

Geomorphology of the Ódáðahraun semi-desert, NE Iceland; a Landsat TM - based land cover mapping

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Abstract – *This research reports investigations on land degradation processes in the Ódáðahraun region, northeastern Iceland, using land cover classification based on Landsat TM satellite data and field studies. The main objective is to increase understanding of the geomorphological features and processes, and their relation to land degradation in the study region. A floating Landsat TM quarter scene from July 1992, covering an area from the northern margin of Dyngjújökull to Öxarfjörður, was subjected to unsupervised Isodata clustering. Extensive field checks with detailed descriptions of various land-cover types allowed subsequent analyses of the classification resulting in 19 land cover classes in three surface categories: lavas, sediments and miscellaneous (including vegetation, snow, ice, etc.). The image interpretation also revealed several sediment bodies, which may indicate the characteristics of the geomorphological processes operating in the region: 1) the elongated SSW–NNE oriented aeolian sand stretches in the western half of the study area, and 2) the distinctive flood deposits along the Jökulsá á Fjöllum course, demonstrating the magnitude of the past catastrophic jökulhlaups (glacial outburst floods). The presented land cover classification will serve as the basis for planning and focusing future investigations on the past and present geoecological processes operating in the region.*

INTRODUCTION

Soil erosion is a major environmental problem in Iceland (e.g. Arnalds, 1987; Arnalds *et al.*, 1997; Arnalds, 2000). Studies across Iceland have demonstrated that soil erosion rates increased substantially after settlement ca. 874 AD, in the form of a 4- to 8-fold increase in the deposition rate of aeolian and tephra materials in soil profiles (e.g. Þórarinnsson, 1961). More generally, Iceland has suffered for centuries from loss of forest cover, resulting in only 1% woodland coverage at present.

Along the Northern Volcanic Rift Zone, north of the Vatnajökull ice cap, vast deposits of gravel, aeolian sand and loess blanket an otherwise barren, severely eroded landscape characterized by abundant lava fields (Figure 1). At the margin of this degraded

region, advancing fronts of windblown sediments destroy vegetated land cover, threatening pasturelands and human settlements. Substantial national efforts have been made for decades to halt the degradation process.

Unfortunately, the environmental factors that maintain and expand this barren semi-desert are still poorly understood (Arnalds, 2000). Human activity, in the form of deforestation and grazing by sheep and horses, is one explanation for this continuing degradation, and a link between land degradation and human impact has been indisputably documented in several studies in the coastal areas of Iceland (cf. Dugmore and Buckland, 1991; Einarsson, 1994; Simpson *et al.*, 2001). An additional explanation for this degradation is the influence of natural processes, namely, volcanic eruptions, tephra falls, glacial outburst floods and cli-

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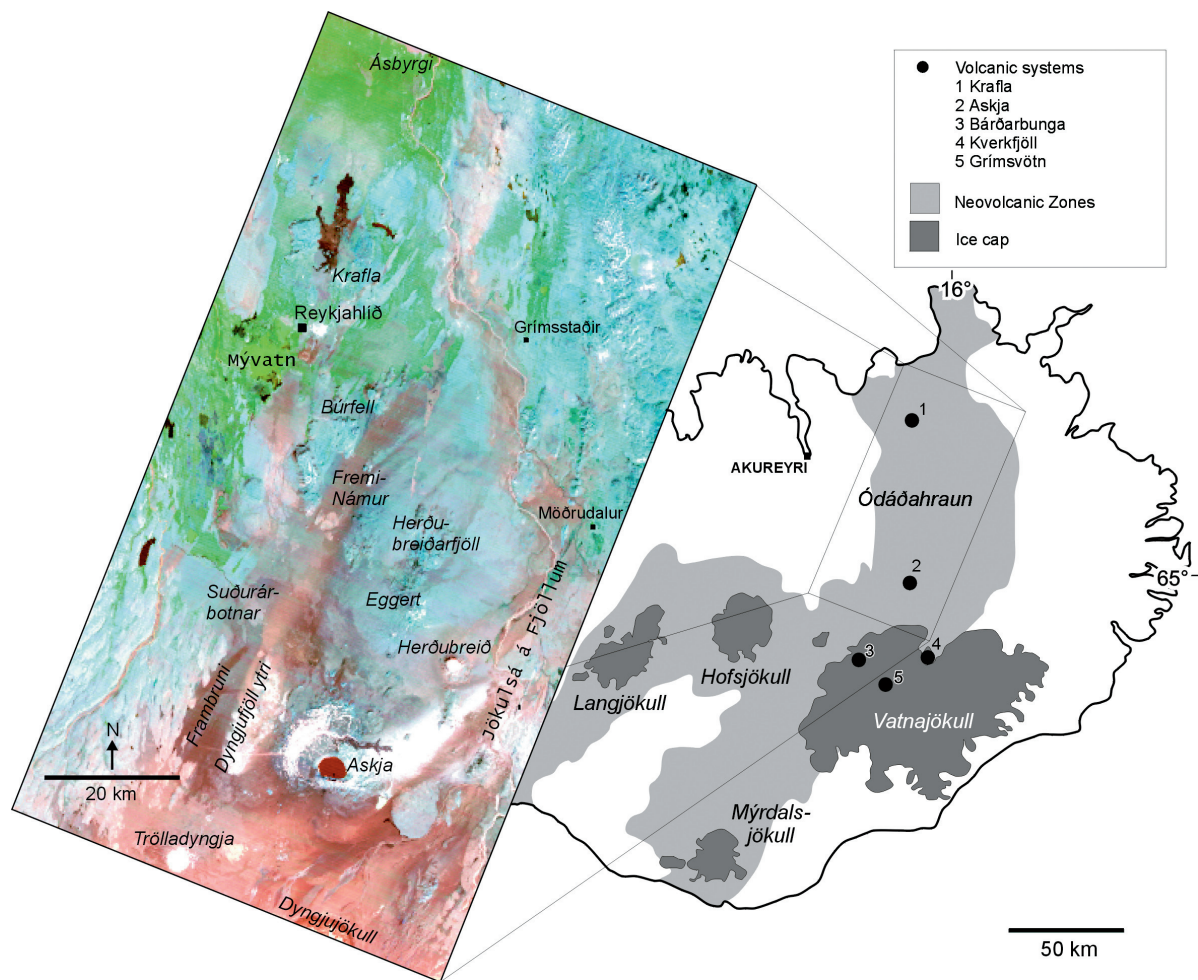


Figure 1. Index map and a Landsat TM colour composite (RGB 321 = normal colour) scene of the Ódáðahraun region. The image was acquired on July 14th, 1992. Green colours indicate vegetated surfaces, which dominate the northwestern corner, and Lake Mývatn. Various tints of grey denote barren postglacial lavas (in the middle) and till covered Tertiary surfaces (in the east and west). Brown colours in the south represent barren sediment surfaces. Fresh lava flows such as Krafla 1975–1984 and Askja 1961 are black, whereas the Askja tephra fan from 1875 is bright and not easily discernible from the snow cover on the western rim of Askja caldera. The volcanic systems adjacent to the study region are also shown. Copyright: Landmælingar Íslands. – *Landsat TM gervitunglamynd af Ódáðahrauni. Myndin var tekin 14. júlí, 1992. Litir eru nokkuð raunverulegir. Gróðurlendi er í grænum litum. Hraun frá síðjökultíma eru mismunandi gráleit en hraun frá Kröflueldum og Öskjugosinu 1961 dökkgrábrún. Laus yfirborðsset af ýmsu tagi eru brúnleit. Birt með leyfi Landmælinga Íslands.*

mate change. Determining whether present-day erosion is a natural or human-induced process has clear implications for decision-making and soil protection measures.

Systematic research in the study region, however, is severely hindered by a lack of detailed land cover maps depicting the distribution of various geomorphological features and sedimentary deposits. The national mapping of the land degradation (Arnalds *et al.*, 1997), and the Geological Map of Iceland 1:500 000 (Jóhannesson and Sæmundsson, 1998) have been the principal sources of information for the region as a whole.

THE OBJECTIVE

As the Ódáðahraun area is remote and difficult to access, very few systematic studies have been conducted in this region. Too little is therefore known about the history of these landscapes and their erosion processes to allow conclusive statements about the relative importance of anthropogenic or endogenous forces in this area. Based on pilot studies in the region (Käyhkö and Worsley, 1997; Käyhkö, 2000), and recently published literature (e.g. Arnalds *et al.*, 1997) we argue that more comprehensive studies on the distribution of sediments and the adjacent geomorphological processes in the Ódáðahraun region are needed in order to unravel the past and present land degradation processes.

In this paper we report a study of the geomorphology of the Ódáðahraun area using a Landsat Thematic Mapper (TM) land cover classification and detailed field studies. Our primary objective was to increase our understanding of the region's geomorphological features and processes, and their relation to land degradation.

CHARACTERISTICS OF THE STUDY AREA

The Ódáðahraun area consists of barren lava flow fields and loose surface sediments with scanty patches of vegetation, and is bordered to the south by Dyngjujökull, an outlet glacier of the Vatnajökull ice cap. The glacially fed river Jökulsá á Fjöllum runs from the

ice cap along the eastern margin of the area towards the north, where it drains into the Atlantic Ocean at Öxarfjörður. Five volcanic systems are located in or near to the study area (cf. Figure 1). Lake Mývatn, situated in the north-west of the study area, marks the western border of the Ódáðahraun lava formation. At present, the advancing northern margin of the Ódáðahraun semi-desert is located near the road no. 1 between Reykjahlíð and Grímsstaðir.

Climate

The area north of Vatnajökull has been characterised by Hallgrímsson (1969) as the most continental of the climate regions in Iceland, with relatively low precipitation, a large annual temperature range, and short spring and autumn seasons. Limited long-term climatic statistics are available for the interior of Iceland and the current study area. The mean annual precipitation for 1931–1960 at Grímsstaðir was a mere 355 mm (cf. Ashwell, 1986); and for 1961–1990 at Reykjahlíð, 435 mm yr⁻¹ (Einarsson, 1994). The mean annual temperature in the Ódáðahraun area was 0°C for 1931–1960, and 0.7°C for 1961–1990.

Southwesterly winds prevail in Iceland. Ashwell (1986) has demonstrated that the Vatnajökull ice cap has a profound regional influence on wind direction, generating a high-pressure field and thus katabatic winds. Ashwell (1986) has also observed that the wind direction varies from southwest to west near the ice cap margin, and from south to southeast further north. Observations made during this study of ventifact orientation generally demonstrate the same pattern of dominantly southwesterly winds. A local, southeastern anomaly in ventifact orientation, however, was observed on the summit plateau of Dyngjujöll ytri.

Tectonic processes

The study area is located at an extensional plate boundary. During rifting events, such as the rifting episode in 1975–1984 at Krafla, widening at these boundaries results in fractures and faults that often occur in swarms and intensively alter the landscape. Our study area covers four *en echelon* tectonic swarms belonging to the volcanic systems of Kverkfjöll, Askja, Fremrinámar and Krafla (Björnsson, 1985). The

northwestern part of our study area coincides with the fifth major fissure swarm in northern Iceland, Þeistareykir.

Fissure fracturing may involve vertical movement, whereby tectonic depression valleys or grabens are developed. One of the largest grabens in our study area, Sveinagjá, is 4–17 m deep and up to 2.5 km wide (Guðmundsson and Bäckström, 1991). During the eruption of Askja in 1875, the northern part of Sveinagjá subsided some 3–6 m. Grabens may act as important natural channels for lava flows, meltwaters and even aeolian sand transport.

Lava-flow processes and morphology

During the early postglacial period, large volumes of lava erupted in the Northern Rift Zone, and magma output was at least an order of magnitude greater than at present times (Guðmundsson, 1986; Sigvaldason *et al.*, 1992). As a consequence, the most spatially extensive geomorphological features in Ódáðahraun are lava fields. A lava field forms during an effusive eruption or a series of eruptions, and commonly consists of many adjacent and overlapping lava flows. At Ódáðahraun, lava eruptions may take place at (1) fissure eruption sites (mainly aa lava flows); (2) centrally located vents resulting to the formation of shield volcanoes (mainly pahoehoe lava flows) or, (3) major central volcanoes of Krafla and Askja (both pahoehoe and aa) (Rossi, 1997a). Lava flows normally occupy topographic depressions but may construct conspicuous positive relief features such as shield volcanoes. They also alter drainage systems and sand transport routes.

The most common type of eruption in the study area is a fissure eruption that is generally short in duration (days to weeks; cf. Rossi, 1997b). In the opening phase of the fissure eruption, the supply rate from the fissure is generally high and a sheet of lava (sheet-flood pahoehoe) usually forms (e.g. the central part of the Krafla lava field). After a few days of eruption, magma outflow concentrates into a single crater vent and an open-channel lava flow (mainly aa) develops (see Rossi, 1997b; Wylie *et al.*, 1999). The roughness of aa surfaces vary from clinkery (stone-sized surface rubble; e.g. many flows at Krafla) to blocky (e.g. Búrfellshraun) (Kilburn and Lopes, 1991; Rossi, 1997b;

Lammi *et al.*, 2000).

Lava flows from shield volcanoes (e.g. Trölladyngja and Kollóttadyngja) normally exhibit pahoehoe morphology. The most widespread lava flows in our study area are dense and hummocky pahoehoe flows that were fed by lava tubes (Swanson, 1973; Walker, 1991; Wilmoth and Walker, 1993; Rossi and Guðmundsson, 1996). Shield volcanoes are essentially monogenetic structures, and lava fields at shield volcanoes presumably form during a continuous string of eruptions lasting from several weeks to several decades (Rossi, 1996).

Other volcanic structures

In addition to lava flows, the northern rift zone contains numerous other volcanic features. Mild explosions at fissure eruption sites have created structures such as spatter cones, spatter ramparts, scoria cones and hornitos. Eruptions with higher explosivity have formed tuff rings and led to caldera collapses at Krafla and Askja.

The most significant volcanic features from the glacial periods are hyaloclastite ridges (e.g. Dyngjufjöll ytri) and table mountains (e.g. Herðubreið). These were formed in subglacial eruptions and consist of sequences of pillow lavas, hyaloclastites and subaqueous and subaerial sheets of lava (Werner and Schmincke, 1999). Postglacial erosional processes have modified these mountains, and released material for fluvial and aeolian transport on the lava fields.

Glacial floods (jökulhlaups)

The average eruption frequency under Vatnajökull during the past century has been approximately one per decade (Larsen *et al.*, 1998). Vigorous volcanic activity beneath the ice cap has produced widespread and recurrent tephra layers as well as catastrophic outburst floods, or jökulhlaups (Björnsson, 1992). Two major volcanic systems, Bárðarbunga and Grímsvötn, lie beneath the glacier. They have developed large subglacial calderas. Kverkfjöll volcano, also regarded as a potential trigger for jökulhlaups, lies at the northern margin of the ice cap, between the outlet glaciers Dyngjufjökull and Brúarjökull. The Grímsvötn system is currently the most active of the three. Geothermal activity gradually melts the overlying glacier

leading to meltwater accumulation within the Grímsvötn caldera lake, causing regular glacial bursts onto Skeiðarársandur in the south. Catastrophic floods in the north, however, are distinctively less frequent than towards Skeiðarársandur in the south (Tómasson, 1973; Björnsson and Einarsson, 1991).

Geomorphological evidence of past floods can be seen throughout the surroundings of Vatnajökull, primarily along Jökulsá á Fjöllum and the Ásbyrgi canyon. Elfsson (1977) reports three prehistoric flood events in the Jökulsá river canyon: 4600 BP, 3000 BP and 2000 BP. Written records kept by local farmers in the area indicate that at least eight jökulhlaups have taken place between 1477 and 1934 (Björnsson and Einarsson, 1991). The most recent major jökulhlaup in the north occurred in 1729 (Ísaksson, 1985). The gauging records of Jökulsá á Fjöllum operated by the National Energy Authority indicate 16 minor jökulhlaup events in the period 1976–2002 (National Energy Authority 2001).

The latest eruption under Vatnajökull in December 1998 was not associated with flooding. The eruption took place inside the Grímsvötn caldera and did not melt enough ice to produce a jökulhlaup. An earlier fissure eruption in November 1996 in Gjálp, north of Grímsvötn, produced large amounts of meltwater and resulted in a jökulhlaup towards the south. Guðmundsson *et al.* (1997) pointed out that an eruption slightly further north would have resulted in a jökulhlaup on the northern margin of the Vatnajökull. Traces of meltwater from two small cauldrons at the southeastern caldera rim of Bárðarbunga, were also detected in Jökulsá á Fjöllum (Kristmannsdóttir *et al.*, 1999). It is widely acknowledged that the area is entering a period of renewed volcanic activity (Larsen *et al.*, 1998), and this potential threat calls for better understanding of geocological conditions in the north.

Aeolian processes

Our study region is almost entirely devoid of vegetation or well-developed soil cover, though eroding steep-edged remnants of loess-type soil, rofabörð, can be found in sheltered spots. Arnalds (1992b) has monitored rofabörð erosion in the field, and a nationwide project by the Agricultural Research Institute (RALA)

has classified erosion into five categories based on the severity of the process (Arnalds *et al.*, 1997).

Aeolian sand is abundant throughout the study area, filling cracks and depressions on the lava fields, and blanketing the sandur between Askja and Dyngjujökull. This sand only rarely forms distinctive dune formations, probably due to the highly irregular and rough terrain, and to inadequate sediment input relative to the weak trapping efficiency of the scant vegetation. Thick sand beds do occasionally form in places favourable for sediment deposition, however, and these may evolve into proper dunes, often covered with sparse lyme grass (*Elymus arenarius*) and fescue species (*Festuca* sp.). At the northern margin of the current study region, advancing fronts of thick wind-blown sediment bury vegetation, threatening the surrounding pasturelands and human communities. The extensive dune fields near the Nýjahraun lava flow are partly vegetated, and the southern stoss faces of dunes are often grass covered and gently sloping, while the northern slip faces are typically steep, barren, and wind scoured (Figure 2).

MATERIALS AND METHODS

A floating Landsat TM quarter scene, acquired on 1992–07–14 and covering an area of ca. 135×70 km was used for constructing a land cover map for the study area. Of the total of seven bands available from the TM sensor, we used the following four bands in the image analysis: 2 (green, 520–600 nm), 4 (near infra-red, 760–900 nm), 5 (middle infra-red, 1550–1750 nm), and 7 (middle infra-red, 2080–2350 nm). The inspection of individual TM bands revealed substantial striping in the visible wavelength bands 1, 2 and 3. As they are also highly correlated, only one visible band (TM 2; green) was included in the clustering. Infra-red bands were included in the analysis due to their suitability for vegetation discrimination, soil moisture determination and mineral and rock type identification. At the time, the digital elevation model was still under preparation and hence, no topographic normalisation was performed for the data. As land cover characteristics in this remote area are poorly understood, we were unable to conduct a supervised classification of the image. Instead, we per-



Figure 2. A thick aeolian deposit near Nýjahraun, along the road no. 1. The dunes in the region show abundant erosion scars suggesting that some alterations in the wind-sediment supply and vegetation system are taking place at present. – *Rofabarð nálægt Nýjahrauni, S-Pingeyjarsýslu. Mikil jarðvegseyðing hefur átt sér stað á þessu svæði.*

formed unsupervised Isodata classification using the Erdas Imagine® version 8.4 software package. The classification parameters were determined as a maximum of 30 statistical clusters with a 5 percent change limit between iterations.

We visited 91 field plots and described them with regard to their lava/sedimentary cover and vegetation (where applicable). GPS was used for navigation to all plots. The statistical clusters were assigned with respective field plot descriptions, thereby resulting in land cover classes. Comparison of the classification with ground data demonstrated that, at the radiometric and spatial resolutions used here, relatively dissimilar lava and sediment surfaces can show comparable reflectance patterns. After thorough signature investigation, some classes with relatively similar ground features were combined (visually) by assigning these classes the same colour on the map. A nomenclature based on the land surface characteris-

tics was built, resulting in 19 classes within three categories. The classified image was rectified and georeferenced (WGS84/UTM28) based on ground control points measured on 1:50 000 topographic maps, and additional GPS points.

RESULTS

The 19 land cover classes generated by our manual inspection of the unsupervised classification result were combined into three land surface categories (Figure 3):

- a) Lava cover; 31.6% of the area with six classes.
- b) Barren sediment cover; 45.4% of the area with two erosional and seven depositional surface types.
- c) Miscellaneous (including vegetation); 23.0% of the area with four land cover classes.

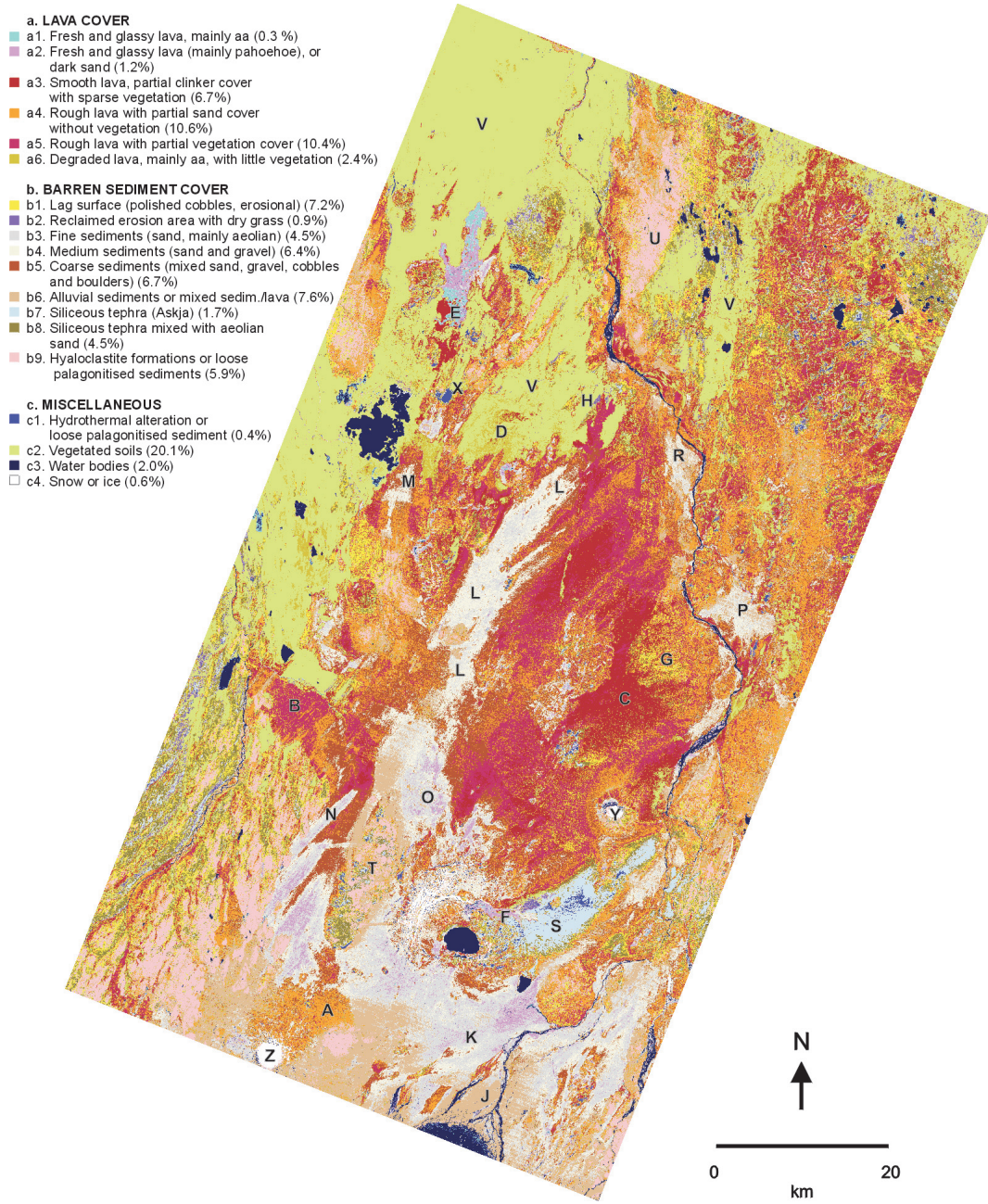


Figure 3. Classified satellite image with the nomenclature and relative proportions of the 19 land cover classes formed in the Isodata unsupervised classification. a) Various types of lava cover with six classes; b) Barren sediment cover types with nine classes, and c) Miscellaneous land cover types with four classes (see text for further details). –*Flokkuð gervitunglamynd af svæðinu norðan Vatnajökuls. Sjá texta á bls. 8.*



Figure 4. An example of the land cover in class a3: Smooth lava, partial clinker cover with sparse vegetation, between Askja and Eggert (8424400, 7229200; cf. Figure 3). The smooth pahoehoe lava surface is partly covered with sand and gravel size sediment. The flora, although scanty, includes *Stereocaulon vesuvianum* as the dominant species, plus *Salix herbacea* and *S. callicarpea*, *Dryas octopetala*, *Empetrum nigrum*, *Thymus praecox*, *Silene acaulis*, *Armeria maritima*, *Cardaminopsis petraea*, *Poa* sp., *Juncus* sp., *Carex* sp. and *Polytrichum piliferum*. Note the rucksack for scale. – Land í flokki a3, helluhraun að hluta þakið gjalli og sandi. Slitrótt gróðurþekja einkennir þessi svæði.

3. mynd. – Flokkud gervitunglamynd af svæðinu norðan Vatnajökuls. Svæðinu hefur verið skipt í 3 megin- og 19 undirflokka eftir gerð yfirborðsins. Stærstu flokkarnir samanstanda af apalhraunum með (a5, 10,4%) eða án slitrótt gróðurs (a4, 10,6%). Gróf, gróðurlaus hraun, að hluta hulin sandi (a4) einkenna svæðið (A) norðan Trölladyngju (Z) og sunnan Dyngjafjalla ytri (T), Útbruna og svæðið meðfram Jökulsá á Fjöllum. Sléttari hraun (helluhraun) með gjalli eða strjálum gróðri (flokkur a3, 6,7%) er að finna vítt og breitt um svæðið. Stærsta helluhraunflákann (C, ca. 105 km²) er að finna norðan Herðubreiðar (Y). Búrfellshraun (D) og Dimmuborgir tilheyra flokknum, gróðurlítill apalhraun (a6, 2,4%). Nýlegum hraunum er skipt upp í tvo flokka, apalhraun (a1, 0,3%) og helluhraun (a2, 1,2%). Hraun frá Kröflueldum (E) og frá Öskjugosinu 1961, (G) falla undir þá báða en auk þess er svartur sandur í flokki a2 þar sem ekki er hægt að greina mun á honum (J, K) og nýlegu helluhrauni á gervitunglamyndunum. Laus jarðefni á yfirborði skiptast í 9 flokka. Mismunandi flokka sanda (b1-b6) er að finna víða um svæðið, G, H, J, K). Stærsta samfella svæðið í flokki b1 (grófur sandur og möl, 7,2%), er um 60 km² (G). Mikinn sandskriðstaum (L), 3–7 km breiðan og um 50 km langan má greina á myndinni. Norðurendi hans hefur verið heftur með sandgræðslu við Nýjahraun (H). Annar taumur liggur að Dimmuborgum (M). Einnig sjást þrjár sandtaumar norður eftir Frambruna. Sá nyrsti (N) er 12 km langur og 2 km breiður. Gamalt jökulhlaupaset (b3–b6) þekur 60 km² við norðurmyinni Dyngjufjalladals (O). Jökulhlaupaskúruð hraun liggja beggja vegna Jökulsár á Fjöllum (P, R). Bæði svæðin heita Grjót og er það eystra 100 km² en það vestara 50 km². Öskugeirinn frá gosinu í Öskju 1875 kemur vel fram á myndinni sem ljósgrár flekkur (S) til norðvesturs. Hólssandur (U) er aðallega myndaður úr árseti frá síðasta hlýskeyði. Jarðhitasvæði í Námafjalli eru dökkblágrá (X).

Lava cover category

Exposed lava cover types are concentrated in the central portion of the study area, between Askja in the south and road no. 1 in the north. The largest classes are a4: Rough lava with partial sand cover without vegetation and a5: Rough lava with partial sand cover, respectively. Class a4 is most abundant between Trölladyngja and Dyngjufjöll ytri in the south (Figure 3; site A), at Útbruni, and along the Jökulsá á Fjöllum. Portions of the Upper Pliocene barren highlands to the east of Jökulsá also fall within this class. Class a5 is scattered throughout our study area, but is concentrated in Suðurárhraun and Frambruni in the west (Figure 3; site B), and areas to the north of Askja (Figure 4). Class a3: Smooth lava, partial clinker cover with sparse vegetation, forms continuous patches, the largest of which (ca. 105 km²) is located approximately 10 km north of Herðubreið, as an apron on the eastern flank of Eggert–Herðubreiðarfjöll (Figure 3; site C).

Another large, continuous area of a5 occurs ca. 15 km SE of Búrfell. Class a6: Degraded lava, mainly aa, with vegetation cover is most abundant between the vegetated area in the north and the barren region, and portions of both Búrfellshraun (Figure 3; site D) and Dimmuborgir belong to this class. Two small classes, a1 and a2, represent fresh, recently erupted lavas. Class a1: Fresh and glassy lava, mainly aa is found primarily on rough portions of Krafla lava flow (Figure 3; site E). Class a2: Fresh and glassy lava, mainly pahoehoe or aeolian sediment is not a satisfactory class, as, in addition to fresh lavas such as Krafla and Askja 1961 (Figure 3; site F), it also includes substantial areas of dark fine (mainly aeolian) sand e.g., in the vicinity of Dyngjufjökull sandur. With the given data, however, it was not possible to separate the two land-cover types.

Barren sediment cover category

The barren sediment category is composed of nine classes. Class b1: Lag surfaces, is abundant in many parts of the study region. Lag surfaces form where fine sediments are blown away, leaving a surface of pebbles or cobbles that are polished by abrasion. The

largest continuous lag area of b1 surrounds an apron of rough lava (a5; see above) on the eastern flank of Eggert–Herðubreiðarfjöll, and totals almost 60 km² in size (Figure 3; site G); another substantial lag area is found to the north of Sellandafjall near Mývatn. Additionally, class b1 is abundant on Tertiary, eroded till surfaces on both sides of the Rift Zone. Class b2: Reclaimed erosion area with dry grass is very limited in area, and abundant only in the northern eroded areas. It occurs on sites where reclamation measures have been taken by sowing grass seeds on eroding surfaces, i.e. on the western edge of the Nýjahraun near road no. 1 (Figure 3; site H). Due to the partial grass cover, some of these areas may actually experience deposition at present.

Classes b3: Fine sediment, b4: Medium sediment, b5: Coarse sediment, and b6: Alluvial sediment cover large areas (in total ca. 25%) in the southern and central parts of the study region. Alluvial sediments (b6) mixed with braided channels dominate the immediate vicinity of the ice margin (Figure 3; site J); these channels often fall into classes a4 and b5, most likely due to high moisture content and exposed lava blocks. Outside the alluvial fringe, fine and medium sediments (b3 and b4) dominate the sandur area between Dyngjufjökull and Askja (Figure 3; site K; Figure 5).

This region experiences vigorous aeolian activity, and may act as a source for the aeolian sediments found further north on the lava fields. The most striking depositional sedimentary feature on the classified image is a 3–7 km wide lobe of aeolian sediment that extends NE from Suðurárbotnar for almost 50 km (Figure 3; site L; Figure 6A). This lobe terminates at Nýjahraun, where sand trapping by lyme grass has resulted in substantial dune fields. The formation is not as distinctive on the ground as it may appear on the image, however, due to the discontinuity of the veneer of fine and medium sediments (b3 and b4) mixed with underlying lava.

An offshoot sand stretch, possibly originating from this formation, extends between Sellandafjall and Bláfjall all the way to Dimmuborgir (Figure 3; site M). Three other distinctive sand lobes extend south on the rough Frambruni lava flow (a4), to the west of Dyngjufjöll ytri. The northernmost stretch is



Figure 5. An example of the classes b3: Fine sediment and b4: Medium sediment, on the Dyngjujökull sandur (8420300, 7200600; cf. Figure 3). In the foreground, the poorly sorted alluvium with boulder-size rocks represents class b4. Class b3 in the background shows fewer boulders, and a surface covered with aeolian sand. Note the person for scale. – *Horft til Herðubreiðar af söndunum norðan Dyngjujökuls. Dæmi um yfirborð í flokkum b3 og b4.*

a lobe of sand ca. 12 km long and 2 km wide (Figure 3; site N), and is gradually growing in length towards the NE by filling depressions on the rough lava surface.

Dyngjufjalladalur is a N-S oriented gorge, between Dyngjufjöll ytri and Askja, with the characteristics of a water-affected canyon. The bottom of the steep-sided valley is covered with thick, poorly-sorted sedimentary deposit that dips gently towards the north. Large matrix-supported boulders, up to one metre in diameter, crop out from the valley bed along a river channel, indicating a very high-energy environment during sediment deposition. Together, these features suggest that a past flood event (perhaps even a jökulhlaup) originated at Vatnajökull and drained towards the north, passing Askja, this time on the western side via Dyngjufjalladalur. An abrupt decrease in

transport momentum apparently occurred when these flood waters exited the narrow gorge, inducing the sandur deposition. To the north of the valley outlet, a 6×10 km sedimentary formation has developed, consisting mainly of classes b3–b6 (Figure 3; site O).

Other evidence of past catastrophic floods can be detected further east, along Jökulsá á Fjöllum. Downstream of several abrupt channel bends, large outwash plains extend several kilometres beyond the current channel, in the direction of flood momentum. The most prominent examples of flood deposits are found near Möðrudalur and Grímsstaðir. The outwash plain surface (Grjót) in Möðrudalur measures ca. 10×10 km on the eastern side of the present river channel, and has a flat, winnowed lag surface with ventifacted boulders (mostly classes b4 and b6) sev-

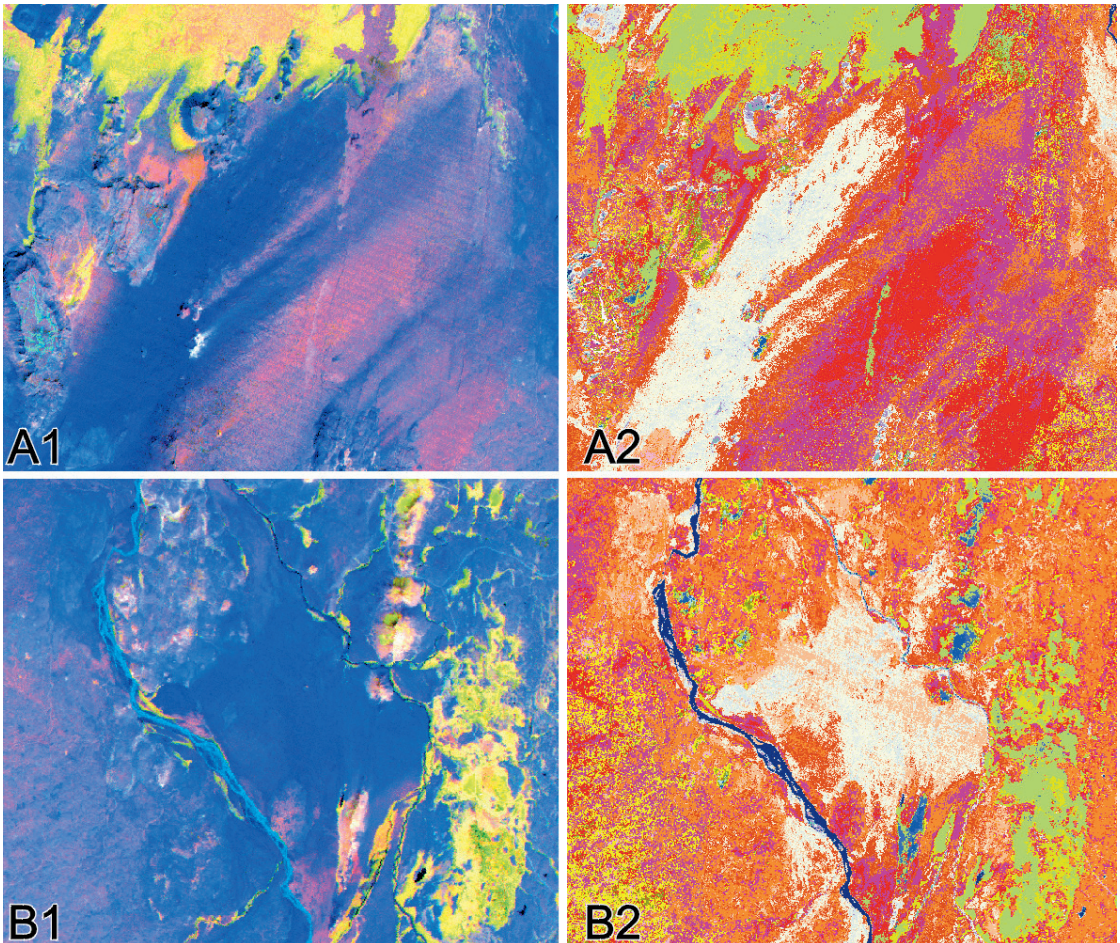


Figure 6. A1: A false colour three-band composite image (RGB 541) of the SW–NE oriented (effective wind direction) aeolian sand stretch between Fremrinámar and Búrfell, seen in dark blue. Vegetation is shown in pale green. The lavas (e.g. Nýjahraun) from the 1875 fissure eruption are visible as a slightly paler N–S stripe. A2: A classified image of the same area as in A1. The sand stretch falls mainly in classes b3 and b4 (cf. Figure 3), surrounded by various lava types (classes a3, a4 and a5). B1: A false colour three-band composite image (RGB 541) of the Möðrudalur settlement and the surroundings (cf. Figure 1). The dark coloured area in the middle is a vast flood deposited delta fan (Grjót), formed when high momentum flood-water escaped the Jökulsá á Fjöllum course (running from bottom to top, in blue) at the river bend. Vegetation is shown in pale green. B2: A classified image of the same area as in B1. The flood plain is mainly in classes b4 and b5 (cf. Figure 3). The Fjallgarðar hyaloclastite ridge, shown in pale blue and running towards the NNE, represents class c1. The striping of the original data (TM sensor problem) causes some classification errors, seen as weak WNW–ESE bands on the image. – *Stækkaðar myndir af foksandsgeirum á milli Fremrináma og Búrfells (A) og á Möðrudalssvæðinu (B). Myndirnar til hægri eru litbreyttar (RGB541) þannig að landslag kemur betur í ljós og gróður er grænleitur. Greina má Bláffjall ofan við A1 merkið og norðaustan þess gróðurlendi í Heilagsdal, síðan Heilagsdalsfjall og Búrfell. Einnig sést Hverfjall efst til vistri og norðurendi Hvammsfjalla í suðurjaðri myndarinnar. Auk Jökulsár á Fjöllum, má vel greina árnar sem renna um Möðrudal á mynd B1. Græna svæðið austan Lóns, Krókár og Hvannár er Framlandið.*

eral metres above the normal river level (Figure 3; site P; Figure 6B). An additional outwash plain (also referred to as Grjót; ca. 5×10 km) has formed to the south of Grímsstaðir, on the western bank between the current channel and the road F88 to Askja (Figure 3; site R).

Siliceous tephra classes (b7 and b8) dominate the tephra fan that formed during the 1875 eruption on the ENE side of Askja (Figure 3; site S). The continuous fan deposit covers ca. 63 km (class b7), and is surrounded by class b8, a mixture of light-coloured tephra and darker sand/lava. The eastern edge of the fan has been eroded (and perhaps, partly buried) by aeolian (and fluvial?) activity. Class b8 can also be found interleaved with hyaloclastite formations or loose palagonitised sediments (b9), the latter being rather light-coloured (i.e. with reasonably high reflectance in visible wavelengths). Dyngjufjöll ytri (Figure 3; site T) is the largest hyaloclastite formation in this area, followed by the N–S oriented ridges (Fjallgarðar) between Möðrudalur and Grímsstaðir in the east. In addition to these subglacially formed sedimentary formations, light-coloured sediments occur in places as loose scree and exposed indurated strata, for example at the Sydra formation to the north of Grímsstaðir (Figure 3; site U). These supposedly (cf. Van Vliet-Lanoë et al., 2001) interglacial fluvial and lacustrine deposits are now being eroded by wind and water.

Miscellaneous category

The miscellaneous category is dominated by the class c2: Vegetated soil (ca. 20% of the total area). Vegetated areas are abundant in the north-west of the study region, around Mývatn (Figure 3; site V). These vary from well-drained dwarf-shrub heaths to wetlands and patches of dense mountain birch scrub, as described in the 1:40 000 Vegetation map of Iceland (1982). The Vegetation Map of Iceland 1:500 000 (Guðjónsson and Gíslason, 1998) depicts three vegetation types for the study region: heath, birch scrub and wetland. Of the 30 classes generated by our unsupervised TM clustering, six were unambiguously identified as vegetation – these were classes in which “greenness” obscured the underlying surface characteristics. Four classes represented well or moderately-drained soils,

and two classes represented wetlands. A typical error in remote sensing studies of the subarctic biome is the partial misclassification of *Betula nana* dominated wetlands as *Betula pubescens* scrub due to their similar reflectance patterns (cf. Käyhkö and Pellikka, 1994). The vegetated area defined in our TM classification agrees well with the area shown on the map by Guðjónsson and Gíslason (1998). The current project, however, does not concern vegetated areas *per se*, which is why vegetation is not considered here in more detail.

Other classes within the miscellaneous category are c1: Hydrothermal alteration or solfatara, c4: Ice and snow, and c3: Water bodies. The largest occurrence of class c1 is the Námafjall solfatara area near Mývatn (Figure 3; site X). During the image acquisition in July, some of the mountain tops, e.g. Herðubreið (Figure 3; site Y) and Trölladyngja (Figure 3; site Z), and the rim of Askja caldera in the west had ice and/or snow cover.

SYNTHESIS AND DISCUSSION

Distribution of land cover types

Unsupervised clustering of the Landsat TM image, followed by manual merging of the classes, revealed the principal characteristics of the land cover types of Ódádahraun. This region is dominated by unvegetated lava fields, often covered with loose surficial sediments consisting of mobile, redeposited aeolian sand. As primary soil cover is almost completely absent from most of the area, this region cannot be considered to be undergoing erosion, *sensu stricto*, as there is no soil cover to be eroded. Instead, this region acts as a transport pathway for the sediment released by glaciofluvial processes at the ice cap margin. Continuous expanses of vegetation, threatened by the advancing semi-desert, occupy the north and north-west of the region. Arnalds (1992a, b) has demonstrated that the margins of Ódádahraun erode by the gradual enlargement by wind action of small erosion scars. This process proceeds until the majority of the landscape has become barren with only few scattered remnants of soil cover (rofabarðs).

Several major sedimentary bodies were identified in the study area: (1) the sandur in front of Dyngjujökull (Figure 3; J & K); (2) three parallel sand tongues on Frambruni lava west of Dyngjufjöll ytri (Figure 3; N); (3) the long stretch of sand running from Suðurárbotnar towards the NE across Fremrinámar and almost reaching the road no. 1 (Figure 3; L); and (4) the jökulhlaup deposits along Jökulsá á Fjöllum (Figure 3; P and R). The elongated form of the aeolian sedimentary deposits suggests a transport process towards the north-east. Identifying the source of these sediments would be very useful, enabling managers to try to bind the sediment at the source (i.e. stop erosion) rather than stopping the transport process at a later stage and thereby creating unstable sediment sinks.

Although our land cover classification succeeded in revealing some characteristics of the land degradation process, the ultimate trigger of this process remains a mystery. In general, the spatial distribution of the barren, severely eroded landscape and the volcanic rift zone coincide well. One can therefore ask to what extent the severe land degradation in Ódádahraun region is the result of endogenous processes, namely volcanic destruction caused by tectonic activity, lava flows, tephra outfalls, and particularly jökulhlaups. Lava flow fields cover a third of the investigated Landsat TM scene area, and the most recent flows erupted less than two decades ago. Is it possible that erupting lava flows would trigger erosion by destroying vegetated land cover? The recently formed (1970s-80s) Krafla lavas provide no evidence of such a triggering mechanism. Instead, rough lava surfaces probably act as sediment traps and sinks, slowing the pace of north-eastward sediment transport. In the case of Frambruni lava, for example, sand can move forward only by tediously filling in the hollows and depressions of the lava field (e.g. in the form of the three sand stretches across the lava flow). In addition, normal faults and fissures are natural sediment traps, and are often filled with aeolian sand. Smooth pahoehoe type lava surfaces, however, may act as important pathways for aeolian sand transport.

In addition to aeolian sedimentary deposits, there are vast flood plain deposits along the Jökulsá á Fjöllum

valley (cf. P and R in Figure 3), illustrating the magnitude of past jökulhlaup events. Our results suggest that flood events proceeded towards the north-west, perhaps extending from the saddle between Sellaðafjall and Bláfjall to the depression currently occupied by Mývatn. With the available data, however, we can only speculate on these matters. Nonetheless, jökulhlaups may have played a significant role in the initiation of the degradation process, as flood waters destroy vegetation by both slashing it and burying it with sediment when flow competence decreases.

Several details of the degradation process remain still unexplained e.g., sediment provenance, the role of climatic change in vegetation decline and the potential effect of anthropogenic factors such as deforestation and grazing by horses and sheep. A final key question with regard to land degradation is the undisturbed state of this region and the age of the erosion process, as it has yet to be discovered whether the whole area has ever been fully vegetated and covered with soil. More detailed dating methods and sedimentological studies combined with palaeoecological reconstructions in the future may throw light on this matter.

Evaluating the classification

The field checks revealed a common problem in remote sensing: how to define an appropriate nomenclature for the classification? Image classification schemes often cluster different land cover types, as observed in the field, into a single class due to similar reflectance. On the other hand, these schemes can also generate several classes despite apparent homogeneity of the site in the field. In real life, furthermore, there is no predetermined nomenclature for describing geomorphological features; nature appears as a complex continuum without sharp boundaries between members. Therefore, we found it unfeasible to subject the classification to a quantitative, statistical evaluation. The current mapping result should rather be evaluated in the appropriate context and in relation to its prospective applications.

The image pixel values (digital numbers), and consequently the results of our classification, are primarily controlled by the colour of the lava and sediment, their textural properties (roughness), and the

type and amount of vegetation cover. Due to the low spatial resolution of the TM sensor (30×30 m), and the clustering method used, it was not always possible to satisfactorily distinguish between land cover types. Problematic land cover types – i.e. those not clustered in a consistent way – included various mixtures of sediment and lavas. Small errors can therefore be detected on the classified image.

The Landsat TM mapping method used here, and our raster-format map product, offer the opportunity to monitor geomorphological processes in this area by regularly repeating the classification process with recently acquired data. The use of multitemporal data, however, would call for additional data manipulation, e.g. atmospheric correction, prior to detailed comparisons.

CONCLUSIONS

1. Six lava cover types and nine sediment cover types were described and mapped by a Landsat TM-based classification of the study area. The most abundant lava classes were rough lava mixed with sediments and rough lava with scattered vegetation, with ca. 10% areal coverage each. The most abundant sediment classes were medium and coarse sediments and alluvial deposits, which dominate the sandur in front of Dyngjujökull.
2. Streamlined sedimentary deposits in the western part of the study area (the three Frambruni sand lobes and the Fremrinámar sand stretch east of Bláfjall and Búrfell) suggest an aeolian sand transport process towards the north/northeast.
3. Major jökulhlaup deposits with adjacent dune fields were detected along the Jökulsá á Fjöllum at Möðrudalur and Grímsstaðir, suggesting that jökulhlaups serve as a potential triggering mechanism for soil erosion.
4. The Landsat TM-based mapping method described here could be used to monitor this region's geomorphological processes by repeat-

ing the classification process with recently acquired data.

5. Due to the spatial resolution of the TM and the clustering method used here, it was not always possible to distinguish between land cover types – this was particularly true for types that form a continuum in the field.

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ÁGRIP

LANDMÓTUN Í ÓDÁÐAHRAUNI Í LJÓSI LANDSAT TM GERVITUNGLAMYNDA

Mikil jarðvegseyðing hefur átt sér stað norðaustan Vatnajökuls síðustu aldirnar. Gervitunglamyndir geta komið að góðum notum við flokkun landslagsgerða og mati á rofþáttum. Skipta má landslags- og yfirborðsgerðum svæðisins í 3 meginflokka (hraun, set og annað) og 19 undirflokka. Marga undirflokkana má auðveldlega greina á gervitunglamyndunum. Landsat TM myndir af svæðinu frá Dyngjújökli í suðri og norður í Öxarfjörð sem teknar voru í júlí 1992 leiða m.a. í ljós hvernig foksandsgeirarnir liggja í Ódáðahrauni og hvar leifar gróðurs er að finna.

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