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The weathering of volcanic tephra and how they impact histosol development. An example from South East Iceland

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ABSTRACT

Little is known about the impact of tephra deposits from explosive volcanic eruptions on soil formation and weathering processes in organic soils. The weathering of tephra of basaltic and rhyolitic origin and their impact on Icelandic histosols were studied through a combination of physical, chemical and mineralogical analyses. Two sampling sites were selected according to the presence of the light coloured rhyolitic tephra from the Öræfajökull eruption in 1362 CE and a dark-coloured basaltic Veiðivötn tephra from 1477 CE in the volcanically active area south of Vatnajökull in South East Iceland.

The determining factor of pedogenesis in the investigated histosols is the OM, but the influence of tephra and aeolian material from external sources must be taken into consideration. The soils are the result of altered plant residues and volcanic material (tephra and aeolian material). Plant remnants, as well as the soil itself, are protected from decomposition by the prevailing anaerobic conditions, a low soil pH and the repeated addition of inorganic matter. Clay formation is low, while metal-humus complexes are predominant. Fe_o/Fe_d ratios indicated a generally low degree of weathering, being higher close to the basaltic tephra.

The mineralogy was dominated by plagioclase and pyroxene, with quartz and zeolite as minor components. In contrast to previous research on Icelandic soils, our investigations revealed layer silicates at both sites. While we found evidence of smectite in the soils at Kálfafell, hydroxy interlayered minerals were found at Reynivellir. In the basaltic tephra, traces of layer silicates could be verified. In contrast, the rhyolitic tephra did not show any pedogenic minerals, suggesting that it had hardly altered since its deposition in 1362 CE. It is not the chemical composition of the inorganic parent material, but the location that may be an influencing factor on the formation of clay minerals in the investigated histosols.

1. Introduction

Iceland is one of the most active and productive volcanic region in the world with eruptions expected to occur every two years on average (Compton et al., 2015; Pagli and Sigmundsson, 2008), forming consolidated rocks and tephra. The bedrock is mainly of basaltic origin while tephra composition ranges from basaltic to rhyolitic (Thordarson and Larsen, 2007).

Many surfaces have been disturbed by erosion and cryoturbation processes, modifying the surface and the soil environment (Gísladóttir et al., 2011; Möckel et al., 2017; Þorbjarnarson, 2016). Frequent tephra deposition and a steady flux of aeolian material from unstable sandy deserts and eroded soils constantly recharge the surface with new material while subsoils are preserved and continue to develop after burial (Arnalds et al., 1995). Thus the weathering of tephra is reflected in the soil layers above, although it may also infiltrate the soil immediately below.

Icelandic soils were formed during the Holocene when glaciers retreated (Arnalds, 2010; Arnalds and Kimble, 2001). A cool period between 1250 CE and 1900, referred to as Little Ice Age (LIA) (Ogilvie and Jónsson, 2001) resulted in advancing glaciers (Björnsson and Pálsson, 2008; Hannesdóttir et al., 2015; Ingólfsson et al., 2010). Due to climate warming since the end of the LIA, new land has emerged with subsequent soil formation (Vilmundardóttir et al., 2014; Vilmundardóttir et al., 2015a; Vilmundardóttir et al., 2015b), with time and climate as the key factors controlling weathering and soil development (Ugolini and Dahlgren, 2002; Vilmundardóttir et al., 2014).

A young weathering state is common for all Icelandic soils,

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attributed to the parent material and the prevailing climatic conditions (Arnalds, 2015). Andosols are the predominant soil order, covering 86% of the island, while histosols cover only 1% of the Icelandic surface (Arnalds and Óskarsson, 2009).

Soil is the largest terrestrial pool of organic carbon (OC) (Batjes, 1996), being an important sink of carbon over a long term scale (Loisel et al., 2014). Histosols of the Northern hemisphere are organic soils, dominated by peat, thus often referred to as peat soils. The development in waterlogged, anaerobic conditions (Bridgham et al., 1995; Clymo, 1987; FAO, 2014) and cold climate lead to reduced decomposition rates and an accumulation of poorly decomposed soil organic matter (SOM) and soil organic carbon (SOC). Despite covering only c. 1% of ice-free land globally, histosols contain the highest portion of SOM (up to 50% or even higher) and SOC (20–40%) in all soil types. Therefore, they play an important role in the global carbon cycle. As the climate gets warmer, the extent of peatland may decrease (IPCC, 2015). Prominent wetland areas with histosols in Iceland are in the west and northwest of the island. Other important areas of histosols are in south Iceland (Arnalds and Óskarsson, 2009).

Even though Icelandic histosols show similar rates of organic accumulation (0.1–0.45 mm yr^{-1}) as reported for peaty soils in neighbouring countries (Gudmundsson, 1978), they exhibit features that separate them from most other histosols on the globe. The parent material is mainly comprised of poorly decomposed plant remains but contains considerable quantities of inorganic material originating from volcanic ejecta and aeolian activity. Despite very limited research, it has been shown that Icelandic histosols exhibit a unique combination of histic and andic soil properties. They are characterized by a considerable amount of metal-humus complexes (Arnalds, 2008; Arnalds and Óskarsson, 2009) and variable SOM content (Möckel et al., 2017). A study on peatland soils in west and north Iceland by Gudmundsson (1978) showed that properties are controlled by the quantity and form of mineral material present.

SOC content and the amount of clay minerals in organic soils are influenced by drainage conditions and the addition of fresh parent material (Möckel et al., 2017). High OM content and low dry bulk density (DBD) (0.17–0.4 g cm^{-3}) lead to a high water holding capacity (Gísladóttir et al., 2010; Gísladóttir et al., 2011; Möckel et al., 2017) in Icelandic histosols. A prevailing low pH and the presence of large quantities of SOM tend to result in an inhibited formation of amorphous secondary minerals (Stefánsson and Gíslason, 2001).

Ammonium oxalate extractable Al and Fe (Al_o, Fe_o) in Icelandic histosols are commonly found to be in the range of 0.7–1.6% Al_o and 0.5–1.2% Fe_o, while the Si_o content is low (Arnalds, 2004). Icelandic soils are highly affected by windblown dust. Up to 80% of the aeolian dust has a volcanogenic origin of basalt composition, rich in heavy metals (Arnalds et al., 2016). The main source of Fe in the soils is basaltic glass but not crystalline material (Arnalds et al., 2014; Arnalds et al., 2016). At low pH conditions in the soil, the amorphous basaltic glass dissolves rapidly (Oelkers and Gislason, 2001), leading to high Fe_o values. Arnalds and Kimble (2001) suggested that high Fe_o, compared to Al_o and Si_o, are further caused by ferrihydrite as a common component of the clay fraction. They also stated dithionite-citrate extractable Fe (Fe_d) values to be generally about half of the Fe_o values.

Histic andosols generally show very similar properties to histosols. They cover about 5.5% of the Icelandic surface area and develop in poorly drained areas where aeolian input, especially from volcanic areas, is considerable. SOC content is high (12–20%) but, due to aeolian input, it is too low to meet the criteria for histosols and therefore, the SOC and andic properties of these soils define it as andosols with histic properties (Arnalds, 2004). García-Rodeja et al. (2004) found low Al_p contents in histic andosols from northwest Iceland to be due to low humification caused by temperature regime and poor drainage.

Chemical weathering of basaltic rocks is a fundamental process in soil formation in volcanic regions (Kardjilov et al., 2006). Gíslason (2008) found chemical denudation rates in Iceland being 1.3 times higher than the world average; despite the cold climate. Linked to the importance of climatic factors on weathering, Eiriksdottir et al. (2013) showed that chemical denudation in Iceland increased by 13% with each 1 °C increase in temperature. Nonetheless, in the southern regions of Iceland, runoff and the age of rocks are the primary factors controlling the chemical denudation rate (e.g. Gíslason, 2008; Gíslason et al., 1994; Gíslason et al., 1996; Stefánsson and Gíslason, 2001). The annual mean surface runoff in Iceland is at a maximum on the south and south eastern fringe of the Vatnajökull ice cap (Jónsdóttir, 2007; Jónsdóttir, 2008). The dissolution rate of glassy rocks (hyaloclastite) is about 10 times faster than those of crystalline basalt (Gislason and Eugster, 1987).

Total chemical weathering rates decrease with increasing age of rocks (Gíslason, 2008). Volcanic glass shows the least resistance to chemical weathering in soils developed from volcanic ejecta. As a result of its properties (e.g. fine particle size and amorphous nature), tephra enhances weathering and interactions in the soil environment (Dahlgren et al., 1993). Despite the overall rapid weathering of tephra, rhyolitic tephra weathers much more slowly than basaltic (Gíslason, 2005) and dissolution rates of "coloured glass" of basaltic andesitic composition are higher than those of rhyolitic "non-coloured glass" (Nanzyo et al., 1993). Furthermore, with increasing silica content, glass dissolution rates decrease. Studies on dissolution rates of natural glasses by Wolff-Boenisch et al. (2004) showed a lifetime of 4500 yrs for natural glass of rhyolitic composition, whereas it is only 500 yrs for natural basaltic glass.

Clay minerals in Icelandic soils developed from volcanic ejecta are formed in subsurface horizons in situ rather than by translocation or leaching and precipitation (Arnalds, 2008; Dahlgren et al., 2004). Amorphous secondary minerals are predominant. With increasing soil age the crystalline weathering phases become more abundant (Crovisier et al., 1992). Crystalline plagioclase and pyroxene are major primary minerals of Icelandic basalt (Arnalds, 2005). Allophane, imogolite and poorly crystalline ferrihydrite are the dominant phases for the clay size fraction of Icelandic soils (Stefánsson and Gíslason, 2001) while layer silicates are rare (Arnalds, 1993).

A recent study by Möckel et al. (2017) showed that aeolian material had an impact on soil properties of histosols in North Iceland. Furthermore, it has been verified that heavy tephra falls influence vegetation and soil (Eddudóttir et al., 2016; Þorbjarnarson, 2016). Nevertheless, the impact of tephra deposits from big explosive eruptions on soil formation and soil weathering processes in histosols is not well studied in Iceland. The island offers unique opportunity to conduct such research, specifically in regions that have been inundated with thick tephra deposits of different chemical composition.

In this paper we present the results from a comprehensive study on histosols in the lowlands south of Vatnajökull glacier, SE Iceland. The volcanically active Vatnajökull area has received numerous tephra deposits of varying thicknesses during the Holocene (Óladóttir et al., 2011). The presence of the light coloured rhyolitic tephra from the Öræfajökull eruption in 1362 CE and a black basaltic Veiðivötn tephra from 1477 CE in this region enables comparison between the weathering behaviour of tephra of different composition and to examine their contrasting mineralogy. The present research will improve the understanding of changes in soil properties and mineralogy in histosols after tephra deposition and will add significant knowledge about the impact of volcanism on weathering processes and histosol development globally. The main purpose is to examine the following research questions:

1) How do different tephra weather?
2) How do tephra influence the weathering processes and development of histosols?

The weathering behaviour of tephra deposits of basaltic and rhyolitic origin and their impact on Icelandic histosols were studied through a combination of physical, chemical and mineralogical methods. As far