Geoderma 189–190 (2012) 635–651

Contents lists available at SciVerse ScienceDirect

Geoderma

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

Climate-dependent chemical weathering of volcanic soils in Iceland

Birgir V. Óskarsson [a,*], Morten S. Riishuus [a], Ólafur Arnalds [b]

[a] Nordic Volcanological Center, Faculty of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland
[b] Agricultural University of Iceland, Keldnaholt, 112 Reykjavík, Iceland

ARTICLE INFO

Article history:
Received 18 May 2011
Received in revised form 27 May 2012
Accepted 30 May 2012
Available online 6 September 2012

Keywords:
Andosols
Major elements
Chemical weathering
Climofunction

ABSTRACT

The major element mobility within soil profiles of brown to gleyic Andosols that developed under diverse climatic conditions in Iceland is assessed. The volcanic soils were selected from areas with good monitoring of annual temperature and precipitation and the degree of weathering and elemental behavior is compared. Icelandic soils are subject to high fluxes of aeolian dust, and at times, to tephra ejecta from volcanic eruptions. The source of dust input is assessed for each profile based on comparison of the chemical signatures found in the less weathered upper horizons with those of volcanic systems supplying material to source areas. Results show that TiO_2, Al_2O_3 and Fe_2O_3(T) and MnO are the least mobile species and generally found enriched within more mature horizons. The mobile base cations MgO, CaO and Na_2O are depleted in these horizons as a result of chemical weathering during pedogenesis. Soils developed in colder climatic conditions with mean annual temperature (MAT) ∽−1 °C give values for the Chemical Index of Weathering (CIW) of 37–45 that reflect only weak chemical weathering. Soils developed in milder climates (MAT = 2–4 °C) are more strongly affected by weathering (CIW = 50–77). The parent material has CIW values of ∽37. Temperature is demonstrated as the dominant variable exerting control on the extent of weathering, with only minor mobilization following the incipient near-surface weathering stage. A robust linear relationship is found between CIW and model MAT ($MAT = 0.21CIW - 8.93$, $R^2 = 0.81$). This climofunction can deliver proxy climate estimations from volcanic soils and paleosols of basaltic origin in cool to subarctic conditions (−2 to +6 °C).

1. Introduction

Soil-forming processes have been active in Iceland since the end of the Last Glacial Maximum. The location of Iceland in the North-Atlantic ocean is strongly influenced by the frequent passage of low atmospheric pressure systems (Einarsson, 1984), and these systems generate strong winds that cause mechanical weathering and translocation of particles in dust storms (Arnalds, 2010). Aeolian volcanic glass derived from unstable sandy surfaces is the dominant constituent in the parent material delivered to Icelandic soils. In addition, frequent volcanic activity with estimated 20–25 eruptions per century throughout the Holocene (Thordarson and Larsen, 2007) results in widespread tephra deposits.

The most common soil type in Iceland is Andosol, a soil that develops in materials of volcanic origin (Arnalds, 2004, 2008). This type of soil constitutes ~86% of all Icelandic soils and is distributed through an area of approximately 78,000 km^2 (Arnalds, 2004). Basaltic tephra tends to weather rapidly (Gislason, 2005) leading to dissolution of some elements from the soil system while re-precipitating other elements as poorly crystallized material, such as allophane, imogolite and ferrihydrate (Arnalds, 2008; Dahlgren, 1994; Shoji et al., 1993; Wada et al., 1992). This provides Andosols with andic soil properties such as low bulk density, variable charge characteristics, thixotropy, high soil water retention and strong phosphate retention (Kimble et al., 2000).

The study of species mobilization within soils has received considerable attention due to its practical applicability in assessing e.g. soil quality (e.g. Maskall and Thornton, 1996; Sterk et al., 1996; Sutton et al., 2002), chemical weathering rates (e.g. Bain et al., 1993; Duan et al., 2002; Nesbitt and Wilson, 1992; Parker, 1970), pedogenetic evolution (e.g. Lijun and Jinye, 1996) and anthropogenic effects on natural systems (e.g. Chipres et al., 2008). The applicability of chemical mobilization extends to studies on paleopedogenetic processes and paleoenvironments (e.g. Gay and Grandstaff, 1980; Kumaravel et al., 2009; Macfarlane and Holland, 1991; Sheldon, 2003). Species mobilization in volcanic soils has been assessed both in vertical profiles on the basis of solid components (e.g. Craig and Loughnan, 1964; Taboada et al., 2007) and dissolved solids in natural catchments (e.g. Delvaux et al., 1989; Gislason, 2005) as well as on weathered tephras (commonly described as paleosols, redbeds or boles) (Bestland, 2002; Ghosh et al., 2006; Hill et al., 2000; Sheldon, 2005).

The chemical mobilization of elements from Icelandic soils is well documented from the perspective of dissolved solids in aqueous systems (e.g. Eiriksdottir et al., 2008; Gislason, 2005; Sigfusson et al., 2008; Stefansson and Gislason, 2001). Vertical inorganic chemical variation within soils is a topic still confined to few studies (e.g. De Vleeschouwer et al., 2008; Taboada et al., 2007).

* Corresponding author. Tel.: +354 5255476.
E-mail address: bvo2@hi.is (B.V. Óskarsson).

0016-7061/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.geoderma.2012.05.030

In this paper we explore the major element chemical variation in Andosol horizons from 16 soil profiles in Iceland. The soils developed in a range of microclimatic and soil-forming conditions over the past ~5000 years. We estimate the extent of chemical weathering of these soils that have developed in a cold oceanic climate, and have received continuous replenishment of primary materials because of high rates of tephra and dust input. A correlation is made between the species-specific chemical mobility and pedogenic processes including the formation of humus and poorly crystallized clays. Finally, soil model ages are constructed and compared with MAT estimates that demonstrate climate-dependent chemical weathering, leading to the formulation of a climofunction applicable to terrestrial paleoclimatology.

2. Geology and climate of Iceland

2.1. Geological setting

Iceland is the youngest expression of the North Atlantic Igneous Province, with its formation attributed to the combined effects of a mantle plume and extensional rifting at the Mid-Atlantic ridge (e.g. Saunders et al., 1997; White, 1988). Since the middle Neogene, volcanism in Iceland has formed about 100,000 km^2 land area with elevations up to 2000 m.a.s.l. Glaciation has played an important role in shaping Iceland both with its erosive power and its interaction with volcanism (e.g. Einarsson and Albertsson, 1988; Geirsdottir et al., 2007). Subglacial eruptions have formed volcanic landforms such as tuyas and hyaloclastite ridges composed largely of quenched glass (e.g. Jones, 1969; Schopka et al., 2006). The effects of volcanism associated with glaciers have also produced vast sedimentary floodplains as consequence of meltwater released both during summer melting and in catastrophic floods (jökulhlaups) (e.g. Gudmundsson et al., 1997). Following deposition, this volcanic material is continuously redistributed with dust delivered as new constituents to Icelandic soils (Arnalds, 2010).

The Icelandic rift zone is divided into volcanic zones (Gudmundsson, 2000) that include discrete volcanic systems and central volcanoes (Fig. 1a). Icelandic volcanic rocks are classified into three magmatic series, the tholeiitic, alkalic and transitional alkalic (Jakobsson et al., 2008). The most common type of melt erupted from these volcanic systems is basaltic tholeiitic in composition while flank zones contribute with mildly alkaline products (e.g. Jakobsson et al., 2008). Central volcanoes have produced intermediate and more evolved eruptive products spanning tholeiites, andesites and rhyolites. The dust and volcanic ejecta that build Icelandic soils include, in addition to volcanic glass, also primary minerals such as plagioclase, augite and olivine that are characteristic for basaltic rock (Baratoux et al., 2011). Unlike Mid-Atlantic Ridge (MAR) basalts, Icelandic basalts are usually high in Ti (Jakobsson et al., 2008).

2.2. Climate

The climate in Iceland is classified as cold oceanic, which is attributed to the geographic location of this landmass slightly below the Arctic Circle and influenced by a branch of the cold East Greenland Current. At the same time, the effects of the Irminger Current, a branch of the warm North Atlantic Current gives rise to comparatively mild conditions (Einarsson, 1984). The climate is warmer on the south coast of Iceland with MAT ~4 − 5°C and MAP ~1000–1600 mm, while colder in the north with less precipitation (~3 to 4°C and MAP ~400–600 mm) (Fig. 1). Glaciers and areas at higher elevations have colder MAT and often form their own microclimate. Warm and cold air masses meet close to Iceland and a mean low pressure center, the Icelandic Low, passes through its southwest side. Consequently, cyclones frequently bring strong winds and precipitation to the country. Although the predominant wind direction is easterly, local topographical features as fjords and valleys do control the frequencies of the wind speeds and directions. Topography will also affect the distribution of maritime air with mountains acting as barriers where cloudiness and precipitation will increase on one side of the high but decrease on the other (Einarsson, 1984).

Suspended dust concentration measurements show that dust is present during much of the year. Distal areas from aeolian sources receive <25 g m^{-2} yr^{-1} deposition, while areas near or within major sandy areas receive >500 g m^{-2} yr^{-1} (Fig. 1b; Arnalds, 2010). Most dust is derived from areas at the margins of glaciers and glacial outwash plains, but also from barren desert areas in the highlands (Fig. 1b; Arnalds, 2004; Ashwell, 1986, 2010). The rates of dust and tephra input decrease with increasing distance from the volcanic zones. As shown in Fig. 1b, the rates of dust input, calculated from well constrained tephra layers (Thorarinsson, 1961), increased significantly after the settlement in Iceland (tephra layer H1, 1104 A.D.) most likely due to intense land use and deforestation (Kristinsson, 1995).

Multiproxy climate records show that the beginning of the Holocene was characterized by a 1.5–3 °C warmer climate than the 1961–1990 reference (see 1961–1990 reference in Fig. 1a). The mid to late Holocene was characterized by cooling and increased glacial activity with periodic milder periods throughout the Middle Ages, but reached the coldest condition during the Little Ice Age (AD 1250–1900) with temperatures 1–2 °C colder than the 1961–1990 reference (e.g. Geirsdottir et al., 2009).

2.3. Soils

Andosols in Iceland have been divided into four types; Brown, Gleyic and Histic Andosols and Vitrisols (desert areas), according to an Icelandic classification scheme related to the World Reference Base (Arnalds, 2004). This division is mostly controlled by the organic carbon content. The carbon content in soils increases almost linearly with poorer drainage but decreases with increased aeolian and tephra input (Arnalds, 2004). Brown Andosols and Vitrisols (carbon content 1–7 wt.% and <1 wt.%, respectively) are predominantly found in the highly permeable and active volcanic zones. Histic Andosols (wetlands, carbon content 12–20 wt.%) are found mostly on the adjacent older and less permeable terrains of Neogene lava piles, while Gleyic Andosols are wetland soils with less carbon (1–12 wt.%) and are found near or within the volcanic zones (Arnalds, 2008).

3. Methods

3.1. Soil profile sampling

A total of 62 samples extracted from 16 soil pedons around Iceland, mostly Gleyic and Brown Andosols, were selected for this study from the Agricultural University of Iceland soil database. The selected pedons were sampled in 2001–02. In addition, 5 surface samples (RE and DY) from this database were also analyzed. From half of the pedons (8) we selected 5 or more horizons in each profile for analysis, while two horizons were selected from each of the remaining profiles. Each sample was taken approximately at the center of the horizon. Bw horizons were preferentially selected from the profiles where only two samples were studied. Methods of sampling and general descriptions (horizons, color, grain size, texture, roots and mottles) are available from Arnalds et al. (2005) with the exception of the profiles HA (Arnalds et al., 2006), COST-N7 and N8 (HS and AH) (Buurman et al., 2004; García-Rodeja et al., 2004; Taboada et al., 2007). Each soil profile developed in similar parent material of basaltic composition, although tephra layers within the profiles may vary significantly from basic to more evolved silicic. Climatic conditions (MAT and MAP) for each soil profile were acquired from weather stations in the vicinity of the profiles (Table 1). The climatic data is from the Icelandic Meteorological Office (www.vedur.is) and the given means are derived from the years 1961–1990.