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

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Rhyolitic hyaloclastites with obsidian fragments exposed at the slopes of Bláhnúkur, Torfajökull
Chapter 3
Physical weathering of glaciovolcanic glass

Abstract
Fragmental volcanic glass or ‘hyaloclastite’ is a common glaciovolcanic eruption product that occurs in basaltic and rhyolitic variants. These types of material are often found in Iceland in periglacial environments where they are susceptible to various forms of physical weathering and particle modification. This includes ice growth during freeze-thaw cycles and abrasion during aeolian transport. Physical weathering of rhyolitic volcanic glasses differs from basaltic glass due to the lack of edifice strengthening and consolidation. However, these materials are much rarer and they have been less studied and this emphasises the need for characterising the various facets of their mechanical modification. In this study we measured the weathering properties of rhyolitic hyaloclastites from the Bláhnúkur edifice in Torfajökull (Iceland) using simulations of freeze-thaw cycles and low-energy aeolian transport. Nearly identical particle size distributions were formed in the freeze-thaw simulations as in brittle fracturing experiments when glass was subjected to uniaxial stress. Brittle fracturing from frost weathering and compressive loading produced similar particle distributions. This comparable behaviour suggests that ice crystallisation and volumetric expansion has the strongest effect on pumiceous particles with vesicles and interparticle pore spaces >1000 µm. In contrast, abundant surface pores >1 µm (measured by high-pressure mercury intrusion) may only contribute to surficial crack propagation. Compared to the effects of ice weathering, particle abrasion during simulations of wind-induced transport was found to be a very slow-going process. Non-stop tumbling of 300-600 µm samples for 15 weeks, or 578-715 km of transport, only led to textural alterations at the limit of detection. Physical weathering of shards and pumiceous particles marginally increased the portion of <10 µm particles, which may increase the risk to health hazards after chronic exposure by inhalation. The experiments presented in this study illustrate too that accessible techniques can be applied to understand fracturing dynamics and the contribution of physical weathering to the formation of new and potentially hazardous respirable sediment textures.
1. Introduction

Fracturing of glassy subglacial eruption products (known as hyaloclastite or as ‘móberg’ in Icelandic) results from the initial magma-ice and magme-melt water interactions during formation and from post-eruptive environmental processes. Recent eruptions from the Eyjafjallajökull have given insights in the eruption evolution (Sigmundsson et al., 2010; Borisova et al., 2012; Magnússon et al., 2012) and deposition of these types of eruption products (Donnovan and Oppenheimer, 2011; Edwards et al., 2012). Such glaciovolcanic eruptions have received much attention due to immediate syneruptive environmental effects (Colette et al., 2011) and health hazards (Gudmundsson, 2011; Carlsen et al., 2012), but these eruptions only illustrated the syneruptive effects of glass fracturing. The Icelandic landscape is littered with examples of deglaciated subglacial edifices where these eruption products are currently being modified. Suspension of ash from recent eruptions (Leadbetter et al., 2012), wind-induced transport in glass-rich sandy deserts (Arnalds et al., 2001, 2012; Baratoux et al., 2011) and contributions of freeze-thaw and aeolian processes to the erosion of hillslopes from subglacial landforms (de Vet and Cammeraat, 2012) exemplify some of the environmental processes that affect glaciovolcanic glasses. Weathering of the basaltic glass often leads to rapid edifice strengthening and reduces effects of physical erosion, while rhyolitic glasses hardly consolidate at all (Jakobsson and Gudmundsson, 2008). The physical modification of this silicic type of glass is primarily driven by mechanical forces created by microscopic (Scherer, 1999) and macroscopic ice growth (Jackson and Chalmers, 1958) and wind-induced transport of sand-sized fractions (Greeley and Iversen, 1985). These processes are especially important in cold periglacial environments where rates of chemical weathering are much lower (Peltier, 1950).

Our understanding of the post-eruptive environmental fate of rhyolitic glaciovolcanic glasses is still poor and emphasises the need for further study. The aim of our study is to understand the scales and contributions of frost-weathering and wind-induced transport to the modification of rhyolitic glaciovolcanic glass. We therefore focus on a specific eruption product from a well-studied subglacial rhyolitic edifice in Torfajökull (Iceland).

1.1 Fracturing by ice

There are different pathways in which the permeable glassy deposits of tindars (hyaloclastite ridges) and tuyas (emergent sub-ice volcanoes which become table mountains after deglaciation) can weather. Most frequently ice wedging and thermal stress produce sufficient mechanical forces inside the rock matrix to promote crack propagation, fracturing and particle excavation. Effects from thermal gradients that exceed 2°C min⁻¹ are much less relevant for the fracturing at the fine particle scale of the granular glass that we consider here (Simmons and Cooper, 1978; Hall, 1999). Ice nucleation in pores therefore occupies a prominent role in the mechanical weathering of these materials (Walder and Hallet, 1986; Scherer, 1999). Since the semantics of the term ‘pore’ differs per discipline, we distinguish here between two scales. The finest scale covers the nanometre-sized surface pores that are present at the surface of individual particles. Interparticle pores on the other hand are the vesicles and voids between packed particles which cover the micrometre to millimetre size range. Especially surface pores are ideal nucleation sites for starting ice growth as these pores maximize the surface area and contact with the growing ice crystal (Scherer, 1999; Scherer and Valenza, 2005). Encroaching ice can entrap water inside pores >100 nm and eventually generate a pressurisation stress that is sufficient for superficial fracturing (Scherer, 1999; Scherer and Valenza, 2005). This mechanism applies to weathering of all granular materials such as eruption products and
industrial materials such as concretes (Scherer, 1999). In contrast, volumetric expansion of ice pressing against the glass matrix during its formation is the dominant process inside much larger voids. Forces generated by the growing ice are strong enough to segregate material, heave particles (Jackson and Chalmers, 1958; Walder and Hallet, 1986; Scherer, 1999) and they can even shatter the toughest granitic rocks (Matsuoka and Murton, 2008).

Fig. 16 - Overview of the Bláhnúkur region near the intersection of the Torfajökull caldera and the Veidivötn fissure swarm on the edge of the Eastern Volcanic Zone (EVZ) and Southern Flank Zone (SFZ) in Iceland (a), fissure data: Einarsson and Sæmundsson (1987). The study area in the southern central highlands (b) is dominated by migration of local hydrological networks and the narrow incision of the stream after the Laugahraun eruption. Fissures and emplacement units were inferred by Tuffen et al. (2001). Sampling sites of hyaloclastites are indicated (c), letters highlight the use of each sample in the experiments in this study; H = high-pressure mercury intrusion, T = Tensile strength testing, A = abrasion experiments. Maps modified from chapter 2.
1.2 Abrasion by wind

Loosely bound granular volcanic glass can also be modified during aeolian transport. Repetitive impacts create cracks and are dependent on the impact velocities from both low-energy rolling and reptation, or from high-energy saltation of particles. Particle morphology and impact velocity therefore dictate the type of surface fracturing (Marshall et al., 2012). Impacts from rounded particles have been shown to produce circular ‘Hertzian’ fractures, while impacts by angular grains with sharp edges produce ‘Boussinesq’ crack systems (Marshall et al., 2012). The latter is mostly relevant for glaciovolcanic glass due to the angular particle morphology. Boussinesq cracks consist of intersecting plains of radially extending fractures from the impact point and lateral pseudo-conchoidal cracks (Greeley and Iversen 1985; Marshall et al., 2012). Shards removed in these fracture zones expose new surfaces which can be chemically reactive and create mineralogical alterations of the sediment over time (Merrison et al., 2010; Mangold et al., 2011). The particle surface therefore preserves a record of the environmental conditions, rates of modification and the maturity of the aeolian system (Heiken and Wohletz 1985; Marshall et al., 2012).

Both mechanical processes discussed above create new materials which are often fine enough to be inhaled. In simulated saltation experiments by Merrison et al. (2010) respirable fractions <10 µm (PM10) increased by 10%. Chronic exposure to such fractions can lead to inflammatory responses in the respiratory pathways and even asthma (Horwell and Baxter, 2006; Gudmundsson, 2011). So far, no distinction has been made between the origins of fine respirable fractions and possible mechanisms that introduce them in the environment. Shedding light on the general contribution of physical weathering to the availability of respirable fractions is therefore also valuable for assessments of respiratory health hazards.

2. Bláhnúkur in Torfajökull, Iceland

Bláhnúkur is one of the youngest glaciovolcanic landforms in the Torfajökull caldera complex, which is presently part of the Fjallabak Nature Reserve. It is located in the southern central highlands of Iceland at the intersection of the Veiðivotn fissure swarm and the caldera complex (Fig. 16). The hyaloclastite layer formed during the effusive eruption of Bláhnúkur is only a few tens of meters thick and covers an older rhyolitic core (Tuffen et al. 2001; McGarvie et al., 2006). The pyramid-shaped edifice rises some 350 meter above the surrounding rhyolite plateau to a summit altitude of 945 m.a.s.l. Local palaeo-ice sheet thicknesses at the time of eruption have been inferred using geologic features, magma degassing and nearby similarly aged tuyas. These features indicate that the area was once covered by an ice sheet of at least 350-400 m thick during the Weichselian and it was confirmed by magma-degassing studies (Owen et al., 2012). The erupted volumes at Bláhnúkur and adjacent Laugahraun show signs of partial mixing of rhyolitic magmas from Torfajökull with basaltic sources (Blake, 1984; Tuffen et al., 2001, 2002a), which is illustrated by millimetre to even centimetre-sized basaltic inclusions in the matrix of the rhyolitic hyaloclastites. Emplacement mechanisms of the subglacial eruption products and lava lobe-hyaloclastite facies are well-described by Furnes et al. (1980) and Tuffen et al. (2001), who propose that mass movements (i.e. sliding and slumping) in the subglacial cavern contributed to the morphogenesis of diagnostic features and strata presently exposed in some of the gorges around the edifice. In this study we focus on the freshly excavated materials inside Grænagil, a roughly NE-SW trending gorge on the north flank of Bláhnúkur. Weathering of the deposits in the gorge is promoted by local meteorological conditions that create ~100 freeze-thaw cycles at an average year temperature of 0.5-1.5°C above freezing (Table 2). Deflation of fine materials on scree sediments and
the overlying steep rock face takes place by moderate winds and gusts during the snow-free months in summer. These two forms of physical weathering are prominent and contribute to the overall erosion of the bright green and grey hyaloclastites exposed inside the gorge (Fig. 17; de Vet and Cammeraat, 2012). The accessibility and geological setting make Bláhnúkur and its eruption products globally the best-studied rhyolitic subglacial edifice. This provides a well-defined basis to use it as a case study for which we can study the physical weathering properties of rhyolitic hyaloclastites driven by local environmental conditions.

3. Experimental simulations of physical weathering

Analogue to the conditions observed in the field we discriminate in our experiments between the two mechanisms that actively contribute to the erosion and modification of the Bláhnúkur hyaloclastites: (i.) the compressive and expansive forces of ice nucleation in relation to fracturing of glasses during freeze-thaw cycles and (ii.) the effects of wind transport on the abrasion and textural modification of sand-sized materials. As these weathering processes are closely linked to particle size, we used only the particle diameters that are involved in these processes in the field. Gravel-sized pumiceous glass particles (2-32 mm in diameter on the Wentworth scale) contain pores of both scales defined in the introduction and these particles were therefore used for understanding the effects of expanding ice in freeze-thaw cycles. Finer glass shards sieved over 300-600 μm mesh were used in the wind abrasion experiments as these are, contrary to the large pumiceous particles, easily mobilised by local winds.

Eight Bláhnúkur hyaloclastite samples were collected from the walls of the Grænagil gorge (Fig. 16c). Rock outcrops of moderate consolidated breccias with pumiceous glass fragments were sampled to depths of 10 cm, where according to Hinkel (1997) the largest effects of freeze-thaw cycles are expected as a result of thermal diffusion and water infiltration. Four samples were collected from a slope section formed by slumping in the subglacial eruption cavern, whereas the other four were taken from a formation formed by sliding (Fig. 16c). These sections correspond with the detailed descriptions of breccias B and C in Tuffen et al. (2001).

### Table 2 - Overview of the thermal conditions at nearby meteorological stations located in Vatnsfell and Lónakvísl in the central highlands of Iceland. Table modified from: de Vet and Cammeraat (2012).

<table>
<thead>
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<th>Meteorological conditions</th>
<th>Year</th>
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<tr>
<td>Minimum recorded temperature [°C]</td>
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<td>-16.1</td>
<td>-17.3</td>
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<tr>
<td>Maximum thermal gradient [°C min⁻¹]</td>
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<td>0.13</td>
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<td>0.19</td>
<td>0.05</td>
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<td>Freeze-thaw cycles</td>
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<td>117</td>
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<td>Lónakvísl</td>
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<td></td>
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<td>-</td>
<td>-</td>
<td>30-9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* From hourly temperature measurements
b Not measured or no data available

F208 road access to Landmannalaugar, data from: Vegagerðin (Icelandic Road Administration)
3.1 Ice-induced fracturing

In experimental simulation of freeze-thaw cycles a trade-off needs to be made between either field-analogue conditions (e.g. Potts, 1970), or by constraining the parameters influencing the freeze-thaw (e.g. Matsuoka and Murton, 2008). The foremost aim was to distinguish between internal damage (pore pressurisation) and external damage (volumetric ice expansion) that causes the glass to fracture during freezing of water inside pumiceous glass particles. Five of the eight sampled locations contained sufficient material of the size fractions for the experiments described below. Three different experiments were set-up, where the latter two were used to interpret the fracturing behaviour in the first experiment:

1. **Environmental laboratory simulations:** tubes were filled with 1.5 grams of 1-3 cm³ sized pumiceous particles and 1.0 ml water was added to saturate the particles by capillary rise in vesicle networks or by full immersion. Sealed tubes (with a repetition of n=12 per sample site) were frozen to -19°C over a period of 16 hours to reach similar temperature extremes as in the field (Table 2) and subsequently thawed over 8 hours at +5°C. After 10 cycles the individual particles fractured to finer particles of various grain sizes. The residue <1400 μm in the 12 tubes was homogenised into a single sample for each site, pre-treated with an Na₄P₂O₇·10H₂O dispersing solution (Eshel et al., 2004) and then measured using a Sympatec HELOS laser-diffraction particle sizer to measure the grain-size variation produced by ice-induced fracturing.

2. **Surface porosity of the glass:** the porosity of bulk samples consisting of ten ~0.25 cm³ particles were measured using high-pressure mercury intrusion at pressures up to 400 MPa (with n=9, independent repetitions) for each of the 5 sampled locations. These measurements were made using a PASCAL 440 porosimeter from Thermo and allowed us to measure the pore diameters at the glass surface and the bulk density. Together with the measured vesicle-free skeletal densities (ρ_{tie}) we obtained the degree of porosity on the exterior of the particle that is accessible to ice. Peaks of modal pore diameters were statistically tested using an analysis of variance (n-way ANOVA) to analyse if these are a common property of the Grænagil particle population or dependent on the sampled location, measurement repetition or the combination of these two.

3. **Brittle fracturing from ice expansion:** ice expanding inside vesicles exerts a force and as such a deflection of the thin glass walls inside the pumiceous particles. When the deflection reaches a critical level it causes fracturing of the glass. Measuring the deflection at which the glass experiences brittle deformation is made possible by uniaxial loading of samples using a tensile strength test bench M359-20CT from Testometric. Similar pumiceous glass particles as in preceding experiments were compressed between two rigid plates to 80% of their original height (also with n=9 independent repetitions). Measurements of the forces were obtained with an accuracy in the range of 10⁻² N per compression step of ~5.8 μm. As these pumiceous particles are very friable, it was not possible to produce a standardised test volume and contact surface for a conventional stress-strain analysis. Fast-Fourier-Transform (FFT) analyses of the compression data were therefore used to calculate the critical deflections at which the material fractured. Peaks representing these critical deflections were extracted from the periodograms produced by the FFT analyses. The cumulative distributions of fracture distances were compared to establish if the deflection for brittle deformation is a collective property for all the sampled locations. Grain-size distributions of the residue <1400 μm were measured for a comparison to the freeze-thaw experiments.
3.2 Aeolian transport simulations

Abrasion of granular sediments during transport can be experimentally simulated using continuous axial tumbling. Such set-ups have been used for understanding interactions and abrasion of particles in pyroclastic density currents (Kueppers et al., 2012), volcanic and fluviatile debris flows (Kaitna and Rickenmann, 2007; Caballero et al., 2012), textural alterations from simulated saltation impacts and subsequent mineralogical alteration of the sediments (Merrison et al., 2010). We studied the abrasion of the angular glass particles using six rubber-covered drums with a 10 cm diameter that rotated at 50 rpm (300 °/s). Fig. 18 shows a schematic description of the set-up. In rotational set-ups unmixing effects from axial segregation (Aranson and Tsimring, 2006) would bias larger particles over smaller particles in their transported distance over time. We filled the drums below the axis of rotation \((a_r)\) to overcome this problem and ensure continuous mixing. We use this set-up as a model for low-energy transport of sediment in summer months by rolling and reptation below saltation thresholds. Reptation is a process in which particles are liberated by (high-energy) saltation impacts that in turn hit the surrounding substrate at much lower impact velocities. Such low-energy aeolian processes account for the majority of mobilised sediments (Kok et al., 2012). The size range of 300-600 µm inside the drums represents a size fraction that is most susceptible to the effects of such low-energy interactions from rolling and reptating particles (Kok et al., 2012). Indications from past tumbling experiments with vesiculated materials suggest that the highest degree of fracturing occurs in the first week or even hours (Kueppers et al., 2012). We therefore had a weekly sample rate during the first five weeks of tumbling and continued the experiment for a total of 15 weeks. After each week of tumbling a ~15 g subsample was extracted from the bulk and treated according to the same protocols as in the other experiments. The measured size distributions were evaluated using Pearson \(X^2\) tests to assess if significant changes to the material and particle distributions had occurred.

**Fig. 17** - Focus-stacked microscope images show examples of particle morphologies of (a) 300-600 µm granular glass fragments and (b) gravel-sized pumiceous particles that comprise the Bláhnúkur hyaloclastites at sample site HTA-6. Visible are the voids and vesicles and the numerous sharp edges of the particles at different particle scales. These properties play a role in the weathering pathways of these materials under the influence of ice and wind. Note the scale difference between the two images.
The particle size distributions formed by the fracturing of the original centimetre-sized particles during the 10 freeze-thaw cycles are shown in Fig. 19 (black lines). The damage from ice growth during freezing most notably created sandy textures. Due to distinct scale effects in ice-induced weathering, porosity measurements and uniaxial loading may allow the interpretation of the measured particle size distributions to determine the type of fracturing. Brittle fracturing of particles during uniaxial compression tests (Fig. 20) shows numerous small peaks. Each peak represents a build-up of force which is suddenly released when the glass fractures. This highly variable signal of successive fracturing events is superimposed on a longer frequency, larger amplitude signal that may represent the effects of the changing contact area during compression (Fig. 20a). Frequency analyses allowed us to extract the recurring critical distances at which fracturing took place, visible as peaks in the periodograms (Fig. 20b). After normalisation we extracted these peaks based on a relative threshold of 0.01% with surrounding data points. The interquartile range (middle 50%) of critical deflections cover a
range of 25-75 μm (Fig. 20c). Inspection of the peak distribution of the five sample sites shows that the notches of the box plots and medians overlap. The range in critical deflections are therefore not significantly different between the sampled locations and can be considered as a collective material property. Particle sizes formed by brittle fracturing are shown in Fig. 19 (blue lines) and are very comparable to the distributions formed by ice-growth during freeze-thaw cycles.

Effects of surficial fracturing by ice can also result from the pressurisation of surface pores. Results of high-pressure mercury intrusion measurements to obtain these pore diameters are shown in Fig. 21. The pore diameters are highly comparable per sampled field location, although at first sight some spatial variability appears to be present between the different locations. On closer inspection the modal pore diameters appear to be of the same order of magnitude and coincide with the distinct peaks present in all the intrusion measurements (compare peaks in e.g. Fig 21b and 21c). Using an analysis of variance we established that the higher abundance of pores with those diameters is not an effect dependent on the sampled location, repetition of measurement or an interaction of both (with $p = 0.12, 0.79$ and 0.86 respectively).

Abrasion by low-energy particle collisions of wind-blown sediments was simulated by continuous axial tumbling for several weeks on end. The experiment parameters and covered distances of the sediment per drum are shown in Table 3. After 15 weeks of tumbling (or 578-715 km of transport, see table 3) the distributions of particle sizes show only minute shifts to smaller textures (Fig. 22). These changes are not statistically significant on the whole of the size distribution with a Pearson's $X^2$ test and often fall within the measurement accuracy.

Fig. 19 - Size distribution of the sediment produced by the fracturing of single pumiceous particles ($d > 10$ mm). Nearly identical particle size distributions are produced after 10 freeze-thaw cycles from ice-induced fracturing (in black) and during brittle fracturing from uniaxial loads (in blue). Pumiceous particles used in the experiments were taken from sampled locations HT-2, and HTA-4 through to 7. Similar-sized particles were used for the physico-mechanical measurements presented in Fig. 20 and Fig. 21.
Fig. 20 - Frequency analyses from the uniaxial loading of gravel-sized pumiceous glass particles with a tensile-test bench. Figure (a) shows the raw data of the measured force at a given deflection for nine different pebble-sized particles from location HT-2 during the compression of an individual particle. Figure (b) shows the dominant periods (peaks marked with blue triangles) of recurring deflection steps at which fracturing takes place, as determined using Fast Fourier Transform analyses. Figure (c) shows boxplots of these critical deflections when brittle fracturing occurs for each of the 5 sample sites inside the gorge (see Fig. 16 for their locations in a map).
Fig. 21 - Porosimetry data measured using high-pressure intrusion of mercury for 5 different sampled locations. Each line in the graph was measured for ten pumiceous glass particles and each graph therefore shows nine independent repetitions ($n=9$). Values for skeletal densities ($\rho_{\text{He}}$) and porosity in each graph are the site-specific averages. All samples with the exception of sample HTA-7 are deposited in a subglacial hot avalanche (see Fig. 16).
However, the peak of respirable fractions <10 μm shows some change by broadening and increased contribution to the sediment. Comparing the surface below the graph of the <10 μm fraction before and after 15 weeks of tumbling using a paired t-test shows that the quantity of respirable fractions significantly increased by 0.03-0.07% ($p \leq 10^{-3}$). This is equivalent to a production of 0.7-1.6 kg of respirable dust per m$^3$ of mobilised sediment, assuming an average skeletal density from data in Fig. 21 of 2.4 g cm$^{-3}$.

5. Discussion

Common basaltic hyaloclastites are a hydrothermally unstable and physically weak type of volcaniclastic rock, which makes them easily chemically weathered by water and heat (Frolava, 2008). Studies of 2-2.5 Ma old basaltic glasses have shown that over time vesicles are filled with secondary minerals which changes physico-mechanical characteristics such as porosity and permeability (Frolava, 2008; Franszon et al., 2010). In contrast, rhyolitic glass is known to be more resistant to chemical weathering than basaltic glass (Jakobsson and Gudmundsson, 2008) and experiences no consolidation or strengthening. No clear indications are visible in microscope images of the material that strong chemical weathering has affected the Bláhnúkur hyaloclastites in Grænagil, although some chemical weathering has led to the formation of clays and zeolites (Denton et al., 2009). Vesicles of the Bláhnúkur glass were prominently clear from filling and cementation by these minerals (see Fig. 17) and this illustrates that little resistance is offered by chemical weathering to physical erosion. Physical weathering processes are therefore especially relevant for modifying rhyolitic glass deposits.

Fig. 22 - Particle size distribution following low-energy abrasion before (in blue) and after 15 weeks or 500-700 km of continuous axial tumbling (in black) using sands from sampled locations HTA-4 through to 7, A9 and A1 (also see Table 3). Modification rates at intermediate stages were insignificant after 1-5 weeks of tumbling and have therefore been omitted in the graph for clarity.
5.1 The effects of ice inside vesicles and surface pores

Bláhnúkur hyaloclastites are dominated by a fine-grained matrix that contains larger pumiceous particles. The dominance of small particle sizes reduces particle fracturing from high thermal gradients, which is further diminished by insulating properties of snow blankets. Measured thermal gradients in the field were found to be below the 2°C min⁻¹ gradients of the fracturing threshold (Table 2) and show that the weathering and modification of these materials requires an additional agent such as infiltration of water. In sub-freezing conditions, ice nucleation occupies a prominent role in the weathering of the Bláhnúkur hyaloclastites as shown by effects of frost heave (ice expansion in pores between particles) in the excavation of particles during winter (de Vet and Cammeraat, 2012). At the level of individual particles, the influence of nucleating ice will differ depending on particle size. The friable and vesiculated nature of the pumiceous glass is instrumental for the fracturing by volumetric ice expansion and will likely affect only the large particles in the breccias. As the distributions formed by freeze-thaw cycles in Fig. 19 are very comparable with the distributions formed uniaxial loading, it leads us to conclude that the distributions in the freeze-thaw experiments are primarily the result of brittle fracturing of the pumiceous glass matrix. Ice expansion is known to generate forces of sufficient magnitude to cause this type of brittle deformation (Matsuoka and Murton, 2008). As water expands 9% in volume during freezing (Potts, 1970) brittle fracturing may result from ice nucleating inside vesicles, but also from the outside of a particle in the interparticle pore spaces. In the latter case this will require pores with a minimum diameter of 1000 μm to produce the 25-75 μm deflection of the glass matrix to cause the same wide-spread brittle
fracturing as in the uniaxial loading experiments. Ice-induced weathering of pumiceous glass particles in the hyaloclastite matrix is therefore the most prominent mechanisms for producing new sandy textures (d<700 μm). These fracturing effects can potentially be higher for the more vesiculated (20-70%) rhyolitic eruption products found elsewhere in Torfajökull (Tuffen et al., 2008) as these particles contain more pores and vesicles for ice nucleation.

For smaller particle diameters, where vesicles are absent, other types of frost weathering may contribute to particle modification. Superficial fracturing of a particle's surface only occurs if the diameter of the surface pore in which stress is being generated, exceeds the size of nearby flaws in the glass (Scherer, 1999). Detailed mercury intrusion measurements show that the modal pore diameters in Fig. 21 are a common property of the Grænagil particle population, characterised by surface pores >1000 nm. Above 100 nm ice is capable of growing from the outside into pores, which closes the pore and pressurises the water inside it to cause superficial fracturing. Pore pressurisation during freezing of the Grænagil glasses is therefore favoured by the μm-sized surface pores that can exceed many small surface flaws. Remarkably, no wide-spread superficial fracturing was observed during pore pressurisation with pressures up to 400 MPa using mercury intrusion (well-above the hydrostatic pressures created by ice encroaching into surface pores). We also see no clear contributory effects of surficial fracturing expressed in the particle size distributions after the freeze-thaw cycles (Fig. 19). Pore-pressurisation may therefore be of minor relevance for the modification of glass fragments in the Bláhnúkur hyaloclastite. This may signify that the glass surface lacks appropriately-sized surface flaws in respect to the measured pore diameters. Rhyolitic volcanic glasses therefore require a prior history of chemical weathering (perlitisation) to obtain flaws that contribute to internal damage during freezing (Denton et al., 2009; 2012). The formation of new surface flaws at the glass surface can also result from physical processes such as aeolian and gravitational transport, which we will discuss in the next paragraph.

Various lines of geomorphological and geological evidence indicate a subglacial formation of Bláhnúkur and these include orientations of columnar joints, glass hydration and perlitisation and the presence of subglacial till deposits (Tuffen et al., 2001). Measured particle properties such as a porosity of 10-20% (Fig. 21) also indicates a phreatomagmatic eruption environment (Mueller et al., 2011) that agrees with an eruption in a melt-water dominated subglacial cavity where rapid degassing, spalling and shattering led to the formation of the Bláhnúkur hyaloclastites. As the volatile content of Bláhnúkur glasses has been shown to depend on the subglacial cavity pressure (e.g. Tuffen et al., 2010; Owen et al., 2012), it suggests that some control is exerted on the chemical parameters that influence the viscosity and strength to syneruptive fragmentation. Surface porosity of glass particles is influenced by degassing of the magma and may therefore follow predictable patterns based on the confining glaciostatic pressure of the overlying ice mass. Such a common property is shown by the comparable peaks of measured surface pore diameters (Fig. 21). This is not unlike quantitative models derived for the relation between much larger vesicles morphologies and pressure by e.g. Macpherson (1984). Although the subglacial setting appears to have been favourable in controlling vesicle formation and fragmentation, parameterisation of these processes has been difficult in experimental settings (Martel et al., 2000). Samples used in this study represent only one ‘pressure depth’ and further scrutiny is required to establish if surface porosity is indeed related to degassing under the eruption cavity pressure and a such the associated palaeo-ice thickness, or whether it represents a property related to post-eruptive chemical weathering processes.
5.2 Simulated aeolian abrasion

Impacting sand grains during saltation produce up to 10 grains that subsequently impact the surrounding surface by reptation and rolling (Cooke et al., 1993). While these high-energy impacts from saltation are far more efficient in reaching favourable impact regimes for particle modification, these interactions are less abundant on the steep slopes if compared to the amount of low-energy interactions from e.g. wind- and gravity-induced rolling downslope (de Vet and Cammeraat, 2012). Low-energy particle interactions from creep, roll and reptation therefore encompass a substantial part of the impacts during aeolian mobilisation of sediments at Bláhnúkur (Kok et al., 2012). Simulations of granular avalanches inside similar rotating drums as our experiments show that avalanche velocities reach avalanche velocities that create particle collisions of 0.3 m s⁻¹ (Yang et al., 2008). These impact velocities are well below the impact regime of 1-10 m s⁻¹ for saltating grains (Marshall et al., 2012) and clearly show that the results of these experiments are reflecting the material’s response to low-energy transport processes in the field. The studied glaciovolcanic glass has been remarkably resistant to this form of abrasion. After 578-715 km of simulated aeolian transport, changes in the sediment’s texture are only noticeable by a marginal broadening of the <10 µm peak. As the Grænagil gorge is ~2 km long, these required distances for noticeable effects exceed the possible travel distances in the field. Similar to the outcomes of our abrasion experiments, no significant abrasion of glass particles was observed for volcanic glasses in other periglacial environments, where transport below and above wind mobilisation thresholds did modify other sediment types (Ayling and McGowan, 2006). Prolonged low-energy aeolian transport clearly lacks the power to substantially change sediments, even when these impacts are the most common type of particle interaction in the field. We therefore conclude that frequent low-energy transport of hyaloclastites by wind or gravity is incapable of significantly altering particle shapes and textures. Modification by frost weathering therefore seems most prevalent for the weathering and modification rhyolitic glasses.

Fig. 23 - The abrasion of the particle surface by impacts of angular grains in many ways resembles the damage caused by stones hitting the windshield of a car, as shown in this image. In amorphous materials such as glass, these ‘Boussinesq’ crack features are common at all scales of glass fracturing. Clearly visible are lenticular cracks radiating away from the impact point and lateral pseudo-conchoidal fractures where small chips of glass have been removed or are prone to removal by ice infiltration. (Windshield courtesy of W. and N. Remijn)
As shown by the changes in sediment texture, low-energy particle impacts may form minute Boussinesq fractures (illustrated in Fig. 23) in which shards can be removed from the particle surface. Even when the quantity of intersecting fracture zones is insufficient for removing shards at substantial rates, physical weathering by ice benefit from the production of these fractures. The formation of new flaws thus increases crack propagation whenever stress is being generated by pore pressurisation and ice expansion during freezing. This ultimately suggests that over time, aeolian and gravitationally transported eruption products in deglaciated environments are more susceptible to combinations of physical weathering processes, compared to eruption products being weathered in situ.

5.3 Physical weathering and health

Conditions favourable for large-scale dust suspension occur frequently and are notorious in the coastal areas and the glass-rich sandy deserts in Iceland (Arnalds, 2010; Leadbetter et al., 2012). These suspension events show that the abundance of fine dust in the environment exceeds the rates of chemical weathering and soil uptake that would otherwise inhibit further distribution. Ashes of the eruptions of Eyjafjallajökull and Grímsvötn in Iceland have raised several health concerns (Gudmundsson, 2011; Carlsen et al., 2012). Reflecting more broadly on the behaviour of basaltic and rhyolitic volcanic glass poses the question at which rate physical weathering contributes to the post-eruptive formation of new respirable fractions in these cold periglacial environments. During the 2010 Eyjafjallajökull eruption glassy ash particles of 300-600 µm were deposited as far as 20 km from the eruption site (Gudmundsson et al., 2012), allowing particle modification by wind-induced abrasion to introduce new respirable fractions into local settlements. However, from our abrasion experiments we find no evidence to support the hypothesis that materials are subject to high-rate secondary fracturing from frequent low-energy aeolian transport. Perhaps only under extremely windy conditions when saltation transport of these materials can occur, surficial fracturing can lead to the production of respirable fractions on sufficiently large rates for detrimental health effects. This view is supported by experimental studies that have shown that abrasion of angular material, even by saltation, is a very lengthy and gradual process (e.g. Greeley and Iversen, 1985). Much more important may be the influences of seasonal interactions in local periglacial conditions as discussed in the preceding section. By freezing of gravel-sized particles alone, more respirable material <10 µm is formed compared to aeolian transport. Since physico-mechanical properties of volcanic glasses vary from eruption to eruption, event-specific experimental simulations would be required to properly assess these physical weathering processes. Similar to other assessment methods for particle sizes (Horwell, 2007), the methods explored here are well-accessible. They can potentially be used to complement health assessments, which so far have structurally overlooked the long-term contribution of physical weathering of glassy eruption products in subarctic or high-alpine periglacial environments.

6. Conclusions

In contrast to basaltic volcanic glasses, rhyolitic hyaloclastites are not consolidated by chemical weathering. This makes these glass deposits much more susceptible to physical weathering and promotes different pathways for the geomorphological development of landforms composed of rhyolitic glass. Laboratory simulations have allowed us to assess the scale-dependency and effects of physical weathering for a rhyolitic glaciovolcanic glass (summarised in Table 4). Measurements of the physico-mechanical properties can be used to understand the aptitude
of glaciovolcanic glass to various physical weathering mechanisms. Fracturing by ice growth clearly drives the formation of new sandy textures in pumiceous glass deposits on relatively short time scales. These processes are favoured by the large surface pores and vesicles formed initially by the subglacial eruption conditions. Modification rates by aeolian transport of glass shards that dominate the bulk of these breccias is near to neglectable. However, pre-existing micro-cracks and the formation of new micro-cracks at the particle surface from aeolian particle transport potentially increase the total rate of modification in combination with frost weathering. These processes highlight the importance of seasonal interactions and the interdependency of physical weathering mechanisms that affect glaciovolcanic eruption products in periglacial environments.

Table 4 - Effects and scales of mechanisms contributing to physical weathering and modification of a rhyolitic volcanic glass, based on laboratory experiments and the physico-mechanical characteristics of the studied rhyolitic glaciovolcanic glass.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Location</th>
<th>Affected particle size (µm)</th>
<th>Process scale (µm)</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice nucleation</td>
<td>pumiceous glass, large vesicles, interparticle pore space</td>
<td>&gt;5000</td>
<td>&gt;25</td>
<td>maximum deflection sustainable by glass walls of vesicles is exceeded, brittle fracturing occurs, leads sandy textures</td>
</tr>
<tr>
<td>volumetric expansion (external damage)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hydrostatic pressure (internal damage)</td>
<td>surface pores</td>
<td>&gt;10</td>
<td>&gt;1</td>
<td>crack propagation, superficial fracturing, chipping, lateral cracks, mineralogical alterations, textural change</td>
</tr>
<tr>
<td>Aeolian abrasion</td>
<td>exposed particle surface</td>
<td>300-600</td>
<td>&lt;10</td>
<td></td>
</tr>
</tbody>
</table>