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Early stage development of selected soil properties along the proglacial moraines of Skaftafellsjökull glacier, SE-Iceland

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ABSTRACT

Soil development was studied along a chronosequence in 2010 in a proglacial environment in SE-Iceland. We investigated morphological, physical, chemical and mineralogical changes in the soil representing over 120-year period. In total, 54 sampling sites were distributed along three moraines deposited in 1890, 1945 and 2003. For comparison, samples were collected from a nearby downy birch (*Betula pubescens* Ehrh.) forest, representing soils in a mature ecosystem likely to establish on the moraines in the future. After 120 years since deglaciation and formation of AC horizon sequence, bulk density decreased from 1.36 g cm^{-3} to 1.07 g cm^{-3}. Concentrations of soil organic carbon (SOC) and total nitrogen (N) increased with time, from being ~zero up to 1.77% of SOC and 0.10% of N. Soil pH (H_2O) declined rapidly and was the only soil property that attained a steady state compared to that under the birch forest. The concentration of oxalate extractable Al and Fe increased over time although at a slower rate of change compared to that for other soil properties. Freshly exposed moraines contained a considerable amount of the extractable elements, indicating a relative abundance of poorly crystalline Al- and Fe-phases in the subglacial moraines. The data support the conclusion that after 120 years of soil formation, proglacial soils are still young and may yet need one or two centuries to develop properties typical of well drained volcanic soils.

1. Introduction

Global climate change has caused significant glacier retreat since the mid 19th century, exposing moraines commencing weathering, plant succession and soil formation. In theory, soil development is governed by five principal factors: climate, topography, biota, parent material and time (Jenny, 1941). Time and climate are the primary determinants of the relative degree of weathering in the pedogenic environment (Ugolini and Dahlgren, 2002). Chronological sequences of glacial recession provide the settings for studying the impact of time on soil formation. In a pioneering work in glaciated areas in Alaska, Crocker and Major (1955) and Crocker and Dickson (1957) studied the rate of development of soil properties in relation to vegetation succession and as a function of time. Since climate change impacts vegetation distribution and increases chemical weathering rate, the rate of soil formation is likely to increase as well as that of soil carbon accretion (Dahlgren et al., 1997). It is precisely this notion which has been the driving force for more chronological studies from glaciated environments (e.g., Alexander and Burt, 1996; Douglass and Bockheim, 2006; Dümig et al, 2011; Egli et al., 2006a, 2006b, 2010; Haugland and Haugland, 2008; He and Tang, 2008; Mavris et al., 2010).

While the strong impact of climate change on glacial environments and subsequent soil formation has attracted global scientific interest (Goryachkin et al., 1999), research information on soil formation in proglacial areas in Iceland is rather limited. Persson (1964) briefly discussed the subject while investigating primary succession on the moraines of Skaftafellsjökull, SE-Iceland. Proglacial areas are sites of high geochemical reactivity due to the abundance of ground permeable parent material and water percolation (Egli et al., 2010; Gíslason, 2008). Thus, these are excellent sites for studying soil formation on a temporal scale, which is of primary interest to envision future soil development under specific climate scenarios. Icelandic glaciers have been retreating since the end of the Little Ice Age (LIA) almost continuously over the past 120 years, or since around 1890 when they reached their maximum extent (Björnsson and Pálsson, 2008; Sigurðsson et al., 2007). The recession is predicted to prevail over the next several decades with significant environmental impact along with the reduction in size of glaciers exposing vast areas, changing drainage patterns, increasing runoff volume and forming of new glacial lakes (Björnsson and Pálsson, 2008).

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Iceland is a volcanic island primarily consisting of igneous rocks of basaltic composition. Andisols (Soil Taxonomy, ST) or Andosols (World Reference Base, WRB) developed from the volcanic ejecta comprise the primary soil order (Arnalds and Óskarsson, 2009). These soils exhibit some distinctive properties unique to the soil order, e.g. low bulk density and accumulation of soil organic carbon (SOC), which is largely due to the formation of noncrystalline secondary minerals (e.g., active Al- and Fe- allophane, imogolite, ferrihydrite, Al/Fe- humus complexes) (Dahlgren et al., 2004; Shoji et al., 1993). Nitrogen (N) is the major nutrient limiting establishment of plants in volcanic deposits within the volcanically active zones in Iceland (Gislason and Eiriksdottir, 2004; Gíslason et al., 1996).

The glassy nature of basalts exhibits high weathering rates despite the prevalence of cool climate (Gislason et al., 2009; Gíslason et al., 1996). Through water-rock/tephra interaction, some minerals are dissolved completely and leached out of the parent material while others are tied up in the weathering residues of the primary mineral, such as clays and hydroxides (Gíslason, 2008). The weathering of Ca-rich plagioclase ($CaAl_2Si_2O_8$) (one of the most abundant primary mineral of basalt), to allophane ($Al_2SiO_5 \cdot 2.53H_2O$), an important secondary mineral in Icelandic soils, is shown in Eq. (1) (assuming that carbonic acid is the only important proton donor (Gíslason, 2008)):

$$CaAl_2Si_2O_8 + 2\ CO_2 + 5.53H_2O \rightarrow Al_2SiO_5 \cdot 2.53H_2O + Ca^{+2} + H_4SiO_4 + 2\ HCO_3^- \tag{1}$$

Ca and half of the Si in Eq. (1) are mobile, whereas Al is immobile and remains *in situ* along with half of the silica. The most common weathering residuals of basalts comprise of allophane and/or imogolite of variable Al:Si ratios and poorly crystalline iron oxide, ferrihydrite, all mostly amorphous and referred to as the 'clay minerals' of Andisols (Arnalds, 2004). The basaltic parent material favors formation of allophane and ferrihydrite, dominating the secondary clay mineral fraction, and their ability to stabilize organic carbon is integral to the high SOC sink capacity of Andisols (Dahlgren et al., 2004). The formation of allophane is inhibited by the presence of large quantities of organic matter and by low pH (generally <5) as the organic materials form complexes with Al or Fe (Arnalds, 2004; Dahlgren et al., 2004). Allophane and ferrihydrite contents in volcanic soils are commonly determined by the indirect measure where Al, Si and Fe are extracted with ammonium oxalate (Al_{ox}, Si_{ox} and Fe_{ox}), which dissolves allophane, allophane-like materials, organic Al and Fe complexes as well as noncrystalline Al and Fe oxides and ferrihydrite (Wada, 1989). Soil reaction in sodium fluoride solution (NaF) is also used as an indicator of andic properties, as it is usually correlated strongly with allophane content (Arnalds, 2008a; Soil Survey Staff, 2010).

Here we present results from a study on an 8–120 year chronosequence in front of the Skaftafellsjökull glacier, SE-Iceland. The aim was to assess short-term (120 years) soil development in glacial till of basaltic origin through a selection of morphological, physical, chemical and mineralogical properties of the soil and to assess whether the young soils have developed the distinctive properties of Andisols.

2. Materials and methods

2.1. Study site

The study area lies within the recessional path of the Icelandic outlet glacier Skaftafellsjökull (the Icelandic term for glacier is jökull) (N64°00′, W16°55′), extending south from the Vatnajökull ice cap to the lowlands (Fig. 1). It is within the boundaries of the Vatnajökull National Park, established in 2008, before it was a part of the Skaftafell National Park established in 1967. Prior to 1967, traditional farming, with sheep grazing and hay-making, was practiced in the area (Ives,

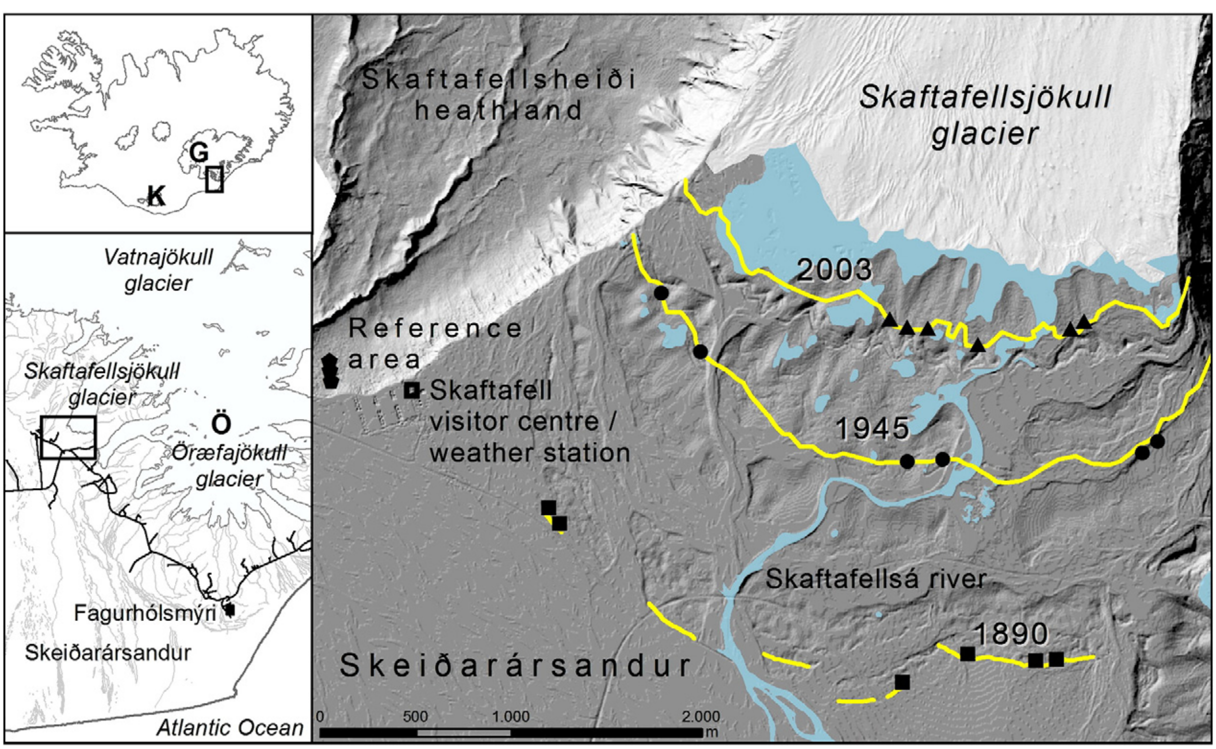

Fig. 1. The research site at the Skaftafellsjökull glacier, SE-Iceland. Samples were collected along three known positions of the glacier terminus, the southernmost one representing the maximum extent of the glacier in around 1890, the one in the middle represents the location of the terminus in 1945, and the northernmost position marks the extent of the glacier in 2003. Triangles, circles and squares along the relevant termini locations represent the location of transects. Soil sampling was also done at the birch (*Betula pubescens* Ehrh.) forest close to the Skaftafell visitor centre, and it served as a baseline on the reference area. Each diamond represents a sampling zone in the forest. See main text for further clarification of field sampling setup. The map shows the position of the terminus and the developing glacial lagoon in 2011, drawn from airborne Lidar – digital elevation model (The Icelandic Meterological Office). The location of the glacier's termini is redrawn based on the work of Hannesdóttir et al. (in review).