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Soil cover of the Fildes Peninsula (King George Island, West Antarctica)

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ABSTRACT

Data on the morphology and major physical and chemical properties of 130 pedons sampled in the ice-free area of the Fildes Peninsula and adjacent Ardley Island (King George Island, West Antarctica) are analyzed, and the soil-geomorphological map of the surveyed area on the scale of 1:10 000 is presented. The soils have been classified according to the WRB (2014/2015) system. The map provides information on the soil cover patterns in relation to geomorphic elements and also reflects the degree of anthropogenic load on the studied territory. Nearly half (42.9%) of the total area is covered by different subgroups of Cryosols. Flat watersheds are mainly occupied by Protic Arenosols (Turbic) (22.9%). Leptosols are mainly represented by the Lithic (Ochric) subgroup covering 13.8% of the area. Fluvisols are locally developed in the tidal zone (3.3% of the total area) and are represented by the Tidalic (Skeletic) subgroup. The unique area of Fibric Cryic Histosol (0.02%) is separately delineated. Various Hyperskeletic Technosols (Toxic, Transportic, and Urbic) are formed under the influence of human loads and cover about 0.9% of the Fildes Peninsula and Ardley Island. The map as the main result of the study can be used for monitoring and forecasting the environmental changes of soil cover pattern under the global climate change and local anthropogenic impact.

1. Introduction

The Fildes Peninsula and adjacent Ardley Island represent periglacial and paraglacial environments covered with soils and soil-like bodies on approximately 30 km^2 of the ice-free area in the southwest of King George Island, the South Shetland Islands, West Antarctica (Fig. 1). This is the largest ice-free area on King George Island and the second largest ice-free area on the South Shetland Islands. Four research stations and the austral summer airport operate on the Fildes Peninsula. This is one of the best-studied areas in the region. The anthropogenic load on the environment is high because of the year-round maintenance of the stations with total staff varying from about 100 wintering people up to 250–300 people during the austral summer season; in addition, up to 200 people per week visit this area as tourists during the high season.

Numerous soil and geomorphological studies have been performed in this area (Zhao and Li, 1996; Zhao and Rongquan 1999; Chen et al., 2000; Simas et al., 2006, 2008; Schaefer et al., 2007; Francelino et al., 2011; Bölter, 2011; Balks et al., 2013; Michel et al., 2006, 2014b; Bockheim et al., 2015; Boy et al., 2016). However, the spatial patterns of soil cover in paraglacial and periglacial environments of maritime Antarctic have never been described in detail and put on to the map. Paraglacial and periglacial environments are known as informative natural models of incipient soil formation. Periglacial landscapes are considered as areas peripheral to ice sheets and glaciers, while paraglacial landscapes are known as recently deglaciated areas that are currently not affected by glacial processes (D'Amico et al., 2014). Soil mapping of such areas provides significant and valuable information on the spatial regularities of biogenic/abiogenic interactions in the soil cover. It also helps us to estimate the degree of the anthropogenic impact on the Antarctic ecosystems and soils and to monitor them.

One of the first attempts to compile soil-geomorphological map of the Fildes Peninsula was made by Chinese colleagues (Zhao and Li, 1996). Despite the numerous analytical data presented, the authors' classification of soils (e.g. "cryic aquic sediment soil" or "subantarctic brown soil") can hardly be compared with any of the modern classification systems. Bockheim and Hall (2002) considered the Antarctic Peninsula and adjacent islands as the area of predominant development of Haploturbels, Haplorthels, Psammiturbels, and Psammortherls. Cryosols, Leptosols, Regosols, and Fluvisols (IUSS World Reference Base for Soil Resources, 2014/15) were described as major soils on the Keller Peninsula of King George Island by Francelino et al. (2006). Schaefer et al. (2007) presented a geo–environmental map of the Arctowski region with 20 soil units. The study of the eco-environmental spatial

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Fig. 1. Keysite and location of studied soils at the Fildes Peninsula and Ardley Island (King-George Island).

characteristics of the Fildes Peninsula by Pang and Li (2012) provided a landscape TuPu model of this area. Information on soils in this model was scarce and did not allow their reliable identification in any of common soil classification systems. International group of researchers (Michel et al., 2014b) presented a detailed geomorphological map of the area with a special emphasis on the high soil variability in terms of the morphological features and physical and chemical properties of studied soils and explained it by varying lithic contributions and mixing of different rocks, as well as by different degrees of faunal influence. Authors successfully used both major soil classification systems (World Reference Base for Soil Resources, 2014/15; Soil Survey Staff, 2014) in order to specify the leading pedogenic processes on meso- and microscale and to separate the soils with most important differences.

In this paper, data on the morphology and major analytical properties of 130 pedons sampled in the area of the Fildes Peninsula and Ardley Island are interpreted; the soils are classified according to the IUSS World Reference Base for Soil Resources (2014/15). On this basis, a new soil-geomorphological map of the studied area has been compiled on a scale of 1:10 000. In comparison with previous soil-geomorphological studies in the region (Schaefer et al., 2007; Michel et al., 2014b; Navas et al., 2017; Oliva et al., 2017), we pay special attention to the morphology and taxonomic diversity of soils with the aim to characterize heterogeneity of the soil cover patterns and to assess the anthropogenic impact on soils in the surroundings of polar research stations on the Fildes Peninsula.

2. Materials and methods

2.1. Study area

King George Island is the largest island (1 400 km^2) in the South Shetlands Archipelago. Only about 5–8% of its area is ice-free (Rakusa-Suszczewski, 2002; Bölter, 2011). The Fildes Peninsula and Ardley Island together comprise the largest ice-free area on King George Island occupying its southwestern part and facing a relatively small (250 km^2) Nelson Island on the opposite side of the 370-m-wide Fildes Strait.

Deglaciation on the Fildes Peninsula started in the Early Holocene; there were several stages of active warming and deglaciation (8.5–5.3, 4.0–2.0, 1.4–0.6 ka BP) separated by stages of relatively slow deglaciation (5.3–4.0 and 2.0–1.4 ka BP) (Verkulitch et al., 2012, 2013). In the recent millennium, some advance of glaciers has taken place in most of the areas; it is likely to correspond to the Little Ice Age (Verkulitch, 2009). The distribution of fauna and flora in Antarctica is largely determined by the age of deglaciation, as well as by the glacial, paraglacial, and periglacial geomorphological processes (Oliva et al., 2017). Data on recent soil formation in the zones of deglaciation, proglacial and paraglacial areas were published previously for the Antarctic Peninsula (Thomazini et al., 2014; González-Guzmán et al., 2017; Navas et al., 2017), as well as for the European alpine environments (D'Amico et al., 2014; Temme et al., 2016).

After the glacial erosion phase at the Fildes Peninsula, ice glacier retreat led to the Holocene glacioisostatic and tectonic uplift coupled with paraglacial and periglacial processes, such as frost weathering, gelifluction, cryoturbation, and nivation (Simonov, 1977; Navas et al., 2008; López-Martínez, et al., 2012). The patterned ground in this region dates back to 720 to 2 640 yr BP (Jeong, 2006). In the South Shetland Islands, permafrost is sporadic or is absent at elevations below 20 m a.s.l. and is discontinuous at the heights of 30–150 m a.s.l. (Serrano et al., 2008; Ramos et al., 2009; Bockheim et al., 2013).

Gentle topography dominates on the Fildes Peninsula with a wide central plain at about 40–50 m a.s.l., several smaller plains at the heights of 80–100 m a.s.l., and three massive flat-topped volcanic remnants with numerous rock outcrops and maximum heights from 120 to 150 m a.s.l. According to Smellie et al. (1984), this area mainly consists of volcanic rocks (andesite basalts and their pyroclastic products) with small outcrops of tuffs, volcanic sandstones, and agglomerates.

The climate is cold and relatively moist with the mean annual air temperature –2.2 °C and the mean annual precipitation about 350–500 mm/yr (data on 2000–2012, Teniente Rodolfo Marsh Martin Aerodrome Meteorological Station) (Michel et al., 2014b). Mean daily air temperatures are above 0 °C up to four months during the austral summer (Wen et al., 1994).

In 2006–2015, the mean thaw depth at the CALM-S site #A18 (CALM Summary Data; https://www2.gwu.edu/~calm/data/south.htm) on the outer edge of the marine terrace covered with green mosses and algae comprised 60 cm (Hrbáček et al., 2018). The average permafrost temperature is slightly below 0 °C near sea level, so this area is close to the climatic boundary of permafrost and has the highest sensitivity to climate changes in the region (Vieira et al., 2010; Michel et al., 2014a).

Shallow water streams and small lakes are widespread on the plains and gentle slopes. The basins of most lakes are of glacial origin, and the valleys of the largest streams are glacial troughs; both kinds of lake basins are mostly located along fractures (Michel et al., 2014a). Melting snow patches in the upper reaches of the streams mostly feed them, but in the case of the thick cover of rock debris with a significant content of fine earth content and the presence of impermeable ice-rich permafrost below the soil profile, additional water may be supplied from the thawing active layer. These water streams are active for only 2.5–3 months per year; some lakes may stay under the ice during the entire summer depending on weather conditions of a particular year.

Abundant mosses and lichens (approximately 109 lichens and 40 bryophytes (Andreev, 1989; Ochyra et al., 2008)), as well as terrestrial algae (e.g., *Prasiola crispa* subsp. *antarctica* (Kützing) Knebel.) are common on the ice-free area of the Fildes Peninsula. There are also two vascular plant species: *Deschampsia antarctica* É. Desv. and *Colobanthus quitensis* (Kunth) Bartl.). Adélie (*Pygoscelis adeliae,* Hombron and Jacquinot, 1841), Gentoo (*P. papua* Forster, 1781), and Chinstrap (*P. antarcticus* Forster, 1781) penguins; Brown (*Stercorarius antarcticus* Lesson, 1831) and South Polar (*S. maccormicki* Saunders, 1893) skuas; and Southern Giant petrels (*Macronectes giganteus* Gmelin, 1789) are common in coastal areas along with Antarctic Fur seals (*Arctocephalus gazelle* Peters, 1875) and Elephant seals (*Mirounga leonine* Linnaeus, 1758) and exert a significant impact on soil development via allochthonous organic matter supply. Major cryogenic surface-forming processes are frost creep, cryoturbation, frost heave, frost sorting, and gelifluction.

2.2. Methods

2.2.1. Field methods

In this paper, data on the morphology of 130 soil profiles described in the study area during field seasons in 2007–2016 are summarized. Site features—structure and density of vegetation cover, depth of the active layer, cryogenic texture of the upper permafrost (if determined), and morphometric parameters of cryogenic landforms (MacNamara, 1969; Campbell and Claridge, 1975; Bockheim and Tarnocai, 1998; Beyer et al., 1999) were also described. Soils were identified on the basis of morphological field descriptions of the whole control section, though the analyzed samples were only taken from the upper soil layers. The upper 10 cm of soil material were sampled to further analyze the total organic carbon (TOC) and nitrogen contents, pH, and particle size.

2.2.2. Laboratory methods

Soil analyses were performed in triplicate in the Chemical Analytical Laboratory of the Institute of Physicochemical and Biological Problems of Soil Science in Pushchino and in the Laboratory of the Department of Applied Ecology of St. Petersburg State University. Soil pH values (H_20 and KCl) in mineral and organic horizons were measured in 1:2.5 and in 1:25 (soil:distilled water and soil:1n KCl solution) extracts, respectively (U.S. Salinity Laboratory, 1954). TOC and nitrogen were determined on a Euro EA3028-HT element analyzer (Holmes, 1963; Yeomans and Bremner, 1988). The content of gravelly and stony material was estimated during the field survey using the dry sieving method.

2.2.3. Soil mapping

The IUSS World Reference Base for Soil Resources (2014/15) was applied to classify the studied pedons. Field data from 130 soil descriptions and topographic information displayed on the 1:10 000-scale map (Instituto Geographico Militar, 1996) were used for the soil-geomorphological mapping of the area. The exact location of studied pedons was determined in the field with a GPS receiver. These sites were selected in order to characterize the diversity of local landforms. The boundaries of soil polygons shown on the map were manually digitized using ArcMap v.10.4.1. (ESRI™) software. The mapping was performed in the Universal Transverse Mercator (UTM) projection, Zone 21 S with the geodetic datum WGS 1984. The total area covered by soil mapping was 28.62 km^2, including 0.48 km^2 (1.69% of the entire ice-free area) under lakes and 0.35 km^2 (1.23%) under perennial snow patches. The combinations of soil subgroups within the polygons were distinguished according to the dominance of the first mentioned soil subgroup and smaller areas occupied by the other subgroups (in case of two or more soil subgroups within the given polygon) (Table 1).

Table 1
Legend for the soil-geomorphological map of the Fildes Peninsula, King George Island.

Mapping unit, #	Environmental characteristics / Human impact*	Soil combination (association) (subgroup level, WRB 2014/15)	Area	
			km^2	%
Arenosols				
1	Flat and poorly drained watersheds and terraces with areas of stone pavement, sparse polygons; sparse suppressed black mosses and crustose and fruticose lichens	Protic Arenosols (Turbic) + Hyperskeletic Oxyaquic Turbic Cryosols (Arenic	6.56	22.92
Cryosols				
2	Second marine terraces with abundant rounded boulders and gravel; thick dense green moss cushions and fruticose lichens	Skeletic Histic Oxyaquic Cryosols + Histic Hyperskeletic Leptosols	0.82	2.87
3	Well-drained watersheds and upper slopes with abundant rock outcrops; well-expressed dense cover of green mosses and fruticose lichens	Turbic Cryosols (Arenic) + Hyperskeletic Leptosols (Arenic)	1.91	6.66
4	Poorly drained flat surfaces in the middle and lower reaches of shallow water streams; green mosses, algal–bacterial mats	Histic Oxyaquic Cryosols (Arenic)	2.03	7.08
5	Relatively well-drained watersheds and moderately steep slopes with areas of patterned ground; green mosses and crustose and fruticose lichens	Skeletic Turbic Cryosols + Cambic Hyperskeletic Leptosols	4.97	17.37
6	Relatively well-drained middle parts of gentle slopes with water supply from melting snow patches; polygonal microrelief; mosses and fruticose lichens	Skeletic Turbic Cryosols + Hyperskeletic Oxyaquic Turbic Cryosols	1.00	3.49
7	Moraine slopes adjacent to the ice dome; sparse small moss cushions and crustose lichens; single grasses	Hyperskeletic Cryosols (Arenic Ochric)	0.44	1.49
Leptosols				
8	Upper reaches of shallow water streams with abundant boulders and bedrock outcrops; abundant green mosses and fruticose lichens	Histic Hyperskeletic Leptosols (Oxyaquic) + Histic Oxyaquic Cryosols	1.14	4.00
9	Rock outcrops and steep cliffs; nearly no vegetation	Skeletic Lithic Leptosols + Skeletic Nudilithic Leptosols	1.67	5.84
10	Small weathered rock remnants; abundant small microareas of mosses and lichens	Lithic Leptosols (Ochric) + Skeletic Nudilithic Leptosols	2.02	7.06
11	Rocks and boulders of taluses of steep slopes; sparse fruticose lichens, single moss cushions	Lithic Leptosols (Ochric)	1.93	6.74
Fluvisols				
12	Tidal zones with permanent input of marine mineral and organic (including ornithogenic) materials; sparse green moss cushions	Tidalic Fluvisols (Skeletic) + Tidalic Fluvisols (Protoornithic, Skeletic)	0.93	3.27
Histosols				
13	Peat deposits underlain by permafrost; green mosses	Fibric Cryic Histosols + Leptic Cryic Histosols	0.02	0.02
Soils formed under the ornithogenic impact				
14	Modern and abandoned penguin rookeries with guano; algal–bacterial mats and nitrophilous algae	Hyperskeletic Cryosols (Protoornithic) + Hyperskeletic Cryosols (Ornithic)	0.27	0.94
15	Rocky coastal areas and small islands with significant impact of seabirds; green mosses and grasses	Lithic Leptosols (Arenic) + Nudilithic Leptosols (Protoornithic) + Hyperskeletic Leptosols (Protoornithic)	0.94	3.29
Soils formed under the technogenic impact				
16	Territory of the stations, vehicle roads	Hyperskeletic Turbic Cryosols (Arenic Densic) + Hyperskeletic Leptosols	0.86	3.00
17	Transported ground of the air stripe, airdrome facilities and surroundings	Hyperskeletic Technosols (Transportic)	0.07	0.25
18	Diesel power stations, petroleum tanks, garages and surrounding areas	Hyperskeletic Technosols (Toxic)	0.10	0.35
19	Outside storages, functioning and abandoned dumpsites	Hyperskeletic Cryic Urbic Technosols	0.07	0.25

* - in case of Technosols.

Authors did not estimate the exact percent of dominant soil subgroups within the polygons. Soils with a relatively high content of allochthonous organic material (e.g., soils affected by flying sea birds, penguins, or seals) were distinguished as a separate group in the legend to the map.

3. Results and discussion

Previous studies of our colleagues were focused on geomorphology and natural and human-affected soils in the ice-free areas of Antarctic Peninsula and adjacent islands (Zhao and Rongquan 1999; Schaefer et al., 2007; Simas et al., 2008; Francelino et al., 2011; Bölter, 2011; López-Martínez et al., 2012; Amaro et al., 2015; Boy et al., 2016; Abakumov et al., 2017; González-Guzmán et al., 2017; Oliva et al., 2017). We would like to pay special attention to the studies aimed at a better understanding of the pattern and heterogeneity of the soil cover and major landforms and their elements in the given region.

The environmental types of the Fildes Peninsula presented by Pang and Li (2012) were grouped into four major groups: "coastal, periglacial, ice water, and artificial," which were further subdivided into 29 environmental landscape units according to soil and biome characteristics. The geomorphological mapping performed by Michel and coauthors (2014b) presented the spatial distribution of topographic, structural, glacial, periglacial, fluvial, marine, and human-made features in the studied area within three main cold morphogenetic subsystems and processes (gravity, gelifluction, and frost creep, and cryoturbation) and fifteen individual periglacial landforms. We consider these two studies to be the most relevant to the issue of soil mapping in the Antarctic region because of the synthesis of vegetation, soil, and geomorphic characteristics and remote sensing data. The results obtained by us also attest to the high spatial heterogeneity of the soil covers on the paraglacial, periglacial, coastal, fluvial, and human-modified geomorphic elements; this natural heterogeneity is further complicated by the active and long-term anthropogenic loads.

A simultaneous analysis of data on the morphology of soil profiles, their geomorphic position, and their physical and chemical properties allowed us to specify six major reference soil groups (IUSS World Reference Base for Soil Resources, 2014/15) composing the soil cover of the Fildes Peninsula and Ardley Island. With respect to the total area occupied by them, these soil groups formed the following sequence: Cryosols > Leptosols > Arenosols > Fluvisols > Technosols > Histosols (Fig. 2). Different soil subgroups or their combinations were arranged into 19 19 elementary soil-geomorphological mapping units (Fig. 3**,** Table 1).

Nearly half (42.9%) of the total area of the Fildes Peninsula and Ardley Island is covered by different subgroups of Cryosols: relatively thick Skeletic Turbic (27.6%), organic-rich Skeletic Histic Oxyaquic (9.9%), human-affected Hyperskeletic Turbic (Arenic Densic) (3%), nearly ahumic Hyperskeletic Cryosols (Arenic Ochric) (1.5%), and affected by birds Hyperskeletic (Ornithic) (0.9%) Cryosols.

Other subgroups of Cryosols shown on the map include Skeletic Lithic (5.8%), Histic Hyperskeletic (Oxyaquic) (4%), and Lithic (Arenic) (3.3%) Cryosols. Flat moderately drained watersheds are mainly occupied by Protic Arenosols (Turbic) (22.9%) relatively rich in fine earth. Leptosols are mainly organic-poor and are represented by the Lithic (Ochric) subgroup covering 13.8% of the area. Fluvisols are locally developed on the peninsula and are only represented by coastal Tidalic (Skeletic) subgroup (3.3%). A small and unique area of Fibric Cryic Histosol (0.02%) was specially examined during the survey. Several subgroups of Hyperskeletic Technosols (Toxic, Transportic, and Urbic) cover together about 0.9% of the area mostly in the surroundings of research stations.

The content of gravel and coarser rock fragments in most of the samples was very high (Table 2). An increased percent of fine earth was found in Protic Arenosols (Turbic), Skeletic Histic Oxyaquic Cryosols, Histic Oxyaquic Cryosols (Arenic), and Tidalic Fluvisols (Skeletic). Nearly all the soils demonstrated relatively low pH values attesting to acid soil reaction. The highest content of TOC was determined in the uppermost horizons of Histic Hyperskeletic Leptosols (Oxyaquic), Histic Oxyaquic Cryosols (Arenic), and Hyperskeletic Cryosols (Ornithic) among mineral soils and in Fibric Cryic Histosols. Other subgroups of Cryosols, Arenosols, and Leptosols had the TOC content varying from 3 to 9%, which attested to significant accumulation of organic material in the topsoil horizons. Human-affected soils, along with Hyperskeletic Cryosols (Arenic Ochric) developed from moraine deposits and Skeletic Lithic Leptosols (Ochric) on the little-weathered hard bedrock, demonstrated the lowest values of TOC. Technosols and Hyperskeletic Turbic Cryosols (Arenic Densic) had very thin intermittent surface organomineral horizons. Normally, the C/N ratio was the highest in soils with the highest TOC content. This indicates that fresh Histic material is always less humified and decomposed. In opposite, soils with a very low TOC content had a higher degree of the organic matter enrichment in nitrogen. Only Hypeskeletic Arenosols were characterized by the high C/N ratio and low TOC content. This could be related to the fact that the organic matter of these soils is represented by undecomposed organic remains not associated with the soil mineral material. In contrast, Histic Oxyaquic Cryosols had low C/N ratio and high TOC content, which could be due to some additional input of the ornithogenic organic material. In soils with a strong ornithogenic effect, the C/N ratio was also low because of the accumulation of zoogenic nitrogen

3.1. *Cryosols*

One of the major concerns of soil mapping in the studied area was to delineate polygons with Cryosols as dominant soils. Sufficient amount of liquid water that activates cryoturbation and cryogenic sorting in a relatively thick active layer with a significant amount of fine earth in the summer season and a reliably detectable table of ice-rich permafrost within the 1-m section characterize such areas. Most of the soils in these areas have clearly expressed features of cryoturbation, which is in agreement with previous studies (Michel et al., 2014b; Bockheim et al., 2015). Cryoturbation also plays an important role in soils that are relatively rich in fine earth (though it comprises $<$ 20 vol%) and do not have lithic contact within the upper 75 cm of the control section. Otherwise, such soils can be identified as Hyperskeletic Leptosols (Arenic, Turbic). Cryosols with clearly manifested underlying permafrost also often occur within the areas dominated by Leptosols and Arenosols.

The most widespread geomorphic positions with a predominance of Cryosols dominate (#5) are well-drained watersheds and moderately steep slopes with patterned ground features and with a cover of green mosses and crustose and fruticose lichens (17.4% of the area of the Fildes Peninsula and Ardley Island). Other areas of Cryosols together comprise another 22.5% of the studied territory and cover different geomorphic positions: from the well-drained watersheds and upper slopes with abundant rock outcrops and boulders and with well-expressed cover of green mosses and fruticose lichens to the poorly drained flat surfaces on the second marine terrace.

Organic-rich soils along small water streams and around shallow lakes in the inland areas were classified as Histic Oxyaquic Cryosols (Arenic) (mapping unit #4; around 7% of the territory). These soils are densely covered with green mosses and algae-bacterial mats, the middle parts of their profiles often display redoximorphic features.

The most impressive and dense vegetation cover consisting of thick bright-green-moss cushions along with well-grown *Usnea antarctica* occupies second marine terraces, where a lot of snow is accumulated every austral winter. This mapping unit (#2) covers nearly 3% of the territory. Skeletic Histic Oxyaquic Cryosols dominate in the soil cover with Histic Hyperskeletic Leptosols (Ochric) in a subdominant position. These soils provide a significant amount of histic material, and they often overlie Holocene raised beaches, where mineral part of the soil profile consists of gravel and rounded boulders with a low amount of

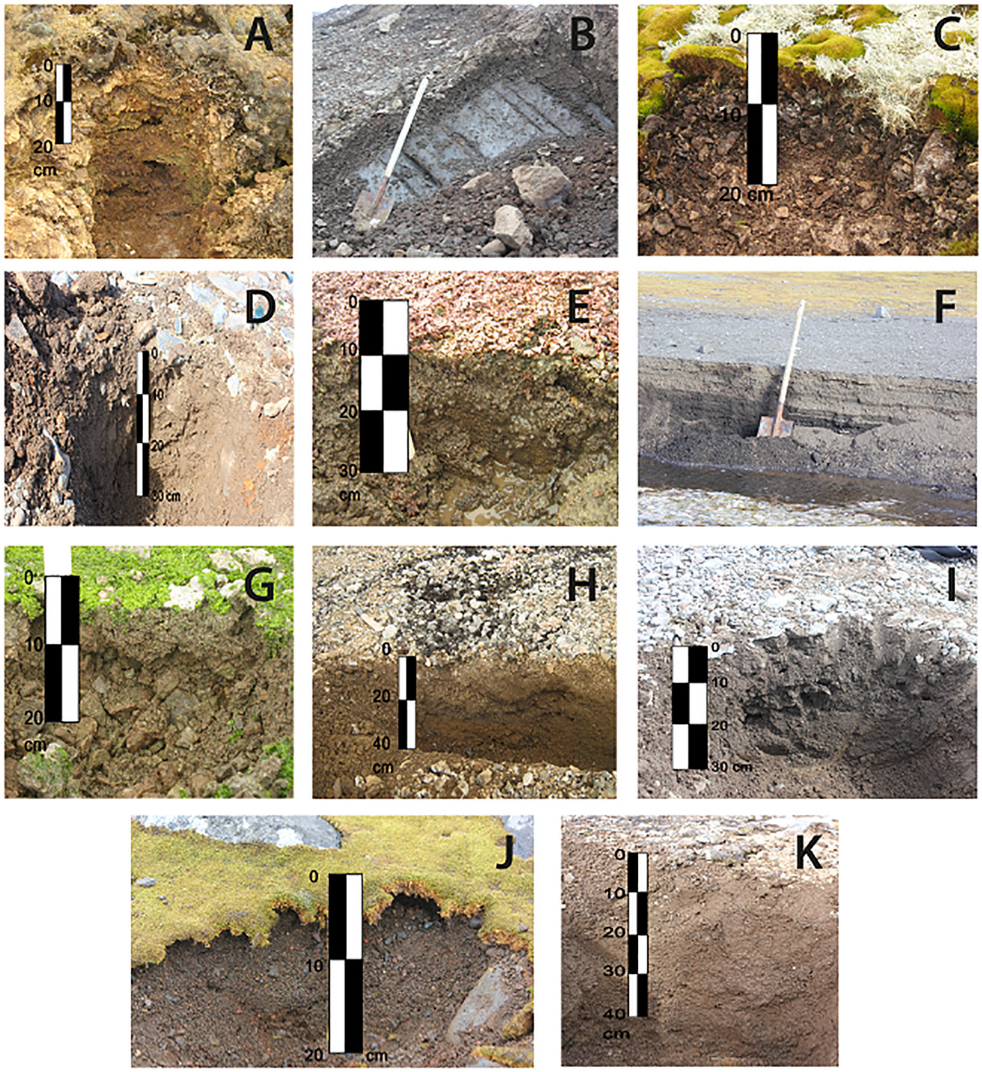

Fig. 2. Major soils of the Fildes Peninsula and Ardley Island (World Reference Base for Soil Resources, 2014/15): A—Fibric Cryic Histosols; B—Hyperskeletic Cryosols (Arenic, Ochric); C—Skeletic Histic Oxyaquic Cryosols; D—Hyperskeletic Cryic Urbic Technosols; E—Histic Hyperskeletic Leptosols (Oxyaquic); F—Tidalic Fluvisols (Skeletic); G—Hyperskeletic Leptosols (Protoornithic); H—Cambic Hyperskeletic Leptosols; I—Protic Arenosols (Turbic); J—Hyperskeletic Leptosols (Arenic); and K—Skeletic Turbic Cryosols.

fine earth. The soils are overmoistened by flowing water during snow melting, which also leads to the loss of fine earth material from the upper horizons.

The mapping unit of Hyperskeletic Cryosols (Arenic, Ochric) (#7; nearly 1.5% of the territory) occupies the youngest areas in terms of deglaciation history (Verkulitch, 2009): the moraine deposits adjacent to the Bellingshausen Ice Dome. Hyperskeletic Cryosols (Arenic Ochric) are relatively rich in fine earth, and the active layer in such places rarely exceeds 50 cm. The vegetation cover is very sparse and suppressed. In some cases, fragmentary stone pavement is developed.

Specific morphology allows distinguishing Hyperskeletic Cryosols (Ornithic and Protoornithic) of modern and abandoned penguin rookeries (mapping unit #14, about 1% of the area). Hyperskeletic Cryosols (Ornithic and Protoornithic) have a relatively thick profile (50 cm and more) highly enriched in allochthonous ornithogenic material. They are formed under the specific vegetation cover consisting of the bacterial mats and nitrophilous algae (*Prasiola crispa* subsp. *antarctica* (Kützing) Knebel).

Human-affected Cryosols (unit #16) with overcompacted uppermost horizons, disturbed moss and lichen cover, and relatively high content of different pollutants in the soil material occupy around 3% of the Fildes Peninsula and Ardley Island in the areas adjacent to research stations and vehicle roads; these soils were classified as Hyperskeletic Turbic Cryosols (Arenic Densic).

3.2. Leptosols

The area of Leptosols on the Fildes Peninsula and Ardley Island is the second largest after Cryosols and comprises about 24% of the territory. Field survey of Antarctic Leptosols, which are super-enriched in gravel and boulders and are often underlain by hard poorly weathered bedrock, demonstrated that it is often impossible to determine the presence of ice-rich permafrost at some depth. We intentionally did not use Gelic supplementary qualifier for these soils. Despite the significant differences in water and temperature regimes of these soils, Leptosols may occupy nearly all geomorphic positions because of the widespread distribution of rock outcrops. These soils also often occur within the areas dominated by Cryosols and Arenosols. Even birds' nesting and molting effect that sometimes is very well expressed do not always lead to significant changes in the soil morphology allowing us to place these soils into other reference soil group. The main morphological features that were taken into account in separation of the areas with a predominance of Leptosols into five mapping units are listed below.

First, this is the thickness of the profile (depth to the lithic contact)

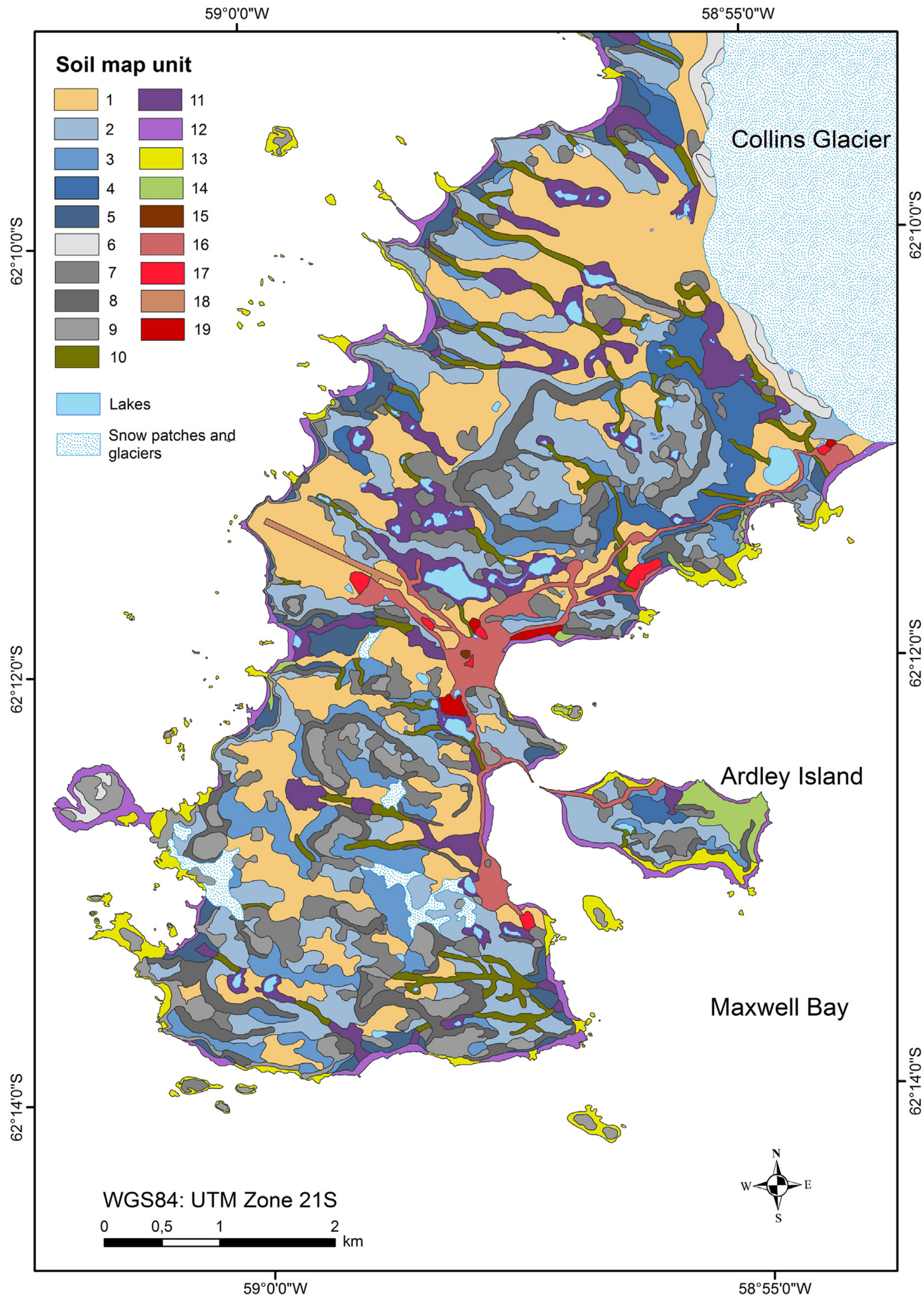

Fig. 3. Soil-geomorphological map of the Fildes Peninsula and Ardley Island (King-George Island). Scale 1:10 000. Mapping units are explained in Table 1.

and the fine earth content. These criteria were used to separate Nudilithic and Lithic Leptosols (units #9–11) from Hyperskeletic Leptosols (#8). These mapping units cover about 19% of the territory, though Leptosols themselves are very locally expressed within such areas. Shallow profiles with abundant coarse rock fragments and sparse vegetation represented by fragmentary moss cushions and small bodies of crustose lichens occur on the poorly weathered rock exposures on the watersheds and steep slopes mainly in the inland areas of the Fildes Peninsula and Ardley Island. Because of the sparse vegetation and weakly expressed interaction between mineral and organic materials, the TOC content in these soils is very low (Table 2); the supplementary qualifier Ochric was used to specify these Leptosols.

Birds' nesting and molting activity results in the development of Leptosols with a Protoornithic qualifier. Prefix "proto" was added to the Ornithic supplementary qualifier in order to underline the low rate of the interaction of ornithogenic material and rock debris despite the relatively high input of allochthonous organic matter. Lithic and Hyperskeletic Leptosols (Protoornithic) comprise soil mapping unit #15

Table 2
Chemical properties and rock fragments / fine earth contents in major soils of the Fildes Peninsula (mean ± SD).

Mapping unit / Soil	TOC, %	Total N, %	C/N ratio	pH		Rock fragments (greater than2 mm), %	Fine earth (< 2 mm), %
				H_20	KCl		
1 / Protic Arenosols (Turbic)	5.16 ± 0.8	0.82 ± 0.04	6.27 ± 1.1	5.75 ± 0.1	5.39 ± 0.2	73.33 ± 6.0	26.66 ± 6.1
2 / Skeletic Histic Oxyaquic Cryosols	8.37 ± 1.1	0.39 ± 0.05	21.43 ± 4.4	6.36 ± 0.5	5.94 ± 0.3	74.33 ± 7.8	29.0 ± 3.1
3 / Turbic Cryosols (Arenic)	7.29 ± 1.6	0.61 ± 0.14	12.27 ± 4.3	4.65 ± 0.4	4.41 ± 0.5	85.83 ± 5.8	17.5 ± 2.3
4 / Histic Oxyaquic Cryosols (Arenic)	27.50 ± 7.7	3.62 ± 2.18	9.66 ± 5.3	5.53 ± 0.2	5.10 ± 0.3	66.0 ± 4.0	34.0 ± 4.2
5 / Skeletic Turbic Cryosols	1.90 ± 0.9	0.37 ± 0.36	10.55 ± 8.8	5.03 ± 0.2	4.48 ± 0.5	92.16 ± 3.3	7.83 ± 2.8
6 / Skeletic Turbic Cryosols	6.21 ± 1.2	0.36 ± 0.07	17.49 ± 5.4	5.56 ± 0.2	5.14 ± 0.1	87.6 ± 5.0	12.3 ± 4.9
7 / Hyperskeletic Cryosols (Arenic Ochric)	0.73 ± 0.4	0.06 ± 0.04	18.39 ± 2.1	4.72 ± 0.2	3.91 ± 0.2	92.0 ± 2.8	8.0 ± 2.0
8 / Histic Hyperskeletic Leptosols (Oxyaquic)	28.95 ± 3.9	0.85 ± 0.11	34.14 ± 5.2	5.66 ± 0.2	4.96 ± 0.3	81.33 ± 4.9	18.66 ± 1.2
9 / Skeletic Lithic Leptosols	0.39 ± 0.1	0.06 ± 0.02	6.96 ± 1.5	5.93 ± 0.2	5.42 ± 0.3	94.5 ± 2.0	5.5 ± 0.5
10 / Skeletic Nudilithic Leptosols	5.16 ± 1.9	0.59 ± 0.15	8.78 ± 2.3	5.52 ± 0.2	5.05 ± 0.2	Not det.	
11 / Lithic Leptosols (Ochric)	0.51 ± 0.3	0.07 ± 0.04	6.90 ± 0.4	5.73 ± 0.1	5.13 ± 0.3		
12 / Tidalic Fluvisols (Skeletic)	7.19 ± 1.3	0.24 ± 0.07	32.05 ± 5.4	5.86 ± 0.2	5.45 ± 0.1	70.0 ± 4.9	30.0 ± 5.0
13 / Fibric Cryic Histosols	48.89 ± 8.7	1.86 ± 0.65	28.21 ± 8.7	4.81 ± 0.8	4.34 ± 0.2	Not det.	
14 / Hyperskeletic Cryosols (Ornithic)	17.5 ± 6.5	3.01 ± 1.25	6.89 ± 3.1	5.70 ± 0.5	5.41 ± 0.8	83.83 ± 6.2	16.16 ± 6.2
15 / Hyperskeletic Leptosols (Protoornithic)	3.87 ± 0.6	1.24 ± 0.07	3.19 ± 0.3	4.96 ± 0.2	4.71 ± 0.3	94.33 ± 3.2	5.66 ± 3.2
16 / Hyperskeletic Turbic Cryosols (Arenic, Densic)	2.15 ± 0.2	0.28 ± 0.14	8.59 ± 3.0	6.03 ± 0.2	5.08 ± 0.1	94.0 ± 2.6	6.0 ± 2.6
17 / Hyperskeletic Technosols (Transportic)	1.56 ± 0.5	0.10 ± 0.03	15.14 ± 5.2	5.53 ± 0.3	4.44 ± 0.4	Not det.	
18 / Hyperskeletic Technosols (Toxic)	1.12 ± 0.3	0.10 ± 0.03	12.57 ± 2.7	4.65 ± 0.3	3.82 ± 0.9	93.5 ± 0.5	6.5 ± 0.5
19 / Hyperskeletic Cryic Urbic Technosols	0.96 ± 0.3	0.18 ± 0.06	5.28 ± 0.4	6.91 ± 0.1	Not det	91.83 ± 3.3	8.16 ± 3.3

that mainly characterizes coastal localities on steep and rocky cliffs of abundant small islands, where flying sea birds (gulls, petrels, skuas, and others) are nesting and molting (around 3.3% of the territory).

One of the significant areas of Leptosol dominance comprises mapping unit #8 represented by a combination of predominant Histic Hyperskeletic Leptosols (Oxyaquic) with Histic Oxyaquic Cryosols in minor position. This mapping unit covers about 4% of the studied area, mainly on moderately steep slopes with satisfactory drainage conditions and with a significant content of fine earth. The plant cover here is very dense and rich and consists of fruticose lichens (mainly, *Usnea antarctica* Du Rietz) on boulders and thick green moss cushions between them. The amount and quality of soil organic matter ensure relatively strong processes of its stabilization in the profile with the formation of organomineral compounds in the uppermost horizon. The amount of water and fine earth in the mineral part of the profile provide for cryoturbation and cryogenic rock sorting processes. Such soils can be classified as Histic Oxyaquic Cryosols, and they occupy a minor position in this soil association.

3.3. Arenosols

Soils of mapping unit #1 occupy about 23% of the total territory; this is the most widespread soil combination with a predominance of Protic Arenosols (Turbic) and with Hyperskeletic Oxyaquic Turbic Cryosols (Arenic) in minor position. This soil combination occurs on relatively poor-drained flat watersheds and very gentle slopes fed with liquid water from the surrounding snow patches. The thickness of soil-forming mineral material here is relatively large (about 50–60 cm), and the fine earth content reaches about 25% (Table 2). The plant cover here is fragmentary and consists of sparse and suppressed black mosses and crustose and fruticose lichens. Patterned ground and stone pavement are relatively well expressed.

3.4. Fluvisols

True Fluvisols (soils with the regular input of fluvic material and evident stratification of the mineral part of the profile) in the studied area are represented by y Tidalic Fluvisols (Skeletic) in association with Tidalic Fluvisols (Protoornithic, Skeletic) (unit #12; about 3.3% of the territory). These soils occupy gently sloping ocean shores affected by tidal processes with regular input of marine mineral material, seawater drops, and seaweeds. The latter represent an important source of allochthonous organic matter in the soil profile. This area is often affected by sea birds, penguins, and mammals, so the soils may also contain zoogenic organic matter in the uppermost horizon, which justifies the use of the Protoornithic qualifier.

3.5. Technosols

A significant issue of soil mapping of the Fildes Peninsula and Ardley Island was to reflect the anthropogenic impact on soils. The soils subjected to relatively low and predominantly mechanical loads were distinguished as Hyperskeletic Turbic Cryosols (Arenic, Densic) and described above. Human-affected soils in other three mapping units were classified as Technosols and were further divided according to the type and severity of the impact. Technosols are not strictly associated with certain geomorphic positions. However, they are mainly concentrated in the coastal areas, where most of the human facilities are located. We distinguish between Hyperskeletic Technosols (Toxic) occupying areas around the petroleum tanks, diesel stations, and garages (unit #18; 0.4% of the total area); Hyperskeletic Cryic Urbic Technosols in the areas of functioning and abandoned dumpsites (unit #19; 0.3% of the total area); and Hyperskeletic Technosols (Transportic) representing transported ground of the air stripe and the area around the airport (unit #17; 0.25% of the total area). Technosols at of the Fildes Peninsula contain up to 1800 mg/kg^{-1} of hydrocarbons (mostly of anthropogenic origin), while unpolluted soils (e.g. Protic Arenosols (Turbic)) in the inland areas of the Fildes Peninsula contain no more than 500 mg/kg^{-1} of hydrocarbons (The Soils of Antarctica, 2015). Human-affected soils (especially, Hyperskeletic Technosols (Toxic)) are enriched in heavy metals: the concentrations of Cu, Pb, Cd, Zn, Ni, and Hg in them are four to ten times higher in comparison with pristine unaffected soils in the inland territory and adjacent islands (Guerra et al., 2012; Amaro et al., 2015; Abakumov et al., 2017).

3.6. Histosols

Last but not least is the unique small area (unit #13) of Fibric Cryic

Histosols and Leptic Cryic Histosols confined to relatively thick peat deposits on the slope of a small hill in the area of the Russian research station Bellingshausen. This small (about 50 m^2) is totally covered by mosses; the active layer depth is about 30–40 cm, and the profile of Histosols is underlain by frozen peat down to 1.2–1.5 m. Only the lowermost frozen peat horizons contain significant amounts of sand and gravel. Radiocarbon age of a less thick frozen peat material in the adjacent area on AI is 3 265 ± 120 BP (Zhao and Rongquan, 1999).

4. Conclusions

The environments of the Fildes Peninsula and Ardley Island are characterized by the considerable diversity of soils, which is related to the diversity of landforms and parent materials, as well as to differences in the snow cover depth, abundance of liquid water, thickness of rock debris, and the coarse fraction/fine earth ratio at the scale of mesorelief. Overall, 19 soil mapping units were distinguished to characterize the heterogeneity of the soil cover. Different subgroups of Cryosols cover nearly half of the total area and mainly occupy relatively well-drained watersheds and moderately steep slopes with a relatively thick cover of rock debris and with additional water supply from melting snow patches. However, Cryosols may also occur as a minor component of the soil cover in other geomorphic positions. Protic Arenosols are relatively rich in fine earth and tend to occupy flat moderately drained watersheds. Leptosols are mainly poor in the organic matter and are represented by the Ochric subgroup. Fluvisols are associated with the tidal zone in the coastal area. Histosols are very localized; their small areas are confined to few sites with accumulation of relatively thick peat material. Technosols occur in the areas adjacent to the airport facilities and research stations and are characterized by relatively high concentrations of hydrocarbons and heavy metals. In the studied area, these are mainly moderately polluted soils. We consider the soil-geomorphological approach to soil mapping to be very helpful in understanding of the spatial patterns and heterogeneity of the soil cover in relation to the diversity of landforms and geomorphic elements and rate of anthropogenic pressure in the studied region, as well as in oases of continental Antarctica.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

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