When the glacier left the volcano: Behaviour and fate of glaciovolcanic glass in different planetary environments

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Slumping and break-up of scree deposits in the Grænagil gorge as a result of water-saturation.
Chapter 2
Erosion of a subglacial edifice

Abstract
Scree cones and slopes are common sedimentary landforms created by rock fall and rock particle fall in mountainous environments. These formative processes are attributed to various weathering and particle detachment mechanisms. However, the aeolian contributions to the weathering of rock faces and formation of scree sediments are poorly understood and often underestimated. A case study in the southern highlands of Iceland provided a geological setting in a subarctic environment where the contribution of various erosion and deposition mechanisms to the development of scree deposits could be studied. Here, moderately-cohesive subglacial volcanic eruption products are continuously undercut by local streams, creating exposed and steep-sided canyon walls where scree cones and slopes are formed by dominant influences of freeze–thaw cycles and the wind on rock particle fall. The stratigraphy and the morphometry of these sedimentary landforms indicate that wet formative processes can contribute but are not as dominant. Avalanching of accumulated material occurs in dry conditions and creates distinct stratified sediments. The aeolian contribution to the scree development was studied by determining the physical requirements of particle detachment using wind tunnel simulations. Simulated threshold wind speeds of the removal of fines show that these wind and gust conditions are common in these areas in Iceland. A detailed particle analysis of the sediment from an isolated scree cone and the contributing rock face showed that sediments were depleted in the silt fractions. Field observations confirmed the influence of deflation where fine material is removed by the wind from exposed sediments whereas larger particles are excavated by the deflation of the surrounding matrix on the overlying rock face. The outcomes highlight the role that aeolian processes can fulfil in subarctic environments. As similar glassy materials are also found on other planets, the studied processes can for example offer insights in hillslope processes at the surface of planet Mars.

1. Introduction

Scree cones and slopes are common sedimentary landforms in mountainous environments across the world. They are formed by the accumulation of material of varying particle sizes which are delivered by rock fall (large boulders, \( >35 \text{ m}^3 \text{ yr}^{-1} \)) and rock particle fall (\(<\text{pebble sized particles, } <5 \text{ m}^3 \text{ yr}^{-1}\)) from overlying slopes (Whalley, 1984; Selby, 2000). Studies focussing in detail on rock particle fall are still relatively scarce, whereas more is known about the evolution of debris cones or talus slopes in various environments (e.g. Sass and Krautblatter, 2007). Processes driving rock particle fall are attributed to weathering mechanisms of rock faces as a result of: (i.) freeze-thaw interactions, (ii.) shrinkage and swelling processes driven by wetting and drying, or (iii.) due to salt weathering (Selby, 2000). In addition to these, other contributing mechanisms are also reported and include plant root penetration and mechanisms involving rapid snow melt, rain storms and earthquakes (Wieczorek et al., 1995; 2000).

When liberated particles are eventually concentrated in sedimentary landforms, the internal angle of friction of the accumulated sediment influences the slope angle. This is an important empirical property which allows the discrimination between formation environments and deposition processes. This approach is illustrated for many geomorphological phenomena on Earth and even on other planetary bodies. For example, at the surface of Mars slope angles are the foremost means for inferring the formation conditions of a particular landform. Distinctions on Mars can be made between alluvial processes, dry mass wasting and aeolian distributed sediments (e.g. Kleinhans, 2010) on the basis of these morphometric properties. On Earth, auto-organisation of particles occurs during avalanching of freshly deposited sediments and results in segregation (slope length-wise sorting) and stratification (layering perpendicular to the slope and avalanche flow direction). These processes occur in various subaerial and subaqueous sedimentary landforms such as immersed deltaic foresets (Kleinhans, 2005), in dry sand-blown dunes (Hunter, 1977; Bristow et al., 2000) or in mountain slope deposits (Sass and Krautblatter, 2007). Lubrication of these avalanches by the interstitial medium influences the morphometry of such sedimentary landforms (Bertran and Texier, 1999). Forceful conclusions about the formation environments of a particular sedimentary landform can therefore be drawn from a combination of the stratigraphy and morphometry (Steijn et al., 1995). For stratified slope deposits we can differentiate between dry rock fall-derived scree cones (30–40\(^\circ\) slope angle) (Rapp, 1959; Sass and Krautblatter, 2007), debris flow dominated deposition (<30\(^\circ\) slope angle), frosted granular flow (<28\(^\circ\) slope angle) and alluvial deposits with characteristic solifluction-lobes and incised stream beds (3-25\(^\circ\) slope angle) (Blair and McPherson, 1994; Steijn et al., 1995). However, the contribution of aeolian processes to rock particle fall and erosion in cold mountainous environments has not been extensively studied or reported for these sedimentary landforms, even though the wind is widely recognised to influence the development and modification of landforms in various environments, especially in the subarctic Icelandic sandy deserts (Arnalds, 2000; 2010; Arnalds et al., 2001). Aeolian erosion of rock walls has been more commonly associated with abrasion by coarse-textured materials (Laithy, 2009) rather than with deflation and entrainment of finer textures from the rock face. We observed aeolian processes contributing to the formation of foot slopes below rock faces of subglacially-formed volcanic glass in a dry environment in Iceland. Local winds and gusts deflated the silt and clay fractions from rock faces, making the coarser fractions instable which induced rock particle fall and which in turn contributed to the formation of scree deposits at the valley bottom. Our aim was to study the physical requirements for
erosion of a subglacial edifice

2. Regional setting and material properties

Our field observations of aeolian contributions to scree formation were made in a geological context unique to Iceland. Here, subglacial, subaerial and submarine volcanic eruptions are widespread. Subglacial eruptions have produced a great variety of distinctive landforms and materials that include tuyas, hyaloclastite sheets and ridges that have come to dominate the present-day post-glacial landscape (e.g. Bourgeois et al., 1998; Gudmundsson, 2000; Wilson and Head, 2002; Schoka et al., 2006; Thodarson and Larsen, 2007; Jarosch et al., 2008; Smellie, 2008; McGarvie et al., 2006; McGarvie, 2009). This landscape is currently influenced by various geomorphological processes which include mass wasting, periglacial, fluviatile and aeolian processes. The volcanic sequences found within the Torfajökull area in the southern highlands resulted from the magmatic activity within the Veidivötn swarm fissure and the activity in the Torfajökull magma chamber (Lippitsch et al., 2005; Gunnarsson et al., 1998; Jónasson, 2007). The highly dissected rhyolite plateau of Torfajökull, currently part of the Fjallabak Nature Reserve, features remnants of quaternary glacial environments such as subaerially formed rhyolites, subglacially formed rhyolitic hyaloclastites and some minor traces of fluvioglacial sediments. The area measures roughly 18x12 km and with a volume of an estimated 225 km³ it is considered to be the largest and most active rhyolite core on an oceanic crust (Gunnarsson et al., 1998).

The Bláhnúkur edifice (Icelandic for ‘blue peak’) is the youngest subglacial eruption in the area around Landmannalaugar (Tuffen et al., 2001). Bounding Bláhnúkur to the north is the subaerial rhyolitic Laugahraun formation that was formed as a post-glacial subaerial lava flow which currently fills a major part of the valley bottom (Blake, 1984; Thordarson and Larsen, 2007). These two adjoining formations illustrate well how different eruption environments influence the material properties found in the present-day landscape (Fig. 7). The lithofacies and formation mechanisms of subglacial rhyolitic hyaloclastites within the surrounding area of Bláhnúkur have been extensively studied by Tuffen et al. (2001, 2002a). These subglacial eruption products were formed during the last glaciation and are deposited on top of the older rhyolite topography, adding an estimated +50 m to the local elevation (Tuffen et al., 2001). The flanks of Bláhnúkur consist of one type of hyaloclastite deposited by different emplacement processes at the time of the formation (Tuffen et al., 2001). The hyaloclastite are considered to have been formed by spalling of brittle lobes of erupted lava under contact with water and ice in the subglacial eruption cavity (Tuffen et al., 2001). The resulting blocky and charded particle morphology has a moderate vesicularity which favours the interpretation of an effusive eruption environment with slow discharge rates <5 m³ s⁻¹ at high basal pressures (Tuffen et al., 2001, 2002a; 2008). The formation that dominates the area of interest are breccias which have been interpreted by Tuffen et al. (2001) as collapse remnants. The composition of this facies consists of breccias with a green to greyish ash matrix containing volatile-rich pumiceous obsidian (Tuffen et al., 2001; Denton et al., 2009); lending the name ’Grænagil’ (green gorge) to the area of interest. These eruption products have been deposited during the early stages of the subglacial eruption.
and can best be interpreted as the remnants of debris avalanches and sections remobilised by slumping. Both processes occurred subglacially in the eruption cavity (Tuffen et al., 2001). The resulting well-drained and moderately-cohesive deposits are found across the entire area of interest and have a predominant coarse-grained sandy texture that is also characteristic for other rhyolitic ashes in the area (Heiken, 1972; Tuffen et al., 2001; Denton et al., 2009). The Bláhnúkur edifice and Grænagil gorge hence provide a unique geological setting with material properties that are favourable for studying aeolian influences on hillslope weathering and scree cone development.

**Fig. 7** - The area of interest in Torfajökull, viewing towards the northeast from the flank of the Brennisteinsalda (+855 m). Clearly visible is the colourful rhyolitic pre-glacial topography that lines the caldera rim. Towards the right, darker subglacially formed hyaloclastites mark the flanks of the Bláhnúkur edifice. Directly next to Bláhnúkur is the subaerial outflow lava Laugahraun ('bathing lava' in Icelandic, referring to the active geothermal hot springs on the far side of the formation).
3. Methodology

A geomorphological field inventory focused on establishing dominant sedimentary landforms within the Grænagil gorge (63°59'04" N, 19°3’51“ W, 620 m.a.s.l.). Previously reported geological sequences and observed development of geomorphologic features over a five year period (2007-2011) were combined to reconstruct the landscape evolution of the area of interest. The stratigraphy and morphometry of distinguishable sedimentary landforms such as scree and alluvial deposits inside the Grænagil gorge were determined and allowed us to infer and link the formation environments to the measured properties. Ten undisturbed cubic decimetre (1 L) rock samples were collected on various locations on the rock face of Bláhnúkur above the Grænagil gorge (henceforth called the ‘source areas’). These samples were used to determine the abundance of deflatable fractions (<150 μm). Collected samples were homogenised prior to further analyses to compensate for sorting processes during transport. Particle-size analyses were carried out for the fraction ≤4.8 mm for each of the obtained samples according to the preparation and sieving protocols described by Gee and Bauder (1986). The 150-2000 μm fraction was processed by sieving the samples over eight ½ φ fractions. The texture of the silt and very fine sand fraction (<150 μm) was measured using a Micromeritics Sedigraph 5100, which uses X-ray to determine grain-size distributions by measuring the settling velocity of particles. The GRADISTAT utility of Blott and Pye (2001) was used for describing and summarizing the particle-size distributions following the arithmetic methods of moments (Friedman and Sanders, 1978).

3.1 Meteorology and wind tunnel simulations

Wind tunnel simulations were carried out in order to measure the physical requirements for the removal of fine hyaloclastites by the wind. Four of the size fractions (<212 μm) were sampled with a repetition of n = 3 and were used for simulations inside a recirculating wind tunnel according to a fixed protocol (Merrison et al., 2007; 2008, also see chapter 4 for more details on this method). Threshold wind speeds (u) and friction velocities (u*fl) were measured for dry (70°C air-dried) samples for an atmospheric pressure of 1024 mbar at 20-25°C. Saltation mechanisms for wind-driven removal of particles may be more difficult to achieve on steep slopes and the contribution of gravity-driven saltation impact is difficult to quantify. Using the method of Merrison et al. (2007) we therefore exclusively measured the detachment threshold (particle removal which includes rolling and sliding) by excluding the influence of wind-induced saltation impact.

Meteorological observation of hourly wind speeds, precipitation rates and temperature were used in conjunction with the measured threshold wind speeds for particle removal to assess the occurrence of favourable weather conditions for wind erosion and the contribution of other processes. We assessed the vulnerability of the hyaloclastite material for shallow mass movements in wet conditions, which could contribute to the formation of the foot slope sediments. Rainfall intensities and durations were therefore compared to empirical thresholds for landslides, debris flows and soil slips from other studies (Caine, 1980; Innes, 1983; Clariza et al., 1996 and Guzetti et al., 2008) for our 5-year observation period. Due to the lack of long-term meteorological records in the surrounding area of Landmannalaugar, we used data from the two closest automated meteorological stations located at Vatnsfell (64°11’39“ N, 19°2’51“ W, 539 m.a.s.l., 24 km distance) at a heading of 2 degrees N and the station Lónakvísl (64°5’53“ N, 18°36’50“ W, 675 m.a.s.l. at 26 km distance) at a heading of 60 degrees NE from Bláhnúkur.
3.2 Comparing grain-size distributions

One scree cone was selected as a case study to measure if the physical conditions required for removal of fine fractions by the wind were reached often enough to affect and modify the texture of the sediment. We tested our hypothesis for a well-defined representative scree cone in the gorge where deflation of the overlying rock face was observed in the field and which had a distinguishable source area of ~50 m² and a defined supply route (chute) that channelized all forms of rock particle fall from different erosion and transport mechanisms to the studied scree cone. Twelve cubic decimetre (1 L) samples were collected in-situ from the upper 10 cm of scree along three transects running from the feed mouth down to the base of the scree cone.

The grain-size distributions of the scree sediment samples were then compared to the overlying source area to determine the selection and depletion of size-ranges in the sediment that could be indicative of aeolian influences. A Pearson’s $\chi^2$ test for independence (Davis, 2002) was used to statistically test the equality of the distributions of the primary source area above the sampled scree cone and the samples obtained from the scree cone itself. A Pearson’s $\chi^2$ test is the sum of the squared differences between the observed (O) particle distribution and the expected (E) distribution in each particle-size class, divided by the expected distribution ($\chi^2 = \Sigma((O-E)^2/E)$). The null-hypothesis (H0) that we used for this statistical comparison was the assumption that the distribution of the parent rock in the source area (E) matched the distribution of the scree sediment (O). In other words: erosion and transport processes do not modify the texture of the sediment. Using the Pearson’s $\chi^2$ test we could falsify the H0 hypothesis by showing that the sediment distribution of the scree sediment was significantly different from the parent material. We tested the null hypothesis (E and O are similar) at the 0.01 significance level.

4. Results

The eruption of Laugahraun in 1477 AD and the subsequent blockade of the valley plays an important role in the geomorphological and hydrological development of the present-day area. The hydrological networks that established after the eruption incised into the less-resistant hyaloclastites at the interface with the Laugahraun outflow lavas. The geomorphology of the area of interest (Fig. 8) is therefore dominated by the narrow incision of the Brennisteinsöludukvísl stream between the resistant outflow lavas and the softer subglacially deposited Bláhnúkur hyaloclastites. The continuation of these hyaloclastites underneath the Laugahraun outflow lavas is only well exposed at the entrance of Grænagil, although remnants can also be found underlying Laugahraun at other locations inside the gorge. From the present morphology we can infer that the stream undercut the hyaloclastites positioned underneath Laugahraun, which caused partial collapses along the southern edge of the formation. Presently, the Laugahraun formation can be characterised as a fairly inert formation and it does not show significant forms of physical weathering, aside from the occasional rock fall. Resistant rock formations of Laugahraun and lava lobes in the hyaloclastites pinch the stream at various locations at the bottom of the gorge. The stream has a wider bed at other sites where the gravely substrate and large surplus in sediment gives the stream a modest braided character. The continuous migration of the streambed causes undercutting and abrasion of the foot slopes is the most active geomorphological processes inside the Grænagil gorge. These processes uphold the conditions for the formation of foot slopes below the steep-sided rock faces inside the gorge.
Above the valley floor, the hyaloclastite slopes of Bláhnúkur described by Tuffen et al. (2001) show a higher magnitude of geomorphological activity compared to Laugahraun. The flanks from the summit down to the valley bottom of Bláhnúkur can be generalised into three main sections. A low inclination (26-29°) top plane leads from the main summit down to a spur situated above the steep-sided rock face overlying Grænagil. The inclined furrowed rock face resides close to, or above the maximum angle of repose (>38°) and is interlaced with numerous chutes with more resistant protruding lava lobes. Various steep-sided subvertical parts of the rock faces extend to an altitude that varies from 40-70 meters above the valley floor. The development of these slopes is strongly influenced by the undercutting at the foot by the Brennisteinsöldukvisl stream and backwards erosion of rills and gullies at the nick-point of the rock face and top plain. Sedimentary deposits are formed directly underneath the rock face. A small number of distinguishable scree cones with slope angles of 36±1.3° (n = 7) have been formed at the foot of the green and grey-coloured rock faces (calibrated Munsell-scale colours of dried samples range from 2.5G 5/2 to 8/10Y). Fluvial influences on the deposition of material is shown by well-developed rills and gullies in the top plain of Bláhnúkur and these features continue into the morphology of the furrowed rock faces. Contrary to the abundance of rills and gullies only one distinct alluvial fan has been formed from these systems in 5 years of field observations inside the gorge (Fig. 9a-b). The morphometry of alluvial landforms consisting of hyaloclastites was characterised by <25° slope angles, which clearly differed from the slope angles of the dominant scree deposits inside the gorge. The low abundance of sedimentary landforms formed by fluvial processes suggested that transport and deposition

Fig. 8 - Geomorphological overview of the Grænagil gorge. A shaded-relief map shows the setting with the Laugahraun and Bláhnúkur formations delineated in grey (a). The simplified geomorphological map of the Grænagil gorge illustrates the processes and landforms of the area of interest (b). Collected rock samples (RS01-RS10) are marked. Sample RS3 is located inside the source area of the studied scree cone.
of material by water does not take place at a large scale. These contributions may only be active during torrential events and rapid large-scale seasonal snow melt in spring and early summer. Shallow mass movements were observed in various scree deposits that have been initiated by oversaturation with water. It is common to see slumping near the interface of the scree with the rock face as a direct result of overland flow or lateral rain (Fig. 9c). Sliding of sediment was found in close proximity to these slumping regions, where a typically 30 cm thick layer is oversaturated with water and drives the sliding across a slipface of predominant gravely strata, which eventually breaks-up of the slope’s face (Fig. 9d). Characteristic layering was mostly absent in the alluvial fan of Fig. 9a-b whereas stratified sediments were more commonly found in the abundant scree deposits. This layering with sharp boundaries is well-exposed at various locations such as in the sampled scree cone (Fig. 10a, 10c) and in adjacent scree slopes. Liberated and excavated particles created discontinuous avalanches of sediment that formed lobes of material and progressively changed the surface texture from small particles at the top of the scree cones to larger particles at the foot of the cone. Erosion occurs as a result of this stratification when the overlying layers are destabilised in dry conditions by undercutting of the stream and experience sliding on the contact surface of the coarse gravely strata.

Due to absent meteorological records inside the area itself, snow cover conditions have been inferred from the accessibility of the F208 road leading directly to Landmannalaugar (Torfajökull) from 2007-2011 (Table 1). More general meteorological records (Einarsson, 1984) also show that slopes in the area have a snow cover ~60-70% of the year with a snow-free period typically from June to September. The thin blanketing layers of fall deposits and sheltering of snow in steep valleys allow ice lenses to survive into the heart of the summer at places, which have preserve records of these processes (Fig. 11).

4.1 Meteorology and wind tunnel simulations

The two nearest meteorological stations allow some speculation about the meteorological conditions controlling the observed types of particle-removal. Measurements of the meteorological conditions at Vatnsfell and Lónakvísl have been summarised in Table 1. The mean annual temperature for both sites is close the freezing point and illustrates the importance of the frequently occurring freeze-thaw cycles in these regions. Although there is some spatial variation in the precipitation, we find that the majority of rainfall events in the summer period (June - September) fall below the thresholds for initiating shallow mass movements (Fig. 12). Within this snow-free season (June - September) wind speeds varied between 8-11 m s\(^{-1}\) while maximum gusts during violent storm events reached wind speeds in excess of 45 m s\(^{-1}\).

Entrainment of substantial amounts of fine material (silt particles) has been observed during episodes of dry and windy weather where larger particles were excavated and subsequently rolled down-slope where they accumulated in the scree sediments (see Fig. 13 and the video material included in the online appendices). Meteorological records indicate that during the observed deflation the average wind velocities and gusts ranged from 11-17 m s\(^{-1}\) from a north-north-easterly (NNE) direction. Wind tunnel simulations showed that threshold wind speeds required for removal of these hyaloclastites by the wind varied from 5 m s\(^{-1}\) for >200 μm sandy particles to 10 m s\(^{-1}\) for finer silt fractions (Fig. 14) in dry conditions. The field conditions are well over the critical threshold wind speeds required for removal of silt and sand-sized particles.
The locations of the obtained samples inside the gorge have been marked in Fig. 8 and the spatial arrangement for sampling of the scree cone is provided in Fig. 10a. From the stratigraphic column (Fig. 10c), it can be inferred that sampling of the upper 10 cm of the sediment provides an average sediment distribution of 4-5 consecutive avalanche events. The results of the texture analyses have been visualised in Fig. 15 and a complete overview of all the samples is included in appendix E. The scree sediments were typically poorly-sorted platycurtic distributed coarse sands (D50 = 821 µm, D90 = 2855 µm) whereas the primary source area was classified as poorly-sorted mesokurtic medium to fine sands (D50 = 297 µm, D90 = 1255 µm). The Sedigraph analyses of the deflatable fractions (<150 µm) of the rock matrix show that the source areas were dominated by a high percentage of coarser silt (10-70 µm) and a small amount of clay-sized particles. A notable difference between the source and deposition areas was identified in the silty size range. The overall distribution of the primary source area has a silt fraction in the order of 5-10% whereas the scree sediments only have a 0.3-0.6% silt content. An opposite trend is found in the larger textures. Source areas contained coarse to very coarse sands in the order of 8-20%. The similar fractions in the scree sediments showed a notable enrichment of which the contribution varies between 21-73% (40% on average).

A statistical comparison of the particle-size distributions using the Pearson’s χ² test shows that the distributions of twelve scree cone samples collected from the one scree

Table 1 - Overview of meteorological conditions from 2007-2011. Values for the stations Vatnsfell and Lónakvísl are calculated from hourly measurements.

<table>
<thead>
<tr>
<th>Meteorological conditions</th>
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<th>2008</th>
<th>2009</th>
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<td>Vatnsfell</td>
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<td>..</td>
<td>30-9</td>
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a June 1st - September 30th summer period
b Not measured or no data available
c F208 road access to Landmannalaugar, data from: Vegagerðin (Icelandic Road Administration)
Fig. 9 - Wet geomorphological processes. In five consecutive years of field observations, snow melt and local rainfall conditions have been able to produce one distinct alluvial fan inside the Grænagil gorge (a). Differences in angles of repose are found between scree and alluvial deposits, clearly resulting from the two different formation environments (b). Excessive water saturation of scree deposits by overland flow across the rock face creates mass movements in the form of slumping with distinct back-rotations (c) and sliding of oversaturated deposits across coarse gravely layers (d).
Fig. 10 - Dry geomorphological processes. Sampling transects over the face of the scree cone (see text) run under a ~36° slope angle from the 1 m wide feed mouth down to the foot of the slope (6.1 m slope length, 12.3 m circumference) (a). Clear stratification is visible inside the scree cone (b). The stratigraphic column shows distinct coarsening upwards within layers which reflects individual avalanche events (c). Stratification is attributed to sorting processes during avalanching of sediment when the maximum static angle of repose is exceeded (d). Kinematic sieving then causes a separation in grain-size where small particles sieve through the coarser particles (e). Fining upwards occurs along the slope length of the scree cone and coarsening upwards is found perpendicular to the flow direction of each individual avalanche (f) (d-f adapted from: Kleinhans, 2005).
Fig. 11 - Icy geomorphological processes. An ice lens preserved in Grænagil on the foot of a northwestwardly exposed scree slope which survived into late-summer of 2009. Two major snow periods illustrate the accumulation of material excavated by freeze and thaw cycles and subsequent avalanching of the sediment.

Fig. 12 - Rainfall intensity-duration (ID) plot showing that the majority of rain events at Lónakvísl (circles) and Vatnsfell (squares) over a 5 year period are below the observed thresholds for debris flows and shallow landslides from other studies.
Fig. 13 - In-situ observation of deflation inside the Grænagil gorge. Fine silt from the Bláhnúkur hyaloclastites is carried aloft by the prevailing wind gusts while being deposited elsewhere in the area. At the time of these observations (15th August 2007) winds and gusts in the southern highlands of Iceland varied between 11-17 m s\(^{-1}\) from predominantly north-north-easterly (NNE) directions.

Fig. 14 - Threshold shear stress measured in wind tunnel simulations for the detachment of dry samples of different textures of Bláhnúkur hyaloclastites. Simulations were carried out at an atmospheric pressure of 1024 mbar at 20-25°C. The error-bars on the x-axis represent the size-range of each fraction.
cone were significantly different from each other ($\chi^2 = 146$, $df = 49$, $p \leq 0.001$). The average distribution of these scree sediments has been calculated to produce a spatially averaged value to compare the scree sediment with the expected distribution of the primary source area that was concentrated in the scree cone. This comparison showed a statistical difference between the source and deposition areas with ($\chi^2 = 34$, $df = 11$, $p \leq 0.0003$). A broader spatial comparison of the particle-size distribution of ten different locations of the Bláhnúkur hyaloclastites (including the primary source area) shows that the distributions of these source areas are comparable throughout the Grænagil gorge ($\chi^2 = 43$, $df = 63$, $p \leq 0.97$), as $H_0$ (i.e. distributions are similar) is not rejected by the Pearson's $\chi^2$ test.

## 5. Discussion

The regional landscape evolution has played an important role in creating the favourable conditions for the development of the rock face and the formation of scree deposits by a multitude of processes throughout the seasons. Studies of geomorphological and sedimentary processes involving the modification and transport of friable glassy hyaloclastites are scarce and comparisons to other studies are therefore difficult. Deposits that resemble the texture of the studied sediments in Iceland in similar cold environments are Grèze-Litée sediments (hillslope sediments with alternating layers of coarse and fine shales) commonly formed in alpine periglacial environments (van Steijn et al., 1984; 1995). The stratigraphy and morphometry of these fine-grained deposits have been studied more intensively and thus provide a reference for comparing and inferring the contributions for various erosion and deposition processes to the sedimentary landforms inside the Grænagil gorge.

![Fig. 15 - Overview of the distribution analyses of sampled source areas and scree sediments in Grænagil. The main graph (a) compares the primary source area (RS03) and another source area 100 meters further down the gorge (RS08) with the sediment sampled in the scree cone. Sediment distributions are comparable for the samples source areas (b) while silt and clay contents are nearly identical throughout the gorge (c).](image-url)
5.1 Processes driven by flowing water

The rainfall intensity-duration conditions during the 5-year observation period show that the vast majority of rainfall events is below the threshold for shallow mass movements (Fig. 12). When taken together with the permeable nature of the hyaloclastite material it suggests that such processes are rare, which is supported by the low occurrence of alluvial landforms in the studied gorge. However, other forms of erosion and transport by overland flow of water could still have occurred. The particle morphology of hyaloclastites and their observed random orientation in the layers exclude the role of (melt)water-related transport processes such as nivation. This view is supported by the questionable contribution of nivation on slopes of flaky Grèze-Litée where particle-orientation is often more pronounced than for these blocky hyaloclastites (van Steijn et al., 1984; 1995). Similarly, slush avalanching (Caine, 1969) during thaw periods from overlying slopes would play a minimal role as indications from oriented particles are absent. The required conditions for this process on the high-angle scree slopes would only occur very infrequently during spring, while being absent throughout the remaining seasons. These processes therefore do not provide sufficient explanation for the abundant stratification of the scree sediments. In wetter conditions overland flow or slope wash, perhaps driven by lateral rain or rapid snow melt on the overlying rock face or on top of top plain, is illustrated by the numerous rills and gullies. However, the amount of water and stream velocity required to move the coarser particles found in the sediment would more likely create incised streambeds and alluvial landforms during torrent events (van Steijn and Hétu, 1997). The straight upper slope in combination with absent concave tailing, incised stream beds and levées also support the exclusion of wet debris flows (Statham, 1973; Blissenbach, 1954; van Steijn et al., 1995). Furthermore, the morphometry of the observed alluvial fan disputes an alluvial formation environment for the scree deposits due to their higher slope angles (van Steijn and Hétu, 1997). These morphometric differences are in line with observations of Rapp (1959) who concluded that in periglacial conditions sedimentary landforms of fine materials below 25° should be derived by other mechanisms than rock particle fall. Alluvial landforms are very scarce in the area and water-related effects are more commonly found in the form of localized slumping of the upper scree slopes and sliding by the oversaturated mass. An alternative hypothesis involving a wet formation environment which could explain the difference between the parent rock and sediment involves eluviation of fine particles through the sediment column. However, we can argue against such processes due to the observed sharp boundaries in the stratigraphy of the sediment (Fig. 10c). Other studies have also questioned similar influences in other geological settings with fine-grained sediments due to sharp sediment boundaries (van Steijn et al., 1984). If in the most optimum case, clay from the sediment column is indeed lost with percolating water, this mechanisms would not be able to sufficiently explain the reduced coarser silt content in the scree sediment. Overall, we do not exclude the influence of wet processes but we find little support for large-scale contributions of rain and snow-melt driven processes to the formation of scree sediment inside the gorge.

5.2 Freeze and thaw cycles

Similar to conditions in other periglacial environments, freeze and thaw cycles are an important process for the physical weathering of Bláhnúkur. Throughout the year some 100 cycles occur as the mean annual temperature in the area is close to the point of freezing. Cyclic loading of the rock face occurs mainly from the weeks after first snow fall (September) until thaw in the following spring (May-June). The friable tuffaceous nature of the hyaloclastites
and the frequent occurrence of freeze-thaw cycles suggest that gelification (water infiltrating in the vesicles of the volcanic material, expanding upon freezing and fracturing the material) could be important. However, a larger amount of fines should be present in these sediments which is not the case. It is more likely that expanding ice in interparticle pore spaces leads to physical weathering of the rock matrix which excavates material rather than fracturing into smaller particles. Intact larger particles in the strata (Fig. 10c) of the scree deposits support the notion that these sediments are derived by excavation rather than the gelification of larger clasts. Snow covers the slopes some 60-70% of the year (Table 1) and in the middle of winter the limited insolation, combined with the low elevation of the sun, a north-westerly exposure and the nearly continuous below-freezing temperatures would only cause significant rates of frost weathering on the overlying rock face. The accumulation of excavated materials on the snow blanket creates a temporal form of sediment storage. The persistent snow cover of these scree slopes during winter therefore prevents avalanching of sediments. After thawing of the snow and ice, the accumulated material during contributes directly to the build-up stage of new avalanches. A significant contribution of semi-frozen materials or frosted granular flow is excluded as this process is inhibited by the continuous snow cover and the observed slope angles exceed the known maximum range for this process (slope angles <28°). Avalanching of the accumulated material therefore occurs presumably in dry conditions, due to the high slope angles measured for these scree slopes.

5.3 Dry avalanching

In the local of the study site environment, discrete avalanching of sediment over the slope face is crucial in lieu of driving (i.) sorting of larger grain sizes along the slope and (ii.) distinct coarsening upward of the sediment perpendicular to the slope. Clear effects of these processes are found in the stratigraphy (Fig. 10c) and point towards a combination of kinematic sieving and length-wise sorting inside each granular avalanche (Fig. 10d-f) (van Steijn et al., 1995; Makse et al., 1997; Aranson and Tsimring, 2006; Sass and Krautblatter, 2007). Dry avalanching processes are therefore considered to be common for the studied high (>36°) slope angle scree deposit. While the sediment build-up takes place continuously, avalanching of the accumulated sediments is limited to dry conditions which creates the characteristic layering.

5.4 Contributions of aeolian processes

Aeolian influences on the development of fine scree deposits are often underestimated and usually associated with the removal of larger clasts in extreme events such as blizzards or by moderate gale force winds (>14 m s⁻¹) (van Steijn et al., 2002). In other studies the aeolian influence on fine sediments is usually of niveo-aeolian origin, whereas only few putative examples are known where wind-induced erosion of overlying rock faces contribute directly to the liberation of coarser materials and clasts (van Steijn et al., 2002). Based on our field observations and wind tunnel simulations of the removal of the volcanic glass we find that this material can be removed by a moderate to fresh breeze (<10 m s⁻¹) and such conditions occur frequently in the southern highlands of Iceland (Table 1). Although the velocities and flow turbulence of the wind may be aggravated by the local topography, both meteorological stations show similar wind conditions over the 5 year observation period in favour of a high occurrence of the observed deflation processes. We therefore believe that the given records in Table 1 reflect the region's meteorological conditions, which allows the use of this data for the research field site.

Analyses of the scree sediments and the source areas showed a clear numerical and statistical
differences between the distributions. The scree cone sediment (D50 = 821 µm, D90 = 2855 µm) is depleted in the silt and enriched in larger sands in comparison to the source area on the overlying rock face (D50 = 297 µm, D90 = 1255 µm). The notable enrichment of large particles and depletion in silt particles suggests a highly selective mechanism to influence the distribution and formation of the scree cone sediments. Aeolian deflation of the rock face and sediments offers a plausible mechanism that is sufficiently explaining the observed differences between the particle-size distributions, whereas fluviatile processes must be less important. Silt is easily carried aloft and away from the hillslopes by prevailing winds and gusts. The transport length of excavated material along the steep rock face further increases this effect by injecting clay and silt fractions into even modest winds. Larger particles are gradually excavated and transported down-slope under the influence of gravity by which they dominate the particle-size distribution of the scree sediments. As such an aeolian deflation mechanism permanently modifies the texture of the sediment by the selective removal of the fine textures. Favourable conditions for aeolian contributions may indeed be limited throughout the year, but their effects during single events can be much stronger compared to other processes which only redistribute the sediment. The contribution of this aeolian deflation mechanisms to the development of the scree slopes is corroborated by field observations during dry and windy conditions (Fig. 13).

Overall, we can conclude that individual rock particle fall and avalanching of accumulated sediment in dry conditions (deposited by a multitude of processes that includes aeolian excavation) control the observed morphometry and stratigraphy of the scree deposits. Aeolian deflation permanently modifies these sediment either in-situ or during transport which explains the observed textural differences between the scree and the original parent rock. Although the deflation mechanism proposed here has not previous been reported, more work is still required to fully understand the scale of these processes in the development of stratified slope deposits of friable volcanic ash in subarctic environments.

5.5 Planetary occurrences of the Icelandic field processes

Volcanic glass such as the Bláhnúkur hyaloclastites in Iceland are an interesting analogue material for Mars due to the parallels between the formation of subglacial eruption products on Earth and the eruption mechanisms in contact with (sub)surface ice bodies on Mars (Allen et al., 1981; Bishop and Pieters, 1995). With some constraints we can use the aeolian mechanism proposed here (deflation of fines by the wind followed by excavation, transport and sedimentation of sands under the influence of gravity) as a model for the recently active gully-systems observed on various crater walls on Mars (Balme et al., 2006). Several hypotheses have been put forward for either dry or wet out-flow forming processes inside these gullies (Hartmann et al., 2003; Hugenholtz, 2008; Pelletier et al., 2008; Coleman et al., 2009). We propose an alternative, erosive aeolian mechanism parallel to depositional aeolian mechanisms suggested for example by Treiman (2003). The micro-topography of pre-existing rills and gullies (formed during past climates) can sufficiently increase the turbulence and shear stress in the present atmosphere of Mars to entrain fine textures from the regolith by processes such as dust-electrification (Merrison et al., 2007; 2011). Larger particles excavated from the regolith then become available for transport down-slope while being channelized through the existing chutes (gullies), analogue to parts of the steep-sided walls in Grænagil on Iceland. Sufficient sediment build-up at intermediate storage areas inside gullies on Martian hillslopes and crater walls can then create localised avalanching when the static angles of repose of the accumulating sediment is exceeded. Triggering of such granular avalanches
from within the gullies on Mars can easily be initiated by winds which are also capable of mobilising larger sand particles in the present environment (Silvestro et al., 2010; Bishop, 2011; Bridges et al., 2012a).

6. Conclusions

Subglacial and post-glacial volcanism have played a prominent role in landscape evolution of the present-day surroundings of Bláhnúkur. The regional development is driven by the basal erosion of the hyaloclastite rock face and undercutting of scree sediments by the Brennisteinsölédukvísl stream inside the Grænagil gorge. Scree sediments are formed by alternating erosion processes on the overlying rock face throughout the seasons, which eventually results to avalanching of sediments in dry conditions across the pre-existing slope deposits. Although we do not exclude the influence of the other depositional processes, agents involving water or other forms of interstitial lubrication lack a morphometric and stratigraphic proof in the sedimentary record. Based on this stratigraphy and morphometry we cannot reject our hypothesis as we found dominant contributions of freeze-thaw cycles in the snow record and influences from the wind which both contribute to the development and modification of these landforms. The influence of the wind is highly relevant in dry conditions when it drives the deflation of fine material in accumulated scree sediment and it causes larger particles to be excavated from the overlying rock face. The threshold conditions required for particle removal in wind tunnel simulations agree with the range of frequently occurring winds in the region. Although the processes involved in the presented case study occur in a specific Icelandic environment, we suggest that deflation processes acting on hillslopes with a moderately-cohesive rock matrix are more widespread in dry and cold environments than presently understood and recognized. We propose that these mechanisms can therefore also occur in the present climatological conditions found on planet Mars.