alter these features (van Ranst and De Coninck 2002; Volungevičius et al., 2019). Their global distribution may be constrained to regions affected by recent glaciation periods, either covered by ice or near the glacial margin, which today refers to soils within the transition zone of the frigid and cryic soil temperature regimes (mean annual temp 0 to 8 °C) (Bockheim, 2015).

While the mobility of iron and various elements in redox-mediated soils has been investigated (Fekiacova et al., 2013; Motuzas et al., 2016; Ponizovsky et al., 2001; Rasmussen et al., 2001; Westergaard and Hansen, 1997; Filipovic et al., 2016), there are few that put it in the context of the soil forming processes influenced by parent material, which considers type, age, degree of weathering and macropore development (Kühn et al., 2006; Bockheim 2015; Szymański et al., 2017; Sauer et al., 2009; Sauer et al., 2013), as well as in the context of land use, which incorporates factors of pedogenic evolution (Szymański et al., 2014; Corru et al., 2007; Citeau et al., 2002; Montagne et al., 2013; Montagne et al., 2016). Further, the mobility and redistribution of other elements within pseudogley features in association with Fe has not been addressed. The aim of this study was to investigate the distribution and mobility of Fe-oxides in pseudogley soils and features in the context of land use and parent material and to examine redistribution of various elements associated with the reducible fraction of Fe. Such a study is relevant for understanding the influence of pseudogley soils and related processes on metal mobility, including that of heavy metals, which may have significance for natural resource management.

2. Materials and methods

2.1. Site and profile characterization

Four soil profiles across Denmark were used for this study; three (Slagelse, Trækris, and Grundf) had previously been sampled (Fig. 1). The Trækris profile has a pseudogley developed from older parent material, with moraine till deposits originating from the Saalian Glaciation (~300–130 ka BP) and with overlying aeolian sand deposits originating from the Weichselian Glaciation (115–20 ka BP) (Granat, 2000). The Slagelse, Munke-skov and Grundfør profiles have pseudogleys developed from younger parent material, with moraine till deposits originating from the Weichselian Glaciation (150–20 ka BP) (Nielsen-Houmark,1981). The Slagelse site has been under deciduous (Quercus and Fagus) forest land cover and the Munke-skov site is covered by a Norway Spruce (Picea abies) stand, but was originally deciduous forest. The Grundfør site was previously under agricultural land use, but is currently a young beech (Fagus) forest. The Trækris site is characterized by bog-vegetation. Additional horizon descriptions and photos are included in the supplementary material.

2.2. Soil sampling and data analysis

Profiles with approximate dimensions of 1 × 2 m were dug and bulk samples collected from the core of each pedogenic horizon (Table 1). Depth of the argic horizon, defined here as the horizons containing pseudogley features, is indicated in Fig. 2a. In the argic horizon, additional samples were taken of the distinct pseudogley features, which required a minimum of 5 mm in width for sampling (Fig. 2b). These features were categorized as albic when collected from the pale or grey material, and ped face when collected from the strong reddish-orange, Fe-rich walls of fractures (Fig. 2b). Matrix samples were collected from the surrounding non-color specific soil with a minimum of 10 mm distance from face or albic material. The matrix sample material sampled from the argic horizon at Trækris was labelled mixed because of difficulty separating it from the face material.

Samples for physical and chemical analysis were air-dried at room temperature, crushed and sieved at < 2 mm (Retsch, 565/Haan, Germany), and pulverized by ball mill (Fritsch Pulverisette, Germany). Soil pH in H2O, total carbon determined by dry combustion (Elementar Vario Macro Cube instrument), and soil texture by hydrometer method (Gee and Bauder, 1979) were performed on the matrix samples from each horizon, and for the mixed sample for 2Bg horizon of Trækris.

Total free Fe, Mn, and Al oxides and (oxy)hydroxides and associated soil elements were extracted in triplicate with 0.3 M citrate-bicarbonate-dithionite (CBD) at pH = 8 (Mehra and Jackson, 1960). The elements were quantified in closed-digested samples and ICP-OES (Agilent Technologies 5100) with drift evaluated based on 1515 apple leaves. Statistics were run using the Excel Data Analysis heteroscedastic t-Test. For analysing data within matrix, face, and albic samples, concentrations were normalized to the albic material and expressed as “percent of albic” as these were expected to have the lowest concentrations. Additionally, a ratio was used to compare elemental distribution in the pseudogley features to Fe distribution in the pseudogley features. This is hereon referred to as the Fe ratio and was calculated according to the following equation:

$$\text{Fe ratio} = \frac{\text{element (mg kg}^{-1}\text{) inface/element (mg kg}^{-1}\text{) inmatrix}}{\text{Fe (mg kg}^{-1}\text{) inface/Fe (mg kg}^{-1}\text{) inmatrix}}$$

3. Results

3.1. pH, carbon, and texture analysis

Most of the profiles showed a general trend of pHH2O increasing with depth. This was most pronounced in the Slagelse and in Munke-skov profiles and less pronounced in the Grundfør profile (Table 1). The pH in the Trækris profile fluctuated with depth but remained within a similar range to the Slagelse and Munke-skov profiles. Percent soil organic carbon (% SOC) was highest in surface horizon of all profiles except that of Trækris, where 1.79% was found in the Bh horizon. Some additional
SOC (0.22–0.25%) was found in the Slagelse 2B/E1 horizon, the Munkeskov Btg/E horizon and the Trækris 2Bg horizon.

### 3.2. Vertical distribution of elements

For all four profiles, CBD extractable Fe concentrations were highest in the clayey horizon: 9348 mg kg⁻¹ for Munkeskov Btg/E, 6009 mg kg⁻¹ for Slagelse 2B/E1, 5396 mg kg⁻¹ for Grundfør Btg/E1, and 3782 mg kg⁻¹ for Trækris 2Bg (Fig. 3). Manganese concentrations were higher near the base of all profiles compared to the upper horizons. Mn was found in higher concentrations at greater depths than Fe; the highest concentration of Mn was found in Slagelse 2B/E2 horizon (713 mg kg⁻¹), followed by Grundfør Btg/E2 horizon (430 mg kg⁻¹), Munkeskov Btg horizon (416 mg kg⁻¹), and Trækris 2Bg horizon (73 mg kg⁻¹). The behavior of Al was less consistent between profiles. Concentrations of Al remained relatively consistent even between upper and lower horizons of the Slagelse profile, with the highest values in the 2B/E1 horizon (918 mg kg⁻¹). Concentrations decreased with depth in the Grundfør profile, with the highest values in the A horizon (1464 mg kg⁻¹). Concentrations increased with depth until the Bs horizon for Munkeskov, with the highest values from Bs matrix (2023 mg kg⁻¹). Highest concentrations from all profile matrix material was found in the Trækris Bhs horizon (6013 mg kg⁻¹).

The vertical distribution of Cr and V was comparable to Fe across all four profiles. Concentrations of Cr were low in the A horizon for all profiles. Concentrations increased with depth until the Bs horizon for Munkeskov, with the highest values from Bs matrix (2023 mg kg⁻¹). Highest concentrations from all profile matrix material was found in the Trækris Bhs horizon (6013 mg kg⁻¹). The vertical distribution of Cr and V was comparable to Fe across all four profiles. Concentrations of Cr were low in the A horizon for all profiles. Concentrations increased with depth until the Bs horizon for Munkeskov, with the highest values from Bs matrix (2023 mg kg⁻¹). Highest concentrations from all profile matrix material was found in the Trækris Bhs horizon (6013 mg kg⁻¹).
Munkeskov, respectively, while those for Grundfør remained relatively consistent with depth.

The next most comparable elements to the Fe vertical distributions in all profiles were Cu and Co. Concentrations of Cu were < 2 mg kg\(^{-1}\) with the highest values in the Btg horizon of Munkeskov (1.79 mg kg\(^{-1}\)). For the Munkeskov and Slagelse profiles, there was a less dramatic variation in Cu concentrations with depth compared to Fe. In the Trækris profile, the increase in Fe occurred at a higher depth than for Cu, while the Fe and Cu trends for the Grundfør profile were similar. For all profiles, Co concentrations were < 6 mg kg\(^{-1}\) with the highest values in the matrix.

Fig. 3. Concentrations of elements in the matrix samples for all profiles according to the lower horizon boundary. Error bars indicate the standard deviation. For exact sampling depths, see Table 1.
material from the Btg/E2 horizon of Grundfør (Fig. 3).

While a number of data points from Ni, Pb, and Cd fell below the minimum detection levels, similar trends to Fe distributions were observed for specific profiles. This was apparent in Slagelse for Cd and Ni, in Grundfør for Pb, in Munkeskov for Ni, and in Trækris for Cd and Ni (Fig. 3). Extracted Ca, Mg, and K remained relatively low for most profile distributions, and slight increase towards the argic horizon. K showed higher concentrations in the upper horizon of Trækris, most likely due to sea spray from the west coast of Jutland, Denmark.

3.3. Horizontal distribution of elements

When considering all CBD extractable elements (Fig. 4), there were significant differences ($p < 0.05$) between the albic and face, albic and matrix, and face and matrix material. For Fe, Cr and V, the face material had significantly higher concentrations than the albic material as well as the matrix material in all profiles. Only for the Trækris profile was Ni significantly higher in the face material compared to the matrix. Only for the Slagelse, Grundfør, and Trækris profiles was Al significantly higher.

Fig. 4. Comparison of element concentrations in pseudogley features (face, albic, and matrix samples) of the (topmost) argic horizon. Data is normalized to the albic material and presented as a percentage of the albic material.
in the face material compared to the matrix. In contrast, Mn was highest in the matrix and not in the face material, with the exception of the Slagelse profile. Similarly, Co and Cu showed concentrations in the matrix material significantly higher than in the face material for Slagelse, Grundfør, and Trækris.

The Fe ratio described in the methods was used to compare closeness of the elements to Fe’s horizontal distribution and accumulation in the face material and thus to determine which of the elements might have been influenced by the reductive dissolution of Fe in the argic horizon (Fig. 5). The Munkeskov profile showed the most elements with ratios closest to a value of one, followed by that of Slagelse, Grundfør, and Trækris. The only elements with ratios from all profiles between 0.5 and 1 were Cr, Ni, and V. A few of the elements showed Fe ratios > 1, e.g. for Pb and Cd in the Munkeskov profiles, for K in the Trækris profile, and for Zn in the Grundfør profile.

4. Discussion

4.1. Element mobility and distribution

Independent of the influence of land use and parent material on vertical trends, V and Cr showed a vertical and horizontal distribution pattern similar to Fe in the four profiles, indicating comparable redox processes and their release from sorption to Fe-oxides. The horizontal distribution was supported by the closeness of the Fe ratios to one from all profiles for both V (0.87) and for Cr (0.80).

Increasing concentrations of dissolved V have been found to be coupled with increasing concentrations of Fe^{2+}, while higher concentrations can result from the re-adsorption onto amorphous Fe-oxides (Shaheen et al., 2019). In the upper soil horizons, V was likely to exist as the oxidized form V^{5+} (Gustafsson and Johnsson, 2004, Gustafsson, 2019). Upon water saturation in the argic horizon, a shift would occur towards the reduced form V^{4+} and VO^{2+} within the albic material (Gustafsson and Johnsson, 2004, Gustafsson, 2019). This would create a horizontal gradient with diffusion towards the matrix and would result in its precipitation in the face material, similar to Fe. The reoxidation process at higher pH (5–7) found in the argic horizon and at a higher redox potential could also lead to the formation of H_{2}VO_{4}^{-}, which is capable of sorbing to metal hydroxides (Larsson, 2014).

For the case of Cr, both Fe and Mn-oxides can play a role. While the anionic species chromate and dichromate (Cr^{6+}) can adsorb to Fe-oxides, the presence of dissolved Fe^{2+} and SOM at pH < 5.3 can facilitate a reduction to Cr^{3+} (Jae and Dixon, 2002; James and Bartlett, 1983). Further, with higher concentrations of Mn oxides, which was observed at the base of most of the profiles, the rate of oxidation back to Cr^{6+} could increase (Jae and Dixon, 2002). These complex interactions, especially in relation to low pH conditions, were likely responsible for the higher concentrations of Cr found at greater depth for the Trækris, Munkeskov, and Slagelse profiles. Given that only Munkeskov had consistent parent material throughout the entire profile, it is not possible to discern whether redox processes were responsible for downward mobility in all pseudogley profiles. In the Slagelse, Grundfør, and Munkeskov profiles, a horizontal redistribution of Cr was observed. In a similar process to V, the reduced Cr^{3+} from periods of water saturation would have migrated towards the face and matrix material where it became oxidized and precipitated.

While Fe is one of the main indicators of pseudogley features due to the visibly Fe-rich ped faces, it is not the only redox-sensitive element that responds to the conditions and the soil forming processes of clay illuviation and later podsolization that are present. Compared to Fe, Mn appeared to be more mobile and depleted from the upper horizons. This was likely a result of pH and redox potential, since Mn has a higher redox potential than Fe. When redox potential (Eh) is high, Mn requires at least a pH between 7 and 8 to precipitate as MnO species, while Fe can form oxide species at lower pH values (Brookins, 1988; McBride, 1994; McBride, 1989). Only Munkeskov and Grundfør profiles had a pH at the base of the profile close to 7 (6.8), and both profiles had consistent parent materials. However, the profile of Grundfør did not show as drastic a depletion in Mn as that of Munkeskov. This could be explained by a higher pH throughout the Grundfør profile, which allows for...
continued Mn oxide mobilisation from less intense redox activity (Cornu et al., 2007). The Slagelse profile, defined by lower pH values (4.5–6.0), contained more Mn in the lower horizons defined by a higher clay content parent material. Since matrix leaching of Mn is commonly observed in well-drained acidic soils (Blume and Schwertmann, 1969), it is unsurprising that there was no Mn found in the sandy and podzolized A-Bhs horizons of Trækris. The denser 2Bg horizon showed significant depletion in the albic material similar to observations from the Munkeskov profile.

The profile behavior of Cu and Co did suggest some downward mobility in the non-differentiated parent material profiles. For Slagelse and Trækris, the upper horizon with a younger parent material showed no real change in concentrations with depth, while the clay-rich horizon with an older parent material showed an increase in concentrations with depth. One reason why Cu may not have shown as a clear of a downward mobility as Fe and Mn was due to pH conditions. Below a pH 5.5, OH groups on the surface of oxide minerals will dissociate, leading to Cu-hydroxide complexes and therefore less Cu²⁺ in solution available for transport (Salam and Helmeke, 1998). This is the case with all profiles’ upper horizons, except Grundsfjr, which had pH > 5.5. At a pH > 5.5, the activity of Cu²⁺ in solution begins to increase, which then allows for increased Cu mobility and potential binding to Fe-oxide surfaces (Salam and Helmeke, 1998). This may have been the case in the 2B/E1 and 2B/E2 horizons in Slagelse, and in the Btg/E1 and Btg/E2 horizons in Grundsfjr. Ponizovsk et al. (2001) also proposed a ternary cation exchange mechanism between Cu²⁺, Ca²⁺ and protons as responsible for increase of Cu²⁺ sorption in a pseudogley-like soil. The mobility of Co was likely dependent on the soil oxide materials, which would have showed a strong sorption preference to Co over clay minerals (McLaren et al., 1986).

Soil pH may have played a role in the distribution of Ni, Cd, and Pb. Most of the data for Cd and Pb fell below the limit of detection (LOD), and thus due to limitations in data, neither Cd nor Pb will be discussed. Ni showed noticeably higher concentrations in the argic horizons of most profiles. With a rise in pH, the dissociation of hydroxide groups from Fe-oxide mineral surface allows metal-hydroxy complexes to form and opens up binding sites on the surface of the Fe-oxides, which was why Ni may have reached higher concentrations at the base of the profiles, with the exception of Grundsfjr. However, Ni was also quite high in the A horizon of Grundsfjr, a likely consequence from agricultural activities, and may have distorted the relationship with depth. Of the other three profiles, only in Munkeskov could mobility be considered because of homogenous parent material. However, an increase in Ni with depth was only observed between the Btg/E and Btg horizons, which had pH 6.8. While downward mobility could not be considered, the data from the pseudogley features could still be used to discern a relationship with Fe. When looking at Ni in the face material compared to the matrix material, it was observed that only the Trækris and Munkeskov profiles supported a Ni-Fe oxide co-precipitation mechanism within the pseudogley features since Ni concentrations were significantly higher in the face material compared to the matrix material and Fe ratios were close to one.

4.2. Land use

The most apparent influence of agriculture and forest on pseudogley element mobility was observed in the profile distribution of Fe at Grundsfjr compared to Munkeskov. A higher pH and clay content throughout the Grundsfjr profile caused little or no Fe mobilisation from the top horizons. According to Eh-pH stability diagrams, Fe is not likely to exist as divalent ions at this pH (Brookins 1988). The same effect was observed in profile distributions of Cr and V, however, it was not observed for Mn, Co, Cu, and Ni. Higher soil pH has also been shown to reduce clay illuviation in pseudogley-like soils as observed in the profile of Grundsfjr with a more consistent clay content from profile surface to base. In addition, high pH has been shown to reduce the volume of albic material and iron-rich faces, which could have led to smaller preferential pathways and less metal translocation (Montagne et al., 2008; Montagne et al., 2013; Montagne et al., 2016; Cornu et al., 2007, 2012; Quénard et al., 2011). Ploughing activity has been shown to expand the A horizon into the E horizon with a gradual degradation of albic material and pseudogley features as tillage erosion lowers the lower boundary of the A horizon (Dondeyne and Deckers, 2019; Glin et al., 2013; Kühn et al., 2006; Volungevičius et al., 2019). While the pseudogley features at Grundsfjr were preserved, there was no obvious E horizon. Volungevičius et al. (2019) found that these physical changes to the horizon structure remained prominent after >70 years with no active agricultural activity. Even as a young forest now covers the Grundsfjr profile, the effects are still apparent.

The other three profiles serve as an example of forested pseudogleys and they share the strongly acidic surface horizons with varying degrees of podsolization (~pH 4–4.5), which in addition to redox activity, enhances some metal mobility in the profiles. The periodically water-saturating conditions present in the upper argic horizons likely arose from lower transpiration rates in winter seasons and more deeply penetrating roots; water absorbed by the trees comes from much further down in the profile thus allowing pseudogley features to develop at the 2 m depth observed. The forest vegetation further produce organic acids that may have enhanced clay illuviation, facilitating coarser-textured pathways of transport within the albic material and mobility of metals, which could explain the conditions at the Munkeskov and Slagelse profiles. Likewise, the deposition of a coarser textured parent material on top of the pseudogley features would have the same affect, which was observed in the Slagelse profile.

The profiles compared did not show a clear distinction in pseudogley pattern or structure based on land use. The findings of Montagne et al. (2008), Montagne et al. (2016) and Cornu et al. (2007, 2012) suggest that cultivation decreases the amount of ochre-colored soil volumes, which is interpreted as the iron-rich face to the albic material. It would follow then that the glossic and retic properties were less distinct under agricultural land use. However, that was not observed at the Grundsfjr profile, which actually had well-defined glossic and retic properties. Therefore, the conclusion is that the land use changed mobility of the elements, but did not interfere with the existing pseudogley features. This may be more closely related to clay weathering rather than illuviation, which was not quantitatively investigated in this study.

4.3. Parent material

The relative ages of the profiles, as defined by the presence of old or young moraine till at depths > 50 cm, was reflected in some of the metal distribution. This was most obvious for the Trækris profile, where higher Fe content in the 2Bg horizon likely arose from weathering processes in the clayey 2Bg horizon as well as podsolization of the upper horizons. Therefore, it is impossible to know the extent of vertical redistribution of Fe due to reductive dissolution. The same could be proposed for Slagelse, whose younger moraine till parent material was overlain with even younger, slightly coarser textured material. The higher Fe content in the 2B/E1 and 2B/E2 compared to the overlying B and E horizons likely results from weathering within the 2B horizon and thus the extent of vertical mobility from reductive dissolution cannot be asserted. Further, the local water table at 115 cm depth at Trækris introduced additional groundwater-induced stagnation on top of the precipitation induced stagnant water, which could have influenced more motting and degraded-retic properties. Here, the albic material was likely a result of gleyisation where groundwater periodically contributed to saturated conditions and horizontal diffusion of Fe into the matrices. Since the level of the water table likely changed over the past 150,000 years, it is difficult to say whether it played a role in the development of a pseudogley structure. High SOC in the subhorizon (1.79% in Bh and 1.9% in Bhs) most likely supports a greater redox potential in the 2Bg horizon, supporting reductive dissolution and reoxidation within that horizon.
and thus the horizontal redistribution of Fe. The upper horizons were acidic (pH 4.6, 5.0, 4.5), lending itself to the mobilization of many soil metal components. However, not all elements accumulated at the base of the Trækris profile with Fe, and this was likely due to competing sorption from Al-oxides, which resulted from accumulation of leached sesquioxide in the Bhs and Bhs horizons. Following Al was Cr and V, which peaked in the Bhs horizon.

Unlike in the Trækris profile, the younger moraine till from the Weichselian Glaciation, found in Slagelse, Grundford, and Munkeskov profiles, experienced less weathering, and low pH conditions likely supported clay translocation to a greater extent, which may have been more essential for the formation of strong pseudogley features displaying gossic and retic properties. This was also supported by the Fe ratio results. The Trækris profile had values furthest from one, while those of Slagelse, Munkeskov, and Grundford had the most elements with Fe ratios close to one.

The younger till profiles also shared high SOC content in their A horizons and noticeable organic matter build-up (Appendix A, Table A.1, A.3, and A.4), whereas the older till showed a leaching effect with higher SOC in Bh and Bhs than Ap and E horizons (Appendix A, Table A.2). Due to the SOC, the younger till may have experienced better conditions for microbially-assisted reduction, which then would have facilitated greater release of Fe-oxides and bound metals and therefore greater mobility.

5. Conclusions

The four Danish pseudogley profiles Slagelse, Trækris, Grundford and Munkeskov reflect the modern and relic redox behavior of periglacial and permafrost-influenced soils and their subsequent effect on element mobility. The reductive dissolution of Fe-oxides facilitates both matrix and preferential transport of Fe to greater depths where dispersion and diffusion is influenced by cycles of wetting and drying. The other elements Co, Cr, Cu, Mn, Ni, and V are mobilized under the pseudogley conditions described. However, agricultural influence changes the behavior of Fe, Cr, and V, with V and Cr that follow Fe’s horizontal redistribution in the argic horizon. Forested land use may allow for the preservation of pseudogley features with other soil forming processes of acidification, podsolization, and clay illuviation. Older, Saalian-age parent material appears to lead to degraded pseudogley features and less horizontal redistribution of elements, which is likely supported by a greater degree of clay weathering, while younger till maintains clear retic and gossic properties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2022.115801.

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