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RADIOCARBON AGE OF SOILS IN OASES OF EAST ANTARCTICA

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ABSTRACT. This article discusses radiocarbon dating results for soils and soil-like systems in the East Antarctic oases, including Schirmacher, Thala Hills, and Larsemann Hills. The organic matter of endolithic and hypolithic systems, soils of wind shelters, and soils under moss-algae vegetation were dated along with micro- and macroprofiles. Organic matter pools formed under extreme climatic conditions and originated not from vascular plants but from cryptogamic organisms, and photoautotrophic microbes have been identified within the oases of the East Antarctica. The organic matter of the most of East Antarctic soils is young and cannot reach a steady state because of the high dynamism in the soil cover due to active erosion. The oldest soil organic matter in East Antarctica was found in the soils formed in wind shelters and endolithic soil-like systems under the protection of consolidated rock surfaces. According to our data, the maximal duration for the formation of organic matter profiles within the oases of East Antarctica is ~500 yr, which is similar to the age determined for High Arctic soils in Eurasia. The absence of older soils, comparable with the Holocene deglaciation, can be due to the extreme conditions resulting in occasional catastrophic events that destroyed the soil organic horizons.

KEYWORDS: Antarctica, soils, soil-like systems, organic carbon, ^{14}C dating, extreme environment.

INTRODUCTION

The more than century-long history of research on Antarctic soils has been reviewed in a recent monograph (Bockheim 2015). Currently, ice-free lands totaling 45,000 km^2 in area constitute 0.35% of the continent, including 0.03–0.3% occupied by small Antarctic oases. An Antarctic oasis is a substantial ice-free area that is separated from the ice sheet by a distinct ablation zone and is kept free from snow by ablation due to the low albedo and positive radiation balance (Riffenburgh 2007). Oases can occupy an area from several tens to several thousand square kilometers. Although Antarctica is known for having the coldest climate on the Earth, there are still some possibilities for soil formation and accumulation of products from organomineral interactions within the oases. The rates of organic matter transformation and accumulation in Antarctic terrestrial ecosystems are significantly different from those in Arctic ecosystems (Tedrow 1991; Bölter and Kandeler 2004). Russian Antarctic research has revealed that the climatic conditions within the East Antarctic oases are quite different from a cold desert, which is commonly thought to be the predominant environment of continental Antarctica. The East Antarctic oases have been designated as mid-Antarctic snow-patch barrens with a moist coastal climate (Goryachkin et al. 2012; Balks et al. 2013). There are numerous published studies on the organic matter of soils and soil-like systems of Antarctica (Beyer et al. 1997, 2004; Beyer 2000; Bokhorst et al. 2007; Hopkins et al. 2009, 2014; Abakumov 2010; Beilke and Bockheim 2013), but many issues are still uncertain, particularly, the rates and periods of soil formation. It is generally believed that most coastal soils in Antarctica can be contemporary with the Late Glacial Maximum or younger (Bockheim 2015). However, there is a lack of radiocarbon dates to support this concept. The present study is aimed to determine the ^{14}C ages of soils and soil-like systems within the oases of East Antarctica. The results reveal possibilities for stable

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organic matter formation in this extreme environment as well as for an uninterrupted development of organogenic soil profiles since the time of deglaciation in the study sites.

OBJECTS AND METHODS

The soils and soil-like systems of three East Antarctic oases and one nunatak were studied (Figure 1). Fieldwork was carried out by the authors as a part of the Russian Antarctic Expedition over the period from 2009 to 2015. The samples were taken from the following locations in East Antarctica: the trans-shelf Schirmacher Oasis (70°45′S, 11°37′E) and the Aerodromnaya Hill nunatak (70°47′S, 11°37′E), both found within the Queen Maud Land near the Russian research station of Novolazarevskaya; the Thala Hills Oasis (67°40′S, 45°20′E) in the western part of the Enderby Land near the Russian research station of Molodezhnaya and the Belorussian Antarctic Station; and the Larsemann Hills Oasis (69°24′S, 76°13′E) in the Princess Elizabeth Land near the Russian research station of Progress.

Among the studied oases, the Thala Hills Oasis is the coldest one, with mean temperatures of the warmest and the coldest months (January and August) being –0.7°C and –18.8°C, respectively. In the Larsemann Hills Oasis, those temperatures are +0.6°C and –15.9°C, and in the Schirmacher Oasis, the mean temperatures are –0.4°C and –17.9°C, respectively. Regarding the soil-forming conditions, the most important features of the local climate are as follows: in summer, the soil and rock surface temperatures at the northern (warmest) slopes are very different from the air temperature and can reach +30°C on average; strong winds (up to 60 m/s) actively redistribute fine particles and sometimes carry even medium-sized stones; precipitation occurs mostly in the form of snow that undergoes immediate redistribution by the wind. It should be mentioned that the mean annual precipitation is from 200 to 300 mm, mainly in the form of snow, with only about 10 mm falling during the summer season.

Figure 1 Map of Antarctica, showing the location of the studied oases and nunatak.

The study sites can generally be characterized by a hilly topography with elevated formations of *roche moutonnée* around the river valleys and numerous lakes. The parent material is gravelly sand and loamy sand, usually with a shallow granite bedrock beneath. The patchy vegetation is represented by mosses, lichens, and algal-bacterial mats. As water availability is the main limiting factor for the development of living organisms here in Antarctica, the vegetation is usually found next to the snow patches that melt in summer or within the refuges that can hold the meltwater.

East Antarctica experiences strong interannual fluctuations of temperature with consequent thawing of glaciers and snow patches and occasional water erosion. These local catastrophic phenomena also favor the redistribution and loss of soil particles. For example, some of our long-term observation sites of soils under moss communities were destroyed by torrential currents of water coming from an actively melting glacier during the warm summer of 2012–2013 in the Schirmacher Oasis. The locations of snow patches also change interannually and interdecadally because of wind-snowfall dynamics in the complicated topography (Aleksandrov 1985). These factors and the strong dependence of vegetation and soil development on the melting water result in very high dynamism for the soil cover in East Antarctica.

^{14}C dating was carried out for soils and soil-like systems for the three oases studied. The samples were taken from locations most favorable for the formation and preservation of organic matter under the extreme climatic conditions of East Antarctica (Figure 2). All the soils are classified as Cryosols using the World Reference Base (WRB) system (IUSS Working Group 2014) or Gelisols in the Soil Taxonomy system (Soil Survey Staff 2010) in case of the shallow permafrost table and Leptosols (WRB) or Entisols (Soil Taxonomy) for the shallow bedrock.

Endolithic and Hypolithic Systems (Figures 2.1, 2.3)

The drought stress, strong winds, and ultraviolet radiation often prevent the development of living organisms at the surface and force them into refuges. The majority of the live and dead biomass in the hard rocks is concentrated under exfoliation plates or crusts, where endolithic soil-like systems are formed. On the land surface, under the stone pavement, hypolithic soil-like systems are formed. Therefore, most of the biotic-abiotic interactions and the formation of organic matter occur not at the surface but inside the mineral matrix, where the profile differentiation takes place and the microprofiles of soils are formed. Formally, endolithic “soils” can be classified as Nudilithic Leptosols (WRB) but cannot be classified in the Soil Taxonomy system. The hypolithic sediments are Protic Turbic Cryosols (WRB) and Typic Haploturbels (Soil Taxonomy).

Soils Sheltered from Winds with Macroprofiles (Figure 2.2)

These are the most developed soils in the oases. They are formed without any obvious influx of allochthonous organic matter of marine or lacustrine genesis, but within rock hollows sheltered from descending winds and filled with eluvial-colluvial deposits. The soils develop under the thick mats of bryophytes and have profiles up to 20 cm deep. They are Haplic Cryosols (Protospodic) (WRB) and Typic Haplorthels (Soil Taxonomy).

Soils under Moss and Moss-Lichen Communities with Macroprofiles (Figure 2.5)

These soils have profiles 15–20 cm deep with a sequence of genetic horizons. They usually develop within natural depressions, and are located next to large snow patches over north-facing slopes. They were classified as Turbic Cryosols (WRB) and Typic Haploturbels (Soil Taxonomy).

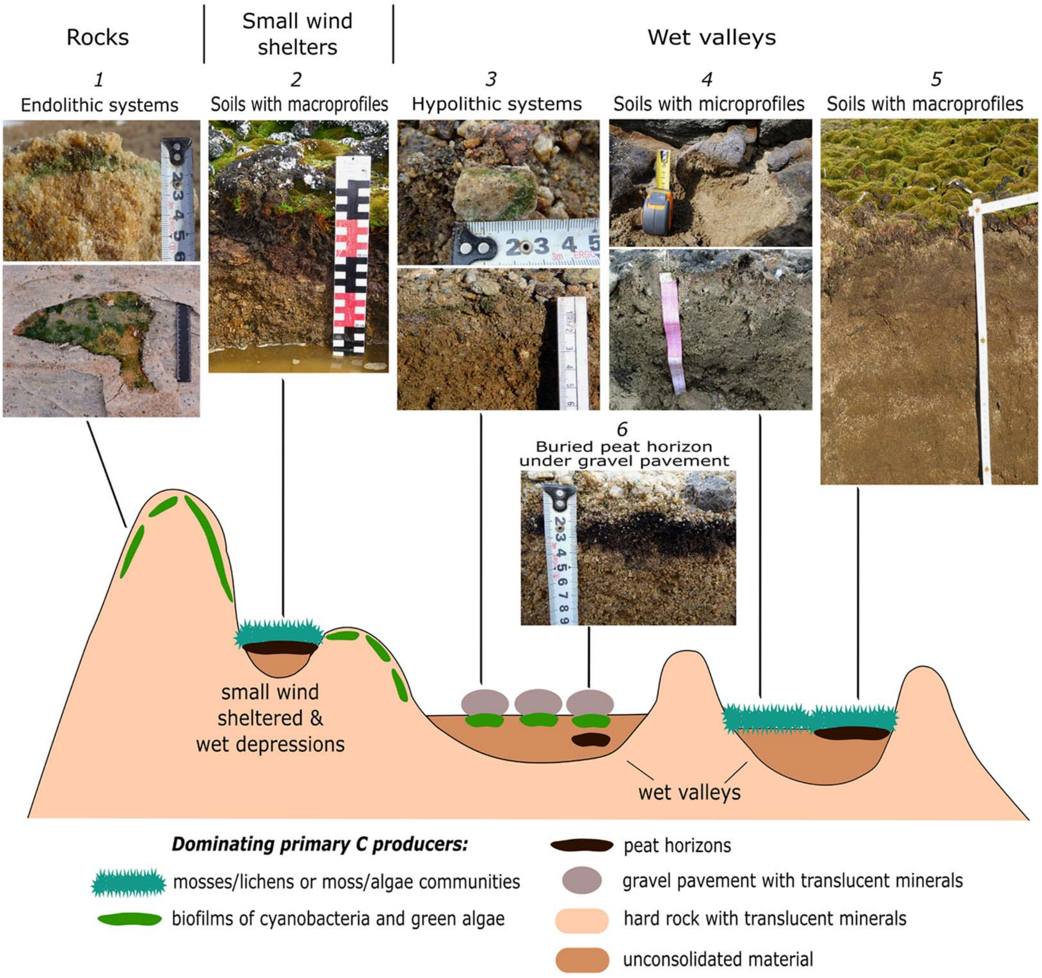

Figure 2 Sampled locations charted upon the schematic landscape conditions of the three East Antarctic oases (Schirmacher, Thala, and Larsemann Hills). The sketch below indicates "hot spots" for the most favorable environment for formation and preservation of organic matter in the modern soils and soil-like bodies of oases.

Soils under Moss-Algal Communities with Microprofiles (Figure 2.4)

These soil profiles reach only the first few centimeters in depth, being confined to the bottom and slopes of wet valleys. They were also classified as Turbic Cryosols and Haplic Cryosols (WRB) and Typic Haploturbels and Haplorthels (Soil Taxonomy).

Detailed descriptions of pedogenetic and physicochemical features of the aforementioned soils exist in the literature (Goryachkin et al. 2012; Mergelov et al. 2012, 2015, 2016; Balks et al. 2013; Mergelov 2014; Zazovskaya et al. 2014, 2015; Dolgikh et al. 2015).

In total, there were about 30 samples taken for ^{14}C dating. Sampling was carried during summer months (January–February) in 2009–2015. Our field studies on soils and soil-like systems were conducted following the Bockheim et al. (2006) guide for describing, sampling, analyzing, and classifying soils of the Antarctic region. The samples taken in the field were transported and stored in the laboratory in a frozen state until treatment. Samples from soils with micro- and macroprofiles and wind-sheltered soils were taken from each genetic horizon of those soils. The zero reference was at the very top of the soil surface, i.e. at the top of the O horizon. It should be mentioned that the soil horizons of these Antarctic soils were significantly different from "classical" horizons of temperate soils. The "litter" horizon (O) from 0.2–0.3 to 1.0–3.5 cm thick consisted of dead parts of mosses that still retained their anatomic structure and very abundant sand grains of eolian origin. The litter was usually underlain by fragmentary (separate lenses and pockets) dry peat, the TJmr horizon, from several millimeters to 2.5–5.0 cm thick, also rich in mineral grains. These organogenic horizons were underlain by the organomineral TB horizon that consisted of sand with living and dead moss rhizoids. The TB horizon often filled in the spaces between the fragments of the TJmr horizons or, more rarely, occurred under the latter. The O, TJmr, and TB horizons usually contained sand-sized grains of light-colored minerals free from iron oxide films. In half of the studied profiles, such bleached grains formed fragmentary layers and lenses 3–5 mm thick between the organogenic horizons and sand layer, i.e. primitive albic horizons. The TB and B horizons often contained small lenses of peat from moss residues. The B mineral horizon and the mineral component of the TB horizon were differentiated from the parent material by their browner color or more intensive yellow-red hue (Zazovskaya et al. 2015). In hypolithic soil-like systems, the zero reference was also at the top of their surface, directly under the stone pavement. The maximum available quantity of organomineral material in the hypolithic soil-like system was sampled for ^{14}C dating. In endolithic soil-like systems, the zero reference was at the surface exposed after manual removal of a spalling plate (also referred to as the *desquamation crust*) 0.5–1.0 cm thick, covered with rock varnish. At the zero-reference surface, there was a community of endolithic organisms with an active participation of green and blue-green algae, a dead biomass, and a fine earth comprising coarse silty and fine sandy fractions. The fine earth material partly penetrated into the deeper rock zone along vertical fissures. Note that we only analyzed spalling plates having no fissures at the surface, so that the aerial input of the fine earth into the rock interior could be excluded. The endolithic biota and the fine earth material compose a specific horizon of active weathering and, probably, pedogenesis. The thickness of such horizons may reach 0.2–1.2 cm. A maximum available quantity of organomineral material of the endolithic soil-like system was sampled for ^{14}C dating (Mergelov et al. 2016).

Specialized techniques of sample preparation and separation of the datable fraction were intended to tackle problems associated with a very small size of the study objects (e.g. endolithic soil-like systems), implying a very small volume of the samples analyzed and a low concentration of organic carbon within them. From the samples less than 100 mg in weight, the datable fraction was separated by a modified technique of mild acid treatment followed by centrifugation, with subsequent determination of the total organic carbon (TOC). The samples were placed in 0.5M HCl and heated to 80°C for 20 min, centrifuged, and decanted. Samples were then rinsed in deionized water and dried at 105°C. This technique was applied to the endolithic and hypolithic soil-like systems as well as carbon-poor soil samples. For the samples containing plant debris, standard techniques including acid-base-acid (ABA) treatment were employed. The samples were placed in 1M HCl and heated to 80°C for 1 hr, centrifuged, and decanted. Then, the samples were washed with 0.1M NaOH and treated with dilute HCl, washed with deionized water, and dried at 105°C. For the organic-rich samples taken from relatively well-developed soil profiles, the humic acids (HA) were also separated and dated. The ^{14}C dates were obtained by liquid scintillation counting methods (LSC) at the Radiocarbon Laboratory of the Institute of Geography, Russian Academy of Sciences (IGAN lab code) and by accelerator mass spectrometry (AMS) at the Center for Applied Isotope Studies, University of Georgia. The latter were marked by the $\mathrm{IGAN_{AMS}}$ index because the sample preparation for

AMS (i.e. graphitization, pressing on a target) was performed in the Radiocarbon Laboratory of the Institute of Geography using an AGE-3 graphitization system (Ionplus). The samples were weighed into tin capsules and combusted in an elemental analyzer that transfers only the CO_2 in helium to the graphitization system. The CO_2 is then trapped on zeolite while the helium carrier gas is removed. The CO_2 is thermally released and transferred to the reactors by gas expansion. The amount of CO_2 is kept constant to provide constant $CO_2/H_2/Fe$ ratios for the graphitization at 580°C (0.9 mg carbon, 4.2 mg iron, H_2/CO_2 ratio = 2.3). The water formed from the reduction is frozen in a Peltier cooled trap (about –5°C). The reaction is stopped automatically after 2 hr when residual gas pressures are stable (for details see Němec et al. 2010; Wacker et al. 2010). The AGE-3 uses a Vario Micro Cube elemental analyzer from Elementar. Graphite $^{14}C/^{13}C$ ratios were measured using the CAIS 0.5MeV accelerator mass spectrometer. The sample ratios were compared to the ratio measured from the oxalic acid II (NBS SRM 4990C) standard. The quoted uncalibrated dates have been given in ^{14}C years (yr BP) before AD 1950 using the ^{14}C half-life of 5568 yr. The error is quoted as 1 standard deviation and reflects both statistical and experimental errors. All the ^{14}C dates obtained were calibrated according to SHCal13 (Hogg et al. 2013) using the CALIB 7.1 program (http://calib.qub.ac.uk/calib/). For the samples prepared from plant debris, which contained a certain percentage of modern carbon ($F^{14}C > 1$), the real age was calculated by the CALIBomb program, taking into account changes in carbon concentration in the Earth crust following nuclear tests (Hua et al. 2013). The calibration curve reflecting changes in ^{14}C concentration in the Southern Hemisphere was used (Hogg et al. 2013).

RESULTS AND DISCUSSION

The ^{14}C dating results are presented in Table 1. Soils with microprofiles occurred within wet valleys of the Larsemann Hills. Samples from the 0–1 cm and 1–2 cm depths of their litter (O) horizons were characterized by $F^{14}C$ values of 1.121–1.105 ($IGAN_{AMS}$4945, 4946). A decrease in the modern carbon content with depth ($F^{14}C$ lowering from 1.121 ± 0.003 to 1.005 ± 0.003) was also identified in a 7-cm-thick peaty soil at the Aerodromnaya Hill nunatak.

The organic matter of hypolithic soil-like systems was dated in four samples, only two of which gave valid results. The other two determinations were discarded because the mass of the graphite obtained in each of them was below 0.05 mg. The two valid samples had measured $F^{14}C$ values of 1.027 ± 0.003 ($IGAN_{AMS}$4930) and 1.127 ± 0.003 ($IGAN_{AMS}$4931). Hypolithic systems are developed under contrasting conditions of desiccation and wetness. The latter provides a brief favorable environment for rapid growth of green algae and cyanobacteria, which results in the formation of morphologically distinct horizons, but without noticeable organic matter accumulation (due to the lack of time). Organic matter of the most typical of East Antarctic soils is young and cannot reach the steady state because of the high dynamism of the soil cover, related to (1) very strong winds, (2) occasional erosion by torrential meltwaters of glaciers and snow patches in the rare warmest austral summers, and (3) the dependence of the vegetation and soils on the meltwaters of snow patches that periodically change their location (see above).

Soil formed under a moss cover and having a 15-cm-thick macroprofile was found within the Schirmacher Oasis. The age of the soil samples gradually increased with depth. The litter (O) horizon, which contained moss debris with its anatomic structure still retained, had a $F^{14}C$ of 1.126 ± 0.003 ($IGAN_{AMS}$4958). Below, there was a fragmentary dry peat (TJmr) horizon with $F^{14}C = 1.014 \pm 0.003$ ($IGAN_{AMS}$4959). These were underlain by the organomineral (TB) and mineral (B) horizons dated to 130 ± 25 BP ($IGAN_{AMS}$4960) and 280 ± 25 BP ($IGAN_{AMS}$4961), respectively.

Table 1 ^{14}C age of soils and soils-like systems in the East Antarctica oases.

Lab code	Sample description	Year sampled	GPS coordinates	Depth (cm)	Dated material	^{14}C yr BP (1σ)	F^{14}C	cal BP (2σ)/CALIBomb AD (2σ)	
Endolithic soil-like systems									
$\text{IGAN}_{\text{AMS}}4892$	Thala Hills Oasis, Vechernyaya, Gnezdovoy, Adeli Colony, organomineral horizon under exfoliation plate, *granite-orthogneiss*	2015	67°39′26″S 46°10′29″E	0–0.5	TOC		1.084 ± 0.003		
$\text{IGAN}_{\text{AMS}}4893$	Thala Hills Oasis, Vechernyaya, Gnezdovoy, Adeli Colony, organomineral horizon under exfoliation plate, *pegmatite*	2015		0–0.5	TOC		1.062 ± 0.003		
$\text{IGAN}_{\text{AMS}}4894$	Thala Hills Oasis, Vechernyaya, Gnezdovoy, Adeli Colony, organomineral horizon under exfoliation plate, *orthogneiss*	2015	67°39′15″S 46°06′38″E	0–0.5	TOC	160 ± 25	0.980 ± 0.003	0–151 215–273 Median probability:	0.707 0.293 109
$\text{IGAN}_{\text{AMS}}4895$	Thala Hills Oasis, Molodejnaya, organomineral horizon under exfoliation plate, *granite*	2015	67°40′17″S 45°51′15″E	0–0.5	TOC	190 ± 25	0.976 ± 0.003	0–27 59–115 136–233 237–284 Median probability:	0.085 0.173 0.489 0.254 185
UGAMS-8825	Larsemann Hills, organomineral horizon under exfoliation plate, granitoid, warm northern aspect, vertical surface	2010	69°23′20″S 76°22′31″E	0–0.5	TOC		1.029 ± 0.003		
UGAMS-8826	Larsemann Hills, organomineral horizon under exfoliation plate, granitoid, horizontal surface	2010	69°23′10″S 76°22′26″E	0–0.5	TOC	480 ± 25	0.942 ± 0.003	468–526 Median probability:	1.000 503
$\text{IGAN}_{\text{AMS}}4952$	Aerodromnaya Hill nunatak, organomineral horizon under exfoliation plate, *granite-gneiss*	2015	70°47′36″S 11°37′25″E	0–0.5	plant debris		1.070 ± 0.003	[1957.88:1958.62] 0.126 [2003.67:2003.78] 0.009 [2004.00:2008.20] 0.865	

Table 1 (*Continued*)

Lab code	Sample description	Year sampled	GPS coordinates	Depth (cm)	Dated material	^{14}C yr BP (1σ)	F^{14}C	cal BP (2σ)/CALIBomb AD (2σ)
Hypolithic soil-like systems								
IGAN_{AMS}4930	Larsemann Hills, wet glacial valley, hypolithic community under gravel pavement, green algae and cyanobacterial biofilms (organomineral horizon)	2010	69°22′24″S 76°23′18″E	0–1	TOC		1.027 ± 0.003	
IGAN_{AMS}4931	Larsemann Hills, wet glacial valley, hypolithic community under gravel pavement, green algae and cyanobacterial biofilms (organo-mineral horizon)	2010	69°24′07″S 76°20′55″E	0–1	TOC		1.127 ± 0.003	
Soils under moss-algal communities with microprofiles								
IGAN_{AMS}4945	Larsemann Hills, O, wet glacial valley, lower part of moss litter with peat microhorizon	2010	69°24′15″S 76°20′39″E	0–1	plant debris		1.121 ± 0.003	[1958.76:1959.22] 0.081 [1993.26:1993.49] 0.011 [1993.77:1993.79] 0.001 [1994.05:1998.01] 0.904 [1999.93:1999.96] 0.002
IGAN_{AMS}4946	Larsemann Hills, O, wet glacial valley, lower part of moss litter with peat microhorizon	2010	69°23′25″S 76°24′14″E	1–2	TOC		1.105 ± 0.003	
IGAN_{AMS}4953	Aerodromnaya Hill nunatak, O, upper part of moss litter with peat microhorizon	2015	70°47′44″S 11°37′55″E	0.5–1	TOC		1.082 ± 0.003	
IGAN_{AMS}4954	Aerodromnaya Hill nunatak, O, lower part of moss litter with peat microhorizon			1–4	plant debris		1.015 ± 0.004	[1955.26:1955.28] 0.004 [1955.96:1957.44] 0.996
IGAN_{AMS}4984	Aerodromnaya Hill nunatak, O, lower part of moss litter with peat microhorizon			1–4	TOC		1.005 ± 0.003	

Soils under moss and moss-lichen communities with macroprofiles									
IGAN$_{AMS}$4958	Schirmacher Oasis O horizon	2013	70°45′45″S 11°46′50″E	0–3	plant debris		1.126 ± 0.003	[1958.77:1959.46] 0.083 [1992.49:1992.54] 0.002 [1993.09:1996.83] 0.914 [1997.36:1997.37] 0.000 [1999.94:1999.95] 0.000	
IGAN$_{AMS}$4959	Schirmacher Oasis TJ horizon			3–5	TOC		1.014 ± 0.003		
IGAN$_{AMS}$4960	Schirmacher Oasis TB horizon			5–10	TOC	130 ± 25	0.984 ± 0.003	0–143 224–254 Median probability:	0.840 0.160 91
IGAN$_{AMS}$4961	Schirmacher Oasis B horizon			10–15	TOC	280 ± 25	0.961 ± 0.003	0–143 224–254 Median probability:	0.840 0.160 91
IGAN-4802	Schirmacher Oasis TJ horizon			3–5	HA	100 ± 30			
IGAN-4801	Schirmacher Oasis TB horizon			5–10	HA	400 ± 30		324–414 427–496 Median probability:	0.521 0.479 412
IGAN$_{AMS}$4955	Aerodromnaya Hill nunatak O horizon	2014	70°47′25″S 11°37′49″E	0–1	TOC		1.049 ± 0.003		
IGAN$_{AMS}$4956	Aerodromnaya Hill nunatak O horizon			1–2	TOC		1.019 ± 0.003		
IGAN$_{AMS}$4957	Aerodromnaya Hill nunatak B horizon			2–7	TOC		1.000 ± 0.003		
Buried soil									
IGAN$_{AMS}$4947	Larsemann Hills, wet glacial valley, microhorizon with raw organic matter (probably very well decomposed peat of moss/algae origin) [Ah/T2]	2010	69°23′24″S 76°24′12″E	2–4	TOC	1105 ± 25	0.872 ± 0.0025	925–985 1022–1051 Median probability:	0.870 0.130 957

Table 1 (*Continued*)

Lab code	Sample description	Year sampled	GPS coordinates	Depth (cm)	Dated material	^{14}C yr BP (1σ)	F^{14}C	cal BP (2σ)/CALIBomb AD (2σ)	
Soils sheltered from winds with macroprofiles									
IGAN$_{AMS}$4940	Thala Hills Oasis, Molodejnaya O, moss litter	2013	67°39′33″S 45°51′23″E	0–3	plant debris		1.185 ± 0.003		
IGAN$_{AMS}$4941	Thala Hills Oasis, Molodejnaya T, peat horizon			5–10	TOC	170 ± 25	0.979 ± 0.003	0–46	0.182
								54–125	0.333
								131–154	0.104
								171–191	0.030
								206–278	0.352
								Median probability:	126
IGAN$_{AMS}$4942	Thala Hills, Molodejnaya AT, well decomposed peat/raw organic matter			13–15	TOC	240 ± 25	0.970 ± 0.003	149–219	0.705
								271–303	0.295
								Median probability:	198
IGAN-4637	Thala Hills, Molodejnaya O, moss litter	2012		0–5	plant debris		1.022 ± 0.02		
IGAN-4554	Thala Hills, Molodejnaya T, peat horizon			5–10	HA	450 ± 50		337–356	0.080
								448–511	0.920
								Median probability:	484
Ki-17840	Thala Hills, Molodejnaya T, peat horizon	2012		5–10	TOC	360 ± 60		286–499	1.000
								Median probability:	391

The organic matter of endolithic soil-like systems was dated in seven samples from the oases of Thala Hills and Larsemann Hills and the nunatak of Aerodromnaya Hill. These samples were similar in their content of organic and mineral compounds, but their ^{14}C ages differed significantly. Four samples had "modern" dates with F^{14}C values of 1.029 ± 0.003 to 1.084 ± 0.003, i.e. the age of carbon in these soil-like systems was about 60–100 yr. Two samples were dated to 160 ± 25 BP (IGAN$_{\mathrm{AMS}}$4894) and 190 ± 25 BP (IGAN$_{\mathrm{AMS}}$4895), with calibration showing that the organic matter remained in those systems for about 300 yr. In fact, the organic matter of an endolithic system is continuously supplemented by the living organisms' biomass; therefore, its ^{14}C date may significantly underestimate the actual age of such a system. Another two samples of endolithic systems, one from a vertical rock exposure (UGAMS-8825) and the other from a horizontal surface of the same rock (UGAMS-8826), were dated. The vertical sample turned out to be modern and the horizontal sample had the date of organic matter 480 ± 25 BP. These data can easily be explained by the former sample's vertical position on the north-facing rock exposure, where the duration of endolithic-exfoliation cycles is shortened because of the gravitational removal of exfoliation crusts, with the temperature conditions being also favorable for weathering and acceleration of organic matter renewal. The latter sample from an exfoliation crack on the horizontal rock surface shows that under relatively stable conditions that favor a steady accumulation of organic matter and its physical retention (on the horizontal surface), the endolithic soil-like systems can be maintained for a long time. An average ^{14}C age of an endolithic system implies that some components of its organic matter are actually older than the average age and some are younger (e.g. the biomass of living organisms). Therefore, we can conclude that the "absolute" age of a stable endolithic system, i.e. the time elapsed from the first colonization of the rock surface by endolithic organisms, can reach over 500 yr.

There are data on very ancient, up to several thousand years old, endolithic systems in Antarctica developed under stable conditions without exfoliation (Johnston and Vestal 1991; Sun and Friedmann 1999). It was hypothesized that such endolithic systems are the slowest growing communities on Earth (Johnston and Vestal 1991). Our observations of rock exfoliation rates and scales as well as ^{14}C dating of the organic matter, which includes some modern dates, allow us to suggest that such very ancient endolithic ecosystems are exceptionally rare and require particularly well-sheltered refuges in Antarctica.

Soils sheltered from winds were represented by two 15-cm-deep profiles located at the Molodezhnyi site within the Thala Hills Oasis. The ^{14}C age increased with depth in samples from both profiles. In the first profile, the top layer (0–3 cm) of peat was characterized by an F^{14}C of 1.185 ± 0.003 (IGAN 4940), determined in plant debris. The corresponding ^{14}C dates were 170 ± 25 BP (IGAN$_{\mathrm{AMS}}$4941) within the 5–10 cm layer and 240 ± 25 BP (IGAN$_{\mathrm{AMS}}$4942) within the 13–15 cm layer, determined in the TOC. In the second profile, the top layer (0–5 cm) of peat was characterized by an F^{14}C of 1.022 ± 0.02 (IGAN 4637) and the bottom layer of peat, by the HA age of 450 ± 50 BP (IGAN 4554) and TOC date of 360 ± 60 BP (Ki-17840, Dolgikh et al. 2015). The small difference between the ^{14}C dates of the HA and TOC indicates that this soil's organic matter is more complex than just amorphous peat material mixed with mineral particles (predominantly sand), and that it is composed of differently aged fractions. Therefore, the ^{14}C analyses of plant debris, TOC, and HA have shown that wind-sheltered peaty soils can have top layers 50–60 yr old and bottom layers developing for around 500 yr.

In addition, there is a sample of a buried under a gravel pavement organic layer (peat) (Figure 2.6), 2 cm thick, supposedly of algal origin, collected in the Larsemann Hills Oasis and dated to 957 cal BP (2σ) (IGAN$_{\mathrm{AMS}}$4947). This is the oldest date obtained by us so far for the soil organic matter of East Antarctic oases. Similar ages are rarely reported in the literature, e.g. there is one wind-sheltered peaty soil, 18 cm thick, located in the Thala Hills Oasis, with an age of 1220 ± 80 BP (Aleksandrov 1985) and there are other peaty soils from the Grearson Oasis (Wilkes Land) with ages of 850 ± 40 and 1420 ± 50 BP (Blume et al. 1997). The ^{14}C ages are observed to increase at greater depths in soils of depressions and valleys, which can also be partially explained by the presence in these accumulative positions of old carbon originating from external sources like paleolacustrine sediments redistributed at a certain stage by wind and glaciers. Other sources like organic matter derived from mature endolithic systems and being redistributed after exfoliation should also be considered (Hopkins et al. 2009).

The most similar environment to the East Antarctic oases is the High Arctic. Contrary to dry valleys, which are closer to the superarid deserts of the world, the landscapes of East Antarctica have much in common with those of Spitzbergen and other High Arctic archipelagos and Taymyr Peninsula; however, the Antarctic ones lack vascular plants and have almost no liquid precipitation. Previous data on High Arctic soils of Eurasia (Goryachkin et al. 2000) showed that their ^{14}C age (hundreds years in upper 20 cm) is close to the oldest of the East Antarctic oases, in soils with macroprofiles and those of wind shelters. The question is still open if we can find so many young soils in High Arctic as in East Antarctica because nobody has taken samples in such extreme conditions in the Northern Hemisphere as we have done for the Southern one. In any case, the soils in East Antarctica are less stable and younger than the High Arctic soils.

All the sites studied have been under subaerial conditions, and ice-free for a considerable period of time. The current deglaciation of the Schirmacher Oasis began in the Early Holocene and developed in three stages, the second of which resulted in the most extensive melting, 6700–2200 cal BP (1σ) (Verkulich et al. 2011). The third stage of deglaciation is currently in progress, and is characterized by further regression of the continental ice sheet, lowering of the lake water tables, and drying of the land. The Larsemann Hills Oasis became ice-free around 44,000 ^{14}C BP, when temperature parameters were several degrees above present values, as was revealed by the ^{14}C dating of lake sediments (Hodgson et al. 2001; Squire et al. 2005). At the same time, lichenometric dating demonstrated that certain summits became ice-free no earlier than 2000 yr ago (Zakharov et al. 1998). The Thala Hills Oasis lacks detailed paleogeographic information, but there are some data on the Late Pleistocene and Holocene history for other parts of Enderby Land. According to the ^{14}C dating of crustacean shells from fluvial deposits, the last deglaciation maximum for coastal lowlands occurred at 7000–3000 cal BP (1σ) (Takada et al. 1998; Zwartz et al. 1998). Raised beaches 20 m above sea level along the Lutzow-Holm coast are of Early Holocene age (Miura et al. 1998). Freshwater lake sediments from the center of Enderby Land are about 10,000 BP (Zwartz et al. 1998). Therefore, the results show that pedogenesis could have lasted for several thousand years at all the sites studied.

Until now, however, we have found no evidence of such an ancient pedogenesis, despite many seasons of field research on soil morphology and spatial distribution, with mapping the key sites of maximal soil diversity within the oases (Mergelov 2014; Dolgikh et al. 2015). ^{14}C dating samples were taken by us mainly from most stable and long-lived soils and soil-like bodies, but the longest period of pedogenesis was dated only ~500 yr. Our older date for the buried peat layer as well as the literature sources on more ancient soils and lake sediments within the oases are indicative of possibly longer duration of pedogenesis following the deglaciation of the study sites. Nevertheless, the pedogenesis can easily be interrupted in the extreme Antarctic environment. Firstly, strong winds reaching 60 m/s and more can remove the moss cover together with organomineral soil horizons as well as exfoliation crusts together with endolithic soil-like systems. Secondly, droughts limit the development of hypergenic processes and confine them to very small wet areas that are in turn affected by severe water erosion. Consequently, the products of chemical weathering and pedogenesis cannot be accumulated *in situ*, but undergo a continuous removal to other areas inside and outside the oases.

CONCLUSION

Organic matter pools formed under extreme climatic conditions and originating not from vascular plants, but from cryptogamic organisms along with photoautotrophic microbes have been identified in the oases of East Antarctica. The organic matter of most East Antarctic soils is young ($F^{14}C > 1$) and cannot achieve a steady state because of the high dynamism of the soil cover due to very strong winds, occasional erosion by torrential meltwaters of glaciers and snow patches in the rare warm austral summers, and the dependence of the vegetation and soils on the meltwaters of snow patches that periodically change their location. The results suggest that endolithic soil-like systems formed on horizontal rock surfaces within the studied East Antarctica oases are ~500 yr old.

The ^{14}C ages of samples from soils in wind shelters as well as soils in open valleys and depressions formed under moss, moss-lichen, and moss-algal communities (with macro- and microprofiles) gradually increase with depth, confirming the actual existence of stable organic and organomineral substances, despite the fact that the original sources of organic matter are poor in polycyclic compounds and the biological cycle is slow. The ^{14}C age is around 500 yr BP for wind-sheltered soils and up to 300–400 yr BP for soils with macroprofiles formed in open valleys under moss communities. According to our data, the maximal duration of organic profile formation within the oases of the East Antarctica is 500 yr. The absence of older soils, comparable in age to the deglaciation of the study sites, can be due to the extreme conditions resulting in the aforementioned catastrophic events that can destroy soil organic horizons.

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