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Soil properties, micromorphology, and mineralogy of Cryosols from sorted and unsorted patterned grounds in the Hornsund area, SW Spitsbergen

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ABSTRACT

Patterned grounds are probably the most interesting features produced by natural processes acting on the Earth's surface. Such features occur mainly in polar areas and in high mountains indicating that the origin of patterned grounds is related to frost action and cryoturbation. In spite of the many studies concerning the mechanism of the formation and the various forms of patterned grounds, very little attention has been paid to the qualitative and quantitative analyses of their mineral composition, and especially the mineralogy of the clay fraction. The analysis of the mineralogy of clay fraction is very important due to the finest particles (especially clay minerals) may play a crucial role in cryoturbation and cryosegregation as the particles are mainly responsible for accumulation of water and rheological properties of the ground. Thus, the main aim of the present study was to verify the hypothesis that the presence of swelling clay minerals in parent material favors the development of sorted patterned grounds. To verify the hypothesis, the physical, chemical, micromorphological, and qualitative and quantitative mineralogical properties of Cryosols from sorted and unsorted patterned grounds in the Hornsund area (SW Spitsbergen) were determined. The obtained results show that Turbic Cryosols from sorted patterned grounds featuring clear frost cracking, frost segregation, and cryoturbation are characterized by a lack of clearly developed soil horizons, loamy texture and low content of soil organic matter. Haplic Cryosols show better developed soil horizonation and contain lower amounts of the silt and clay fractions, higher content of the sand fraction and soil organic matter in comparison with Turbic Cryosols exhibiting strong cryoturbation. Micromorphological analysis of Turbic Cryosols indicates frost action manifested by a vesicular microstructure; round, oval, and deformed (mammillated) vesicles as dominant voids; vertically-oriented rock fragments; and silt and silt–clay cappings occurring on rock fragments. In addition, the occurrence of Fe–Mn nodules showing a sharp boundary indicates mixing of soil material. Micromorphology of the studied Turbic Cryosols indicates that cryoturbation prevails over cryosegregation. The soil material of the studied Cryosols is composed mainly of quartz, K-feldspar, plagioclase, dioctahedral mica (muscovite and/or illite), biotite, augite, hornblende, garnet, chlorite, swelling clays (smectite, vermiculite), goethite, and in some cases also calcite and traces of kaolinite. Majority of the minerals are most likely primary minerals inherited from parent material due to weak chemical weathering in the severe Arctic climate conditions and relatively young soils. However, weak chemical weathering of biotite and formation of vermiculite and mixed layered clay minerals also take place. Quantitative mineralogical analysis shows that besides texture and moisture, the mineral composition of soil material may also play some role in the susceptibility to cryoturbation and the formation of sorted and unsorted patterned grounds. However, the small differences in mineral content between the studied Turbic Cryosols and Haplic Cryosols indicate that the mineral composition of parent material is not a crucial characteristic responsible for the formation of sorted patterned grounds.

1. Introduction

Patterned grounds are most likely the most interesting features produced by natural processes acting on the Earth's surface, which have been extensively studied by many soil scientists, geologists, and geomorphologists since the beginning of the 20th century (e.g. Elton,

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1927; Washburn, 1956; Etzelmüller and Sollid, 1991; Klimowicz and Uziak, 1996; Ugolini et al., 2006; Hallet et al., 2011). Such features occur mainly in polar areas and in high mountain areas indicating that the origin of patterned grounds is related to frost action.

Cryoturbation is the most important soil-forming process acting in polar areas as well as other regions with permafrost (Bockheim and Tarnocai, 1998; Bockheim et al., 2006; Ugolini et al., 2006; Kovda and Lebedeva, 2012). This process has a strong influence on agriculture, forestry, and the construction of roads and buildings (Brown, 1967; Jones et al., 2010). Effects of frost action on soils can be observed on the macroscale as well as microscale (i.e. under a microscope) (Van Vliet-Lanoë, 1998; Bockheim et al., 2006; Kovda and Lebedeva, 2012). On the macroscale, cryoturbation may be noted as discontinuous (broken) soil horizons, incorporation of the surface horizon into the subsoil and vice versa (so-called involutions, intrusions or injections), vertical orientation of rock fragments in the soil profile, and occurrence of sorted circles, polygons or stripes on the soil surface (Ping et al., 1998; Bockheim and Tarnocai, 1998; Bockheim et al., 2006; Ugolini et al., 2006). On the microscale, frost action is manifested by the occurrence of platy and/or lenticular microstructure, vesicles as the dominant voids, silt or clay–silt cappings on rock fragments and aggregates, vertically-oriented coarse mineral grains and clasts, and the presence of banded fabric (Van Vliet-Lanoë, 1998, 2010; Van Vliet-Lanoë et al., 2004).

According to the literature, the origin of patterned ground in polar areas is connected with strong freezing of the ground, which is responsible for the formation of contraction cracks and cryoturbation of loose and initially unsorted sediments, and the presence of moisture within the ground, which promotes the formation of ice lenses and ice needles (Washburn, 1973; Van Vliet-Lanoë, 1998). In addition, the texture of parent material plays a very important role in the formation of sorted patterned grounds (Elton, 1927; Etzelmüller and Sollid, 1991; Klimowicz and Uziak, 1996; Van Vliet-Lanoë, 1998).

In the literature, many hypotheses concerning the formation of patterned ground can be found and many of these are summarized and discussed in review papers by Elton (1927), Washburn (1956), and Dąbski (2006). In spite of the many research studies concerning the origin, properties, mechanisms of formation as well as forms of patterned grounds, very little attention has been paid to the qualitative and quantitative analyses of their mineral composition (Etzelmüller and Sollid, 1991; Uziak et al., 1999; Ugolini et al., 2006) and especially the mineralogy of the clay fraction (Szerszeń, 1974; Szerszeń and Chodak, 1983; Darrow et al., 2009; Kovda and Lebedeva, 2012; Mendonça et al., 2013). The mineral composition of soil affects not only the process of cryoturbation, but also the preservation of cryogenic microstructures, which are the basis for the interpretation of soil-forming processes (Van Vliet-Lanoë, 1998). On the one hand, a high content of swelling clay minerals increases the frost susceptibility of soil material, while on the other hand, the cryogenic microstructures are poorly preserved due to freeze–thaw processes (Van Vliet-Lanoë, 2010; Dagesse, 2011, 2013; Kovda and Lebedeva, 2012).

The main aim of the present study was to verify the hypothesis that the presence of swelling clay minerals in parent material favors the development of sorted patterned grounds. To verify the hypothesis the physical, chemical, micromorphological, and qualitative and quantitative mineralogical properties of Cryosols from sorted and unsorted patterned grounds in the Hornsund area, SW Spitsbergen, Svalbard were determined.

2. Materials and methods

2.1. Study area

The present study was carried out in the Fuglebekken catchment in the close vicinity of the Polish Polar Station and in the Revdalen Valley along the north coast of Hornsund fjord (Fig. 1). The bedrock of the study area consists mainly of old metamorphic schists (with mica, garnet, and calcite) and paragneiss. In some places, marble, quartzite, and amphibolite also occur (Czerny et al., 1993; Majka et al., 2010). The study area is located on uplifted marine terraces of the Holocene (Lindner et al., 1991) with marine deposits containing boulders, stone, gravel, and sand. Locally, the marine deposits contain a higher amount of fine material, i.e. silt and clay fractions, and are characterized by a loamy texture. The Hornsund area is characterized by suboceanic climate conditions with a mean annual temperature of −4.2 °C and mean annual precipitation of about 430 mm (Marsz and Styszyńska, 2007). The study area is characterized by substantial diversity of soils and plant communities. Haplic Cryosols, Turbic Cryosols, Hyperskeletic Cryosols, and Lithic Leptosols are the most common soils in the study area (Szymański et al., 2013), all these soils show various thermal and moisture regimes during the growing season (Migała et al., 2014). A lichen-prostrate shrub community, dominated by *Catrariella delisei*, *Ochrolechia frigida*, polar willow (*Salix polaris*), and saxifrage (*Saxifraga oppositifolia*), and covering dry and well-drained terraces, a wet moss community with a predominance of *Sanionia uncinata*, *Warnstorfia sarmentosa*, *Straminergon stramineum*, and *Aulacomnium palustre*, restricted to areas with a poor drainage, as well as an epilithic moss–lichen community, found on dry sites of most rock outcrops, with a great abundance of the moss *Racomitrium lanuginosum*, the lichens *Cetraria islandica* and *Cladonia mitis* and *S. polaris*, are the most important and widespread tundra vegetation types in the study area (Szymański et al., 2013; Wojtuń et al., 2013; Migała et al., 2014).

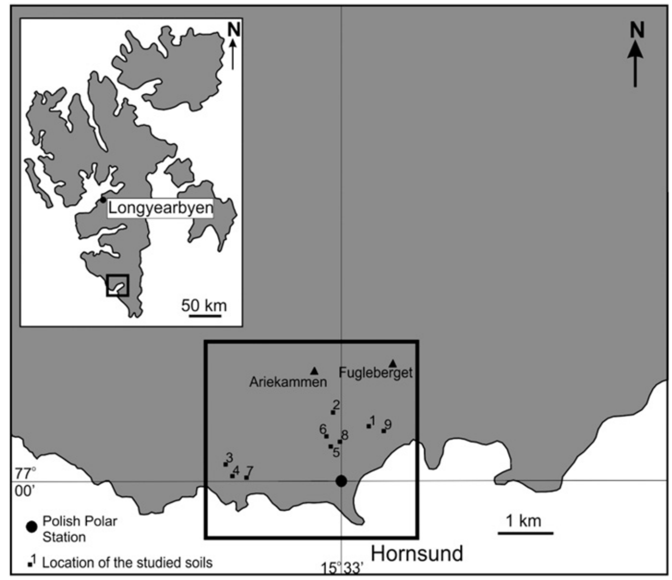

Fig. 1. Location of the study area and the studied soil profiles.

2.2. Field and laboratory methods

Field studies were conducted in the summer of 2011. During the fieldwork, nine representative sites showing various evidence of frost segregation were selected for detailed study. The sites and soils were grouped into: (1) sorted patterned grounds with Turbic Cryosols showing gravelly polygons, circles or stripes surrounding finer, loamy materials (profiles 1, 2, 3, and 4) (Fig. 2A–C); 2) unsorted patterned grounds with Turbic Cryosols characterized by high-centered, convex polygons limited by fissures, which are not filled with coarse material (profiles 5, 6, and 7) (Fig. 2D–F); and 3) Haplic Cryosols showing very weak evidence of frost segregation, i.e. only stony pavement on their surface and lack of gravelly polygons or circles and cracks on their surface (profiles 8 and 9) (Fig. 2G, H). The last two soil profiles were selected for comparison purposes. The morphology of the soil profiles was described, samples for laboratory analyses were collected from each