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

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View down-wind in the hypobaric (low-pressure) wind tunnel before the start of a new experiment.
Chapter 4
Wind transport at the fluid threshold

Abstract
Sands are actively transported in the present surface environment of Mars. Recent observations show that volcanic glass is an important component in active dune systems and other aeolian sediments. The mobility of these sediments may benefit from rolling induced by aeolian drag forces. In this study we experimentally determined detachment thresholds for volcanic glass that include the removal by rolling. Discrete heaps of particles were subjected to wind shears of 0.1–0.6 N m⁻² under atmospheric pressures of 240–1024 mbar inside a wind tunnel simulator. The observed flat threshold for larger particle diameters (>150 µm) was best explained using a semi-empirical model that includes detachment by rolling. This model produced a much better fit to the data than models that describe saltation. Using a residual analysis of the variability in measured particle properties we evaluated the obtained model fit and found no dependencies on variations in particle properties that affected the fitting accuracy. The model could therefore be validly applied to the detachment threshold of volcanic glass and was therefore used to predict the removal on Mars. These model predictions show that volcanic glass with larger particle diameters can be detached by rolling from existing surface wind shears. As rolling is further enhanced by the thick laminar sublayer, it provides a possible mechanism for the initial mobilisation of particles by the wind. A wide morphological variety and range in particle diameters is found to be susceptible to this form of removal at wind speeds than are lower than fluid thresholds for saltation. Recent sand mobility may therefore have benefited from rolling as a contributing or as a saltation triggering process.

1. Introduction

Surface wind flow drives aeolian processes and the erosion of surface features on Venus, Earth, Mars and Titan (Iversen and White, 1982; Arvidson et al., 1983; Bourke et al., 2010; Kok et al., 2012). On Mars, various aeolian landforms appear to be much more active in the present-day surface environment than previously thought possible (Silvestro et al., 2010; Hansen et al., 2011; Bridges et al., 2012a; Gardin et al., 2012; Horgan and Bell, 2012b). Sand mobility is observed to be fairly common (e.g. Bourke et al., 2008, 2010; Fenton, 2006; Sullivan et al., 2005, 2008; Chojnacki et al., 2011; Silvestro et al., 2011) and sand fluxes of dune systems can be comparable to dunes on Earth (Bridges et al., 2012b). The geomorphologic evidence of these processes implies that active saltation of sand-sized particles occurs in the present low-pressure (6-10 mbar) surface environment. However, wind speeds in the atmospheric boundary layer measured by Mars lander instrumentation (Hess et al., 1977; Sutton et al., 1978; Schofield et al., 1997; Magalhães et al., 1999; Holstein-Rathlou et al., 2010) and predictions from global atmospheric circulation models (e.g. Haberle et al., 2003; Michaels and Rafkin, 2008) show that winds above 10 m s\(^{-1}\) are very rare on Mars. Much higher wind speeds are required to reach the fluid or static threshold when particles are lifted from the bed by the force of the wind (Greeley et al., 1974, 1980; Iversen and White, 1982; Greeley and Iversen, 1985). The apparent contradiction of saltation on Mars is solved to some extent by results from numerical simulations that have shown that saltation can be sustained by splashing and reptation of particles by much lower wind speeds at the impact or dynamic threshold (Kok 2010a, 2010b; Kok et al., 2012). For this to be possible, particles still need to be mobilised at a much higher fluid threshold first. Beneficiary contributions to the mobilisation of particles may result from rolling by aeolian drag, which is known to occur for larger particle diameters at lower fluid thresholds than saltation (Cleaver and Yates, 1973; Nickling, 1988; Manukyan and Prigozhin, 2009).

This work focuses on experimentally quantifying fluid thresholds that include detachment of particles by rolling as one of the possible processes that can contribute to the observed sand fluxes and the onset of saltation on Mars. Experimental simulations of aeolian processes can be carried out in Martian atmospheric conditions using specialised low-pressure (hypobaric) wind tunnels (e.g. Greeley et al., 1974; Greeley and Iversen, 1985; Merrison et al., 2008). Simulations under atmospheric pressures higher than those on Mars are also possible as these can be normalised for the difference in atmospheric density using empirical relations (Merrison et al., 2007; Kok et al., 2012) and this approach is used in the presented study (more details are discussed in section 2). Simulating particle removal under Martian gravity (\(g = 3.71 \text{ m s}^{-2}\)) is cumbersome and is only possible during partial-gravity parabolic flights (White et al., 1987) or by using gravitationally-adjusted particles in ground-based hypobaric wind tunnels (e.g. Merrison et al., 2007). Many studies of particle mobility on Mars have therefore relied on semi-empirical models to extrapolate results of wind tunnel simulations in terrestrial gravity to the gravitational or atmospheric conditions on Mars.

Obtaining results in wind tunnel simulations that are applicable for the Martian particle population is dependent on the selection of a proper analogue material. Recent spectral observations show that volcanic glass is an important component of aeolian sediments and the massive dune fields in the Northern highlands and polar sand seas (Horgan and Bell, 2012a; Carrozzo et al., 2012) where wind-induced erosion and transport of glass-rich material is actively taking place (Hansen et al., 2011; Bridges et al., 2012a; Horgan and Bell 2012b). While this type of glass can be produced by various forms of explosive volcanism (Wilson and Head, 2007), the localised and concentrated deposits bare striking resemblances to glass-rich sediments that are formed in Iceland during glaciovolcanic eruptions (Horgan and Bell, 2012a).
Crater surface dating shows that peaks of glacial and volcanic activity coincided throughout Mars’ geologic history, which increased the likelihood for magma to encounter ice during eruptions (Neukum et al., 2010). The abundance of Martian magma-ice interactions capable of producing glassy sediments is further evidenced by a wide variety of surface features. These features include tuyas; emergent sub-ice volcanoes that melted upward through an ice sheet (Allen, 1979; Ghatan and Head, 2002; Head and Wilson, 2007; Hovius et al., 2008; Fagan et al., 2010; Martínez-Alonso et al., 2011) and features that resemble subglacially formed volcanic ridges known as tindars (Wilson and Head, 2002; Chapman et al., 2003; Komatsu et al., 2004; Zealley, 2009; Pedersen et al., 2010). As these types of volcanic eruptions are commonly dissociated from erupting in subaerial conditions, physico-mechanical properties of the formed glass particles are controlled by the glaciostatic (ice overburden) pressure of the overlying ice mass and the explosive fragmentation of quenching by melt water. The formative conditions of Martian glasses were therefore well-comparable to the glasses that constitute similar landforms in Iceland (van Bemmelen and Rutten, 1955; Wilson and Head, 2002; Schopka et al., 2006; Thodarson and Larsen, 2007; Jarosch et al., 2008; Smellie, 2008; McGarvie, 2009).

As physico-mechanical particle properties cannot be distilled from orbital measurements such as those made by Horgan and Bell (2012a), important clues can be obtained from their terrestrial analogues. In the absence of any superior characterisation of Martian volcanic glass at this point in time, we have used an unaltered volcanic glass (meaning not modified by aeolian transport or other physical modification processes) as an analogue material for studying the aeolian behaviour of particles in glass-rich Martian dunes. The particle properties of the selected analogue glass allowed us to determine a realistic upper limit for particle detachment by rolling due to their irregular shape. Fitting of a semi-empirical model for rolling from Merrison et al. (2007) to obtained experimental data, combined with a residual analysis of the model fit with the variability of particle properties made it possible to assess the sensitivity and validity of the new model for predicting the removal of these volcanic glass by winds on Mars. This study therefore complements earlier wind tunnel simulations by addressing the fluid threshold regime that includes rolling, while using a material that is comparable to a significant portion of aeolian sediments at the surface of Mars.

2. Theory of particle detachment in a low-pressure atmosphere

2.1 Paradox of particle removal on Mars

Atmospheric density plays a vital role in promoting or limiting particle mobility on Mars. The force exerted by the wind on a surface, or shear stress, is directly proportional to the product of the fluid mass density of the atmosphere ($\rho$) and the friction velocity ($u_*$) of the flow squared ($\tau = \rho u_*^2$). The atmospheric density is most strongly affected by variations in atmospheric pressure and large variations have occurred in the geologic past of Mars. Simulations of atmospheric evolution show that Martian surface pressures once peaked around 500-1000 mbar, which was similar to conditions on Earth and as such favourable for aeolian processes (Kass and Yung, 1995; 1996). Erosion of the atmosphere from interactions with solar winds led to a rapid decline early in Mars’ history (Kass and Yung, 1995; Dennerl, 2006; Dennerl et al., 2006; Bharadwaj et al., 2007). The present surface pressures of 6-10 mbar are only considered to increase to 10-15 mbar during periods of higher obliquity (Kieffer and Zent, 1992; Laskar et al., 2004; Phillips et al., 2011). This persistent low-density state of the Martian atmosphere causes diurnal winds to infrequently exceed the fluid threshold ($u_{*th}$) for saltation of sand particles (Sullivan et al., 2005). In rare cases threshold conditions have been
observed in dust devils with wind speeds in excess of 10-20 m s\(^{-1}\) (e.g. Ringrose \textit{et al.}, 2003; Greeley \textit{et al.}, 2006) and during the dust storms in which the Viking landers measured gusts as high as 25-30 m s\(^{-1}\) (Arvidson \textit{et al.}, 1983). Friction velocities derived from these surface measurements and reconstruction from ripples and dune systems are in good agreement with each other and give a maximum range of \(u_{\text{sat}} \approx 2-4\) m s\(^{-1}\) for the highest winds on Mars (Sullivan \textit{et al.}, 2005; Parteli and Herrmann 2007a, 2007b; Kok \textit{et al.}, 2012). The main reason why saltation on Mars is effective for mobilising sediment is that once particles are injected in the airstream, they will hop higher and farther as a result of the low atmospheric pressures and the lower Martian gravity (Claudin and Andreotti, 2006; Almeida \textit{et al.}, 2008; Kok \textit{et al.}, 2012). This substantially increases the final impact velocity of a saltating particle and lowers the impact threshold \((u_{\text{sat}})\) to \(~10\%\) of the initial fluid threshold (Kok, 2010a; 2010b). Saltation at the impact threshold is therefore easy to sustain on Mars once it has been set in motion due to the large ratio of the impact and fluid thresholds. However, getting an aeolian system to this

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**Fig. 24** - The forces and flow properties involved in the detachment of particles with diameter \(d\) by wind. The atmospheric boundary layer is subdivided in a turbulent flow and a viscous laminar sublayer (with thickness \(\delta_{\text{vis}}\)). The threshold wind speed \((u)\) at a given height \((z)\) can be normalised for measurement height \((u_{*\text{ft}})\) and in combination with the atmospheric density \((\rho)\) they define the shear stress exerted by the wind. Forces acting on a particle at the moment of detachment include a lift force \((F_L)\) and a rotational force created by the aeolian drag of the particle \((F_T)\). These have to overcome the interparticle adhesion forces \((F_{\text{adh}})\) and particle weight \((F_n)\) for detachment. Threshold scaling for saltation (b) is dominated by the lift force for lifting a particle completely off the bed. In the case of detachment by rolling (c) the linear increase in shear stress from the surface produces a rotational force (torque) that removes particles with diameters above \(~150\) \(\mu\text{m}\) without leaving the bed. This difference in scaling with particle diameter causes the threshold shear stress for rolling to be lower than the threshold for saltation (modified from: Merrison \textit{et al.}, 2007 and Melosh, 2011).
state is also inherently more difficult due to the higher fluid thresholds in the low-pressure environment (Kok et al., 2012). Bagnold (1954) was one of the first to realise that saltation at the fluid threshold is often preceded by rolling, which was confirmed by observations of others (e.g. Chepil, 1959). On Mars the contribution of rolling can be enhanced due to the structure of the atmospheric boundary layer. Very close to the surface, viscous forces resulting from the friction of the flow with the surface create a laminar sublayer. The thickness of this layer (δvis) is approximated by \(5\mu/(\rho \cdot u*)\), where \(\mu\) is the dynamic viscosity of the atmosphere (Kok et al., 2012; White, 2006). With 2 mm the laminar layer on Mars is roughly 5 times thicker than on Earth due to differences in kinematic viscosity (Kok et al., 2012) and fully engulfs sand-sized particles (63 ≤ \(d\) ≤ 2000 \(\mu\)m). Particles are shielded by this laminar sublayer from the turbulence of the upper part of the boundary layer, which prevents the removal by saltation; a property that adds to the paradox of saltation on Mars (Greeley, 2002). As particles are subjected to the aeolian drag from the flow inside the laminar sublayer, the structure of the Martian atmospheric boundary layer promotes the removal by rolling without leaving the surface. This makes sediment mobility possible at lower fluid thresholds than saltation (Cleaver and Yates, 1973; Nickling, 1988).

### 2.2 Thresholds for saltation and rolling

Aeolian field studies and experimental simulations have focussed primarily on the fluid thresholds of saltation for understanding wind-induced sediment fluxes (e.g. Bagnold, 1954; Greeley et al., 1974, 1980; Greeley and Iversen, 1985). Much advancement has been made in the development of semi-empirical models for describing saltation by e.g. Iversen and White (1982) and the subsequent improvement and simplification by Shao and Lu (2000). These semi-empirical models show that threshold friction velocities scale proportional to the particle diameter (\(d\)), with \(d^{-0.5}\) for small particles and \(d^{0.5}\) for large particles (Shao and Lu, 2000). The scaling of thresholds expressed in terms of the shear stress (\(\tau\)) can be illustrated using the force balance in Fig. 24a, where forces resulting from the wind flow, such as a lift force (\(F_l\)) and the torque (\(F_t\)) created by the drag of a particle, have to overcome the impeding properties of the particle. These particle forces include the normal load (\(F_n\)) resulting from the weight of the particle in the terrestrial (or Martian) gravity field and an adhesion force (\(F_{adh}\)) between particles from compositional interactions, surface friction or moisture adhering to the particle's surface (Ziskind et al., 1995). For small particle diameters (<100 \(\mu\)m) the force balance is dominated by adhesion forces and removal is primarily governed by the lift force. Fluid thresholds for larger particle diameters (>100 \(\mu\)m) are dominated by the particle's weight. Simplistically, fluid thresholds for saltation (Fig. 24b) of larger sand-sized particles scale with \(d^3/d^2\) as the regime is dominated by the lift force (scaling with \(d^2\)) that has to overcome the impeding force of gravity from the particle's weight (scaling with \(d^3\)) to lift the particle off the bed. When rolling is included (Fig. 24c) particles are not required to be lifted from the bed. Mobilisation is therefore dominated by aeolian drag force acting on the particle as it protrudes into the boundary layer, here the shear stress increases linearly with height above the surface (i.e. also with grain size) leading to a rotational force (torque) which scales as \(d^3\). Since the force of gravity also scales with \(d^3\) the fluid threshold for detachment including rolling therefore scales with a dimensionless constant (\(d^3/d^3\)) for larger particle diameters and the threshold shear stress will be lower than the threshold for saltation. In this work we will refer to fluid thresholds that include detachment by rolling as the detachment threshold for clarity. Merrison et al. (2007) developed an experimental method and a semi-empirical model for detachment of spherical glass particles that includes
rolling (Eq.1). It integrates the forces in the force balance, where lift ($F_L = C_L \rho u_{st}^2 d^2$) and torque ($F_T = C_T \rho u_{st}^2 d^3$) have to overcome the normal load ($F_n = \pi d^3 g \rho_{He}/6$) and a simplified adhesion term ($F_{adh} = C_{adh} d$) for particle removal. Solving these terms for the threshold condition for particle detachment $F_L + F_T \geq F_n + F_{adh}$ gives the threshold shear stress ($\tau_{th}$):

$$\rho u_{st}^2 = \left( \frac{(\pi/6)g \rho_{He} d^3 + C_{adh} d}{C_L d^2 + C_T d^3} \right)$$  \[Eq.1\]

Using the fluid mass density ($\rho$) of the atmosphere makes it possible to calculate the shear stress ($\tau_{th}$) at a given threshold friction velocity ($u_{st}$). This fluid mass density is given by the relation $\rho = \frac{p m}{\kappa T}$, with the atmospheric pressure ($p$), molecular weight ($m$), Boltzmann-constant ($\kappa$) and temperature ($T$). The threshold friction velocity ($u_{st}$) can be derived from the turbulent wind speed ($u_{RMS}$), which was the measured dependent variable in our wind tunnel simulations (see section 3.3). The particle diameter ($d$) and the particle’s skeletal density ($\rho_{He}$) are known independent variables. The lift ($C_L$), torque ($C_T$) and adhesion ($C_{adh}$) fitting parameters reflect various particle properties in each term of the force balance approach. Fitting eq. 1 to obtained experimental data (for $g = 9.81 \text{ m s}^{-2}$) can therefore be used to predict detachment thresholds on Mars (with $g = 3.71 \text{ m s}^{-2}$).

3. Approach to wind tunnel simulations

3.1 Analogue glass and particle properties

Post-depositional chemical weathering of volcanic glasses on Mars has leached mobile cations and produced a high-silica, almost obsidian-resembling, particle exterior (Horgan and Bell, 2012a). In order to obtain analogue glass grains with a similar high-silica exterior that were also formed in a subglacial volcanic environment, we sampled the volcanic glass formed during the subglacial eruption of the Bláhnúkur volcano in Torfajökull, Iceland (Tuffen et al., 2001; de Vet and Cammeraat, 2012). These fragmental rhyolitic volcanic glasses are characterised by blocky particle morphologies with a low vesicularity of 10-20% and were formed under glaciostatic pressures of 2-4 MPa (Tuffen et al., 2001; Owen et al., 2012). The fresh and unaltered properties make the Bláhnúkur glass a suitable physico-mechanical analogue for determining an upper detachment limit for rolling of glassy sediments on Mars. Samples were collected on recently excavated slopes and eight $\frac{1}{2} \phi$ fractions ≤1200 μm (size-ranges included in appendix G) were extracted according to the soil preparation and sieving protocols of Gee and Bauder (1986). Various particle properties of these fractions were measured for understanding how the variability in the particle properties affects the fitting of the semi-empirical model. In the force balance (Fig. 24, Eq.1) the terms for lift and torque are expected to be influenced by the particle morphology, adhesion is mostly driven by particle surface properties and the composition of the material, whilst the gravitational term can differ as a result of minute mass density variations. Several techniques were therefore used to quantify various physico-mechanical properties. Mineralogical compositions were measured using established techniques (listed below, point 1-2) and we explored other techniques to quantify particle surface properties and shape parameters (points 3-5). This suite of particle property characterisations included:

1. **bulk mineralogy**, using X-ray powder diffraction (XRD) with an x-ray diffractometer and Cu(Ka) radiation. Full scans were made for a 2θ range of 5°-70° at a scan speed of 0.02° 2θ/s. Reflection patterns were analysed and compared using the X’Pert HighScore Plus mineralogical reference database.
2. **major element ratios**, measured by means of spot-measurements using Energy Dispersive X-ray (EDX) at 20.0 keV with a Hitachi S3500N scanning microscope on polished cross-sections of randomly selected glass particles \((n=10)\).

3. **specific surface area** \((S_a)\), measured using adsorption of \(N_2\) (at 77 K) on the particle surface (Rouquerol *et al.*, 1999) with a Thermo Scientific Surfer. The specific surface area per weight-unit was calculated with the BET (Brunauer-Emmet-Teller) 2-parameter equation from the measured isotherm.

4. **skeletal densities** \((\rho_{he})\), obtained using gas displacement pycnometry with a Micromeretics 1305 pycnometer (Bielders *et al.*, 1990) for several repetitions per size fraction \((n=9)\).

5. **shape properties**, measured using the object-based image analysis software eCognition, which segmented microscope imagery of particles into individual polygons using scale, shape and compactness parameters of respectively 50, 0.4 and 0.5. The created polygons were classified and extracted from the imagery \((n=50)\) and automatically described using eight different shape-describing algorithms (Trimble, 2011).

### 3.2 Hypobaric wind tunnel simulations

Wind tunnel simulations with Icelandic volcanic glass were carried out inside the AWTS-I hypobaric wind tunnel, which is described in detail in Merrison *et al.* (2008). A schematic illustration of the wind tunnel is included in appendix F. A horizontal test surface was placed inside the tunnel’s unobstructed airflow to exert a quantifiable shear stress by the flowing wind onto an array of samples. The aim here was to determine the shear stress \((\tau_{thr})\) required for particle removal by measuring the threshold friction velocity \((u_{*ft})\) at a given fluid mass density \((\rho)\). Experiments were carried out for four different fluid mass densities using atmospheric pressures at 240, 480, 920 mbar (where the fluid mass density of the atmosphere doubled with each step) and 1024 mbar using ambient air within a temperature-range of 298-303K. We followed the approach of Merrison *et al.* (2007) where discrete heaps of granular material (‘pellets’) were placed inside the wind tunnel and photographed from above while the wind speed was increased until the material was removed. Pellets with a 10 mm diameter and a 1 mm thickness were created using an aluminium mask to reproduce a consistent volume per pellet. During each wind tunnel run, four different size-fractions (with three replicates, \(n=3\)) were placed on a rough surface to inhibit sliding and to provide a realistic sand bed. We used sand paper with a 45 μm grain-size for the small fractions (≤212 μm) and 254 μm grain-size for the coarser fractions (≥212 μm) to be roughly comparable with the particle diameter. Fractions were evenly distributed across the width of the test section to determine the mean detachment shear stress and to average the ~10% flow gradient due to non-uniformity of the flow inside the tunnel.

### 3.3 Photometry and data analyses

Images of particle removal were pre-processed to reduce noise and preserve pellet edges using a median filter with 15x15 and 25x25 kernels for the two respective substrates. The reflectivity of a pellet was used to evaluate particle removal by extracting the average spectral histogram of the image measured across the pellets (L1) and removing the background in front (L3) and behind (L2) the pellets. A 75 pixel-wide mean around the centre of the pellet was used and the reflectivity was normalised from beginning to full removal by the
wind (steps summarised in Fig. 25). The threshold shear stress ($\tau_{th}$) was then calculated from the measured flow turbulence ($u_{RMS}$) for the condition when >90% of the pellet was removed by the wind using the relation $\tau_{th} = \rho u_{RMS}^2$, where the friction velocity is given by $u_{eff} = u_{RMS} / 2.1$ (Merrison et al., 2008). Based on the force balance (Fig. 24) where particles are positioned on top of particle comparable in size, we used two different surfaces with a comparable particle size to create realistic torque conditions for removal of the last particles in the pellet. A disadvantage of this approach was the need to compensate for a difference in surface roughness ($z_0$) affecting the upwind flow turbulence in the boundary layer when comparing the two surfaces. We therefore added a 212-300 μm reference pellet to the sample array on the fine substrate and a 150-212 μm reference pellet on the coarse substrate. The relative difference between the removal of the two reference pellets on the two different substrates was then used to adjust the observed threshold shear stress of the coarse fractions (>212 μm).

The data analyses for the fitting of the semi-empirical model to the observed threshold data from the wind tunnel simulations consisted of two steps. In the first step, the relation between particle size and threshold shear stress from Eq.1 was evaluated by fitting it to the

Fig. 25 - Steps in data processing for the fine fractions (≤212 μm). From the original photo (A) a grey-scale conversion averaged the three spectral bands and was followed by median-filtering (B). This procedure was repeated for each step-wise increase of the wind speed to obtain the relative reflectance of pellets in each image (C) by extracting the average reflectivity of the image background (L2, L3 in subset B) from the reflectivity measured across the pellets (L1). The reflectance per size fraction was then normalised in order to extract the flow turbulence ($u_{RMS}$) for a 90% detachment threshold (D1-D4). Refer to section 3.3 for further details.
data. Optimal values for $C_T$, $C_L$ and $C_{adh}$ were found by applying a nonlinear weighted least-squares criterion using the nls function in R (R Development Core team, 2011), which uses the nl2sol algorithm (Dennis et al., 1981). In the second step, the unexplained variance was investigated by evaluating relationships between model residuals and the various particle properties of the volcanic glass. Specifically, Spearman correlations between the model residuals and each mean and standard deviation of the measured particle properties (see appendices F and G) were estimated and tested. In case a significant relation between the model residuals and any of these particle properties is found, the material property could be proposed as a parameter for improvement of the semi-empirical model in addition to the particle diameter and particle mass density. Finally, the most significant model is used to predict the threshold for removal by rolling of particles in the surface conditions on Mars.

4. Results

The blocky and low-vesicular morphology of the Icelandic volcanic glass used in the wind tunnel simulations is shown in the focus-stacked microscope images (Fig. 26). The extraction of various shape properties with eCognition (appendix G), identified minute variations in shape for the eight size fractions. Increasing trends for the elliptic fit, radius enclosed ellipse and rectangular fit with particle diameter were found, while decreasing trends of the asymmetry, border index, radius inclosing ellipse, length/width ratio and roundness with particle diameter occur (mathematical definitions can be found in Trimble, 2011). The gradients in particle shape suggests that the angular and asymmetric silt and fine-sand sized fractions differ in shape compared to more rounded and blocky large fractions, but the variability in shape also created a large standard deviation from these trends.

Skeletal densities of the individual size-fractions had a pronounced non-linear relation with the particle diameter (Fig. 27) that is indicative of the presence of vesicles and closed-porosity and, to a minor extend, small compositional differences. The latter was evidenced by EDX measurements of the major element ratios in individual glassy particles (appendix H). Most notable are the high carbon levels that are indicative of dissolved carbon dioxide in these hyaloclastites. The bulk mineralogy of the material was dominated by a broad reflection features extending from $2\theta = 15^\circ$-$40^\circ$, which is consistent with amorphous volcanic glass (Fig. 28). Only minor sharp features on top of the refractograms indicate the low abundance (<10%) of primary feldspathic minerals such as anorthite and albite. The contribution of these crystalline particles varies with particle diameter and is below the detection limit for some size fractions.

A particle property of relevance for the adhesion term in the force balance is the specific surface area. Isotherms of $N_2$ sorption (Fig. 29) show so-called type-II isotherms (Rouquerol et al., 1999), which are characteristic for a weak interaction of the adsorbent with the amorphous particle surface. Although these type-II isotherms did not allow us to differentiate between a non-porous or macro-porous surface, macroporosity (>50 nm) is expected to result from outgassing of the magma and fracturing of the volcanic glass. This in turn affects the shape, surface roughness and friction between particles that relates to the shape parameters with particle diameter. BET-2 parameter fitting of the data indicates that the fractions have small specific surface areas (Fig. 27), ranging from 1.51 m$^2$/g for the smallest fraction (<63 μm) to 0.53 m$^2$/g for the largest fraction (850-1190 μm). These measurements illustrate that surface properties do not scale predictably with $d^{-1}$ for particles from a natural environment.
Fig. 26 - Focus-stacked microscope photographs of the volcanic glass used in the wind tunnel simulations. Small fractions show predominantly asymmetric angular particles considered to be the end-members of particle and vesicle fracturing at the time of the subglacial formation (a-d). The mid-range fractions (c-e) have the largest skeletal densities >2.34 g cm⁻³ whereas vesicularity and closed porosity (gas bubbles trapped inside particles) are more dominant at the larger fractions (f-h). Scale bar applies to all images.
The removal of the small heaps of sand in the wind tunnel simulations showed a threshold-dominated response when pellets are subjected to wind shear (Fig. 25). Heaps of volcanic glass were typically removed in only two or three steps by which the wind speed was increased. The evolution of the pellet diameter (Fig. 25c) showed that detachment of the 63-75 μm fraction is an exception and spans several steps in wind speed. A comparison of the 4 obtained thresholds clearly illustrated that higher friction velocities ($u_{*\text{ft}}$) are required in environments with lower atmospheric pressures due to the lower fluid mass density (Fig. 30), as $u_{*\text{ft}} = (\tau/\rho)^{0.5}$.

A more convenient comparison of thresholds in different atmospheric pressures was shown by the shear stress that normalises the observed thresholds for the fluid mass densities (Fig. 31). Good agreement was seen between the threshold measurements made at four different pressures once plotted against shear stress. A fit of the semi-empirical model to the observed threshold shear stress (blue line, Fig. 31) was achieved by imposing non-negativity bounds on all three fitting parameters ($C_T$, $C_I$, and $C_{\text{adli}}$). The lower detachment threshold for the <63 μm fraction is presumably caused by low-density dust aggregate formation and to a minor extent by artefacts in image processing resulting from non-removable silt between the grains of the used grit paper (Fig. 25). A weighted least-squares scheme was therefore used, where the weight for the <63 μm size-fraction was set to 1% compared to the weights for the other size-fractions due to the ‘unrepresentativeness’ of the threshold (relative to the model in Eq.1) at this small size-fraction. The resulting fitting parameter values produced a significant fit to the data. The parameter values are listed in Table 5 (fifth column). A residual analysis, using the Spearman correlation between the model residuals and the measured material properties, did not lead to the identification of any pattern in the residuals that could be explained by the measured grain properties. The analysis for example showed no significant correlation

![Fig. 27](image.png)

**Fig. 27** - Non-linear variations of the skeletal density ($\rho_{\text{He}}$) and specific surface area ($S_a$) of the particles measured using N$_2$ sorption for each of the size fractions. Horizontal error bars reflect the ½ φ sieving steps used to separate the Icelandic glass samples into usable fractions (Gee and Bauder, 1986).
Fig. 28 - XRD powder diffraction patterns from 10°-45° 2θ at a scan speed of 0.02° 2θ/s, given for four of the eight volcanic glass fractions and industrial glass beads for reference purposes. Reflection patterns are offset by 300 counts for comparison and d-values (in Å) are given for the most prominent features and highlight the low abundance of crystalline particles in the amorphous matrix of the used volcanic glass.

Fig. 29 - Isotherms of the N₂ sorption on the volcanic glass surface. Isotherms were used to determine the specific surface area (Sₐ) for each of the size fraction used in the wind tunnel simulations. A larger adsorbed volume (at low relative pressures) equals a larger specific surface area. The desorption isotherm for the <63 μm fraction is given as a reference.
coefficients for the morphological variables ($n=8$) or the mineralogical variables ($n=5$). When assuming a real correlation of 0.6 and a significance of 0.05, the power of these analyses is low: 0.33 for the morphological variables and 0.16 for the mineralogical variables. After the residual analysis the semi-empirical model was used without any modification with the newly found values for the fitting parameters to predict the threshold for rolling of volcanic glass particles on Mars (Fig. 32). A comparison of the detachment threshold is also given for the spherical glass particles from Merrison et al. (2007), which shows that the differences between the threshold of irregular-shaped volcanic glass and spherical glass particles are quite significant and most pronounced for particle diameters <200 μm.

5. Discussion

5.1 Volcanic glass on Earth and Mars

Parallels in formation processes of volcanic glass during glaciovolcanic eruptions on Earth and Mars make it possible to use Icelandic volcanic glass as analogue material. While Wilson and Head (2007) show that subaerial eruptions in low atmospheric pressures create highly vesiculated materials, Horgan and Bell (2012a) argue, based on geographic occurrence, abundance and possible emplacement mechanisms that the detected glass deposits on Mars may have been formed by magma-ice interactions during sub-ice eruptions. Explosive fragmentation during such magma-ice interactions does not take place under low atmospheric pressure and the formation of glassy eruption products is therefore controlled by the glaciostatic pressures of the overlying ice body (e.g. Tuffen, 2007; Jakobsson and Gudmundsson, 2008). The glaciostatic pressure ($p_{\text{ice}}$) is given by $p_{\text{ice}} = \rho_{\text{ice}} \cdot g \cdot h$, with $\rho_{\text{ice}}$ the ice density.

Fig. 30 - Threshold friction velocity $u_{*,0}$ (m s$^{-1}$) for removal of volcanic glass by rolling under hypobaric pressures of 240, 480, 920 and 1024 mbar. For Mars these pressures are purely palaeobarometric in nature, but they served as four independent experiments for fitting of the semi-empirical model to the calculated shear stress (a value independent of the atmospheric density, see Fig. 31). Note the ‘flat’, horizontal threshold for removal of particles >150 μm.
density, \(g\) the gravitational acceleration and \(h\) the overlying ice thickness (also see appendix D). Based on glacier reconstructions using the summit heights of Martian tuyas (Fagan et al., 2010) and ice densities of 1220 kg m\(^{-3}\) (e.g. Zuber et al., 2007), eruptions on Mars may have occurred under glaciostatic pressures of 0.2–9 MPa. This range is comparable to the pressures of 2–8 MPa under past Icelandic ice sheets of 255–960 m thick with ice densities of 850 kg m\(^{-3}\) (Licciardi et al., 2007). While variability may occur depending on the conditions under the glacier, physico-mechanical particle properties of Martian volcanic glass are generally comparable to glassy materials in Iceland, as others have proposed before (e.g. Allen et al., 1981; Bishop and Pieters, 1995; Chapman and Tanaka, 2002).

### 5.2 Evaluation of threshold models

Models are widely used for describing and predicting aeolian processes on Earth and the other terrestrial planets (Bagnold, 1954; Iversen and White, 1982; Greeley and Iversen, 1985). Recent developments in the field of aeolian studies show that simple boundary layer models are incomplete as turbulent processes occur with different dependencies on physical parameters such as the particle properties discussed in this work (Ibrahim and Dunn, 2006; Nino et al., 2003). Simple standard models of Iversen and White (1982) and Shao and Lu (2000) do not account for such dependencies and are also based on sparse empirical measurements that validate their results. Compared to these studies, some differences in the magnitude of thresholds are found with our work in the form of an offset on the vertical axis. Put in terms of the friction velocity: particles were removed at minimum friction velocities of 0.2 m s\(^{-1}\) in other studies (e.g. Bagnold, 1954; Iversen and White, 1982), while the jagged volcanic glass used here requires a minimum of 0.4 m s\(^{-1}\) (at 1024 mbar, Fig. 30). The systematic offset in friction velocity could be explained by empirical difference in the experimental approach. Specifically due to the different design and type of wind tunnel and the different experimental technique used to determine removal of particles, different approximations have been made for the complex conversion of measured turbulent wind speed into friction velocity (and shear stress) compared to e.g. Greeley and Iversen (1985). The magnitude of friction velocity is dependent on the particle and sand-bed properties, surface roughness and flow turbulence, which in this work differs from previous studies. As the obtained results are realistic values for the removal of these particles, a factor of two difference in absolute magnitude (scaling) of the friction velocity is arguably acceptable based on the experimental approach and considering the inherent turbulent (stochastic) nature of particle removal.

Models developed by Iversen and White (1982), Greeley and Iversen (1985), Shao and Lu (2000) and the model in this study are all semi-empirical in nature and fitting parameters in these models can therefore be adjusted to fit any new data set for different materials. This has to occur within the predefined bounds of fitting parameters to obtain physical results for valid application. In order to evaluate the goodness of the obtained model fit in our study, we conducted a residual analysis where the residual of our null-model was related to the residuals in the model fit and the available compositional, particle surface and shape properties of the volcanic glass. Only univariate correlations between model residuals and the particle properties were considered due to the available sample size in our study. This approach was motivated by the structure that was observed in the residuals of the model fit in Fig. 31; an under-estimation in the 200–400 \(\mu\)m particle range while the model slightly over-estimates the observations at the remaining particle diameters. We therefore aimed at determining if the variability in particle properties could explain the observed structure in the residuals.
of the model fit. It turned out that none of the correlation coefficients differed significantly from zero. As the significant model fit is not dependent on the variation in particle properties per particle diameter, the obtained fitting parameters for \( C_T \), \( C_L \) and \( C_{adh} \) are therefore valid for describing the wind-induced removal of irregular-shaped volcanic glass. The obtained fitting parameters are also comparable to what Merrison et al. (2007) found for spherical particles. The torque is of a similar magnitude and the lift parameter is a factor of 8 higher but still reasonably close to the predicted range of 1–10. The adhesion term differs by a factor of 16 compared to spherical glass particles, but the high value is within the expected range of \( 10^{-5} \)–\( 10^{-4} \) N m\(^{-1} \) (Merrison et al., 2007).

While our results conform to other studies and the values of the fitting parameters fall within the predicted ranges (Table 5), it is also evident from Fig. 32 that there are clear differences in threshold scaling compared to spherical glass particles that can be attributed to the effects of the different particle properties. The most pronounced difference of the threshold compared to spherical particles occurs for particles <212 μm, where adhesion is much more important in the force balance due to the smaller particle mass. In this size range the adhesion force can be up to 100 times stronger than the gravitational force from the particle’s weight and thresholds therefore depend largely on the properties of the particle surface (Shao and Lu, 2000). The simplified adhesion term in the used model may benefit from further parameterisation to explain the observed difference in the thresholds of irregular and spherical particles. The specific surface area (\( S_a \)) could potentially be a powerful proxy for adhesion properties as it depends on the particle’s surface roughness, which in turn results from the surface microtopography from asperities, macroporosity and micro-fractures. Such surface properties have a considerable influence with decreasing particle diameter on the adhesion and pull-off forces required for particle mobilisation at the threshold condition (Jones et al., 2002; Katainen et al., 2006).

We expect that if particle properties could be varied independently for different samples of glass particles, a better parameterisation could be found for the fitting parameters in order to filter out the effects of specific particle properties on each of the terms in the force balance. Alternatively, if collinearity between different particle properties appears to be inevitable, collecting a much larger sample size may also help to achieve improvements in the parameterisation. Further experimental simulations and research will thus be required to enhance our understanding of the interrelationship of fluid thresholds that include rolling and the physical particle properties of natural materials. This requires wind tunnel simulations where the particle diameter is varied independently from the (relevant) adhesion and shape

### Table 5 - Parameter values for \( C_T \), \( C_L \) and \( C_{adh} \) of Eq. 1 with the predicted range from theory and measured values for spherical glass particles (Merrison et al., 2007). The last columns give the least squares parameter estimates for the model fit in this study to threshold data for volcanic glass, with DoF = 29, \( R^2 \)-adjusted = 0.030.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Predicted range</th>
<th>Spherical glass</th>
<th>Volcanic glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_T )</td>
<td>-</td>
<td>1–10</td>
<td>1.45</td>
<td>11.04</td>
</tr>
<tr>
<td>( C_L )</td>
<td>m(^{-1} )</td>
<td>*</td>
<td>4.4\times10(^4)</td>
<td>4.382\times10(^4)</td>
</tr>
<tr>
<td>( C_{adh} )</td>
<td>N m(^{-1} )</td>
<td>10(^{-5})–10(^{-4})</td>
<td>2.7\times10(^{-5})</td>
<td>3.383\times10(^{-4})</td>
</tr>
</tbody>
</table>

* lacks a relevant experimental framework to define a range
parameters with sufficient independent replicates. While such well-constrained materials are not readily available, natural particles with a suitable variety in physical properties could be obtained from edifices with different subglacial eruption conditions, as currently found in Iceland.

Overall, no evidence results from our experiments and residual analysis that, in addition to average particle diameter and mass density, other particle properties are required for describing thresholds that include rolling at the fluid threshold. The semi-empirical model of Merrison et al. (2007), originally developed for wind removal of spherical glass particles, is therefore also valid for describing the threshold of natural glass particles and predicting the removal in the environmental conditions on Mars.

5.3 Particle removal by rolling and the application on Mars

Detachment thresholds measured in our experiments are 'flat' (the curves approximate the horizontal) for larger particle diameters and scale independent of the particle diameter (Fig. 30). This threshold behaviour from around >150 µm agrees with what is expected for fluid thresholds that include detachment by rolling and it is unlike the threshold scaling for saltation that is dominated by lift (e.g. Greeley and Iversen, 1985; Shao and Lu, 2000). This is also illustrated when our model is used to simulate detachment by only lift (with $C_T = 0$), which then causes the model to explain the observed data very poorly (Fig. 31, thin blue line). As expected, Eq.1 gives

![Fig. 31](image-url) - Shear stress required for detachment of volcanic glass by rolling. Measurements of removal in the wind tunnel are plotted against the shears stress under four different atmospheric pressures and are modelled by the best fit (solid blue). The importance of rolling in explaining the flat, horizontal threshold is illustrated when the torque term in the model fit is set to zero (dashed blue) and by the inability of saltation models (dashed black) to fit well to the data for the larger particle diameters (>150 µm). Thresholds are given for a 1g (9.81 m s⁻²) environment and error bars on the x-axes of these figures show the steps of ½ φ sieving (Gee and Bauder, 1986), while the error bars on the y-axes reflect the step size in the wind speed between two consecutive photos.
the same result as other saltation models when the torque from aeolian drag is excluded (Fig. 31, upper dashed line). Using the same method to find the best parameter fit of Eq.1, we also fitted Shao and Lu’s model \( \tau_{\text{thr}} = \rho \cdot Y_1 \cdot d + \frac{Y_2}{d} \) (where \( Y_1 \) and \( Y_2 \) are empirical fitting parameters) to obtain the best fit to the data with \( Y_1 = 188, \frac{Y_2}{d} = 2.4 \cdot 10^{-5} \) (or \( A_N = 0.099 \) and \( \gamma = 2.94 \cdot 10^{-3} \) in Shao and Lu’s less-simplified model). The relative goodness of fit (AIC) of this saltation model is much lower than a model fit that includes rolling (AIC values of 472 vs. 443, where a difference of 2 is already significant; Burnham and Anderson, 2002). Saltation models can therefore be rejected as an alternative explanation for the observed ‘flat’ threshold data for larger particle diameters. The fact that the minimum threshold in the best saltation model fit has been shifted so far to larger particle diameters, requiring a much bigger relative adhesion force to achieve this, is in itself also an indication that a different removal process is occurring. This strongly supports the interpretation that spherical and jagged volcanic glass particles are indeed removed by rolling above diameters of ~150 µm and it allows our model to be used for predicting this behaviour.

The modelled detachment threshold on Mars (Fig. 32) predicts a minimum shear stress of 0.09 N m\(^{-2}\) to permit rolling of volcanic glass with a mass density of 2.34 g cm\(^{-3}\). The highest known friction velocities of 2-4 m s\(^{-1}\) on Mars (Sullivan et al., 2005; Parteli and Herrmann 2007a, 2007b; Kok et al., 2012) are capable of producing shear stresses of 0.08-0.3 N m\(^{-2}\). The obtained threshold values fall within this range and existing surface winds can therefore mobilise these particles. The threshold also allows us to assess the variability in shear stress required for detachment of volcanic glass. The lower limit of this range is given by the model...
fit from Merrison et al. (2007) for the removal of non-cohesive spherical particles that detach most easily. The upper limit is given by the data from this work that defines the upper threshold for a material that is mobilised with more difficulty due to the irregular particle properties. This variation in thresholds (solid area, Fig. 32) is applicable to a wide variety of glassy materials that includes everything between the well-rounded particles observed in certain aeolian sediments (Sullivan et al., 2008; Goetz et al., 2010) and fresh volcanic glass that has undergone little modification from aeolian abrasion. While there is still some debate on the exact diameters of saltating particles (Kok et al., 2012) we find evidence for wind-induced mobility of larger sandy particles in ripples and dune systems (e.g. 700-1800 µm particles observed in the ‘Eldorado’ outcrops, Sullivan et al., 2008) by rolling at threshold conditions that are roughly comparable to those of smaller particle diameters (~200 µm). Larger grains in surface sediment can therefore still play a role in present-day aeolian processes, rather than reflect the deposition in past climates (Sullivan et al., 2008).

Various other processes have also been proposed for explaining the behaviour of aeolian sediments on Mars. Current resolutions of global circulation models are unable to accurately simulate the much higher winds that are created by topographic forcing of the wind flow and convective processes (Fenton and Michaels, 2010). Favourable winds at the fluid threshold may thus occur very locally and this is probably part of the solution of the saltation paradox (Kok et al., 2012). Other mechanisms for aeolian activity focus on the emission of dust and include processes that are based on thermal gradients from solar insolation, ‘thermophoresis’ (Wurm et al., 2008), and electrostatic interactions that lead to low-density dust aggregates that are easily detached by modest winds (Merrison et al., 2007, 2011; Sullivan et al., 2008; Bridges et al., 2010). Emerging views on sand mobility also propose favourable effects of grain electrification on particle trajectories and increased sand fluxes, but still have to be studied in further detail (Renno and Kok, 2008; Rasmussen et al., 2009). Other effects dependent on the mobilisation history of an aeolian system, or hysteresis, may be suitable too for explaining particle mobility at lower friction velocities (discussed in more detail by Kok, 2010a). While these processes are viable for explaining the high sand fluxes on Mars, they are based on a state in which particles are already set in motion. We consider the contribution of rolling vital for the initial mobilisation of sediment by surface winds on Mars. As a rolling particle gains kinetic energy, it becomes easier to entrain it into the turbulent flow. Nickling (1988) showed that gradual transitions occur from rolling to saltation of particles. On Mars these transitions may play an important role in sediment mobility and as a potential trigger for saltation. The thickness of the laminar sublayer on Mars is beneficiary for the detachment of particles by rolling as the sublayer reduces the contact with flow turbulence to drive saltation. These benefits are only applicable in flow conditions before the onset of saltation as the laminar sublayer will most probably be disturbed when saltation starts and vertical mixing between the two layers occurs (Kok et al., 2012).

In this study we have focussed primarily on the quantification of the detachment threshold for removal of larger sand-sized particles by rolling in turbulent flow conditions. As our experiments in the hypobaric wind tunnel did not fully simulate the effects of the laminar sublayer, further research into the behaviour of particles inside a well-developed laminar sublayer (one that is several times thicker than the average particle diameter) may be vital for characterising the full contribution of rolling in aeolian systems on Mars.
6. Conclusions

The paradox of saltation on Mars draws much attention but so far lacks a mechanistic framework for achieving saltation from an idle state at the fluid threshold. In this experimental study we focussed on the contributions of rolling as a possible means for mobility of coarser sediments at lower fluid thresholds than saltation. Glassy materials were recently identified as an important constituent of sand dunes and other aeolian sediments on Mars. We therefore used an unaltered, fresh volcanic glass from Iceland to experimentally determine an upper threshold for wind-induced detachment for this type of sediment. Observed removal of large particles in wind tunnel simulations was not consistent with saltation thresholds and it was only well-explained by rolling. As the particle properties in glass-rich sediments on Mars may vary from fresh (angular) to highly abraded (spherical), depending on their eruption age and transport history, we were able to delineate the possible variation in detachment threshold of glass-rich sediment on Mars. We showed that a large size-range and morphological variety of particles can be removed by rolling at the fluid threshold in winds that occur in the present surface environment. Due to the thicker laminar sublayer, rolling from aeolian drag may also be much more important on Mars if compared to Earth. It could therefore by a viable process that contributed to the recently observed aeolian mobilisation of sands.

Box 2

Atmospheric density and buoyancy effects

Physical models and experiments are important didactic tools in education. For atmospheric density, a compelling experiment is the Dasymeter (‘Daah-zea-meter’) that was invented in 1650 by Otto von Guericke. The experiment consists of a light-weight glass sphere that is suspended on a balance for showing the principle of Archimedes in gasses. A counterweight is shifted along the arm to reach equilibrium with the buoyancy forces acting on the sphere immersed in the atmosphere. Inside a vacuum the reduced gas density decreases the buoyancy forces that act on the sphere, thereby offsetting the balance. ESA-astronaut Tim Peak took a Dasymeter with him during the NEEMO 16 mission on board the Aquarius dive station off the coast of Key Largo (Florida, USA). The experiment was part of the ‘Science Under Pressure’ programme where followers were challenged via social media to hypothesise about the outcomes of the experiment. The experiment in the denser 2.5 bar atmosphere illustrated how the buoyancy increases in the denser atmosphere. Similarly, the lift term \( F_L \) in Eq.1 also incorporates buoyancy effects for particle detachment. •

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Fig. B3 Equilibrium position 1 bar, ‘topside’

Fig. B4 Equilibrium 2.5 bar, inside Aquarius