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Proglacial sediments in High Arctic glacier foreland: A case study of Werenskioldbreen, Svalbard

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Abstract: The glacier environment exhibits a high sensitivity to global climate change, leading to progressive deglaciation and the exposure of previously ice-covered land. The newly exposed terrain provides a valuable opportunity to observe rapid ecosystem changes, such as the accumulation of glacial sediments, the development of soil-forming and progressive alterations in water and biogeochemical cycles. While developing hydrological and hydrogeological models for the Werenskioldbreen proglacial expanding zone, we encountered a significant problem due to insufficient data for parameterizing glacial sediments, which constitute the environment for water flow and storage. This study provides detailed insight into the physicochemical parameters of glacial sediments and classifies them in terms of grain size distribution, hydraulic conductivity, pH and the content of carbon (C_{org}), nitrogen (N_t) and phosphorus (P_t). We found that the marginal outwash plains of Werenskioldbreen are characterised by gravelly sand, sandy gravel and silty sand (28.6%, 23.8% and 19% of the total sample contents, respectively). The lateral moraine contains sandy clayey silt, silty sandy gravel or sandy gravelly silt (7.1%, 4.8% and 2.4 % of the total sample contents, respectively). The chemical parameters of young glaciofluvial sediments have lower values than those of moraines. C_{org} ranged from 0.07% to 2.70%. N_t was < 1.00 g kg^{-1} for 95% of the samples and < 0.5 g kg^{-1} for 81% of them. P_t was between 0.48 and 1.18 g kg^{-1}. In line with the studies on this subject already published, we confirm that there is clear a relationship between the type of geomorphological form, its age, and the physicochemical parameters of glacial sediments.

Keywords: Arctic, Spitsbergen, glacial sediments, grain size, hydraulic conductivity.

Introduction

Numerous long-term studies of the polar environment indicate its high sensitivity and vulnerability to the impact of global climate change (Hanssen-Bauer *et al.* 2019; IPCC 2019, 2021). Svalbard is no exception in this regard, as evidenced by long-term observations of the air temperature and changes in precipitation structure (Førland *et al.* 2011, 2020; Isaksen *et al.* 2016; Hanssen-Bauer *et al.* 2019). The most sensitive to climate change are ice masses. The glacier mass loss and recession continue to intensify (Schuler *et al.* 2020; Bhattacharya *et al.* 2021; Kochtitzky *et al.* 2022; Rounce *et al.* 2023). Especially significant are the recession and ice-loss of land-based glaciers, which are exposing new terrains of the expanding proglacial zone (D'Agata *et al.* 2020; Bosson *et al.* 2023). These unexplored areas provide a great opportunity to study the development of the ecosystem over time (Bernasconi *et al.* 2011). Bosson *et al.* (2023) conclude that in general the loss of glacier area between 2020 and 2100 will range from 22 ± 8% to 51 ± 15%, depending on the analysed climate scenario.

Ongoing climate changes in glacierised catchments affect the surface and subsurface phenomena such as permafrost and thickness of active layer (Etzelmüller *et al*. 2011; Biskaborn *et al.* 2019; Christiansen *et al*. 2021), affecting a potential volume of water storage within the foreland (Müller *et al.* 2022). A global study by Bosson *et al.* (2023), highlights the importance of glacier's negative mass balances, their volume and surface area loss, the glacier's contribution to the catchment water supply, which will act as a negative or positive feedback that will, respectively, limit or enhance climate change. Glacier retreats generate dynamic local geomorphological changes (Ballantyne 2002; Midgley *et al.* 2018) and hydrology, particularly in modifying drainage pathways and water circulation times (Huss and Hock 2018; Nowak *et al*. 2021). Changes in catchment's water circulation, altering the water balance, may lead to the increased supply and mass transport of chemical and organic compounds (Milner *et al.* 2009, 2017; Battin *et al*. 2023). Rivers play important role in transport of biogeochemical material, but also act as biogeochemical reactors (Battin *et al.* 2023), supporting biogeochemical deposition in glacial sediments (Khedim *et al.* 2021).

The main aim of the present study is to classify the Werenskioldbreen proglacial sediments in order to determine various input parameters required for hydrological and hydrogeological modelling. Such an approach was motivated by a lack of good quality, up-to-date data for the study area. The demand for such data will increase as the extent of the proglacial zone enlarges and the active zone becomes deeper (Ming-ko Woo 2014; Yang *et al.* 2021; Stachniak *et al.* 2022). This research focuses on the following physicochemical parameters: grain size, hydraulic conductivity, pH and the content of carbon (C_{org}), nitrogen (N_t) and phosphorus (P_t). The authors also compared the results with previous research from the 1980s, when the area's geomorphology was slightly different and less diverse (Karczewski and Wiśniewski 1979), and added new data, especially concerning the increasing outwash plains from which surface and groundwater are discharged. The characterisation of the physical data, supported by selected chemical analyses of the sediments, can also be used to interpret soil-forming processes or future vegetation expansion studies.

Study area

The Werenskioldbreen basin is situated in Wedel-Jarslberg Land, south-west Spitsbergen (Fig. 1). It has an area of 44.1 km^2, 59% of which is glaciated, as of 2017 (Ignatiuk *et al.* 2022). Werenskioldbreen is a land-based, valley-type glacier (Jania 1988; Hagen *et al.* 1993) with a frontal zone directly frozen to the ground, continually receding at a rate of *ca.* 25 m per year (Ciężkowski *et al.* 2018). Mountain ranges, ice-cored lateral moraines and the terminal moraine clearly outline its basin's boundaries. The inner marginal zone is closed with only one outlet in the south-western corner of the terminal moraine, through which the Breelva river drains from the catchment area towards the sea. This basin has been studied since the 1960s by members of Polish expeditions. Bibliography of hydrological studies conducted in the Hornsund area, including the Werenskoldbreen area, from 1959 to 1993 has been compiled by Jania (1995). Additionally, a detailed description of the basin from that period was provided by Leszkiewicz (1987). It can be concluded that this basin is a longstanding research laboratory and has long history of hydrological observations, including continuous glaciological and hydrological monitoring (Majchrowska *et al.* 2015; Ignatiuk *et al.* 2022).

According to long-term meteorological data acquired at the Polish Polar Station in Hornsund, located 16 km from the Werenskioldbreen basin, the mean annual air temperature for 1979–2018 in this area was −3.7ºC (maximum −1.3ºC, minimum −6.0ºC) and the mean annual precipitation was 478 mm (Wawrzyniak and Osuch 2020). The mean estimated air temperature increase was 1.14ºC per decade; moreover, precipitation trend analyses showed an increase of 61.6 mm per decade for the annual precipitation totals (Wawrzyniak and Osuch 2020).

Studies conducted by Førland *et al*. (2011) in various regions of Svalbard, based on meteorological data from the period 1912–2011 (Svalbard Airport 1912–2011, Bjørnøya 1920–2011, Hopen 1946–2011, Ny-Ålesund 1943–2011), also reveal a similar trend of temperature increase. The average annual temperature has increased by 1.0–1.2ºC per decade, and annual precipitation has increased by *ca.* 2–4% per decade. Additionally, projections of future conditions indicate a continuing trend of warming rate for the Svalbard Airport, which equals 0.6ºC per decade. It is a much higher warming than that observed during the last 100 years at 0.25ºC per decade (Førland *et al.* 2011), and much higher than the global average rate of warming of 0.18ºC per decade (Wawrzyniak and Osuch 2020; NOAA 2023). As a result, the increase of air temperature results in the rising of ground temperature and deepening of the active layer in Hornsund (Wawrzyniak *et al.* 2016; Osuch *et al.* 2019) and in Svalbard in general (Etzelmüller *et al.* 2011; Christiansen *et al.* 2020). Permafrost and the depth active layer, which are sensitive to climate change, have a significant impact on geomorphological, hydrological, hydrogeological and soil processes (Ming-ko Woo 2014) in the Werenskioldbreen foreland.

The Werenskioldbreen bedrock is part of the Hecla Hoek Formation and includes complexes of metamorphic and seafloor rocks (Birkenmajer 1990). The bedrock consists of three Proterozoic tectonic blocks: (*i*) the Sofiebogen Group with the Jens Erikfjellet Formation in the northern part of the basin, composed of greenstones, greenschists and carbonate-chlorite-quartz schists (Czerny *et al.* 1992; Mazur *et al.* 2009); (*ii*) the Deilegga Group in the north-eastern part of the basin, consisting mainly of various phyllites and laminated quartzite schists with numerous quartz intrusions and thin overlying carbonate rocks (Birkenmajer 1990; Czerny *et al.* 1992); and (*iii*) the Eimfjellet Group in the central and southern part of the basin, which includes the Elveflaya Formation consisting of marble-quartzite and granite-quartzite metaconglomerates, calcite marbles, quartzites and quartzitic schists, mica-carbonate-quartz and quartz-muscovite schists (Mazur *et al.* 2009). The Angellfjellet massif is built of amphibolites and mica schists with intercalations of quartzites of the Eimfjellet Group (Czerny *et al.* 1992; Mazur *et al.* 2009).

The marginal zone of the Werenskioldbreen foreland extends for *ca.* 2.5 km from the grounding line to the terminal moraine (Fig. 2). The most significant part of this zone consists of ground moraine overlying bedrock or older glacial sediments, covered by moraine cobbles and partly by the outwash deposits of proglacial rivers (Migała *et al.* 2013). Other primary geomorphological forms include sandurs with ramparts and dirty cones, sandur fans and plains, and moraines (Olszewski and Szupryczyński 1980; Karczewski *et al.* 1984). Recessional moraines, up to several metres in height, form in front of the glacier terminus (Migała *et al.* 2013). In the northern and central parts of the marginal zone, towards the terminal moraine, there are patches of internal sandur. These forms are continuously transformed owing to the highly dynamic thermo-erosional changes in inactive glacier ice degradation, solifluction and ongoing fluvioglacial processes (Karczewski and Wiśniewski 1979; Migała *et al.* 2013).

As a result of the changes in this environment, the glacier's marginal zone is expanding, and fresh glacial sediments are being continuously exposed (Ciężkowski *et al.* 2018). Previous studies of Werenskioldbreen proglacial sediments (Karczewski and Wiśniewski 1979) indicate that their properties are related to the activity of physical processes within the geomorphological relief, *i.e.*, glacial forms. Those authors mentioned two major lithofacies of sediments as being morainic lithofacies formed by glacial accumulation, and glaciofluvial lithofacies created by meltwater processes. Both have similar genetic characteristics but were deposited under stable sedimentary conditions at various places. Accordingly, the sediments in the sandur fans and plains consist of poorly sorted sand and gravel, transformed by fluvioglacial processes. The frontal, lateral and medial moraines are composed of moraine till with an admixture of sand and gravels, often debris-covered and converted by the thermo-erosive degradation of buried ice (Migała *et al.* 2013).

The foreland surface drainage system includes a network of rivers, lakes and flooding areas supplied directly by glacier outflows, which form river channels or indirectly by glacier surface water runoff and rainfall. The central subglacial outflow – Kvisla, is located in the northern part of the glacier and drains 60–75% of proglacial waters (Piechota *et al.* 2012). The remaining well-identified outflows are Black Spring, also called Wiesława, Duszan in the central part of the forefield, and Angell in the southern part of the glacier front. These rivers, when finally merged, form the Breelva river. The water drainage system within this catchment is a developing research subject and has already been partially modelled (Pälli *et al.* 2003; Piechota *et al.* 2012; Grabiec 2017; Decaux *et al.* 2019; Stachniak *et al.* 2022).

The hydrogeology of the cold regions and proglacial areas such as the Werenskioldbreen basin is still a rare but strongly evolving field of research (Cooper *et al.* 2011; Marszałek and Staśko 2013; Dragon *et al.* 2015; Yang *et al*. 2021). This is a continuous permafrost area that commonly occurs at an average depth of between 1 m and 2.5 m in the non-glaciated terrain (Osuch *et al.* 2019; Christiansen *et al.* 2021). This involves the possibility of different levels of circulation or occurrence of groundwater, as cited by Modelska and Buczyński (2023), referring to Williams and van Everdingen (1973) conclude that the shallowest and most prevalent zone is located above the permafrost (suprapermafrost); beneath is the permafrost layer (intrapermafrost), while the deepest zone is below the permanent permafrost (subpermafrost).

Within the Werenskioldbreen foreland zone, there is a groundwater circulation in the shallow active layer zone (suprapermafrost) (Modelska and Buczyński 2023). Still, there is a possible deeper water infiltration inside permafrost within locally present taliks (Olichwer and Tarka 2018), possibly occurring in places of water bodies and along river channels (French 2007; Liu *et al.* 2022). The first 3D groundwater model-based studies of Werenskioldbreen foreland by Stachniak *et al.* (2022) present the components and characteristics of the groundwater balance, concluding that the groundwater is responsible for *ca.* 2% of the total runoff from the catchment area and that for the presented model conditions, also indicate that the groundwater filled 50% of the possible storage capacity, and show the preferential groundwater flow paths as two subsystems of shallow northern and southern groundwater circulations.

Methods

The fieldwork was carried out in the Werenskioldbreen catchment in the summer of 2017. The positions of the sediment sampling sites were determined by the need to collect fairly representative information on the sediment distribution throughout the glacier's foreland, as well as by their accessibility. A total of 42 sediment samples were collected from 18 locations (Fig. 2, Appendix 1 in Zenodo database; https://zenodo.org/records/12825842). Sampling depths did not exceed 1 m. The number of samples and sampling sites in some zones were limited because they were difficult to access due to frequent flooding or the groundwater table was shallow, which limited the profiling depth. The data collected and processed in this paper are intended for use in developing models for investigating hydrological and hydrogeological processes, so the sampling distribution was not homogeneous, concentrated mainly in areas with better sediment permeability. Areas covered with coarsely weathered material and bedrock outcrops were not taken into consideration. The largest numbers of sediment samples were taken in the south-western part of the foreland in the sandur and outwash plains in order to identify in detail the potential for water infiltration (Fig. 2). The shallow samples (< 50 cm) were taken during the installation of piezometers, drilled manually with a Dutch auger (diameter 7 cm, sample volume 0.3–0.5 kg). Unfortunately, in these deposits, this sampling method was not effective for deeper levels because of the exceedingly loose, coarse-grained material in the borehole, including pebbles and cobbles or presence of water. Therefore, a significant number of samples was obtained from shallow manual digging boreholes, and by profiling natural exposures like the channels of old streams, in natural landslides or ground crevices, *i.e.*, in lateral moraines. Samples for macroscopic examination and further laboratory analysis were collected from each different sediment in the profile. Macroscopic characterisation in the field was carried out in accordance with standards PN-EN ISO 14688-1 and PN-EN ISO 14688-2 introduced into the catalogue of Polish Standards in 2006 and are cited in PN-EN 1997-2:2009, known as Eurocode 7: Geotechnical engineering design - Part 2: Identification and investigation of soils (PN-EN 1997-2: 2009 Eurocode 7, PN-EN ISO 14688-2:2006, 2006).

The physical and chemical analyses, carried out in the Soil and Sediment Analysis Laboratory at the University of Silesia in Katowice, included granulometric analysis, pH, C_{org}, N_t and P_t. In order to examine the grain size distribution of the sediments, sieve analysis was used for the 63–0.063 mm fractions and hydrometer (aerometric) analysis for the fractions < 0.063 mm (grain size classes according to the standard PN-EN ISO 14688-2:2006, 2006). Fractions > 63 mm (cobbles, boulders and large boulders), abundant over the entire study area, were discarded prior to testing to avoid biased analyses. Part of this classification was previously used for characterising the hydrogeological properties with the aim of developing a numerical hydrogeological model of the research area published by Stachniak *et al.* (2022). In this paper, in order to discuss the foreland sediments in detail, the number of samples was reduced to the most representative ones.

Sediment pH was determined according to the instrumental method for routine determinations of pH in a 1:5 (V/V) suspension of sediment in water (pH - H_2O) and in a 1 mol l^{-1} solution of potassium chloride (pH - KCl) using a glass electrode (PN-ISO 10390:1997, 1997). Only the pH - H_2O results are considered further here, but the pH - KCl results are set out in Appendix 1: Table 2 and Table 3. The C_{org} was determined using the titrimetric (classical) Tyurin method (Jankauskas *et al.* 2006; Shamrikova *et al.* 2022), N_t was measured using a modified version of the Kjeldahl method (Sáez-Plaza *et al.* 2013) in accordance with the Polish standard PN-ISO 11261:2002 (2002), and P_t was determined using Bleck's method as modified by Gebhardt (1982).

The hydraulic conductivity of sediment samples was calculated based on grain size compositions using the methodology of Rosas *et al.* (2014), who derived 20 calculation formulas for hydraulic conductivity in the MULTI H_K program written in the VBA language (Visual Basic for Applications). The program is managed using a customised macro in MS Excel. Eleven of the twenty formulas were included in the calculations (Hazen 1892; Terzaghi 1925; Kozeny 1927, 1953; Carman 1937, 1956; Harleman *et al.* 1963; Beyer 1964; Vukovic and Soro 1992; Chapuis *et al.* 2005; Chen *et al.* 2012). The results were selected according to the terms of applicability of the formulas relative to the properties of the samples. The formulas taken for calculations are presented in Appendix 3 (Zenodo database; doi: 10.5281/zenodo.12825842). Formulas recommended for river sedimentary depositional environments worked best. The results were grouped according to the classified sediment type and were also checked against the ranges of hydraulic conductivities for a given sediment type in the literature (Pazdro and Kozerski 1990; Singhal and Gupta 2010; Barnet *et al.* 2012).

Results

Physical characteristics of the glacial sediments. — Results of this article and additional detailed data on glacial sediments are provided in Appendixes 1 to 3 and have been published in an open-access database in Zenodo (https://zenodo.org/records/12825842). Most of the field samples were loose, the predominant type of structure being single grains or massive with granular admixture, except the moraine samples. Nine types of sediments were identified, most of which were classified as gravelly sand (29% of all samples), sandy gravel (24% of all samples), silty sand and silty fine sand (19% of all samples) (Table 1). Detailed results of the sediment's granulometric composition are shown in Appendix 2. The Werenskioldbreen marginal outwash plains, mostly sandur fans and plains, are characterised by alternate layers with various types of sands and gravels of very high permeability (Fig. 3). Figure 4 shows that, in this section of the study area, the part of the profile near the surface has a greater proportion of fine fractions than the deeper part of the profile. The lateral moraine, constituting the boundary of the study area, is formed of sandy clayey silt with silty sandy gravel or sandy gravelly silt, with a significant admixture of cobbles. In the near-surface part of the profile, a higher proportion of the fine fraction than in other samples occurs; however, at greater depths, the share of coarser fraction is higher than for the sandur fans and plains (Fig. 4).

The obtained hydraulic conductivity (k) ranges were generalised for individual sediment types (Table 1). The spread of results is not significantly large, ranging in *ca.* k 10^{-2}. In addition, figure in Appendix 3 illustrates the offset of the obtained results from the empirical formulae, where the most accurate ranges are the boxes containing 50% of the results. The boxplots indicate high values of k for sandy gravel and gravelly sand (10^{-5} to 10^{-3} m s^{-1}). For various types of sand, values range between 10^{-6} and 10^{-5} m s^{-1}, while the lowest values (10^{-8} to 10^{-7} m s^{-1}) are typical for sandy clayey silt.

Chemical properties of the glacial sediments. — For the analysis of particular chemical parameters, most samples were grouped according to the three main zones from which they had been sampled (Fig. 2; Appendix 1): Zone 1 (Z1) – the northern part of the Werenskioldbreen foreland representing the outwash plain – sandur fans and plains, sandur with ramparts and cones on inactive glacier ice, and the Breelva river bank; Zone 2 (Z2) – the southwestern part of the foreland representing the outwash plain – sandur fans and plains formed near the river outlet, excluding profile U1, which wastypical material deposited by surface runoff; Zone 3 (Z3) – the southern lateral moraine. The three remaining samples, collected on the Elveflya plain (profile US16) and the Breelva and Kvisla river beds (profiles US17 and US18), were not attributed to zones Z1–Z3 as they were distinctive in location. These samples were thus not comparable with the others. However, they were treated as additional information points for particular regions of the study area.

The sediment pH (H_2O) ranged from 7.14 to 8.47 (Table 2). However, 69% of the samples had pH ≥8.2. The mean pH relative to the three sampling zones was: 8.21 for Z1, 8.31 for Z2 and 7.94 for Z3. The results from zones Z1–Z3 were typical for outwash plains of young glaciofluvial sediments, sparsely covered with vegetation. These values are shown in Fig. 5, and the variability of pH with depth in the profiles from particular sampling zones is illustrated in Fig. 6. The mean pH in the Werenskioldbreen foreland sediments was 8.28, based on 31 samples; after excluding the samples from the lateral moraine and the Elveflya glaciofluvial plain. For all the samples, the mean pH was 8.20. Four of the five samples with pH < 8.0 were collected on the southern lateral moraine Z3 (US2, 40–100 cm; US3, 20–35 cm; US3, 50–80 cm; US4, 0–5 cm), where the dynamics of physical processes were much more stable than on the frequently flooded Werenskioldbreen outwash plains. Profiles US2 to US4 contained more vegetation, and initial soil development was at a more advanced stage, *e.g.*, the blue-grey gleyic horizon in US3 (Appendix 1). This profile also had the lowest pH of all the samples, *i.e.*, 7.14, at 50–80 cm depth (Table 2). The highest pH (8.47) was measured in samples US5 and US13 in zones Z1 and Z2, respectively. The former was situated in the northern foreland, on an outwash plain crisscrossed by numerous watercourses, formed mainly during the ablation season by subartesian outflows. The latter was likewise situated on a proglacial floodplain but in the southwestern part of the research area. Here, there is a vast outwash plain (sandur), composed mainly of gravels and sands of different fractions, deposited and flushed by glacial meltwaters. Analysis of pH variability with increasing depth of individual profiles shows that, in most of them, pH increased all along the profile or remained the same (profiles US8 to US13, US15 and US16). In six profiles, pH decreased (US2 to US5, US6 and US7). Three of these profiles were located on the southern lateral moraine (US2 to US4), and two (US6 and US7) were on the Kvisla and Breelva riverbanks

The Soil Organic Carbon Content (C_{org}) ranged from 0.07% to 2.7% (Table 2). Thirty samples (71% of all samples) had $C_{org} < 1.0\%$. In ten samples (24% of all samples), $C_{org} > 1.0\%$, reaching a maximum of 1.5%. C_{org} exceeded 2.0% in only two samples: 2.47% (US5, 40–50 cm) and 2.7% (US4, 0–5 cm). The high C_{org} in the deepest part of US5 is somewhat unusual, although this value increases gradually with depth throughout the profile. Moreover, C_{org} was higher in the deeper parts of US7 and US15, located in the northern foreland section (Z1) (Table 2). The lowest C_{org} (0.07%) was measured in two samples located in the westernmost part of the forefield (Table 2). The highest C_{org} (2.7%) was from the moraine, which is, theoretically, a more stable region in terms of environmental dynamics. Relative to the three sampling zones mean C_{org} was: 0.94% for Z1, 0.74% for Z2 and 0.89% for Z3 (Fig. 4 and Fig. 6); mean C_{org} for all samples was 0.82% (Figs. 7 and 8).

The total nitrogen content (N_t) for 40 of the 42 sediment samples was 0.0 to 1.0 g kg^{-1}; in 34 samples $N_t < 0.5$ g kg^{-1}. Mean N_t in the three sampling zones was: 0.30 g kg^{-1} for Z1, 0.30 g kg^{-1} for Z2, and 0.52 g kg^{-1} for Z3 (Figs. 7 and 8). Mean N_t for all the samples was 0.37 g kg^{-1}. There were only two samples that exceeded 1.0 g kg^{-1} of N_t such as US15 (0–5 cm, N_t = 1.25 g kg^{-1}) and US4 (0–5 cm, N_t = 1.46 g kg^{-1}), the latter value being the highest N_t in all the samples. The lowest N_t (0.01 g kg^{-1}) was recorded in profile US13 (40–55 cm) in the central part of Z2.

The depth dependence of N_t in the profiles was similar to that of C_{org}. In 8 profiles N_t decreased with depth (US2, US4, US7, US9 to US11, US15, US16). In profile US6, N_t remained at almost steady concentration, increasing only slightly in its deepest part. N_t increased (as does C_{org}) in US3 and US5. In US8, US12, and US13 (all located in Z2), on the other hand, there was a noticeable difference in comparison with the C_{org} trend as N_t increasd slightly with depth. In US13, the higher N_t in its deepest part can be explained by the finer, more compacted fraction in the 55–70 cm interval (Fig. 4). In the fine silty sands, N_t was 0.3 g kg^{-1}, but only 0.01 g kg^{-1} in the overlying loose gravelly sands (40–55 cm). The variability of N_t with depth in a selection of profiles from all three sampling zones is shown in Fig. 8.

The mean total phosphorus content (P_t) reached 0.60 g kg−1 in zone Z1, 0.62 g kg^{-1} in Z2 and 1.06 g kg^{-1} in Z3 (Figs. 7 and 8). Mean P_t was 0.71 g kg^{-1} for all the samples. Figure 6 illustrates the variability of P_t with depth in certain profiles from the three sampling zones.

Of the four parameters analysed, P_t gave the clearest indication of sediment zonation. Values ranged from 0.48 (US5, 10–40 cm) to 1.18 (US4, 0–5 cm) g kg^{-1}, while in only eight profiles (19% of the total) $P_t > 0.99$ g kg^{-1}. All these samples were collected in Z3. P_t was lower (0.78 g kg^{-1}) in only one sample, obtained from a lateral moraine (US3, 35–50 cm). In this particular interval, pH was also significantly higher. P_t in the remaining 81% of the samples was rather low (0.48–0.80 g kg^{-1}). In most cases, concentrations varied the same way with increasing profile depth. In 10 out of 14 profiles (US2, US5 to US11, US15, US16), P_t decreased with depth, although in US10, it increased slightly in the middle interval but decreased again below. P_t exhibited the same concentration in US4 and US12 but was higher in US3, which correlated with a simultaneous increase in C_{org} and pH decrease. P_t was also higher in the deepest interval (55–70 cm) of US13. Unlike C_{org} and N_t, P_t varied slightly in the three most common sediment types. For 12 gravelly sand samples, excluding two samples (US4, 5–15 cm and 15–30 cm), the standard deviation of the values was 0.03 (max. = 0.58, min. = 0.48 g kg^{-1}). For ten sandy gravel samples, it was 0.07 (max. = 0.66, min. = 0.48 g kg^{-1}) and for eight silty sand samples, it was 0.06 (max. = 0.80, min. = 0.65 g kg^{-1}).

Discussion

Physical characteristics of the Werenskioldbreen foreland sediments. — The sediment studies conducted in glacier forelands frequently coincide with research on the dynamics and development of ecosystems in newly exposed areas resulting from deglaciation. These studies include exploring primary succession, chemical weathering, and soil development, focusing on changes in their physicochemical composition over time following deglaciation (Anderson *et al.* 2000; Egli *et al.* 2010; Bernasconi *et al.* 2011; Mavris *et al.* 2012).

In the 1970s in the Werenskioldbreen's marginal zone, Karczewski and Wiśniewski (1979) conducted a comprehensive grain-size study of the exposed sediments. At that time, the area's geomorphology was less diverse. The glacier and lakes covered part of the eastern foreland. Between 1973 and 2013, the glacier recession exposed an area of 1.7 km^2 of foreland (Ciężkowski *et al.* 2018). Several other authors explored the sediments of the Werenskioldbreen foreland, focusing mainly on ground or lateral moraines and investigating soil formation (Kabala and Zapart 2009, 2012) or vegetation succession (Pirożnikow and Górniak 1992).

Karczewski and Wiśniewski (1979) suggested that sedimentary properties should be categorised according to lithotypes, claiming that it would be possible from an analysis of a sediment's granulometric composition and its statistics to identify the lithotype group and sediment material with similar genetic characteristics. They subsequently indicated that similar sediment characteristics could be expected for specific glacial forms. The largest number of samples analysed in our study represent marginal lithofacies of the glaciofluvial zone, *i.e.* the outwash plain. These sediment samples came from geomorphological forms such as sandur fans and plains, sandur with ramparts and cones, characterised by more dynamic changes as a result of surface and groundwater flows, and inactive glacier ice melting (Fig. 2). The other sediment samples represent morainic facial group lithotypes – lateral moraine.

Additionally, it should be noted that a similar approach is already being used for the case of other glacial forelands (Hodkinson *et al.* 2003; Tanner *et al.* 2013; Szymański *et al.* 2019; Khedim *et al.* 2021; Kim *et al.* 2022), where studies of proglacial sediments showed relations similar to these discussed in this study, namely the occurrence of the same or similar sediment types with respect to the geomorphological forms and similar characteristics of their physical and chemical properties with respect to sediment layer age (Hodkinson *et al.* 2003; Wietrzyk *et al.* 2018; Khedim *et al*. 2021). Also, comparable analyses of environmental dynamics in proglacial areas, using surface geomorphological forms (polygons or zones), were carried out in studies of vegetation cover and succession (Moreau *et al.* 2008; Szymański *et al.* 2019), where the sediment composition was treated as an environmental factor for vegetation growth (Jones and Henry 2003; Moreau *et al.* 2008).

Following this idea, the authors Stachniak *et al.* (2022) successfully categorised Werenskioldbreen's geomorphological forms, to which they applied generalised physical parameters during the hydrogeological model development. We assume that the identified physical parameters of the Werenskioldbreen foreland sediments are typical in the proglacial environment and may be applicable for the parameterisation of models for similar environments. For this purpose, we interpreted and typified the terrain's geomorphology based on maps and orthophotographs, and we characterised the environmental dynamics on which the sediment properties depend (Appendix 1).

The grain-size analysis indicates that the lateral moraine contains sandy clayey silt with silty sandy gravel or sandy gravelly silt with a significant contribution of rock cobbles classified by using Eurocode 7: Geotechnical engineering design - Part 2: Identification and investigation of soils (PN-EN 1997-2: 2009 Eurocode 7; PN-EN ISO 14688-2:2006, 2006). Pirożnikow and Górniak (1992) found that within moraine sediments, the main fractions consisted of coarse sands and colloidal clay. Moreover, the fossil and sub-fossil soil levels had different physical features, with a grain size distribution identified as typical of heavy clays, with variable contributions of the skeleton (fine and medium gravel). For example, in Dama Glacier (Switzerland), the surface soil texture (0–5 cm) ranged from silty sands within the chronosequence to loamy sands, with additional clay content increase in the oldest soils (Bernasconi *et al.* 2011). Kabala and Zapart (2012), using the nomenclature of the FAO guidelines (FAO 2006), described the textural classes of these moraine sediments as sandy loam, loam or silty loam. Following the FAO World Reference Base, they also classified the soils within the moraines (fluted, flat and terminal moraine) as Turbic Cryosols and Leptic Regosols (IUSS 2007). In the literature, moraine material is usually referred to as moraine till or sandy-silty till (Lind and Lundin 1990; Kabala and Zapart 2012), or simply till (Strobel 1993). The nomenclature of the sediments varies according to the standard adopted. The percentage of the silt or clay fraction often underlies the classification and nomenclature. Therefore, it is essential to consider the raw data on grain size composition, which are fundamental for calculating sediment's physical parameters, especially when used in hydrological or/and hydrogeological modelling studies.

The authors of this paper have intentionally avoided the term 'soils', as in a major part of the foreland, soil formation is hindered or impossible due to active runoff, which reworks glacial deposits (Pirożnikow and Górniak 1992; French 2007). However, in areas where this process is less active, a favourable location for soil development is possible for the poorly formed Cryosols, especially Leptic Cryosol, Cambic Glacic Cryosols and Letic Gleysols (Kabala and Zapart 2009, 2012). In similar locations almost 20 years earlier, these were described as very shallow lithosol and regosol soils (Pirożnikow and Górniak 1992).

The granulometric results and fraction distribution for each sediment type are similar to previous findings (Karczewski and Wiśniewski 1979; Kabala and Zapart 2012). The highest amount of the fine fraction, *i.e.*, < 0.05 mm by Karczewski and Wiśniewski (1979), was represented by a flat ground moraine (57%), while both the lateral moraine and frontal rampart showed similar values of > 30%. In our results, it is *ca.* 8% of the < 0.002 mm grain size fraction, 20–50% of the 0.063–0.002 mm fraction. In addition, the percentages of the fine fraction in the frontal and lateral moraines decrease even further down the slope due to water runoff, causing the gravitational displacement of material (Karczewski and Wiśniewski 1979). Our results also indicate that the surface sediment contains a higher percentage of fine fractions than the lower section of the profile. Kabala and Zapart (2009, 2012) report that in six soil profiles located along the southern lateral moraine of Werenskioldbreen, the skeleton fraction forms 40–60% of the soil mass, the silt fraction (0.002–0.05 mm) constitutes up to 40–45% of all the fine fractions, and the clay fraction (< 0.002 mm) reaches 9 to 15%. In turn, marginal outwash plains, mostly sandur fans and plains, have > 40% content of the coarse fraction (> 3 mm and 3–0.05 mm, by Karczewski and Wiśniewski 1979). Furthermore, the deeper the profile, the greater (up to 95%) the proportion of the 2.0–0.063 mm and 63.0–2.0 mm grain size fractions. This enables water to infiltrate deeper into the ground and flow faster in the bottom part of the active layer. The knowledge of the diversity of sediment types in profiles and their spatial distribution is crucial for developing hydrological and hydrogeological models. Data from this research was used for the development of a groundwater flow model within the permafrost active layer in the forefield of the Werenskioldbreen glacier basin (Stachniak *et al.* 2022). Based on the model results, the preferential flow paths in the subsurface were determined.

Several studies of glacial sediments have been conducted in the foreland of Midtre Lovénbreen (Svalbard), an alpine-type polythermal valley glacier that is retreating and exposing foreland sediments, currently reworked by runoff (Moreau *et al.* 2008; Midgley *et al.* 2018). Hodkinson *et al.* (2003) investigated vegetation succession on glacial sediments in relation to the age of surface sediments. They analysed sediment samples taken along a 1.7 km-long transect across the proglacial area, 70% of which constituting of moraine. They concluded that the older the sediment deposits, the more significant the proportion of the finer fraction in the surface 4 cm-layer. The proportion of finer sediment particles (< 2 mm) gradually increased from 40 to 50% during the early stages of succession (2, 16, 37 *etc.* years) to > 97% on a site with 150 years old sediments (Hodkinson *et al.* 2003). Pedogenesis was also slow on newly exposed moraines, with a high proportion of coarse particles in the regolith material (Hodkinson *et al.* 2003).

The poor sorting of glacial sediments and the mixed fine fractions from surrounding moraine tills gave rise to hydraulic conductivities lower than those reported in the literature (Domenico and Schwartz 1998; Singhal and Gupta 2010). Our results represent similar ranges of values compared to studies from other regions with glacial sediments, and their value ranges are narrower (Lind and Lundin 1990; Strobel 1993; Marciniak *et al.* 2011; Stachniak *et al.* 2022; Wąsik *et al.* 2023). However, it is important to bear in mind that, given the scarcity of results obtained with analogous methods, we compared our results with hydraulic conductivity data obtained with different methods, however, for the same type of proglacial sediments. Using empirical formulas to estimate hydraulic conductivity from grain size data is an indirect method. Rosas *et al.* (2014) thoroughly highlight the potential inaccuracy of such estimates and gave numerous suggestions for the applicability of specific formulae, which the authors have taken into consideration in this study. Nevertheless, it is still a relatively precise method for obtaining hydraulic conductivity allowing for a narrower range of values than following the literature ranges provided by Singhal and Gupta (2010) or Pazdro and Kozerski (1990). The present results were applied to generate the 3D groundwater flow model of Stachniak *et al.* (2022), where the hydraulic conductivity ranges were most satisfying.

Analyses of active layer sediments similar to those in the Werenskioldbreen foreland were conducted in the nearby Brattegg River catchment, a geomorphologically slightly different environment. Wąsik *et al.* (2023) studied the permeability of geomorphological forms using two in situ methods, the Porschet method and the double-ring infiltrometer within rocky initial soils, sorted patterned ground, pebbly alluvial sediments, boulder blankets, solifluction stripes, talus, and no sorted patterned ground. They distinguished seven permeability categories among those sediments. The lowest values referred to loams and sandy loams (10^{-9} to 10^{-6} m s^{-1}), similar to our results for silty or sandy sediments (Sa, saclSi, sagrSi, Si). The sand with debris showed the same range of values as our sand (10^{-7} to 10^{-5} m s^{-1}), the multi grained sand was similar to our gravelly sand (10^{-5} to 10^{-4} m s^{-1}), sand-gravel debris was equivalent to our sandy gravel (10^{-5} to 10^{-3} m s^{-1}). We do not have a suitable fraction for "pebbly debris" which presents the highest permeability; the loamy debris was also similar to silty sandy gravel (10^{-6} to 10^{-4} m s^{-1}). Considering *in situ* methods as better representing the natural environment, and despite different but somewhat related nomenclature, we conclude that the present results have similar ranges.

Chemical characteristics of the Werenskioldbreen foreland sediments. — The laboratory analyses were undertaken primarily to calculate the parameters that can be used to develop transport models of nitrogen and phosphorus cycling. Stachnik *et al.* (2022) also investigated the water and sediment chemistry (SEM-EDS) to elucidate the influence of Werenskioldbreen proglacial sediment weathering on meltwater chemistry. The values of the physicochemical parameters as pH, the concentrations of organic carbon (C_{org}), total nitrogen (N_t) and total phosphorus (P_t) depend on time after deglaciation, *i.e.*, the age of the soil and the intensity and advancement of the physical and chemical processes taking place, which in turn are strongly dependent on the climate change (Dolezal *et al.* 2008; Bernasconi *et al.* 2011; Mavris *et al.* 2012). In line with other reviewed studies from proglacial areas (Hodkinson *et al.* 2003; Darmody *et al*. 2005; Egli *et al.* 2010; Bernasconi *et al.* 2011; Khedim *et al.* 2021), our results confirm that following deglaciation and the stabilisation of geomorphological activity, sediments have become enriched with carbon- and nitrogen- and phosphorus-containing organic compounds. The active fluvioglacial processes on the outwash plain, sandur fans and plains favour neither organic matter accumulation nor soil formation processes; hence, the values of C_{org}, N_t and P_t are lower than in the stable zones of moraines.

The results obtained from the samples collected on the southern lateral moraine of Werenskioldbreen correlate with those from a profile on the terminal moraine, described by Kabala and Zapart (2009, 2012). The mean pH for the marginal zone of Werenskioldbreen, estimated by Pirożnikow and Górniak (1992) for a few sampling points, was slightly less alkaline than our results at 7.8 to 7.9 (in H_2O). In contrast, in the Midtre Lovénbre marginal zone, Hodkinson *et al.* (2003) found that the upper horizons of glacial sediments were alkaline (pH > 7.0) and that freshly exposed moraines had a high initial pH of 7.0 to 8.0. In our results, the exceptionally high pH representing the US5 profile came from the northern part of the foreland. This is a highly dynamic, geomorphologically diverse area, and the numerous watercourses flowing through it might supply carbonates from the bedrock (Bukowska-Jania 2003, 2007; Stachnik *et al.* 2016), increasing the sediment pH. Except for the moraine profiles US2, US3 and US4, the rest of the collected samples had Ph > 8.0, highlighting the dominant alkaline character of the sediments.

Our results for organic and underlying mineral horizons began to diverge, and the first signs of acidification were discernible in the broader range of values recorded in the organic surface horizon, with pH occasionally < 6.5, reflecting topographic variation in organic matter accumulation. These results are related to older sites with stable environments > 100 years old; also, in Darmody *et al.* (2005) studies, it is confirmed that the pH of proglacial sediments generally decreases with time.

The C_{org} values obtained for Werenskioldbreen sediments nearly 30 years ago by Pirożnikow and Górniak (1992) were lower than ours (0.20 to 0.55%), indicating an ongoing pedogenesis. Kabala and Zapart (2012) reported that organic carbon accumulation in the upper 3 cm-layer increased with sediment age and that C_{org} in fine sediment fractions ranged from 4.5 g kg^{-1} in freshly deglaciated till to 19.2 g kg^{-1} in the oldest soil. Moreover, C_{org} was slightly higher at greater depths (3–10 cm). The older the moraine (stable material), the greater the area covered by tundra vegetation, hence the higher the value of C_{org}. The variability of C_{org} in US7 and US15 profiles can be explained by the variable deposition conditions of glaciofluvial sediments, mediated by the intensity of chemical compound leaching. Profile US7 illustrates the contrast between the three main horizons (Fig. 4): the first (0–15 cm) consists of highly compacted silty sand (high C_{org}), the second (15–40 cm) of loose, poorly packed, gravelly sand (low C_{org}), and the third (40–60 cm) of highly compacted gravelly sand showing high C_{org}. Loosely packed sediments, with wider gaps between the grains, were more susceptible to leaching, which could have been responsible for the lower C_{org} in the samples. There was no apparent correlation between C_{org} on the lateral moraine and the more variable foreland traversed by numerous watercourses, subjected to intensive leaching and devoid of vegetation. An analysis of C_{org} concerning its variability with profile depth shows that C_{org} concentration decreases with depth in eight profiles (US2, US4, US6, US8, US10 to US13), where there is a high permeability of sediment types, but increases with depth in five (US3, US5, US7, US15 and US16), where the permeability is low (Fig. 3 and Fig. 6).

The high N_t in the near-surface part of moraine profile US4 seems to be rather valid, as the vegetation there is much better developed than in the foreland and also because the presence of birds. In contrast, the high N_t in the silty sand from profile US15 is doubtful, although it may be substantiated by the sparse vegetation growing in some parts of the foreland. Moreover, the samples came from a more stable part of the terrain, where fluvioglacial processes are less dynamic. Thus, such a high value could be due to soil aging. The explanation for the relatively high N_t (0.95 g kg^{-1}) in US16, situated on the Elveflya glaciofluvial plain, might be similar. N_t is also relatively higher (0.86 g kg^{-1}) in US1 than in the other samples. Sampling point US1 was situated on the drained bottom of a stagnant pond, one of many found within the Werenskioldbreen foreland. Such water bodies contain highly silty formations (lacustrine deposits), often with a distinctive, slightly organic odour.

The other studies of proglacial environments conclude that the organic carbon (C_{org}) and total nitrogen (N_t) concentrations in top soils increase with time (Darmody *et al.* 2005; Dolezal *et al.* 2008; Bernasconi *et al.* 2011; Khedim *et al.* 2021). Khedim *et al.* (2021) indicate that these parameters generally increase over time at every location but do so much faster in warmer forelands and where precipitation is the highest (Khedim *et al.* 2021). C_{org} is very low < 2 g kg^{-1}, in all soils under 25 years old, with concentrations rising from 10 to 20 g kg^{-1} in soils > 100 years old. These authors refer very low values of N_t in soils < 25 years old (0.04 to 0.46 g kg^{-1}), but on relatively gentle slopes, N_t increases to > 1 g kg^{-1} in mountain soils, formed for > 50 years since deglaciation. In contrast, at the highest elevations in steeper terrain, N_t increased after 150 years since deglaciation. Additionally, Bernasconi *et al.* (2011) prove that total organic carbon content seems to have been reduced to low values during the glacier's re-advance, soils found just beneath the moraines contain significantly less organic matter than what would be anticipated based on their age.

It should be noted that in some of our results, variations from these trends in individual soil layers may be due to locally changing meteorological conditions and environmental dynamics, *e.g.*, the evolving river network in plains or the progressive solifluction caused by melting of moraine ice cores. Hodkinson *et al.* (2003) also highlighted that N_t varied in their results from 9 to 546 kg ha^{-1} and concluded that N_t generally increased in sediments where conditions were stable and where soils were older and more developed. On the other hand, it decreased in areas with unfavourable microclimates, in the closer proximity to the glacial ice and in near or total absence of nesting birds (Hodkinson *et al.* 2003).

The P_t measurements obtained nearly 30 years ago for Werenskioldbreen sediments by Pirożnikow and Górniak (1992) were, as in the case of C_{org}, lower than our results. The percentage of P_2O_5 in their study ranged from 0.03% (0.13 g kg^{-1}) to 0.06% (0.26 g kg^{-1}). The phosphorus in glacierized catchments may be delivered from sediments suspended in glacier meltwater. According to Hodson *et al.* (2004), the presence of primary phosphorus-containing minerals physically eroded from bedrock is related to low weathering calcite/apatite-rich mineral phases. These authors studied the Svalbard glacier basins of Austre Brøggerbreen and Midre Lov´enbreen and concluded that sediment yields from glaciers can significantly contribute to the NaOH–P loading of ice-marginal waters (Hodson *et al.* 2004).

The high concentrations of P_t coincide with the more intensive tundra vegetation on the moraines than on the foreland, although small patches of flora were found also in the central and southern parts of the foreland, near the Gull Lake. This lake is inhabited by Black-legged Kittiwakes, whose faeces supply organic matter to the sediments. In a small, non-glaciated catchment of the Fuglebekken, Szymański *et al.* (2016) found that C_{org}, N_t and P_t were the highest in surface soils fertilised by seabird faeces, also along watercourses and their tributaries near which the seabird colonies were located. In our study area, the situation is similar, with the presence of seabird colonies supplying guano and stimulating vegetation grow in around the lake.

Conclusions

Even though progress in proglacial environment monitoring research is ongoing, we have faced the problem of a need for more precise data on the properties of young proglacial sediments exposed by the retreating glaciers in the High Arctic. This study provides new insight into the current sediment physicochemical properties for the dynamically evolving proglacial zone of Werenskioldbreen, southern Spitsbergen.

The conditions for developing soil-forming processes arise in areas sheltered from being washed out by glacier melt waters. Additionally, the climate warming observed in the Arctic in recent years simultaneously favours the more extended vegetation season. Also, in the Werenskioldbreen proglacial zone, the vegetation begins to spread, resulting in higher C_{org}, N_t, and P_t values in locations where small patches of plants were found.

Based on our results, we can assume that the identified physical parameters of the Werenskioldbreen foreland sediments are typical for the proglacial environment and, therefore, can be applied when developing hydrological models of other glacier forelands with similar characteristics. Data from the present study are available in the open-access database Zenodo.

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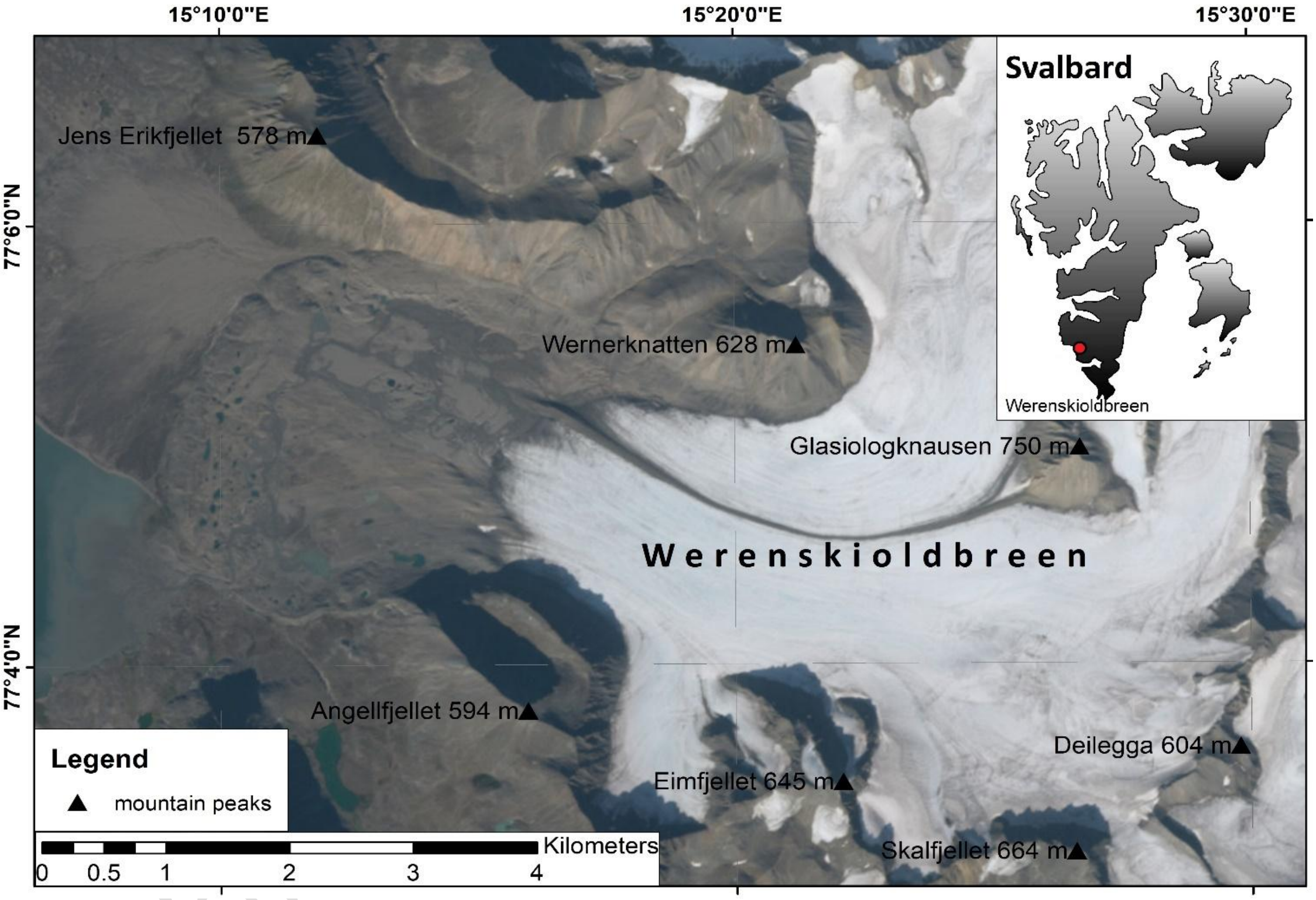

Fig. 1. The Werenskioldbreen study area, south Spitsbergen (base map data: Svalbard Satellite Imagery from the Norwegian Polar Institute Map Data and Services and Polish Polar DataBase: (1) the DEM for Werenskioldbreen area from Dornier images (Błaszczyk *et al.* 2022) at http://ppdb.us.edu.pl/geonetwork/srv/eng/catalog.search#/metadata/87a556ed-6b8f-4d06-9c20-1a5b6b23d280 and (2) the Ortomosaic for Werenskioldbreen area from Dornier images at http://ppdb.us.edu.pl/geonetwork/srv/eng/catalog.search#/metadata/c99085cb-7e4c-43dd-866b-f2f909b44937.

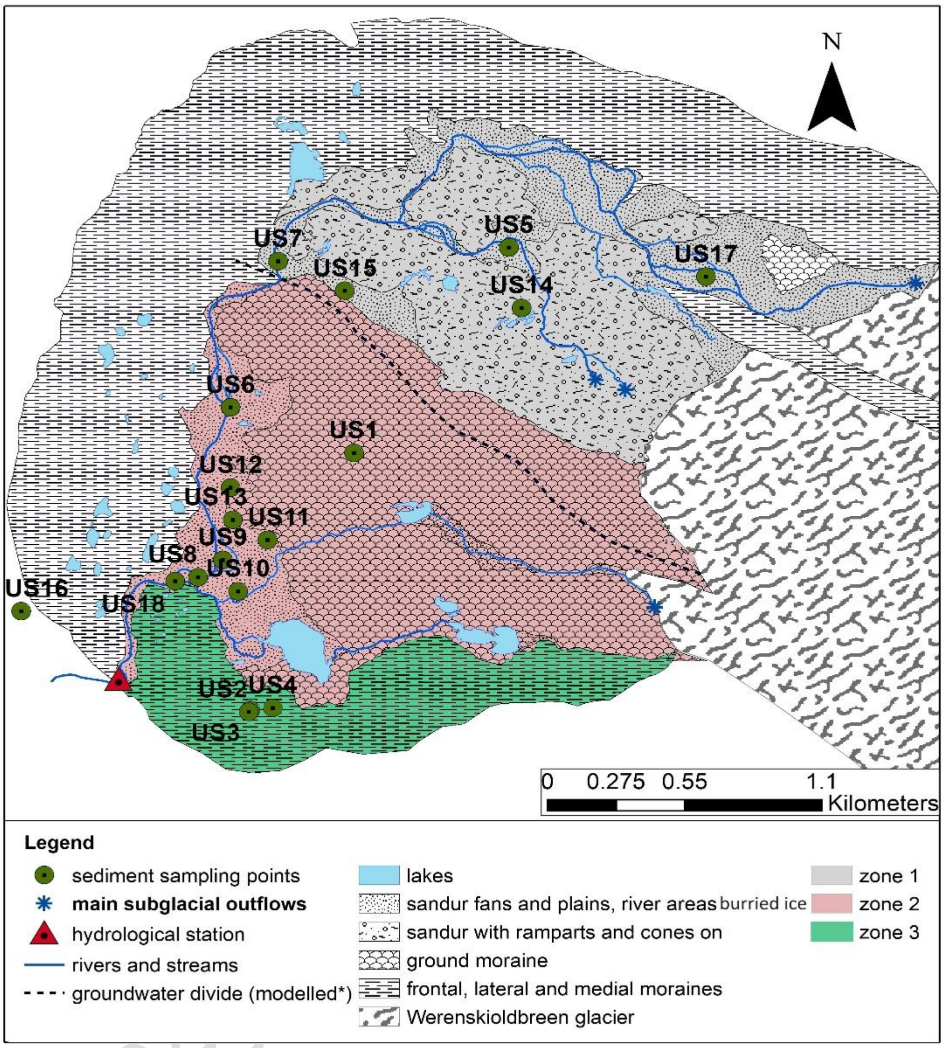

Fig. 2. Location of sampling profiles in the Werenskioldbreen forefield and simplified geomorphology, based on an orthophotomap from 2017 (Stachniak *et al.* 2022), and maps from the Norwegian Polar Institute Map Data and Services. Different zones are delineated on the basis of an analysis of physicochemical parameters: zone 1 (Z1): the northern part of the Werenskioldbreen foreland representing the outwash plain – sandur fans and plains, sandur with ramparts and cones on buried ice, and the Breelva river bank; zone 2 (Z2): the south-western part of the forefield representing the outwash plain – sandur fans and plains formed near the river outlet (excluding sample U1, which is material deposited by surface runoff); zone 3 (Z3): the southern lateral moraine. Modelled groundwater divide by Stachniak *et al.* (2022).

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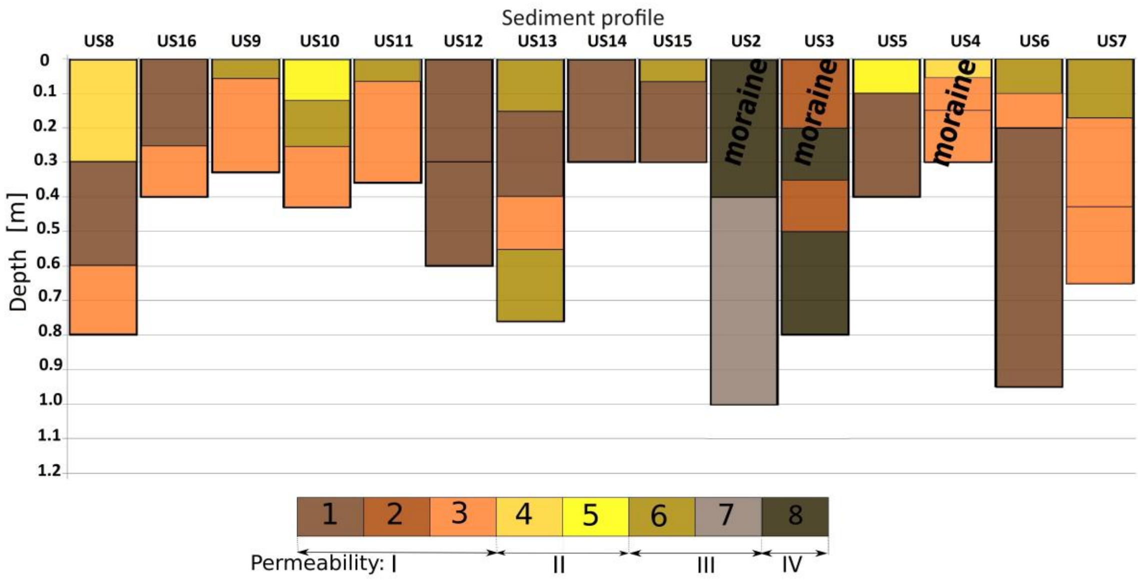

Fig. 3. Lithological variability of near-surface sediments with depth in the Werenskioldbreen foreland. Type of sediment: 1 – sandy gravel, 2 – silty sandy gravel, 3 – gravelly sand, 4 – gravelly silty sand, 5 – sand, 6 – silty sand, 7 – sandy gravelly silt, 8 – sandy clayey silt. Permeability characteristics and indicative filtration coefficients (taken from the literature) by Pazdro and Kozerski (1990): I – very good permeability (> 10^{-3} m s^{-1}); II – good permeability (10^{-3} to 10^{-4} m s^{-1}); III – poor permeability (10^{-5} to 10^{-6} m s^{-1}), VI – semi-permeable sediment (10^{-6} to 10^{-8} m s^{-1}) or impermeable sediment (< 10^{-8} m s^{-1}).

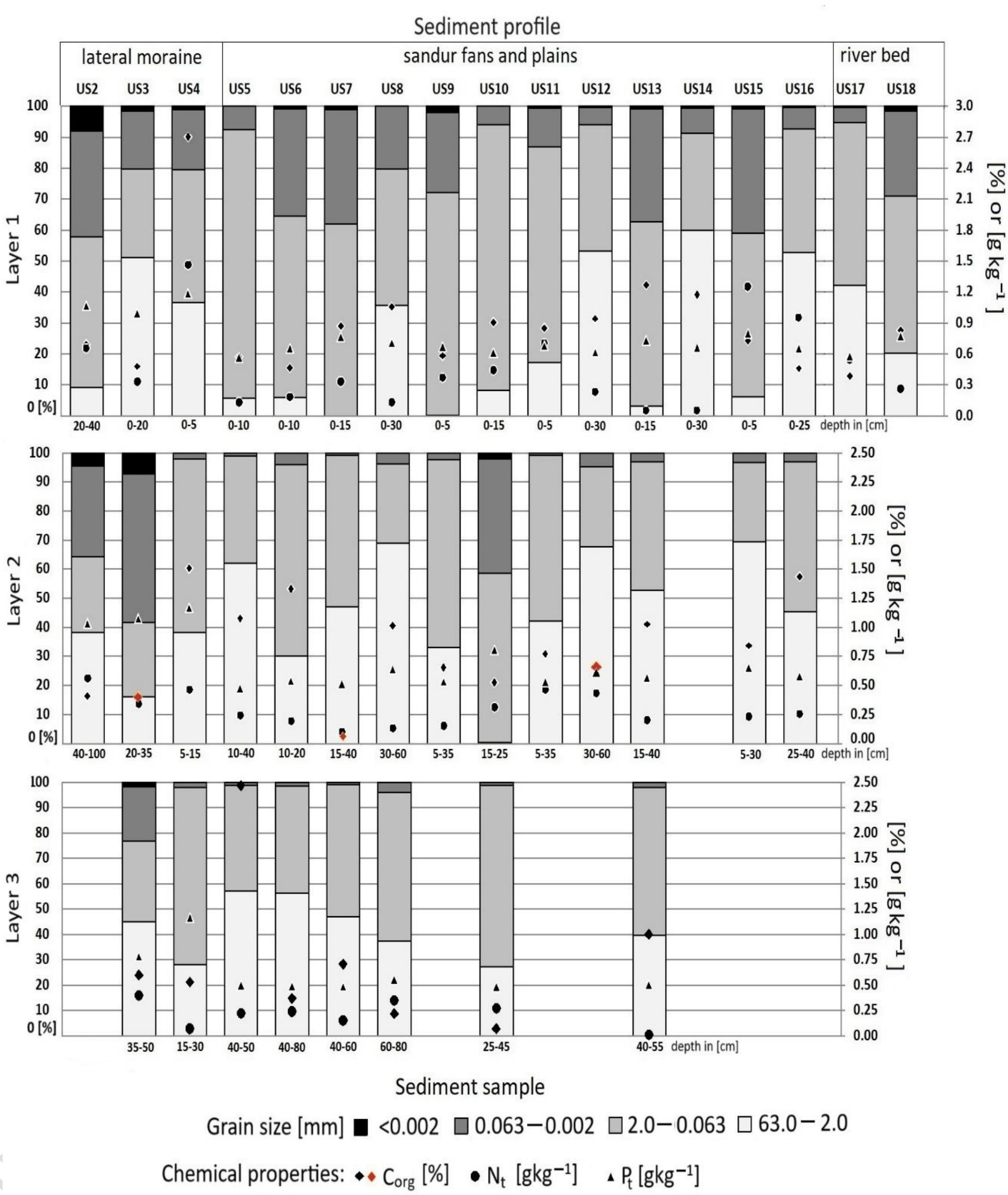

Fig. 4. Grain size composition (left scale) and their chemical parameters (right scale) for each sediment sample (layer depth range in a given figure) representing the first three layers of sediments from the Werenskioldbreen foreland. Chemical properties: C_{org} – Soil Organic Carbon content, N_t – total nitrogen content, P_t – total phosphorus content. The details are listed in Table 2. Sample US1 contains surface material only.

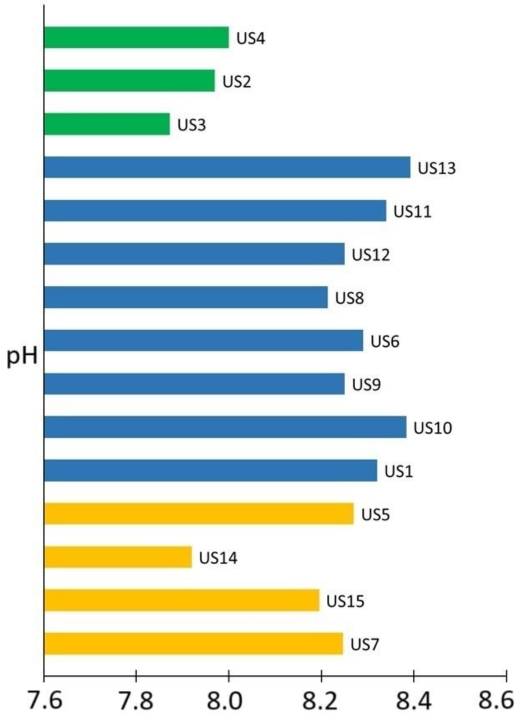

Fig. 5. Mean pH of pore water in selected profiles in the three sampling zones: Z1 (orange), Z2 (blue) and Z3 (green).

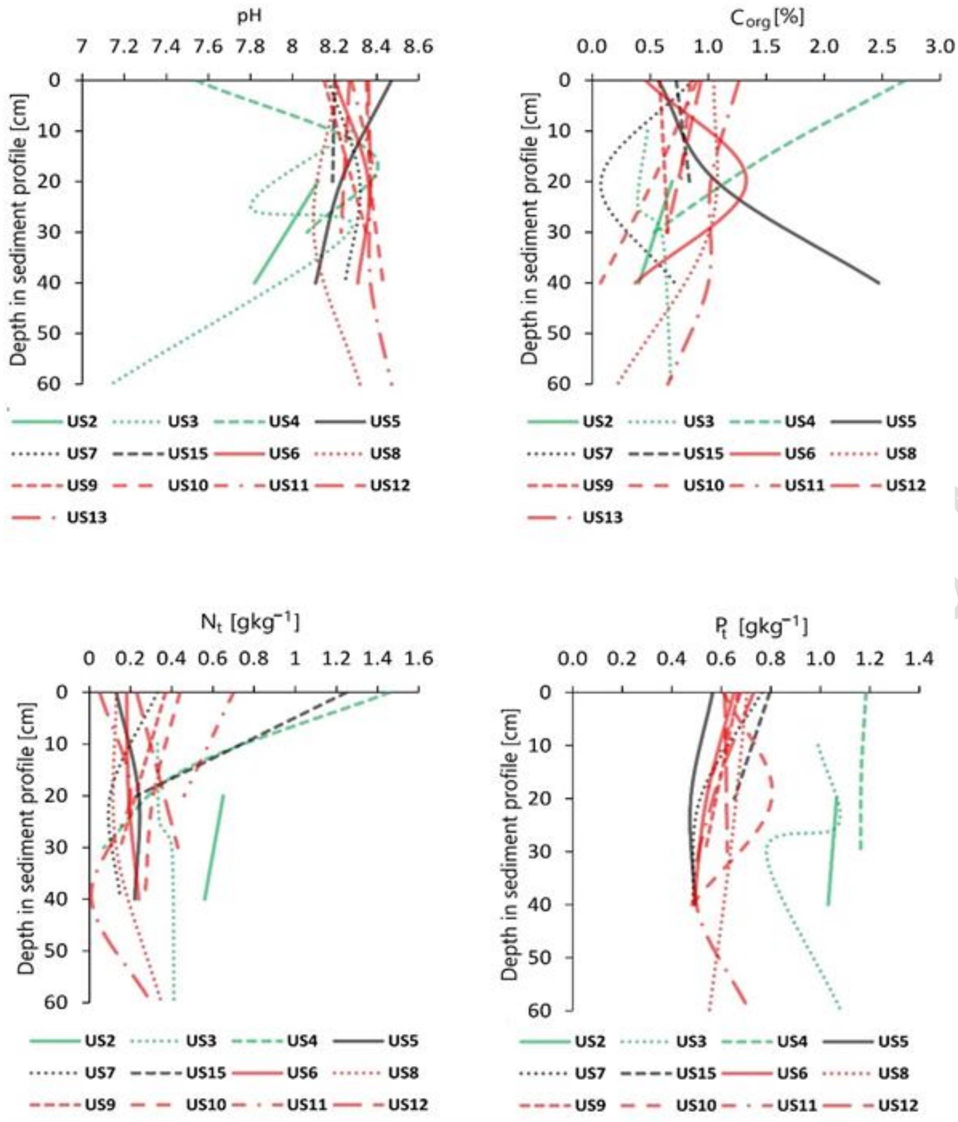

Fig. 6. Values of chemical parameters (pH, C_{org}, N_t, P_t) in the sediments and their variability with respect to profile depth. The colored lines represent specific zones, *i.e.*, Z1 – grey lines, Z2 – red lines, Z3 – green lines.

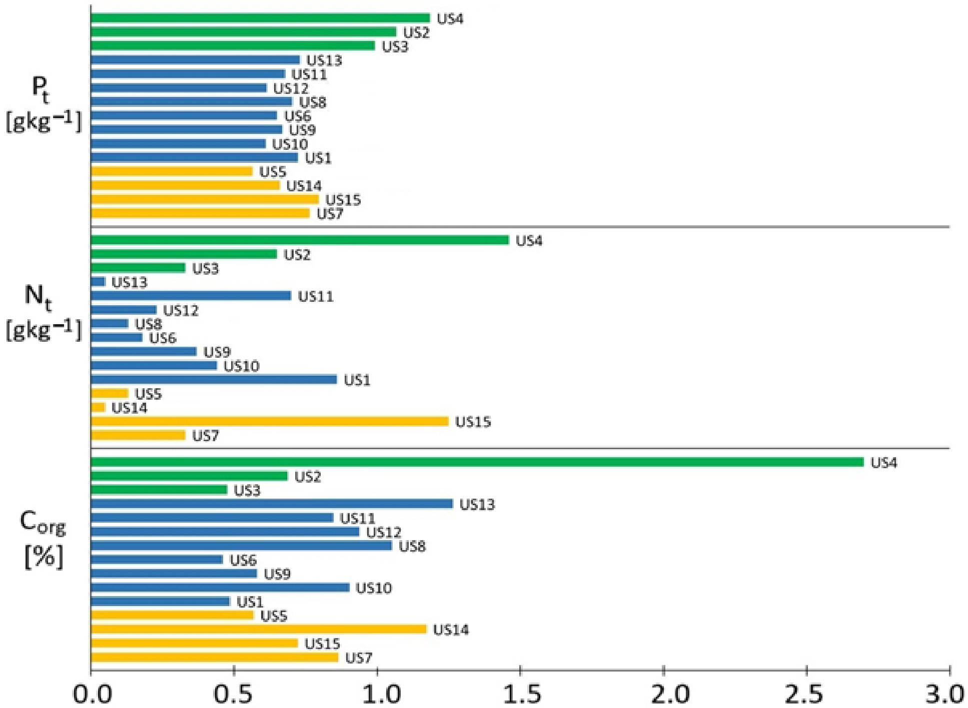

Fig. 7. The content of phosphorus (P_t), nitrogen (N_t) and carbon (C_{org}) in the near-surface parts (Layer 1) of selected profiles from the three sampling zones: Z1 (orange), Z2 (blue), and Z3 (green).

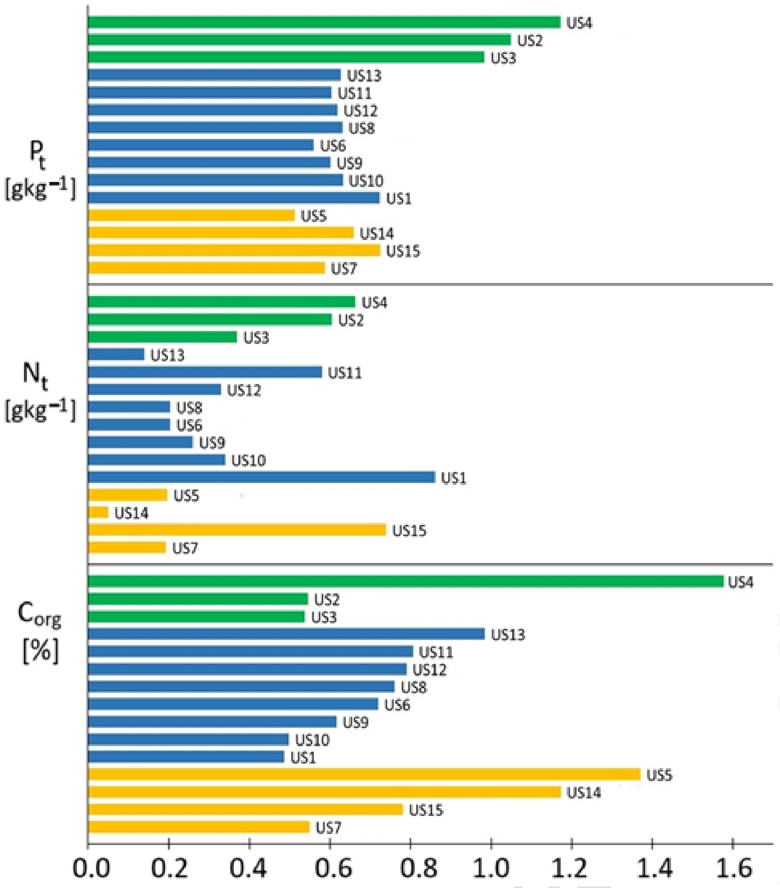

Fig. 8. The mean of phosphorus (P_t), nitrogen (N_t) and carbon (C_{org}) in selected profiles from the three sampling zones: Z1 (orange), Z2 (blue), and Z3 (green).