Andisols of Deserts in Iceland

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ABSTRACT

Desert areas cover 35 to 45 000 km^2 of Iceland or about 35 to 45% of the country. These surfaces have very low vegetation cover as a result of several environmental factors and anthropogenic impacts. A good understanding of the soils of the deserts is a key factor for successful restoration of these ecosystems. Very limited data has previously been published about the soils of Icelandic deserts and limited research has been reported on soils that form in basaltic tephra materials under similar conditions elsewhere in the world. The purpose of the research reported here was to gain a basic understanding of properties, variability, and classification of the soils of Icelandic deserts. Eight soil pedons, representing a variety of desert surfaces, were described, sampled, and analyzed for key physical and chemical properties. The morphology was generally characterized by a frost-heaved gravel layer at the surface, with finer subsurface horizons with abundance of volcanic glass. The soils had low organic content ($<$10 g kg^{-1}), and very low levels of N. Water holding capacity was generally $<$50 g kg^{-1} at 1.5 MPa. Phosphorus retention is 24 to 93% in A and B horizons. The soils were near neutral in reaction but the pH in NaF solution was commonly around 10. Mineralogy was dominated by volcanic glass, but allophane and ferrihydrite are also present. The results of this study show that most Icelandic deserts soils are Typic Virtricryands according to soil taxonomy. Icelandic Andisols combined are 5 to 7% of the world's Andisols.

THE BARREN WASTELANDS in Iceland have traditionally been called deserts in English in spite of the humid climate (Anderson and Falk, 1935). The original meaning of the term *desert* is desolate or abandoned which well describes the Icelandic deserts (Arnalds, 2000a). They cover an area of 35 to 45 000 km^2 or about 35 to 45% of Iceland. The volcanic characteristics of the parent material and limited vegetation cover in a moist climate regime make them unique in a global perspective as most desert type soils are not found in humid climates.

Many of the present Icelandic desert areas were previously fully vegetated and the surface covered with fertile Andisols (Arnalds, 1999, 2000b). Erosion has removed nearly all of the original soil and vegetative cover from the surface during the past 1100 to 1200 yr. Vikings settled Iceland after 874 CE. Most of the soil erosion is considered human induced after the settlement by animal grazing and wood harvesting. Other factors are also important, such as a cooling trend since 2500 BP, growing sources of eolian sand associated with the formation of glaciers, and glacial river flooding (Arnalds, 2000b).

It is a national priority to restore many of these desertified ecosystems to forests, heathlands, wetlands, and other fully vegetated systems. Basic understanding of desert soil characteristics and their classification is important for restoration research and projects. Many Icelandic deserts have been revegetated by seeding of grasses, fertilization, and by natural succession after the areas are protected from grazing. This can result in effective sequestration of organic C to balance industrial emissions of greenhouse gases, while simultaneously restoring the ecological value of the land (Aradottir et al., 2000; Arnalds et al., 2000).

Andisols cover about 1.2 million km^2 globally (Kimble et al., 1999). The Andisols of Icelandic deserts are a substantial portion of the world's Andisols. Very limited data have previously been published about these soils, and limited research has been reported on soils that form in basaltic tephra materials under similar conditions.

The purpose of the research reported here was to gain a better understanding of key properties, variability, and classification of the soils of Icelandic deserts.

Physiography and Soils

Iceland is an island in the North Atlantic Ocean between 63° and 66° northern latitudes. The climate is humid, maritime, cold-temperate to low-arctic. Most Icelandic soil temperature environments are defined as cryic, potentially with some frigid areas along the south coast and inland valleys and most have an udic soil moisture regime. Permafrost is found in isolated areas in the interior (Thorhallsdottir, 1997), especially south of Hofsjokull Glacier (Fig. 1). The island is mountainous, with some rising to $>$2000 m, but highland plains commonly range between 500 and 900 m. Lowland areas and river plains characterize the coastline. Rainfall varies between 600 and 2000 mm yr^{-1} but large desert areas in the north-central and northeast highlands receive only 400 to 600 mm annual precipitation.

Three factors predominantly influence the Icelandic soil environment (Arnalds, 1999): (i) frequent volcanic activity and the volcanic nature of the soil parent materials; (ii) cold maritime climate with intensive cryogenic processes; and (iii) extremely active soil erosion by wind, water, and gravity, aided by cryogenic processes. These factors combined, have created vast unstable desert areas that are the source of steady eolian sedimentation in the country.

Icelandic soils began to form when the Pleistocene glacier retreated about 10 000 yr ago. Since then, many surfaces have been disturbed by volcanic tephra deposition, lava flows, soil erosion, solifluction, landslides, sand encroachment, and glacio-fluvial flooding. Many surfaces continue to rise because of frequent deposition of volcanic and eolian materials.

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Abbreviations: CEC, cation-exchange capacity; subscript d, dithionite-citrate extractable; subscript ox, ammonium oxalate extractable; subscript pyr, Pyrophosphate extractable.

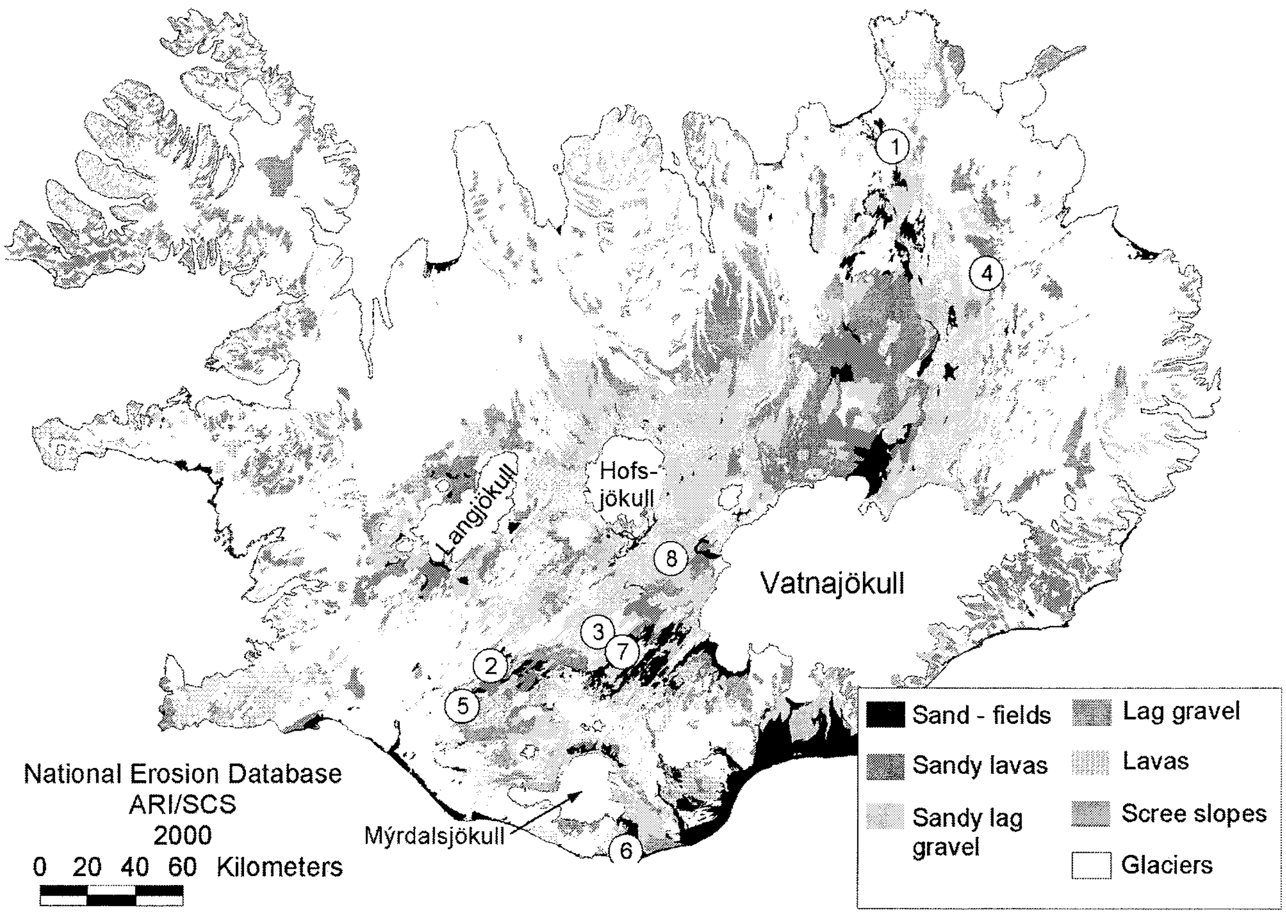

Fig. 1. The extent and surface morphology of Icelandic desert. Numbers indicate approximate pedon locations.

All Icelandic soils exhibit andic soil properties to some degree. They are traditionally divided into three major groups (Johannesson, 1960; Helgason, 1963, 1968; Olafsson, 1974; Arnalds, 1999, 2000b): brown allophanic Andisols of freely drained sites with 20 to 50 g C kg^{-1} and clay content ranging from 0.2 to 0.4 kg kg^{-1}, organic soils of wetland positions (Histosols and Andisols), and soils of the barren deserts. The desert soils are Cryands (Arnalds, 1990), but have also been classified as Regosols, Arenosols, Leptosols, and Gleysols according to the 1988 FAO system (Gudmundsson, 1994). Helgason (1963, 1968), Olafsson (1974), and Arnalds et al. (1995) provided data for the freely drained soils while Olafsson (1974) and Gudmundsson (1978) studied the wetland soils. Data from a number of pedons are presented in Johannesson's pioneer work (Johannesson, 1960). Earlier work on desert soils includes that of Arnalds et al. (1987) and Gudmundsson (1991) in relation to reclamation studies, and Arnalds (1990) data for two glacial till pedons. These datasets are incomplete for classification of the soils.

Cryoturbation is extensive and occurs with a great intensity in Iceland. Most slopes have well developed solifluction features and hummocks form on freely drained sites (e.g., Schunke and Zoltai, 1988). Cryoturbated features are common in soil profiles, and are often intensified at higher elevations.

Soil erosion has been and still is a major problem in Iceland. Processes are quite varied and include erosion by wind, water, landslides, and cryogenic processes. Erosion in Iceland is described in more detail by Arnalds (1999, 2000b) and Arnalds et al. (2001b).

Geomorphic Surface Types of Deserts

The barren surfaces have been surveyed at the scale of 1:100 000 as a part of the Icelandic national assessment of soil erosion (Arnalds et al., 2001b). The survey, based on fieldwork and satellite images, distinguished between erosion forms. Deserts were divided into seven main categories based on surface geomorphology. An example of an Icelandic desert surface is shown in Fig. 2. The most common surfaces are the lag gravel (melar in Icelandic), sandy lag gravel, sand fields, lava surfaces, and sandy lava surfaces (Table 1; Fig. 1).

The lag-gravel surface usually consists of about 10 000-yr old glacial till (basal moraine), however barren alluvial floodplains are also classified as lag gravel in the survey. The lag gravel has a stony surface because of frost heaving of the coarse fragments, underlain by finer materials consisting of varying amounts of poorly weathered crystalline materials, volcanic glass, and weathering products such as allophane. These surfaces are continuously under the effect of eolian additions, which accumulate under the stony surface. Vegetative cover is usually 2 to 5% of the surface and is characterized by

Fig. 2. Icelandic desert. Sandy lag gravel surface. The surface has only 1 to 2% plant cover. Under the gravely surface (desert pavement) are sandy loam A and B horizons with volcanic glass, ferrihydrite, and allophane. Water retention is very low.

mosses, lichens, and small herbs with extensive root systems. Many of these surfaces used to be covered with fertile, brown colored Andisols, which were vegetated, but have since become denuded and truncated because of soil removal by erosion. Native N-fixing species are uncommon in deserts, but introduced legumes, especially the Alaskan lupine (*Lupinus nootkatensis* Donn. ex. sims.), have been shown to be aggressive pioneers. The use of introduced species for reclamation is controversial in Iceland.

Iceland has large sand fields where eolian processes are quite active in spite of a humid climate. The sand fields have two main origins: glacio-fluvial deposits and volcanic ash (Arnalds et al., 2001a). Some of the sand fields are recent (<200 yr old) and have formed by catastrophic floods from thermal area water reservoirs underneath glaciers or during subglacial volcanic eruptions. These surfaces are often nearly devoid of vegetation (0.5–2% cover). Most of the sand fields consist almost entirely of volcanic glass, ranging in size from silt to >2 mm in diameter.

The sand fields are unstable eolian environments, which cause redistribution of glacial materials and volcanic ash over large areas. Loess is deposited throughout the country, but more coarse materials are moved by saltation from the sand sources over various surfaces. When sand is moved by wind over lag gravel areas, the rocky surface allows for considerable sand accumulation under the gravel surface. Wind erosion is most common during summer because snow cover often prevents wind erosion in winter. During winter, frost heaving lifts up the gravel, allowing for still more sand accumulation. The sand layer accumulated by this process under the surface can sometimes be >50 cm thick. Such areas are classified as sandy lag gravel areas. Sand can also be transported by wind over lava surfaces and sandy lava surfaces are common geomorphic surfaces in Iceland (Table 1).

Table 1. Extent and geomorphic division of Icelandic deserts. Based on the National Erosion Survey (Arnalds et al., 2001b; erosion severity 3, 4 and 5; considerable–very severe erosion).

Geomorphic type	Extent
	km^2
Lag gravel	6 580
Lava surfaces	2 085
Sandy fields	4 233
Sandy lava surfaces	4 743
Sandy lag gravel	12 910
Brown soil remnants	451
Scree slopes	4 025

MATERIALS AND METHODS

Sites

Eight locations were selected for characterization, representing a variety of geomorphic surfaces in Iceland (Fig. 2). The general characteristics of the sites are presented in Table 2. Four of the sites are lag-gravel areas, two sand fields (~500- and 100-yr old volcanic deposits), one is sandy lag gravel, and one (Pedon 5) is representative of a revegetated (by the Icelandic SCS) desert area. The elevation varies from near sea level to 700 m, with a wide range of climatic conditions. The sites receive annual precipitation ranging from about 600 to >2000 mm.

Soil Sampling and Analysis

Soils were sampled and described according to the Soil Survey Manual (Soil Survey Staff, 1993). Samples were analyzed at the National Soil Survey Laboratory, Lincoln, NE. Samples were air dried and passed through a 2-mm sieve before shipping. Laboratory methods that were used are described in the *Soil Survey Laboratory Methods Manual* (Soil Survey Staff, 1996; key to methods indicated in parentheses). Particle-size analysis was done by a pipette method after pretreatment to remove organic matter and soluble salts (3A1). Water retention at 1.5 MPa was determined by pressure-membrane extraction (4B1a). Phosphorus retention was analyzed as described by Blakemore et al. (1987) (6S4b). Soil reaction was determined in 1:1 soil/water solution (8C1f), and 1:2 soil/0.01*M* $CaCl_2$ solution (8C1f), and in a 1:50 soil/1*M* NaF solution after stirring for 2 min (8C1d). Organic C and total N were determined by dry combustion and measurement of evolved CO_2 and N_2 (6A2e; 6B4a). Cation-exchange capacity (CEC) was analyzed by ammonium acetate extraction (pH 7), using a mechanical vacuum extractor and measuring the NH_4^+ by steam distillation (5A8). The extractable bases (Ca, Mg, Na, and K) were determined by atomic absorption in the extract from the CEC procedure. Ammonium oxalate extraction was conducted in the dark by mechanical vacuum extractor with oxalate solution buffered at pH 3.0. The Al, Fe, and Si extracted were determined by Inductively coupled plasma optical emission spectrometry (ICP) (6C9). The soils were extracted with sodium pyrophosphate and dithionite citrate for Al and Fe, which were measured in the extract by atomic absorption spectrophotometer (6C8). Volcanic glass was determined for the coarse silt and sand fractions by optical analysis using a petrographic microscope (7B1).

RESULTS AND DISCUSSION

Morphology

Morphological features are summarized in Table 3. The lag-gravel surfaces (Pedons 2, 3, 4, and 8a) and an alluvial desert surface (Pedon 1) have desert pavement surfaces, which are given a C horizon designation. The surface gravel has its origin in the underlying C horizons (till) and has been moved by frost heave to the surface.

Table 2. Site descriptions.

Pedon	Vegetative cover	Elev.	Site name	Parent material	MAP†	Average air temp. July	Average air temp. Jan.
	%	m			mm	°C	°C
1	2	25	Assandur	Alluvial–lag gravel. Basaltic volcanic glass and rock fragments	600	10	−2
2	2	100	Selsund	Lag gravel–till. Basaltic and rhyolitic pumice, volc. glass and rock fragments	1600	10	0
3	0.5	540	Sigalda	Lag gravel–till. Glacial till, mixed basaltic volc. glass and rock fragments	1200	7	−5
4	1	570	Thjodfell	Lag gravel–till. Glacial till, mixture of basaltic volcanic glass and rock fragments	900	8	−5
5	90	100	Gunnlaugsskogur	Revegetation–soil remnants. Eolian basaltic volc. glass and rock fragments over old Andisol surface	1600	10	−1
6	1	30	Myrdalssandur	CE 1918–flood, tephra. Glaciofluvial floodplain with basaltic volcanic glass and pumice	1800	10	0
7	1	600	Veidivotn	CE 1480 tephra. Tephra deposits, mixture of glass and pumice	>2000	7	−6
8	2	700	Kvislar	Lag gravel–till. Glacial till, mixture of basaltic volcanic glass and rock fragments	1200	7	−7

† Mean annual precipitation.

Table 3. Selected morphological features.

Horizon	Depth	Color†	Field texture‡	Structure§	Moist consistence	Boundary
	cm					
			Pedon 1. Assandur. Alluvial lag gravel			
C	0–2	NA#	g	single grain		
2Bw1	2–11	7.5YR 3/2	vglsa	weak fine med granular	v friable	abrupt wavy
2Bw2	11–20	7.5YR 3/2	glsa	weak fine med granular	v friable	abrupt smooth
3C	20–40+		gsa	single grain		
			Pedon 2. Selsund. Lag gravel–till			
C	0–1	NA	g	single grain		
2Bw1	1–9	2.5YR 2.5/0	lsa	weak fine granular/sbk	v friable	abrupt wavy
2Bw2	9–19	10YR 3/2	gsal	weak fine granular/sbk	friable	abrupt wavy
3C	19–39+	2.5YR 2.5/0	glsa	structureless/single grain	v friable	
			Pedon 3. Sigalda. Lag gravel–till			
C	0–2	NA	g			
2A1	2–22	10YR 3/2	sal	weak fine/med granular	v friable	diffuse wavy
2A2	22–34	10YR 3/2	sal	weak fine/med granular	v friable	clear wavy
3C	34–50+	2.5YR 2.5/0	lsa	single grain		
			Pedon 4. Thjodfell. Lag gravel–till			
C	0–3	NA	gsa	single grain		abrupt wavy
2Bw	3–10	10YR 3/2	lsa	weak fine granular/single grain	v friable	abrupt wavy
3C	10–22+	10YR 4/2	glsa	structureless	friable	
			Pedon 5. Gunnlaugsskogur. Revegetation–soil remnants			
A1	0–12	7.5YR 3/2	sal	weak fine/med granular	friable	clear wavy
2A1	12–38	10YR 3/1	lsa	weak granular	v friable	abrupt wavy
3Bw	38–109	7.5YR 4/4	sil	weak med sbk (solid lava)	firm	abrupt irregular
4R	109+					
			Pedon 6. Myrdalssandur. CE 1918–flood, tephra			
A	0–4	7.5YR 2.5/0	glsa	weak fine granular	v friable	abrupt wavy
C1	4–8	7.5YR 2.5/0	glsa	single grain		abrupt smooth
C2	8–13	7.5YR 2.5/0	glsa	single grain		abrupt wavy
C3	13–25+	7.5YR 2.5/0	glsa	single grain		
			Pedon 7. Veidivotn. CE 1480 tephra			
A1	0–6	7.5YR 2.5/0	sal	weak fine granular, structureless	v friable	clear wavy
A2	6–10	10YR 3/1	sal	weak fine granular, structureless	v friable	abrupt wavy
AC	10–12	7.5YR 2.5/0	lsa	weak fine granular, single grain	v friable	abrupt wavy
2C	12–40+	NA	gsa	single grain		
			Pedon 8. Kvislar. Lag gravel–till			
C	0–1	NA	g			abrupt wavy
2A	1–11	5YR 2.5/1	lsa	weak fine-med granular	v friable	clear irregular
3Bw	11–55+	10YR 3/3	gsil	weak med-coarse sbk	friable	

† Colors are for moist soil.
‡ g stands for gravel or gravelly, vg for very gravelly, sa for sand, si for silt, l for loam.
§ Slash means that structure exhibits both structural types or size classes and sbk stands for subangular blocky.
# NA, not available.

Under the two horizons are 2Bw horizons (Pedons 2, 4, and 8), which in some cases could be considered A/C horizons. At the bottom C horizons, which represent the glacial till. The C-A-Bw-C or C-Bw-C sequence is common for lag gravel desert soils in Iceland. Pedons 6 and 7 are formed in about 500- and 100-yr old tephra deposits and lack the desert pavement surface. Both of these pedons have an A-C sequence indicative of young soils. Pedon 5 has more vegetative cover than the others and therefore different pedon characteristics such as a thicker A horizon with higher organic content.

The surface texture as determined in the field ranges from gravelly to sandy loam. The subsurface horizons (field texture) range from gravelly sand to sandy loam and silt loam (Table 3). The finer texture of the subsurface horizons is important in relation to plant growth as discussed later.

Color of moist A and B horizons is dominated by the dark colored basaltic tephra and crystalline lava materials while relatively unaltered basaltic glacial till in 3C horizons has grayish colors. Organic materials stain the soil particles in Pedon 5, but yellowish rhyolitic tephra grains also influence the colors. Colors are similar to Andisols with grassland vegetation cover in Alaska (Ping et al., 1989), however the chromas tend to be lower (darker) because of the basaltic origin of the parent materials.

The structure is weak and often difficult to determine and resembles reports of Andisols elsewhere (Shoji et al., 1993). In the glacial till pedons, there is usually sufficient evidence of pedological alteration to warrant a cambic horizon. The consistence is very friable in most places. Slight Fe cementation is encountered in the 3Bw in Pedon 5, but not enough for an m or sm designation.

Table 4. Selected physical properties.

Horizon	Depth	Coarse fragments†	Particle-size distribution‡ Sand	Silt	Clay	Water retention§ 1.5 MPa
	cm	%				g kg^{-1}
Pedon 1. Assandur. Alluvial lag gravel						
C	0–2	NA#	96.9	3.1	<1	NA
2Bw1	2–11	85	84.7	15.3	<1	33
2Bw2	11–20	37	77.0	23.0	<1	27
3C	20–40	NA	97.4	2.6	<1	13
Pedon 2. Selsund. Lag gravel–till						
C	0–1	NA	93.3	6.7	<1	46
2Bw1	1–9	17	91.7	6.9	1.4	50
2Bw2	9–19	18	76.0	21.9	2.1	75
3C	19–39	57	98.5	<1	<1	54
Pedon 3. Sigalda. Lag gravel–till						
2A1	2–22	11	78.8	20.0	1.2	36
2A2	22–34	13	80.2	19.7	1.1	34
3C	34–50	NA	79.6	19.4	1.0	39
Pedon 4. Thjodfell. Lag gravel–till						
C	0–3	NA	90.6	8.0	1.4	NA
2Bw	3–10	10	78.2	19.8	2.0	64
3C	10–22	42	70.9	27.4	1.7	88
Pedon 5. Gunnlaugsskogur. Revegetation–soil remnants						
A1	0–12	<1	77.0	20.9	2.1	96
2A1	12–38	4	90.6	7.5	1.9	70
3Bw	38–109	<1	60.8	37.0	2.2	254
Pedon 6. Myrdalssandur. CE 1918–flood, tephra						
A	0–4	31	85.3	12.9	1.8	18
C1	4–8	35	87.3	11.2	1.5	20
C2	8–13	17	99.3	<1	<1	20
Pedon 7. Veidivotn. CE 1480 tephra						
A1	0–6	11	86.7	12.1	1.2	12
A2	6–10	25	72.6	25.9	1.5	17
2C	12–40	17	77.7	20.7	1.6	16
Pedon 8. Kvislar. Lag gravel–till						
2A	1–11	26	93.1	5.2	1.7	39
3Bw	11–55+	62	62.5	33.5	4.0	78

† Coarse fragments based on weight.
‡ Particle size based on pipette method.
§ 1.5 MPa water content on air-dried samples.
\# NA, not available.

Physical Properties

Physical properties of the soils are summarized in Table 4. Coarse fragments are a significant proportion of the soils, and range in size from a few mm to between 30 and 40 cm in diameter where the parent materials consist of glacial till. Coarse fragments in Pedons 6 and 7 are pumice, 0.7 to 10 cm in diameter.

Conventional particle-size determination shows sand-sized grains ranging from 62 to 93% in A and B horizons, but such methods fail to show the clay fraction in andic material because of stable aggregates of allophanic materials (Wada, 1985). The particle size determined by the pipette method is, however, indicative of the physical behavior of the soil, especially water permeability. All the sites are expected to have high infiltration rates. The 1.5 MPa water contents are low and commonly <0.50 g kg^{-1} because of the coarse nature of the soil material. The results suggest that low water retention and water shortage is one of the most limiting factors that prevent plant growth in some of the Icelandic deserts. Water shortage is intensified by the lack of vegetative cover. The dark color (low albedo) causes the surface to reach >35°C on sunny days, increasing evaporation. Desiccation during frequent dry winds is also likely to be considerable. Vegetation patterns are often related to water availability as demonstrated by scattered vegetation in depression areas. Determination of 1.5 MPa water content was done on air-dried materials, which generally results in lower water retention in Andisols (Maeda et al., 1977). Further work related to the water characteristics of these soils has been initiated.

The low fertility and low water holding capacity of some of the pedons (<20 g kg^{-1} 1.5 MPa water retention in tephra pedons) draw attention to how difficult it may be to define the desert environment. Some of the world's more arid soils may be covered with vegetation, a part of ecosystems that are adapted to drought. Other environments may be humid but the soil is infertile and unable to store and supply water, leading to water-shortage periods and a lack of vegetation cover.

Bulk density was not measured in the present study. The bulk density is difficult to obtain because of the loose structure of the soil and coarse fragments. Present work being conducted to develop methods to measure bulk density of soils of Icelandic deserts generally indicates values ranging from 0.5 g cm^{-3} in tephra soil to >1.7 g cm^{-3} in dense alluvial deposits (Agricultural Research Institute, unpublished data, 2000).

Table 5. Selected chemical characteristics.

Horizon	N_2O	$CaCl_2$	NaF	OC†	Extractable bases Ca	Mg	Na	K	Summation bases	CEC‡ pH7	P recovery
	pH			$g\ kg^{-1}$	$cmol_c\ kg^{-1}$						%
					Pedon 1. Assandur. Alluvial lag gravel						
C	NA§	NA	NA	4.9	0.5	0.3	0	0.1	0.8	2.4	24
2Bw1	6.8	6.0	10.0	2.9	3.2	1.4	0.1	0.2	4.9	6.1	39
2Bw2	7.2	6.3	9.9	1.8	3.8	1.6	0.1	0.2	5.7	6.0	35
3C	6.9	6.1	9.8	0.4	1.5	0.7	0	0.1	2.3	2.5	17
					Pedon 2. Selsund. Lag gravel–till						
C	6.3	5.6	10.0	2.2	2.9	1.7	0.4	0.2	5.2	8.4	47
2Bw1	6.6	5.8	10.0	2.4	3.3	1.7	0.1	0.2	5.3	8.2	51
2Bw2	7.2	6.3	10.0	4.0	11.0	5.3	0.4	0.4	17.2	20.3	67
3C	7.2	6.4	9.8	2.4	10.3	4.7	0.3	0.3	15.6	15.5	43
					Pedon 3. Sigalda. Lag gravel–till						
2A1	7.1	6.2	9.7	1.1	6.3	2.1	0	0.2	8.6	10.8	49
2A2	7.2	6.3	9.5	0.8	8.5	2.7	0	0.2	11.4	12.4	38
3C	7.2	6.5	9.6	0.5	11.3	4.1	0.1	0.3	15.8	15.8	52
					Pedon 4. Thjodfell. Lag gravel–till						
C	6.3	5.9	9.9	2.5	9.7	2.9	0.1	0.3	13.0	15.8	56
2Bw	7.1	6.3	9.9	4.0	12.6	4.1	0.2	0.3	17.2	19.6	63
3C	7.9	6.7	9.4	1.4	25.0	8.9	0.7	0.6	35.2	35.5	56
					Pedon 5. Gunnlaugsskogur. Revegetation–soil remnants						
A1	6.5	5.7	10.0	14.7	5.3	1.8	0.2	0.2	7.5	13.0	81
2A1	6.8	6.0	9.8	7.5	5.5	1.9	0.1	0.2	7.7	10.6	65
3Bw	6.9	6.2	10.1	29.4	17.8	6.9	0.4	0.4	25.5	34.6	93
					Pedon 6. Myrdalssandur. CE 1918–flood, tephra						
A	6.8	5.9	9.8	0.9	0.9	0.7	0.1	0.1	1.8	3.1	32
C1	6.9	6.0	9.8	0.5	1.3	0.8	0.1	0.1	2.3	3.2	35
C2	6.7	5.9	9.6	0.2	1.2	0.8	0.1	0.1	2.2	2.7	17
					Pedon 7. Veidivotn. CE 1480 tephra						
A1	6.8	6.1	9.5	1.3	0.7	0.3	0	tr	1.0	1.6	29
A2	7.0	6.4	9.6	1.1	2.4	0.8	0	tr	3.2	3.4	43
2C	7.2	6.5	9.4	0.6	2.7	1.0	tr	0.1	3.8	3.9	27
					Pedon 8. Kvislar. Lag gravel–till						
2A	6.5	5.9	9.6	1.7	2.5	1.1	0	0.1	3.7	6.6	50
3Bw	7.1	6.3	9.6	3.1	12.6	4.8	0.4	0.4	18.2	21.6	78

† Organic C.
‡ Cation-exchange Capacity.
§ NA, not available.

Chemical Properties

Chemical properties of the soils are summarized in Table 5. The soils are nearly neutral in reaction (H_2O), which is typical of Icelandic desert soils (Arnalds et al., 1987; Gudmundsson, 1991). The pH of Andisols in Iceland under vegetative cover is usually one unit or more lower than in the soils with no vegetative cover (Arnalds et al., 1995). All the soils show high pH values near 10 in NaF solution, suggesting andic properties. Such values are similar or higher under full vegetative cover (Arnalds et al., 1995).

Organic C values are generally <3 g kg^{-1} which is quite low compared with undisturbed Andisols in Iceland, which commonly contain 30 to 80 g C kg^{-1} in A and B horizons. Pedons 2, 4, and 8 show higher organic C values in subsurface horizons compared with the surface, which is characteristic of soils with lag-gravel surface, while such a trend is not found in soils of the other surface types. The surface horizons of the lag gravel pedons are more sandy than the subsurface because of eolian deposition and frost heave of coarse materials, which also explains lower organic C values at the surface. Organic C is <1 g kg^{-1} in Pedon 6, which has developed in recent (1918 CE) volcanic deposits.

Studies of organic C content in desert soils have implications for understanding the global C cycle and the development of the Framework Convention for Climate Change (FCCC). Arnalds et al. (2000a) indicated the vast potential of Icelandic desert soils to sequester C. Following revegetation efforts, Arnalds et al. (2000) estimated average sequestration rates in soils of >0.6 Mg C ha^{-1} yr^{-1} (0.06 kg C m^{-2} yr^{-1}) which can be maintained for >50 yr. Considerable sequestration rates can be continued for thousands of years because of steady eolian flux from sandy deserts and occasional tephra deposition. As a result, Icelandic Andisols often store >40 kg C m^{-2}, which is similar to other Andisols of the world and considerably higher than other soil orders (often about 10 kg C m^{-2}; Eswaran et al., 1993). Therefore a potential exists to sequester a large part (perhaps $>50\%$) of Iceland's current industrial emissions of CO_2 in the Icelandic desert soils while restoring the ecological balance and value of the land.

Nitrogen contents are also low, or about 1/15 of the organic C (values not reported in Table 5). The low N availability also adds to the infertility of the desert soils.

The sum of exchangeable cations is >10 $cmol_c$ kg^{-1} in many A and B horizons, which is surprisingly high considering the coarse nature of the soils and low or-

Table 6. Chemical dissolution and glass counts for the soils.

	Oxalate			Na_{pyr}†		Al_d‡	Fe_d			
Horizon	Al	Fe	Si	Al	Fe	Al	Fe	$(Al+1/2Fe)_{ox}$§	Al_{ox}/Si_{ox}	Glass#
	g kg^{-1}									%
				Pedon 1. Assandur. Alluvial lag gravel						
C	7.2	15.6	7.7	1	2	–	–	15.0	0.94	
2Bw1	6.3	14.0	6.2	<1	1	–	–	13.3	1.02	56
2Bw2	2.8	7.6	3.4	<1	1	–	–	6.6	0.82	69
				Pedon 2. Selsund. Lag gravel–till						
C	6.9	17.1	7.3	1	2	2	10	15.5	0.95	–
2Bw1	8.6	21.1	10.3	1	2	2	12	19.2	0.83	65
2Bw2	12.4	27.6	12.9	1	2	3	19	26.2	0.96	61
3C	7.8	15.9	10.8	<1	2	2	9	15.8	0.72	–
				Pedon 3. Sigalda. Lag gravel–till						
2A1	10.0	18.8	7.5	<1	2	2	12	19.4	1.3375	
2A2	10.1	19.4	6.9	<1	1	2	12	19.8	1.46	66
3C	8.5	18.9	5.7	<1	2	2	9	18.0	1.49	–
				Pedon 4. Thjodfell. Lag gravel–till						
2Bw	11.2	17.6	8.1	1	2	3	16	20.0	1.38	68
3C	11.1	21.4	6.3	<1	2	2	12	21.8	1.76	49
				Pedon 5. Gunnlaugsskogur. Revegetation–soil remnants						
A1	17.8	33.5	15.3	2	3	5	24	34.6	1.16	–
2A1	11.4	23.4	10.6	1	2	4	18	23.1	1.08	60
3Bw	30.9	43.1	24.1	2	4	11	56	52.5	1.28	85
				Pedon 6. Myrdalssandur. CE 1918–flood, tephra						
A	5.7	14.8	5.4	1	2	1	6	13.1	1.06	–
C1	4.0	11.5	4.2	<1	2	1	5	9.8	0.95	74
C2	2.2	8.0	2.5	<1	1	1	4	6.2	0.88	83
				Pedon 7. Veidivotn, CE 1480 tephra						
A1	6.1	11.9	6.5	1	2	1	5	12.1	0.94	–
A2	9.3	16.8	9.6	<1	2	2	6	17.7	0.97	76
2C	5.1	10.6	5.7	<1	2	1	4	10.4	0.89	73
				Pedon 8. Kvislar, Lag gravel–till						
2A	9.7	19.3	8.2	1	2	3	13	19.4	1.18	55
3Bw	19.4	33.9	15.4	<1	3	4	25	36.4	1.26	57

† Subscript pyr represents pyrophosphate extractable.
‡ Subscript d represents dithionite-citrate extractable.
§ Subscript ox represents ammonium oxalate extractable.
# Glass counts for coarse silt and sand.

ganic content. The charge is explained by the presence of allophane and ferrihydrite in the soils. The young soils of Pedons 6 (eruption and flood 1918 CE) and 7 (eruption 1480 CE) have a much lower sum of exchangeable cations. Calcium is the most common cation followed by Mg^{2+}. Both Na^+ and K^+ are minor in comparison.

The CEC measured at pH 7 is generally between 6 and 20 $cmol_c$ kg^{-1} in A and B horizons of soils in lag gravel (till, Pedons 2, 3, 4, and 8), but is lower in soils that are developing in recent tephra deposits (Pedons 6 and 7).

Dissolution and Mineralogy

Ammonium oxalate extractable Al, Fe, and Si (Al_{ox}, Fe_{ox}, and Si_{ox}) are indicative of short-range order minerals characteristic of Andisols, such as allophane, imogolite, and ferrihydrite. The oxalate values indicate a considerable amount of andic materials with Al_{ox} generally ranging between 5 and 10 g kg^{-1} (Table 6). Studies have shown that considerable amounts of allophane and ferrihydrite are found in Icelandic soils together with some imogolite (Wada et al., 1992; Arnalds et al., 1995). Ammonium oxalate extractable Fe values are high compared with the Al_{ox} and Si_{ox} values, suggesting that ferrihydrite is as common as allophane, which may render the $(Al_{ox} - Al_{pyr})/Si_{ox}$ method less reliable to estimate allophane as ferrihydrite may contain adsorbed Si and structural Al (Parfitt and Childs, 1988). Multiplying Si_{ox} by a factor of 6, (factor adjusted for the $(Al/Si)_{ox}$ ratio as suggested by Parfitt, 1990) results in values that commonly range between 40 and 80 g kg^{-1} allophane in A and B horizons of the lag gravel, and 30 to 60 g kg^{-1} in the more recent tephra surfaces.

The $(Al/Si)_{ox}$ ratio is relatively low, commonly around one. The younger tephra materials (Pedons 6 and 7), have lower $(Al/Si)_{ox}$ ratios than the older till derived parent materials. Such low $(Al/Si)_{ox}$ ratios are less common in Andisols of the world than higher values (Parfitt and Kimble, 1989). Ping et al. (1988) reported higher ratios for Alaskan Andisols formed in similar parent materials and under similar climatic conditions. These low ratios may be indicative of Si sorbed to ferrihydrite (e.g., Dahlgren, 1994).

Pyrophosphate extractable Al (Al_{pyr}) values are low (0–1 g kg^{-1}) reflecting low organic matter content and limited complexing of Al by humus substances. The high pH (about 7 in deserts, 6 under vegetation) results in very low Al^{+3} solubility (Shoji et al., 1993), which reduces Al-humus complexing. This can also explain the low Al_{pyr} which are found in these soils. Arnalds et al. (1995) also observed low Al_{pyr} for organic-rich horizons in Icelandic soils under vegetation. Subtracting Al_{pyr} from Al_{ox} does not have an marked effect on the $(Al/Si)_{ox}$ ratio presented in Table 6.

Dithionite-citrate extractable Fe (Fe_d) values are generally about half of the Fe_{ox} values. The Fe_{ox}/Fe_d ratios are commonly less than one in Andisols (see Shoji et al., 1993), which has been explained by acid oxalate soluble magnetite (Rhoton et al., 1981; Shoji and Fujiwara, 1984). This high Fe_{ox} compared with Fe_d is characteristic for Icelandic soils (Wada et al., 1992; Arnalds et al., 1995).

The overall clay contents of the soils as reflected by dissolution techniques are relatively low, but still indicate substantial amounts of secondary minerals in the soils. Active weathering in the soils of Icelandic deserts was supported by geochemical studies of run-off water from desert areas in Iceland (Gislason et al., 1996). It is also possible that eolian deposition of partially weathered materials increases the clay content of the Bw horizons because of redistribution of allophanic soil materials by wind erosion. It is also likely that some of the finer materials found in soils of the till surfaces are remnants of the older soil surface that covered the areas before erosion truncated the surface. If this is the primary source of the clays in soils of the deserts, simple pedological determination of soil clays can demonstrate where desert till surfaces were covered with vegetation and allophane-rich Andisols in the past.

Glass contents range from about 50 to >80% (Table 6). Volcanic glass dominates the tephra deposits at Pedons 6 and 7, but remains high in the glacial till soils. Other studies show that primary minerals that dominate basaltic rocks are also common, such as plagioclase, olivine, and other Fe-bearing minerals (e.g., Arnalds, 1990).

Classification of Soils of the Icelandic Deserts

Icelandic soils influenced by volcanic ejecta have not been adequately placed in international classification systems. The andic nature of the freely drained soils under vegetation is well established (Gudmundsson, 1994; Arnalds et al., 1995), but little is known about the classification of soils of the Icelandic deserts. These desert soils differ from other Icelandic Andisols in that they are coarser, lower in organic matter, contain larger amounts of volcanic glass, have much less allophane, and they are usually much shallower. The limited plant growth makes these soils unsuitable for grazing and other land use which is sustained on other types of Icelandic soils.

Soil taxonomy currently does not provide adequate means to differentiate these desert soils from other Icelandic Andisols. The $(Al + 1/2Fe)_{ox}$ generally ranges between 10 and 20 g kg^{-1} in all the pedons except in the more developed Pedon 5, which has relatively high $(Al + 1/2Fe)_{ox}$ values (23–52 g kg^{-1}). The $(Al + 1/2Fe)_{ox}$ levels, high glass counts, and P-retention values of $>25\%$ (weighted average) indicate andic soil properties, which result in an Andisol classification for soils of the Icelandic deserts. All the soils investigated in the present study have a cryic soil temperature regime, resulting in all these soils being classified as Cryands at the suborder level. Because water retention at 1.5 MPa suction is $<15\%$ for all pedons, soils are classified as Vitricryands, and all soils key out in Typic subgroups.

The central concept of Andisols includes both vitric (relatively unweathered) and allophanic soils (Parfitt and Clayden, 1991). We feel that soil taxonomy does allow a good understanding of Icelandic soils in a global perspective, but may not meet all the special needs for day-to-day use in Iceland. Such needs require separation of the desert soils from the more weathered and vegetated allophanic Andisols, which have contrasting land use potentials. This level of detail is not possible at the subgroup or family level of soil taxonomy (Soil Survey Staff, 1998), since all the pedons, except Pedons 5 and 8, classify as ashy, shallow, amorphic Typic Vitricryands. To make useful taxonomic separations, some Icelanders would prefer to separate soils with contrasting characteristics in Iceland (i.e., vitric vs. allophanic) at the suborder or great group level. The reason is that land use associated with these soils is quite different and the desert areas are large (up to 35 000 km^2 excluding very shallow and rocky soils on lava surfaces and scree slopes). A possible solution is to differentiate between Vitricryands with low organic C content where vegetation is lacking, and Virticryands richer in organic materials under vegetation.

Other classification systems place soils of the Icelandic deserts in different taxonomic groupings. According to the FAO World Reference Base (Food and Agriculture Organization, 1998) the soils classify as Andosols with vitric properties. The possible classification is Arenic Andosol for the sandy Pedons 6 and 7, while Vitric Andosol seems appropriate for Pedons 1, 2, 3, 4, and 8. Soils under vegetation classify as other soil groups such as Haplic, Eutric, and Gleyic Andosols. Gudmundsson (1994) has translated and applied the FAO system (Food and Agriculture Organizaion–Unesco, 1988) to Icelandic soils. In his adoption, he selected to classify the glacial till soil such as Pedons 1, 2, 3, and 8, as Regosols, and the sandy tephra soils as Arenosols (Pedons 6, 7, and perhaps 8). Some of the till soils would also classify as Leptosols (shallow soils) according to his approach. Gudmundsson's version of the FAO system has the important benefit of separating Icelandic soil with contrasting characteristics at the highest taxonomic level. This is at the cost of recognizing the andic and vitric influence as a dominant feature of the soils, and can cause some problems in international communication, where the same criterion must be used as basis for the same soil names. For domestic use in Iceland, the New Zealand system (Hewitt, 1998) may provide some alternatives by separating Allophanic, Pumice, and Recent soils. However, a much greater variety of Icelandic soils, both desert and other soil types, must be sampled before suggesting a national classification system for Icelandic volcanic soils.

Soil taxonomy recognizes as much as 60 000 to 80 000 km^2 of Icelandic soils as Andisols. Because Andisols are believed to cover about 1.2 million km^2 of the Earth's surface (Kimble et al., 1999), Icelandic Andisols represent ~5 to 7% of the world's Andisols. In view of this, it seems legitimate to consider the characteristics of Icelandic Andisols to further refine their taxonomic placement in soil taxonomy.

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