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Diversity and main properties of soils of the Gronfjord area (Svalbard archipelago)

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Abstract

Svalbard archipelago is characterized by specific climate conditions, high air temperature and relative air humidity, which are not typical for high latitudes. Such conditions affect soil-forming processes. Classification and morphological structure of the soil cover on the Spitsbergen archipelago are still poorly understood. The aim of current research was to reveal diverse soil taxons in the Gronfjord area and characterize framework of its formation. As the results of this work, the authors provide the description of the investigated soils and their taxonomy in accordance with World Reference Base for Soil Resources (IUSS Working Group 2015) and the new Russian soil classification system. Chemical parameters of the soil, as well and the data on soil horizons properties were measured using vertical electric resistivity sounding method. In total, 15 soil profiles were made and the studied soils were referred to six Soil Reference Groups with domination of Leptosols and Regosols. The profiles were made in different landscapes that allowed to determine the similarities and differences in soil cover of the area. The main factors affected soil formation are cryogenic processes combined with gleyfication and cambic alteration of soil material.

Key words: soil, Svalbard archipelago, Gronfjord area, soil diversity, soil formation

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Introduction

Soils in the area of Gronfjord (NW Svalbard) are the result of a unique combination of diverse soil-forming processes. Relatively high Arctic average annual air temperatures and humidity are the reasons for specific bioclimatic conditions affecting soil formation. The features of soil formation in the investigated region differ from processes in the similar latitudes in terms of weathering of fine earth and redistribution of soil and ground particles in space due to increased intensity of solifluction and erosion rates.

The first known studies related to soil characteristic were carried out by German specialists (Gripp et Todtmann 1926). They focused geomorphological and topographic descriptions of the upper part of the bay and moraine. Over the past hundred years, a number of researchers have studied the Quaternary deposits of the region (Lavrushin 1969, Troitsky 1975, Tarasov et Kokin 2010, Snyder et al. 2000, Kokin 2010, *etc*.).

However, the structure and geochemical peculiarities of the soil cover in the area of the Gronfjord and the archipelago in general began have been studied only in last decades. Among the main studies related to topic, the following addressed several aspects: Targulyan et Kulikov 1983, Forman et Miller 1984, Mann et al. 1986, Dobrovolsky 1990, Plichta et Kuczynska 1991, Kashulina 2003, Pereverzev et Litvinova 2010, Alekseev et Abakumov, 2016.

In 2012, the monograph "Soils of the coasts of the fjords of the Western Spitsbergen" in Russian was published by V. N. Pereverzev. The monographs present the results of the study of the soils of the coasts formed on different soil-forming rocks. The thickness of the soil layer in different landscapes, soil structure, basic processes of soil formation and some natural factors that lead to unique phenomena in the upper soil layer were described as well.

It should be noted, that in the classification and morphological structure of the soil cover on the Spitsbergen archipelago, the aforementioned authors have presented different results for the same study areas. The reason for this variance can be the gaps in certain criteria for characterizing Arctic soils still existing up to now.

Nowadays, the soil surveys in the vicinity of the Gronfjord continue, but not as actively as in the more populated areas (Barentsburg and Longyearbyen), due to the inaccessibility of some localities and poorly developed infrastructure. This work is also aimed to fill the gaps in the soil map of the archipelago and improve understanding of the natural processes leading to soil formation.

Soil is an important natural reservoir and the most significant source of biogenic carbon in terrestrial ecosystems (Knoblauch et al. 2015). Soil CO_2 emission, also called soil respiration, includes the processes of microbiological decomposition of organic substances and autotrophic respiration of the roots. The emission of carbon dioxide is a summary (resumptive) indicator of the biological activity of soils. The rate of carbon dioxide production by soil respiration is one of the important indicators of the state of microbiocenoses of soils (Hoffmann et al. 2017, Görres et al. 2014) .

The indicator of the emission of carbon dioxide is related to the amount of available biogenic elements and to the hydrothermal conditions of the soil. The greatest emission is observed in the upper horizons of the soil, where a large number of biological processes occur, associated with the biotic activity of organisms (Schneider et al. 2012).

The main purpose of this research work was to study the morphological features, soil formation factors and taxonomic diversity of the Svalbard soils in the Gronfjord area. To achieve the main goal, the following objectives were outlined: (1) to make soil pits in different landscapes and analyze morphological features of the soil profiles, (2) to make chemical analyses of certain soil horizons, (3) to carry out vertical electric sounding study.

Material and Methods

Study area

Study area of the Gronfjord is located on the south-Western coastline of the Western Spitsbergen Island. It occupies the area between 77° 91’ and 78° 10’ N and 14° 00’ and 14° 85’ W. It relates to south-western branch of the Eastfjord. Study sites were established in the coastal area of Gronfjord and adjacent areas. The climatic characteristics are summarized from the data reported from the meteorological observations in Barentsburg (Antsiferova et al. 2014) in Table 1.

Climate parameters	**Values**
Mean annual air temperature (ºC)	-5.8ºC
Mean air temperature (ºC): of the warmest month (July) of the coldest month (February)	 8ºC -18ºC
Number of days with mean daily air temperature: above 0ºC above 5ºC	 120 60
Freezing depth (m)	1.8-2.5
Depth of the active layer (m)	1.5-2.0
Snow thickness (m)	0-1
Annual precipitation (mm) in summer (mm)	563 87
Thickness of permafrost (m)	100

Table 1. Climate parameters of the Gronfjord area.

Study area is characterized by high latitudes climate conditions (Table 1). However, Warm Atlantic waters affect Arctic marine climate. Last few decades there is a tendency to warmer climate was carried out (Antsiferova et al. 2014).

Weather regime is characterized by the periods of significant cooling at winter with large amount of snowfalls. Snow coverage appears in October.

Despite rather low amount of precipitations, waterproof characteristics of the ground and low evaporation do not allow water to penetrate in the lower horizons, which leads to overmoistening of the territory by stagnant meltwater and transformation of the area to a wetland. Small thickness of the soil (1.5 m) and weak development are typical for soil profiles. Soil formation process goes slowly, but faster than in other areas on these latitudes. Vegetation coverage decomposition goes also with low rates caused by low content of organic matter and low temperatures (Kashulina 2003).

Distribution of plants on archipelago is heterogeneous and site-dependent. In general, vegetation is of tundra type, where

Salix polaris, Cerastium alpinum, Luzula confusa, Saxifraga cespitosa, Trisetum spicate predominate.

One of the most significant factors which affect the relief formation, responsible for the destruction, transport and redeposition of the raw mineral material. On the study area, the soils originated from glaciers the Aldegonda and Western Gronfjord formation of were studied. There are a number of exogenous processes associated with the glacier activity, such as thermokarst, erosion by meltwater and periglacial-marine sedimentation (Mavlyudov 2016). As for modern landforms fluvial forms (terraces, deltas, floodplains) and cryogenic forms (pingo) are typical.

Methods

Field methods

The field data for the present paper are the data obtained by the authors during field research in September 2017 in the area of Gronfjord, Svalbard, surroundings of Barentsburg settlement. In this research, 15 soil pits were made and described in the area of Gronfjord. Spots for soil pits were chosen in different environmental conditions and landscapes. In the field, parent materials were identified and the composition of vegetation cover as well. The thickness of the active layer was measured and in 5 spots method by vertical electrical sounding. The soils were classified according the Russian soil classification system (Shishov et al. 2004) and World Reference Base for Soil Resources ([1] - IUSS Working Group 2015). 11 samples of soils (1 liter-volume) and living organic material (0.1 liter) were taken from some spots for chemical analysis: 10 of the investigated pits from the uppermost soil horizons and 1 sample (TH 4) from the bottom horizon.

Laboratory methods

Soil samples were air dried, grounded and passed through a 2 mm sieve. Carbon and nitrogen content were measured in elemental analyzer (Euro EA 3028-HT, Eurovector, Italy), pH values were measured in laboratory with use of pH meter, soil – water (salt) ratio in suspension 1:2.5.

Vertical electric resistivity sounding

In 5 choosing spots, electric resistivity was measured using vertical electrical sounding (VERS) method (Pozdnyakov 2008, Gibas et al. 2005). The advantage of this method is possibility to stratify vertically the soil based on different physical properties without making soil profile and digging. In this study, Landmapper ERM-03 instrument (Landviser, USA) was used for the VERS measurements. The measurements were performed using four-electrode (AB + MN) arrays. Here the distance between the A and B electrodes was changed from 0.2 m to 6 m, while the distance between the M and N electrodes was constant – 0.1 m. The depth of penetration of the electrodes to the soil was about 5 cm. The upper 3 meters of soil profile was studied. VERS was accompanied with 1D layer model (ZonDIP program) of apparent and real resistivity's processing and visualization. This model provides the data on apparent resistivity values changes with the depth (ρ), the layers thickness (h) and layer depth (z). The purpose of the program ZonDIP is to determine the resistivity of the rectangular blocks that produce an apparent resistivity pseudo-section that agrees with the actual field measurements.

Results

Soil morphological characteristics

Location of the studied pits is shown in the Fig 1. The pits were made in different landscapes such as: sea terraces (TH 1, 2, 10, 11, 12); moraine in glacier valleys (TH 3, 8, 9, 13); river terraces affected by cryogenic processes (TH 4, 5, 6); erosional terraces on the mountain slope (TH 14, 15).

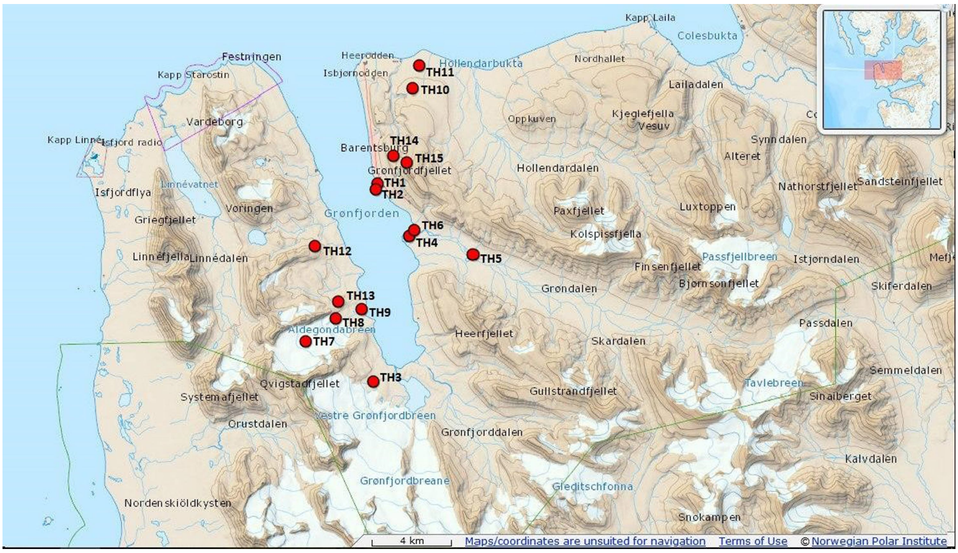

Fig. 1. Locations of the 15 soil pits.

Morphological description of soils is given in Table 2 - Appendix. Horizons identification was performed according to Russian Soil classification (Shishov et al. 2004) with correlation to the WRB ([1] - IUSS Working Group 2015). Soils types were identified according to WRB ([1] - IUSS Working Group 2015). Images of soil profiles are given in Fig. 2.

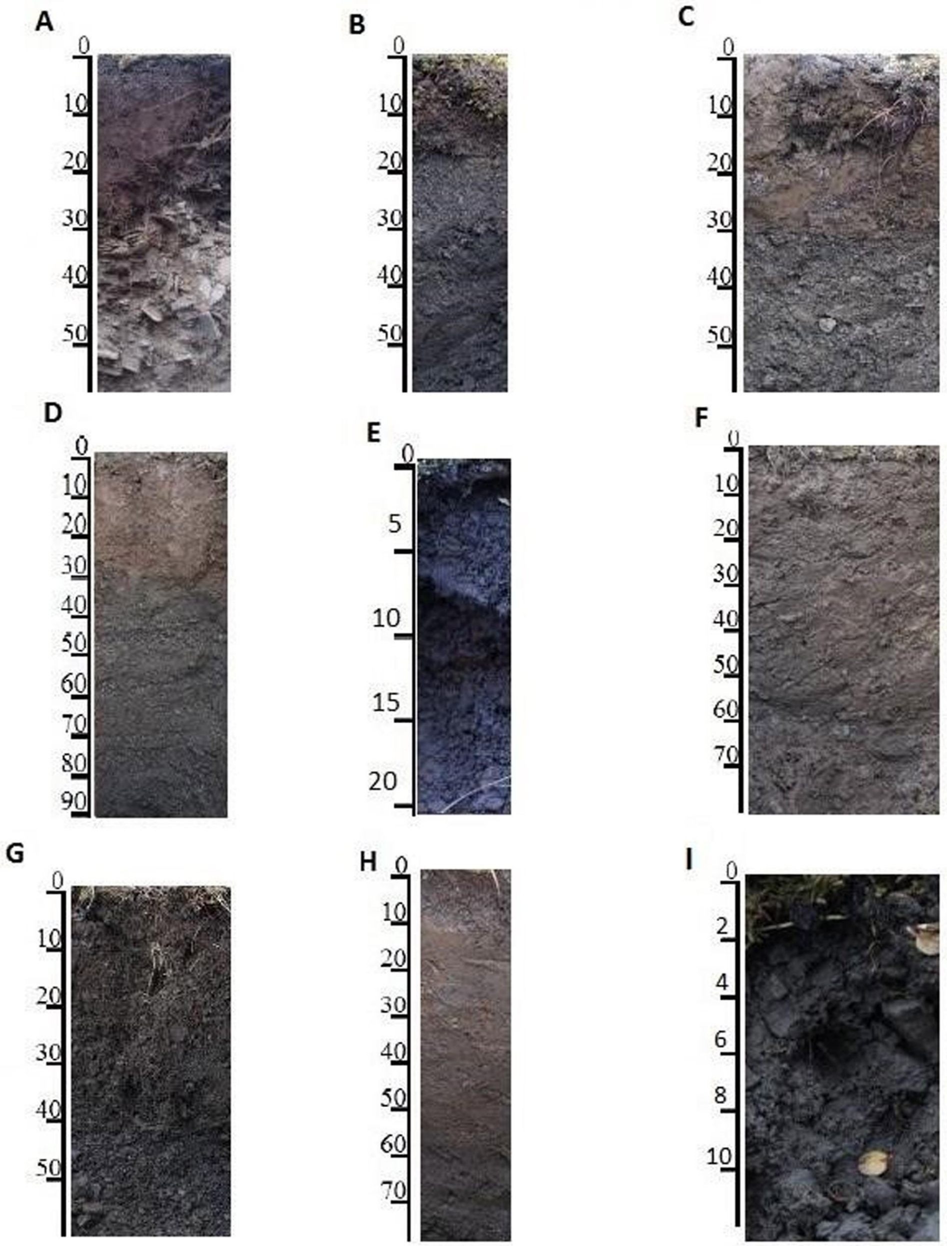

Fig. 2. Soil profiles: A – Umbric Leptosols (TH 2), B – Turbic Umbric Cryosols (TH 4), C – Turbic Umbric Cryosols (TH 5), D – Umbric Cryic Fluvisols (TH 6), E – Umbric Leptosols (TH 8), F – Umbric Turbic Gleysols (TH 10), G – Cryic Cambisols (TH 11), H – Turbic cryic Cambisols (TH 12), I – Skeletic Regosols (TH 13).

Vertical electrical sounding results

Results of soil VERS measurement (Table 3, Fig. 3) show differences in ER values within the soil profile. In general, there were significant changes in ER values with soil depth, particularly in those layers, where contact between active layer and permafrost table was reached.

Three investigated sites (TH 5, TH 6, TH 12) have similar apparent resistivity pattern: Ω1<Ω2>Ω3<Ω4. In general, trend of increasing ER in the line from the upper permafrost border to the lower limit of VERS measurement. It can be explained by the fact that deeper permafrost layers have more homogeneous structure due to a lesser amount of cracks (Abakumov et Tomashunas 2016).

VERS section name	P-modelled resistivity (Ωm)	Z-bottom layer depth (m)	H - permafrost table (m)
TH 4	122.0	0.00	
	56.6	0.10	
	2800.0	0.95	0.90
TH 5	115.0	0.00	
	277.2	0.05	
	71.0	0.20	
	1582.0	0.90	0.90
TH 6	366	0.00	
	968.8	0.05	
	103.9	0.20	
	5142.2	0.80	0.80
TH 10	50.7	0.00	
	127.4	0.04	
	4.2	0.20	
	79.8	0.80	0.80
TH 12	72.1	0.00	
	173.6	0.05	
	76.6	0.10	
	3955.0	0.90	0.90

Table 3. Electric resistivity (Ω m) and depth (m) of different layers of investigated sites.

Umbric Turbic Gleysols from the TH 10 (*see* Fig. 1) show different trends of ER value changes downward the profile with fluctuation features: Ω1<Ω2>Ω3>Ω4. Here, the soil had the lowest values of ER and it's maximum was observed within the depth of 0.04 m (not of 0.8 m where transition zone between active layer and permafrost table is located). It can be interpreted by salinization of parent material.

In contrast to other soils, Turbic Umbric Cryosols (TH 4) had just 3 layers based on different physical properties: Ω1>Ω2<Ω3. It is a discrepancy of ER within field and model values. According to field investigation, the maximum values of ER were related to the third layer (3000 Ωm). However, in accordance with calculated model curve, the third layer have a values of 150 Ωm and it was less than first layer (300 Ωm).

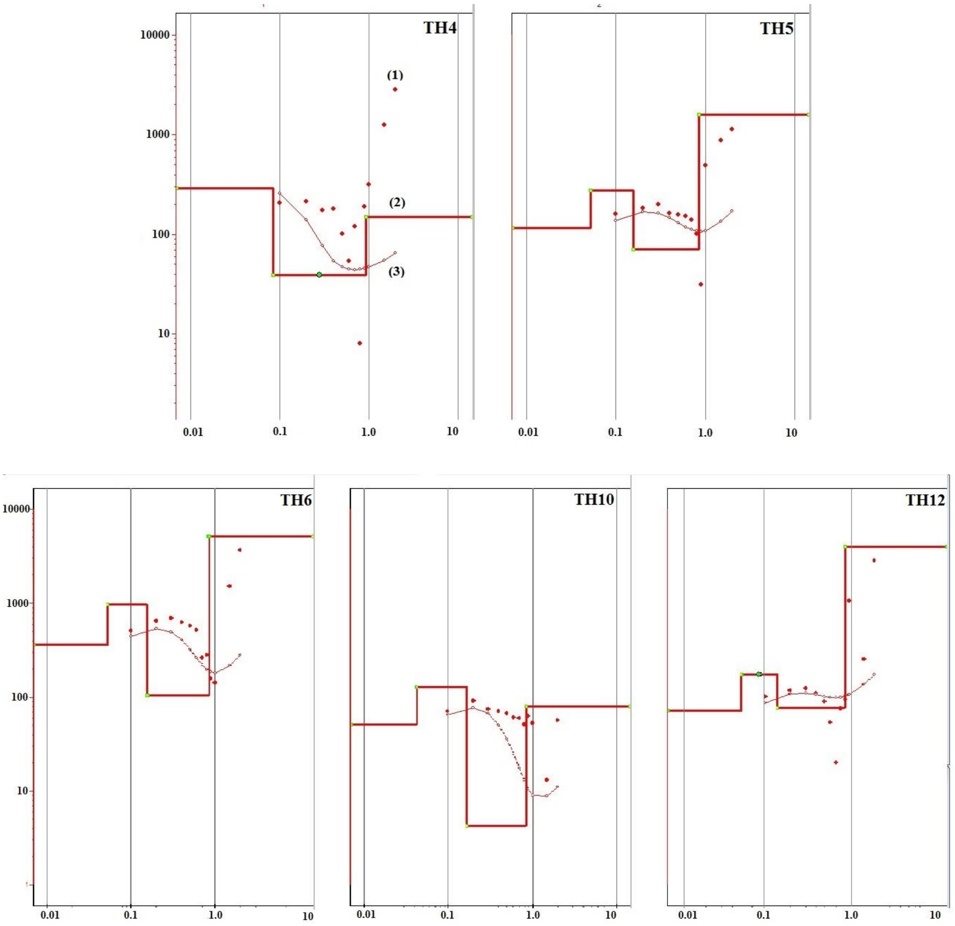

Fig. 3. Electric resistivity curves and models of soil profiles at investigated sites. Dotted line (1): denotes measured values; solid red line (2): denotes the layer model; thin lines (3): denotes calculated model curves. Vertical scale: ER values (Ωm); horizontal scale: AB/2 distance (m).

Chemical analyses of soils

Soil respiration of studied soils varied within the wide range: from 71.5 to 743 mg CO_2/(100g soil day^{-1}) in the uppermost layer (0-10 cm) and 76.8 mg CO_2/(100g soil day^{-1}) in the lower layer (45-50 cm). The minimum rates of the soil respiration related to 2 samples from the marine terraces with mudboils on the surface. Such rates of respirations showed relatively low biological activity of the soils due to low cover of vegetation in connection frost effects. The highest respiration rates were observed in Umbric Stagnic Fluvisols (TH 1) located at outcrop that characterized by high amount of organic substances. Soil respiration was attributed to the ecological conditions of the soil, for TH 1 it is characteristic up to 743 mg CO_2 / (100g soil day^{-1}), this is a high value not typical of the Arctic environment. It can be caused by favorable conditions for microorganisms (physical parameters of the soil, high content of easily accessible organic compounds, namely by high content of ware soluble organic matter), a powerful AY horizon and stratified sediment, are a favorable environment for the growth of soil microbiota. A low level of soil respiration (Table 4) could be attributed to the fact that an unfavorable environment is created in the soil, this may be due to the low level of easily accessible organic matter, and the negative hydrothermal situation. Soils that are in a prolonged condition of overmoistening, (TH 10) and clear gleyification processes do not allow the microbial community to fully develop. Anaerobic conditions are a limiting factor for the microbiomass microorganisms.

The highest C/N ratio is observed in the sample from the slope of the mountain (TH 15). The lack of organic substances may be explained by presence of the leaching processes down the slope. The lowest C/N ratio might be related to the sample from marine terrace with high amount of mossy vegetation (TH 12). The lowest C content was in the glacio-fluvial sediments (cryoconite), which was classified like primitive soils (windblown dust made of a combination of small rock particles, soot and microbes which is deposited and builds up on snow, glaciers, or ice caps) with extremely low rates of organic matter and absence of the litter fall (TH 7). The value of C/N is an indicator of the enrichment of humus with nitrogen, the lower the ratio, the higher the enrichment. All soils are low (11-14) and very low (> 14) enrichment of humus with nitrogen, this is an indication that organic nitrogen from non-decomposed plant residues does not accumulate here, we may hypothesize that it is immediately consumed by plant communities (Orlov 1985). The main source of carbon is undecomposed organic remains, which, due to severe climatic conditions, cannot be fully involved in the circulation of organic matter and accumulate in permafrost-affected soils. The carbon content in the soils is also not high (2-28%), except for the TH 1 profile (41.5%), where accumulation of organic substances and their deposition takes place due to the stratified mass (Zubrzycki et al. 2013, 2014). The main reason for observing high C/N values is the low nitrogen enrichment of the net primary production (NPP), it is generally limited to biogenic elements in Arctic tundra conditions. This ecosystem is called N-limited, and has low concentrations of dissolved and total nitrogen. Therefore, competition arises in the Arctic tundra between microorganisms and plants for nitrogen compounds (DIN, amino acids and other organic N forms) (Sanders et al. 2010, Jones et Kieland 2002, Schimel et Bennett 2004, Hobbie et Hobbie 2006).

The underdeveloped soils of Spitsbergen do not accumulate a significant amount of organic material caused by high erosion of soils, young age and severe climatic conditions prevented active humus formation in this region.

Active cryogenic processes (cryogenic mass change) also affect the process of humus formation and humus accumulation, the redistribution of the organic part along the profile, from the surface to the permafrost table, leads to the fact that the humus formed in the upper horizons moves down the profile and accumulates on the boundary with the permafrost table, which in this case is a geochemical barrier.

The value of soil pH varied from 5.0 to 8.4. Very strongly acidic pH (5.0) is observed in Haplic Regosols (TH 3) characterized by elementary stage of soil formation near glacier tongue. Moderately alkaline pH was measured in samples from TH 4 and TH 13 there parent material is enriched with carbonates.

Sample code	**pH H_2O**	**pH $CaCL_2$**	**Soil basal Respiration, mg CO_2/(100g soil day^{-1})**	**Total organic carbon, %**	**C/N**
TH 1	6.4	5.9	743.0	41.5	24.8
TH 3	5.0	4.0	87.8	8.8	18.3
TH 4 (topsoil)	7.5	7.0	99.0	3.4	25.0
TH 4	8.4	n.d.	76.8	3.2	71.9
TH 7	7.2	6.5	82.2	2.0	14.8
TH 7 (bottom)	7.4	6.7	82.7	2.0	13.9
TH 10	5.3	4.4	71.5	3.1	12.8
TH 11	5.9	4.7	76.7	18.0	28.0
TH 12	6.4	5.7	110.0	8.2	11.3
TH 13	8.1	n.d.	82.7	4.9	32.8
TH 15	5.2	4.2	417.0	28.0	50.7

Table 4. Chemical parameters of the investigated soils (pH, soil respiration, carbon content, C/N ratio).

Discussion

The main distinctive feature of investigated landscape is a deep presence of the permafrost table. This noteworthy phenomenon has great influence on soil-forming factors and processes for the Svalbard soils. Owing to fact that soil table locates deeper than usual for such areas, a soil in study domain does not significantly affected by frost, they are just cooling.

The assertion that the permafrost table typically locates at or below the deep of 1 meter is arisen by data derived from vertical electric resistivity sounding (VERS). This method was used to assess the depth of the active layer and determine the depth of the superficial layer of the permafrost. According to VERS an approximate mean value of the permafrost depth is 1 meter.

In places where cryogenic processes take place (TH 4, 5, 6, 10, 11, 12) the majority of soils were identified as Cryosols and Cambisols, and in some places as Fluvisols and Gleysols. These soils have formed under such conditions as mixing of soil material, cryogenic mass exchange of soil horizons, frost heaving, separation of coarse soil materials from fine and cracking. Cryosols are mineral soils formed in a permafrost environment. The subsurface layers (cryic horizon) are permanently frozen, and if water occurs in the form of ice. Cryogenic processes are the dominant soil-forming processes in most Cryosols ([1] - IUSS Working Group 2015). In current work, Cryosols were investigated in the areas with non-sorted circles (mudboils). There were two types of soil profiles: in the low-altitude areas (between the mudboils) and in the high-altitude areas (on the mudboils). First structure is characterized by AY horizon and therefore has higher humus content and more clear stratification. In opposite to it, in the second structure cryoturbation may be observed, such as cracks and lifting of bigger material on the surface. So it may be seen as cryoturbation inhibit the processes of humus accumulation. However, at the same time cryoturbation contribute to more deep penetration of organic matter to deep horizons. Gleysols comprise soils saturated with groundwater for long enough periods to develop reducing conditions resulting in gleyic properties, including underwater and tidal soils ([1] - IUSS Working Group 2015).

Some soils are characterized by low thickness, *e.g.* thin moraine related sediments (cryoconite, moraine loam). Four pits were made on moraines of Western Gronfjord and Aldegonda glaciers (TH 3, TH 8, TH 9, TH 13). Here the profiles were the most simple because of the short time since the glacier retreat. Therefore, the soils were unstratified and had only the upper organogenic horizon O (1-3 cm). The Soil Reference Groups in these areas were regarded as Regosols and Leptosols. Leptosols are very thin soils over continuous rock and extremely rich in coarse fragments. Leptosols are particularly common in mountainous regions. Regosols are very weakly developed mineral soils in unconsolidated materials, but in opposite to Leptosols are not very thin or very rich in coarse fragments. Regosols are typical for mountainous terraces and related ridges. One particular noteworthy soil pit (TH 9) on the moraine landscape was made in the lower part of the moraine ridge protected from the wind and located from the side of the sea. Here accumulation of cryoconite material also was observed, but the vegetation was significantly different from other spots: the vegetation cover was more diversified and its thickness was also higher. Therefore, the microclimate is softer and the soil is also more fertile due to physical-geographical factors.

On the slope of the Olaf mountain, one additional soil group was determined – Cambisols. Cambisols are the soils with pronounces features of texture class changing in the middle part of the solum, this changes are typical for cambic horizons and related to in-situ weathering process. The horizon differentiation is weak. Transformation of parent material is evident from structure formation and mostly brownish discoloration, increasing clay percentage, and carbonate removal ([1] - IUSS Working Group 2015). The main soil-forming factors for this soil – more humid climate on western slope, faced to the Gronfjord, humid climate, active denudation processes and weathering of the soil minerals.

The soil profiles located close to the Gronfjord were characterized by direct impact of marine deposits, contrastingly to the more distant ones. These soils were regarded as Fluvisols. Fluvisols are genetically young soils in fluvial, lacustrine or marine deposits. They occur in river plains and fans, valleys, lake depressions and tidal marshes on all continents and in all climate zones. There are no groundwater and no high salt contents in the topsoil. Fluvisols have profiles with evidence of stratification and weak horizon differentiation (but a distinct topsoil horizon may be present) ([1] - IUSS Working Group 2015).

To sum up, 6 Soil Reference Group were determined (Table 1). The most abundant soil group in the vicinity of the Gronfjord was Leptosols.

Soil Reference Group	SRG with qualifiers	RSC
1. Fluvisol	TH 1. Umbric Stagnic Fluvisol	TH 1. Stratozem gray-humus gleyey on proluvial fan deposits
	TH 6. Umbric Cryic Fluvisol	TH 6. Stratozem gray-humus on eluvium stony deposits
2. Leptosol	TH 2, TH 8. Umbric Leptosol	TH 2. Litozem gray-humus on quaternary gravel-pebble deposits TH 8. Litozem on cryoconite
	TH 9, TH 15. Skeletic Leptosol	TH 9. Litozem on deposits of marine terrace TH 15. Litozem on eluvium stony debris
3. Regosol	TH 3. Haplic Regosol	TH 3. Pelozem on moraine material
	TH 13. Skeletic Regosols	TH 13. Pelozem on moraine material
4. Cryosol	TH 4, TH 5. Turbic Umbric Cryosol	TH 4. Cryozem coarse-humus on loamy material
		TH 5. Cryozem gray-humus on rubble material of pingo
5. Gleysol	TH 10. Umbric Turbic Gleysol	TH 10. Cryometamorphicgray-humus on clay material
6. Cambisol	TH 11. Cryic Cambisol	TH 11. Burozem on deposits of marine terrace
	TH 12. Turbic Cryic Cambisol	TH 12. Cryometamorphicgray-humus gley on eluvium stony deposits
	TH 14. Haplic Cambisol (Inclinic)	TH 14. Burozem on sloping eluvium stony deposits

Table 5. Classification of soils according to WRB and the new Russian soil classification system.

Conclusions

The soils of the Gronfjord area of the Spitsbergen archipelago (Norway) were investigated by several approaches. Relatively warm and humid climate for these latitudes and presence of continuous permafrost result in formation of high pedological diversity and soil formation implementation in developed fine earth parent materials.

Totally 15 soil pits were investigated and classified according to WRB ([1] - IUSS Working Group 2015) and Russian national soil taxonomy. The soils studied were refered to six Soil Reference Group - Leptosols, Cambisols, Fluvisols, Regosols, Cryosols, Gleysols. The dominant soil group was Leptosols and Regosols that are weakly developed and extremely rich in coarse fragments. This soil type was located mostly on ridges and terraces, combined by massive crystallic rocks. Cambisols are located on gentle slopes covered by parent materials with high content of fine material. Crysols and Gleysols were typical for valleys, terraces, pingo and other landforms with pronounced accumulation of quaternary sediments. Fluvisols were dominant on marine terraces.

The main soil-forming processes in the study area were:

- processes of accumulation of marine sediments in geological dynamic fluvial valleys;

- processes of parent material alteration: weathering, erosion and redistribution of particles of topsoil layer within the various relief forms;

- processes of primary soil formation and humus accumulation after glacier retreat under periglacial processes with mixing of a soil material, disrupting of soil horizons, organic intrusions, frost heaving, frost cracking;

- processes of subsoil horizons formation: cambic type of in situ weathering, cryogenic mass exchange and reductic transformation of mineral part (gleyfication, stagnificatiion, formation of redoximorphic features).

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[1] IUSS WORKING GROUP WRB, 2015, World Reference Base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. Update 2015. World Soil Resources Report 106. FAO, Rome.

Appendix - Table 2.

Soil	Horizon	Depth of sampling (cm)	Soil horizon description
TH 1. The soil pit was an outcroplocated on the cape Finniset (shore of Gronfjord). A coastal abrasion was well-expressed in this area. The shore was a cliff.			
Umbric Stagnic Fluvisols	AY	0-10	Dark gray structureless horizon; loose; friable; moist; sandy loamy. The boundary is clear uneven.
	RY	10-45	Gray-colored; stratification of layers is well-pronounced; light loam; with inclusions of gravel. The boundary is clear, uneven.
	G	45-50	Bluish; signs of gleying process are noticeable.
	DR	50 ↓	Loose parent material.
TH 2. The pit was made on the abrasive ledge of the east coast of the Gronfjord with moss-cereal vegetation. There were high amount of quaternary deposits of gravel-pebble material.			
Umbric Leptosols (Litozems gray-humus on quaternary gravel-pebble deposits)	AY	0-10	Dark gray brownish; loose; sandy loam.The transition is clear and smooth.
	AC	10-25	Medium loamy; brownish gray; weak granular; compacted.
	C	26 ↓	Parent substrate with gravel and pebble material.
TH 3. The profile located on the glacier Western Gronfjord (in the depression of a relief) in sediments of the ground moraine.			
Haplic Regosols (Pelozems on moraine material)	O	0-1	Dark gray; moist; compacted.
	C	1↓	Loam on moraine with stratified structure; with inclusions of gravel-pebble material and sand lens.
TH 4. The pit located on the butte (the place of the confluence of the GronRiver and Gronfjord). The pit includes 2 profiles: the soil at the mudboil (type of non-sorted circles); the soil in the depression between mudboils.			
Turbic Umbric Cryosols (Cryozems coarse-humus on loamy material)	1) Soil in the depression:		
	AO	0-13	Gray brownish; loose; moist; with plant inclusions; roots reach a depth of 13 cm. The transition is clear, smooth.
	Cr	13-53↓	Brown grayish; compacted; loamy; moist; there is the presence of pebbles from a depth of 42 cm; there was a presence of eluvium material from 52 cm.
	2) Soil at the mudboil:		
	Cr1	0-7	High amount of gravel-pebble material that have risen to the surface due to the frost heaving process.
	Cr2	7-53↓	brown grayish; compacted; loamy; moist; the process of cryoturbation was noticeable.
TH 5. The pit was studied on the frost mound located on the pingo (the right bank of the river Gron). There was cryogenic crack between the frost mound and depression between another frost mounds.			

Turbic Umbric Cryosols (Cryozems gray-humus on rubble material of pingo)	1) Soil at the frost mound:		
	Cr	0-26	Gray brownish; dense; moist; loamy; there are cryogenic cracks and fragments of eluvium. The boundary is clear, smooth.
	C	26-56 ↓	Gravel-pebble parent material; loamy; moist.
	2) Soil in the depression:		
	O	0-8	Dark gray; consists of plant remains; compacted; slightly stratified. The transition is clear, smooth.
	AY	8-13	Gray brownish; homogeneous; moist; with inclusions of plant residues. The transition is clear and gradual.
	C	13-56 ↓	Gravel-pebble parent material; loam; moist.
TH 6. The pit was carried out on the right terrace of river Gron, near the coastline (on the depositions of the sea terrace).			
Umbric Cryic Fluvisols (Stratozems gray-humus on eluvium stony deposits)	AY	1-3	Dark gray; moist; with inclusions of plant residues; skeletal fraction is 80%. Transition is clear, without cryoturbation.
	Cr	3-8(21)	Brownish gray; with inclusions of plant residues; skeletal fraction is 10%; noticeable cryoturbation features. The transition is clear, uneven with the cryoturbation.
	R	8(21) ↓	Dark gray; rare inclusions of plant residues; the skeletal fraction predominates over fine particles.
TH 7. A sample of cryoconite accumulated in a crack was obtained on the Aldegonda glacier.			
TH 8. The pit located on the ground moraine of the Aldegonda glacier in the place of the cryoconite pool.			
Umbric Leptosols (Litozems on cryoconite)	O	0-1	Black; moist; homogeneous. The boundary is clear, sharp, even.
	C	1-13↓	Grayish black; wet; loamy; with inclusions of a pebble.
TH 9. The pit was made at the bottom of the moraine ridge. This type of soil is called a soil of wind shelters.			
Skeletic Leptosols (Litozems on deposits of marine terrace)	O	0-2	Black with brownish gray part in the bottom part; compacted; with inclusions of roots; 50% - gravel-pebble material. The boundary is clear, sharp.
	C	2-15↓	Gray; with inclusions of moraine deposits (particles of different granulometric composition). 50% - fine soil fraction.
TH 10.The pit was made on the marine terrace.			
Umbric Turbic Gleysols (Cryometamorphic gray-humus soils on clay material)	O	0-1	Black; moist; stratified; interrupted on the surface by the mudboils. The boundary is clear, even.
	AY	1-7	Gray; loamy; moist; compacted; with inclusions of roots. The structure is fine-

			plated. The transition is clear, gradual.
	CRm	7-60	Pale-grayish; loamy; moist; compacted. The structure is granular.
	G	60-68 ↓	Bluish gray; dense; clayey; features of gleying process is well-pronounced; the structure is plated.
TH 11.The pit was formed on the first marine terrace.			
Cryic Cambisols (Burozems on deposits of marine terrace)	O	0-2	Black; moist; stratified; interrupted on the surface by the mudboils. The boundary is clear, even.
	AY	2-10	Grayish; loose; skeletal fraction is 10%. The boundary is clear, sharp.
	BFcr	10-18	Reddish brown; compacted; moist; loamy. The structure is fine granular. Cryoturbation features are well-pronounced. There are inclusions of segregation ice (ice lenses). The transition is gradual, uneven.
	C	18-60 ↓	Gray; moist; with different granulometric composition; non-homogeneous. The boundary is clear, smooth.
TH 12.The pit was investigated on the sea terrace with mossy vegetation.			
Turbic Cryic Cambisols (Cryometamorphic gray-humus glei soils on eluvium stony deposits)	O	0-3	Black; moist; stratified.
	AY	3-7	Brownish gray; moist; loamy; with inclusions of a gravel material and roots.
	CRm	7-54	Bluish gray, red-ox-morphological features are well-pronounced; moist; loamy; a presence of roots is 1%.
	C	54-90 ↓	Inclusions of sand and gravel material. A presence of aquifer located above the permafrost table.
TH 13.The pit was made on the left lateral moraine of the glacier Aldegonda. Vegetation is moss-willow.			
Skeletic Regosols (Pelozems on moraine material)	W	0-3	Dark gray; bound; interwoven with roots; with abundant presence of organic residues.
	C	3-14 ↓	Loose; moist; clay; inclusion of gravel-pebble material is 80%.
TH 14.The pit was made on the structural terrace of mount Olaf.			
Haplic Cambisols (inclinic) (Burozems on sloping eluvium stony deposits)	O	0-4	Dark gray; moist; with presence of organic residues.
	AY	4-10	Grayish brown; loose; fine granular.
	BW	10-20↓	Reddish brown weathering horizon.
TH 15.The pit was made on the pass of mount Olaf.			
Skeletic Leptosols (Litozems on eluvium stony debris)	O	0-2	Dark gray; with the presence of undecomposed and weakly decomposed residues.
	W	2-10	Bound; loose; with the remains of a plant material.
	AY	10-25 ↓	Gray; consist of gravel skeleton; loamy.

Table 2. Morphological features of 15 studied soils.