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

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Barchan dunes imaged by HiRISE in the Vastitas Borealis region, situated in the Northern Lowlands on Mars.
Chapter 6
Synthesis - environmental fate on Earth and Mars

1. Synthesis
The final chapter of this dissertation provides a synthesis of the preceding chapters. The first section aims at discussing the environmental fate of volcanic glass on Earth and those found at different latitudes on Mars. The second section provides a more general conclusion of this dissertation and gives a tabular summary of the individual answers to the research questions, based on the chapter conclusions and synthesis. In the third and final section of this chapter, new directions are proposed for future research into the environmental behaviour of glaciovolcanic glass on Earth and Mars.

1.1 Glaciovolcanic glass in Iceland
During the eruption of volcanoes underneath or in contact with ice, magma shatters explosively and this result to the formation of fine-grained glassy breccias. This is certainly the case for the hyaloclastites of Bláhnúkur, whose formation was fully subglacial. The edifice is an a-typical tindar in the sense that it did not form from the start as a fissure eruption, but rather erupted along fissures through a pre-existing rhyolite core. Although chemical weathering (perlitisation) of rhyolitic glass takes place and leads to the formation of zeolites and clays (Denton et al., 2009), silicic glasses are generally found to be metastable and no consolidation and strengthening by their weathering products occurs. This is the key-difference between chemical weathering of basaltic and rhyolitic glasses. The lower cohesion of Bláhnúkur’s rhyolitic glass outcrops causes the edifice to be actively modified by local environmental processes. Weathering of these outcrops is largely controlled by the granular nature of glass breccias that are composed of various particles diameters, creating different weathering pathways due to different physico-mechanical properties per particle size. The fine-grained glass matrix of Bláhnúkur also contains much larger centimetre-sized fragments of pumiceous glass. Yearly average temperatures in these central highlands are close to freezing and create large amounts of freeze-thaw cycles in the material. The availability of liquid water from precipitation and snow melt drives the cryogenic weathering of these large pumiceous glass particles when temperatures fluctuate around zero. The expansion of freezing water drives
frost heave which is an effective mechanism for detaching a wide range of sand-sized particle diameters from the breccia matrix. Ice expanding inside the vesicles of the centimetre-sized pumiceous glass particles is especially important as it is the primary process for the post-eruptive formation of new sandy textures. The physical weathering of the Bláhnúkur glass during freeze-thaw cycles in the exposed top layer of the rock face ultimately decreases the cohesive strength of these deposits and makes the outcrops more susceptible to erosion by water and wind. The latter was found to be the most noticeable geomorphic agent inside the gorge as the local topography acts as a ‘wind tunnel’ and aggravates local winds to well above the threshold for detachment of particles. Although the loose sandy weathering products can be persuaded to roll down-slope by modest wind speeds, strong gusts cause significant deflation and winnowing of fines from the rock face and scree sediments (chapter 2). These winds carry large quantities of silt and clay off-site and the most appreciable differences in the textures of sediments and the original rock face occur in the range of these small particle diameters. The deflation of natural present respirable fines and those additionally formed by fracturing during weathering increase the risk to respiratory health hazards, although the many thousands of hikers that visit the site yearly will certainly experience no adverse effects due to the very low exposure rates. From the physical weathering experiments (chapter 3) it becomes clear that the combined influences of aeolian and cryogenic processes on volcanic glasses in general can create respirable fines, making these conclusions relevant to other areas that are composed of large amounts of basaltic and rhyolitic glaciovolcanic glass.

While the majority of studies of subglacial landforms performed to date have focussed on the abundant basaltic hyaloclastite (móberg) formations in Iceland, many rhyolitic subglacial locations have been identified and await further exploration (Fig. 1; McGarvie, 2009). Geomorphological processes set in these rhyolitic hyaloclastites are driven by the interaction of the environment with the unique physico-mechanical properties of eruption products. However, one important difference with basaltic edifices is that these silicic glasses experience lower rates of chemical weathering (Jakobsson and Gudmundsson, 2008). The resulting lack of consolidation and vesicle filling changes the hydrological properties and causes the physical erosion of rhyolitic features by environmental processes to differ substantially from their basaltic (tholeiitic) counterparts. In this dissertation a well-studied and well-accessible edifice was the focus of process-based studies and I have addressed the erosion characteristics on landscape and particle scales. Although it has given new insights in the physical weathering of silicic glass deposits, further study is still needed to understand how weathering of these rhyolitic tindars compares to basaltic edifices. As other geomorphological studies of tuya and tindar weathering with a process-oriented approach are scarce, it is clear that there is a bright future for further research.

1.2 Volcanic glass in different surface environments on Mars

Silicic volcanism has not occurred on planet Mars, or at least no evidence for it has been found so far (McSween et al., 2009). Properties of observed volcanic glasses resemble terrestrial silicic eruption products due to their high-silica, almost obsidian exterior (Horgan and Bell, 2012a). This property certainly does not have a magmatic origin, but it is rather a product of the chemical weathering of basaltic glass. Not only makes this the chemical signature of the particle exterior comparable to rhyolitic glasses in Iceland, but it also creates deposits that are not cemented and therefore easily eroded or mobilised by environmental processes. Large quantities of glaciovolcanic glasses with silicic exteriors are presently found in large sand seas in the Northern Lowlands and the circumpolar erg (Lancaster and Greeley, 1990),
covering an estimated 10 million km². A large segment of the erosion of volcanic glass on Mars therefore occurs from transport by mostly unidirectional winds (Hayward et al., 2008), rather than from in-situ weathering of local outcrops. Two observations become immediately apparent. Volcanic glasses on Mars are found in cold periglacial conditions and secondly, glass is contained in aeolian landforms (‘glass dunes’) which make aeolian and cryogenic processes prevalent in the transport and modification of the material. A clear distinction can therefore be made on Mars based on the latitude of their occurrence. Observations of the polar areas shows that dunes and other high-latitude landforms are frosted and defrosted with yearly cycles (e.g. Bourke et al. 2008; Smith et al. 2001). This occurs primarily by CO₂ and H₂O ice deposition from the atmosphere onto the surface of particles. The minute quantities of water-ice were observed during seasonal changes in the North polar environment, mostly in the form of wind-mobilised frost that caused brightening of dunes (Pommerol et al., in press). Although water-ice deposition certainly occurs, it is highly improbable that sufficiently large rates of water are released during thawing in the present environment to initiate water-based debris flows that have been postulated by some authors on other places on Mars (Costard et al. 2002; Christensen, 2003; Lanza et al., 2010). The small portion of this seasonal frost plays an important role in the chemical weathering of the observed glass-rich sand deposits. Leaching of soluble cations after melting of deposited water-ice from the atmosphere was proposed by Horgan and Bell (2012a) as an explanation for the high-silica spectral signatures once aeolian abrasion removed iron-rich rinds from the particle. As a much larger portion of the seasonal ice deposition is CO₂ ice (Hansen et al., in press). The build-up of this ice on the particle surface and inside pores will not result to the same type of cryogenic erosion that is observed in the field environment in Iceland. Cryogenic erosion by the expansion of freezing of water is in this respect quite unique as only water is known to expand by 9% during crystallisation (chapter 3). Carbon dioxide ice does not possess this property and even though it contributes to the destabilisation of dunes (Hansen et al., 2011; Horgan and Bell, 2012b), it is incapable of fracturing materials. The seasonal CO₂ layer also plays an important role in a new geomorphic process that was recently discovered during defrosting when gas is trapped below the ~60 cm thick ice layer, causing outbursts of gas and particles through cracks in the ice (Hansen et al., in press; Portyankina et al., in press). Although particles are transported only for short distance in this fashion, it is highly dependent on the seasons and the contribution to particle erosion will be minimal. The seasonal ice layer is therefore mostly effective as a form of ‘cryogenic induration’ that inhibits all other forms of sands mobility throughout ~70% of the Martian year. Modification of glass-rich sediments is therefore limited in circumpolar dune systems to the abrasive effects of short-lived aeolian transport in unfrosted conditions.

The occurrence of this cryogenic induration differs across the planet as seasonal frosting and defrosting only occurs in this extent near the poles. It is of much lesser importance in the northern lowlands as the seasonal ice layer only extends down to latitudes of ~70°N (Hansen et al., in press). Horgan and Bell (2012a) detected glass-rich deposits at lower latitudes than 70°N, well outside the influence sphere of seasonal polar ice deposits. The absence of seasonal frosting and cryogenic induration at lower latitudes causes aeolian processes to prevail. This makes the glass-rich sediments at these latitudes much more susceptible to wind-induced modification throughout the Martian year. Dune complexes in the lowlands were shown to be aeolian active (e.g. Hansen et al., 2011) and observations by Bridges et al. (2012a) seem to indicate that migration rates of dunes are much higher at more temperate latitudes than those near the pole. The introduction of the slope angle shifts the force balance by a relative lowering of the normal load (Eq.1), which lowers the thresholds compared to particle detachment on
horizontal surfaces (Rasmussen *et al.*, 1996). The comparable migration rates of dunes to those on Earth (Bridges *et al.*, 2012b) may in part be sustained by the mobilisation by winds on the inclined surface of the stoss side of sand dunes. Once saltation is triggered by wind-induced rolling of particles and sustained, it can drive the migration of dune systems, causing high impact velocities that inflict substantial damage to particles (e.g. Greeley and Iversen, 1985; Marshal *et al.*, 2012).

1.3 Timing and latitudinal dependency of modification rates on Mars

Explosive fragmentation of magma causes volcanic glass particles to be very irregular in shape directly after their formation. Physical weathering processes then cause the material to lose its irregular morphology. However, conditions may not always be favourable in the present surface environment to drive the transport and modification of aeolian grains on Mars. Wind shear stress measured at the Phoenix landing site during defrosted conditions (the lander was destroyed by ice encroachment in the next season) were below the measured threshold conditions in chapter 4, required for detachment of particles by rolling (Holstein-Rathlou *et al.*, 2010). The absence of dune and ripple-forming winds in the area suggest that surface conditions can indeed be unfavourable to transport particles at sufficiently large rates to cause substantial modification. Combined with the seasonal reduction of aeolian activity by cryogenic induration it is conceivable that glasses formed in more recent subglacial eruption near the poles, shown by Fagan *et al.* (2010) and Hovius *et al.* (2008), are likely less-weathered than glass grains sourced and reworked from the basal unit under the present polar ice cap. The lower modification rates of geologically young glass particles may potentially have preserved physical properties and volatile signatures that reflect their formation conditions. Polar glaciovolcanic glasses may therefore be ideal materials for geochemical palaeo-ice reconstructions of Martian eruption environments. Overall, the weathering of volcanic glasses over very long periods of geologic time appears to be highly dependent on geographic location as a consequence of the environmental conditions at different latitudes on Mars. This is notably different from Earth as the latitudinal extent of volcanic glass is much smaller in Iceland and therefore confined to less-prominent differences in environmental conditions.

1.4 Relating particle observations to particle behaviour

Observations of single, well-rounded dark particles (allegedly dark mafic glass) seem to support the notion that the environmental fate of volcanic glass on Mars is mainly driven by aeolian modification (Goetz *et al.*, 2010; Horgan and Bell, 2012a). However, this observation at the Phoenix landing site represents only one sand grain and its relevance is therefore highly debatable. This touches on a sensitive topic with respect to the paradigm of current surface explorations on Mars. Over the past decades abundant orbital observations have been made, while only few Mars landers have explored the properties of granular sediment in great detail. Lander instrumentation has frequently been designed to determine geochemical properties rather than physical particle properties that control the threshold of aeolian mobilisation. Especially physical properties are quintessential for understanding the process dynamics of planet-wide sands mobility on Mars, which is the most active process in the present surface environment. Obtaining physical particle properties is therefore limited to the analysis of extreme-close up images. Of the sparse observations that have been obtained, there is a general tendency to present these observations as more ‘general properties’ in spite of the known difficulties of linking remote-sensed imagery to properties of sediment (e.g. Sullivan *et al.*, 2008). Observed sediment properties may undoubtedly share properties that are common
for Mars’ global particle speciation, but data on observed grain properties should still be used conservatively. I have used available imagery of well-rounded mafic grains in the Columbia Hills on Mars as a substitute for abraded volcanic glass for study how well-rounded materials respond to the local wind flow at the surface of Mars. The detachment of particles by rolling (chapter 4) and transport by saltation causes sediment to reflect the local wind flow at the scale of individual particles. Assuming that well-rounded morphologies are indeed a common environmental ‘end-state’ of surficial sediments shows that the method developed in chapter 5 can be more generally applied to various aeolian sediments on Mars. This kind of aeolian behaviour of sand grains has to date not been detected and documented at the surface of Mars and potentially marks a new development in the surface exploration of Mars.

1.5 Are there possibly more glaciovolcanic edifices on Mars?

I have focussed this dissertation primarily on the context of glass-rich sand dunes in the Northern lowlands on Mars. These volcanic glasses on Mars are most likely produced by glaciovolcanism. Surface features formed by glaciovolcanic eruptions appear to be abundant on planet Mars, yet diagnostic bedded glass deposits still escape detection (e.g. Chapman 1994, Keszthelyi et al., 2010). Morphometric properties are therefore invaluable for determining whether a landform was created by sub-ice volcanism or not. In terrestrial sub-ice eruptions the hyaloclastite beddings are formed by granular avalanches of glass particles. The lower angles of repose of tuya flanks on Mars relative to those in Iceland (Fagan et al., 2010) illustrate that gravity effects may be involved in the deposition of these hyaloclastites, as shown by recent experiments (Kleinhans et al., 2011). As the morphometric properties of tuya are likely dependent on the lower gravity of Mars, the identification of glaciovolcanic landforms needs to account for these gravity-dependent differences if they are identified in the basis of terrestrial morphometry. Perhaps many more glaciovolcanic edifices may exist, but now escape detection due to their ‘incompatible’ landform morphometry.

2. Main conclusion and summary related to the research questions

In this dissertation I have discussed the environmental fate of glaciovolcanic glasses on Earth and Mars. While the latitudinal extent and environmental extremes are much larger on Mars than in Iceland, the processes affecting the modification are not dissimilar on Mars and reflect well how these materials are transported on Mars, albeit on differing time-scales. Glaciovolcanic glasses on Mars are observed and identified primarily in aeolian landforms such as dune systems, highlighting that the environmental fate is mainly driven by the interaction of the material with the atmosphere. The modification of these materials progresses from an initial irregular state via physical and chemical weathering to aeolian sediments that are primarily detected on the basis of silicic particle exteriors. Near the North Pole on Mars, these glasses are sourced from the basal unit of the current polar ice cap and their weathering history in the present environment is largely dependent on how they entered the circumpolar environment via subglacial floods. Some of the detected glass may be a product of more recent subglacial volcanism that formed the North Polar Tuyas and high-angle Crater Cones, making these glasses geologically younger than the glass sourced from the basal unit and reworked in the present environment. The lower alteration state results from the cryogenic induration of aeolian sediments by seasonal ice that covers vast areas in the circumpolar environment. These particles may therefore have retained the physico-mechanical and geochemical signatures that are indicative of their eruption environments. In contrast to the seasonal dependence of the transport and erosion of glaciovolcanic glasses
near the pole, glasses in the Northern lowlands are probably derived from glaciovolcanic eruptions in Acidalia Planitia and in the Chasma and Valles of the Tharsis volcanic province. These geologically old glasses experience weathering throughout the Martian year and can be characterised as highly abraded from aeolian transport over long geologic time. Comparing this fate on Mars to that on Earth shows that glaciovolcanism occurred at a much wider range in latitudes on Mars by which there difference in latitude also causes a larger variety in weathering pathways. In the environmental ‘end-state’, glass particles will have obtained a well-rounded morphology most commonly from long-term aeolian abrasion. These particles are then capable of reflecting the local wind directions from transport by rolling or saltation. The sediment fabric of aeolian deposits thus harbours detailed information on Mars’ aeolian activity.

Table 9 – Overview of the main chapter conclusions.

<table>
<thead>
<tr>
<th>Research question</th>
<th>Earth Iceland</th>
<th>Mars North Pole (&gt;70°N)</th>
<th>Northern Lowlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulating environmental processes on weathering?</td>
<td>Freeze-thaw cycles with water, wind erosion in dry conditions. Influences of water to lesser extent.</td>
<td>Seasonal frosting causes induration of sediment while cryoventing redistributes sands. Wind erosion occurs only in defrosted conditions.</td>
<td>Mainly by winds at threshold conditions, more particle mobility than at pole due to lack of cryogenic induration by seasonal ice.</td>
</tr>
<tr>
<td>Influence physico-mechanical properties on weathering?</td>
<td>Expansion of freezing water in vesicles causes fracturing of larger particles. In spite of angular particle shape, little abrasion occurs during rolling.</td>
<td>If vesiculated, no fracturing due to predominant CO₂ ice from atmospheric deposition.</td>
<td>General lack of seasonal ice; no effects from ice deposition or water-ice induced fracturing.</td>
</tr>
<tr>
<td>Means of particle mobilisation and transport by wind?</td>
<td>Deflation; fine particles carried away in suspension from outcrops by moderate winds. Large particles are excavated and roll down-slope</td>
<td>Detachment by rolling. For large particles this mobility is possible at a lower threshold than saltation and may be promoted by the presence of a thick laminar sublayer in a low-pressure atmosphere. As such, rolling is important as a trigger to initiate the mobility and transport of sands by saltation.</td>
<td></td>
</tr>
<tr>
<td>Information on particle mobility retained in the sediment fabric?</td>
<td>Saltation drives long-axis orientation that allows wind directions during last glacial period. Object-based image processing improves interpretation of palaeowind flow.</td>
<td>Long-axis orientation occurs during saltation of well-sorted aeolian sediment (100-300 µm), but much orientation is lost due to high impact velocities. Based on slopes and contextual interpretation, other modes of transport include gravity and wind-induced rolling. Fabric strength measurements using e.g. OBIA can be used to discriminate between wet and dry sedimentation.</td>
<td></td>
</tr>
</tbody>
</table>

3. Directions for further research

The age differences of the glassy material on the two planets are quite substantial (Fig. 3, chapter 1), but the chemical stability from the silicic particle exterior of these glasses on Mars (Horgan and Bell, 2012a) makes them long-lived and in some ways comparable to the materials
studied in the southern central highlands in Iceland. However, the erosion characteristics of glaciovolcanic eruption products are still a poorly studied topic in Iceland and on Mars. This is quite notable as these landforms have the potential to yield valuable insights in the palaeoclimatic conditions and they have the added dimension on Mars as potential habitats to sustain microbial life due to the presence of liquid water and higher temperatures (Cousins and Crawford, 2011). As the collective of putative glaciovolcanic locations on Mars will encompass a wide variety of materials with different exposure ages and weathering histories, the glasses on Mars vary from potential fresh to ‘end stages’ after several Myr-Gyr of exposure to erosion processes in various surface environments.

In this dissertation I have discussed several questions surrounding the behaviour of volcanic glasses on Mars, and by no means have I been able to discuss all relevant questions. In this final section I will highlight a few new challenges that I consider to be most important for the continued study of the environmental fate to these materials. These suggestions cover proposed experiment to study the state and degree of modification of particles in Martian glass-rich aeolian sediments, and secondly, the need for understanding how the variation in particle properties relates to mobilisation thresholds.

3.1 Unifying transport rates with particle modification and spectral properties

Rolling of sediment has been shown in chapter 4 to occur in the surface environment of Mars, and this mode of transport may occur frequently as it encompasses a substantial part of wind-induced sediment mobilisation (Kok et al., 2012). While it was found that rolling does not lead to significant alteration of sediments, more energetic saltation inflicts significant damage that causes textural and morphological modifications of wind-blown sediments. Observations of well-rounded glassy grains at the Phoenix landing site (Goetz et al., 2010) therefore raise two questions. First, if these glassy particles were originally blocky and vesiculated as a result of their eruption environment (Heiken, 1972; Wilson and Head, 2007), then these particles must have been transported over prolonged periods and distances to obtain their rounded morphology. It is generally accepted that these rounded particle morphologies on Mars are formed by aeolian transport. However, no decisive values of modification rates for Mars exist. While the validity of the aeolian abrasion mechanism for the observed particle shape is certainly not questioned here, it does raise several questions on the exact path of this modification. The required time and distances may be troublesome for very locally confined glass deposits, considering the unidirectional wind patterns from the atmospheric circulation that is reflected in many of the low-latitude dune fields (Gardin et al., 2012). In other words, particle modification has to be united with the probable ages of the sediments and migration flux (travelled distances) of these sediments through time, taking into consideration the invariant or perhaps time-dependent variance in wind patterns. Secondly, if these particles have a silica-rich exterior from leaching of elements in acidic environments making them chemically stable as proposed by Horgan and Bell (2012a), then the chemical weathering inferred from these spectral properties may be difficult to unify with the reworking by post-depositional abrasive transport. These glassy deposits are found in massive dune fields formed by saltation, but were initially introduced by catastrophic floods. If iron-bearing rinds were formed directly after deposition, than transport may have plausibly led to chipping of the exterior and removed any existing pre-existing rinds to expose the now high-silica exterior. As these rinds are only thin, several micrometres at best, much more chipping would be required to obtain the well-rounded morphology of particles for which such rinds were tentatively observed (Goetz et al., 2010). From an initial blocky shape, the
amount of chipping required to obtain well-rounded particles may in fact be so high that it also removes much of the leached high-silica glass. In other words, if we observe high-silica particles on Mars, than these particles may either still be fresh morphology-wise, or acidic leaching occurred that postdates an episode of substantial aeolian modification. In the polar areas this sequencing of abrasion and leaching may perhaps be favourable due to the highly variability in the extent of seasonal polar ices and the deposition of water ice from the atmosphere. Solving this conundrum may be possible using aeolian transport simulations with experimentally leached glasses that cover the high-energy impact regimes, such as in the study of Merrison et al. (2010) or Marshall et al. (2012). This may be instrumental for understanding the depositional and weathering timeline. In conjunction with these abrasive and chemical weathering processes, the ‘jökulhlaup’ type deposition in the northern lowlands would also causes substantial mobilisation of sediment predating the emplacements events. Unmixing analyses of sediments (e.g. Prins et al., 2007) from the glass-rich sandy deserts in Iceland may give insight in how catastrophic floods and post-depositional redistribution of sediments by winds influences the signature of current glass-rich deposits in Iceland and similar deposits on Mars.

3.2 Hypobaric wind tunnel simulations in hypogravity

Semi-empirical models developed for removal of particles have reached a mature explanatory level for aeolian processes on Earth and Mars. However, filtering out the effects of material properties on the raising of thresholds, as shown in chapter 4, is still difficult. Future studies may use analogue glass deposits for which the eruption environment has also been well-established as in Torfajökull. This undoubtedly hefty sampling effort in Iceland may allow further characterisation of upper thresholds for sediment behaviour in glass-rich dune fields

![Diagram](image-url)

**Fig. 41** - Illustration of a carousel-type wind tunnel, modified from White et al. (1987). The outer drum rotates to achieve a desired gravitational acceleration (e.g. 3.71 m s\(^{-2}\) for Mars) while the inner drum rotates at a much higher speed (ω>500 RPM) to achieve a boundary layer between the inner and outer walls (Taylor, 1935). The inset shows the two opposing boundary layers (δ\(_i\) and δ\(_o\)) created by the rotation of the inner drum with radius \(R_i\), relative to the outer drum with radius \(R_o\). Successful particle removal experiments were carried out during parabolic flights and testing shows that valid flow parameters at a given height above the surface (\(r\)) can be obtained (White et al., 1987). Not shown in the illustration are the anti-vortex vanes required to minimize secondary flow patterns.
on Mars. The most notable effects of particle properties were observed for small particle diameters where adhesion dominates the threshold. This allows new directions in wind tunnel simulations to be defined. Potential experiments can involve comparable detachment experiments at fluid threshold conditions by employing a magnetic field to artificially increase the magnitude of adhesion forces based on ferromagnetic and paramagnetic particle properties. This approach is comparable to the use of magnetism to increase adhesion forces in the experiments of Hutton et al. (2004) to understand the role of interparticle forces in granular avalanching of sediments. Much more efficient is the use of a variable pressure, carousel-type wind tunnel during parabolic flight that provides a practical solution to fitting a wind tunnel in small-volume space such as an aircraft (Fig. 41). Initial pilot-studies have shown that great refinement in the understanding of adhesion forces can be achieved from particle removal studies in hypogravity (Greeley and Williams, 1987; White et al., 1987). The shift in the force balance towards the interparticle forces in hypogravity thus allows further parameterisation of the ‘simple’ adhesion term (see Fig. 32 and Eq.1 in chapter 4) and subsequently the parameterisation of other model fitting parameters as well. The type of wind tunnel is ideal for studying the detachment of particle by rolling as the rotational components of the tunnel requires no complex conversions of particle trajectories and inertial systems, compared to the use of this tunnel for saltation studies (White et al., 1987). While it was shown in chapter 5 that particles can orient to the local wind flow by saltation, it remains unclear to what extent particles can orient in situ, without ever leaving the bed. Experimental simulations using the proposed carousel-type wind tunnel may provide an excellent opportunity for studying in situ particle mobility to give valuable insights in flow-orientation processes.

3.3 Triggers of sub-ice eruptions

Glaciovolcanism on Mars appears to have benefited from coinciding peaks of volcanism and glaciations (Neukum et al., 2010). I have outlined a possible new hypothesis for the promotion of these subglacial eruptions in the introduction of this dissertation. Lithosphere unloading might have been a trigger on Mars due to the absence of distinct plate tectonics and the dominance of plume-based volcanism. The volcanic features around the North Pole would make it possible to determine if temporal clusters exist where some of the tuya features (Appendix A) are related to post-glacial (subaerial) eruptions. Impact crater dating (Hartmann and Neukum, 2001) of these features can be complicated due to the scale of individual edifices, but it may be possible using the relative age differences of the area surrounding tuyas or other volcanic features (e.g. from Fagan et al., 2010). Regional palaeo-ice reconstructions applying known parameters of the rheology and composition of the Martian polar ice caps (Bibring et al., 2004; Zuber et al., 2007; Phillips et al., 2008, 2011) can be used to determine the possible extent of the ice during these eruptions. This would give a contextual analysis for testing the proposed hypothesis as the eruption trigger of the polar volcanic features and tuyas.

This dissertation aimed at characterising the environmental behaviour of glaciovolcanic glass in Iceland and on planet Mars. Several new insights in the behaviour of glass on Mars have been obtained within the research framework of this dissertation. Local erosion, transport and modification of volcanic glass have been studied and new niches for further research have been proposed. The combined study of volcanism and ice on Earth and Mars shows that the geomorphological understanding of the environmental fate of glaciovolcanic glasses benefits from the characterisation of its material properties with dedicated experiments.