Catena 137 (2016) 596–604

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Soil development on basic and ultrabasic rocks in cold environments of Russia traced by mineralogical composition and pore space characteristics

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ARTICLE INFO

Article history:
Received 13 September 2014
Accepted 26 November 2014
Available online 17 December 2014

Keywords:
Silicate weathering
Mineral associations
Pore space characteristics
Soil formation
Amphibolites
Serpentinous dunite

ABSTRACT

Recent soils from basic (amphibolite and meta-gabbro amphibolite) and ultrabasic (serpentinous dunite) rocks formed in cold and humid climates of Northern Eurasia (Russia) were studied to detail the characterization of soils and rocks with special attention to the interdependence of porosity system and rock mineralogy. The study plots were located in taiga and tundra zones of East Fennoscandia and the Polar Ural Mountains. A variety of methods was used including optical microscopy, X-ray diffraction and Rietveld analysis, and three supplemental methods for the determination of pore space characteristics in rocks: (i) mercury intrusion porosimetry, (ii) a modification of this method using the intrusion of a molten alloy (Wood's metal), and (iii) scanning atomic-force microscopy. The results illustrate that the specification of the porosity system is a significant factor in tracing the clay mineralogy in soils formed from hard rocks. Ultrabasic rock is the most sensitive to weathering, as determined by (i) the high value of small pores, especially those with a radius of <10 nm, (ii) the elongated form of the pores and surface roughness, and (iii) zones with an accumulation of phyllosilicates in regions with higher porosity causing the formation of soil enriched by clay minerals.

Despite the presence of low proportions of phyllosilicates in both types of basic rocks, only soil from meta-gabbro amphibolite is enriched by clay minerals and is most probably affected by small pores (<10 nm). The absence of phyllosilicate accumulation along the pores and the predominantly empty space inside the pores indicates the limitation of potential sources of phyllosilicates for developing soils from meta-gabbro amphibolite. Insignificant phyllosilicate accumulation in shallow soil from amphibolite, in which the fine size fractions are mostly the result of rock disintegration, is supposedly due to a particularly narrow pore size distribution with a predominance of pores between 100 and 1000 nm.

1. Introduction

In cold environments, freezing–thawing cycles significantly affect pedogenesis, especially in the case of soil formation from hard rocks. Rock disintegration results in an increase in surface area, which is sensitive to chemical weathering (Arnaud and Whiteside, 1963; Allen, 2002), element release and the appearance of secondary minerals (Velde and Meunier, 2008). Adopting the approach of Velde and Meunier (2008) the interactions between primary minerals and solutions often take place within confined or semi-confined microenvironments such as pores rather than in a bulk solution. This approach is particularly relevant to studies of the early stages of clay mineral development on weathering and the environment in which this particular study takes place: extreme cold, where weathering occurs slowly.

The transformation of minerals in the soil environment has even been reported for extremely cold conditions, such as in the arctic tundra of Northern Alaska (Gelisols) (Borden et al., 2010), the ice-free areas of King George Island, Antarctica (Cryosols) (Simas et al., 2006), and the taiga zone from the Central Yakutia plain with its extra-continental climate (Cryosols) (Lessovaia et al., 2013). Nevertheless, the number of observations of pedogenesis from hard rocks traced by mineralogical composition and pore space characteristics is still low. Data from tundra and taiga zones of Eurasia, especially mineralogy and micromorphology, show that clay minerals in the soils from hard rocks are

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http://dx.doi.org/10.1016/j.catena.2014.11.020
0341-8162/

Fig. 1. Location of the key plots in East Fennoscandia (1) and the Polar Urals (2).

mostly inherited; they are not detected in the soil if they are absent in the hard rock (Sedov et al., 1992; Chernyakhovskii, 1994). However, other investigations have shown that considerable amounts of smectite, which is absent in the rock, appear in the fine earth derived from that rock (ultrabasic type) and soils (Lessovaia et al., 2012). Based on these divergent findings, the aim of this study is to produce a detailed characterization of soils from basic and ultrabasic rocks formed in cold climates in Northern Eurasia (Russia) with special attention to the interdependence of the porosity system and rock mineralogy.

2. Materials

Holocene soils from basic and ultrabasic rocks formed in cold and humid climates were studied. The first study plot was located in the taiga zone of East Fennoscandia (GPS coordinates: 67°32′ 65″ N and 33°46′ 08″ E) (Fig. 1). The "dot" (intermittent) distributed residual ridges (selgas) of amphibolite are surrounded by the acidic moraine material from the last glaciation. Local accumulation of fine earth was observed only in small cavities in the rock. Very shallow soils, classified as Lithic Leptosols according to WRB (2006), have been developing at this site. The second study plot was situated in the taiga zone of the Polar Urals that is a part of the Ural Mountains in the Arctic Circle (GPS coordinates: 66°48′ 31.2″N and 65°46′ 20.1″E). A more mature profile of Epileptic Entic Podzol (Pit Y-05-07) on a flat outcrop of meta-gabbro amphibolite is described here. The third study plot was located on the flat summit in the mountainous tundra of the Polar Urals (the Rai-Iz massif that is made up of ultrabasic rock) at an altitude of 664 m (GPS coordinates: 66°52′ 03.3″ N and 65°19′ 33.6″′ E), and permafrost began at a depth of 30 cm. Due to intensive gleization, the fine earth that accumulated on the blocks of serpentinous dunite had a bright color. The soil is classified as Haplic Cryosol (Reductaquic) (Pit Y-02-07).

3. Methods

The fine soil (the <1 mm fraction) was separated by dry sieving. Bulk chemical composition of the <1 mm soil fraction and rock samples was determined by X-ray fluorescence analysis (Tefa-611, EG&G Instruments Ortec). The proportion of Fe^{2+} in the rock samples was determined by colorimetric wet-chemical analysis (Schuessler et al., 2008). Soluble Fe forms in the <1 mm fraction were obtained through extractions with dithionite (Mehra and Jackson, 1958) and oxalate (Fe and Al) (Jackson et al., 1986). pH-values were measured potentiometrically in H_2O with a soil:water ratio of 1:2.5. C-content was determined by wet combustion using the Tyurin (1931) method. For the upper horizons that contained fair amounts of organic matter, loss on ignition was determined. The content of the <1 μm fraction of the soil was determined by sedimentation with the pipette method.

Mineral association of the rock samples from the lithic contact were studied in thin sections by optical microscopy (Zeiss Axioplan 2 and Polam P-312 microscopes). Three supplemental methods for the determination of the pore space characteristics were applied: (i) mercury intrusion porosimetry (MIP) for the quantification of total porosity and pore size distribution, (ii) a modification of this method using the intrusion of a molten alloy (Wood's metal) and subsequent electron microscopy on the polished sections to determine the micro-morphology of the connective pores and to detect closed pores, and (iii) scanning atomic-force microscopy (AFM) to obtain quantitative pore dimension data.

MIP was carried out with a combined instrument (Pascal 140 + 440, POROTEC) for measuring macro- and mesopores with radii in the range of 58000–1.8 nm. The instrument only determines the percentage of open (connective) pores that are Hg-accessible. The measurements were conducted by incrementally increasing the pressure up to 400 MPa. The pore size distribution was determined according to the

Table 1
pH, C-content, share of <1 μm fraction, chemical composition and dithionite and oxalate soluble Fe and Al of the studied soils.

Horizon, depth (cm)	pH H_2O	C/LI (%)	<1 μm (%)	Chemical composition of soil, the <1 mm fraction (% in ignited sample)									Fe_2O_3d	Fe_2O_3o	Al_2O_3o	Fe^{2+} (wt.%)
				SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	MnO	TiO_2		(%)		
Lithic Leptosol on amphibolite, Pit X-05-3																
A 0–2	4.4	32.0/44.8	–	61.44	11.30	10.32	8.43	1.62	0.67	1.40	0.19	2.93	1.09	0.74	0.41	–
Bw 2–6	4.5	7.6	9.7	61.44	11.96	11.39	8.01	2.17	0.30	1.07	0.14	2.75	1.07	0.48	0.26	–
R	–	–	–	54.76	12.04	17.23	10.57	2.87	0.12	0.86	0.18	1.26	–	–	–	–
Epileptic Entic Podzols on meta-gabbro amphibolite, Pit Y-05-07																
O2 0–3	4.5	26.3/71.2	–	70.16	11.49	6.95	3.97	3.03	1.24	1.56	0.11	0.89	0.88	0.38	0.31	–
Bw 3–5	4.4	3.7	15.3	73.44	11.43	6.82	2.05	2.39	0.98	1.58	0.08	0.98	1.95	0.60	0.59	5.06
Bhs 5–10	4.9	2.5	16.7	71.03	12.60	7.73	2.20	2.77	0.96	1.56	0.08	0.93	2.17	0.46	0.96	3.92
Bs 10–24	5.6	1.0	9.7	67.83	14.25	7.69	2.60	3.74	1.10	1.56	0.10	0.80	1.65	0.50	1.48	–
BC 24–30	6.1	0.6	7.7	66.50	14.36	7.70	2.99	4.48	1.11	1.88	0.12	0.76	1.26	0.39	1.32	5.05
R	–	–	–	55.87	16.27	10.44	8.06	5.64	0.39	2.51	0.19	0.40	–	–	–	–
Haplic Cryosols (Reductaquic) on serpentinous dunite, Pit Y-02-07																
Ah 0–4	7.2	4.5/16.3	7.8	54.59	5.05	10.62	1.35	25.88	0.75	0.63	0.23	0.38	2.68	1.79	0.08	6.22
Bg 4–15	7.0	4.7	6.8	56.00	5.70	11.25	1.43	22.57	0.86	0.96	0.20	0.42	4.05	2.57	0.11	5.85
Bgf 15–30	8.0	1.9	17.4	65.92	8.66	7.10	1.44	13.23	1.35	1.20	0.07	0.65	1.53	0.66	0.11	4.37
R	–	–	–	44.52	0.72	12.87	0.85	40.34	0.10	<0.05	0.21	0.02	–	–	–	–

Abbreviations and notes: C — total carbon; LI — loss on ignition; <1 μm — content of particle size <1 μm in the <1 mm fraction; '–' — no data available; d — dithionite and o — oxalate extractable Fe_2O_3 and Al_2O_3; Fe^{2+}(wt.%) determined by colorimetric wet-chemical analysis, R — rock samples from lithic contact.