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Sandy deserts of Iceland: an overview

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Iceland has over 20,000 km^2 of sandy deserts with active aeolian processes. The sandy areas have black surfaces due to their basaltic origin, and the sand is often dominated by volcanic glass. The sand originates largely from glacial margins, glacio-fluvial deposits and volcanic eruptions, but also sedimentary rocks. The sand has a wide range of textural properties according to the nature and distance from the sand source.

The sandy areas are spreading. Rich and vegetated ecosystems are replaced by sandy deserts with low fertility and water-holding capacity. Threshold values for Icelandic sand were determined with automatic sensors and dust traps. The threshold values are influenced by the surface roughness and the texture of the sand. Wet sand is observed to move during storm events, and coarse, light density tephra >1 mm is easily moved by the wind.

Keywords: Iceland; wind erosion; sand-fields; threshold; aeolian processes

Introduction

Iceland is an island in the North-Atlantic Ocean which has extensive sandy deserts. These deserts are seldom reported in surveys of large sandy areas of the world. The climatic environment and the composition of the sand make these deserts unusual, especially when the vastness of these areas is considered.

The sandy deserts are more than 20,000 km^2, extending from coastal sand-fields to remote deserts in the highlands, with a broad range of general surface characteristics. Their climate ranges from rather arid (<400 mm) to very humid (>2000 mm annual precipitation) regimes. The parent material of the sand is mainly basaltic volcanic glass together with porous tephra and basaltic crystalline materials. The black sandy surfaces characterize over 20% of Icelandic surfaces.

Iceland is a windy island and the sandy areas are subjected to intense aeolian processes that have devastated large areas that were formerly covered with productive ecosystems. The aeolian activity influences the nature of all Icelandic soils due to aeolian sedimentation.

The purpose of this paper is to describe the sandy deserts in Iceland, their formation, and aeolian behaviour. It is based on a recent survey on the extent, morphology and erosion severity of Icelandic sandy deserts in the scale of 1 : 100,000 and concurrent experiments to determine some of the aeolian characteristics of the sandy areas.

Physiography

Iceland is a 103,000-km^2 island in the North Atlantic Ocean, between 63° and 66° northern latitudes. The climate is humid cold temperate to low arctic. Permafrost is nearly absent. The island is mountainous with lowland areas and river plains along the coastline. Rainfall varies between 600 and 2000 mm year^{-1} in lowland areas, but is $<$400 mm year^{-1} in some of the interior highlands.

Glaciers now cover about 10,000 km^2 (or about 10%) of the country. The sediment load of the glacial rivers is high and large quantities of sediments are deposited on floodplains and at the glacial margins. Some of the interior glaciers cover active volcanic areas, which results in periodic floods of melt water from sub-glacial thermal areas which contribute large quantities of silt and sand to aeolian sources at the margins and along floodplains. Catastrophic floods associated with volcanic eruptions are also important contributors to the sand sources (Arnalds *et al.*, 1997). In addition to the sandy areas that are primarily of glacial and glacio-fluvial origin, there are widespread volcanic ash deposits associated with the active volcanic zone in Iceland. The volcanic ash and glacial sandy deposits are subjected to intense aeolian activity.

The Pleistocene glaciers receded about 10,000 years ago. The receding glaciers left behind lag gravel surfaces (till), which later became vegetated. Volcanic activity has produced large areas of lava surfaces since glaciation. However, much of these surfaces later became covered with a mantle of a different nature as the vegetation trapped aeolian materials. This mantle is commonly 20–200 cm thick, and in it, soils have developed (see Arnalds, 2000). Recent lava surfaces also occur without the aeolian mantle.

Soils that form in volcanic ejecta are classified as Andisols (U.S. Soil Taxonomy) or Andosols (FAO) according to international classification schemes. The parent materials of Icelandic Andosols have been referred to as aeolian-andic materials (Arnalds *et al.*, 1995). Soils that form in aeolian-andic materials under vegetative cover at freely drained sites are typical Andosols. Poorly drained soils may be classified as Andosols or Histosols, depending on the amount of aeolian influx at the site. These dominant soil types presently characterize about 50,000 km^2 in Iceland (Arnalds, 1999*a,b*).

Soils of barren desert landscapes are the third overall soil type, comprising a variety of soils, the sandy deserts being most extensive. Classified satellite images show that more than 37,000 km^2 of the country are barren deserts, with additional 10–15,000 km^2 of disturbed areas with limited plant production (LMI, 1993). These deserts have to a large extent formed after the arrival of man about 1125 years ago, due to wide-spread soil erosion and sand encroachment. The erosion has exposed the old lava or till surfaces again, by completely removing the aeolian-andic mantle. The soils are eventually blown and washed away from the area. The causes for this extensive ecosystems degradation are the combination of colder climate, use by man of a very fragile ecosystem, and the intensified aeolian activity associated with growing glaciers (see Arnalds, 2000).

Classification of the sandy deserts in Iceland

The survey of Icelandic sandy deserts was made as a part of an overall assessment of soil erosion in Iceland (Arnalds *et al.*, 1997). The survey was based on the classification of erosion forms that can be identified in the field, and estimation of erosion severity (Arnalds *et al.*, 1997). Six erosion forms were used to designate erosion associated with vegetated areas, and seven to describe barren deserts. Sandy areas were divided into three overall morphological classes: sand-fields, sandy lava and sandy lag gravel. Advancing sand fronts (encroaching sand) is also a special erosion form, according to the Icelandic erosion classification system.

Figure 1. Sand-field in the central highlands. The mountain is vegetated above an 'abrasion line'. A glacier is on the left.

Each of the erosion forms in the Icelandic erosion classification system has an erosion severity scale from 1–5, 1 being the lowest level of erosion and 5 symbolizing very severe erosion. The erosion severity scale represents estimates of the stability of the surface. The three highest severity classes are associated with barren sandy deserts: 3 (considerable erosion), 4 (severe erosion) and 5 (very severe erosion). Following is a brief description of each sandy landform.

Sand-fields represent areas with bare sand on the surface and no protective vegetation or gravel layer to reduce sand drift (Fig. 1). These areas are normally assigned erosion severity class 5. However, if some vegetation or gravel is found on the surface, lower classes are assigned. These fields are similar to many other sand-fields of the world, except for the basaltic nature, the black colour of the sand, and the scarcity of dunes.

Sandy lavas occur where sand has drifted over Holocene lava fields, where large amount of tephra is deposited on lava surfaces in volcanic eruptions, or where floods leave sediments in lavas. The result is a special geomorphic unit, the sandy lava (Fig. 2). The underlying lavas are quite variable before the sand is deposited onto them. The rougher lava fields can accumulate large amounts of sand in depression areas, while lava sticks out in-between. The rough surface reduces wind speeds and these lavas can act as a major obstacle in the path of sand encroachment, until the depressions are filled up with sand. Relatively flat lava-fields fill up more quickly with sand and take on the characteristics of the sand-fields. Sandy lavas, which are still accumulating blowing sand were given erosion severity class 4, whereas they were designated as 5 as soon as the depressions were full of sand. The average sand thickness (depth to lava surface) is often 10–50 cm thick, depending on lava roughness.

Figure 2. An example of sandy lava surface in central north-east Iceland.

Sandy lag gravel occurs where sand drifts over lag gravel surfaces ('melur') and accumulates at the surface (Fig. 3). The lag gravel is most often the old surface left by the Pleistocene glacier. A large part of the present sandy lag gravel was previously covered with 50–200 cm thick Andosols that had developed in a aeolian-andic mantle. Erosion has since removed this mantle from the surface, mostly during the last 1200 years (Arnalds *et al.*, 1997; Arnalds, 2000). When sand drifts over the gravely surfaces, it accumulates on the leeward side of rocks. Intense frost-heave lifts up the gravel during winter, which causes the sand to become buried under the gravel layer (Fig. 4). The surface is therefore gradually rising as more sand drifts over these surfaces. The sand layer under the surface can range from a few cm to >50 cm thick. The evolution of sandy lag gravel surfaces follows a similar path to that described by McFadden *et al.* (1987) and Wells *et al.* (1995) for the Californian Mojave Desert, where aeolian dust has raised an older desert pavement. Some of the sand can become detached again during extreme storm-events (wind and rain-splash erosion). These surfaces were designated erosion severity class 4 unless there were signs that the surface was becoming stable, such as lichen crusts and other vegetation.

The extent of sandy surfaces

The extent of the Icelandic sandy surfaces is presented in Table 1 and Fig. 5. Their total extent is nearly 22,000 km^2, or about 21% of the total area of Iceland. The extent of the Icelandic deserts is only partly dependent on the total amount of precipitation, but shows better correlation with the active volcanic belt rift zone cutting from south and south-west to north-east Iceland. On this zone, the major glaciers and the ash-producing volcanoes are found.

The sandy lag gravel surfaces are most extensive (about 13,000 km^2), comprising a large part of the Icelandic highlands. These fields have formed by sand drifting over till surfaces, sometimes from distant sources. The same applies to sandy lava-fields, but the effect of volcanic ash deposition, flooding and sand drift from distant sources is often difficult to sort out in these areas.

Figure 3. Sandy lag gravel surface. Frost-heaving lifts up stones. Aeolian additions are accumulated under this gravely surface. The surface is dark due to the basaltic nature of the sandy materials. Vegetation is very sparse, with both low fertility and low water-holding capacity. A glacier (Myrdalsjokull) seen in the background.

Many of the sand-fields are floodplains at glacial margins exemplified by Skeidararsandur (900 km^2), which was last flooded by catastrophic flood after the 1996 eruption under Vatnajokull Glacier. The sand-fields include unstable volcanic ash fields in interior Iceland. Sand-fields also occur where topography reduces wind speed, causing sand accumulation.

The largest continuous sandy lava-fields are in the Odadahraun lavas north of Vatnajokull Glacier (about 6000 km^2, including sandy lag gravel areas). They are also common in other areas of the country, for example near Mt. Hekla, south and west of Langjokull and in South Iceland.

The origin of the sand

All Icelandic sand materials are of volcanic origin, either deposited as volcanic ash or reworked by physical weathering of volcanic rocks by glaciers and other physical factors. The sand also causes further breakdown of volcanic rocks during aeolian (and fluvial) processes. The sand is mostly basaltic volcanic glass (e.g. Arnalds, 1990; Sigurdardottir, 1992; Jonsson, 1995), creating very dark surfaces.

Volcaniclastic parent materials are reported in many other areas of the world (Edgett & Lancaster, 1993), but are not nearly as extensive as quartz-rich, carbonatic, or clay/silt aggregate materials. Edgett and Lancaster conclude that dark hued, basaltic sand-fields could provide an analogue for aeolian processes on Mars.

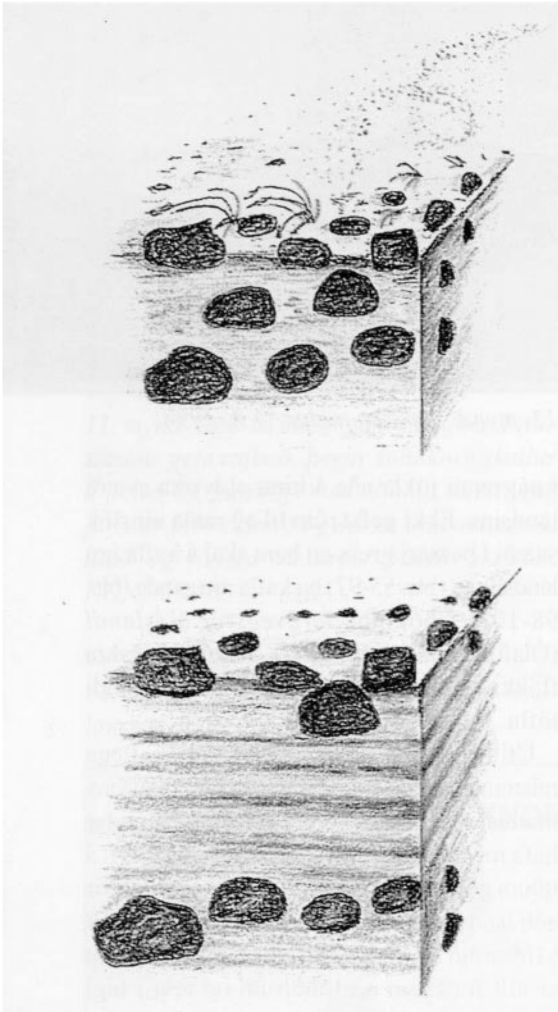

Figure 4. Sand accumulation in sandy lag gravel areas. A sandy layer is formed under a gravely surface above the original till surface. Some of this sand can be moved again during high intensity storm events.

Table 1. *Extent of sandy geomorphic surfaces in Iceland*

Surface type	Erosion severity			
	3	4	5	Total
Sand-fields	318	1087	2828	4233
Sandy lag gravel	5407	6217	1286	12910
Sandy lavas	1366	1757	1620	4743
Total				21886

All data are in km^2.

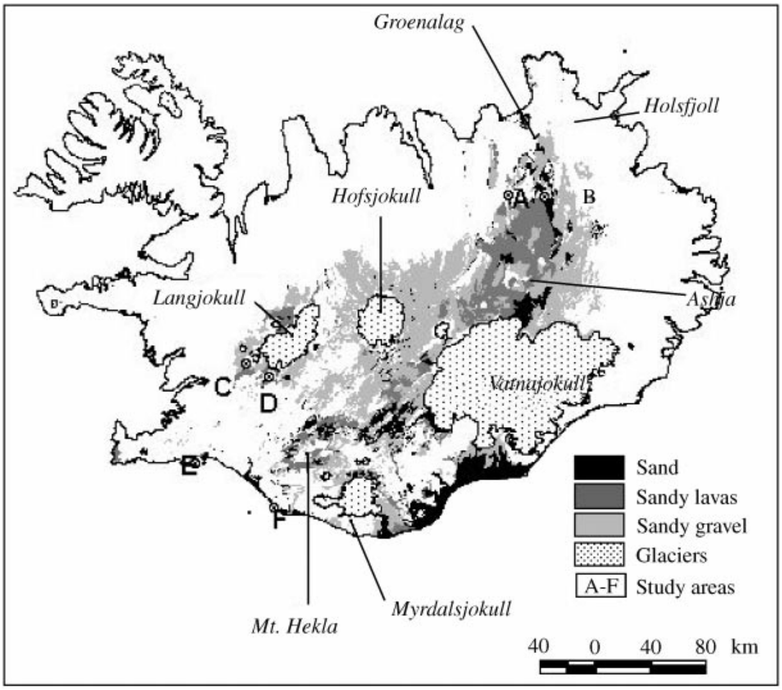

Figure 5. Sandy deserts of Iceland. Sampling sites referred to in tables are marked on the map (AF).

In their survey, Edgett and Lancaster mention the basaltic volcaniclastic parent materials of Icelandic sand-fields, but do not have specific literature to cite. Basaltic volcanic materials have also been reported in several other active volcanic areas such as Hawaii and other states of the USA, and in New Zealand (Edgett & Lancaster, 1993). The world's largest volcaniclastic sand-fields occur in Iceland, judging from Edgett & Lancaster's (1993) paper and the survey presented for Iceland in this paper.

The world's large sandseas normally owe their existence to the combination of dry climate and large supply of sandy parent materials (Pye & Tsoar, 1990). However, the climate in Iceland is not dry and the sand has two principal sources: glaciers and volcanic eruptions.

Physical weathering by glaciers produces a vast amount of silt and sand that is transported from underneath the glacial margins by glacial rivers. A substantial portion of terminal moraines is also made of silt and sand. The fate of the sand, after it appears from underneath the Icelandic glaciers, is quite varied:

Some glacial rivers disappear a short distance from the glacial margin because of a very porous surface such as thick sandy deposits and lava fields. The water re-appears later as spring water at lower elevations. The sediment load is deposited where the water enters the ground, creating an unstable sand-field and a source for aeolian transport. Examples of these conditions are found south and north of Langjokull Glacier, and at the north-western margin of Vatnajokull.

Lagoons often form near the glacial margins. They are to subjected to frequent changes in conditions at the glacial margin, which may be receding or advancing. When the lagoons dry out, their sandy deposits are very unstable and become a major source for aeolian materials that can spread the sand over large areas. Examples are old lake bottoms at the southern edge of Langjokull (Gisladottir, 2000).

Receding glaciers leave behind loose sediments with a wide range of particle size, including silt and sand. Aeolian processes are active for a period after the materials appear from underneath the glacier, but diminish as the gravel gradually covers more of the surface with frost heave and selective sorting by the wind. Icelandic glaciers have been receding since about 1920.

Flooding in glacial rivers is perhaps the single most influential factor in providing sand sources for the formation of sandy deserts. When floods recede, large quantities of sediments are left behind which become sources for expanding sandy areas. Good examples are the periodic floods in the Skafta River, originating from thermal areas underneath Vatnajokull Glacier. Volcanic eruptions that occur under the large glacial ice shields can cause floods as the volcanic materials melt the glacier. The floods leave behind vast quantities of sandy materials, consisting largely of volcanic glass, as exemplified by the Skafta floods (Palsson & Zophoniasson, 1992). Such flood events created some of the sand-field areas such as Skeidararsandur, south of Vatnjökull Glacier, Myrdalssandur and Skogarsandur, south of Myrdalsjokull Glacier, sandy areas along the Jokulsa a Fjollum River, north of Vatnajokull Glacier, and possibly others such as Maelifellssandur, north of Myrdalsjokull Glacier. Such floods are likely to have played an active role in the formation of the large sand-fields and sandy lava-fields in the Odadahraun area north of Vatnajokull (Arnalds *et al.*, 1997).

Pleistocene glacial ice accumulated sandy deposits that can become unstable if vegetation degradation causes such deposits to be exposed. An example of such an area is Holasandur, north of Lake Myvatn in north Iceland. Sandy sediments in hills and mountains, formed in sub-glacial eruptions, can also be an important source of sand (Gisladottir, 2000).

The second main source for sandy deposits is volcanic ash (tephra). The largest eruptions can produce several km^3 of volcanic tephra, such as the major eruptions of Mt. Hekla (Larsen & Thorarinsson, 1977). Ash deposits are widespread in central South Iceland and on the main volcanic fissure swarm north-east towards Vatnajokull Glacier. The area around the Askja Caldera in north-east Iceland is also characterized by tephra deposits. These deposits can be blown long distances, and mix with the sand of glacial origin along the way.

Sandy sedimentary rock in mountain strata can accumulate under the base of the mountains as a result of hill-slope erosion processes. The sand can subsequently start to spread, but this origin of sand is more local compared with the extent of the first two major sources of sand.

Encroaching sand (advancing sand fronts)

Advancing sand fronts are an entity of the Icelandic erosion classification system. By definition, advancing fronts are active tongue-shaped sandy surfaces extending into vegetated areas. These fronts start as sedimentary features (encroaching sand) that abrade and bury the vegetation with sand and destroy it. Sand fronts continue to move as a continuous flux of sand abrades the Andosol mantle that was there in place, and finally the new surface may be 1–2 m lower than the original surface. The result is that are infertile sandy system replaces the fertile soils and vegetated system.

Advancing sand fronts are a major problem in Iceland, and the Icelandic Soil Conservation Service makes every effort to halt the encroachment where it occurs. An advancing front can move over 300 m in a year, even in single storms (Arnalds, 1990). Encroaching sand has invaded and desertified large areas in South Iceland during the last part of the 19th century (Arnason, 1958), and formed distinctive sand tongues up to 6 km wide and >10 km long. Such fronts are also active in north-east Iceland (Fig. 6). The Icelandic Soil Conservation Service was established in 1907, in part to battle encroaching sand.

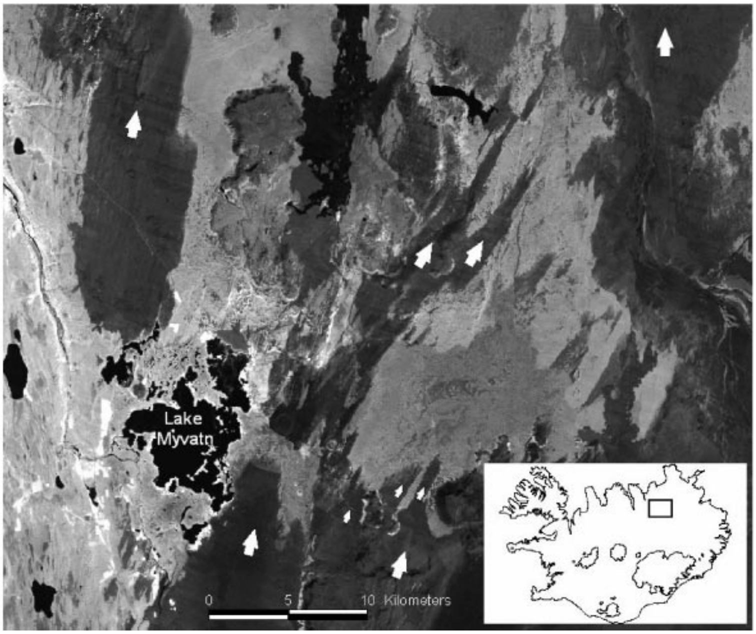

Figure 6. A Landsat satellite image showing advancing sand fronts in north-east Iceland. The black sand (dark on image) moves in north-east direction (arrows) as a result of dry south-westerly winds. Vegetation has a lighter colour, with white showing recently cut hay fields. A recent lava-flow appears dark at the top.

Texture and morphological features

The texture of the aeolian surfaces varies with the origin of the sand source and distance from it. As measured by sand traps in the ground, BSNE traps and surface samples, the mean diameter can reach 1 mm in the tephra deposits, but commonly ranges between 0·2 and 0·5 mm in active aeolian areas (Table 2). Sigurdardottir (1992) analysed a number of surface samples from aeolian areas in north-east Iceland and found the mean to be commonly around 0·2 mm.

No comprehensive survey has been made of the morphological features of sandy areas in Iceland, although they are often mentioned (e.g. Sigurdardottir, 1992; Gisladottir, 2000). Such information would provide a valuable comparison to the more conventional desert areas of the world, due to their different parent material and environmental setting. Small aeolian features, such as ripples, characterize the overall morphology. The grass *Leymus arenarius* is common in sandy areas and tends to accumulate sand in small dunes, 1–4 m high. Such dunes are common throughout the country. Large dunes, >5 m high, are rare, but are found at a few locations, such as near Kvensodull in north Iceland (poorly developed Brachanoid ridge).

Fluvial processes are also important in the sandy deserts. Sand is transported in snow-melt floods to lower positions which create new source areas for aeolian transport, as witnessed in north-east Iceland (Arnalds, 1990). In addition to fluvial and aeolian processes, cryogenic processes are also important, first for the accumulation of sand in gravel areas as described before, but also because needle ice formation is common and intense. Ice needles force newly-established seedlings to the surface, and therefore play an important role in keeping the deserts barren.

Table 2. *Some textural properties of different sand areas and drifting sand (dry sieving)*

Location		Surface type	Sample type	Mean (mm)	Sorting	Skewness	Kurtosis
A	Myvatn N Interior	Sand-field	Surface trap⋆	0·26	0·71	0·01	1·07
A	—	Sand-field	Surface trap⋆	0·26	0·68	0·01	1·07
A	—	Sand-field	BSNE 7 cm†	0·19	0·47	0·00	1·10
A	—	Sand/Sandy gr.	Surface trap⋆	0·16	0·56	0·00	1·10
A	—	Sand-field	BSNE 7 cm†	0·15	0·58	0·00	1·10
A	—	Sand-field	Surface trap⋆	0·25	0·59	0·01	1·07
A	—	Sand-field	Surface trap⋆	0·24	0·56	0·01	1·08
A	—	Sand-field	BSNE 10 cm†	0·18	0·57	0·00	1·09
B	Blafell, N Interior	Sand/Sandy gr.	Surface trap⋆	0·21	1·36	− 0·06	1·23
C	Thorisjokull, S Interior	Advanc. front	Surface sample	0·38	1·40	− 0·04	0·78
C	—	Sandy lava	Surface trap⋆	0·35	1·39	0·02	1·04
C	—	Sandy lava	Surface trap⋆	0·73	1·36	0·11	0·88
D	Hagavatn, S Interior	Sand-field‡	Surface trap⋆	0·08	0·84	0·82	1·10
D	—	Sand-field	Surface trap⋆	0·98	3·41	− 0·21	0·93
E	Thorlakshofn, SW Coast	Sand-field	Surface trap⋆	0·36	0·45	0·00	1·09
F	Landeyjarsandur, S Coast	Sand-field	Surface trap⋆	0·41	0·34	0·00	1·10
F	—	Sand-field	BSNE 10 cm†	0·30	0·37	− 0·07	1·17

⋆ Trap dug in the ground (see Sigurjonsson *et al*., 1999; Gisladottir, 2000). Represents mostly saltating materials.
† Height of trap above ground.
‡ Fresh fine glaciofluvial deposits (dried out lake bottom).

Table 3. *Some aeolian parameters of sandy areas in Iceland*

Location		Surface	Zo (mm)	Ut (2m)★ ($m\ s^{-1}$)	U★t ($m\ s^{-1}$)
A	Myvatn	Sand-field	0·7†	4·8	0·24
A	Myvatn	Sand-field	0·7†	7·4	0·37
B	Myvatn	Sandy gravel	0·9	10·2	0·53
C	Thorisjokull	Sandy gravel	2·8	10·6	0·64
C	Thorisjokull	Sandy gravel	1·5	10·4	0·58
E	Thorlakshofn	Sand-field	0·7†	6·0	0·30
F	Landeyjasandur	Sand-field	0·7	8·3	0·42

★ Wind measured at 2 m height.
† Estimated from other measurements of similar surfaces.

Aeolian processes

Some of the aeolian characteristics have been measured in a wind tunnel (Arnalds, 1990) and, more recently, in the field. Field measurements were done with the aid of electronic equipment (Sensit; see Gillette & Stockton, 1986; Stockton & Gillette, 1990; Stout & Zobeck, 1991; and Stout, 1998 for further description). Wind-blown materials were sampled with BSNE dust traps (Fryrear, 1986; Fryrear *et al.*, 1991), with simultaneous measurements of wind speed, wind direction, air and soil temperature, and relative humidity. The purpose of the measurements was to determine threshold velocities for sandy surfaces in Iceland and to begin to investigate the flux associated with aeolian processes. The methods and some of the results were described by Sigurjonsson *et al.* (1999) and Gisladottir (2000).

The results are summarized in Table 3. Surface roughness, as reflected by Zo, indicates relatively level areas. The windspeed when wind erosion began was measured at 2 m height above the ground (a standard height used by Icelandic meteorological stations), but is also indicated as threshold velocity (U★t) in Table 3. Wind speeds (at 2 m height) when wind erosion begins commonly ranges between 5 and 10 $m\ s^{-1}$ with threshold velocities (U★t) between 0·24 and 0·68 $m\ s^{-1}$. Both higher and lower numbers have been recorded in the field. These numbers are in the same range as those recorded in the wind tunnel by Arnalds (1990). The wind tunnel studies showed also that coarse, porous tephra deposits are easily moved by wind. A sample of the tephra soils with 80% of grains larger than 1 mm was moved by relatively low wind speed (U★t of 0·4 $m\ s^{-1}$).

The numbers in Table 3 indicate quite variable weather conditions that initiate wind erosion, depending on surface characteristics such as roughness and texture. The moisture conditions of the air when the values presented in Table 3 were obtained are varied, but data presented by Gisladottir (2000) show that relatively wet sand can be moved during storm events in Iceland. Studies in wind tunnels, such as by Hotta *et al.* (1984) and McKenna-Neuman & Nickling (1989), show that sand becomes resistant to wind erosion when it becomes moist. However, rain-splash and aeolian transport during the wet storms are difficult to separate under field conditions with the automated methods we have applied.

Attempts have been made to measure the flux of sand on various sandy surfaces, using both the BSNE dust traps and the SENSIT sensors. Preliminary results show sand-flux over 200 $kg\ m^{-1}\ h^{-1}$ in moderate storms on sand-fields, but the relationship between wind-speed and flow is still being studied.

Implications

The spread of sandy deserts in Iceland is a continuous environmental threat. The ecosystems which are lost are fully vegetated and rich ecosystems which have high biological value and are important for water cycling. The sandy deserts lack water-holding capacity and the black surfaces become warm and dry on sunny days. Water shortage therefore impedes plant growth, which gives Icelandic deserts similar properties to the arid deserts of the world, in spite of the more moist climate in Iceland. Aeolian, fluvial and cryogenic processes are all active on these surfaces. It has always been a priority to halt the spread of the sandy deserts.

Modelling of aeolian processes of the Icelandic deserts can be used as an important tool to prioritize soil conservation efforts, where advancing fronts could become a threat, to predict what effect climatic changes may have on the deserts, and to reconstruct the development of sandy areas in Iceland. During the next phase of the research reported herein, steps will be taken to make such models.

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