



*When the Glacier Left the Volcano: Behaviour and Fate of Glaciovolcanic Glass
in Different Planetary Environments*

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Summary in English

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Volcano-ice interactions have been studied since 1900. Subsequent refinements in our understanding of a volcano's response to the overlying ice mass have shown the complex dynamics of these eruption environments and interrelationships with material properties. Iceland is a prominent location where young landscape features such as *tuyas* (emergent sub-ice volcanoes that have melted upwards through the ice) and *tindars* (subglacially formed ridges) can be studied. On planet Mars similar surface features have been identified as early as 1979 based on topographic features that are comparable to Icelandic *tuyas* and *tindars*. Landforms on Earth and Mars are composed of glassy breccias that are known as 'hyaloclastites' and these glasses are a unique material for these eruption environments. Recent spectral evidence from the surface of Mars shows that glaciovolcanic glass is highly abundant in the circumpolar aeolian sediments and the large sand sea on Mars. Substantial work on the environmental dynamics of these eruption products is still lacking for understanding the mechanisms and thresholds that control the erosion, mobility and modification rates of these materials on Mars. Subglacial eruptions in Iceland and on Mars have occurred under similar glaciostatic and water-ice dominated conditions. These parallels between the formation environments make terrestrial hyaloclastites an ideal physico-mechanical analogue material in field studies and experiments to study the behaviour of glassy sediments on Mars.

The aim of this dissertation was firstly to fill the gap in the knowledge of physical erosion mechanisms and transport thresholds of glaciovolcanic glass. Secondly, this dissertation aims to investigate if the role and effects of atmospheric pressure and wind flow in these geomorphological processes differ on Mars. The selection of a suitable analogue material was driven by the physico-mechanical properties as these are determined by the subglacial eruption environment (rather than by the geochemical or mineralogical properties). These criteria resulted in the selection of the rhyolitic particle population from the Bláhnúkur edifice in the Torfajökull area in Iceland. The edifice is globally the best-studied location which means that the well-characterised formation and material properties of the particle population give an ideal basis to the process-oriented studies in this dissertation.

The erosion characteristics of an edifice composed of hyaloclastites are studied in chapter 2. While the erosion of steep-sided slopes in the Grænagil gorge show that numerous processes drive the erosion of the overlying slope, only a few processes are dominantly reflected in the sedimentary record. The sediment influx of sedimentary landforms such as scree slopes is primarily driven by freeze-thaw erosion and deflation of the overlying slopes. Particle transport is therefore mostly confined to dry and cold conditions when discrete avalanches can form foot slopes with high angles of repose. These processes are also reflected in the stratigraphy of the scree slopes, as these show stratification (layering) from dry avalanching and depletion in small size fractions by winds. Deflation of small particles and effects of freeze-thaw cycles are therefore considered to be the prime mechanisms for the erosion of poorly cohesive glass deposits.

The insights at a landscape scale are complemented in chapter 3 with the effects that these erosion processes have on a particle scale. Samples from the Bláhnúkur hyaloclastites were used in experimental simulation to study transport-induced abrasion of sand-sized fractions. Abrasion from aeolian and gravity transport was simulated by subjecting 300-600 µm sized particles for 15 weeks to continuous rolling and avalanching, which corresponds to transport distances of 500-715 km. Physico-mechanical properties of larger particles, such as porosity and tensile strength, were measured using high-pressure mercury intrusion and uniaxial loading to understand the scale effects of freezing of water inside pores. Similar particles were simultaneously subjected to 10% of the yearly amount of freeze-thaw cycles. Damage to the material in the experiments was then related to the measured physico-mechanical properties of the glass. These analyses show that rolling of particles during avalanching and by wind is only marginally modifying sediments. Effects of ice nucleation during freeze-thaw cycles are more effective in modifying larger particles and it forms new, finer sediment textures. This fracturing was increased the amount of respirable particle sizes (<10 µm, or PM₁₀) which increases the risk to respiratory health hazards.

In chapter 4 and 5 the transition is made to the planet Mars in order to understand how the observed processes in Iceland influence the transport and modification of volcanic glass in the different surface conditions. Here, wind appears to play an important role. However, wind transport is very paradoxical on Mars. Wind speeds in the thin atmosphere are insufficient to frequently meet the threshold conditions for particle mobilisation, while planet-wide migration of dunes has been observed with speeds that are comparable to terrestrial dunes. The most common and lowest threshold for particle detachment and mobility is by rolling. Wind tunnel simulations in chapter 4 were therefore used to determine a realistic range for the rolling of sediments at fluid threshold conditions. Using removal experiments under different atmospheric pressures allowed the fitting of a semi-empirical model to describe these rolling processes. Different particle properties such as shape, specific surface area and density were measured to assess the dependence of the model on variations in material properties per particle fraction. Although no clear dependences were found, the analysis confirmed that particle density and diameter also control the detachment threshold for wind-induced rolling. This validated the use of the semi-empirical model for predicting the removal of volcanic glass by rolling on Mars. The model predicts an upper limit for rolling that falls within the range of known wind speeds on Mars. Rolling of sand grains may be further enhanced as the structure of the boundary layer promotes rolling in the Martian atmosphere. Rolling as a means of particle mobility is therefore proposed as an important precursor to saltation as it can contribute to the lowering of the threshold that is responsible for the observed migration of dunes.

Despite the detection of extensive glass deposits on Mars, little is known about the exact properties and the rate at which this material has been physically modified by exposure to the local environment. The initially angular grains in these glass-rich dune systems may have been gradually abraded over geologic time by the impacts of other grains during saltation, which produces well-rounded particles. Many of the sand grains observed by Marslanders in aeolian sediment indeed have these well-rounded shapes. The obtained streamlined shape leads to interesting phenomenon; sand grains can orient their long-axis to the local wind flow. This causes aeolian sediments to record near-surface wind flow patterns in a measurable entity known as the 'imbrication' of the sediment. In chapter 5 a new method is developed that makes it possible to measure sand grain orientation using Object-Based Image Analysis

(OBIA). In this process images are decomposed into smaller image segments. These segments are reclassified to delineate the boundaries of individual sand grains and allow the calculation of the orientation. This strategy was first applied to thin-sections (~30 µm thick microscope slides) of terrestrial inland dunes where pre-existing studies also determined palaeowinds with different techniques. Good agreement was found with the directions determined in these studies and it validated the applicability of the OBIA technique for other settings. The method was then applied to images of sand grains at three sites along the traverse of Mars Exploration Rover 'Spirit' through the Columbia Hills. Winds in this area are highly variable due to topographic forcing, but inferred directions using the OBIA method give an additional type of data for reconstructing the genetic wind directions of aeolian bedforms in this area. Inferred wind directions correlate well to headings determined using oriented features such as dunes and ripples. As sand grains orient easily to the local wind flow, their orientation reflects the most recent high-energy wind events in an area. Detachment of particles by rolling and subsequent transport by saltation allows wind flow patterns to be measured at the smallest possible physical and temporal scale possible in the present surface environment on Mars.

Chapter 6 provides a synthesis of the preceding chapter in this dissertation in order to characterise the behaviour of volcanic glass on Mars. Dry environmental processes are dominant in regulating the weathering of glass deposits in Iceland and on Mars. Unlike Earth, effects of frost weathering are very limited as the atmospheric deposition of CO₂ ice in polar dunes systems lacks the expansive force of water during freezing. This makes erosion related to aeolian processes by far the most important for the modification of glass grains on Mars. Although the physico-mechanical properties of angular glass cause the wind thresholds for removal to be higher than for well-rounded sediments, both extremes in particle shape can be mobilised by rolling during high-energy wind events such as storms and thermal vortices. Cryogenic induration of dunes near the pole substantially reduces aeolian mobilisation to only a short period of the Martian year. Physical weathering of glass is therefore highly dependent on latitude. The possible presence of geologically young glaciovolcanic glass associated to north polar tuyas suggests that these materials may have retained their original properties due to frequent seasonal induration and lower rates of aeolian transport (and modification). Future geochemical surface studies on Mars may therefore be able to use these glasses for inferring subglacial formation conditions and reconstructions of past glaciers.

This dissertation has addressed several questions for understanding the environmental fate of glaciovolcanic glass on two contrasting planetary surfaces. At the same time, new niches for further work on the environmental characterisation of glaciovolcanic glasses have been identified to aid the future investigation of this part of the Martian particle population. From the aeolian studies in chapter 4 and 5 the most promising direction is the further amelioration of interparticle adhesion and the associated threshold response. Low-gravity wind tunnel studies may therefore shed important light on these aspects of the force balances for particle removal on Mars.